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Bedrock Geologic Map of the Hubbard Brook Experimental Forest, Grafton County, New Hampshire

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ABSTRACT

The bedrock geology of the Hubbard Brook Experimental Forest in Grafton County, New Hampshire consists of metasedimentary rocks of the Silurian Rangeley and Perry Mountain Formations that have been intruded by Devonian granitoids and Cretaceous-Jurassic mafic dikes. The metasedimentary rocks were affected by at least two episodes of deformation in the Devonian Acadian orogeny. The dominant regional foliation is second-generation (S2/D2) and formed during the development of sillimanite-muscovite mineral assemblages. The eastern portion of the forest is underlain by schists of the Rangeley Formation, overlain in the southern part of the forest by quartzite and schist of the Perry Mountain Formation. The western part of the forest contains the southern portion of a large body of Early Devonian Kinsman Granodiorite, mostly massive but locally well foliated, which intruded Rangeley Formation schists semi-concordantly during D2. Volumetrically minor dikes of Late Devonian granite and tonalite cut lithologic contacts and S1 foliation within the Rangeley Formation and appear to be syn- or post-D2. The map pattern is dominated by northeast- to northwest trending, moderately to steeply north dipping F2 and F3 folds; map-scale F1 folds are defined by the Perry Mountain-Rangeley contact. Previous division of Rangeley stratigraphy in this region into “upper” and “lower” parts was not found to be applicable at 1:10,000-scale mapping, and rocks previously mapped as part of the Small Falls and Madrid formations are reassigned to the Rangeley.

Steeply dipping fractures in the area show a preferred northeast orientation, consistent with subsurface fracture orientations in the USGS CO well field near Mirror Lake. In addition to the predominant northeast trend of fractures in the area as a whole, northwest-striking principal fracture trends show a slight clustering in the central and east-central part of the area. East-west trending principal fractures show a cluster in the northwestern part of the area, localized occurrence in the central and eastern part of the area, and limited occurrence elsewhere. North-south striking principal fracture trends show limited distribution across the map. Cretaceous-Jurassic mafic dikes and normal faults show preferred northeast orientations, similar to the fractures, suggesting that the extensional stress field that controlled dike orientation in the Mesozoic also produced the dominant brittle fabrics in the area.

INTRODUCTION

The Hubbard Brook Experimental Forest in central New Hampshire is a long-term hydrological and ecological research site of the U.S. Forest Service, established in 1955, which occupies nearly the entire Hubbard Brook watershed. Since 1990 the area around Mirror Lake, in the eastern part of the watershed, has been the site of hydrologic research on the flow of ground water in fractured bedrock by the Toxic Substances Hydrology Program of the USGS. Until recently, however, the only larger-scale published geologic map of the region was Moke’s 1945 map of the Plymouth 15-minute quadrangle (Moke, 1945). Barton (1997) published the first detailed bedrock geologic map of the area.

Barton's map shows the eastern part of the watershed to be underlain mostly by metasedimentary rocks of the Lower Silurian Rangeley Formation, which he subdivided into an upper and lower member in accord with the regional geologic mapping of Lyons and others (1997) for the bedrock geologic map of New Hampshire. Three other Silurian metasedimentary units stratigraphically above the Rangeley, the Perry Mountain, Smalls Falls, and Madrid Formations, were also mapped in the Hubbard Brook watershed by Barton (1997), while Lyons and others (1997) mapped Perry Mountain Formation and Lower Devonian Littleton Formation in the watershed. Both maps show bodies of Devonian granodiorite, tonalite, and granite, and Barton (1997) also mapped mafic Cretaceous-Jurassic dikes.

Our mapping study was funded by the USGS Toxic Substances Hydrology Program and was undertaken for the following reasons: 1) to ascertain whether the area might have a greater number of mappable lithologic units than shown on Barton's (1997) map, and to verify the stratigraphically higher formations shown on the map; 2) to have sufficient data to draw geologic cross-sections through the Mirror Lake research site; 3) to gather more data on brittle fracture distribution and orientation; and 4) to assess the degree to which the subsurface lithologies, ductile structures, and fractures observed at the two Mirror Lake well fields correlate with the geology of the surrounding region.

Field stations were located and digitally plotted using a satellite-based global positioning system (GPS) according to procedures described in Walsh and others (1999). Measurements were made of the penetrative ductile structures such as foliation and fold axes, and of conspicuous fractures, which are commonly expressed as joint faces. Detailed fracture analysis of the kind conducted on the I-93 roadcut (Barton, 1997; Hsieh and others, 1993) was not attempted in our regional-scale investigation.

BEDROCK LITHOLOGY

Metasedimentary rocks

The Hubbard Brook Experimental Forest is underlain by sillimanite-grade metasedimentary rocks of the Silurian Rangeley and Perry Mountain Formations, which have been intruded by a large body of Lower Devonian Kinsman granodiorite, small elongate bodies of Devonian tonalite and granite, and Cretaceous-Jurassic mafic dikes (Plate 1, Fig. 1). Much of the Rangeley Formation exposed in the area consists of weakly layered schists which are subdivided into lithologic map units on the basis of subtle differences in modal mineralogy, texture, and weathering characteristics. The major units in the Rangeley Formation include schist and granofels (Srg), rusty schist (Srr), biotite schist (Srb), sillimanite schist (Srs), and schist and granofels with garnet and tourmaline (Srgt). Much less abundant in the Rangeley are fine-grained granofels (Srfg), rusty tourmaline schist (Srrt), and well-layered rocks including layered quartzite and granofels (Srlg), calc-silicate granofels (Srcs), and quartzite (Srq). Perry Mountain Formation rocks include well bedded quartzite and sillimanite schist (Sp) and massive sillimanite schist (Spp)(Fig. 1).

Where the rocks are coarse-grained and more massive in the Rangeley Formation (schists such as Srg and Srr) there are local zones in which inclusions of fine-grained, finely foliated to layered quartzite and calc-silicate granofels (Srcs) occur in a matrix of coarse-grained massive schist (Fig. 1C). The internal foliation of these inclusions commonly contains tight to isoclinal folds, and the foliation is truncated at the contact with the surrounding schist (Fig. 1C). Where several of these inclusions occur together they appear to be randomly oriented with respect to internal foliation and the long axes of the inclusions. The inclusions formed when the more competent beds in the metapelitic sequence became disarticulated and rotated during deformation. Metamorphic recrystallization of the more pelitic beds during and after deformation produced the massive to poorly foliated matrix of schist and granofels.

Despite the extensive deformation and metamorphic recrystallization of this region, the rocks exposed in the eastern Hubbard Brook watershed appear to correlate with the Rangeley-Perry Mountain type-section exposed in western Maine for the following reasons: 1) the more pelitic composition of the Rangeley compared to the Perry Mountain; and 2) the transitional increase of quartz-rich layers at the Rangeley-Perry Mountain contact (Moench and Boudette, 1987; R. Moench, oral comm., 1998). The map distribution of the Rangeley and Perry Mountain formations indicates that the premetamorphic stratigraphy generally youngs from north to south across the field area. Rocks mapped as belonging to the Small Falls and Madrid formations by Barton (1997) are here interpreted as layered granofels within the Rangeley (Srlg). Rocks mapped as Littleton Formation within the western part of the watershed by Lyons and others (1997) were remapped as Rangeley Formation.

Igneous rocks

The Hubbard Brook watershed contains the southern termination of a large body of Kinsman Granodiorite (Dkg), which extends north-northeast about 40 km into the central White Mountains, and includes the type area on Kinsman Mountain. Kinsman Granodiorite is two-mica-bearing, mostly massive and coarse-grained, and commonly has a porphyritic texture with large phenocrysts of plagioclase and microcline (Fig. 1E). The granodiorite is locally well foliated, with foliation expressed either by oriented feldspar phenocrysts in what may be an igneous flow foliation, or by a micaceous schistosity that is tectonic in origin. The two foliations never occur together and textural crosscutting relationships have not been observed, permitting the interpretation that the two fabrics are contemporaneous. Locally the Kinsman contains segregations of fine-grained aplite and coarse-grained pegmatite, and dikes of white to tan porphyritic fine-grained granodiorite (Dkfd) and white fine-grained aplite (Dap).

