OBSERVATIONS IN GRANITE QUARRIES FACILITATE UNDERSTANDING THE HYDROGEOLOGY OF THE GEORGIA PIEDMONT

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Abstract. Because the crystalline bedrock of the Piedmont Province in Georgia is so poorly exposed, it can be difficult to readily understand how water flows in the subsurface and why bedrock well yields in the Piedmont are so variable. Quarries provide an easy way to visually observe how the hydrogeology in this terrain operates. There are numerous quarries in the Elberton area and elsewhere that show excellent exposures of both the overlying regolith and bedrock, the principal components of the aquifer system of the Piedmont. Within the exposed bedrock, it is readily apparent that water is transmitted in only a few fractures. Most fractures show evidence of little or no water movement. Fractures that yield relatively large amounts of water are mostly shallow, are generally extensive, and appear to be connected to the overlying regolith, the principle reservoir for groundwater. Deeper fractures appear to transmit little water, perhaps because they are less abundant and have smaller apertures due to the overlying lithostatic load. Even those fractures that appear to transmit relatively large amounts of water may actually have very small apertures. Calculations using the cubic flow law indicate that fracture apertures for typical flow rates are quite small, with very small fracture porosities, despite their appearance at the surface of the quarry to the contrary.

INTRODUCTION

The crystalline bedrock of the Piedmont Province in Georgia is so poorly exposed that it is difficult to readily visualize how water flows in the subsurface. Granite quarries in the Elberton area provide a way to visually observe how the hydrogeology in this terrain operates. These quarries generally show excellent exposures of both the overlying regolith and bedrock, the principle components of this aquifer system. They afford a number of vertical exposures of granite that expose numerous fractures, only some of which appear to transmit water. This paper discusses some general aspects of the hydrogeology of the Piedmont and then provides observations from a quarry near Carlton, Georgia that show how and why water is transmitted in some fractures and not others and why only a few fractures transmit relatively abundant amounts of water.

PIEDMONT HYDROLOGY

An excellent summary of the hydrogeology of the Georgia Piedmont is contained in Segment 6 of the Ground Water Atlas of the United States published by the U.S. Geological Survey (Miller, 1990). Much of the information summarized here is from this reference.

The Piedmont aquifer consists of both a variably thick regolith and the underlying metamorphic and igneous crystalline basement. The regolith consists of a relatively thick zone of saprolite overlain by soil, and in some areas, alluvium. In general, all three have similar hydrologic properties in that water flows through porous media. Regolith thickness is highly variable, but in general, is thickest in valleys and low areas and thinnest on hilltops. It is not uncommon for the regolith to be greater than 30 m (~100') deep in some valleys, especially if significant amounts of alluvium exist.

Crystalline bedrock has very different hydrologic properties than the regolith. This is because the primary porosity of the igneous and metamorphic basement rock is negligible. Water movement principally occurs in fractures. Many of these fractures are near-horizontal exfoliation planes that were formed by release of stress during exhumation. Other fractures are steeply inclined and thus intersect the exfoliation fractures. In the lower weathering horizon, this combination commonly results in spheroidal weathering. In general, bedrock fractures are more open and numerous near the surface, and become less abundant and have smaller apertures at depth due to increased lithostatic pressure. The amount of water stored in the regolith is much greater than in the crystalline bedrock because of their vastly differing porosities. In the regolith, water is stored in the pore space between the mineral grains; this can have a porosity of over 40%. In the crystalline bedrock, all the porosity occurs in fractures and is thus very small, often less than one percent. Thus due to the much greater porosity, the saprolite stores most of the available groundwater, which is in turn feeds to the underlying fractures. The most favorable situation in terms of bedrock groundwater supply would be a set of exfoliation fractures connected to a vertical fracture system that in turn extends up to a thick regolith. In contrast, bedrock fractures not connected to the regolith, or with very small apertures would not be expected to yield much if any water.

