PRESENCE OF TYRRELL SEA WATER IN DEEP GROUNDWATER NEAR JAMES BAY, ONTARIO

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ABSTRACT
Samples of deep groundwater in an area about 100 km west of Attawapiskat in Northern Ontario suggest that infiltration of water from the Pleistocene-age Tyrrell Sea that inundated this region about 8,000 years ago was extensive -- to depths as great as 200 m -- and not limited to the shallow coastal marsh areas of Hudson Bay and James Bay. Results of stable isotope ratio analyses indicate a strong relationship between chloride (salinity) and isotopic composition. Projecting the relationship between chloride and ^{18}O to the isotopic composition of Vienna Standard Mean Ocean Water (VSMOW), it is deducted that the chloride concentration of the Tyrrell Sea water was about 15,000 mg/L. The sodium chloride-dominated water is distinctive both in major ion composition and isotopic signature from another high salinity water that is dominated by calcium chloride and occurs in the low permeability crystalline basement (Canadian Shield) rocks that occur at depths of about 300 m.

RÉSUMÉ
Des prélèvements de nappes phréatiques profondes dans une region se trouvant à environ 100 km à l'ouest d'Attawapiskat dans le nord de l'Ontario suggèrent que l'infiltration d'eau en provenance de la mer Pléistocène Tyrrell qui a inondé cette région il y a 8 000 ans a été étendue (jusqu'à 200 m de profondeur) et ne s'est pas limitée aux marécages côtiers peu profonds des baies d'Hudson et de James. Les résultats des analyses de ratio d'isotopes stables indiquent une forte relation entre le chlorure (salinité) et la composition isotopique. En se basant sur la projection du rapport entre le chlorure et le ^{18}O sur la composition isotonique du Standard de l'eau océanique moyenne de Vienne (VSMOW), il est déduit que la concentration en chorures de l'eau de la mer de Tyrrell est d'à peu près 15 000mg/L. L'eau dominée par le chlorure de sodium se distingue par sa composition ferrique importante et sa signature isotopique d'autres eaux à haute salinité dominées par le chlorure de calcium et rencontrées dans les roches cristallines peu perméables du socle du Bouclier Canadien, à environ 300 m de profondeur.

1. INTRODUCTION

A portion of the James Bay Lowlands located approximately 100 km west of the community of Attawapiskat (Figure 1) is the site of several Jurassic-age kimberlites (Kong et al., 1999), including the Victor kimberlite that is currently in the pre-production stage of mine development. As part of the design and permitting requirements for the Victor project, a series of studies were undertaken to understand the hydrogeologic and hydrogeochemical conditions at the Victor Site.

The Victor site is underlain by approximately 275 m of Silurian- and Ordovician-age carbonates, mudstones, and sandstones of the Hudson Bay Platform. This Paleozoic sequence disconformably overlies Precambrian granitic rocks, and in turn is overlain by approximately 5 to 30 m of Holocene (7,000 to 8,000 years old) glacial till, glacio-fluvial and glacio-lacustrine deposits, marine clays, and peat (Figure 2).

Wisconsinan glaciation retreated about 13,000 years ago, leaving behind a marine incursion -- the Tyrrell Sea -- that began in this area about 8,000 years ago (Craig, 1968; Price and Woo, 1988). Since that time, the land has rebounded from the glacial loading at an average rate of about 1 m per century. The study area lies at an elevation of about 80 m above mean sea level between the Attawapiskat and Nayshkootayaow Rivers. The terrain is very subdued, with less than about 10 m of relief in the broad area between the rivers. The rivers have cut down through the limestone bedrock, forming cliffs as high as 30 m.

