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Influence of rock fabric on fracture attribute distribution and implications for groundwater flow in the Nashoba Terrane, eastern Massachusetts

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Abstract

Attributes (i.e. trace-length, spacing, termination and orientation) of joints and foliation-parallel fractures (FPFs) are used to assess the influence of lithology and fabric on fracture type and distribution in metamorphic and igneous rocks of the Nashoba terrane, Massachusetts. Orientations of NE–SW and NW–SE trending joints are consistent throughout the region, whereas FPFs are sub-parallel to the axis of the terrane. Joint spacing generally decreases to the northeast across the terrane reflecting lithologic changes from metamorphic to igneous rock types. Although trace-length and spacing frequency distributions of both joints and FPFs are best described by lognormal functions, FPFs possess narrower fracture spacing than joints. Median fracture trace-lengths of all FPFs are comparable to those of all steep joints, but the median fracture spacing is half that of all steep joints. Trace-lengths of FPFs vary as a function of the degree of development of foliation. Fracture attributes and groundwater flow models suggest that FPFs may significantly increase fracture connectivity and potential for groundwater recharge. FPFs may account for as much as 30% of flow in fracture networks suggesting that in addition to joints, FPFs play a significant role in groundwater hydraulics that may include imparting flow anisotropy on the groundwater system.

Keywords: Joints; Foliation-parallel fractures; Groundwater; Lognormal distribution; Nashoba terrane

1. Introduction

Crystalline bedrock aquifers serve as important sources of groundwater in regions where unconsolidated cover yields less than satisfactory amounts of groundwater. Bedrock aquifers are also progressively sought to supplement water supplies currently being derived from surface water bodies where demand for potable water is rising due to population increase and urban development. However, the degree to which the demand for more sources of groundwater is met depends on the ability to successfully drill wells that intersect highly conductive zones in crystalline bedrock. The productivity of crystalline bedrock aquifers is predominantly controlled by the occurrence and interaction of discrete fractures because the crystalline rock has negligible matrix permeability. The amount of water that a crystalline aquifer can yield is hence controlled in large part by the apertures, trace-lengths, spacings and connectivity of fractures in the rock (Long and Witherspoon, 1985; Berkowitz, 1995; Odling, 1997).

Fracture attribute analysis provides a technique for evaluating the character and development of fractured rock units. Although fracture orientation has been used to assess fracture development history (e.g. Engelder and Geiser, 1980; Bahat and Grossmann, 1988), few studies have applied fracture attribute analysis (e.g. spacing and trace-length) to crystalline rocks (e.g. Caine and Tomusiak, 2003; McCaffrey et al., 2003). Use of fracture attributes in previous works has focused on attributes derived from sedimentary rocks where thickness of sedimentary units controls the distribution of attributes (e.g. Gross, 1993).

Recently, it has been shown that fractures other than classic joints and faults influence the water-bearing and transmissive capacity of foliated metamorphic rocks (e.g. Williams et al., 2004, 2005). In rock units where joints appear as tight hairline

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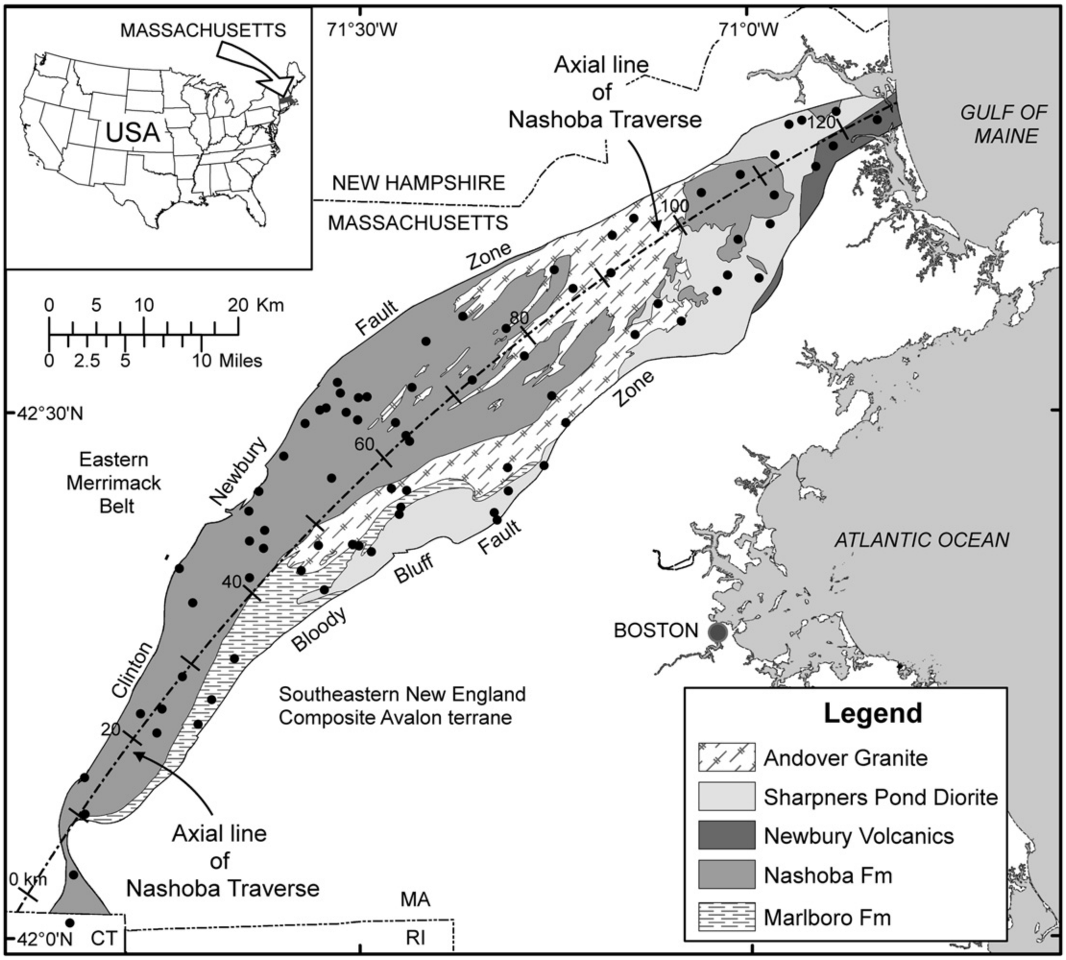

Fig. 1. Simplified bedrock geologic map of the fault bounded Nashoba terrane located in eastern Massachusetts. Stations with fracture data are shown as black circles. Rock groups on the map are based on major rock units from the bedrock geologic map of Massachusetts (Zen et al., 1983). Dashed line represents the Nashoba axial traverse from which fracture data in 10 km wide windows were collected. Numbers represent distance in kilometers from the origin along the axis.

fractures, the significant water bearing sources are fractures parallel to the dominant foliation. The importance of these foliation-parallel fractures (FPFs) as significant conduits of groundwater flow is beginning to be realized (Lyford et al., 2003; Williams et al., 2004, 2005). However, attribute data on these potentially critical pathways of groundwater flow in foliated metamorphic terranes are still scarce. Therefore, an in-depth analysis of the influence of fracture properties, additional to joints and faults, is required to better characterize the influence of subsurface brittle features on groundwater flow systems in crystalline terranes, especially those with significant development of FPFs.