FRACTURE APERTURE AND POROSITY

Steady flow of an incompressible fluid in a smooth, parallel-walled fracture is described by Stoke's equation, the integration of which yields (Neuman, 1995)

$$v_1 = -\frac{\rho g}{\mu}\frac{b^2}{12}\frac{dh}{dy}$$

where v_1 is the average velocity, D is the density of the fluid, : is the viscosity, g is the acceleration due to gravity, b is the fracture aperture, and dh/dy is the hydraulic gradient. By analogy with Darcy's Law,

$$v_1 = -K\frac{dh}{dy} \quad \text{or}$$

$$K = \frac{\rho g}{\mu} k_f \quad \text{and} \quad k_f = \frac{b^2}{12}$$

where k_f is the fracture intrinsic permeability. For a system of parallel fractures with a spacing L, the porosity is b/L and the intrinsic permeability is fb^3/L. This is known as the cubic flow law, with the intrinsic permeability of a set of fractures proportional to b^3.

Daniel *et al.* (1989) estimate hydraulic conductivities from 3 x 10^{-6} to 4 x 10^{-5} cm/sec for wells in the North Carolina Piedmont with well yields of 3 to 40 gpm. Assuming horizontal fracture spacing of 2.5 m and hydraulic conductivity of 10^{-5} cm/sec, the effective hydraulic aperture would be 0.15 mm with porosity less than 10^{-4}. The observation that deep wells in the Piedmont rarely have yields that exceed 100 gpm supports the notion that fractures larger than 0.5 mm are highly unlikely in the crystalline basement. Figure 1 shows porosity and fracture apertures for a fracture spacing of 2.5 meters for a range of hydraulic conductivities.

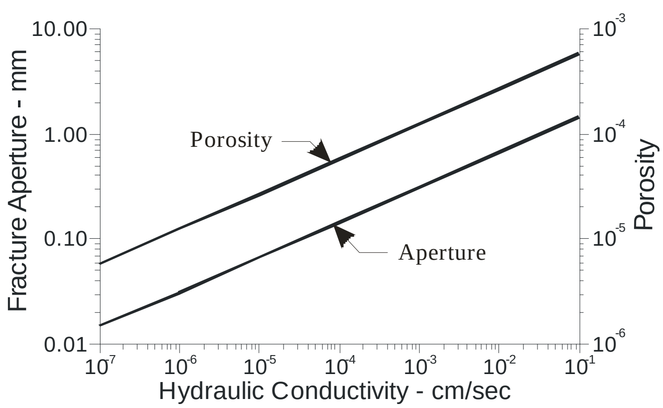

Figure 1. Porosity and aperture estimates.

WELL YIELDS

The amount of groundwater available in the Piedmont is generally low and quite variable. The water yield from any particular bedrock well depends on a number of factors. Of principle importance is whether the well intersects bedrock fractures that are open and connect to some kind of water reservoir, be it the overlying regolith or some open water body, like a river or lake.

In general, well yields in granites are low compared to most other crystalline rock types. In a study in the Blue Ridge of North Carolina with similar rock types as the Georgia Piedmont, average well yields in granite were observed to be 17 gpm (gallons per minute), mica gneiss 19 gpm, and schist and granite gneiss, 23 pgm. It should be noted that these *averages* have highly skewed distributions with many wells having very low yields (Daniel *et al.*, 1989).

In the Elberton area, these differences should be similar or greater. It is assumed that water yields in bedrock wells in the Elberton Batholith should be small compared to the metamorphic country rock in the area, because the latter have had a more complex deformation history, which would be favorable to development of more fractures. In contrast, the Elberton Batholith was intruded after the major phase of deformation, and thus is fractured principally by exfoliation processes. Variations in regolith thickness over the Elberton Granite compared to older metamorphic rocks is the factor that is expected to further enhance differences in well yield from metamorphic versus igneous rock. It is our observation that in general, the thickness of the regolith is greater over the metamorphic rock than the granite because the granite is finer grained and more homogeneous.

