# Bedrock Geology and Seismotectonics of the Oscawana Lake Quadrangle, New York

U.S. GEOLOGICAL SURVEY BULLETIN 1941

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By NICHOLAS M. RATCLIFFE

Included are a detailed geologic map and descriptions of rock and geologic structures typical of the Hudson Highlands of New York that are considered seismogenic source zones for microseismicity in southeastern New York

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# Bedrock Geology and Seismotectonics of the Oscawana Lake Quadrangle, New York

*By* Nicholas M. Ratcliffe

**Abstract**

Bedrock of the Oscawana Lake quadrangle, New York, consists largely of Middle Proterozoic hornblende-granulite-facies gneisses, biotite granites, and rare mafic rocks intruded and deformed during three Middle Proterozoic events between 1.2 and 0.95 Ga. Metavolcanic rocks and paragneiss units serve as the hosts for granitic and migmatitic gneisses, including, in decreasing age, the Reservoir Gneiss, hornblende granite gneiss, the Canada Hill Granite, and abundant pegmatite. Three Middle Proterozoic fold phases consist of tight to open folding along northeastern trends. Folding was accompanied by intense mylonitization along Proterozoic shear zones. Late Proterozoic metadiabase dikes crosscut the Middle Proterozoic gneiss and the older structures. Folding and faulting in the early Paleozoic affected Lower Cambrian cover sequence rocks and truncated limbs of tightly appressed synclines along Paleozoic shear zones. Fabric and mineralogic studies of numerous Paleozoic shear zones indicate that right-oblique thrust faulting accompanied metamorphism from lower greenschist facies to kyanite-staurolite grade in the amphibolite facies in the Taconic orogeny. Strain in the basement rocks during the Taconic deformation was accommodated largely, if not entirely, along ductile deformation zones that were concentrated, in some cases, in reactivated Middle Proterozoic faults.

Although Mesozoic and younger brittle faulting was not intense, it appears to have been widespread. Abundant evidence for Mesozoic reactivation of older structures exists. Current seismic activity, which is based on historical and instrumental records, suggests that seismicity associated with the Ramapo seismic zone extends into the Oscawana Lake area. No fault features requiring Holocene movement have been detected; however, in place stress determinations and fault-plane solutions indicate that faulting on northwest-trending fractures (not found in this investigation) rather than on regional northeast-trending tectonic grain may be causing the microseismicity.

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## INTRODUCTION

The bedrock geology of the Oscawana Lake quadrangle, New York, is dominated by Middle Proterozoic gneiss, granofels, schist, and granite and by the Proterozoic and the Paleozoic structures that these rocks contain. Three important fault zones marked by mylonitic rocks that formed in the Middle Proterozoic, were reactivated in the Ordovician trend northeast across the quadrangle. These zones divide the gneissic rocks into four somewhat distinct areas (pl. 1). Strain in the gneisses is concentrated near the fault zones and is associated with high-grade mylonitization (Proterozoic) and phyllonitization (Ordovician).

The area west of the Dennytown fault system (of probable Ordovician age) consists of Middle Proterozoic gneiss and granite, which is typical of the main mass of the Hudson Highlands in the West Point and the Popolopen Lake areas to the southwest. Detailed unpublished mapping of the West Point and the Peekskill quadrangles by Helenek and Ratcliffe (1982) has shown that the classic units—such as the Storm King Granite of Berkey (1907), the Canada Hill Granite, and the quartz-plagioclase-gneiss, the rusty-paragneiss, and the calc-silicate defined by Dodd (1965) and Helenek (1971)—can be traced into the western part of the Oscawana Lake quadrangle.

The narrow zone of strongly deformed Middle Proterozoic rocks east of the Dennytown fault system and west of the Canopus fault system consists of a linear, steeply dipping, but isoclinally folded, belt of hornblende-pyroxene gneiss, calc-silicate rock and marble, magnetite-rich epidote quartzite, and other well-layered paragneisses extensively intruded by biotitic, two-feldspar, granitic gneiss and pegmatite. This belt contains the magnetite-producing horizons of the Dennytown magnetite district (Colony, 1923) and the magnetite calc-silicate belt in the valley of Canopus Creek.

Middle Proterozoic rocks between the Canopus fault system and the Peekskill Hollow fault system differ from rocks to the west by containing abundant white biotite-granite gneiss and augen gneiss previously mapped as the Reservoir Granite of Berkey and Rice (1921) and redefined as the Reservoir Gneiss by Ratcliffe and Burton, 1991.

Although this granitic gneiss contains inclusions of the paragneiss, the amphibolite, and the calc-silicate gneiss it intrudes, large areas of the Reservoir appear to be migmatitic, two-feldspar, granitic gneisses thoroughly penetrated by true granite. The percentage of truly intrusive rock within the Reservoir (Ygg) unit is problematic and perhaps cannot be determined because of the intermixing of rock types. Hornblende-granite gneiss that closely resembles the Storm King Granite on Bear Mountain crops out on Candlewood Hill. Amphibolitic gneiss and coarse-grained hornblende-pyroxene plagioclase rock and a probable metagabbro body near Wiccopee Reservoir are similar to amphibolitic gneisses [referred to as amphibolite II by Dodd (1965)] that are associated with rusty paragneiss in the Popolopen Lake and the Peekskill quadrangles on Dunderberg Mountain west of the Canopus fault.

The Canopus fault zone is an age-composite fault zone that exhibits Middle Proterozoic and Paleozoic motion. Middle Proterozoic effects include zones of highly tectonized migmatite and of mylonite intruded by lit-par-lit pegmatite-aplite stringers and by abundant biotite and (or) hornblende pegmatite. Middle Proterozoic mylonitization of this zone is expressed by biotite-rich blastomylonite and syntectonic migmatitic gneiss. These high-grade features are associated in time and space with zones of intense deformation and intrusion of the Canopus pluton in the Peekskill quadrangle (Ratcliffe and others, 1972) dated at about 1,120 Ma (Ratcliffe and Aleinikoff, 1990). Dikes and other igneous rocks of the Canopus pluton crosscut Middle Proterozoic mylonites of the Canopus fault zone, thus establishing the age of strike-slip faulting there (Ratcliffe and Aleinikoff, 1990). Superposed on these faults are zones of Paleozoic (Ordovician) retrogression that contain chlorite- and biotite-grade (lower greenschist facies) mineral assemblages.

East of the Peekskill Hollow fault system, basement gneisses are strongly tectonically layered (transposed) but otherwise closely resemble the gneiss sequence and granite gneiss in the block immediately to the west. Paleozoic mylonitic structure and foliation and staurolite-kyanite-grade metamorphic minerals are present throughout this easternmost zone.

Only small areas of Paleozoic cover rocks are present in the quadrangle and occur as tight faulted synclines of the Poughquag Quartzite. The Poughquag that extends into the map area along the northern border of the quadrangle is continuous with a much wider belt of quartzite that mantles the gneisses west of the Dennytown fault system in the adjacent Hopewell Junction quadrangle (pl. 1). East of the Canopus fault system, the Poughquag is only locally present because gneiss is thrust over carbonate rocks of the Wappinger Group in the Hopewell Junction and the Poughquag quadrangles, thus cutting out the quartzite.

## STRATIGRAPHY OF MIDDLE PROTEROZOIC PARAGNEISS AND METAVOLCANIC ROCKS

A complex sequence of well-layered paragneiss, such as calc-silicate rocks, aluminous schists, hornblende-diopside-plagioclase gneiss, and magnetite quartzite, constitutes a fairly well defined succession of gneisses of metasedimentary origin (pl. 1). Interspersed with these rocks are various types of biotitic two-feldspar gneiss and amphibolite that are possibly of metavolcanic origin. At the presumed base of the section, biotite-quartz-plagioclase leucogneisses of probable keratophyric (volcanic) origin are found. A schematic correlation chart (pl. 1) shows the inferred interrelations of the paragneiss and metavolcanic units. Several lithologic units, such as amphibolite, calc-silicate rock, and several varieties of rusty-weathering paragneiss, appear at different stratigraphic positions.

### Biotite-Quartz-Plagioclase Leucogneiss (Ybqp)

White to light-greenish-gray, light-orangish-tan- to gray-weathering, biotite-quartz-plagioclase (oligoclase) leucogneiss (Ybqp) that contains less than 10 percent biotite and 20–30 percent quartz forms an important outcrop belt northwest and southwest of Canopus Lake. The unit is distinguished by its indistinct layering and smooth-weathering massive outcrops. The unit locally contains brown-weathering spots that may be altered hypersthene, although it has not been identified in thin section. Scattered, indistinctly layered pods of amphibolite too small to map are found throughout the leucogneiss.

### Cat Hill Gneiss (Ycl) New Name

A unit of garnet-bearing biotite-oligoclase-quartz leucogneiss (Ycl) enters the quadrangle from the southwest where it is extensively developed on Cat Hill in the Peekskill quadrangle. In the Oscawana Lake quadrangle, distinctive white to bluish-gray, light-gray- to chalky-white-weathering, biotite-quartz-oligoclase granofels and gneiss (Ycl) characterize this unit. Anhedral 2- to 3-mm oligoclase and quartz form a granular mosaic in which minor (commonly less than 7 percent) amounts of reddish-brown pleochroic biotite are intergrown (fig. 1). Locally, up to 15 percent of microcline microperthite may be present. Layering is indistinct, although the rock is well foliated. The unit closely resembles the biotite-quartz-plagioclase gneiss and leucogneiss of Dodd (1965), which is closely associated with similar biotite-hypersthene-quartz-plagioclase gneiss of the western Hudson Highlands. In the Oscawana Lake quadrangle, biotite is commonly altered to muscovite, and plagioclase, to epidote and sericite. Although the massive nature of this unit suggests

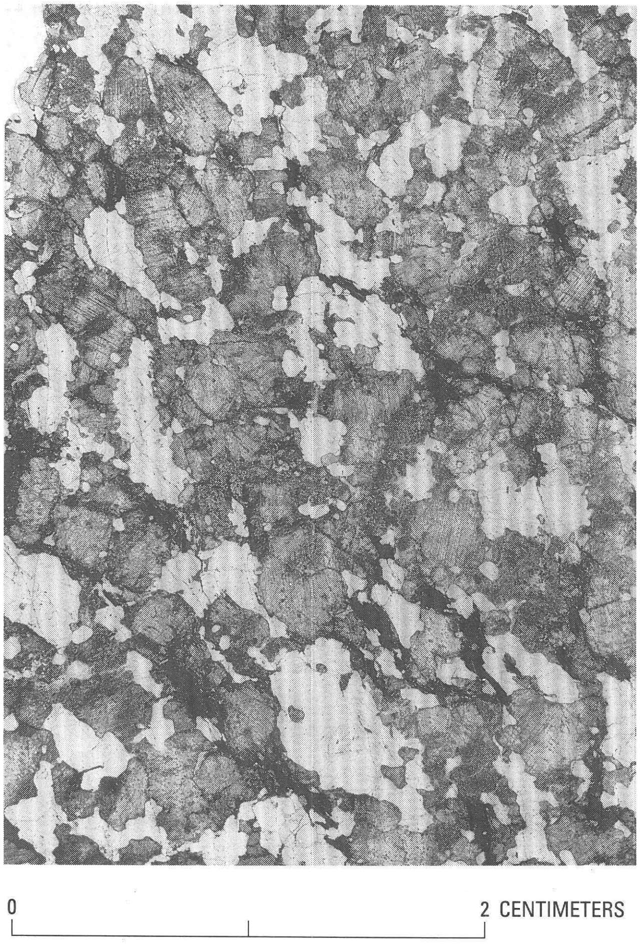



**Figure 1.** Biotite-quartz-plagioclase leucogneiss from the Cat Hill Gneiss (Ycl) from the western shore of Oscawana Lake showing clear anhedral quartz and partially saussuritized plagioclase (gray) and dark-brown biotite. Plane-polarized light.

an intrusive rock, the fine grain size and the lack of relict igneous textures suggest a metavolcanic protolith.

Chemical analyses of four samples of the Cat Hill Gneiss from just south of the quadrangle and two samples of biotite-quartz-plagioclase leucogneiss (Ybqp) are given in table 1. The average $FeO^*$:$FeO^*+MgO$ is 0.77, but total FeO is low, and the rock is rich in normative plagioclase, which has a very low An content (average An content is $An_{19}$). In the normative albite-anorthite-orthoclase classification of O'Connor (1965) (fig. 2*C*), the rocks are trondhjemites or dacitic metavolcanic rocks (figs. 2*A*, *B*). In AFM plots, the rocks are alkali rich, but $Na_2O$ is markedly enriched relative to $K_2O$ (see fig. 6). However, trends deviate moderately from the field of calc-alkaline dacite to rhyolite, identified in figure 2*C*; this deviation suggests some alteration. The Cat Hill Gneiss and biotite-quartz-plagioclase leucogneiss are petrographically similar to rocks of the Losee Metamorphic Suite of Drake (1984). $Na_2O$ to CaO ratios, however, are lower, and normative quartz is higher than in the Losee. $Na_2O$ enrichment is extreme in the Losee, where albitization of volcanic rocks to produce quartz keratophyres has been proposed (Drake, 1984). Rocks of the Oscawana Lake area appear to be more normal, less altered calc-alkaline dacite to rhyolite.

*Indicates total iron oxide expressed as FeO.

## Biotite-Quartz-Feldspar Gneiss (Ybqf)

Three belts of dark- to medium-gray, biotite-rich, quartz-microcline-plagioclase gneiss (Ybqf) and thin, unmapped amphibolite occur in the northwestern part of the map (pl. 1). In these belts, Ybqf appears to interfinger with biotite-quartz-plagioclase leucogneiss (Ybqp). Locally, (Ybqf) hosts a zone of biotite-rich magnetite gneiss (shown by a special line symbol on pl. 1) within this and other units. The gneisses are uniformly well layered, dark- to medium-gray, biotite gneiss and contain scattered zones of garnet-bearing biotite gneiss and magnetite-studded gneiss. In comparison to other units, rocks mapped as Ybqf are very rich in biotite, are strongly layered, and contain lighter colored migmatitic layers. Although Ybqf resembles the biotite-quartz-plagioclase gneiss unit (Ybg) exposed in the central and the eastern parts of the map, it differs from Ybg because it lacks the well-bedded quartzofeldspathic gneiss and the quartzites common in Ybg.

## Rusty-Weathering Paragneiss Units (Yrg, Yrs, Yrq)

Variably rusty weathering biotite-quartz-plagioclase gneiss (Yrg), rusty sillimanitic schist (Yrs), and minor, unmapped, sulphidic amphibolite directly overlie the biotite-quartz-plagioclase leucogneiss (Ybqp) west of the Dennytown fault system, whereas other units elsewhere are found beneath the rusty paragneisses and above Ybqp. A central belt of Ybqp forms the core of an overturned $YF_1$ antiform that is refolded by southwest-plunging $YF_2$ structures. The southern limb of the $YF_1$ structure contains rusty paragneiss (Yrg) abundantly intruded by the Canada Hill Granite and pegmatite of the Canada Hill Granite. The northern overturned limb contains largely Ybqp and sillimanite-rich schist (Yrs).