Table 1
Assigned rock groups, degree of penetrative fabric development, and ages of formations and rock types in the Nashoba terrane

Group	Formations	Rock types	Foliation development	Age
Newbury Volcanics	Newbury Volcanic Complex	Rhyolite, andesite	None	Silurian/Devonian
Sharpners Pond Diorite	Sharpners Pond Diorite, Biotite granite to granodiorite, Indian Head Pluton	Diorite, granodiorite, gneiss	Weak	Silurian
Andover Granite	Andover Granite	Granite, gneiss	Weak	Ordovician/Silurian
Nashoba Formation	Nashoba, Tatnic Hill, Boylston schist, Shawsheen gneiss, Fish Brook gneiss, Light gray muscovite granite	Gneiss, schist, mylonite	Moderate to strong	Ordovician
Marlboro Formation	Marlboro, Homogeneous feldspathic gneiss	Gneiss, schist, amphibolite, mylonite	Strong	Ordovician

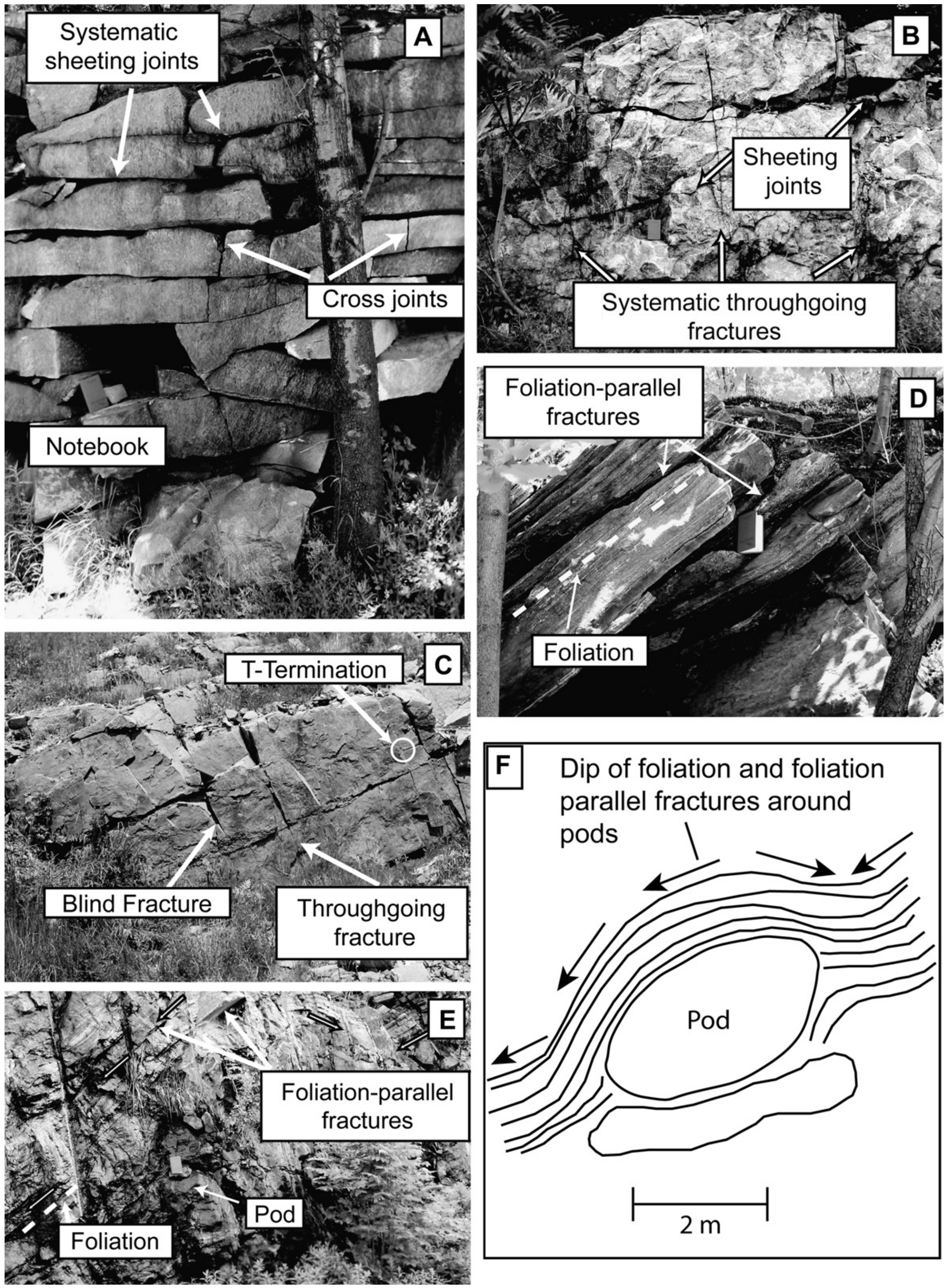

Fig. 2. Photographs of rocks showing different fracture types and style in the Nashoba terrane. (A) Plutonic rocks of the Andover Granite displaying high intensity sheeting joints. Vertical cross joints abut against sheeting joints. Diameter of tree is ~30 cm. (B) Wider fracture spacing for systematic through-going fractures and sheeting joints in the Sharpners Pond Diorite. (C) Through-going, blind and T-fracture termination styles in a moderately foliated gneiss of the Nashoba Formation. (D) Well developed FPFs in strongly foliated gneiss of the Nashoba Formation. (E) Locally within the gneisses of the Nashoba Formation, foliation and FPFs vary markedly in orientation especially around igneous intrusions such as pods. Arrows illustrate varying dips of foliation planes around intrusive bodies. (F) Sketch illustrating the change in dip of foliation and FPFs around a pod.

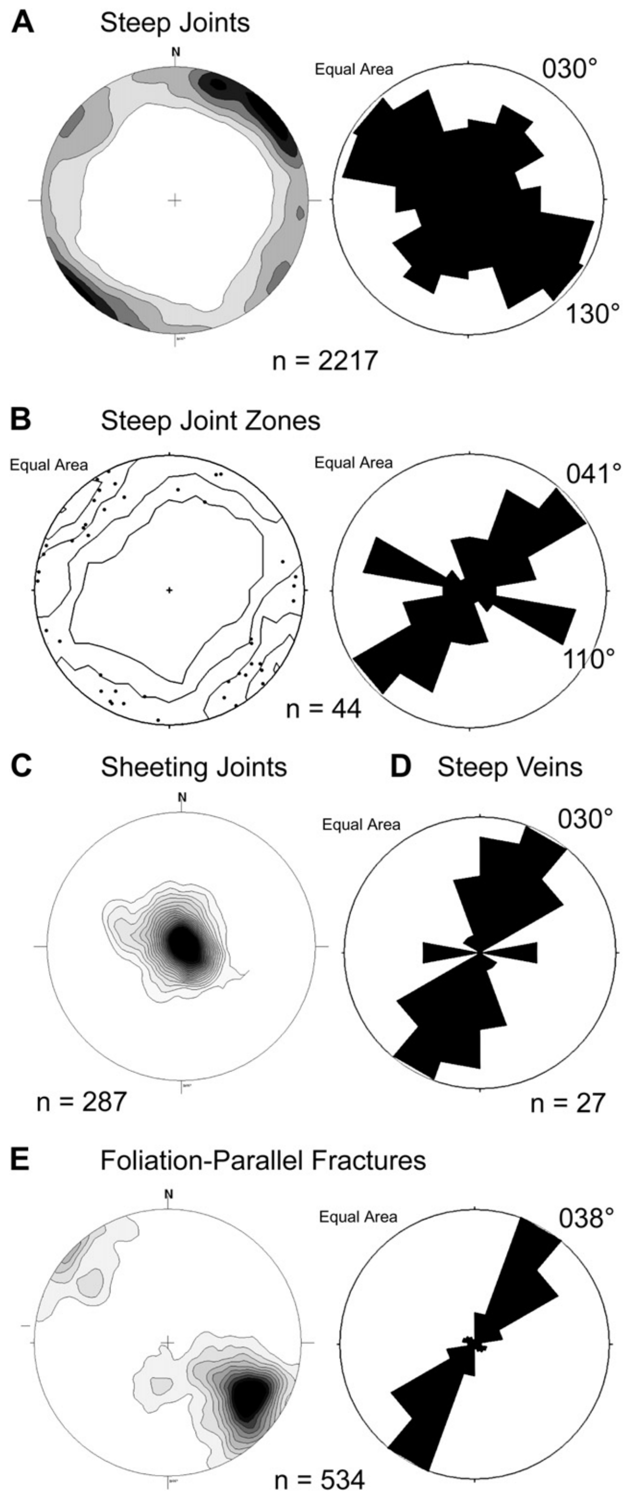

Fig. 3. Contour stereoplots (lower hemisphere, equal area) and rose diagrams showing the orientations of different fracture types. (A) 1% area-contour plot of poles to joints with steep dips. Rose diagram shows two major sets trending ~030° and ~130° are prominent. (B) Kamb contour plot of poles to joint zones with steep dips. Contour interval = 2.0, and significance level = 3σ. Rose diagram shows two prominent sets. (C) 1% area-contour plot of poles to sheeting joints. (D) Rose diagram of steeply dipping veins trending ~030°. (E) 1% area-contour plot of poles to FPFs and rose diagram showing fractures trending ~038°.

