New Jersey Geological and Water Survey Information Circular

New Jersey Geological and Water Survey borehole geophysics program

The New Jersey Geological and Water Survey (NJGWS) makes use of several borehole geophysical tools to understand the deeper subsurface through the exploration of wells and borings. These tools assist with defining rock properties, locating the contacts between rock units, identifying and measuring fractures, and determining fluid properties and flow direction. When used in multiple wells in a small area, these tools provide a greater understanding of rock structure and groundwater flow patterns at depth. This is especially true when the same water-bearing fractures are identified in multiple wells. While geophysical methods can provide considerable subsurface information by themselves, to fully understand water flow and aquifer properties it is necessary to include aspects of a traditional hydrogeologic study using the same wells. These might include pump tests and dye tracer tests. Hydrogeologic studies are typically used to aid in the understanding of contaminant transport, for delineating and planning the remediation of contaminated sites, or to locate potential groundwater resources.

Borehole Geophysical Tools

Televiewers provide a single two-dimensional image of the entire borehole wall (figure 1). This allows for the exact depths and orientations of features to be identified and analyzed. There are two main types of televiewers: **Acoustic Televiewers** (ATV) and **Optical Televiewers** (OPTV).

An **ATV** images the subsurface by sending sound waves into a water filled borehole. The waves reflect off the interface between the water and the borehole wall and return to the instrument. The instrument uses the two-way travel time and the amplitude of the returning wave to generate acoustic images of the borehole wall (Morin, 2000). Changes in rock type, void spaces, and mineralization typically create acoustic impedance contrasts that can be seen in the acoustic logs (figure 1). Thus, ATVs are typically used for finding unit contacts, thin beds, and differentiating between open fractures and filled veins (Williams and Johnson, 2004). ATVs are limiting in that they cannot determine exact rock types and that they can only note veins if they have different acoustic properties than the surrounding bedrock.