The contact of the granodiorite with country rock varies in character. In exposures on a ridge north of Hubbard Brook and in road cuts south of the brook, the contact is sharp where the adjacent schist is fine-grained and well layered, and texturally gradational where it is coarse-grained and massive. In contrast, at the contact of schist with granodiorite along the southwest margin of the body, both schist and granodiorite are strongly foliated. A finer-grained, chilled border facies of the granodiorite was not observed. These textural variations, both internal to the Kinsman and at its contacts, are evidence for the synkinematic character of the intrusive body.

The metasedimentary rocks are also intruded by small, elongate bodies or dikes of white, medium-grained, two-mica granitoid (Dg) that were mapped by Barton (1997) as 370-365 Ma Devonian Concord Granite (Fig. 1F). The dikes occur as outcrop-scale bodies shown by symbols on Plate 1 or as small mappable intrusions. The dikes range from tonalite to granite in composition, are massive to weakly foliated, and intrude across lithologic contacts. The 13 outcrop-scale Dg dikes generally are steeply dipping, and most strike northeast with bimodal peaks at 16° and 42° (Fig. 2). Dikes of Concord Granite are more abundant in the eastern part of the field area. Dikes of white coarse-grained pegmatite (Dp) are also thought to be of Concord affinity and occur both as outcrop-scale dikes and as mappable intrusive bodies. The 33 outcrop-scale Dp dikes generally are steeply dipping, strike to the northeast and northwest, and show bimodal strike peaks at 299° and 42° (Fig. 2).

Shown intruding the Devonian and Silurian rocks are 27 diabase and lamprophyre dikes of Cretaceous-Jurassic age (KJd, shown as symbols only) which are widely scattered and generally less than one meter wide and probably meters to tens of meters long (Fig. 1G). The mafic dikes are steeply dipping, trend mostly northeast, and show a unimodal peak at 43° (Fig. 3). Mafic dikes in this region have been described as lamprophyric in composition and are associated with the White Mountain Plutonic-Volcanic Suite (McHone, 1984; Lyons and others, 1997).

DUCTILE DEFORMATION AND METAMORPHISM

Structure

The metasedimentary rocks of the Silurian Rangeley and Perry Mountain Formations were subjected to extensive deformation and metamorphic recrystallization prior, during, and after intrusion of Early Devonian Kinsman Granodiorite, nearly all before the emplacement of Late Devonian Concord Granite. Most primary sedimentary structures were obliterated, with the exception of graded beds in the uppermost Rangeley and Perry Mountain Formations, and some of the fine layering preserved in calc-silicate and granofelsic pods in the Rangeley Formation. The paucity of primary structures and high degree of deformation contrasts with the type locality for these rocks, where relatively mild deformation has preserved sedimentary structures and stratigraphy despite staurolite to sillimanite-grade metamorphism (Moench and Boudette, 1987; R. Moench, personal comm., 1998).

The S1 foliation produced during D1 is defined by oriented micas parallel to fine-scale compositional layering, and is generally only present in well-layered rocks like Srlg or Srcs or the finely layered inclusions of quartzite and granofels in more massive granofels and schist. S1 is axial planar to isoclinal F1 folds, which are rarely seen in well-layered rocks but are more common in finely-layered inclusions (Figs. 1C, 4). Map-scale F1 folds are expressed by the contact between the Perry Mountain Formation and the underlying Rangeley formation as tight, east-west-trending folds. No F1 fold axes were seen in the vicinity of these mapped F1 fold closures and their plunges are uncertain. The F1 fold axial trace seen in the coticule in figure 4 is perpendicular to the F2 fold axial traces. S1 layer-parallel schistosity and bedding in the area generally exhibits a steeply dipping orientation throughout the area (Fig. 5).

The dominant foliation in the area is a penetrative second-generation (S2) schistosity, produced during D2, that is mostly northeast trending and steeply dipping (Fig. 5), and commonly at an angle to lithologic contacts. An angular discordancy between S1 and S2 is most distinctly seen at the margins of the finely layered inclusions, which are internally dominated by S1 in contrast to the S2-dominated surrounding schist (Fig. 1C). Locally, the dominant foliation was mapped informally as “Sn” where unequivocal age relationships could not be determined at the outcrop. Most of what we mapped as “Sn” is probably S2 or a composite, sub-parallel S2 and S1 foliation, and figure 5 shows the similar orientations for “Sn” and S2, and “Fn” and F2 fold axes. The S2 fabric is commonly wispy and discontinuous, and it is not accompanied by a strong compositional layering. In thin section, S2 is expressed by aligned flakes of muscovite and biotite, and locally by layers rich in fibrolitic sillimanite. S2 is roughly axial planar to outcrop- to map-scale, open to tight, northeast-trending and moderately- to steeply-northeast-plunging F2 folds (Fig. 5), which are best displayed at the eastern end of the watershed. F2 and “Fn” fold axes are generally steeply plunging to the northeast (Fig. 5).

Our observed relations between F1 and F2 folds contrasts with the map of Lyons and others (1997) and their cross-section (B-B’), which passes about six miles to the northeast of Mirror Lake. Their map and section show a pattern dominated by a single generation of folds with northeast trending axial traces and gently plunging fold axes in the upper and lower Rangeley Formation. In contrast, our mapping to the south shows older east-west trending F1 folds deformed by northeast-dominated F2 folds with steeply plunging fold axes (Plate 1).

Third-generation folds (F3) produced during D3 are present in the form of broad map-scale and outcrop-scale folds that trend largely to the north to northeast in the eastern half of the watershed (Figs. 4 and 5). The S3 fabric is locally mapped as a strongly penetrative schistosity or shear fabric confined to narrow (cm-wide) zones that cut S2 and S1 at a low angle. A few widely scattered zones of weakly developed ductile shear fabric have been found that measure no more than a few tens of cm thick. These truncate S2 schistosity at low angles and are probably D3 in age, but do not appear to have had a high amount of displacement.

The main intrusive rock in the area, the Kinsman Granodiorite, clearly crosscuts map-scale S1-parallel compositional layering in the host rocks, and appears to truncate an F1 axial trace expressed by the Perry Mountain-Rangeley contact, making the Kinsman post-D1. The truncation of the axial trace of the F1 synform occurs in the area between Zig Zag Brook and Kineo Brook. Locally a well-developed tectonic foliation is present within and along the margin of the Kinsman, indicating that it was intruded during regional deformation and is probably syn-D2 in age. Locally along the southwest margin of the granodiorite, a strongly developed, northwest-trending foliation occurs both in and adjacent to the intrusive body. This may be S2 foliation that exploited the intrusive contact and has therefore deviated from the general northeast trend.

The smaller, dike-like bodies of Concord Granite also cut compositional layering and S1 at high angles, are mostly subparallel to regional S2 foliation, and have a weakly to moderately developed internal foliation. For this reason they are also thought to be generally syn-S2, perhaps intruding slightly later during D2 than the Kinsman.

Metamorphism

The regional metamorphic grade of the rocks in the Hubbard Brook watershed is sillimanite-muscovite, according to mineral assemblages that equilibrated during D2. No sillimanite-potassium feldspar equilibrium assemblages have been found. The age of this metamorphism can be bracketed between the Silurian to Early Devonian ages of the Rangeley, Perry Mountain, and Littleton Formations, on the one hand, and the Early to Late Devonian ages of the granitic intrusives, during the Acadian orogenic event (Armstrong and others, 1992).

Petrographic evidence suggests that metamorphic conditions were different prior to the D2 deformation event, perhaps being hotter and/or drier. Garnets are generally highly embayed and are locally rimmed by biotite or chlorite. Potassium feldspar is only found as large scattered porphyroblasts in both schist and Kinsman Granodiorite, and these are commonly rimmed by muscovite and myrmekitic quartz and plagioclase, clearly indicating breakdown of potassium feldspar. Roundish aggregates of fine-grained quartz, plagioclase, and muscovite in some rocks may indicate completely recrystallized potassium feldspar. Rare prismatic sillimanite may be older than the fibrolite now prevalent. Large, randomly oriented porphyroblasts of sillimanite in the Rangeley schists and particularly in the Perry Mountain schists are generally syn-D2 and show syn- to post-D2 fibrolitic recrystallization.

Taken together, the evidence suggests that regional metamorphic grade may have reached sillimanite-kspar prior to or during intrusion of the Early Devonian Kinsman Granodiorite. The metamorphic effect of the intrusive rock on the country rock was definitely not prograde and may have been retrograde, via the addition of water that changed metamorphic assemblages from sillimanite-kspar to sillimanite-muscovite. Sericitization of plagioclase porphyroblasts and presence of chlorite in the Kinsman suggests that the process of hydration continued to lower temperatures within the intrusive body.

