Photolineament Factor: A New Computer-Aided Method for Remotely Sensing the Degree to which Bedrock is Fractured

Kenneth C. Hardcastle

Abstract

Photolineaments are often utilized during exploration for groundwater resources in fractured bedrock; photolineaments are thought to denote areas where the bedrock may be relatively more fractured and, therefore, capable of storing and transporting significant volumes of groundwater. It is suggested that three key characteristics can be used to rank an area's potential *to store and transmit large volumes of groundwater: (1) the number of photolineaments, (2) the number of directional photolineament families,* and *(3) the total length of photolineaments which occur within or traverse an area of defined radius. The normalized sum of these three photolineament parameters is referred to here as a photolineament factor value. A new computerized approach for processing the thousands of photolineaments typically collected for large study sites (>10 km² or 2500 acres) yields a contourable grid of photolineament factor values. Such a contour map facilitates rapid quantitative ranking and selection of discrete areas for further evaluation. Results from a 900 km² (220,000 acre) study area in the Georgia Piedmont illustrate this new approach.*

Introduction

Many subsurface features, such as fracture zones, faults, geologic contacts, and other bedrock discontinuities, have a surface expression which can be detected through analysis of aerial photographs and satellite images. These subsurface features can greatly influence groundwater systems and are, therefore, important to determine in any program of groundwater resource exploration. The surface expressions of these subsurface features are often linear to curvilinear topographic depressions or tonal discontinuities. "Fracture trace" or photolineament analysis, in conjunction with detailed geologic mapping, is often applied as a practical means of delineating possible water-bearing bedrock features because of the demonstrable relationship between some photolineament and bedrock features (Rich, 1928; Blanchett, 1957; Lattman, 1958; Lattman and Parizek, 1964; Wobber, 1967; Alpay, 1973; Caswell *et al.*, 1986; Mabee, 1992; Yin and Brook, 1992). For example, existing high-yielding wells generally occur proximal to geologic contacts in the Greater Atlanta Region (Cressler *et al.*, 1983), proximal to fracture-correlated photolineaments in crystalline metamorphic rocks in Maine (Mabee *et al.*, 1990), and near lineaments in carbonate rocks in central Pennsylvania (Siddiqui, 1969).

At least one key assumption underlies groundwater studies which utilize photolineaments: the photolineaments identified are "real," that is, they are not merely an artifact of either the observers bias(es) and/or cultural activities. One approach for gaining confidence on the reality of photolineaments is to collect and analyze data sets comprised of photolineaments observed by multiple analysts, on multiple scales of imagery, and/or during multiple observational trials. Such an approach is demanded by the inherent subjectivity of photolineament data collection (Wise, 1982); approximately 30 percent or less of photolineaments observed on an image are seen in the same place with the same orientation by different analysts (Mabee *et al.*, 1990; Podwysocki, 1974). Data sets developed with this approach, however, typically contain thousands of photolineaments for all but small study areas (<500 acres). Such large data sets require computerized analytic methods for practical process times.

Two analytic methods known by the author are considered viable for processesing large lineament data sets: (1) a double filter process resulting in relatively few photolineaments (Mabee *et al.*, in press), and (2) the photolineament factor method described in this paper. Both methods can be used simultaneously for two different and complimentary products: (1) discrete "*fracture-correlated coincident* photolineaments" (Mabee *et al.*, in press), and (2) a contour map of photolineament factor values which enables identification and ranking of sub-areas of interest (this paper).

The new computerized method described in this paper is appropriate for analysis of large photolineament data sets. Results of this method facilitate ranking of discrete areas with regard to their potential ability to store and transmit groundwater. It is assumed that three characteristics allow such ranking: (1) the number of photolineaments, (2) the number of directional photolineament families, *and* (3) the total length of photolineaments which occur within or traverse an area of defined radius. The normalized sum of these three parameters is the photolineament factor value. The occurrence of numerous photolineaments suggests the linear features have a "strong expression," that is, they are reproducible or "real." Many directional families suggest there are numerous intersections of photolineaments. A large total length suggests the features are aerially extensive and, therefore, likely to be intercepted by other linear features.

The computer program derives photolineament factor

Photogrammetric Engineering & Remote Sensing,
Vol. 61, No. 6, June 1995, pp. 739–747.

0099-1112/95/6106–739$3.00/0

Emery & Garrett Groundwater, Inc., 170 Waukewan Street, Meredith, NH 03253.

values for each node in a square grid comprised of partially overlapping collection circles (the grid covers the entire study area). Gaussian curves are fit to normalized azimuth frequency histograms of the photolineaments to derive the number, trend, and relative prominence of directional families at each node (based on an algorithm of Wise *et al.* (1985)). The method described is designed to rapidly and semi-quantitatively isolate areas of interest and is most applicable to large study areas such as towns and counties. A 900 km^2 study area in the Georgia Piedmont illustrates this new method. It is important to note that areas with *low* photolineament factor values are also revealed. These areas may be relatively less fractured and less likely to transmit groundwater and, therefore, could be potential targets for land uses such as waste disposal.

Method

Photolineaments are drawn on different scale aerial photographs and/or satellite images, digitized into a computer, and then the computer program is used to generate a contour map of photolineament factor values.