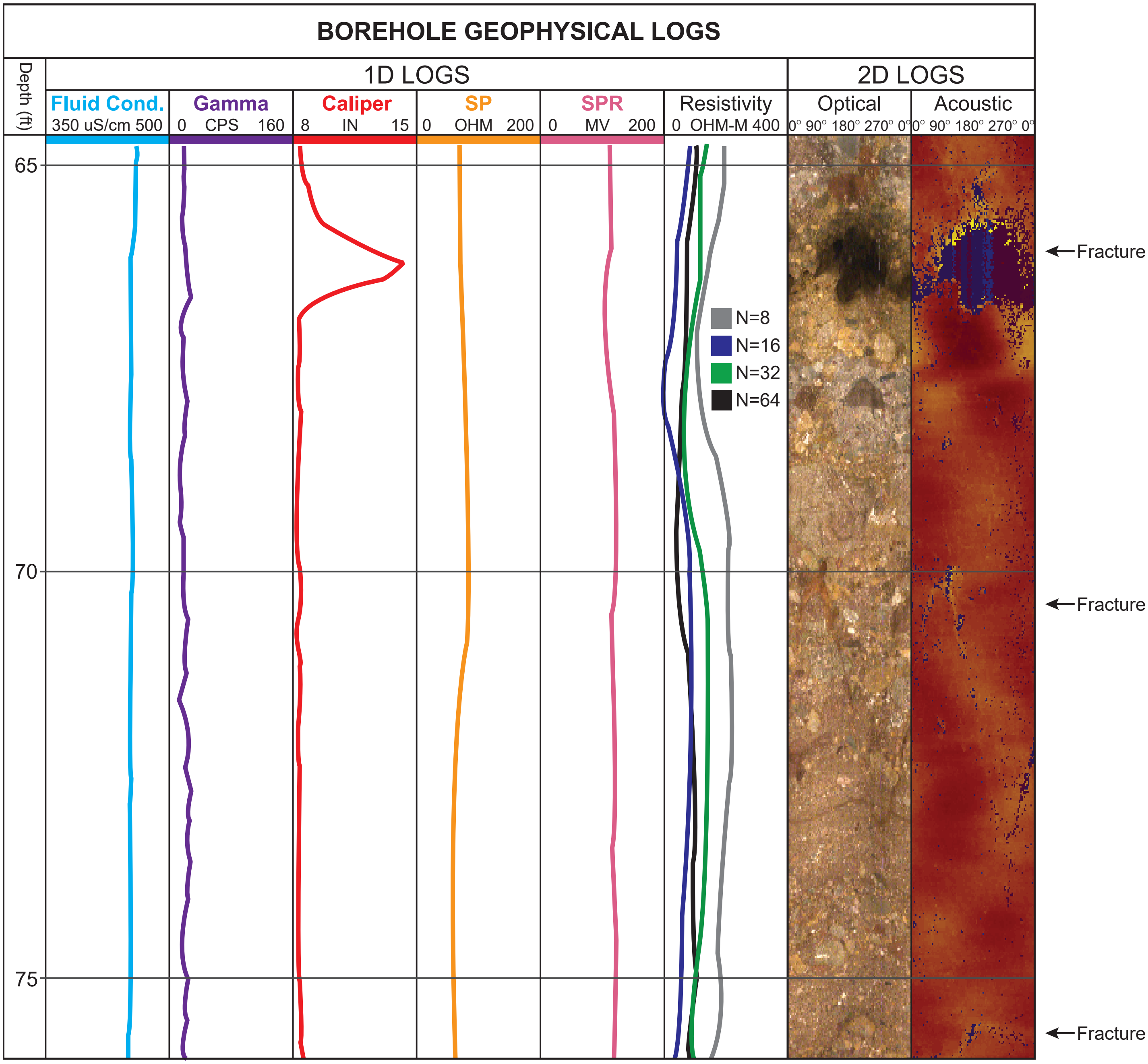
An **OPTV** captures 360° photographic rings, collected at 1 mm depth intervals, and stacks them to create a single image of the entire borehole. OPTV images are useful for identifying rock types, bedding orientation, specific rock properties, contacts, fractures, and veins. OPTVs are limiting in that water quality dictates image quality. Cloudy water can make images blurry or difficult to see. The best approach is to generate both an ATV and OPTV log and to analyze them side-by-side (Williams and Johnson, 2004).

Geophysical logs provide one-dimensional images of borehole properties at depth. The logging tool measures its particular parameter through the depth of investigation and combines values into a vertical log (figure 1). The types of logs collected depend upon the investigation and the known bedrock and water properties at depth. The NJGWS has the capabilities to deploy: the single point resistance tool, the resistivity tool, the spontaneous potential tool, the caliper tool, the gamma tool, the fluid conductivity tool, and the electromagnetic induction tool.

The **Single Point Resistance** (SPR) tool uses two electrodes, one in the borehole and one on the ground surface. The tool emits a DC current, records the loss of voltage between electrodes, and measures the apparent single point resistance. The electrode in the borehole measures the formation's resistance at each depth. As SPR is highly dependent on water content, the SPR is useful for locating fractures and differentiating between aquifers and confining units. SPR is also useful for locating zones of salt and fresh water. SPR is limiting in that the depth of penetration is variable, oxidation/reduction reactions at the in-hole electrode affect the recorded measurements, and the tool can only be used in water or mud-filled open holes (NJDEP, 2005).

The **Resistivity** tool measures the resistivity of a material to carrying an electrical current. Unlike the near surface application, the electrode spacing is built into the tool. This results in a fixed distance of investigation. Traditionally, there were two types of resistivity devices: The long normal with 64 inches between electrodes and the short normal with 16 inches between two electrodes. Modern devices collect four traces with 8 inch, 16 inch, 32 inch, and 64 inch spacing. The shorter spacing yields the resistivity of the borehole wall, whereas, the longer spacing provides the resistivity further into the formation. The resistivity tool can be used to assist with locating specific formations, but can only be used in water or mud filled open holes (NJDEP, 2005).

