Control of Fractured Bedrock Structure on the Movement of Chlorinated Volatile Organics in Bedrock and Overburden Aquifers, Newark Basin of New Jersey

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Abstract

We have developed a conceptual model of groundwater flow in a portion of the Passaic Formation and overlying glacial till in the Newark Basin of the Piedmont Physiographic Province in Northern New Jersey. This model was developed based on the findings of a hydrogeologic investigation of a property where historic releases of chlorinated volatile organic compounds have caused contamination of groundwater in overburden and bedrock aquifers. We have concluded from this case study that major bedding partings and intense fracturing within beds control the migration of dissolved contaminants in groundwater. These water-bearing units are expressed in the topography of the buried bedrock surface and therefore readily mapped by relatively simple investigation techniques. Our analysis of logs and cores from bedrock wells confirmed that the buried valleys parallel with strike are associated with highly fractured beds. Buried valleys in the bedrock surface are pathways for the migration of contaminants in the overlying till. These valleys control the geometry of a co-mingled volatile organic plume in the overburden aquifer that exceeds 4,100 feet in length. We also conclude that the presence of near-vertical fractures parallel to the strike of bedding play a significant role in contaminant migration on a local scale; however, on a regional scale covering thousands of feet the highly fractured bedrock units control the geometry and flow of plumes.

We derived the conceptual model of groundwater flow in this study area by analyzing the interrelationships between key factors identified through coring, outcrop characterization, mapping of the buried bedrock surface, well testing and characterization of the distribution and movement of dissolved volatile organics in groundwater and surface water. The fractured interbedded shales, siltstones and mudstones of the Passaic Formation are a major source of groundwater in the study area and are tapped by residences for drinking water. The benefits of developing a conceptual model accounting for major groundwater migration pathways early in the site investigation included the proper placement and construction of monitoring wells, an early recognition of potential receptor issues, and a graphical construct that explained possible cause and effect relations to both the client and regulators.

Introduction

We performed this hydrogeologic study for a private industrial client in order to characterize the impact of historic releases of chlorinated volatile organic compounds (VOCs) into the overburden at their site on groundwater quality. The initial phase of the study characterized the impacts within the unconsolidated aquifer, which primarily consists of 20 to 40 feet of unconsolidated glacial till. We collected groundwater samples over a 40-acre area using direct-push methods, permanent monitoring wells and residential wells.

A groundwater investigation performed in 2003 identified multiple co-mingled plumes of chlorinated and non-chlorinated VOCs originating from multiple sources, including our client’s site and several off-site locations. These plumes have migrated in the overburden groundwater along preferential pathways. The total length of the co-mingled plumes, primarily defined by trichloroethylene (TCE), in the overburden aquifer exceeds 4,100 feet. The plume geometry indicates strong control by the underlying bedrock structure.

In addition to characterizing impacts within the unconsolidated aquifer, we installed and sampled bedrock monitoring wells and sampled several residential wells which were using the groundwater from the fractured rock aquifer for drinking water. Findings of the initial bedrock groundwater investigation showed that dissolved chlorinated and non-chlorinated VOCs have migrated over 4,000 feet in a direction generally parallel to the strike of bedding.
This paper describes the key findings of the hydrogeologic investigation and how that information was unified into a conceptual model of groundwater flow and contaminant migration. The model is based on the analysis of associations between data collected through soil sampling, rock coring, outcrop characterization, mapping of the buried bedrock surface, packer testing, groundwater level monitoring, surface water sampling, and groundwater sampling.

**Site Description and Background**

*Physical Setting*

The site is located in a heavily populated area of the state of New Jersey, U.S.A. with mixed commercial and residential land use (Figure 1). The local topography in the area of the site is relatively flat to gently sloping undulating uplands, with elevations of 100 to 140 feet above mean sea level (MSL). The site is on the western slope of a regional topographic high.

![Site Location Map](image)

**Figure 1. Site Location Map**

*Hydrogeologic Setting*

The site is located in the Newark Basin of the Piedmont Physiographic Province. The Newark Basin is a northeast-to-southwest trending basin which consists of non-marine sedimentary rocks and is one of several Late Triassic and Early Jurassic Newark Supergroup rift basins located along eastern North America (Olsen, 1980). The Newark Basin covers an area of about 140 miles long, from southeastern Pennsylvania northeast to the southeastern tip of New York State. The sedimentary rocks in the Newark Basin generally strike northeast to southwest and dip 5 to 25 degrees to the northwest (Olsen, 1980). The rocks of the Newark Basin were deformed during the extension of the rift basin. Several large normal faults have been mapped in the Newark Basin, generally perpendicular to strike (Olsen, 1980). The primary orientation of joints in the basin include low-angle joints or faults along bedding planes and steeply dipping joints occurring sub-parallel and subnormal to bedding (Herman, 2001).

