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BEDROCK GEOLOGY IN THE VICINITY OF THE ROCKLAND AVENUE WELL SITE, MAYNARD, MASSACHUSETTS

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On the cover:
Map view photograph of F2 folds in the Nashoba Formation. North is to the bottom and west is to the right. The outcrop is located north of the Spencer Brook fault, northwest of Stow Road. Quarter for scale.

INTRODUCTION

The Rockland Avenue public water supply well site is located approximately 3 km north of downtown Maynard, Massachusetts (fig. 1). New geologic mapping was conducted in the vicinity of the well site during June 2000 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. 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 terminology in this report are referred to Jackson (1997).

STRATIGRAPHY

Previous work indicates that the well site is located within the Nashoba Formation (Hansen, 1956; Zen, 1983). The work by Hansen (1956) in the Hudson and Maynard quadrangles places the well site entirely within the biotite gneiss and schist unit of the Nashoba Formation, and shows several nearby belts of unnamed amphibolite. Compilation work by Zen (1983) for the bedrock geologic map of Massachusetts combines the belts of amphibolite and intervening biotite gneiss and schist into the Boxford Member of the Nashoba Formation. On the State map, therefore, the well site is located within the Boxford Member. Zen (1983) also identified the Spencer Brook and Assabet River faults in the vicinity of the well site (fig. 1). The new mapping (fig. 1) indicates that the 1:24,000 scale work by Hansen (1956) portrays the distribution of amphibolite in the Nashoba Formation more accurately than the 1:250,000 scale compilation by Zen (1983). Both Hansen (1956) and Zen (1983) overstate the amount of amphibolite, and the new mapping indicates far less amphibolite than the previous maps (fig. 1).

Nashoba Formation

The Nashoba Formation in the vicinity of the well site consists of medium- to dark-gray, locally rusty weathering, well foliated to massive, coarse-grained muscovite-biotite-quartz-plagioclase schist and gneiss. Although rusty weathering in the Nashoba rocks is widespread, sulfide mineralization along fractures, foliation, and in the rock matrix is particularly evident in the outcrops immediately south of the well site (figs. 2 and 6). In this area, the Nashoba rocks are very rusty weathering. Locally, porphyroblasts of garnet, sillimanite, and potassic feldspar up to 1 cm in diameter occur in the schist. In places, the rock contains leucosomes of quartz and sodic and potassic feldspar that define a coarse texture in the schist. Where the rock is most leucocratic it is more properly called biotite-quartz-feldspar migmatite gneiss. The schist and gneiss unit (On in fig. 1) contains layers of massive, coarse-grained biotite-hornblende-plagioclase amphibolite (Ona in fig. 1) at several places in the area. The age of the Nashoba Formation is Early Ordovician based on a U-Pb igneous zircon date of 499 +6/-3 Ma by Hepburn and others (1995) from a metavolcanic rock in the correlative Fish Brook Gneiss from North Andover, Massachusetts.