The **Spontaneous Potential** (SP) tool measures the voltage difference between a fixed electrode on the ground surface and an electrode in the borehole. Unlike the SPR and resistivity tools, no voltage is applied at either electrode. The voltage difference is caused by electrochemical activity downhole between electrolytes of different electric potential. Commonly when the probe passes a boundary between porous sand and less permeable clay there is an inflexion on the log. Thus, SP is typically used to find clay layers, permeable layers, and conductive beds. SP cannot be used above



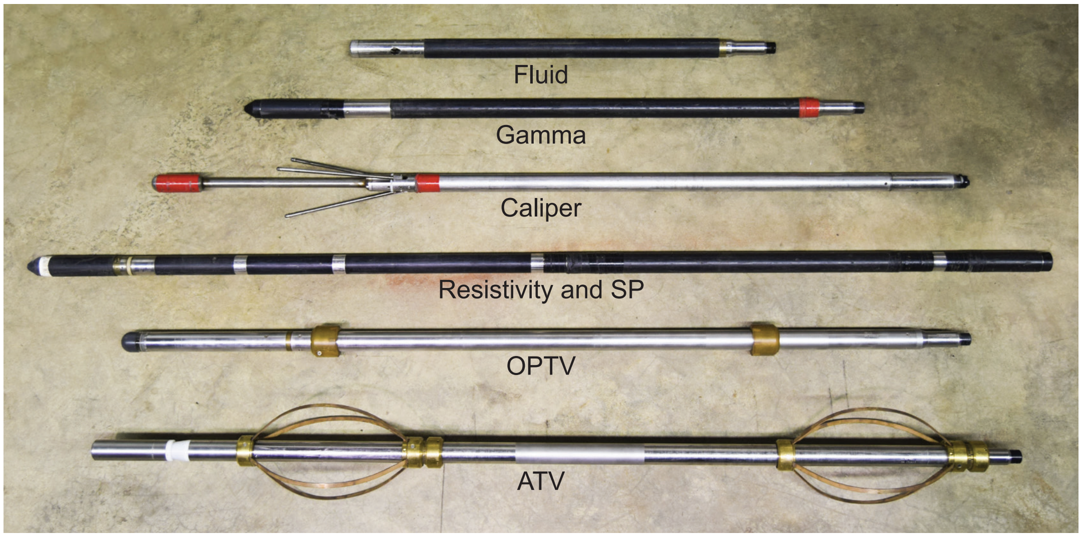


Figure 1. Borehole geophysical tools and data from the interval of 65 feet to 76 feet from the monitoring well at Spring Brook Country Club, Morris Twp., Morris County. The electromagnetic induction (em) tool was not run at this site, so there is no data for this tool presented (data collected by M. Spencer and M. Gagliano).

Figure 2. Location of Prospect Park Quarry monitoring wells (*left to right*): Paterson Quadrangle in New Jersey, Prospect Park Quarry in Paterson Quadrangle, and monitoring wells (BW-1, BW-2, and BW-3) in Prospect Park Quarry.

the water level or in oil filled boreholes. The method struggles to take accurate measurements in highly resistive formations (NJDEP, 2005).

The **Caliper** tool provides a continuous record of the borehole diameter at depth. Traditional caliper tools have three arms, equidistant from one another, which expand outward to measure the borehole diameter. Current ATVs include caliper capabilities, measuring borehole diameter using sound waves amplitude and travel time. Caliper logs are useful for identifying open fractures, breakout of the wall rock into the borehole, and intervals of borehole collapse (USGS, 2013). This log type is limiting in that it does not show sealed fractures.

