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BEDROCK GEOLOGY IN THE VICINITY OF THE KNOWLES AND ANDREAS WELL SITES, WEST NEWBURY, MASSACHUSETTS

By Gregory J. Walsh[1]

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[1]U.S. Geological Survey
P.O. Box 628
Montpelier, Vermont 05601

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On the cover:
Photograph of the Eliot Formation near the Clinton – Newbury fault. The cross sectional view is looking to the east (north is to the left) and shows the well-developed S2 foliation. The outcrop is located south of Indian Hill and north of the Clinton – Newbury fault.

INTRODUCTION

The Knowles and Andreas public water supply well sites are located approximately 1 km apart in the town of West Newbury, Massachusetts (fig. 1). New geologic mapping was conducted in the vicinity of the well sites during June 2000 to characterize the bedrock geology beyond 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. The purpose of this study is to describe the characteristics of the bedrock that may influence groundwater flow and to identify potential directions of anisotropy in the fractured bedrock. Readers unfamiliar with any terminology in this report are referred to Jackson (1997).

STRATIGRAPHY

According to the bedrock geologic map of Massachusetts (Zen, 1983), both well sites are located within the Ordovician-Silurian Eliot Formation (fig.1). The well sites are located approximately 0.5-1.0 km west of the intrusive contact with the Silurian Newburyport Complex and 1-2 km north of the Clinton-Newbury fault (Shride, 1976; Zen, 1983). The new mapping indicates that the original work by Shride (1976), later compiled by Zen (1983), is generally correct with the exception that the contact between the Eliot Formation and the Newburyport Complex has been revised (fig.1).

Eliot Formation

The Eliot Formation in the vicinity of the well sites consists of medium- to light-gray, locally rusty weathering, well foliated and compositionally laminated, slightly calcareous quartz-muscovite phyllite. Bedding and the oldest foliation, S1, are essentially parallel and defined by compositional laminations consisting of alternating mm-scale layers of quartz-carbonate and phyllitic material (mostly muscovite, with minor chlorite and biotite). Bedding is very poorly preserved and, where it is not strictly parallel to S1, consists of alternating layers of phyllite and quartzose phyllite generally less than 5 cm thick. Locally, the Eliot Formation contains solution cavities or vugs oriented in the plane of the S2 cleavage, and to a lesser extent in the plane of the bedding, S1 schistosity, S3 cleavage, or fractures (fig. 2). The vugs contain quartz-calcite veins and have an aperture of less than 1 cm. In places, the Eliot Formation contains trace amounts of pyrite. The age of the Eliot Formation is constrained by Ordovician detrital zircons (as young as 440 Ma) from the Berwick Formation (Aleinikoff and others, 1995), and from an U/Pb age of 418 ± 1 Ma from the cross cutting Newburyport Complex (Lyons and others, 1997). According to Zen (1983) and Robinson and Goldsmith (1991) the Berwick Formation is stratigraphically above the Eliot Formation in the Merrimack belt. Lyons and others (1997) suggest otherwise, and place the Eliot above the Berwick.