Bedrock in the site area consists of a reddish-brown mudstone with interbedded shales, siltstones, and sandstones. Monitoring wells used in this investigation are completed into the Metlars and Livingston members of the Passaic Formation of the Newark Supergroup. We based this conclusion on a review of unpublished geologic data from the New Jersey Geological Survey (Volkert, 2003), and on rock core and bedrock outcrop data that we collected. The Livingston Member is generally described as primarily a red mudstone, with some intervals of purple mudstone and one dark gray shale interval (Olsen et al., 1996). The Metlars Member overlies the Livingston Member and is characterized by several black shale layers, including one at the base of the member (Olsen et al., 1996).
Unconsolidated glacial drift (Rahway Till) overlies the bedrock in the area. The thickness of the till deposits range from a few feet to 100 feet thick, with an average thickness of about 25 feet (Anderson, 1968). The thickness of the cover in the study area ranges from approximately 20 to 40 feet. The glacial deposits are associated with the Wisconsinan Glaciation in the Pleistocene Period, the most recent glaciation in New Jersey. The glacial sediments in the vicinity of the site consist mainly of reddish brown silts and clays with gravel, as well as some sand layers with gravel. The terminal moraine for the Wisconsinan Glaciation is located approximately one-half mile west of the site and trends northwest-southeast (Stanford et al, 1995). The terminal moraine is evidenced by higher surface topography. The glacial deposits are thicker in the terminal moraine, but chiefly comprised of the same till material. Alluvium has been mapped along local drainage features.

The Passaic Formation is the primary aquifer for water supply in the area. The water table is often encountered within the glacial till, but the low permeability till is not generally used as a groundwater resource (Anderson, 1968). Groundwater flow and storage in the Passaic Formation is primarily through secondary porosity, including bedding plane partings and other fractures and joints, as well as dissolution cavities (Herman, 2001). Tests performed on wells in the Passaic Formation have found a yield range from 2 to 660 gallon per minute (gpm) with an average yield of 75 gpm (Anderson, 1968). The response of the Passaic Formation aquifer to pumping is directional and anisotropic. Response time is quicker and drawdown has been found to be greater between wells aligned along the strike of formation (Michalski, 1990).

The closest surface water body to the site is a stream located approximately 2,000 feet west of the site. The stream is an engineered and re-aligned drainage, enclosed within a concrete channel for most of its length, and receives stormwater discharge from the surrounding residential neighborhood. The stream flows to the south for approximately 2,500 feet and then turns to the east where the concrete channel continues for another 1,000 feet. Along the natural portion of its channel the stream flows in a steeply walled drainage valley characterized by numerous bedrock outcrops.

**Water Quality in Study Area**

Releases of spent solvents on-site have resulted in chlorinated VOC impacts in groundwater within glacial till overburden and within the fractured mudstone and shale bedrock. The primary VOC detected is TCE. The New Jersey Department of Environmental Protection (NJDEP) currently requires that TCE in groundwater be delineated to a human health-based groundwater quality standard (GWQS) of 1 microgram per liter or 1 part per billion. The concentration of TCE in the overburden and bedrock aquifers has never been detected at concentrations greater than 10,000 micrograms per liter in the study area and is generally less than 1,000 micrograms per liter. Free and/or residual product is not considered to be present based on current and historic groundwater data showing that concentrations have never equaled or exceeded one percent of the water solubility of any contaminant. We characterized the impacts to the overburden and bedrock aquifers by a suite of chlorinated VOCs through groundwater sampling of test borings, monitoring wells and surface water. Groundwater sample data indicates that there are off-site sources of chlorinated solvents contributing to this plume, but these off-site sources have not yet been identified. In addition to chlorinated VOCs, we also identified a co-mingled petroleum plume approximately 2,000 feet in length with an identified off-site source. The primary petroleum-related VOC detected in the overburden and bedrock aquifers is methyl tertiary butyl ether (MTBE).

