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BEDROCK GEOLOGY IN THE VICINITY OF THE LEICESTER WELL SITE, PAXTON, MASSACHUSETTS

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On the cover:
Photograph of Little Asnebumskit Hill from the west side of the dam at the north end of Asnebumskit Pond. View is to the south, left is east.

INTRODUCTION

The Leicester public water supply well site is located approximately 1 km east of downtown Paxton, Massachusetts (fig. 1). New geologic mapping was conducted in the vicinity of the well site in June 2001 to characterize the bedrock geology more accurately than what was available in published reports. The characterization of the bedrock geology is part of an ongoing study on estimating contributing areas to public-supply wells and hydrologic responses to pumping in fractured-bedrock aquifers (Lyford and others, in press). This report is the third of three similar geologic studies on the fractured bedrock in eastern Massachusetts (Walsh 2001a, b). The purpose of this study is to describe the characteristics of the bedrock that may influence ground water flow and to identify potential directions of anisotropy in the fractured bedrock. Readers unfamiliar with terminology in this report are referred to Jackson (1997).

PREVIOUS WORK

The geology of the Paxton 7.5-minute quadrangle depicted by Zen and others (1983) on the State bedrock geologic map represents 1:250,000-scale compilation of unpublished work by Peter Robinson and his students M.T. Field, I.E. Belvin, R.P. Tollo, and R.D. Tucker at the University of Massachusetts in the 1970s. A discussion of the compilation work for the State map, published by Robinson and Goldsmith (1991), presents a comprehensive treatment of the regional geology. Robinson and Goldsmith (1991) includes a number of sketch maps showing the bedrock geology in the vicinity of Paxton, and the supporting evidence for features drawn on the State map.

The new mapping (fig. 1) agrees fairly well with the work by Zen and others (1983) and Robinson and Goldsmith (1991) in regards to the distribution of units in the vicinity of the well site. The new mapping shows the contacts more accurately, at a scale of 1:25,000, locates small igneous bodies, shows outcrop distribution, and illustrates structural relations not portrayed on the previously published maps.

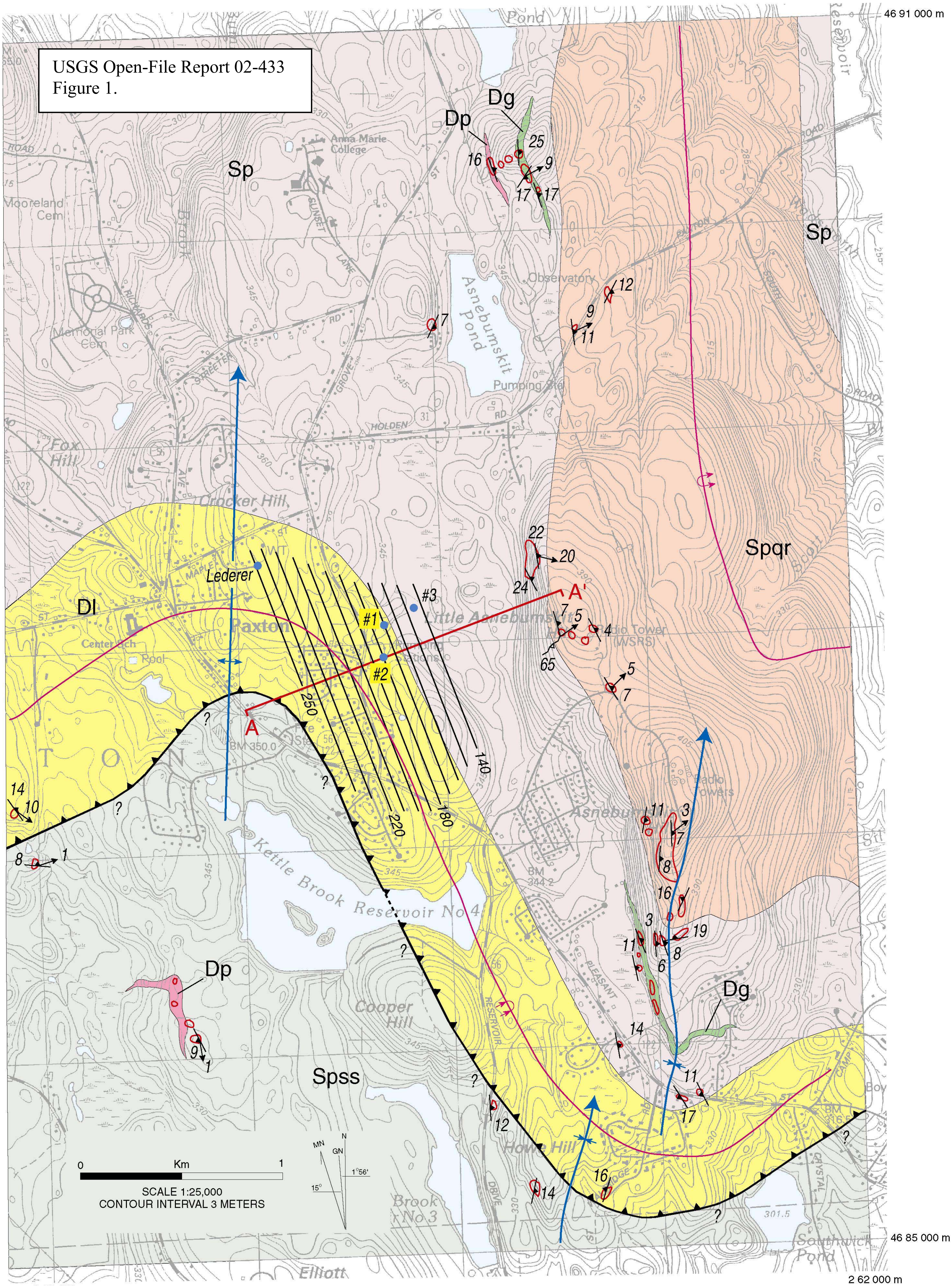
STRATIGRAPHY

The well site is located within the Silurian Paxton Formation and Devonian Littleton Formation (fig. 1), and is considered part of the Merrimack Belt by Zen and others (1983). Other rock units in the area include Devonian pegmatite and granite sills (fig. 1).