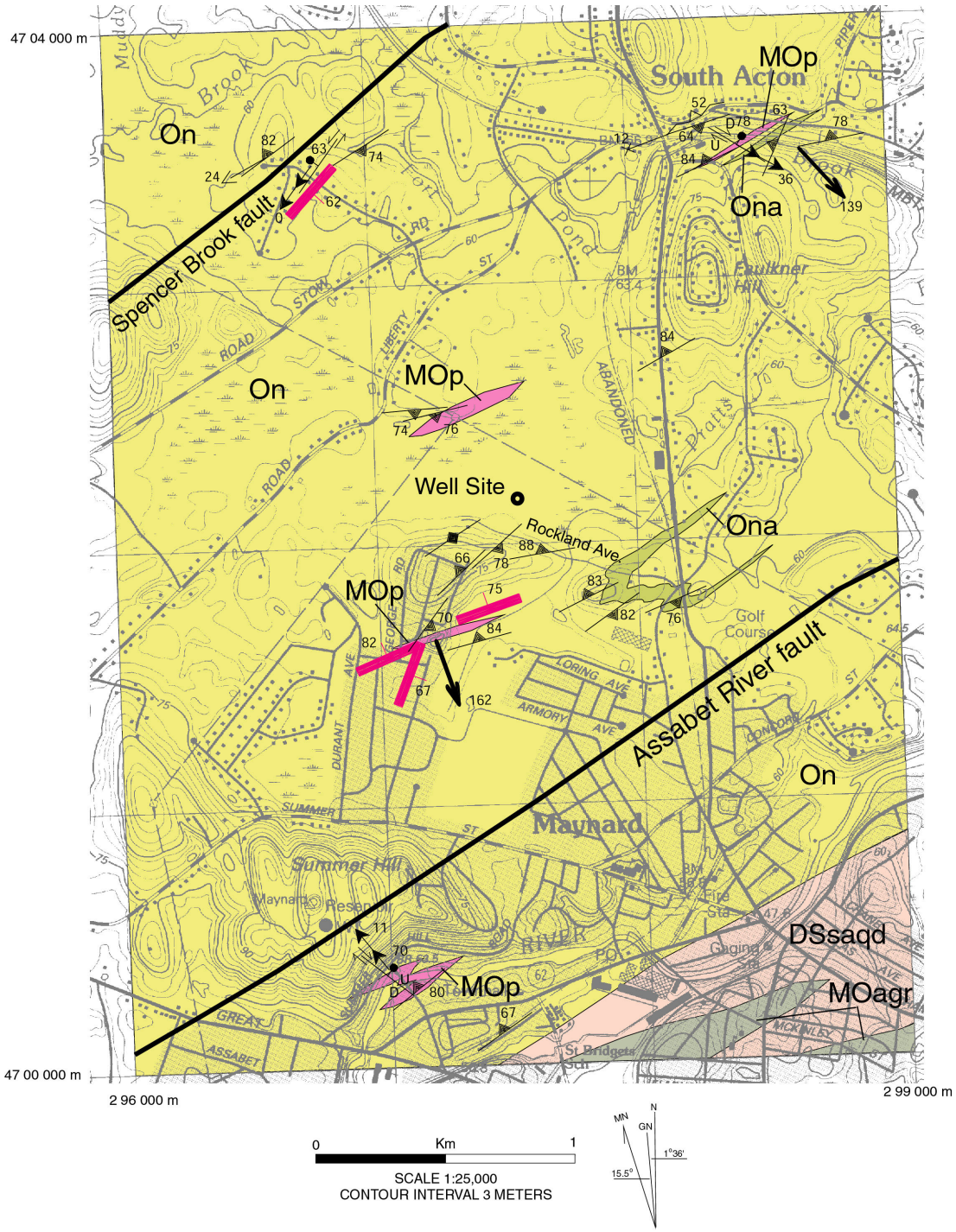

Figure 1. Bedrock geologic map in the vicinity of the Rockland Avenue well site in Maynard, Massachusetts. Geology based on reconnaissance mapping in June 2000 and modifications after Zen (1983). Base map from the 1987 Maynard, Massachusetts, 7.5 x 15 minute topographic map (scale 1:25,000).

