Hydraulic Head and Atmospheric Tritium to Identify Deep Fractures in Clayey Aquitards: Numerical Analysis

Elfatih A. Farah, Beth L. Parker, and John A. Cherry

Abstract: Surficial aquitards with substantial clay content on top of water supply aquifers are common in North America and Europe. The integrity of these aquitards to protect the aquifers beneath strongly depends on the presence and characteristics of natural fractures that provide pathways for contaminant transport. Previous literature shows that vertical profiles of hydraulic head and atmospheric tritium in these aquitards are useful for inferences about fractures. To develop an improved strategy for acquisition of head and tritium data from surficial aquitards, a discrete-fracture network numerical model (FRACTRAN), was used to simulate hydraulic head and atmospheric tritium distributions along 2-D vertical cross sections for an idealized, near-surface, aquitard-aquifer system with tension (desiccation) fractures. Tension fractures typically have increasing lateral spacing at greater depth, making identification of deep fractures connecting fully through the aquitard challenging. The simulations were conducted for a cross section cut through a flat lying surficial aquitard, 15 m thick on top of a flat aquifer with horizontal flow. The water table is at the top of the aquitard and groundwater flow is downward through the aquitard into the aquifer. Atmospheric tritium enters the groundwater system at the water table and is transported downward through a statistically generated network of fractures. During this transport, diffusion causes tritium mass transfer from the fractures into the low permeability domain between these fractures. Examination of the simulation results indicates that assessment of vertical profiles of hydraulic head and tritium, which can be readily obtained using depth- discrete, multilevel-monitoring systems is advantageous for recognizing the presence of fracture pathways. However, using hydraulic head and tritium measurements obtained from measurement points along horizontal lines through the aquitard (horizontal profiles), is most effective. This can be accomplished by drilling several vertical holes, all to the same depth, along a line deep in the aquitard to obtain the ^{3}H and head data from core analysis and buried pressure transducers, respectively or from monitoring wells with short length intakes at the bottom.

Keywords: groundwater, aquitard integrity, fractures, contaminant transport, hydraulic head, tritium

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Riassunto: *Gli acquitardi poco profondi e con un sostanziale tenore in argilla, situati al tetto di acquiferi sfruttati a scopo idropotabile, sono comuni sia in America Settentrionale che in Europa. L'integrità di questi acquitardi, necessaria per preservare la qualità degli acquiferi sottostanti, dipende fortemente dalla presenza e dalle proprietà delle fratture naturali che possono costituire vie preferenziali per il trasporto di contaminanti.*

Precedenti studi in letteratura mettono in evidenza l' utilità dei profili verticali di carico idraulico e di concentrazione di tritio di origine atmosferica all'interno di questi acquitardi, al fine di inferire informazioni su tali fratture. Per sviluppare una strategia efficiente all'acquisizione di dati di distribuzione di carico e concentrazione di tritio in acquitardi poco profondi, è stato impiegato FRACTRAN, un modello numerico a rete di fratture discrete (discrete-fracture network), con l'obiettivo di simulare la distribuzione delle due grandezze lungo sezioni verticali bi-dimensionali di un sistema idealizzato acquitardo-acquifero, poco profondo e con acquitardo caratterizzato da fratture da tensione per disseccamento. Le fratture da disseccamento tendono a presentare un tipico incremento della spaziatura laterale all'aumento della profondità per cui la loro identificazione lungo l'intero spessore dell'acquitardo costituisce una notevole sfida. Le simulazioni numeriche hanno riguardato una sezione verticale, a stratificazione orizzontale, costituita da uno strato acquitardo superficiale, di spessore pari a 15 m, posto al di sopra di un acquifero con flusso di falda orizzontale. La tavola d'acqua è situata al tetto dell'acquitardo ed il flusso di falda è verticale all'interno dell'acquitardo diretto verso l'acquifero sottostante. Il tritio atmosferico penetra nella zona satura in corrispondenza della tavola d'acqua e viene trasportato verso il basso mediante una rete di fratture ricostruita statisticamente. Durante il trasporto la diffusione determina un trasferimento di massa del tritio dalle fratture all'interno dei domini a bassa permeabilità situati fra le fratture. L'esame dei risultati della simulazione indica che una attenta analisi di profili verticali di distribuzione del carico idraulico e della concentrazione di tritio, ottenuti sperimentalmente tramite sistemi di campionamento multi-livello a profondità discrete, permette di riconoscere la presenza di percorsi preferenziali di trasporto attraverso fratture. Ancora più efficace allo scopo, comunque, risulta la possibilità di effettuare misure di carico idraulico e di concentrazione di tritio tramite misure puntuali lungo transetti orizzontali attraverso l'acquitardo (profili orizzontali). In un sito di studio, laddove sia di interesse identificare le fratture idraulicamente attive, sarà importante pianificare sia come acquisire i dati di carico e di

concentrazione di tritio sia la profondità e la spaziatura orizzontale dei punti di campionamento lungo il transetto. Si presume che ogni punto di campionamento sia assegnato ad un foro di sondaggio perforato sino alla profondità desiderata. Verrà prelevato un campione di terreno infondo al foro per l'analisi del tritio e verrà installato un trasduttore di pressione per la misura del carico. In alternativa potrebbe essere installato un piezometro con un tratto filtrato molto breve (tubo micro fessurato circondato da dreno in sabbia) al fine di determinare sia il carico che la concentrazione di tritio. L'uso dei piezometri richiederà un maggiore tempo di acquisizione a causa del valore molto basso della conducibilità idraulica (K) degli acquitardi argillosi. Un piezometro può necessitare da settimane a mesi per raggiungere un equilibrio a causa del basso valore di K. L'esame dei profili orizzontali ottenuti tramite la simulazione mostra che l'efficacia del transetto orizzontale di carico idraulico e concentrazione di tritio al fine di identificare le fratture idraulicamente attive dipende dalla profondità del profilo. In un sito reale di indagine sarà necessario definire la profondità del profilo in base allo spessore dell'acquitardo al fine di ottimizzare la scelta della maggiore sensibilità possibile per l'identificazione delle fratture idraulicamente attive distribuite sull'intero spessore dell'acquitardo. I risultati della simulazione indicano che una maggiore profondità del profilo entro l'acquitardo incrementa l'efficacia di identificazione delle fratture idraulicamente attive.

Introduction

Groundwater systems are comprised of aquifers and aquitards. With the exception of unconfined aquifers, the water now contained in most fresh water aquifers has in the past traveled through one or more aquitards. Aquitards on top of aquifers protect the aquifer to some degree from contamination originating at ground surface. However, the degree of protection provided, known as aquitard integrity, depends on many factors including the hydrogeologic nature of the aquitard and the type of contamination. The term 'surficial aquitard' refers to a laterally extensive aquitard that occurs as the uppermost hydrogeologic unit, commonly on top of an aquifer. The integrity of the surficial aquitard is the key component in determining the vulnerability of the aquifer to contamination. The amount of literature concerning the transport and fate of contaminants in aquitards is small relative to that which concerns aquifers. The presence or lack of vertical, deeply penetrating fractures greatly effects aquitard integrity. If a surficial aquitard has no fractures, it can be expected to have strong integrity, conversely, if open connected fractures are present down to substantial depth, the integrity of the aquitard is weak. Cherry et al. (2006) provide an overview of the literature concerning the hydrogeology and integrity of aquitards.

