Hydrogeologic Significance of the Correlation Between Well-Yield Variography and Multiscale Bedrock Geologic Structures

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Abstract

A spatial analysis of ground-water yields has been performed that expands upon previous work by Drew and others (1999) in which the spatial continuity of 939 water well yields within the Pinardville quadrangle, New Hampshire, has been associated with the fracture properties of the crystalline basement rocks. This expanded analysis was performed on updated and new geologic map data, new fracture set data and analyses, and a set of water well yields that was expanded by 752 newly located well to1,691wells. Variogram mapping of the water well yields formed the basis for the synthesis of the spatial continuity in well yield with the geological data. A variety of associations were found that directly relates the spatial properties of well yields to the characteristics and structure of the crystalline bedrocks in the quadrangle.

Introduction

A variogram map is a two-dimensional portrayal of the directional spatial continuity of a regional variable. In this paper, the yields of water wells drilled into the fractured crystalline rock are treated as regional variables and are analyzed by using variogram maps. Interpretation of the patterns of anisotropy that have been seen in variogram maps of the yields of water wells has been associated with fracture patterns mapped in the bedrock and, consequently, with the tectonic history of the region (Drew and others, 1999). In the present analysis and interpretation of water-well yields, variogram maps and variograms of the Pinardville quadrangle, New Hampshire, as shown in figure 1, have been compared with frequency-azimuth plots of fractures within the crystalline rocks in close proximity to the well data.

Geologic Framework

Rock units within the Pinardville quadrangle consist of highly variable

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metamorphosed sedimentary and igneous types, as well as postmetamorphic granites and pegmatite (figure 1). Although the spatial extent and distribution of individual rock units are highly variable, they can be grouped into two major tectonic units. The Central Maine Belt (CMB) consists of complexly intercalated pelitic, psammitic, and calc-silicate metasedimentary rocks of Silurian age intruded by metaigneous granite of Devonian age. All these rocks were multiply deformed and metamorphosed to sillimanite-muscovite grade during the Devonian Acadian Orogeny and then again during the Permian Alleghenian Orogeny (Armstrong and others, 1999a, b). The Massabesic Gneiss Complex (MGC) consists of Late Proterozoic age paragneiss with frequent stringers or pods of hornblende-bearing amphibolite that are also presumed to be Late Proterozoic in age, Cambrian to Late Proterozoic age felsic layers that are interpreted to be as dikes, and local swarms of Permian pegmatite and granite that were deformed and metamorphosed in at least the Acadian and the Alleghenian Orogenies. No demonstrable evidence exists for either Late Proterozoic deformation or metamorphism, although neither can be ruled out. In addition, much of the original Late Proterozoic gneiss underwent subsequent migmatization during Permian high-grade metamorphism (sillimanite-orthoclase-muscovite grade) so that at least 50 percent of the surface exposure of the MGC is Permian migmatite granitoid. Although migmatization almost completely reconstituted the host paragneiss in these zones, many relict biotite-rich pods or layers (restite) contain intact vestiges of the original gneissosity in its premelt orientation.

These two different tectonic units, or terranes, are separated by a Permian transpressional, ductile fault zone—the Powder Hill. Rocks of the CMB occur to the north of the east-northeast-trending fault. Rocks of the Massabesic Gneiss Complex MGC occur to the south. Fault fabric relations and kinematic analysis show that the MGC moved to the northeast and up (present coordinates) with respect to the CMB along the transpressional fault system (Armstrong and others, 1999b). Metamorphic phase equilibria and geothermobarometry from both belts indicate that the MGC moved into juxtaposition with the CMB at a depth of approximately 15 to 18 kilometers (km) below the Earth's surface from an original crustal depth of about 25 to 30 km (Larson and Laird, 1999). This estimate is consistent with the mapping and field observations of Armstrong and others (1999a, b), which show that Permian melt-related textures are very widespread in the MGC, especially when compared with the paucity of such textures in the CMB, and were related to the obliteration of much of the CMB's preexisting ductile anisotropy.

We will use the grouping of rocks into the MGC and the CMB terranes for statistical analysis and comparison of deformation fabrics and ground-water well yield throughout the rest of the paper.

Brittle Fabric

Currently, we are collecting information that shows that preexisting anisotropy in crystalline rocks, in particular foliation, plays a very important role in the style and

Description

q	Permian to Mesozoic silicified zones
Paleozoic intrusive rocks	
Pdg	Damon Pond granite
Ppg	Granite and pegmatite
Dp	Pegmatites
Dsg	Spaulding Granite
Rangley Formation (Silurian)	
Srmg	Migmatite schist and gneiss
Sr	Light gray biotite-muscovite schist
Srlb	Layered biotite granofels
Srcs	Layered calc-silicate and granofels
Srr	Rusty biotite-muscovite schist
Srb	Biotite schist and granofels
Massabesic Gneiss Complex (Late Proterozoic to Permian)	
PDmg	Migmatite gneiss
PZmg	Layered migmatite and restite
Zmlg	Layered paragneiss and orthogneiss
Zma	Amphibolite gneiss