The bulk of Yrg is rusty, biotite-rich, quartz-plagioclase gneiss that has lenses of sillimanitic quartzite (Yrq) and biotite-sillimanite schist (Yrs). Locally, the schist (Yrs) is rich in garnet and sillimanite and is characterized by large clumps and sprays of sillimanite. Minor graphitic sulphidic quartzite is present. Distinctions within Yrg are difficult to map, especially in the belt intruded by the Canada Hill Granite, where some especially sillimanite-rich

**Table 1.** Partial chemical analyses of major-oxide (in weight percent) and normative-mineral compositions of the Cat Hill Gneiss (Ycl) and biotite-quartz-plagioclase leucogneiss (Ybqp)

[CIPW, Cross Iddings Pierson Washington. Analysis by X-ray spectroscopy, U.S. Geological Survey, Lakewood, Colo. Analysts: J. Taggart, A. Bartel, D. Siems]

| Sample no. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Field identification no. | 11894[1] | 11895[2] | 11893[2] | 11896[2] | 13339[3] | 13345B[4] |
| **Major-oxide composition** | | | | | | |
| $SiO_2$ | 74.50 | 73.80 | 72.60 | 72.10 | 74.40 | 70.60 |
| $TiO_2$ | .02 | .07 | .07 | .11 | .09 | .44 |
| $Al_2O_3$ | 14.50 | 14.90 | 15.80 | 15.50 | 14.10 | 15.50 |
| $Fe_2O_3$ | 1.25 | 1.06 | 1.03 | 1.41 | .91 | 2.66 |
| MnO | .08 | .08 | .04 | .05 | .02 | .02 |
| MgO | .13 | .34 | .36 | .44 | .30 | .94 |
| CaO | .75 | 1.99 | 2.11 | 1.91 | 2.57 | 2.33 |
| $Na_2O$ | 3.84 | 4.56 | 5.23 | 5.35 | 4.54 | 4.15 |
| $K_2O$ | 4.30 | 2.09 | 1.85 | 1.47 | 1.34 | 2.44 |
| $P_2O_5$ | .05 | .05 | .05 | .05 | .05 | .06 |
| Loss on ignition | .59 | .73 | .55 | .80 | .76 | .79 |
| Total | 100.01 | 99.67 | 99.69 | 99.19 | 99.08 | 99.93 |
| **CIPW normative composition** | | | | | | |
| Q | 33.5 | 34.2 | 29.8 | 30.3 | 36.8 | 30.2 |
| Or | 25.4 | 12.4 | 10.9 | 8.7 | 7.9 | 14.4 |
| Ab | 32.5 | 38.6 | 44.3 | 45.3 | 38.4 | 35.1 |
| An | 3.4 | 9.6 | 10.1 | 9.1 | 12.4 | 11.2 |
| C | 2.3 | 1.6 | 1.5 | 1.8 | .6 | 1.9 |
| di | .0 | .0 | .0 | .0 | .0 | .0 |
| hy | 1.5 | 1.8 | 1.7 | 2.2 | 1.4 | 3.9 |
| mt | .6 | .5 | .5 | .7 | .4 | 1.3 |
| il | .0 | .1 | .1 | .2 | .2 | .8 |
| ap | .1 | .1 | .1 | .1 | .1 | .1 |
| Total (less $H_2O$) | 99.3 | 98.9 | 99.0 | 98.4 | 98.2 | 98.9 |
| FeO (as total oxide) | 1.13 | .95 | .93 | 1.27 | .82 | 2.39 |
| FeO/FeO+MgO | .903 | .753 | .729 | .750 | .737 | .720 |
| An (normalized An/An+Ab) × 100 | 9.5 | 19.8 | 18.6 | 16.8 | 24.4 | 24.1 |

[1] Gray biotite-quartz-plagioclase leucogneiss from southern end of Cat Hill, Peekskill quadrangle.
[2] Equigranular biotite-quartz-plagioclase±garnet leucogneiss from Cat Hill, Peekskill quadrangle.
[3] Biotite-quartz-plagioclase gneiss, Route 301 east of Canopus fault zone, 400 m west of Sagamore Lake.
[4] Biotite-garnet-quartz-plagioclase gneiss, Route 301, 800 m west of Sagamore Lake.

layers are recognized. The discontinuous quartzite is a steel-gray, vitreous-weathering, magnetite-rich unit that locally contains beds of magnetite that are 0.1–0.2 m thick. In certain areas, the rusty gneiss sequence is punctuated by prominent calc-silicate units and hornblende-pyroxene gneiss that appear near the base and laterally replace the rusty paragneiss sequence. All the units (Yrs, Yrg, Yrq) are clearly metasedimentary and constitute important map units throughout the Hudson Highlands.

## Diopside-Hornblende-Plagioclase Gneiss (Yhg)

Well-layered hornblende- and plagioclase-spotted gneiss (Yhg), with or without diopside, consists of approximately 50 percent of each of these major constituents and is interlayered with black, needle-hornblende amphibolite in a belt immediately overlying the biotite-quartz-plagioclase leucogneiss (Ybqp) east of the Dennytown fault system. Diopside forms cores in larger hornblende and gives the rock a distinctive spotted or dark-mottled appearance. Dark amphibolite (Ya), which consists of more than 65 percent hornblende, laterally replaces the hornblende-diopside gneiss; the distinction is not always easy to define. Locally, at or near the contact of either amphibolite (Ya) or Yhg with the underlying leucogneiss, a thin, discontinuous belt of white, fine-grained, sugary-textured, albitic aplite forms a prominent unit. The origin of this unit is uncertain, but it appears to be either a metamorphic segregation or a reaction zone between pegmatite (Yp) and Yhg.

## Amphibolite (Ya)

Dark, fine-grained, hornblende-plagioclase amphibolite (Ya), which contains more than 60 percent hornblende,

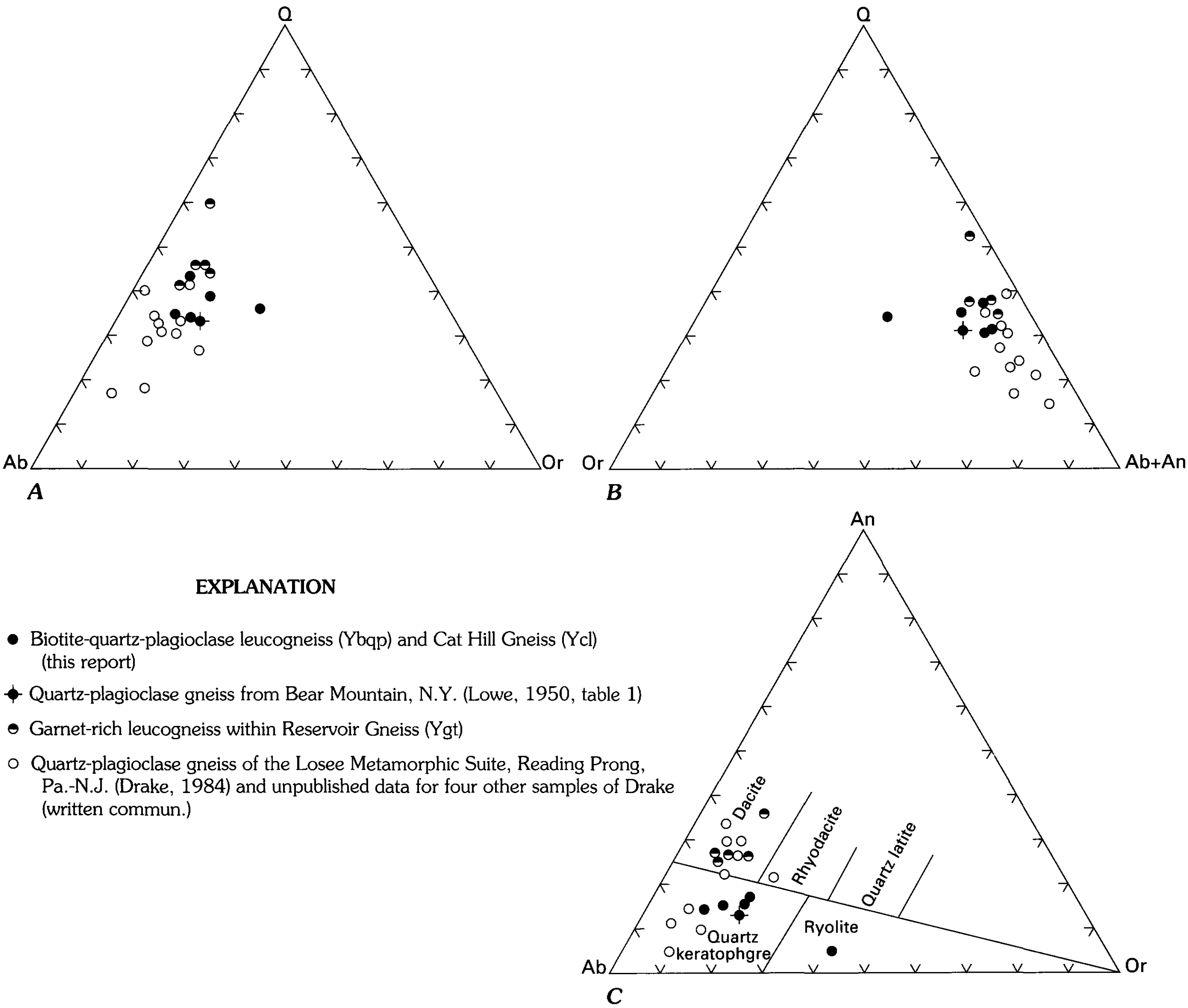


**Figure 2.** Samples of the Cat Hill Gneiss (Ycl), biotite-quartz-plagioclase gneiss (Ybqp), and garnet-rich leucogneiss (Ygt) from the Oscawana Lake and the Peekskill quadrangles in relation to rocks of the Losee Metamorphic Suite and Lowe's (1950) quartz-plagioclase gneiss at Bear Mountain. *A*, Ab-Q-Or diagram. *B*, Or-Q-Ab+An diagram. *C*, Ab-An-Or diagram of O'Connor (1965).

forms a prominent rock type throughout the map area (pl. 1). Although the individual amphibolites occur at different stratigraphic positions, they are not distinguished as separate stratigraphic units. The protoliths of the amphibolites probably were intermediate to mafic volcanic rocks. Locally, black, rusty-weathering, sulphidic amphibolite, which consists almost entirely of hornblende, is associated with calc-silicate rocks in a belt just east of the Dennytown fault system and in another belt that extends northeast from Stillwater Pond. These amphibolites may be metamorphosed, lime-rich, black shales.

## Calc-Silicate Rocks, Marble, and Closely Associated Other Paragneiss (Ycs, $Ycs_1$, $Ycs_2$, Ym)

Distinctive, punky-weathering, diopside-hornblende-knotted rock, phlogopite-calcite-graphite and diopside marbles; and coarse hornblende-diopside-plagioclase rock form discontinuous belts of calc-silicate rocks at several positions above the diopside-hornblende-plagioclase gneiss (Yhg) and the amphibolite (Ya) units. Three general levels are recognized in the calc-silicate and the metasedimentary belts of Canopus Creek valley and near Clear Lake—the lower unit ($Ycs_1$) overlies Yhg directly. Ym, which is a coarse-grained calcite marble, underlies the diopside-epidote-quartz gneiss (Yde), and the upper unit ($Ycs_2$) overlies Yde. $Ycs_2$ is the largest and regionally the most important belt of calc-silicate rock. This belt is repeated by folding in the Gilbert Corners $YF_2$ antiform. The eastern belt is traceable southwestward into the wide belt of calc-silicate rocks and marble (Ym) in Canopus Hollow of the Peekskill quadrangle. Where identification of specific units ($Ycs_1$ or $Ycs_2$) is uncertain, the rocks are referred to only as Ycs.

A belt of rusty-weathering paragneiss and biotite-garnet schist (Yrg) overlies $Ycs_1$ along the ridge east of Canopus Lake and to the southwest. This belt of rusty schist passes upward through interbedding into a distinctive steel-gray, lustrous, graphite-bearing, vitreous garnet quartzite and garnet quartzite and ribbed schist (Yrq). In this area, important deposits of magnetite occur in the Yrg near the contact with Yrq, and a string of abandoned magnetite mines (not shown on pl. 1) extends from Canopus Lake southwest to Dennytown.

### Diopside-Epidote-Quartz Gneiss (Yde)

The quartzite (Yrq) in the Gilbert Corners antiform passes upward through interbedding and the loss of quartzite stringers into a pale-green- to pinkish-gray-green-weathering, well-layered, diopside-epidote-microcline-quartz gneiss (Yde). Layers consist of markedly variable proportions of quartz and diopside, and epidote is scattered uniformly throughout. Locally, Yde contains up to 15 percent microcline. The diopside gneiss grades upward into a diopside-spotted plagioclase gneiss and then into a diopside-rich calc-silicate and marble unit ($Ycs_2$). The protolith of the diopside-epidote-quartz gneiss probably is a siliceous-calcareous volcaniclastic rock. The diopside-epidote-quartz gneiss is exposed in the Clear Lake $YF_2$ synform, where it appears in inverted sequence underlying rusty paragneiss (Yrg). A third belt appears in the extreme northwest of the map area (pl. 1) where it overlies Ybqf and underlies Yrg.

### Garnet-Magnetite-Biotite-Quartz-Feldspar Gneiss (Yrgt)

Fine- to medium-grained, well-foliated to massive, garnet-magnetite-biotite-quartz-feldspar gneiss (Yrgt) is found associated with the rusty paragneiss and the calc-silicate gneiss in the area north of Stillwater Pond. The well-layered, massive types are light to medium gray and locally studded with magnetite. In both areas, K-feldspar is variable in abundance but commonly is subequal to plagioclase, and the rocks are granodioritic in composition. Hornblende is a minor constituent in this gneiss. Coarse-grained, more granitic segregations are common. In outcrop, the gneiss is strongly tectonically banded in zones 3–5 cm thick. Locally, it passes into a gray garnet-studded, biotite, two-plagioclase, microcline gneiss. It is uncertain as to whether this unit is a metavolcanic or a metaintrusive rock, but the massive variant may be a felsic intrusive rock.

### Biotite-Quartz-Plagioclase Gneiss (Ybg)

Well-layered, fine-grained, biotite-rich, quartz-plagioclase gneiss (Ybg); interlayered amphibolite; and rusty-weathered paragneiss constitute a poorly defined unit, which has been mapped principally in the southeastern part of the area (pl. 1) where exposures are poor. Locally, the unit is nonrusty weathering and very rich in biotite and magnetite. The association with well-layered paragneiss, garnet-biotite gneiss, and minor calc-silicate rocks suggests that, as mapped, Ybg may contain many of the units similar to those found in the rusty paragneiss sequence and may be laterally equivalent rather than entirely younger, as portrayed in the correlation of map units on plate 1.

## MIDDLE PROTEROZOIC GRANITIC ROCKS

Four different granitic gneiss and granite bodies of Middle Proterozoic age are recognized in the Oscawana Lake quadrangle. The oldest and most enigmatic of these are the Reservoir Gneiss (Ygg) and the similar biotite-microcline-plagioclase granite gneiss exposed in the Gilbert Corners antiform, which is also mapped as the Reservoir Granite. A hornblende-biotite granite gneiss at Candlewood Hill (Yhgr) appears to be intrusive into the Reservoir Gneiss, biotite-microcline-plagioclase granite gneiss, and the paragneiss-metavolcanic suite. The Canada Hill Granite and pegmatitic granite of the Canada Hill are only weakly deformed and largely intrude rusty sillimanitic paragneiss (Yrg, Yrq, Yrs) and quartz-plagioclase-rich leucogneisses (Ybqp, Ybqf). The Canada Hill lacks the $YF_2$ structure and is clearly a relatively late migmatitic and anatectic granite (Helenek and Mose, 1976, 1984). Late pegmatites that are the same age as or younger than the Canada Hill crosscut all Middle Proterozoic rocks.

### Reservoir Gneiss (Ygg, Ygt)

Basement rocks of the Oscawana Lake quadrangle east of the Canopus fault area are dominated by large areas of granitic gneiss (Ygg). Berkey and Rice (1921) identified this unit as the Reservoir Granite and noted the highly complex intrusive and migmatitic textures found in many exposures. The unit displays clear intrusive contacts against more mafic rocks, and inclusions of amphibolite and

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**Figure 3.** The Reservoir Gneiss (Ygg) from a powerline outcrop 1.2 km southwest of the southern end of Sagamore Lake showing abundant strained quartz, large microcline microperthite, and highly saussuritic plagioclase. Crossed nicols.