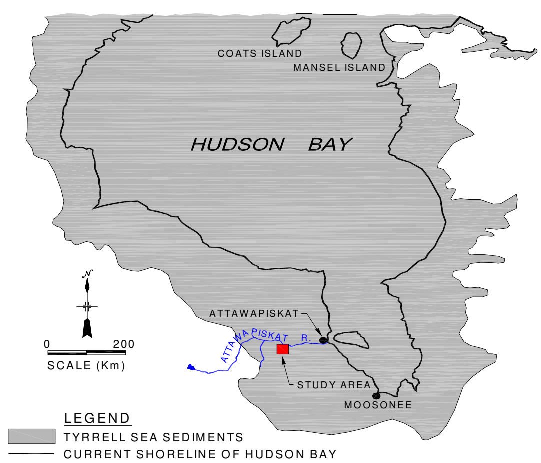

Figure 1. Location of study area showing maximum extent of Tyrrell Sea

The shallow groundwater levels are generally very near ground surface, whereas water levels in piezometers screened near the bottom of the Paleozoic section and in the crystalline basement are generally a few meters above ground surface.

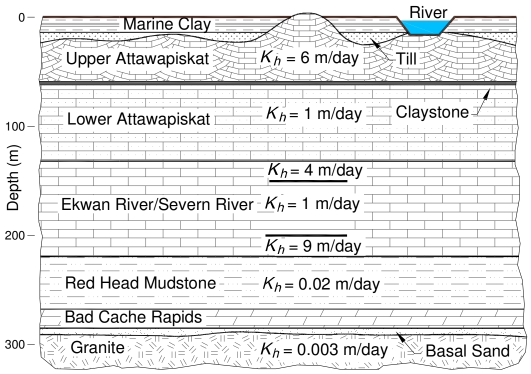

Figure 2. General hydrostratigraphy and mean values of horizontal hydraulic conductivity

2. HYDROSTRATIGRAPHY

Precambrian granite and gneiss of the Superior Province comprise the basement rocks in the area. Short-term packer-injection and airlift-recovery tests in the upper portion of these crystalline rocks indicated horizontal hydraulic conductivity (K_h) values of less than 3 x 10^{-3} m/day, the lowest hydraulic conductivity of any of the hydrogeologic units in the area

2.1 Ordovician Sedimentary Rocks

Rocks of the Mid-Ordovician Bad Cache Rapids Group lie disconformably over the granitic basement. The base of the Bad Cache consists of 0 to 5 m of sandstone lying upon the eroded surface of the granite. The remainder of the Group in this area consists of about 12 to 15 m of thin- to medium-bedded, carboniferous dolostones with thin black shale interbeds. Based on limited packer tests, the entire Bad Cache Rapids unit, including the basal sand, has a K_h of about 1 x 10^{-2} m/day. The Churchill River Formation, which overlies the Bad Cache Rapids Group beneath much of the Hudson Lowlands, has not been differentiated in drill cores from the study area (HCI, 2004).

Rocks of the Ordovician-age Red Head “mudstone” lie disconformably upon the Bad Cache Rapids Group and represent a second marine transgression. The unit in this area consists of bright red and green to grey, interbedded limey shales, limey siltstones, and poorly sorted silty sandstones. Anhydrite fills both high- and low-angle veins in the rocks. The hydraulic conductivity of the Red Head mudstone unit is generally low, in the range of 1 x 10^{-2} m/day. However, a regionally extensive, 5 to 7 m thick sequence of thin-bedded limestone and friable sand, about 20 m below the top of the Red Head, has an average *K* value based on airlift-recovery tests of about 8 m/day.

2.2 Ekwan River and Severn River Formations

Silurian limestone with minor dolostone and shale lie disconformably upon the Red Head rocks. Both the lower Severn River Formation and the upper Ekwan River Formation rocks are characterized by planar-bedded to massive limestone interbedded locally with thin carboniferous shales and limey siltstones.

The Ekwan River/Severn limestones constitute the principal bedrock aquifer in the study area, with an average hydraulic conductivity across its 86 m thickness of about 4 m/day. The more permeable zones are the thin-bedded limestones and silty limestones at the top of the unit and the fossiliferous limestone near the base.