This paper concerns a new approach for investigating the integrity of non-indurated surficial clayey aquitards of the type that are most common in the parts of North America and Europe that were glaciated during Pleistocene time. This approach also has relevance to other types of surficial aquitards where fractures can provide preferential pathways for contaminant transport. The most common surficial aquitards of Pleistocene age were deposited in lakes formed of glacial melt water (glaciolacustrine aquitards) or by direct deposition from glaciers as glacial till (till aquitards). These aquitards commonly have more that 10-15 percent content of clay-sized particles along with substantial silt and various amounts of sand. They are referred to here as 'clayey aquitards' because the clay content is generally the strongest contributor to the physical properties. All surficial clayey aquitards have a weathered zone at their top where wetting, drying, freezing and thawing over geologic time has caused fractures, known as tension fractures, to form (Karrow, 1971). These fractures connected in networks may penetrate deep and in some cases through the entire vertical thickness of the aquitard, thereby providing preferential groundwater flow paths from top to bottom.

Williams and Farvolden (1967) were the first to conduct field studies concerning a surficial aquitard (in Illinois, USA) with focus on determining the presence of fractures relevant to contaminant pathways. They showed that water level measurements over time in piezometers can provide strong evidence for higher hydraulic conductivity attributed to fractures. Grisak and Cherry (1975) and Fortin et al (1991) used hydraulic tests at sites in southern Manitoba and southern Saskatchewan, respectively, to show the rapid response of piezometers in aquitard to aquifer pumping attributed to fracture networks penetrating all the way through the aquitards. For thicker clayey aquitards in Ontario, Saskatchewan and Manitoba, Desaulniers et al. (1981), Keller et al. (1989), and Remenda et al. (1996) respectively used environmental isotopes, primarily oxygen-18 and deuterium, to show where the deepest zones have no evidence of fractures and the bulk hydraulic conductivity is very low, the groundwater in this zone originated primarily or completely during Pleistocene time. Hendry and Wassenaar (2011) used high resolution vertical profiles of ^3H, δD, $\delta^{18}O$,^{14}C-DIC, ^{14}C-DOC, ^{36}Cl, ^4He and transport modeling to show that pore water below 35m depth in a Saskatchewan aquitard is of Pleistocene age.

In surficial clayey aquitards of Quaternary age, the tension fractures below the weathered zone are primary vertical and have increased lateral spacing with depth. This increase in fracture spacing renders the deeper fractures hard to locate and makes determination of the maximum depth of the fractured zone problematic. McKay and Fredericia (1995) used visual observations in a deep excavation to quantify the increase in fracture spacing to a depth of more than 6 m in a thick glaciolacustrine aquitard in southwestern Ontario. However, visual evidence of fractures cannot be conclusive much below the distinctly weathered zone.

Atmospheric tritium (^3H, half-life 12.3 years) began entering the groundwater zone as a component of all recharge water since the early 1950's when above-ground, nuclear tests began. Figure 1 displays the longest continuous record for tritium in precipitation, from a monitoring station at Ottawa, Canada. Use of tritium in groundwater studies in fractured porous media was initiated by Foster (1975) in a study of the fractured chalk aquifer in the UK. Then Hendry (1982) used vertical profiles of ^3H in a clayey aquitard of glacial origin in southern Alberta, Canada, to conclude that there are fully penetrating connected fractures through the entire vertical thickness of this aquitard (12-52 m). Ruland et al (1991) used vertical profiles of ^3H in the aquitard investigated by McKay and Fredericia (1995) to identify the apparent maximum depth of groundwater flow to a depth of 12 m below surface, extending well below the weathered zone. Harrison et al (1992) used a numerical discrete-fracture-network model (FRACTRAN) developed by Sudicky and McLaren (1992) for cross sectional 2-D simulations of downward groundwater flow and the transport of trichloroethylene (TCE) through an idealized surficial horizontal aquitard with fractures overlying a sand aquifer. For cases where some of the fractures but not all are fully penetrating, the simulations showed that vertical profiles

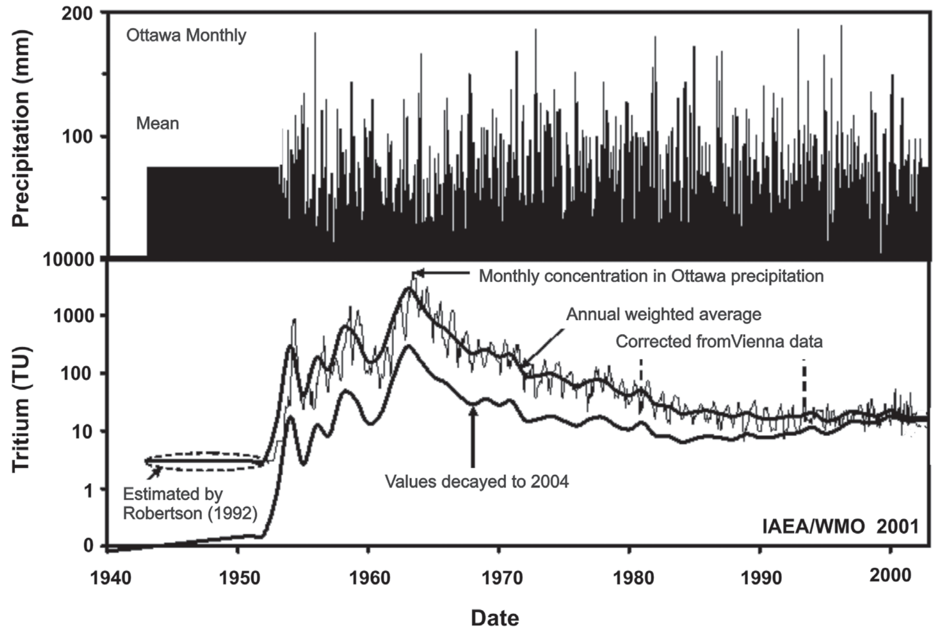

Fig. 1: Tritium fallout in Ottawa precipitation 1943-2003 used in the simulations. *FRACTRAN, supplied with the tritium half-life and annual weighted average, automatically generates the tritium values decayed to 2004 assumed to be in groundwater around Ottawa. One tritium unit is equivalent to 1 tritium atom in 10^{18} hydrogen atoms (Freeze and Cherry, 1979).*

of hydraulic head are different between locations along the cross section and therefore spatial comparison of head profile shapes is a method for identifying presence of fully penetrating fractures in aquitards overlying aquifers. Simulations also showed the patterns of TCE distribution with sensitivity to aperture and other factors.

The challenge in field investigations is to determine whether fully penetrating fractures exist with apertures sufficiently large to allow transport of dissolved contaminants because these in particular present the greatest prospects for migration of dissolved contaminants through aquitards into underlying aquifers. The approach developed in this paper is aimed at creating a strategy for identifying presence of these fractures. We caution however, that fractures too small for effective transport of dissolved contaminants may be large enough for flow of dense non-aqueous phase liquids (DNAPLs), as shown experimentally by O'Hara et al (2000).

