Evidence for recent groundwater flow through Late Wisconsinan till near Toronto, Ontario

R.E. Gerber and K.W.F. Howard

Abstract: The Northern till is a thick (~50 m) Late Wisconsinan diamict unit that occurs throughout south-central Ontario. The till has generally been regarded as massive and uniform, with a very low vertical hydraulic conductivity. It is similar to many other till units of mid-continental North American glaciated terrain in that it is believed to inhibit recharge to underlying aquifers and afford a high degree of protection to these aquifers from surface and near-surface sources of contamination. Standard methods of estimating hydraulic conductivity (K) for the Northern till, such as laboratory testing of core samples (other studies) and rising–falling head field piezometer tests (this study and other studies), characteristically yield values on the order of 10^{-11} to 10^{-9} m/s. Typically, these values indicate advective traveltimes through the till on the order of hundreds to thousands of years. In contrast, isotopic evidence (^{2}H, ^{18}O, and ^{3}H) from till pore waters indicates the presence of modern (post-1952) waters at depths of up to 50 m, suggesting either that certain facies of the till are considerably more permeable or that minor sand lenses or hydrogeologically active secondary permeability structures are locally important. In some areas, vertical flow velocities may approach 1 m/year. By comparing pore-water isotopic data from cores acquired using mud (sodium bentonite) and dry rotary methods, this study further demonstrates that representative pore-water samples can be obtained using a drilling fluid providing care is taken in preparing core samples for analysis.

Key words: till, aquitard, permeability, recharge, contaminant transport, isotopes.

Résumé : Le Northern till est une unité diamict d'environ 50 m d'épaisseur du Wisconsin supérieur qui se retrouve à travers le centre sud de l'Ontario. Le till a généralement été considéré comme massif et uniforme, avec une très faible conductivité hydraulique verticale. Il est semblable à plusieurs autres unités de la surface du milieu du continent nord-américain affectée par les glaciers en ce qu'il empêche la recharge des aquifères sous-jacents et offre un fort degré de protection à ces aquifères contre les sources de contamination venant de la surface ou près de la surface. Les méthodes standard pour estimer la conductivité hydraulique (K) du Northern till, comme les essais en laboratoire sur des carottes d'échantillon (autres études) et les essais à charge variable dans des piézomètres sur le terrain (cette étude et d'autres), donnent de façon caractéristique des valeurs de l'ordre de 10^{-11} à 10^{-9} m/s. Typiquement, ces valeurs indiquent des temps de parcours par advection à travers le till de l'ordre de centaines à des milliers d'années. Par contre, une évidence fournie par les isotopes (^{2}H, ^{18}O et ^{3}H) dans les eaux interstitielles du till indiquent la présence d'eaux contemporaines (post 1952) à des profondeurs atteignant 50 m, suggérant soit que certains facies du till sont considérablement plus perméables, soit que de minces lentilles de sable ou des structures de perméabilité secondaire hydrogéologiquement actives sont importantes localement. À certains endroits, les vitesses d'écoulement vertical s'approchent de 1 m/année. En comparant les données d'isotopes provenant de carottes obtenues en utilisant de la boue (bentonite de sodium) ou des méthodes de forage rotatif à sec, cette étude démontre de plus que des échantillons représentatifs d'eau interstitielle peuvent être obtenus en utilisant une boue de forage à la condition que l'on prépare avec soin les carottes d'échantillons pour l'analyse.

Mots clés : till, aquitard, perméabilité, recharge, transport de contaminant, isotopes.

[Traduit par la rédaction]

Introduction

Glacial deposits, including till, cover approximately 13 × 10^6 km^2 of North America (Stephenson et al. 1988). Till deposits are generally perceived as having a very low primary permeability and a low to moderate secondary permeability, the latter limited to depths of less than 15–20 m. The less permeable facies are generally thought to limit the amount of groundwater recharge to underlying aquifers and also provide protection from contaminant sources such as landfills, industrial spills, and agricultural chemicals.

The Northern till is a regional Late Wisconsinan diamict unit in south-central Ontario, which underlies the surficial

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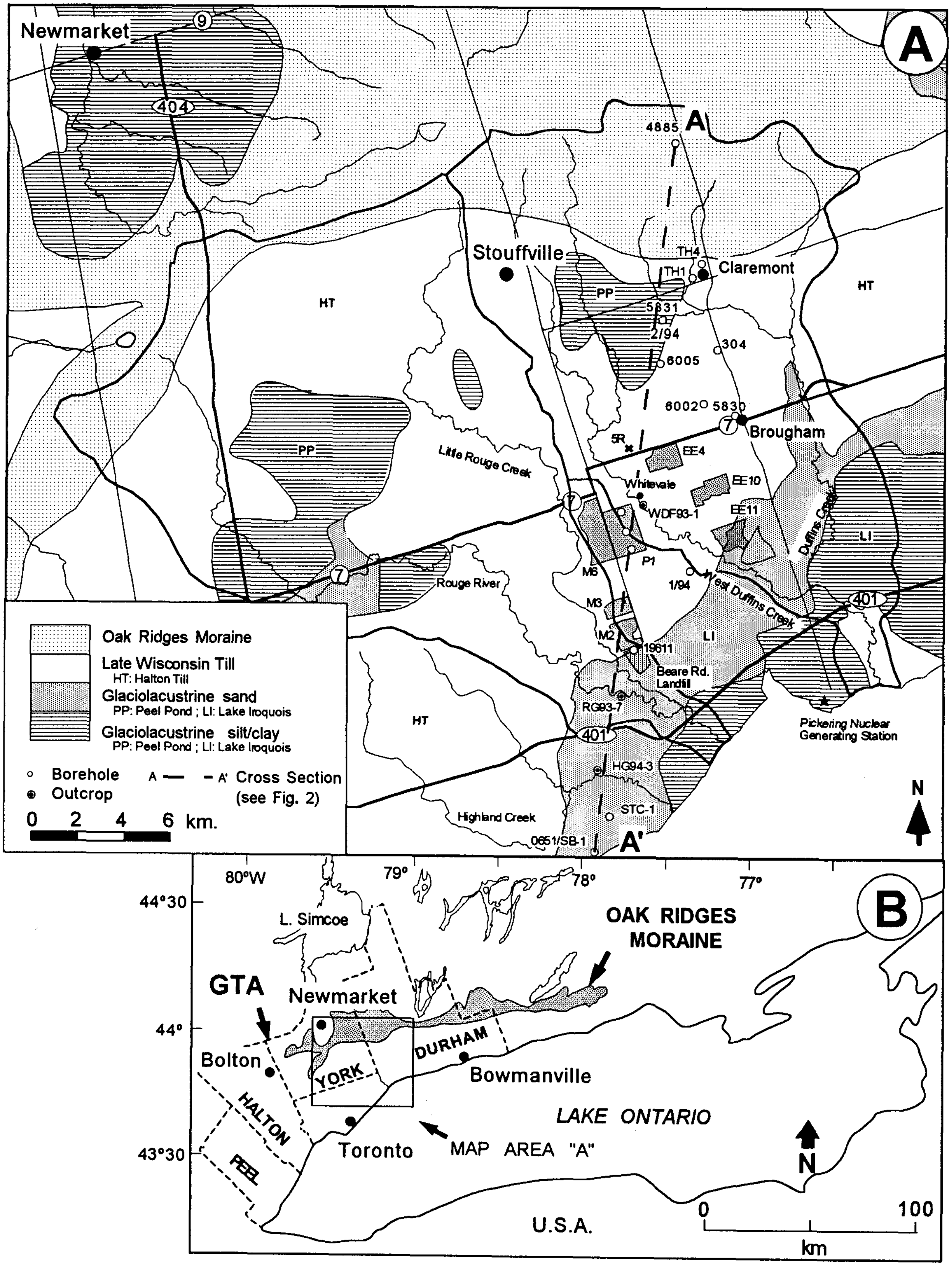
Fig. 1. Study area. Surficial geology from Barnett et al. (1991) and J. Westgate (unpublished data on file with the Ontario Geological Survey).



Oak Ridges Moraine, Halton Till, and glacial Lake Iroquois and Peel Pond deposits (Fig. 1). Many local and regional aquifers are confined by the till, which in places reaches 60 m in thickness (Boyce et al. 1995). Regional hydrogeological studies in southern Ontario have focused on the water resource potential of aquifer units with little attention given to the role of tills (Singer 1974, 1981; Funk 1977; Sibul et al. 1977; Ostry 1979; Vallery et al. 1982). In most studies, the hydraulic behaviour of till deposits is either inferred from aquifer pump tests or determined from grain size analysis of till sediments and slug tests conducted within till units.

Until the early 1980's, tills in south-central Ontario were generally thought to inhibit recharge to underlying aquifers and afford a high degree of protection to these aquifers from surface and near-surface sources of contamination. In 1981, however, a study of the Beare Road landfill (Fig. 1) postulated the existence of fractures in the till to explain the presence of leachate in an underlying aquifer (Hydrology Consultants Ltd. 1981). A few years later, Howard and Beck (1986) suggested that the presence of Ca-HCO_3 groundwaters in deep aquifers within the Duffins Creek drainage basin indicated significant vertical groundwater flow through regionally extensive tills. More recently, several landfill siting studies (sites P1, EE4, EE10, and EE11; Fig. 1) have suggested, based on isotopic and piezometer response data, that the Northern till may be quite permeable (e.g., M.M. Dillon Limited 1990; Interim Waste Authority 1994*a*, 1994*b*, 1994*c*, 1994*d*, 1994*e*). However, because the critical data (isotopes) were obtained from cores and piezometers installed within boreholes that were drilled with a tritiated fluid (Lake Ontario), the results were considered inconclusive. These landfill site investigations initiated considerable debate as to the representativeness of sampling techniques from which the isotopic data were derived, particularly with regard to the use of a drilling fluid. This is of concern, since the high density of the Northern till precludes the use of auger drilling.