The aim of this paper is to present the results of fracture characterization data collected from 78 stations in the Nashoba terrane of eastern Massachusetts (Fig. 1). Over 3000 discontinuities that included joints and FPFs were identified and fracture attributes (i.e. trace-length, spacing, termination and orientation) were recorded. The data were evaluated to determine (1) the influence of lithology, and in particular rock fabric on fracture attributes and, (2) the potential influence of fracture type and distribution on subsurface fluid flow properties.

2. Geologic setting

The Nashoba terrane is a fault-bounded sliver of early Paleozoic high-grade metamorphic rocks dominated by thick sequences of mafic volcanic and volcanogenic sedimentary rocks and intrusive plutonic rocks (Goldsmith, 1987; Hepburn et al., 1993). The Nashoba is separated from the Merrimack belt to the northwest by the Clinton-Newbury fault zone and from the composite Avalon terrane on its southeastern flank by the Bloody Bluff fault zone (Fig. 1). Thick sequences of calcareous metasiltstones, pelites and impure quartzites underlie the region of the Merrimack belt northwest of the Nashoba terrane whereas the Avalon terrane just to the southeast is underlain by calc-alkaline plutonic-volcanic and metasedimentary units (Zen et al., 1983; Robinson and Goldsmith, 1991).

For this study, five significant rock groups based on areal coverage, location, lithology and number of outcrops in particular units, were identified and assembled: (1) the Newbury Volcanics, (2) the Sharpners Pond Diorite, (3) the Andover Granite, (4) the Nashoba Formation, and (5) the Marlboro Formation (Table 1). Simplification of the geology of the Nashoba terrane into five groups enables an analysis and comparison of attributes without the added complication of evaluating attributes based on a large number of variables (i.e. rock types).

Ordovician age strata of the Nashoba terrane include the Nashoba (i.e. metasedimentary rocks) and Marlboro (i.e. mafic volcanic and associated sediments) Formations (Hepburn et al., 1993). In the Silurian, these rock units were deformed and metamorphosed to gneisses, schists and amphibolites under sillimanite and sillimanite K-feldspar zone conditions (Bell and Alvord, 1976; Goldsmith, 1991). The units of the Marlboro Formation are interpreted to have a volcanic, convergent margin arc or marginal basin origin (DeNitto et al., 1984; Acaster and Bickford, 1999). Although the Nashoba Formation has subordinate units of rusty weathering sillimanite bearing schists, impure quartzites and marbles, and calcsillicate gneisses and amphibolites, the formation is composed predominantly of biotite-feldspar quartz gneisses and schists that originated from a volcanic source area (Abu-Moustafa and Skehan, 1976; Hepburn et al., 1993).

Plutonism in the terrane was widespread from late Ordovician to early Silurian when the Sharpners Pond Diorite and the Andover Granite intruded the stratified units of the Nashoba and Marlboro Formations (Goldsmith, 1987). The Sharpners Pond Diorite, an intermediate composition dioritic to tonalitic calc-alkaline magma unit, underwent little or no deformation as evidenced by a weak foliation (Hepburn et al., 1993).

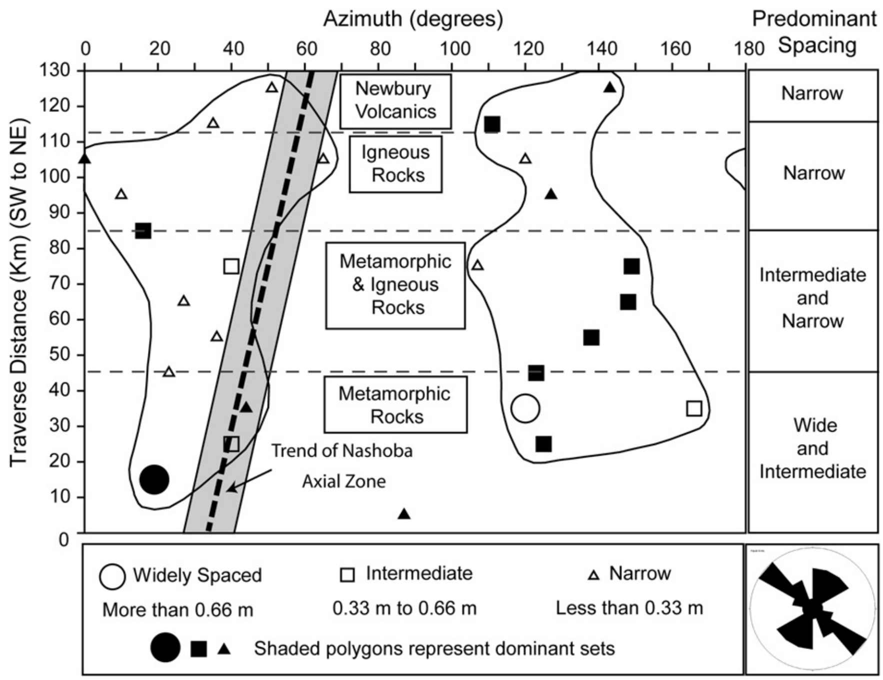

Fig. 4. (A) AVTD plot derived from azimuths of steeply dipping joints within 10 km wide sampling windows along the Nashoba axial traverse (Fig. 1). Dark band shows trend change of the axial zone. A rose diagram created by data retained after applying the AVTD method shows a bimodal distribution of joint sets trending ∼030° and ∼130°. Joint spacing decreases along the traverse from the southwest to the northeast possibly as a consequence of rock type.

Rock units of the Andover Granite vary in both composition and texture. Granitic composition ranges from metaluminous to peralunimous, and texture varies from foliated biotite and biotite-muscovite granite to unfoliated garnet-bearing muscovite granite and pegmatite.

The Newbury Volcanics, which occur in the northeast Nashoba terrane as a series of andesitic and rhyolitic volcanic rocks with a continental-arc origin, are interbedded with sedimentary rocks containing Silurian/Devonian fossils (Shride, 1976; Zen et al., 1983). A flow-banding texture is prominent in the rhyolites. Although units of the Newbury Volcanics are tilted, they are unmetamorphosed.