This paper builds on the modeling work of Harrison et al (1992) and the field work of Ruland et al (1991). Harrison et al used FRACTRAN, a numerical model developed by Sudicky and McClaren (1992) for groundwater flow and contaminant transport in discrete fracture networks to simulate 2-dimensional groundwater flow on a cross section in an idealized horizontal aquitard on top of a surficial aquifer. Our purpose here is to use FRACTRAN simulations to demonstrate conceptually a new approach for identifying the presence of fully penetrating fractures using a combination of hydraulic head and tritium distributions. In this approach, measurements of hydraulic head and ^3H are made along vertical profiles as done in the field by Ruland et al (1991) and head profile simulations by Harrison et al (1991) but also with transport simulations for ^3H to assess its effectiveness in combination with head as an indicator of active fractures. In addition to using the conventional vertical profiles, the value of horizontal profiles is examined with the vision that it would be feasible in field investigations to obtain profiles along both vertical and horizontal planes for both head and atmospheric ^3H.

For purpose of discussion in this paper, there are four categories of vertical fractures: fully penetrating, partially penetrating, embedded and basal as well as horizontal fractures (Fig. 2). Partially penetrating fractures (PPFs) exist more frequently than fully penetrating fractures (FPPs), based on the literature review of field investigations. They include; (1) fractures that start from the ground surface and terminate somewhere within the matrix, referred to as PPFs in this paper since that is it their common name in the literature; (2) those that start from somewhere within the matrix and end at the aquitard bottom, basal fractures (BFs); and (3) those start and end within the matrix, embedded fractures (EFs).

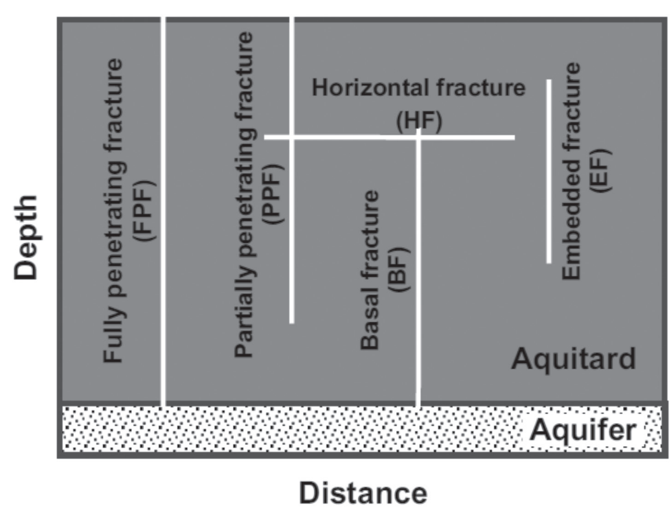

Fig. 2: Fracture nomenclature and acronyms used in this paper. *Nomenclature is based on fracture connectivity to the ground surface and the aquitard bottom.*

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Atmospheric Tritium as a Diagnostic Tracer

Atmospheric tritium is useful in many types of groundwater studies because it has been entering the groundwater zone as a component of groundwater recharge everywhere at levels elevated above background since the early 1950's and the input function for this tritium in recharge is well known across the globe (Clark and Fritz, 1997). The most detailed record for tritium in precipitation is that measured in Ottawa, Canada, where the first of the many global monitoring stations was established in 1953 and this station has functioned continuously since then. Figure 1 shows the record from this station, expressed as values when measured and decayed to 2004. The record since 2004 has followed the same trend. The Ottawa record is nearly identical to the records at the other monitoring stations except that the other stations have either slightly higher or slightly lower readings depending on where the record was taken, but the relative graph shape is the same. The simulations presented in this paper used tritium levels for 2005. Since then there has been half a half-life of decay, but this does not significantly change any results presented in this paper. In the presentation of the results, it has been assumed, for practical purposes, that the detection limit for tritium analysis is 0.1 TU's. The actual lowest detection limit offered by a laboratory that does analysis on a commercial basis is 0.02 and therefore the assumption of 0.1 detection limit is conservative.

In granular aquifers, ^3H distributions are governed by the groundwater flow system modified by dispersion and radioactive decay (12.3 year half-life); but these modifying processes, commonly do not strongly inhibit the interpretation of ^3H distributions for a groundwater age and flow. Foster (1975) was the first to recognize that, in fractured porous media where the active flow is dominantly or exclusively in fractures, diffusion-driven mass transfer of ^3H from the fractures into the low-permeability matrix can cause strong retardation of the ^3H front, which severely limits the usefulness of ^3H as an indicator of groundwater age or flow rates. However, Ruland et al. (1991) showed that the ^3H distribution in a thick fractured clayey aquitard is indicative of the presence of hydraulically active fractures below the weathered zone. They detect post-1952 water, > 1 TU, below 12 m depth. Presence of this water at such depth in a thick clayey aquitard is indicative of the presence of open fractures. Moreover, they showed that outward diffusion has formed tritium envelopes around fractures. These envelopes can extend 1–2.5 m from the fracture. Even though matrix diffusion strongly retards the migration of ^3H along a fracture, the presence of detectable ^3H deep in a clayey aquitards indicates influence of fractures or other rapid pathways on flow. In the context of ^3H values, the results are relevant to aquitards located anywhere in the northern hemisphere, allowing for adjustment of the absolute values in the input record.

Physical System and the Model

This study used a finite-element numerical model (FRACTRAN) developed by Sudicky and McClaren (1992) using the Laplace Transform Galerkin (LTG) formulation for two-dimensional rectangular domains of unit thickness to simulate steady-state groundwater flow and transport of ^3H in a flat lying aquitard overlying an aquifer, as shown in Fig. 3a. The general nature of the two-layer, aquifer-aquitard system represented in cross section for the simulations in this study is that used by Sudicky and McClaren (1992) for demonstration of the capabilities of FRACTRAN for flow and transport in fractured porous medium. The water table is at the top of the aquitard and the potentiometric surface of the aquifer is substantially below the water table. Therefore, the flow through the aquitard is downward into the aquifer where the flow is horizontal**.** The aquitard is represented in two ways, first as an unfractured porous medium in which all of the flow is intergranular and second with a network of discrete fractures in the porous medium so that there is flow in both the fractures and the low-permeability medium between the fractures. In this case, most fractures are vertical and there is decreasing spacing between fractures at greater depth. The distribution of fractures was generated statistically and each generated network of fractures is one realization for the system. FRACTRAN was selected for the simulations because it is exceptionally efficient for simulations in this type of hydrogeologic system. A similar two-layer, aquifer-aquitard system was also used by Harrison et al (1992) who use FRACTRAN for simulations for the transport of dissolved TCE through the fractured aquitard where the TCE originated at a small source near the water table. However, for the simulations of atmospheric tritium transport presented in this paper, the tritium input using the Ottawa tritium record occurs everywhere across the water table.

