Report as of FY2006 for 2003MA19G: "A Regional Approach to Conceptualizing Fractured-Rock Aquifer Systems for Groundwater Management"

Publications

- Articles in Refereed Scientific Journals:
  - Manda, A.K; S.B Mabee, D.U. Wise, In prep, Influence of rock fabric on fracture attribute distribution and implications for groundwater flow in the Nashoba Terrane, Eastern Massachusetts, to be submitted to Journal of Structural Geology.
  - Diggins, J.P., D.F. Boutt, A.K. Manda and S.B. Mabee, 2006. Estimating bulk permeability of fractured rock aquifers using detailed outcrop data and discrete fracture network modeling. Geological Society of America Annual Meeting, Philadelphia, Abstracts with Programs, v.38, no.7, p.223.
- Conference Proceedings:
  - Manda, A.K, S.B. Mabee and D.F. Boutt, 2006. Characterizing fractured crystalline bedrock aquifers using hydrostructural domains in the Nashoba terrane, eastern Massachusetts. Geological Society of America Annual Meeting, Philadelphia, Abstracts with Programs, v.38, no.7, p.25.
  - Boutt, D.F., A.K. Manda, S.B Mabee, J.P. Diggins, 2006, Characterizing fractured crystalline bedrock aquifers using discrete fracture networks in the Nashoba Terrane, Eastern Massachusetts, Eos Transactions, American Geophysical Union, v. 87, no. 52, Fall Meeting Supplement, Abstract H13D-1429.
  - Manda, A.K., S.B. Mabee and S.A. Hubb,. 2005. Field mapping and fracture characterization techniques predict groundwater preferential flow paths in fractured bedrock aquifers, Nashoba terrane, MA. EOS Transactions, American Geophysical Union, v.86, no. 52, Fall Meeting Supplement, Abstract H23E-1477.

Report Follows

Problem Statement

The use of fractured-bedrock aquifers to meet private, public and commercial water supply needs is increasing in the New England region. Municipalities and water suppliers are finding it increasingly difficult to locate and develop water supplies in overburden aquifers because of contamination and a lack of suitable sites. In addition, recent droughts in the northeast have forced many communities and homeowners to drill new wells. As a result, water suppliers are going deeper into bedrock aquifers. Yet information on the factors that influence the availability and recharge characteristics of fractured bedrock aquifers in highly deformed crystalline metamorphic rocks is limited.

The availability of water in fractured rock aquifers is particularly critical in New England because growth and development along the coast, major transportation corridors and in rural communities adjacent to large metropolitan areas is rampant. For example, the I-495 corridor in Massachusetts, a circumferential highway 30 miles west of Boston, has become the focus of recent growth. Professional office buildings, research and development parks associated with the computer industry, warehouses and light industry are springing up along this corridor, as are housing and condominium developments. Municipalities and water suppliers are simply unprepared for the onslaught of development and need help in understanding the complex dynamics of the ground water system.

Sustaining and managing ground water resources in fractured bedrock requires an evaluation of 1) the availability of water, 2) the source and vulnerability of recharge to water supply wells and 3) the impact of water withdrawals from the bedrock on streams, wetlands and unconsolidated aquifer systems that overlie the bedrock. These evaluations all require basic information on the physical characteristics of the ground water system.

Objectives

The objectives of this project are to gather regional bedrock characteristics that relate to the occurrence and movement of ground water in bedrock and use this information to begin constructing regional conceptual models of the fractured-rock aquifers in the Nashoba terrane in Massachusetts. The approach utilizes existing information augmented by the collection of low-cost field data to develop regional conceptual models of the ground water flow system. Water managers can then use these conceptual models as an initial framework for formulating an understanding of bedrock flow behavior and recharge characteristics.

