SITE CHARACTERIZATION FOR THE SMITHVILLE PHASE IV BEDROCK REMEDIATION PROGRAM

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ABSTRACT

During the early 1980s an estimated 50,000 L of DNAPL containing Polychlorinated Biphenyls (PCB), Trichlorobenzene (TCB), and Tetrachloroethylene (TCE) penetrated a clay till and the upper strata of a flat-lying dolostone (the Lockport Formation) underlying a PCB transfer site in the town of Smithville, Ontario. Because a specific fracture zone in the dolostone formation was used as a source for the town water supply, this resulted in the closure of the supply and the construction of a pump-and-treat system in the shallow bedrock. During the mid-to late-1990s, a detailed investigation was conducted to evaluate the best option for eventual remediation of the site. To assist in determining the optimal remedial technique, a detailed conceptual model for groundwater flow and contaminant transport was developed. The conceptual model was developed from extensive field and laboratory investigations. The results show that groundwater flow in the Lockport formation is predominated by horizontal bedding-plane fractures of significant lateral extent. Although the number of these features is not large (perhaps 5-8 depending on location), there is at least one lateral connection that allows for a continuous pathway over the regional scale. The groundwater velocity in this fracture feature is relatively rapid (5-100 m/day), although the transport of aqueous-phase contaminants is considerably slower due to the effects of adsorption and particularly matrix diffusion. Based on the results of the site characterization, the site owner (Province of Ontario) determined that the existing pump-and-treat program was sufficient in containing the DNAPL source and no new remedial attempts would be undertaken.

RÉSUMÉ

Pendant le début des années ’80, environ 50 000 L de DNAPL contenir les diphényles polychlorés (PCB), le trichlorobenzène (TCB), et le tétrachloroéthylène (TCE) a pénétré un argile jusqu'à ce qu'et les strates supérieures d'un dolostone à plat (la formation de Lockport) sous-tendant un emplacement de transfert de carte dans la ville de Smithville, Ontario. Puisqu'une zone spécifique de rupture dans la formation de dolostone a été employée comme source pour l'approvisionnement de leau du ville, ceci a eu comme conséquence la fermeture de l'approvisionnement et la construction d’un système pompe-et-traitent dans la roche en place peu profonde. Pendant les années 1990s, une recherche détaillée a été conduite pour évaluer la meilleure option pour la remédiation du site. Pour aider à déterminer la technique remédiation optimale, un modèle conceptuel détaillé pour l'écoulement d'eaux souterraines et le transport de contaminant ont été développés. Le modèle conceptuel a été développé à partir des investigations étendues de champ et de laboratoire. Les résultats prouvent que l'écoulement d'eaux souterraines dans la formation de Lockport est prédominé par des ruptures horizontales d'literie-avion de l'ampleur latérale significative. Bien que le nombre de ces fractures ne sons pas grand (peut-être 5-8 selon l'endroit), il y a au moins un raccordement latéral qui tient compte d'une voie continue au-dessus de la balance régionale. La vitesse d'eaux souterraines dans ce fracture de rupture est relativement rapide (5-100 m/day), bien que le transport des contaminants d'aqueux-phase soit dû considérablement plus lent aux effets de l'adsorption et en particulier de la diffusion de matrice. Basé sur les résultats de la caractérisation d'emplacement, le propriétaire d'emplacement (province d'Ontario) a déterminé que le programme de pompe-et-traitent que existe était suffisant en contenant la source de DNAPL et aucune nouvelle tentative réparatrice ne serait entreprise.

1. INTRODUCTION

During the late 1970's and early 1980's, PCB and solvent waste destined for destruction in the United States was handled and stored at a small chemical waste management site (CWML site) located on the northern perimeter of the town of Smithville in southern Ontario. In 1985, contamination was detected in the groundwater underlying the site. Over the next few years, it was discovered that PCB oils and associated solvents (DNAPL) had penetrated approximately six metres of clay-till overburden and invaded the upper horizons of the bedrock below. The uppermost formation in this area is the Lockport dolostone, which is comprised of four members totaling a thickness of approximately 40 m. Aqueous phase contamination emanating from the DNAPL source and carried by groundwater flowing in the fracture network which pervades the Lockport had traveled a distance of approximately 600 m by 1988 (Figure 1). The discovery of the migration of contaminants in the bedrock led to the shut-down of a local municipal pumping well and the construction of a pump-and-treat system which was completed in the upper 4 m of bedrock within the assumed source area. The pump-and-treat system has been in continual operation since that time.