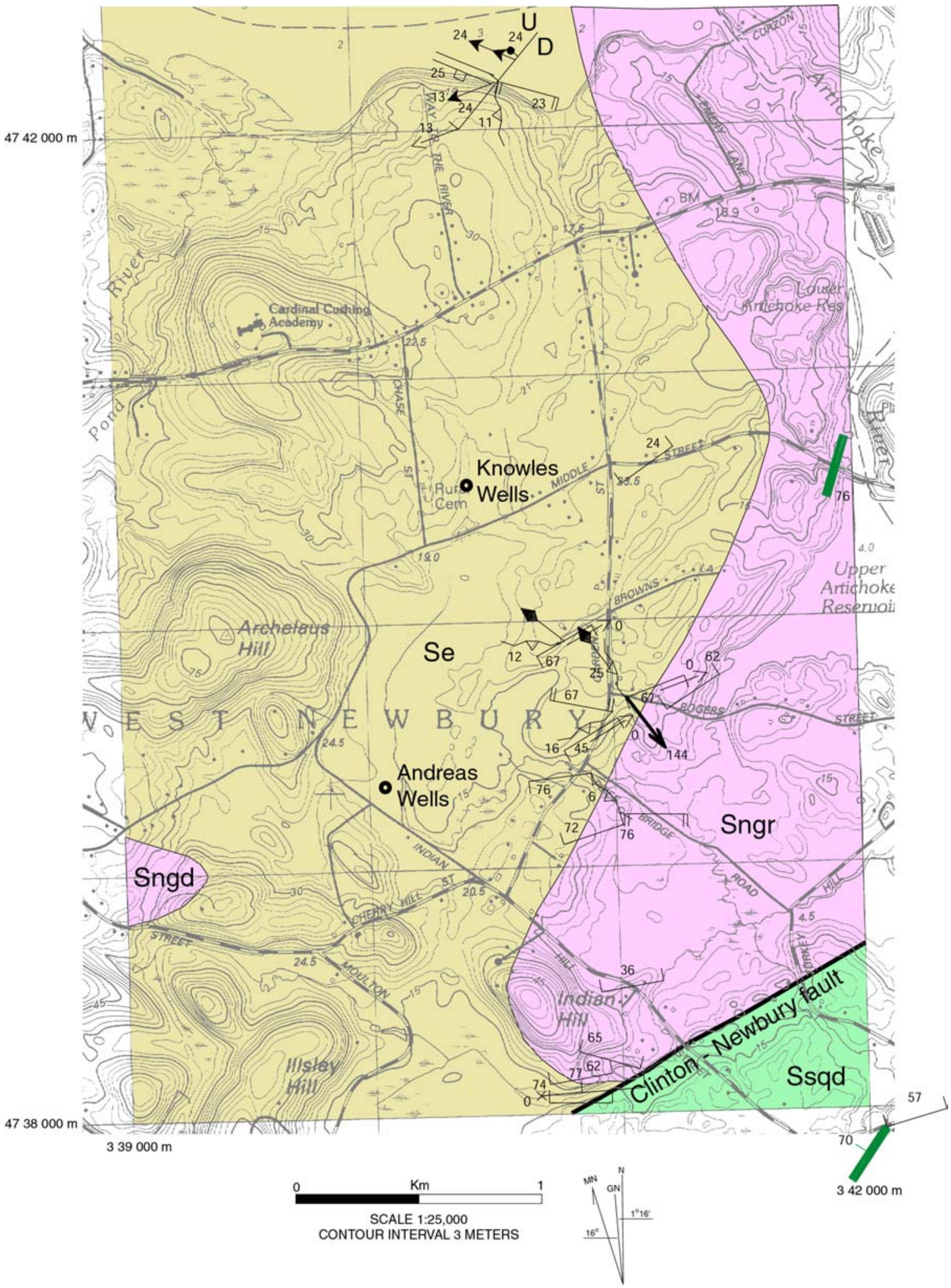

Figure 1. Bedrock geologic map in the vicinity of the Andreas and Knowles well sites in West Newbury, Massachusetts. Geology based on reconnaissance mapping in June 2000 and modifications after Shride (1976) and Zen (1983). Base map from the 1987 Newburyport, Massachusetts – New Hampshire, 7.5 x 15 minute topographic map (scale 1:25,000).

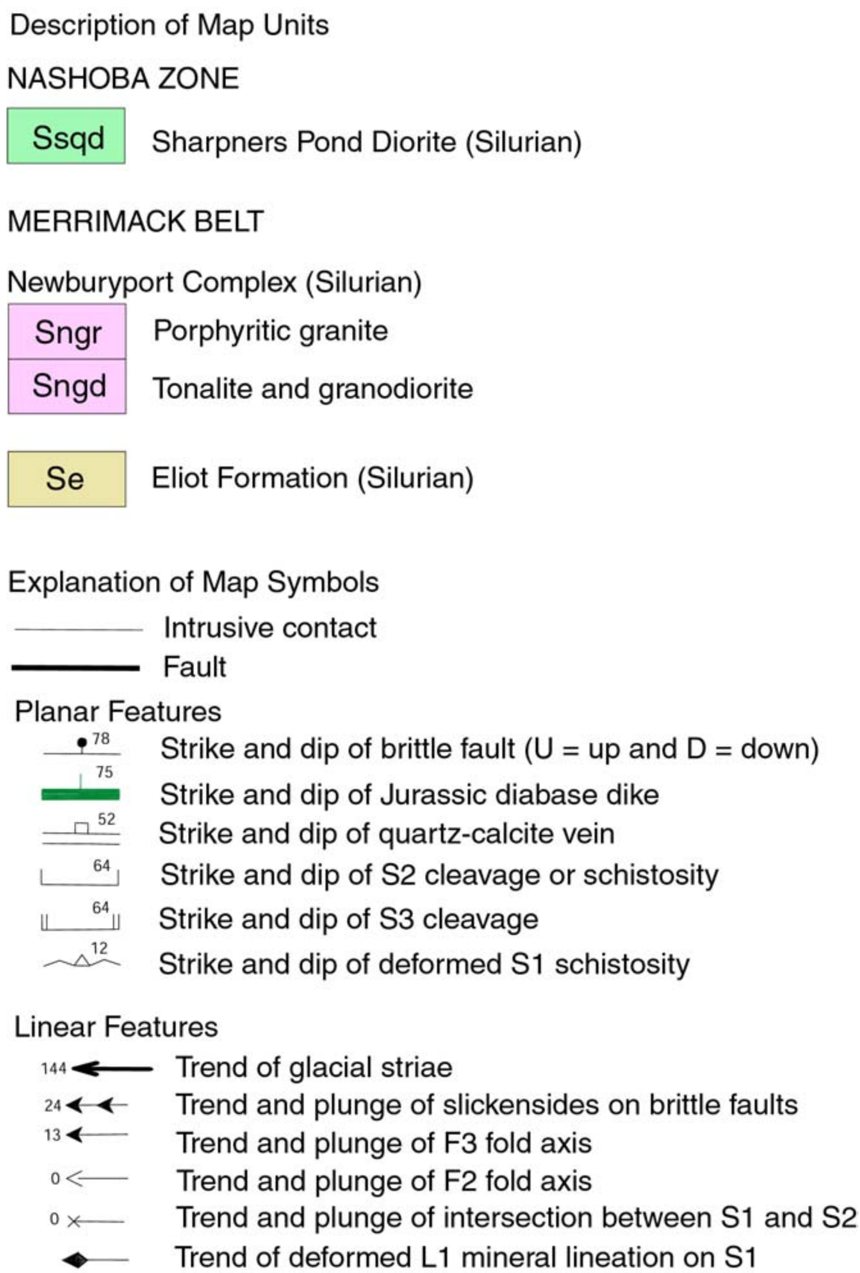

Figure 1. Continued.