2.3 Attawapiskat Limestone

The Attawapiskat Formation lies conformably upon the Ekwan River limestone. In this area, the formation includes, informally, upper and lower sub-units separated by a regionally extensive, 2-m thick claystone horizon -- locally referred as the blue-green claystone -- that occurs at a depth of about 50 to 60 m below ground surface. Macro-scale (5 to 20 mm) dissolution voids occur locally, but are sparse and poorly connected. Hydraulic conductivity values measured in packer tests and airlift-recovery tests range from about 0.2 to 4.0 m/day, with an average value of about 1.0 m/day.

The claystone unit between the upper and lower Attawapiskat hydrostratigraphic units might constitute an aquitard with a vertical hydraulic conductivity (K_v) of about 1 x 10^{-3} m/day (HCI, 2006).

Airlift-recovery tests in the upper Attawapiskat limestone yield an average K_h value of about 6.0 m/day.

2.4 Quaternary Deposits

The Quaternary sedimentary cover locally includes a basal till consisting of a very compact, clay-rich matrix with heterolithic, sub-angular to sub-rounded pebbles and cobbles. The thickness of the basal till is highly variable, but averages about 5 m. A clayey, sandy silt, 0 to 20 m thick, occurs above the basal till and contains sparse pebbles and shell fragments. A plastic marine clay -- the Tyrrell Sea clay -- overlies the silts and till everywhere except very locally upon exposed bioherms. This clay averages about 7 to 8 m thick in most areas, but has been found to be as much as 20 m thick within the study area. Sieve analyses indicate the nominal Tyrrell Sea “clay” in this area of the James Bay Lowlands is lean, and many of the samples have more properly been logged as clayey silt (AMEC, 2003). Silty sand (rarely thicker than 1 m) locally overlies the marine clay; these represent beach-ridge deposits laid down with the final retreat of the Tyrrell Sea (Martini, 1982). About 3 m of organic sediments have accumulated above the clay and sand.

3. GROUNDWATER FLOW

Shallow (i.e., in the overburden and upper Attawapiskat limestone) groundwater levels range seasonally from right at the ground surface to a few meters below ground surface. Near and between the major rivers, shallow groundwater can be as deep as 11 m below ground surface, demonstrating good drainage to the deeply incised rivers. There is a slight downward hydraulic gradient between the overburden sediments and the uppermost bedrock (to depths of about 30 to 40 m) beneath much of the area, and this gradient is greatest in the spring and summer. Groundwater levels increase gradually with depth in the lower Attawapiskat and Ekwan/Severn limestones and increase more steeply in the Ordovician rocks of low hydraulic conductivity such that groundwater levels near the crystalline basement contact are generally 3 to 5 m above ground surface. This upward gradient appears to be steepest along the courses of the major rivers.

Local recharge to the bedrock must penetrate the low permeability Tyrrell Sea marine clay or through the exposed bioherms (which make up only about 1 percent of the land surface). Consequently, the average local recharge to the bedrock is estimated to be about 10 mm/year, or about 1.5 percent of precipitation (HCI, 2004). Regional recharge to the groundwater system occurs at exposures of the carbonate and sandstone units at higher elevations about 10 to 100 km to the northwest.

Groundwater flows laterally from northwest to southeast at a gradient of about 0.001 (HCI, 2004). The groundwater flow in the limestone units occurs primarily within fractures, bedding planes, and dissolution features. In addition, some thin sandstones also contribute to the horizontal groundwater flow. Numerous thin, but laterally extensive, interbedded clay units obstruct vertical flow. As a result, the K_h of the carbonates (as well as the underlying mudstones) is much greater than the K_v.

4. WATER CHEMISTRY

Samples of groundwater were collected from monitoring wells installed in the Victor study area primarily by airlift pumping from packer-isolated intervals in coreholes. Additional samples were obtained from any of the flowing wells completed in the deeper units or from wells near the Nayshkootayaow River.