Strike-slip fault

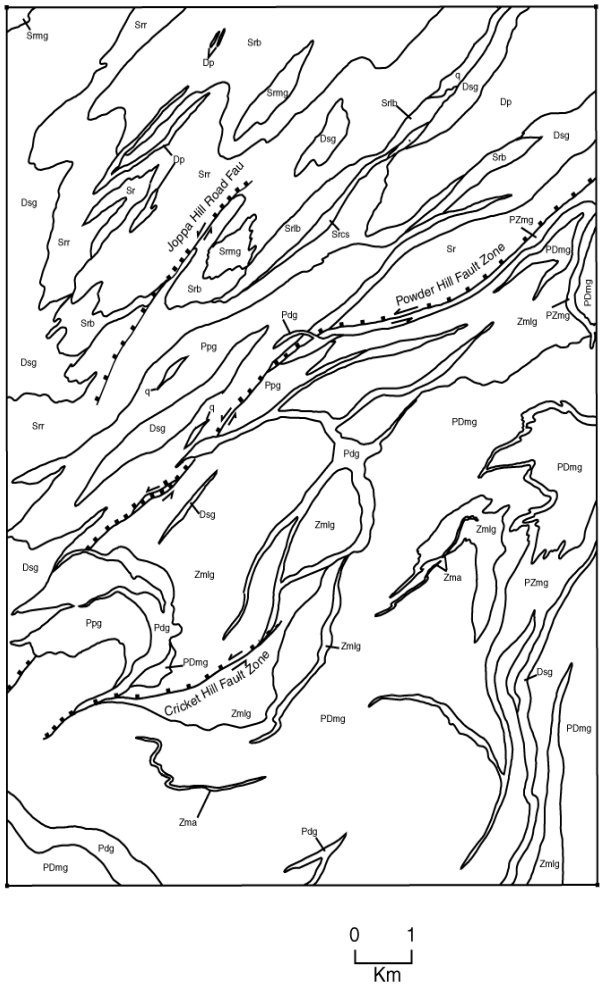

Figure 1. Geologic map of the Pinardville quadrangle, New Hmapshire (from Armstrong and others, 1999b).

frequency of subsequent brittle fracture evolution. Because these fractures are the primemovers of ground water in crystalline rock terranes, an intimate knowledge of the geometries and styles of ductile foliation (the anisotropy) in different rocks is extremely important for developing a regional perspective of how fractures form and are distributed in the different rocks and terranes under study and how the different fracture networks control ground-water behavior. In the Pinardville quadrangle, the two different terranes contain very different fracture patterns that are believed to be a function of contrasting ductile fabric histories.

Fractures Within the Central Maine Belt

Within the CMB, metasedimentary rocks dominate and are highly layered with pervasive layer-parallel foliation. Subsequent brittle fracture evolution, mostly during extensional tectonics in the Triassic and Jurassic and related to the rifting and opening of the Atlantic Ocean, utilized the preexisting ductile anisotropy. As a consequence, the CMB is dominated by steep dipping foliation parallel joints and cross-joints normal to foliation. Locally, this pattern is obfuscated by pervasive and discreet zones of fractures that are parallel to 1- to 2-meter (m)-thick Mesozoic lamprophyric dikes. These zones, however, are short ranged in trace length (10-50 m) and appear to have no significant long-range connectivity with each other or with the more-regional foliation parallel (and normal) system. Granite bodies within the CMB locally contain shallow-dipping fractures, which are less than 45 degrees and known as sheeting fractures. These fractures tend to be more widely spaced and infrequent in areas where they cut the older ductile foliation at a high angle. In areas where the foliation is nearly parallel (and shallow dipping), the sheeting fractures are more closely spaced and abundant. This relation further emphasizes the profound role that preexisting ductile foliation plays in the subsequent development of fractures and their control on ground-water behavior.

Fractures Within the Massabesic Gneiss Complex

In contrast to the CMB, preexisting ductile anisotropy in the MGC is restricted to vestiges of the gneissosity not completely destroyed by high-temperature and high-pressure metamorphic melting processes, which are known as migmatization. Regional Permian migmatization and wholesale melting of the MGC created a textural homogenization of the Complex that is believed to be the primary reason for the evolution of very different fracture patterns compared with those of the CMB. Along with the northeast-trending fractures that may be parallel to and thus utilize relict vestiges of the ductile fabric (similar to the strong foliation-parallel anisotropy in the CMB), the MGC contains well-developed, north-trending, steep dipping fractures. In addition, the MGC contains spatially limited northwest- and east-west-trending fractures at few localities. Overall, the northeast-trending orientation is most common for the steep-dipping fractures measured in the MGC.

Also in contrast to the CMB, sheeting fractures are very common especially in the highly migmatized units of the MGC—migmatite gneiss (PDmg) and layered migmatites

restites (PZmg). Field-based structural analysis has shown that the majority of sheeting fractures in these units occur along the folded S1/S2 ductile foliation (gneissosity). Thus, for sheeting fractures to occur in this manner, the rocks must be fairly quartz-feldspar rich and must contain a relatively shallow preexisting planar anisotropy (foliation).

Because rocks of the PDmg and the PZmg units contain abundant quartz and feldspar from the migmatization of layered paragneiss and othrogneiss (Zmlg) rocks and still retain at least vestiges of the preexisting gneissosity, they commonly contain sheeting fractures in areas where the anisotropy is relatively shallow dipping. Thus, the majority of sheeting fractures within the Pinardville quadrangle occur within the MGC migmatite units and are well-constrained to the crest of the doubly plunging antiform where the anisotropy is subhorizontal. In areas where this anisotropy steepens, such as on the crest-to-limb transition of the structure, the sheeting fractures abruptly terminate.

In addition to the MGC migmatite units, Permian pegmatite and granite units within the MGC and along the Powder Hill Fault Zone, which is the within the MGC and the CMB rocks, also contain abundant sheeting fractures. According to Armstrong and others (1999a, b), these granites have intruded the MGC and the CMB rocks in close proximity to the developing transpressional fault systems. Thus, some parts of these granitoid bodies are highly foliated, whereas others are completely unfoliated. Thus, some of the sheeting fractures within these units follow the preexisting anisotropy, and others seem to mimic the trend and incline of local topographic features.