Photolineament Data Collection

Photolineaments observed through oblique and stereoscopic viewing are drawn on clear acetate overlays placed on aerial photographs and/or topographic maps. Coverage extends at least one average photolineament length beyond the study area boundaries to insure complete coverage. Numerous scales of photographs are typically used so as not to miss features which may be scale dependent (Table 1), but two or three scales of imagery analyzed two or more times each is another way of developing a large database of photolineaments (Mabee *et al.*, 1990). Once drawn, register points are identified on each image, and the end points of each photolineament are digitized into a computer. Each photolineament is described by its length, azimuth (in degrees east of north), and the latitude and longitude of each of its two end points. To draw and digitize photolineaments is the most time consuming portion of the photolineament analysis described in this paper. It is common to spend 1 to 2 hours drawing and another hour digitizing photolineaments for *each* photograph. There may be many photographs of a particular scale to cover large study areas. At this time, only straight photolineaments are considered.

Limitations of Photolineament Data

The accuracy of the geographic location of each photolineament is proportionally lower on proportionally smaller scale photographs because the photographs cannot be registered exactly to geographic coordinates and there are slight photographic aberrations due to lens curvature, airplane pitch, and photographic edge effects (Table 2). Trend accuracy is about $\pm 1°$ assuming a location accuracy of ± 0.5 mm on the photograph register points and photolineament end points (Table 2). Zoom-Transfer Scopes can be used to correct for some of these inaccuracies, but the large time involved to transfer each photolineament is prohibitive for large data sets. To mitigate the inaccuracies mentioned, the photolineament factor method is designed as a "first-cut" tool to isolate areas, not specific (drilling) targets.

Analyses of photolineament density (number per area) are biased by photolineaments observed on larger scale images because more photolineaments are generally observed on larger scale images within a given area. However, there is not a simple relationship between the number of photolineaments observed and the scale of the image, because of differences in image type, image clarity, land use, etc. (Table 3). This bias towards larger scale photolineaments, however, translates into a constructive bias towards photolineaments which are more accurate in geographic position when analyzing a photolineament data set collected from different scales of imagery (Tables 2 and 3).

Table 1. Typical Scales of Imagery Used in Photolineament Analysis

Scale	Image	Feature
1:24,000	Topographic map	Topographic lineaments
1:58,000	CIR* aerial photograph	Photolineament
1:80,000	B&W** aerial photograph	Photolineament
1:130,000	CIR aerial photograph	Photolineament
1:250,000	B&W photomosiac of SLAR*** images	Photolineament
1:1,000,000	B&W photograph of side illuminated, raised plastic relief map****	PseudoLandsat photolineament

*CIR = color infrared ** B&W = black and white *** SLAR = Side Looking Airborne Radar **** Wise and Grady, 1985

Of course, the results of any analysis are dependent upon the nature of input data. In the case of photolineaments, the photolineaments must be correlated with features in the bedrock if they are to be used as indicators of such. In the photolineament factor method, input data can be preprocessed or input untouched. Pre-processing should focus on filtering out those photolineaments which cannot be correlated with bedrock features, such as those which reflect cultural features: i.e., powerlines, roads, human-made drainage ditches, etc. If comprehensive data on the bedrock's fabric elements exist, which will only be available in environments where bedrock is nearly everywhere exposed, then the photolineament data can be filtered to include only those photolineaments with trends that match the trends of bedrock fabric features.

In all studies, correlation must be sought to justify use of any photolineament analysis results. Correlation is generally a two-step process of comparison between trends of photolineaments and bedrock structural fabric data elements: (1) rose diagrams are generated for photolineament data based on different sub-groupings of the data set (i.e., cumulative, within various radius sub-areas around mapped outcrops, those photolineaments that are underlain by specific rock types and/or geologic settings, etc.), and (2) specific photolineaments which traverse exposed bedrock are compared with mapped structures.

Photolineament Factor Algorithm

To quantify the degree to which bedrock in a given location may be fractured or contain other discontinuities such as fault zones or pronounced differential weathering along compositional layering, three photolineament parameters are assessed: the number of photolineaments, the number of directional photolineament families, and the total length of photolineaments. The normalized sum of these three parameters is defined as the photolineament factor value. The occurrence of numerous photolineaments suggests the linear features have a "strong expression," that is, they are reproducible or "real." Many directional families suggests there are numerous intersections of photolineaments. A large total length suggests the features are aerially extensive and, therefore, likely to be intercepted by other linear features.

TABLE 2. ACCURACY OF PHOTOLINEAMENTS FROM DIFFERENT SCALE IMAGES

Scale	Approx. Average Length of Photolineaments*	Approx. Trend Accuracy	Approx. End Point Location Accuracy
1:58,000	2.0 km	±0.8°	±29 m
1:80,000	2.5 km	±0.85°	±40 m
1:130,000	4.0 km	±0.9°	±65 m
1:250,000	9.0 km	±0.75°	±125 m

* based on 95 percent level on a probability versus length plot of the photolineaments from each scale of image.

Initially, a study area is divided into a number of nodes in a square grid (Figure 1). Each node is the center of a circle of specified radius for collection of photolineament data. (A circle is used instead of a square, because square collection areas are inaccurate due to the unequal distances from the center of the square to different points along its edges.) The spacing of the nodes and the radius of the circles varies with each study area and photolineament data set. Generally, these are chosen so that the circles overlap neighboring circles by 30 percent to 50 percent in area to smooth the data by area averaging (similar to many other contouring algorithms). In addition, to yield meaningful statistics for the number of directional families (Wise, pers. comm., 1985), the radius of the collection circle is selected through trial and error so that an average number of ≈15 or more photolineaments pass through the collection circles.

