Assessing the Role of Structural Geologic Elements in Aquifer Hydraulics and Plume Migration


Abstract

Geologic structural features provide the dominant control on migration of a dense aqueous-phase ground water (DAPL) plume at the Avtex Fibers Superfund Site in Front Royal, Virginia. From 1940 to 1989, the plant manufactured fibers such as rayon, polyester, and polypropylene and disposed of waste materials in unlined surface impoundments along the river floodplain. Three impoundments that contain waste viscose, a rayon precursor, are the source of a significant carbon disulfide (CS$_2$) ground water plume. The intense structural deformation has created significant bedrock anisotropy resulting in preferential flow along bedrock strike, producing a narrow ground water plume that extends from the viscose basins southwest beneath the adjacent South Fork of the Shenandoah River toward residential drinking water supply wells. Although a significant amount of geologic, hydrologic, water quality data has been collected during prior studies, the vertical extent of the plume and its migration was not fully delineated nor understood.

Beginning in late 2002 FMC Corporation (FMC) initiated a deep bedrock aquifer characterization study to assess the vertical extent of contamination within the folded and fractured bedrock system at depth, and to improve the understanding of the hydraulic flow regime within the deeper aquifer. The dense nature of the contaminant plume coupled with the steeply dipping anticline and adjacent syncline, drives the plume downward and required FMC to investigate far deeper than the existing monitoring well network. The study used a variety of tools including packer sampling, borehole geophysics and installation of 600-foot deep multi-port wells to evaluate structural elements, preferential flow pathways, and the plume geometry. A 7-day pumping test was conducted to evaluate bulk aquifer hydraulic properties to support the evaluation of potential ground water extraction remedies.

The information collected from the work further supports prior observations that the DAPL plume is migrating within a tightly folded anticline and adjacent syncline at approximately 45° askew from the bedrock hydraulic gradient that would be interpreted from water levels alone, demonstrating the magnitude of structural control. Water quality data coupled with borehole geophysics and historic hydraulic conductivity test result show that the plume extends to a depth of about 400 feet below grade, where further downward migration is retarded by a combination of upward gradients, low permeability zones, and reduced open fractures due to increasing lithostatic loads.

The study showed that appropriate investigative tools, used in systematic order, provided the best information for meeting the project objectives. Although used for evaluating a problem in deep fractured bedrock, the benefits (e.g., reduced time, lower cost, higher quality data) of utilizing the tools in a systematic fashion can be applied to shallower bedrock systems and unconsolidated formations with similar success.
Introduction and Study Objective

The Avtex Fibers Superfund Site, located in Front Royal, Virginia, lies on the east bank of the South Fork of the Shenandoah River (River), within the Valley and Ridge physiographic province. Historical practices and geologic conditions have created a unique environmental problem at the Site (Travers, Martin, Ruby, Cutler and Keating, 2002). From 1940 to 1989, the plant manufactured fibers such as rayon, polyester, and polypropylene. During plant operations, a variety of waste materials were disposed in unlined surface impoundments, which in part rest directly on fractured bedrock in the river floodplain. The three most recently used disposal basins, 9, 10, and 11 (Figure 1), contain approximately 250,000 cubic yards of aged waste viscose, a cellulose-based by-product of the rayon manufacturing process. The deeper portions of basins 9 and 10 contain a dense aqueous phase liquid (DAPL) that is believed to be similar to the fluid initially released from waste viscose in the basins (Travers et al., 2002). The liquid, which is miscible with water and has a specific gravity of 1.05, is believed to be the source of a significant ground water plume containing carbon disulfide (CS$_2$), arsenic, antimony, ammonia-nitrogen, and elevated pH and TDS. This DAPL plume emanates from the viscose basins and migrates along fractures through the bedrock aquifer toward and beneath the adjacent Shenandoah River. The migration of the plume beneath the river, which constitutes a regional discharge boundary, suggests that plume movement is strongly controlled by density effects and geologic structures.