Specific tasks of this project involve: 1) Fracture Characterization and Domain Analysis - collection and synthesis of fracture characterization data over the region and mapping of the spatial distribution (domain analysis) of fracture sets and their characteristics, 2) Compilation and Analysis of Existing Well Data - compilation and statistical analysis, including variography, of available well data to link spatial continuity of well yields to characteristics of the fractured rock system, 3) Borehole Geophysics - collection of optical and acoustic televiewer data from selected boreholes to verify sheeting joints, 4) Compilation of Regional Litho-Group Map - development of a mapping classification system that uses the notion of “litho groups” to characterize bedrock units in terms of their fracture characteristics, physical properties and

geologic setting (eg., overburden type and thickness) and 5) Conceptual Model - preparation of a qualitative conceptual model of ground water flow behavior in each litho group category.

Relationship of Project to USGS and Other Activities

This project is part of a much larger, more comprehensive study being conducted by the USGS WRD Northborough office on the Geohydrology of the Nashoba Terrain, Massachusetts. This larger scale project involves the collection of data at three scales: regional, quadrangle and the local well-field scale. Recent work by the USGS in Connecticut and New Hampshire indicates that an understanding of ground water occurrence and movement in fractured rock aquifers can be made by combining the results of 1) fracture, geologic, well, and geophysical analyses performed at the regional level, 2) detailed mapping of bedrock lithology and physical characteristics that affect water occurrence and flow at the quadrangle scale, and 3) hydrogeologic and geophysical investigations at the well-field scale. This larger scale project is a joint effort that involves the participation of USGS scientists from the Water Resources Discipline, USGS mappers from the BRASS (Bedrock Regional Aquifer Systematics Study) program, the Office of the Massachusetts State Geologist, and University of Massachusetts scientists (this project). Table 1 describes the tasks that each agency will perform and shows how the work will be coordinated.

Table 1. Coordination Plan and Approximate Timetable

Task	Activity	Timetable	Responsible Party
Existing Data (Regional Scale)	Base map	2003	USGS[1]
	Geologic map	2003	USGS
	Imagery	2003	USGS
	Fracture data/analysis	completed	This Project[2]
	Existing well data/analysis	completed	This Project
	Add'l well data in field	completed	This Project/USGS
	Borehole fracture data	underway	This Project/USGS
	Litho-group map	completed	This Project
Geologic & Fracture Data (Quadrangle Scale)	Map Quad #1-Grafton	completed	USGS BRASS[3]
	Map Quad #2-Marlboro	completed	State Geologist[4]
	Map Quad #3-Nashua S.	completed	USGS BRASS[3]
	Map Quad #4-Hudson	completed	State Geologist[4]
	Map Quad #5-Ayer	completed	State Geologist[4]
	Map Quad #6-Milford	underway	
Conceptual Model Devel.		completed	This Project/USGS
Test and Verify Model (Well Field Scale)		underway	This Project/USGS
Prepare and Publish Reports		Late 2007	This Project/USGS

[1] Start date of USGS cooperative project is March 2003, Bruce Hansen, USGS
[2] Start date of this project is September 30, 2004 (no cost extension granted)
[3] USGS BRASS = Bedrock Regional Aquifer Systematics Study project, Greg Walsh, USGS, began mapping in summer 2004; finishing Nashua South quadrangle in 2007

[4] State Geologist – Mapping funded by the STATEMAP component of the National Cooperative Geologic Mapping Program, Marlboro completed in June 2004, Hudson preliminary map completed in June 2005, Ayer quadrangle completed 2006, Milford will be finished in fall 2007.

Please note that although the USGS portion of the work was supposed to start in 2003, funding did not become available for the project until spring of 2007. The University of Massachusetts and the USGS are working collaboratively on the collection of borehole geophysical data on selected wells in the Nashoba terrane. We are collecting fluid resistivity, temperature, gamma, electromagnetic induction, acoustic and optical televiewer and heat pulse flowmeter data. These data, along with well field pumping test data, will be used to verify the conceptual models.