In this paper we present the results of recent work to determine the isotopic (^{2}H, ^{18}O, and ^{3}H) signature of pore water within the Northern till. Use of these isotopes will allow the relative age of recharging groundwaters to be established and will provide insight into the bulk hydraulic conductivity of the till. If the bulk hydraulic conductivity (K) of the till is greater than matrix K (i.e., secondary permeability structures are present), then isotopic signatures will be representative of modern precipitation. If the bulk K is equal to matrix K, then modern water will not be present at depth within the till.

The pore-water samples were obtained from the Northern till using both air-drilled and mud-drilled rotary boreholes. Extraordinary measures were taken to maintain the integrity of the samples from a medium that is very difficult to drill and instrument. The mud-drilled boreholes allow the integrity of the mud data set from previous investigations to be evaluated. Contamination of the mud-drilled cores would be indicated by mixing of sample pore waters with a drilling fluid with a distinct ^{2}H and ^{18}O signature (evaporative). The use of air-drilled boreholes prevented contamination by drilling fluid and allowed the integrity of samples derived from mud-drilled boreholes to be determined.

The work was conducted on the Northern till at two sites. Site 1/94 was chosen because of its proximity to numerous isotopic studies of Northern till groundwaters associated with landfill site investigations (sites P1, EE4, EE10, M6, and EE11 shown in Fig. 1). Site 2/94 was chosen to check that conditions at site 1/94 and vicinity are representative of the till on a regional basis.

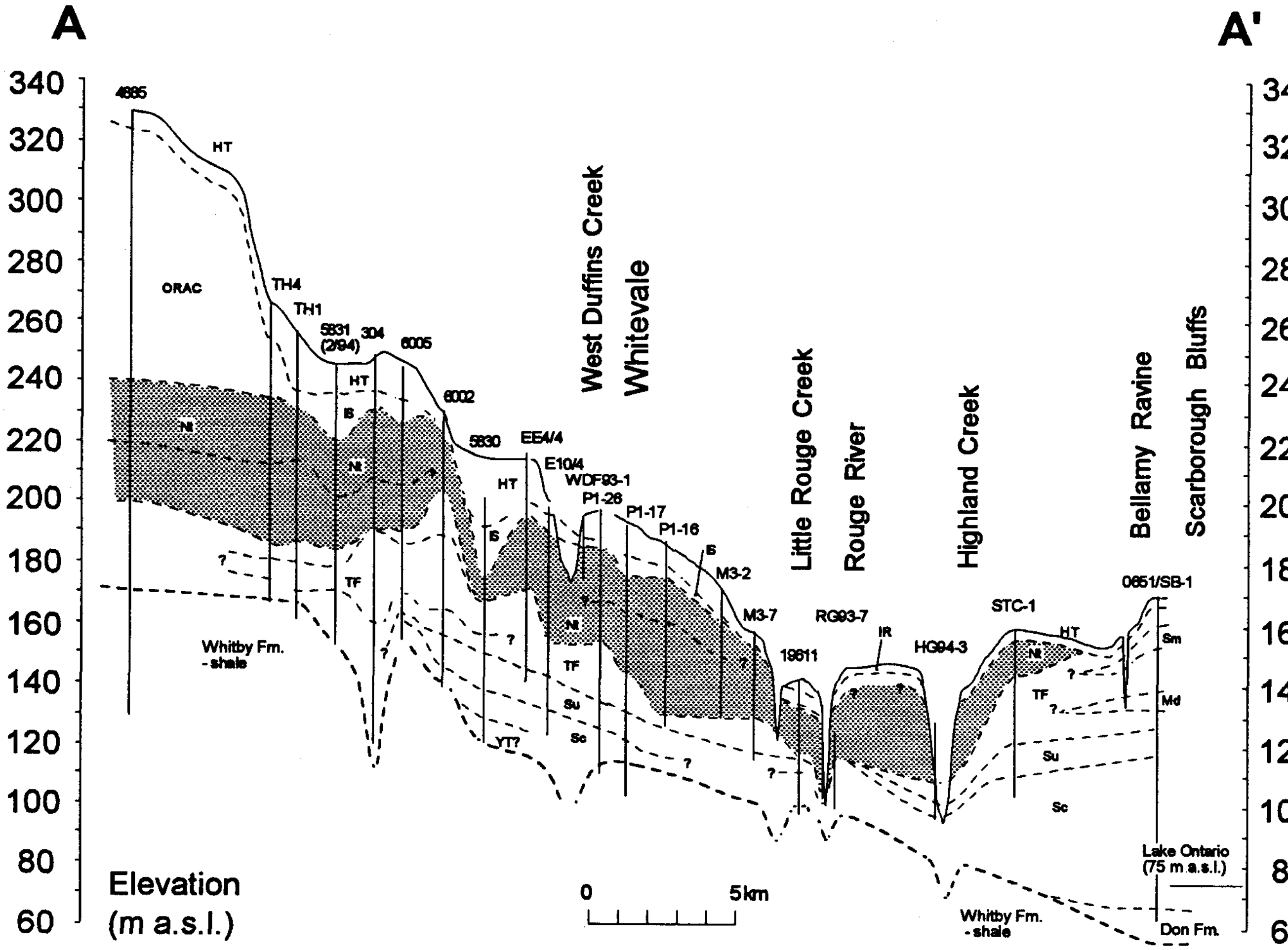
Regional geology and hydrogeology

The Quaternary stratigraphy for the study area has been studied extensively, and the summary presented in Fig. 2 is derived from a wide range of sources (Karrow 1967; Gwyn and DiLabio 1973; Sibul et al. 1977; M.M. Dillon Limited 1990; Barnett et al. 1991; Barnett 1992; Berger and Eyles 1994; Interim Waste Authority 1994*b*, 1994*c*, 1994*e*; Sharpe et al. 1994; and principally Boyce et al. 1995). The Northern till was deposited by the southward-flowing Laurentide ice sheet at the time of its maximum extent and occurs throughout south-central Ontario (Boyce et al. 1995). The Northern till is an overconsolidated, sandy silt to silty sand till (20–54% sand, average 38%; 34–59% silt, average 47%; 7–23% clay, average 15% (M.M. Dillon Limited 1990) with gravel to boulder size clasts of predominantly limestone of local origin and secondary gneiss and granite from a distant shield source. Incorporation and deformation of underlying glaciolacustrine sand, silt, and clay (Thorncliffe Formation) occurs at the base of this till.

The Northern till plays an important role in the hydrogeology of south-central Ontario. Sibul et al. (1977) mapped 14 overburden aquifer systems within the study area. The bedrock is not considered to be a good aquifer. The overburden aquifers are classified as either shallow or deep, with deep aquifers occurring below the Northern till in Middle and Early Wisconsinan deposits of the Thorncliffe and Scarborough formations. Shallow aquifers occur above the Northern till within the Oak Ridges Aquifer Complex and the Mackinaw Interstadial deposits (Fig. 2). The horizontal component of groundwater flow is southward through the study area from the Oak Ridges Moraine towards Lake Ontario, with local deflections in both shallow and deep aquifers toward major creeks and rivers. The Rouge River, Little Rouge Creek, West Duffins Creek, and Duffins Creek are major discharge areas for the shallow aquifers. The vertical component of groundwater movement is generally downwards towards shallow and deep aquifers. Upward groundwater flow from shallow and deep aquifers occurs along river valleys. Groundwater also flows upward along the south flanks of the Oak Ridges Moraine, particularly west of Stouffville (Fig. 1), where the Oak Ridges Aquifer Complex is confined by the Halton Till (Fig. 2) (Sibul et al. 1977). The Oak Ridges Moraine is a major recharge area for both shallow and deep aquifers.

While all aquifers have previously been considered to exist as discrete lenses of permeable sands and gravels within low permeability tills, silts, and clays (Haefeli 1970; Sibul et al. 1977), hydrochemical studies by Howard and Beck (1986) suggest that many of these aquifer systems (shallow and deep) are interconnected regionally and receive a significant component of recharge via the overlying till. This latter conclusion is supported by a regional water balance study (Gerber and Howard 1996).

Fig. 2. Regional north–south cross section. See Fig. 1 for cross section location.



Stage	Unit	Age (Yrs.)	Lithology	Thickness (m)
Late Wisconsinan	Lake Iroquois (IR) Deposits	<12 500	Beach sands, gravels and lacustrine silt and clay deposited in high-level lake.	< 5m
	Halton Till (HT)	13 000	Silty/sandy till interbedded with sand and gravel.	< 25m
	Oak Ridges Aquifer Complex (ORAC)	13 000	Sand and gravel outwash	<100m
	Mackinaw Interstadial (IS)	13 300	Sandy fluvial gravel with lacustrine silt and clay	< 15m
	Northern till (Nt)	13 500-25 000	Silt till	< 60m
Middle Wisconsinan	Thorncliffe Formation (TF)	30 000-45 000	Deltaic sands, lacustrine silt and clay Sm Seminary diamict; Md Meadowvale diamict	< 40m
Early Wisconsinan	Sunnybrook Till (Su)	50 000	Clay till with laminated silty clay	< 20m
	Scarborough Formation (Sc)	70 000	Deltaic sands and glaciolacustrine silts and clays	< 40m
Sangamonian	Don Formation	125 000	Fluvial, interglacial clay and sand	
Illinoian	York Till (YT)	125 000	Sandy, shale-rich till	< 5m
	Whitby Formation	Late Ordovician	Black shale	

Table 1. Summary of piezometer installation details and measured hydraulic conductivity data from this study.

