

## Solvent plume characteristics elucidated from a DNAPL experiment at the Borden site

Kathryn A. Laukonen<sup>1</sup>, Beth L. Parker<sup>2</sup> & John A. Cherry<sup>3</sup>

### Abstract

An experiment was initiated at the Borden research site in which a small volume of a three-component solvent DNAPL (10% TCM by weight, with the remainder PCE and TCE) was infiltrated below the water table over 17 hours into a 3 m thick, nearly homogeneous, sand aquifer. Monitoring over two years of the resultant natural-gradient dissolved phase plume using detailed transects at several locations along an 80 m fetch showed extreme variability in solute concentration characterized by multiple high-concentration zones. Dispersion caused the concentration maxima to decline by a factor of 3 and solute concentrations were still 32% of the effective TCM solubility with no TCM degradation after a travel distance of 75 m. Dissolved solvent concentrations at effective TCM solubility were found in sampling points as far as 5 m down-gradient from known DNAPL locations. The variable direction flow field (58° in the horizontal plane) at the site had minimal impact on the width of the plume. The solvent plume is much different than would be perceived from conventional monitoring wells.

### Introduction

The surficial sand aquifer at Canadian Forces Base Borden, located 100 km northwest of Toronto, Ontario, has been used for many experiments involving chlorinated organic chemicals (Cherry *et al.*, 1996). In the past, the major experiments with chlorinated solvent DNAPLs involved either burial of the residual DNAPL in homogenized sand below the water table by excavation so that natural groundwater flow produced a dissolved phase plume (Rivett *et al.*, in press) or infiltration of free-phase DNAPL into water-tight enclosures constructed of sealable joint-sheet piling (Kueper *et al.*, 1993; Brewster *et al.*, 1995; Broholm *et al.*, 1999). In the most recent Borden experiment described here, a small volume of free-phase solvent DNAPL was infiltrated into the groundwater zone without an enclosure so that the subsurface DNAPL source, with complex geometry influenced by aquifer heterogeneity, would produce a plume under natural flow conditions.

### Site Description and Methods

At the experimental site the aquifer consists of approximately 3 m of fine to medium grained sand overlying a 0.2 to 0.3 m transition zone containing fine sand, silt and some pebbles and cobbles. All this overlies a 7m thick clayey aquitard. Measurements of hydraulic conductivity in the sand aquifer in the experiment area show variations by less than a factor of three within the first 3 m of sand (from 4 to 9 x10<sup>-5</sup> m/s) but K values decrease an order of magnitude in the transition zone. Measurements of water table elevation (weekly) show that the lateral hydraulic gradient varies by a factor of 2 (0.012 to 0.024) and the average linear groundwater velocity by a factor of 4 (6 to 28 cm/day). The lateral flow direction has a 588 swing over time.

On April 9, 1999 a small volume of free-product DNAPL comprised of 10% TCM, 45% TCE, 45% PCE, by weight, was infiltrated into the sand aquifer from the bottom of an open injection

---

<sup>1</sup> M.Sc. Student, Earth Science Department, University of Waterloo, 200 University Ave. W., Waterloo, ON N2L 3G1, ph: (519)888-4567 x2567 fax: (519)883-0220 e-mail: kalaukon@uwaterloo.ca

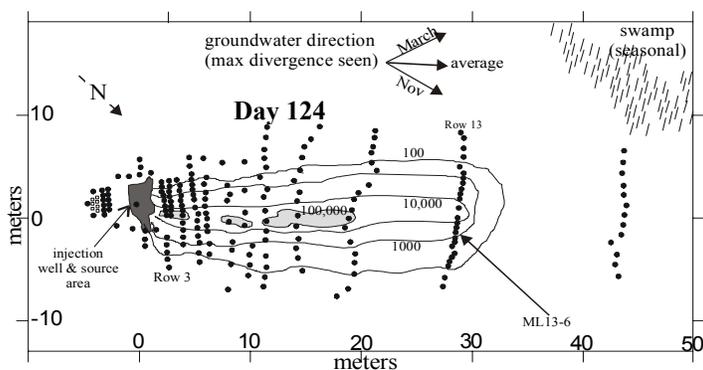
<sup>2</sup> Research Assistant Professor, Earth Science Department, University of Waterloo, 200 University Ave. W., Waterloo, ON N2L 3G1, ph: (519)888-4567 x5371 fax: (519)883-0220 e-mail: blparker@uwaterloo.ca