Work Accomplished on *This Project* in Past Year

Work completed during the period March 1, 2006 to February 28, 2007:

1. Tasks 1 (Fracture Characterization and Domain Analysis), 2 (Compilation and Analysis of Existing Well Data) and 4 (Compilation of Regional Litho-Group Map) are complete.
2. Task 5 (Conceptual Model) is underway. Discrete fracture network models are being run for individual outcrops to test the concept of hydrostructural domains. Model results will be compared with well field pumping test data and the borehole geophysical data. Existing pumping test data has been collected and is being analyzed.
3. Task 3 (Borehole Geophysical Surveys) is underway during the summer of 2007.
4. Currently building discrete fracture network models of individual outcrops and assigning hydraulic conductivity values to several domains for testing against well-field scale pumping test and borehole geophysical data.

Although the project ends on September 29, 2007, Alex Manda will be continuing the model validations through the 2007/2008 academic year in order to complete his Ph.D.

Work Accomplished by Collaborators (Table 1)

USGS – The USGS WRD Northborough office was finally funded in spring 2007. The scope of services has changed slightly. In addition, to assisting with the borehole geophysical data collection, the USGS will also be conducting a statistically based yield probability study for the Nashoba terrane. They will use the fracture data collected in this study and in the quadrangle scale mapping completed by the Office of the Massachusetts State Geologist.

Office of the Massachusetts State Geologist – The office of the Massachusetts State Geologist has contributed in the following way using funds supplied by the National Cooperative Geologic Mapping STATEMAP and EDMAP programs and from the Massachusetts Department of Environmental Protection.

1. A preliminary bedrock geologic map and a fracture characterization map is currently being prepared for the Milford quadrangle. These maps provide detailed lithologic and fracture characterization data as well as information on the distribution of permeable

overburden deposits at the quadrangle scale. These data will be used as a test for the regional scale and quadrangle scale hydro-structural domain maps to be prepared under this project. We now have new bedrock and fracture characterization maps for three quadrangles that provide a north south transect across the Nashoba terrane.

2. We have also begun bedrock geologic mapping in the Westford and Blackstone quadrangles.
3. A fracture characterization map is being prepared for the Wilmington quadrangle.
4. In addition, using funds from the EDMAP component of the National Cooperative Geologic Mapping Program, we have new bedrock and fracture characterization maps for the Concord quadrangle, which completes an east-west transect across the Nashoba terrane.
5. A well database consisting of over 1000 wells has been assembled for the Milford quadrangle.

USGS BRASS Program – Greg Walsh from the USGS BRASS program completed bedrock and fracture mapping in the Nashua South quadrangle. Greg is finalizing the map in summer 2007.

Summary of Results

The following is a description of results, achievements and goals related to this project. The specific objective is first stated before a description of the status of that objective is given. Highlighted below are both the goals that have been achieved and those that are till pending. Note that this grant has supported Alex Manda, Ph.D. candidate, for the previous 2.5 years.

1) Fracture Characterization and Domain Analysis - collection and synthesis of fracture characterization data over the region and mapping of the spatial distribution (domain analysis) of fracture sets and their characteristics. Completed (see previous annual reports).

2) Compilation and Analysis of Existing Well Data - compilation and statistical analysis, including variography, of available well data to link spatial continuity of well yields to characteristics of the fractured rock system. Completed (see previous annual reports).

3) Borehole Geophysics - collection of optical and acoustic televiewer data from selected boreholes to verify sheeting joints.

Borehole geophysical data is currently being collected at selected wells in the Nashoba terrane. Patrick Diggins, MS candidate at the University of Massachusetts and Jason Sorenson, a USGS employee, are working together to collect this data. Dr. David Boutt (Hydrogeology professor at the University of Massachusetts), Dr. Stephen Mabee (MA State Geologist) and Bruce Hanson (formerly of USGS and now with the MA Department of Conservation and Recreation) are assisting with data collection. In addition to optical and acoustic televiewer logging, we are also collecting fluid resistivity, gamma, temperature, electromagnetic induction and heat pulse flowmeter data. This will identify how much and which fractures are producing water in the borehole. These data will be compared to outcrop fracture characterization data and

model results. As of this writing, three wells have been logged. We have use of the geophysical equipment until the end of August 2007. The goal is to log 25 to 30 wells during this time.