In October of 1995, researchers from the National Water Research Institute (now with Queen’s University) along with partners from the University of Waterloo, McMaster University, and the University of Utah, entered into an agreement with the Smithville Phase IV Bedrock Remediation Program to refine an existing conceptual model for groundwater flow and contaminant transport in the Lockport Formation underlying the former CWML site. The purpose of the study was to define and characterize the physical hydrogeological features of most relevance to the groundwater flow system and to the off-site transport of the aqueous-phase contaminants.

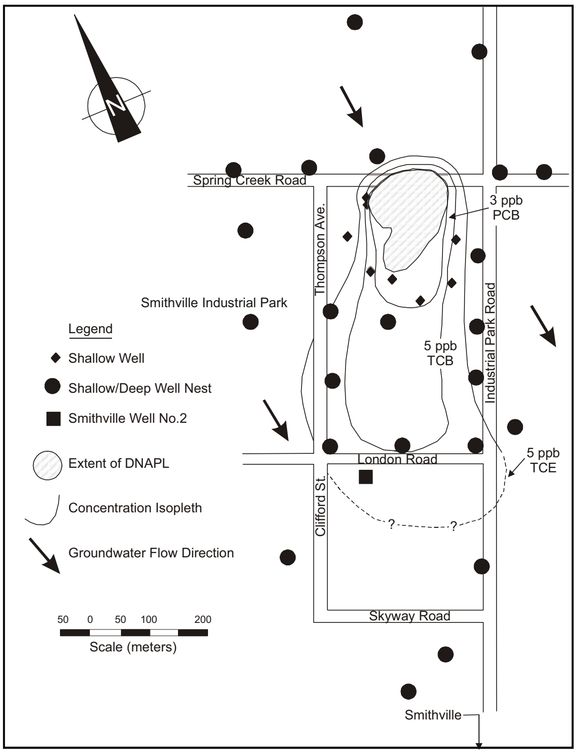

Figure 1. Spatial extent of the PCB, TCB, and TCE plumes in the vicinity of the CWML Site, Smithville (Modified from McIelwain et al., 1989).

2. FIELD INVESTIGATIONS

The investigations were undertaken at three different scales: the regional scale, the site scale and the scale of a discrete fracture. The primary and most costly component of the investigation was the drilling and completion of 20 new boreholes located throughout the region and within the confines of the site (Figure 2). The boreholes were drilled and cored through the entire section of the Lockport formation, finishing in the upper beds of the underlying Rochester shale (typical length of 55 m). Eighteen boreholes were drilled in the inclined orientation (55°-57° from horizontal). Eleven of the boreholes were completed with multi-level piezometers, and the other nine completed with temporary casing. The core from each borehole was examined in detail for both structural (horizontal and vertical fractures, stylolites, vugs etc.) and lithological features. The orientation of the vertical fractures was determined using simple trigonometric relationships with bedding. The boreholes completed with temporary casing are located within about 300 m of the contaminant source and include two borehole clusters (groups of 4-5 boreholes drilled in an approximately 50×50 m area). The overall distribution of boreholes provides a basis for a comparative statistical analysis at both the local and regional scales. The borehole clusters were also used for the completion of pumping tests and local-scale tracer experiments. Standard geophysical sondes (gamma, inductance, temperature, caliper and inclinometer) were completed in 15 of the 20 new boreholes.

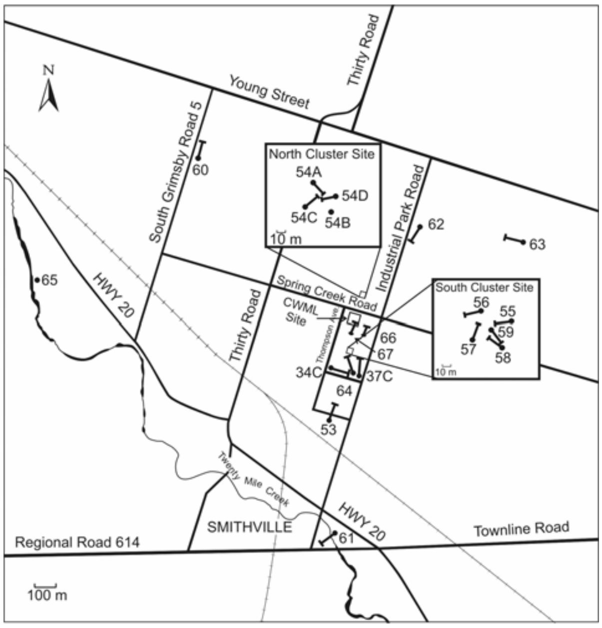

Figure 2. Location of boreholes constructed during this study.