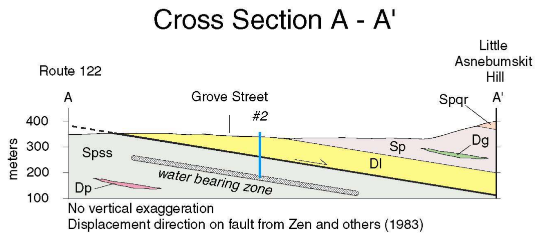
Paxton Formation

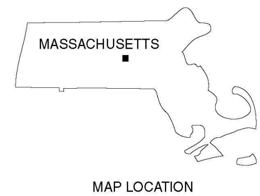
The Paxton Formation contains three distinct metasedimentary units (fig. 1): biotite and calc-silicate granofels (Sp), sulfidic schist (Spss), and sulfidic quartzite and schist (Spqr).

Figure 1 (next page). Bedrock geologic map in the vicinity of the Leicester well site in Paxton, Massachusetts.



Bedrock Geology in the Vicinity of the Leicester Well Site, Paxton, Massachusetts





Description of Map Units

Dp	Pegmatite (Devonian)
Dg	Granite (Devonian)

Littleton Formation (Devonian)

Dl	Gray mica schist and quartzite

Paxton Formation (Silurian)

Sp	Biotite granofels and calc-silicate granofels
Spss	Sulfidic schist
Spqr	Sulfidic quartzite and schist

Explanation of Map Symbols

Lithologic contact

? Conjectural thrust fault; teeth on upper plate, dotted where concealed by water

Axial trace of overturned F1 anticline

Axial trace of overturned F1 syncline

Axial trace of F4 anticline showing plunge direction

Axial trace of F4 syncline showing plunge direction

180 Structure contours on hypothetical water bearing zone beneath well site; elevation in meters (see Figure 9)

A A' Line of cross section

Outcrops examined in this study

Planar Features

7 Strike and dip of inclined S2 schistosity

65 Strike and dip of inclined deformed S1 schistosity

Linear Features

5 Trend and plunge of F2 fold axis or S1/S2 intersection

Wells

#1 Production wells at Leicester well site (#1 - #3)

Lederer Observation well discussed in text

Figure 1 (continued). Bedrock geologic map in the vicinity of the Leicester well site in Paxton, Massachusetts. Geology based on reconnaissance mapping in June 2001 and modifications after Zen and others (1983). Assisted by Jason R. Sorenson. Base map from the 1983 Worcester North, Massachusetts, 7.5 x 15 minute topographic map (scale 1:25,000). Structure contours on a hypothetical water-bearing horizon are from the three-point solution given in Figure 9.

The biotite and calc-silicate granofels unit (Sp) is a purplish gray, biotite-plagioclase-quartz granofels that contains thin interbedded green and pink, white-weathering, calc-silicate granofels layers. The calc-silicate rocks contain quartz, plagioclase, diopside, actinolite, clinozoisite, sphene, scapolite, grossular garnet, graphite, and calcite (Robinson and Goldsmith, 1991). Bedding thickness is on the order of tens of cms in the area and is locally difficult to distinguish in the small weathered outcrops; regionally it is reported to range from 2 to 30 cm thick in the biotite granofels and 1 to 5 cm thick in the calc-silicate granofels (Field, 1975; Tucker, 1977; Robinson and Goldsmith, 1991). A distinguishing characteristic of the unit is the slabby nature of the outcrops and the distinct parting exhibited by the rock along the foliation (fig. 2). The biotite and calc-silicate granofels unit is exposed from the well site eastward, largely on the west flanks of the ridge formed by Little Asnebumskit Hill and Asnebumskit Hill (fig. 1). Near the contact with the sulfidic quartzite and schist unit (Spqr), the Sp unit is more micaceous, sulfidic, and rusty weathering over a narrow zone, although the contact is not exposed in the area.

Figure 2. Photograph of the Paxton Formation granofels (Sp) illustrating the slabby nature of the rock due to parting fractures along the gently dipping plane of the S2 schistosity. Photo taken at the south end of Asnebumskit Hill. Cross-sectional view is to the north, left is west.

The sulfidic schist unit (Spss) is rusty weathering, sillimanite-muscovite-plagioclase-quartz schist. According to Robinson and Goldsmith (1991) the sulfide mineral is pyrrhotite. Locally, the unit contains abundant black tourmaline. Bedding was difficult to discern in the limited exposures of this unit. The rock also exhibits distinct parting along the foliation. The unit is exposed in the southern part of the map area (fig. 1). Robinson and Goldsmith (1991) noted that the sulfidic schist was generally absent from the Paxton Formation in the vicinity of the type locality at Paxton Falls, just west of the map area, 2.5 km west of downtown Paxton. The new mapping shows that the sulfidic schist is present in this area, at least to a limited extent.

Robinson and Goldsmith (1991) point out that the distribution of sulfidic versus non-sulfidic schist in the Paxton Formation presents a difficult mapping problem because of the similarity of the sulfidic schist to the Partridge Formation. Consequently, on the State map the two Paxton Formation units were combined into a single unit. Contacts between the sulfidic schist unit (Spss) and the other Paxton Formation units are not exposed.