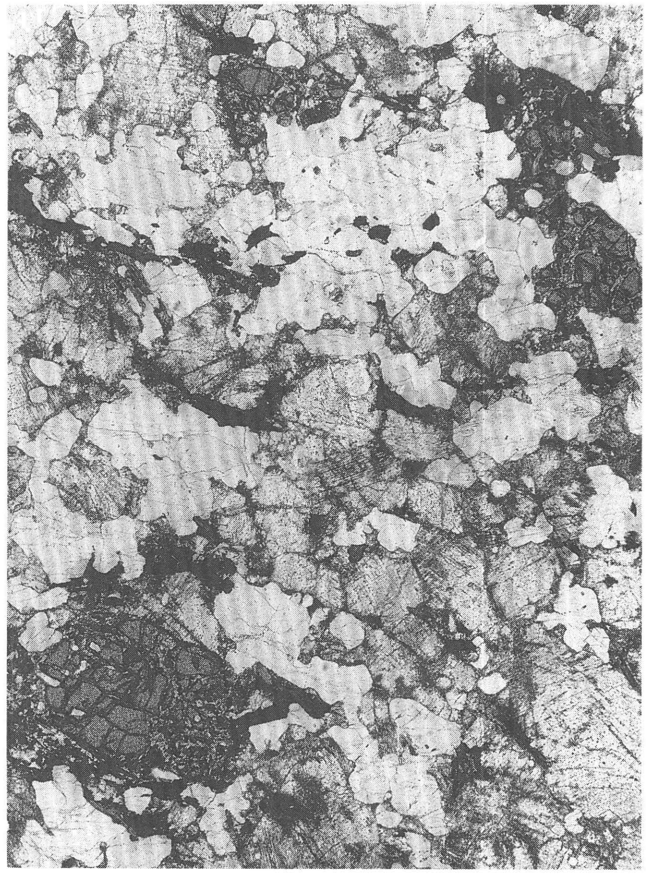

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**Figure 4.** Garnet-rich leucogneiss (Ygt) within the belt of the Reservoir Gneiss north of Sagamore Lake (table 2, sample 13335B). Plane-polarized light.

biotite-quartz-plagioclase paragneiss are abundant. However, contacts with other felsic gneisses are always indefinite or gradational, and it is not certain if all the rocks mapped here as Ygg are totally intrusive. In fact, in this quadrangle, Ygg is characterized by a distinctive migmatitic texture in which clear granitic fractions form lensoidal areas subparallel to the axial surfaces of $YF_2$ isoclinal folds. A typical thin section of the Reservoir Gneiss is shown in figure 3. Locally, massive granitic pegmatite and homogenous granite are present; for example, on Granite Mountain and in the central belt extending from Boyd Corner's Reservoir to Oscawana Lake. Broad areas of garnet-rich leucogneiss shown as Ygt (fig. 4) in the central and the northeastern parts of the map (pl. 1) contain abundant plagioclase, minor microcline, and 1–3 percent garnet (fig. 4). On plate 1, these garnet-bearing rocks are shown separately by patterned area and the symbol "Ygt." However, this distinction cannot be mapped accurately, and boundaries between Ygg and Ygt are indefinite. Clearly, areas mapped as the Reservoir Gneiss contain appreciable amounts of plagioclase-rich rocks that may be older than the granitic part of the Reservoir. Considerable portions of Ygg may be biotitic migmatitic gneiss that only appears to be comagmatic with the true intrusive part of the unit. Therefore, because the name "Reservoir Granite" may be misleading and is not recommended for use, it has been changed to "Reservoir Gneiss" (Ratcliffe and Burton, 1991).

Major-element chemical analyses of Ygg from areas of granitic gneiss that are common to much of the basement rock terrane east of the Ramapo-Dennytown-Canopus fault zone (Ratcliffe and Burton, 1991, table 13, first 13 analyses) indicate that the granitic gneiss is peraluminous—$SiO_2$, 70–79 percent; CaO, 1–2 percent; $Na_2O + K_2O$, 6–8 percent; and $K_2O{:}K_20 + Na_2O$, 0.3–0.6 percent. The composition of the average of 13 samples, in percent, is $SiO_2$, 73.4; $Al_2O_3$, 13.8; $Fe_2O_3$, 0.6; FeO, 1.6; MgO, 0.3; CaO, 1.16; $Na_2O$, 4.0; $K_2O$, 4.0; $H_2O$, 0.6; $TiO_2$, 0.1; and trace amounts of $P_2O_5$, MnO, and $CO_2$. Plots of normative Ab-An-Or ratios calculated from these

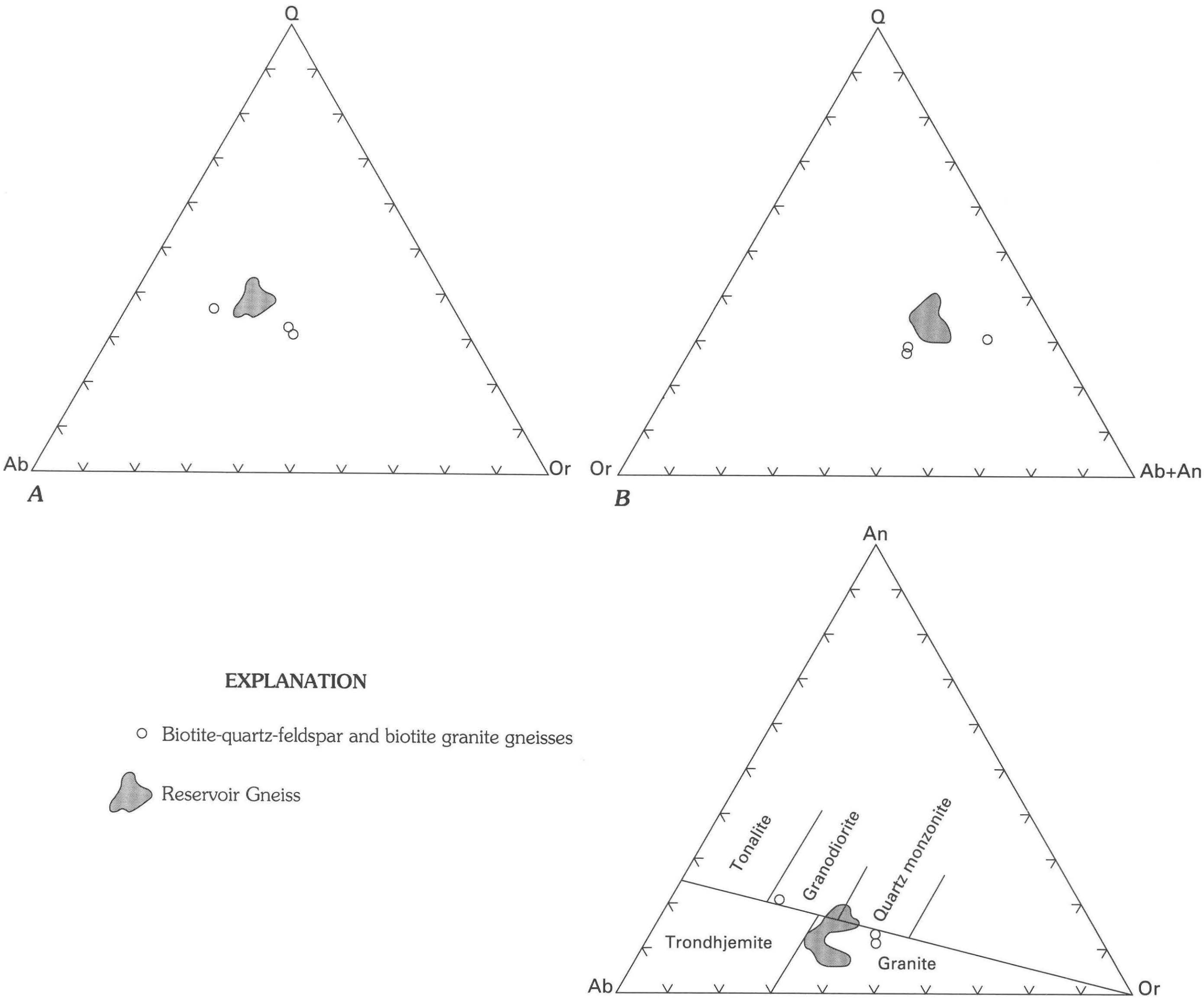


**Figure 5.** Samples of the biotite-quartz-feldspar and the biotite granitic gneisses (Ygg) from the Gilbert Corners antiform shown in relation to the main Reservoir Gneiss belt. *A*, Ab-Q-Or diagram. *B*, Or-Q-Ab+An diagram. *C*, Ab-An-Or diagram of O'Connor (1965).

analyses fall predominately in the granite field (fig. 5*C*). In all normative plots, the 13 analyzed samples cluster tightly together (fig. 5).

The granitic gneiss is a coarse-grained (2- to 5-mm average size), two-feldspar rock that contains either microcline or local microcline perthite and either albite or oligoclase (depending upon metamorphic grade). Lower grade samples from the western part of the quadrangle contain original plagioclase grains charged with small grains of epidote. Exposures in the eastern part of the quadrangle contain well-twinned fresh grains of oligoclase that presumably are reconstituted metamorphic plagioclase. The principal mafic mineral is brown biotite. Near shear zones, muscovite, garnet, and epidote are abundant.

Ten samples of Ygg collected at Peekskill, N.Y., in a belt of rocks that are traceable along strike into Ygg of the Poughquag quadrangle yield an isochron age of 1,225±28 Ma (1 sigma) [Helenek and Mose, (1976); D.G. Mose, George Mason University, written commun., 1983]. At the Peekskill sample site, the Paleozoic metamorphic overprint is garnet grade, which is approximately equivalent to the grade of Ygg in the central part of the Poughquag quadrangle. Another collection of similar rocks from the Poughquag and the Lake Carmel quadrangles has yielded an errorchron of 1,296±77 Ma (Helenek and Mose, 1976, p. B1–B13), but this set contains samples of biotite-quartz-plagioclase gneiss that were incorrectly included in the regression. Zircon from the Reservoir Gneiss at the Peekskill locality

**Table 2.** Partial chemical analyses of major-oxide (in weight percent) and normative-mineral compositions of garnet-biotite-quartz-plagioclase gneiss (Ygt) from the Oscawana Lake quadrangle

[CIPW, Cross Iddings Pierson Washington. Analysis by X-ray spectroscopy, U.S. Geological Survey, Lakewood, Colo. Analysts: J. Taggart, A. Bartel, D. Siems]

| Sample no. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Field identification no. | 13336A[1] | 13336B[2] | 13337[3] | 13338[4] | 13335B[5] |
| **Major-oxide composition** | | | | | |
| $SiO_2$ | 79.20 | 67.70 | 71.40 | 73.20 | 72.70 |
| $TiO_2$ | .06 | .27 | .15 | .18 | .19 |
| $Al_2O_3$ | 12.30 | 15.40 | 15.50 | 14.60 | 15.20 |
| $Fe_2O_3$ | .94 | 5.72 | 2.41 | 2.28 | 2.24 |
| MnO | .02 | .16 | .07 | .04 | .04 |
| MgO | .22 | .93 | .49 | .41 | .43 |
| CaO | 2.56 | 4.20 | 3.10 | 3.08 | 3.22 |
| $Na_2O$ | 3.47 | 3.44 | 4.51 | 4.03 | 4.17 |
| $K_2O$ | .67 | 1.30 | 1.08 | 1.56 | 1.15 |
| $P_2O_5$ | .05 | .17 | .08 | .05 | .06 |
| Loss on ignition | .46 | .61 | .77 | .51 | .54 |
| Total | 99.95 | 99.90 | 99.56 | 99.94 | 99.94 |
| **CIPW normative composition** | | | | | |
| Q | 50.5 | 30.6 | 33.0 | 36.0 | 35.9 |
| Or | 4.0 | 7.7 | 6.4 | 9.2 | 6.8 |
| Ab | 29.4 | 29.1 | 38.2 | 34.1 | 35.3 |
| An | 12.4 | 19.7 | 14.9 | 15.0 | 15.6 |
| C | 1.3 | 1.1 | 1.5 | 0.8 | 1.4 |
| di | .0 | .0 | .0 | .0 | .0 |
| hy | 1.3 | 7.2 | 3.1 | 2.7 | 2.7 |
| mt | .5 | 2.6 | 1.2 | 1.1 | 1.1 |
| il | .1 | .5 | .3 | .3 | .4 |
| ap | .1 | .4 | .2 | .1 | .1 |
| Total (less $H_2O$) | 99.6 | 98.9 | 98.8 | 99.3 | 99.3 |
| FeO (as total oxide) | .85 | 5.15 | 2.17 | 2.05 | 2.02 |
| FeO/FeO+MgO | .797 | .851 | .820 | .836 | .827 |
| Den | 2.32 | 2.39 | 2.35 | 2.35 | 2.35 |
| An (normative An/An+Ab) × 100 | 29.7 | 40.4 | 28.0 | 30.5 | 30.6 |

[1] Leucocratic biotite-garnet gneiss, Route 301 near Sagamore Lake.
[2] Biotite-rich layer in sample 1.
[3] Biotite-garnet-plagioclase leucogneiss, southwestern end of Sagamore Lake.
[4] Biotite-garnet-microcline-plagioclase granodiorite gneiss, southwestern corner of Sagamore Lake.
[5] Garnet-biotite-quartz-plagioclase gneiss, Route 301, 800 m west of Sagamore Lake.

sampled by Mose has a U-Pb upper intercept concordia age of approximately 1,136±43 Ma (John Aleinikoff, U.S. Geological Survey, written commun., 1986). Given the coarse-grained and granitic nature of the Reservoir Gneiss at the Peekskill sample site and the intrusive relations exhibited there, the 1,136±43-Ma zircon age may be interpreted as being a minimum age for the formation of the Reservoir Gneiss, either as an igneous intrusive or as a migmatite. The zircon data suggest that the Reservoir Gneiss may be generally equivalent to Storm King Granite plutonism of pre-$YF_2$ time. This plutonism has been dated by zircon age at about 1,120 Ma (Ratcliffe and Aleinikoff, 1990).

Garnet-biotite-quartz-plagioclase leucogneiss (Ygt), which is within the more typical Reservoir Gneiss, is petrographically and modally different from the bulk of the Ygg unit. Such lenses in Ygg northwest of Sagamore Lake contain up to 5 percent garnet and have low (10–20 percent) modal K-feldspar and abundant biotite. Chemical analyses in table 2 show these enclaves to be peraluminous, rich in $Na_2O$ and FeO, and moderately rich (68–79 percent) in $SiO_2$ rocks. Normative An-Ab-Or values indicate a tonalite (fig. 2) or dacitite distinct from the Reservoir Gneiss. On the An-Ab-Or and the Q-Ab-Or normative plots, these gneisses resemble calc-alkaline to low-K, silicic volcanics. Average normative plagioclase is $An_{32}$, and FeO:FeO + MgO equals 0.83. Trends toward low-Fe enrichment and decreasing A values suggest calc-alkaline characteristics (fig. 6).

The area of Ygg mapped within the Gilbert Corners antiform, which extends northward to near Canopus Lake, contains predominantly light- to pinkish-gray, biotite-rich,

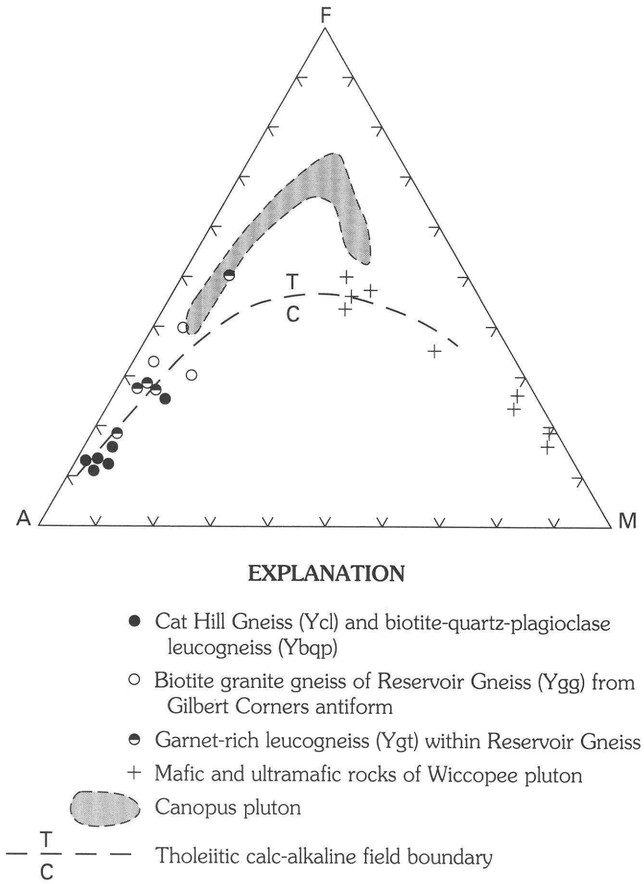


**Figure 6.** Low calc-alkaline enrichment trend for the Wiccopee pluton and selected possible metavolcanic rocks of the Oscawana Lake quadrangle. For comparison, shaded area shows trend for iron-rich ferrodiorites to ferromonzonites of the Canopus pluton in the Peekskill quadrangle.

granitic gneiss. This unit has a particularly strong tectonic banding that is infiltrated by medium-grained stringers of granite. Overall, this unit lacks the coarse-grained granitic texture of the less deformed Ygg east of the Dicktown fault, and it is unclear whether the units are the same. Three chemical analyses of granitic gneiss from the Gilbert Corners antiform in table 3 are iron-rich, $FeO_{tot}$ (3.49–4.52 percent), metaluminous granite and granodiorite on the basis of the normative An-Ab-Or plots (see fig. 5*C*).