Hydrologic Framework

Beyond the spatial statistical analysis of private domestic wells, which is described below, little quantitative information is available regarding the hydrologic behavior of the ground-water system in this area. Suffice it to say that ground-water flow in crystalline rocks, which lack any primary porosity or permeability, is restricted to secondary porosity— the existing brittle fracture network. In particular, ground-water flow in these rocks is much like the flow of traffic on a regional road network—to get from one place to another at any significant distance, one often must resort to a circuitous route rather than a direct one. This is certainly true for this type of regional and most local ground-water flow. For water to travel any appreciable distance, a network of fractures with an appreciable amount of void space through which the water can move, vertically or horizontally or both, must be an effectively interconnected. First, water must enter the ground-water system through a series of steep-dipping fractures that connect with the recharge zones (the land surface or stream beds). Second, the fracture network must allow the lateral transfer of water across the area. This can occur through the movement of water along the intersection of two or more sets of steep-dipping fractures or steep-dipping fractures with sheeting fractures. In either case, the networks of intersecting fracture sets develop directions of preferred movement or spatial anisotropy.

Spatial Analysis of Private Domestic Ground-Water Wells

The goal of this study is to develop an internally consistent hydrogeologic framework by using the collected geologic and brittle-fracture data. These data can also be used to assess potential geologic anisotropy (layering, foliation, and fractures) on local (tens to hundreds of meters) and regional (kilometer) scales. This directional information will be compared with ground-water well-yield spatial anisotropy that has been estimated from exploratory statistical analysis and, in particular, variography. Similarities in directional results will allow us to make some observations regarding the geologic controls on ground-water behavior at different scales and to evaluate the utility of spatial statistical analysis of private domestic water well information in determining the nature of ground-water movement and communication in fractured crystalline rocks.

In Drew and others (1999), two-dimensional variogram maps of private domestic bedrock ground-water well yields were shown to contain information regarding the anisotropy of the continuity of well yields that were thought to be related to the tectonic fabric of the bedrock. Interpretations from this study were limited owing to the lack of detailed geologic information, especially fracture-fabric data, that would allow comparison with the variography. In this investigation, a more-detailed analysis is developed that uses recently acquired geologic data, such as a 1:24,000-scale geologic map, structural analysis, and fracture fabric analysis (Armstrong and others, 1999a, b). Also, another 752 wells were added to the water-well-yield data set from the previous study to improve the variogram computation.

Exploratory Statistics

Mean Yields by Rock Type

A detailed analysis of the exploratory statistics regarding well yield in the Pinardville quadrangle is treated in Drew and others (1999). Table 1 lists the mean yield for all private domestic wells north and south of the Powder Hill Fault separated by given rock types, low-yield wells [40 gallons per minute (gpm) or less] within the same rock types, wells grouped together within the CMB and the MGC terranes (north and south of the fault, respectively), and all wells within the Pinardville quadrangle.

The mean yield of all wells across terranes is somewhat higher in the MGC (15.6 gpm) than in the CMB (14.2 gpm) (table 1). A one-way analysis of variance, however, indicated that the difference in the means at the 5-percent significance level is not statistically significant. Within the individual terranes, average yields are slightly more variable. For example, within the MGC, the average yield ranges from 13.5 gpm in the PDmg rocks to 16.9 gpm in the Zmlg rocks.

Table 1. Mean yield by rock type and terrane

Rock unit (see figure 1)	Terrane	All wells			Low-yield wells		
		Mean yield	Standard deviation	Number of wells	Mean yield	Standard deviation	Number of wells
PDmg	MGC	13.5	21.0	664	8.3	8.4	607
Zmlg	MGC	16.9	23.3	325	9.6	8.8	285
Sr (all units)	CMB	15.1	21.9	311	8.9	7.9	277
Ppg/Pdg	Both	17.0	29.5	220	9.2	9.1	197
Dsg	Both	14.1	16.4	93	9.9	8.8	84
MGC	MGC	15.6	24.7	1,163	9.0	8.7	1,042
CMB	CMB	14.2	20.4	528	8.8	8.2	477
All Units	MGC and CMB	15.2	23.4	1,691	8.9	8.5	1,519

Variography

High-Yield Wells

Variogram maps for bedrock water wells were calculated for the different geologic units throughout the Pinardville quadrangle, as well as for subsets within the different units on different parts of the anticlinorium structure within the MGC. According to Drew and others (1999), the origin and distribution of 81 high-yield wells (40 gpm or more) appear to be controlled by a different set of geologic processes than low-yield wells (less than 40 gpm) (New Hampshire Department of Environmental Services, 1997). In addition, no spatial continuity was identified in the maps or in the directional variograms (Drew and others, 1999). Because the data base was expanded from 939 wells to 1,691 in this investigation, the number of high-yield wells has commensurately increased to 172. Inspection of the variogram map for these high-yield wells reveals little anisotropy (figure 2). Similarly, the omnidirectional variogram reveals little spatial continuity in the high-yield wells (figure 3). As yet, only anecdotal information points to an interaction between the characteristics of the surficial material above the fractured bedrock and the fracture system as influencing the flow of ground water for these high-yield wells. This material occurs in a variety of glacial facies, such as blanket tills and tills in drumlins and a various outwash facies. The large economic value of these high-yield wells would be served if their spatial occurrence could be better explained.

We will maintain the protocol established in Drew and others (1999) for the remainder of this investigation, which is based on nearly twice as many wells, new field mapping, and structural and fracture pattern data. This protocol consists of analyzing the spatial continuity of the low-yield wells independently of the high-yield wells. In the following discussions, we make reference to regional (scale) anisotropies in certain cases in which patterns within variogram maps appear to be directional at only large-lag values.