Sand pack		Screen							
Top (m bgs)	Bottom (m bgs)	Top (m bgs)	Bottom (m bgs)	Borehole diameter (mm)	Unit	Piezometer	Piezometer diameter (mm)	*K* (m/s)	No. of slug tests
Site 1/94									
8.2	10.5	8.9	10.5	203	Halton Till	1/94-3	51	7×10^{-7} [a]	2
19.8	22.2	20.7	22.2	203	Interstadial Sand	1/94-2	51	4×10^{-6} [a]	3
30.2	31.7	30.5	31.1	96	Northern till (sand seam)	1/94-4	19	2×10^{-8} [a]	1
41.4	44.1	42.3	43.8	123	Thorncliffe Formation	1/94-1	51	1×10^{-5} [a]	1
Site 2/94									
6.7	9.5	7.5	9.0	203	Interstadial Sand	2/94-4	51	2×10^{-5} [a]	2
11.6	13.7	12.2	13.7	203		2/94-3	51	1×10^{-5} [a]	3
36.8	37.9	37.2	37.8	123	Northern till	2/94-5A	19	5×10^{-11} [b]	—
42.5	43.5	42.9	43.5	123		2/94-5B	19	7×10^{-11} [b]	—
27.8	29.9	28.0	29.6	123	(sand seam)	2/94-1	51	3×10^{-6} [a]	2
60.2	64.8	61.9	63.4	123	Thorncliffe Formation	2/94-2	51	4×10^{-5} [a]	1

Note: m bgs, metres below ground surface.
[a]Hydraulic conductivity (*K*) estimates from slug tests. Average of Hvorslev (1951) and confined or unconfined slug test estimates using AQTESOLV (Duffield and Rumbaugh 1991).
[b]Hydraulic conductivity calculated from recovery to static water level within piezometer installed in dry borehole.

Methods and materials

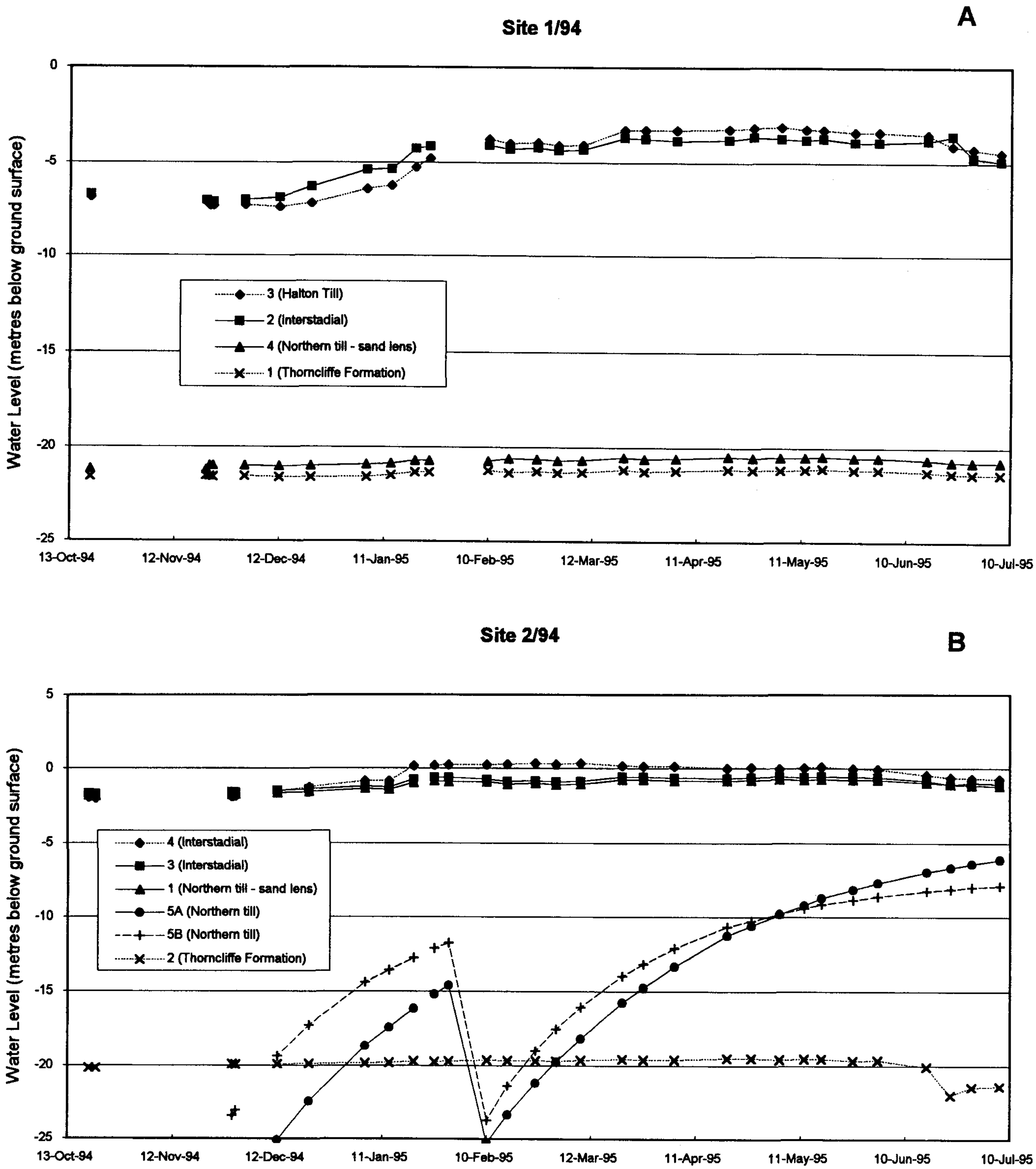
A series of boreholes were drilled at each of two locations (sites 1/94 and 2/94; Fig. 1) during September–October 1994. At least one borehole at each site penetrated the full thickness of the Northern till and was geophysically logged (natural gamma) prior to piezometer installation to help define overburden stratigraphy. For the purpose of borehole construction and to enable data collection, hollow-stem augers were used to provide continuous samples at 1.5 m intervals through the deposits that overlie the Northern till. When the very dense Northern till was encountered, the hole was advanced by hydraulic rotary coring (85 mm diameter core) using either mud or air as a drill bit coolant. Wet, or higher hydraulic conductivity zones (e.g., as observed in the Mackinaw Interstadial deposits and sand seams – boulder pavements within the Northern till), were controlled with cemented casing to prevent water inflow into the borehole. These zones could not be cored by the air rotary method, as clogging of the bit and rods prevented air circulation.

All boreholes were installed with either a 19 mm or 51 mm inner diameter PVC piezometer. The piezometers were constructed of Schedule 80, flush-threaded PVC pipe with rubber O-rings at the joints and a length of commercially slotted PVC screen. Silica sand was placed around the screen intake to a depth of approximately 1/3 to 1 m above the top of the screen. Bentonite pellets were used to form a 1 m thick seal above the sand pack. In some instances, the bentonite pellets were replaced by a fine-grained silica sand if the borehole water was too silty to allow proper pellet settlement. The remaining annulus was filled to ground surface with a bentonite slurry grout (BENSEAL®sodium montmorillonite granular bentonite, AQUA-GROUT™ catalyst, and water) or bentonite gravel. To install piezometers 2/94-5A, 2/94-5B in a dry borehole, 0.3 m of crushed native till was placed between the sand pack and overlying bentonite gravel. This was done in an effort to prevent or delay the possibility of grout migrating into the underlying screened interval, which could have an effect on sample integrity (Remenda and van der Kamp 1996). Piezometer installation details are included in Table 1.

Piezometers were evacuated prior to in situ testing and again prior to sampling. To develop the wells drilled with mud, a minimum of 10 well volumes were removed until the parameters pH, conductivity, and temperature stabilized. Prior to sampling, three well volumes were removed. Wells installed with the air rotary method (2/94-5A and 5B) were not developed prior to sampling because of the slow recovery time (>6 months in 19 mm PVC piezometer; see Fig. 3B). This was not considered important, since installation in a dry borehole is unlikely to cause isotopic contamination of the formation water.

Two types of samples were collected for isotope analysis. Pore waters were extracted from till core samples (hereafter referred to as "pore-water samples"). For control purposes, samples of drilling water and mud were also collected. As the mud rotary boreholes were drilled with tritiated water from Lake Ontario (mean concentration 69–94 TU where 1 TU = 1 ^{3}H atom per 10^{18} H atoms), considerable effort was made to prevent contamination of the pore-water samples. Upon retrieval, till core samples were scraped with a clean dry carpet knife to remove the outer layer (5–10 mm) of the sample in contact with drilling fluid and (or) drilling equipment. Drilling mud, which had formed casts around gravel and cobbles, was also removed. Samples were then sealed in at least three layers of commercial grade shrink wrap before being wrapped in at least two layers of aluminum foil. To obtain sufficient pore water for isotope

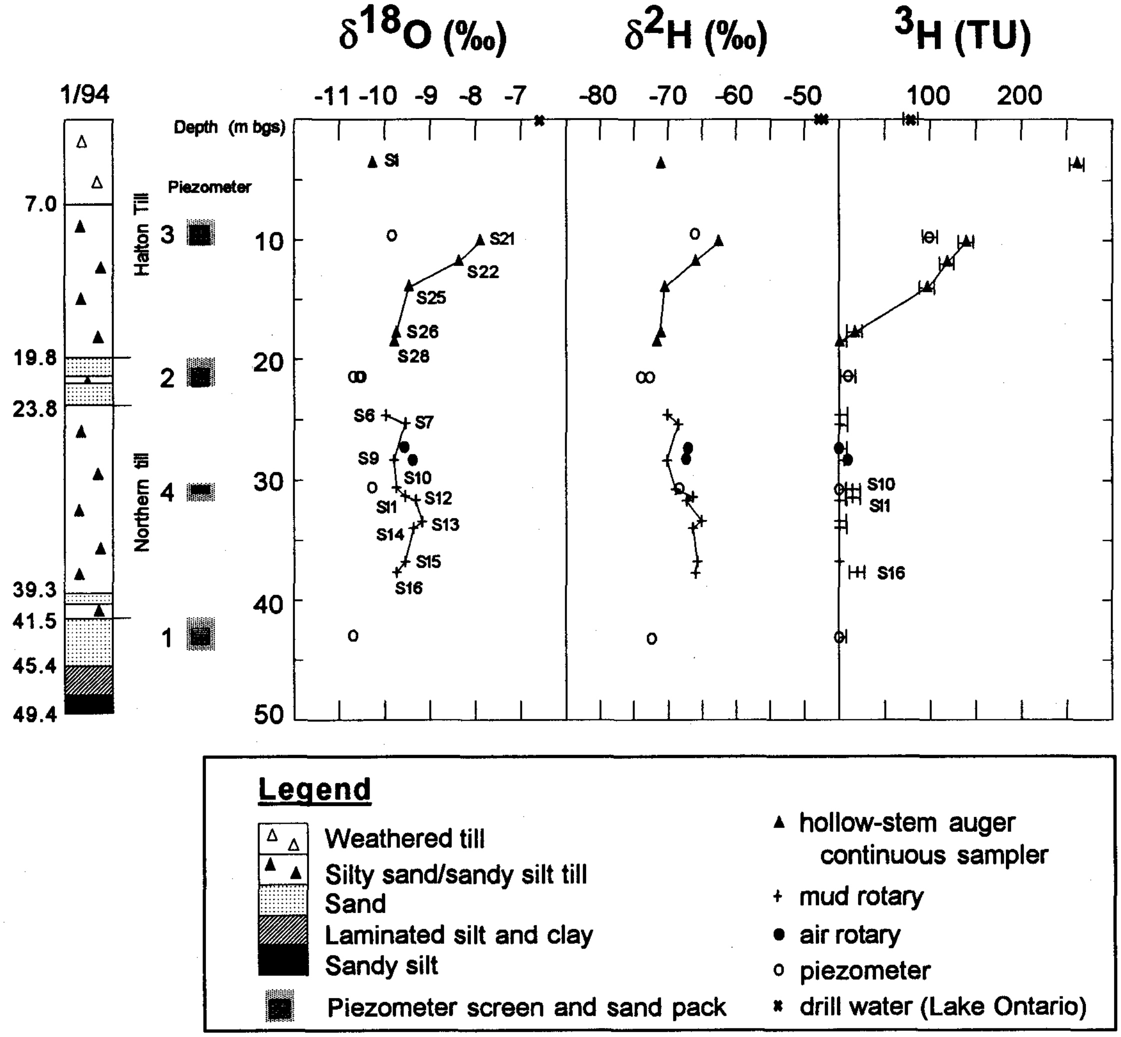
Fig. 3. Water levels for site 1/94 (A) and site 2/94 (B) from October 19, 1994, to July 7, 1995. Water levels for piezometers 2/94-5A and 2/94-5B affected by sampling event on January 30, 1995.