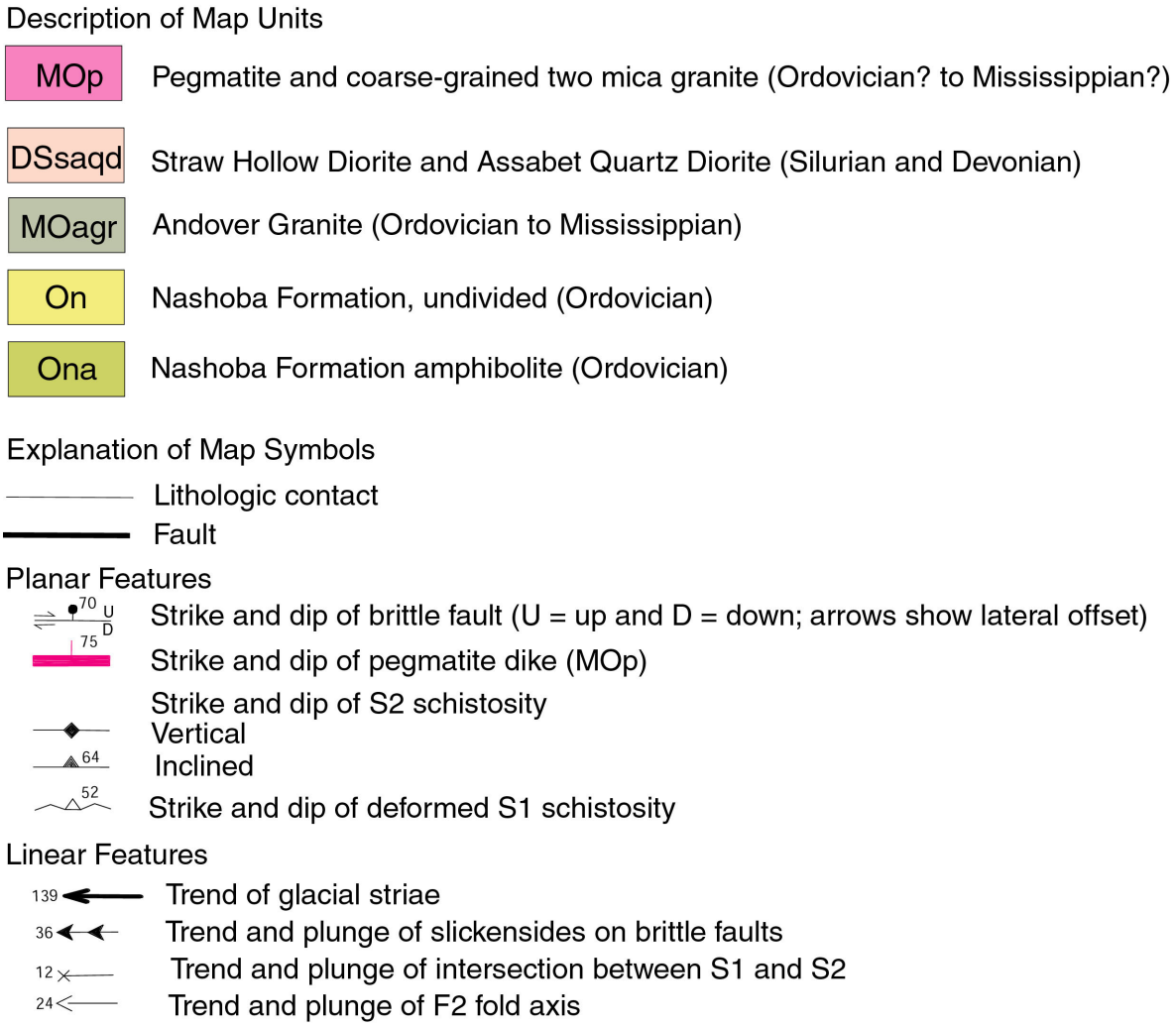

Figure 1. Continued.

Non-foliated to weakly foliated pegmatite and very coarse-grained muscovite-biotite granite intrude the Nashoba rocks at almost all exposures. Generally tabular, granitic and pegmatitic dikes (0.3 to 1.0 m thick) are shown on the geologic map by a symbol, and larger bodies of granite and pegmatite are mapped separately (MOp on fig. 1). Hepburn and others (1995) report a 425 ± 3 Ma U-Pb monazite age for the sillimanite and sillimanite-K-feldspar metamorphism in the Nashoba Formation. Some of the granites and pegmatites in the Nashoba rocks may have intruded during this Silurian high-grade metamorphic event, while others may be as young as Devonian or Mississippian (Acaster and Bickford, 1999) or as old as Ordovician based on ages from other intrusive rocks in the Nashoba Formation. Previously mapped intrusive rocks in the area include the Straw Hollow Diorite and Assabet Quartz Diorite, and the Andover Granite (fig.1). Acaster and Bickford (1999) date the Straw Hollow Diorite at 385 ± 5 Ma (Devonian) and Wones and Goldsmith (1991) consider the Assabet Quartz Diorite to be Silurian. Hepburn and Bailey (1998) relate the Straw Hollow Diorite and Assebet Quartz Diorite to an Early Silurian to Early Devonian plutonic event. Ages for the Andover Granite range from Ordovician to Silurian (Hepburn and others, 1995; Wones and Goldsmith, 1991) to Early

Mississippian (Acaster and Bickford, 1999). On the geologic map (fig. 1), the contacts for the Andover, Straw Hollow, and Assabet rocks are derived from Zen (1983) because these intrusive rocks are not exposed in the vicinity of downtown Maynard.

STRUCTURAL GEOLOGY

Ductile Structures

The oldest foliation in the area is a layer-parallel foliation (S1) that was observed in only two outcrops of the Nashoba Formation, but was measurable only in one due to the high degree of transposition and later recrystallization (fig. 1). At both locations, the compositional banding consists of alternating micaceous and quartzo-feldspathic horizons that are deformed and transposed by the more pronounced second-generation schistosity (S2). Although bedding was not apparent in this study area, Hansen (1956, p. 32) reports that the gneissic banding is roughly co-planar with locally "well-preserved original bedding" in the Nashoba Formation. In most exposures, the S1 foliation is deformed and transposed by the S2 foliation and overprinted by sillimanite to sillimanite-K-feldspar grade metamorphic recrystallization. Despite the structural and metamorphic overprint, the S1 foliation did exhibit parting at one of the two outcrops where it was observed near downtown South Acton. There, the S1 foliation strikes southwest and dips moderately to the northwest (242°, 52°, fig. 1) [1].

The second-generation planar fabric in the area is a penetrative schistosity (S2) in the Nashoba Formation, and a foliation that ranges in character from a cleavage to gneissosity in the granitic and pegmatitic rocks (MOp) where it is present. The S2 foliation is expressed by the co-planar alignment of micaceous metamorphic minerals (mostly biotite and muscovite). The S2 fabric consistently strikes northeast and dips steeply to the southeast and northwest (figs. 1 and 3). The average strike and dip of S2 is 243°, 89° (fig. 3). In the Nashoba Formation, the S2 foliation is the dominant planar ductile fabric, and is evident in all exposures. Parting along S2 surfaces is common in all rocks and these surfaces are considered fractures. Folds associated with the second-generation fabric (F2) are isoclinal with shallow plunges to the southwest (fig. 1). The intersection lineation between S1 and S2 plunges gently to the southwest in approximately the same orientation as F2 fold axes (fig.1). With respect to the distribution of F2 folds, Hansen (1956, p. 52) noted that, “scarcely an outcrop does not display them.” The new mapping, however, indicates that F2 folds are scarce in the vicinity of the Rockland Avenue well site.