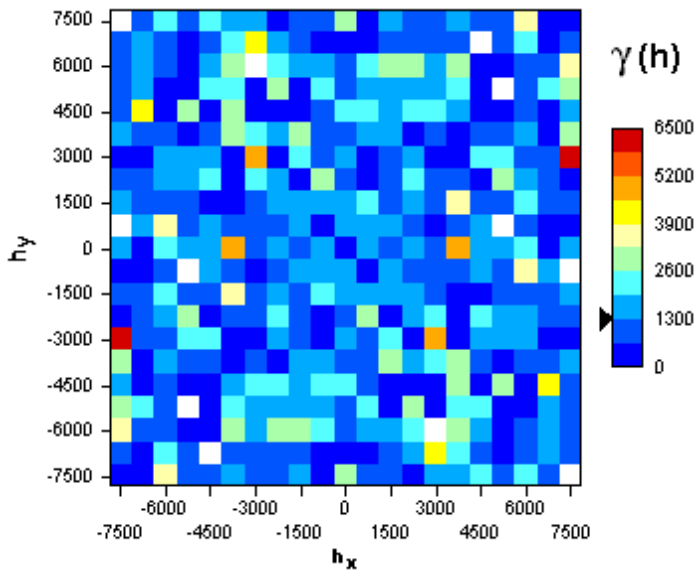

Figure 2. Variogram map for all high-yield wells.

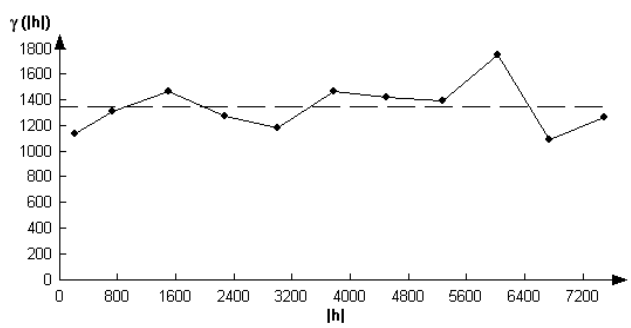

Figure 3. Omnidirectional variogram for all high-yield wells.

We discuss these occurrences only to suggest the potential structural implications with the understanding that the behavior of a variogram map can be subject to significant variability especially at large lags owing to data-pairing constraints.

Low-Yield Well Variography versus Rock Type

The Powder Hill Fault is a regional-scale ductile fault along which the CMB and the MGC terranes have been juxtaposed (figure 1). Northwest of this fault, the bedrock consists of middle-grade metamorphic rocks and granite (CMB). Southeast of this fault, the bedrock consists of high-grade metamorphic rock, migmatites, and granites (MGC). As reflected in the variogram map and directional variograms, the patterns of spatial continuity of water-well yields are different in these terranes, and these differences can be associated with the tectonic, structural, and thermal histories of these terranes. In the following discussion we will make reference to regional and large-lag concurrently. The

first term refers to a geologic property and the second term to a pattern shown on a variogram map.

Central Maine Belt—All Rocks

Although the variogram map for the CMB hints of a relatively low variance anisotropy with an east-northeast azimuth (figure 4), the central portion of this variogram map has an generally isotropic exponential form, which is indicated in the omnidirectional variogram for the CMB (figure 5). This short-ranged isotropy is attributed to fact that the rocks in the Rangeley Formation (Sr group of rocks) do not contain sheeting fractures. The fractures in these rocks are high-angle fractures that are not continuous over any great distance. Hence, we expect any continuity would have a short range.

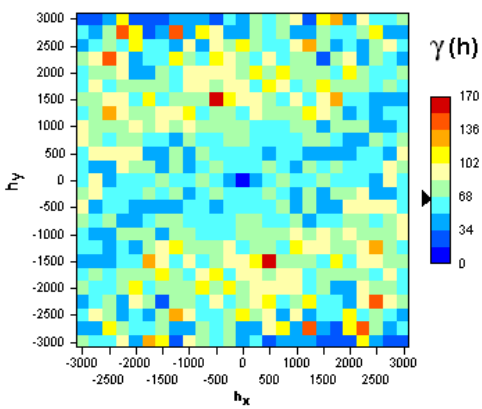

Figure 4. Variogram surface for the Central Maine Belt.

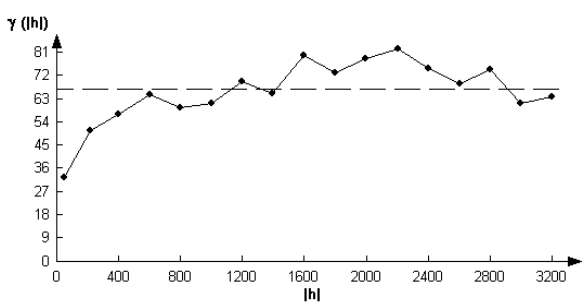

Figure 5. Omnidirectional variogram for low-yield wells within the Central Maine Belt.

The variogram map for the low-yield wells in the CMB is a composite of the individual variogram maps for the Sr rock group and the Spalding Granite (Dsg), which are the two rock types that compose this terrane in the quadrangle (figure 4). The variogram maps for the Sr rocks (figure 6) and the associated omnidirectional variogram (figure 7) have a remarkably similar pattern to the composite variograms shown in figures 4 and 5, whereas the companion variogram map and omnidirectional variogram for the Dsg rocks (figures 8, 9) have no spatial structure. Thus, the composite variogram

reflects the spatial structure in the Sr rocks.

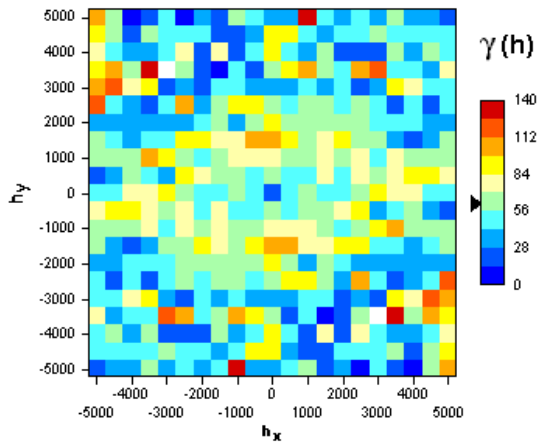

Figure 6. Variogram map from the Rangeley Formation.