Each new borehole was hydraulically tested using a straddle packer system having a packer spacing of 2 m. A complete contiguous profile was obtained for each hole. A total of approximately 360 tests were conducted using this spacing. From the results of the core logging and the initial hydraulic testing, it was determined that the packer spacing for the hydraulic tests was too large (i.e. the mean fracture spacing was less than the packer spacing for some horizons). Thus, many of the boreholes were re-tested using a packer spacing of 0.5 m. These included the boreholes from the south cluster site (55-59), boreholes 34C, 37C, 64, and the uppermost 20 m of boreholes 54A-54D. A total of 886 tests were conducted using 0.5 m spacing. In addition, as a means of locating specific fractures and fracture zones, a number of tests (~150) were conducted using 0.1 m packer spacing.

Following the completion of the hydraulic testing, temporary or permanent well completions were installed. The temporary completions consisted of two pneumatic packers spaced approximately six m apart and located at a depth that coincides with a low-permeability unit (the lower Vinemount member) which was determined from the hydraulic testing to be pervasive throughout the region. The permanent completions were constructed using Westbay multi-level piezometers. The Westbay system consists of a PVC casing linked by water-filled packer elements. A pressure-measurement and water-sampling device was used to provide access to groundwater contained in the intervals isolated exterior to the casing. The permanent completions were constructed in boreholes located regionally, with six completions in the vicinity of the site (boreholes 34C, 37C, 53, 64, 66, and 67). A total of 85 intervals ranging in length from 2-10 m were isolated using the permanent system. The number of intervals per borehole range from 5-10.

Following the installation of the permanent casing, measurements of hydraulic head in each interval were obtained on a weekly basis. Because the permanent completions were constructed in a phased procedure over the span of two years, a complete record of hydraulic head only exists for the period of July, 1997, to July, 1999. Measurements of hydraulic head have also been obtained over the same period from three multi-level monitoring wells (17 intervals) installed during previous studies.

Groundwater samples were collected in July and November, 1997, from six of the boreholes completed with Westbay installations located regionally and from three multi-level monitoring wells located in the vicinity of the site. The samples were collected from the Westbay intervals using a stainless steel sampling chamber (volume of 500 mL) connected to an electronic actuating device that draws in groundwater from the isolated zone. Samples from the multi-level monitoring wells were obtained using a Waterra hand pump. After removing the sample to ground surface, electrical conductivity, Eh, alkalinity, and pH were measured on the unfiltered samples. Groundwater samples were also collected and filtered for measurement of inorganic constituents and dissolved organic carbon (DOC). A total of 120 samples were collected for the analysis of inorganic constituents between the two sampling events. Samples were also collected for the analysis of stable isotopes (^{18}O and ^{2}H) and tritium in July and November of 1997

During the course of the field investigations, several measurements of groundwater velocity were obtained from discrete fractures and fracture zones in the uppermost member of the Lockport formation. The measurements were obtained in un-cased boreholes using the point dilution method. To conduct the experiment, a salt tracer is released into an isolated interval and continually mixed. The subsequent decay in concentration is directly proportional to the velocity of the groundwater passing through the borehole. Unfortunately, this experimental method is difficult to conduct and only six reliable measurements were obtained.

The vertical properties of the fracture network were investigated by conducting several pumping tests in the south cluster site. The tests were conducted using boreholes 56 or 58 as the pumped well with the other boreholes used as observation wells. To conduct a test, a horizontal fracture located at 14 m depth was isolated using straddle packer systems in both the pumped and observation boreholes. A second horizontal fracture 2 m below the pumped fracture was also isolated with straddle packer systems. The pumping was conducted from only one isolated interval usually for a period of 15-30 hrs. A constant pumping rate of 6-8 L/min was targeted for each test. Drawdown was measured in the observation wells using pressure transducers installed in each interval. Inter-borehole distances between the pumped and observation wells ranged from 17 to 36 m.