analysis, sampling was constrained to sections of continuous core that were greater than 0.3 m in length. When drilling with mud, particular care was taken to avoid sampling sections where mud had penetrated into the core along clast-focussed fractures or along any structures such as sand–silt laminae. Formation waters from more permeable zones were pumped from piezometers using dedicated Waterra inertial pumps (hereafter referred to as "groundwater samples").

Isotope analyses (oxygen-18 (^{18}O), deuterium (^{2}H), and tritium (^{3}H)) were conducted at the University of Waterloo Environmental Isotope Laboratory using conventional

Fig. 4. Distribution of $\delta^{18}O$, δ^2H, and ^3H with depth for site 1/94.



preparation techniques. Results for oxygen-18 and deuterium are expressed as delta units (δ) in per mil (‰) where

$$[1] \quad \delta^2H\,(\text{or } \delta^{18}O) = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000$$

R_{sample} and R_{standard} refer to the ratio of ^2H to ^1H (hydrogen) or ^{18}O to ^{16}O in the sample and standard, respectively. All results were normalized to Vienna standard mean ocean water (V-SMOW = 0‰) with a precision of ±2.0‰ for δ^2H and ±0.2‰ for $\delta^{18}O$. Tritium (^3H) contents of water were measured by liquid scintillation counting after electrolytic enrichment of water (±0.5 TU) and by direct counting (±8 TU). Pore water was extracted from the soil cores at the University of Waterloo Environmental Isotope Laboratory using an azeotropic distillation technique similar to that described by Revesz and Woods (1990).

In situ tests of hydraulic conductivity included slug tests where a measured volume of water was removed from a piezometer. Water-level recovery data were analyzed using the Hvorslev (1951) method and the AQTESOLV software package (Duffield and Rumbaugh 1991) for unconfined (Bouwer and Rice 1976) and confined (Cooper et al. 1967) slug test analysis. Results are reported in Table 1.

Results and discussion

Hydrogeology

The stratigraphy encountered at site 1/94 is shown in Fig. 4. The Halton Till is 19.8 m thick with a weathered (brown) profile 7 m thick. This weathered zone is characterized by mottling within the matrix and along bedding planes, fractures, and root casts. Oxidized vertical fractures are visible through the entire depth of the weathered zone. While lenses and layers of sand and silt are present, the matrix material is predominantly a silty sand. The Mackinaw Interstadial unit is 4 m thick and consists of fine- to medium-grained sand interbedded with till. The Northern till is 15 m thick and the matrix is predominantly silty sand grading into sandy silt within the bottom 1.5 m. Sand and silt lenses (perpendicular to core axis) are present, generally being less than 0.02 m thick. Silt laminae are also present at angles up to 45° to the core axis. The

Table 2. Summary of hydrogeology of sites 1/94 and 2/94.

Unit		Predominant groundwater flow direction	*K* (m/s)	*i*
Site 1/94				
Halton Till	Aquitard	Vertical downward	7×10^{-7}	0.02–0.05
Mackinaw Interstadial	Aquifer	Horizontal south to southeast	4×10^{-6}	0.01
Northern till	Aquitard	Vertical downward		−0.8
Thorncliffe Formation	Aquifer	Horizontal south to southeast	1×10^{-5}	0.007
Site 2/94				
Halton Till	Aquitard	Vertical downward		
Mackinaw Interstadial	Aquifer	Horizontal south to southwest	1×10^{-5}	0.01
Northern till	Aquitard	Vertical downward	6×10^{-11}	−0.4
Thorncliffe Formation	Aquifer	Horizontal southeast	4×10^{-5}	0.005

Note: Vertical hydraulic gradient through Northern till measured by head difference between piezometers in Mackinaw Interstadial aquifer and Thorncliffe Formation aquifer (negative value denotes downward flow).

Thorncliffe Formation consists of interbedded sand, silt, and clay. Due to the limited thickness of the Northern till and presence of numerous wet sand seams within the till at this site, extensive dry (air rotary) drilling was not possible.

Groundwater flow conditions at sites 1/94 and 2/94 are summarized in Table 2. Groundwater flow within the Halton Till includes horizontal flow along sand layers and lenses, with vertical flow along fractures. Groundwater within the Mackinaw Interstadial aquifer generally flows towards the south to southeast at a horizontal hydraulic gradient of 0.01. Flow within this unit can be variable, influenced by surface topography and the topography of the underlying Northern till. Within the Thorncliffe Formation, groundwater flow is south to southeast with a horizontal hydraulic gradient of 0.007, which is similar to gradients that have been reported elsewhere for nearby sites P1, M6, and EE11 that range from 0.01 to 0.009 (M.M. Dillon Limited 1990; Interim Waste Authority 1994*d*, 1994*e*). Slug test analysis of piezometer 1/94-1 indicates a *K* value of 1×10^{-5} m/s (Table 1). Estimates of *K* from nearby sites P1, EE4, EE10, M6, and EE11 vary from a high of 3×10^{-4} m/s to a low of 1×10^{-8} m/s (Table 3) and decrease with increasing silt content.

The vertical hydraulic gradient through the Northern till based on the head difference between piezometers 1/94-2 and 1/94-1 is 0.8 downwards. This large vertical hydraulic gradient is caused by drainage of the Thorncliffe Formation aquifer to West Duffins Creek, which has eroded below the base of the Northern till south of Highway 7 (Fig. 1). A sand seam within the Northern till has an estimated *K* value of 2×10^{-8} m/s (1/94-4), which is similar to other estimates of Northern till sand seams but much larger than till matrix estimates from lab analysis (Table 3) and long-term pump testing at site EE11 (3×10^{-10} to 3×10^{-11} m/s; Interim Waste Authority 1994*e*). The difference between laboratory- and field-based testing is typical of a heterogeneous media containing secondary permeability features (Williams and Farvolden 1967; Grisak and Cherry 1975; Keller et al. 1986).

The stratigraphy encountered at site 2/94 is shown in Fig. 5. The Halton Till is 6.7 m thick with a weathered (brown) profile 4 m thick. This weathered zone is characterized by mottling within the matrix and along bedding planes, fractures, and root casts. Oxidized vertical fractures are again visible through the entire depth of the weathered zone. Alternating layers of till, silt, sand, and gravel of the Mackinaw Interstadial extend for 10.7 m beneath the Halton Till.

The Northern till is much thicker at this site (36.7 m) than at site 1/94, but as at site 1/94, the matrix is predominantly silty sand grading into clayey silty sand within the bottom 3.1 m. Sand and silt lenses (perpendicular to core axis) are present and are generally less than 0.05 m thick. Fractures between gravel and cobble-sized clasts were visible in some of the cores and were illuminated by the penetration of drilling mud into the core extending along fractures between clast mud casts. Any core samples that exhibited clast-focused fracturing with mud penetration were excluded from isotope analysis. The Thorncliffe Formation consists of interbedded sand, silt, and clay 10.7 m thick.

Groundwater flow directions within the Mackinaw Interstadial aquifer at site 2/94 are south to southwest at

Table 3. Summary of hydraulic conductivity data from other studies.