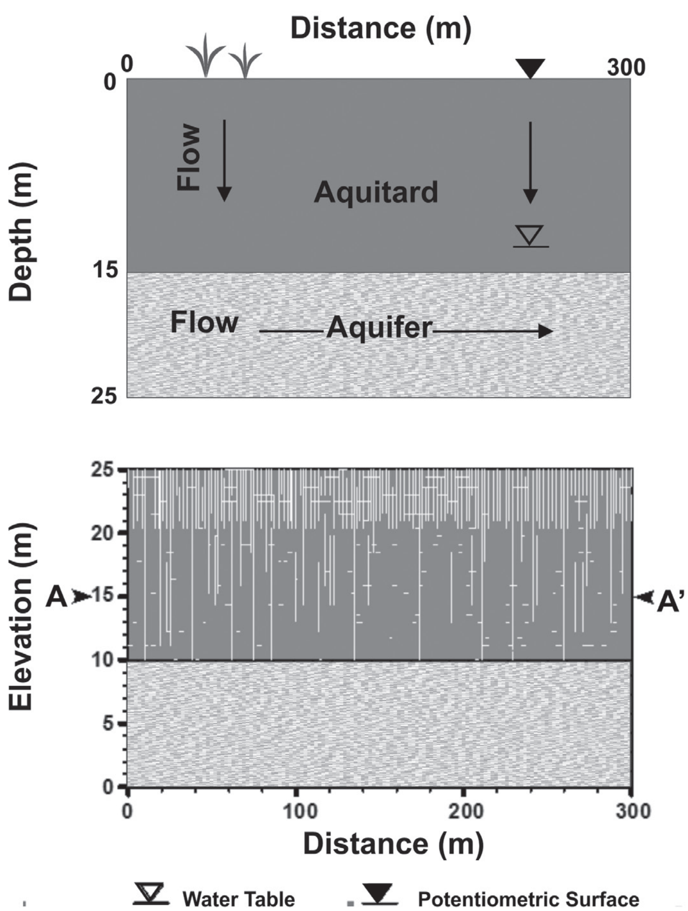

Fig. 3: *(a) Physical system and (b) computer generated fracture-network of field-scale domain used in numerical simulations. For parameters refer to Table 1, and for fracture-network features Table 2.*

Tab. 1: *Selected/estimated values for parameters used in numerical simulations*

Parameter	Value	Unit
Porous-media/tritiated-water (HTO) parameters		
Clayey aquitard		
Porosity (Φ)	0.40	
Dry bulk density ($\rho_{b\text{-}dry}$)	1.60	g/cm^3
Particle mass density (ρ_s)	2.67	g/cm^3
Matrix hydraulic conductivity (K)	2.5×10^{-10}	m/s
Matrix longitudinal dispersivity (α_l)	0.00	m
Matrix transverse dispersivity (α_t)	0.00	m
HTO groundwater/matrix partition coefficient (K_{oc})	0.00	cm^3/g
HTO groundwater/matrix distribution coefficient (K_d)	0.00	cm^3/g
Matrix/fracture-surface retardation factor for HTO (R_m)	1.00	
HTO free-solution (water) diffusion coefficient (D_o) at 15 °C	1.84×10^{-5}	cm^2/s
HTO effective diffusion coefficient (D_e) at 15 °C	6.6×10^{-6}	cm^2/s
Apparent tortuosity (T)	0.36	
Hydraulic gradient (i)	0.01	
Sandy aquifer		
Porosity (Φ)	0.30	
Dry bulk density ($\rho_{b\text{-}dry}$)	1.80	g/cm^3
Particle mass density (ρ_s)	2.57	g/cm^3
Matrix horizontal hydraulic conductivity (K_h)	10^{-4}	m/s
Matrix vertical hydraulic conductivity (K_v)	10^{-5}	m/s
Matrix longitudinal dispersivity (α_l)	1.00	m
Matrix transverse dispersivity (α_t)	0.02	m
HTO groundwater/matrix partition coefficient (K_{oc})	0.00	cm^3/g
HTO groundwater/matrix distribution coefficient (K_d)	0.00	cm^3/g
Matrix/fracture-surface retardation factor for HTO (R_m)	1.00	
Apparent tortuosity (T)	0.70	
HTO effective diffusion coefficient (D_e) at 15 °C	1.29×10^{-5}	cm^2/s
Hydraulic gradient (i)	0.002	
Fracture parameters		
Longitudinal dispersivity (αl)	0.10	m
Retardation factor (R_m)	1.00	
Length (L)	Table 2	
Hydraulic aperture ($2b$)	25	μm
Vertical-fracture spacing ($2B$)	Table 2	
Horizontal-fracture spacing	Table 2	
Tritiated water (HTO) characteristics at 15 °C		
Density (ρ)	1106.96	kg/m^3
Viscosity (μ)	1.67×10^{-3}	kg/m•s

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The thickness of the aquitard as well as the nature and characteristics of the fractures were selected to represent an idealization of a field area with a surficial clayey deposit of glaciolacustrine origin of moderate thickness with tension type fractures such as occur in southern Ontario and other parts of the mid-continent region of North America. Many surficial aquitards of this type have thickness in the range of 5-30 m. For these simulations, a thickness of 15 m was selected. Based on what is known about the depth of penetration of tension type fractures in such deposits (e.g. Burke, 1997; McKay and Fredericia, 1995), this thickness allows for full penetration of a few fractures per 100m of horizontal extent. Tables 1 and 2 display the parameter values used for the simulations. The non- fractured aquitard material was assigned a hydraulic conductivity of 2.5×10^{-10} m/s, which is the typical order of magnitude for clayey non-indurated deposits that have more than about 10-15 percent clay size particles. The matrix porosity value assigned was 40 percent, which is in the mid range for surficial glaciolacustrine deposits. In the fracture network the vertical fractures are strongly dominant (Fig. 3b, Tab. 2), consistent with observations by D'Astous et al (1989), McKay et al (1993), McKay and Fredericia (1995) and others.

One of the most important parameters in the model is the fracture aperture. All fractures have the same aperture. Harrison et al (1992) conducted a sensitivity analysis on fracture aperture for TCE transport in a aquitard-aquifer system similar to that in this study and found that when the aperture was set at 50 microns, transport through the fully penetrating fractures (travel time) was very rapid, less than a year. When the aperture was set at 10 microns, the travel time was very slow, many decades or more. In our simulations an aperture of 25 microns was assigned, which is consistent with values obtained from field studies where the hydraulic aperture is obtained using the 'cubic law' (e.g. McKay et al, 1993) for fractures in the weathered zone of a surficial glaciolacustrine aquitard in southwestern Ontario.

Tab. 2: *Input specifications used in simulation program to generate randon and regular fractures. Data based on McKay (1991).*

Fracture set	Depth range (m)	Maximum length (m)	Spacing (m)
Vertical			
Random			
1st	0.0–2.0	2.0	1.5
2nd	2.0–3.5	2.5 *	2.0
3rd	3.5–10.0	5.5 *	10.0
4th	0.0–15.0	15.0	30.0
Regular	0.0–15.0	15.0	125.0
Horizontal			
Random			
1st	0.0–4.0	5.0–10.0	–
2nd	4.0–15.0	1.0–3.0 *	–

*The option of fracture may extend beyond its range was selected in the simulation program.

Results and Discussion

Comparison of Fractured and Unfractured Cases

The distribution of head and tritium for the unfractured and fractured cases are very different, as illustrated in the comparison shown in Fig. 4. When no fractures are present, the lines of equal head are straight and nearly horizontal (Fig. 4a) but when fractures exist and some of them are fully penetrating directly or by fracture connections, then most of the leakage through the aquitard flows down through these fractures creating paths of preferential flow which dominate the hydraulic head pattern. These fractures cause the distinct peaks and troughs in the hydraulic head pattern. The troughs that are in the basal part of the aquitard and intersect the top of the aquitard are particularly important. Fig. 4d provides conceptual vertical head profiles which could be attained by taking measurements at different locations positioned randomly along the cross section. The vertical head profile for the unfractured case (F-F' in Fig. 4d) is a nearly straight line. The vertical head profile for the unfractured case would be nearly identical at all locations along the cross section. By contrast, vertical head profiles for the fractured case (B-B', C-C', D-D' and E-E' in Fig. 4d), are quite different from one location to the next, as fractures of various length and connectivity are intersected at each of these locations. If only two profiles were obtained in a field study and if there were substantial differences in shape in the deep part of the aquitard, then this would be strong evidence for the existence of deep fractures for aquitards that have minimal textural heterogeneous

Distribution of Head and Tritium

Fig. 5 shows model results for hydraulic head and tritium distribution along the cross section in the fractured case. Simulations demonstrate that distorted head distributions in clayey aquitards indicate the presence of fractures. The head distribution shown in Fig. 5a is highly variable along the cross section, vertical head profiles taken through this distribution would be very different from one location to another with the exception of profiles taken in the area located inside the dashed box. This dashed box represents an area with no deep penetrating fractures, thus head profiles taken in the area would be very similar to one another and resemble a profile through an unfractured clay.

