Developing Remedial Strategies in a Mixed Porous Medium/ Fractured Rock System
Lemberger Site – Whitelaw, Wisconsin

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Downhole techniques for fractured rock characterization reveal the complexity of matrix diffusion in transport through fractured but porous dolomite. The Lemberger site located near Whitelaw, Wisconsin was once a depository for spent liquids and fuels that resulted in a groundwater plume containing chlorinated volatile organic compounds (CVOCs). Early remedial efforts focused on controlling groundwater migration using pump-and-treat measures that removed millions of gallons of groundwater with very low concentrations of CVOCs.

A bedrock characterization study was implemented to determine the nature of the residual contaminant mass. Characterization combined traditional downhole geophysical tools with imaging from a digital optical borehole imager (OBI) and a heat-pulse borehole flowmeter. These data were used to identify intervals of fracture or conduit flow for discrete interval testing of the rock matrix for CVOCs. Rock matrix samples of select intervals from bedrock core were collected with increasing distance from fractured and/or porous zone pathways. Bedrock matrix sampling was used to determine whether the distribution of residual concentrations of CVOCs would allow insight into the nature of the residual mass of contamination.

Direct observation of the bedrock core and confirmed by the OBI revealed a high degree of primary vuggy porosity, with large voids found near the soil/bedrock interface. Deeper bedrock contained extensive zones with visible porosity, but very few voids or large interconnected fractures. Typical conceptual models suggest that matrix diffusion should result in an early pattern of increasing concentration with increasing distance from the fracture, followed by the reverse, as the CVOCs diffuse back out into the groundwater. Chemical analysis of these rocks revealed a complex distribution of CVOCs possibly as a result of diffusion at a variety of temporal scales. The complexity introduced by the porous bedrock, coupled with smaller fractures, results in an equally complex distribution of CVOCs in the rock.

389 to 402

Background

A plume of dissolved volatile organic compounds (VOCs) originates at the Lemberger Transport and Recycling (LTR) Landfill, where waste liquids containing spent solvents were reported to have been disposed in trenches directly on top of bedrock, and possibly also in buried drums. A groundwater pump-and-treat system was installed to control the extent of the VOC plume and to restore the groundwater quality. An evaluation of the effectiveness of the groundwater remediation system. The report concluded that groundwater remediation efforts are hindered by a potentially substantial residual mass of VOCs that has likely migrated through fractures in the bedrock and diffused into the rock matrix.

The presence of the diffused residual VOC mass within the rock matrix results in an ongoing, long-term source of dissolved VOCs to the groundwater. Estimates of the time required for the VOC sources to be removed by natural degradation processes in the aquifer range from 65 to 200 years. However, computer modeling of the groundwater plume shows that if the contaminant sources could be completely removed or contained, the timeframe for remediation of the groundwater plume could be substantially reduced (RMT, 2004). If the mass of VOCs at and near the source zone is highly diffused into the rock matrix, any remediation technology that cannot completely remove the residual VOCs from the rock matrix will be largely ineffective.

Groundwater in bedrock at the Lemberger site is presumed to flow through fractures that occur primarily along lithologic boundaries (bedding planes) and structural features (joints and fractures) and through porosity in the rock matrix. Although the nature of the contaminant mass that resides in the rock matrix cannot be accurately characterized without risking the further spread of contamination, the literature on chlorinated solvent Dense Non-Aqueous Phase Liquid (DNAPL) behavior in fractured bedrock suggests that any mass resulting from past liquid waste disposal operations likely migrated into fractures, and then diffused into the rock matrix soon after waste disposal.

A better understanding of the nature of the bedrock is also important because fractures in the bedrock control the migration of dissolved contaminants in groundwater, and the porosity of the rock influences the rate of diffusion of constituents into and out of the rock matrix. Groundwater modeling has shown that, if the source mass of VOCs has largely diffused into the rock matrix as expected, it is likely to be technically impracticable to achieve the groundwater cleanup standards at the site for up to two centuries, due to the ineffectiveness of the pump-and-treat remedy.