Figure 2 (following page). Brittle structure map in the vicinity of the Rockland Avenue well site in Maynard, Massachusetts. Fracture orientation data include joints, joint sets, and joint zones grouped from nearby solid colored outcrops indicated by arrows and leaders. Data portrayed on rose diagrams and lower hemisphere equal-area projections (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.

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

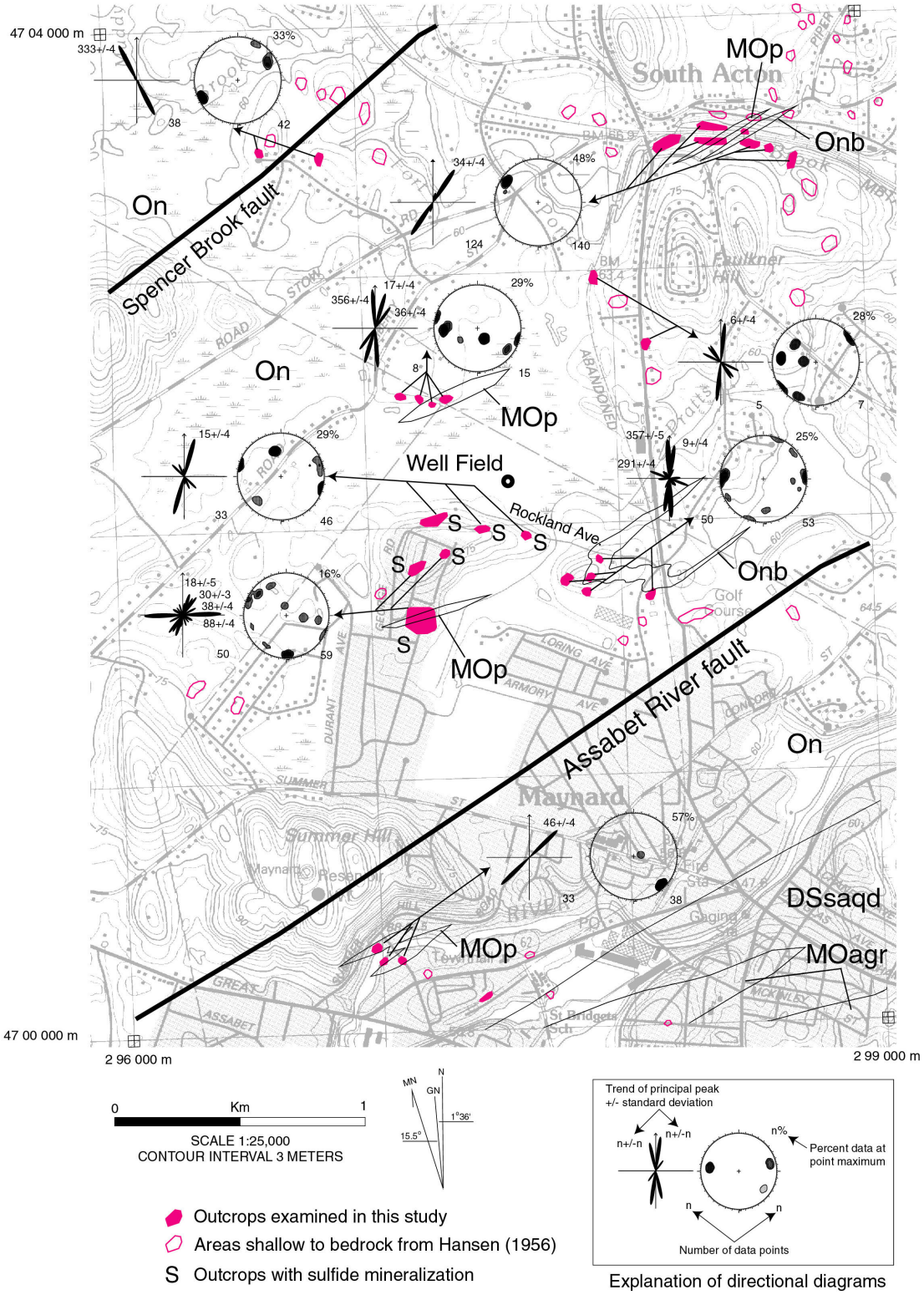
47 04 000 m
47 00 000 m
2 96 000 m
2 99 000 m
MOp
Onb
On
Spencer Brook fault
Well Field
Rockland Ave
Assabet River fault
DSsaqd
MOagr
South Acton
Maynard
Summer Hill
Faulkner Hill
Golf Course
0 Km 1
SCALE 1:25,000
CONTOUR INTERVAL 3 METERS
Outcrops examined in this study
Areas shallow to bedrock from Hansen (1956)
S Outcrops with sulfide mineralization
Trend of principal peak
+/- standard deviation
Percent data at point maximum
Number of data points
Explanation of directional diagrams

Figure 2.