Ductile shear zones, foliation, and folds at various scales are present in the terrane. Brittle structures in the terrane include joints and FPFs (Fig. 2). Intra-terrane faults in the Nashoba terrane are sub-parallel to the inter-terrane faults that

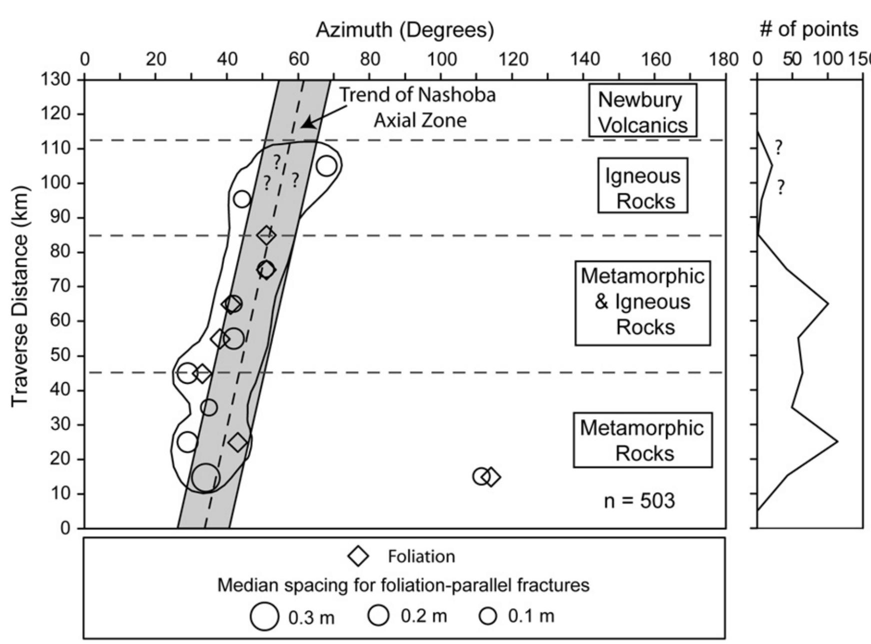

Fig. 5. AVTD plot for FPFs with steep dips. The general trend of the FPFs and foliation sub-parallels the trend of the Nashoba axial zone. The spacing of FPFs is generally narrow.

separate the Nashoba from the Avalon terrane and the Merrimack belt. Kinematically, the inter-terrane faults have been described as strike-slip features that underwent a complex history from the Precambrian to the Mesozoic (Goldsmith, 1991; Goldstein, 1992; Rast et al., 1993).

3. Data collection and analysis

3.1. Brittle fracture description

Most of the stations in the study area were road cuts with three-dimensional views of fractures. A technique similar to the selection method (Marshak and Mitra, 1988) was used to collect fracture data from each station. In this method, fracture sets are first identified visually by walking along the outcrop face. Once an estimate of the number of fracture sets is determined, fracture characteristics are collected from fractures belonging to each set. Usually, every other fracture in a particular set is recorded depending on the size of the outcrop and physical access. Fracture spacing is always measured as the perpendicular distance to the next fracture exhibiting the same orientation, recognizing that it becomes increasingly more difficult to measure the spacing of fractures sub-parallel to the outcrop face. In such cases, an effort was made to project the planes of these sub-parallel fractures away from the outcrop face using two people with field notebooks. In some instances, it was not possible to record the spacing.

All orientation data were plotted in the field using a Biemsderfer plotter (Wise, 2005). General clusters were noted on a plot, assigned to a set and compared visually with those sets identified in the initial walking survey. The advantage of the selection method is reduced field time during data collection compared with the line survey method. In this study, fracture spacing was used instead of intensity (the number of fractures per unit length) because intensity does not provide variance of fracture spacing distances between adjacent fractures (Bertotti et al., 2007).

Brittle features identified in the study region are joints, joint zones, sheeting joints, veins and FPFs (Fig. 3). Joints, the most abundant type of fractures in the terrane (Fig. 3A), are dilatational features (Mode I) that form by displacement of fracture walls approximately normal to the fracture plane (Pollard and Aydin, 1988; Peacock, 2001). Joint zones consist of closely spaced joints of similar orientations (Fig. 3B). For this study, sheeting joints are defined as sub-horizontal fractures that typically have dips less than 25° (Fig. 3C). Sheeting joints are assumed to be pervasive because they were recorded at 74% of the stations in the terrane. Although veins are sub-parallel to the trend of one of the major joint sets (Fig. 3A and D), most joints in the terrane are unfilled fractures. The majority of veins in the study region had quartz mineralization.

FPFs consist of fractures that are parallel to the dominant penetrative fabric in crystalline rocks (Figs. 2D and 3E). These fractures are parallel to both the strike and dip of the fabric which serves as an orientation of weakness when rocks undergo brittle deformation closer to the surface (Eyal et al., 2006). FPFs are not abundant in the three igneous units (Andover Granite, Sharpners Pond Diorite and the Newbury Volcanics) because there is no foliation or the degree of foliation development is weak (Table 1).

3.2. Fracture orientation analysis

Equal-area nets of all fracture types show at least one northeast trend for the major sets of steeply dipping fractures (Fig. 3). Two regional joint sets trending 030° and 130° are prominent in the contoured equal area nets and rose diagrams (Fig. 3A). Although equal-area nets representing fractures at each station can be used to evaluate the spatial distribution of fracture orientations within a region, a modified version of the azimuth versus traverse distance (AVTD) plot provides an easier way to summarize and analyze regional fracture orientation data (Wise and McCrory, 1982). Because the AVTD method relies on using features that can be represented by strike alone, only steeply dipping fracture planes (≥60° dip) are used in its construction. Although dip information and a fraction of the data (~20%) are sacrificed for strike during the construction of an AVTD plot, the method still provides a practical tool for evaluating spatial changes in fracture orientation. A rose diagram created by joint data retained after applying the AVTD method (Fig. 4) shows two major trends that parallel those in Fig. 3A, suggesting that strike information was not being biased by the filtering process of the AVTD method.

Major orientations of fracture planes derived from all stations that fall within 10 km wide sampling windows placed along the axial line of the Nashoba terrane were plotted as a function of traverse distance (Figs. 4 and 5). Two populations of joints clustering about ~030° and ~130° (Fig. 4) correspond to the major fracture orientations (Fig. 3A), whereas the trends of FPFs change in parallel with the Nashoba axial zone (Fig. 5).

3.3. Fracture termination

An assessment of fracture terminations for all steep joints reveals that through-going joints are the most abundant

Table 2
Fracture trace-length statistics for all steep joints, steep joint sets clustered about 030° and 130° (±5°), and FPFs

Fracture type	Trace-length (m)					
	Uncensored mean	Censored mean	Censored median	Censored min	Censored max	Censored n
Steep joints	10.3	2.19	1.50	0.05	40.0	2106
030° joints	11.7	2.52	2.00	0.10	14.0	156
130° joints	10.0	2.50	1.50	0.20	20.0	201
All FPF	10.6	2.71	1.50	0.12	22.0	462

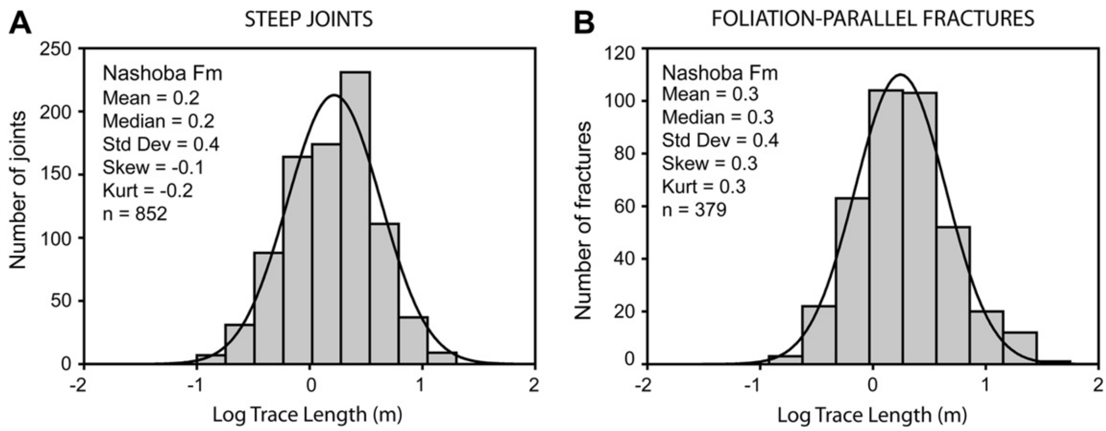

Fig. 6. Examples of frequency distribution plots of the trace-length of (A) joints, and (B) FPFs derived from the Nashoba Formation. Note that the statistics are in log base 10.