To calculate the number of directional families, a rose diagram is constructed at every node in the grid. Each family is defined by separate "rose petals" with heights ≥ 50 percent of the tallest petal (normalization makes the tallest peaks of each rose diagram = 100 percent). The "cut-off" height of 50 percent is arbitrarily selected, but ensures use of only those directional families which are prominent. Rose diagrams are constructed using an algorithm which fits Gaussian curves to normalized azimuth frequency histograms of the photolineament data (Figure 2; Wise *et al.*, 1985).

After values have been derived for the three parameters at all nodes, each parameters values are normalized using the average value for that parameter. The average value is based on that parameter's range within the study area. Normalization enables independent weighting of each parameter. The normalized values for each of the three parameters are then added together for a single sum value referred to as the photolineament factor value (Figure 1). Each of the normalized values are weighted independently during the summation step to facilitate enhancing one or more parameters which may be thought to be more or less important in terms of a study's objectives. For example, if long photolineaments are thought to be the most significant parameter, then the normalized value for photolineament length can be multiplied by some constant, such as three, then summed with the other two parameter values, each multiplied by only one. Photolineament factor values are plotted at each node in the grid and contoured to aid in visualization and selection of discrete areas for further evaluation (Figure 1).

Other weighting scenarios and variations on the photolineament factor algorithm are currently being explored. For example, specific trends may be suspected to be more important to the groundwater system than others based on field work, such as identification of brecciated brittle fault zones which consistently trend north and northeast. Nodes with photolineament families with these trends could be positively weighted to help reveal areas containing large numbers of photolineaments with such trends. Another consideration possibly important for weighting photolineament data are the regional, resolved normal stresses on the vertical planes assumed to be represented by the photolineaments. Those with the least amount of resolved normal stress are most likely to be "open" and therefore potentially capable of storing and transmitting appreciable amounts of groundwater. For example, if the regional stress field is dominated by west-directed, horizontal compression, then those planar elements in the bedrock detected as photolineaments which trend east-west have the least amount of resolved normal stress (zero, in fact, if they are collinear with the compression direction) as compared to features with different trends. Qualification of the relevance of any of these weighting scenarios can, in part, be achieved through comparison of contour maps of photolineament factor values with both existing well data and by actual drilling of test wells. Such qualification is currently underway; preliminary results are presented below.

All software used runs on a PC under the DOS operating environment. A modified version of USGS' GSMAP software is used to digitize the photolineaments. Photolineament analysis software is based in part on the work of Wise *et al.*, (1985) and incorporates a Gaussian curve-fitting algorithm written by F. Salvini. Earlier versions of this software for domain analysis *without* the photolineament factor algorithm were developed by D. Wise, S. Mabee, and the author. Processing a 100 by 100 grid and a file of 10,000 lineaments requires about 10 minutes on a 486 machine. Contouring is done by Schrieber's QUICKSURF and final map products are in Autodesk's AUTOCAD.

Example

A recent study of groundwater resources in Cobb County, Georgia, (about 900 km² area) utilized the described photolineament factor algorithm as one component of its exploration program (Emery & Garrett Groundwater, Inc., report, 1991). The study showed that there is very good correlation between the trend of photolineaments and both foliation and tectonic fracture families on both local and county-wide scales which justified use of photolineaments and the photolineament factor algorithm to identify areas of interest. These areas were then evaluated in detail for their groundwater potential.

Setting

Cobb County is underlain by unglaciated, multiply deformed, crystalline rocks (Hurst, 1956; Higgins and McConnell, 1978). Regional layering and foliation trends northeast but varies locally. Key fracture family trends identified are, in order of prevalence: 92°, 116°, 145°, 68°, 43°, 24°, and 2° (all

TABLE 3. NUMBER OF PHOTOLINEAMENTS OBSERVED ON DIFFERENT SCALE IMAGES FOR A 900-KM² STUDY AREA

Scale	n	n>300 m
1:24,000	9210	5527
1:58,000	4529	4506
1:80,000	2885	2885
1:130,000**	2146	2146
1:250,000**	868	868
1:1,000,000**	75	75

** all photolineaments within 20 km of the center of the study area which, therefore, results in slightly larger numbers because the collection area includes some area not covered by the larger scales.