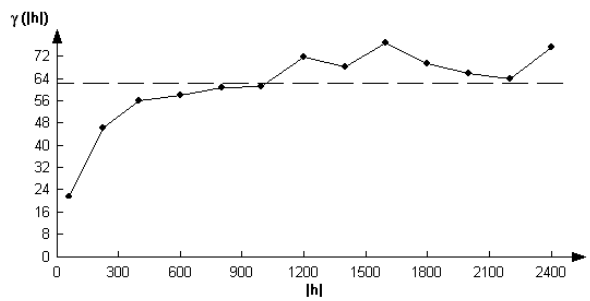

Figure 7. Omnidirectional variogram for low-yield wells in the Rangeley Formation.

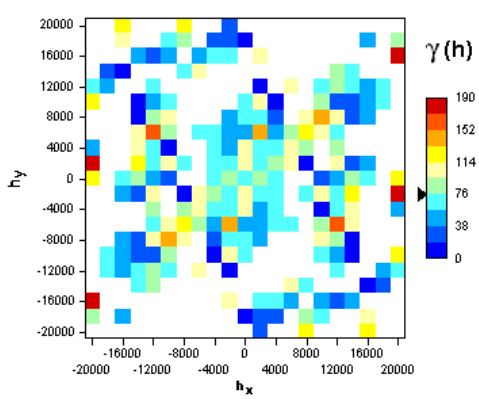

Figure 8. Variogram map for the Spaulding Granite.

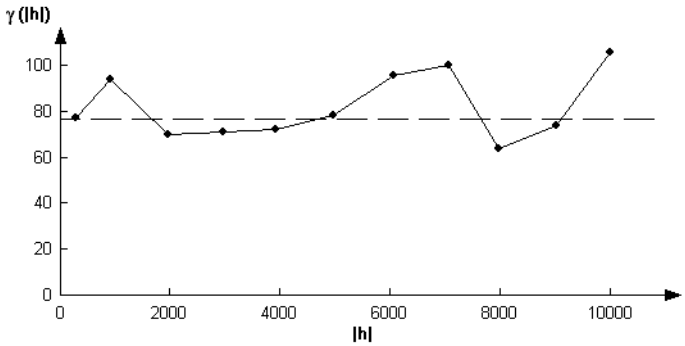

Figure 9. Omnidirectional variogram for wells within the Spaulding Granite.

Massabesic Gneiss Complex—All Rocks

The MGC rocks are located southeast of the Powder Hill Fault (figure 1). The variogram map for the low-yield wells in the MGC shows a large lag (regional scale) north-northeast-trending anisotropy (at a scale exceeding 12,000 feet; figure 10) and local continuity with a range of about 300 feet (figure 11). The regional anisotropy may reflect the regional flow of ground water in the bedrock aquifer system driven by changes in large-scale topographical effects (the first-order effect of flow) whereas the local continuity shown in the omnidirectional variogram may reflect a local pattern of ground-water flow associated with local changes in topography (Alley and others, 1999).

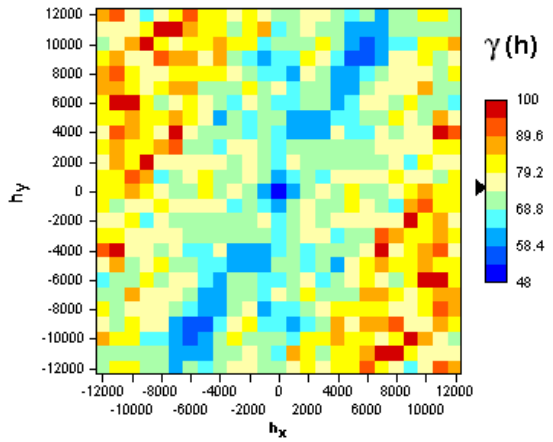

Figure 10. Variogram map for low-yield wells within the Massabesic Gneiss Complex.

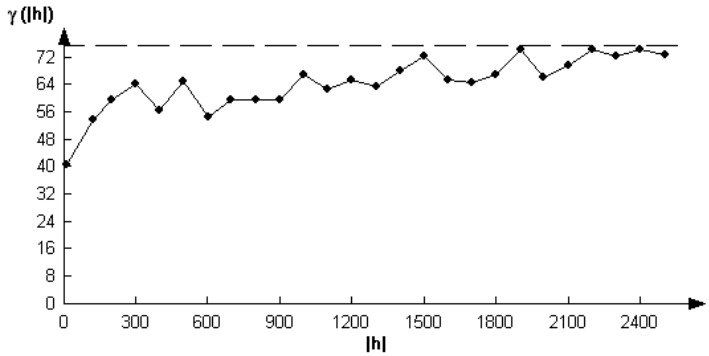

Figure 11. Omnidirectional variogram for wells from all rocks within the Massabesic Gneiss Complex.

Massabesic Gneiss Complex—Layered Paragneiss and Othrogneiss Rocks

The Zmlg rocks of the MGC terrane comprise layered paragneiss and orthogneiss that represent part of the residual fraction (restite) from the magmatic processes that created the granites and migmatites of the PDmg rocks in the MGC during the Permian. The variogram surface for the low-yield wells in the Zmlg does not show any evidence of anisotropy (figure 12). The omnidirectional variogram for the low-yield wells drilled into the fracture systems in Zmlg rock shows no pattern of spatial continuity (figure 13).