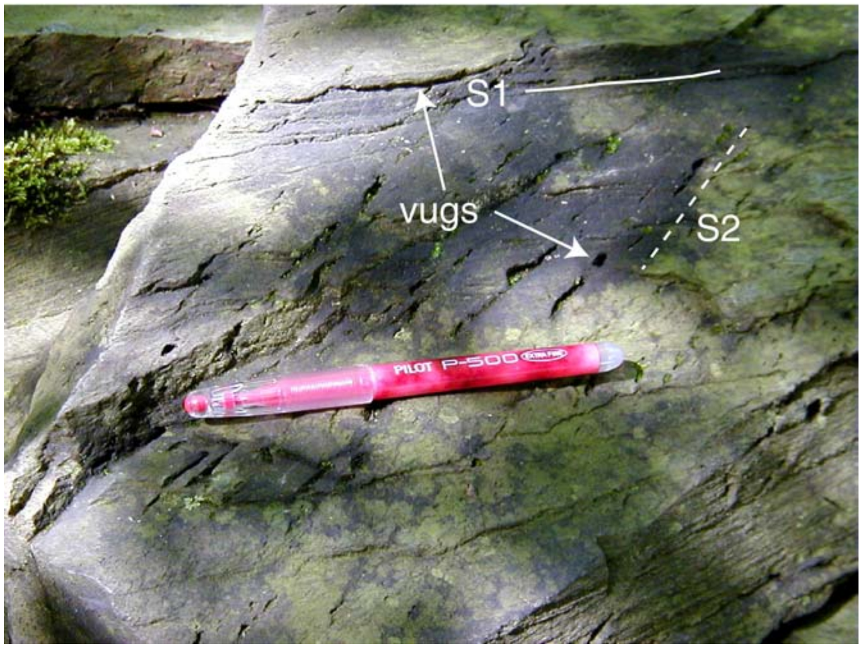

Figure 2. Photograph of vugs in the Eliot Formation. The vugs generally form parallel to the S2 cleavage or schistosity, but also form parallel to S1 and fractures. The vugs may, in part, be the result of dissolution of calcite in quartz-calcite veins.

Newburyport Complex

The Newburyport Complex consists of medium-gray to greenish gray and light olive-gray, medium grained, rusty weathering, equigranular, biotite and/or hornblende granodiorite to quartz monzonite. The Newburyport Complex contains trace amounts of pyrite that impart a rusty weathering to the rock. The Newburyport Complex is weakly foliated in the north and strongly foliated in the south. The degree to which the foliation is developed is a function of proximity to the Clinton-Newbury fault as the foliation nearer the fault is more penetrative, or strongly developed. The Newburyport Complex intrudes the Eliot Formation and post-dates the S1 schistosity in the Eliot, but pre-dates the S2 cleavage. Cross cutting relationships were not observed, however, in the study area.

Sharpners Pond Diorite

The Sharpners Pond Diorite is a medium- to dark-gray, fine-grained biotite-hornblende diorite that contains inclusions of amphibolite and feldspathic biotite gneiss. The rocks of the Sharpners Pond Diorite are exposed south of the Clinton-Newbury fault and are not exposed in the vicinity of the well sites. An U/Pb zircon age of 430 ± 5 Ma (Zartman and Marvin, 1991) established a Silurian age for the Sharpners Pond Diorite.

Jurassic Dikes

Two Jurassic diabase dikes were observed in the area. The 3- to 5-m-thick dikes are dark-gray to black, aphanitic diabases that cut the Newburyport Complex and Sharpners Pond Diorite. The dikes strike northeast and dip steeply (fig. 1). In both cases, the dikes are sub-parallel to northeast trending joints in the bedrock and are cut by northwest trending joints. Similar dikes occur throughout Massachusetts and have been assigned a Jurassic age on the State map (Zen, 1983), but may also be Triassic (Wones and Goldsmith, 1991) or even Devonian to Carboniferous (Ross, 1984). The ages of similar dikes range throughout the Mesozoic elsewhere in New England (Foland and Faul, 1977).

STRUCTURAL GEOLOGY

Ductile Structures

The oldest foliation in the area is a largely bed-parallel schistosity (S1) that occurs only in the Eliot Formation (figs. 1 and 2). Locally, the S1 schistosity contains an early mineral lineation defined by aligned quartz. It is presumed that this lineation is sub-parallel to a poorly preserved, cryptic generation of F1 folds. None of the F1 folds were observed in the area, and this interpretation is conjectural. The layer-parallel S1 schistosity is expressed by the co-planar alignment of metamorphic minerals (mostly muscovite, quartz, and chlorite). Where the Eliot is laminated, the laminations define S1. Locally, this foliation is the dominant planar fabric in the Eliot Formation. More commonly, however, the S1 foliation is deformed and transposed by the younger fabrics. The orientation of S1 is sub-horizontal to gently dipping (1° to 30°) throughout the area and is everywhere deformed by the younger fabrics.