## Hornblende-Biotite Granite Gneiss at Candlewood Hill (Yhgr)

Pale, pinkish-gray- to white-weathering, green hornblende-biotite-microcline-mesoperthite and gneissic granites form a distinctive unit (Yhgr) in the central part of the map area (pl. 1). Near contacts with diopside-epidote-quartz gneiss (Yde) and biotite-quartz-plagioclase gneiss (Ybg), it grades into a fine-grained, white-weathering aplitic rock (Yap). In the central part of the unit, hornblende

**Table 3.** Partial chemical analyses of major-oxide (in weight percent) and normative-mineral compositions of biotite-quartz-feldspar granitic gneiss from the Gilberts Corners antiform in comparison to average value for 13 samples of the Reservoir Gneiss

[CIPW, Cross Iddings Pierson Washington. From Ratcliffe and Burton (1991, table 1). Analysis by X-ray spectroscopy, U.S. Geological Survey, Lakewood, Colo. Analysts: J. Taggart, A. Bartel, D. Siems]

| Sample no. / Field identification no. | 1 / 3353A[1] | 2 / 13353B[2] | 3 / 13355[3] | Reservoir Gneiss |
|---|---|---|---|---|
| **Major-oxide composition** | | | | |
| $SiO_2$ | 69.70 | 68.00 | 69.20 | 73.4 |
| $TiO_2$ | .51 | .68 | .43 | .1 |
| $Al_2O_3$ | 13.70 | 13.50 | 15.40 | 13.8 |
| $Fe_2O_3$ | 4.49 | 5.80 | 3.46 | .6 |
| FeO | | | | 1.6 |
| MnO | .04 | .09 | .05 | .04 |
| MgO | .56 | .64 | 1.30 | .3 |
| CaO | 1.80 | 2.18 | 2.68 | 1.6 |
| $Na_2O$ | 3.46 | 3.25 | 4.30 | 4.0 |
| $K_2O$ | 4.99 | 4.68 | 2.31 | 4.0 |
| $P_2O_5$ | .14 | .22 | .15 | .6 |
| Loss on ignition | .30 | .31 | .72 | .3 |
| Total | 99.69 | 99.35 | 100.00 | 100.3 |
| **CIPW normative composition** | | | | |
| Q | 25.0 | 24.9 | 27.1 | |
| Or | 29.5 | 27.7 | 13.7 | |
| Ab | 29.3 | 27.5 | 36.4 | |
| An | 7.1 | 8.4 | 12.3 | |
| C | .0 | .0 | 1.3 | |
| di | .8 | .8 | .0 | |
| hy | 4.0 | 4.4 | 5.5 | |
| mt | .2 | 3.2 | 1.7 | |
| il | 1.0 | 1.3 | .8 | |
| ap | .3 | .5 | .4 | |
| Total (less $H_2O$) | 99.2 | 98.7 | 99.2 | |
| FeO (as total oxide) | 4.04 | 5.22 | 3.11 | |
| FeO/FeO+MgO | .879 | .892 | .709 | |
| An (normative An/Ab+Ab) × 100 | 19.5 | 23.5 | 25.3 | |

[1] Green hornblende-biotite-granite gneiss.
[2] Well-foliated, more biotite-rich variant of sample 1.
[3] Well-foliated, light-gray, biotite granite gneiss.

and feldspar crystals up to 2 cm in length are found. Although the unit is homogeneous, it is strongly foliated and well lineated; the hornblende lineation is characteristic of an $YF_2$ structure (fig. 7). The coarsest and best preserved rocks, which are near the crest of Candlewood Hill and west of Clear Lake, exhibit relict igneous textures; however, the bulk of the rock is penetratively deformed and contains abundant tight $YF_2$ folds. In modal mineralogy and field aspect, this rock closely resembles the Storm King Granite at Bear Mountain (Lowe, 1950) and hornblende granite gneiss on Breakneck Ridge in the West Point quadrangle (pl. 1, inset). A belt of similar pinkish hornblende granite

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**Figure 7.** Hornblende-biotite-granite gneiss at Candlewood Hill (Yhgr) from the crest of the hill 0.3 km west of Mud Lake showing ductilely deformed and nonannealed quartz resulting from Paleozoic deformation, anhedral microcline microperthite, and plagioclase. A small, dark crystal of hastingsite is aligned in prominent foliation of $YF_2$ age, which is coplaner with Paleozoic fabric. Crossed nicols.

gneiss (Yhgr), which is exposed in the northwestern corner of the map (pl. 1), also is correlated with the Storm King Granite. Certain unmapped areas of pinkish hornblende granitic gneiss within Ygg on Granite Mountain and Prospect Hill also may be small areas of Yhgr.

The Storm King Granite from Dunderberg Mountain, which is on the western shore of the Hudson River in the Peekskill quadrangle has a U-Pb concordia age for zircon of about 1,130 Ma (Ratcliffe and Aleinikoff, 1990). The Storm King is intrusive into quartz-plagioclase leucogneiss, diopside-epidote-quartz gneiss, and layered paragneiss identical to the sequence near Clear Lake. Likewise, a mappable border of white aplite (Yap) or fine-grained granite similar to Yap forms the contact rock at the border of the Storm King on Dunderberg Mountain (Ratcliffe and Helenek, 1982).

## Aplite (Yap)

White-weathering, massive, fine-grained, plagioclase-microcline aplite (Yap) forms a widely distributed, but minor, unit. It is spatially associated with hornblende-plagioclase and diopside-hornblende-plagioclase rocks either near contacts with granitic gneiss (Ygg, Yhgr) or near zones of abundant pegmatite (Yp). The rock is finely foliated and deformed everywhere. The origin of the rock is uncertain—it may be either a metasomatic product of calc-silicate rocks in contact with granites or a metamorphic-anatectic product. The highly deformed concordant habit favors an early origin, before the $YF_2$ event, rather than a late origin, during the Canada Hill Granite intrusion or younger events. Elsewhere in the Hudson Highlands, the contact zones between the Storm King Granite and calc-silicate rocks or amphibolite are marked by similar occurrences of white aplite. For example, extensive areas of this rock are found at the northern end of Bull Mountain in the West Point quadrangle and on Dunderberg and Manitou Mountains in the Peekskill quadrangle, where the author has mapped it as a border facies of the Storm King.

## Canada Hill Granite and Associated Pegmatite (Ych)

Distinctive bluish-gray biotite-microcline-plagioclase granite and pegmatite (Ych), which has a resinous luster, form abundant stringers and larger masses within Yrg and Ybqf and Ybqp west of the Dennytown fault. When traced southwestward, these discontinuous granite stringers merge to form the main mass of the Canada Hill Granite of Berkey and Rice (1921) on Canada Hill in the Peekskill quadrangle (pl. 1, regional map). "Canada Hill Granite" is here adopted for use by the U.S. Geological Survey. Ghostlike inclusions of Yrg and patches rich in garnet and sillimanite characterize this unit. The dominant mafic mineral is biotite. The ratio of alkali feldspar to plagioclase varies greatly but commonly is about 1. The quartz content is high, commonly 20–25 percent. Representative photomicrographs of the Canada Hill Granite are given in figures 8 and 9. The Canada Hill has been interpreted as being an anatectic granite and migmatite complex derived from the partial melting of biotitic, two-feldspar gneiss and rusty paragneiss units in the West Point and Bear Mountain area (Helenek and Mose, 1984). Rb-Sr whole rock studies by Helenek and Mose (1984) yielded an isochron of 913±45 Ma (1 sigma) that has a high initial ratio of 0.7186±0.0017. Aleinikoff and others (1982) determined a 1,010±6-Ma zircon U-Pb concordia upper intercept age for the Canada Hill from one of the Helenek and Mose (1984) sample sites in the Crystal Lake pluton in the West Point quadrangle.

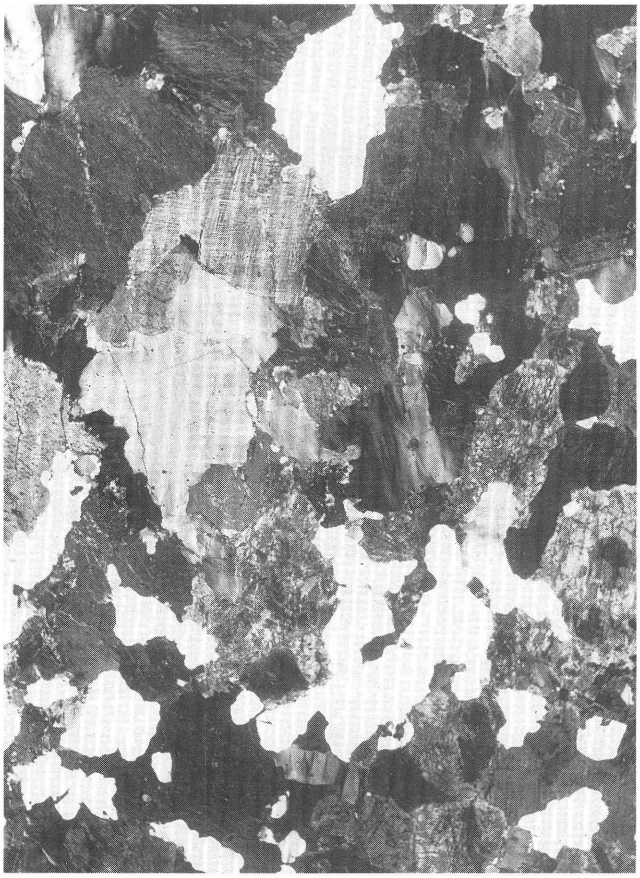

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**Figure 8.** The Canada Hill Granite (Ych; table 4, sample 13351C) from Route 301 at Fahnestock Corners showing nongneissic allotriomorphic granular texture of quartz (clear), microcline microperthite, and altered plagioclase. Crossed nicols.

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**Figure 9.** The Canada Hill Granite pegmatite (Ych; table 4, sample 13352) showing nondeformed quartz, brown biotite, and plagioclase. In outcrop, rock crosscuts sillimanite schist that displays intense $YF_2$ structure. Crossed nicols.

The 1,010±6-Ma zircon age from the Canada Hill is probably more accurate than the younger Rb-Sr age (Aleinikoff and Grauch, 1990).

Six samples of the Canada Hill Granite from road cuts along N.Y. Route 301 between Canopus Lake and Fahnestock Corners (table 4) have generally high (74 percent) $SiO_2$ and very low total FeO contents. $Na_2O$ and $K_2O$ are highly variable. The rocks are peraluminous and contain up to 2.8 percent normative corundum. Anorthite content of the normative plagioclase is low ($An_{12}$–$An_{21}$). In a normative An-Ab-Or plot, the Canada Hill plots as a granite and granodiorite (fig. 10*C*).

The samples of the Canada Hill Granite—13346B, 13349, and 13351C—plot close to the Quaternary minimum in the An+Ab–Or–Q diagram of Winkler (1974, p. 30) for bulk compositions that have an An:Ab of approximately 3. The distribution of the remaining samples (table 4) and the three listed above also plot along the trace of the quartz-plagioclase cotectic. Normative An content of the analyzed rocks increases from $An_{12}$ to $An_{21}$ along the trace of the cotectic toward increasing total plagioclase (sample 13352). These data are consistent with a partial melting (anatectic) origin for the Canada Hill. The changing bulk compositions and the increasing An content of the plagioclase reflect increasing amounts of partial melt (Winkler, 1974, p. 290). Helenek's data (Helenek and Mose, 1984) from the Crystal Lake pluton and from his samples (C–5, C–7, C–8) east of the Hudson River, which are plotted in figure 10, illustrate that, although the Canada Hill plots in a rather narrow range of high quartz content, the normative An-Ab-Or values are wide ranging. This variation is consistent with bulk compositions that contain increasing percentages of partial melt. The high $Al_2O_3$ content of the Canada Hill and its association with sillimanite-garnet-biotite-quartz-plagioclase schists and paragneiss (Yrg, Yrq, Yrs) suggest that the anatectic origin proposed by Helenek and Mose (1984) is correct. The composition fields of the Canada Hill in plots of normative Q-Ab-Or, Q-Or-An+Ab, and An-Ab-Or

**Table 4.** Partial chemical analyses of major-oxide (in weight percent) and normative-mineral compositions of the Canada Hill Granite (Ych)

[CIPW, Cross Iddings Pierson Washington]

| Sample no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Field identification no. | 13346B[1] | 13349[2] | 13350[3] | 13351C[4] | 13352[5] | 81–3[6] | C-5[7] |
| **Major-oxide composition** | | | | | | | |
| $SiO_2$ | 74.30 | 74.50 | 75.70 | 75.40 | 75.40 | 71.3 | 74.3 |
| $TiO_2$ | .07 | .03 | .02 | .02 | .51 | .17 | .23 |
| $Al_2O_3$ | 14.20 | 14.60 | 14.30 | 13.70 | 12.70 | 14.7 | 14.0 |
| $Fe_2O_3$ | .65 | .28 | .22 | .36 | 2.28 | | .08 |
| FeO | | | | | 2.1 | .79 | |
| MnO | .02 | .02 | .02 | .02 | .02 | .05 | .00 |
| MgO | .28 | .16 | .12 | .10 | .74 | .57 | .29 |
| CaO | .95 | .81 | 1.57 | 1.13 | 1.96 | .86 | 1.08 |
| $Na_2O$ | 3.51 | 2.76 | 3.98 | 3.58 | 4.11 | 2.83 | 3.15 |
| $K_2O$ | 4.68 | 5.59 | 3.07 | 4.53 | 1.14 | 6.61 | 5.04 |
| $P_2O_5$ | .13 | .10 | .08 | .07 | .05 | .1 | .12 |
| Loss on ignition | .51 | .71 | .55 | .61 | .59 | .44 | .42 |
| Total | 99.30 | 99.56 | 99.63 | 99.52 | 99.50 | 99.73 | 99.50 |
| **CIPW normative composition** | | | | | | | |
| Q | 33.7 | 35.3 | 37.4 | 34.7 | 41.5 | | 33.7 |
| Or | 27.7 | 33.0 | 18.1 | 26.8 | 6.7 | | 30.1 |
| Ab | 29.7 | 23.4 | 33.7 | 30.3 | 34.8 | | 26.8 |
| An | 3.9 | 3.4 | 7.3 | 5.2 | 9.4 | | 4.5 |
| C | 1.9 | 2.8 | 1.8 | 1.0 | 1.3 | | 1.6 |
| di | .0 | .0 | .0 | .0 | .0 | | .0 |
| hy | 1.2 | .6 | .5 | .6 | 2. | | 1.6 |
| mt | .3 | .1 | .1 | .2 | 1.1 | | .3 |
| il | .1 | .1 | .0 | .0 | 1.0 | | .5 |
| ap | .3 | .2 | .2 | .2 | .1 | | .3 |
| Total | 98.8 | 98.9 | 99.1 | 99.0 | 98.8 | | 99.4 |
| FeO (as total oxide) | .59 | .25 | .20 | .32 | 2.05 | | — |
| FeO/FeO+MgO | .684 | .630 | .645 | .775 | .737 | | — |
| An (normative An/An+Ab) × 100 | 11.5 | 12.6 | 17.8 | 18.5 | 21.3 | | 14.2 |

[1] Gray, resinous, pegmatitic biotite granite, Route 301 east of Fahnestock Corners.

[2] Bluish-gray, coarsely foliated (retrograded), muscovite-biotite-sillimanite-microcline perthite granite crosscutting sillimanite schist, Route 301 east of Fahnestock Corners.

[3] Massive garnet-microcline-perthite granite, southern side of Route 301, opposite sample 2, east of Fahnestock Corners.

[4] Bluish-gray, massive biotite-microcline-perthite granite crosscutting sillimanite schist at Fahnestock Corners.

[5] Biotite-oligoclase-quartz pegmatite crosscutting sillimanite schist at Fahnestock Corners.

[6] Zircon sample site in Canada Hill Granite crosscutting paragneiss, Route 9W, Crystal Lake pluton, West Point quadrangle (Aleinikoff and Grauch, 1990).