Due to the upper amphibolite-facies conditions during regional metamorphism and intrusion of the Kinsman, prograde contact metamorphic effects related to the intrusion are rare. A sample of Rangeley Formation (unit Srg) collected just east of the Kinsman contact along the road south of Hubbard Brook and between Canyon Brook and Cascade Brook contains the assemblage plagioclase-quartz-cordierite-kyanite-biotite. This assemblage may be a relict high-temperature contact-metamorphic reaction involving partial melting (biotite + kyanite goes to cordierite + melt) or, alternatively but less likely, the cordierite may be a retrograde depressurization product of kyanite breakdown.

BRITTLE DEFORMATION AND FRACTURES

Brittle faulting does not appear to have played a significant role in the tectonic history of the Mirror Lake area, at least in terms of the distribution of lithologies. No major through-going fault zones were identified, although it is possible that some topographic lows contain faults that are buried in glacial deposits.

There is evidence for map-scale brittle faulting at three localities in the Hubbard Brook watershed. At a place known informally as “the gorge” in Hubbard Brook (about one kilometer west of Mirror Lake at the 900-1000-foot elevation levels) a northeast-trending, steeply southeast-dipping fault is marked by offset contacts, slickensided vein quartz and local fault gouge (Fig. 6A). Slickenlines at the contact plunge downdip, and the fault is interpreted to be a normal fault. In the southeastern tributary of Kineo Brook, between the elevations of 2250 and 2350 feet, a second northeast-striking steeply dipping normal fault cuts the Kinsman Granodiorite. The fault is characterized by a zone of intense jointing, locally developed slickensided surfaces showing normal (down-to-the-east) movement, and an approximately 5 to 10 m wide zone of grus in the granodiorite. The northeast-trending brittle fault identified in the I-93 roadcut by Barton (1997) was found by the authors to be a steeply southeast dipping, highly weathered zone of concentrated jointing with shallow southwest plunging slickensides with normal (down-to-the-east) displacement, but little significant offset (Fig. 6B). At one locality in the roadcut, a pegmatite body is traceable across the fault zone.

A total of 16 outcrop-scale brittle faults were mapped in the area (Plate 1). Thirteen show normal movement, one shows reverse movement, and the movement sense could not be determined on two others. Most of the faults strike to the northeast and dip steeply to moderately to the southeast (Fig. 7). Slickensides plunge predominantly down dip to the southeast (Fig. 7).

Fractures measured in the field area consist mostly of well-exposed joint faces, but also include joint sets, joint zones, and the faults discussed above. Plate 2 is a fracture map of the area and shows the orientation of fractures in contoured lower hemisphere equal area projections of poles to fractures (stereonets) and frequency-azimuth (rose) diagrams for steeply dipping fractures (dips ≥ 60°). Stereonets and rose diagrams on Plate 2 are drawn in 1-km grid cells that were used for selecting the data points from the GIS database. Bullseye contour patterns near the centers of the stereonets (Plate 2) indicate sub-horizontal sheeting fractures, which were observed throughout the field area.

The steeply dipping fractures, however, have regional differences in preferred orientation. Fracture trends in the area as a whole show a preferred northeast strike with secondary maxima in the 270°-290° azimuth range (Fig. 8). Fracture trends shown on Plate 2, however, show spatial variability across the map (Figs. 9 and 10). Northeast-striking principal fracture trends are the most widespread and uniformly distributed across the area (Fig. 9). Northwest-striking principal fracture trends show a general cluster in the central and east-central part of the area (Fig. 9). East-west trending principal fractures show a cluster in the northwestern part of the area, localized occurrence in the central and eastern part of the area, and limited occurrence elsewhere (Fig. 10). North-south striking principal fracture trends show limited distribution across the map, but do occur in the vicinity of the FSE and CO well fields (Fig. 10).

COMPARISON WITH OTHER GEOLOGIC STUDIES AT MIRROR LAKE

Our geologic mapping in the Mirror Lake area provides a regional context to the downhole geologic investigations conducted at the USGS FSE and CO well fields as well as the site-specific study of the I-93 roadcut by Barton (1997), and therefore provides some measure of the transferability of the previous in situ studies. Our study also points out discrepancies that can arise from comparison of borehole and roadcut data with those from natural outcrops within a larger area.

For instance, the regional mapping shows that bodies of granite occupy no more than a few percent by volume of the bedrock exposures in the eastern Hubbard Brook watershed, in contrast to the borehole logs compiled by Johnson and Dunstan (1998), where granite and pegmatite make up about 70 percent of the section drilled at the FSE well field, with the remainder schist. At the CO well field and the I-93 roadcut the proportions are reversed, with schist making up 70% of the total rock and granite the remainder (Barton, 1997; Johnson and Dunstan, 1998). Our reconnaissance of the I-93 roadcut generally confirmed the proportions of schist and granite as mapped by Barton, with a significant proportion of the granitic material being migmatite derived from the metasedimentary country rock. Migmatite was rarely observed in outcrop in the Hubbard Brook watershed, however.

The increase of mapped bodies of granite from west to east towards the Mirror Lake research site, and the relatively high abundance of granite and/or migmatite at the two well fields and the roadcut compared to outcrops elsewhere in the watershed, suggest that the research site is in a zone that experienced a higher degree of granitic intrusion and partial melting than areas immediately to the west; hence the geology is locally variable and site-specific relationships may not be representative of a larger area.

The preferred northeast orientation of the steeply dipping fractures that we observed for the Hubbard Brook watershed (Fig. 8) agrees fairly well with the fracture data of Barton (1997) for the I-93 roadcut, which in addition show a preferred dip in a southeast direction. In both data sets there is also a weaker northwest fracture trend and gently dipping to subhorizontal sheeting fractures. Measured orientations of fractures in boreholes in the CO well field also show a strong northeast preferred orientation for steeply-dipping fractures, after correction for vertical sampling bias, as well as a subhorizontal set probably related to sheeting (C. Johnson, 1999). The CO fracture data have a preferred northwest dip direction, opposite that of the roadcut, whereas our outcrop data show no preferred dip direction for steeply dipping fractures in the area surrounding the two well fields. In addition, our data shows principal east west and north-south fracture trends in the vicinity of the two well fields that are not widespread in the Hubbard Brook watershed.

SUMMARY

The Mirror Lake research site and much of the Hubbard Brook watershed are underlain by highly deformed, sillimanite-grade metasedimentary rocks of the Silurian Rangeley and Perry Mountain Formations. Contacts, bedding, and first-generation schistosity (S1) in these units are locally parallel to, but also crosscut by, the regionally dominant second-generation schistosity (S2), which in turn is broadly folded by north- to northeast-trending F3 folds. In the vicinity of the FSE and CO well fields, lithologies generally trend east-west and contacts are deformed by a penetrative northeast-striking, steeply dipping S2 schistosity and plicated by upright S3 cleavage. The well fields and the I-93 roadcut appear to be situated in a zone of more intense granitic intrusion and partial melting than areas to the west up the Hubbard Brook watershed.

Orientations of brittle fabrics in outcrop indicate that fractures in the Hubbard Brook watershed have a strong preferred northeast orientation, in general agreement with fracture orientations determined from the I-93 roadcut and the well fields. Cretaceous-Jurassic mafic dikes and normal faults also have preferred northeast orientations, suggesting that the stress field that produced the dominant brittle fabrics was the same NW-SE extension that induced intrusion of dikes.