Not displayed in Fig. 5 are the tritium profiles for the unfractured case because they, like the head profiles shown in Fig. 4a, are a set of nearly horizontal lines. The tritium distribution for the fractured case (Fig. 5b), shows extremely irregular equal concentration lines. Fully penetrating fractures show up on the tritium distribution much more distinctly than on the head distribution. This difference in distinctness between the pattern of the equal head lines and the pattern of equal tritium concentration lines is primarily because the head pattern is at steady state while the tritium pattern is transient. The tritium distribution represents a time when there are still strong concentration gradients due to diffusion-driven mass transfer from the fractures, where advective tritium transport occurs, into the low permeability, diffusion-dominated matrix.

Influence of Fractures on Tritium Distribution

The presence of different fracture types causes complex hydraulic head and tritium pattern irregularities and an approach is needed to detect and differentiate them. From a hydraulic view point, there are two types of fractures defined by their relation to the surrounding matrix: those that receive flow (receivers) and those that emit

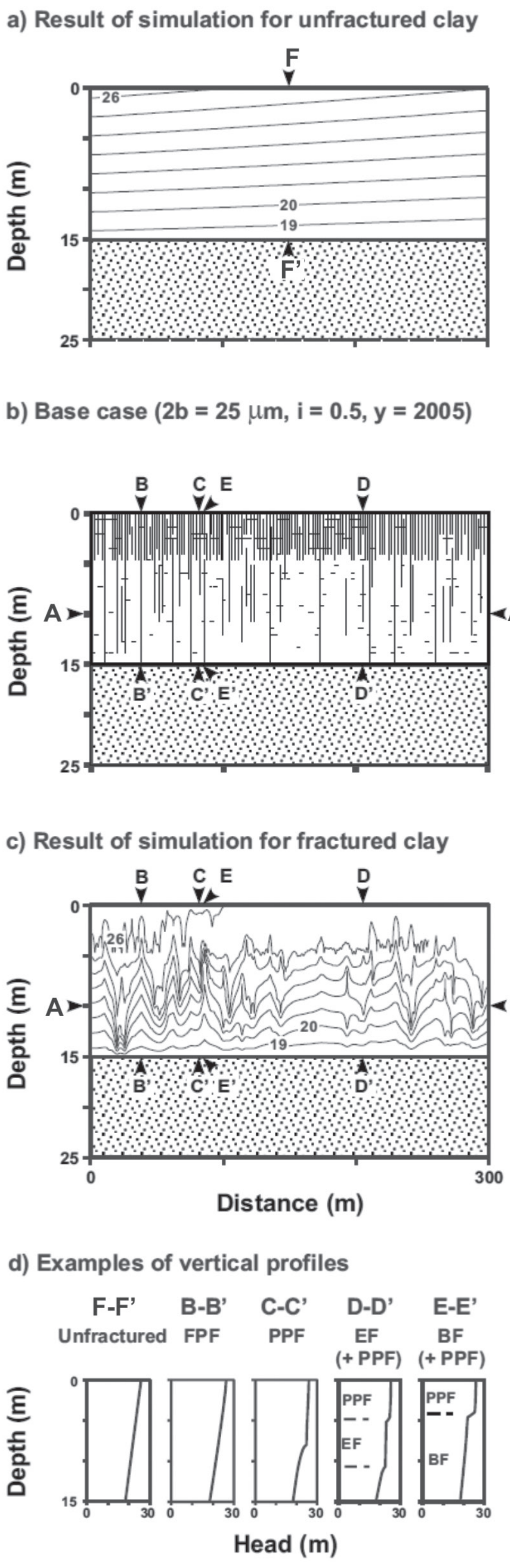

Fig. 4: *Difference of head distribution in (a) unfractured clay, and (c) fractured clay. (b) Shows the base case used for simulations of fractured clay. (d) Examples of vertical profiles at the local of each fracture type.*

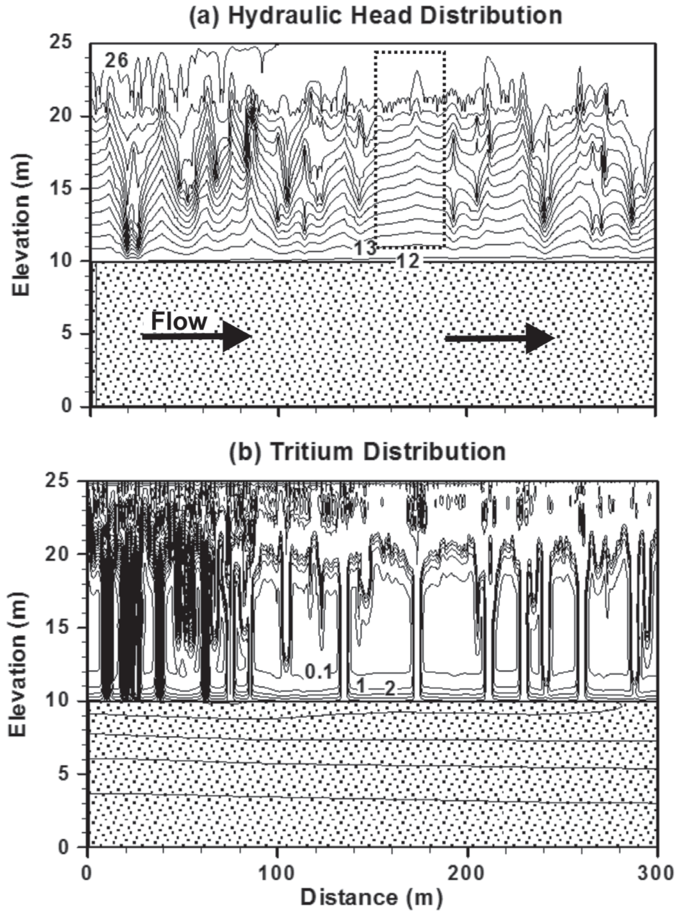

Fig. 5: Hydraulic head and tritium distributions. *(a) Peaks and troughs of hydraulic head, the dashed box shows an area where there are no deep fractures (b) and peaks of tritium represent fracture localities with fully penetrating fractures. Fully penetrating fractures show stronger influence on tritium distribution than head distributions.*

flow (donors). They are distinguished by the head pattern associated with each type. To illustrate, a segment of the cross section, between 70 and 130 m along the horizontal scale shown on Fig.3 is examined here in detail. For this segment, Fig. 6 displays the head and tritium in cross sectional view and as profile along the 5 and 10 m lines. As indicated in cross section on Fig. 6 (a), peak shaped head contours are associated with FPFs and BFs, whereas V-shaped contours (troughs) are associated with PPFs. This means that FPFs and BFs are receivers of water flow because the hydraulic head decreases towards them. These fractures receive from the matrix and discharge water to the underlying aquifer. EFs are associated with vertically elongated rhomb shaped contours (peaked contours at the top of the fracture and trough shaped contours near the bottom). EFs therefore act as both receivers and donors, receiving influx from the surrounding matrix in their upper portion and discharging it from their lower portion. The same applies to HFs in the vertical flow context as they receive influx from the matrix above them and discharge it into the matrix below them. Therefore, the number of donor and receiver fractures present in an aquitard reflects the degree of fracture connectivity to the ground surface and the top of the aquifer.