[7] Canada Hill Granite from roadcut, Route 301 in Oscawana Lake quadrangle (Helenek and Mose, 1984).

(fig. 10) differ markedly from other granitic rocks of the Hudson Highlands.

The Canada Hill Granite is best interpreted as being a late synmetamorphic (anatectic) granite generated by partial to extensive melting of paragneiss. The high biotite and the sillimanite contents of the paragneiss coupled with the low biotite and the high, but variable, potassium feldspar contents of the Canada Hill suggest that biotite plus sillimanite melting reactions were important. The high garnet content of the Canada Hill near contacts indicates incomplete melting and retention of garnet as a restite phase. Where pegmatites of the Canada Hill (Ych) crosscut sillimanite-rich Yrg near Fahnestock Corners, sillimanite is altered to muscovite along the walls of the pegmatite. Structural and petrographic data clearly indicate that intrusion of the Canada Hill postdated the $YF_2$ deformation and the regional sillimanite lineation. The data suggest that anatexis during the Canada Hill event was accompanied by sufficiently high $pH_20$ and low-enough temperatures for muscovite to be stable.

## Pegmatite (Yp)

White to pinkish-white biotite and (or) hornblende granite pegmatite is common throughout the area and

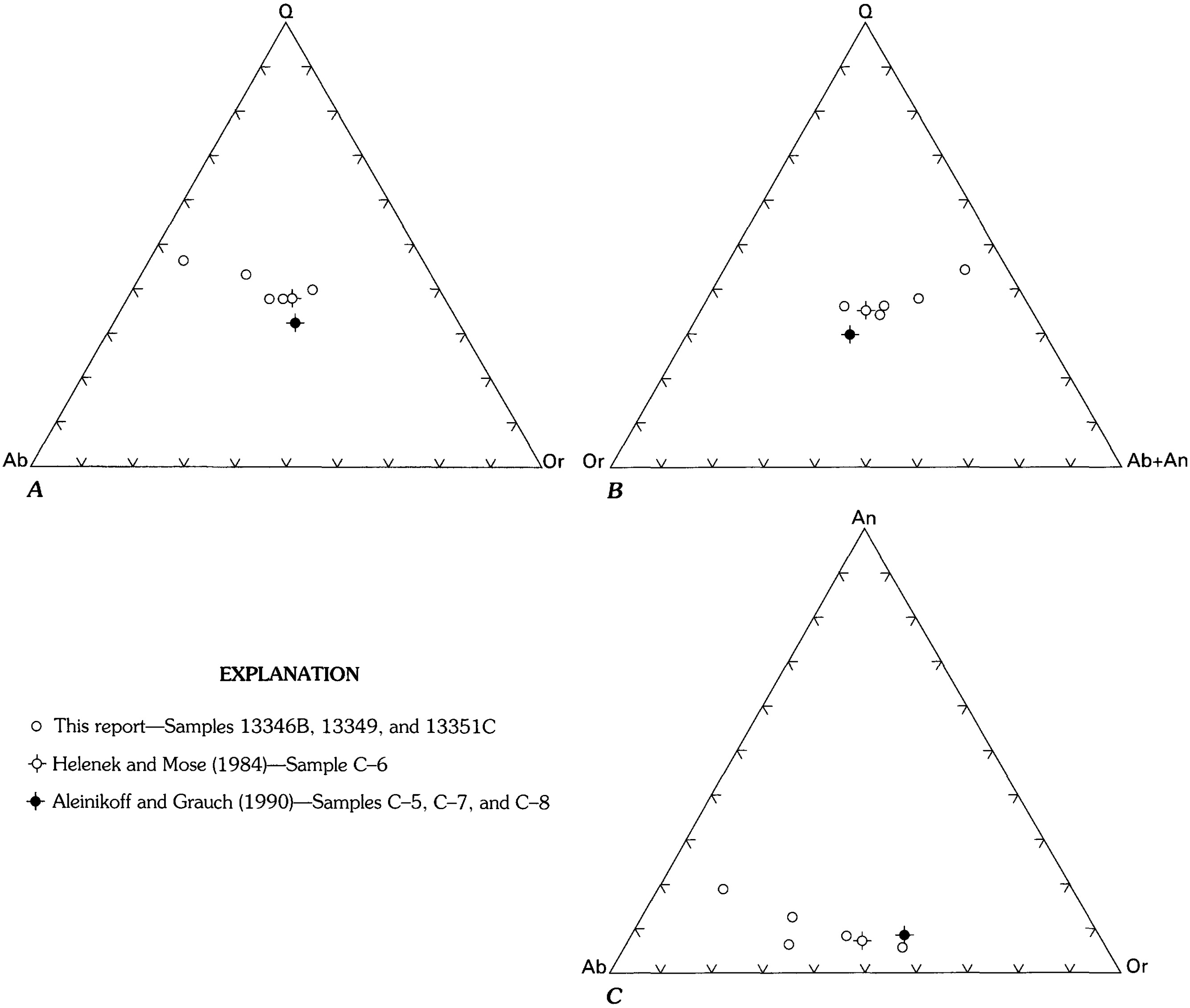
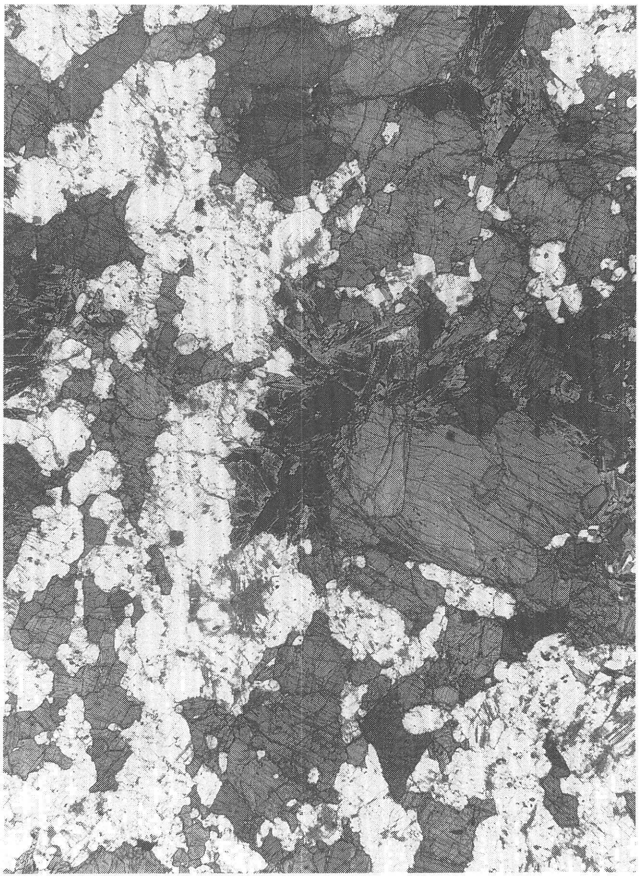



**Figure 10.** Samples of the Canada Hill Granite (Ych). *A*, Ab-Q-Or diagram showing a sample from the Oscawana Lake quadrangle. *B*, Or-Q-Ab+An diagram showing a sample from the Crystal Lake pluton in the West Point quadrangle. *C*, Ab-An-Or diagram showing a sample from the Crystal Lake pluton in the West Point quadrangle. (From Helenek and Mose, 1984; Aleinikoff and Grauch, 1990.)

commonly is aligned along the prominent $YF_2$ gneissosity. Several different generations of pegmatite probably exist, but these could not be mapped. Much of the Canada Hill Granite is pegmatitic, and these areas are mapped as Canada Hill Granite. Pegmatites (Yp) cut nearly all other units and, locally northeast of Canopus Lake, crosscut Proterozoic fault zones. Preliminary zircon U-Pb ages from pegmatites that cut amphibolite and leucogneiss at Camp Smith in the Peekskill quadrangle may range from $1,023 \pm 59$ to 964 Ma (Aleinikoff and others, 1982). Pegmatites appear to be undeformed and to postdate the $YF_2$ structures as well as the $YF_3$ structures.

## MIDDLE PROTEROZOIC MAFIC INTRUSIVE ROCKS

Three mafic plutonic suites are recognized—the Wiccopee pluton, which is the oldest and is composed of a complexly deformed and metamorphosed diorite-amphibolite-pyroxenite suite (Ywd, Ywu, Ywh, Ywp); hornblende ferrodiorite dikes (Yd); and metadiabase dikes (Zd). The rocks of the Wiccopee pluton were deformed by the $YF_2$ event and are intruded by migmatitic granite of the Reservoir Gneiss. The hornblende ferrodiorite dikes cross cut the $YF_2$ structures, and the metadiabase dikes (Zd)



0 2 CENTIMETERS

**Figure 11.** Biotite-hornblende metagabbro from the Wiccopee pluton (Ywd; table 5, sample 13734B) showing large subhedral green hornblende, brown biotite, and gray plagioclase. Plane-polarized light.

crosscut the $YF_3$ structure and locally crosscut pegmatites (Yp).

## Metagabbro and Associated Ultramafic Rocks of the Wiccopee Pluton (Ywd, Ywh, Ywp, Ywu)

Northwest of the California Hill fault near the center of the quadrangle, coarse-grained hornblende-biotite-labradorite metagabbro (Ywd) crops out in an elongate mass about 3 km long. The rock varies from foliated hornblende amphibolite near its borders with the amphibolite unit (Ya) to a coarse-grained rock that has recognizable radiating or partial stellate crystals of plagioclase up to 3 cm long. More commonly, the rock is equigranular and partly foliated and consists of subequal amounts of labradorite and pale-brownish-green, chunky hornblende (Ywd, fig. 11). Locally, igneous textures are clearly displayed in the main mass of the pluton but are commonly indistinct. The rock passes into a much more mafic hornblende-phlogopite rock that lacks plagioclase or into an olivine ($Fo_{85}$)-phlogopite-hornblende rock or a labradorite-hornblende-biotite rock that has a relict coronal structure suggestive of replacement of monoclinic pyroxene (Ywp). This rock is interpreted as being an altered pyroxenite. At its southern, northern, and eastern margins, the mass appears to grade into amphibolite or into hornblende-plagioclase diorite gneiss (Ywh) that generally lacks igneous textures. The Ywh unit is mineralogically similar to the Ywd, although Ywh has a smaller grain size and a stronger foliation, and igneous features that are relatively common to Ywd have been largely destroyed.

Plagioclase zoning is absent throughout the metagabbro and the hornblende-plagioclase gneiss. Coarse (2- to 4-cm) plagioclase crystals locally consist of smaller polyhedral grains that have triple junctions within a single form that clearly indicates remetamorphism. Locally, areas of serpentine in thin sections suggest replacement of magnesian pyroxene and (or) olivine. The Wiccopee pluton has no clear intrusive relations because it and its country rocks are all infiltrated and intruded by granitic gneiss and pegmatite of the Reservoir Gneiss (Ygg) and pegmatite (Yp).

Small areas of ultramafic rock (Ywu), either olivine-antigorite rock or serpentinite, crop out west of Tinker Hill in the California Hill fault 1.5 km north of the Taconic Parkway and in a dikelike feature 0.5 km west of the Taconic Parkway at the northern edge of the map (pl. 1). These occurrences of ultramafic rock are associated with hornblende-plagioclase gneiss and (or) amphibolite. Chemical analyses (table 5) of two samples (8 and 9) from the Tinker Hill area are silica-poor magnesian rocks. Semi-quantitative spectroscopic analyses indicate very high chromium values of up to 7,200 parts per million.

Two layers approximately 0.5 m thick were sampled. Sample 8 consists of 70 percent forsterite ($Fo_{92}$) in reticulated grains up to 0.5 cm in diameter that are veined with serpentine. Sample 9 consists of approximately 40 percent colorless, low-birefringent, monoclinic, polysynthetically twinned pyroxene (probably augite) that has a 2V of approximately 50° and a C to Z extinction angle of 35°, 40 percent serpentine after olivine, and about 10 percent relict olivine.

The chemical, the field, and the petrographic data suggest that these rocks are part of a layered mass of peridotite and pyroxenite. The ultramafic rock is in contact with massive hornblende amphibolite and gabbroic gneiss on the western flanks of Tinker Hill and appears to be surrounded on the west and the north by the Reservoir Gneiss (Ygg) and pegmatite (Yp). These granitic rocks intrude metagabbro, and the protolith of the country rock is not identifiable because of $YF_2$ deformation and migmatization.

The dikelike feature near the northern border of the map (pl. 1) has been traced 1 km north outside the quadrangle as a narrow (less than 10-m-wide) dike of serpentinite in which several abandoned quarries are

**Table 5.** Partial chemical analyses of major-oxide (in weight percent) and normative-mineral compositions of mafic rocks from the Wiccopee pluton

[CIPW, Cross Iddings Pierson Washington. Analysis by X-ray spectroscopy (except samples 8 and 9), U.S. Geological Survey, Lakewood, Colo. Analysts: J. Taggart, A. Bartel, D. Siems. Samples 8 and 9 analyzed by rapid-rock technique. Analyst H. Smith]

| Sample no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Field Identification no. | 6310[1] | 6321[2] | 6534[2] | 6234[3] | 13736A[4] | 13734A[5] | 13734B[6] | 6325A[7] | 6325B[8] |
| **Major-oxide composition** | | | | | | | | | |
| $SiO_2$ | 48.30 | 48.30 | 49.30 | 42.10 | 49.10 | 49.40 | 50.70 | 38.1 | 44.4 |
| $TiO_2$ | .43 | 1.28 | .60 | .02 | 1.54 | 1.55 | 1.23 | .03 | .04 |
| $Al_2O_3$ | 5.17 | 18.70 | 17.10 | .55 | 16.50 | 16.00 | 16.90 | .68 | 1.9 |
| $Fe_2O_3$ | 8.76 | 10.00 | 7.45 | 9.74 | 11.90 | 10.50 | 10.10 | 3.9 | 5.1 |
| FeO | | | | | | | 4.4 | 4.1 | |
| MnO | .18 | .14 | .12 | .09 | .19 | .18 | .16 | .2 | .2 |
| MgO | 20.90 | 6.59 | 9.93 | 35.40 | 6.16 | 6.94 | 6.03 | 41.8 | 28.5 |
| CaO | 13.20 | 8.71 | 12.40 | .02 | 8.82 | 10.90 | 8.85 | 1.2 | 9.4 |
| $Na_2O$ | .76 | 3.17 | 2.16 | .15 | 3.25 | 3.12 | 3.27 | .03 | .1 |
| $K_2O$ | .33 | 2.08 | .52 | .02 | 1.65 | .75 | 1.33 | .04 | .1 |
| $P_2O_5$ | .13 | .35 | .07 | .05 | .32 | .25 | .21 | .01 | .01 |
| $H_2O^+$ | | | | | | | 7.6 | 6.1 | |
| $H_2O^-$ | | | | | | | .4 | .21 | |
| Loss on ignition | 1.19 | .55 | .63 | 10.70 | .73 | .66 | .64 | | |
| $CO_2$ | | | | | | 1.3 | 1.0 | | |
| Total | 99.35 | 99.87 | 100.28 | 98.84 | 100.16 | 100.25 | 100.72 | 99.39 | 100.16 |
| **CIPW normative composition** | | | | | | | | | |
| Or | 2.0 | 12.3 | 3.1 | .1 | 9.8 | 4.4 | 7.9 | | |
| Ab | 6.4 | 23.8 | 18.3 | 1.3 | 27.5 | 26.4 | 27.7 | | |
| An | 9.7 | 30.7 | 35.4 | .2 | 25.6 | 27.4 | 27.5 | | |
| ne | .0 | 1.7 | .0 | .0 | .0 | .0 | .0 | | |
| C | .0 | .0 | .0 | .4 | .0 | .0 | .0 | | |
| di | 43.5 | 8.4 | 20.4 | .0 | 13.1 | 20.2 | 12.2 | | |
| hy | 10.2 | .0 | 8.1 | 41.4 | 2.8 | 5.5 | 12.7 | | |
| ol | 21.8 | 14.6 | 9.5 | 42.10 | 11.7 | 6.9 | 3.3 | | |
| mt | 2.8 | 4.0 | 3.0 | 2.2 | 4.4 | 4.4 | 4.0 | | |
| il | .8 | 2.4 | 1.1 | .0 | 2.9 | 2.9 | 2.3 | | |
| ap | .3 | .8 | .2 | .1 | .7 | .6 | .5 | | |
| Total (less $H_2O$) | 97.5 | 98.7 | 99.1 | 87.7 | 98.5 | 98.7 | 98.1 | | |
| FeO (total oxide) | 7.88 | 9.00 | 6.71 | 8.77 | 10.71 | 9.45 | 9.09 | | |
| FeO/FeO+MgO | .278 | .581 | .407 | .200 | .639 | .581 | .605 | | |
| An (normative An/An+Ab) × 100 | 60.2 | 56.3 | 66.0 | 21.8 | 48.2 | 51.0 | 49.9 | | |

[1] Forsterite-amphibole metaperidotite from the core of the pluton.
[2] Coarse-grained hornblende metagabbro, from the northern end of the pluton.
[3] Foliated serpentinite in the California Hill fault zone northeast of the pluton.
[4] Coarse-grained metahornblende diorite, from the southern side of the pluton.
[5] Fine-grained, well-foliated, augite-hornblende-plagioclase gneissic rock associated with sample 7, from the northern end of the pluton.
[6] Biotite-hornblende metadiorite from the northern end of the pluton.
[7] Augite-olivine-serpentine rock from a small sill-like exposure on the Oscawana Lake Road, on the western base of Tinker Hill.
[8] Forsterite serpentinite, same locality as sample 8.

located. The rock consists totally of serpentine replacing equant olivine grains that are 2–3 mm in diameter. Coarse-grained veins of feldspar and zinnwaldite crosscut wall rocks near the ultramafic rock.