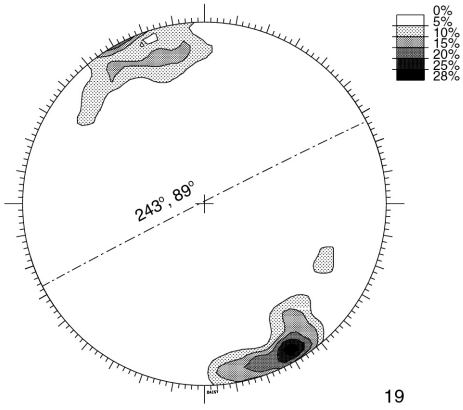

Figure 3. Lower hemisphere equal area projection of contoured poles to S2 foliation. The average strike and dip of S2 is 243°, 89°. The percent data of the contoured points is indicated at the upper right of the stereonet. The number of points in the data sets is indicated in the lower right of the diagram.

Brittle Structures

The major brittle structures in the area are faults and joints (figs. 1 and 2). Three outcrop-scale faults were observed in the area and are shown by symbols on the geologic map (fig. 1). Two of the outcrop-scale faults show right lateral, southeast directed motion and one shows left lateral, southwest directed motion. Two regionally significant faults, the Spencer Brook and Assabet River faults, cut the Nashoba Formation in the vicinity of the Maynard well site and are generally parallel to the S2 foliation (fig. 1). These faults are not exposed in the study area, however, and their locations are derived from Zen (1983). According to Goldsmith (1991), the Spencer Brook and Assabet River faults are responsible for late stage, east directed, west side up, right lateral imbrication of internal units within the Nashoba block. The Spencer Brook and Assabet River faults, and other internal faults within the Nashoba block, have multiple ages of movement that may be characterized by older mylonitization and younger "brecciation, alteration, silicification, and zones of gouge" (Goldsmith, 1991, p. H8). Two of the outcrop-scale faults in the area have the same relative displacement as the Spencer Brook and Assabet River faults, and these faults may be related to later brittle activity on the regional faults. In addition, Goldsmith (1991) states that the Nashoba block contains many faults that are not shown on the State map by Zen (1983) due to relatively insignificant displacement. The position of the Maynard well site between the Spencer Brook and Assabet River faults is, therefore, a location that is characterized regionally by an abundance of faults, both mapped and unmapped, with significant and insignificant displacements.

The orientation of joints, joint sets, and joint zones (or fracture zones) measured in this study include those with trace lengths greater than 20 cm (Barton and others, 1993). Spacing of joint sets ranges from 3 cm to 1 m with an average of 30 cm. Aperture, where it isn't negligible, is largely a measure of sulfide-vein thickness oriented along fracture surfaces in the Nashoba Formation (see fig. 6). Aperture ranges from negligible to 3 mm, and averages 2.4 mm where measured. 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 site is 19 percent blind, 60 percent crossing, and 21 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 three outcrops immediately south of the well site (fig. 2) are depicted in a rose diagram that has a principal peak of 15° ± 4°. The 15° peak is the maximum peak in the diagram and, therefore, has a normalized peak at 100 percent. Three other peaks are present in the normalized data (all three trend north-northwest), but they are less than 50 percent of the maximum peak (43, 34, and 19 percent; values not shown on diagram) and are, therefore, not considered principal peaks.

The majority of the joints, joint sets, and joint zones observed in the area are steeply dipping, but shallowly dipping fractures or sheeting joints are also present as shown in the stereonets (figs. 2, 4, and 5). Outcrops in the On and Onb members of the Nashoba Formation closest to the well site show a heterogeneous distribution of principal fracture trends (fig. 2). Principal trends in the Nashoba Formation within 1 km of the well site include 291°, 356°-357°, 6°-9°, 15°-18°, 30°, 36°-38°, and 88° (fig. 2). Fracture data from the On member for the entire area, however, contain only a single principal fracture trend at 35° ± 6° (fig. 5), which is statistically the same as the 36°-38° trend within 1 km of the well site (fig. 2). The same trend is also the maximum principal trend for all joint sets, joint zones, and throughgoing fractures in the area (34° in fig. 4B-D). A throughgoing fracture is one that transects the entire outcrop, rather than terminates within the outcrop area. Although the 34°-38° trend is present near the well site, many other trends are also present in the heterogeneous data, and the data from figure 4 could be misleading. Furthermore, approximately 40 percent of all the fracture data comes from the group of outcrops in South Acton, where a single principal trend at 34° shows no heterogeneity and is the result of a locally pervasive joint set at this locality. Another regionally throughgoing trend is 46° (fig. 4D), but it is not a principal trend within 1 km of the well site (fig. 2).