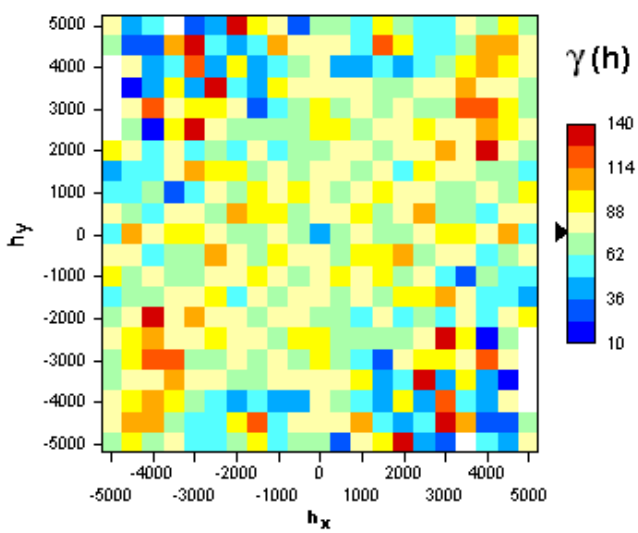

Figure 12. Variogram map from wells within the layered paragneiss and orthogneiss unit

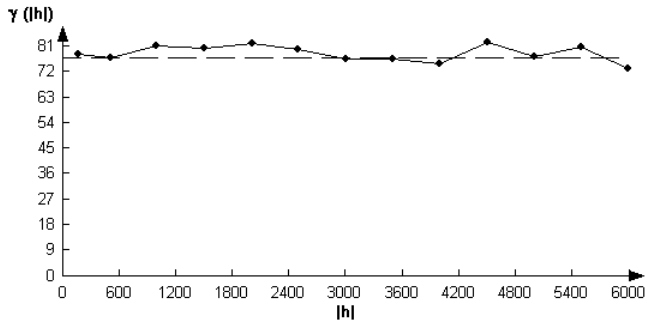

Figure 13. Omnidirectional variogram for low-yield wells within the layered paragneiss and orthogneiss unit.

Massabesic Gneiss Complex—Migmatite Gneiss Rocks

Unlike the Zmlg rocks of the MGC, the PDmg rocks, which are the principal melt fraction of the MGC, have a north-northeast regional anisotropy (figure 14), as well as weak local spatial continuity (figure 15) with a range of approximately 3,000 feet, which developed from sheeting and high-angle fractures.

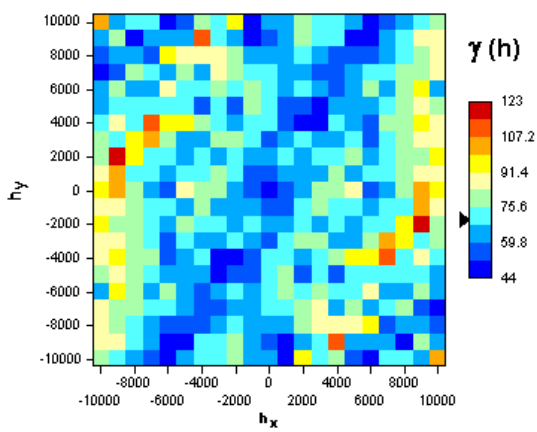

Figure 14. Variogram map for low-yield wells within the migmatite gneiss rocks.

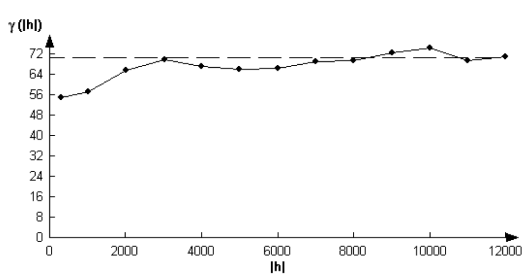

Figure 15. Omnidirectional variogram for low-yield wells within the migmatite gneiss rocks.

Damon Pond Granite and Granite and Pegmatite Rocks

The variogram map for two additional Permian-age granitic bodies, the Damon Pond Granite (Pdg) and the granite and pegmatite rocks (Ppg) that were principally mapped in the vicinity of the Powder Hill Fault in the Pinardville quadrangle, depicts a local isotropy with a range of about 500 feet (figures 16, 17) and a large-lag east-northeast regional anisotropy (figure 16). The east-northeast regional-scale anisotropy has about the same direction of the strike of most of these granitic and pegmatitic bodies (compare figure 16 with figure 1). The transpressive tectonic regime that juxtaposed the CMB and the MGC controlled the emplacement of these granitic and pegmatitic bodies and influenced their shape, as well as their internal foliation.

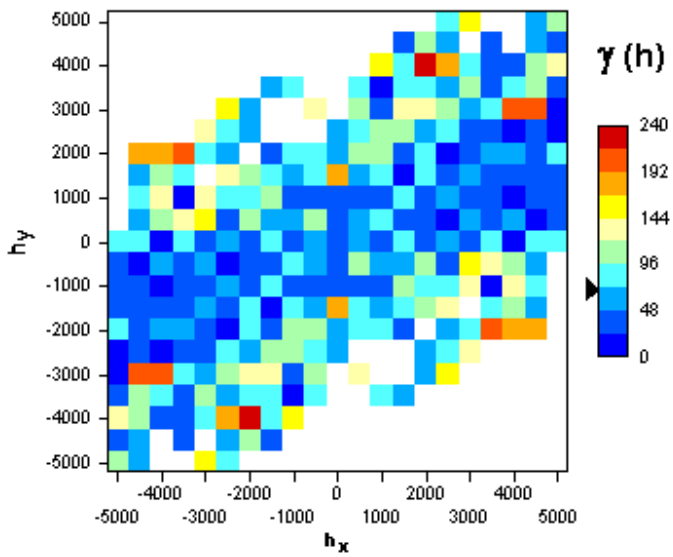

Figure 16. Variogram map for wells within the Damon Pond Granite and the granite and pegmatite rocks.