The samples were analyzed for major cations (Ca^{2+}, Na^+, K^+, and Mg^{2+}), major anions (Cl^-, sulphate, alkalinity), and bromide. Stable isotope ratio analyses (SIRA) for deuterium (^2H) and ^{18}O were also conducted.

Waters considered to have high total dissolved solids (TDS) concentrations were classified into two types:

- a sodium chloride dominated water, subsequently referred to as Type 1 water, and
- a calcium chloride dominated water, subsequently referred to as Type 2 water.

Chloride concentrations as great as 6,600 mg/L have been measured in the Type 1 waters. In the Type 2 samples, chloride concentrations have been as high as 3,500 mg/L. The spatial distribution of these two waters is shown on Figure 3.

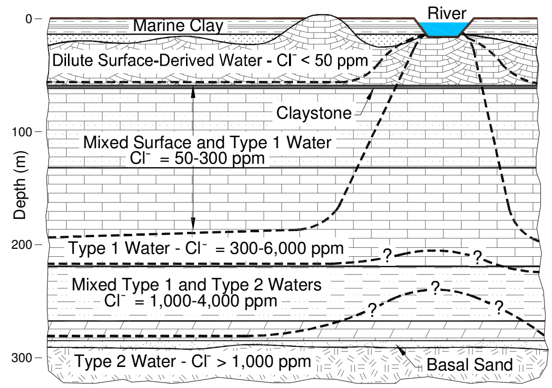

Figure 3. Spatial distribution of Type 1 and Type 2 waters

Stiff diagram "fingerprints" of selected water samples from the Victor study area are shown in Figure 4. On the basis of several factors, the Type 1 water appears to be derived from seawater. First, the chemical fingerprints of several of the Type 1 samples and seawater are very similar. Secondly, the Br/Cl ratios of 0.003 for these samples are essentially the same as the value for seawater of 0.0034 reported by Turekian (1969). To further evaluate this possible seawater origin, a series of mixing calculations were conducted using *PHREEQC* (Parkhurst and Appelo, 1999) in which various proportions of seawater and dilute water were mixed. The result of one of these calculations is included in Figure 4. Based upon these calculations, it appears that the samples of Type 1 water typically have between 10 and 33 percent seawater.

The Type 2 waters have major ion compositions similar to Canadian Shield brines, although much more dilute. In the Type 2 samples, the Br/Cl ratio is commonly 0.009, which is comparable to the value of 0.01 for Canadian Shield brines reported by Frape and Fritz (1987). The isotopic signature, to described below, of this water is primarily from meteoric water; and there has been little evaporation of this water prior to its recharging the bedrock.

The least diluted samples of Type 1 water occur in the lower Ekwan and Severn River limestones, above the contact with the Red Head mudstone (Figure 3). At progressively higher levels within the Silurian section, the groundwater is progressively more diluted. The groundwater is quite dilute (Cl^- < 50 mg/L) in the upper Attawapiskat limestone above the blue-green claystone. Structures that might be associated with the Nayshkootayaow River appear to contain Type 1 water throughout the entire sedimentary section.