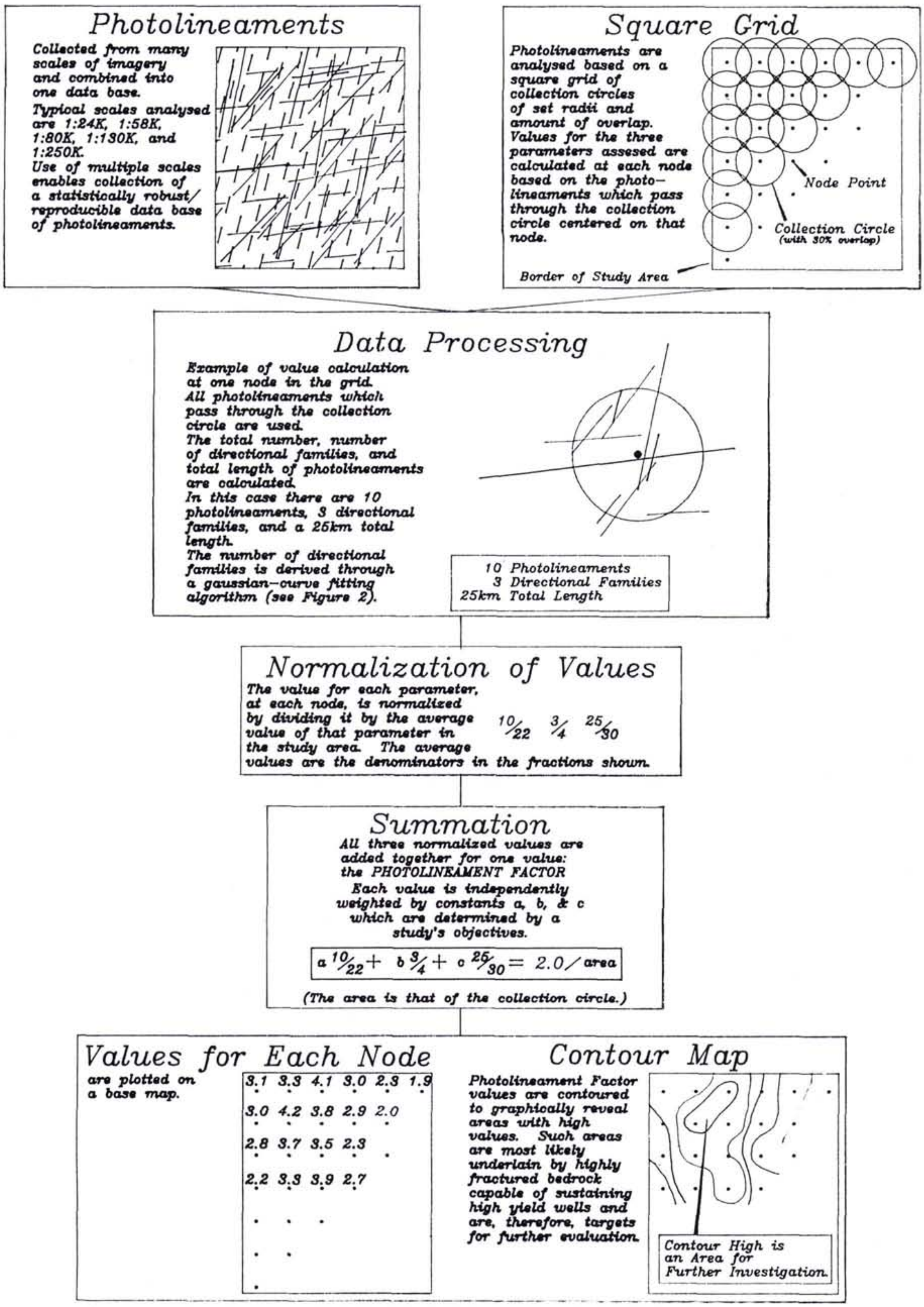

Figure 1. Schematic flow chart for the computer-aided method of deriving photolineament factor values for contour maps.

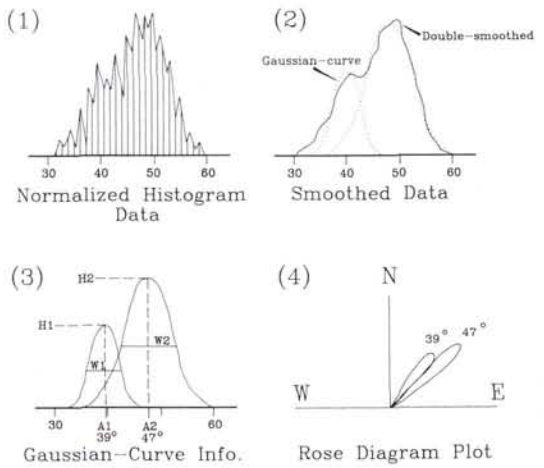

Figure 2. Description of Gaussian curve-fitting algorithm which determines the trend, width, and relative height of directional families. (1) Normalized data from 30°-60° portion of a histogram (normalization makes the maximum peak on all histograms have the same height). (2) Same data smoothed by twice passing a 10° running average over the data with Gaussian curves for comparison. (3) Gaussian curves fit to the smoothed data with centerpoint/azimuth (A1, A2), peak height (H1, H2), and width at half-height (W1,W2) for each gaussian noted. (4) Same curves as in (3) but plotted in rose diagram form. Modified after Wise *et al.*, 1985.

directions in degrees east of north). These trends are defined by the synoptic, Gaussian-curve-based rose diagram of 1432 fractures measured in detail at about 100 outcrops scattered throughout the County. The 43° and 68° trends include both fractures and layering/foliation of the host rocks. The latter can represent discontinuities related to locally well developed differential weathering along compositional layering which can have significant impacts on groundwater systems (Crawford, pers. comm., 1991). These seven trends are matched or overlapped by the trends of photolineament families (EGGI report, 1991). As expected, this correlation is best at the local scale where comparison is made between fractures recorded in outcrops and the photolineaments that occur within 2 km of the outcrops studied (EGGI report, 1991; Hardcastle, 1992). The local scale of 2 km is used for comparison because fracture families can differ in outcrops separated by as little as 2 km in the County based on the available data (EGGI report, 1991). Detailed discussion of the fracture fabric, bedrock geology, and correlation of these with photolineaments is offered elsewhere (EGGI report, 1991).