Tracer experiments were also conducted to investigate the potential for vertical inter-connectivity within the fracture network, to evaluate the extent of horizontal fractures, and to explore the role played by matrix porosity in the transport of aqueous-phase compounds. The experiments were conducted in a variety of formats at either the north or south cluster sites. A few experiments were conducted using the injection-withdrawal format where injection was conducted in one horizontal fracture and withdrawal was conducted from another. Several experiments were conducted using the injection-withdrawal format in a single horizontal fracture where injection was conducted in one borehole and withdrawal conducted from another intersected by the same fracture. These experiments were of short duration, lasting no more than three days. Two large-scale experiments were also conducted at the south cluster site using the radially-divergent format. For these experiments, a radial flow field was established by injecting water from a nearby fire hydrant at a rate of approximately 4-7 L/min. Following a pulse injection of tracer, arrival at the surrounding observation wells was monitored using small-volume sampling techniques. These experiments were of much longer duration requiring as much as nine days to attain peak tracer concentration at an inter-borehole distance of 125 m. The conservative tracers Lissamine FF and Bromide were employed for all experiments. Initial concentrations ranged from 100 mg/L for Lissamine FF and 1000 mg/L for Bromide.

3. LABORATORY INVESTIGATIONS

Because it was recognized that matrix diffusion may strongly influence the transport of aqueous compounds, several elements of the study were focused on measurements of matrix porosity and diffusion in core samples. The principal element for this study was the completion of 32 radial diffusion experiments. The experiments were conducted using saturated core collected during the drilling program. Sections of core 0.10-0.20 m in length with a reservoir 12.5 mm in diameter drilled through the center, were encapsulated using a Teflon sleeve and two stainless-steel end caps. A port allowing for access to the reservoir was incorporated into one of the end caps. The experiments were conducted by mixing a known concentration of tracer into the reservoir, and monitoring the subsequent decay in concentration due to diffusion into the rock, over time. Various combinations of conservative tracers were employed during this study, including Bromide (as KBr), Lissamine FF, Nitrite ($NaNO_2$), and Difluorobenzoic acid (DFBA). Initial concentrations ranged from 500 mg/L for Lissamine FF to 1000 mg/L for Bromide. Approximately 10-20 samples of tracer were obtained to define the decay in concentration over the course of each experiment. Following the completion of the experiments, the total porosity was determined for each sample using gravimetric methods.

The transport of organic contaminants in fractured rock may be influenced by the presence of organic carbon. To explore the presence and distribution of organic carbon in the Lockport formation several types of measurement were undertaken. It was initially recognized that the stylolitic horizons observed in core may contain large amounts of organic carbon and thus act as significant sinks for the aqueous-phase contamination. During the process of core-logging, the location and physical description of stylolitic features were recorded. Over 20 samples of stylolitic material were collected from the core and in addition to 10 samples obtained from stylolites exposed in a local quarry, analyzed for organic carbon content. The measurements were obtained using a Leco 12 Carbon Analyzer.

Although natural organic carbon is known to be present in dolostone and carbonate rocks exclusive of the presence of stylolites, measurement of the low concentrations often observed requires considerable effort. Thus, to conduct these measurements, samples were collected from several horizons distributed throughout the Lockport formation and analyzed using four different methods. The samples were pulverized and analysis for organic carbon conducted using the Leco12 Carbon Analyzer, a Leco RC412 Carbon analyzer, and a UIC Carbon Analyzer with a pre-acidification step. The latter analyses were conducted by the Department of Geology, Washington State University. Batch experiments were also conducted using TCE as the sorbing compound. Back calculation of the percent organic carbon was determined from the batch experiments using the K_d-K_{oc} relation for TCE.

Additional laboratory studies were focused on determination of the rock composition. A total of 32 core samples, collected from the various members of the Lockport dolostone, were prepared and submitted for chemical and mineralogical analyses. The analyses were conducted using X-ray Diffraction (XRD), x-ray fluorescence (XRF) and infra-red spectrometry techniques. All analyses were conducted by the Geological Survey of Canada.

4. RESULTS

Based on the results of the core logging, hydraulic testing, measurement of hydraulic head and aqueous geochemistry obtained from the boreholes distributed regionally, a conceptual model for groundwater flow at the regional scale can be developed. The Lockport formation in this area was found to be divisible into four members identified as the Eramosa, Vinemount, Goat Island, and Gasport members from uppermost to lowermost. The formation dips to the south with a mild gradient of 1-2 %. Based on observations of hydraulic head in each member, groundwater was observed to flow in the Lockport formation in an approximately southeasterly direction towards Twenty Mile Creek.