(41%), followed by joints with T-terminations (31%) and blind (28%) fracture terminations. Through-going fractures span the entire outcrop, blind fractures begin and end within the outcrop, and fractures with T-terminations abut against other fractures. Although FPFs that were through-going were the most abundant (42%), the proportion of FPFs with blind terminations (34%) was more than those with T-terminations (24%). At stations where foliation has a moderate to shallow dip, sub-horizontal (sheeting) joints are absent.

3.4. Fracture trace-length distribution

Fracture trace-length was determined by measuring lengths of fractures along the outcrop in any direction without regard to the number of segments that constituted the fracture. Most fractures in the study area consist of fracture segments that are not offset from other segments (Fig. 2). Although distributions of fracture traces are influenced by the presence of other fractures, the distributions are also affected by censoring and truncation effects. A threshold size for trace-length of 5 cm was therefore used to maximize sampling and minimize the effect of truncation. The data are also affected by censoring because outcrop size relative to the largest fracture is small. To minimize the effect of censoring, fracture data were first collected where possible, from the largest outcrops (at least 85% of outcrops have long dimensions ≥5 m). The mean uncensored trace-length was then calculated and compared to the mean censored trace-length to evaluate the degree of censoring on the data. The mean uncensored trace-length is given by (Priest and Hudson, 1981):

$$u = \frac{-\log[(n-r)/n]}{c} \qquad (1)$$

where $1/u$ is the mean uncensored trace-length, n is the number of fractures sampled, r is the number of uncensored fractures, and c is the length at which censoring occurs. We calculated r by using the percentage of fractures that had T-terminations and blind fracture terminations (e.g. 59% for all steep joints). Because most fractures are steeply dipping, c is assumed to equal the median outcrop height (∼4 m).

Fracture trace-length statistics for all steep joints, steep joints that cluster about 030° and 130° (±5°), and FPFs are summarized in Table 2. The results indicate that the mean uncensored trace-lengths are ×4 the censored values. These results suggest that censoring affects the mean values of mesoscopic fractures to a much greater extent than truncation. Unfortunately, Eq. (1) provides only mean values of trace-lengths whereas fracture attribute evaluations and creation of numerical models of discrete fracture networks usually require frequency distributions and/or median values. Accordingly, data used for comparisons and modeling throughout the remainder of this paper are based on the censored population.

Power-law and exponential distribution functions poorly describe the censored trace-length data of the joint and FPF populations. Instead, visual inspection, statistical parameters and goodness-of-fit tests reveal that the statistical distributions that best describe the length populations of traces for steep joints and FPFs are lognormal (Fig. 6). Although fewer FPFs than steep joints were recorded in the study region, FPFs have comparable trace-lengths to all steep joints (Table 2). The median trace-length for all FPFs is equal to that of steep joints and joints in the 130° set (1.5 m), whereas the median trace length for joints in the 030° set is 0.5 m longer (Table 2). The maximum length for all steep joints is almost ×2 that for FPFs. This difference is probably an artifact of censoring.

Table 3
Fracture trace length statistics for all steep joints and FPFs according to rock groups

Statistic	Fracture trace-length (m)									
	Marlboro		Nashoba		Newbury		Andover		Sharpners	
	Joints	FPF	Joints	FPF	Joints	FPF	Joints	FPF	Joints	FPF
Mean	2.18	2.33	2.25	3.17	1.32	–	2.32	1.23	2.17	0.87
Median	1.50	1.50	1.50	2.00	1.00	–	1.73	1.00	1.30	0.60
SD	2.10	2.60	2.30	3.50	1.00	–	2.10	0.30	3.00	0.80
Min	0.05	0.25	0.10	0.12	0.10	–	0.10	0.20	0.13	0.20
Max	15.0	15.0	20.0	22.0	5.50	–	25.0	3.00	40.0	3.00
n	289	62	852	379	102	0	486	32	377	20

Table 4
Fracture spacing statistics for all steep joints, steep joint sets clustered about 030° and 130° (±5°), and FPFs

Fracture type	Spacing (m)				
	Mean	Median	Min	Max	*n*
Steep joints	0.28	0.30	0.01	10.0	1715
030° joints	0.59	0.30	0.02	5.00	125
130° joints	0.71	0.40	0.01	10.0	157
All FPF	0.28	0.15	0.01	5.00	437

Plots of frequency distributions of fractures in all rock types, and results from goodness-fit tests can be found in the supplementary materials that accompany this paper.

The median lengths of traces for FPFs appear to vary as a function of the degree of foliation development. Rock groups with moderately/strongly developed foliation (Nashoba and Marlboro Formations) have the longest FPF traces, whereas rock units with weakly developed foliation (Andover Granite and Sharpners Pond Diorite) have the shortest FPF traces (Table 3). The median trace lengths for joints in different rock units are close to 1.5 m, except in the Newbury Volcanics where the median trace length is 1 m. These observations suggest that the degree of development of foliation has a greater influence on the median trace lengths of FPFs than joints.

3.5. Fracture spacing distribution

Fracture spacing statistics for all steep joints, steep joints that cluster about 030° and 130° (±5°), and FPFs were also collected (Table 4). In general, joint spacing decreases from the southwest to the northeast in the terrane: widely spaced joints are more common in the metamorphic and igneous rocks that dominate in the southwest of the terrane, whereas joint spacing is narrower in the northeast, where plutonic and volcanic rocks dominate (Fig. 4). Widely spaced joints are also more prevalent in the set clustered about ∼130° than ∼030° (Table 4; Fig. 4). Frequency distributions of spacing reveal a lognormal distribution for steep joints in each lithologic group of the Nashoba terrane (e.g. Fig. 7A), which are similar to those observed in sedimentary and other crystalline rocks (e.g. Rives et al., 1992; Narr and Suppe, 1991). FPFs in the Nashoba terrane range in fracture spacing from less than 0.1 to about 5 m with a median spacing of 0.15 m, half that of steep joints (Table 4). Frequency distributions of FPFs are also best described by lognormal functions (e.g. Fig. 7B).

Median spacing for steep joints in particular lithologic groups was plotted as a function of traverse distance (Fig. 8A). The values plotted are derived from fracture sets that are in particular windows along the Nashoba axial traverse. All joint sets in moving windows of the Marlboro Formation, Sharpners Pond Diorite and Newbury Volcanics have median spacing of less than 0.5 m (Table 5). In contrast, the Andover Granite and Nashoba Formations have a wider range of median spacing for joint sets. These results suggest that the spatial distribution of fractures is not uniform, but varies markedly especially at the regional scale where the clustering of joints in and around smaller scale features such as joint zones may influence the regional distribution of fractures. An example of the variation of median fracture spacing within steep joint zones in the Nashoba terrane is shown in Fig. 9. A plot of median joint spacing versus distance from map-scale faults (1:250,000) (Zen et al., 1983) reveals that fracture density is unaffected by proximity to those faults (Fig. 10), implying that joints either pre- or post-date the faults in the study region (e.g. Peacock, 2001).

The AVTD plot in Fig. 5 suggests that the median fracture spacing for FPFs is not affected by lithology. However, a detailed analysis of fracture median spacing for FPFs reveals that median spacing differs within lithologic groups (Fig. 8B). Median spacing for fractures in the Andover Granite and the Nashoba Formation range narrowly between 0.05 and 0.4 m. In contrast, the median spacing for fractures in the Marlboro Formation has a wider range of between 0.05 and 1 m. The aggregation of various rock types in the Marlboro Formation accounts for this wide distribution.