<sup>3</sup> Professor, Earth Science Department, University of Waterloo, 200 University Ave. W., Waterloo, ON N2L 3G1, ph: (519)888-4567 x4516 fax: (519)883-0220 e-mail: cherryja@uwaterloo.ca

pipe located at 1.8 m below ground surface and 0.9 m below the water table. The DNAPL distributed within, roughly, a 5m x 5m x 1.7m area of the aquifer. A detailed 3D monitoring network with over 3200 sampling points, positioned on 13 transects across the plume with points spaced 0.15 m vertically and 0.5 to 1 m laterally, was sampled frequently during a 2 year period over an 80 m travel distance. This provided detailed cross sections of the aqueous-phase solvent concentrations, breakthrough curve data and whole-plume snapshots. This paper focuses on the TCM distribution in the plume. In the year prior to the DNAPL experiment, a natural-gradient slug-type tracer experiment using bromide was conducted (Laukonen *et al.*, 2000).

### Discussion and Major Observations

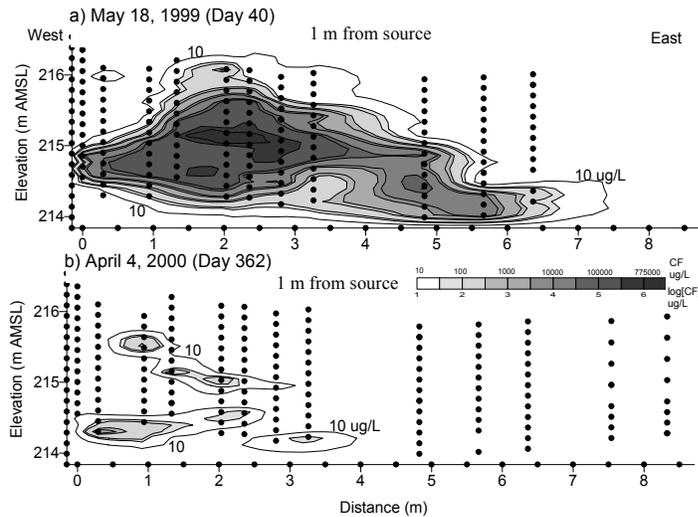
Figure 1 shows the experimental site in plan view with the locations of the multilevel samplers. The contours represent the highest TCM (chloroform) concentration in each sampler profile 124 days after the DNAPL release. The plume exhibits at least 3 distinct local maxima. By day 370 the TCM plume is detached from the source zone due to the depletion of TCM from the source. After 2 years nearly all the TCM mass has left the system and maximum concentrations are less than 3 mg/L. However, the aqueous PCE and TCE concentrations remain high throughout the study area due to their source zone longevity, a result of their greater fraction of the total initial DNAPL volume and their lower relative solubility. Previous experiments using TCM as well as investigations at the current experimental site have established that dissolved phase TCM undergoes no significant sorption or degradation over at least 70 m of travel (Rivett *et al.*, in press). The local maxima (or areas of separated high concentrations) and plume behavior change as the plume evolves. Figure 2 shows an example of this from a transect located ~1m from the source. At early time (Figure 2a) the plume has a more "traditional" concentration distribution with a high concentration core and a surrounding lower concentration fringe. The plume changes markedly as the TCM depletes from the source due to dissolution. After one year (Figure 2b) the TCM plume resembles the solvent plume shape observed at many industrial sites, which show completely separated zones of high concentrations generated from the up-gradient, lingering DNAPL zones.