The second-generation planar fabric in the area varies from a spaced cleavage to a penetrative schistosity (S2) in the Eliot Formation, and a cleavage to gneissosity in the Newburyport Complex and Sharpners Pond Diorite. The S2 fabric consistently strikes northeast and dips steeply to the southeast and northwest (figs. 1 and 3). All rocks in the area exhibit parting along S2 surfaces and these surfaces are considered fractures. Folds associated with the second-generation fabric (F2) deform S1 and bedding and vary from open to isoclinal with generally consistent sub-horizontal plunges to both the northeast and southwest (figs. 1 and 3). The average strike and dip[1] of S2 is 249°, 80° and the average trend and plunge of F2 fold axes is 250°, 3° (fig. 3). The combination of sub-horizontal S1 and steeply dipping S2 with sub-horizontal F2 fold axes produces a corrugated texture to the surfaces of most outcrops of the Eliot Formation seen in the vicinity of the well sites (fig. 3). The corrugated S1 surface and northeast trending F2 fold axes may explain the northeast trending bedrock-cored ridges evident on the topographic map (figs. 1 and 3), and may characterize the bedrock topography in the Eliot Formation.

[1] Strike and dip directions are presented in right-hand-rule.

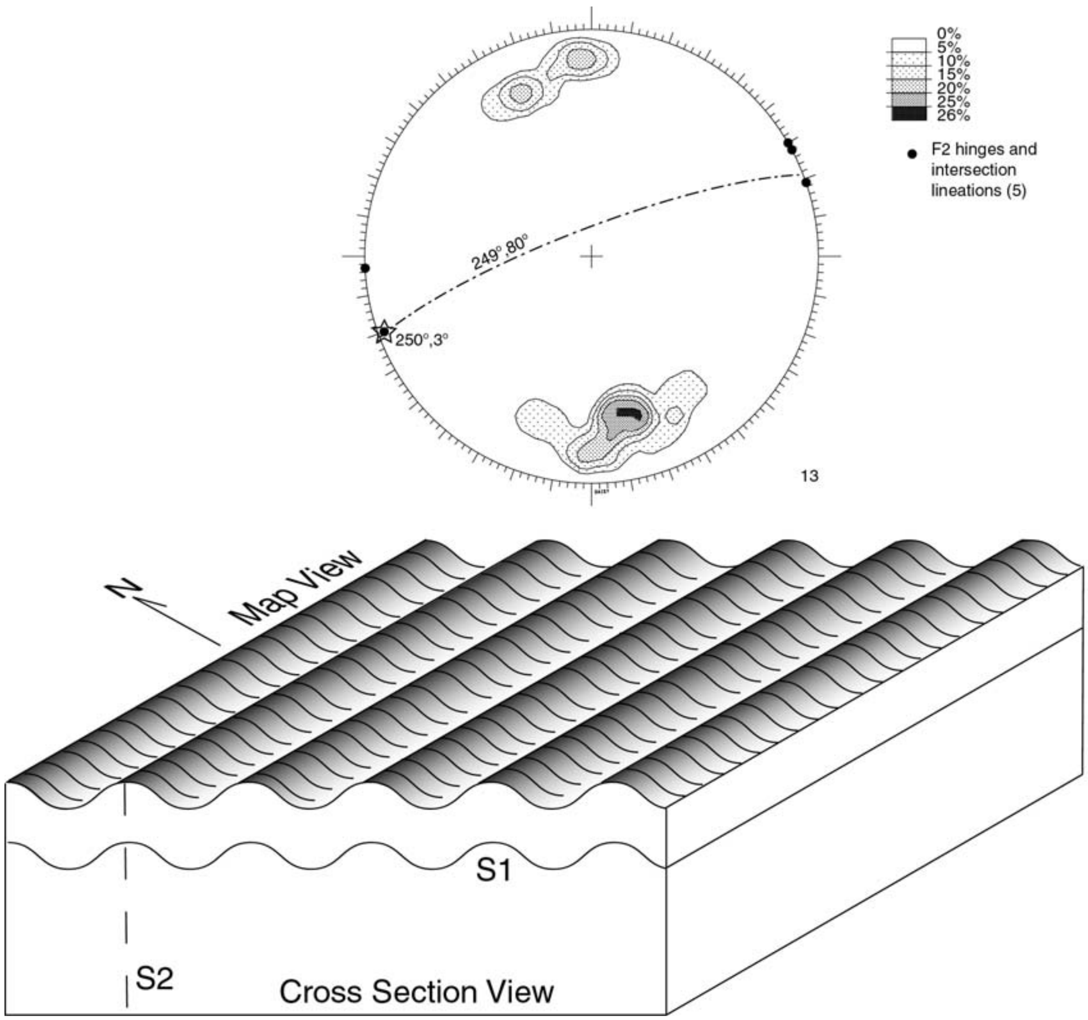

Figure 3. Top – Lower hemisphere equal area projection, or stereonet, of contoured poles to S2 foliation (12) and F2 fold axes and intersection lineations (5). The average strike and dip of S2 is 249°, 80° (dashed line) and the average trend and plunge of F2 is 250°, 3° (star). Bottom – A schematic block diagram of the deformed sub-horizontal surface of the S1 schistosity in the Eliot Formation. The S1 schistosity is corrugated by northeast to southwest trending, shallowly plunging to horizontal F2 folds. The corrugated S1 surface and northeast to southwest trending F2 fold axes may explain the trend of bedrock-cored ridges evident on the topographic map, and may characterize the bedrock topography in the Eliot Formation.