In the horizontal head profiles (Fig.6b, 6c), the receivers show as troughs and the donors show as peaks. PPFs are donors because the

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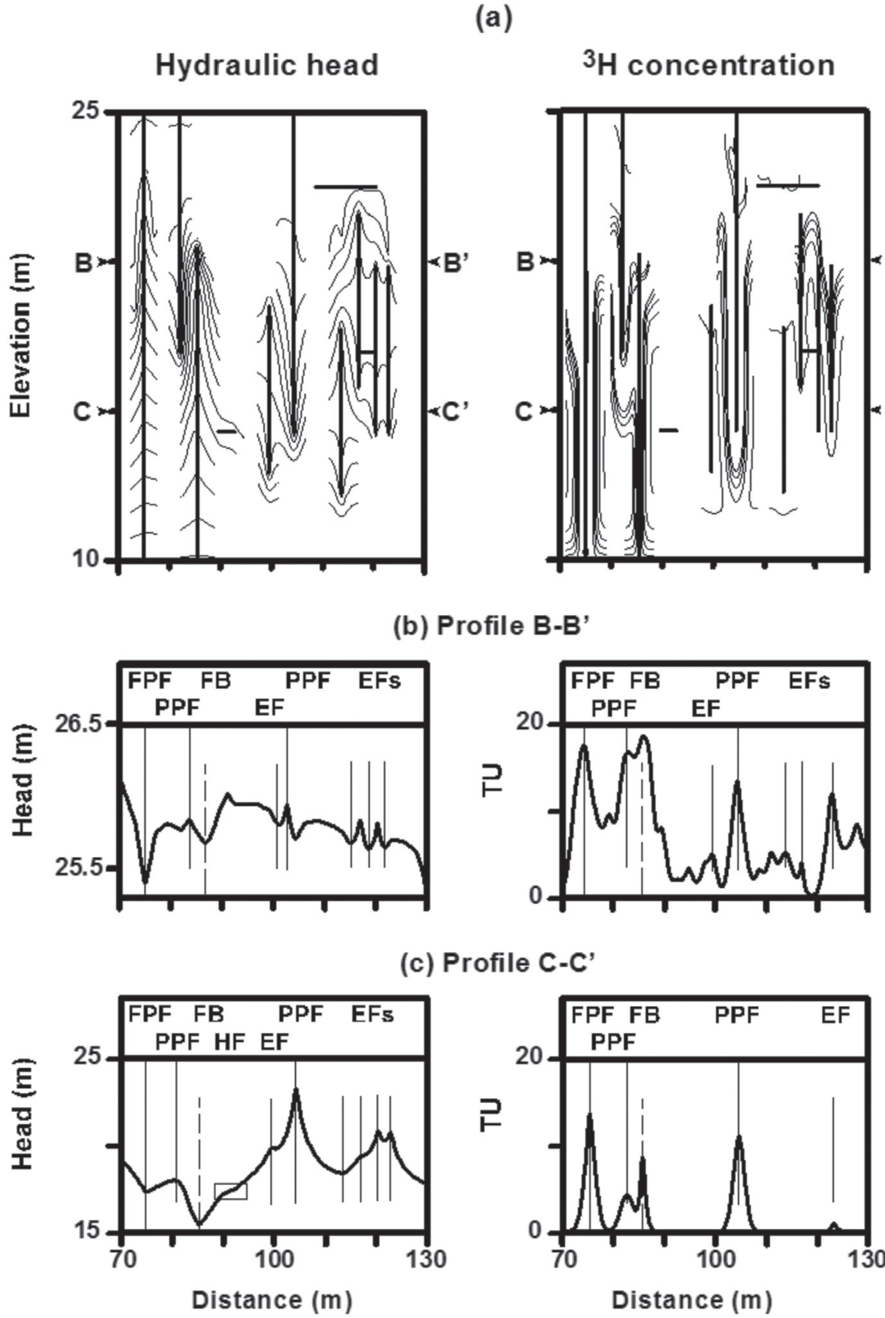

Fig. 6: *Details of the hydraulic head and tritium distribution along the segment of the simulation cross section between 70-130m horizontal scale to show the characteristic features associated with the different types of fractues: a) contour lines focused near each fracture,b) horizontal profiles at 5m depth and c) horizontal profiles at 10 m depth.*

hydraulic head increases towards them (i.e. they discharge flux from the ground surface to the matrix).

The head pattern characteristics described above appear in cross-sectional simulations and horizontal profiles only where there is a fracture and one of opposite characteristic located in close proximity. This is due to the large difference in head between these fractures, which causes the contours within the matrix to be distributed accordingly. Conversely, in the case of a single fracture, the contours are stacked at the fracture-matrix interface, and therefore could not be seen on the simulation cross-sections. Consequently, the distribution of ^{3}H is controlled by the fracture type. Higher concentrations of ^{3}H are transported down the aquitard through receiving-fractures compared to donating-fractures. Dominant advective transport through the open fractures means that limited time is available for lateral diffusive transport into the matrix resulting in longer and thinner ^{3}H peaks representing FPFs and BFs. On the other hand, higher concentrations of ^{3}H defuse into the matrix from donating-fractures because there is more time in this case for diffusion as such fractures terminate within the matrix. Therefore, as shown in Fig. 6 (b) and (c), relatively rounded ^{3}H peaks are associated with PPFs. Moreover, chances for back-diffusion are higher in the case of receiving fractures compared to donating-fractures. Although, ^{3}H envelopes are wider around FPFs compared to PPFs, ^{3}H is concentrated close to the fractures in case of FPFs compared to smoother distribution in case PPFs. The amount of transported tritiated-water and diffusion type govern the shape of ^{3}H distribution around each fracture-type. A larger amount of tritiated water is transported down the aquitard through receiving-fractures, FPFs and BFs, compared to donating-fractures, PPFs. Therefore, thinner ^{3}H peaks are associated with FPFs and BFs compared to those associated with PPFs. As the contribution of HFs to such vertical transport of tritiated water is insignificant, no associated pattern is noticed on horizontal profiles of ^{3}H distribution.

Consideration of Profile Positions and Sample Spacing

In a field study where it is desired to apply the combination of head and ^{3}H along horizontal profiles, it would be necessary to decide on the manner in which the head and ^{3}H data would be acquired and also the depth of the profile or profiles and the horizontal spacing of the sample points. It is expected that each sample point would be a drill hole to the specified profile depth and at the bottom of the hole. A core sample would be taken for analysis of ^{3}H and a pressure transducer would be installed in the hole for head measurements. An alternative method would be installation of a monitoring well with a short open interval (i.e. short screen and sand pack). The well would serve for acquisition of both head and ^{3}H data. The use of monitoring wells would require more time for data acquisition because the very low hydraulic conductivity of clay-rich aquitards typically requires weeks or months for the water levels in the wells to equilibrate.