The groundwater contamination was first discovered in 1982, when residents in the Rivermont Acres area, located on the west side of the river, complained of odors in their wells (most likely from hydrogen sulfide (H$_2$S), a degradation product of CS$_2$) (Travers et al., 2002). In 1986, the U.S. Environmental Protection Agency (EPA) added the Site to its National Priorities List (NPL) of hazardous waste sites to be cleaned up under the Superfund program. Since that time, Avtex Fibers, Inc., and later FMC Corporation (FMC), conducted certain investigations and clean-up actions at the Site.

More recently, because of uncertainty regarding the location of the DAPL plume at depth in the bedrock aquifer FMC conducted a supplemental deep aquifer characterization. As described herein, the primary objective of the investigation was to delineate the vertical extent of DAPL plume contamination within the highly folded and fractured bedrock system at depth, and secondarily, to improve the understanding of the hydraulic flow regime within the deeper aquifer.

Site Geology

Site geology has been previously studied utilizing outcrops, bedrock cores and geophysical logs. The geology consists of 20 to 30 feet of weathered soils and river alluvial deposits underlain by a thick section of finely bedded calcareous shales and argillaceous limestones of the Martinsburg Formation (Rader and Biggs, 1975). The principal regional structural geologic features consist of the over-steepened and locally overturned east limbs of the Massanutten Synclinorium and west limbs of the Blue Ridge Anticlinorium. Folding is observed at multiple scales, with all fold axes trending northeast-southwest. At the site level, the ground water plume is confined within a tightly folded anticline and adjacent syncline, with fold axial planes steeply dipping to the southeast. Intense fracturing is observed in shallow bedrock parallel to bedding planes, within fold hinges and along shear zones (reverse faults). These principal structural geologic elements (bedding, folding and reverse faulting) share a common northeast-southwest strike and produce an intense strike-parallel anisotropy within the fractured bedrock aquifer (Rader and Biggs, 1975).

Characterization Methods and Results

A review of the existing Site data indicated that additional geologic information and contaminant profiling was needed below the depth monitored by the pre-existing monitoring well network (approximately 300 feet bgs) to meet the study objectives. Between October 2002 and July 2003, a deep bedrock aquifer characterization study was conducted utilizing borehole geophysics and packer sampling to resolve the location of contamination at depth. The boreholes were then completed as monitoring wells and a series of pumping tests were conducted to provide information regarding the hydraulic flow regime within the deeper aquifer.
Figure 1. Locations of stream gauges, existing monitoring wells and new wells TW-01, 336, 601, 602, 603 and 604.
Assessing Contaminant Location at Depth

Borehole Drilling and Geophysical Logging

A total of six additional deep-bedrock boreholes were installed using a truck mounted Ingersoll-Rand T-4 drill rig. The boreholes were drilled at five locations, as shown on Figure 1, to termination depths between 300 and 600 feet below ground surface (bgs). Caliper (borehole diameter), natural gamma, normal resistivity, single point resistance, temperature, fluid conductivity, optical and acoustic televiewer logs were made of the open boreholes to identify potential fracture zones in the bedrock. A heat pulse flow meter (HPFM) was then used to investigate potential fracture zones in the boreholes and quantitatively measure the rate and direction of ground water flow in these zones.

The information collected from the borehole geophysics indicated that the bulk of the shale bedrock is extremely tight with the majority of observed fractures oriented along bedding planes. With the exception of well 603, the HPFM did not indicate significant flow (>0.1 feet per minute) at any of the tested fractures. This lack of significant flow from any of the fractures is potentially a result of the increased lithostatic loads and mineralization with depth. At well 603, numerous hairline fractures were encountered between 100 feet bgs and 550 feet bgs with upward flow at rates between 0.2 and 1.2 feet per minute. The information collected from the borehole geophysics was then used to select specific fracture zones to be isolated using inflatable packers and sampled for water quality.