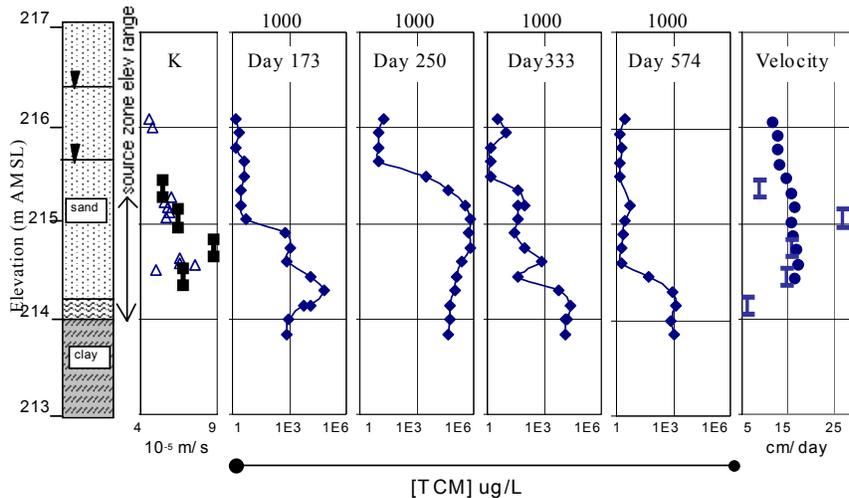
**Figure 1:** Multilevel sampler locations and extent of TCM plume at Day 124 (August 10, 1999) based on highest concentration in each sampling bundle. Local maxima are shown in shading. Contours are 100; 1,000; 10,000; 100,000 µg/L TCM.

The plume displays a vertically stratified shape down-gradient of the source. Hydraulic conductivity measurements from cores, well slug tests, and darcy flux measurements from bromide tracer breakthrough curves as well as borehole dilution measurements (Laukonen *et al.*, 2000) show a faster groundwater flow zone at approximately 214.5 to 215 m AMSL (Figure 3). TCM is first seen in this portion of the aquifer as the plume travels through the monitoring network. Figure 3 shows a TCM concentration profile in a single multilevel monitor located 28 m down-gradient of the source. Over 1.5 years the TCM plume first breaks through at mid-aquifer depth, followed by a vertically consistent profile for almost 100 days. Then, the profile

shows a lingering concentration at the bottom portion of the aquifer, which may be caused by back-diffusion from the underlying clayey aquitard and/or a persistent pool of DNAPL near the bottom of the aquifer at the source. This experiment shows that the release of a chlorinated solvent DNAPL into a relatively homogeneous sand can result in a plume with a complex spatial distribution that changes greatly as the source zone becomes depleted due to dissolution by natural groundwater flow.



**Figure 2:** Transect at Row 3 (~1 m from the source) showing TCM concentration contours at Day 40 (a) and Day 362 (b). Note the presence of several local maxima and their change in location over time. Also note the change in plume structure as the source zone residual DNAPL dissolves away. TCM relative solubility is 1000 mg/L.



**Figure 3:** TCM concentration profiles with depth in single multilevel (ML13-6) over time correlated to aquifer geology, hydraulic conductivity and average linear groundwater velocity.

Brewster, M.L., Annan, A.P., Greenhouse, J.P., Kueper, B.H., Olhoef, G.R., Redman, J.D., Sander, K.A. (1995) Observed migration of a controlled DNAPL release by geophysical methods. *Ground Water*, **33**(6): 977-987.

Broholm, K., Feenstra, S., Cherry, J. A. (1999) Solvent release into a sandy aquifer. 1. Overview of source distribution and dissolution behavior. *Environmental Science & Technology*, **33**: 681-690.

Cherry, J.A., Barker, J.F., Feenstra, S., Gillham, R.W., Mackay, D.M., Smyth, D.J.A. (1996) Borden site for groundwater contamination experiments:1978-1995. In: Kobus, H., Barczewski, D., Koschitzky, H.-P. (eds.) *Groundwater and Subsurface Remediation- Research Strategies for In-Situ Remediation*, Springer-Verlog, Berlin, pp101-127.

Kueper, B.H., Redman, D., Starr, R.C., Reitsma, S., Mah, M. (1993) A field experiment to study the behavior of tetrachloroethylene below the water table: Spatial distribution of residual and pooled DNAPL. *Ground Water*, **31**(5): 756-766.

Laukonen, K.A., Parker, B.L., Cherry, J.A. (2000) Internal characteristics of a bromide tracer zone during natural flow in the Borden aquifer, Ontario, Canada. *Tracers and Modelling in Hydrogeology*, Proceedings of the TraM2000 Conference, Liège, Belgium, May 2000, IAHS Publ. No. 262, pp 227-233.

Rivett, M., Feenstra, S., Cherry, J. (in press, 2000) A controlled field experiment on groundwater contamination by a multicomponent DNAPL: Creation of the emplaced source and overview of dissolved plume development. *Journal of Contaminant Hydrology*.