Generally, the S2 foliation is more penetrative in the southern part of the map area closer to the Clinton-Newbury fault. Locally, in the southern part of the area, the S2 foliation is mylonitic. The increase in penetrativeness of S2 near the Clinton-Newbury fault suggests movement along the fault during the second-generation deformation event. Second-generation (F2) fold axes throughout the area have consistently shallow to sub-horizontal plunges suggesting a strike-slip component of motion along the Clinton-Newbury fault during the development of S2 and F2 in the area. Regionally, the Clinton-Newbury fault is a terrane boundary between the Merimack belt to the west and the Nashoba block to the east (Zen, 1983). Goldsmith (1991) states that the Clinton-Newbury fault is a composite fault zone with three different periods and directions of offset: 1) Acadian to late Paleozoic east-directed thrust and reverse motion, 2) late Paleozoic high-angle strike slip motion, and 3) Mesozoic high-angle normal motion characterized by brittle deformation.

A third-generation planar fabric (S3) in the area is expressed as a weak, east-west striking, south-dipping, slip cleavage, and was observed at only two locations in the area. At an outcrop of the Eliot Formation on the south bank of the Merrimack River, the slip cleavage exhibits normal, or down to the south, relative displacement. Quartz-calcite veins also occur parallel to the S3 cleavage.

Brittle Structures

The major brittle structures in the area are joints and joints sets (fig. 4). A single outcrop-scale reverse fault was observed in the area and is shown on the geologic map (fig. 1). The orientation of joints and joint sets measured in this study include those with trace lengths greater than 20 cm (Barton and others, 1993). Spacing of joint sets ranges from 2 cm to 0.5 m with an average of 19 cm. Aperture, where it isn't negligible, is largely a measure of vein or vug thickness. The vugs may, in part, be the result of calcite dissolution in quartz-calcite veins oriented along fracture surfaces in the Eliot Formation. Aperture ranges from negligible to 5 mm. The connectivity of the fractures is expressed as a percentage of blind, crossing, and abutting fractures after Barton and others (1993). The ratio in the vicinity of the well sites is 36 percent blind, 51 percent crossing, and 13 percent abutting suggesting good interconnectivity.

Fracture data are plotted on rose diagrams and stereonets using the Structural Data Integrated System Analyzer software (DAISY 2.19) by Salvini (2000). 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 fracture trends on rose diagrams have normalized peaks greater than 50 percent of the highest peak (Hardcastle, 1995). For example, steeply dipping fracture data from the outcrop on Middle Street east of the Knowles well site (fig. 4) are depicted in a rose diagram that has principal peaks of 34° ± 4° and 308° ± 4°. The 308° peak is the maximum peak in the diagram and, therefore, has a normalized peak at 100 percent. The 34° peak has a normalized peak greater than 50 percent (72 percent; value not shown on diagram) and is considered a principal peak. One other peak is present in the normalized data (it trends east-west), but is less than 50 percent of the maximum peak (43 percent; value also not shown on diagram) and is, therefore, not considered a principal peak.

Figure 4 (following page). Brittle structure map in the vicinity of the Andreas and Knowles well sites in West Newbury, Massachusetts. Fracture orientation data include joints and joint sets grouped from nearby solid colored outcrops indicated by arrows and leaders. Data portrayed on rose diagrams and stereonets. Trend of principal peaks and one standard deviation indicated on rose diagrams. Rose diagrams portray data from the strike of steeply dipping fractures (dips > 60°). Stereonets portray all data as contoured poles to the strike and dip of fractures. 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.