	Halton Till slug	Interstadial Sand slug	Northern till		Thorncliffe Formation slug
			Lab	Slug	
Site P1					
Mean	9×10^{-7}	—	3×10^{-11}	1×10^{-10}	6×10^{-6}
Max.	2×10^{-5}	—	9×10^{-11}	6×10^{-10}	1×10^{-5}
Min.	2×10^{-9}	—	2×10^{-11}	4×10^{-11}	3×10^{-6}
No.	31	—	18	11	2
Site EE4					
Mean	8×10^{-8}	—	—	8×10^{-7}	1×10^{-5}
Max.	1×10^{-6}	—	—		3×10^{-4}
Min.	2×10^{-8}	—	—		2×10^{-6}
No.	4	—	—	1	8
Site EE10					
Mean	4×10^{-7}	—	5×10^{-11}	3×10^{-9}	1×10^{-6}
Max.	6×10^{-6}	—	8×10^{-11}		5×10^{-6}
Min.	2×10^{-8}	—	4×10^{-11}		9×10^{-8}
No.	5	—	4	1	4
Site EE11					
Mean	8×10^{-8}	4×10^{-5}	2×10^{-11}	3×10^{-9}	1×10^{-6}
Max.	1×10^{-6}	5×10^{-4}	4×10^{-11}	3×10^{-6}	5×10^{-6}
Min.	5×10^{-9}	5×10^{-6}	1×10^{-11}	7×10^{-12}	2×10^{-7}
No.	10	5	9	15	20
Site M6					
Mean	2×10^{-7}	2×10^{-6}	4×10^{-11}	6×10^{-11}	3×10^{-7}
Max.	5×10^{-7}	9×10^{-5}	7×10^{-10}	2×10^{-8}	3×10^{-6}
Min.	5×10^{-8}	3×10^{-8}	2×10^{-11}	3×10^{-12}	1×10^{-8}
No.	3	7	6	6	3

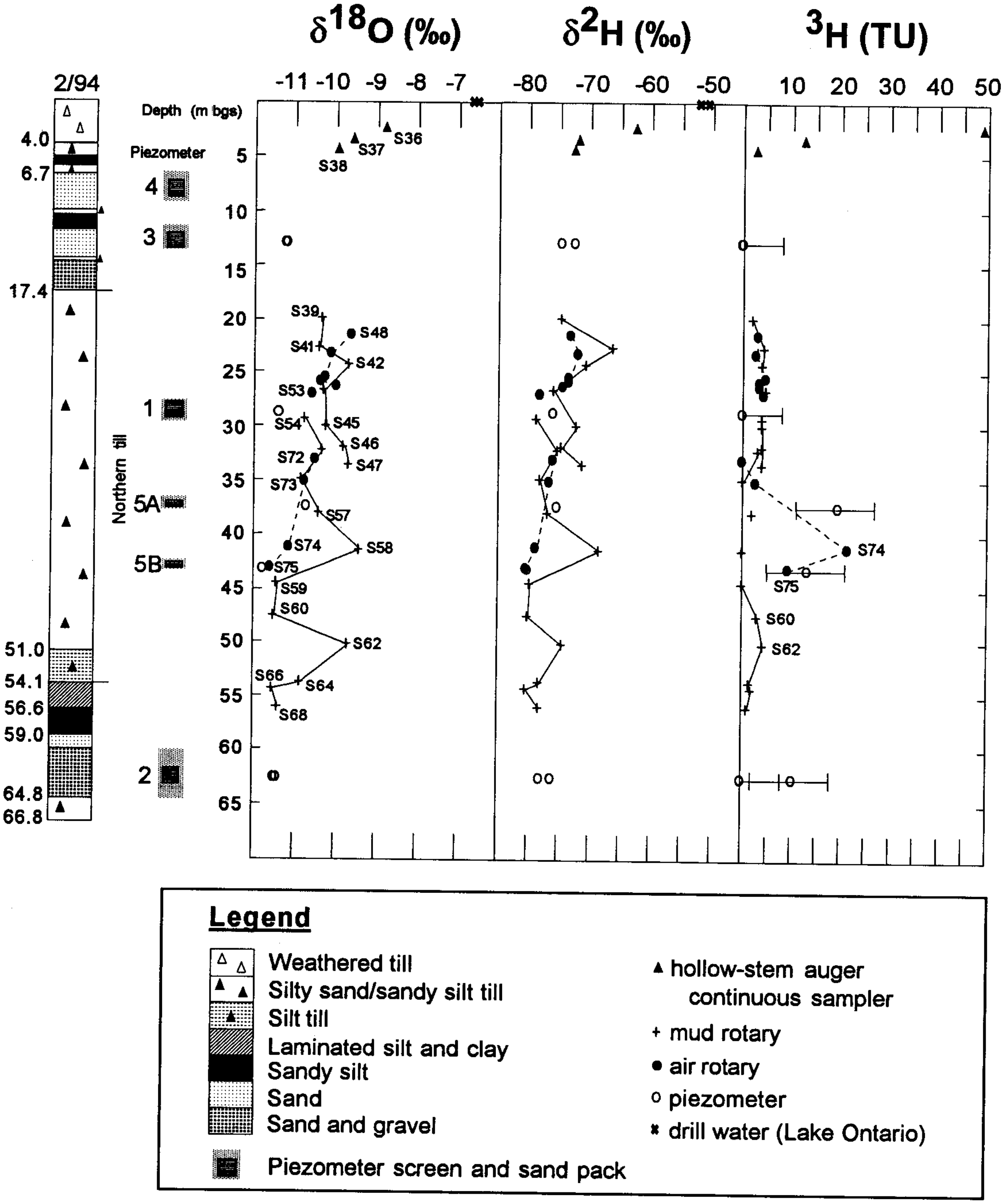
Notes: All values in m/s. Data from M.M. Dillon Limited (1990) and Interim Waste Authority (1994*a*, 1994*b*, 1994*c*, 1994*d*, 1994*e*) for sites P1, EE4, EE10, M6, and EE11. Mean refers to geometric mean.

a horizontal hydraulic gradient of 0.01. Groundwater within the Thorncliffe Formation aquifer flows toward the southeast at a horizontal hydraulic gradient of 0.005. The vertical hydraulic gradient through the Northern till based on the head difference between piezometers 2/94-3 and 2/94-2 is 0.4 downwards. The results of field evaluations of the hydraulic conductivity of the Northern till are given in Table 1. The hydraulic conductivity of sand seams within the Northern till (piezometer 2/94-1) are much higher (in this case five orders of magnitude) than estimates for the till matrix material (piezometers 2/94-5A and 2/94-5B).

Deuterium (^{2}H) and oxygen-18 (^{18}O)

^{2}H and ^{18}O are stable isotopes of the water molecule which are considered to be conservative for meteoric waters and unlikely to be altered significantly by mineral–water reactions at low temperatures (<50°C) (Lawrence and Taylor 1972). Since both isotopes are strongly influenced by the climatic conditions at the time of recharge (Fontes 1980), the ^{2}H and ^{18}O content of groundwater can provide a useful indication of its origin. The isotopic composition of shallow groundwater is normally expected to reflect the average annual isotopic composition of local precipitation; however, some systems are able to preserve a seasonally varying input (Fritz et al. 1987). The degree of enrichment or depletion of the heavy isotope depends, in part, on the average annual surface air temperature (Dansgaard 1964). As a result, more depleted values generally indicate meteoric waters that were recharged in a cooler climate. Fritz et al. (1987) report δ^{18}O of shallow modern groundwaters for the study area ranging from −9 to −12‰, which is similar to the weighted mean and long-term average for the Ottawa precipitation monitoring station (International Atomic Energy Agency 1992). In comparison, old groundwaters (~10 000 years) in unfractured aquitards from various locations in Canada and the northern United States are depleted in δ^{18}O relative to modern meteoric waters by at least 5‰ (Desaulniers et al. 1981, 1982; Simpkins and Bradbury 1992; Remenda et al. 1994). Desaulniers et al. (1981) interpret δ^{18}O of −17‰ in deep clay till groundwater near Sarnia to represent waters 11 000 to 14 000 years old. Sklash et al. (1992) also report depletion in clay till pore water down to −15‰ near Windsor that suggests an age of at least 7000 years.

Fig. 5. Distribution of $\delta^{18}O$, $\delta^{2}H$, and ^{3}H with depth for site 2/94.



The absence of significant contamination by drilling fluid is illustrated by plots of $\delta^{2}H$ versus $\delta^{18}O$ in Fig. 6 (site 1/94) and Fig. 7 (site 2/94). Craig (1961) showed that $\delta^{2}H$ and $\delta^{18}O$ are linearly correlated along a meteoric water line which can be defined globally ($\delta^{2}H = 8\ \delta^{18}O + 10$) and locally for each geographic region. Meteoric waters that deviate from this line are interpreted as having been modified by evaporation, mixing with nonmeteoric waters or biologic transformations (Fontes 1980; International Atomic Energy Agency 1981). Most pore-water samples lie on or within precision ranges of the Ottawa Meteoric Water Line (OMWL; $\delta^{2}H = 7.63\ \delta^{18}O + 6.53$; Fritz et al. 1987). Drilling fluid, obtained from Lake Ontario, is tritiated (average 77.6 TU, $N = 10$), and displays $\delta^{2}H$ and $\delta^{18}O$ concentrations that lie on an evaporation trend away from the meteoric water line (slope of 4 to 6) consistent with the surface water source. $\delta^{2}H$ and $\delta^{18}O$ data for the mud rotary core samples (shown in Figs. 6 and 7) do not exhibit evidence of contamination with the drill water (Lake Ontario).

Samples W12, W13, and W14 (Fig. 7) represent changes in the character of the drilling mud at approximately 1 h intervals and illustrate the effects of the mixing of drilling fluid with formation waters. W12 represents the signature of the mud batch before drilling commenced, reflecting

Fig. 6. Site 1/94 deuterium vs. oxygen-18. S21 and S22 are pore waters from auger sampling (i.e., no drilling fluid), believed to represent enrichment of precipitation by lake effects.

