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FRACTURE TRACE MAPPING AND WATER WELL YIELD IN THE PIEDMONT REGION OF SOUTH CAROLINA

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Submitted to

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ABSTRACT

An extensive program of lineament and fracture trace mapping by the use of aerial remote sensing techniques was conducted in the Piedmont Region of South Carolina. The fracture traces were mapped on a variety of aerial remote sensor products including color infrared Landsat imagery, black and white infrared Landsat imagery, Skylab color photographs, high altitude color and color infrared photographs, black and white aerial photographs, and photo index sheets. It was concluded that an analysis of different types of aerial remote sensor products is needed to accomplish a thorough fracture trace mapping program. Also, it was determined that numerous lineaments and fracture traces exist in each county of the South Carolina Piedmont Region. A cooperative well drilling program undertaken in an effort to correlate well yield with fracture trace location was not entirely successful. Also, attempts to correlate well yield and well location with respect to mapped linear features met with only partial success. A continuing program of working with cooperative well drillers in an effort to generate additional data relating well yield and fracture trace location and further research to correlate well yield and fracture trace location are recommended in the Piedmont Region of South Carolina.

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INTRODUCTION

The Piedmont Region of South Carolina generally has an abundant supply of water for domestic and industrial use. In recent years much emphasis has been placed on the development of surface water as a source of water supply. However, only limited attention has been given to increased utilization of groundwater to supply water needs.

Groundwater obtained from wells represents a very important source of water supply in the Piedmont Region of South Carolina. While surface water represents the major source of urban water supply, groundwater is the primary source of rural water supply. Wells also constitute the source of water supply for many small municipalities in the Piedmont Region. Many industries, particularly in rural areas, also obtain all or a part of their water supply from wells. Several rural water distribution systems also rely on groundwater obtained from wells as a source of water supply. In many instances groundwater is the only economically feasible source of water supply for rural subdivisions, trailer parks, and recreational developments.

Surface water is most economical for water supply when adequate quantities of surface water are available locally, the amount of water required is large, and the users are concentrated in a small area. Under these conditions, the cost of surface water supply reservoirs and distribution facilities is relatively low when spread over the large quantities of water supplied to users. In much of the Piedmont Region of South Carolina, the population densities are relatively low and the resultant demand for water is so low that surface water cannot be used as an economical source of water supply. In these areas groundwater represents a more economical source of water. Thus, groundwater must be considered an important part of the total water supply. For example, Bloxham, et al. (1970) estimated that approximately one third of the population of Spartanburg County was dependent on groundwater for water supply.

Groundwater has several important advantages which make it particularly appropriate as a water supply. In many instances, groundwater can be delivered to the user at significantly less cost than water from a surface water supply. This is possible because the costs of purchasing large areas of land and constructing dams, associated control facilities, treatment plants, and long water transmission lines can be avoided. Groundwater is particularly economical when compared with a surface water supply in instances where isolated concentrations of development occur at widely spaced intervals over large areas and the extensive transmission systems required for surface water distribution are not required.

The high quality of many groundwater supplies means that little or no water treatment is necessary. Also, water supplied by groundwater is less susceptible to interruption from periodic drought than is surface water. In many instances groundwater is much less subject to pollution than surface water. In addition, the detrimental environmental effects associated with developing surface water supplies can be avoided. Consequently, groundwater should be given appropriate consideration as an important water source.

Another use for groundwater has developed in recent years in response to higher energy costs. Since groundwater has a relatively constant temperature, it can be used as a source of energy for heating and cooling residences. This involves the installation of a heat pump that uses well water as a heat sink or heat source depending on the ambient temperature. Significantly greater well yields must be available for this operation as compared to typical domestic water needs. Well drillers are beginning to receive a significant number of requests for water wells to be used in conjunction with residential heat pump installations. These installations are particularly attractive when combined with certain solar energy equipment applications which make the entire project, including the well drilling, eligible for a 40 percent federal tax credit. These installations represent a competing use for groundwater that could begin to conflict with the use of groundwater as a source of water supply if it developed into a widespread practice. However, the high cost of these installations will probably serve to limit this operation to a relatively small proportion of family residences.

In many areas in the Piedmont Region of South Carolina, groundwater is available in sufficient quantities to make the process of locating wells to extract the water a relatively easy task. However, other areas appear to have a limited amount of groundwater available and considerable difficulty can be experienced in obtaining an adequate water supply without drilling several wells. One serious problem with the use of groundwater as a source of water supply in the Piedmont Region is that well yields vary over a wide range. Wells with yields between zero and 100 gallons per minute can be found within a short distance of one another. Typical or average well yields are commonly in the range of 10 to 20 gallons per minute in most counties in the Piedmont Region. However, a significant proportion of the wells that are drilled have a yield so low that the well cannot provide a sufficient amount of water to serve the needs of a single family dwelling. When higher yielding wells are required to meet the water needs of a subdivision, an industry, or a small city, the problem of obtaining wells with sufficient yield becomes even more difficult. The typical approach is to drill several wells so that the combined yield will meet the estimated water needs or a single well with a yield that is sufficiently high to satisfy the water requirements will be found. This approach is expensive and frequently not successful. If a procedure was available that would increase the likelihood of obtaining a higher yield in each well drilled, it would reduce the cost of developing groundwater as a source of water supply and decrease the probability of failure to obtain the quantity of water needed.

The expense of drilling several dry holes or wells with an inadequate yield to satisfy the owner's water needs can become quite high. The present cost of a drilled well is typically between one and two thousand dollars or more depending on the depth of the well. Therefore, the ability to obtain the required well yield with as few drilled wells as possible is an important factor in determining the economics of groundwater as a source of water supply. One objective of this research project was to develop information that can be used to locate well sites that have a higher probability of producing high yields so that the cost of developing groundwater supplies can be minimized.

BASIC CONCEPT

A knowledge of the basic concept on which the fracture trace mapping approach to water well location is based is an important factor in understanding the program of research conducted in this study. The primary purpose of this chapter is to cover the background material necessary to develop this understanding.

The existence of linear features on the surface of the earth has been recognized since the early days of the development of aircraft and aerial photography. Although geologists were interested in the nature and the significance of these linear features from the earliest days of knowledge of their existence, the idea of using the features as a means for locating high yield water wells did not develop for many years because information on the hydrogeological significance of the linear features was not available. As aerial photographs began to be more readily available following World War II, geologists began to place a considerable amount of emphasis on the mapping and analysis of the linear features observed on aerial photographs. In an effort to standardize the terminology used in describing the features, Lattman (1958) suggested the following definitions for the linear features:

> Fracture trace - A fracture trace is a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs, and expressed continuously for less than one mile. Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classifed as fracture traces. Included in this term are joints mapped on aerial photographs where bare rock is observed.

> Lineament - A lineament is a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs or mosaics, and expressed continuously or discontinuously for many miles. The restrictions placed on the term "fracture trace" as regards origin apply equally to the term "lineament," Lattman (1958, page 569).

This terminology has been widely adopted and now seems to represent the common usage for the terms fracture trace and lineament. However, many authors do not appear to be very careful in differentiating between fracture traces and lineaments on the basis of feature length. In fact, the necessity to differentiate between the two types of features on the basis of length has never been well documented and some investigators have rejected this concept in favor of referring to both types of features as airphoto linear features (Boyer and McQueen, 1964). Also, the phrase fracture trace mapping has been widely adopted to identify the entire process of detecting both fracture traces and lineaments on aerial photographs and other aerial remote sensing products. In this report, the terms lineament, fracture trace, and linear feature are used interchangeably except in cases where the length of the feature is significant.

One significant development that has occurred in the mapping of linear features since Lattman suggested the terminology discussed above in 1958 is the use of satellite photography and imagery that was developed as part of NASA's space program. The availability of the small scale spaceborne sensor products has been particularly useful in identifying the longer lineaments. In addition, new aerial remote sensors such as radar imaging devices have been developed that are very effective in detecting the existence of lineaments, fracture traces, and faults.

Lattman (1958) noted that the term fracture trace is used as opposed to the term fracture because the surface expression of the linear feature is an indirect indication of some subsurface discontinuity. The fracture is not observed except in the case of features that are mapped on aerial photographs of an area where bare bedrock is exposed at the surface. Since the true nature of the subsurface discontinuity is usually unknown, the linear feature on the ground surface is more appropriately identified as a fracture trace. In an analogous manner, the term lineament simply identifies a long linear feature on the surface of the earth that is associated with a long subsurface discontinuity that may be continuous or discontinuous and for which the origin and characteristics are unknown. Fracture traces and lineaments may be associated with a variety of discontinuities such as joints, faults, fractures, shatter zones, or other miscellaneous features of unknown origin.

The most important aspect of the fracture traces and lineaments from a hydrogeological viewpoint is the discontinuity in the underlying bedrock associated with the features. Many rock types are almost impermeable when the rock exists as a continuous mass. This is particularly true for the igneous and metamorphic rocks that predominate in the Piedmont Region of South Carolina. Therefore, the ability to obtain an adequate supply of groundwater in an area underlain by a continuous bedrock mass is very difficult or even impossible. However, wells drilled in the same bedrock that intersect natural discontinuities have the potential to provide an adequate water supply for many purposes.

Although the nature of the subsurface discontinuity associated with fracture traces and lineaments cannot be observed under normal circumstances, there have been a number of situations where the characteristics of the subsurface feature could be examined. These situations have typically occurred where the fracture trace or lineament intersected a vertical cliff, deep highway cut, rock quarry, or some other type of excavation that would expose a cross-section of the discontinuity for a considerable depth. Several investigators have been able to find examples of exposed subsurface discontinuities associated with fracture traces and lineaments and have described the nature of the features. Lattman and Matzke (1961) found a zone of joint concentration underlying a fracture trace for which a cross-section was exposed by a vertical cliff in sandstone in Wyoming. The fracture trace was expressed as an alignment of drainage features along a straight, shallow, topographic trough on the aerial photographs.

As would be expected, the characteristics of the subsurface discontinuities that have been examined have been quite variable. The features have varied from narrow bands that are only two or three feet wide and which contained multiple closely spaced rock fractures to wide zones that are 20 to 100 feet wide and which contained only a few widely spaced rock fractures. The most important characteristic of the fracture zones from a hydrogeological standpoint is that individual fractures in the fracture zone are usually connected to provide a continuous system for water storage and transmission. The majority of the subsurface fracture zones that have been examined have been approximately vertical and have contained several vertical fractures.

The fact that most fracture traces that have been mapped on aerial photographs by several investigators in different geographic areas are straight, regardless of topography, was interpreted by Trainer and Ellison (1967) as an indication that the associated fracture zones are vertical or nearly vertical. In addition to the vertical fractures, the fracture zones usually contain a series of horizontal joints that connect adjacent vertical fractures. This is an important characteristic when the objective of a well drilling program is to intersect one or more fractures with a vertical well.