The **Gamma** tool measures naturally occurring gamma radiation emitted from the formations penetrated by the borehole. These logs are often used to differentiate between lithologies and to correlate rock types between boreholes. Gamma logs are especially helpful for locating layers of clay and shale, which typically contain more radioactive material than sandy sediment. The method struggles to find particularly thin beds (NJDEP, 2005).

The **Fluid Conductivity** tool releases a DC current and measures the voltage drop across two closely spaced electrodes. The voltage drop is indicative of the conductivity (FCond) of the borehole fluid and the tool tracks fluid conductivity with depth. Logs reflect changes in the dissolved-solids concentration of the borehole fluid. Fluid conductivity tools are generally used in conjunction with other tools in order to determine formational characteristics (NJDEP, 2005).

The **Electromagnetic Induction** (EM) tool uses electromagnetic

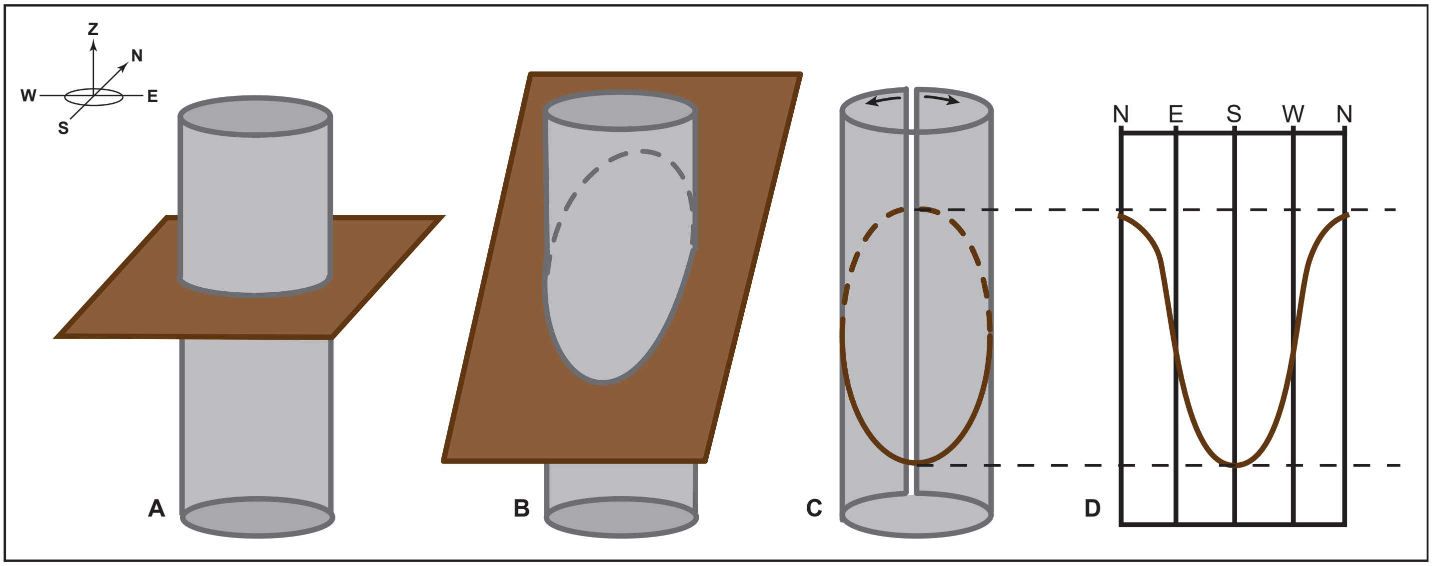


Figure 3. "Unrolling" OPTV data diagram. (A) gently-inclined plane intersects the borehole wall creating a low amplitude cut, whereas, (B) a steeply-inclined plane intersects the borehole wall creating a high amplitude cut and (C) trace. (D) the steeply-inclined trace "unrolled" shows a high amplitude curve with a steep dip to the south (adapted from Hubbard and others, 2008).

energy to measure the conductivity of the borehole and surrounding formations. As conductivity is the inverse of resistivity, the NJGWS rarely utilizes the EM tool as it yields results similar to the resistivity tool. However, the EM tool can be run in air filled and PVC-cased holes, which the resistivity tool cannot. Thus, the EM tool is usually reserved for instances where the resistivity tool cannot be used (NJDEP, 2005).