Purpose

This paper presents an assessment of the bedrock characteristics and the potential for migration of DNAPL residuals away from the subsurface source zones. The findings of the bedrock investigation would support a future assessment of the feasibility of various remediation technologies for addressing the VOC source areas beneath the LTR landfill.

Scope

The investigation included drilling three borings into bedrock immediately adjacent to the northern side of the LTR landfill, and three additional borings further downgradient. The six borings were analyzed using a series of field tests and sampling soil, rock, and groundwater for chemical analysis at each borehole. To complete these efforts, RMT teamed with the Wisconsin Geological and Natural History Survey (WGNHS), who provided downhole geophysical and imaging equipment and technical expertise.

Approach

The results of the field investigation were used to refine the conceptual model of the nature of the VOC source mass remaining beneath the LTR landfill, which was presented in the June 2004 report (RMT, 2004). The conceptual model is that DNAPL containing chlorinated solvent constituents initially migrated from the disposal locations on the landfill into the bedrock primarily through vertical fractures, then diffused into the bulk water-saturated rock matrix. Preliminary calculations using estimates of site-specific physical parameters of the bedrock at the LTR landfill, as well as information obtained from recent technical literature, suggest that, over the several decades since the waste solvents were disposed in the landfill, it is likely that most, or possibly all, of the VOC residual mass has diffused into the rock, with very little mass remaining as concentrated DNAPL within the primary fracture network. With this model, it is the slow back-diffusion of the VOCs out of the low-permeability matrix of the bedrock and into the groundwater that flows through the various source zones that constitutes a long-term source of dissolved contaminants to the groundwater.

Fracture and Hydraulic Analysis

Bedrock fractures were analyzed using a variety of observational, hydraulic, and geophysical methods on several different scales. On a regional scale, aerial photos of the site were examined to identify large-scale lineaments, while on a local scale, the surface of the bedrock near the LTR site was examined for fractures. Fractures were also examined at the vertical faces of a nearby bedrock quarry located approximately 1,000 feet to the southwest of the site. Bedrock cores were collected on the immediate northern side of the landfill, and fractures were identified and characterized (aperture size, spacing, orientation, etc.). Downhole geophysical methods, including optical borehole televiewer imaging, were used to characterize the fractures at depth. Groundwater temperature profiles, electrical resistivity, gamma logs, and borehole caliper logs were measured and prepared to identify important features such as clay seams or distinctive lithologies to assess potential cross-correlations between boreholes.

Hydraulic analysis of the boreholes included discrete-interval slug testing of individual fractures or other permeable zones in each borehole to determine the hydraulic conductivity. A heat pulse borehole flowmeter (HPFM) was used to identify zones or intervals within each borehole that yield water. Single borehole pumping tests were performed to determine how groundwater flow from local fractures would respond to pumping from the aquifer.

Characterization of VOC Distribution

To satisfy the project objectives, boring locations were strategically selected immediately adjacent to the LTR landfill, including within a buried “bedrock trough,“ near the landfill waste and cap limits. These areas offered the most likely locations that were expected to be representative of conditions directly below the former waste disposal areas, and were expected to be illustrative of how dissolved VOCs migrated through fractures and diffused into the bedrock matrix. Both the matrix of the bedrock and the groundwater were analyzed to determine the concentration of VOCs in discrete portions of the borehole.

Soil and bedrock core samples at each borehole were closely observed during the fieldwork for DNAPL identification. This was accomplished by monitoring concentrations of organic vapors that would suggest DNAPL, with special emphasis placed at the soil/bedrock interface. The overlying soil down to the bedrock surface was sampled continuously and examined for the potential presence of DNAPL. The rock was sampled matrix from the fractures, using special sample preparation and handling methods. Corresponding grab samples of groundwater were collected from discrete intervals at known or suspected permeable zones using a pair of straddle packers.