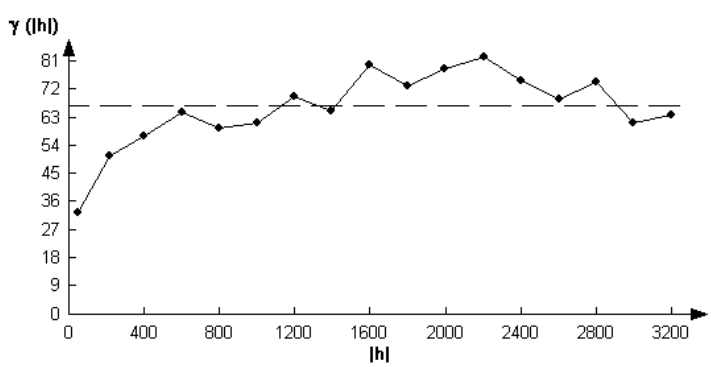

Figure 17. Omnidirectional variogram for low-yield wells within the Damon Pond Granite and the granite and pegmatite rocks.

Locational Variography in the Massabesic Gneiss Complex

The relations between patterns of spatial continuity in variogram maps of low-yield wells and variation of the configuration of high-angle and sheeting fractures along a regional anticlinorial in the MGC are examined below (figures 1, 18). The distribution of wells along a regional anticlinorial structure, as well as tectonic elements, and variogram maps and fracture-set data are shown in figure 18.

The structure itself is doubly plunging; the axial trace of the cross fold simply defines the location where the primary structure shows a general plunge reversal from the northeast to the southwest. Figure 18 also includes frequency-azimuth plots of steep-dipping fractures, and equal-area plots of sheeting fractures for all data within three blocks.

The variogram map for Block 1 contains a subtle northwest-trending anisotropy (figure 18). Steep-dipping fractures from this area are predominantly from the north-northeast-trending fracture sets (010- to 020-degree strike). The sheeting fractures have a variety of attitudes and shallow plunges as would be expected from the several bends in the axial trace of the anticlinorium in this block. On average, these sheeting fractures show a northwest-strike trend that is similar to the anisotropy shown in the associated variogram map for this block (figure 18). The high-angle fractures that trend 015 degrees are the conduits of recharge, and the sheeting fractures are the prime control on well yield and its variability on this part of the structure, as well as all along the structure. Therefore, we interpret that the trend of the anisotropy in the variogram map for Block 1 depicts an aspect of the continuity in the behavior of how the sheeting fractures deliver water to the well bore (figure 18).

Block 2 is located on the near horizontal culmination of the structure (figure 18). Notice that once again, the dominant steep-dipping fracture set is north-northeast trending (015 degrees). The sheeting fractures dip gently about the horizontal plane, which is consistent with sheeting-fracture development along the preexisting foliation in this area. The Block 2 variogram map shows a pattern of isotropy, which is coincident with the gentle domal attitude of the sheeting fractures on this part of the anticlinorium. As with the more-complex configuration of the sheeting fractures in Block 1, the continuity in the yield of the wells in this block appears to be directly associated with the variation in the attitude of the sheeting fractures.

Block 3 occurs along the tight, moderate amplitude northeastern part of the anticlinorium. Preexisting fabrics in this area are tightly folded, and the dominant fracture set (015-020 degree) utilizes this foliation. This orientation appears in the sheeting fracture data as well, because these fractures occur on the same folded foliation in areas where the fabric folds approximately horizontally. The variogram map from Block 3 shows a similar trending anisotropy. Note that of the three blocks, this is the only one in which all three directional elements (steep-dipping fractures, sheeting fractures, and variogram) are similarly aligned. This variogram map most likely