Variations in bedrock well yields in the Piedmont can be quite large. For example, in a community near Watkinsville, Georgia, well yields are highly variable (anecdotal observations made by DBW). This area, typical of the Piedmont, consists mostly of granite gneiss with a variably thick regolith (0 to 50 m). A number of bedrock wells in the area barely have enough water to support a single household (~ 5 gpm), and many wells that were drilled did not yield any water. Many property owners with households report only minimal amounts of water (< 7 gpm). One known exception is DBW's own residence, which has a 90 m (~300') deep drilled bedrock well that yields an estimated 35 gpm. Clearly, if a well in the Piedmont has a relatively high yield, then the well must intersect an open, interconnecting fracture system that is connected to a relatively large storage reservoir.

QUARRY OBSERVATIONS

The Keystone Memorials Blue Quarry near Carlton, Georgia is typical of quarries in the Elberton area and illustrates many of the aspects of Piedmont hydrogeology discussed above. Some pertinent observations from this site are as follows.

1. In much of the quarry, exfoliation fractures are relatively abundant near the surface and diminish with depth. This is consistent with the notion that such fractures form from stress release, which is most manifested near the surface.
2. A number of fractures near the top of the quarry exhibit evidence of having transmitted water. Water-bearing fractures can be observed by noting a wetting front on quarry walls, red iron staining or weathering along the length of the fracture, or, for fractures that consistently transmit water, pine trees on small quarry ledges adjacent to the fracture.
3. Many fractures on quarry faces appear to be dry. This may in part reflect the fact that the fracture is not connected to the regolith and/or that the fracture aperture is exceedingly small. Many areas around the quarry have recently been stripped of regolith, and thus their water supply, which may explain why some fractures show evidence of past water movement, as indicated by red staining, but no recent wetting on quarry faces.
4. Most exfoliation fractures in deeper parts of the quarry show no evidence of water movement. This is consistent with the idea that such fractures have very small apertures due to the overlying lithostatic pressure. There is, however, one fracture near the bottom of the quarry that shows a small wetting zone. Perhaps this particular fracture is connected to a vertical fracture system hidden within the bedrock that extends to the regolith.
5. One prominent exfoliation fracture on the south side of the quarry (clearly visible in Figure 2) appears to have a fairly continuous supply of water as evidenced by small trees and shrubs growing on an old horizontal ledge. This horizontal fracture is intersected by a steeply dipping fracture that extends to the surface near the regolith, and back from the quarry face to where the regolith was not stripped. Such an environment would be ideal for delivering water to deeper bedrock fractures before the quarry was excavated, and still delivers water because connection to a water supply in the saprolite was not severed.
6. Some of the quarry fractures appear to be relatively large. This appearance may be misleading, however, because the fractures at the surface may be artificially enlarged during quarrying, and are not consistently this size to the saprolite. This is also true when viewing some fractures in boreholes with a televiewer.

Figure 2. View of the south end of the Keystone Memorials Blue Quarry near Carlton, Georgia, showing water bearing fractures in one area as noted by evidence of wetting and the occurrence of trees and scrubs. Note the horizontal water-bearing fracture is connected to a steeply dipping fracture that extends upward to the surface.

CONCLUSIONS

Observations in granite quarries are can be useful for understanding the hydrogeology of the Piedmont and in particular the wide variations in well yields. Taking the Keystone Memorials Blue Quarry as an example, imagine, for example, if wells were drilled in regular intervals around the quarry edge. Looking around the quarry faces, ask yourself how many of these wells would intersect a water-bearing fracture? If the well does intersect any fracture, then judge for yourself whether the fractures would yield a significant amount of water. By doing this, it is not hard to imagine why most wells in the Piedmont yield little or no water, whereas a lucky few can be relatively productive.

Calculations of fracture porosity and permeability show that fine fractures observed at a quarry are representative of the kind of water-bearing fractures delivering water to a typical Piedmont well. Some quarries have a few fractures with large apertures. These fractures are misleading, however, because they cannot be this large throughout the bedrock, or water yields would be far greater than reported.

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