The effectiveness of horizontal profiles of head and ^{3}H for identification of hydraulically active fractures depends on the depth of the profile. At an actual study site on a clayey surficial aquifer, the thickness of the aquifer would commonly be known before an aquitard integrity study would begin. It is necessary to select the profile depth with a desire to achieve the greatest sensitivity for identification of hydraulically active fractures that are on flow pathways through the entire aquitard thickness. Examination of simulation results of horizontal profiles from varying depths through the aquitard showed that profiles taken deep in the aquitard are more effective for identification of fractures than those taken at shallower depth. In aquitards with primarily tension type fractures, like the one simulated in this study, the selection of the orientation of the horizontal profiles is not an issue because these fractures are typically polygonal and therefore any orientation of a horizontal line will intersect approximately the same number and types (depth, penetration) of fractures.

Fig.7 shows a version of the simulation results for the head and ^{3}H displayed along cross section A-A' (Fig. 4b) situated at 10m below ground surface. These profiles are not based on the complete simulation results; only the data at 3 m spacing is included, to represent drill holes at 3m spacing. Also shown on Fig.7 are the locations of each fracture and the fracture type that were used in the simulation. Examination of Fig. 7 shows that with this 3m spacing nearly all of the fractures occurring at the 10m depth are evident. This figure also illustrates the general finding that fractures are more identifiable based on the ^{3}H distribution than the head distribution. Graphs similar to Fig. 7 were prepared for horizontal sample spacings of 1, 3, 5 and 10m and it was possible at this depth (10m) to detect and determine the type of the hydraulically active, vertical fractures at percentages of 94, 88, 68 and 38, respectively. Spacings of 1,3 and 5m resulted in all of the fully penetrating and partially penetrating, basal fractures to be identified. Similar results were obtained for profiles taken a few meters shallower and a few meters deeper across the aquitard.

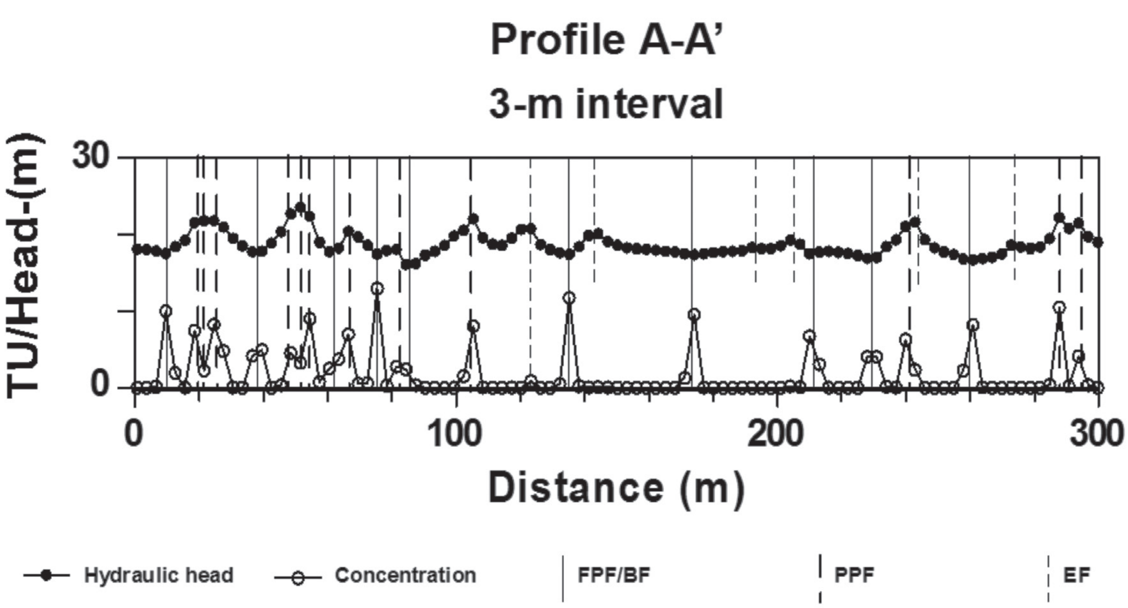

Fig. 7: Head and ^{3}H along horizontal profile A-A' positioned at a depth of 10 m in the 15m thick aquitard**.** *Simulated values at 3m spacing only are shown. Fracture locations on the simulated cross section are marked according to fracture type. Fig.3 shows the exact distribution of all of the fractures on the simulation cross section.*

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Conclusions and Implications

For determining the integrity of aquitards, identification of the presence or absence of deeply penetrating fractures that may provide pathways for contaminant transport to the underlying aquifer is the key challenge. For investigations of the integrity of surficial aquitards with shallow water table having tension-type fractures with wider spacing at depth, the FRACTRAN simulations show that profile combinations of hydraulic head and ^{3}H are effective and particularly so when horizontal profiles are used deep in the aquitard. Fig. 8 shows a conceptual example of the nature of head and ^{3}H values along a horizontal profile deep in an aquitard with various types of fractures including one that is fully penetrating. If no fractures were present at depth, then the head and ^{3}H profiles would be straight lines or nearly so. The diagnostic irregularities in the profiles are conclusive evidence there are hydraulically significant fractures providing flow connections all the way through the aquitard. However, if an aquitard has much variability of hydraulic conductivity due to textural (grain size) variations, then this form of heterogeneity may also cause variability in the head and ^{3}H profiles, but this type of heterogeneity will impart a much different style to the profile shapes.

Profiles obtained using measurement devices installed in holes drilled horizontally would seem to be the most efficient way to obtain the horizontal profiles, however horizontal drilling relative to vertical drilling is not cost competitive or practical in investigations of thin surficial aquitards, less than tens of meters thick, because of the relatively high cost to mobilize and drill with this type of equipment and because reliable systems for measuring head and collecting groundwater samples from horizontal holes in soft materials are not yet fully developed. In conventional practice at contaminated sites on clayey aquitards, drilling equipment for vertical holes is readily available and efficient installation of monitoring wells or multilevel systems is possible. Using vertical holes, more drilling effort is needed to produce horizontal profiles than for vertical profiles because each monitoring point on a horizontal profile requires a separate hole, whereas in a vertical hole, many monitoring points can be obtained using a depth-discrete multilevel monitoring system such as those described by Einarson and Cherry (2002). Angled holes can be drilled using conventional drilling machines, however angled holes are rarely used in shallow site investigations and, relative to conventional vertical holes, they present additional challenges for installation of monitoring wells and multilevel systems. If only vertical profiles are measured, the presence of fully penetrating fractures can be discerned if there are substantial differences in the shapes of the head profiles and/or deep penetration of ^{3}H at one or more locations. However, if there is no evidence from the vertical profiles of deep ^{3}H or head profile shape differences between profiles, then deep fractures may nevertheless exist but are not intersected by the profiles. The acquisition of head and ^{3}H values along horizontal lines increases the likelihood of detecting evidence of deep fractures. Either head or ^{3}H profiles may provide evidence for deep fractures, however the combination of head and ^{3}H offers the most certainty when drawing conclusions. Tritium is particularly important in aquitard integrity studies because it behaves similar to all dissolved mobile contaminants; it is strongly influenced by diffusion-driven mass transfer between the fractures where advection is dominant and the low-permeability matrix where groundwater flow is very slow.