Prospect Park Quarry – A deep subsurface investigation

In 2015, the NJGWS logged three monitoring wells at the Prospect Park Quarry in Passaic County (figure 2) to better understand the fractured bedrock aquifer system before the quarry was filled in and developed (Beetle-Moorecroft, 2016). The location was an ideal case study because: 1) there were three monitoring wells near one another, 2) the contact between the Orange Mountain Basalt and the Passaic Formation was visible in OPTV records of two of the wells, and 3) ample exposed bedrock in the quarry allowed comparison of rock characteristics inferred from logs to those visible in outcrop. Based on the characteristics of the formations and the scope of the investigation, the NJGWS staff collected optical, caliper, gamma, spontaneous potential (SP), single point resistance (SPR), and fluid conductivity logs.

Because a borehole is cylindrical, optical logs are 360° digital photographs that must be “unrolled” to a two-dimensional sheet to be viewed and analyzed (figure 3). As an example, Borehole BW-1 (figure 4), once the optical data was “unrolled,” the one-dimensional logs were plotted on the same sheet for comparison and analysis. The optical logs provided: bedding, fracture, and vein data, as well as the location contact between the Orange Mountain Basalt and the Passaic Formation. The gamma and SP logs confirmed the contact at 131 feet and the presence of shale beds at 134 feet and 146 feet. The caliper log confirmed open fractures at 122 feet and 145 feet and measured the diameter of the borehole at each fracture. Some of the fractures were also visible in the SPR log. The fluid conductivity tool confirmed that the water properties remained constant at depth.

