Evaluation of heterogeneity and field-scale groundwater flow regime in a leaky till aquitard

Richard E. Gerber · Joseph I. Boyce
Ken W.F. Howard

Abstract Recent work in southern Ontario, Canada, demonstrates anomalously high vertical groundwater flow velocities (>1 m/year) through a thick (as much as 60 m), sandy silt till aquitard (Northern till), previously assumed to be of very low permeability (hydraulic conductivity <10^{-10} m/s). Rapid recharge is attributed to the presence of fractures and sedimentary heterogeneities within the till, but the field-scale flow regime is poorly understood. This study identifies the nature of physical groundwater pathways through the till and provides estimates of the associated groundwater fluxes. The aquitard groundwater flow system is characterized by integrating details of the outcrop and subsurface sedimentary characteristics of the till with field-based hydrogeologic investigation and numerical modeling. Outcrop and subsurface data identify a composite internal aquitard stratigraphy consisting of tabular till beds (till elements) separated by laterally continuous sheet-like sands and gravels (interbeds) and boulder pavements. Individual till elements contain sedimentary heterogeneities, including discontinuous sand and gravel lenses, vertical sand dikes, and zones of horizontal and vertical fractures.

Hydrogeologic field investigations indicate a three-layer aquitard flow system, consisting of upper and lower zones of more hydraulically active and heterogeneous till separated by a middle unit of relatively lower hydraulic conductivity. Groundwater pathways and fluxes in the till were evaluated using a two-dimensional aquitard/aquifer flow model which indicates a step-wise flow mechanism whereby groundwater moves alternately downward along vertical pathways (fractures, sedimentary dikes) and laterally along horizontal sand interbeds within the till. This model is consistent with observed hydraulic-head and isotope profiles, and the presence of tritiated pore waters at various depths throughout the till. Simulations suggest that a bulk aquitard vertical hydraulic conductivity on the order of 1×10^{-9} m/s is required to reproduce observed hydraulic-head and tritium profiles.

Résumé Une étude récente dans le sud de l'Ontario (Canada) démontre l'existence de vitesses d'écoulement vertical souterrain anormalement élevées (>1 m/an) au travers d'un imperméable (la moraine du nord) constitué par une moraine sablo-silteuse épaisse (jusqu'à 60 m), supposée à l'origine présenter une très faible perméabilité (conductivité hydraulique inférieure à 10^{-10} m/s). La recharge rapide est attribuée à la présence de fractures et d'hétérogénéités sédimentaires à l'intérieur de la moraine; mais le régime d'écoulement à l'échelle du terrain est mal connu. Cette étude identifie la nature des cheminements physiques des eaux souterraines au travers de la moraine et fournit les estimations des flux souterrains associés. Le système d'écoulement au travers de l'imperméable est défini par des détails d'intégration des affleurements et par les caractères sédimentaires souterrains de la moraine obtenus à partir de travaux hydrogéologiques de terrain et d'une modélisation numérique. Les données concernant les affleurements et le souterrain permettent d'identifier une stratigraphie de l'imperméable interne composite consistant en des lits de moraine (éléments de moraine) séparés par des lits de sables et de graviers en continuité latérale (interlits) et des pavages de blocs. Les éléments individuels de moraine contiennent des hétérogénéités sédimentaires, y compris des lentilles discontinues de sables et de graviers, des structures verticales de sables et des zones de fractures horizontales et verticales.

Les travaux hydrogéologiques de terrain indiquent qu'il s'agit d'un système d'écoulement à trois couches imperméables, composé de zones supérieure et inférieure de moraine hydrauliquement plus active et hétérogène séparée par une unité médiane à conductivité hydraulique relativement plus faible. Les lignes d'écoulement et les flux dans la moraine ont été évalués au moyen d'un modèle d'écoulement imperméable-aquifère à deux dimensions, qui indique un mécanisme d'écoulement en

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R.E. Gerber (✉)
Department of Geology, University of Toronto,
22 Russell Street, Toronto, Ontario M5S 3B1, Canada
e-mail: gerber@geology.utoronto.ca
Fax: +1-416-9783938

J.I. Boyce
Applied Geophysics Group, School of Geography and Geology,
McMaster University, Hamilton, Ontario L8S 4K1, Canada

K.W.F. Howard
Groundwater Research Group,
University of Toronto at Scarborough, 1265 Military Trail,
Scarborough, Ontario M1C 1A4, Canada

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escalier par lequel l'eau souterraine s'écoule alternativement vers le bas le long de cheminements verticaux (fractures, structures sédimentaires verticales) et horizontalement le long des interlits horizontaux de sable dans la moraine. Ce modèle est conforme aux charges hydrauliques et aux profils isotopiques observés, ainsi qu'à la présence d'eau porale tritiée à des profondeurs variées dans la moraine. Les simulations suggèrent qu'il est nécessaire que la conductivité hydraulique verticale de l'imperméable dans son ensemble soit de l'ordre de 1×10^{-9} m/s pour pouvoir reproduire les profils observés de charge hydraulique et de tritium.

Resumen Los últimos trabajos llevados a cabo en el sur de Ontario (Canadá) demuestran la existencia de velocidades verticales anormalmente elevadas del flujo de aguas subterráneas (>1 m/a), a través de un acuitardo de till arenoso (el till del Norte) que desarrolla un gran espesor (hasta 60 m). Hasta ahora, se suponía que el acuitardo tenía una permeabilidad muy baja, con valores de la conductividad hidráulica inferiores a 10^{-10} m/s. Se atribuye esta rápida recarga a la presencia de fracturas y heterogeneidades de sedimentación dentro del till, pero el régimen de flujo a escala de campo no es apenas conocido. Este estudio identifica la naturaleza de las vías físicas de las aguas subterráenas a través del till, y proporciona estimaciones de los flujos asociados. El sistema de flujo en el acuitardo se caracteriza porque integra detalles del afloramiento y de las características sedimentológicas del till con datos procedentes de investigaciones hidrogeológicas de campo y de modelación numérica. Los datos de los afloramientos y del subsuelo identifican una estratigrafía interna del acuitardo, que se compone de lechos tabulares (elementos del till) separados por intercalaciones lateralmente continuas de arenas y gravas y de cantos rodados. Los elementos individuales del till contienen heterogeneidades sedimentarias, incluyendo lentejones de arena y grava, diques verticales de arena y zonas de fracturars horizontales y verticales.

Las investigaciones hidrogeológicas de campo determinan un sistema acuitardo compuesto por tres capas: las zonas superior e inferior contienen till más heterogéneo y conductivo que la unidad intermedia. Las vías y flujo de aguas subterráneas en el till se han evalúado mediante un modelo bidimensional acuitardo/acuífero, que sugiere un mecanismo de flujo tipo escalón, según el cual las aguas subterráneas se mueven alternativamente hacia abajo (a través de vías verticales, como fracturas y diques de sedimentación) y lateralmente (a lo largo de niveles de arenas dentro del till). Este modelo es coherente con los niveles piezométricos y perfiles isotópicos observados, así como con la presencia de agua intersticial con tritio a diversas profundidades en el till. Las simulaciones numéricas sugieren que se necesita una conductividad vertical promedio del acuitardo de unos 10^{-9} m/s para reproducir la piezometría y los perfiles de tritio.

Keywords heterogeneity · groundwater flow · hydraulic properties · confining units · Canada

Introduction

Monitoring and remediation of groundwater contaminants in mid-latitude glacial terrains are increasingly dependent upon an ability to characterize, and ultimately model, the three-dimensional distribution of heterogeneity (sediment variability) and hydraulic conductivity (K) in complex glacial deposits (Anderson 1989; Nyborg 1989; Sminchak et al. 1995; Boyce and Eyles 2000). Pleistocene tills, because of their widespread extent, are the primary substrates of concern for hydrogeologic characterization of landfills and other surface contaminant sources in formerly glaciated regions (Stephenson et al. 1988). In southern Ontario, Canada, thick tills are the predominant surface materials and have long been regarded as low-permeability aquitards, capable of restricting movement of groundwater and contaminants to underlying aquifers (e.g., Sibul et al. 1977). This view has led to the widespread practice in southern Ontario of siting landfills in regionally extensive fine-grained till deposits. Recent hydrogeological work, in contrast, has identified the presence of an active groundwater flow system and relatively rapid rates (>1 m/year) of vertical groundwater flow within a thick (as much as 60 m), regionally extensive till unit (Northern till) that underlies much of southern Ontario (Boyce et al. 1995; Gerber and Howard 1996; Gerber 1999). An outstanding unresolved problem is that the mechanisms and physical pathways of groundwater flow through the till are not well understood.

Most previous work on groundwater movement in tills has emphasized the role of near-surface fracturing and deep post-glacial weathering to explain shallow groundwater movement in till deposits, particularly for the case of clay-rich tills (Williams and Farvolden 1967; Grisak and Cherry 1975; Grisak et al. 1976, 1980; Desaulniers et al. 1981; Sharp 1984; Keller et al. 1986, 1988; Cravens and Ruedisili 1987; Hendry 1988; D'Astous et al. 1989; Fredericia 1990; Jorgensen and Fredericia 1992; Simpkins and Bradbury 1992; McKay and Fredericia 1995; Klinck et al. 1996). Other work has focused on the importance of till-matrix characteristics (texture, level of compaction, micro-fabrics) or intra-till sedimentary structures (e.g., sand lenses) as potential controls on permeability (Nyborg 1989; Haldorsen and Kruger 1990; Sminchak et al. 1995). What is not currently well understood, however, is the *field-scale flow regime* in till deposits and the relative hydrogeologic importance of various pathways (i.e., fractures, sedimentary structures) in contributing to horizontal and vertical groundwater fluxes.

This paper presents the results of a detailed field and numerical model-based study of the groundwater flow regime within the Northern till aquitard in southern Ontario. The primary objectives are to identify the nature of physical groundwater pathways through the till and to provide estimates of groundwater fluxes associated with identified pathways. Permeability-enhancing sedimentary structures and fractures within the till were invento-

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ried and characterized, based on the analysis of outcrop and subsurface data. This includes analysis of both the field-scale internal geometry of the till sheet and detailed mapping of the geometry, lateral continuity, and sedimentary characteristics of smaller-scale intra-till heterogeneities. The observed sedimentary structures and fractures were simulated with a two-dimensional numerical flow model to determine the overall influence the features have on the flow system. A conceptual groundwater flow model for the till is presented that has wider applications for evaluation of deep groundwater recharge and contaminant transport in glacial terrains elsewhere.