**Overburden Aquifer and Surface Water**

A finding of our hydrogeologic investigation was that the overburden plume was approximately 4,100 feet long and 300 feet wide. The plume geometry indicates strong control by the underlying bedrock structure. From the most upgradient source area, the overburden plume follows the general direction of bedrock strike for 2,000 feet and then turns approximately 35 degrees and follows a buried bedrock valley for another 2,000 feet before attenuating (Figure 2). Surface water in a stream located at the base of the local slope-aquifer system is impacted by the same suite of chlorinated volatile organic compounds where the plume footprint crosses it. However, the overburden plume also undercuts and extends beyond the stream boundary, preferentially following a buried bedrock valley.
**Bedrock Aquifer**

The ongoing bedrock investigation has confirmed impacts by chlorinated VOCs to a depth of at least 200 feet below grade in a source area and dissolved constituents over 4,000 feet from identified source areas. The data collected to date also indicates that flow is primarily to the southwest along the strike of the formation. The study site is located on a topographic high in a groundwater recharge zone, evidenced by consistent vertical downward hydraulic gradients in overburden-bedrock well clusters.

**Bedrock Structure**

*Surface Topography of Buried Bedrock and Overburden Groundwater Flow*

A conclusion of the ongoing bedrock investigation is that at least two of the buried bedrock valleys that locally control flow in the overburden aquifer are associated with highly fractured zones. These valleys were identified by contouring the top of bedrock surface elevation as encountered in borings drilled using direct push and hollow-stem auger methods (Figure 2). The initial 1,000 to 2,000 feet of the overburden and bedrock plumes extend along strike and appear to be controlled by two highly fractured bedding planes (Units A and B). The distal portion of the overburden plume appears to be controlled by a bedrock valley which we interpret as being associated with a regional fracture zone.

![Figure 2](image.png)

**Legend**

- Approximate extent of trichloroethylene in overburden groundwater above 1 ug/l
- Top of bedrock surface contour in feet, contour interval four feet (dashed where inferred)
- Trace of fractured zone in the top of bedrock surface
- Site boundary
- Stream
- Road

*Figure 2.* Map of study area showing the TCE plume in overburden over the top of bedrock contours and identified fracture zones.
The overburden groundwater contours generally follow surface topography, however they more clearly mimic the top of bedrock surface. Based on hydraulic head contours, overburden groundwater flow is generally to the southwest from the site and follows the top of bedrock into a bedrock valley to the southwest. Figure 3 shows a three-dimensional block diagram of the study area. The gridded surface is the top of bedrock and the shaded area is the approximate extent of TCE in the overburden aquifer.

![Figure 3](image)

**Figure 3.** Three-dimensional representation of bedrock surface with the extent of TCE in overburden groundwater shaded.

*Fractures and Jointing*

We measured the orientation of bedding planes in local outcrops and found an average strike of N 51 degrees E and dip to the northwest of 14 degrees. We also measured two primary sets of joints in the outcrops. The predominant joint trend, approximately 44 degrees east of north, is subparallel to bedding with a near vertical dip ranging from 54 to 87 degrees to the southeast and northwest. The second most common joint orientation has a shallow dip of 9 to 15 degrees to the northeast and is oriented approximately perpendicular to bedding. The photograph in Figure 4 shows bedding and the two major joint sets at an outcrop in the study area. These measured orientations are consistent with regional data and are shown on two rose diagrams in Figure 5.

![Figure 4](image)

**Figure 4.** Bedding and two sets of cross-cutting vertical joints in outcrop.
We obtained detailed bedrock lithology information from cores collected from bedrock wells on-site. The predominant lithology in the recovered rock core is red-brown mudstone with a moderate hardness, weak strength, moderate weathering, and moderate fracturing. Interbedded purple mudstone and red, very fine sandstone was also encountered. A photograph of the rock cores is included as Figure 6. Fracturing along bedding partings was most commonly observed, but near-vertical joints were also documented. Green alteration zones were observed along fracture zones identified as water-bearing zones. Secondary calcite crystals were observed sealing some fracture zones and infilling root zones. During coring, vertical fractures were observed at roughly ten-foot intervals. Major water bearing zones were identified by intense fracturing, significant alteration of the core, and intense weathering. Often near-vertical fractures were associated with these major water bearing zones; however due to intense fracturing the fracture dip could not be obtained for some of these zones. Spayd (1985) has identified near-vertical fractures in the Passaic Formation as a significant pathway.

![Rose Diagrams showing the orientation of bedding strike (A) and the strike of joints (B) as measured in outcrop.](image)

**Figure 5.** Rose Diagrams showing the orientation of bedding strike (A) and the strike of joints (B) as measured in outcrop.

**Figure 6.** This section of core shows a steeply dipping near vertical fracture, as well as several shallow dipping fractures oriented similar to bedding. Secondary calcite mineralization along root zones is also shown.