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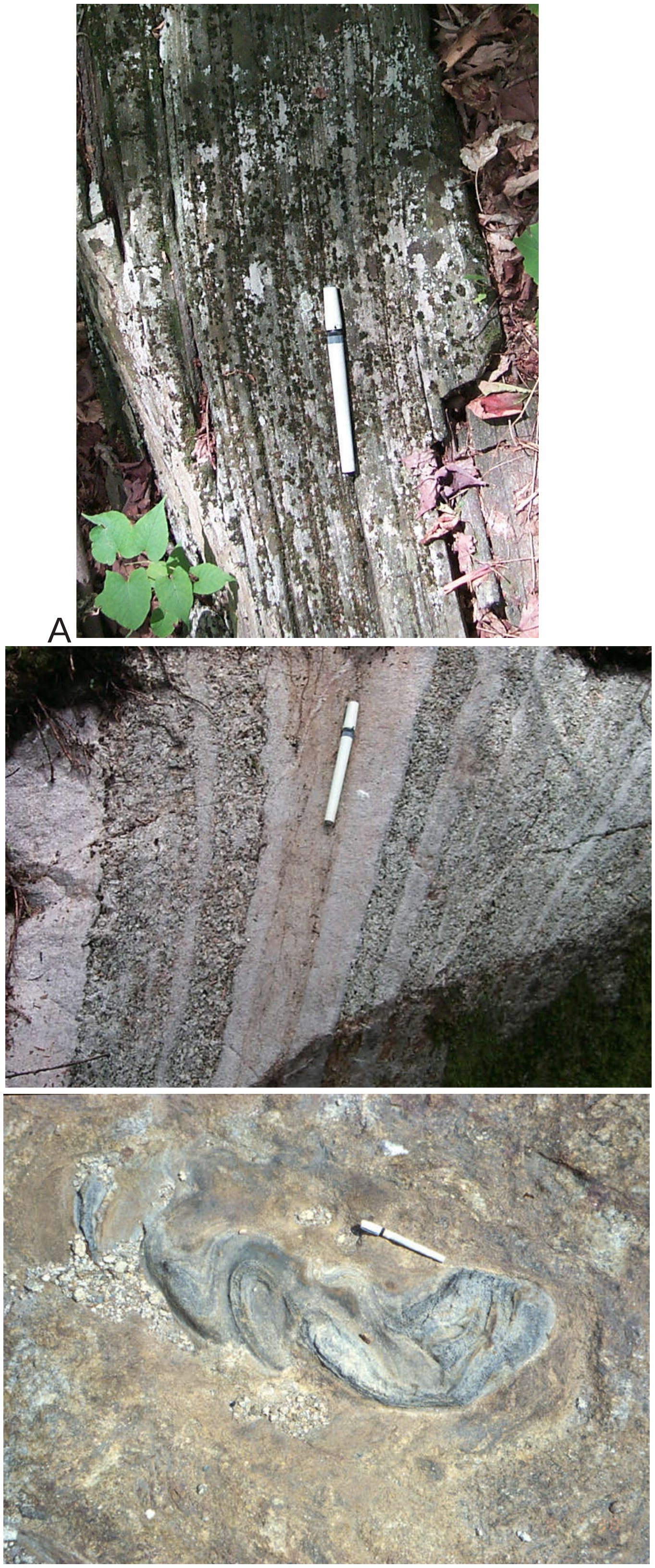


Figure 1. Selected bedrock lithologies and textures in Hubbard Brook watershed: A, Bedding in Rangeley Fm. fine-grained layered granofels (Srlg); B, Alternating quartz-rich and metapelitic (sillimanite-rich) layers (S1 fabric) in Perry Mountain Fm. (Sp); C, Finely-layered granofels inclusion (Srcs) in Rangeley Fm. rusty schist (Srr); D, S2 fabric in Rangeley Fm. biotite schist (Srb); E, Megacrystic texture in Kinsman Granodiorite (DKg); F, Dike of Concord Granite (Dg) cutting biotite schist (Srb); G, Diabase dike (KJd) cutting Rangeley Fm. granofels (Srg). Scales: pen in Figs. 3A-3D is 14 cm long; largest megacryst in 3E is 2 cm long; hammer in 3F, 3G is 44 cm long.

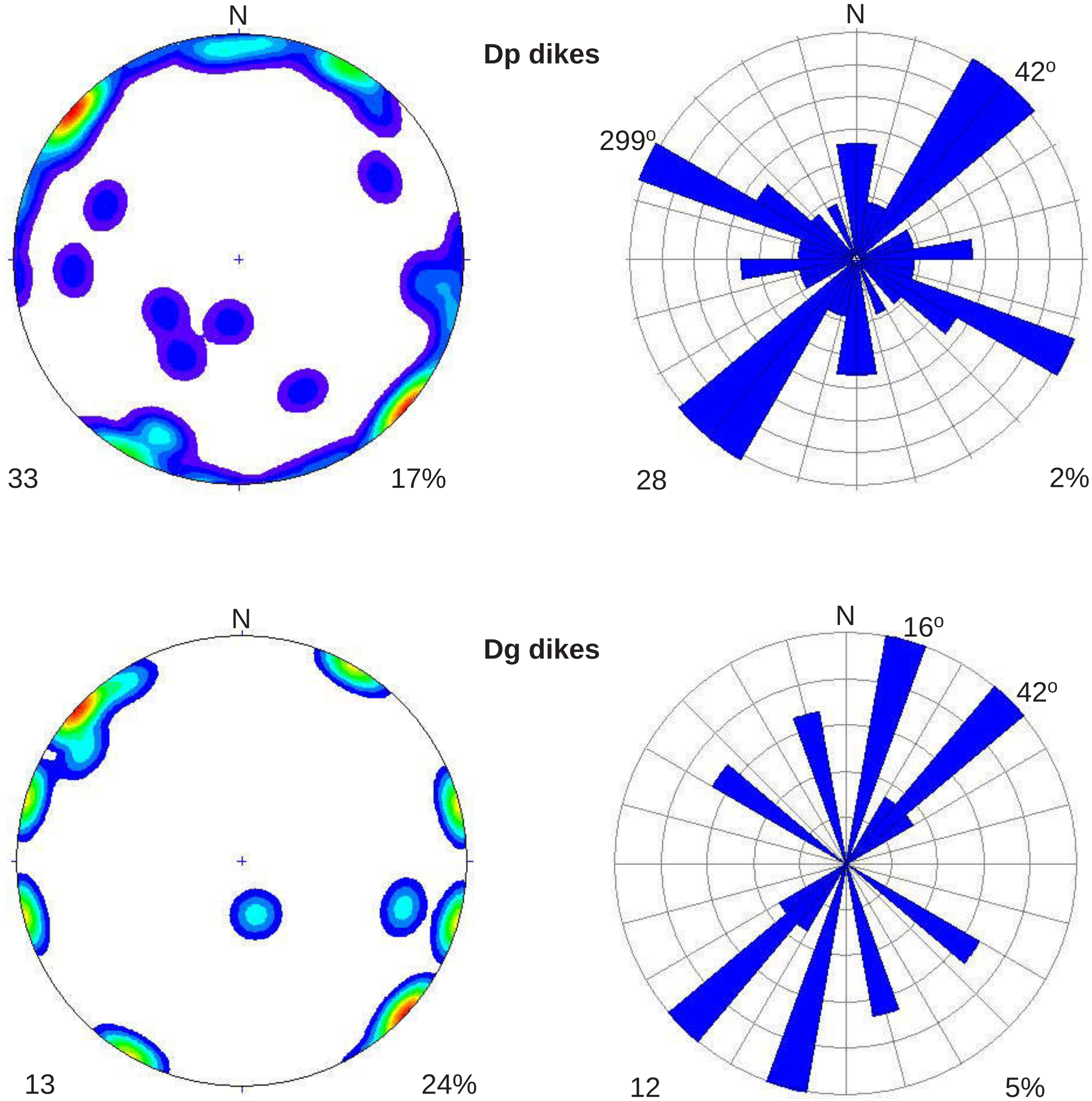


Figure 2. Lower hemisphere equal area projections (left) of poles to strike and dip of pegmatite dikes (Dp, top) and granitic dikes (Dg, bottom) and frequency-azimuth (rose) diagrams (right) of steeply dipping (>= 60°) dikes. N = North. Number of points in the dataset indicated by number at lower left of each diagram. Contour intervals differ on each stereonet, and percentage of total data for point maxima are indicated to the lower right. Azimuth data in rose diagram petals are binned in 10° increments, with azimuths of maxima also shown. Spacing of reference circles differs on each rose diagram and is indicated as a percentage to the lower right.