The sulfidic quartzite and schist unit (Spqr) contains quartzite and interbedded, rusty weathering, sillimanite-muscovite-plagioclase-quartz schist. The quartzite is vitreous and the bedding is very poorly exposed. The quartzite and schist unit contains abundant vein quartz. The sulfidic schist in Spqr closely resembles the sulfidic schist unit Spss. The sulfidic quartzite and schist unit (Spqr) is exposed in glacially polished pavement outcrops along the ridge formed by Little Asnebumskit Hill and Asnebumskit Hill (fig. 1). Vertical exposures on the outcrops of the Spqr unit are rare in the area due to the flat pavement-style outcrops. The Spqr - Sp contact gently dips gently to the east, with the Spqr unit forming a resistant cap rock above the biotite and calc-silicate granofels unit (Sp). The topographic expression resembles a gently dipping hogback (cross-section A-A’ in fig. 1 and cover).

The age of the Paxton Formation is presumably Silurian based on regional stratigraphic correlations with fossiliferous rocks and its position beneath the overlying Devonian Littleton Formation and above the Lower Silurian Clough Quartzite (Robinson and Goldsmith, 1991).

Littleton Formation

The Littleton Formation (Dl) consists of interbedded gray to dark-gray biotite-muscovite-quartz schist and gray quartzite. The Littleton is poorly exposed in the area and occupies a narrow belt that passes through the south-central part of the map area. Only two outcrops of Littleton Formation were observed in the map area, and the location of the contact with the surrounding Paxton Formation is only slightly modified from the State map of Zen and others (1983). The contacts between the Paxton and Littleton formations are not exposed. The Early Devonian age of the Littleton Formation is based on correlations with fossiliferous rocks in New Hampshire (Billings and Cleaves, 1934, 1935; Billings, 1937; Boucot and Arndt, 1960).

Devonian pegmatite and granite

Dikes and sills of biotite granite (Dg) and granitic pegmatite (Dp) intrude the metasedimentary rocks in the area. The biotite granite occurs as two 3- to 5-m-thick mappable sills of medium to coarse-grained, weakly to moderately foliated granite that intrudes the Paxton biotite and calc-silicate granofels (Sp) just west and south of the contact with the sulfidic quartzite and schist unit (Spqr) (fig. 1). The granitic pegmatite (Dp) occurs as two 3- to 5-m-thick mappable sills of coarse-grained, very weakly foliated pegmatite that intrudes the Paxton Formation. The granite and pegmatite bodies are called sills because they are intruded parallel to the layering in the country rock, in this case the regionally pervasive foliation (fig. 3). Smaller, irregular masses of pegmatite occur at most outcrops, and are grossly parallel to the foliation, but these bodies are too small to map individually and their orientations are generally too irregular to measure. The pegmatite masses generally contain abundant tourmaline. Both the granites and pegmatites are presumably Devonian in age because they are syn-tectonic intrusive bodies that intruded parallel to and are foliated by the same regional fabric, and this regional foliation is a product of the Devonian Acadian orogeny (Robinson and Goldsmith, 1991).

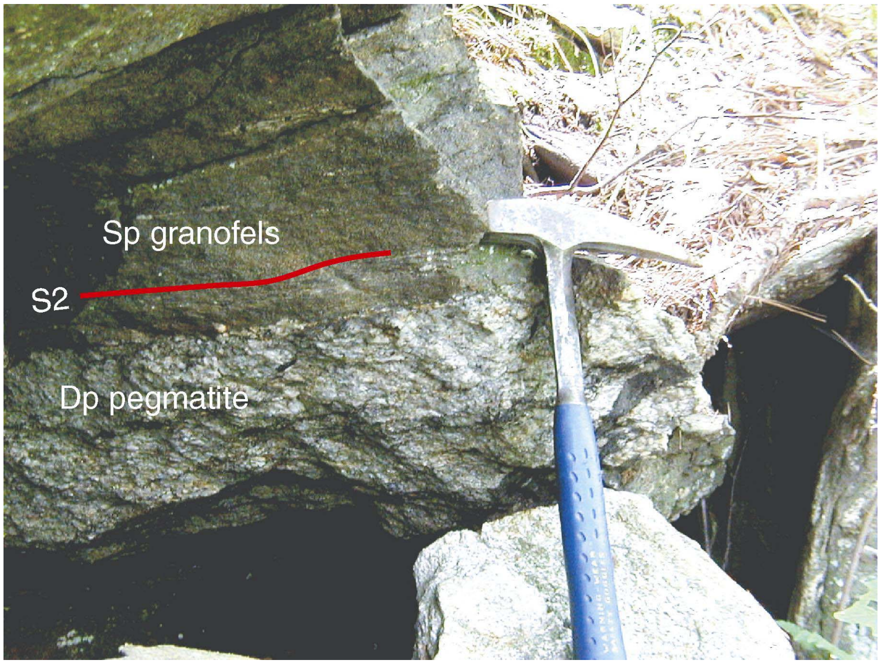


Figure 3. Photograph of the Paxton Formation granofels (Sp) intruded by a small outcrop-scale pegmatite (Dp) sill on the northwest side of Little Asnebumskit Hill. The pegmatite intrudes the granofels sub-parallel to the S2 schistosity and also contains the S2 foliation. Cross-sectional view is to the south, left is east.

STRUCTURAL GEOLOGY

Ductile Structures

The oldest foliation in the area is a highly folded schistosity (S1) that was observed in only one outcrop of the Paxton Formation on Little Asnebumskit Hill (figs. 1 and 4). The S1 foliation consists of folded micaceous layers in the sulfidic quartzite and schist unit (Spqr) (fig. 4). The S1 schistosity is highly plicated and transposed by the second-generation planar fabric (S2). No first-generation folds (F1) were observed in the area, and Robinson and Goldsmith (1991) state that these folds are rarely recognized at outcrop scale. Robinson and Goldsmith (1991) interpret the major map scale folds shown on Figure 1 as early F1 structures. Closures of the major map scale F1 folds are outside of the map area, and the overall map pattern is dominated by layering that is parallel to the second-generation fabric (S2).