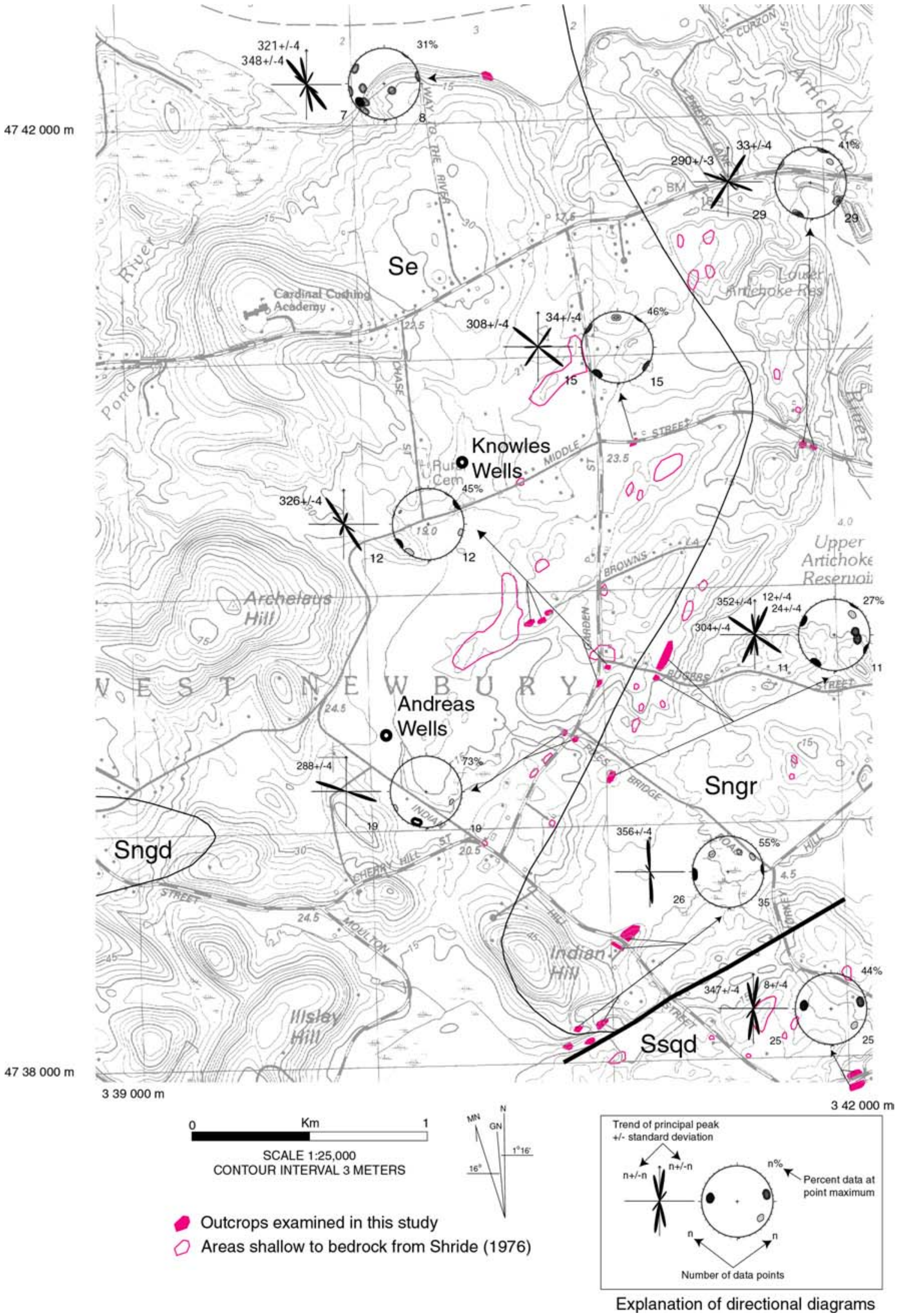
47 42 000 m
47 38 000 m
3 39 000 m
3 42 000 m
Se
Sngr
Sngd
Ssqd
Knowles Wells
Andreas Wells
WEST NEWBURY
Archelaus Hill
Indian Hill
Illsley Hill
Cardinal Cushing Academy
Lower Artichoke Res
Upper Artichoke Reservoir
321+/-4
348+/-4
31%
290+/-3
33+/-4
41%
308+/-4
34+/-4
46%
326+/-4
45%
352+/-4
12+/-4
24+/-4
304+/-4
27%
288+/-4
73%
356+/-4
55%
347+/-4
8+/-4
44%
0
Km
1
SCALE 1:25,000
CONTOUR INTERVAL 3 METERS
MN
GN
N
1°16'
16°
Outcrops examined in this study
Areas shallow to bedrock from Shride (1976)
Trend of principal peak +/- standard deviation
n+/-n
n%
Percent data at point maximum
n
Number of data points
Explanation of directional diagrams

Figure 4.

The majority of the joints and joint sets observed in the area are steeply dipping (fig. 4). The data may have a directional bias, however, because very few of the exposures in the area have vertical faces on which shallow dipping fractures can be observed. Outcrops in the Eliot Formation closest to the well sites show a preponderance of northwest striking steeply dipping fractures. Although the northwest direction is consistent, the trends are not and vary from outcrop to outcrop. Principal trends in the Eliot Formation closest to the well sites are 288°, 326°, 308°, and 34° (fig. 4). Principal fracture trends in the Eliot Formation as a whole are 288°, 307°, and 34° (fig. 5).

A throughgoing fracture is one that transects the entire outcrop, rather than terminates within the outcrop area. Of the principal trends in the Eliot Formation, the 34° and 307° trends (fig. 5) are throughgoing in the study area (33° ± 6° and 303° ± 4° in fig. 6). Other throughgoing trends are 355° and 8°, but are present only in the Newburyport Complex and Sharpners Pond Diorite (figs. 5 and 6).

SUMMARY

1) The Knowles and Andreas well sites are located entirely within the Eliot Formation – a slightly calcareous quartz-muscovite phyllite.

2) The Eliot Formation contains an early, sub-horizontal, layer-parallel schistosity that is not found in the other rocks in the area. A second generation of deformation produced a sub-vertical northeast-trending cleavage and schistosity (S2) and sub-horizontal fold axes (F2). The average strike and dip of S2 is 249°, 80°. The combination of S1 and S2 in the Eliot Formation produced a corrugated surface with ridges parallel to the F2 fold axes. The corrugated S1 surface and northeast to southwest trending F2 fold axes may explain the trend of bedrock-cored ridges evident on the topographic map, and may characterize the bedrock topography in the Eliot Formation.