The characteristics of the subsurface fracture zones also appear to vary by rock type. Situations have been observed in which a subsurface fracture zone consisted of closely spaced fractures in one rock type and more widely spaced fractures in another rock type at a different elevation within the same fracture zone. The fracture zone is generally connected to the layer of residual soil at the soil-rock interface so that the soil layer can serve as a groundwater recharge zone for the fractures in the rock. In fact, there is usually a deeper layer of residual soil along lineaments and fracture traces than in adjacent areas. Apparently the fractured rock along these natural linear features weathers more rapidly to produce a deep layer of saprolite. The more rapid weathering of the rocks within fracture zones is one reason that most lineaments and fracture traces occur as linear topographic depressions. The topographic depressions provide an enhanced opportunity for groundwater recharge along the natural linear features. Also, the deeper layer of residual soils along fracture traces gives the fracture zone a greater potential for groundwater storage and transmission. Trainer (1967) concluded that extensive weathering of vertical fractures near the surface was probably accompanied by subsurface weathering and possible widening of other fractures that are not expressed as fracture traces. Thus, the existence of a fracture trace at the surface may be an indirect indication that a number of open fractures are present in the underlying bedrock.

Only a limited amount of information is available on the depth of the fracture zones, much of which is inferred from indirect evidence. The most thorough investigation of subsurface feature characteristics has been conducted in Pennsylvania in areas underlain by sedimentary rocks. Little information is available on the nature of subsurface discontinuities in igneous and metamorphic rocks typically found in the Piedmont Region of South Carolina.

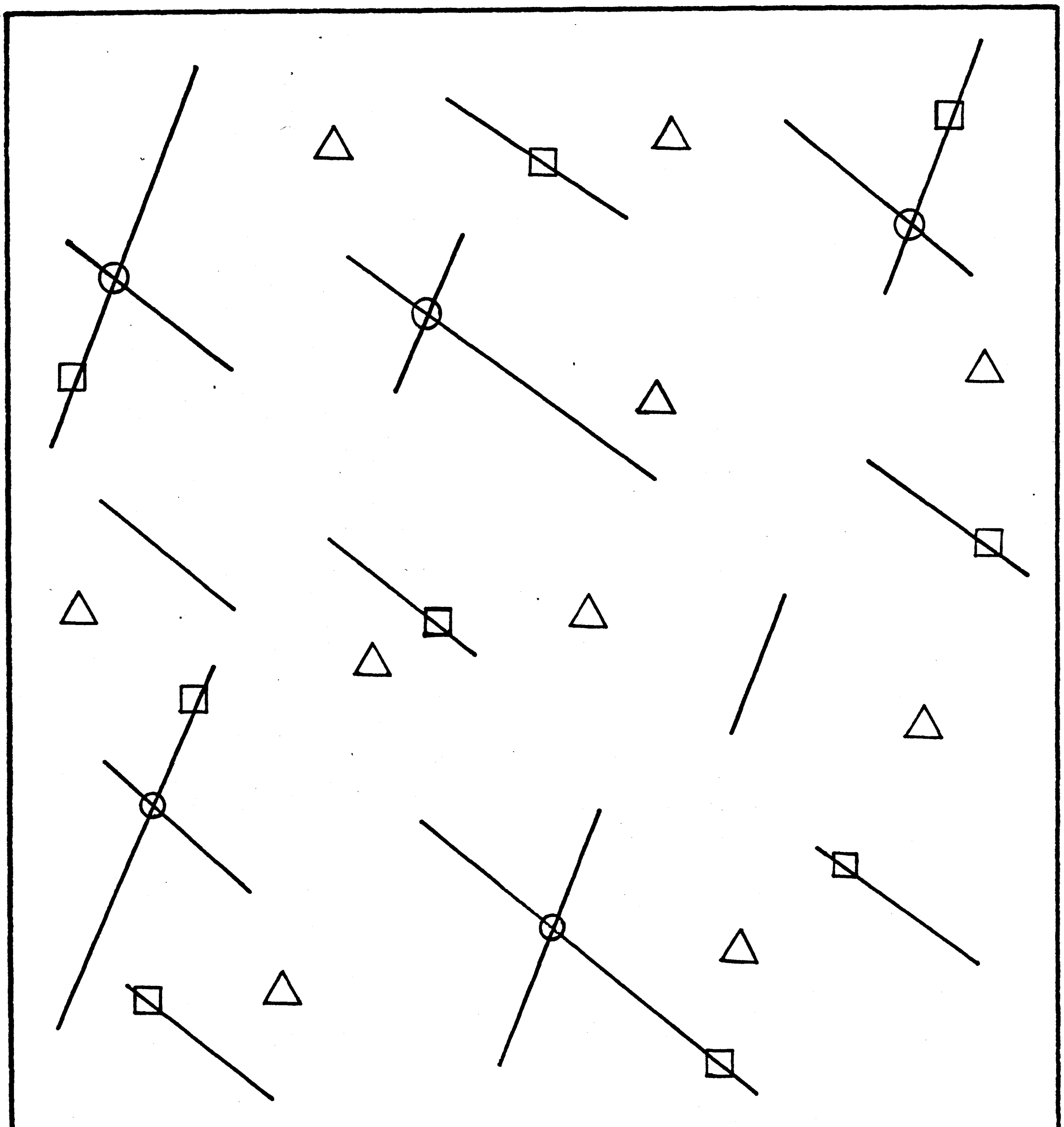
The fractures in the rock associated with the fracture traces and lineaments provide the primary locations for the storage and transmission of groundwater. This is particularly true in impervious rocks that do not contain a significant amount of internal pore space such as igneous and metamorphic rocks. Therefore, the ability to obtain an adequate yield in a water well drilled in impervious rock generally depends on intersecting one or more fractures in the rock.

Drilling a water well at a random location in an area where the underlying bedrock is composed of an essentially impervious rock type produces a low probability of achieving an adequate well yield for most purposes. The potential for obtaining a satisfactory well yield is heavily dependent on the ability to intersect one or more subsurface fractures that provide the discontinuity necessary for groundwater storage and transmission. With random drilling, the likelihood of achieving such an intersection is not very high in many rock types that have widely spaced joints, fractures, or other discontinuities.

The probability of wells intersecting one or more subsurface fractures is increased significantly if the wells are drilled along a fracture trace or lineament. Consequently, the average yield of the wells can be expected to be higher for wells that are located on a fracture trace or lineament. However, because the subsurface fractures associated with fracture traces and lineaments are generally close to vertical, a well drilled along a single linear feature may fail to intersect a fracture and the well will have a low yield that causes it to be unsatisfactory for a particular purpose.

The probability of wells intersecting one or more fractures is increased if the wells are drilled at the intersection of fracture traces or lineaments. This enhanced potential is probably related to two factors. First, a concentration of subsurface rock fractures usually occurs at the intersection of two linear features. Second, the likelihood of the wells intersecting an essentially vertical subsurface fracture is increased when the wells are located at the intersection of two linear features. If three linear features intersected at a point, the potential for obtaining a high yield in a well drilled at such a location would be even greater.

The conceptual relationship between fracture trace location and well yield is shown graphically in Figure 1. The concept has been verified by studies of well yields in Pennsylvania which have shown



Legend

△ Low yield wells drilled at random locations

□ Medium yield wells drilled on lineaments or fracture traces

○ High yield wells drilled at the intersection of lineaments and/or fracture traces

— Lineaments and fracture traces

Figure 1. Illustration of the Conceptual Relationship between Fracture Trace Location and Well Yield.

that the yields of wells drilled along fracture traces and lineaments have higher average yields than wells drilled at locations not associated with linear features (Parizek, 1976). Also, wells drilled at the intersection of two linear features were found to have a higher average yield than wells drilled along a single fracture trace (Lattman and Parizek, 1964). Depending on rock type, average yields for wells drilled along fracture traces and lineaments have been reported to be higher by factors ranging from 5 to 100 as compared to the average yield of wells drilled at sites not associated with fractures. Unfortunately, the verification of the concept is only valid in areas of sedimentary rocks such as those found in Pennsylvania. However, there is no basis for assuming that the concept is invalid in areas underlain by the igneous and metamorphic rocks typically found in the Piedmont Region of South Carolina.

It is important to recognize that the concept of using the fracture trace analysis technique to locate sites for water wells will not guarantee success in every instance. Any particular well may fail to intersect a sufficient number of subsurface fractures to provide the well yield needed to satisfy a particular objective. Also, a particular fracture or set of fractures that may be intersected in a specific well may not have a sufficient storage and transmission capability to produce a significant well yield. However, the use of the fracture trace mapping approach to locate sites for water wells has the potential to maximize the likelihood of obtaining a well yield that is in the upper portion of the range of well yields that occur in a particular area (Meiser and Earl, 1982). This approach will permit groundwater to be used successfully as a source of water supply for many water needs at a more economical cost than other alternatives.

One potential problem that exists with wells that are located on fracture traces and lineaments is that the drilling operation may be more difficult. The primary source of these problems is the highly fractured and deeply weathered rock associated with subsurface fracture zones. A number of problems can be encountered such as caving conditions, loss of drilling fluid, difficulties in drill bit rotation, and stuck drill bits. In some instances, these difficulties may cause the well driller to suggest that the well drilling operation be abandoned and a new location selected. However, it is important to convince the well driller that these problems are evidence of exactly the type of subsurface conditions that are desirable for obtaining maximum well yield. An experienced well driller can take actions to overcome most of these problems and continue to drill until a satisfactory well yield is obtained.

Another important factor that must be considered in drilling wells in fracture traces is the depth of the well. Normally, the assumption is made that increasing the well depth will enhance the chances of intersecting subsurface fractures. However, the fractures probably become less frequent, narrower, and have less capability for storing and transmitting significant amounts of groundwater at greater depths. Therefore, if a well has not intersected one or more fractures after the well has penetrated to some reasonable depth, there is a considerably reduced probability that fractures will be intersected at a greater depth. Under these circumstances it is probably more economical to abandon the well and start drilling at another location. Unfortunately, the information that is needed for use in making the decision on the depth at which drilling should be discontinued is generally not readily available because so little is known about the characteristics of fractures with increasing depth. Also, the extent to which subsurface fractures exist at considerable depth probably varies significantly between different areas. In some instances, local well drillers may have developed an empirical knowledge of the decreasing likelihood of intersecting fractures as a function of increasing well depth. Meiser and Earl (1982) suggested a maximum well depth of 250 to 300 feet was appropriate for igneous and metamorphic rocks unless evidence of shattered rock, steadily increasing well yield, or other factors existed which were encouraging.