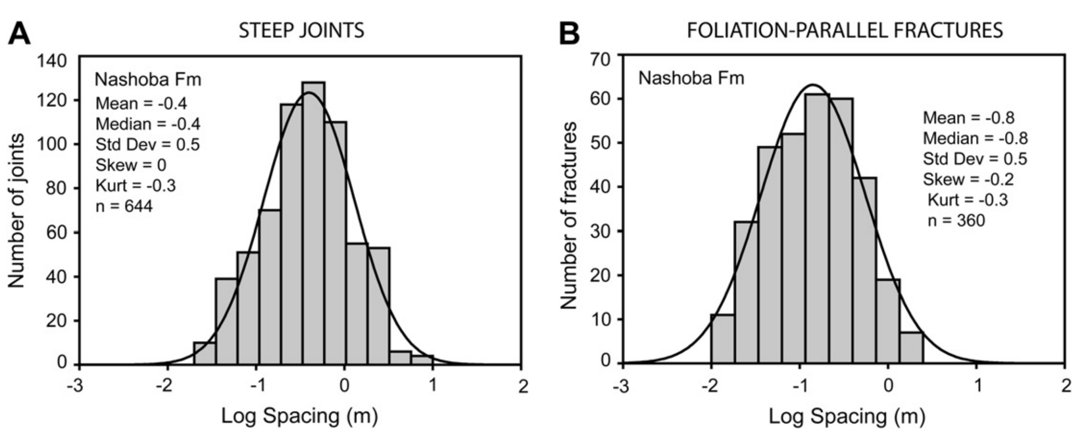

Fig. 7. Examples of frequency distribution plots of the spacing of (A) joints, and (B) FPFs derived from the Nashoba Formation. Note that the statistics are in log base 10.

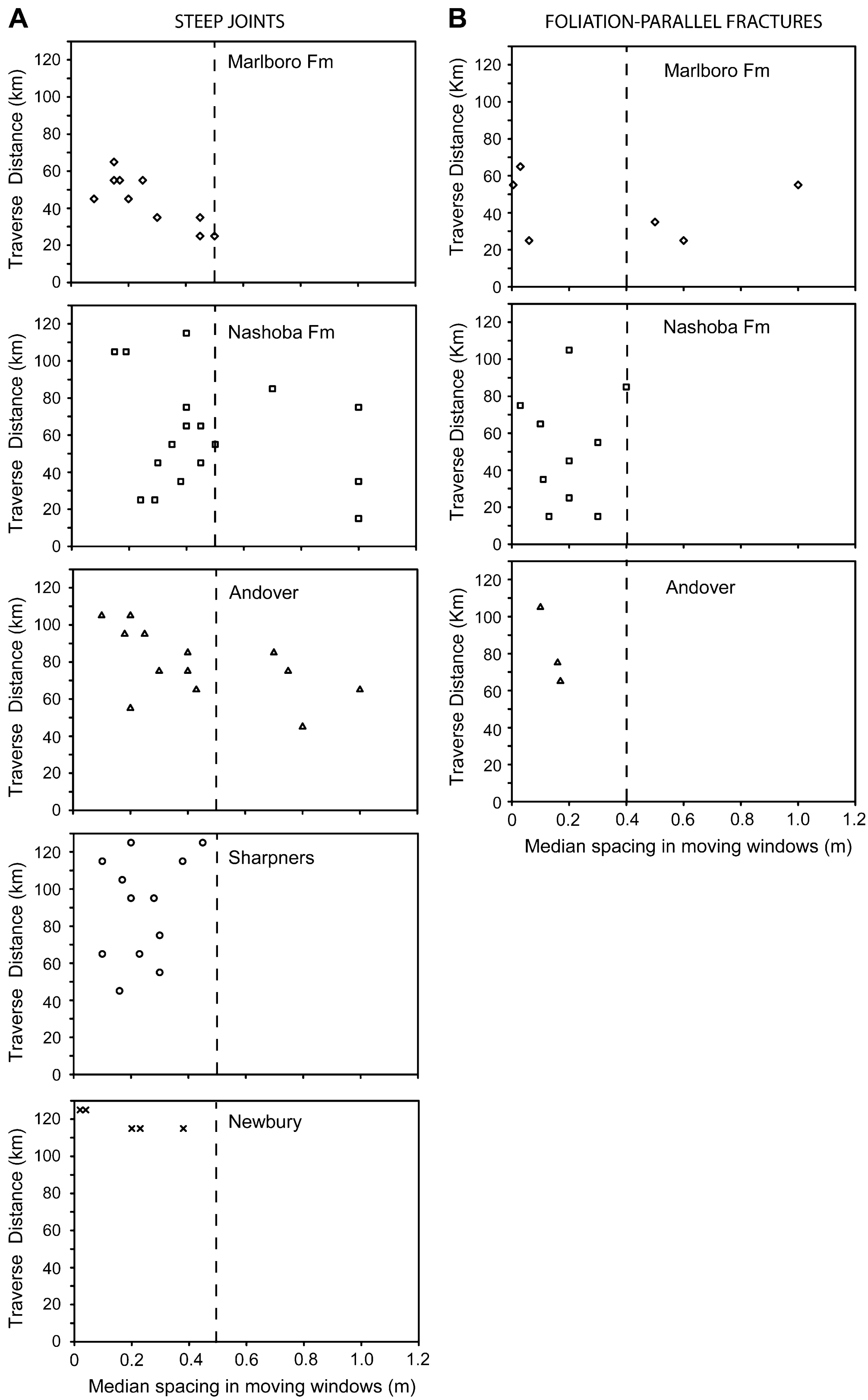

Fig. 8. Plots of median fracture spacing as a function of traverse distance and major rock group. (A) Steeply dipping joints in various rock groups. Joints in the Nashoba and Andover Formations show a wide distribution of median joint spacing. Median joint spacing in the other rock groups is consistently less than 0.5 m (vertical line). (B) FPFs in foliated rock groups. FPFs in the Marlboro Formation have a wide distribution, whereas the median spacing for FPFs in the Nashoba Formation and Andover Granite is consistently less than 0.4 m (vertical line).

Table 5
Fracture spacing statistics for all steep joint and FPF attributes according to rock groups

Statistic	Fracture spacing (m)									
	Marlboro		Nashoba		Newbury		Andover		Sharpners	
	Joints	FPF	Joints	FPF	Joints	FPF	Joints	FPF	Joints	FPF
Mean	0.43	0.45	0.70	0.27	0.31	–	0.71	0.20	0.41	0.20
Median	0.25	0.10	0.40	0.15	0.10	–	0.40	0.14	0.20	0.15
SD	0.50	0.80	1.00	0.30	0.50	–	1.00	0.20	0.60	0.20
Min	0.01	0.01	0.02	0.01	0.01	–	0.02	0.02	0.01	0.03
Max	3.40	5.00	10.0	2.50	2.00	–	10.0	0.80	7.00	0.80
n	249	55	644	333	92	0	393	30	337	19

3.6. Discrete fracture network modeling

Numerical simulations of groundwater flow were conducted to assess the influence of FPFs on hydraulic properties of discrete fracture networks using procedures adapted from Caine and Tomusiak (2003). A model region (Fig. 11) was populated with fractures using statistics of fracture sets derived from the Hudson quadrangle, Massachusetts (Table 6). Groundwater flow was then simulated through the fractures in three mutually perpendicular directions: east–west, north–south and top–bottom. Two scenarios, the first with joints and FPFs, and the second with only joints were used to assess changes in hydraulic properties. Hydraulic conductivity results show that the most conductive flow direction was top–bottom, and the least was east–west for both scenarios (Table 7). However, hydraulic conductivity was consistently greater for models with the additional FPFs (scenario 1) as compared to those lacking FPFs (scenario 2).

These results indicate that FPFs account for ~20–30% of the conductivity of the modeled fracture networks. In addition, the large conductivity value in the top–bottom direction suggests that the fracture networks used in these scenarios have a high potential for recharge. According to the results (Table 7), conductivity is high in the N–S direction because all steeply dipping fracture sets (joint sets A, B, C and FPFs) are slightly off parallel to the N–S direction (Table 6). The inference made here that the trends of the joints and FPFs control the permeability of the domain is supported by Zhang et al. (2004) who determined that a major joint set was subparallel to the principal vector of a permeability tensor in a fractured rock mass in their field area. A detailed description of numerical simulations of groundwater flow in discrete fracture networks is beyond the scope of this paper.