Bedrock Characterization

Bedrock Texture and Fabric

The uppermost 100 feet of bedrock in the area of the Lemberger site are relatively flat, buff to gray colored, massive to thickly bedded, porous and vuggy, microcrystalline to granular, highly fossiliferous, Silurian dolomite of the Manistique or Engadine Formation of the Niagaran Series. There are abundant, large fossils, most notably tabulate corals (*e.g., Favosites*), stromatoporoids, and shelled invertebrates (Plate 1). The rock was classified as a fossil packstone, grainstone, and boundstone . The bedrock is pitted, vuggy, and contains moldic cavities. While many of the cavities are open, some contain secondary drusy calcite mineralization, while others contain iron staining and iron-rich mineral ingrowths. Jointing and fracturing was noted in all cores and outcrops.

Fractures and Fossilized Zones – Density, Distribution, Interconnectiveness, Aperture, and Weathering

Fracture characterization is a key element in understanding the nature of groundwater flow and contaminant transport at the Lemberger site. This study included observations on a variety of scales (7.5-minute quad, outcrop, individual core, etc.) in order to identify correlations between the occurrence of bedrock features observed in individual specimens, between borings, and across the study area.

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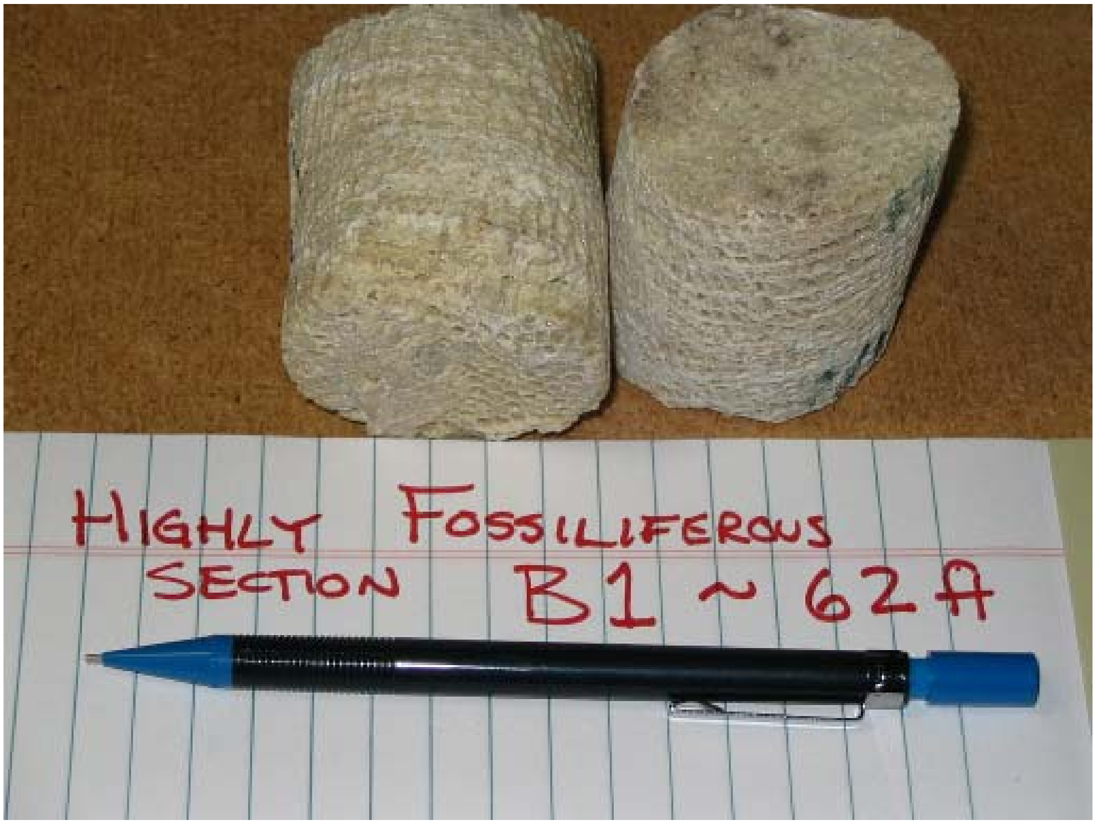

Plate 1 – Photograph of porous section of rock core in a coralline interval

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Regional Fracture Trace Analysis