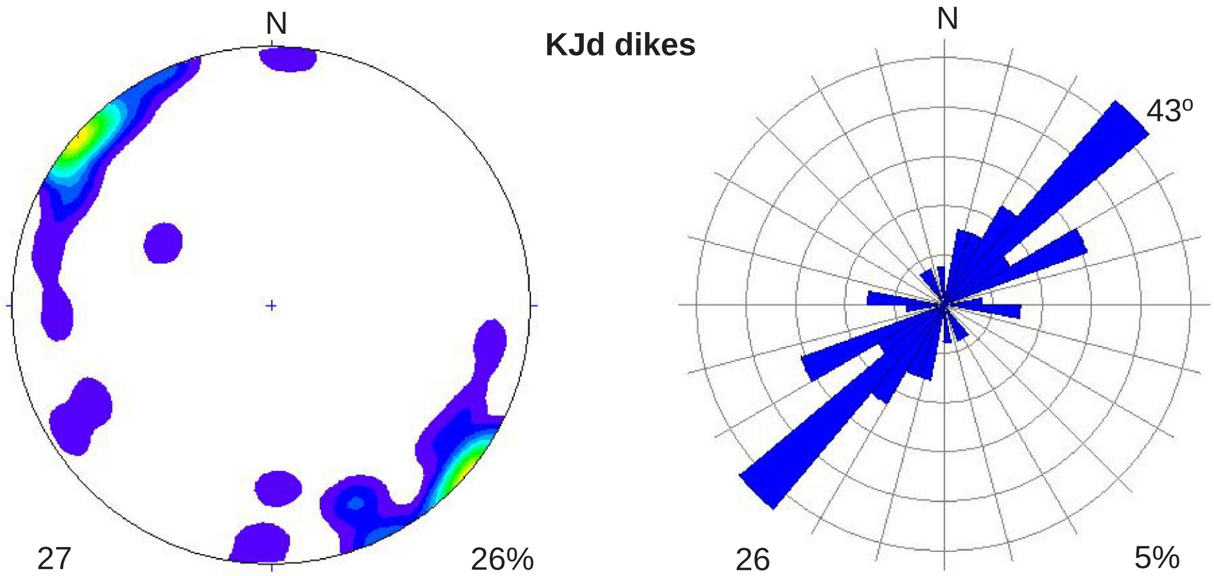


Figure 3. Lower hemisphere equal area projection (left) of poles to strike and dip of Cretaceous-Jurassic dikes (KJd) and frequency-azimuth diagram (right) of steeply dipping dikes (dip >= 60°). See Figure 1 for more detailed explanation of diagrams.

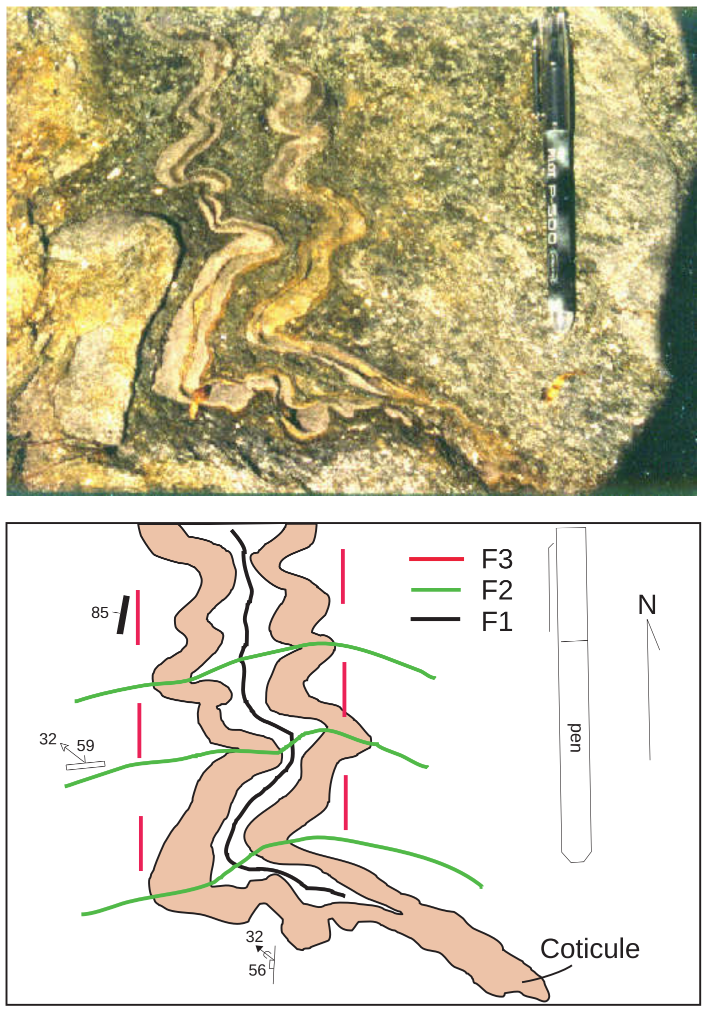


Figure 4. Map view outcrop photograph (top) and sketch (bottom) of refolded folds in layered coticule of Rangeley Fm. quartzite (Srq). Coticule layer outlines F1 fold that is refolded by F2 and F3 folds. The outcrop is located just east of the easternmost exposures of the Perry Mountain Formation along the southern border of the study area and corresponds to the southeastern corner of the Hubbard Brook Experimental Forest. Structure symbols for folds agree with symbols on Plate 1. Pen for scale is 14 cm long. Outcrop station 4417 in database.

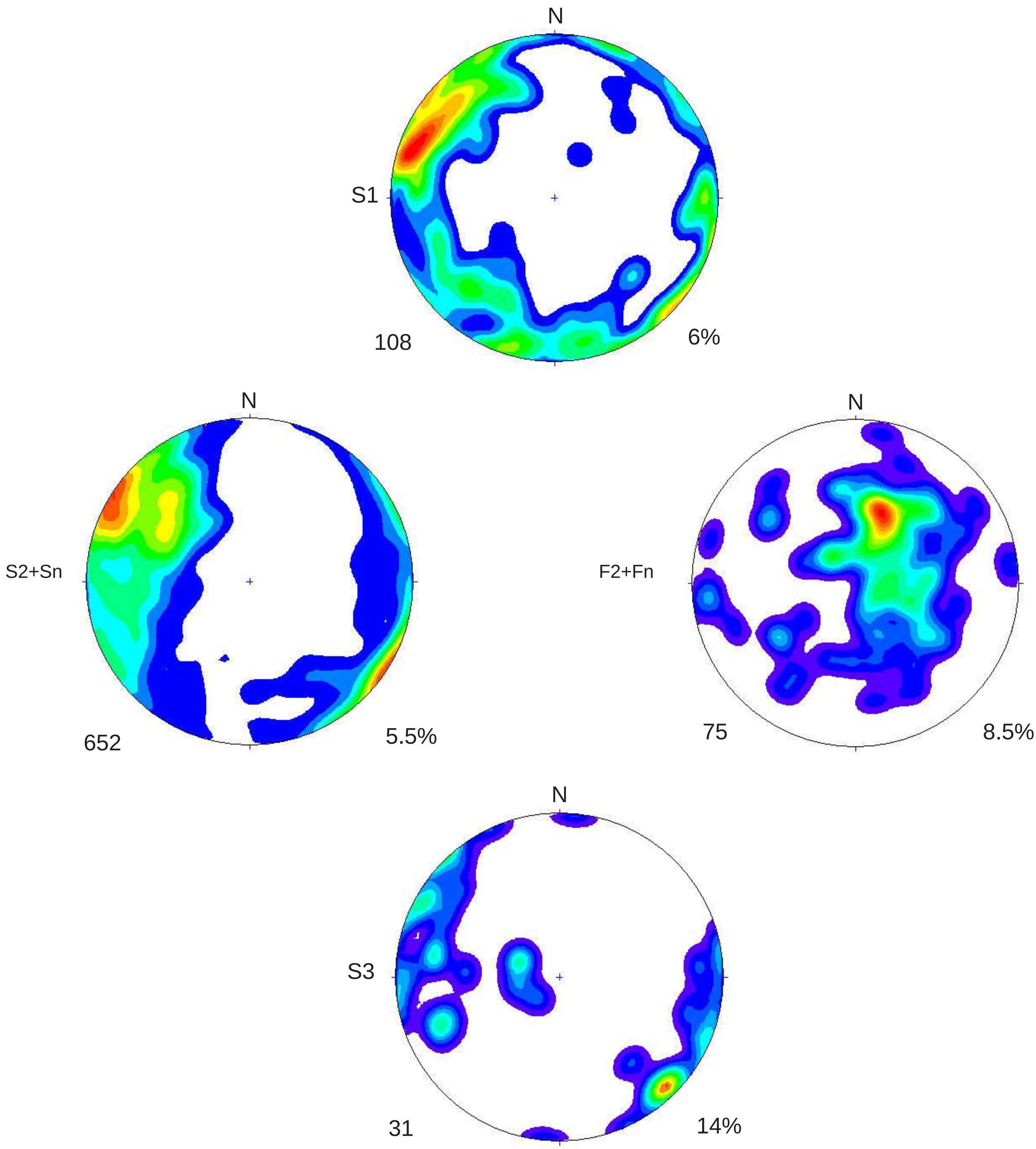
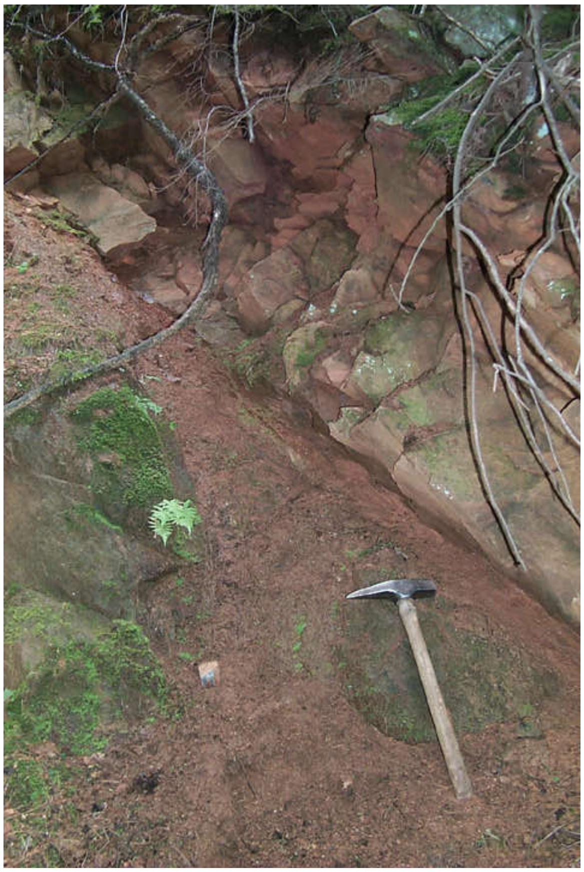