The second-generation planar fabric in the area ranges from a penetrative schistosity to mylonitic fabric (S2) in the metasedimentary rocks, and a foliation that expresses itself as a schistosity or gneissosity in the granitic and pegmatitic rocks (Dg and Dp). The S2 foliation is expressed by the co-planar alignment of micaceous metamorphic minerals (mostly biotite and muscovite). The S2 fabric generally strikes northwest and dips very gently northeast (figs. 1 and 5). The average strike and dip of measured S2 is 352°, 10° (fig. 5), but it should be noted that most of the data comes from east of the well site. In this report, strike and dip directions are presented in right-hand rule as follows: with the right hand palm-side up, the thumb points down the direction of dip and the fingers point in the direction of strike. Little data is available west and north of the well site where the S2 foliation is presumably folded. In all the rocks, the S2 foliation is the dominant planar ductile fabric, and is clearly evident in all exposures. Parting and fracturing along S2 surfaces is common in all rocks, especially the Paxton Formation granofels

(Sp) (fig. 2). Outcrop-scale folds associated with the second-generation fabric (F2) are tight to isoclinal with hinges (L2) that plunge gently to the northeast, east, and southeast (figs. 1 and 5). Map-scale F2 fold closures are not recognized in the area. The intersection lineation between S1 and S2 (L2) plunges gently in the same orientation as F2 fold axes (figs. 1 and 5). F2 folds are less common than the S1/S2 intersection lineations in the vicinity of the Leicester well site (fig. 6).

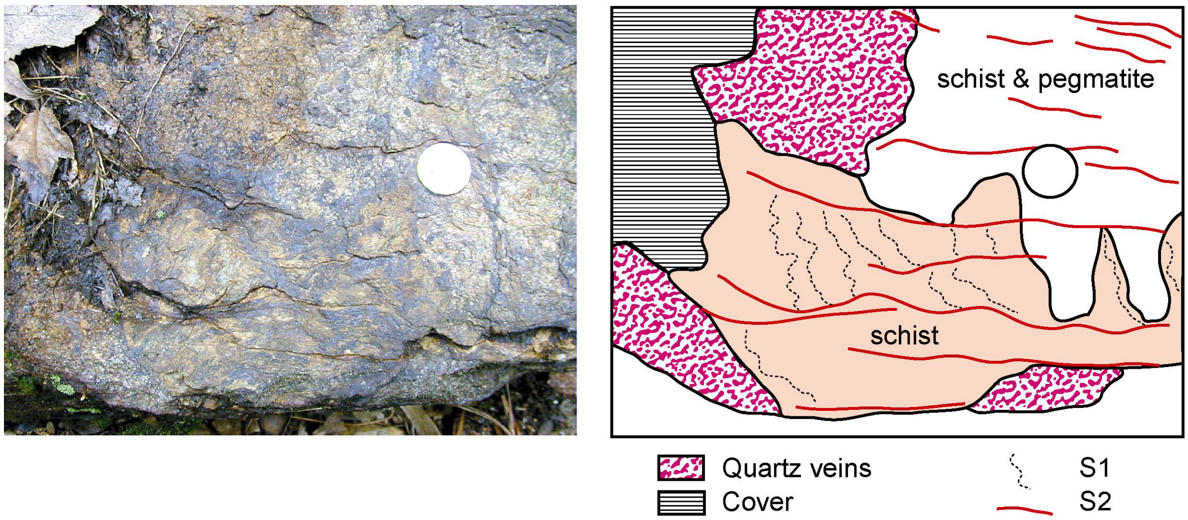


Figure 4. Photograph and sketch of the Paxton Formation sulfidic quartzite and schist unit (Spqr) from just west of the summit of Little Asnebumskit Hill. The figure illustrates the cryptic nature of the deformed S1 schistosity, seen at only this one locality. The S1 schistosity is deformed by the S2 schistosity. The outcrop contains quartz veins and zones rich in pegmatite. The S1 schistosity is only discernable in areas where the rock is schistose. Quartzite layers are not present in this figure. The view is a cross-section looking east with north to the left. Quarter for scale.

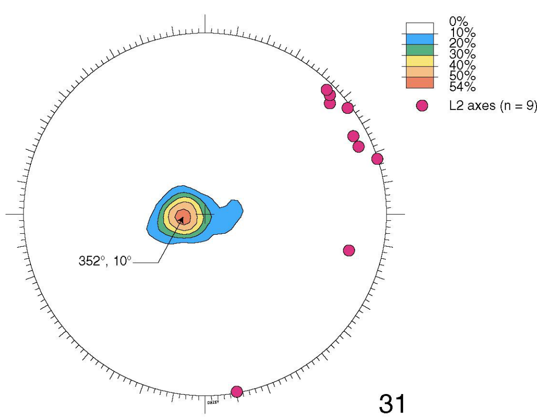


Figure 5. Lower hemisphere equal area projection of contoured poles to S2 foliation. The average strike and dip of S2 is 352°, 10°. The percent data of the contoured points is indicated at the upper right and the number of poles in the data sets is indicated in the lower right. Nine fold axes and S1/S2 intersection lineations (L2 axes) are shown as solid circles.

Figure 6. Photograph of Paxton Formation sulfidic schist (Spss) showing pronounced S1/S2 intersection lineation (parallel to pencil) and gently dipping parting fractures parallel to S2 schistosity. Photo taken at outcrop on hilltop southwest of Kettle Brook Reservoir No. 4. Oblique map view looking to south, left is east.

The S2 fabric is regionally associated with the second-phase Acadian deformation event of nappe backfolding, mylonitization, and flattening (Robinson and Goldsmith, 1991). In this study, the southern contact between the Littleton Formation and the Paxton Formation is shown conjecturally as a thrust fault (fig. 1). Robinson and Goldsmith (1991) interpret the belt of Littleton Formation as an overturned syncline; however, the new mapping reveals that the Paxton rocks on either side of the Littleton Formation are not the same. On the revised map (fig. 1) the Littleton still represents an overturned syncline, but its lower limb is truncated along a thrust fault that generally parallels the S2 foliation, thereby accounting for the apparent lack of symmetry about the Littleton Formation. The extrapolation of the thrust fault to the west correlates with the discontinuous thrust fault shown on both the map and cross-section D-D' of Zen and others (1983) at the same structural level. The dip to the northeast is the result of folding of the originally sub-horizontal eastward-directed thrust through the horizontal. As a result of this rotation, the original thrust direction indicated in cross section A-A' only appears to show a normal sense of displacement.