CHARACTERISTICS OF THE STUDY AREA

Geology

In the initial stages of this investigation, the study area was considered to be the entire Piedmont Province of South Carolina. This physiographic province encompasses parts or all of 22 counties in western South Carolina and covers an area of approximately 12,100 square miles. The study area covers the portion of the state west of the fall line which is the boundary between the Piedmont Province and the Coastal Plain Province. A map indicating the counties included in the Piedmont Province and the study area is shown in Figure 2.

No effort was made to exclude the relatively small area in western South Carolina that is part of the Blue Ridge Province and the Foothills Region from the study area. The Foothills Region is a narrow band of terrain in the upper Piedmont province that provides a transition from the rolling Piedmont to the more rugged Blue Ridge Province. From the viewpoint of this study, it was not believed that the small portions of South Carolina included in the Foothills Region and the Blue Ridge Province were sufficiently different from the much larger Piedmont Province to justify excluding them.

The Piedmont Province is a region of well-dissected terrain that exhibits a rolling topography. The province has been described as a broad plateau with a surface that slopes eastward at approximately 20 feet per mile from a maximum elevation of approximately 2,000 feet in the west to approximately 400 feet in the east (Murray, 1961).

The crystalline bedrock in the area is generally deeply weathered and a layer of residual soil that varies in thickness from a few feet

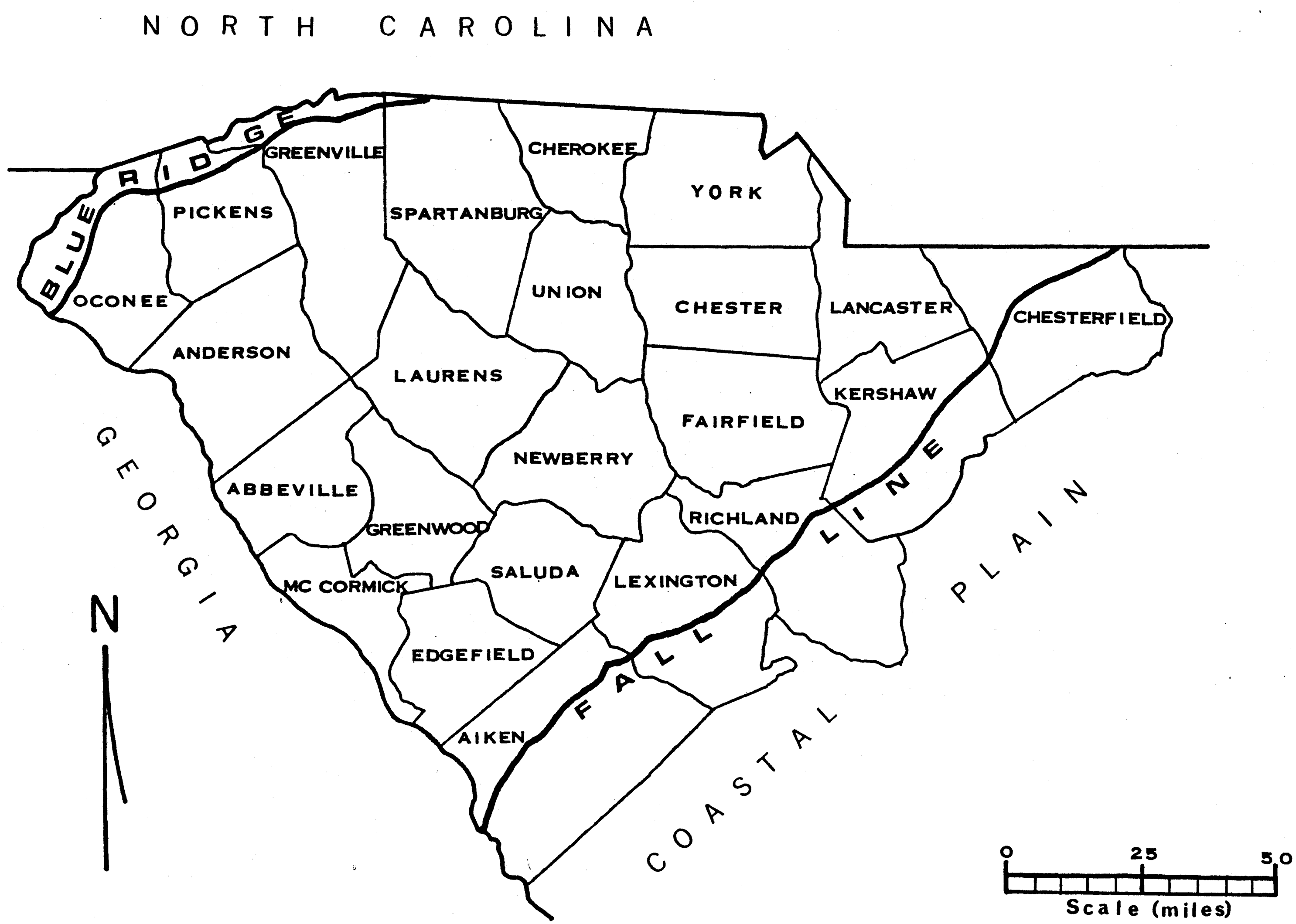


Figure 2. Map Showing the Counties in the Piedmont Province of South Carolina.

to as much as 150 feet exists over much of the region. Although the bedrock type can vary significantly over short distances, the rock generally consists of a few metamorphic and igneous rock types which can be considered to typify the bedrock conditions in the area. The metamorphic rocks are most common and consist primarily of various types of schist and gneiss. Commonly occurring metamorphic rock types include mica schist, biotite gneiss, and granitoid gneiss. In the eastern portion of the Piedmont, metasedimentary rocks such as slate and various metavolcanic rocks are more common. The igneous rocks are commonly granite and quartz monzonite. Minor igneous rock types such as diabase, gabbro, and pegmatite occur in the form of intrusive dikes at many locations. The rocks in the Piedmont Province have been extensively folded and faulted and the detailed stratigraphy of the region is quite complex.

Well Yields

Generally, the metamorphic and igneous rocks underlying the Piedmont Province are essentially impervious. The storage and transmission of groundwater occurs primarily in the complex system of joints, faults, fractures, and other discontinuities that exist in the rock. As a result of this condition, well yields in the area vary greatly. Many wells drilled in the Piedmont Province have a yield that is so near zero that they are abandoned as dry holes. On the other end of the scale, wells with yields of several hundred gallons per minute (gpm) have been drilled at many locations. Wells with yields that vary by a factor of one hundred can often be found within a short distance of one another. Unfortunately, detailed studies of groundwater resources and well yields have been conducted in only a few counties of the Piedmont Province.

Studies in Greenville County (Koch, 1968), Pickens County (Johnson, _et al._, 1968), and Spartanburg County (Bloxham, _et al._, 1970) have documented the wide variation in well yield and provided other useful data on groundwater resources and utilization. Bloxham, _et al._ (1970) reported that the average yield of wells inventoried in Spartanburg County was about 20 gpm, while the median yield was only 7 gpm. However, they noted that most domestic wells are not drilled with the objective of developing maximum yield and therefore statistical data on well yields can be misleading. The average yield of a series of wells drilled to obtain maximum yield was 53 gpm.

Koch (1968) inventoried 519 drilled wells in Greenville County and reported an average yield of 17 gpm. The average yield of 86 wells drilled to obtain maximum yield was 34 gpm. Twelve percent of all wells had a yield between 25 and 50 gpm and only four percent of all wells had yields greater than 50 gpm. These data are probably rather typical of well yields in other counties of the Piedmont Province of South Carolina. Koch (1968) noted that data on dry holes and wells that were not used because of insufficient yield was not readily available and generally not included in his inventory. Therefore, the well yield data is somewhat biased because of this deficiency. However, many wells drilled for domestic purposes are not drilled to a depth sufficient to obtain maximum yield if an adequate yield to meet the owner's needs is obtained at a shallow depth.

Johnson, et al. (1968) reported that the average yield of 192 wells inventoried in Pickens County was 21 gpm with a range of well yields from 0.5 to 500 gpm. The average yield of a series of wells drilled to obtain maximum yield was 48 gpm. It should be noted that the data base did not include dry holes and abandoned low yield wells that failed to provide sufficient water to meet the needs of the owner and therefore the averages are somewhat biased.

Snipes (1981) inventoried 237 drilled wells in Anderson and Oconee Counties. The average yield of the wells for which data was available was 33 gpm and the median yield was 8 gpm. Snipes, et al. (1983) conducted an inventory of 280 wells in Abbeville County. The average yield of 119 drilled wells for which data was available was 28 gpm and the median yield was 20 gpm. The average well yields in Abbeville, Anderson, and Oconee Counties appear to be unrealistically high. This condition is probably due to the fact that dry holes and very low yield wells were under-represented in the sample of wells included in the inventories. An unusual characteristic of the well yield data in Abbeville County was that the median yield of wells situated on ridges (35 gpm) was higher than the median yield of wells in valleys (25 gpm) and nearly flat areas (20 gpm). This is in contrast to the data in Anderson and Oconee Counties (Snipes, 1981). The unique situation in Abbeville County was concluded to be related to the structural control of the ridges associated with folding and faulting (Snipes, et al., 1983).

FRACTURE TRACE MAPPING PROGRAM

Methods and Materials

The specific techniques employed in locating lineaments and fracture traces on the remote sensor products were the procedures described by Lattman (1958), Trainer (1967), Wobber (1967), and others. In order to maximize the effectiveness of the fracture trace mapping program, the process of detecting natural linear features on the remote sensor products was conducted in a slow and meticulous manner. The photographs under study were scanned systematically in a search for evidence of tonal, vegetative, drainage, or topographic anomalies that were indicative of lineaments and fracture traces. In an effort to insure that all visible natural linear features were detected, the photographs were examined a second time after a time lapse of several days. The photographs were also examined under different viewing angles and lighting conditions in an effort to detect the more subtle linear features. The individual performing the fracture trace mapping worked continuously for a maximum period of two hours to avoid the effects of fatigue and eye strain on performance as suggested by Trainer (1967). The linear features detected were marked on the photographs with a china marking crayon.

A variety of aerial remote sensor products were used in the fracture trace mapping program. The primary product used consisted of standard photo index sheets at a scale of one inch equals one mile prepared by the United States Department of Agriculture - Agricultural Stabilization and Conservation Service (USDA-ASCS) aerial photography program. These index sheets are black and white photographs of uncontrolled mosaics prepared from contact print aerial photographs.