Figure 5. Lower hemisphere equal area projections of poles to strike and dip of planes and axes to trend and plunge of fold hinges or intersection lineations. S1: poles to layer parallel schistosity and bedding. S2+Sn: poles to second-generation schistosity, foliation, and axial surfaces; composite first- and second-generation foliation; and dominant schistosity of undetermined age. F2+Fn: axes to F2 folds, dominant folds of undetermined age, and S1/S2 intersection lineations. S3: poles to S3 schistosity, foliation, and cleavage. See Figure 1 for more detailed explanation of diagrams.



A

B

Figure 6. Brittle structures near Mirror Lake and in Hubbard Brook: A, Fault zone with normal (down to the right) movement sense juxtaposes Srr (hanging wall) and Srg (footwall), Hubbard Brook gorge; hammer 44 cm long. B, Fault zone in I-93 roadcut with small offset has two splays, one above people and one to right.

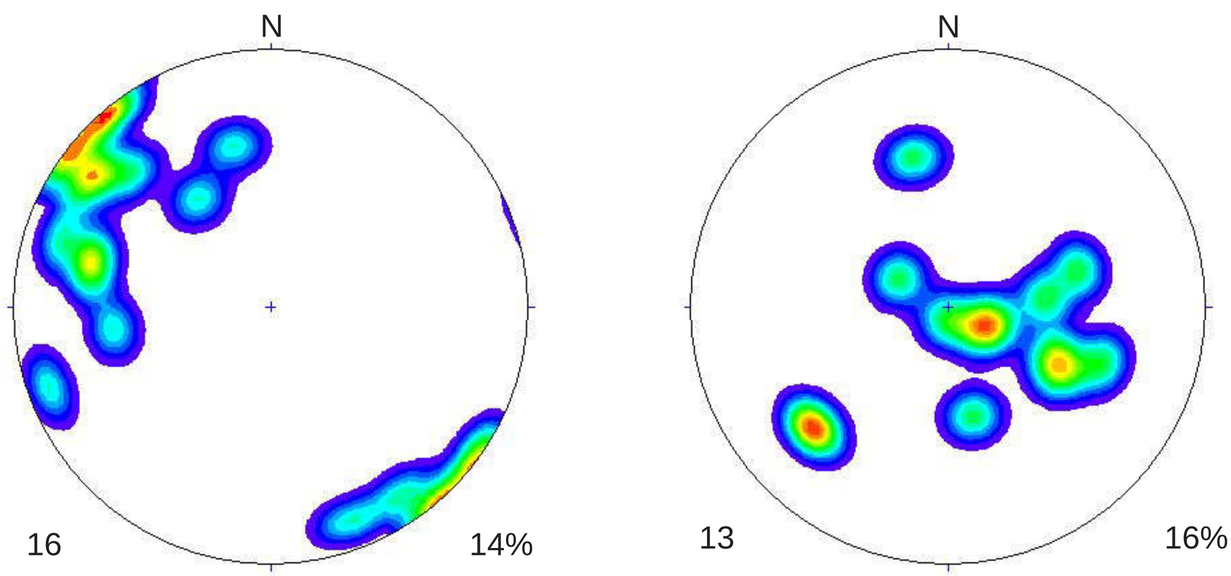
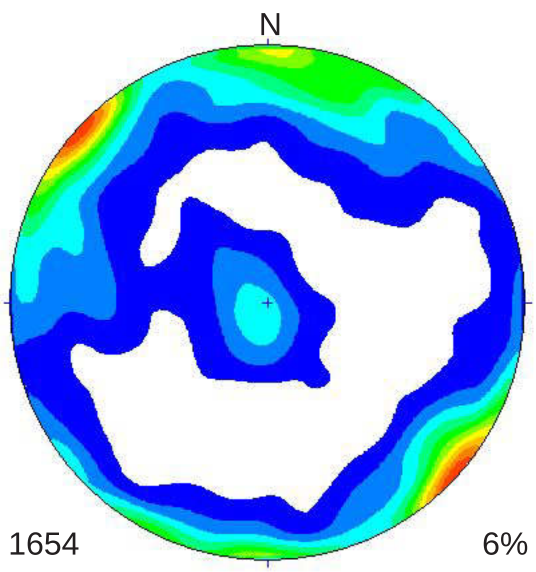


Figure 7. Lower hemisphere equal area projections of poles to strike and dip of faults (left) and trend and plunge of slickensides (right). See Figure 1 for more detailed explanation of diagrams.



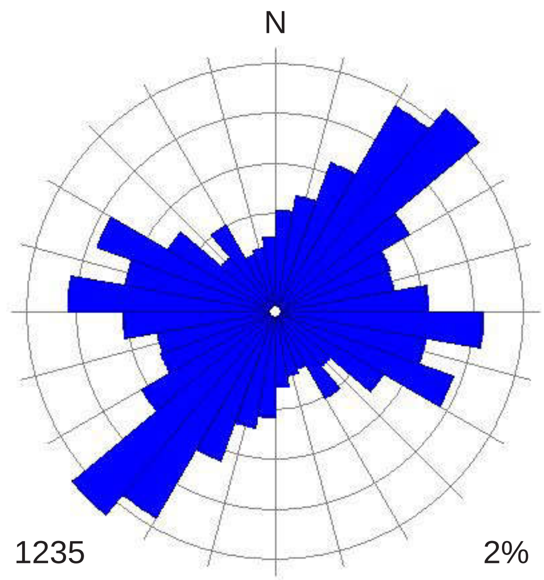


Figure 8. Lower hemisphere equal area projection (left) of poles to strike and dip of all fractures and frequency-azimuth diagram (right) of steeply dipping (>= 60^o) fractures. Note that the majority (75%) of fractures in the area are steeply dipping. See Figure 1 for more detailed explanation of diagrams.