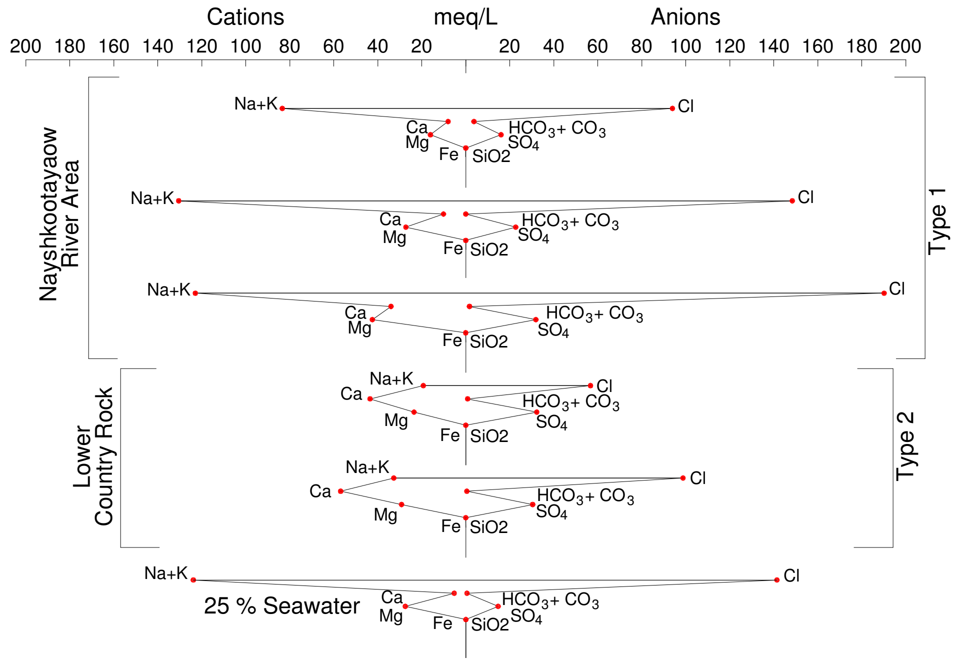

Figure 4. Stiff diagram "fingerprints" of Type 1 and Type 2 waters

Unambiguous Type 2 water occurs in the crystalline basement rocks and lowermost Ordovician rocks (including the basal sandstone). Limited groundwater samples from the Red Head mudstone suggest it comprises a mixing zone of Type 1 and Type 2 waters.

4.1 Stable Isotope Ratio Analysis

SIRA is used to define differences in the average weight of water molecules in different water samples. In most cases, these differences are very slight, typically less than one percent; but even such small differences can provide information on the source of the water molecules. SIRA can also define changes to waters as a result of interactions with rocks and through evaporation.

Stable isotope ratios are normally reported using the δ notation (Clark and Fritz, 1997), where

$$\delta R_{sample}\,(\text{permil}) = \left[\frac{R_{sample}}{R_{std}} - 1\right] \times 1000 \qquad (1)$$

where:

R_{std} = the isotopic ratio (either D/H or $^{18}O/^{16}O$) in Vienna Standard Mean Ocean Water (VSMOW),
R_{sample} = the isotopic ratio in the sample, and

permil indicates in thousandths (or 0.1 percent).

Figure 5 shows the δD and $\delta^{18}O$ values for groundwater samples collected at the Victor site. The figure indicates that both of the waters have a dominantly meteoric water origin, but that the Type 1 and 2 have distinctly isotopic signatures. The Type 2 water is isotopically lighter, suggesting colder conditions during its origin. The Type 1 water is slightly heavier and shows a wider range of δD and $\delta^{18}O$ values. Neither water type appears to contain a significant component of Canadian Shield brines in terms of isotopic composition.

4.2 Estimation of Tyrrell Seawater Salinity

The regression curve in Figure 6 indicates that the Type 1 waters have a strong correlation between their isotopic composition and their Cl concentration with an increase in Cl concentration corresponding to an increase in $\delta^{18}O$ value. When this regression is projected to the $\delta^{18}O$ isotopic composition of Vienna Standard Mean Ocean Water of 0.0 permil, the estimated chloride concentration is 15,000 mg/L. Converting this chloride concentration to a total salinity for standard seawater, a value of 27 g/L (27,000 mg/L) is obtained. This is very near the range of 21 to 25 g/L reported by Price and Woo (1988) for the post-glacial Tyrrell Sea.

The extent of this water is also significant as many of the Type 1 waters are derived from sampling intervals between 100 and 160 mbgl (in the lower Attawapiskat and Ekwan River Formations), and some samples have been collected from depths as great as 215 mbgl (in the Severn River Formation). As previously noted, the deep groundwaters also have artesian heads a couple of meters above the ground surface.