The relatively small scale of the photo index sheets was ideal for detecting prominent fracture traces and lineaments that were visible as tonal anomalies. The index sheets were most useful for mapping lineaments that were several miles in length and longer more prominent fracture traces. At a scale of one inch equals one mile, the index sheets provided a limited ability to identify many of the shorter fracture traces unless they were expressed as relatively prominent drainage or topographic anomalies. The net result of this situation was that the rather sparse network of prominent linear features could be mapped by using photo index sheets but the denser system of short linear features must be mapped by using a larger scale remote sensor product.

For several counties in the study area, index sheets prepared from aerial photographs taken in different years were available. Examination of these multiple coverages indicated several instances in which a lineament would be visible on an index sheet made in one particular year when the same lineament was not evident on index sheets made in another year. This shows that the ability to detect fracture traces and lineaments is sensitive to such factors as soil moisture, vegetation, and land use which are time dependent. This situation also indicates that multiple coverages of index sheets should be used in fracture trace mapping programs whenever possible.

One serious limitation of using photo index sheets was that stereoscopic viewing of the terrain could not be accomplished. Also, special care was exercised in detecting fracture traces on the basis of tonal anomalies on mosaics to insure that the tones were not associated with photograph processing effects in the photographs that were used to prepare the mosaic. Special care was also taken to avoid the designation of linear manmade features such as fence lines, property lines, pipelines, and field boundaries as natural linear features.

Another type of photograph that was used extensively was black and white contact print aerial photographs at a scale of 1:20,000 produced by USDA-ASCS. The primary advantage of these photographs was that the topography of the area covered by the photographs could be examined by stereoscopic viewing. This capability was particularly important in searching for linear topographic anomalies and examining the topography in the vicinity of fracture traces identified on the basis of tonal, vegetative, and drainage anomalies.

Contact print aerial photographs at a scale of 1:20,000 were particularly useful for mapping fracture traces which are less than one mile in length. This was true because the scale was such that these features occur in lengths of one to three inches on the photographs and were generally observed quite readily. In some cases, fracture traces mapped on individual contact prints would be aligned to form a lineament several miles long when the photographs were assembled into a continuous picture of the area. Previous experience has shown that fracture traces shorter than one inch on the photographs were generally not detected on either contact prints or mosaics. Many fracture traces that were evident as tonal anomalies were observed on the contact prints. Fracture traces that were observed on the basis of drainage anomalies were mapped rather infrequently on the contact prints.

Another sensor product that was used extensively in the fracture trace mapping program was Landsat imagery. Landsat imagery in the form of color infrared images at a scale of 1:250,000 was available for the entire study area. The color infrared images had been produced by making a composite image of the band 4 image (green wavelengths), the band 5 image (red wavelengths), and the band 7 image (near infrared wavelengths). The resulting false color image shows vegetation in a reddish color with different types of vegetation being shown in slightly different shades of red. Also, multiple coverages taken during different seasons of the year were available in some areas. Since the scale of these images corresponds approximately to a value of one inch equals four miles, only the longer lineaments could be observed on this sensor product.

Several lineaments could be observed on the Landsat images on the basis of tonal anomalies. Although the Landsat imagery could not be viewed stereoscopically, it was apparent that many of the tonal anomalies were actually associated with topographic features. In several instances, lineaments could be observed on a Landsat image taken during one season that was not evident on another Landsat image of the same area taken during another season. This would appear to indicate that the lineaments were associated with tonal or vegetative anomalies that only existed during certain months of the year or that a heavy growth of vegetation was masking the features during the summer months. In addition to several lineaments for which no known explanation was available, prominent lineaments were observed in association with known geologic features such as the Brevard Fault Zone and the Warwoman Fault in adjacent areas of Georgia.

A set of Landsat images in a black and white format was also available for use in the fracture trace mapping program. These images were the band 7 images which is one of the two near infrared wavelength bands monitored by the Landsat multispectral scanner. The near infrared wavelength bands produce an image in which bodies of water are shown in a black tone which contrasts markedly with the much lighter toned land areas. The black and white infrared image was particularly effective in mapping prominent linear features that were expressed as drainage anomalies. A number of significant linear features which were observed as topographic anomalies were also detected using this imagery. In many instances, topographic anomalies were displayed more prominently on the black and white infrared imagery than on the color infrared images. Generally, linear features that were several miles in length were observed on the 1:250,000 scale images. The results obtained by using the black and white infrared Landsat imagery indicated that this remote sensor product is an important supplement to color infrared Landsat imagery. Using both Landsat sensor products significantly increased the ability to detect major lineaments in the study area.

A set of Skylab color photographs was available for the portion of the study area along the Savannah River. The photographs were taken in February, 1974, as part of the S190B experiment. The color photographs used in the fracture trace mapping were enlargements at a scale of 1:125,000. A number of prominent lineaments were detected on the photographs on the basis of topographic anomalies. The color tone of the photographs was rather uniform and not useful for detecting tonal and vegetative anomalies. Although the resolution of the Skylab color photographs was better than the Landsat color infrared imagery, the Skylab photographs appeared to have no significant advantage over the

Landsat imagery for fracture trace mapping. The multispectral image capability and the fact that complete coverage with imagery taken in different seasons is available make Landsat imagery more effective for fracture trace mapping than Skylab photographs.

Two sets of high altitude aerial photographs taken as part of a NASA program in 1969 that covered a limited portion of the study area were also available for use in the fracture trace mapping program. The two sets of photographs consisted of color and color infrared photographs taken from the same camera positions. The photographs were taken from an altitude of 57,000 feet above the ground surface and had a scale of 1:120,000. The available photographs covered the northern portions of Pickens, Greenville, and Spartanburg Counties. It was anticipated that studying the color and color infrared aerial photographs of the same area alternatively would be an ideal test to determine the relative capabilities of the two types of photographs in fracture trace mapping.

Careful examination of the color and color infrared aerial photographs revealed a number of lineaments in the area for which photographic coverage was available. The lineaments were observed on the basis of tonal, vegetative, drainage, and topographic anomalies. The available photographs provided stereoscopic coverage and the ability to view the terrain in three dimensions was particularly useful in searching for linear topographic anomalies. The vegetative anomalies were most evident on the color infrared photographs. The color photographs were not good quality photographs and did not appear to provide any advantage over black and white photographs for fracture trace mapping. Partial cloud cover also adversely affected the usefulness of both the color and color infrared photographs. The lineaments detected on the high altitude color and color infrared photographs were generally longer than two miles because of the relatively small scale of the photographs.

Results

One of the most striking linear features detected during the mapping program was a major lineament that extended for approximately 60 miles across northern Pickens, Greenville, and Spartanburg Counties. The lineament was first observed on a frame of Landsat imagery taken on January 30, 1973 and was not readily visible on Landsat images taken on other dates. The feature has a strike of approximately N80°E and is slightly curved. A notable characteristic of the lineament is that it occurs as a linear depression for a distance of approximately 28 miles on the southwestern end and then as a sharply defined ridge for a distance of approximately 12 miles. Although not visible on the Landsat imagery, the lineament could be traced farther to the northeast for an additional 20 miles on photo index sheets and aerial photographs in Spartanburg County as a very subtle ridge. The ridge portion of the lineament is known locally as Pax Mountain in northern Greenville County. For this reason, the lineament has been herein designated as the Pax Mountain lineament. Figure 3 shows the location of the Pax Mountain lineament in western South Carolina. The southwestern end of the lineament appears to be just east of Lake Jocassee. Although the lineament could not be detected in Oconee County on the southwestern side of Lake Jocassee, it did appear that the lineament could be related

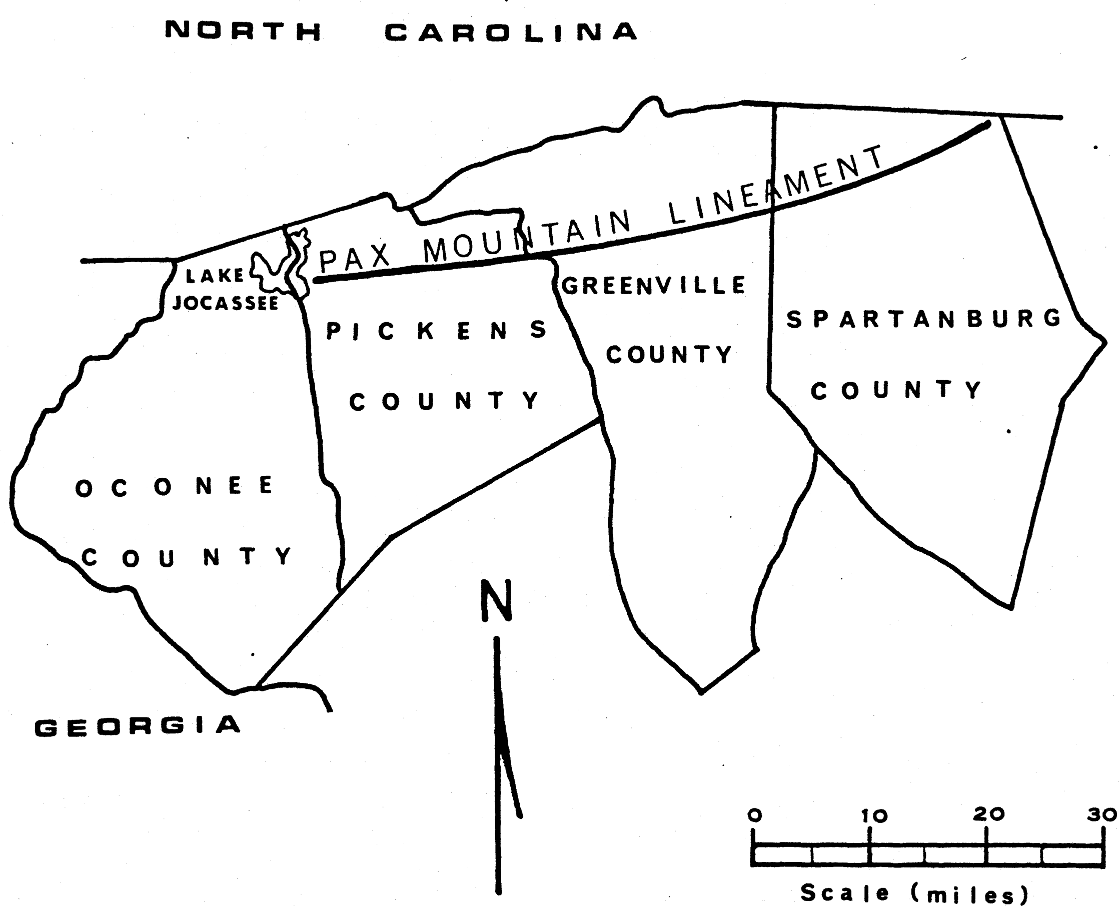


Figure 3. Map Showing the Location of the Pax Mountain Lineament in Western South Carolina.

to the Warwoman Fault in northeastern Georgia, assuming a significant offset in the vicinity of Lake Jocassee. The southwestern end of the Pax Mountain lineament is also near the intersection of the lineament and the Brevard Fault Zone which could account for the termination of the lineament.