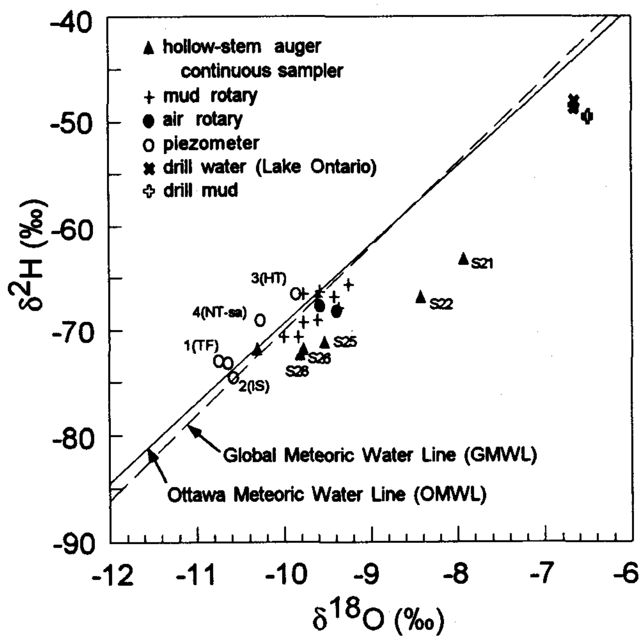
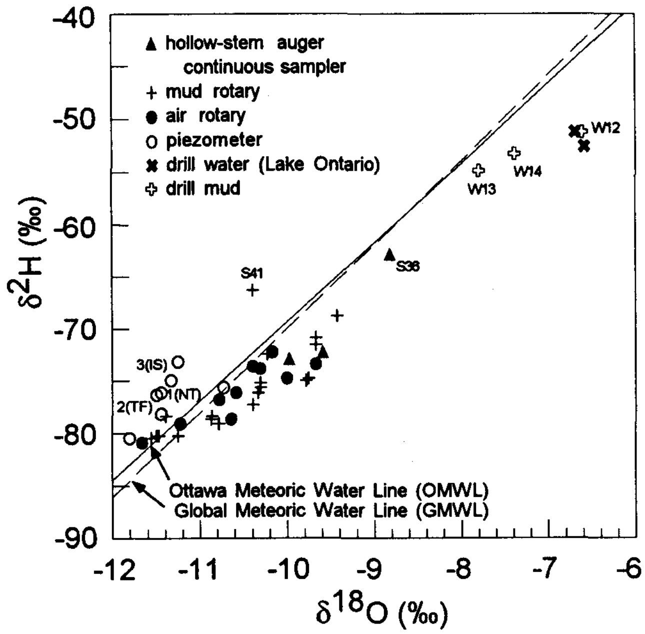


Fig. 7. Site 2/94 deuterium vs. oxygen-18. GMWL from Craig (1961). OWML from Fritz et al. (1987).



the Lake Ontario water used to mix the mud. Sample W13 represents the drilling mud after 1 h of drilling (4.6 m of Northern till penetrated), indicating mixing with meteoric formation waters. One hour later (sample W14) the mud has become more enriched, consistent with addition of drilling water and mixing with formation waters after a further 3 m of drilling through the Northern till.

$\delta^{18}O$ values for pore waters and groundwaters at site 1/94 range from −8.0 to −10.8‰, with δ^2H values ranging from −62.8 to −74.1‰ for the 22 samples analyzed (18 pore waters, 4 groundwaters; see Fig. 4). There do not appear to be any significant depletion trends with depth as all samples occur within the range of modern meteoric waters as discussed above (−9 to −12‰). This contrasts with $\delta^{18}O$ profiles within thick unfractured, low permeability clay and clay till deposits in Saskatchewan, Manitoba, North Dakota, and Ontario, which are dominated by diffusive transport and exhibit characteristically smooth transitions from modern meteoric water to relatively depleted (glacial ice water) at depth (Desaulniers et al. 1981; Remenda et al. 1994).

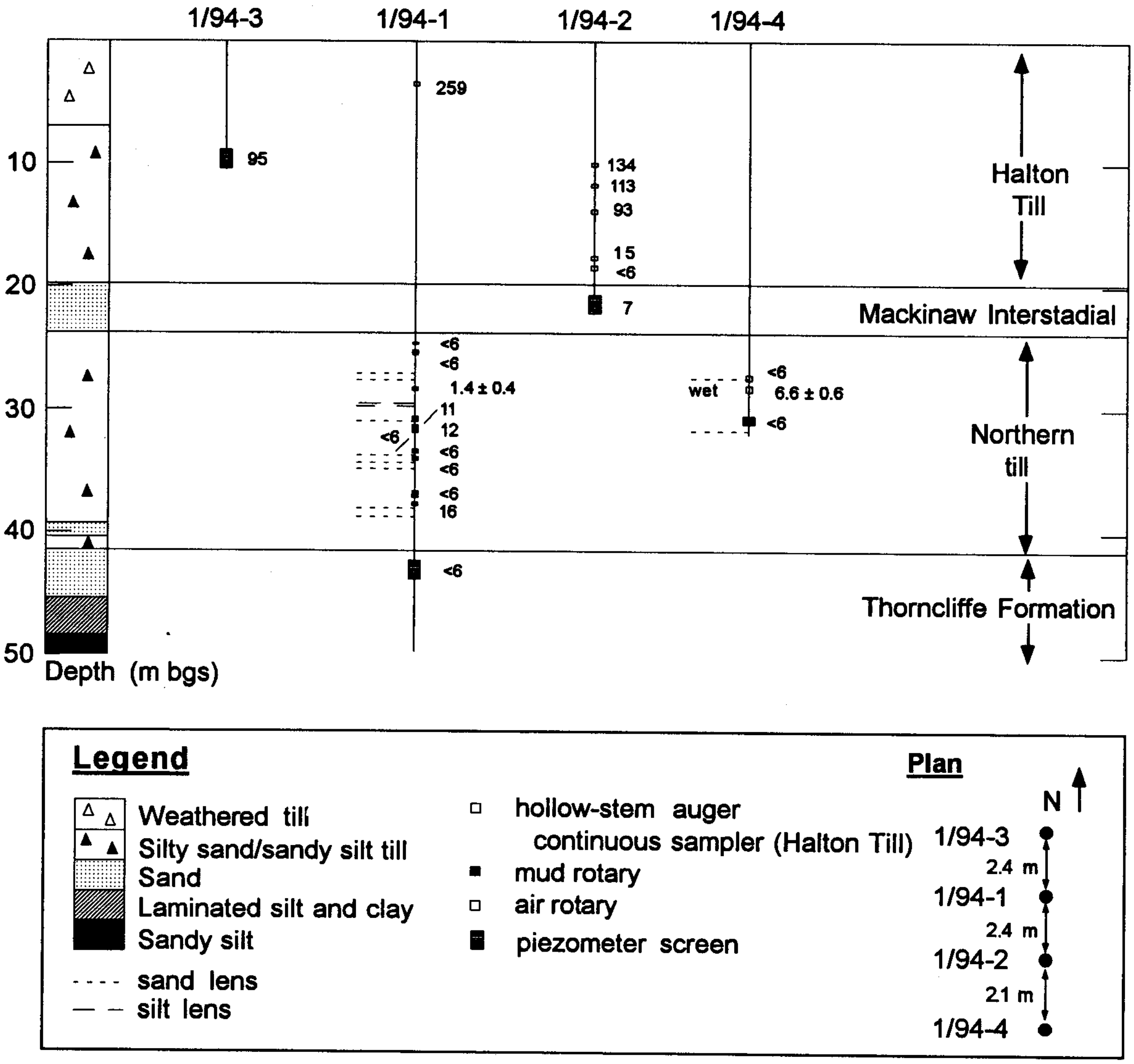
Two split-spoon samples obtained from auger drilling (i.e., no drilling fluid) at site 1/94 (Fig. 6, samples S21 and S22) are slightly more enriched and plot away from the OMWL. These samples may represent infiltration of summer precipitation, modified by local lake effects (Lake Ontario), along vertical fractures.

At site 2/94, both δ^2H and $\delta^{18}O$ have modern meteoric water signatures (Fig. 7). However, both show slight depletion trends with increasing depth (Fig. 5) and are more depleted with depth (minimum δ^2H of −80.7‰ and minimum $\delta^{18}O$ of −11.8‰) than at site 1/94. While there is a general depletion trend with depth, the profiles have a scattered appearance typical of media dominated by secondary permeability features, and unlike the smooth transition with depth to more depleted values in unfractured media (Desaulniers et al. 1981; Remenda et al. 1994). The trend to slightly more depleted waters at depth may also suggest that infiltration does not reflect average annual precipitation but represents precipitation during the winter, spring, and fall when groundwater recharge for this area occurs (Sibul et al. 1977; Singer 1981; Gerber and Howard 1996). Average monthly $\delta^{18}O$ values at the Ottawa monitoring station are less than −10.8‰ for the months of October through to March. For the months of April to September, $\delta^{18}O$ values are more enriched, being greater than −9.7‰ (International Atomic Energy Agency 1992). Another possibility is that these waters simply represent recharge from an earlier time period when the average annual air temperature was cooler than the modern average. According to paleoclimate reconstructions for southern Ontario using stable isotope ratios from fossil plant cellulose and lake marl (Edwards and Fritz 1986, 1988), this would correspond to an early postglacial period when the mean annual air temperature increased from 0°C (12 000 years ago) to modern conditions (6.8°C) approximately 7000 years ago. Edwards and Fritz (1986) suggest a meteoric water $\delta^{18}O$ composition greater than 11 000 years ago of −16.6‰ that is comparable to deep clay till groundwaters near Sarnia (−17‰) reported by Desaulniers et al. (1981). The presence of elevated ^3H in these pore waters (see Fig. 5 and discussion below) precludes waters of this age or suggests that mixing of young (post-1952) and old (>7000 years ago) waters is occurring.

Tritium (^3H)

Tritium is a radioactive isotope of hydrogen that is produced naturally in the upper atmosphere by cosmic-ray

Fig. 8. Site 1/94 cross section showing two-dimensional tritium distribution. All values are ±8 TU unless noted otherwise.