Interpretation of the lithology, the vertical distribution of transmissivity (2-m spacing), the distribution of hydraulic head, electrical conductivity (EC), $d^{18}O$, d^2H, tritium, and dominant ionic species for three boreholes (60, 53, 61) located along an approximately north-south transect reveals the general features of the flow system (Figure 3). In general, features of high transmissivity are observed to be variously prevalent in all of the members. These features are interspersed with low-T zones of unfractured rock, and with a persistently low-T feature present in the lower Vinemount member. In the up-gradient borehole (63), a substantial hydraulic gradient is present across this feature, with uniform hydraulic head present above and below. This suggests that groundwater flow in this area is dominated by horizontal fractures in two distinct systems above and below the feature, with limited interaction in between. The distribution of EC, stable isotopes, and tritium are approximately uniform, however, across the feature, suggesting a common source of recharge, located in the up-gradient direction. Based on regional mapping of the quaternary deposits, it is surmised that the recharge occurs in areas 2-3 km to the north of the site where the overburden thins to less than a metre.

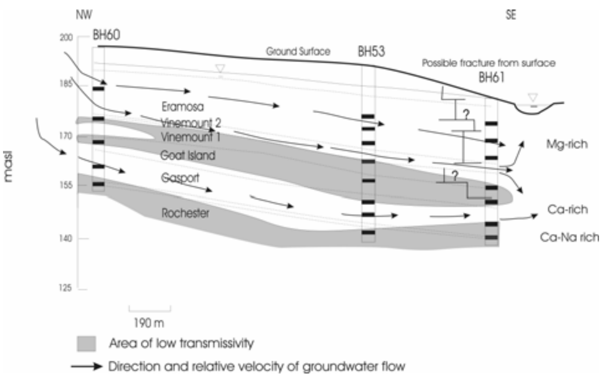

Figure 3. A cross-sectional diagram illustrating the general features of the groundwater flow system in a north-south transect.

In the area immediately to the south of the CWML site (borehole 53), the topography is relatively flat-lying and the hydraulic gradient across the low-T feature in the lower Vinemount is observed to be negligible. Unlike the up-gradient borehole, the isotopic and geochemical signatures of the water in the upper and lower flow systems are quite different. Although horizontal flow likely remains dominant at this location, the rate of groundwater migration in the lower flow system is considerably diminished in comparison to that in the shallow system. Because the transmissivity remains high at this location particularly in the lowest member, the presence of a slower flow system implies a lesser degree of horizontal fracture interconnection at depth and diminished hydraulic gradients. Although measurements of groundwater velocity obtained from point dilution experiments range from 5-100 m/day in individual fractures pervading the Eramosa member, there are no measurements obtained from the lower flow system to corroborate the interpretation that the lower flow system is slower here.

Borehole 61 is located adjacent to Twenty Mile Creek and approximately 500 m in the direction down-dip from borehole 53. There is less overburden and more thickness of the Eramosa member at this location. The highest T in the borehole occurs in the upper Vinemount member. The low T horizon is also present in the lower Vinemount. The highest hydraulic head is also associated with the high-T zone in the Vinemount, with significant vertical gradients away from this feature both above and below. The high hydraulic head is indicative of good lateral connection with groundwater in the up-gradient direction. Based on the geochemical signature, however, it is unlikely that the source of this water is in that direction. Rather, because the EC is low, the stable isotopes approximately uniform with depth, and tritium is present in the high-T zone, it is suggested that the groundwater is freshly-recharged likely from upstream locations where the river is in direct contact with the underlying bedrock. It is important to note, that groundwater flow in the system below the Vinemount appears to have a similar distribution of hydraulic head to the overlying upper Eramosa, suggesting that this system may underflow the creek completely. For a more complete discussion of the regional groundwater flow system and potential groundwater discharge see Zanini et al. (2000) and Oxtobee and Novakowski (2002)