The S2 fabric is gently warped in the area by very broad, upright, north trending folds that are not expressed at the outcrop scale. Robinson and Goldsmith (1991) attribute this warping to the fourth stage of Acadian deformation, and state that it is regionally associated with arches and depressions. This deformation event is responsible for folding the S2 foliation into a generally flat-lying, but undulating, orientation in the area. Axial traces, labeled F4, show the trend of these late folds in the area (fig. 1). In the western Merrimack Belt, this late warping extends over a large area that is evident on the State map and cross-section D-D' (Zen and others, 1983).

Brittle Structures

The major brittle structures in the area are steeply dipping joints and parting fractures along the S2 foliation. No outcrop scale faults or uniform joint sets were observed in the area. The orientation of joints measured in this study includes those with trace lengths greater than 20 cm, following the protocol of Barton and others (1993). Joint aperture is generally less than 1 mm and the joints are not filled with vein minerals. Joint connectivity is a ratio of the percentage of blind (or dead), crossing, and abutting fractures (Barton and others, 1993). The ratio in the vicinity of the well site is 67 percent blind, 15 percent crossing, and 18 percent abutting, suggesting poor interconnectivity. Although the joints do not appear to be well connected, 59 percent of the joints are throughgoing, meaning they transect the entire outcrop rather than terminate within the outcrop area. These findings suggest that the steeply dipping joints may be regionally extensive but poorly connected.

Joint orientation data are plotted on rose diagrams and stereonets using the Structural Data Integrated System Analyzer software (DAISY 2.44) by Salvini (2001). The DAISY software uses a Gaussian curve-fitting routine for determining peaks in directional data (Salvini and others, 1999) that was first described by Wise and others (1985). The rose diagrams include strike data for steeply dipping fractures (dips > 60°, after Mabee and others, 1994). In this study, principal joint trends on rose diagrams are defined as having normalized peaks greater than 50 percent of the highest peak (Hardcastle, 1995). For example, steeply dipping fracture data from the outcrops southwest of Kettle Brook Reservoir No. 4 (fig. 7) are depicted in a rose diagram that has principal peaks of 314° ± 4° and 0° ± 4°. The 314° peak is the maximum peak in the diagram and, therefore, has a normalized peak at 100 percent. The 0° peak has a normalized height of 86 percent (value not shown on diagram). Four other peaks are present in the normalized data (all four trend northwest), but they are less than 50 percent of the maximum peak (288° ± 4° at 28%, 301° ± 4° at 24%, 321° ± 4° at 26%, and 338° ± 4° at 29%) and are, therefore, not considered principal peaks. The values are not shown on the rose diagram, and the 321° peak is difficult to see at the plotted scale because the petal for the principal peak at 314° obscures it.

In this study, joint data are plotted separately from parting fracture data. The parting fractures occur along the plane of the S2 foliation at every outcrop, and their orientation can be considered the same as S2, and consequently are visible as strike and dip symbols. The vast majority of the joints observed in the area dip steeper than 60°.

Joint Data by Rock Type

The igneous rocks in the area are more fractured than the metasedimentary rocks. This is quite evident at outcrops containing sills of granite or pegmatite where numerous joints cut the intrusive rocks but do not extend into the schists or granofels. Although the igneous rocks occupy a much smaller area than the metasedimentary rocks (fig. 1), one third of the joint measurements in this study come from outcrops in the granites and pegmatites. Fewer fractures were measured in the metasedimentary units here than in the metasedimentary units in two similar studies previously conducted in eastern Massachusetts (Walsh 2001a, b). In West Newbury, 154 fractures were measured in a 13 km^2 area (average = 12 per km^2) (Walsh, 2001a), and in Maynard, 400 fractures were measured in a 12 km^2 area (average = 33 per km^2) (Walsh, 2001b). In Paxton, only 122 fractures were measured in a 24 km^2 area (average = 5 per km^2). These averages reflect the limited outcrop in the Paxton area. The area covered in this study is roughly twice the size of the previous two studies because the outcrop density is considerably less.