Five partial chemical analyses of the hornblende-gabbroic rock of the coarse-grained core of the Wiccopee pluton (Ywd; samples 2, 3, 5–7) and one pyroxenite (sample 1) and three serpentinite (samples 4, 8, 9) samples are given in table 5. The gabbro has a narrow range (48–51 percent) of $SiO_2$ and relatively high (approximately 17 percent) $Al_2O_3$, MI equals (FeO:FeO+MgO) values that range from 0.41 to 0.64. $TiO_2$ values range from 1.23 to 1.55 percent. AFM values of the four samples shown in figure 6 plot near A, 20–25; F, 43–49; and M, 27–35. Samples 1, 3, 4, 8, and 9, however, are strongly enriched in magnesium, which is consistent with an accumulation of pyroxene and (or) olivine. These analyses compare closely with Nockolds' (1954) average values for 38 pyroxene gabbro samples, except for the slightly more dioritic or lower CaO and MgO values for the Wiccopee rocks. AFM relations suggest maximum iron enrichment of about 50 percent, which is consistent with a calc-alkalic gabbro. Magnesian pyroxene and olivine cumulate rocks indicate that hornblende was not the liquidus phase. Relict, coarse hornblende in pegmatitic gabbro indicates primary hornblende crystallization, which is consistent with a calc-alkaline origin.

Northeast of the Wiccopee pluton, coarse-grained, warty-textured, hornblende-plagioclase gneiss or metagabbro (Ywh) is common in an irregular belt that extends into the Lake Carmel quadrangle. Similar coarse-grained, hornblende-bearing dioritic or gabbroic rocks are present in abundance on Mount Nimham in the Lake Carmel quadrangle where metapyroxenites are associated with the metagabbro.

The Wiccopee gabbro is markedly richer in magnesia and lime but much poorer in total iron oxide than similar ferrogabbro and ferrodiorites of the Canopus pluton of the Peekskill quadrangle (fig. 6). Rocks of the Canopus pluton exhibit a strong iron enrichment trend and are comagmatic with ferromonzonite and quartz monzonite, which are distinctly different from the potassium-poor rocks of the Wiccopee pluton.

Each occurrence of ultramafic rock appears to be igneous rather than serpentinized forsteritic marble or calc-silicate rock. The association with metagabbroic rocks and amphibolite suggests that mafic and ultramafic plutonism affected the paragneiss and metavolcanic sequence before $YF_2$ deformation and metamorphism.

Field data show that the Wiccopee metagabbro was infolded with the Reservoir Gneiss during the $YF_2$ and the $YF_3$ fold events. Map (pl. 1) relations showing this infolding are present along the southwestern margin of the pluton. Long and Kulp (1962) reported a K-Ar biotite age of 810 Ma from the Wiccopee metagabbro. Dallmeyer and Sutter (1976) reported $^{40}Ar/^{39}Ar$ plateau ages of 710 and 913 Ma for biotite and hornblende, respectively, from gabbroic rocks (Ywd; pl. 1, sample 10). These data indicate that the Wiccopee metagabbro and associated diorite gneiss (Ywh) are Middle Proterozoic and that they have not been strongly affected by Paleozoic remetamorphism.

Ultramafic rocks, serpentinite, peridotite, and pyroxenite associated with coarse hornblende metagabbro(?) and amphibolite also are present on Mount Nimham in the Lake Carmel quadrangle. Although these ultramafic rocks petrographically resemble the Wiccopee occurrences, they are much better exposed.

## Hornblende Ferrodiorite and Ferromonzonite (Yd)

Two belts of unusual intermediate igneous rocks (Yd) crop out in the northwestern corner of the map. The larger belt consists of hornblende-biotite-oligoclase-potassium feldspar monzodiorite and ferromonzonite. This rock forms a continuous belt between hornblende granite gneiss (Yhgr) and biotite-quartz-feldspar gneiss (Ybqf). The rock varies from medium coarse grained to porphyritic and shows excellent undeformed igneous flow structure. The porphyritic variety consists of 35-percent unzoned, sodic, oligoclase phenocrysts up to 7 mm long set in a fine-grained (0.5- to 1-mm), allotriomorphic, granular matrix (fig. 12). Hornblende, biotite, and magnetite show excellent flow structure. In the matrix, potassium feldspar and quartz form more equant interstitial grains. Magnetite or ilmenomagnetite and abundant apatite form up to 6 percent of the rock. The rock is a ferromonzonite transitional into a hornblende-quartz monzonite. Mineralogically and texturally, the unit resembles the ferrodiorite-ferromonzonite of the Canopus

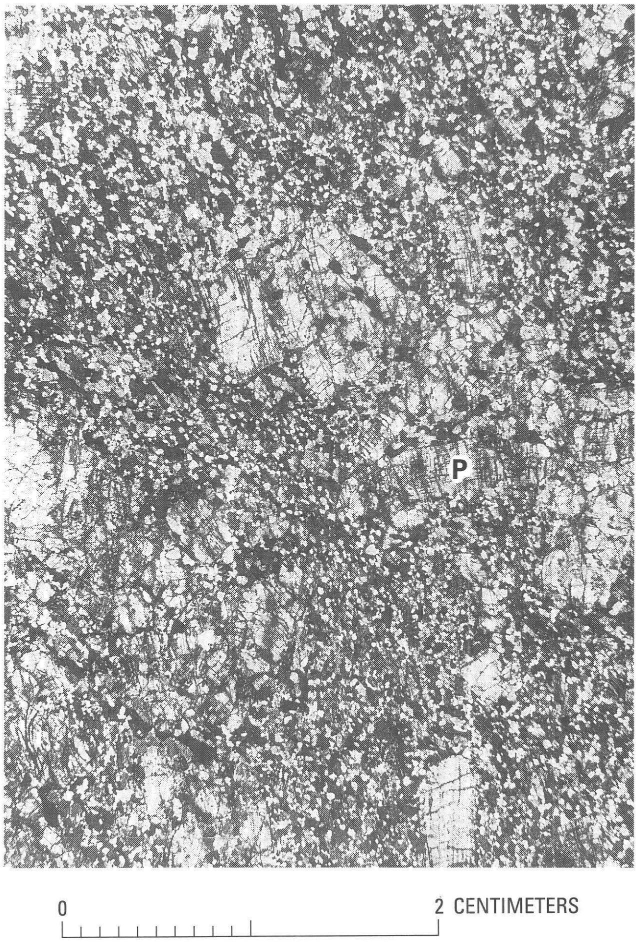



**Figure 12.** Hornblende ferrodiorite (Yd) from the northwestern part of the Oscawana Lake quadrangle on the western flank of Round Mountain showing one large, 7-mm-long, euhedral plagioclase phenocryst (P) and smaller subhedral phenocrysts of brown hornblende, plagioclase, and biotite in a flow-oriented matrix. Flow structure slopes upward from left to right. Plane-polarized light.

pluton in the Peekskill quadrangle (Ratcliffe and others, 1972).

The smaller body of altered pyroxene ferrodiorite, which is located west of the hornblende-biotite granite gneiss, is poorly exposed and crops out only in a small area. The rock is coarse grained and equigranular and consists of about equal percentages of clinopyroxene and sodic andesine, which has a subophitic texture. Brown hornblende, biotite, and quartz are minor minerals. Magnetite and apatite are important accessory minerals. Texturally and mineralogically, this diorite resembles some dioritic rocks that are associated with the Canopus pluton. Both occurrences of Yd appear to lack the strong $YF_2$ foliation, which is also a characteristic of the Canopus ferrodiorite-ferromonzonite suite.

One small dike of highly altered diorite (Yd) is mapped on the northwestern shore of Canopus Lake and intrudes biotite-quartz-plagioclase leucogneiss (Ybqp). This rock contains abundant brown hornblende, plagioclase, and clinopyroxene. Original pyroxene phenocrysts up to 0.5 cm long and slender plagioclase crystals up to 0.7 cm long form a crude diabasic texture and intergranular brown hornblende. Faults of the Dennytown fault system offset the dike, and attempts to locate the displaced segments were not successful.

The association of these ferrodiorite to ferromonzonitic rocks is uncertain, but each occurrence lacks the regional foliation of the $YF_2$ event. All contain brown hornblende and intermediate plagioclase and are dioritic to ferromonzonitic in composition. Similar igneous rocks of the Canopus pluton in the Peekskill quadrangle also intrude gneisses that have the $YF_2$ structure. U-Pb zircon age from monzonite of the Canopus pluton indicates a crystallization age of about 1,020 Ma (Aleinikoff, 1989).

Because these dikes contain brown hornblende as well as well-twinned sodic andesine or oligoclase, they differ from the metadiabase dikes, which are discussed in the section "Late Proterozoic Metadiabase Dikes (Zd)" and the lamprophyre of probable Ordovician age, which contains phenocrysts of red-brown kaersutite and are locally abundant outside the quadrangle (Ratcliffe, 1981). Unfortunately, mafic dikes of these three different groups cannot always be distinguished in the field, and thin section study is required for identification.

## DISCUSSION OF THE CHEMISTRY OF THE WICCOPEE AND BIOTITE-QUARTZ-PLAGIOCLASE GNEISS SUITE

Granite gneisses of the Reservoir Gneiss (Ygg) intrude an older suite of plagioclase-rich gneiss (Ycl, Ybqp) and include enclaves of garnet-bearing leucogneiss (Ygt) and infiltrate hornblende dioritic and gabbroic rocks of the Wiccopee pluton and associated amphibolite. This older suite of plagioclase-rich gneisses and plutonic rocks has calc-alkaline chemical affinities ranging from gabbro to tonalite and trondhjemite. Biotite-quartz-plagioclase leucogneiss (Ybqp, Ycl) and Ygt are not clearly intrusive units, although they are poorly layered and could have been coarse-grained plutonic rocks before Grenvillian metamorphism. In figure 13, the normative An-Ab-Or and Q-Ab-Or plots show that biotite-quartz-plagioclase leucogneiss (Ybqp) and Ygt have compositions similar to those of calc-alkaline dacitic to rhyolitic rocks, which are somewhat enriched in $Na_2O$. Ybqp, Ycl, and Ygt are interpreted as altered metacalc-alkaline volcanic rocks, dacites and rhyolite, intruded by calc-alkaline gabbroic rocks (Ywh, Ywd, Ywp) and by hypabyssal sills, which are now amphibolite (Ya).

Chemical analyses of the biotite-quartz-plagioclase leucogneisses (Ycl, Ybqp) from the Oscawana Lake quadrangle are nearly identical in normative An-Ab-Or contents to the Losee Metamorphic Suite of Drake (Drake, 1984, fig. 10) from New Jersey and Pennsylvania. The strong $Na_2O$ enrichment in these rocks suggested to Dodd (1965), Drake (1969), Young (1971), and Jaffe and Jaffe (1973) that similar gneisses were altered dacitic to rhyolitic volcanic rocks and (or) quartz keratophyres. Normative An-Or-Ab and Q-Ab-Or (fig. 14) plots of the available data for these rocks in relation to Ewart's (1979) compilation of Tertiary and Holocene volcanic rocks show Ycl and Ybqp to be somewhat intermediate between calc-alkaline rhyolite-dacite suites and his sodic rhyolite suites; this supports the general conclusions of earlier workers. Nonetheless, the lack of well-developed compositional layering in most of the leucogneiss suggests that some of the mass may have been intrusive trondhjemite and tonalite. Minor interlayered amphibolite may represent basaltic flows or tuffs. Samples of the Cat Hill Gneiss (Ycl) and biotite-quartz-plagioclase leucogneisses from the Oscawana Lake area are not as enriched in $Na_2O$ as the typical Losee and appear to be more siliceous, less altered rocks of more clearly calc-alkaline origin.

In table 6, some chemical parameters distinguish the major quartzofeldspathic units in the Oscawana Lake area. Chemical analyses of granitic gneisses mapped as the Reservoir Gneiss (Ygg) are not strictly comparable. Three samples of the same unit from the Gilbert Corners antiform, which was also mapped as Ygg, are distinctly lower in $SiO_2$, higher in total iron, and, in part, metaluminous compared to the bulk of the Reservoir Gneiss. More data are necessary before the belt of Ygg in the Gilbert Corners antiform can be clearly separated from the Reservoir Gneiss because of the variability and the complexities of the Reservoir Gneiss. Biotite-quartz-plagioclase leucogneiss (Ybqp), the Cat Hill Gneiss (Ycl), and garnet-rich leucogneiss (Ygt) in the Reservoir Gneiss belt of granitic gneiss are similar except for the markedly higher normative anorthite ($An_{31}$) content of the plagioclase in the Ygt unit.