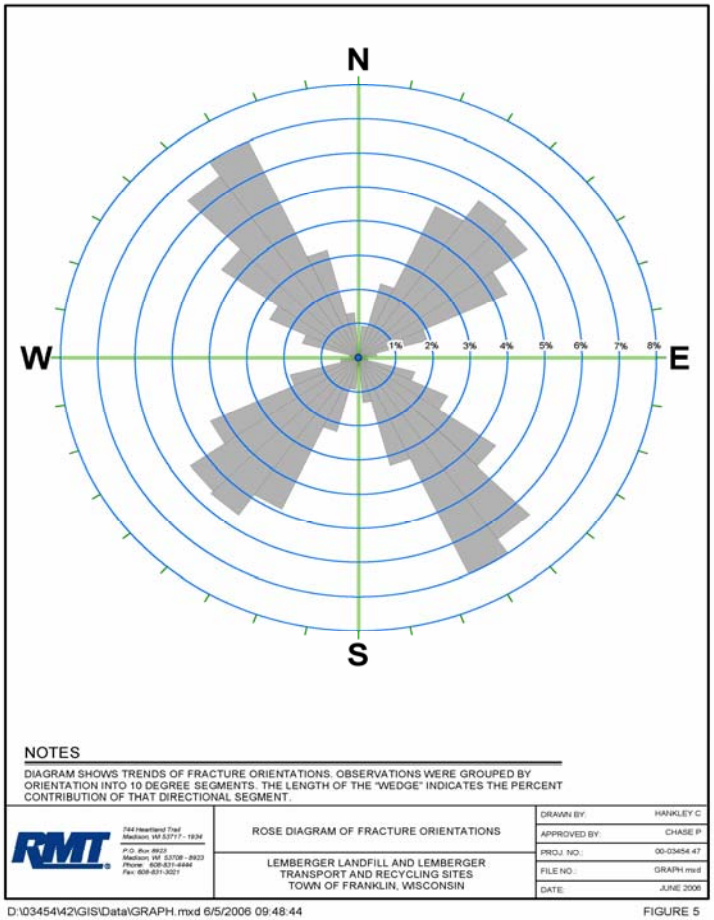
Aerial photos of various scales dating back 50 years were evaluated for lineaments in the area of the Lemberger Landfill. Additionally, previous fracture trace analyses (Stieglitz and Dueppen, 1995) were evaluated and supplemented. Lineament traces in the area of the Lemberger site are shown on Figure 1. The unconsolidated deposits downgradient of the LTR site are layered fine-grained and sandy tills on the order of 30 to 50 feet thick. Such thicknesses typically obscure expressions of fractures that may be present on the bedrock surface at depth.

Fracture orientations in the Silurian dolomite of eastern Wisconsin have been evaluated at numerous locations from Door County to Racine. The arithmetic mean orientation of the fracture sets is N32°W N56°E, (Jansen, 1995).

Fracture Observations from Exposed Bedrock Surfaces

Two prominent bedrock exposures are located within ¼ mile of the LTR landfill. The first exposure is an area of bedrock surface located adjacent to the (south) western edge of the LTR landfill. Approximately 30 vertical feet of massive to thickly bedded, sparsely fractured dolomite are exposed primarily on the eastern and southern walls of the quarry.

A total of 121 fracture orientations were measured. A frequency plot (rose diagram) of the fracture orientations is presented on Figure 1. The diagram shows the frequency of fracture orientation measurement in the scanline surveys of the bedrock surface. The diagram shows bi-directional (0 degrees = 180 degrees, 90 degrees = 270 degrees) azimuthal bearings. The most prevalent fracture orientations were N30°W and N45°E, which agrees well with previous investigations of the Silurian dolomite in eastern Wisconsin (Stieglitz, 1995; Jansen, 1995).



NOTES

DIAGRAM SHOWS TRENDS OF FRACTURE ORIENTATIONS. OBSERVATIONS WERE GROUPED BY ORIENTATION INTO 10 DEGREE SEGMENTS. THE LENGTH OF THE "WEDGE" INDICATES THE PERCENT CONTRIBUTION OF THAT DIRECTIONAL SEGMENT.