3) All rocks exhibit parting, or fracturing, along S2 and, to a lesser extent, along S1.

4) Vugs are present in the Eliot Formation, and are largely parallel to the S2 cleavage, but also occur along S1 and some fractures. The vugs may, in part, be the result of dissolution of calcite in quartz-calcite veins.

5) Principal fracture trends in the Eliot Formation as a whole are 288°, 307°, and 34°. Of the principal trends in the Eliot Formation, the 307° and 34° trends are throughgoing.

6) Directional anisotropy in the fractured bedrock may be a function of:

- Corrugated sub-horizontal S1 with F2 fold axes trending at 70°
- Bedrock topography, which may be controlled by the folded surface of S1
- Steeply dipping S2 with vugs, trending at 69°
- Steeply dipping fractures, trending at 307° and 34°

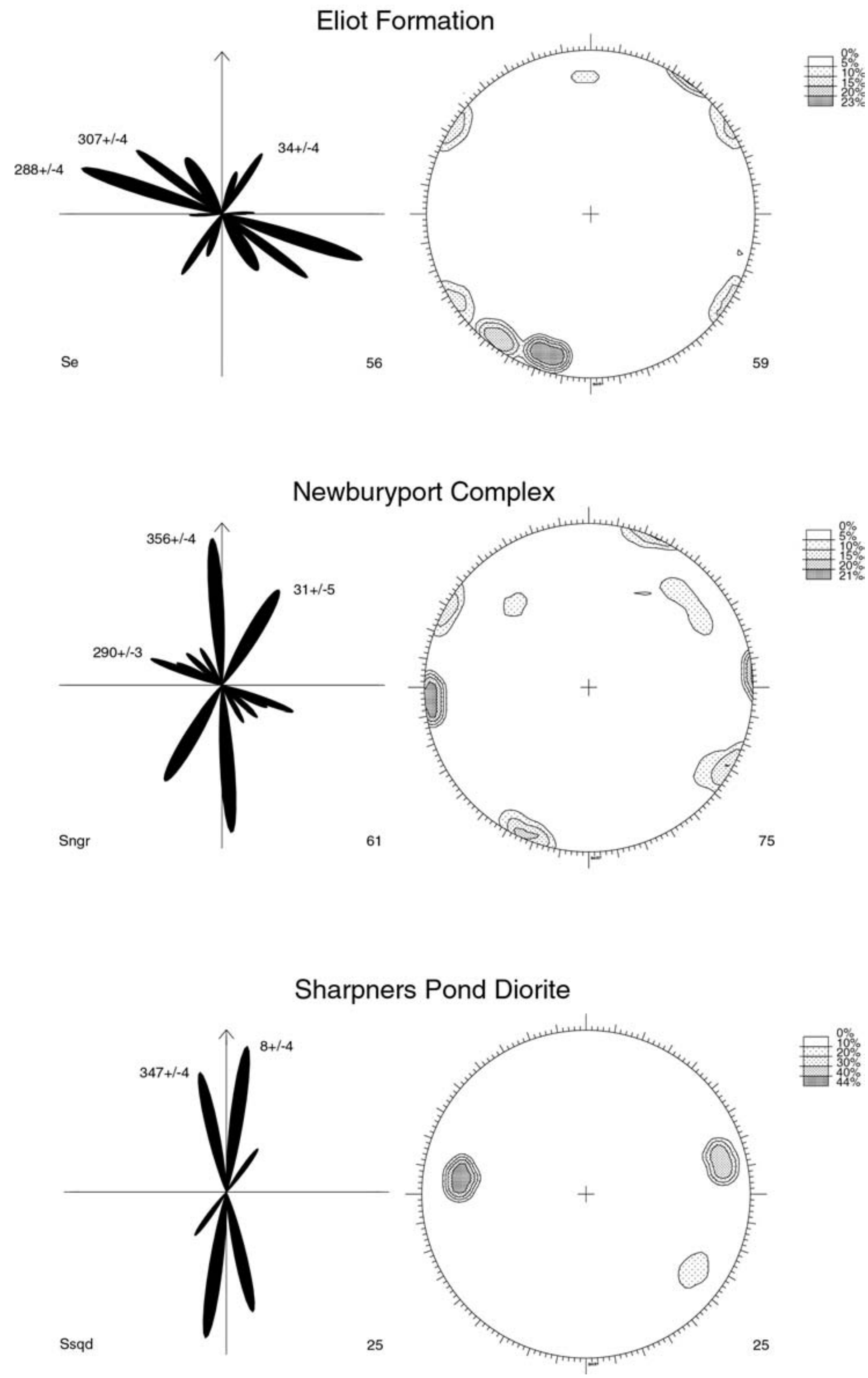

Figure 5. Rose diagrams and stereonets for fractures separated by rock type. See figure 4 for an explanation of the diagrams.