Sulfide mineralization along fracture surfaces is unique to the area immediately south of the well site (figs. 2 and 6). A subset of the fracture data from only the mineralized fractures again shows a heterogeneous pattern of both steeply and shallowly dipping surfaces (fig. 7). Principal trends in the sulfide-mineralized Nashoba Formation south of the well site include 317°, 338°, 9°, 60°, and 88° (fig. 7). A comparison between principal trends within 1 km of the well site and sulfide mineralized fractures (figs. 2 and 7) reveals that only the 9° and 88° trends are present in both data sets. The 9° and 88° trends, therefore, represent a distinct subset of the fracture heterogeneity around the well site because of the sulfide mineralization and the limited spatial distribution within 1 km of the wells.

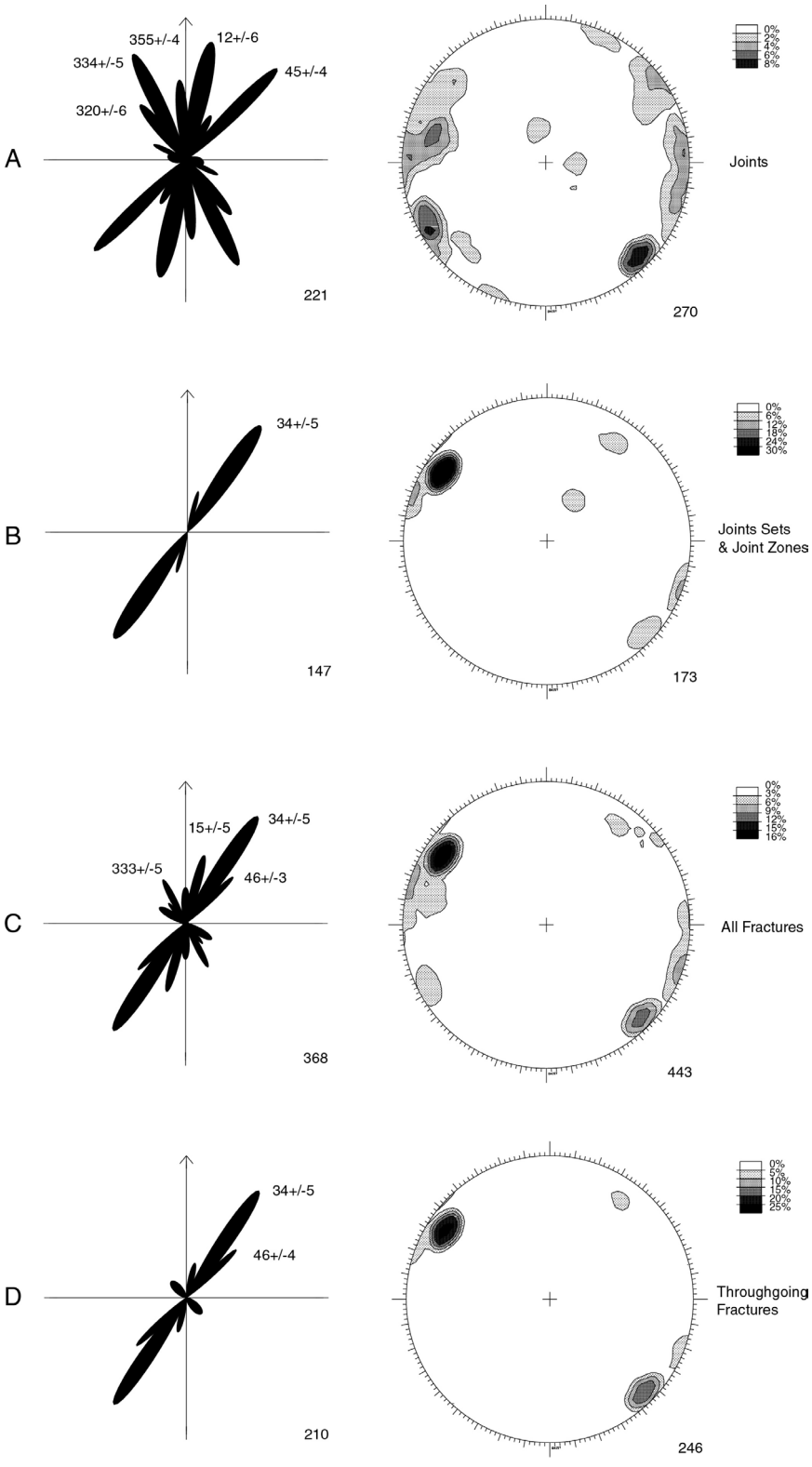

Figure 4. Rose diagrams and stereonets for fractures from the study area separated by type. A) Joints only; B) Joints sets and joint zones (or fracture zones) only; C) All fractures (combined data from A and B); and D) Throughgoing fractures as a subset of C. See figure 2 for an explanation of the rose diagrams and figure 3 for an explanation of the stereonets.