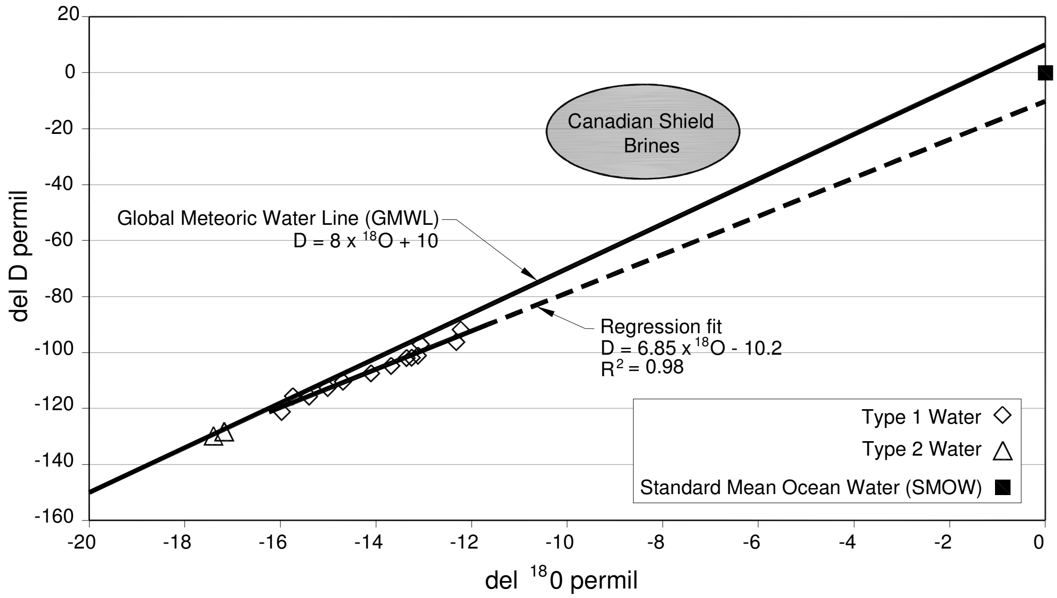

Figure 5. Stable isotope ratios of δD and $\delta^{18}O$ from Type 1 and Type 2 groundwaters

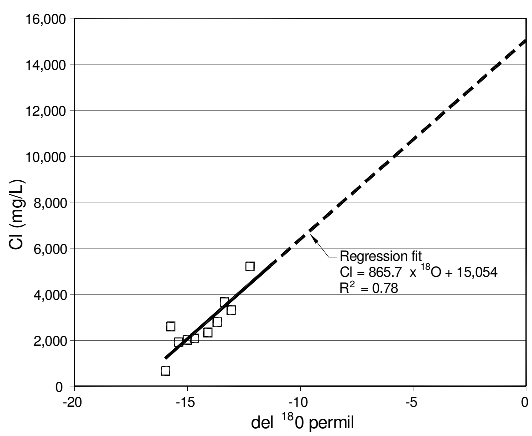

Figure 6. Relationship between chloride concentration and $\delta^{18}O$ value for Type 1 waters

5. CONCLUSIONS

The results of this hydrogeologic and hydrogeochemical investigation suggest that Tyrrell Sea water is not just limited to the shallow coastal marshes near James Bay (as proposed by Price and Woo, 1987), but also extends into deep bedrock strata such as the Ekwan River/ Severn River carbonates at locations more than 100 km from the current shoreline of the bay. Thus, it appears that all of the saline waters in the James Bay lowlands are not necessarily related to Canadian Shield brines. Consequently, simple field measurements such as electrical conductivity will not enable field classification of saline waters. Analyses of major ions, Br, and stable isotopes are required to classify these high TDS waters with any certainty.

The presence of at least two chemically distinct waters at the Victor site provides a means of identifying the possible sources and origins of different waters in the area.

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