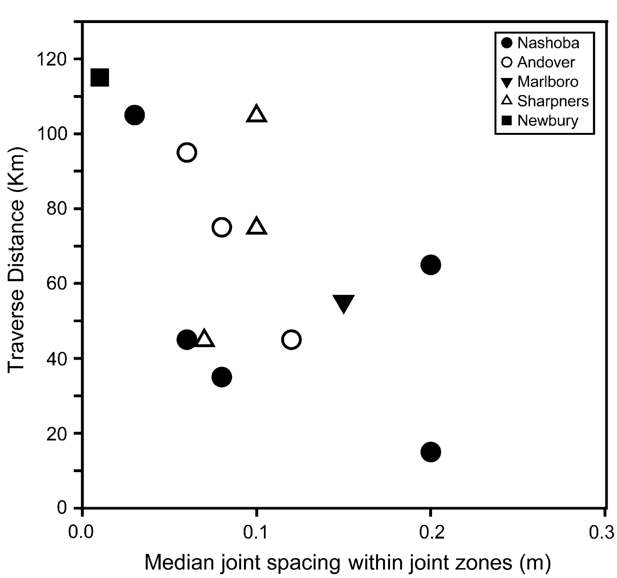

Fig. 9. Plot of median spacing of steep joints within joint zones versus traverse distance. The median joint spacing within joint zones is equal to or less than 0.2 m in all rock groups. Joint zones are up to 10 m wide.

4. Discussion

Brittle features not only influence the physical and mechanical characteristics of rocks, but also control fluid migration and storage in the subsurface (Taylor et al., 1999; La Pointe, 2000). In this study, fracture networks on the surface are assumed to represent those in the shallow subsurface (≤100 m). Fracture attributes collected from outcrops therefore shed light on fluid flow in the shallow subsurface. Fracture orientation, spacing and trace-length distributions control groundwater movement and storage because these parameters determine the density and connectivity of fracture networks.

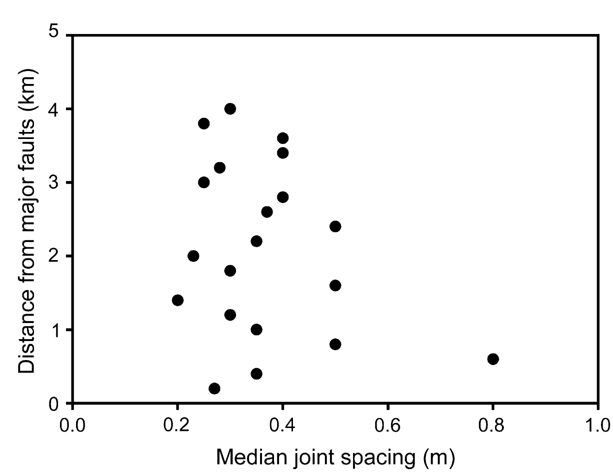

Fig. 10. Plot of median joint spacing versus distance from inter- and intraterrane faults.

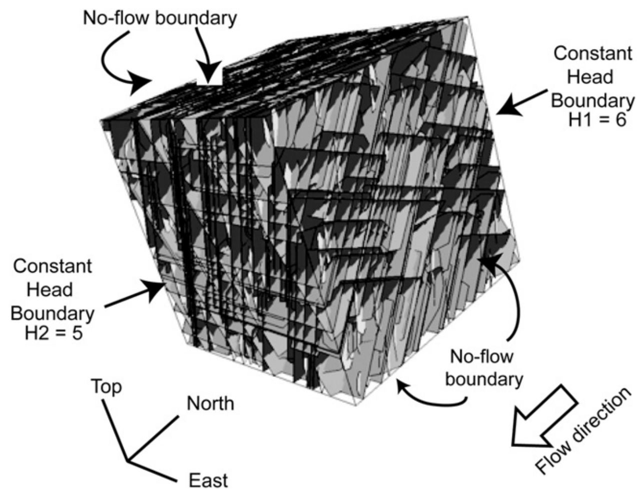

Fig. 11. An example of the set up and boundary conditions used to simulate groundwater flow in discrete fracture networks. In this example, groundwater was simulated to flow in fractures from north to south under a hydraulic gradient of 0.1. Flow in other directions was simulated by switching the boundary conditions of the 10 × 10 × 10 m model region.

The presence of multiple fracture types and sets in the study region (e.g. two steeply-dipping joint sets, sheeting joints and FPFs; Fig. 3), a large proportion of through-going and T-termination fractures, and the results of numerical simulations suggest that fracture networks in the terrane are well connected. Fracture sets with narrow spacing not only act as additional conduits through which water can flow and be stored, but also enhance the connectivity of fracture networks by increasing the number of intersections with other fractures (Long et al., 1982; Renshaw, 1999; Caine and Tomusiak, 2003). An increase in fracture trace-length also increases the connectivity of fracture networks (e.g. Long and Witherspoon, 1985). The effective result of increasing connectivity by adding fracture sets with narrow spacing and/or long trace-lengths is to enhance the permeability of fracture networks (Long et al., 1982; Long and Witherspoon, 1985).

Fracture spacing, it appears, is influenced by the presence of multiple rock units such as amphibolites, schists and gneisses interlayered in the Marlboro Formation (Fig. 12). Gneisses have the widest spacing between FPFs, whereas amphibolites and schists have the narrowest. The Nashoba Formation has a smaller range of fracture spacing possibly because it has fewer rock types, and is therefore not as interlayered as the Marlboro Formation. Moreover, the median spacing for FPFs in the different rock types of the Nashoba Formation are comparable because massive gneissic rocks are the more prevalent units in the Nashoba Formation. These observations suggest that the spacing distribution of all FPFs in a particular rock type will be influenced by the location of pre-existing foliation. If the foliations are planes of weakness to be reactivated as FPFs (Eyal et al., 2006), then fracture spacing will vary as a function of the rock type and the degree to which particular planes fail under shear stresses. It is evident that in both the Marlboro and Nashoba Formations (Fig. 12), FPFs in addition to joints, will influence fracture connectivity particularly where FPFs have the narrowest spacing and longest trace-lengths (e.g. mylonites and gneisses in the Nashoba Formation).

In regions where joints are either poorly developed and/or have negligible apertures, transmissive FPFs may control the groundwater flow regime (Lyford et al., 2003). FPFs may therefore, not only increase fracture connectivity, but may also impart flow anisotropy on the groundwater system (Fig. 13). Although this conclusion, and those drawn from results of numerical simulations, are made with simplistic assumptions in mind (i.e. all fractures participate in flow, all fractures act as parallel, smooth-walled conduits, and apertures for all fractures are the same) this procedure is usually undertaken in groundwater modeling studies as a necessary first step to isolate the role of connectivity in fracture networks (e.g. de Dreuzy et al., 2001; Min et al., 2004). Thus, the results presented here are upper bound estimates only.

The same aperture was utilized for all fracture sets and types in the numerical simulations because apertures of open fractures are subject to local variations in stress fields and rock properties (Barton and Hsieh, 1989; Vermilye and Scholz, 1995). These variations may cause fracture apertures in surface outcrops to be considerably different from those in the subsurface, although other corresponding attributes (e.g. trace-length and spacing) may be comparable. Furthermore, apertures of open fractures may be significantly affected by exposure to surface weathering and measurement techniques that do not take into account fracture roughness (Barton and Hsieh, 1989; Hakami and Barton, 1990; Hsieh et al., 1993).