Background

The study region includes a 750-km^2 area situated 40 km east of Toronto; locations are shown in Fig. 1. This area includes several existing municipal waste landfills and proposed waste sites investigated during recent government-funded searches for regional landfill sites (Fig. 1; M.M. Dillon Ltd. 1990; IWA 1992a, 1992b). A primary focus of the landfill investigations was to evaluate the suitability of the Northern till aquitard as a low-permeability landfill barrier (‘attenuation layer’) that would inhibit the movement of leachate to underlying aquifers. Site investigations involved detailed characterization of the subsurface geology and hydrogeology of candidate sites based on an extensive program of drilling and coring, well monitoring, and hydrochemical sampling and analysis (M.M. Dillon Ltd. 1990; IWA 1994a, 1994b, 1994c, 1994d, 1994e). This work identified unexpectedly rapid rates of recharge through the till, as evidenced by the presence of young (<40 years), tritiated pore waters at various depths throughout the aquitard and locally within an underlying aquifer (Thorncliffe Formation). Ongoing university-funded work at several sites (P1, EE11, UT1/94, UT2/94; Fig. 1) has been aimed at better resolving the nature of groundwater flowpaths through the Northern till based on isotopic analyses, surface and borehole geophysics, and regional groundwater modeling studies (Boyce et al. 1995; Boyce and Koseoglu 1996; Gerber and Howard 1996, 2000; Boyce and Eyles 2000). The following sections summarize this work as background to the discussion of 2-D modeling of groundwater flow in the Northern till.

Physical and Hydrogeologic Setting

The study area is located on a low-relief till plain that extends northward from Lake Ontario to the Oak Ridges Moraine (Fig. 1). The moraine comprises a west–east trending sand and gravel-cored ridge that forms a major groundwater recharge area and drainage divide in south-central Ontario (Sibul et al. 1977; Singer 1981; Howard et al. 1997). Pleistocene deposits have a maximum thickness of more than 200 m below the western end of the moraine (Duckworth 1979; Barnett et al. 1998). The surficial geology of the study area, shown in the section of Fig. 2, consists of an uppermost package of late Pleistocene till deposits (Halton and Northern tills) overlying glaciolacustrine sediments and Ordovician shale bedrock. The Northern till is a thick (as much as 60 m), regionally extensive till unit that can be traced northward of the study area below the Oak Ridges Moraine; the till was deposited by southward-flowing ice during the last (Late Wisconsin) glacial maximum (Boyce et al. 1995). The surficial Halton Till records a final ice re-advance toward the northwest from the Lake Ontario basin and is separated locally from the underlying Northern till by thin, discontinuous interstadial sand and gravels that are correlative with the Oak Ridges Moraine. Locally, the Halton Till is draped by thin glaciolacustrine clays and silts deposited in small ice-marginal glacial lakes during ice retreat (Lake Markham deposits, Fig. 1).

The Northern till is an overconsolidated diamict consisting of a mixture of granitic, gneissic, and carbonate pebble- and boulder-sized clasts suspended in a silt to silty-sand matrix. Because of its regional extent, thickness, and texture, the Northern till forms an important regional aquitard that confines several underlying overburden aquifer systems (Sibul et al. 1977; Gerber and Howard 1996; Howard et al. 1997; Gerber and Howard 2000). Within the study area, deep aquifers occur within thick deltaic sands and silts of the Thorncliffe and Scarborough Formations (Fig. 2). These aquifers are the primary source for domestic and agricultural water supplies in rural areas northeast of metropolitan Toronto. Locally, shallow aquifers are also exploited within thin interstadial gravels that separate the Northern and Halton tills (Fig. 2).

Hydrogeologic Evidence for Rapid Groundwater Recharge

Recent work has focused on quantification of groundwater recharge mechanisms and fluxes within the Northern till, based on isotopic analysis of till pore waters (Gerber and Howard 1996; Gerber 1999). Isotope profiles shown in Fig. 3 illustrate the presence of tritiated waters at various depths within the till and indicate that a component of recent meteoric water recharged since 1953 has entered the system. At nest locations P1–16 (Fig. 3c) and P1–17 (Fig. 3d), tritium occurs in the till at each of the depths sampled. More detailed sampling at nest locations UT1/94 (Fig. 3a) and UT2/94 (Fig. 3b) indicates the presence of tritiated and non-tritiated waters and suggests a mixing of recent and older meteoric waters. Analysis for tritium has not been conducted at piezometer nest location EE11–1 (Fig. 3e). Stable-isotope profiles ($\delta^{18}O$, $\delta^{2}H$) for all five sites (Fig. 3a–e) show little or no depletion in stable-isotope ratios with increasing depth. These profiles are in sharp contrast with the profile of smoothly increasing $\delta^{18}O$ depletion with depth that would be expected for a relatively low-permeability, homogeneous aquitard with net downward vertical ground-

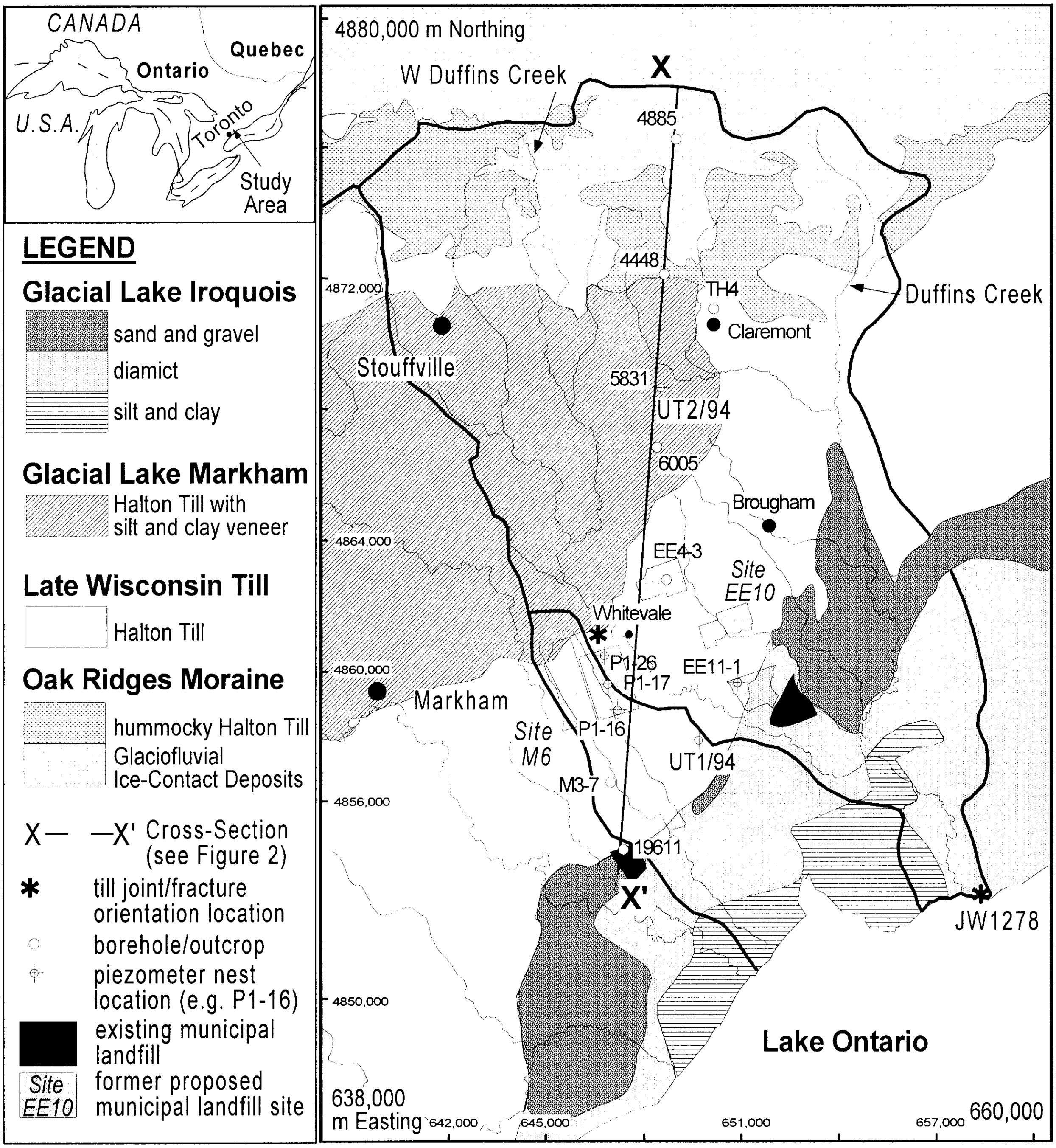

Fig. 1 Study area showing location of investigated sites and generalized surficial geology. (Modified after Barnett et al. 1991; Barnett 1996; Barnett and McRae 1996; Sharpe and Barnett 1997; Westgate, unpublished data 1978)

water flow (Remenda et al. 1994, 1996). In these more homogeneous low-permeability aquitards, solute transport is dominated by diffusion, and advective transport is likely to be negligible. The irregular stable-isotope profiles and the presence of tritiated waters exhibited at five separate Northern till study sites (Fig. 3) strongly suggest the presence of permeability-enhancing sedimentary structures such as sand beds, fracture discontinuities, or both, within the till.