4) Compilation of Regional Litho-Group Map - development of a mapping classification system that uses the notion of "litho groups" to characterize bedrock units in terms of their fracture characteristics, physical properties and geologic setting (e.g., overburden type and thickness).

This task is completed. We have substituted the term, 'hydrostructural domain' in place of 'litho group' to describe assemblages of rocks that have similar physical properties and hence similar hydraulic characteristics. Major criteria for determining hydrostructural domains are rock type, number and distribution of fracture sets, type of fractures present or absent, degree of fracture development, fracture spacing and nature of fracture termination. See previous annual reports for details.

5) Conceptual Model - preparation of a qualitative conceptual model of ground water flow behavior in each litho group category.

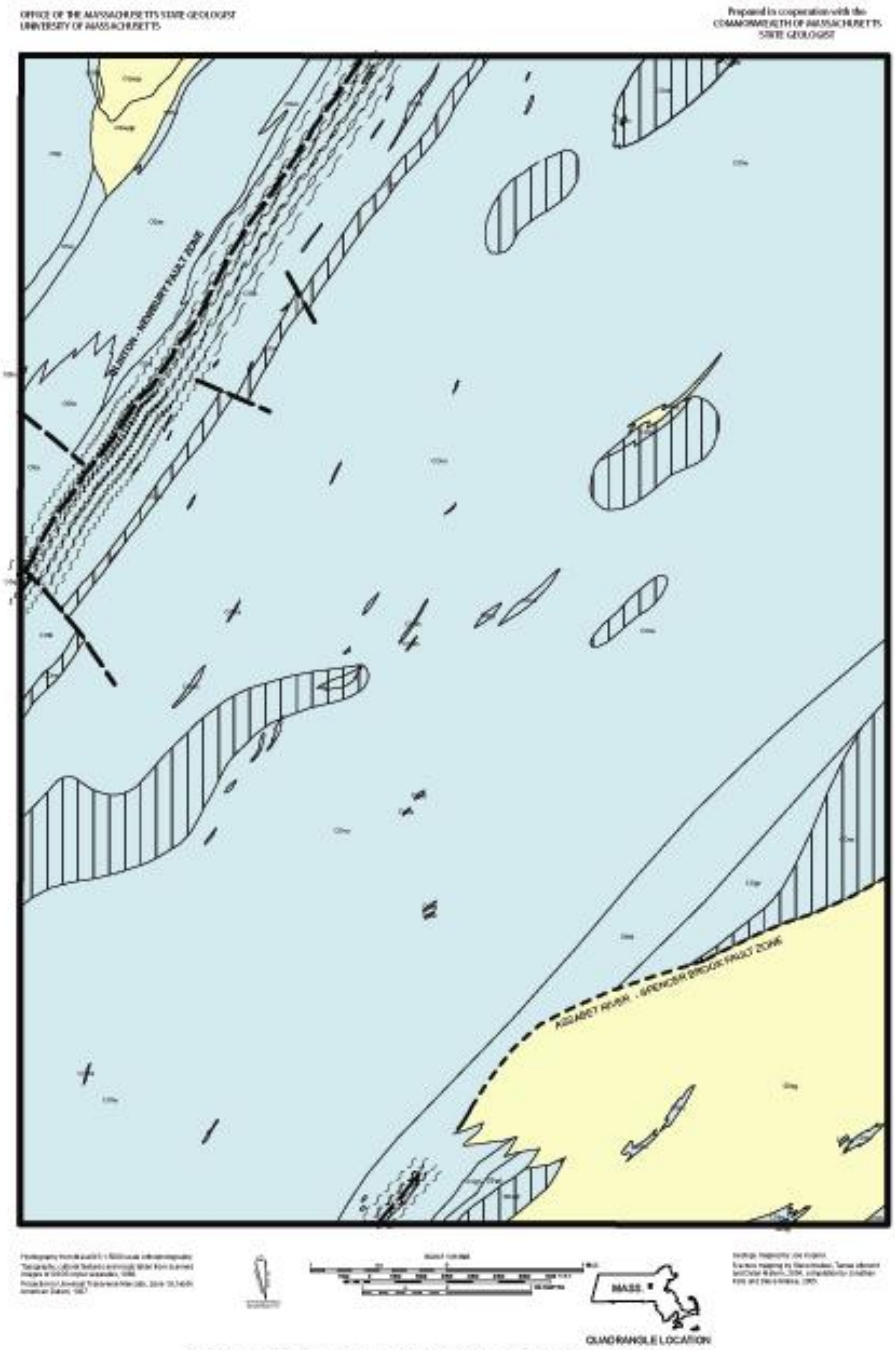
Most of the work in the previous year has focused on this task. We have extended our work beyond the conceptual model phase and are now performing numerical modeling to test and validate the conceptual model and the notion of "hydrostructural domains". A summary of this work follows.