Photolineament Factor Analysis

The correlation documented between photolineaments and bedrock fractures/discontinuities supported using the photolineament factor method. Results of the photolineament factor analysis helped locate areas presumably underlain by highly fractured bedrock and/or bedrock containing numerous or pronounced discontinuities which might be favorable for groundwater development. All 1:24,000-, 1:58,000-, and 1:80,000-scale photolineaments greater than 300 m in length ($n \approx 13{,}000$) were processed for photolineament factor values using a 300-m radius collection circle overlapping 30 percent. These photolineament data were used because they represented the three largest of six scales of imagery analyzed and, therefore, have the highest geographic accuracy (better than about ± 40 m). No pre-processing was conducted to remove the few photolineaments which represent cultural features. In the unglaciated crystalline terrain of the central and southern Appalachian Mountains, east coast of North America, photolineament data are used by the author without pre-processing. This simplification is thought justified because: (1) the relatively few photolineaments which reflect cultural features "fall out" statistically, unaffecting results (Hardcastle, unpublished data); and (2) studies of correlation show that most photolineaments do match fabric elements measured in the bedrock (Hardcastle, 1992). Average values in the collection circles for the number of photolineaments, number of directional families, and total length of photolineament were 19, 4, and 26 km, respectively. The three photolineament parameters were evenly weighted. Derived photolineament factor values were contoured and plotted on mylar for superposition on the USGS 7$^1/_2$-minute topographic maps of the quadrangles which covered the study area. Approximately 70 areas with relatively high photolineament factor values were identified in this 900-km2 study area (EGGI report, 1991).

One of the eight quadrangles which covered part of the study area is used for illustration of the photolineament data and results of analysis with the photolineament factor algorithm. Photolineaments in this quadrangle reveal a prominent northeast-trending fabric which occurs in a northeast-trending swath (Figure 3a). This swath is underlain by a layered package of variably erosionally resistant quartzites, gneisses, and schists (Higgins and McConnell, 1978). Simple visual evaluation of these photolineament data would generally result in focus on the pronounced fabric in the area of the northeast-trending swath. The photolineament factor method, however, reveals areas of potential interest throughout the quadrangle (Figure 3b). The numeric values of the contours enable quantitative ranking of these areas.

As expected, areas with high photolineament factor values occur in regions of intersections and along second and higher order streams. The non-glaciated, crystalline bedrock in the region is characterized by a rectilinear drainage pattern (Cressler *et al.*, 1983) which is thought to reflect the erosional control imparted by fracture systems and differential weathering of layering in the bedrock.

A few contour highs occur along drainage divides because of the greater than average number of photolineaments and number of directional families of photolineaments which begin or terminate in these areas (Figure 4). Weighting the parameter for photolineament length in the photolineament factor algorithm removes these "anomalous" high value areas (Hardcastle, unpublished data). The areas identified with high photolineament factor values are sometimes obvious and also not so obvious on the topographic map, but are clearly shown and therefore can be ranked objectively based on the photolineament factor value contours (Figure 4).

It must be emphasized that areas with high photolineament factor values are not necessarily areas with large groundwater resources nor are they specific drilling targets.