Another unique feature of the lineament is that a rather unusual quartz-rich cataclastic rock can be found along the entire length of the lineament. Initially, this rock was termed ultramylonite by Conley and Drummond (1965). Subsequently it was described as a flinty crush rock by Birkhead (1973). Based on microscopic studies, Snipes (1981) termed the rock as a microbreccia following the classification of Higgins (1971). The primary characteristic of the rock is that it has been extensively fractured and the fractures have been largely filled by quartz veins. The rock is assumed to have been fractured by the shearing action of movement along a fault. Conley and Drummond (1965) traced the fault zone for a distance of 27 miles in Greenville and Spartanburg Counties, the northeastern portion of the Pax Mountain lineament. The microbreccia zone appears to be approximately vertical. Both Birkhead (1973) and Conley and Drummond (1965) report other numerous exposures of this rock type in a series of dikelike zones that are roughly parallel to the Pax Mountain lineament in adjacent areas of North and South Carolina.

Because of the sparse distribution of drilled wells in the area near the Pax Mountain lineament, the hydrogeologic significance of the feature is not known. The fractured nature of the rock along the lineament could be effective in increasing well yield. However, the effect of the quartz veins which appear to fill the fractures, at least at the surface, would indicate that the potential for drilling high yield wells along the lineament is very low. In fact, the vertical microbreccia zone may act as a dam to retard groundwater flow. If such a condition exists, wells drilled up slope from the lineament could represent a more likely location for high yield wells. A more extensive study of well yields in the vicinity of the Pax Mountain lineament should be conducted in an effort to define the hydrogeological characteristics of the feature. The influence of the Pax Mountain lineament on well yields may be significantly different along the southwestern portion where the lineament is expressed as a topographic depression as compared to the northeastern portion where the feature is expressed as a ridge which would be indicative of more resistant rock.

An example of a prominent lineament detected on both photo index sheets and contact prints is illustrated in Figure 4 as it is displayed on the contact print. This feature consists of a linear drainage anomaly and a linear topographic anomaly that are aligned. The lineament is approximately three miles long and is located in Oconee County. Although this feature is unusually prominent, it indicates the extent to which drainage and topography can be influenced by a fracture zone. The feature is even more obvious when the aerial photograph is viewed stereoscopically.

Based on the quantity and distribution of linear features detected in the fracture trace mapping phase of the research program, it is evident that an abundant supply of fracture traces exists in each county of the Piedmont Region. The typical pattern of linear features consists

Figure 4. Coincident Alginment of Linear Drainage and Topographic Anomalies to Form a Prominent Lineament in Oconee County, South Carolina.

of a sparse system of long lineaments and a denser system of short fracture traces. Although some areas had a density of mapped linear features that was slightly higher or lower than the typical average density, the overall distribution of linear features was relatively uniform. Certainly, the number and length of the mapped linear features is sufficient to provide an ample opportunity for locating water wells along lineaments or fracture traces in an effort to obtain a higher well yield by taking advantage of the subsurface fracture zones associated with these features.

The report by Snipes (1981) contains maps of Anderson and Oconee Counties which illustrate the orientation and density of the linear features mapped in the fracture trace mapping program. The report by Snipes et al. (1983) also includes a map which shows the pattern of lineaments and fracture traces in Abbeville County. The majority of the linear features shown in these two reports was detected using the various aerial remote sensing products employed in the fracture trace mapping program. It is anticipated that other studies will be initiated in the future to examine the relationship between the location of mapped linear features and well yield. Thus, the linear features mapped in this study by the use of aerial remote sensing techniques will continue to serve as a valuable source of information related to the characteristics of the potential groundwater resources of the Piedmont Region.

During the fracture trace mapping program, it was observed that the ability to detect natural linear features was affected by the type of land use in the area being examined. In particular, dense urban development tended to obscure the topographic, tonal, vegetative, and drainage anomalies that were readily visible in adjacent rural areas. This situation has previously been noted by Wobber (1967). In conducting fracture trace mapping studies in recently developed suburban areas, it was more effective to use photo index sheets or aerial photographs that were taken several years ago when land use in the area was primarily rural. Thorough fracture trace mapping was also difficult in heavily forested areas.

For the overall study area, no attempt was made to field check the fracture traces and lineaments that were identified during the mapping program. The lack of field checking was a result of the large area that was being mapped, the restricted study period, and budgetary limitations. It is recognized that field checking should be an integral component of a comprehensive fracture trace mapping program. Field checking should be conducted to insure that the mapped fracture traces are not associated with manmade features such as fence lines, property lines, pipelines, power lines, or other similar features. In a fracture trace mapping program to locate potential sites for high yield wells in a limited area, field checking would be conducted routinely in the process of selecting the most promising fracture traces as observed from ground level and from the air.

WELL DRILLING PROGRAM

In the initial stages of developing the research program, it was anticipated that funds would be available to fund the drilling of a small number of wells to provide data on the yield of wells drilled along fracture traces and lineaments. This well yield data could then be compared to similar data obtained for wells previously drilled at random locations in the same area to test the basic premise of the research project that wells drilled along linear features would have a significantly higher yield than wells drilled at random locations. However, the final project budget did not provide adequate funds to support a well drilling program and a restriction was also added that no project funds could be used for well drilling. This development placed a serious limitation on the options available for testing the basic premise of the research project.

In an effort to overcome the problem of a lack of funding for well drilling, a prominent local well driller was contacted to determine whether or not a cooperative program of assisting in locating wells that were being drilled for private owners could be developed. Mr. Bill M. Hughes of Hughes Well Drilling Company in Anderson, South Carolina, was interested in the concept being examined in the research project and agreed to cooperate with project personnel in the selection of specific sites for wells that were to be drilled for private clients. This arrangement was particularly beneficial to project personnel because it provided an opportunity to obtain a limited amount of well yield data for wells drilled at locations related to linear features at a minimal cost. The arrangement also allowed the Hughes Well Drilling Company to provide customers with a more sophisticated well location service at no cost to the company or the client.

One serious limitation of this cooperative program was that project personnel generally did not get involved in selecting locations for wells until one or more wells located by mutual agreement between the well driller and the client had been drilled and found to provide an inadequate yield to serve the owner's needs. Thus, the well drilling program typically involved the selection of sites for additional wells in areas where problems had previously been experienced in obtaining adequate well yields. Another factor that severely restricted the cooperative well drilling program was the fact that the wells had to be located on a client's particular parcel of land. In several instances the land parcels were rather small and well sites that were directly related to observed linear features could not be located on the client's land. In these cases, less desirable well locations had to be selected in an effort to serve the needs of the client. However, these well locations that were selected on the basis of a compromise between ideal locations determined by fracture trace analysis and the client's limited land holdings were not completely effective in testing the basic premise of the research project.

The cooperative well drilling program was limited geographically to Anderson, Greenville, Oconee, and Pickens Counties. The Hughes Well Drilling Company was most active in this area and, therefore, the area provided the greatest opportunity for cooperative well location activities. Also, restricting the program to these areas near Clemson University served to minimize travel costs in conducting field reconnaissance missions and monitoring of well drilling operations. The following sections describe the results obtained in the well drilling program.

Area 1

The first and largest project in the well drilling program involved an area on the shore of Lake Keowee in eastern Oconee County as shown in Figure 5. The site contained approximately 350 acres and was to be developed into a residential community for retired families and others who would be attracted to the recreational opportunities and aesthetic qualities of Lake Keowee. The most economical source of water for domestic use had been determined to be well water. Six unsuccessful wells had been drilled on the property when project personnel became involved in the project. These six wells had yields that ranged from two to ten gallons per minute (gpm). These well yields were considered to be totally inadequate in relation to the needs of the development. Based on estimates of the number of families that would be located on the property in the initial stages of development, wells with a total yield of approximately 200 gpm were required. A large tank for storage of well water would be used to serve peak demand.

After an examination of the data produced in the fracture trace mapping program in Oconee County and the adjacent area of Pickens County, it was found that there were no significant fracture traces or lineaments that had been identified on the property. A careful review of several different dates of photo index sheets covering the area at a scale of one inch equals one mile failed to detect any particularly prominent linear features. In fact, the area immediately east of Lake