SUMMARY

1) The Rockland Avenue well site is located entirely within the Nashoba Formation – a coarse-grained muscovite-biotite-quartz-plagioclase schist and gneiss with minor amphibolite.

2) The Nashoba Formation contains a poorly preserved, layer-parallel foliation (S1) that is transposed by a regionally penetrative second-generation schistosity (S2). The average strike and dip of S2 is 243°, 89°.

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

4) The well site is located between the Spencer Brook and Assabet River faults – a location that regionally contains an abundance of faults characterized by mylonitization, brecciation, alteration, silicification, and zones of gouge. The faults are generally parallel to the S2 foliation.

5) Fracturing in the vicinity of the well site is heterogeneous. Principal fracture trends within 1 km of the well site include 291°, 356°-357°, 6°-9°, 15°-18°, 30°, 36°-38°, and 88°.

6) Fracture trends of 34°-38° and 46° are regionally throughgoing. The 34°-38° trend is both a locally pervasive joint set away from the well site and a principal trend within 1 km of the well site. The 46° trend is not a principal fracture trend within 1 km of the well site.

7) Sulfide mineralization along fracture surfaces is well developed in the area immediately south of the well site. Principal trends in the sulfide-mineralized zone include 317°, 338°, 9°, 60°, and 88°. The 9° and 88° trends represent a subset of the fracture heterogeneity around the well site because of the mineralization and the limited spatial distribution within 1 km of the wells.

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

- Parting along steeply dipping S2 foliation that trends 243° (or 63°)
- Principal fracture trends near to the well site including 291°, 356°-357°, 6°-9°, 15°-18°, 30°, 36°-38°, and 88°.
- Principal trends in the sulfide-mineralized zone including 317°, 338°, 9°, 60°, and 88°.
- Principal trends unique to the sulfide-mineralized zone and within 1 km of the well site including 9° and 88°.
- Sub-horizontal sheeting fractures.