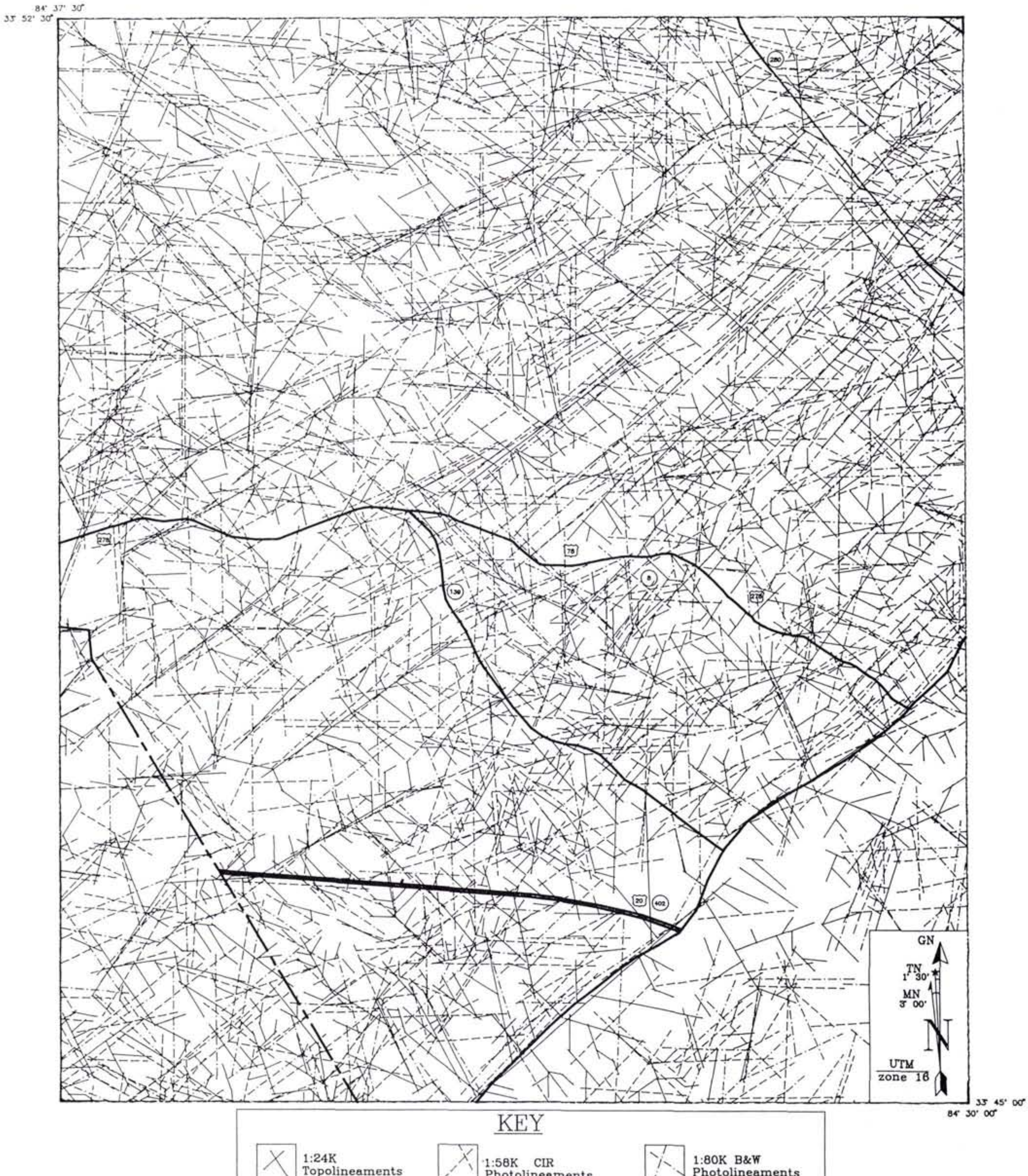

Figure 3. (a) Raw photolineament data for one of eight 7½-minute quadrangle map areas which cover the example study area.

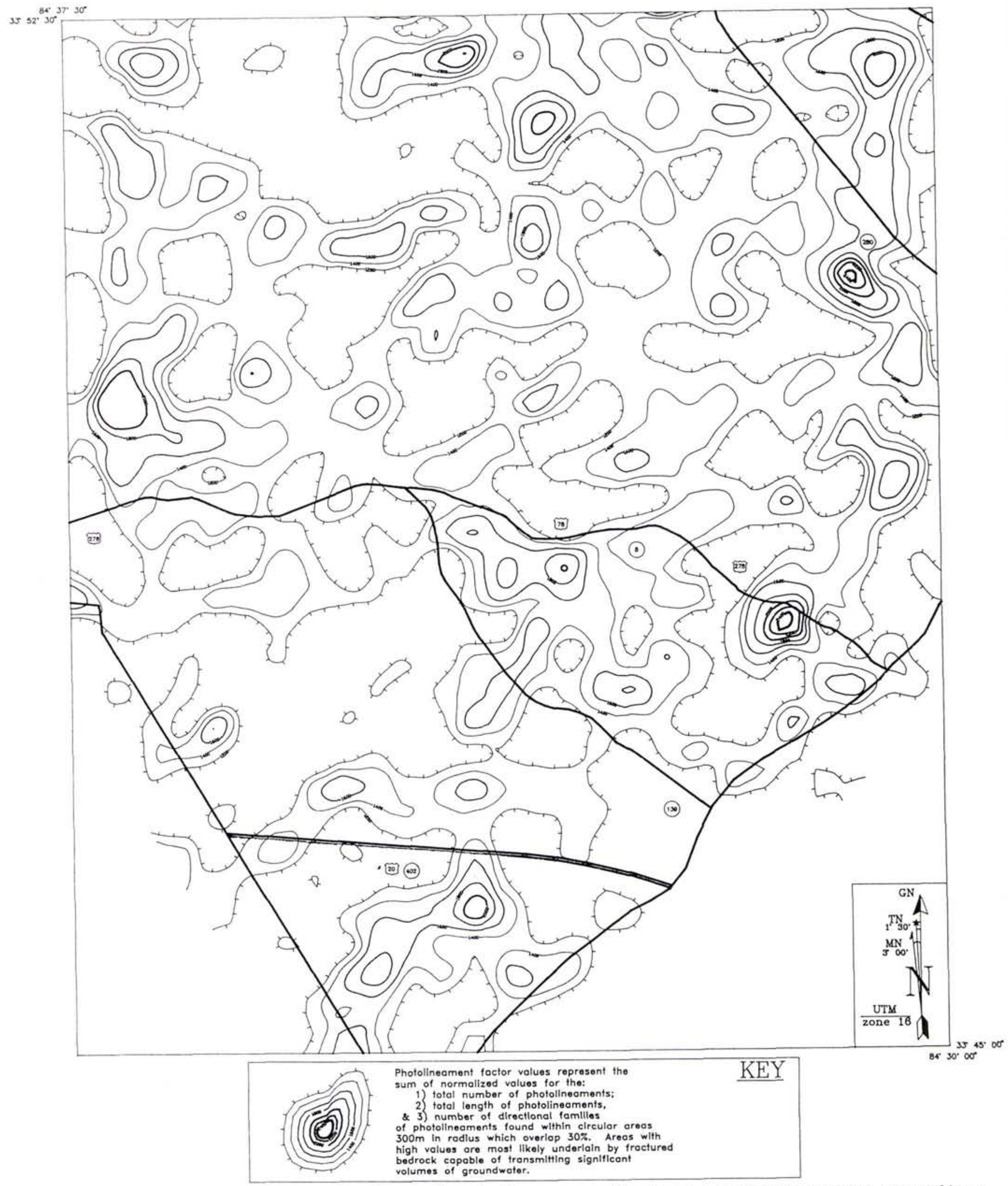

Figure 3. (b) Contour map of photolineament factor values for the same quadrangle area, graphically revealing areas of interest.