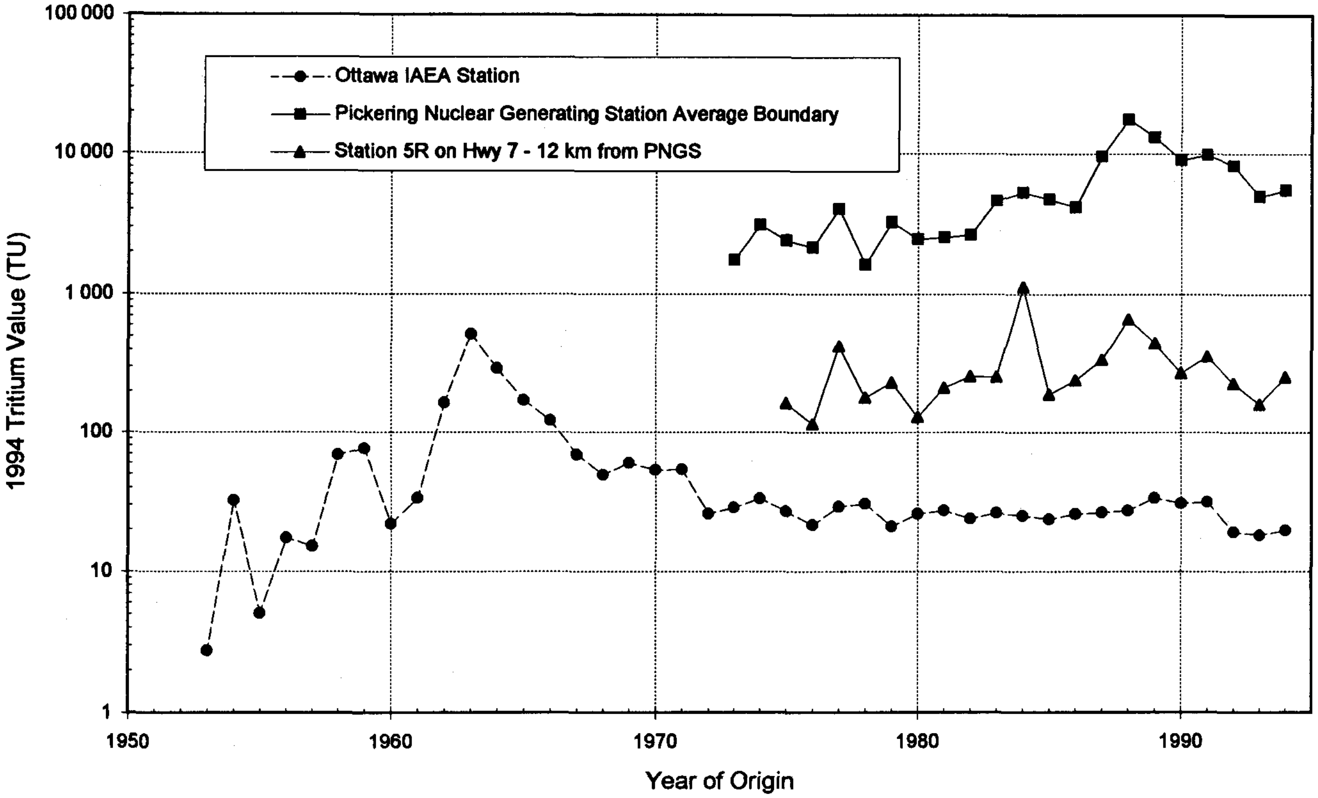


bombardment and has a half-life of 12.43 years. Since 1953, tritium has also been produced anthropogenically by thermonuclear weapons testing, the result being that the tritium content of precipitation has increased by several orders of magnitude. Nuclear power plants are also known to locally increase the tritium content of precipitation. Prior to 1953, the tritium content of precipitation was <25 TU (Faure 1986), with a peak in the average monthly concentration at Ottawa of 5817 TU during June of 1963 (International Atomic Energy Agency 1969). Brown (1961) estimated a pre-1953 concentration of 15 TU for precipitation in the Ottawa valley region. Assuming this value and incorporating radioactive decay, 1994 tritium concentrations in meteoric waters greater than 1.5 TU (i.e., incorporating analytical precision which ranged from ±0.5 to ±2.7 TU for enriched tritium analyses) are considered to contain some water recharged since 1952. Other workers (Ruland et al. 1991) interpret tritium levels above 1 TU within clay till near Sarnia to indicate mixing with at least some post-1952 precipitation.

Tritium profiles for site 1/94 are plotted in Fig. 4 with a cross section of this site shown in Fig. 8. ^{3}H values within the Halton Till range from a high of 259 TU (±8) at 3.35 m below ground surface (bgs) to a low of <6 TU (±8) at 18.29 m bgs. The sample at 18.29 m bgs is situated 1.5 m above the top of the Interstadial sand unit (aquifer) having a groundwater value of 7 TU (±8). The vertical hydraulic gradient through the Halton Till at this site is 0.02 to 0.05 downwards between February and September, with upward gradients of 0.009 to 0.09 during October to early January.

Tritium values greater than 100 TU at this site are considered representative of meteoric waters modified by fallout from the Pickering Nuclear Generating Station (Fig. 1), and recharged since 1972 when this facility started operating. Figure 9 illustrates average annual tritium concentrations

Fig. 9. Average annual tritium in precipitation. Tritium contents decayed to 1994 values. Annual averages from monthly sampling data. 1953–1987 Ottawa IAEA station data from International Atomic Energy Agency (1992); data for 1988–1994 from Bob Drimmie, (University of Waterloo, personal communication). Pickering Nuclear Generating Station data from Ontario Hydro (1973–1994). Pickering Nuclear Generating Station and monitoring station 5R shown on Fig. 1. Pickering A 4 reactors began operating between 1971 and 1973, Pickering B 4 reactors began operating between 1982 and 1985.

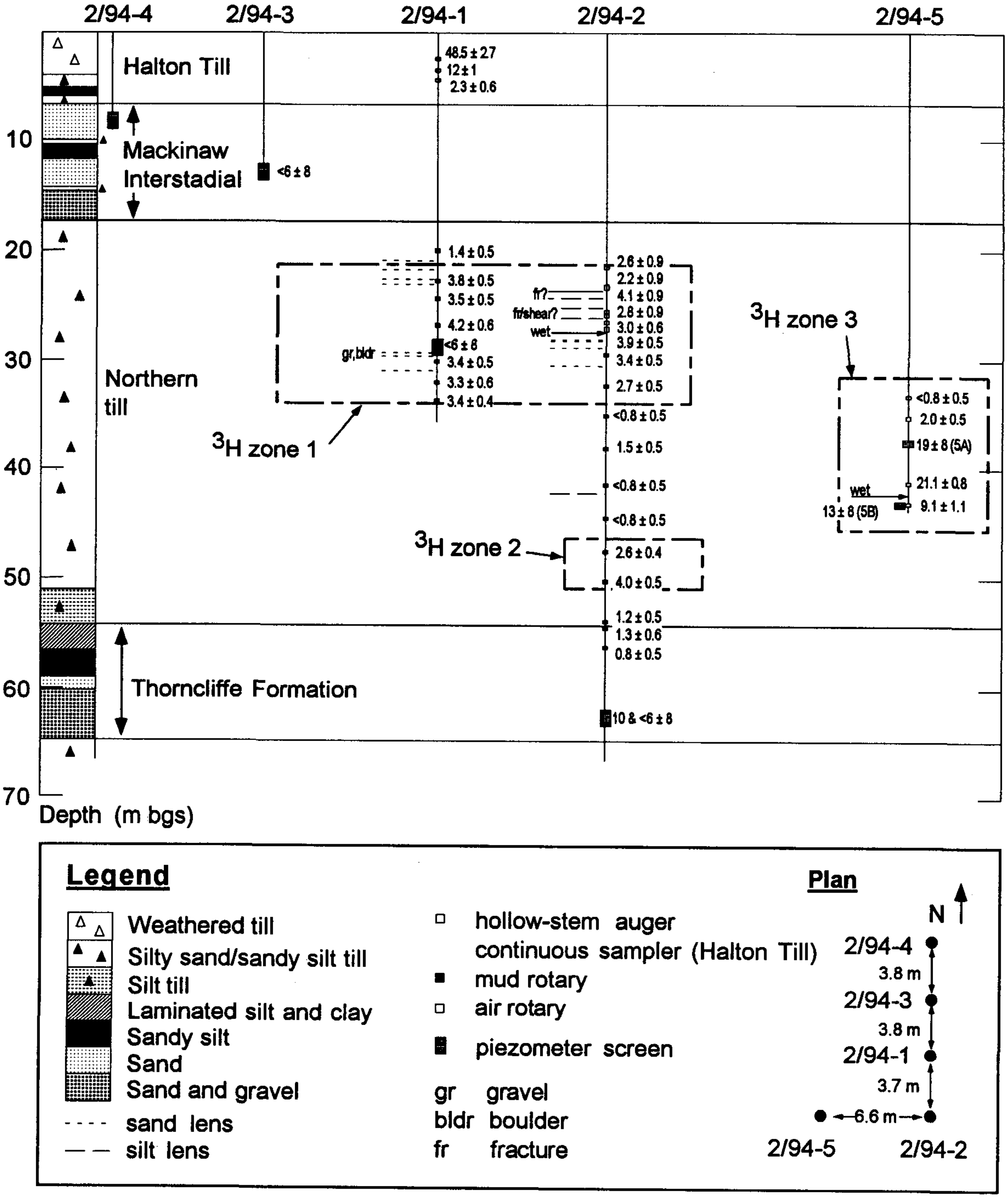


in precipitation at the Ottawa IAEA (International Atomic Energy Agency) station and Ontario Hydro Pickering Nuclear Generating Station monitoring stations. Data from the Ottawa IAEA station reflect natural cosmogenic and nuclear weapons testing fallout. Although recharge during the period from 1962 to 1966 (nuclear weapons testing peak) could have 1994 tritium values greater than 100 TU, mixing within the shallow groundwater zone by lower concentration precipitation since 1966 is expected to have diluted the bomb peak signal to values below 100 TU.

The depth of penetration at site 1/94 of precipitation with tritium greater than 100 TU indicates that average linear vertical groundwater velocities (V) for the Halton Till are at least 0.6 m/year (13.9 m in 22 years). This estimate is regarded as a minimum value because upward flow occurs during part of the year (October to early January) and the pore waters could represent mixing with recharge since 1972. Assuming a downward velocity (V) of 0.6 m/year, a downward gradient of 0.02 to 0.05 and a porosity (n) of 0.17 (M.M. Dillon Limited 1990), a bulk value of the vertical hydraulic conductivity (K_v) of the Halton Till at this site would be 7×10^{-8} to 2×10^{-7} m/s. Slug testing of piezometer 1/94-3 yielded an estimate of K of 7×10^{-7} m/s, which is within the range of values seen at other sites (Table 3). The range of K for the Halton Till reflects the variability of matrix composition (silty sand to sandy silt) and the presence of fractures and sand, silt, and clay layers. The vertical K (K_v) value estimated from the depth of penetration of tritium supports the horizontal K (K_h) values estimated from slug test analyses (Table 3) and therefore indicates the presence of pervasive secondary permeability structures within the Halton Till at this site. The depth of active groundwater flow is indicated by the presence of tritium below the weathered zone. Fractures, although not visible in the drill core within the unweathered Halton Till, must be present to deliver post-1972 waters to depth.