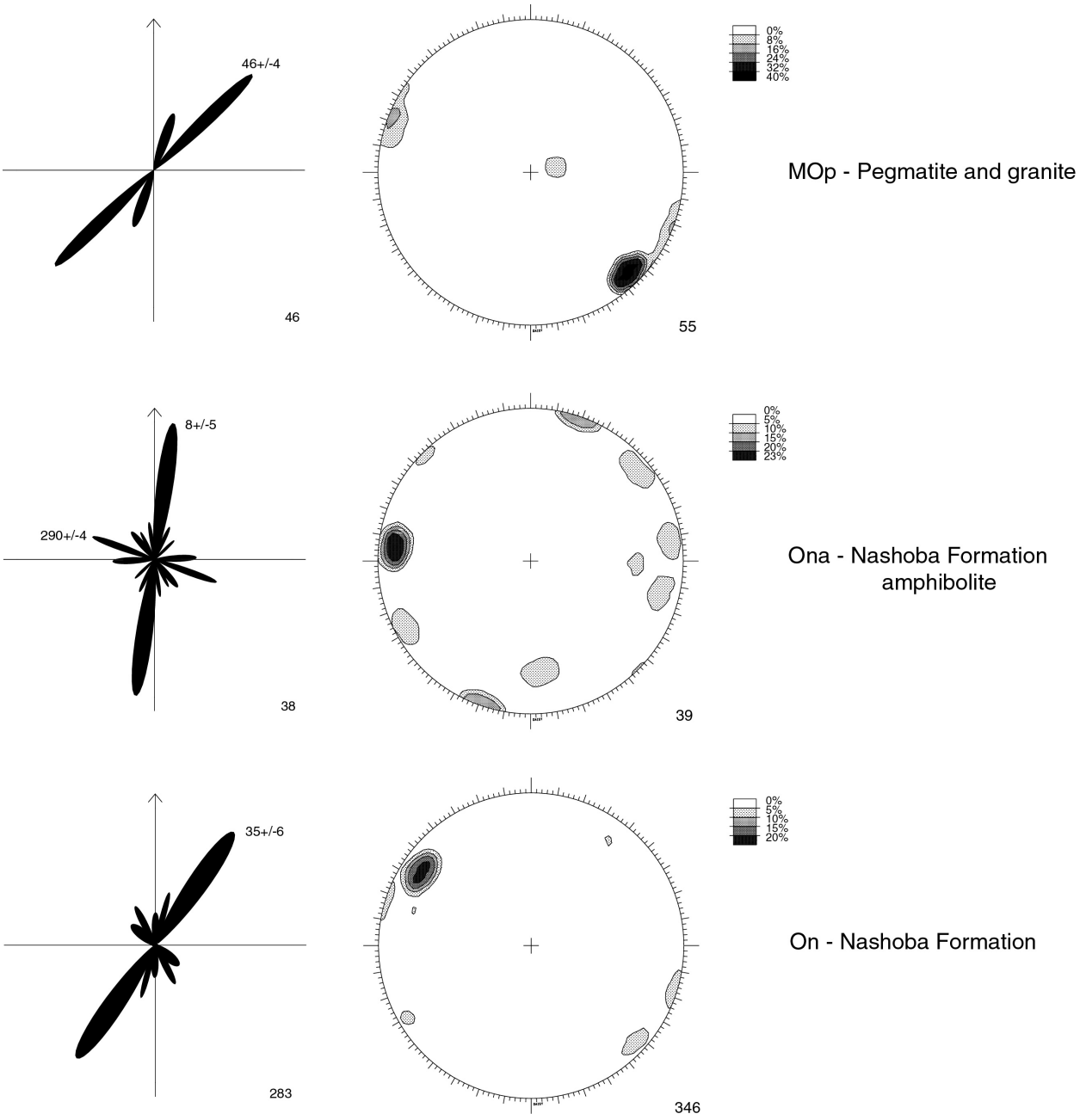

Figure 5. Rose diagrams and stereonets for fractures separated by rock type. See figure 2 for an explanation of the rose diagrams, and figure 3 for an explanation of the stereonets.

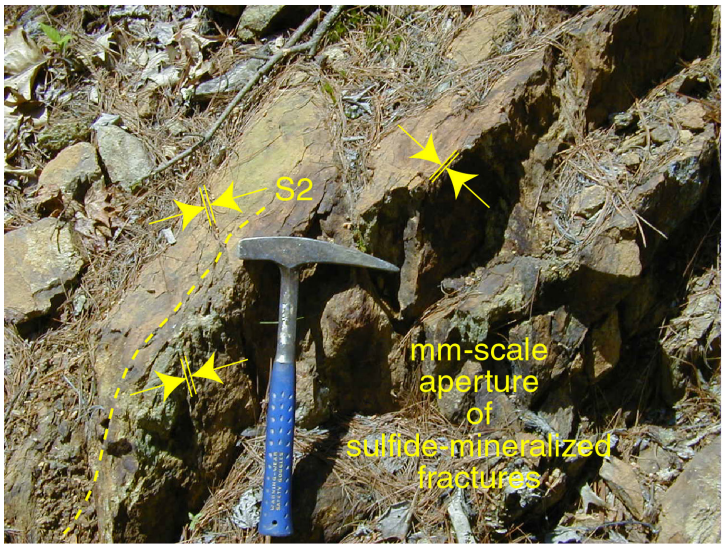

Figure 6. Photograph of the rusty weathering, sulfidic, biotite schist of the Nashoba Formation (Unit On, fig. 1) exposed south of the well site along Rockland Avenue. The dashed line shows the trace of the S2 schistosity, and the double arrows show the mm-scale aperture of sulfide-mineralized fractures. The left side of the photo is to the east and the view is to the south.

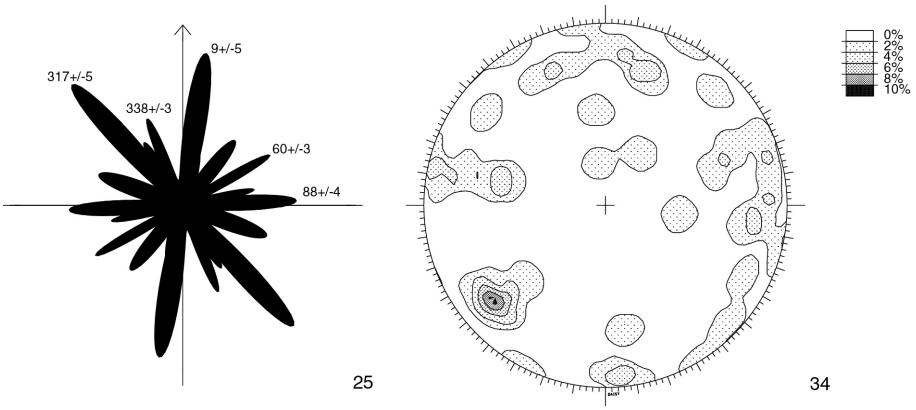

Figure 7. Rose diagram and stereonet for sulfide mineralized fractures. See figure 2 for an explanation of the rose diagrams, and figure 3 for an explanation of the stereonets.

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