A low-permeability homogeneous or uniformly fractured aquitard would also show a uniform vertical hydraulic gradient (i_v) through the unit. Such a gradient does not occur in the Northern till, where hydraulic heads at relatively shallow depths are higher than expected and hydraulic heads at greater depth within the till are less than expected for a homogeneous aquitard (Fig. 3). Anomalous head profiles in tills have previously been attributed to malfunctioning of piezometers due to casing leakage (van der Kamp and Keller 1993). In the Northern till, this irregular pattern is also observed in

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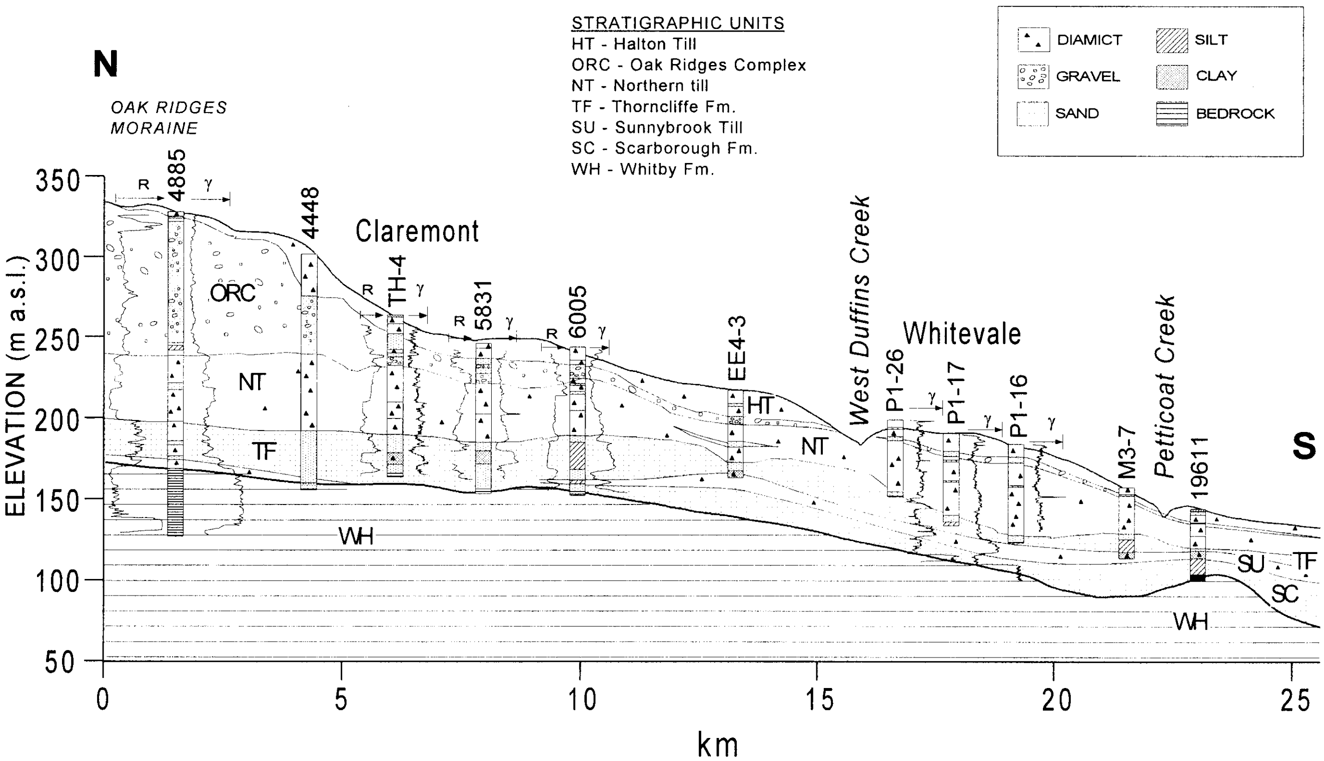


Fig. 2 North–south cross section showing subsurface geology and hydrostratigraphy of the south slope of the Oak Ridges Moraine and study area. Borehole geophysical resistivity (*R*) and gamma (γ) logs are shown where available. See Fig. 1 for cross-section location. (After Boyce 1997)

buried vibrating wire-type piezometers in which there is no casing leakage, zero storage, and hence no piezometer time lag. This situation suggests that the observed hydraulic-head anomalies reflect hydrogeologic conditions and are not a result of malfunctioning piezometers.

Slug-test estimates of K for the Northern till range over 7 orders of magnitude, from 10^{-12} to 10^{-5} m/s (Gerber and Howard 2000). The isotope profiles, hydraulic-head profiles, and slug-test data all indicate the presence of heterogeneities or zones of higher K within the till. These data are supported by regional, three-dimensional groundwater flow modeling of the aquitard, which provides constraints on the range of possible K values for the till (Gerber and Howard 2000). The calibrated model outputs indicate a range of estimated Northern till regional bulk K values from 5×10^{-10} to 5×10^{-9} m/s, with a maximum (downward) vertical darcy flux of 35 mm/year. These bulk K estimates are consistent with those from a two-dimensional numerical analysis of annual hydraulic-head transients in adjacent aquifers (Gerber 1999). The estimates are significant in that they are as much as 2.5 orders of magnitude greater than K estimates for the till matrix material estimated from slug tests and laboratory triaxial permeability testing (1×10^{-11} to 1×10^{-10} m/s; Gerber and Howard 2000). The maximum K value for sand bodies within the Northern till, as estimated by in-situ K testing (slug tests), is 1×10^{-5} m/s (M.M. Dillon Ltd. 1990; IWA 1994e; Gerber and Howard 1996).

Field Methods

Detailed site investigations were carried out at six sites near Whitevale, Ontario. A total of 85 boreholes were drilled and continuously cored to depths of as much as 60 m using HQ (94 mm) wire-line diamond drilling. Test pits were excavated with a backhoe to depths of 2–5 m at five locations at site EE11. The vertical succession of lithofacies, fractures, and other sedimentary structures in the core was logged in detail, and samples were collected at various intervals for physical-property (grain size, porosity, water content, hydraulic conductivity) and isotopic analysis. Selected deep boreholes at each site were geophysically logged using natural gamma, electromagnetic (EM) conductivity, and temperature probes and were correlated with nearby well-exposed till outcrops (Boyce and Eyles 2000).

A broad range of hydrogeological field testing and monitoring was completed at each site, including measurement of hydraulic heads, slug and pumping tests, and groundwater sampling and analysis (Gerber 1999). Borehole-drilling methods, piezometer installation, tritium sampling, and analysis details are included in Gerber and Howard (1996). A brief summary is included here. Boreholes were advanced using hollow-stem augers, mud rotary, and air rotary. Boreholes were installed with either a 19- or 51-mm inner diameter, Schedule 80, flush-threaded PVC pipe with rubber O-rings at the joints. Commercially slotted PVC screen formed the intake at