Packer Sampling for Plume Characterization

Packer sampling of the 600-foot boreholes was used to determine water quality within specific fracture zones. This enabled subsequent construction of monitoring wells targeting the appropriate depth zones that could be used to effectively monitor the vertical extent of contamination over time. Data from packer sampling also influenced the decision to use multi-level water sampling systems in two boreholes to monitor multiple zones of interest. Boreholes 602 and 603 are located in the center of the CS₂ plume and therefore, to prevent carrying down of contamination to the deeper aquifer packer sampling was conducted during drilling and prior to the geophysical logging. These boreholes were sampled in 40-foot continuous zones beginning at the bottom of their permanent steel casings, 402 feet bgs and 162 feet bgs, respectively. Each 40-foot zone was drilled and then isolated using an upper inflatable packer. The packer was then removed and the next 40-foot zone was drilled, sealed with an inflatable packer, purged, and sampled. The first zones below the steel casing in boreholes 602 and 336, at 402 to 440 feet bgs and 160 to 200 feet bgs, respectively, were sampled with PVC bailers. Packer sampling of boreholes 601, 603 and 604 was completed under a separate mobilization following completion of the boreholes. Intervals were selected based on the results of the geophysical logging and the heat pulse flow meter. Straddle packers (i.e., packers inflated above and below the zone of interest) were installed to isolate zones of interest in these boreholes.

Field parameters (i.e., pH, temperature, specific conductance, turbidity, dissolved oxygen and oxidation-reduction potential) were recorded for each packer-sampled zone within the boreholes. Following stabilization of the field parameters, field tests for arsenic and H₂S were performed and water samples were collected for volatile organic compound (VOC) analysis. Water samples from boreholes 601, 603 and 604 were also analyzed for inorganics, and conventional parameters (e.g., alkalinity, ammonia nitrogen, chloride, sulfate, sulfide, total dissolved solids). Not all of the zones of interest generated sufficient recharge to be sampled.

The packer sampling data, in combination with historic monitoring data, indicate that preferential flow along bedrock strike has resulted in an elongate, narrow ground water CS₂ plume that extends from the viscose basins to the southwest towards and beneath the River (Figure 2). A significant decrease in CS₂ concentrations (46,000 to 9 µg/L) was observed between well 336 and well 604 at a corresponding depth of about 350 feet below the River. [Note, the land surface at well 604 is about 150 feet higher than at the Site.] The decrease in CS₂ concentrations downstrike of the River is believed to be due to dilution and dispersion along the flow path, in addition to an opposing (eastward) hydraulic gradient. The vertical migration of dense contaminants appears to be limited to a depth of about 400 feet. Both wells 602 and 603 showed several orders of magnitude decreases in CS₂ concentrations below 400 feet bgs. The decrease in CS₂ concentrations is consistent with the extremely
low flow rates measured with the HPFL and the minimal sustainable yield of the intervals measured during packer sampling.

Figure 2. Approximate distribution of carbon disulfide plume in deep bedrock wells (2000 and 2003).
Understanding The Hydraulic Flow Regime

Well Installation

In addition to understanding the lateral and vertical extent of the DAPL plume, it is important to also understand the migration of the plume. To better understand the mechanisms of flow in the deep bedrock aquifer that control the migration of the plume, and assess methods for controlling or remediating the plume, boreholes 336, 601, 602, 603 and 604 were completed as monitoring wells. New well TW-01, which was intended for use as a pumping well, was left as an open borehole from 40 to 300 feet bgs.

The decision was made to construct conventional monitoring wells in boreholes 601, 602, and 336 because of the low yield of the fractures and the consistent CS₂ concentrations across the sampled intervals. The wells were completed with 4-inch Schedule 80 PVC and 0.01-inch slotted well screens at 290 to 350 feet bgs, 480 to 560 feet bgs, and 240 to 280 feet bgs, respectively. Boreholes 603 and 604 were completed with Water FLUTE™ multi-level water sampling systems. The Water FLUTE™ systems were used as a cost-effective approach (compared with drilling additional boreholes to install multiple single wells) for future monitoring of four discrete zones within each borehole. Well 603 monitors the following zones:

- Zone 1 – 150 to 190 feet bgs,
- Zone 2 – 260 to 300 feet bgs (with permanent pressure transducer installed),
- Zone 3 – 425 to 465 feet bgs, and
- Zone 4 – 490 to 530 feet bgs (with permanent pressure transducer installed).

Well 604 monitors the following zones:

- Zone 1 – 225 to 265 feet bgs (with permanent pressure transducer installed),
- Zone 2 – 360 to 400 feet bgs,
- Zone 3 – 435 to 475 feet bgs (with permanent pressure transducer installed), and
- Zone 4 – 540 to 580 feet bgs.