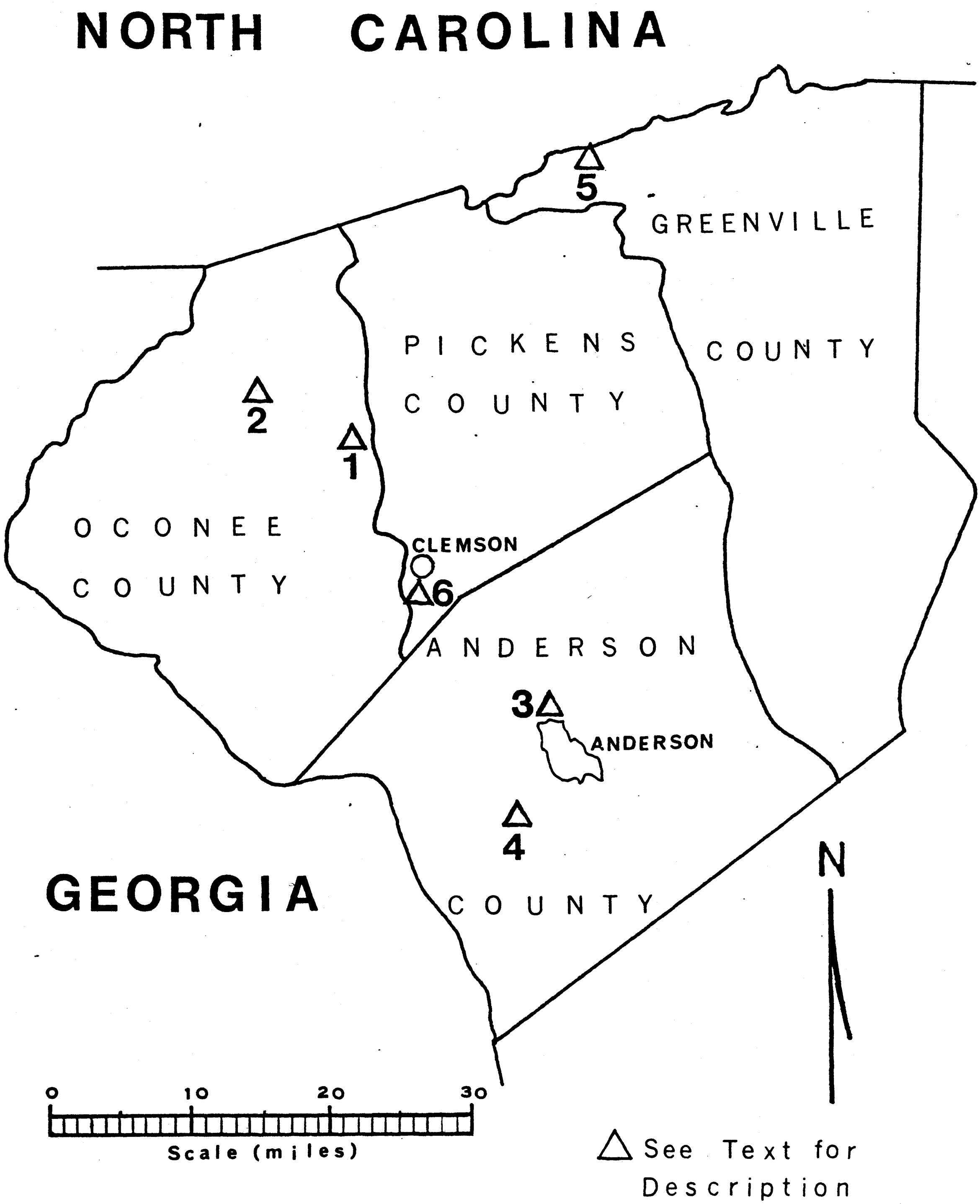


Figure 5. Map Showing the Location of the Areas Involved in the Well Drilling Program.

Keowee in Pickens County had previously been noted to be an area with a sparse distribution of linear features. Using stereoscopic viewing techniques, a detailed examination of a set of contact print aerial photographs taken with panchromatic film at a scale of 1:20,000 failed to reveal any prominent fracture traces; although several short, linear anomalies were observed in the drainage system. Also, one example of an abrupt change in direction of a drainage feature was observed. Although the fracture trace analysis was not successful in identifying any prominent linear features on the property, it was thought that the anomalous drainage features could be used as a basis for selecting several promising well locations.

A series of four well locations were selected on the property at the intersection of the linear drainage features and tributary drainageways. The well locations selected were numbered in order of drilling priority based on the judgement of project personnel. Well site 1 was located approximately 100 feet from the shore of Lake Keowee near the intersection of two short drainage features that joined to produce a rather distinctive linear valley. The drainage features that were related to well site 1 were ephemeral drainageways which carried storm runoff but did not flow continuously.

Well site 2 was located at a point where a long linear, ephemeral drainage feature appeared to make an almost 90° change in direction. The linear valley also seemed to cut rather abruptly across the topography in the area. This well site was located approximately 400 feet from the shore of Lake Keowee.

Well site 3 was located at the intersection of a short drainage feature and the longest and most prominent drainage feature on the property. The large drainage feature was a significant topographic feature that was aligned with a large cove on Lake Keowee that extended for approximately 1,500 feet into the property. Well site 3 was located approximately 300 feet down slope from a well that had been drilled previously and found to have a well yield of only two gpm. The large drainage feature on which well site 3 was located changed from an ephemeral feature to a continuously flowing stream near well site 3.

Well site 4 was located approximately 200 feet down slope from well site 2 at the intersection of a short tributary drainageway and the longer drainage feature on which well site 2 was located. This well site was approximately 150 feet from the shore of Lake Keowee. Both drainageways related to well site 4 were ephemeral. It was anticipated that well site 4 would be drilled only if well site 2 was found to have an adequate well yield.

After a conference between project personnel, the well driller, and representatives of the property owners, the decision was made to initiate the drilling program using the drilling priority system selected by project personnel. The decision to proceed with the drilling program was to be made by the property owners based on the well yields obtained in each well drilled.

The well at well site 1 was drilled to a depth of 240 feet using a 6-inch diameter bit. The drilling process was monitored by project personnel to obtain data on rock type and well yield. Based on the behavior of the drill, several zones of fractured rock or rock discontinuity were penetrated by the well. However, these zones did not have large amounts of water associated with them. Bedrock was encountered at a depth of 12 feet and was classified as mixed granite and metamorphic rock. Water production zones were encountered at depths of 20 feet and 156 feet. A test of well yield using the compressed air on the drilling rig to pump the water to the surface and rather rough volume measuring techniques indicated a well yield of approximately six gpm. Based on the experience of the Hughes Well Drilling Company, this method of estimating well yield usually results in conservative estimates of the sustained well yield as determined by pumping tests (Snipes, 1981). Since no significant changes in rock type or fractured rock zones were enountered in drilling below 200 feet, the well drilling was stopped at a depth of 240 feet. The well yield obtained was so low that this well was considered to be unsuccessful. However, the well could be used at a later date to supply water to a tank storage system if other higher yield wells could be obtained.

The well at site 2 was drilled to a depth of 205 feet using a 6-inch diameter bit. Although several changes in rock color were observed as the well was drilled, no significant water production zones were encountered. Several zones of fractured rock were also penetrated but these zones did not contain any significant amounts of water. The well yield was estimated to be less than one gpm. This well was considered to be essentially a dry hole and was abandoned. Bedrock was encountered at a depth of 42 feet and consisted primarily of granite and amphibole gneiss.

Due to the low well yields obtained in the first two wells drilled, the owners decided to cease drilling operations temporarily. After approximately six months of deliberation, the decision was made to drill one additional well in another portion of the property where a well with a yield of approximately 40 gpm had been drilled several years earlier. The area where the well was to be located was essentially a peninsula that extended into Lake Keowee and contained approximately 40 acres. The area also included the sites where two dry holes had been drilled several years earlier when the area was initially developed as a residential subdivison.

Project personnel examined the area carefully using all available remote sensing products. No significant linear features were observed in the area. One possible well location was selected along one of the longer ephemeral drainage features on the property. The well site was approximately 300 feet from the existing well with a yield of 40 gpm and 100 feet from the Lake Keowee shore line. The well site was also located on the opposite side of a ridge running through the property from the two dry holes and also at a much lower elevation.

The well was drilled to a depth of 300 feet and a yield of approximately 12 gpm was obtained based on a test conducted with the aid of the drill rig. The well appeared to penetrate several fracture zones or rock discontinuities as the well was drilled. However, some of these fracture zones did not produce any increase in well yield. Bedrock was encountered at a depth of 11 feet and water production was obtained at depths of 20 feet and 170 feet. The rock was classified as a variable colored granite with several thin layers of amphibole gneiss at different depths. No significant fracture zones or changes in rock type were encountered below 240 feet and drilling was discontinued at a depth of 300 feet. The well yield obtained was disappointing but it was concluded that the well could make a significant contribution to the needed water supply if adequate storage was available. The long term solution to the water supply problem for this proposed development is still unresolved, partially because the depressed real estate and housing markets have delayed the development of the property. Based on the number of low yield wells and dry holes that have been drilled on this property, it is concluded that the area has a serious problem in obtaining a sufficient amount of well water to serve the needs of the proposed development.

Area 2

Another area where aerial remote sensing techniques were used to select a well site was also located in eastern Oconee County as shown in Figure 5. The 20-acre parcel of land was located south of the community of Tamassee and approximately one-half mile west of South Carolina Highway 11. The present land owner had drilled three dry holes on the property when project personnel were contacted for assistance by the well driller. The three dry wells had been drilled to depths of 285 feet, 325 feet, and 445 feet in a relatively uniform muscovite schist with no indication of fractures being encountered. It had also been determined that the previous land owner had drilled three dry holes on the property, but this information was not mentioned to the present owner when the land was sold and no data on well location and other well characteristics was available for these wells. All of the dry holes had been drilled near the area where the property bordered the road because this was the optimum location for a home site. A well with a yield of approximately 5-10 gpm which was sufficient to provide water for domestic use at a single family residence was needed.

A review of the previous fracture trace mapping indicated that no significant linear features had been identified in the immediate vicinity of the property. Stereoscopic examination of 1:20,000 scale aerial photographs revealed a short linear drainage feature that intersected the longer drainage feature running through the property. A well site was selected at the intersection of the two drainage features. Two of the dry holes had been drilled in the upper portion of the longer drainage feature but at a higher elevation than the proposed well site. When this well was drilled to a depth of 125 feet, production zones were encountered at depths of 60 and 120 feet and a well yield of approximately 15 gpm was obtained. This well yield was considerably more than was required to satisfy the owner's water needs. The successful well penetrated amphibole and biotite gneiss between depths of 27 and 125 feet, a different rock type from the rock in which the previously drilled dry holes had been drilled. Bedrock was encountered at a depth of 27 feet.

Area 3

Another extensive involvement of project personnel in selecting locations for wells was related to a proposed residential subdivision in a suburban area just north of the city limits of Anderson, South Carolina. The area was located near the center of Anderson County as shown in Figure 5. The site contained approximately 50 acres and was located adjacent to a small arm of Lake Hartwell. Based on the previous experience of the well driller in the general area of the property, it was anticipated that considerable difficulty would be experienced in obtaining sufficient well water to serve the projected needs of the subdivison residents.

Project personnel reviewed the fracture trace mapping data that had been produced earlier for Anderson County and found that no significant linear features had been detected in the vicinity of the property. An examination of the available aerial remote sensor products also failed to identify any prominent fracture traces. However, stereoscopic viewing of contact prints taken with panchromatic film at a scale of 1:20,000 revealed that several potential locations for wells existed on the property. These potential well sites were primarily related to linear valleys that were serving as ephemeral drainage features. Four potential well locations were selected by project personnel on the basis of the aerial photographic study results. Since the water system for the proposed subdivision was to be owned and operated by the Hughes Well Drilling Company, the property owners were not involved in making decisions concerning the well drilling program.

Well No. 1 was located along a short, broad topographic depression that carried storm runoff from a considerable portion of the site. However, the local area was so heavily forested that it was difficult to assess the significance of the drainage feature. The well was drilled to a depth of 365 feet and found to have a yield of approximately 12 gpm based on a test using the drill rig. Bedrock was encountered at a depth of 18 feet and water was obtained at a depth of 270 feet. The bedrock was relatively uniform granite. Although the yield of this well was disappointing, it was concluded that the well could provide a significant contribution to the water supply for the subdivision with the storage system that was to be constructed.

Well No. 2 was located approximately 300 feet from Well No. 1 along the same topographic feature but at higher elevation. The well was drilled to a depth of 420 feet and found to have a yield of less than one gpm. Bedrock was encountered at a depth of 21 feet and consisted of uniform granite. This well was abandoned.