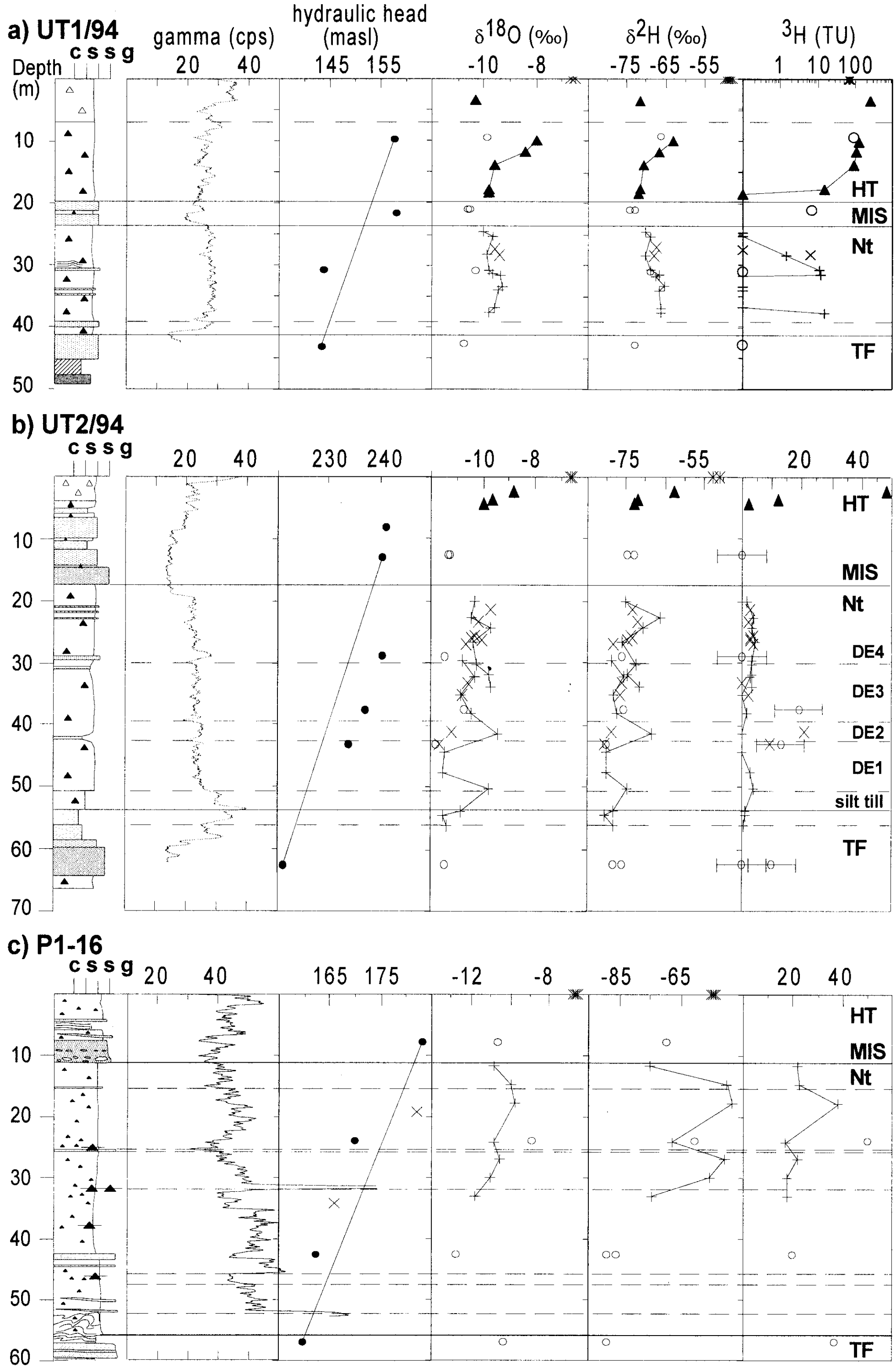


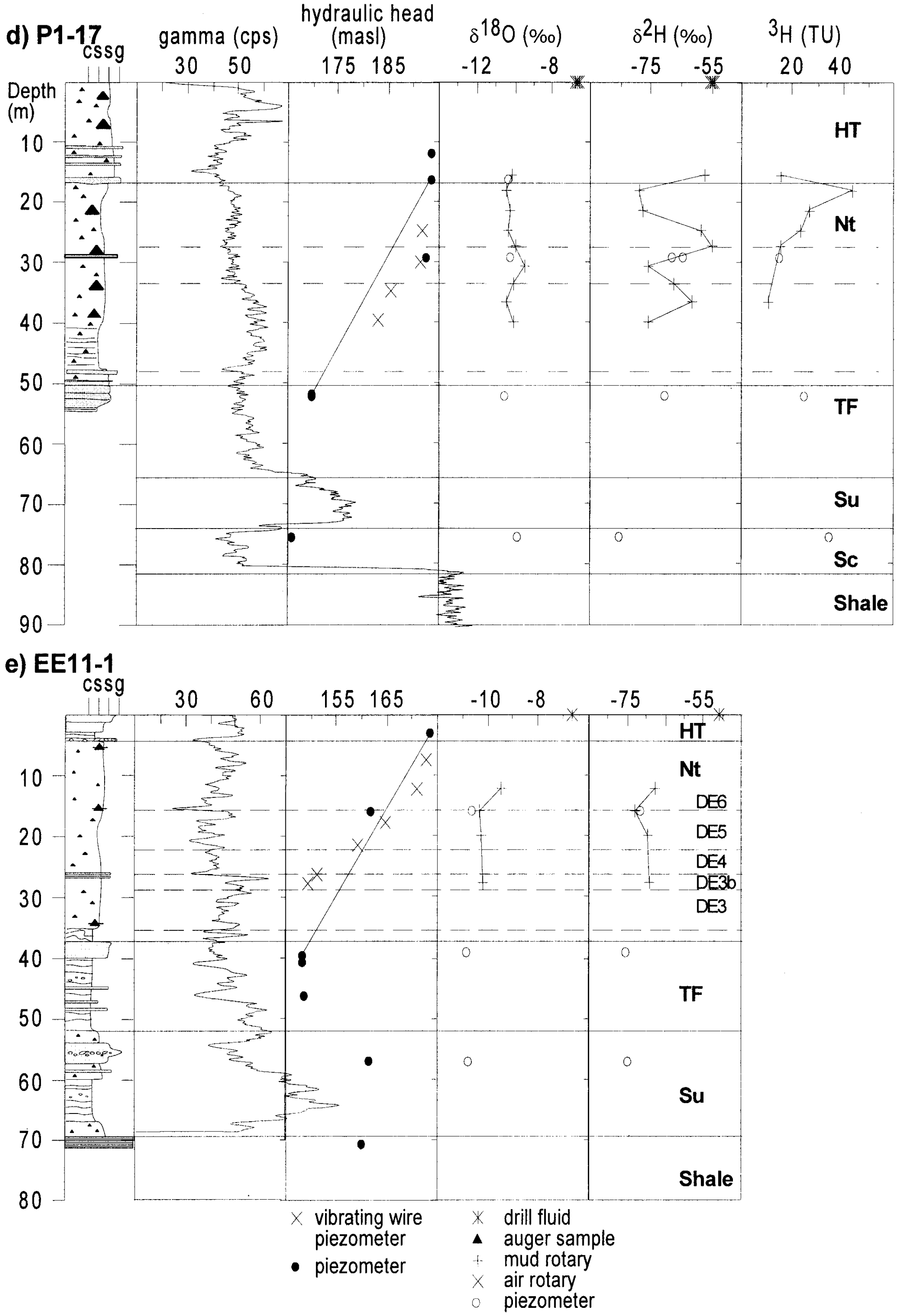
Fig. 3 Composite profiles showing core log, natural gamma log, hydraulic head, and stable isotopes ($\delta^{18}O \pm 0.2$‰; $\delta^{2}H \pm 2$‰) for five investigated sites (**a** UT1/94; **b** UT2/94; **c** P1–16; **d** P1–17; **e** EE11–1). Tritium precision ranges not shown occur within extent of sample symbol. *HT* Halton Till; *MIS* Mackinaw Interstadial deposits; *Nt* Northern till; *TF* Thorncliffe Fm; *Su* Sunnybrook Diamict; *Sc* Scarborough Fm. See Fig. 1 for site locations. Note that tritium is plotted on logarithmic scale in **a**. (Data from M.M. Dillon Ltd. 1990; IWA 1994e; Gerber and Howard 1996)

lengths less than or equal to 1.5 m. Silica sand was placed within the borehole annulus to a depth 1 m above the top of the screen. Bentonite pellets were used to form a 1-m-thick seal above the sand pack. The remaining annulus was filled to ground surface with a bentonite slurry grout or bentonite gravel.

Two types of samples were collected for isotopic analysis. Formation waters were pumped from piezometers and pore waters were extracted from till core samples using a standard azeotropic distillation technique (Gerber and Howard 1996). Analyses for ^{18}O, ^{2}H, and tritium were conducted at the University of Waterloo Environmental Isotope Laboratory using conventional preparation and analysis techniques.

Geokon 4500S vibrating wire pressure transducers were installed at multiple levels within selected bore-

Fig. 3d, e



holes. The pressure transducer was situated in the middle of a 0.75- to 1-m interval of silica sand. The open borehole between installation levels was filled with bentonite pellets.

Aquitard Geometry and Heterogeneity

A key component of this study involved identification of permeability-enhancing sedimentary structures in the till, based on analysis of outcrops, core samples, and borehole geophysical logs collected at six separate study sites (Fig. 1; sites P1, EE4, EE10, EE11, UT1/94, and UT2/94). Analysis was conducted at two scales: (1) ex-

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amination of the site-scale *internal architecture* (geometry) of the till, and (2) categorization of smaller-scale, *intra-till heterogeneity* observed in cores and in outcrops.

Site-Scale Aquitard Geometry

Evaluation of the site-scale geometry of the Northern till involved subdivision of the aquitard into architectural elements, which are defined as distinct ‘packets’ of strata with internally consistent sedimentary characteristics or facies (Miall 1988, 1992). This approach, termed ‘architectural-element analysis’, was originally developed for characterization of heterogeneity and permeability trends in hydrocarbon reservoirs (Friend 1983; Miall 1992; Davis et al. 1993) but has recently been adapted for use in glacial deposits (Boyce and Eyles 2000). A major advantage for hydrogeologic characterization studies is that boundaries between architectural elements frequently correspond to changes in K and porosity and are useful for defining hydrostratigraphic units (Lake and Carrol 1986; Anderson 1989; Boyce and Eyles 2000).

Architectural elements were identified in the Northern till based on recognition of distinctive assemblages of ‘like’ sedimentary facies and the presence of bounding erosion surfaces in drill core logs, borehole geophysical data (gamma, EM conductivity, temperature), and outcrops (Boyce and Eyles 2000). This analysis reveals that the Northern till is a composite till unit, consisting of three distinctive architectural-element types, which are shown schematically in Fig. 4. Table 1 summarizes the characteristic scale and geometry of elements based on field and laboratory data.

Diamict elements consist of tabular till beds as much as several metres in thickness that record vertical aggradation of the Northern till during successive depositional events. Examples are illustrated in Fig. 5. Till elements are bounded by horizontal to gently dipping erosion surfaces that are overlain by thin sand and gravel beds (see below) or discontinuous boulder concentrations (Figs. 4 and 5b). Correlation of bounding erosion surfaces in drill core and gamma logs at the P1 site demonstrates that individual till elements have an areal extent of at least 4 km^2 (Boyce and Eyles 2000).

Interbed elements consist of sheet-like beds of glaciofluvial sand and gravel that separate individual till elements. Interbeds are as thick as 2 m and can be correlated as continuous beds over distances of 500–1,000 m in borehole data (Boyce and Eyles 2000). Pumping tests and piezometer responses during drilling of individual sandy interbeds suggest that the interbeds are hydraulically interconnected (IWA 1994e). The presence of active groundwater flow in interbeds is also indicated by the presence of well-developed seepage faces in outcrop (Fig. 5a).

A third architectural-element type, categorized here simply as a ‘deformed zone’ (Figs. 4 and 5d), consists of glaciotectonically deformed lacustrine sand and silt incorporated into till elements by folding and thrusting. Deformed zones have a limited lateral extent and thickness (<10 m; Table 1) and are preferentially developed at the base of the Northern till where ice has locally detached and deformed underlying Thorncliffe Formation sediments (Fig. 6d). The presence of deformed zones results in an increase in the bulk K at the base of the Northern till, which is in direct hydraulic communication with the underlying aquifer (Fig. 5d; Gerber 1999).

Table 1 Summary of architectural elements and sedimentary facies identified in the Northern till aquitard. Characteristic scale of architectural elements given as length (*L*), thickness (*T*), area (*A*), and L/T ratio. (After Boyce and Eyles 2000)

Architectural elements in Northern till		Code	Outcrop (2-D) geometry	Approx. scale	L/T	Inferred processes
Diamict element		DE	Tabular diamict beds, planar to gently undulatingbounding contacts; boulder pavement often marking upper surface	>100 (L), <10 m (T), >10^3 m^2 (A)	>10	Subglacial aggradation of deformation till
Interbed	Coarse	I-c$_1$	Laterally continuous, sheet-like sands and gravels separating diamict elements	>100 m (L), <5 m (T),) 10^3 m^2 (A	>25	Ice-bed separation; erosion and deposition by subglaciofluvial meltwater sheet flow
		I-c$_2$	Laterally discontinuous sand and gravel body, with pinch and swell geometry	<10 m (L), <1 m (T), 10^2 m^2 (A)	<10	Ice-bed separation; localized incision by subglaciofluvial meltwater sheet flow
	Fine	I-f	Laterally continuous tabular silt and mud units separating diamict elements	>10 m (L), <1 m (T), 10^2 m^2 (A)	>10	Ice-bed separation, low-energy sedimentation in subglacial water body
Deformed zone		DZ	Undulatory zone of deformed till and thrusted sediments at base of till sheet; variablethickness and spatial extent	Variable (L), <10 m (T), 10^2 m^2 (A)	?	Subglacial deformation of pre-existing strata