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ROSE DIAGRAM OF FRACTURE ORIENTATIONS

LEMBERGER LANDFILL AND LEMBERGER
TRANSPORT AND RECYCLING SITES
TOWN OF FRANKLIN, WISCONSIN

DRAWN BY:	HANKLEY C
APPROVED BY:	CHASE P
PROJ. NO.:	00-03454.47
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Figure1. Rose diagram of fracture orientations measured in quarry exposure.

Borehole Fracture Characterization

Fractures were analyzed through direct observation of the bedrock core and through remote sensing techniques (single-point resistivity, borehole flow meter, natural gamma, caliper, OBT, etc.). WGNHS provided the equipment and expertise to conduct the downhole surveys. Fractures are readily apparent by visual observation (Photo 5) and the images produced by the OBT. The other remote sensing techniques provided supporting documentation to better characterize the fractures.

The OBT proved to be effective in providing detailed borehole images. Significant fracture porosity, with voids up to 1 foot in width, is found in the upper 10 to 15 feet of bedrock in each boring. Fractures are less common at depth, but are found in some cores Most open fractures observable with the optical televiewer are coincidental with bedding, with few exceptions. Few fractures display the characteristic sinusoidal curvature indicative of a subvertical fracture. The occurrence and density of fractures are observed to vary widely between cores, but in general, fracture frequency and aperture thickness decrease with increasing depth. Moreover, many of the largest fractures occur in the vadose zone, or at the sediment-rock interface.

Borehole Fossilized Zones

The bedrock cores are typically highly fossiliferous and vuggy throughout. The rock fabric is largely massive, with poorly developed bedding. Much of the rock appears to be a fossil packstone with thick sequences of boundstone, with corals and stromatoporoids forming the rock matrix (Photo 6). Such zones were identified throughout the cores and are believed to act as zones of preferential flow that mimic flow through a porous medium. Secondary porosity is also developed throughout the rock through dissolution of calcite/aragonite of the fossils during dolomitization, resulting in pervasive secondary porosity that often results in moldic vuggy porosity which may not be as interconnected as found in the reefal facies.

Fossil zones in these Silurian dolostones have recently been recognized by others as being important contributors to groundwater storage and flow in the Dolomite Aquifer in Door County (Gianniny *et al.,* 1996; Muldoon et al. 2001; Muldoon and Bradbury, 1998). Intervals of enhanced porosity could not be correlated between borings, apparently due to the massive, reefal rock matrix in the borings at the Lemberger site that is dissimilar to the rocks in Door County (Bradbury *et al.,* 2006).

Borehole Geophysics Results

Downhole geophysical surveys were conducted sequentially with four separate tools equipped with submersible probes. Fluid temperature, electrical conductance, and resistivity were measured with a single downhole tool, while all other tools logged only one parameter.

Single-Point Resistivity (SPR)

SPR was successful in determining areas of increased fracture porosity as documented by the OBT and the bedrock core. Twelve intervals of decreased resistance were identified, and only seven of those could be attributed to identifiable fracture zones on the OBT log. The other zones of decreased resistance are attributed to intervals with more homogeneous high porosity, such as fossiliferous units.

Optical Borehole Televiewer (OBT)

OBT provided detailed images that form the basis for the borehole logs. The images clearly show open voids and vugs on a simulated plane that depicts the wall of the borehole.

Fractures are more common and have larger apertures in the shallower portion of the core, and especially in the vadose zone. The logs reveal that many of the horizontal features are open, *i.e.,* are free of internal sediment, but are often zones of broken rock. Quite often, the core from these zones was of poor quality with poor recovery due to badly broken rock. The rock in these zones is believed to be softened from weathering, but the OBT provides an excellent image of the rock that coring fails to record.

Close examination of the logs reveals numerous porous zones that appear as intervals with numerous small dark lines that represent small vugs and pores. Many of these intervals exhibit quiescent flow from the borehole flowmeter yet have high hydraulic conductivity values. In these zones, the core is useful, for it reveals the nature of the porosity as either vugs or coralline zones.