Hydrostructural domains are packages of rocks that have similar fracture intensities and thus are likely to possess comparable hydraulic properties. However, this study has identified that other than fracture intensity, fracture trace length and the number of fracture sets also influence the hydraulic properties of rocks. Thus, the number of fracture sets and fracture trace lengths have been included in identifying hydrostructural domains for the regional study of the Nashoba terrane. A hydrostructural domain map of the Nashoba terrane that shows how fracture attributes that influence the transmissive properties of rock units vary within the Nashoba terrane was created.

Numerical simulations of groundwater flow in the hydrostructural domains for the Nashoba terrane were conducted using discrete fracture networks in 10 m^3 box regions with sides that had either specified heads or fluxes. However, these simulations were unsuccessful because the parameters required for building discrete fracture networks exceeded the maximum threshold for model running. The groundwater flow code MAFIC was incapable of simulating flow in fracture networks created from the fracture data of the Nashoba terrane. In spite of the inability to simulate flow in the fracture networks representing hydrostructural domains at the regional scale, it was apparent that the number of outcrops used to create domains was insufficient to adequately capture the true hydraulic character of the discrete fracture networks; spatial heterogeneity of fractures was not adequately captured at this scale.

To overcome the problems encountered with the Nashoba regional study, fracture characterization and numerical model simulation were conducted at the quadrangle scale. A hydrostructural domain map for the Hudson quadrangle was created where the density of stations was higher per square mile than that at the regional scale. Also different criteria were used to

define the hydrostructural domains at this scale so as not to encounter the same problems as those in the regional study. Three domains were delineated: steeply dipping layered rocks (SDLR), steeply dipping layered rocks with strong tendency to part parallel to foliation (SDLRSPPF), and massive rocks (MASSIVE) (Fig. 1, Tables, 1, 2 and 3). Numerical models of groundwater flow in fracture networks were derived from outcrop-scale field data and simulated as 10 x 10 x 10 meter cubes. Flow was calculated in an east west, north-south, and vertical direction (top to bottom) by controlling boundary conditions. Results showed that the most transmissive domain in the E-W and N-S directions was MASSIVE, whereas in the top to bottom direction the most transmissive domain was SDLRSPPF (Fig. 2). The least transmissive domain in the N-S and top to bottom directions was SDLR, whereas in the E-W direction the least transmissive domain was SDLRSPPF (Fig. 2). This analysis was conducted on fracture networks that were assumed to have similar fracture apertures.



EXPLANATION OF HYDROSTRUCTURAL DOMAINS

Massive Rocks - Rocks exhibiting no foliation or occasional weak foliation.