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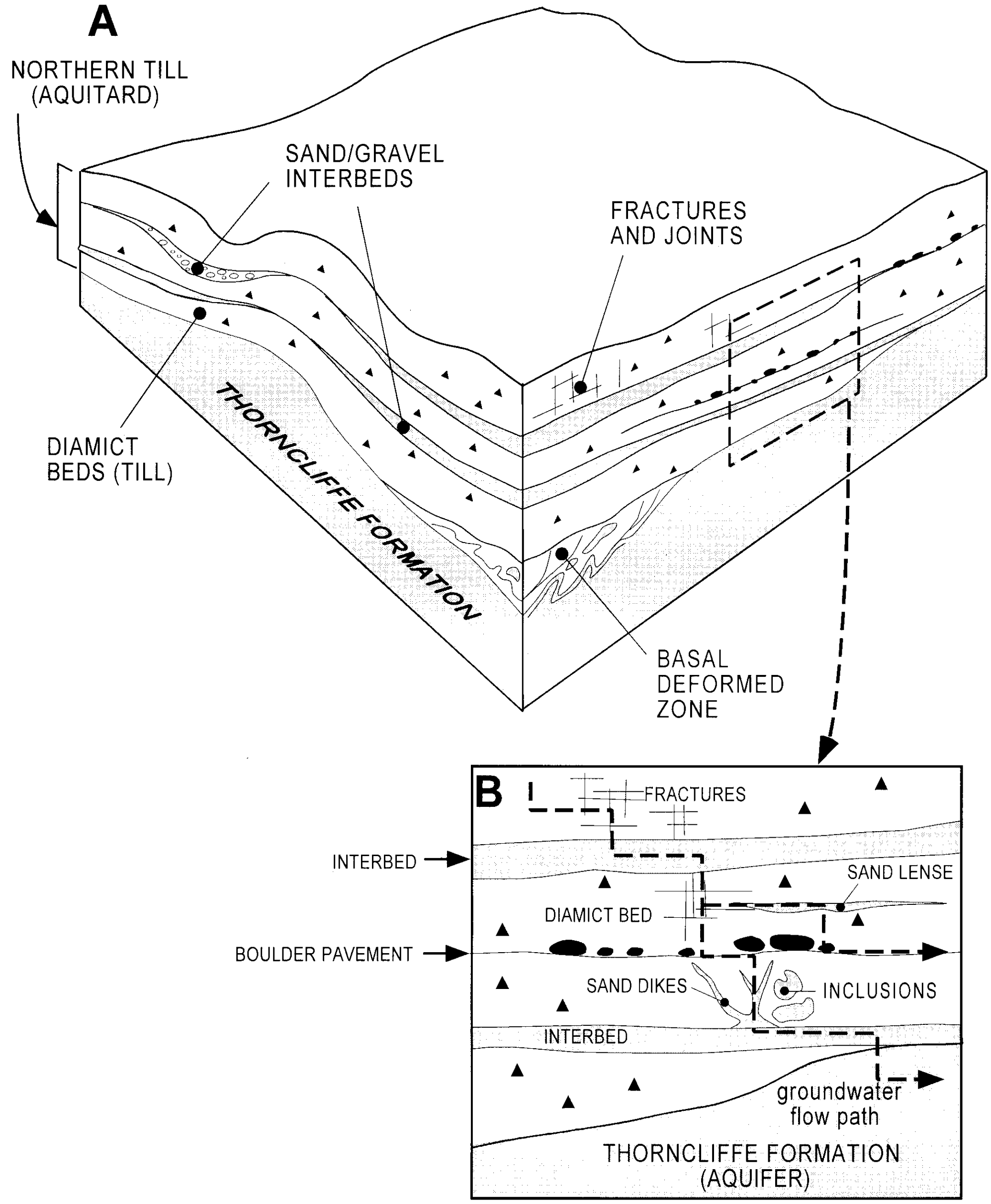

Fig. 4 **a** Large-scale composite internal architecture of the Northern till aquitard; **b** small-scale sedimentary heterogeneities identified in cores and outcrops. Elements not shown to scale. See Tables 1 and 2 for approximate scales

Intra-till Heterogeneity

The distribution of smaller-scale intra-till heterogeneities was evaluated by detailed inventory of sedimentary structures in cores and in outcrops. Emphasis was placed on description of the lateral continuity, thickness, spacing and characteristic geometry of sedimentary structures; characteristics are summarized in Table 2. The occurrence of fracturing and jointing in the aquitard was also evaluated based on analysis of outcrops, test-pit exposures, and core samples obtained from two angled (45°) boreholes drilled at the P1 site (Fig. 1). Field data show that fracture spacings are highly variable and that fractures tend to be more closely spaced in the upper part of the till. The minimum fracture spacing observed in test pits was 0.02 m within the upper 2 m of the till (IWA 1994e). The maximum fracture spacing observed in outcrop is as much as 50 m but is difficult to quantify due to the limited extent of Northern till exposures (<200 m).

Figure 6 and Table 2 illustrate some examples of intra-till heterogeneities. The most commonly observed intra-till structures are silt and sand laminae and thin (<5 cm) silt, sand, and gravel lenses that have limited lateral continuity (<5 m; Fig. 6b, c). The presence of sand and silt lenses in the subsurface is indicated by sand and silt partings in core samples, and by zones of decreased gamma counts (Fig. 3) and variations in EM conductivity on geophysical logs (Boyce and Eyles 2000). Drill-core data from sites P1, M6, and EE11 show that sand lenses are more abundant within the upper 5 m and the lower 10 m of the till, where they are associated with zones of no core recovery and saturated, soft, sandy till. In contrast, the middle section of the till (ca. 35 m thick) is made up of much more compact, homogeneous

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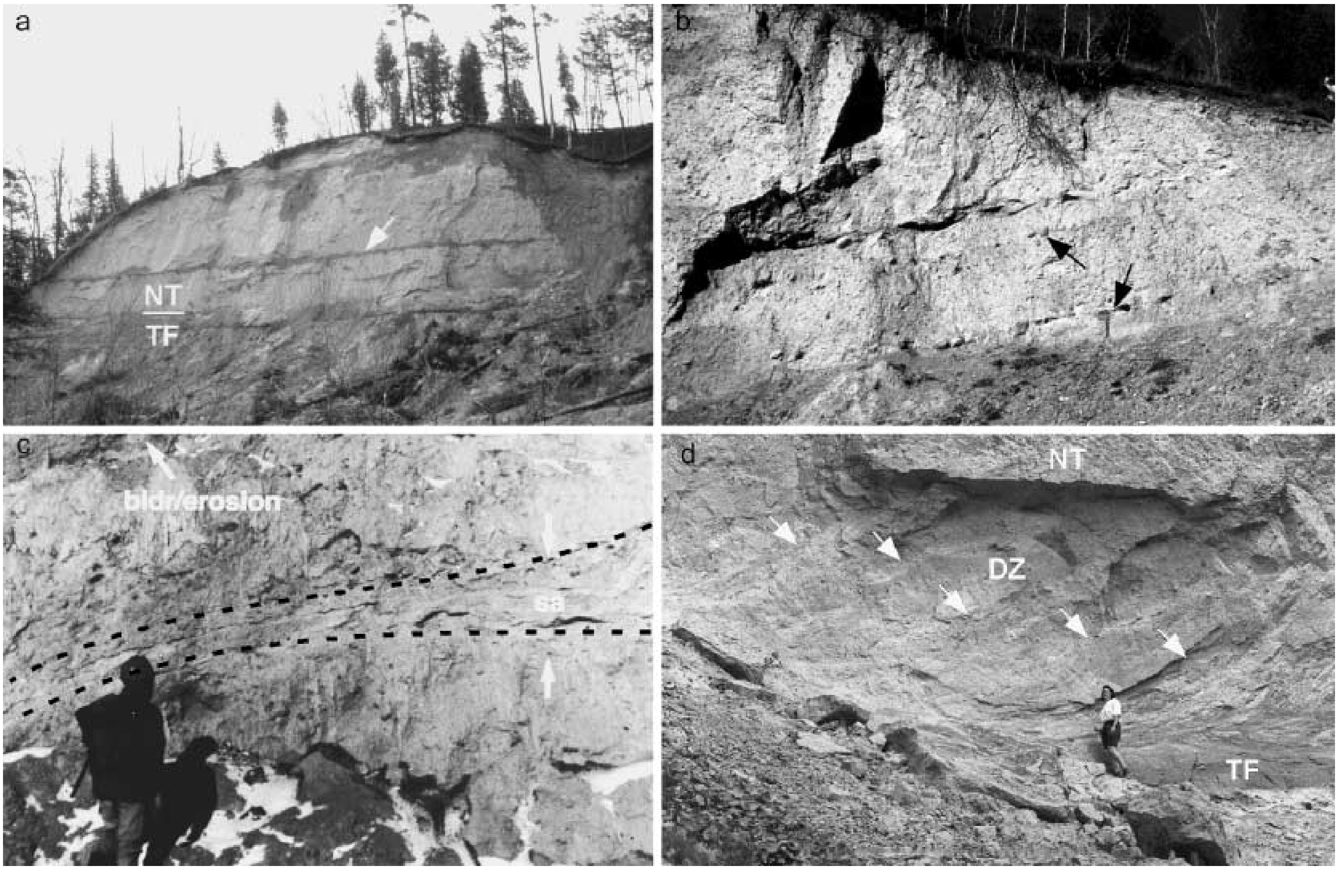

Fig. 5 Principal architectural elements within Northern till. **a** Sand interbeds marked by seepage (*arrow*); *NT* Northern till; *TF* Thorncliffe Formation; **b** Diamict element bouonded by linear boulder concentrations (*arrows*); **c** sand interbed with included till clasts; *bldr/erosion* erosion surface marked by boulder concentrations; *sa* sand; **d** basal deformation zone (*DZ*) showing thrusting and incorporation of *TF* deposits (*arrows*). Person for scale standing in *TF* sands

till elements that contain widely spaced (ca. >2.5 m) sand and silt lenses. Sminchak et al. (1995) demonstrate that similar sand lenses in tills in Ohio are hydraulically interconnected and are predominant pathways for horizontal groundwater movement.

Other sedimentary structures providing potential groundwater pathways include blocks and deformed inclusions of sorted sediment (Fig. 6d), localized clast concentrations, linear concentrations of pebbles, sand dikes, diapirs, and fractures. Examples of fractures are illustrated in Fig. 7. Sand dikes and diapirs (Figs. 6a and 7a) result from over-pressuring of sorted sediment lenses and interbed elements under glaciostatic load, and they occur over a wide range of scales. Thin sand-filled dikes at shallow depths in the till at two locations have oxidation halos, indicating active vertical groundwater movement. Dikes are vertical to subhorizontal and are as much as 10 cm wide.

Test pits and well-exposed outcrops reveal the presence of vertical and horizontal joints within the upper part of the Northern till. In test pits, joints extend as much as 2 m into the upper surface of the Northern till, with minimum spacings of 0.02–0.04 m. Below this depth, no vertical oxidized joint surfaces are visible; however, well-developed vertical joints and horizontal fractures developed and rapidly widened approximately 1–2 h after excavation of test pits. Vertical joints commonly consist of two sets at approximately 90°. Similar joint sets exposed in two till outcrops show preferred orientations at 70–80° and 330–340° azimuth, as shown in Fig. 8.

Horizontal fractures consist of undulatory and crudely planar partings in the till (Fig. 7d) and have variable spacing and continuity. Fracture apertures were not measured because the width of horizontal and vertical discontinuities in the till varies considerably and quantitative measurement is complicated by progressive widening of fractures as a result of stress-release within test pits.

The presence of fractures and joints at depth within the Northern till could not be positively identified based on logging of more than 3,000 m of core samples, including two 45°-angled boreholes continuously cored to 70 m depth. The general absence of fracture discontinuities in core may reflect closure of apertures with depth, wide joint spacing, inadequate sampling volume (borehole spacing >50 m), the inability to positively distinguish fractures from core breaks induced by the drilling process, or some combination of the above. Several well-exposed outcrops on West Duffins Creek (Fig. 7b, c, and

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Fig. 6 Small-scale intra-till heterogeneities in Northern till. **a** Vertical sand dike; **b** silt laminations in till core; **c** sand lens in till; **d** sorted sediment inclusions derived from underlying Thorncliffe Fm

d), however, do demonstrate the presence of widely spaced vertical joints within the till that penetrate the entire thickness of the till outcrop (Gerber 1999).