Hydraulic Analysis

Estimates of groundwater flow and hydraulic conductivity were obtained from a battery of analytical techniques, including laboratory (falling head) tests, borehole flowmeter, and discrete interval slug. Results of these tests are used to characterize discrete intervals of groundwater flow in the Dolomite Aquifer at the Lemberger Site.

Borehole Flowmeter Results

The borehole flowmeter results were found to correlate well with fractures identified from the core descriptions and the OBT. Results of the static measurements indicate that many intervals are quiescent (no measurable flow). In intervals with measurable flow under ambient conditions, the data indicate downward flow at rates less than 1.0 gpm.

Flowmeter results under pumping conditions indicated that a slight flow was induced in all the tested intervals. The highest rates were recorded in B6, where flowrates of up to 0.5 gpm were measured. Most intervals tested were less than 0.2 gpm. These measurements indicated that most intervals are capable of production when flow is induced from pumping, but show little measurable flow under ambient conditions. This suggests that the majority of permeable features contribute to groundwater storage, but flow is either slow and diffuse through the rock matrix and/or dominated by very few widely separated fractures.

Discrete-Interval Slug Tests

Forty discrete-interval slug tests were analyzed to estimate hydraulic conductivity at 30 intervals of interest as defined by observations from the OBT and the geophysics. Table 2 summarizes the hydraulic conductivity values obtained from the slug tests. Hydraulic conductivity values ranged from 1.78 x 10 -6 cm/s to 2.33 x 10 -1 cm/s. The highest values were typically at fractures, although values as high as 2.01 x 10-3 cm/s were found in generally porous zones. On a larger scale, zones of enhanced porosity and fractures undoubtedly intersect, resulting in a matrix that exhibits the properties of a porous media.

Contaminant Distribution

Determination of the distribution of VOCs in the bedrock was a primary goal of the investigation. A variety of techniques were applied to determine the role that matrix diffusion and/or fracture flow plays in the transport of VOCs from the Lemberger site.

Bedrock Matrix Concentrations

Samples of the rock matrix were collected and analyzed for VOCs from selected intervals adjacent to fractures from borings at the downgradient edge of the LTR (borings B1, B2, and B3). Table 1 summarizes the distribution of 1,1,1-TCA and TCE in the rock matrix and includes the VOC results for the corresponding groundwater samples collected from the same interval for B1 and B2. Table 5B summarizes the VOC data for the rock matrix samples only for B3. Most samples were collected from three sucessive intervals below the fracture. Multiple samples were collected at these fractures to determine if there was a trend of diffusion into the matrix with depth or analyte.

Results of the rock matrix sampling indicate that VOCs have diffused throughout the rock matrix and show no evidence of increasing or decreasing concentrations with distance from the fractures. No evidence of VOC mass depletion along the fracture trace is evident, which, if observed, would suggest that VOCs are diffusing from the rock matrix back into the groundwater in the fracture flow network.

Nature of Groundwater Contamination

The distribution of 1,1,1-TCA in groundwater measured in discrete intervals is summarized in Table 1, and is illustrated on the cross section (Figure 2). The concentrations of VOCs are most dependent on the proximity of the boring to the LTR and not on individual features within each boring. Therefore, concentrations are highest in B1 and B2 (and presumably B3), and much lower in the borings located further from the LTR sources. The nature of VOCs in groundwater is similar to that found in the rock matrix, that is, both the rock and the groundwater have higher concentrations of chlorinated alkanes (1,1,1-TCA and its daughter products) over alkenes (TCE and its daughter products). Concentrations in individual fractures are similar to those in nearby monitoring wells, suggesting that the current monitoring well network accurately depicts the nature and extent of VOC concentrations.