The results of the hydraulic testing conducted using 0.5-m spacing in the boreholes of the south cluster site and vicinity show several features of the flow system that can not be interpreted from data collected at a larger packer spacing (Figure 4). In particular, the following observations and conclusions can be drawn: i) the low-T zone in the lower Vinemount may be several metres or as thin as one metre in thickness depending on location, ii) in some horizons, particularly at the base of the Eramosa, the average spacing of the bedding-plane fractures is less than the packer separation (thus, the need for hydraulic testing using 0.1-m spacing), iii) specific bedding-plane features both in the Eramosa and in the Gasport member can be correlated amongst the boreholes of the cluster site and with boreholes 64 and 37C (correlation over distances of as much as 125 m), iv) individual features often consist of more than one discrete horizontal fracture, and v) these features dominate the distribution of transmissivity in each borehole.
The results of the pumping tests conducted at the south cluster site showed no perceptible drawdown in the lower (un-pumped) fracture. Drawdown in the pumped fracture, however, showed evidence of significant leakage from vertical sources (i.e a flattening of the drawdown curve at late time). Because of the non-uniqueness of these results, it is difficult to resolve between the possible contribution of vertical fractures versus that from double porosity. The mean spacing of vertical fractures measured from drill core was approximately 1.5 m for the Eramosa member. This suggests that vertical connection through fracture pathways should exist between these two horizontal fractures. Unfortunately, the results of the inter-fracture tracer experiment were also inconclusive, as the arrival of tracer at the withdrawal borehole was not detected. These results suggest that although a vertical interconnection between the main fracture features may exist, this connection is weak, at least in the vicinity of the south cluster site.

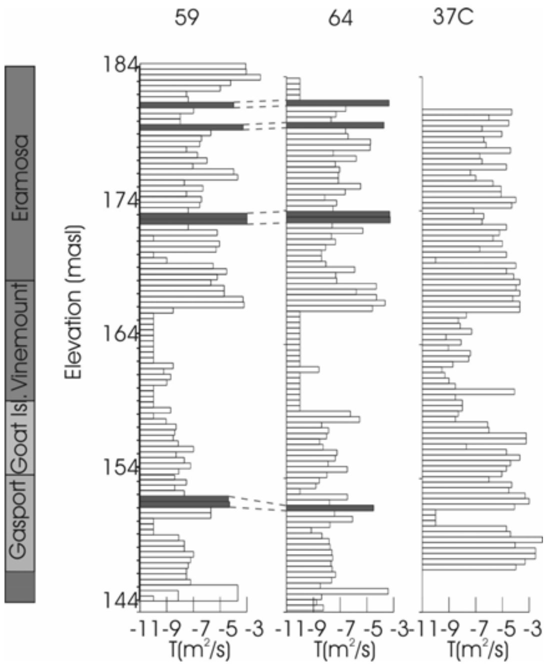

Figure 4. The results of the contiguous measurements of transmissivity using the 0.5 m packer spacing in the boreholes located in the vicinity of the south cluster site. The highlighted zones indicate fracture features that are likely correlated between boreholes.

The correlation of the upper fracture features between the south cluster site and borehole 64 (ie. upper two features in Figure 4) was confirmed by the results of the large-scale tracer experiment conducted in the radially-divergent format. Although connection was established over this distance (i.e. south cluster to 64), further transport to either boreholes 34C or 37C was not observed. A large-scale tracer experiment conducted in the correlated feature present in the Gasport member (at approximately 41-m depth), showed direct connection only within the confines of the south cluster site. Hydraulic response to water injection during the tracer experiment was observed at borehole 64, suggesting horizontal connections at depth are present over this distance, but weaker than those observed in the Eramosa member.

The results of the diffusion experiments showed that the estimates of effective porosity determined using conservative tracers are very similar to the estimates of total porosity obtained using gravimetric methods. The range of effective porosity measured spanned 4.6% to 10.6 % with a mean of 7.1%, and the agreement between effective and total porosity was approximately equal throughout the range. The mean of the total porosity was 7.2%. Thus, measurements of total porosity provide a good prediction of the influence that porosity will impart on the solute transport process. The range in porosity is particularly evident in the estimates obtained from the slices of the long section of core collected from borehole 64. Values as low as 2% and as high as 18% were observed to occur almost immediately adjacent one another (Figure 5). Although it was suspected that increases in matrix porosity occured adjacent to fractures, this was rare and some of the zones of highest porosity were observed to be in intact rock. It is presumed that the zones of enhanced porosity are likely related to diagenetic processes.