Groundwater Flow Modeling

Groundwater flow simulations were conducted with the overall objective of identifying the hydrogeologic importance of the sedimentary structures and fractures as pathways for groundwater movement through the Northern till. As demonstrated by field data, the spacing and width of sand bodies and fractures are variable and difficult to characterize from limited outcrops and test pits. The relative scale and spacing of vertical non-matrix structures can be evaluated, however, through numerical modeling, which constrains the possible range of fracture spacings required to reproduce the observed isotopic profiles and hydraulic-head conditions in the aquitard. The aquitard-aquifer system was modeled using the finite-element model FRACTRAN, which permits two-dimensional simulation of steady-state groundwater flow and transient contaminant transport in porous or discretely fractured porous media (Sudicky 1989; Sudicky and McLaren 1998). Within the model, rectangular finite elements represent the porous media, whereas one-dimensional line elements represent fractures and other structures. The groundwater flow system for the study area is considered to be at steady state based on the long-term streamflow and hydraulic-head data (Gerber 1999; Gerber and Howard 2000).

Selection of model-input parameters was constrained by geologic and hydrogeologic field data, including: (1) till matrix and sand-body K estimated by laboratory triaxial tests and slug tests, measured hydraulic heads, isotope profiles, and depth of tritium penetration; and (2) maximum vertical fluxes from a regional three-dimensional groundwater flow model (Gerber and Howard 2000) and a two-dimensional analysis of hydraulic-head transients (Gerber 1999). The use of such constraints is critical because the solutions to the equations of flow are non-unique and may be satisfied by a large number of combinations of input parameters (Anderson and Woessner 1992). The modeling procedure involved successive runs of each scenario with incremental changes of a single parameter within the ranges constrained by field data. The results of each run were then evaluated to determine the effects of perturbation of each parameter in turn on the overall behavior of the groundwater flow system. The groundwater flow simulations first consider a generic case followed by an application to a site-specific case.

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Table 2 Summary of characteristics of small-scale heterogeneities identified within individual till elements. Approximate scale is given as length (*L*), thickness (*T*), and area (*A*). (Modified from Boyce and Eyles 2000)

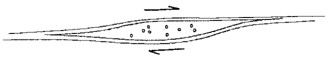
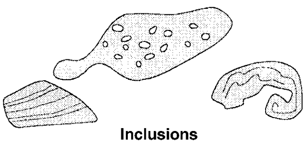
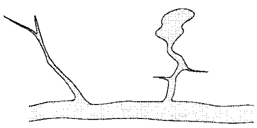
Structure	Outcrop (2-D) geometry	Approx. scale	Inferred processes
 Laminae	Discontinuous horizontal to undulatory siltand clay partings in diamict matrix	<1 m (L), <1 mm (T)	Minor reworking of diamict by meltwater flows or subglacial shearing of included sediments within deforming till
	Lensate or planar beds t of sorted sedimen	<5 m (L), <10 cm (T)	Subglaciofluvial deposition at ice-bed interface
 Lenses	'Augen-like' shear lenses	<1 m (L), <50 cm (T)	Shearing of sediment inclusions within deforming till
 Inclusions	Pods, blocks, and irregular-shaped raftsof sorted sediment	<5 m^2 (A)	Incorporation and partial assimilation of sorted sediments within deforming till layer
 Clast clusters	Irregular or pod-like concentrations of granule- to pebble-sized clasts	<1 m^2 (A)	Nucleation of clasts around lodged boulders in till
 Stone lines	Linear concentrations of granule- to pebble-sized clasts	<1 m (L), <10 cm (T)	Localized erosion and reworking of upper surface of till
 Clastic dikes and diapirs	Vertical to subhorizontal clastic dikes and diapirs	<5 m (L), <10 cm (T)	Subglacial over-pressuring and liquefaction of sorted sediment interbeds

Table 3 Hydraulic input parameters for aquitard/aquifer system. D_d is the free solution coefficient 1.8×10^{-5} cm^2/s; ω is an empirical coefficient taking into account effects of solid phase on diffusion. ω is typically 0.5–0.01; 0.7 for sand in column experiment (Freeze and Cherry 1979). Dispersivities and diffusion coefficient from Sudicky and McLaren (1992). Aquitard D* is similar to the value of 5×10^{-6} cm^2/s estimated for Saria-area till (Desaulniers et al. 1981; Desaulniers 1986)

Parameter	Symbol	Units	Aquitard	Aquifer and interbeds
Hydraulic conductivity	K	m/s	1.E-10	1.E-05
Porosity	n		0.15	0.30
Longitudinal dispersivity	α_L	m	0	0.1
Transverse dispersivity	α_T	m	0	0.01
Effective diffusion coefficient ($D^*=\omega D_d$)	D*	cm^2/s	7.2E-06	1.3E-05

Model Domain and Input Parameters

The generic model domain consists of a 40-m-thick aquitard overlying a 5-m-thick aquifer. The domain is a rectangular cross section that is 45 m thick and 1,000 m long. The physical system is discretized using 401 horizontal nodes (delta x max=2.5 m) and 184 vertical nodes (delta z max=0.25 m), for a total of 73,784 nodes and 73,200 elements. The top of the aquitard is defined by a constant-head boundary that decreases from a maximum of 46 m at the left corner to 45 m at the right corner. Constant-head boundaries at each end of the aquifer are fixed to give a bulk i_v through the aquitard of 0.5 downward and an aquifer horizontal hydraulic gradient of 0.001 from left to right, consistent with observations from the study area (Gerber and Howard 2000). The hydraulic parameters for the aquitard and aquifer are summarized in Table 3. All fractures are given an aperture of 25 µm and a longitudinal dispersivity of 0.1. Because quantitative fracture aperture data are not available for the Northern till, a value of 25 µm is used based on tracer tests conducted in weathered clay till near Sarnia, Ontario (D'Astous et al. 1989; McKay et al. 1993). The experimental data from clay tills near Sarnia indicate that fracture apertures are as great as 43 µm, but they are generally less than 25 µm. Fracture apertures in the

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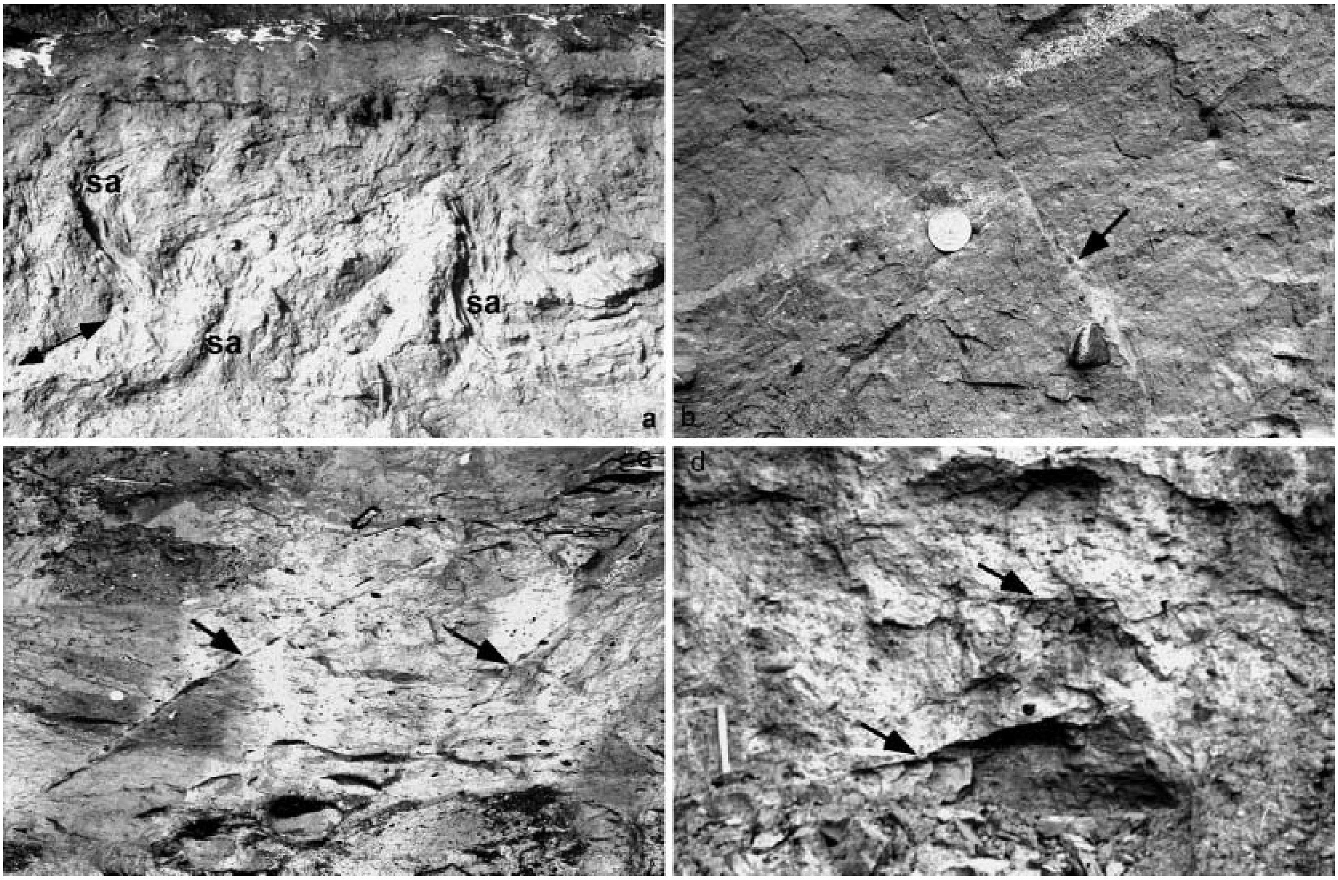

Fig. 7 Northern till non-matrix structures. **a** Deformed (folded and subsequently faulted) sand diapir (*sa*); fault trace marked by *arrow*; **b** vertical fractures infilled with silt with no visible alteration halo; **c** vertical fractures with visible alteration halo; **d** low-angle shear surfaces that intersect horizontal fractures

Sarnia area do not decrease with depth, as would be expected with an increase in confining stress with depth (Sims et al. 1996). Injection of silt into fractures as observed within Northern till outcrops (Fig. 7b) may allow fractures at depth to remain open and therefore have a larger aperture width. The hydraulic conductivity for the fractures (K_f) is 5×10^{-4} m/s, according to the following relationship (Snow 1968, 1969):

$$K_f = (b)^2 \frac{\rho g}{12\mu} \tag{1}$$

where ρ is fluid density, g is the acceleration due to gravity, b is the fracture aperture, and μ is the kinematic viscosity of water. The matrix K for the Northern till consistently ranges from 1×10^{-11} to 1×10^{-10} m/s (Gerber and Howard 2000). Equation (1) assumes flow through frac-