In figure 13, the normative compositions of the pre-Reservoir gneisses are compared to those of the Reser-

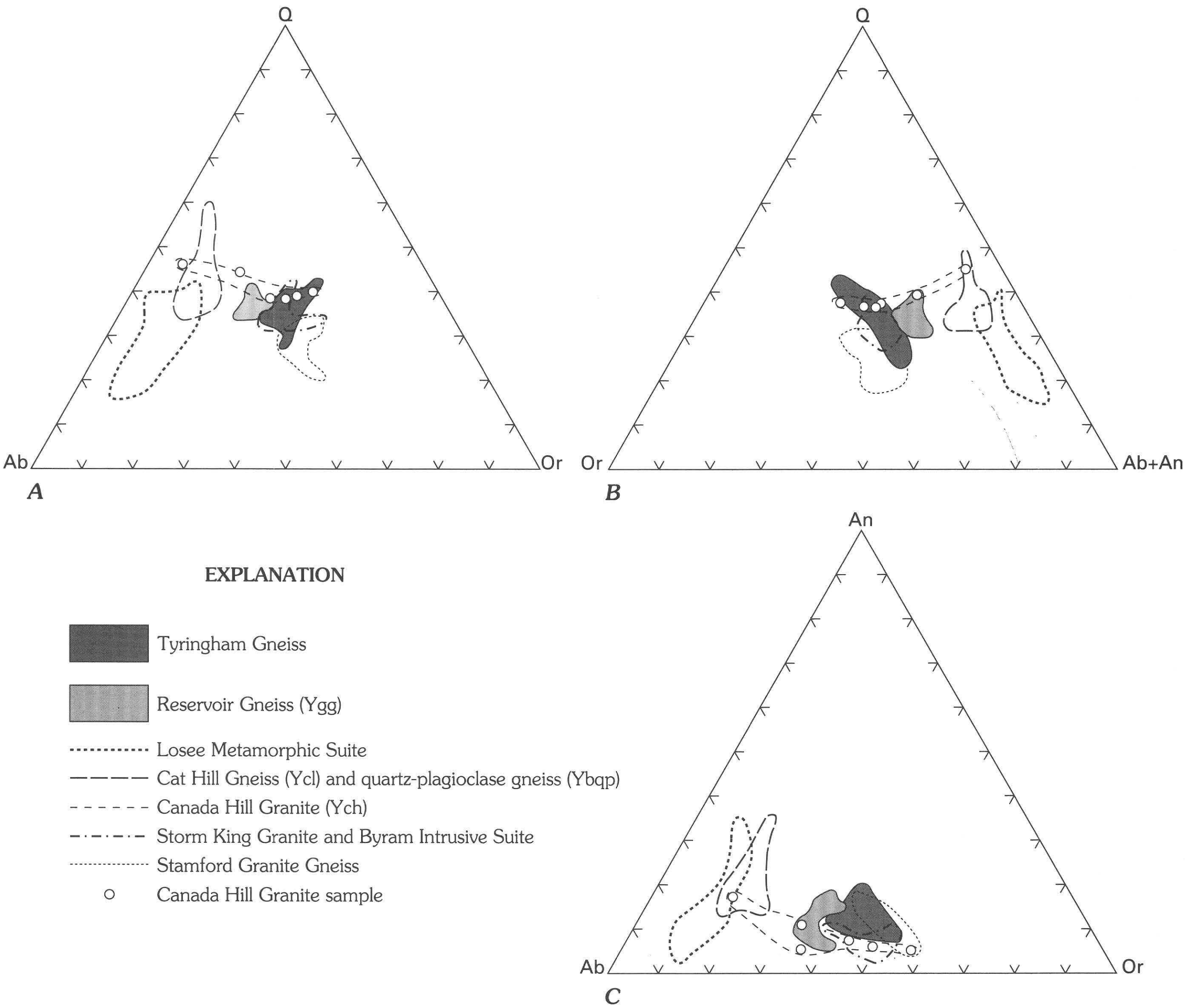



**Figure 13.** Selected quartz- and feldspar-rich rocks of the Losee Metamorphic Suite of the Reading Prong in relation to similar rocks of the Hudson Highlands. *A*, Ab-Q-Or diagram. *B*, Or-Q-Ab+An diagram. *C*, Ab-An-Or diagram. Data from table 1, Lowe (1951), Drake (1984), Helenek and Mose (1984), and Ratcliffe and Burton (1991).

voir Gneiss (light-shaded field), the Storm King Granite, the Byram Intrusive Suite, and the Canada Hill Granite, all of which are intrusive or migmatitic granitoids of the Hudson Highlands. In addition, the compositions of the Tyringham Gneiss of the Berkshire massif and the Stamford Granite of the Green Mountains and the Berkshire massif are shown. The Tyringham, the Storm King, and the Reservoir granites are syntectonic or early syntectonic granitoids, whereas the Stamford and the Canada Hill are late tectonic to posttectonic granites. The Storm King, the Byram, and the Tyringham granite suites contain hastingsite-biotite granodiorite that is weakly peraluminous to metaluminous. These rocks commonly exhibit large phenocrysts of microcline-perthite. The Stamford Granite is a coarse-grained, peraluminous, $K_2O$-rich, biotite-garnet, rapakivi-like granitoid that lacks strong Grenvillian deformation structures. The bulk of the granitic rocks analyzed from the Oscawana Lake quadrangle is distinct from and easily distinguishable by major-element compositions and normative mineralogy from other granitoids from the Hudson Highlands and the Grenvillian basement of New York, Connecticut, and Massachusetts.

## LATE PROTEROZOIC METADIABASE DIKES (Zd)

Twenty metadiabase dikes that crosscut Proterozoic structure have been mapped on plate 1. Chemical analyses

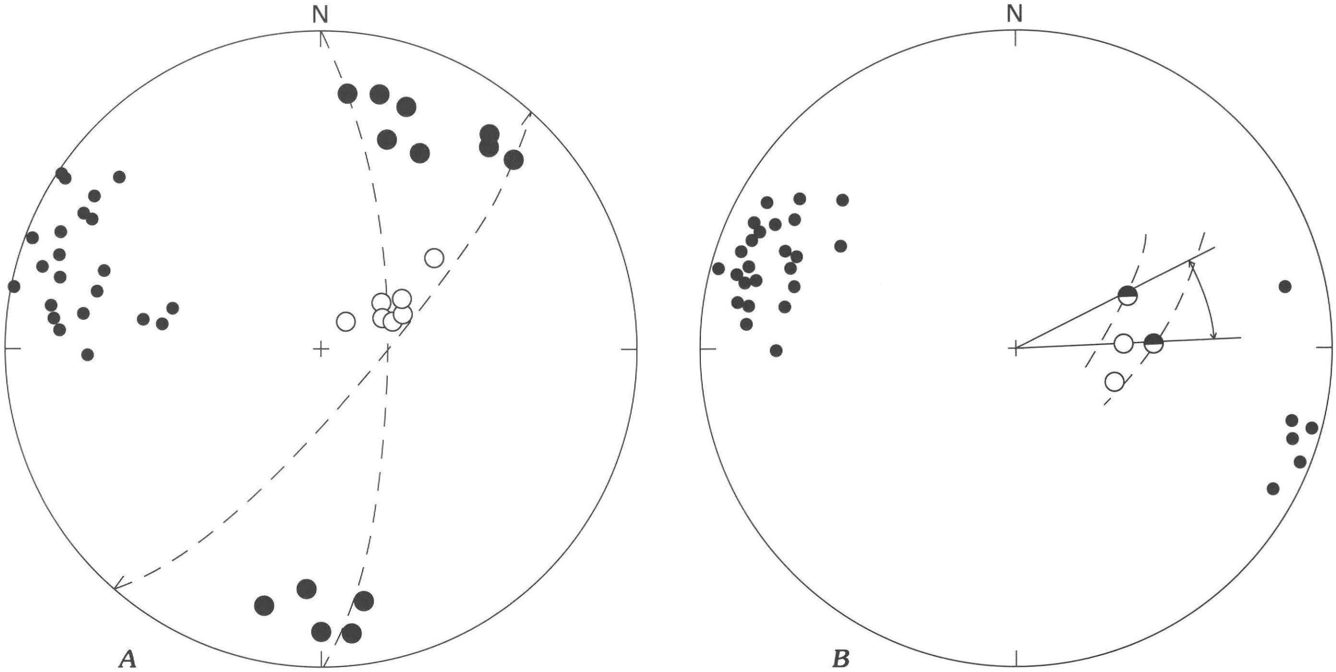



**Figure 14.** Structural elements associated with the Dennytown fault system and the metamorphic structure in the Poughquag Quartzite. *A*, Poles to foliation (dots), plunges of bedding-foliation intersection (filled circles), and plunges of long axes of deformed quartz pebbles (open circles) in the Poughquag Quartzite synclines to the north and the west of Canopus Lake; dashed planes illustrate range of foliation. *B*, Poles to mylonitic foliation in fault zones that bound the Poughquag Quartzite (dots), plunges of long axis of quartz pebbles in mylonite (open circles), and range of lineations (mullions) on fault surfaces (shown by arc and half-filled circles); dashed lines show partial great circles of mylonites that contain prominent elongation lineations shown.

of these dikes show them to be distinctive high-$TiO_2$, high-$P_2O_5$, and low-MgO rocks that have strong chemical and petrographic similarities to dikes of the Catoctin Formation of Virginia, basalts in the Tibbit Hill Volcanic Member of the Pinnacle Formation of Vermont, and basaltic rocks in the Taconic allochthon (Ratcliffe, 1987a,b). The dikes are chilled and can be traced fairly well by float. They are metamorphosed, locally well foliated, and offset by ductile fault zones in the basement rocks. In the eastern part of the area (pl. 1), the dikes contain chlorite, actinolite, and abundant epidote and biotite, especially in sheared zones. Seven analyses representing five dikes from the

**Table 6.** Comparison of some chemical and normative parameters of major granitic rocks from the Oscawana Lake area

| | Gilbert Corners | | | Reservoir Gneiss[1] | |
|---|---|---|---|---|---|
| Granitic rock unit | Ybqp | Ygt | Ygg | Ygg | Ych |
| Number of samples | 6 | 5 | 6 | 13 | 5 |
| FeO/FeO+MgO | 0.74–0.911 | 0.81–0.86 | 0.73-0.9 | 0.74–0.99 | 0.65–0.79 |
| | Avg. = 0.78 | Avg. = 0.84 | Avg. = 0.84 | Avg. = 0.86 | Avg. = 0.71 |
| FeO total | 1.04–2.68 | 0.94–5.7 | 3.4–5.8 | 1.1–2.5 | 0.22–2.1 |
| Normative (An/An+Ab) × 100 | 9–25 | 28–40 | 19–25 | 11–29 | 12–22 |
| | Avg. = 19 | Avg. = 31 | Avg. = 23 | Avg. = 19 | Avg. = 16 |
| An-Ab-Or classification | Trondhjemite | Tonalite | Granite-granodiorite. | Granite-granodiorite. | Granite. |
| Normative corrundum | 0.6–2.3 | 0.8–1.4 | | 3.2–0 | 1–2.8 |
| | Avg. = 1.65 | Avg. = 1.22 | | Avg. = 0.91 | Avg. = 1.8 |
| | Peraluminous | Peraluminous | Metaluminous | Peraluminous | Peraluminous. |
| Normative diopside | | | .8 | 2.4–0 | |
| $SiO_2$ (in weight percent) | 67–79 | 67–79 | 69–68 | 70–79 | 74–76 |

[1] Data from Ratcliffe and Burton (1991, table 1).

**Table 7.** Chemical analyses of major oxides (in weight percent) of metadiabase dikes in the Oscawana Lake and the Mohegan Lake quadrangles

[From Ratcliffe (1987a). Analyses by X-ray fluorescence spectroscopy and atomic absorption techniques from Shapiro (1975)]

| Metamorphic grade | Biotite zone | | Garnet zone or higher | | | | |
|---|---|---|---|---|---|---|---|
| Location | Oscawana Lake Road | | California Road | Clear Lake | Tinker Hill | | California Hill |
| Sample no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Field identification no. | 6381B[1] | 6381A[2] | 6243 | 6573 | 6326A[3] | 6326B[4] | 6218A |
| $SiO_2$ | 47.7 | 48.7 | 48.9 | 49.0 | 48.9 | 49.3 | 50.5 |
| $Al_2O_3$ | 14.0 | 13.5 | 13.7 | 12.9 | 13.4 | 14.1 | 13.1 |
| $Fe_2O_3$ | 5.1 | 4.2 | 2.9 | 4.4 | 4.4 | 3.9 | 3.4 |
| FeO | 10.2 | 10.0 | 12.6 | 9.8 | 10.6 | 10.8 | 11.7 |
| MgO | 5.2 | 5.9 | 4.9 | 4.5 | 5.0 | 5.2 | 4.6 |
| CaO | 8.9 | 8.2 | 9.3 | 9.9 | 8.8 | 7.7 | 9.4 |
| $Na_2O$ | 2.9 | 2.8 | 1.9 | 1.9 | 2.9 | 3.8 | 2.2 |
| $K_2O$ | .94 | .77 | .43 | 1.1 | 1.6 | 1.1 | .34 |
| $H_2O^+$ | 1.6 | 1.7 | 0.67 | 1.3 | .92 | .91 | .50 |
| $H_2O^-$ | .15 | .12 | .11 | .13 | .17 | .12 | .22 |
| $TiO_2$ | 3.3 | 3.2 | 3.4 | 3.6 | 3.2 | 3.4 | 3.3 |
| $P_2O_5$ | .57 | .57 | .47 | .64 | .56 | .55 | .50 |
| MnO | .25 | .24 | .20 | .22 | .26 | .26 | .24 |
| $CO_2$ | .05 | .36 | .02 | .39 | 1.0 | .03 | .08 |
| Total | 100.86 | 100.26 | 99.50 | 99.78 | 101.71 | 101.17 | 100.08 |
| Total sulfur | .21 | .16 | .14 | .23 | .24 | .21 | .27 |

[1] Coarse-grained variant of sample 6381.
[2] Fine-grained variant of sample 6381.
[3] From chilled margin of dike of sample 6326.
[4] From interior of dike of sample 6326.

Oscawana Lake and the adjacent Mohegan Lake quadrangles are given in table 7.

The dikes occur only within Middle Proterozoic gneiss and never cut the Cambrian cover sequence rocks; one dike is offset along the California Hill fault. An $^{40}Ar/^{39}Ar$ biotite plateau age of 436±3 Ma from the mylonite zone indicates that the dikes are pre-Taconic (Ratcliffe and others, 1985). The chemistry, the cross-cutting relations, and the presence of chill contacts against Proterozoic gneiss of approximately 915 Ma, according to $^{40}Ar/^{39}Ar$ cooling ages, suggest that the dikes are late Proterozoic in age and are probably related to pre-Iapetan rifting (Ratcliffe, 1987a).

## STRATIGRAPHY OF PALEOZOIC ROCKS—POUGHQUAG QUARTZITE (Ꞓpp, Ꞓpq, Ꞓpc)

Poughquag Quartzite of Early Cambrian age rests unconformably on gneisses of this quadrangle in a north-plunging syncline along the northern border of the map (pl. 1), in a faulted syncline near Canopus Lake, and along the southeastern side of Peekskill Hollow near the eastern edge of the map. Locally, the basal beds are coarse-grained, gritty metaconglomerate (Ꞓpc) containing pebbles of reddish jasper and rare fragments of underlying gneiss. The bulk of the Poughquag is a well-jointed, moderately well bedded, orangish-tan to gray, vitreous metaquartzite (Ꞓpq) that contains worm tubes. Light-orangish-gray- to tan-weathering phyllitic quartzite (Ꞓpp) overlies the vitreous metaquartzite in the core of the syncline north of Canopus Lake.

Elsewhere, the quartzite is in fault slices found in sheared zones in the gneiss. Near the faults, the gneiss and the quartzite are mylonitized. Fault slivers extend down the Dennytown fault zone and along the Peekskill Hollow fault. Exposures in Peekskill Hollow are rare, and the presence of the Poughquag Quartzite and (or) the Wappinger Group in the valley is likely.

## STRUCTURAL GEOLOGY

Basement rocks of the Oscawana Lake quadrangle have experienced a long and complex tectonic history. Structural features, such as folds, sharply defined faults, less well defined zones of ductile deformation, and brittle faults, have affected the rocks from the Middle Proterozoic (1.1 Ga) to the Mesozoic (175 Ma).

The sequence, the character, and the interrelation of structural features formed over this time period are the subjects of this discussion. The relation of current earthquake activity to structural features will be discussed in the section "Earthquakes and Geologic Structure."

The regional setting of the Oscawana Lake quadrangle can be seen on plate 1. The quadrangle is located on the boundary between the western and the eastern Hudson Highlands, which is marked by the Ramapo-Dennytown-Canopus fault system. This composite fault name points out a significant tectonic feature of this area, namely that the trend of the major Mesozoic normal faults of the Ramapo system, Paleozoic faults of the Dennytown fault system, and Middle Proterozoic faults of the Canopus fault system and shear zones are coincident. Faulting along this prominent feature and elsewhere in the area (pl. 1) has taken place during multiple events that were widely spaced throughout geologic time since the Middle Proterozoic. Reuse of faults during tectonic events is referred to as fault reactivation. Implicit in this concept is the idea that structural grain, once established in an area, may serve to concentrate stress during subsequent events because of inherent differences in strength between previously faulted and unfaulted rocks. Repeated reactivation results in accentuation of features and enhanced structural contrasts across such zones. The net result of such activity produces fault zones that have composite structures of different ages and physical characteristics formed at different crustal levels.

The Oscawana Lake area also spans the area between Paleozoic chlorite-grade metamorphism in the northwest and sillimanite-grade metamorphism in the southeastern corner. As a consequence, basement rocks and their original hornblende-granulite mineral assemblages are variably retrograded, and the structural style of their redeformation changes southeastward as a function of increased rock ductility under increased temperature. Accurate determination of the grade of Paleozoic remetamorphism is not possible from the mineral assemblages because of the quartzofeldspathic nature of the basement rocks and the localized mineralization in the shear zones. Nonetheless, a general increase in the grade of remetamorphism toward the southeast can be determined from a study of mineral assemblages in shear zones. East and south of the quadrangle, high-grade schist, marble, and complexly redeformed rocks of the Manhattan Prong are exposed where they are intruded by mafic plutonic rocks of the Cortlandt complex (Ratcliffe and others, 1985).

Immediately north of the quadrangle, the Poughquag Quartzite and the Wappinger Group form a north-dipping, right-side-up section overlying the gneisses west of the Canopus fault system (Ratcliffe and Burton, 1991, fig. 2). East of this point, basement rocks within the Canopus fault system and other nested faults of the Poughquag-Clove Valley thrust carry fault system basement gneiss and its Poughquag Quartzite cover over rocks of the Wappinger Group.