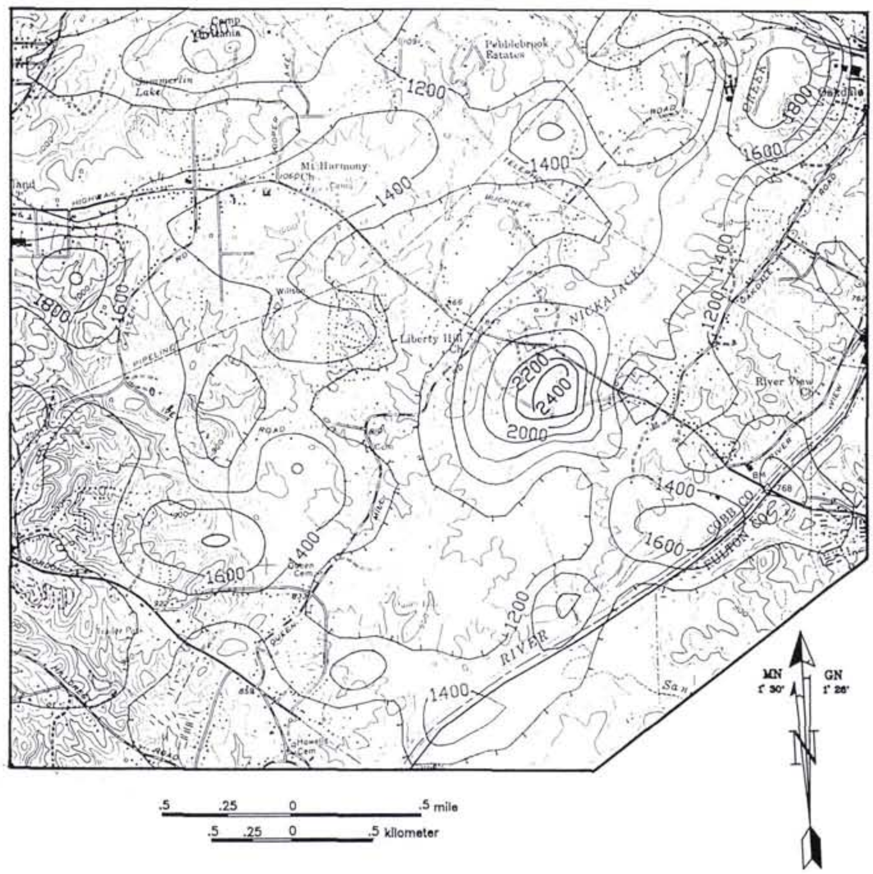

Figure 4. Portion of the photolineament factor contour map (Figure 3b) superimposed on a portion of the USGS 7½-minute topographic map of the quadrangle. Contours facilitate rapid, quantitative separation of discrete areas of interest. Note the high values along parts of the Chattahoochee River and Nickajack Creek, especially where the Creek makes abrupt changes in direction. These areas are targets for detailed investigation of their groundwater potential.

Many of the 70 areas with the relatively high photolineament factor values identified were later deemed unsuitable for groundwater resource test well drilling because of inappropriate land use, low recharge characteristics, poor yielding bedrock type, and/or other hydrogeologic concerns (EGGI report, 1991). Specific drilling targets are not identified with the photolineament factor method because of the nature of the algorithm, the location inaccuracies of the photolineament data, and, in this study, the use of collection circles with 300-m radii.

Thirty-three of the areas identified, however, were deemed "favorable" based on detailed hydrogeologic evaluation of their potential to yield groundwater and were recommended for testing to the Cobb County-Marietta Water Authority (EGGI report, 1991). Geophysical analyses and test well drilling are currently underway in a number of these "favorable areas." Preliminary results in one such "favorable zone" is a combined air-lift yield in excess of 1,000,000 gpd (gallons per day) from three of three wells drilled. This volume of groundwater greatly exceeds that produced by most wells in the region.

Summary

Three photolineament parameters are thought to indicate the degree to which bedrock may be fractured and, therefore, provide a guide for selecting discrete areas where groundwater resources may exist: (1) the number of photolineaments, (2) the number of directional photolineament families, *and* (3) the total length of photolineaments. The normalized sum of these three parameters, calculated for photolineaments which occur within or traverse an area of defined radius, is termed here as the photolineament factor value. A new computerized algorithm facilitates rapid processing of the large photolineament data sets ($n >> 1000$) typically collected for studies of regional groundwater resources (> 10 km^2 or 2500 acres). The resulting contour map enables quantitative ranking and selection of discrete areas for further evaluation.

Acknowledgments

Numerous people have contributed to the ideas and computer programs discussed in this paper. I wish to thank S. Mabee, D. Wise, F. Salvini, and L. Hills for their significant inputs in software programming. S. Mabee, J. Emery, D. Tinkham, and J. Brooks are also appreciated for illuminating and thought provoking discussions and for reviews of early versions of this manuscript. Thanks are also extended to two anonymous reviewers. Use of the sample data from Cobb County, authorized by P. Karr of the Cobb County-Marietta Water Authority, is greatly appreciated.

