GROUND WATER EXPLORATION AND DEVELOPMENT IN IGNEOUS AND METAMORPHIC ROCKS OF THE SOUTHERN PIEDMONT/BLUE RIDGE

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Abstract. Concepts of ground water movement in igneous and metamorphic rocks in areas with a subtropical climate, such as that of the southeastern United States, have evolved over many decades. However, because of the dearth of research directed toward an understanding of the variables involved, much of the data set concerning the hydrogeology of igneous and metamorphic rocks is empirical data generated by ground water exploration and development. Some of the concepts derived from these empirical observations and from limited applied research, have been presented and discussed in various papers dealing with the hydrogeology of igneous and metamorphic rocks in the southern Piedmont/Blue Ridge.

Igneous and metamorphic rocks have, in many places, very diverse properties that change over short distances both vertically and horizontally. Our experience over the last 35 years indicates that, because of this, ground water movement is often most influenced by the *relative properties* of various rock units or discontinuities rather than by *absolute properties* of a particular rock unit or discontinuity. This relationship greatly complicates attempts to understand the hydrogeology of igneous and metamorphic rocks-, and emphasizes the need for a strong and broad data base where it is desirable to make predictions concerning ground water. This paper discusses some of the major controls of ground water occurrences in igneous and metamorphic rocks. Determining and evaluating these controls on a site-specific basis greatly enhances the probability of successful ground water exploration, development and management.

MAJOR CONTROLS OF GROUND WATER MOVEMENT IN IGNEOUS AND METAMORPHIC ROCKS

Rock Type

As in any study of shallow subsurface earth processes, the study of ground water in igneous and metamorphic rocks demands knowledge of the rock types involved. Metamorphic rocks and intrusive igneous rocks have very little primary porosity or permeability. Secondary porosity and permeability develop as these rocks are subjected to tectonic stresses and weathering stresses.

Because different rock types will react differently to the same stresses, it is important in any study area to determine: the areal distribution of each rock type; projections of these into the shallow subsurface; the major minerals, and general compositional percentages; grain size distribution; and the texture. Each of these has a direct bearing on the rock's reaction to tectonic stress, physical weathering stress, and chemical weathering stress.

The areal distribution of rock types and the variations within a single rock type are critical. Often the difference between adjacent rock units has more influence on ground water than the characteristics of either individual rock unit. There is perhaps no rock type that is totally devoid of large-yield wells with good water quality. There are, however, rock types which are "more likely" or "less likely" to have positive values in the variables. This allows some predictability concerning well yield and water quality, and is of utmost importance in exploration and development.

Discontinuities

A "discontinuity", as the term is used here, refers to any feature that interrupts the homogeneity of the rock. In igneous and metamorphic rocks, the most common discontinuities are: compositional layering, foliation, joints, faults, and irregular random fractures. Of these, only compositional layering and foliation can be primary features; they may also be secondary, as are all the others. Regardless of their origin, once formed, all of these discontinuities have the potential to enhance the porosity and permeability of the rock, providing storage and pathways for movement of ground water.

Each discontinuity is a plane of "different" strength/weakness in relation to the boundaries of the interface. As such, it will react differently to stress, whether tectonic or non-tectonic. Weathering, either chemical or physical, will proceed along the discontinuities at a rate different than that outside the discontinuities. A determination of the presence of discontinuities, and an understanding of their nature, size, abundance, structural attitude, degree to which they are interconnected, and areal distribution are critical to a study of ground water in any area of igneous or metamorphic rocks.

Much of the work related to hydrogeology of igneous and metamorphic rocks is categorized as "hydrogeology of fractured rock". Certainly fractures are important, but not all-important; and we are not implying that research and application referred to as "fracture hydrogeology" ignores all other discontinuities. However, from reading the literature and seeing the practice, we do believe that the emphasis on "fractures" to the virtual exclusion of consideration of other discontinuities and other variables has hampered development of a fuller understanding of the "hydrogeology of igneous and metamorphic rocks". Equal emphasis should be placed on <u>all</u> discontinuities and <u>all</u> variables, and the relationship of each to the others.

Topography

Topography is a major factor in determining the percentage of precipitation runoff, and its direction and velocity. As such, it exerts a major influence on infiltration and consequent chemical and physical weathering. Just as basically and by the same token, topography exerts control on ground water recharge.

Topography is greatly influenced by rock type and discontinuities. The *relative* resistance to physical and chemical weathering is a major control. Consequently, the juxtaposition of rock units of greatly contrasting physical and chemical properties can offer good ground water exploration targets. Linear discontinuities along such contacts are often enhanced by joint sets and faults which may have a pronounced influence on development of topographic features.