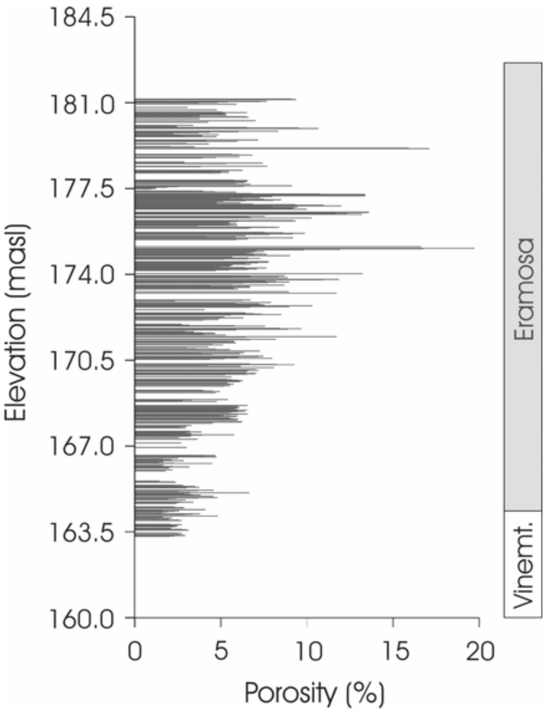

Figure 5. The distribution of matrix porosity with respect to depth as obtained from measurements of porosity conducted on 10-20 mm slices of rock core.

The impact of matrix diffusion was directly illustrated in the results of injection-withdrawal tracer experiments conducted using tracers having different molecular diffusion coefficients (Lissamine FF and Bromide). The breakthrough curves for each tracer was shifted in time according to the degree of loss and return from the fracture to the matrix through diffusion (Figure 6). Experiments were conducted in opposing directions and the results were found to be highly repeatable. The large-scale divergent experiments were also found to be strongly influenced by matrix diffusion, with peak tracer concentrations declining by over two orders of magnitude in only 125 m of travel distance.

The measurements of organic carbon showed that the organic carbon present in the bulk rock matrix was low in comparison to published values for carbonates. Typical values for the Eramosa, Vinemount and Goat Island members ranged from 0.00%-0.13%. The Gasport member was found to have virtually no organic carbon with the highest measured concentration at 0.04%. The stylolites were also found to contain minimal organic carbon and measurements of 0.00%-0.07% were typical. However, bituminous layers, of which only a few were noted in the core record, were found to have abundant organic carbon, with mean values of approximately 3%. The results of the batch experiments were inconclusive and were not included in the interpretation of organic carbon content.

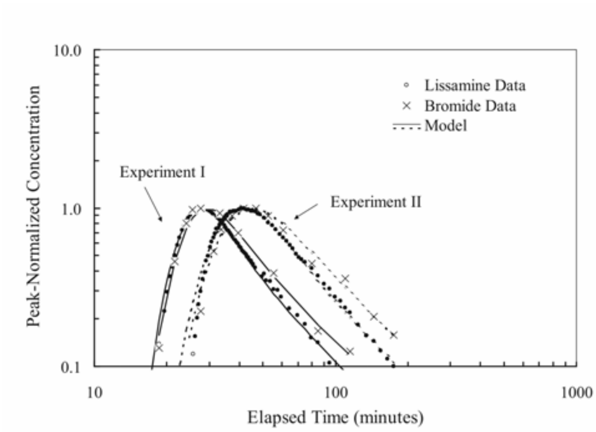

Figure 6. Results of two injection-withdrawal tracer experiments conducted in opposing directions between two wells.

Using theoretical calculations, it was shown that even though only small percentages of organic carbon are present in the bulk rock, the effect on the retardation of migrating organic contaminants such as TCE, is significant. Values of the retardation factor, R, determined from the estimates of organic carbon in the Lockport ranged from 3-15, with values of 8-15 most typical for the upper Eramosa.

5. SOURCE ZONE INVESTIGATIONS

In the fall of 1998, the last two boreholes (66 and 67) were drilled in the immediate vicinity of the assumed distribution of the DNAPL source underlying the CWML site. As with previous boreholes, these were drilled through the entire thickness of the Lockport formation at this location. The purpose of the drilling program was to indirectly investigate the horizontal and vertical extent of the DNAPL at the site so as to aid in the selection of remedial alternatives. The additional boreholes also help to delineate the distribution of hydraulic head both in the vertical and horizontal directions. Following drilling, hydraulic testing was conducted using a 2.0-m packer spacing, and discrete groundwater samples were obtained from the permeable zones in each borehole using a double packer and submersible pump system. Additional sampling was conducted in boreholes 56 and 34C to confirm previous work. The sampling in 34C was conducted prior to the installation of Westbay casing in this borehole.