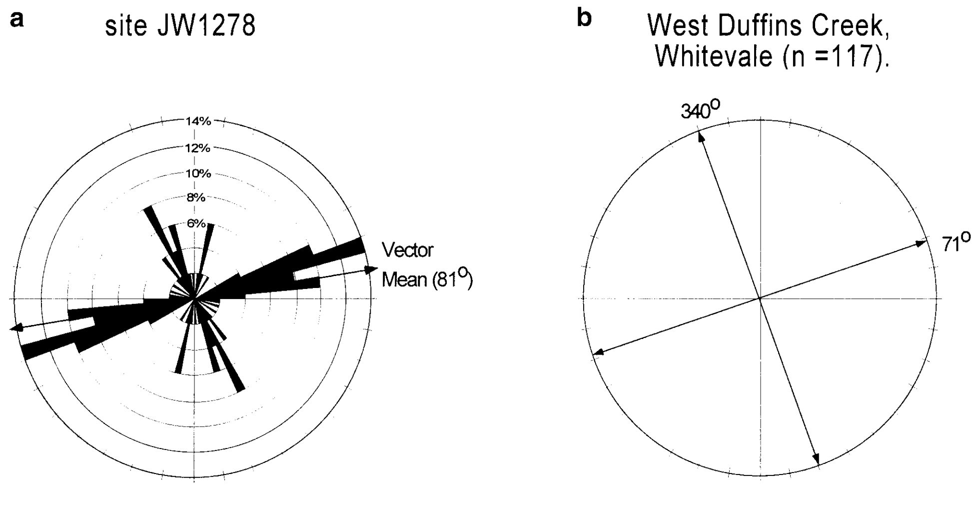

Fig. 8 Representative fracture orientations in Northern till. Locations are shown in Fig. 1. **a** Vertical joints in Northern till, n=50 (Westgate, unpublished data 1978); **b** mean trend of vertical joints in Northern till, n=117 (Eyles and Scheidegger, unpublished data 1992)

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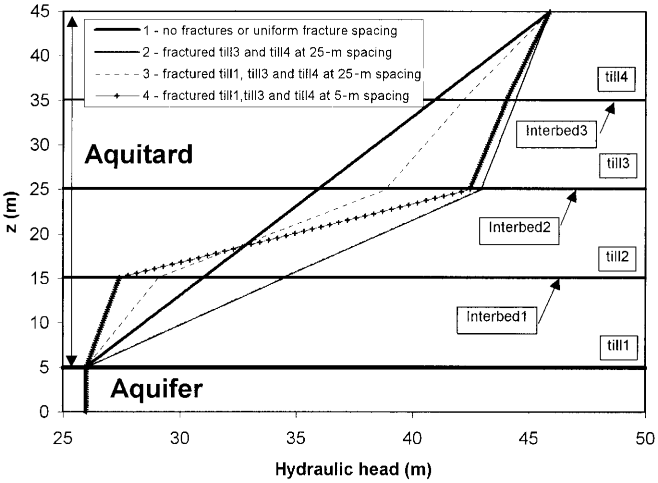

Fig. 9 General aquitard/aquifer system showing relation between FRACTRAN calculated hydraulic head and depth at *x*=500 m

tures is analogous to laminar flow between two parallel plates. The effects of fracture roughness are ignored in this analysis.

Modeled Head Profiles

The observed hydraulic-head profiles in the Northern till aquitard (Fig. 3) show a tripartite subdivision. Hydraulic-head values in the upper part of the aquitard are higher and the hydraulic heads at depth are lower than would be expected for a homogeneous or uniformly fractured aquitard. The change from higher-than-expected hydraulic head to lower-than-expected hydraulic head occurs within the till element with the lowest *K*.

The effects of fracturing on the aquitard hydraulic-head profiles are shown in modeled profiles in Fig. 9. For each simulation, the aquitard was modeled as four discrete till elements of equal thickness, each separated by a sand interbed 10 cm thick. Simulation 1 shows a pattern of uniform hydraulic-head decline down through the aquitard for the case of an unfractured or a uniformly fractured aquitard. The remaining scenarios, shown as simulations 2, 3, and 4 (Fig. 9), illustrate the effects of non-uniform fracturing of the aquitard. The presence of fractures within individual till elements tends to increase the hydraulic connection between adjacent aquifers (see simulation 2, Fig. 9). The largest vertical head decline occurs across the area of lowest *K*, or in this simulation the non-fractured till elements (till 1 and till 2), consistent with the hypothetical case presented by Harrison et al. (1992). The calculated hydraulic-head profiles shown for the configuration where till elements 1, 3, and 4 are fractured (Fig. 9; simulations 3 and 4) reproduce a tripartite hydraulic-head profile very similar to observed profiles (Fig. 3). The effects of varying fracture spacing are illustrated by comparing simulations 3 and 4 in Fig. 9. An increase in the fracture spacing from 5 m (simulation 4) to 25 m (simulation 3) decreases the degree of hydraulic connection between the aquitard and adjacent aquifers, as indicated by the increase in i_v across till element 2 (till 2). In the above cases, till element 2 has been modeled as unfractured. Alternatively, this unit could have been modeled with more widely spaced fractures than the other till elements. The largest head decline, or greatest i_v, occurs over the lowest *K* interval within the till. Although till element 1 (till 1) is represented as fractured in this scenario, other permeability pathways such as deformed zones, consisting of included Thorncliffe Formation sands and silts, are also likely to be of importance.

Modeled Tritium Profiles

Isotope profiles through the Northern till at five locations within the study area (Fig. 3) show zones of tritiated water at various depths within the aquitard. For the Northern till, the presence of tritiated waters at concentrations above 1 tritium unit (TU) suggests some component of meteoric water recharged since 1952, as discussed by Gerber and Howard (1996). The presence of alternating tritiated and non-tritiated waters within the aquitard, as sampled in vertical boreholes, suggests the presence of both vertical and horizontal structures or pathways.

The conceptual model of solute migration through the Northern till consists of a combination of horizontal and vertical flow, here referred to as “step-wise” flow. Horizontal flow occurs along interbeds, whereas vertical flow occurs along fractures and sand dikes. The presence of tritium halos associated with horizontal interbeds, as discussed in Gerber and Howard (1996), provides evidence of active flow along till interbeds. Pumping of piezometers installed within interbeds induces a drawdown within adjacent interbed piezometers at numerous nest locations at site EE11 (IWA 1994e). The presence of seepage from interbeds at outcrops also suggests that active flow occurs along these till structures (Fig. 5a).

For a non-fractured or uniformly fractured aquitard, contaminant transport is vertically downward, generally following the bulk i_v. Although bulk hydraulic gradients through aquitards are generally considered to be vertical, Harrison et al. (1992) present a hypothetical case where a highly fractured clay aquitard has significant local horizontal hydraulic gradients induced and controlled by conductors such as fractures. For the case where a step-wise structure exists and vertical fractures are staggered at 25-m intervals within the till beds, contaminants follow a step-wise pathway even though significant bulk horizontal gradients do not exist. In this case, groundwater flow is vertical along fractures and horizontal along the interbeds. Tritium migration vertically downward within a fracture and a stepped structure through an aquitard is simulated using FRACTRAN, with the arrangement discussed above and input parameters listed in Table 3. Vertical fractures are simulated here to represent

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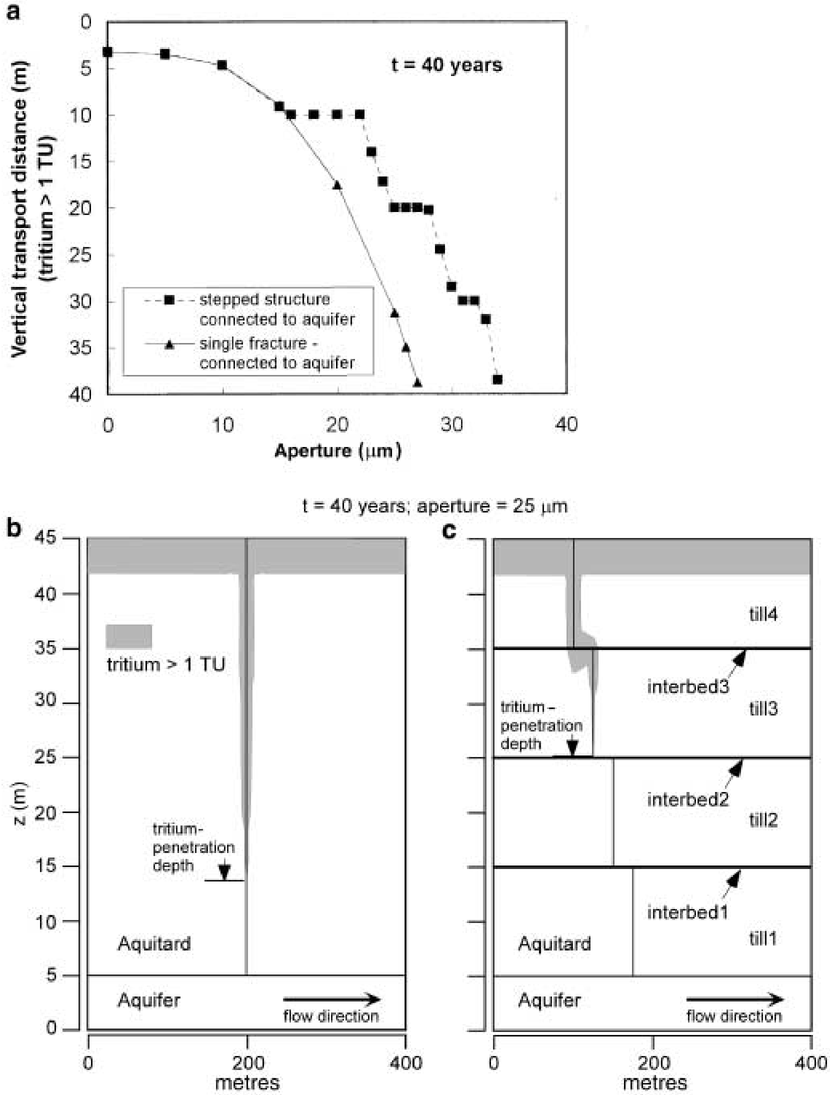

Fig. 10 **a** Calculated (FRACTRAN) tritium migration along fractures and interbeds through the aquitard. Tritium input function from Ottawa IAEA station using 6-month averages (Sudicky and McLaren 1998). Two-dimensional tritium profiles at t=40 years where fracture aperture =25 μm are shown in **b** case of single vertical fracture and **c** case of step-wise fracture, where vertical fracture spacing is 25 m along sand interbeds

dipping fractures or continuously dipping structures. Figure 10a compares the depth of migration within the two different pathway configurations as a function of pathway width or aperture. The two-dimensional tritium distribution for a single fracture and a stepped structure for the case where the fracture aperture is equal to 25 μm are shown in Fig. 10b and c, respectively. The vertical transport distance for each configuration converges at a depth equal to 3 m, which is the distance of tritium migration within the till matrix by advection/dispersion and predominantly diffusion. This result is consistent with Ruland et al. (1991), who calculate tritium diffusion within Sarnia clay till to range from 1–2.5 m in 27 years (1963–1991), which extrapolates to 1.6–3.9 m of diffusion in 42 years (1952–1994). The key factors for deep solute migration include the presence of deep structures in hydraulic communication with the underlying aquifer and the effective aperture widths for these structures (Fig. 10). The presence of dipping pathways or a combination of horizontal and vertical pathways leads to conditions conducive to forming irregular isotope profiles, as observed by sampling within vertical boreholes (Fig. 3).