For large-yield wells, sustainability of production is always a concern. Topography is a major factor in predicting recharge potential; 3^{rd} order, or greater stream valleys are desirable for large sustainable yields. There are many notable exceptions to this, but where the exceptions will occur is not predictable.

Depth of Weathering

Weathering generally increases the porosity and permeability of igneous and metamorphic rocks. However, some processes taking place in this zone, such as the growth of clay minerals, mineral deposition in fractures, and development of iron oxide "hardpan", can significantly decrease the permeability of the weathered zone.

At the interface between unweathered rock and weathered rock, there is commonly a "transition zone" where chemical weathering has changed the chemistry and created open spaces but not yet destroyed the rock's texture. This weathered rock, referred to as "saprolite", is generally more permeable than the overlying residuum, and in some places is more permeable than the underlying fresh rock and serves to concentrate ground water along a tabular zone of enhanced permeability. A thick (several 10's of feet) soil weathered zone above the saprolite will store ground water and allow it to move into the saprolite and fresh rock on a continuous basis; provided it can be recharged, and permeability has not been too severely limited by the growth and concentration of clay minerals.

A soil/weathered rock/saprolite thickness of approximately 30 to 60 feet seems optimum for successful ground water development. Less thickness seems to inhibit infiltration and storage of water; greater thickness (greater than 150 to 200 feet in many instances) seems to inhibit movement of water into the more permeable fresh rock, where it can be recovered. Here, too, there are notable exceptions: large-yield wells where fresh rock is at or very near the surface; and large-yield wells where soil/weathered rock/saprolite has a thickness in excess of 200 feet. Regardless of the choices, and other variables being equal, moderate thicknesses are preferred.

Because the rate of weathering is so strongly influenced by mineralogy and texture, topographic position may be misleading. In many instances, rocks in the lower part of a drainage basin may form "pavement" exposures unsuitable for drilling; while different rock types topographically higher in the same basin may show great potential.

Nature and Extent of the Recharge Area

The amount and rate of recharge at any given point (well) is, of course, a function of the nature and extent of the recharge area. The nature of the recharge area is evaluated in the manner already discussed by determining the rock types and discontinuities, and relating these to topography and depth of weathering.

Alluvial and colluvial material in the recharge area will have characteristics different from residual material and saprolite, and need to be evaluated differently. Grain size and sorting of the alluvium will have major influence on ground water movement; as will the nature of the underlying material and the topography of the interface between the alluvium and the underlying material. Clay layers and iron-oxide hardpan in particular will be major impediments to water movement through the alluvium.

ENHANCING PERMEABILITY OF METAMORPHIC AND INTRUSIVE IGNEOUS ROCKS

The tectonic stresses which create fractures in metamorphic and intrusive igneous rocks are a major factor in developing secondary porosity/permeability, which enhances ground water movement. A second factor in permeability enhancement is compositional layering. Where it is well developed, compositional layering forms zones of weakness which react to both physical and chemical stress, enhancing ground water movement.

A third factor in porosity/permeability enhancement, which may be critical in creating the setting for many high-yield wells, is the non-tectonic process of unloading. With compositional layering and fracture networks already in place, unloading through erosional development of broad valleys could be the "stress release" which causes opening of the fracture system, further weakens the compositional layering planes, and allows ground water to move more freely and to greater depths. As these processes continue they feed on their own success.

The "stress release" envisioned here is not a release of "built-in" stress such as might be associated with deep-seated igneous plutons. Rather, it is more comparable to a "bulge", where rock expands upward and outward due to removal of overlying rocks in restricted geographic areas such as broad valleys, causing opening of previously developed discontinuities such as compositional layering and tectonically induced joints and random fractures.

Joints and Random Fractures

Rocks may react to stress by breaking. Where these breaks are planar or curvi-planar and no movement has occurred parallel to the fracture surface, they are called joints. Numerous parallel breaks in any given area are referred to as a joint set. In much of the southern Piedmont/Blue Ridge, rocks contain two dominant joint sets, and in many areas there are several subsidiary joint sets.

Joints enhance the permeability of rocks a little or a lot, depending on: the roughness of the joint surface; the spacing; the width of the openings (dilation); the nature of any infilling; the degree to which they are through-going; and the degree to which they are interconnected.

Joints should be described and measured throughout a study area, and used in helping evaluate potential for ground water movement in each lithologic unit. Different rock types react differently even when subjected to the same stresses. This has a direct influence on the ground water storage and transfer capabilities of the various lithologic units.

Random fractures, those with no discernable pattern, can be abundant. These can exert considerable influence on ground water but, because of their randomness, are not as useful in evaluating ground water resources.