Water FLUTE™ wells 603 and 604 were each constructed with pressure transducers in two zones to allow for monitoring of water levels and vertical hydraulic gradients.

Pumping Tests and Water Level Monitoring

The information collected from pumping tests and water level monitoring was used to improve the understanding of the hydraulic flow regime within the deeper aquifer. A step-drawdown pumping test, 6-hour constant-rate pumping test and a 7-day constant-rate pumping test were conducted at test well TW-01, which is open to the shale bedrock from 40 feet bgs to 300 feet bgs. The 6-hour constant-rate pumping test was conducted to determine a suitable pumping rate for the week-long constant-rate pumping test. As part of the 7-day constant-rate pumping test evaluation, water levels were collected from monitoring wells for two weeks before, during, and one week following the test. Ground water levels in 88 observation wells, and the pumping well, were monitored in one of three ways:

1. Water levels in 86 observation wells, and the pumping well were monitored manually on three dates to provide a “synoptic” set of ground water elevations. Measurements were made just before pumping began, near the end of the pumping test, and after approximately 6 days of recovery;
2. Water levels in 12 of the observation wells were measured manually once daily over the four week monitoring period, and
3. Water levels in 29 of the observation wells and the pumping test well were measured using InSitu® pressure transducers (which compensated for barometric pressure changes), which generally provided pressure head measurements every 15 minutes over the four week monitoring period. These are considered “continuously” monitored wells.
In addition, precipitation data was collected from the on-site rain gauge and the NOAA Front Royal Meteorological Station (443229) during the pumping test, monitoring period. The River elevation was measured using both continuous measurements in a stilling well installed adjacent to TW-01, and measurements from the staff gauges installed upstream and downstream of the Site. The precipitation and River elevation data was used to evaluate subtle changes in water elevations during the pumping test resulting from rain events.

Water Levels and Pumping Test Drawdown Patterns

Ambient Site-wide water level measurements indicate that the hydraulic gradient for the bedrock aquifer is primarily westerly (Figure 3), toward the River; however, the water quality data indicate that the plume is migrating to the southwest at an approximate 45° angle to the bedrock hydraulic gradient. The deviation in plume direction is a result of the high anisotropy of the bedrock system, with increased conductivity and hydraulic communication parallel to the strike of the bedrock (approximately N20°E to N35°E) and decreased hydraulic conductivity perpendicular to bedrock strike (i.e., cross-strike).

The high degree of anisotropy in the bedrock system is evident in the pumping-related drawdown for the intermediate and deep bedrock aquifer systems during the 7-day pumping test. During the test, no pumping-related drawdown was observed in the intermediate bedrock well PW-03, cross-strike of the plume, although it is located only 300 feet from the pumping well (Figure 4). In contrast, drawdowns of 18 and 17 feet were observed in intermediate bedrock wells GM-02B and 216, which are 600 feet and 1,200 feet along bedrock strike, respectively (Figure 4). Similarly, 0.5 feet of pumping-related drawdown was observed in well 601, cross-strike of the plume, although it is located only 300 feet from the pumping well (Figure 5). In contrast, drawdowns of up to 16 feet were observed in wells 336 and 316, which are 600 feet and 1,200 feet along bedrock strike, respectively (Figure 5).

With few exceptions, observed drawdown in the shallow, intermediate, and deep bedrock wells indicate that pumping at approximately 40 gpm in the center of the plume on the east side of the River resulted in at least 0.5 feet of drawdown in all monitored zones with significant plume-related contamination, defined by zones with a carbon disulfide concentration above the risk based concentration of 1.0 mg/L. This strong correlation between observed drawdown and plume geometry further suggests that the tightly folded and dipping anticlinal and synclinal structures are controlling the migration of the plume.