Steeply-Dipping Layered Rocks - Foliated rocks exhibiting dips greater than 60°. Sheeting is generally not well developed except in a few islolated locations.

Steeply-Dipping Layered Rocks with strong Partings Parallel to Layering - Partings are pervasive, generally through-going and generally extend across the outcrops.

Figure 1. Hydrostructural domain map of the Hudson quadrangle, eastern Massachusetts.

Table. 1 Fracture statistics for MASSIVE[1] hydrostructural domain

Fracture Set	Strike and dip of fracture set	Median Spacing (m)	Median Trace Length (m)
1	150/83	0.60	0.80
2	089/51	0.25	2.10
3	027/68	0.85	2.00
4	193/66	0.20	1.75

[1]Massive rocks with no or little foliation

Table. 2 Fracture statistics for SDLR[2] hydrostructural domain

Fracture Set	Strike and dip of fracture set	Median Spacing (m)	Median Trace Length (m)
1	123/86	1.35	1.10
2	034/70	0.60	1.60
3	246/81	0.20	1.80
4	022/05	0.50	2.00

[2]Steeply Dipping Layered Rocks

Table. 3 Fracture statistics for SDLRSPPF[3] hydrostructural domain

Fracture Set	Strike and dip of fracture set	Median Spacing (m)	Median Trace Length (m)
1	142/73	0.5	1.1
2	226/71	0.2	1.5
3	015/75	1	1.6
4	007/11	0.35	2.9
5	219/74	0.3	1.5

[3]Steeply Dipping Layered Rocks with Strong tendency to Part Parallel to Foliation

The results suggest that foliated rocks showing a strong tendency to part parallel to foliation have a significant influence on flow because the features are penetrative, through-going and pervasive in the outcrop (note the high vertical transmissivity). In contrast, strongly foliated rocks that do not tend to part parallel to foliation and which are annealed, do not show as strong a vertical flow. In such rocks, the presence of cross joints (E-W flow direction) is equally important in controlling flow. Massive rocks have good flow characteristics because in the field they tend to have better developed sheeting joints providing greater connectivity. Also note that E-W flow in all three domains are very similar suggesting that these fractures have similar properties that are independent of the domain.

The results appear also to be surprising. The most transmissive domain, based on the assessment of fracture attributes and observed number of fracture sets, is predicted to be SDLRSPPF (Table 3). This domain has comparable fracture trace length and spacing to MASSIVE domain (Table 1).