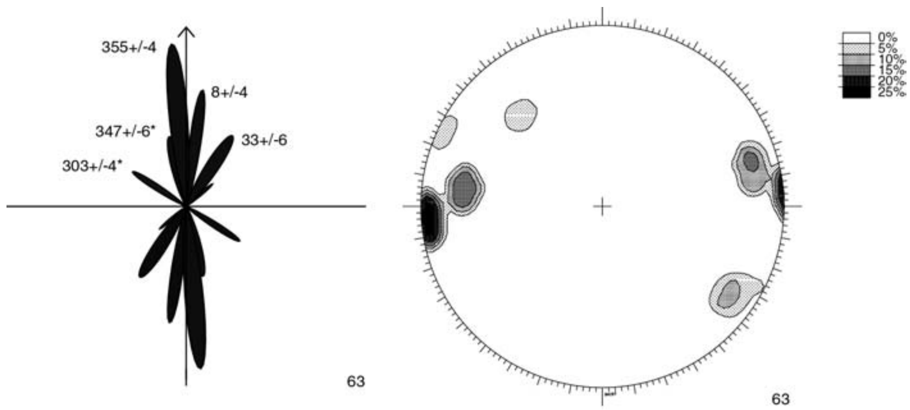

Figure 6. Rose diagram and stereonet for regionally throughgoing fractures. See figure 4 for explanation of diagrams. * The 303° and 347° trends have normalized peaks less than 50 percent of the highest peak (39 and 44 percent, respectively). These peaks, therefore, are technically not "principal" peaks based on the 50 percent definition by Hardcastle (1995), but they are recognized as principal peaks in other diagrams (fig. 5).

REFERENCES

Aleinikoff, J.N., and Walter, M., and Fanning, C.M., 1995, U-Pb ages of zircon, monazite, and sphene from rocks of the Massabesic Gneiss Complex and Berwick Formation, New Hampshire and Massachusetts: Geological Society of America Abstracts with Programs, v. 27, p. 26.

Barton, C. C., Larsen, E., Page, W. R., And Howard, T. M., 1993, Characterizing fractured rock for fluid-flow, geomechanical, and paleostress modeling: Methods and preliminary results from Yucca Mountain, Nevada, U.S. Geological Survey Open-File Report 93-269, 62 p.

Foland, K.A., and Faul, H., 1977, Ages of the White Mountain intrusives – New Hampshire, Vermont, and Maine, USA: American Journal of Science, v. 277, p. 888-904.

Goldsmith, R., 1991, Structural and metamorphic history of eastern Massachusetts: U.S. Geological Survey Professional Paper 1366-E-J, p. H1-H63.

Hardcastle, K.C., 1995, Photolineament factor: A new computer-aided method for remotely sensing the degree to which bedrock is fractured: Photogrammetric Engineering and Remote Sensing, v. 61, no. 6, p. 739-747.

Jackson, J.A, ed., 1997, Glossary of Geology, Fourth Edition: American Geological Institute, Alexandria, Virginia, 769 p.

Lyons, J.B., and Bothner, W.A., Moench, R.H., and Thompson, J.B., Jr., 1997, Bedrock geologic map of New Hampshire: U.S. Geological Survey, scale 1:250,000.

Mabee, S.B., Hardcastle, K.C., and Wise, D.U., 1994, A method of collecting and analysing lineaments for regional-scale fractured-bedrock aquifer studies: Ground Water, v. 32, no. 6, p. 884-894.

Robinson, P., and Goldsmith, R., 1991, Stratigraphy of the Merrimack belt, central Massachusetts: U.S. Geological Survey Professional Paper 1366-E-J, p. G1-G37.

Ross, M.E., 1984, Mafic dikes from Boston to Cape Ann, *in* New England Intercollegiate Geological Conference, 76th Annual Meeting, Danvers, Mass., Oct. 12-14, 1984, Geology of the coastal lowlands, Boston to Kennebunk, Maine, Salem, Mass., Salem State College, Department of Geological Sciences, p. 81-102.

Salvini, F., 2000, Structural Data Integrated System Analyzer software (DAISY 2.19), Dipartimento di Scienze Geologiche, Universita degli Studi di “Roma Tre”, Rome, Italy.

Salvini, F., Billi, A., and Wise, D.U., 1999, Strike-slip fault propagation cleavage in carbonate rocks: the Mattinata Fault Zone, Southern Apennines, Italy: Journal of Structural Geology, v. 21, p. 1731-1749.

Shride, A.F., 1976, Preliminary map of bedrock geology of the Newburyport East and Newburyport West quadrangles, Massachusetts - New Hampshire, U.S. Geological Survey Open-File Report 76-488, scale 1:24,000.

Wise, D. U., Funiciello, R., Parotto, M., And Salvini, F., 1985, Topographic lineament swarms: Clues to their origin from domain analysis of Italy: Geological Society of America Bulletin, v. 96, p. 952-967.

Wones, D.R., and Goldsmith, R., 1991, Intrusive rocks of eastern Massachusetts: U.S. Geological Survey Professional Paper 1366-E-J, p. I1-I61.

Zartman, R.E., and Marvin, R.F., 1991, Radiometric ages of rocks in Massachusetts: U.S. Geological Survey Professional Paper 1366-E-J, p. J1-J19.

Zen, E-an, editor, and Goldsmith, Richard, Ratcliffe, N.M., Robinson, Peter, and Stanley, R.S., compilers, 1983, Bedrock geologic map of Massachusetts: U.S. Geological Survey, scale 1:250,000.