The formation contact between the Orange Mountain Basalt and the

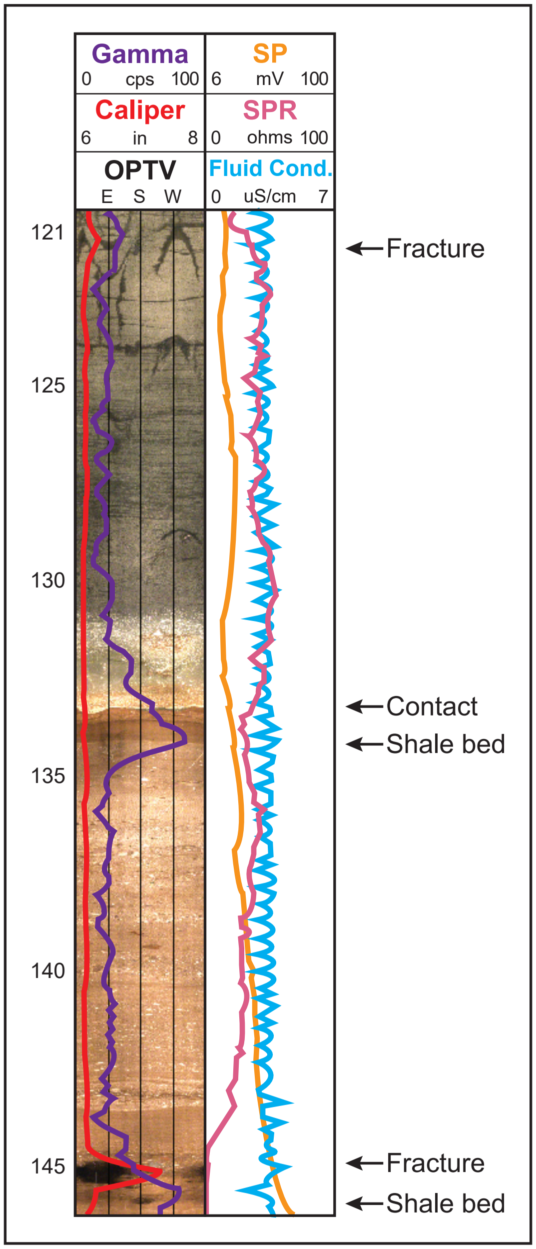
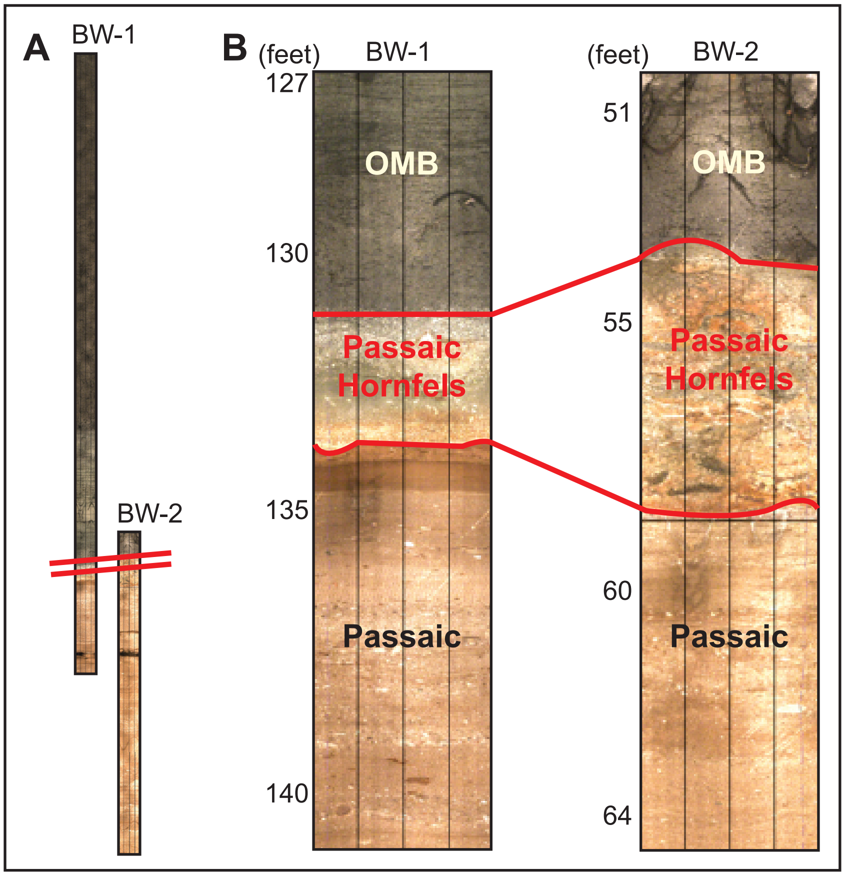


Figure 4. BW-1 log excerpts from 121-145 feet. The optical log provides a continuous two-dimensional picture of the borehole wall. Bedding planes and layering are marked by subtle color differences within each unit and fractures appear darker in color than the surrounding bedrock. Shale beds can be identified by gamma (red) spikes, SP (orange) highs, and SPR (pink) lows, which can be seen above 135 feet and just below 145 feet. The permeability contrasts were sufficient to create a substantial SP response only at the shale bed just below 145 feet. Fractures visible in the optical log correlate with clear spikes in the yellow caliper log just below 121 feet and 145 feet. The blue fluid conductivity log shows relatively consistent conductivity throughout.

Figure 5. (A) the optical logs of BW-1 and BW-2 and (B) excerpts showing the formation contacts between the Orange Mountain Basalt (OMB) and the Passaic Formation in BW-1 (131 feet) and BW-2 (54 feet). Just below the contact, the Passaic formation was heated and altered, creating a hornfels zone outlined in red. BW-1 and BW-2 are located at different elevations and locations within the formation. Thus, the tops of the two boreholes do not align in (A).