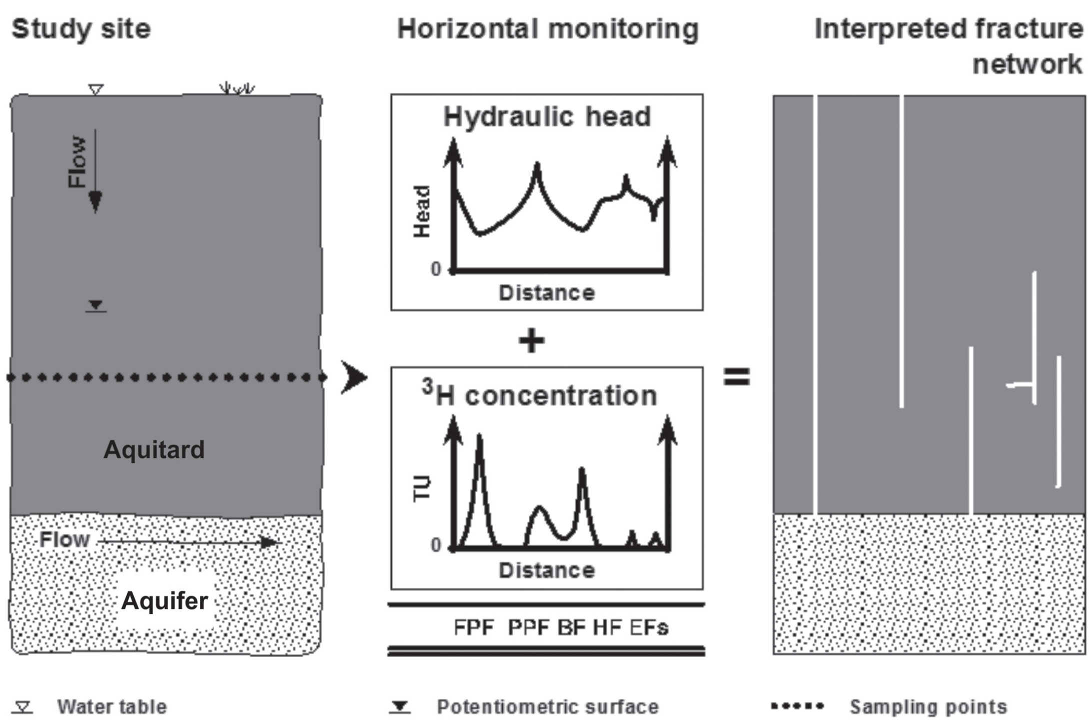

Fig. 8: Conceptual example of horizontal profiles of head and ^{3}H along a line deep in a fractured aquitard. *At the fully penetrating fracture on the measurement line, the head is lowest and the ^{3}H is highest because there is minimum resistance to flow and most rapid ^{3}H transport on this continuous pathway through the aquitard. The other peaks and troughs for each fracture are less accentuated because these fractures are not continuous so that the flow has to pass through segments of the aquitard where flow is intergranular and therefore slow.*

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REFERENCES

Burke, M. B. 1997. Depth of active groundwater flow in the fractured clay of the St. Clair Plain, Southwestern Ontario. M.Sc. Thesis, Dept. of Earth Sci., Univ. of Waterloo, Ontario, Canada, 98 p.

Clark, I. D. and P. Fritz 1997. Environmental isotopes in hydrogeology. Lewis Publishers, 328 p.

D'Astous, A.Y., W.W. Ruland, J.R.G. Bruce, J.A. Cherry and R.W. Gillham. 1989. Fracture effects in the shallow groundwater zone in weathered Sarnia area clay. Canadian Geotechnical Journal, Vol. 26, no. 1, pp. 43-56.

Desaulniers, D .E., J. A. Cherry, and P. Fritz 1981. Origin, age and movement of pore water in argillaceous Quaternary deposits at four sites in southwestern Ontario. Journal of Hydrology, 50:231-257

Einarson, M.D. and J.A. Cherry. 2002. A New Multilevel Ground Water Monitoring System Using Multichannel Tubing. Groundwater Monitoring and Remediation, Vol. 22, No. 4, pp. 52-65.

Fortin, G., G. van der Kamp, and J.A. Cherry. 1991. Hydrogeology and hydrochemistry of an aquifer-aquitard system within the glacial deposits, Saskatchewan, Canada. Journal of Hydrology, Vol. 126, No. 3-4, pp. 265-292.

Foster, S. S. D. 1975. The chalk groundwater tritium anomaly – a possible explantation. Journal of Hydrology, Vol. 25, pp. 159–165.

Freeze, R. A., and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs,NJ.

Grisak, G. E., and J. A. Cherry 1975. Hydrologic characteristics and response of fractured till and clay confining a shallow aquifer. Canadian Geotechnical Journal, Vol. 12, No. 1, pp. 23–43.

Harrison, B., E.A. Sudicky, and J.A. Cherry 1992. Numerical analysis of solute migration through fractured clayey deposits into underlying aquifers. Water Resources Research. Vol. 28, No. 2, pp. 515–526.

Hendry, M.J. 1982. Hydraulic Conductivity of a Glacial Till in Alberta. Groundwater. Vol. 20 No. 2, pp. 162-169.

Hendry, M.J. and L.I. Wassenaar. 2011. Millennial-scale diffusive migration of solutes in thick clay-rich aquitards: evidence from multiple environmental tracers. Hydrogeology Journal. Vol 19, pp. 259-270.

IAEA/WMO 2001. Global Network of Isotopes in Precipitation. The GNIP Database. Accessible at: http://isohis.iaea.org.

Karrow, P.F. 1971. Quaternary geology of the Stratford-Conestoga area Ont. Ottawa Canada Geol. Survey paper 20-34, 11p.

Keller, C.K., G. van der Kamp and J.A. Cherry 1989. A multi-scale study of the permeability of a thick clayey till. Water Resources Research, Vol. 25, no. 11, pp. 2299-2317

McKay, L. D., J. A. Cherry, and R. W. Gillham 1993. Field Experiments in a Fractured Clay Till: 1. Hydraulic conductivity and fracture aperture. Water Resources Research, Vol. 29, No. 4, pp. 1149–1162.

McKay, L. D. and J. Fredericia 1995. Distribution, origin, and hydraulic influence in a clay-rich glacial deposit. Canadian Geotechnical Journal, Vol. 32, pp.957–975.

McKay, L.D., Gillham, R.W., and J. A. Cherry 1993 Field Experiments in a Fractured Clay Till, 2. Solute and Colloid Transport. Water Resources Research, Vol. 29, No. 12, pp. 3879–3890.

O'Hara, S. K., B. L, Parker, P. R. Jørgensen, and J. A. Cherry 2000. Trichloroethene DNAPL flow and mass distribution in naturally fractured clay: Evidence of aperture variability. Water Resources Research, Vol. 36, No. 1, pp. 135–147.

Remenda, V.H., van der Kamp, G. and Cherry, J.A., 1996. Use of vertical profiles of $\delta^{18}0$ to constrain estimates of hydraulic conductivity in a thick, unfractured aquitard. Water Resources Research, Vol. 32, No. 10, pp. 2979-2987

Ruland, W. W., J. A. Cherry, and S. Feenstra 1991 The depth of fractures and active ground-water flow in clayey till plain in Southern Ontario. Ground Water, 29(3), 405–417.

Sudicky, E. A. and R. McLaren 1992. The Laplace Transform Galerkin Technique for large-scale simulation of mass transport in discretely-fractured porous formations. Water Resour. Res., (28)2: 499-514.

Williams R. E. and R.N. Farvolden 1967. The influence of joints on the movement of groundwater through glacial till. J Hydrol 5: 163–17

DOI 10.4409/Am-051-12-0045