References

Alpay, A.O., 1973. Application of Aerial Photographic Interpretation to the Study of Reservoir Natural Fracture Systems, *Jour. of Pet. Technology*, 25(1):37-45.

Blanchet, P.H., 1957. Development of Fracture Analysis as an Exploration Method, *Am. Assoc. Pet. Geol. Bull.*, 41:1748-1759.

Caswell, W.B., D.B. Hill, and M.F. Eichler, 1986. *Lineaments, High-Yield Bedrock Wells, and Potential Bedrock Discharge Areas in the Maine Portion of the Portland and Bath 2-Degree Sheets*, Open-File Rep. No. 86-67, Maine Geol. Survey.

Cressler, C.W., C.J. Thurmond, and W.G. Hester, 1983. *Ground Water in the Greater Atlanta Region, Georgia*, Georgia Geological Survey Information Circular 63, Georgia Geologic Survey, Department of Natural Resources, Environmental Protection Division, Atlanta, Georgia.

Emery and Garrett Groundwater Inc (EGGI), 1991. *Groundwater Exploration and Development Program, Phase I, Vol. 1*, submitted to the Cobb County Marietta Water Authority, Cobb County, Georgia, 98 p.

Hardcastle, K.C., 1992. Correlation of Lineaments and Fracture Fabric in the Piedmont: Implications for the Study of Fractured Bedrock Aquifers, *So. East. Geol. Soc. Amer., Abs. and Prog.*, 24(2):19.

Higgins, M.W., and K.I. McConnell, 1978. The Sandy Springs Group and Related Rocks of the Georgia Piedmont: Nomenclature and Stratigraphy, *Short Contributions to the Geology of Georgia*, Georgia Geol. Survey, Bull. 93, pp. 50-55.

Hurst, V.J., 1956. *Geologic Map of Kennesaw Mountain-Sweat Mountain area, Cobb County, Georgia*, Georgia Geol. Survey Map RM-2, 1:24,000 scale.

Lattman, L.H., 1958. Technique of Mapping Geologic Fracture Traces and Lineaments on Aerial Photographs, *Photogrammetric Engineering*, 24:568-576.

Lattman, L.H., and R.R. Parizek, 1964. Relationship between Fracture Traces and the Occurrence of Ground Water in Carbonate Rocks, *Jour. of Hydrology*, 2:73-91.

Mabee, S.B., 1992. *Lineaments: Their Value in Assessing Groundwater Availability and Quality in Bedrock Aquifers of Glaciated Metamorphic Terranes - A Case Study*, PhD dissertation, Univ. of Massachusetts, 567 p.

Mabee, S.B., K.C. Hardcastle, and D.U. Wise, 1990. Correlation of Lineaments and Bedrock Fracture Fabric: Implications for Regional Fractured-Bedrock Aquifer Studies, Preliminary Results from Georgetown, Maine, *Proc. FOCUS Conf. on Eastern Reg. Groundwater Issues*, (3):283-297.

———, in press. A Method of Collecting and Analyzing Lineaments for Regional-Scale Fractured-Bedrock Aquifer Studies, *Groundwater*.

Podwysocki, M.H., 1974. *An Analysis of Fracture Trace Patterns in Areas of Flat-Lying Sedimentary Rocks for the Detection of Buried Geologic Structure*, NASA publication X-923-74-200, Goddard Space Flight Center, Greenbelt, Maryland, 67 p.

Rich, J.L., 1928. Jointing in Limestones as Seen from the Air., *Amer. Assoc. Pet. Geol. Bull.*, 12(8):861-862.

Siddiqui, S.H., 1969. *Hydrogeologic Factors Influencing Well Yields and Aquifer Hydraulic Properties of Folded and Faulted Carbonate Rocks in Central Pennsylvania*, Ph.D. Dissertation, The Pennsylvania State University, 502 p.

Wise, D.U., 1982. Linesmanship and the Practice of Linear Geo-Art, *Geol. Soc. Amer. Bull*, 9:886-888.

Wise, D.U., and L.T. Grady, 1985. *Topography of the Southern Appalachians*, Dept. of Geology and Geography, University of Massachusetts.

Wise, D.U., R. Funiciello, M. Parotto, and E. Salvini, 1985. Topographic Lineament Swarms: Clues to their Origin from Domain Analysis of Italy, *Geol. Soc. Amer. Bull.*, 96:952-967.

Wobber, F.J., 1967. Fracture Traces in Illinois, *Photogrammetric Engineering*, 33:499-506.

Yin, Z.Y., and G.A. Brook, 1992. The Topographic Approach to Locating High-Yield Wells in Crystalline Rocks: Does it Work, *Groundwater*, 30:96-102.

(Received 15 April 1993; accepted 16 June 1993; revised 12 August 1993)

Kenneth C. Hardcastle

Ken Hardcastle is a structural geologist with Emery and Garrett Groundwater, Inc., specializing in the development and protection of groundwater resources. Current research focuses on the interpretation and utilization of data collected at bedrock exposures and from aerial and digital images. Primary studies of tectonics and the occurrence and movement of groundwater are in the eastern United States. He received his doctoral degree from the University of Massachusetts at Amherst in 1989.