The results of the sampling show that very little contamination remains in the former plume area down-gradient of the source zone (Figure 7). TCE concentrations of less than 10 μg/L were measured in borehole 67 and no contamination was detected in borehole 66. The contaminated zones in 67 are located at the top and bottom of the Eramosa unit. At the top of bedrock (top of Eramosa) in borehole 67, small amounts of PCB, 1,2,3-TCB and 1,2,4-TCB were also detected. No evidence of TCE degradation products (cis- and trans-DCE) were measured in any of the samples. Concentrations of TCE in boreholes 56 and 34C are consistent with concentrations measured in the mid-1990s. Some TCE was measured in the lower units of 34C (< 5 μg/L).

The results of the hydraulic testing showed the distribution of transmissivity in the new boreholes to be similar to that obtained from previously-drilled boreholes located elsewhere in the study area. The distribution is dominated by permeable fracture features in the Eramosa, Upper Vinemount, and Goat Island members, and by a low-transmissivity unit at the base of the Vinemount. Measurements of hydraulic head in the new boreholes show weak vertical hydraulic gradients in the site vicinity. Adjacent to the assumed source area the hydraulic gradients are slightly upwards, governed by the presence of the extraction well system. At boreholes located down-gradient from the source in the former plume area, both downward and upward gradients are observed, with only one borehole having a downward gradient across the low-transmissivity interval at the base of the Vinemount member.

Based on these results, it is hypothesised that DNAPL in the source area penetrated to the base of the Eramosa member and no further. The presence of TCE contamination at depths greater than the low-transmissivity unit in the Lower Vinemount is attributed to the presence of weak downward hydraulic gradients present outside the immediate vicinity of the DNAPL source. The diminishment of the TCE concentrations observed over time is most likely the result of a reduction in solute transfer from the non-aqueous phase to the flowing groundwater due to DNAPL weathering or elimination.

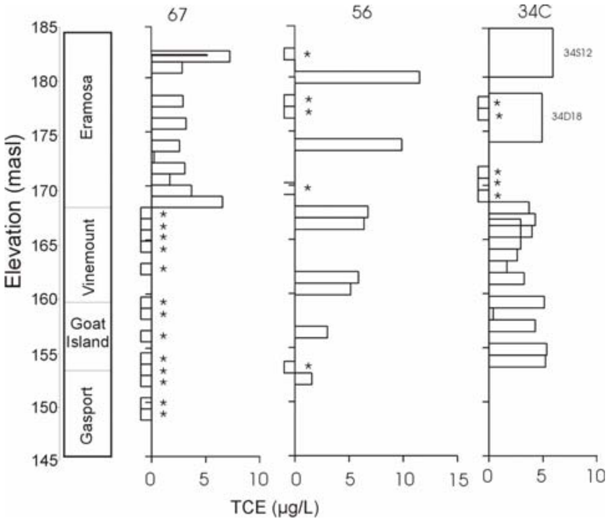

Figure 7. The distribution of TCE concentration in boreholes 67, 56, and 34C.

6. DISCUSSION AND CONCLUSIONS

Considering that TCE concentrations in the plume area were several thousand μg/L at one point during the late 1980's, the minimal levels of concentration prevalent at present is remarkable. The processes responsible for the diminishment in concentration are likely a combination of hydraulic containment in the source area, source weathering, and possibly TCE degradation. Based on the hydraulic conditions in the vicinity of the source, it is highly likely that weathering of the DNAPL has virtually eliminated the source of aqueous phase contamination in the horizon below the pump and treat system. Because weathering in the capture zone of the pumping system is likely to be similar, consideration should be given to cessation of the pump and treat system.

The presence of low level concentrations of TCE as observed in the former plume area at all depths will continue to persist irregardless of the operation of the pump and treat system. This is because the TCE in the fractures is transported by reverse diffusion from residence in the matrix. The matrix was loaded with contamination during the period when concentrations in the fractures were high and gradient from the fracture to the matrix were large. With the concentrations in the fractures significantly reduced, weak reverse gradients have been established resulting in a slow "bleed" of contaminants back into circulating groundwater in the fractures. Based on rudimentary modelling conducted using a simple analytical solution to transport in a single fracture, this reverse diffusion process can be shown to require 20 times the duration of initial exposure to high concentrations, for the levels to diminish to background. In the case of the CWML site, this will results in many hundreds of years of persistently low levels of concentration.

7. REFERENCES

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