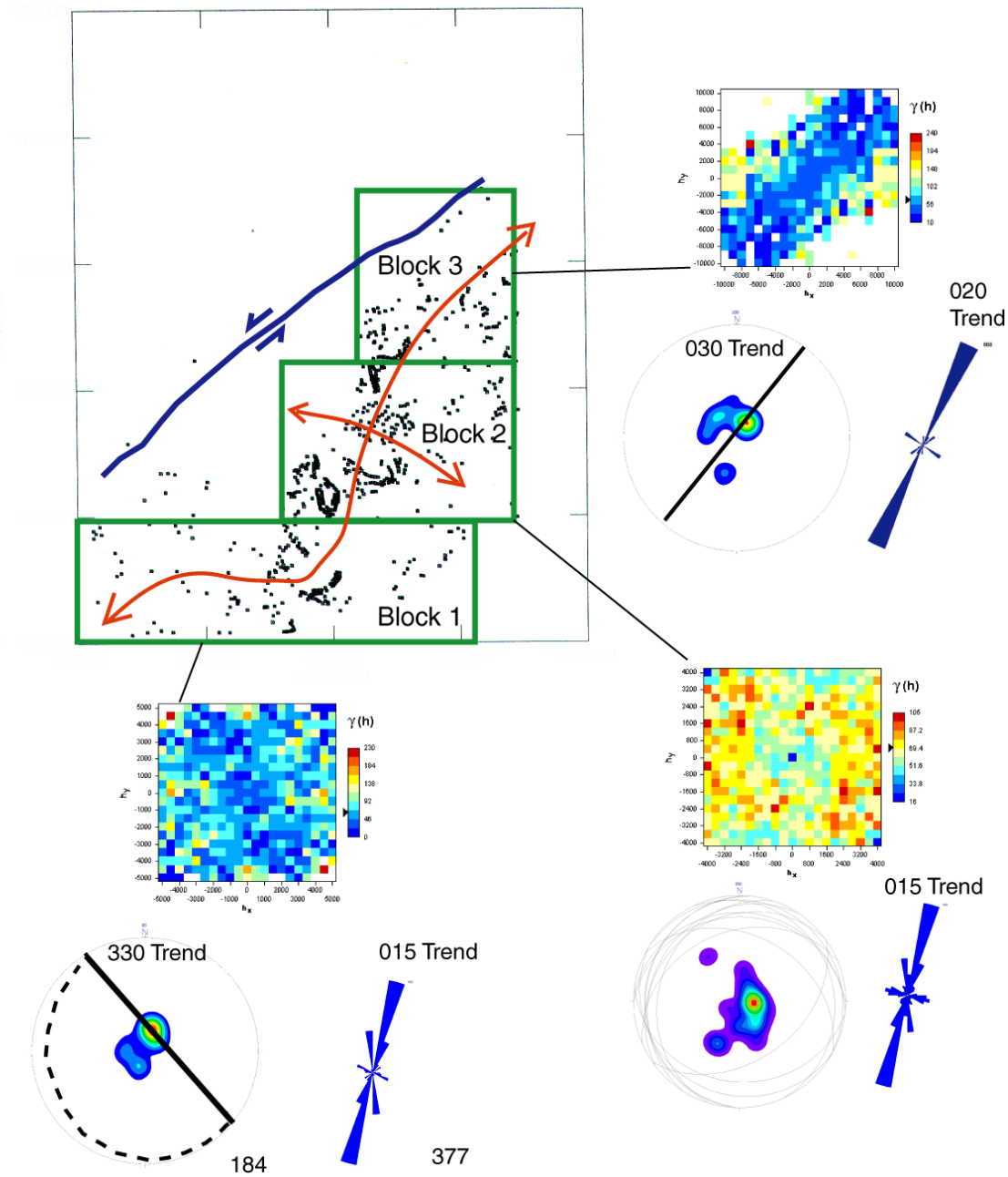

Figure 18. Relations between patterns in variograms maps and in fractures for the anticlinorium south of the Powder Hill Fault in the Pinardville quadrangle, New Hampshire.

represents ground-water behavior in which both sets of fractures contribute to the ground-water-flow directional anisotropy. Furthermore, the steep-dipping fractures may provide the vertical water flow component (including recharge), whereas the sheeting fractures provide most of the horizontal movement of ground water.

The average yield of the low-yield wells along the anticlinorium in the three blocks ranges from 9.0 gpm in Block 2 to a low of 7.0 gpm in Block 1. The average yield of the low-yield wells in Block 3 is 8.8 gpm. We speculate that the irregular strike of the structure in Block 1 may be associated with a sealing off of some of the sheeting fractures and/or the connection between the high-angle recharge fractures and the sheeting fractures. Another possibility is that the sheeting fractures did not, on average, develop as well in this section of the structure.

Summary

With the acquisition of new geologic field data (bedrock and fracture mapping) and an expansion in well coverage, the analysis of the spatial characteristics of water-well yields has been expanded to include comparisons across tectonic terranes (CMB versus MGC) of rock types within terranes, and along sections of an anticlinorium structure within the MGC. The average yield of all wells was higher in the MGC (15.6 gpm) than in the CMB (14.2 gpm) presumably because of the sheeting fractures that developed in the MGC.

The analysis for the spatial continuity of well yields proceeded along the same line of investigation in an earlier study by Drew and others (1999) in which the high-yield wells (40 gpm or more) were analyzed separately from the low-yield wells. Very little, if any, spatial continuity is found in the distribution of high-yield wells in the Pinardville quadrangle. The yields of these wells may be related by the interaction of several processes that involve the characteristics of surficial material and its interaction with the underlying fracture system in the crystalline bedrock. The bulk of our analysis was focused on the spatial characteristics of low-yield wells for which a wide variety of isotropies and anisotropies were related to terranes, rock type, and fracture types within rock types and according to structural settings.

The variogram map for low-yield wells in the CMB shows a local isotropy with a range of about 600 feet and a regional (large-lag) east-northeast anisotropy, although properties of the variogram map at large lags become data limited. The presence of these two contrasting spatial statistical attributes is believed to reflect the local and regional topographic effect on the flow of ground water. The same types of short-range isotropy and regional anisotropy are present in the variogram map for all the low-yield wells in the MGC terrane.

The variogram maps for the low-yield wells drilled into individual rock types vary in a more-complex manner—from the Zmlg rocks that have a variogram map and an omnidirectional variogram with no discernable spatial structure to the PDmg rocks that have small local isotropy (large nuggets) and regional anisotropies to the Sr rocks that have a strong local isotropy and no regional anisotropy.

With the new geologic and water well data, we have been able to examine the behavior of water yield along an anticlourium structure in the MGC. This structure has a

central domal segment where sheeting fractures dip in a shallow manner off the dome (, figure 18, Block 2). The variogram map in this area of the structure shows a pattern of isotropy that is consistent with the domal structure. This section of the anticlinorium has the highest average yield (9.0 gpm) for the low-yield wells. None of the average yields in areas analyzed along the structure (figure 18, Blocks 1-3), however, were significantly different at the 5-percent level. The section of this anticlinorium to the north is tightly folded and plunges to the northeast. The variogram map shows a regional anisotropy orientated in this same direction. The average yield of the low-yield wells drilled in this section of the anticlinorium is 8.8 gpm. The segment of the anticlinorium to the southwest of the central dome has a snakelike axis that twists first to the south and then back toward the west and then back to the southwest. The structural data for the attitude of the sheeting fractures in this region shows considerable variation in strike and dip with an average strike to the northwest. The variogram map for the low-yield wells drilled in this section of the anticlinorium also has an anisotropy in this same direction. The average yield of the low-yield wells in this section of the anticlinorium is 7.0 gpm. The irregular strike of the axis of the anticlinorium in this section may have sealed off some of the sheeting fractures and/or the connection between the high-angle recharge fractures and the sheeting fractures on this anticlinorium.

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