Faults

Igneous and metamorphic rocks in the Piedmont/Blue Ridge have been extensively faulted. There are faults coincident with lithologic contacts, faults which cut across lithologic units, and faults within single mappable units.

The major criteria for faulting in the southern Piedmont/Blue Ridge are: discontinuity of lithologic units; omission or repetition of lithologic units in a sequence; and the presence of shear textures, mylonite, or breccia. In many cases the size of the area mapped for a particular study does not allow a valid application of this approach to determine whether any given lithologic contact is also a fault contact.

However, such a determination is of little, if any, value to the purpose of most hydrogeologic studies. If there is no evidence of brittle fault deformation along lithologic contacts in a given study area, the most important determination hydrogeologically is differences in the mineralogy and texture of adjacent rock units.

Most of the faults in the southern Piedmont/Blue Ridge occurred at great depths, under high confining pressures and elevated temperatures. Consequently, brittle deformation was minimal and/or was healed during the tectonic processes, and produced little, if any, increase in porosity or permeability.

Many geologic maps show some lithologic contacts as faults. This does not mean that deformation associated with faulting has enhanced permeability along that contact. The faulting may have, in fact, decreased permeability of the rock. For example, shearing and mylonitization reduce particle size, and are often accompanied by silicification; both tend to decrease permeability. The value of such a fault from a ground water perspective would be in whether or not it juxtaposed lithologic units with great differences in lithology and/or texture.

Lithologic Contacts

Lithologic contacts can exert considerable influence on ground water movement. The magnitude of the influence is directly related to the differences in the units which are juxtaposed, and the structural attitude of these units. Where similar lithologic units are in contact, the contact zone has little influence. Many mappable units have greater internal differences in lithology and texture than the differences across contacts. In such cases, the contact zone would not enhance ground water movement.

Compositional Layering and Foliation

Most rocks of the southern Piedmont/Blue Ridge are compositionally layered and foliated, although the degree of development of these features varies greatly. More often than not, compositional layering and foliation are parallel, but this must be determined on a site-specific basis. Structural attitude of these planar features varies from vertical to horizontal, with moderate angles of inclination being most common.

Areas underlain by rocks with horizontal or low-angle lithologic units, compositional layering, and foliation generally show considerable potential for ground water. Areas where the same features are steeply dipping or vertical show less promise. The discontinuities defined as compositional layering and foliation can be extremely important in ground water studies. They define planes and zones of weakness which serve as preferred pathways in a primary sense; and they are further weakened by weathering processes associated with ground water movement. Additionally, they guide partings resulting from "unloading" stress release.

Where there are great differences in the mineralogy and texture of compositionally layered rocks, differential weathering along this discontinuity may give compositional layering a stronger influence on ground water than that of joints. A well-developed foliation parallel to compositional layering enhances the influence of layering. Too often, these discontinuities have been ignored in studies of the hydrogeology of "fractured" rock.

GROUND WATER RESOURCES OF THE PIEDMONT/BLUE RIDGE REVIEW AND CONSIDERATIONS

The ground water potential of the igneous and metamorphic rocks of the Piedmont/Blue Ridge is tremendous. However, in the southeast this source of water has historically been either ignored or grossly underrated. There are exceptions, but a for the most part hydrogeological consideration of these rocks was, until recently, cursory, local, and half-hearted. And there is some justification for this; for hydrogeology cannot be adequately assessed until the geology is understood, and in the Piedmont/Blue Ridge it is only recently that we have had results from long-term geologic studies and detailed analyses of regional areas sufficient for a general understanding of ground water conditions.

Even now, very little of the Piedmont/Blue Ridge has published geologic maps of sufficient accuracy and detail that they can be used for water-well siting without on-site geologic mapping. All geologic mapping is extremely slow and site studies are very time-consuming, particularly if the geologist is not acquainted with the local stratigraphy. Further, after the geologic mapping is accomplished, there are still many other on-site observations to be made which are essential for proper evaluation of ground-water potential and/or selection of drilling sites.

Most of the water wells drilled in the southern Piedmont/Blue Ridge have been drilled at sites selected on the basis of four criteria:

1) It's convenient to get the rig in,
2) It won't cost anything (much) to prepare the site,
3) It's close to where the water is needed, and
4) It's close to a source of power.

Even with these bases, which have no bearing on the amount of water likely to be encountered in a drilled hole, there have been many adequate wells completed. This fact should be reason enough to pursue an understanding of ground water in metamorphic and igneous rocks with a goal of obtaining a higher water yield per dollar spent in exploration and development.