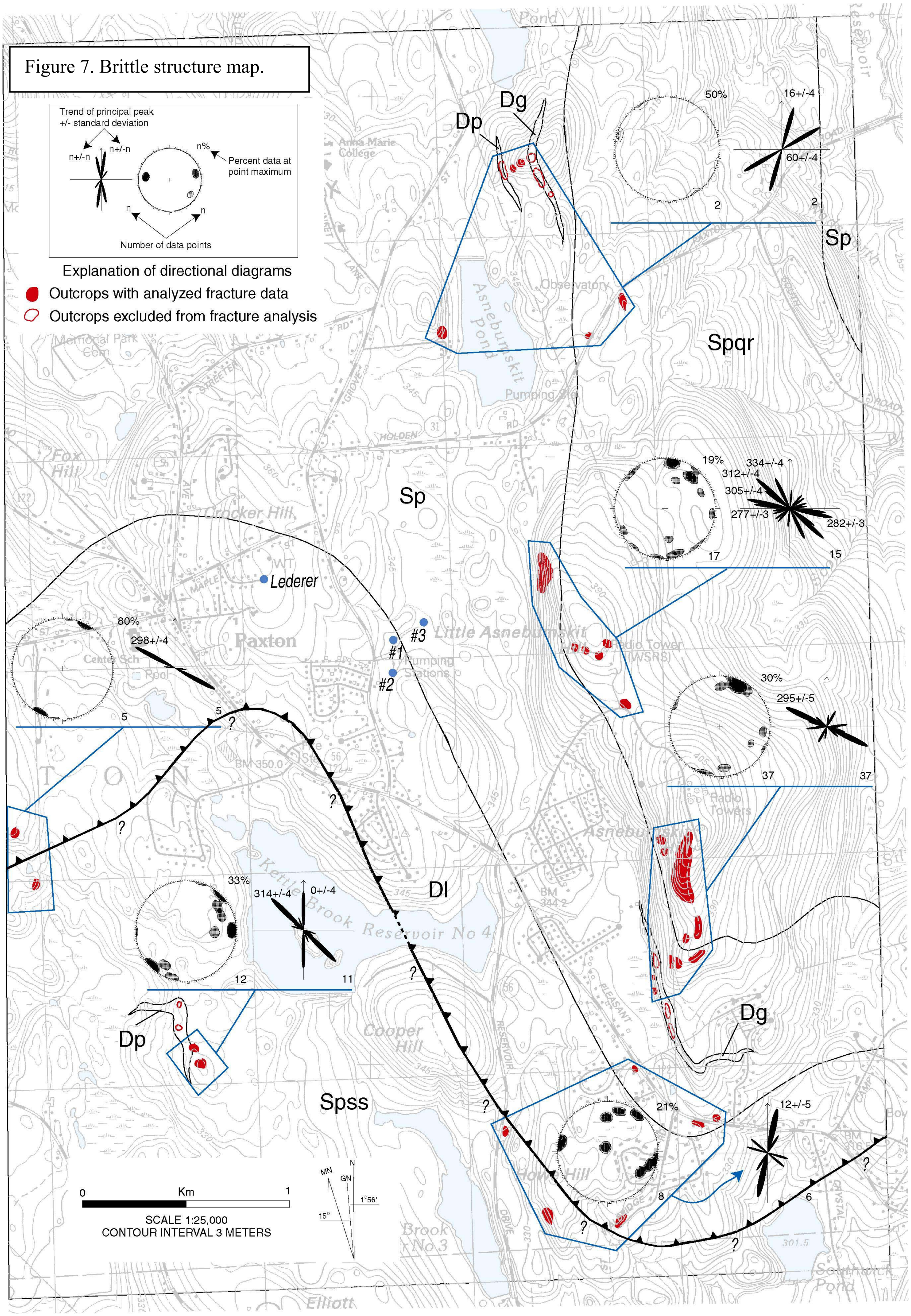


Figure 7. Brittle structure map.
Trend of principal peak +/- standard deviation
n+/-n
n%
Percent data at point maximum
Number of data points
Explanation of directional diagrams
Outcrops with analyzed fracture data
Outcrops excluded from fracture analysis
Dg
Dp
50%
16+/-4
60+/-4
2
Sp
Spqr
19%
334+/-4
312+/-4
305+/-4
277+/-3
282+/-3
17
15
Lederer
#1
#2
#3
80%
298+/-4
5
30%
295+/-5
37
33%
314+/-4
0+/-4
12
11
Dl
Spss
21%
12+/-5
8
6
0 Km 1
SCALE 1:25,000
CONTOUR INTERVAL 3 METERS
MN
GN
N
15°
1°56'

Figure 7 (previous page). Brittle structure map for metasedimentary rocks in the vicinity of the Leicester well site in Paxton, Massachusetts. Fracture orientation data include joints grouped from nearby solid colored outcrops. Data are portrayed on rose diagrams and lower hemisphere equal-area projections (stereonets). The azimuth of principal peaks and value of one standard deviation indicated on rose diagrams. Rose diagrams portray data from the strike of steeply dipping joints (dips > 60°). Stereonets show contoured poles to the planes of all joints. The percent data at the contoured point maximum is indicated at the upper right of each stereonet. The number of points in the data sets is indicated in the lower right of each diagram.

In addition to the greater degree of fracturing, the granites and pegmatites also have statistically different fracture orientations (fig. 8). Principal trends of steeply dipping joints in the intrusive rocks include 1°, 54°, and 68° (fig. 8, top). Principal trends of steeply dipping joints in the metasedimentary rocks include 281°, 296°, and 313° (fig. 8, bottom). Jointing of the igneous rocks might generally be considered second order (Singal and Gupta, 1999) because the fractures appear to be restricted by rock type. A plot of throughgoing fractures for the intrusive rocks (fig. 8, bottom) shows, however, that two of the four principal throughgoing trends (278° and 301°) do in fact correlate with two throughgoing principal trends (280° and 295°) recognized in the metasedimentary rocks (fig. 8, bottom). These findings indicate that the most abundant joints in the igneous rocks are spatially restricted to the outcrops of granite and pegmatite (ie. second order). The less abundant throughgoing joints in the igneous rocks are, however, a subset of the regionally throughgoing first order fractures in the metasedimentary rocks. A comparison of throughgoing joints versus all joints in the metasedimentary rocks shows the same principal peaks in both sets (fig. 8), indicating that regional first order joints dominate the data in these rocks.

Fracture Map

The spatial distribution of joint orientations in the metasedimentary rocks is shown in Figure 7. Joint data from the intrusive rocks is excluded from this map because the spatial distribution is limited and corresponds only to the two outcrop belts in the Sp unit, one north of Asnebumskit Pond and the other south of Asnebumskit Hill.

Outcrops in the metasedimentary rocks show a relatively uniform distribution of principal fracture trends (fig. 7). Principal trends common to three of the five outcrop groups include 295°-305° and 310°-314° (fig. 7). Principal trends common to two of the five outcrop groups include 282°-286° (fig. 7). Principal trends unique to single outcrop groups include 334°, 277°, and 12° (fig. 7). The three most common principal trends in the spatial data agree with the principal trends recognized in the metasedimentary rocks as a whole (281°, 296°, and 313°, fig. 7). These three trends probably represent the most regionally significant, first order systematic fractures in the area.