Comparison of the water levels observed during the pumping test-monitoring period to the rainfall data indicates that precipitation and associated recharge may have moderately influenced ground water levels during the test. Water levels in monitoring wells located adjacent to the River were found to be closely correlated to the water level in the River (which is generally, but not always, correlated to precipitation). Water level in wells located outside of the influence of the River demonstrated only a slight tendency to increase or decrease (i.e., <0.5 feet) in response to wet or dry periods.
Figure 3. Ground water elevation contours for the deep bedrock aquifer under ambient conditions.
Figure 4. Pumping-related drawdown (after pumping for approximately 160 hours) in intermediate bedrock wells during the July 2003 pumping test.
Figure 5. Pumping-related drawdown (after pumping for approximately 160 hours) in deep bedrock wells during the July 2003 pumping test.
Aquifer Hydraulic Properties

The bedrock aquifer hydraulic properties give further support to the understanding of the plume’s migration. Given the current knowledge of the system, application of the Papadopulos model to the data yields reasonable bulk aquifer property estimates (at the field scale) of the intermediate and deep bedrock in the plume area. The storage coefficient, S, is estimated at 7.3x10^-5, and is assumed in the model not to vary directionally. This value is within the range of storage coefficients for confined aquifers (10^-5 to 10^-3; Driscoll, 1986). The aquifer transmissivities along geologic strike and cross-strike are 2.1x10^-4 m²/s and 1.2x10^-5 m²/s, respectively. The aquifer thickness for this analysis was assumed to extend from the top of the intermediate zone (100 feet bgs) to the depth of the bottom of the pumping well and monitoring zone (300 feet bgs), and thus assumed to be 200 feet (61 m). The hydraulic conductivity in the plume area, determined from the transmissivity divided by the assumed thickness of the aquifer, was thus estimated to be 3.4x10^-4 cm/s along strike and 2.0x10^-5 cm/s perpendicular to strike (cross-strike). This range of hydraulic conductivities is reasonable given the observed preferential plume migration along strike.

The recent pumping test data is consistent with hydraulic conductivities measured during a 1993-94 remedial investigation of the Site where 461 packer tests were conducted on 175, 10-foot intervals at 17 different open borehole wells completed in the bedrock aquifer. The hydraulic conductivities range from 3.2 x10^-3 cm/sec to 4.3x10^-7 cm/s with a geometric mean of 7.7x10^-5 cm/s. As shown on Figure 6, while the range of conductivities is very large, the maximum hydraulic conductivity of the bedrock aquifer decreases with depth, likely as a result of tightening of fractures due to lithostatic load, reduced near surface weathering features, and increased mineralization within fractures.

![Figure 6](image)

Conclusions

The deep bedrock aquifer characterization work further supports past observations that the principal structural geologic elements of folding and fracturing play a significant role in the bedrock aquifer hydraulics, and that structural elements are the primary control on plume migration at the Site. The intense structural deformation has created significant bedrock anisotropy with increased conductivity and hydraulic communication parallel to the strike of the bedrock (approximately N20°E to N35°E) and decreased hydraulic conductivity perpendicular to bedrock strike (i.e., cross-strike). Within the plume, the hydraulic conductivity along strike is estimated to be
17 times greater than the hydraulic conductivity cross-strike. This has resulted in preferential flow along bedrock strike, generating an elongate, narrow ground water plume that extends from the viscose basins southwest toward the River.

The plume axis (and bedrock strike) trends approximately 45° from the bedrock hydraulic gradient, demonstrating the magnitude of structural control. The lateral migration is most inhibited by the over-steepened and overturned east limbs of the synclines and western limbs of anticlines. The packer sampling data further show that the DAPL plume extends to a depth of about 400 feet below grade; where downward migration is retarded by a combination of upward gradients, fold geometry, low permeability zones, and reduced open fractures probably the result of increasing lithostatic loads. The significant decrease in CS₂ concentrations on the west side of the River is believed to be largely due to the opposing (eastward) hydraulic gradient.

FMC and the EPA are using the data gathered from this deep bedrock aquifer characterization to further evaluate potential remediation options for the DAPL plume. Both geophysical logging and packer sampling assured that permanent monitoring wells would be completed in zones with significant contamination and sufficient recharge for sample collection. The use of multi-level wells for monitoring the deep bedrock aquifer decreased the time and cost associated with installation of the monitoring points and provides a more cost-effective means of characterization than installation of multiple wells. While the systematic utilization of the tools in this study were beneficial to understanding the vertical extent of the DAPL plume and the hydrologic regime at the Site, this same approach could be applied to shallower bedrock systems and even unconsolidated formations with similar success.

References


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