Well No. 3 was located as close as possible to a linear but rather subtle topographic low that extended along one property boundary. When the well was drilled to a depth of 425 feet, water was encountered in two production zones at depths of 105 feet and 275 feet. Bedrock was encountered at a depth of 74 feet and consisted of granite with a considerable number of quartz veins. The well was initially thought to have a yield of approximately 30 gpm based on a short-term test with the drill rig. However, a longer term pumping test indicated that the sustained yield of the well was only about 8 gpm.

Well No. 4 was located down slope from Well No. 3 in the same linear topographic feature. Well No. 4 was drilled to a depth of 445 feet and found to have a yield of approximately 30 gpm. Bedrock was encountered at a depth of 45 feet and consisted of relatively uniform granite. Water production was obtained at depths of 90 feet and 325 feet.

The total yield from the three successful wells was considered to be adequate to serve the needs of the subdivision with the storage tank planned for the water system. Thus, this was considered to be a successful application of the use of aerial remote sensing techniques for selecting well locations. The well yields obtained were particularly significant in view of the number of low yield wells and dry holes that were known to exist in the area surrounding the site.

Area 4

Another well location project was also located in Anderson County just south of the Anderson city limits as shown in Figure 5. This project involved finding a water supply source for a single dwelling unit that had already been constructed. One well drilled to a depth of 505 feet in mixed granite and amphibole gneiss on the property before project personnel became involved had a yield of only two gpm which was considered inadequate. Considerable difficulty had been experienced in the surrounding area previously by the well driller in obtaining well yields sufficiently high to provide an adequate water supply for single family residences. Because the lot on which the house was located was very small, permission was obtained to locate the well on an adjacent tract of undeveloped land.

Although no fracture traces had previously been mapped in the immediate area, careful stereoscopic examination of aerial photographs taken at a scale of 1:20,000 on panchromatic film revealed a long, linear feature expressed as a slight topographic depression. A well site was selected along this feature at a distance of approximately 550 feet from the house. A well drilled to a depth of 125 feet at the site selected had a yield of approximately 33 gpm. The well encountered bedrock at a depth of 39 feet and productive zones were struck at depths of 40 and 55 feet in rock classified as biotite schist and granite. This well yield exceeded the needs of the single family by at least a factor of three. This was another example of a successful well location project using aerial remote sensing techniques.

Area 5

Another area in which project personnel were involved in selecting well locations was at Ceasar's Head in northwestern Greenville County as shown in Figure 5. Although this area is actually in the edge of the Blue Ridge Province, it was thought that the geology of the area was sufficiently similar to the Piedmont Region that including the project in the well drilling program would be worthwhile. The primary factor that makes the Ceasar's Head area different from the Piedmont Region is the higher elevation of the area. The Ceasar's Head area has an average elevation of approximately 3,000 feet as compared to an average elevation of approximately 1,000 feet in the nearby Piedmont Region.

Ceasar's Head is a resort community of approximately 500 acres with about 50 homes that are occupied primarily during the summer months. The existing water supply system consisted of a spring which flowed into a concrete storage tank. During the late summer when peak water demand occurred, the spring experienced a period of low flow and coliform bacteria contamination also developed. One existing private well at Ceasar's Head was known to have a yield of only two gpm.

An examination of the data developed in the fracture trace mapping program indicated that the Ceasar's Head area had not been included in the previous study area. A review of the available aerial remote sensor products revealed that no prominent fracture traces existed in the limited area of concern. However, two short topographic features that could possibly be classified as fracture traces were observed by stereoscopic viewing of 1:20,000 scale contact prints taken with panchromatic film. Two well sites were selected along these linear features and the priority for drilling the wells was determined. The highest priority well site was located approximately 200 feet up slope from the existing spring.

The initial well was drilled to a depth of 245 feet and determined to have a yield of approximately 100 gpm. The bedrock was encountered at a depth of 15 feet and consisted primarily of quartz monzonite with occasional fragments of biotite gneiss and pegmatite. The quartz monzonite was relatively coarse grained at depths less than 50 feet and medium to fine grained at greater depths. The monitoring of the well drilling operation indicated that a zone of extensively fractured rock was penetrated in the production zone which occurred at depths between 20 and 45 feet. Because of the high well yield obtained in the initial well, no attempt was made to drill the second well. Therefore, this project was also considered to be a successful application of the techniques being studied.

Area 6

Another well location project involved an area on the Clemson University campus in southwestern Pickens County as shown in Figure 5. A source of water for an irrigation system was desired for a peach orchard that was being used in the agricultural research program. The well location needed to be as close as possible to the orchard in order to minimize the cost of pipe.

Since no lineaments or fracture traces had previously been mapped in the area, a stereoscopic examination of 1:20,000 scale aerial photographs was conducted. No prominent fracture traces were observed in the vicinity of the orchard. However, a rather subtle linear drainage feature was noted which provided a potential well location. A well site was selected along this feature and the well was drilled to a depth of 300 feet. Bedrock was encountered at a depth of 60 feet and consisted primarily of a uniform granite. The well yield obtained was approximately 30 gpm which was thought to be adequate for the intended irrigation system.

Although the research program was successful in using aerial remote sensing techniques to locate several wells with yields that were adequate to serve the needs of the property owners, the well drilling program does not provide conclusive evidence of a positive correlation between well yield and location with respect to fracture traces. Even in cases where successful wells were located and drilled in areas where well drilling had been unsuccessful, the evidence necessary to prove the validity of the underlying premise of the research project is lacking. The primary factor that limits the use of the data obtained in the well drilling program is the fact that none of the well locations were located on prominent fracture traces or lineaments that had been identifed in the previous fracture trace mapping program. In fact many of the well sites selected on the land parcels involved in the well drilling program were not directly related to significant linear features. Many of these well sites were selected on the basis that they appeared to be the most promising locations on the very limited parcel of land owned by a particular client of the well drilling company. In several instances, the well sites selected were recognized to be compromises between the objective of locating the wells on fracture traces and satisfying the needs of a particular land owner by finding a suitable well site on a small parcel of land.

A serious shortcoming of the well drilling program is that there was no opportunity to drill wells at the intersection of two mapped linear features. The location of the land parcels where the cooperative well drilling program provided an opportunity to drill wells happened to be areas where no intersections of linear features could be detected. One factor that was a major reason for this situation was that the parcels of land involved were generally very small. Also, the largest land parcel involved in the cooperative well drilling program was located in an area where the density of linear features had previously been noted to be lower than average. Therefore, prime locations for potential high yield wells such as the intersection of prominent lineaments and fracture traces were not available at any of the areas involved in the well drilling program.

CORRELATION OF WELL YIELD AND FRACTURE TRACE LOCATION

One phase of the research project involved an effort to correlate well yield with the location of mapped linear features. The study concentrated on Greenville County because a considerable amount of data was available on the yield of wells at specific locations in this county. The report entitled Groundwater Resources of Greenville County, South Carolina by Koch (1968) contained data on the location and yield of 701 wells. One serious deficiency of the data in this report was that the well location was described in terms of latitude and longitude only to the nearest five seconds which failed to define the location as accurately as was needed for this project. Primary attention was given to high yield wells which was defined as wells with yields of 25 gpm or greater.

The high yield wells and the lineaments and fracture traces were plotted on a base map in an effort to examine the degree to which the high yield wells were located on or near linear features. Considerable difficulty was experienced in accurate plotting of both wells and linear features. Many of the lineaments had been mapped on Landsat imagery and photo index sheets that had a different scale than the base map. When the linear features were transferred to the base map, a significant amount of error could have been encountered. However, the lack of an adequate system of map control made it difficult to detect the existence of the error or to make the necessary corrections in lineament location. Also, the plotting of the high yield well locations was also subject to considerable error because of the low accuracy of the reported well latitude and longitude values. In view of the magnitude of error in the location of the linear features and wells, some difficulty in correlating the well yield with the location of linear features was to be expected.

When the locations of the high yield wells were compared to the plotted lineaments and fracture traces, several instances where the high yield wells appeared to be related to the linear features were evident. The majority of the instances where the location of the high yield wells coincided closely with the plotted linear features occurred in south central Greenville County where the high yield wells appeared to be somewhat concentrated. In several other instances, the high yield wells were near mapped linear features but offset by a sufficiently large distance that some doubt was created concerning the relationship between the high yield well location and the linear features. Since no information is available on the width of the fracture zone associated with lineaments and fracture traces, it is difficult to determine whether or not some of the high yield wells were significantly influenced by the nearby linear features. Some of these instances of high yield wells being located near but not on plotted linear features may have been caused by errors in plotting the well or the fracture trace location. Several of the high yield wells in Greenville County did not appear to be related to any linear features that had been detected. Based on the degree to which the location of the high yield wells coincided with the plotted linear features in Greenville County, there was an implication that the locations were related. However, it was not possible to determine conclusively that the high yield well locations were correlated with the location of linear features.

In an effort to introduce a degree of quantitativeness into the correlation process, a statistical approach using linear regression techniques was employed. Data on the shortest distance to the nearest mapped linear feature was measured and recorded on a data sheet along with the yield of each high yield well. This data was used as input to the Statistical Analysis System computer program in an attempt to determine if well yields decreased linearly with increasing distance from the linear features. The results of the computer program indicated that a very low level of linear correlation existed between well yields and the distance to the nearest linear feature. Based on these results, it was concluded that a statistical approach could not be used effectively to establish the existence of a linear correlation between well yield and fracture trace location. The fact that the zone of influence in which lineaments and fracture traces affect well yield is limited to the width of the fractured rock zone is the most probable explanation for the failure of well yield to be linearly correlated with distance of the well from the nearest fracture trace. Thus, wells that are located within the zone of fractured rock associated with a particular linear feature can have a higher than normal yield and wells located outside of this zone can have a lower yield, but well yield will not be linearly correlated with distance from the nearest fracture trace because the influence of the fracture trace is limited to the fracture zone. Also, the relationship between well yield and fracture trace location is complicated by the fact that some rock fractures probably exist underground that are not evident in any type of surface expression that would permit them to be mapped by aerial remote sensing techniques.

The results of the statistical analysis are in contrast to the results obtained by Siddiqui and Parizek (1971) which indicated that location of wells with respect to fracture traces was one of five hydrogeologic variables that could be statistically correlated with well yield in carbonate rocks in Pennsylvania.