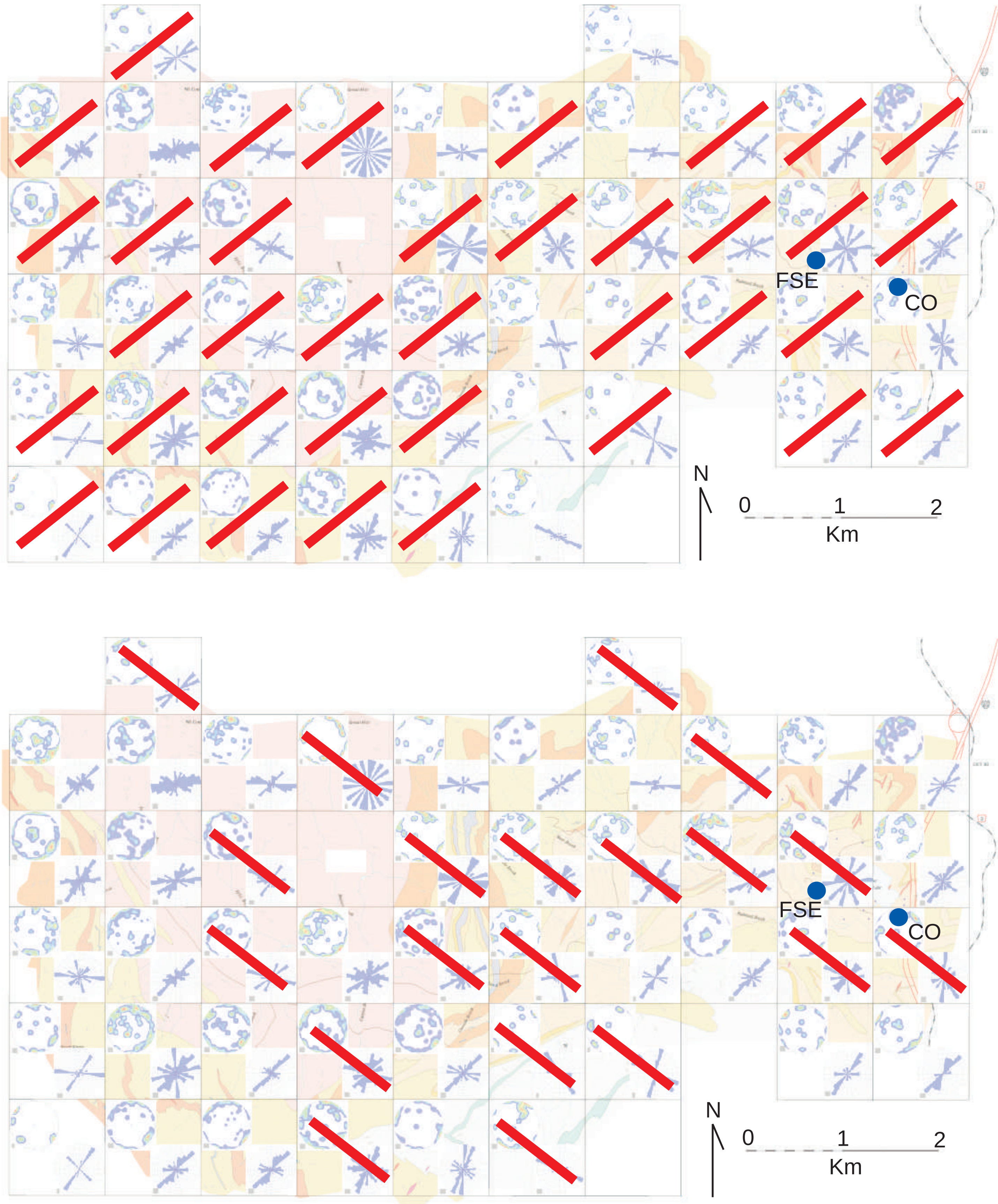


Figure 9. Summary of principal northeast and northwest fracture trends. Grid cells from Plate 2 that contain principal trends in either the northeast (top) or northwest (bottom) direction are highlighted. Locations of well fields FSE and CO indicated with a solid circle.

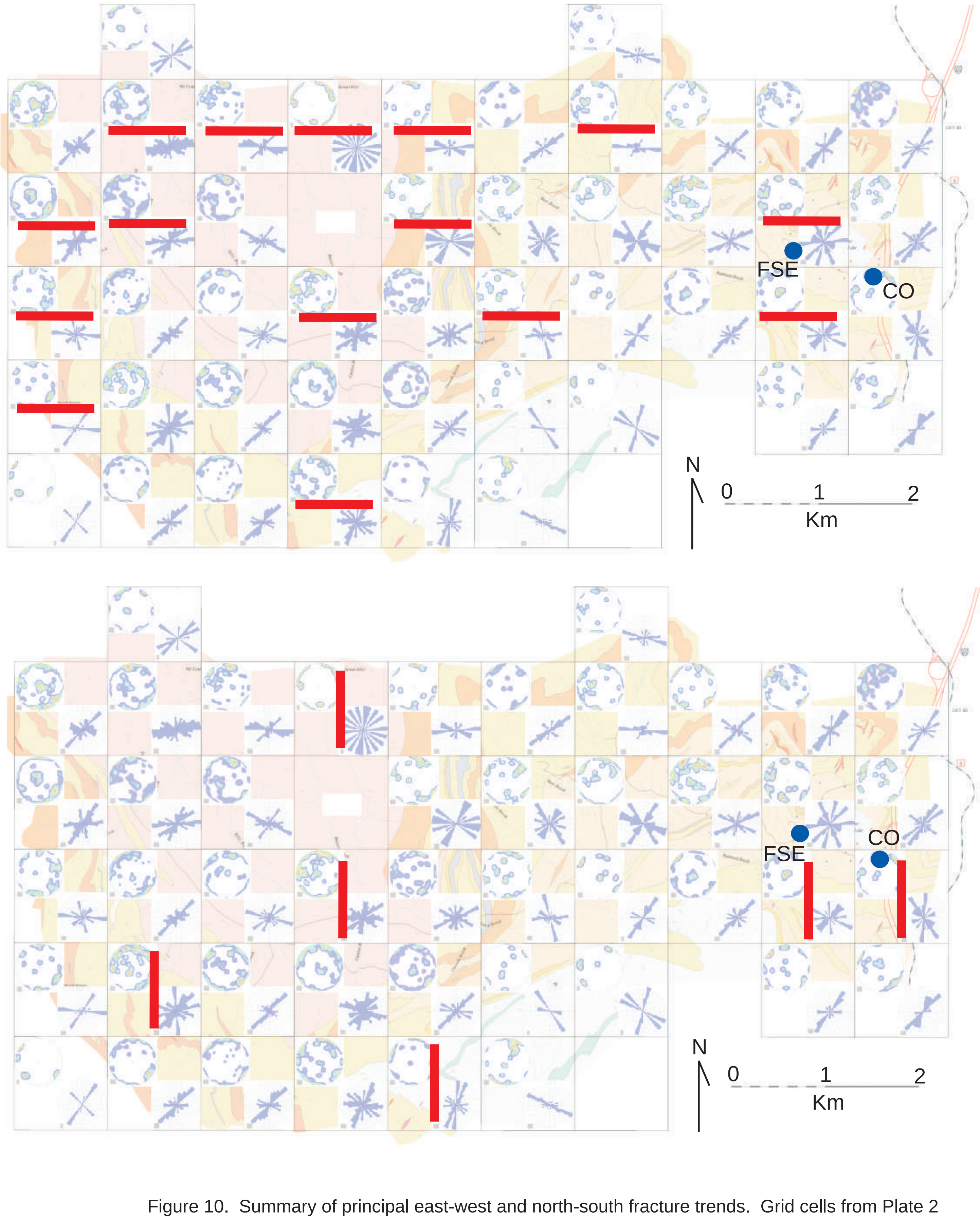


Figure 10. Summary of principal east-west and north-south fracture trends. Grid cells from Plate 2 that contain principal trends in either the east-west (top) or north-south (bottom) direction are highlighted. Locations of well fields FSE and CO indicated with a solid circle.

DESCRIPTION OF MAP UNITS

(Minerals listed in order of increasing abundance;
ages from Lyons and others, 1997)

Post-Metamorphic Intrusive Rocks

Rocks of the White Mountain Plutonic-Volcanic Suite

KJd

Diabase and lamprophyre dikes (Cretaceous and Jurassic) – Dark-gray to black, brown weathering, fine-grained, locally porphyritic, diabase or lamprophyre dikes. Occur as near-vertical dikes 5 cm to 4 m thick. Thinner dikes, generally less than 50 cm, are aphanitic and may locally contain phenocrysts of olivine, hornblende, pyroxene, and plagioclase. Thicker diabasic dikes are porphyritic with large (up to 1 cm) phenocrysts of plagioclase in addition to phenocrysts found in the thinner dikes. Dikes contain accessory serpentine, chlorite, epidote, and magnetite, and local amygdules filled with calcite or dolomite. A 3-m-thick dike at an elevation of 950 feet in Hubbard Brook, in an area one kilometer west of Mirror Lake informally referred to as “the gorge”, contains plagioclase phenocrysts (up to 1 cm) of andesine to labradorite composition, in a groundmass of microlitic plagioclase, serpentinized olivine, iron oxide, and secondary calcite and epidote.