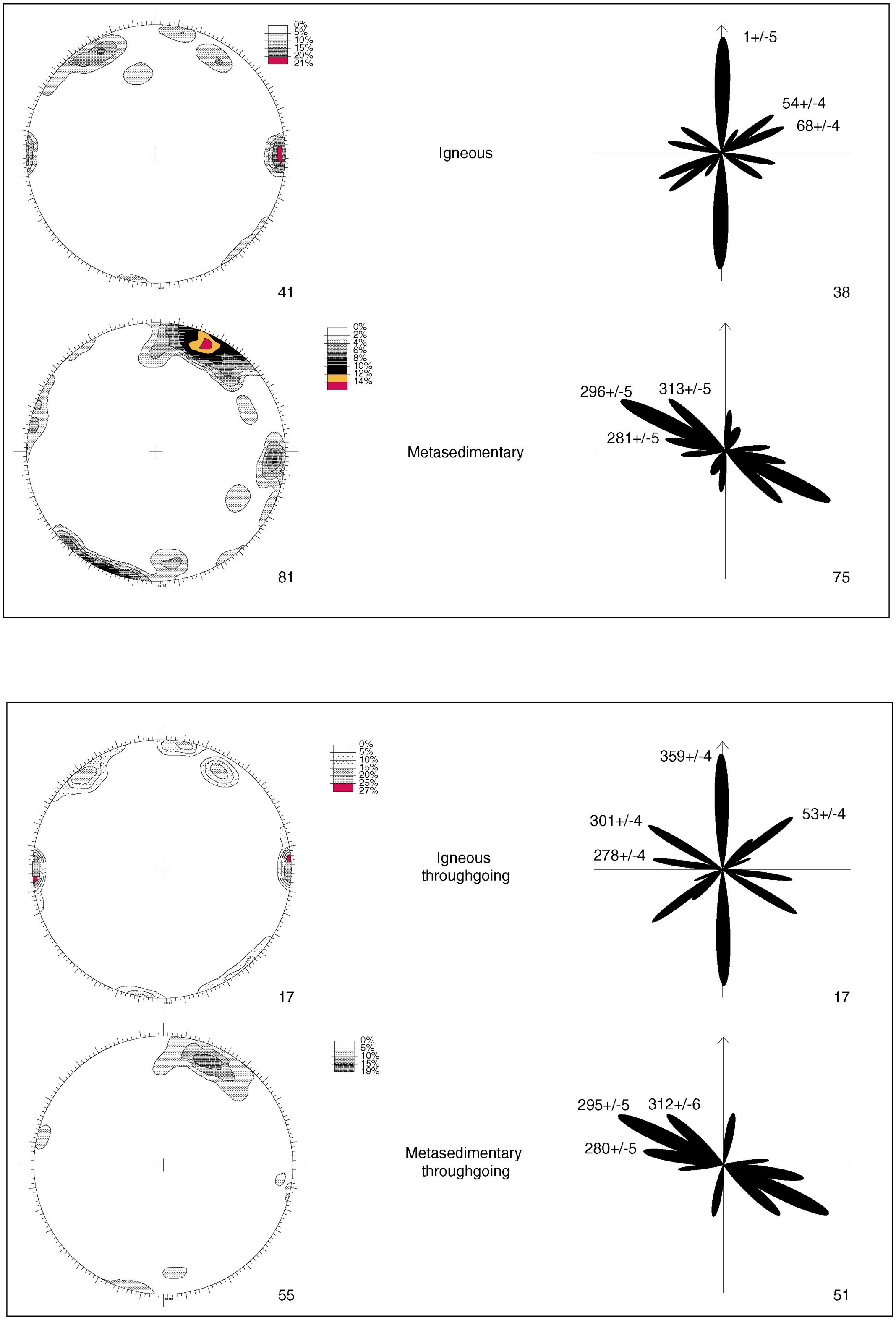
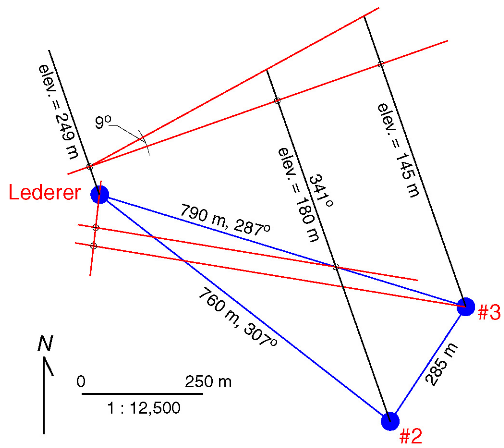


Figure 8. Rose diagrams and stereonets for joints from the study area separated by rock type. The bottom four diagrams show a subset of the top four diagrams and include only throughgoing joints. See figure 6 for an explanation of the diagrams.

WELL SITE ANALYSIS

The Leicester well site contains three bedrock production wells (fig. 1). The wells were drilled between 1908 and 1955. Since the wells are currently in operation, only limited borehole logging has been completed in well #3, and little is known about the borehole characteristics of wells #1 and #2 (Lyford and others, in press). Despite the limited borehole information, a hypothetical conceptual model is presented to explain aquifer test results presented by Lyford and others (in press).