A less extensive effort was also made to examine the relationship between well yield and fracture trace location in Pickens County. The report entitled A Reconnaissance of the Water Resources of Pickens County, South Carolina by Johnson, *et al*. (1968) contained data on the location and yield of 192 wells in Pickens County, including a well in Easley, South Carolina, with a reported yield of 500 gpm. However, the well location data was available only in the form of a map at a scale of 1:125,000. The mapped linear features were plotted on an overlay of this map so that the well location and fracture trace location could be compared. Considerable difficulty was experienced in accurately locating the fracture traces on the overlay in transferring the linear features from the remote sensing products which were at different scales than the overlay. Also, some doubt about the accuracy of the well locations on the base map also existed because of the fact that the wells were shown by a circle with a diameter of approximately 0.3 mile at the map scale.

The examination of the relationship between well yield and linear feature location was concentrated on the wells with yields of 25 gpm or more. Several of the high yield wells appeared to be located on the mapped linear features. However, there was a significant number of high yield wells that did not appear to be related to any mapped linear feature. Several instances were also observed in which high yield wells were near but not directly on mapped lineations or fracture traces. Some of these situations may be related to errors in well location or fracture trace location. However, it is not possible to determine the extent to which location errors effected the correlation of well yield and fracture trace location.

Because of the difficulties that had been experienced in correlating well yields in Greenville and Pickens Counties, it was decided to take a different approach using the available data in Spartanburg County. The approach used was to conduct a field reconnaissance of some of the high yield wells in an effort to locate the wells on aerial photographs and determine whether or not the wells appeared to be located on linear features observed on the aerial photographs. Data on well yield and well location was available for 291 wells in the report entitled Water Resources of Spartanburg County, South Carolina by Bloxham, et al. (1970). The well location data was available only in the form of plotted location on a map at a scale of 1:125,000.

An attempt was made to visit the vicinity of several selected wells with yields of 25 gpm or more and to define the actual well site on contact print aerial photographs at a scale of 1:20,000. Considerable difficulty was experienced in locating many of the wells, particularly in areas that were moderately to densely developed. However, several high yield wells were located with an acceptable accuracy on the available aerial photographs. Examination of the aerial photographs indicated that some of the wells did appear to be located on or near short fracture traces. None of the wells were located on the more prominent lineations that had been mapped in the area. Also, some high yield wells were found that did not appear to be located on or near lineaments or fracture traces. After several well sites had been examined, it was concluded that the information being developed was not satisfactory to prove conclusively that the high yield wells were directly related to readily observable linear features. Therefore, the field reconnaissance phase of the investigation was terminated.

Although the attempt to correlate well yield with fracture trace location was not entirely successful, there was an indication that the high yield of some wells could be explained by the proximity of subsurface fracture zones associated with lineaments and fracture traces. The available data base of well yield and well location information was not sufficiently accurate to allow an exact correlation of well yield with fracture trace location. However, neither was there sufficient evidence to reject the basic premise of the research project that wells located on mapped natural linear features have higher yields than wells drilled at random locations. Further efforts to compile well location and well yield data should be undertaken to provide a broader and more accurate data base that can form the basis for future correlation studies.

One significant development that has occurred in recent years which will be a significant aid in future studies of groundwater resources is the well numbering system initiated by the South Carolina Water Resources Commission. This program was initiated in 1978 and involves a well numbering system based on the geographic coordinates of the well that will make well location in the field much easier and more accurate than has been the case in the past. The well numbering system defines the well location to within a square block of land that is one minute of latitude by one minute of longitude. Each well in the square block is numbered and the precise location defined on the well report form. All well drillers in the state are required to complete a two-page data sheet on all new wells that defines the location and important characteristics such as the owner, driller, total depth, casing depth, well yield, date, topographic position of the well, and other pertinent data. The well driller usually attaches a well log to the standard well report to define changes in rock type with depth and water production levels. This information is submitted to the South Carolina Water Resources Commission on a standard well report form for filing and the information is available for retrieval as the need arises. As more of these standard well reports are accumulated, a significant data base will be developed for analyzing well yield in relation to a number of well parameters and geographic location.

SUMMARY AND CONCLUSIONS

An extensive program of fracture trace and lineament mapping by the use of aerial remote sensing techniques was conducted in the Piedmont Region of South Carolina. The study utilized a variety of aerial remote sensing products to map linear features in each of the 22 counties in the Piedmont Region. The remote sensor products that were used included color infrared Landsat imagery, black and white infrared Landsat imagery, Skylab photographs, high altitude color and color infrared aerial photographs, black and white aerial photographs at a scale of 1:20,000, and USDA-ASCS photo index sheets.

Based on the results of the fracture trace mapping program, the following conclusions are warranted concerning the fracture trace mapping process.

1. Different types of aerial remote sensor products are needed to conduct a thorough fracture trace mapping program. Small scale products such as Landsat imagery are best suited for detecting long lineaments. Also, black and white infrared Landsat imagery (Band 7) is quite effective in revealing long lineaments that are expressed as linear topographic and drainage anomalies. Photo index sheets at a scale of one inch equals one mile provide an effective means of mapping medium size lineaments and fracture traces (0.5 - 3.0 miles in length) that are expressed as tonal, vegetative, topographic, or drainage anomalies. Contact print aerial photographs taken with panchromatic film at a scale of 1:20,000 are most useful for mapping short fracture traces regardless of the mode of

expression. The ability to view the contact prints stereoscopically is a very important asset that is essential in mapping the shorter and more subtle linear features.

2. Numerous lineaments and fracture traces exist in each county of the South Carolina Piedmont Region. The density of the lineaments and fracture traces detected in this study is variable, but only to a limited degree. Some areas appear to have a higher density of long, prominent lineaments as observed on Landsat imagery. A significant portion of these prominent lineaments may be related to the geologic structure associated with the northeast trending Inner Piedmont, Charlotte, King's Mountain, and Carolina Slate Belts. Some small areas with a dense system of shorter fracture traces were observed. These areas are probably zones with a dense system of intersecting joint sets where the joints have significantly influenced topography and drainage features.

3. The most prominent linear feature detected in the fracture trace mapping program has been designated herein as the Pax Mountain lineament. This feature was first observed on a Landsat image taken on January 30, 1973. The lineament has a strike of approximately N80°E, is slightly curved, and can be traced on Landsat imagery, photo index sheets, and contact prints for roughly 60 miles. The southwestern end of the feature is just east of Lake Jocassee in Pickens County and the lineament extends across northern Pickens, Greenville, and Spartanburg Counties. The Pax Mountain lineament is unique because the southwestern portion of the feature is a topographic

depression and the northeastern portion of the feature is a topographic ridge. The most prominent section of the ridge portion of the lineament is known locally as Pax Mountain in northern Greenville County. A rather unusual quartz-rich cataclastic rock classified as a microbreccia can be found along the entire length of the lineament. The rock has been extensively fractured by the shearing action of movement along a fault and the fractures have been largely filled by quartz veins. The hydrogeological characteristics of the fracture zone associated with the Pax Mountain lineament have not been determined.

4. The type of land use in the area being examined can have a significant effect on the ability to conduct a thorough and successful fracture trace mapping program. In particular, the ability to use tonal anomalies to detect fracture traces can be adversely affected by land use patterns. Tonal anomalies were best observed in areas of agricultural land use where bare fields or cropland with sparsely spaced plants existed. Heavy forest cover and dense urban development tended to mask topographic, drainage, vegetative, and tonal anomalies that were readily visible in other areas. In general, fracture trace mapping in urban areas was very difficult because the linear features that were being mapped were almost impossible to detect against the background of streets, buildings, paved parking lots, and other manmade development. Special care must be made in both urban and rural areas to avoid confusing

natural linear features with power lines, pipelines, and other manmade linear features.

The cooperative well drilling program undertaken in an effort to correlate well yield with fracture location was not entirely successful. Although a number of well sites selected by the use of aerial remote sensing techniques were found to have yields that satisfied the water needs of the owners, it is not possible to state unequivocably that the well yields obtained were higher than would have been obtained from a random drilling program. In some instances, the well drilling program was not successful in obtaining well yields of sufficient magnitude to meet the objectives of the well drilling program. However, the well drilling program was seriously limited by the fact that the small parcels of land involved in the various well location projects made it impossible to locate any wells on prominent lineaments or fracture traces or, most importantly, at the intersection of mapped linear features. Based on the overall results of the well drilling program, it is concluded that some evidence of the ability to use aerial remote sensing techniques to locate sites for high yield wells does exist. However, additional research is needed to confirm the validity of this approach to water well location in the Piedmont Region.

Attempts to correlate well yield and well location with respect to mapped linear features for previously compiled inventories of wells in Greenville, Pickens, and Spartanburg Counties also met with only partial success. When plotted on the same base map, several high yield wells did appear to be located along mapped linear features. However, many other instances were observed where high yield wells were located near but at a significant distance from a lineament or fracture trace. Also, several situations were noted where the location of high yield wells appeared to be totally unrelated to mapped linear features. An attempt to use linear regression techniques to relate well yield and the shortest distance to a mapped linear feature indicated that a very low degree of linear correlation existed between these two parameters. Because of the partial success achieved in this phase of the research program, it is concluded that additional effort should be devoted to the correlation of well yield and well location with respect to mapped linear features in the Piedmont Region of South Carolina in order to provide a stronger incentive to use aerial remote sensing techniques and fracture trace mapping as a basis for water well site selection.

RECOMMENDATIONS

A continuing program of working with cooperative well drillers in the Piedmont Region of South Carolina should be inititated in an effort to generate additional data relating well yield to lineament and fracture trace location. Personnel familiar with fracture trace mapping techniques using aerial remote sensing products could assist well drillers in locating sites for wells on linear features whenever clients needed high yield wells to satisfy their water demand. Whenever the well sites selected in this program were drilled, the well yields obtained could be compared to the yield of other wells in the vicinity that had been drilled at locations unrelated to mapped fracture traces. In this manner the data needed to test the premise that wells drilled on linear features have higher yields than wells drilled at random locations could be accumulated. Also, the opportunity to drill wells at the intersection of prominent fracture traces would likely arise during the program. The data obtained from these wells would provide an additional opportunity to examine the extent to which fracture traces influence well yield. A long term working relationship with one or more well drillers would give more frequent opportunities to select well sites on large parcels of land where potential well sites are more likely to be available on prominent lineaments and fracture traces or at the intersection of mapped linear features.

Additional efforts should be undertaken to define the relationship between well yield and fracture trace location in the Piedmont Region. The present study has shown that an abundant quantity of natural linear features exists in most areas of the Piedmont Region. The development of a strong positive correlation between well yield and fracture trace location would serve to encourage the wider use of aerial remote sensing techniques for selecting promising sites for high yield wells. The potential increase in well yield that could be achieved by locating wells in the fracture zones associated with the mapped linear features could be an important factor in enhancing the use of groundwater as a source of water supply in the Piedmont Region of South Carolina.

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