Measurable values of tritium (>6 TU) within the Northern till were found in 4 of 10 mud rotary cores (borehole 1/94-1) and 1 of 2 dry rotary cores (borehole 1/94-4) (Fig. 8). At borehole 1/94-1; the value of 1.4 TU (± 0.4) at 28.2 m bgs is assumed to represent pre-1953 water. Tritiated pore waters within the till at this site occur adjacent to sand lenses and are attributed to diffusion into the matrix surrounding hydraulically active secondary permeability features. Ruland et al. (1991) and Yanful and Quigley (1990), working in a clay till near Sarnia, report tritium diffusion from active fractures and base of landfill 2 m

Fig. 10. Site 2/94 cross section showing two-dimensional tritium distribution.



into the matrix since 1967. Matrix diffusion is illustrated by a value of 11 TU (±8) immediately above a 0.05 m thick sand lens at 31 m bgs, while 0.3 m below the sand lens, a tritium value of 12 TU (±8) occurs. Another sample at 37.5 m bgs indicates 16 TU (±8) 0.46 m above saturated silt and sand seams located 1 m above the top of the Thorncliffe Formation. A dry rotary core (borehole 1/94-4) shows tritiated pore waters (6.6 TU ± 0.6) within the till situated 3.2 m above a 0.15 m thick sand layer situated at 31.7 m bgs. This sand layer may be connected to that encountered within borehole 1/94-1 at 31 m bgs. Dry drilling was abandoned in borehole 1/94-4 at 31.7 m bgs because of excessive moisture within the borehole (i.e., saturated conditions).

It is also evident that some sand seams may not be connected to vertical fractures nor are they in hydraulic connection with the Mackinaw Interstadial aquifer. For example, samples from borehole 1/94-1 at depths of 31.7, 33.4, 34, and 36.8 m bgs are adjacent to sand lenses within the till, but do not contain detectable tritium (<6 ± 8 TU). It is more likely that this interpretation merely reflects the analytical precision for these samples as pore-water yields were insufficient to enable enriched tritium analysis which has a lower detection limit of <0.8 TU (±0.5).

Tritium profiles for site 2/94 are shown in Fig. 5, with a cross section of the site shown in Fig. 10. Tritium values within the Halton Till at this site decrease rapidly from 48.5 TU (± 2.7) at 2.44 m bgs to a value of 2.3 TU (±0.6) at a depth of 4.27 m bgs near the base of the weathered zone. Assuming that 2.3 TU (±0.6) at a depth of 4.27 m bgs represents recharge since 1952, average linear vertical groundwater velocities for the Halton Till at this site would be 0.1 m/year downward. This estimate is lower than the estimate for site 1/94 and is consistent with the presence of a more clay-rich facies of the Halton Till at this site.

Tritiated pore waters within the Northern till at site 2/94 indicate the presence of horizontal and vertical secondary permeability structures. For the purpose of the following discussion, the tritiated pore waters have been separated into three zones (Fig. 10). Zone 1 occurs within boreholes 2/94-1 and 2/94-2 between depths of 21.3 and 33.8 m bgs, with tritium values ranging from 2.2 TU (±0.9) to 4.2 TU (±0.6). This was confirmed using both mud and dry rotary coring methods. Dry coring in borehole 2/94-2 terminated at 27.3 m bgs due to the presence of wet conditions. This depth is similar to that at which limestone cobbles and boulders were encountered in borehole 2/94-1 (27.1 m bgs). It is not known if tritium zone 1 extends west to borehole location 2/94-5 because this zone was cased off to allow dry drilling access.

Tritiated zone 2 (Fig. 10) occurs near the base of the Northern till (2.6 TU ± 0.4 at 47.4 m bgs and 4.0 TU ± 0.5 at 50.41 m bgs) just above where the till matrix changes to more silt-rich material. These waters are also interpreted as representing an age similar to waters encountered in zone 1, incorporating recharge from the period 1953–1956. It is not known if this zone is laterally extensive as drilling had to be terminated in borehole 2/94-5 at a higher elevation because of wet conditions.

Tritiated zone 3 was encountered in borehole 2/94-5 starting at a depth of 35 m bgs and extending to 43.9 m bgs where, once again, the borehole was terminated because of wet conditions. Tritium concentrations range from 2 TU (±0.5) to 21.1 TU (±0.8). These dry core values are confirmed by groundwater samples from piezometers 2/94-5A and 2/94-5B (Fig. 10). There appears to be no horizontal extension into borehole 2/94-2 to the east; however, any possible connection with tritium zones 1 and 2 is unknown at this time. This zone is interpreted as the intersection of a vertical to subvertical fracture zone with fractures not obvious in drill core. Sand infilled vertical fractures are visible within the Northern till along the bed of West Duffins Creek. Assuming vertical flow, an average linear vertical groundwater velocity based on the depth of tritium at this site would be on the order of 1 m/year (50.4 m in 41 years).

Comparison to other studies

The results discussed above present evidence of active horizontal (to shallow dipping) groundwater pathways through the Northern till. While pathways have not been explicitly identified in boreholes, they may include horizontal to shallow northward-dipping sand and boulder horizons (erosional surfaces) as discussed by Boyce et al. (1995) and visible in outcrop along West Duffins Creek. Evidence is also provided for the presence of vertical fractures or pathways such as shown by tritium zone 3 at site 2/94 (Fig. 10). While vertical fractures are visible in outcrop, the applicability of extending these fractures to inland areas is questionable in that outcrop fracturing could be caused by stress release resulting from removal of material by river down-cutting through the Northern till.

The results of this study are consistent with the findings of other, more regional studies including the regional water balance recharge estimates of Gerber and Howard (1996) and hydrochemistry studies of Howard and Beck (1986), both of which suggest areas mapped as Late Wisconsinan till in the study area are extensively permeable. The findings are also consistent with occurrences of leachate migrating through the Northern till at a former landfill site at Beare Road (Hydrology Consultants Ltd. 1981).

Hydrogeologic investigations conducted on the Northern till also demonstrate a variability of the hydraulic conductivity estimates with the scale of the test method. In general, experimental investigations are conducted on temporal and spatial scales, which are small compared with the scale of interest. Problems arise when trying to extrapolate small-scale behaviour to a larger scale. Small scale refers to flow experiments in tight media, which can be completed in a practical time period and includes both laboratory and in situ testing (Neuzil 1986). Secondary hydraulic conductivity is commonly 2–3 orders of magnitude greater than the matrix hydraulic conductivity. The former is rarely revealed by relatively small-scale laboratory tests (Williams and Farvolden 1967; Grisak and Cherry 1975; Keller et al. 1986). For the Northern till, secondary hydraulic conductivity (10^{-6} to 10^{-8} m/s within sand seams) is at least three orders of magnitude greater than the matrix hydraulic conductivity (10^{-11} m/s). Secondary permeability is commonly reported in till studies throughout North America and in parts of Europe (Grisak et al. 1976; Hendry 1983, 1986, 1988; Sharp 1984; Keller et al. 1988, 1989; D'Astous et al. 1989; Fredericia 1990; Ruland et al. 1991; Simpkins and Bradbury 1992; Jones 1993; McKay et al. 1993). Recognizing that hydraulic conductivity can increase with the scale of the test method (Bradbury and Muldoon 1990), it is clearly necessary to utilize larger scale methods, such as transport of hydrochemical or isotopic tracers, if the hydrogeology of these complex deposits is to be fully understood. Analysis of groundwater flux and solute transport through fractured deposits also needs to consider advective–dispersive flow through the fractures and diffusive transport within the unfractured matrix (Foster 1975; Grisak and Pickens 1980; Grisak et al. 1980).

Conclusions

The findings of this study have implications for recharge to aquifers within Early to Mid Wisconsinan units (Thorncliffe Formation and Scarborough Formation) and for contaminant transport from surface to deeper aquifers. Such information is critical to groundwater resource planning presently under consideration for the Oak Ridges Moraine and the Greater Toronto Area (GTA). The study demonstrates that horizontal and vertical pathways exist in the Northern till allowing waters younger in age than 1952 to migrate through over 30 m of till to reach depths greater than 50 m bgs (average linear vertical groundwater velocity of approximately 1 m/year locally). The bulk hydraulic conductivity of the Northern till is controlled by secondary permeability features. These features include boulder pavements, sand layers, and fractures (many of which are not visible by alteration haloes in core samples), which are commonly found in till deposits (Stephenson et al. 1988; Haldorsen and Kruger 1990). While other till studies from North America and Europe have similarly documented rapid transport, much of the active flow is normally restricted to shallow depths (within the weathered zone or just below) or to thin areas of till (<15 to 20 m) (Grisak and Cherry 1975, Manitoba; Keller et al. 1988, Dalmeny, Saskatchewan).

The study presented here differs from those described from other areas of North America in that augering to obtain core was not practicable through the overconsolidated and very dense Northern till. It is demonstrated, however, that reliable pore-water samples can be obtained using mud rotary drilling techniques providing care is taken to prepare samples immediately after retrieval. Preparation involves removing the outer rind on the core, removing drill mud casts from along clasts, and ensuring that drilling mud has not penetrated along clast-focussed fractures or thin sand and silt layers. The similar pore water δ^2H and $\delta^{18}O$ signatures obtained from both mud rotary and air rotary methods and the distinct mud rotary pore water δ^2H and $\delta^{18}O$ signatures from that of the drilling fluid show that measures to reduce sample contamination were effective. Since the water content within the Northern till varies, a minimum length of 20 cm of core is necessary to obtain enough pore water to complete enriched tritium analysis near the maximum precision of ±0.5 TU. Samples are probably biased towards the more competent, massive sections of till core, where it is more likely to contain older, less-tritiated water. The findings of this study also support the integrity of pore-water samples collected using similar methods (mud rotary) during landfill site investigations conducted at sites P1, EE4, EE10, and EE11 (M.M. Dillon Limited 1990; Interim Waste Authority 1994*b*, 1994*c*, 1994*e*).

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