Passaic Formation was visible both in boreholes BW-1 and BW-2 (figure 5). Layering in the basalt and bedding in the Passaic Formation were shallowly dipping and variable in orientation. This suggested the presence of cross bedding in the Passaic and possible change of lava flow direction in the basalt. The fracture data overall was variable. The dominant fracture set in the Passaic was striking 11 degrees with a dip of 69 degrees southeast. In the basalt, the dominant set had a strike of 23 degrees and a dip of 77 degrees southeast (figure 6). This suggests that most of the groundwater movement in both formations is likely along these dominant fractures.

In the investigation of the Prospect Park Quarry, outcrop data and geophysical logs were combined and analyzed to better understand the local aquifer system. The formation contact between the Orange Mountain Basalt and the Passaic was at 131 feet in BW-1 and at 54 feet in BW-2. Bedding in both units was shallowly dipping, and occasional clayey layers were found in the Passaic Formation. The dominant fracture set in both units was steeply dipping to the southeast.

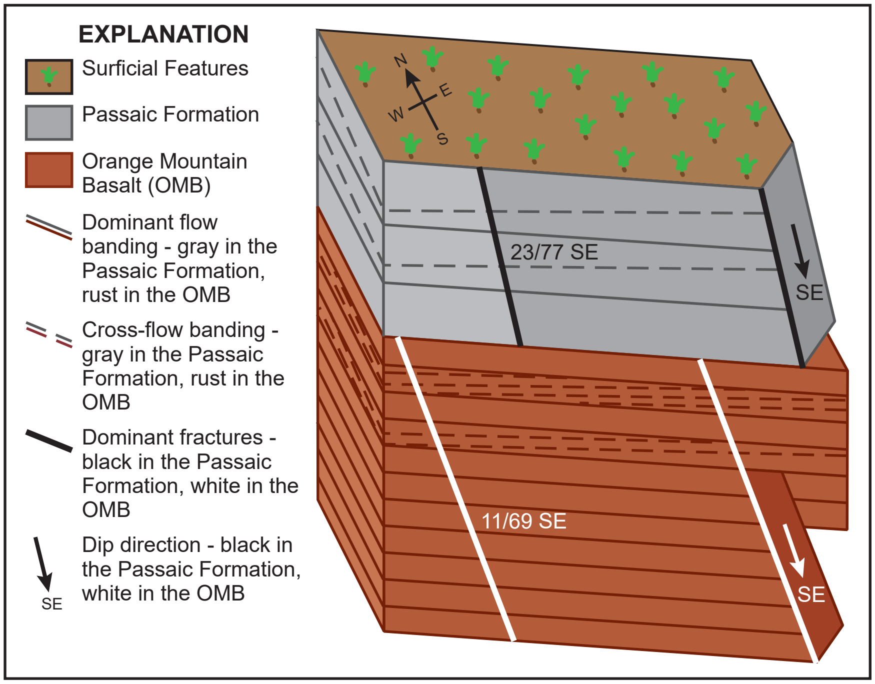


Figure 6. Schematic diagram of dominant layering and fracture orientations. The diagram shows data captured from borehole imagery translated to an outcrop. The brown surface, plants, and dirt represent surficial deposits; the gray area represents the Orange Mountain Basalt (OMB); the rust area represents the Passaic Formation. Both formations contain gently dipping (almost horizontal) layering. The OMB exhibits cross-flow banding, where the Passaic Formation contains cross bedding. The dominant fracture set in the OMB is striking 23 degrees with a dip of 77 degrees to the southeast, the black arrow indicates the dip direction of the fracture; the dominant fracture set in the Passaic striking 11 degrees with a dip of 69 degrees to the southeast, the white arrow points down the dip of the fracture.

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Additional Resources

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Banner photographs (*left to right*): Borehole logging, Morris Township, Morris County, *photo by M. Spencer;* well borehole image, Washington Township, Morris County.