Figure 7 illustrates a cross-section across the site. The relationship of two preferential pathways (designated Unit A and Unit B) to the bedrock surface and existing wells is shown. A bedding dip of 15.4 to 15.7 degrees to the northwest was calculated using borehole logs and observations of the top and bottom of a purple mudstone.
bed (Figure 7) encountered during the drilling of two wells separated by 1,000 feet. This is consistent with bedding dip measured at outcrop. Figure 7 does not show the numerous other distinct water-bearing zones along bedding and ubiquitous near-vertical jointing observed in rock cores, which also play significant roles in groundwater flow and contaminant migration.

![Figure 7. Cross-section through the site showing highly fractured bedding units, marker bed and existing monitoring wells.](image)

**Packer Testing and Near-Vertical Joints**

Packer testing was conducted during the installation of a deep well on-site. This testing was done after the overburden was sealed with steel casing grouted in place, and after the borehole had been cored from 45 to 200 feet bgs. Packer testing was conducted at two intervals noted as water-bearing zones in the core, at 100 to 110 feet and 190 to 200 feet. The third tested interval, from 140 to 150 feet, was identified as a water bearing zone and also had elevated volatile organic readings as measured by a photoionization detector. Pneumatic packers were used to seal off each interval for sampling. Testing was conducted from the deepest interval to the shallowest. Each packed interval was purged until field parameters, including pH, temperature, specific conductivity, dissolved oxygen and oxidation-reduction potential, had stabilized with a minimum purge of three volumes of the packed interval. After purging, analytical samples were collected for VOC analysis following USEPA Method SW846-8260B.

The results of the packer testing indicate that near vertical joints may have prevented a good seal from forming and caused communication around the packers. During the purging of the packed intervals, groundwater levels were collected above the packers and in nearby wells. The water level above the packers dropped from 1.3 to 2.1 feet during purging of the packed intervals. During the two deeper tests, approximately 0.35 feet of drawdown was observed in a bedrock well screened from 100 to 110 feet located approximately 20 feet to the north. The analytical results also indicated that vertical communication between the packed zones occurred. The same suite of VOCs was detected in all three samples. In addition, the concentrations of these compounds were similar, the percent difference of the two parameters at the highest concentrations, TCE and carbon tetrachloride, was less than 50%.

After packer testing, a permanent monitoring well was installed at this location from 190 to 200 feet below ground surface. Significantly lower concentrations were found in the permanent monitoring well than in the packer testing sample collected at the same depth. Groundwater samples were collected using low-flow groundwater sampling techniques (USEPA Region II, 1998), and pumped at a rate of only 0.02 gallons per minute, while during packer testing the interval was pumped at a rate of 1 to 1.5 gallons per minute. The high rate of pumping during packer testing appears to have induced communication between water-bearing zones through vertical fractures.
Conclusions

The comprehensive hydrogeologic investigation completed was unified into a hydrogeologic conceptual model for the study area. The key components of this model include:

- Fractures provide the primary migration pathway for groundwater flow and contaminant migration in the bedrock, including bedding plane partings, near-vertical joints and other fractures.

- The formation contains distinct and laterally continuous water-bearing zones along parted and fractured bedding planes separated by more massive units, which all strike northeast-southwest and dip locally 12° to 16° to the northwest.

- The fractured water-bearing units and more massive units are expressed in the topography of the buried bedrock surface and therefore readily mapped by relatively simple investigation techniques.

- Logs and cores from bedrock wells confirmed that the buried valleys parallel with strike were associated with highly fractured beds.

- Buried valleys in the bedrock surface are pathways for the migration of contaminants in the overlying till and control the geometry of a co-mingled volatile organic plume that exceeds 4,100 feet in length.

- Regularly spaced near-vertical jointing exists in bedrock outcrops and in cored sections.

- Wells open to different water-bearing units are in communication through the near vertical jointing.

- The presence of near-vertical fractures subparallel to the strike of bedding plays a significant role in contaminant migration on a local scale, however on a regional scale covering thousands of feet the highly fractured bedrock units control the geometry and flow of plumes.

The benefits of developing a conceptual model of the major groundwater migration pathways early in an investigation include ensuring proper placement and construction of monitoring wells, rapidly recognizing potential receptors, and having a graphical construct that explains possible cause and effect relations to both the client and regulators. We are using the current site conceptual model to plan additional bedrock investigations, which will include locating wells and open-hole intervals to monitor the identified pathways.

References


Volkert, R., 2003, personal communication.
Biographical Sketches

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