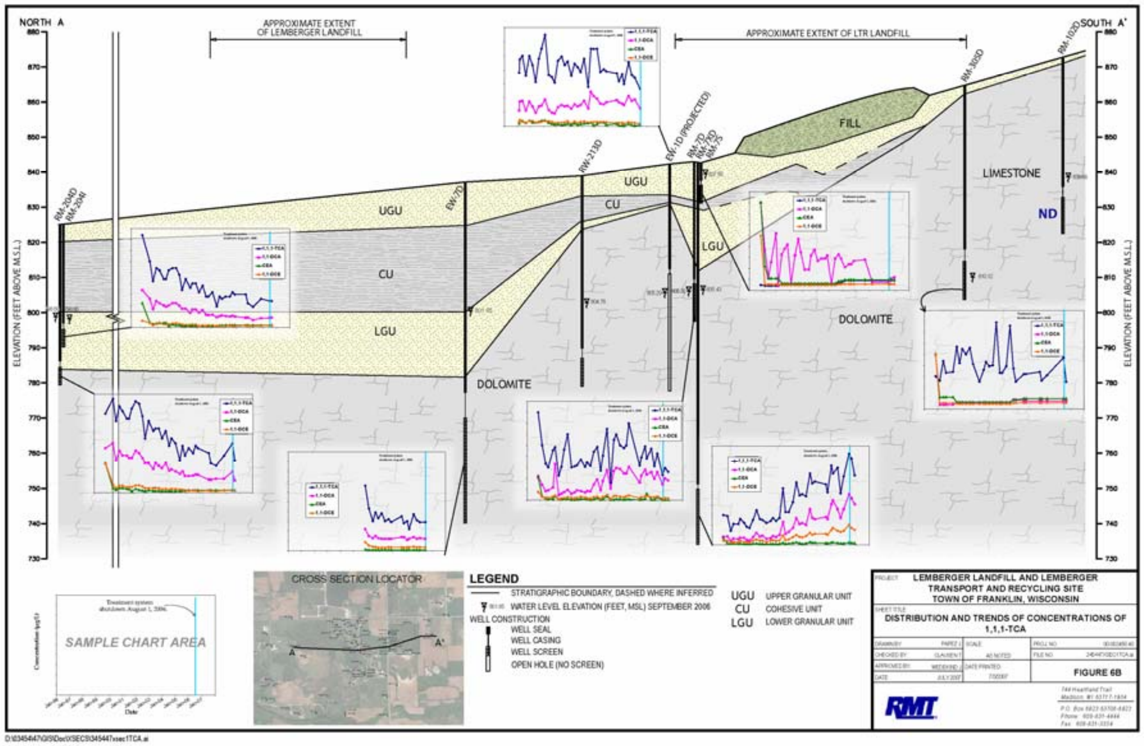

Figure 2. Cross section illustrating trends of 1,1,1-TCA (blue line at top) concentrations in groundwater along axis of plume. Note decreasing concentrations at plume margins and increase daughter products (1,1-DCA and 1,1-DCE)

The similarity of the nature of VOC concentrations measured in the fractures versus in the existing monitoring wells suggests that the current conceptual model adequately depicts the nature and distribution of contaminants. This investigation has also determined that residual NAPL does not reside in fractures at locations beyond the LTR landfill footprint. This supports the current conceptual model that the DNAPL source material migrated into the bedrock fractures in the saturated zone beneath the LTR landfill, and has diffused into the rock matrix. The current groundwater plume is maintained through VOC diffusion back out of the rock matrix and into the groundwater.

Discussion and Conclusions

The most significant aspect of the study identified the high degree of porosity in the bedrock matrix and the relative lack of solutional weathering. The most important finding, however, was that no large-scale flow features were found that may have been missed by the original extraction well network. This supports the conclusion that the original extraction wells were installed in a representative zone of the aquifer. Despite the identification of many fractures and transmissive zones of enhanced porosity, flowrates from those features were found to be minor, and taken as a whole, the bedrock examined in the study appears to be representative of the overall site, and supports the conclusion that the aquifer in the vicinity of the LTR landfill is of very low yield.