Although the authors recognize that relations between fracture trace-length, spacing (intensity) and aperture have been reported in the literature (e.g. Olson, 2003; Ortega et al., 2006; Baghbanan and Jing, 2007), they did not find it prudent to collect and then relate fracture aperture to other fracture attributes because the results would be misleading, particularly because they are considering un-mineralized open fractures in surface exposures. Nevertheless, assessing trace-length and

Table 6
Statistics of fracture sets derived from the Hudson quadrangle used in discrete fracture network modeling

Set	Strike and dip[a]	Median spacing (m)	Median trace length (m)
Joints A	142/73	0.5	1.1
Joints B	226/71	0.2	1.5
Joints C	015/75	1.0	1.6
Sheeting	007/11	0.4	2.9
FPF	219/74	0.3	1.5

[a] Right hand rule.

Table 7
Results of numerical modeling experiments

Fracture Sets	Hydraulic conductivity × 10^{-9} (m/s)		
	E–W	N–S	Top–bottom
Joints and FPF	3.2	4.6	6.7
Joints only	2.6	3.6	4.6

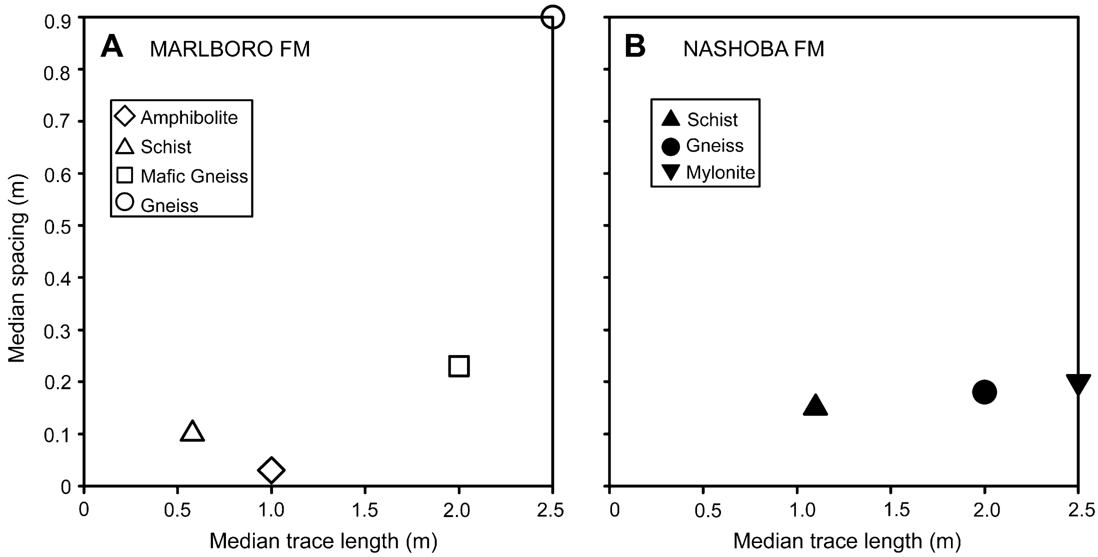

Fig. 12. Plots showing variation of median fracture spacing with median trace-length for (A) FPFs from the Nashoba Formation, and (B) FPFs from the Marlboro Formation.

spacing distributions of joints and FPFs without aperture data has value because a relative assessment of the physical and hydraulic characteristics of these features increases our understanding of the role that they play for fluid flow in natural fracture networks.

5. Summary and conclusions

Attributes of over 3000 joints and FPFs were recorded at 78 stations in the terrane. Fracture orientation, trace-length and spacing data were analyzed to assess the influence of lithology

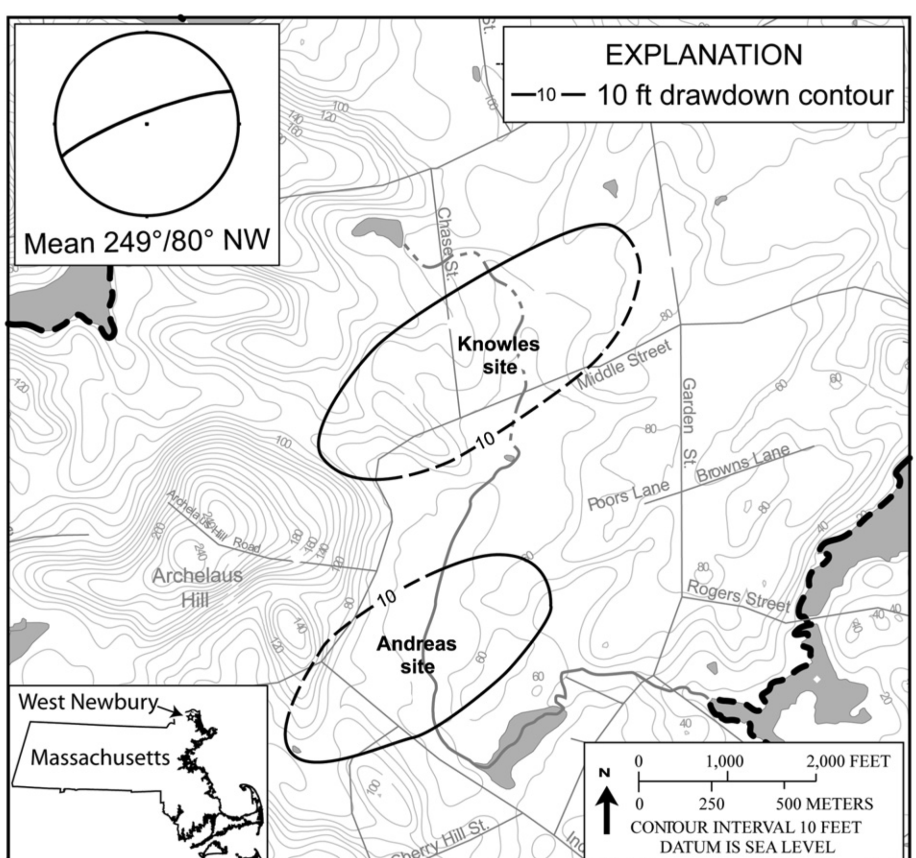

Fig. 13. Illustration of the effect FPFs on hydraulic properties as shown by elliptical drawdown contours during a USGS aquifer test at the West Newbury site, eastern Massachusetts. The long axes of the ellipses are sub-parallel to field measured FPFs with mean orientation of 249°/80° (insert equal area net) (modified after Walsh (2001) and Lyford et al. (2003)).

and fabric on fracture attributes, and to assess the influence of fracture types and attributes on groundwater flow.

(1) Two regional joint sets with trends of 030° and 130° are the major sets in the terrane. The orientation of joints is independent of rock type while foliation and FPFs are sub-parallel to the axis of the Nashoba terrane. Sheeting joints are also pervasive in the terrane.
(2) Trace-length distributions for joints and FPFs are best described by lognormal distributions. Although the median trace-lengths for steep joints and all FPFs are comparable, the median trace-lengths for FPFs vary as a function of the degree of foliation development.
(3) Spacing distributions for joints and FPFs are best described by lognormal distributions. In general, joint spacing is influenced by lithology and decreases from the southwest to the northeast across the terrane. The median fracture spacing for all FPFs is half that of all steep joints.
(4) The median spacing varies markedly between steep joints and FPFs in different rock groups. Although joint spacing is narrow in joint zones, proximity to map scale inter- and intra-terrane faults does not influence joint spacing. The wide distribution of median spacing for FPFs in particular rock groups is explained by lithologic differences and the presence of multiple units with varying degrees of penetrative fabric development. FPFs in the Marlboro Formation appear clustered because there are many more rock units that are interlayered and the median fracture spacing within units vary distinctly.
(5) The similarity of fracture characteristics between FPFs and joints suggests that FPFs may provide supplementary avenues for groundwater storage and recharge in addition to joints.
(6) Qualitative assessments of attributes of fractures (i.e. spacing and trace-length) reveal that FPFs may enhance the transmissive properties of fracture networks by increasing fracture connectivity and/or may impart flow anisotropy on fractured media. Numerical modeling experiments show that FPFs account for between 20 and 30% of flow in fracture networks.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.jsg.2007.12.006.

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