During an aquifer test at the well site in August 2001, two of the production wells (#2 and #3, fig. 1) showed hydraulic connection to each other and to a single bedrock observation well (Lederer, fig. 1) (Lyford and others, in press). Production well #1 is approximately 46 m (150 ft) deep and receives water from a water bearing fracture at an approximate depth of 18 m (60 ft). During the aquifer test, well #1 showed direct connection to shallow ground water but no discernable connection to deeper wells #2 and #3. Well #2 is 164 m (537 ft) deep and presumably contains a significant water bearing fracture near the bottom of the borehole. Well #3 is 213 m (700 ft) deep and contains a significant water bearing fracture at a depth of 196 m (643 ft), identified by caliper log and flow meter log (Lyford and others, in press). The Lederer well is 122 m (400 ft) deep and the location of water bearing zones is uncertain. Assuming that the bottom of the Lederer well is where the driller encountered sufficient water for domestic use, a geometric calculation using the “three point” technique (fig. 9) indicates a potential water bearing fracture that connects the three wells with a strike and dip of 341°, 9°. This model assumes that much of the water in well #2 and the Lederer well enters the wells near the bottom of the boreholes. The possible existence of other water bearing zones at other locations within these two boreholes cannot be ruled out at this time. The hypothetical water bearing fracture zone presented here, however, does provide a conceptual model that agrees with the available aquifer test data, borehole data, and structural data. Structural contours drawn on the hypothetical water bearing zone beneath the well site (figs. 1 and 9) show the similarity to the regional strike of the geologic units and the expected dip of the S2 foliation in the area near and to the east of the well site. The conceptual model, therefore, includes significant lateral connectivity between the responding wells along a gently dipping fracture zone with only limited vertical connectivity. This conceptual model may not be valid at larger distances from the well site because the S2 foliation is folded and the orientation cannot be a simple tabular zone with a uniform strike and dip.



Well	*Lederer*	*#2*	*#3*
Surface elev. in m (ft)	371 (1217')	344 (1130')	341 (1119')
Depth to WBF in m (ft)	122 (400')	164 (537')	196 (643')
WBF elev. in m (ft)	249 (817')	180 (593')	145 (476')

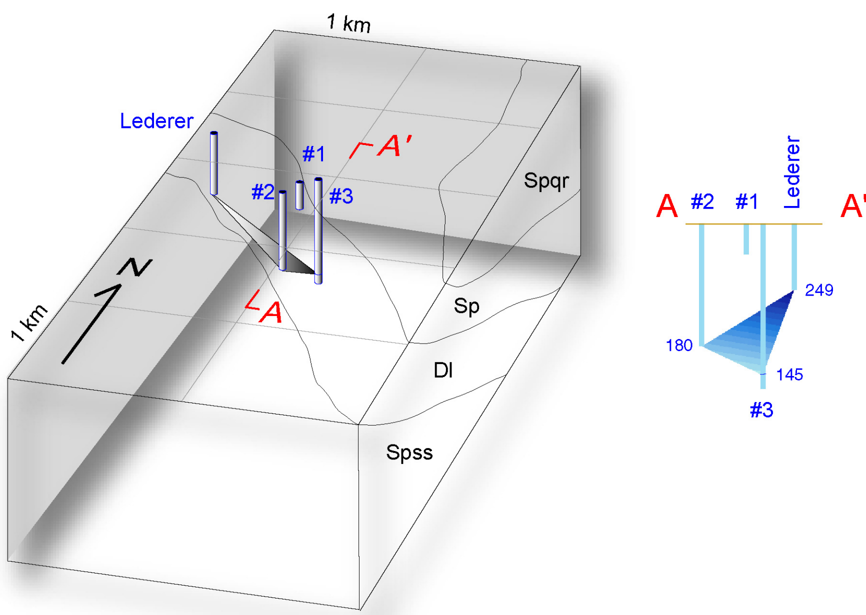


Figure 9. Top: Geometric calculation using a "three point" technique for a conjectured gently dipping water bearing fracture intersected in wells #2, #3, and the Lederer well. The calculated strike and dip of the water bearing fracture is 341°, 9°. Bottom: Three dimensional block diagram, viewed from the southeast, showing the calculated water-bearing zone and a north-south cross-section (A-A') showing the projected position of three wells at the well site and the Lederer observation well. The depth to the water bearing zone (in meters) is shown in the wells in cross-section A-A'. The vertical exaggeration in the block diagram and the cross-section is 3x.

SUMMARY

1) Production wells at the Leicester well site are located within the metasedimentary Paxton and Littleton Formations.

2) All metasedimentary rocks exhibit extensive parting or fracturing along the regionally pervasive S2 schistosity. The average strike and dip of S2 near the well site is 352°, 10°.

3) The igneous rocks are more fractured than the metasedimentary rocks and the principal fracture trends in the granites and pegmatites differ from those in the schists and quartzites. Both the igneous and the metasedimentary rocks, however, contain the same throughgoing principal fracture trends.

4) Jointing in the vicinity of the well site is relatively homogeneous in the metasedimentary rocks. The principal joint trends within the metasedimentary rocks in this area include 281°, 296°, and 313°. These trends also represent the common regional trends in the spatially distributed data (282°-286°, 295°-305° and 310°-314°).

5) A hypothetical geometric analysis at the well site permits a conceptual model that includes a gently dipping (341°, 9°) water-bearing fracture zone sub-parallel to the regional pervasive foliation with limited vertical connection by steeply dipping fractures. This analysis should be restricted to the well site and to those wells showing connectivity because the foliation is folded and cannot be represented by a simple tabular zone everywhere.

6) Directional anisotropy in the fractured bedrock may be controlled by:

- Parting fractures along the gently dipping S2 foliation (352°, 10°)
- Principal joint trends in the metasedimentary rocks of 282°-286°, 295°-305° and 310°-314°.

7) This study is the third of a three-part study on the fractured crystalline metamorphic bedrock in the vicinity of high-yielding wells in eastern Massachusetts. From this study and the two previous reports (Walsh 2001a, b), the following conclusions can be made:

- Sites with a relatively lower density of steeply dipping fractures (Paxton) may show less vertical hydraulic connectivity than sites with a greater density of steeply dipping fractures (West Newbury and Maynard).
- Sites with a gently dipping foliation (Paxton and West Newbury) show extensive fracturing or parting along the foliation surfaces. These fractures may significantly control aquifer characteristics.
- Quartz-calcite mineralization and unmineralized voids or vugs (West Newbury) may provide considerable secondary porosity in low-grade (sub-garnet) metamorphic rocks.
- Highly fractured and mineralized zones (Maynard) produce areas with the highest well yields, and these zones may be linked to regionally extensive brittle faults.
- Directional anisotropy in fracture orientations can be identified in metamorphic rocks through geologic mapping and fracture analysis.

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