A thorough assessment of VOCs in the subsurface soil and at the soil-bedrock interface was performed by a focused investigation to identify preferential pathways for DNAPL at the northern edge of the LTR landfill. Borings (such as B2) were strategically placed in known and suspected subsurface bedrock depressions that could be a preferential DNAPL location at the LTR landfill perimeter. No evidence of DNAPL was detected in any of the borings. Although the bedrock at B2 had the highest concentrations of VOCs in the groundwater and in the rock matrix, concentrations were similar to those detected in the existing monitoring wells. This suggests that, while a bedrock depression at B2 may have indeed once been a preferential VOC migration pathway, no residual source material is currently present at the northern edge of the LTR landfill, and current monitoring has adequately characterized the nature and extent of VOCs.

Finally, the distribution of VOCs in the subsurface was thoroughly characterized and found to be widely disseminated in the groundwater and diffused into the bedrock matrix. The previous conceptual model suggested that there could be residual NAPL residing as ganglia, blebs, lenses, etc., within the fracture network. However, such conditions were not observed at the downgradient edge of the landfill. The porous nature of the rock has allowed diffusion throughout the rock matrix, and there is no evidence of residual NAPL. This is consistent with findings in other studies where matrix diffusion effects have been found to be "strong and persistent" (Parker *et al.*, 1997; Sterling *et al.*, 2004). Groundwater concentrations analyzed from discrete intervals are similar to those found in samples from the current monitoring well network, suggesting that there is no preferential VOC transport through individual "master conduits" or zones of enhanced porosity. These findings indicate that the current primary conceptual model is sound, and could be refined slightly to account for the lack of residual NAPL outside the LTR landfill footprint and that the general wide distribution of relatively low concentrations of VOCs in bedrock is likely a result of VOCs diffusing into the rock matrix in the dissolved phase.

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Table 1
Summary of VOC Concentrations for Selected Rock Matrix and Groundwater Samples

BORING	DEPTH INTERVAL (ft bgs)	ROCK MATRIX(1)		GROUNDWATER (packer)		
		1,1,1-TCA (ng/kg)	TCE (ng/kg)	FRACTURE DEPTH (ft bgs)	1,1,1-TCA (µg/L)	TCE (µg/L)
B1	61.0-61.1	731	329			
	61.24-61.34	783	755			
	61.49-61.59	417	837	61.8	170	37
	66.7-66.8	300	451	66.4	170	35
	67.05-67.15	563	303			
	67.4-67.5	330	294 U			
	69.82-69.92	639	280 U	69.5	180	36
	70.18-70.28	731	305 U			
	70.5-70.6	783	301 U			
	72.62-72.78	417	275 U	72.3	180	37
	72.96-73.13	2,377	283 U			
	73.3-73.45	295 U	295 U			
	78.3-78.4	1,076	269 U	78	190	41
	78.63-78.75	300	254 U			
	79.0-79.15	563	256 U			
	80.8-80.9	330	490			
	81.2-81.3	639	491			
	81.5-81.6	266 U	266 U	80.5	180	41
	86.3-86.4	450	253 U	86	160	34
	86.62-86.72	260 U	260 U			
	86.95-87.05	272 U	272 U			
B2	47.09-47.18	654	252 U	46.8	690	48
	47.35-47.43	292 U	292 U			
	47.68-47.76	471	284 U			
	52.42-52.51	587	306 U	52.8	750	49
	53.05-53.12	839	300 U	53	640	44
	55.72-55.8	920	271 U	55.5	760	52
	55.98-56.08	1,034	272 U			
	62.6-62.7	326	259 U	62.9	700	43
	63.16-63.24	265 U	265 U			
	63.4-63.5	301 U	301 U			
	63.67-63.75	273 U	273 U			
	67.05-67.15	1,150	261 U	66.8	590	41
	67.3-67.4	1,044	342			
	67.59-67.69	846	282 U			
	67.5-67.6	848	265 U			
	68.05-68.15	263 U	263 U	67.8	540	36
	68.35-68.45	522	300 U			
	68.62-68.7	258 U	258 U			
	75.6-75.7	541	270 U	75.4	490	36
	75.83-75.93	700	269 U			
	76.1-76.19	276 U	276 U			

Notes:

Shaded values indicate detections in rock samples.

U = Not detected. Value given is detection limit.

bgs = below ground surface / blanks = No sample

Footnote:

(1) Rock matrix results reported as dry weight.