Syn- to Post-Metamorphic Intrusive Rocks

Rocks of the New Hampshire Plutonic Suite

Dg

Two-mica granite to tonalite (Late Devonian) – White to light-gray, massive to weakly or moderately foliated, medium to fine-grained, muscovite-biotite-quartz-plagioclase tonalite, and potassium-feldspar-bearing granodiorite and granite, probably correlative with Concord Granite. Occurs as elongate, irregular dike-like or tabular sheet-like bodies meters to tens of meters thick to outcrop-scale dikes that crosscut compositional layering and schistosity in schists. Local internal foliation (S3 generation?) defined by aligned micas. Shown by symbol and map unit.

Dp

Pegmatite (Devonian) – Light gray to white, very coarse-grained muscovite-biotite-quartz-plagioclase-potassium feldspar pegmatite and coarse-grained granitic pegmatite. Varies from folded and weakly foliated irregular masses to tabular, unfoliated dikes. Occurs in schists as elongate, irregular dike-like or tabular sheet-like bodies tens of m thick to outcrop-scale dikes that crosscut bedding, compositional layering and first-generation schistosity (S1). May have internal foliation of second generation (S2). Shown by symbol and map unit.

Dap

Aplite (Devonian) – White to light gray, massive to weakly or moderately foliated, fine-grained, tonalitic to granitic aplite. Occurs as thin, outcrop-scale dikes that crosscut compositional layering and schistosity in schists and flow foliation in Kinsman. Local internal foliation (S3 generation?) defined by quartz-rich segregations. Shown by symbol only.

Dkg

Kinsman Granodiorite (Early Devonian) – Light gray, massive to locally well-foliated, coarse-grained microcline-muscovite-biotite-quartz-plagioclase granodiorite. Microcline occurs as rectangular megacrysts, up to 5 cm long, that are partially recrystallized to muscovite-quartz-plagioclase. Locally contains segregations of fine-grained aplite and coarse-grained pegmatite. Contains dikes of white to tan, porphyritic, fine-grained granodiorite (Dkfd).

Metasedimentary Rocks of the Central Maine Trough

Perry Mountain Formation (Middle? to Lower?Silurian)

Sp

Bedded quartzite and sillimanite schist – Gray, light-gray weathering, very coarse grained, quartz-plagioclase-sillimanite-muscovite-biotite schist with sillimanite (up to 4 cm long) and garnet (up to .5 cm diameter) porphyroblasts sharply interbedded with light-gray plagioclase-quartz granofels and granular to vitreous light-gray quartzite. Sillimanite occurs as fibrolite and large randomly oriented porphyroblasts. Bedding ranges from several cm to 1 m, but is typically 10 to 20 cm thick. Graded beds are locally preserved. Unit is locally rusty weathering near the lower contact with the Rangeley Formation. Contact with the lower Rangeley Formation is characterized by a simultaneous decrease in quartzite beds and trend towards more massive, poorly bedded rusty schist with thin, disarticulated tan to gray granofels lenses as the contact is crossed down-section. The contact near the westernmost exposures of the Perry Mountain Formation, on the ridge south of Canyon Brook, is gradational over a distance of 10 to 30 m. There, the Rangeley Formation schist (Srr) is unusually coarse-grained due to the abundance of coarse sillimanite-fibrolite porphyroblasts.

Spp

Pelitic member, massive sillimanite schist – Gray, light-gray weathering, massive, very coarse grained, quartz-plagioclase-sillimanite-muscovite-biotite schist with sillimanite (up to 4 cm long) and garnet (up to 0.5 cm diameter) porphyroblasts. Sillimanite occurs as fibrolite and large randomly oriented porphyroblasts. Unit occurs as pelitic lenses within quartz-rich Sp.

Rangeley Formation (Lower Silurian)

Srb
Biotite schist – Gray to dark grayish brown and white, massive to well foliated to laminated, medium- to coarse-grained sillimanite-garnet-muscovite-biotite-plagioclase-quartz schist. Intergrown muscovite, biotite, and fibrolite define the coarse foliation. Grayer, more biotite-rich than rusty schist (Srr), and better foliated than massive schist (Srg). Locally contains white, lens-shaped sillimanite-muscovite-quartz aggregates that give the rock a flaser-like appearance.

Srr
Rusty schist – Rusty to tan weathering, gray to dark-gray, massive to well foliated to layered, medium-grained sillimanite-garnet-plagioclase-biotite-muscovite-quartz schist. Rusty weathering and greater muscovite content distinguishes Srr from biotite schist (Srb), and Srr is rustier and better foliated than massive schist (Srg). Locally contains lenticular inclusions of fine-grained, well-bedded quartzite or calc-silicate granofels (Srcs, where mappable) that represent the disarticulated remnants of more competent beds.

Srrt
Rusty tourmaline-bearing schist -- Rusty to tan weathering, gray to dark-gray, massive to well foliated to layered, medium-grained tourmaline-sillimanite-garnet-plagioclase-biotite-muscovite-quartz schist. Contains 1-3 percent tourmaline and minor graphite, and local inclusions of fine-grained granofels.

Srg
Coarse-grained massive schist– Gray to dark-gray to white, tan weathering, massive to weakly foliated, coarse-grained garnet-sillimanite-muscovite-biotite-plagioclase-quartz schist. Weathering produces massive outcrops with little visible internal texture and throughgoing fabrics. Rare potassium feldspar porphyroblasts are partially recrystallized to plagioclase-quartz-muscovite. Locally contains lenticular inclusions of fine-grained, well-bedded quartzite or calc-silicate granofels (Srcs, where mappable) that represent the disarticulated remnants of more competent beds.

Srgt
Coarse-grained garnet-tourmaline schist– Gray to dark-gray to white, tan weathering, massive to weakly foliated, coarse-grained garnet-tourmaline sillimanite-muscovite-biotite-plagioclase-quartz schist locally rich in tourmaline and garnet porphyroblasts. Otherwise similar to Srg in aspect.

Srq

Quartzite – Gray to very dark-gray to ruddy, massive vitreous quartzite and lesser, gray, rusty weathering, finely layered, locally ribbed quartz-rich schist, garnet quartzite, and coticule.

Srs
Sillimanite schist – White to light gray, weakly-foliated to ribbed, garnet-plagioclase-muscovite-biotite-sillimanite-quartz schist. Commonly massive-weathering with ribbing only locally conspicuous. Ribbed texture is an S2-generation fabric defined by concentrations of fibrolitic sillimanite; minor prismatic sillimanite (pre-S2?) also present.

Srfg
Fine-grained granofels – Gray to dark-gray or white, tan weathering, massive, fine-grained actinolite-biotite-plagioclase-quartz granofels. Forms resistant, blocky ledges in Hubbard Brook “gorge” between 1100 and 950 feet.

Srlg
Layered quartzite and granofels – Gray to black, well-bedded, fine-grained graphite-biotite-muscovite-plagioclase-quartz granofels and impure quartzite. Quartz-rich beds form mm- to cm-thick ribs on weathered surface. The only Rangeley unit in which primary bedding is mostly preserved; similar lithologies are found as disarticulated inclusions in more massive schist (Srr and Srg).

Srcs
Calc-silicate granofels – Fine-grained, finely-foliated quartz-rich schist and calc-silicate granofels, including pale-green to white quartz-epidote-amphibole (tremolite-actinolite) granofels with dark-green amphibole porphyroblasts and accessory sphene and biotite; dark-gray and white amphibole-(tremolite-actinolite)-biotite-quartz granofels with accessory plagioclase-sphene-epidote-garnet; dark-green plagioclase-hornblende amphibolite rock with accessory sphene-biotite-quartz; and amphibole-(tremolite-actinolite)-garnet quartzite. Commonly occurs as disarticulated inclusions or boudins in more massive, coarser-grained schist (Srg).and rusty schist (Srr).