Whereas surface water is "seeable" and "measurable", drilling a hole in the ground is considered "risky". It took several drought years in succession, and then a gradual realization that even in "normal" times surface water supplies will not be able to meet the growing water demands of an expanding and more demanding population- and now, suddenly we are trying to catch up on the concepts and understanding of metamorphic and igneous rock geology, hydrogeology and hydrology; which we must have in order to successfully explore for, produce, and properly manage this considerable, extensive, and extremely valuable natural resource.

We have enough information now to understand that ground water movement and ground water production in igneous and metamorphic rocks are controlled largely by six factors: (1) rock type(s), which includes all inherent characteristics of the rock, but primarily mineral composition and texture; (2) discontinuities resulting from compositional differences, joints, random fractures, and/or faults; (3) topography; (4) depth of weathering (5) area of recharge; and (6) spatial relationships of rock types and discontinuities to each other, and to topography, depth of weathering, and area of recharge.

Precise siting of wells in relation to these six factors is critical if water needs are to be satisfied and, particularly, satisfied at the least possible cost. The need may be a home owner who requires 3,000 gallons of water a day; a small town, industry, office complex, or housing development needing 300,000 gallons of water a day; or a larger town, county, or industry requiring 3,000,000 gallons a day. For the individuals involved, each quantity is important. Because it is possible to have extreme differences in the amount of property available for exploration, the small water demand often requires just as much precision and effort in well siting as does the large.

Ground water potential of the Piedmont/Blue Ridge is tremendous and very much under-utilized. Employing careful and precise exploration and development methods described in this paper has proven to be a cost-effective means for developing ground-water supplies in the southeastern Piedmont/Blue Ridge. These methods have substantially improved the ability to develop large supplies needed for business, industrial, and municipal supply, far beyond what is generally thought possible.

SUMMARY AND RECOMMENDATION

Exploration for, and development of, ground water in deformed igneous and metamorphic rocks in regions with a sub-tropical weathering environment have been little studied, and are poorly understood. Much of the funded research and many of the recent and current studies in this regard seem to focus on the physics of ground water movement in *fractured* rock. During the last several decades these studies have been driven by environmental containment and remediation problems and concerns. For this, the objectives and goals are quite different from that required for exploration and development of water as a resource, where the quantity, quality, and sustainability of the resource is of utmost importance.

Thirty years of exploration and development of ground water resources in igneous and metamorphic rocks of the southeastern United States has convinced us that, among the many factors that influence ground water in these rocks, the single most important factor is *rock type*. Rock type directly influences all other parameters, i.e., type of weathering, depth of weathering, and topography. Without knowing the detailed geology of an area/site, all other factors influencing ground water lack a full and meaningful context.

For success in ground water exploration and development in igneous and metamorphic rocks, more than an understanding of the physical parameters controlling ground water movement is necessary. The interrelationships, both inherent and spatial, of rock type, structure, type and depth of weathering, and topography must be known and understood (Figure 1). Each of these variables has numerous significant variations. Combine this with observations that the influence of each of these variables on ground water is relative rather than and absolute it becomes obvious that ground water exploration and development data in metamorphic and igneous rocks must be site specific.

Many Hydrologists/Geologists/Hydrogeologists making decisions on ground water exploration and development -- and writing laws/rules/guidelines regulating such -- lack either the ability or the time, or both, to geologically map the areas of concern. Though rarely of sufficient detail for

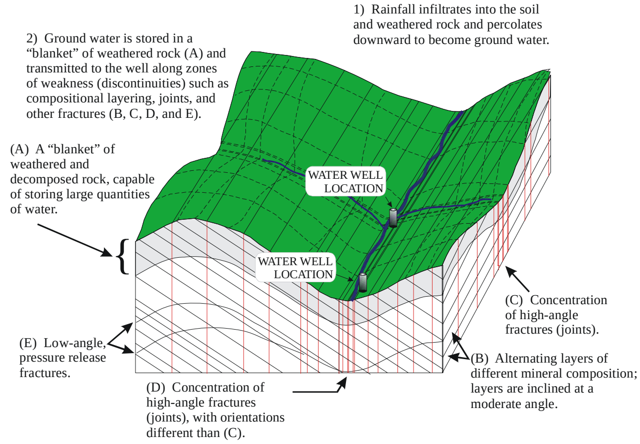

Figure 1. Hydrogeologic features in igneous and metamorphic rocks of the southern Piedmont/Blue Ridge.

siting water well drilling locations, 1:24,000-scale geologic maps serve as an excellent beginning for more detailed study and analysis. Without such maps, geologists unfamiliar with the area of interest must spend a tremendous amount of time just getting familiar with mappable lithologic units. For this and many other reasons, it is critical that influential organizations lobby for and support 1:24,000-scale geologic mapping by experienced qualified geologists in organizations such as the U.S. Geological Survey, State Geological Surveys, and Universities.