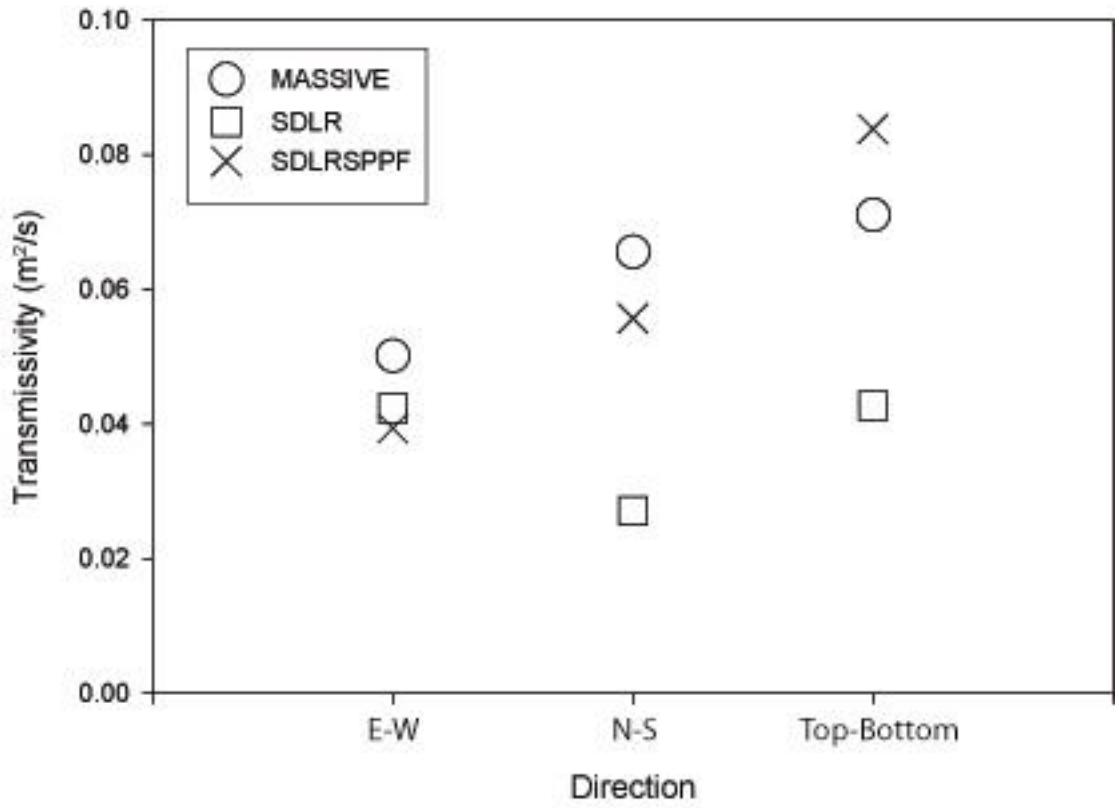


Figure 2. Plot showing the transmissivity derived from different domains in different directions.

However, the SDLRSPPF domain has more fracture sets that have markedly varying orientations suggesting that this domain should be more conductive because it has higher fracture connectivity than the MASSIVE domain. In reality, as the simulation results reveal, the MASSIVE domain is more conductive in two of the three directions in which the simulations were conducted.

The SDLRSPPF domain is not the most transmissive unit in the E-W and N-S flow directions. In fact, SDLRSPPF is the least transmissive domain in the E-W direction. Even though fracture trace length and fracture intensity for SDLRSPPF and MASSIVE domains appear to be comparable, there are subtle differences in the total number of fractures present in each model, and hence the total volume that fractures take up in each model. The MASSIVE domain has more fractures and hence a higher fracture volume than the SDLRSPPF. This increases the potential permeability of the domain thereby imparting a higher transmissivity on the MASSIVE domain.

The qualitative assessment of the hydrostructural domains needs to be validated with hydraulic data from the field area. Unfortunately, well yield data that is currently available at the regional and quadrangle scales is not sufficient to characterize the transmissive properties of fractured crystalline rocks. An ongoing USGS/UMASS collaborative project will collect

hydraulic data that will be used to validate the numerical simulation results of this study. When these data are available, validation of the hydrostructural domains at the quadrangle scale will continue.

Recommendations from data analysis and numerical model simulations

The following recommendations are provided to help with collecting robust data sets in the future that can adequately capture the transmissive properties of discrete fracture networks in numerical models:

- Aperture data needs to be collected from outcrops using feeler gauges or other measuring devices. An estimate of fracture aperture derived from outcrops will help to constrain numerical models so that they match natural fracture networks.
- The proportion of fractures that have a particular termination style needs to be determined at the outcrop. This can be done by counting the total number of fractures along either the entire outcrop or along sections of the outcrop (e.g. 10 m sections) and counting fractures that have particular termination styles along that particular section. Results from this procedure will then be used to help determine the connectivity of the fracture network.
- Fracture sets that terminate against other sets need to be documented in the field. This information required during model building to accurately replicate the natural fracture network, affects the conductivity of the fracture networks.
- The proportion of fractures that are conducting within particular fracture networks needs to be determined. Data that can be used to determine the proportion of conducting fractures within a particular fracture network include detailed well drillers' reports or conducting new well tests.
- The proportion of fractures that belong to a particular fracture set needs to be determined.