Attempts were made to model the effects of vertical sand dikes 0.01–0.1 m wide, which transect the entire aquitard through the various diamict elements. Scenarios tested included the presence of one vertical dike to nine dikes (0.01 m wide) at 100-m spacings over the 1,000-m model width. In all scenarios tested, calibration to the observed vertical hydraulic-head profiles was not achieved because of the generation of a significant mound within the underlying aquifer created by excessive vertical leakage (>35 mm/year) reaching the aquifer. It is concluded that single sand dikes at least 1 cm wide do not traverse the entire thickness of the till aquitard. More likely, such structures occur within an individual diamict element, as observed, leading to hydraulic connection of adjacent interbed units (Fig. 4b).

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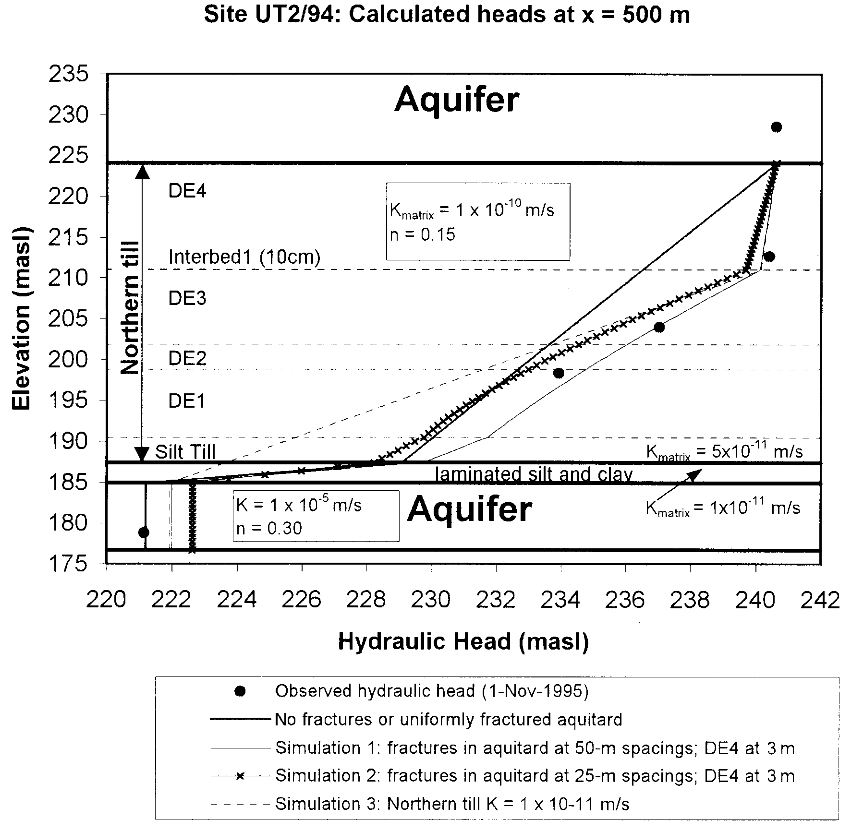

Fig. 11 Geologic configuration and observed and calculated (FRACTRAN) hydraulic-head profiles for site UT2/94

Site UT2/94

The generic FRACTRAN model described was then applied to modeling the flow system at field site UT2/94 (Fig. 1). As shown in Fig. 11, this site is underlain by 36.7 m of Northern till. The till is composed of five discrete till elements separated by sand or silt interbeds (Fig. 11). The till subdivisions are based on core descriptions and the gamma log (Fig. 3b). Isotopic data demonstrate that tritiated waters are present at various depths throughout the entire thickness of the aquitard (Fig. 3b). FRACTRAN simulations for this site aimed at determining the approximate fracture spacings required to reproduce observed hydraulic-head profiles, and to deliver tritium (>1 TU) to depth within the aquitard. The domain in this case is a rectangular cross section 47 m thick by 1,000 m long. The K and porosity values used for various units are summarized in Fig. 11, and the tritium input function is based on data from the Ottawa IAEA precipitation sampling station. In order to reproduce the observed hydraulic-head profile (Fig. 11; simulation 1) and deliver tritium at concentrations greater than 1 TU along fractures to an elevation of 190 m asl (metres above sea level) within the aquitard (Fig. 3b), a fracture spacing of 3 m for DE4 and 50 m for the remainder of the aquitard is necessary. A fracture aperture of 35 µm is necessary to deliver tritium through 39 m of Northern till at concentrations greater than 1 TU at this depth. This aperture value is consistent with those reported by Jorgensen et al. (1998) for fractured clayey till in Denmark; values range from 27–84 µm, based on column experiments and numerical modeling, and are stated by the authors to be similar to values reported for other clay till sites in Europe and North America. Using a model-calculated flow rate (Q) equal to 21.5 m^3/year, an observed bulk i_v down through the aquitard of 0.53, and an area of 1,000 m^2, the calculated bulk vertical K for the Northern till for this site is 1×10^{-9} m/s. To reproduce tritium concentrations greater than 1 TU at various depths within the aquitard, dipping structures or a combination of structures forming a step-wise preferred flow path must extend through the entire aquitard to provide a hydraulic connection to the underlying aquifer.

The depth of tritium migration along fractures is extremely sensitive to fracture aperture. For example, a fracture aperture of 30 µm, compared to 35 µm used above, allows for tritium concentrations greater than 1 TU only to an elevation of 210 m, within DE3 (Fig. 11). The effects of decreasing the fracture spacing from 50 m to 25 m allows too much flux to enter the aquifer, which raises hydraulic-head estimates to 2 m greater than those observed (simulation 2, Fig. 11). In this simulation, tritium concentrations greater than 1 TU enter the aquifer and migrate horizontally in the direction of groundwater flow. Decreasing the Northern till matrix *K* value (compared to simulation 2) has negligible effect on the predicted hydraulic-head profile (simulation 3, Fig. 11) and on the depth of tritium concentrations greater than 1 TU. The calculated profiles are more sensitive to fracture spacing and aperture values.

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The simulations discussed above are provided to illustrate the importance of non-matrix structures, in this case horizontal interbeds and vertical fractures, to groundwater flow through the Northern till. Possible fracture spacings and apertures were estimated, because these characteristics are difficult to measure given the lack of visual evidence such as matrix alteration halos. Although the simulations presented here consider only horizontal and vertical structures because of model limitations, other possible pathways cannot be ruled out, such as dipping erosional surfaces (Fig. 5b), sand bodies (Fig. 5c), and shear zones (Fig. 7), as discussed above. Using site UT2/94 (Fig. 11) as an example, a DE4 fracture spacing of 3 m leads to simulated tritium values greater than 1 TU within the entire aquitard down to an elevation of 217 m asl. These predicted concentrations are not observed at this site (Fig. 3b); rather, tritiated and non-tritiated pore waters exist within the upper parts of the Northern till. A fracture spacing of 3 m was simulated in order to increase the hydraulic communication of Interbed 1 with the overlying aquifer. This arrangement suggests that Interbed 1 is more likely a sloping structure in direct hydraulic communication with the overlying aquifer. Also, the tritium profile through the aquitard contains alternating tritiated waters and non-tritiated waters with depth. This distribution indicates that structures necessary to deliver tritiated waters to depth have a "step-wise" configuration and/or a dipping component to reproduce this profile in a vertical borehole. Tritiated waters from cores at depth within the aquitard would represent diffusion into the matrix material surrounding more hydraulically active structures. Thus, the cores containing tritiated waters are probably from intervals in close proximity (ca. 3 m) to non-matrix structures.

Conclusions

Field data and model-based studies presented in this paper provide further support for the presence of an active groundwater flow system within the Northern till, and they identify the physical pathways for groundwater flow through the aquitard. Figure 4b shows a conceptual groundwater flow model for the aquitard based on field and modeling results. Sand and gravel interbeds, because of their thickness and lateral continuity, provide primary pathways for horizontal groundwater movement. Pumping tests and isotope profiles indicate that interbeds at different depths within the till are in direct hydraulic communication and have hydraulic conductivities as great as 10^{-5} m/s. Field observations suggest that fractures and other vertically oriented sedimentary structures (e.g., sand dikes and dipping erosional surfaces) provide the primary vertical interconnecting pathways between interbeds. Isotope profiles and modeling results are consistent with this step-wise groundwater flow mechanism (Fig. 4b), whereby groundwater moves laterally along sand interbeds and vertically downward within fractures and other vertically oriented sedimentary structures.

Model estimates of bulk aquitard vertical *K* are approximately 1×10^{-9} m/s, based on flux through the aquitard calculated during "best-fit" simulations to reproduce hydraulic-head and tritium profiles. This estimate is consistent with previous *K* estimates derived from isotopic data (Gerber and Howard 1996) and regional groundwater flow modeling (Gerber and Howard 2000), which indicate a maximum vertical bulk K for the aquitard of 5×10^{-9} m/s. These estimates are as much as 2.5 orders of magnitude greater than matrix K estimates from slug and laboratory triaxial permeability testing, which consistently range from 1×10^{-11} to 1×10^{-10} m/s. Widely spaced vertical fractures (>20 m) with aperture widths of about 35 µm and sand bodies impart the higher bulk *K* to the aquitard.

In contrast to previous work, which emphasizes fracture flow in tills, this paper demonstrates the importance of aquitard heterogeneity and stratigraphic architecture as important controls on the groundwater flow regime in till deposits. The geology and hydrogeology of the Northern till may be typical of thick, subglacial tills deposited below Pleistocene mid-latitude ice sheet. The field and model results presented here likely have broader application to evaluation of contaminant transport and groundwater recharge in other glacial terrains.

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