On a regional scale, the rocks of the Hudson Highlands appear to form a rooted, upright anticlinorium that has an upright, west-dipping, conformable section of mantling Paleozoic rocks. Recent Vibroseis data from a seismic line extending northwest from the Hudson River at Tomkins Cove, N.Y., to the center of the Popolopen Lake, N.Y., quadrangle reveal southeast-dipping reflectors at 1.5–2.5 s of two-way traveltime that may project up dip to the Cornwall thrust (Ratcliffe and Costain, unpub. data). As a result of the drilling at and the tunnel construction of the Storm King crossing of the Delaware aqueduct at Breakneck Ridge, the Cornwall thrust, which is exposed at the Hudson River, is known to have a southeast dip of 45° or greater (Berkey and Rice, 1921). The leading edge of the Cornwall thrust is not exposed northeast of the Hudson River because the west-dipping Mesozoic Beacon-Lagrangeville fault truncates the small, isolated klippen of Proterozoic gneiss that extends north from the Hudson River.

Major faults in this quadrangle and their periods of activity from northwest to southeast across the map area are listed as follows:

- Clove Creek-Sylvan Lake fault zone—Paleozoic;
- Dennytown fault system—Paleozoic;
- Indian Lake shear zone—Middle Proterozoic and Paleozoic;
- Canopus fault zone—Middle Proterozoic, Paleozoic, and Mesozoic;
- Stillwater Pond shear zone—Middle Proterozoic and Paleozoic;
- Dicktown fault—Middle Proterozoic and Paleozoic;
- California Hill fault—Middle Proterozoic and Paleozoic; and
- Peekskill Hollow fault system—Middle Proterozoic?, Paleozoic, and Mesozoic?.

On plate 1, mylonitic foliation, lineation, folds, and gneissosity that formed during Middle Proterozoic events are shown in red, and structures of Paleozoic or younger age are shown in black. In those cases where Paleozoic overprint is intense in zones of coincident Proterozoic and Paleozoic deformation (for example, along the Canopus fault zone), only the Paleozoic structures are commonly shown, although high-grade mylonites are present.

## Middle Proterozoic Structures

Axial traces of three fold phases of Middle Proterozoic age—$YF_1$, $YF_2$, and $YF_3$—are shown on plate 1. The oldest folds ($YF_1$) in the Oscawana Lake quadrangle are highly conjectural. An axial trace is shown passing through the biotite-quartz-plagioclase leucogneiss (Ybqp) belt west of the Dennytown fault. Sillimanite and hornblende lineations aligned in $YF_2$ axial surfaces in this area plunge south, which suggests that the $YF_1$ axial surface also may dip south, thus producing the south-plunging intersection lineation shown in the western part of the cross section *A–A′* shown on plate 1. The intersections between south-dipping gneissic layering and steeply dipping $YF_2$ axial surfaces plunge to the south and indicate the probable southerly dip of the $YF_1$ axial surface. Another possible $YF_1$ trace is shown in the center of the Gilbert Corners $YF_2$ antiform. North of Stillwater Pond, the garnet-biotite-quartz-feldspar gneiss (Yrgt) unit defines a third $YF_1$ axial trace. These possible $YF_1$ axial traces are spatially associated with the tight $YF_2$ folding that is parallel to the Canopus and other Proterozoic fault zones. If these $YF_2$ folds in the vicinity of the Canopus fault zone are actually late-forming $YF_2$ structures spatially associated with the fault, then the $YF_1$ traces may not correlate with the regional $YF_1$ folds.

In the area of the Wiccopee pluton, a possible $YF_1$ axial trace is shown passing through the hornblende-plagioclase diorite gneiss (Ywh) belt north of Wiccopee Reservoir. This interpretation is conjectural because the symmetrical repetition of the Reservoir Gneiss about Ywh may not be caused by folding but actually may indicate separate belts of intrusive granite. Two additional $YF_1$ structures are shown in the eastern part of the map (pl. 1) in areas of amphibolite (Ya) and biotite-quartz-plagioclase gneiss (Ybg).

Three fold sets have been traced throughout the Hudson Highlands of New Jersey (Dallmeyer, 1972a,b) and New York (Helenek and Mose, 1984; Ratcliffe and Burton, 1991). Proterozoic $F_1$ ($YF_1$) folds are recognized locally in the Hudson Highlands by symmetrical repetition of units around the hinge areas of tight $YF_2$ folds. The original orientation of the $YF_1$ fold system is uncertain, but it may have had subhorizontal (recumbent) Middle Proterozoic axial surfaces. All rock units except the intrusive hornblende granite gneiss (the Storm King Granite), pegmatites, the Canada Hill Granite, and some mafic plutons, such as the Canopus pluton (Ratcliffe, 1971) in the Peekskill quadrangle, have been involved in the $YF_1$ folding. Some granites, such as the hornblende-biotite granite gneiss (Yhgr) and the Reservoir Gneiss, may have been intruded parallel to limbs of the $YF_1$ structures.

$YF_2$ folds are isoclinal, upright, and northeast trending and exhibit a strongly developed gneissosity or foliation parallel to their axial surfaces. Transposition of earlier layering into the $YF_2$ foliation is common. Deformation was accompanied by hornblende-granulite facies metamorphism. The $YF_2$ foliation contains a coarse hornblende, biotite, or sillimanite mineral lineation that plunges either steeply northeast or locally southwest, as in the northwestern part of the map (pl. 1). The aeromagnetic pattern of the Hudson Highlands (Henderson and others, 1966), which are west of the Canopus fault from the Hudson River south into New Jersey, is controlled by northeast-trending, highly magnetitic gneisses on the limbs of the $YF_2$ isoclines.

$YF_2$ structures in the Oscawana Lake quadrangle are shown as northeast-trending, tightly appressed antiforms and synforms west of the Canopus fault system. Plunges are to the northeast and the southwest, as is a strong mineral lineation. In the area of the Gilbert Corners $YF_2$ antiform, plunges are north-northeast, and minor and major folds are nearly isoclinal. Abundant pods and stringers of biotite and (or) hornblende pegmatite are intruded parallel to the limbs of $YF_2$ folds. Tight folding in the Stillwater Pond area and to the northeast produces repetition of the calc-silicate and paragneiss units about steeply dipping axial surfaces (pl. 1, cross section *A–A′*).

East of the Dicktown fault, $YF_2$ structures are numerous and define complexly folded patterns. Axial surfaces commonly dip moderately to steeply to the northeast. $YF_2$ minor folds plunge in a reclined fashion down the dip of $YF_2$ axial surfaces. These relations are well displayed around the southern closure of the Wiccopee Reservoir $YF_3$ synform. Although $YF_2$ axial surfaces are steeply dipping to the north along the axis of the synform, they generally dip to the north and the northwest. The longitudinal cross section *B–B′* shown on plate 1 displays the change in attitude of $YF_2$ folds. Individual folds have high amplitude and are isoclinal and commonly reclined.

Aeromagnetic patterns east of the Canopus fault zone (Harwood and Zietz, 1974) are broad, low-amplitude features that mimic the distribution of $YF_2$ and $YF_3$ folds. Thus, the contrast in aeromagnetic patterns east and west of the Canopus fault zone is not controlled by different geologic units, but by the structural configuration of the units. Elongated high-amplitude features in the west are formed by subvertical magnetic units, whereas the broad features in the east are formed by gently plunging, more open $YF_2$ and $YF_3$ features.

Near the Hudson River, $YF_3$ structures, such as the Bear Mountain and the Canada Hill synforms, postdate the Canada Hill Granite and are younger than $1{,}010\pm6$ Ma (Aleinikoff and Grauch, 1990). $YF_3$ structures in the Oscawana Lake area vary in intensity and appear to be related, in part, to deformation between steeply dipping strike-slip shear zones of Proterozoic age, such as the Canopus fault zone (Ratcliffe, 1971) and the steeply dipping shear zones that surround the large S-shaped area of Ygg and Yhg-Ya southwest and northeast of the Wiccopee Reservoir in the central part of the map (pl. 1). Clockwise rotation of $YF_2$ structures in the S-shaped domain is well illustrated by the map data. A similar zone of clockwise rotational strain is found on the western side of the Canopus fault in the Peekskill quadrangle where the Canopus pluton has been deformed into a smaller S-shaped mass (Ratcliffe and others, 1972). Locally, $YF_3$ folds and mylonitic structures are intense, such as those along California Hill where late-forming, magnetite-rich pegmatites crosscut and infill shear zones. Throughout the quadrangle, the northeast-trending pegmatites, which formed during or after the $YF_3$ event, are intruded along or at an angle to the $YF_3$ axial traces. Because clockwise rotational strain, $YF_3$ folds, and mylonitization along the Canopus fault zone (Ratcliffe and others, 1972) are dated by the age of the Canopus pluton at about 1,020 Ma (Ratcliffe and Aleinikoff, 1990), the $YF_3$ structures in this quadrangle may not be the same age as those in the Bear Mountain area, which are known to postdate the Canada Hill Granite (intruded at 1,010 Ma).

The open folds shown west of the Canopus fault in the area of Canada Hill from Fahnestock Corners northeast do not appear to affect the Canada Hill Granite. The $FY_2$ foliation in the Canada Hill Granite is thought to be a fabric inherited from the parent paragneiss. This interpretation is consistent with the observation that the Canada Hill is locally nonfoliated and clearly crosscuts sillimanite schist. If the age of the Canada Hill is $1,010 \pm 6$ Ma, as Aleinikoff and Grauch (1990) maintain, then the $YF_2$ folds that are replaced and intruded by the Canada Hill are older. Therefore, the late folds, such as the Gilbert Corners antiform, may be associated either with strike-slip faulting and deformation along with the Canopus fault zone at about 1,120 Ma or with post-Canada Hill (1,010-Ma) $YF_3$ deformation.

Proterozoic deformation zones within the belt of rocks between the Indian Lake and the Stillwater Pond shear zones contain abundant, biotite-rich, 0.1- to 50-m-wide blastomylonitic shear zones. These zones are characteristically black, white-feldspar-spotted, brown-biotite-rich rocks that have recrystallized quartz and feldspar fabrics. Plagioclase forms 1- to 3-mm porphyroblasts within the biotite-rich matrix. These biotite-rich shear zones are associated with high-strain zones that consist of tightly isoclinally folded gneiss that has pods and stringers of pegmatite intruded subparallel to the axial surfaces. These blastomylonitic zones lack the distinctive quartz rodding and the fine-grained fabrics of the sericite-quartz-chlorite phyllonitic texture characteristic of the younger Paleozoic shear zones that commonly overprint these structures. Zones of blastomylonite are well developed along the foot of Candlewood Hill, above and along the East Canopus fault, along the Stillwater Pond shear zone, and locally along the Dicktown and the California Hill faults. The tightly folded gneisses between the Canopus fault zone and the Dicktown fault are locally augen gneisses that have a strong, high-grade, tectonic fabric that dips steeply southeast subparallel to the tight $YF_3$ folds. Blastomylonites, augen gneiss, intense folding, associated migmitization, and pegmatite intrusion in this zone mark a clearly recognizable Middle Proterozoic deformation front associated with the Canopus fault system.

To the east of the Dicktown fault and the Canopus fault zone, folds of $YF_3$ generation are commonly broad and open and have upright axial surfaces. Plunge direction commonly is northeast, but the amount of plunge, which is highly variable, depends upon the attitude of $YF_2$ layering that is folded. Away from shear zones, a weak foliation, which is expressed by oriented biotite, is present in open structures. Near fault zones, oriented biotite and brown hornblende form in zones of intense folding and high strain.

Within the area of the Wiccopee Reservoir synform, $YF_3$ axial surfaces trend northeast and dip southeast, except at the northern end where they are folded. A similar zone of disrupted $YF_3$ trends occurs along the western slopes of Granite Mountain near the Peekskill Hollow fault zone. This folding is the result of Paleozoic deformation associated with thrust faulting. East of this point, Paleozoic foliation and mylonitization are pervasive, and $YF_3$ structures have not been recognized. $YF_3$ axial traces in the Wiccopee Reservoir area trend north-northeast across the complexly deformed granite gneiss and dioritic gneisses. At the southern end of the Wiccopee Reservoir synform, the structure is tightly folded (pl. 1, cross section *A–A′*).

The age of the Middle Proterozoic structures is tightly constrained by the data from geochronologic studies of the igneous rocks affected by these structures. In addition, metadiabase dikes of probable Late Proterozoic age (Zd) crosscut the $YF_3$ structures. These dikes do not intrude the Poughquag Quartzite. On the basis of chemistry and Paleozoic metamorphic overprint (Ratcliffe, 1987a), they are correlated with the Catoctin Formation of the Blue Ridge Mountains of Virginia. Metadiabase dikes in the Oscawana Lake quadrangle are offset and mylonitized by Ordovician shear zones at California Hill where an $^{40}Ar/^{39}Ar$ biotite plateau age of $436 \pm 3$ Ma indicates that the dikes are pre-Late Ordovician (Ratcliffe and others, 1985).

## Late Proterozoic Structures

The Late Proterozoic dikes probably are related to a period of rifting that preceded the formation of Iapetus, which was the Late Proterozoic through Middle Ordovician proto-Atlantic Ocean. No faults related to this rifting are recognized within the Oscawana Lake quadrangle, although brittle movement along any of the major fault zones in pre-Poughquag time cannot be ruled out. Locally near metadiabase dikes, the adjacent wall rocks contain platy brittle fractures subparallel to dike walls. Fracture surfaces coated with epidote are common near metadiabase dikes. Fracturing associated with the dikes commonly extends beyond exposures of the dikes as zones of intense fracturing. Outside this quadrangle, one wall of the metadiabase dikes commonly has been reactivated, as shown by ultramylonite or pseudotachylyte. It is likely that the fracturing and the epidote mineralization postdate intrusion and probably formed during the Paleozoic or the Mesozoic. Because of the epidote mineralization found in association with the pseudotachylyte, it is unlikely that the reactivation and the minor faulting along mafic dikes are Holocene.

## Paleozoic Structures

Structures produced in the Paleozoic, probably of Taconian age, are obvious in shear zones where inliers of Lower Cambrian Poughquag Quartzite are surrounded by mylonitic zones. Faulted Poughquag Quartzite forms strings of fault slivers that extend southwest from the northern border of the map (pl. 1) along the Dennytown fault zone. Similar slivers of quartzite are found along the Peekskill Hollow fault. Folds in the Poughquag are upright, gently plunging, synclinal structures that contain a steeply southeast-dipping, axial-planar foliation. Bedding-cleavage relations seen in the small syncline north of Canopus Lake indicate that this foliation is a first-generation structure. Outside the quadrangle to the northeast and the northwest, cover sequence rocks of Early Cambrian through Middle Ordovician age contain multiple fold phases. These structures are not discernible in the limited exposures of the Paleozoic rocks present in this quadrangle.

Proterozoic gneiss exposures in a zone immediately beneath the Poughquag Quartzite are strongly foliated, retrograded, and very rich in muscovite, magnetite, and tourmaline. This zone, which is up to 20 m thick, contains the prominent foliation in the overlying quartzite. This zone of highly retrograded and altered gneiss is interpreted as being a metamorphosed regolith that formed beneath the Lower Cambrian unconformity. Paleozoic strain elsewhere in the basement rocks is distributed along discrete zones of ductile deformation or in wider ductile-deformation zones. These zones, which are widely spaced in the northwestern part of the map (pl. 1), are expressed by fine-grained, 0.5- to 1-m-thick, phyllonite zones that pass outward into zones of spaced foliation and semibrittle fracture zones. A strong downdip lineation is most pronounced within the more intensely deformed zones. Several muscovite-chlorite-albite-epidote greenschist phyllonite zones are present within the basement rocks southwest of the syncline in the Poughquag Quartzite that mantles the gneiss in the northwestern corner of plate 1 near Wiccopee Creek.

A comparison of the regional metamorphic fabrics found in synclines of Poughquag Quartzite and in mylonitic zones bounding these synclines is illustrated by stereograms that depict structural elements in and around the Dennytown fault system (fig. 14). In the stereograms shown in figure 14*B*, the poles of mylonitic foliation from shear zones bordering the synclines and from disconnected slivers of Poughquag Quartzite in the Canopus Lake shear zone are shown. In figure 14*A*, poles of foliation and other metamorphic structures within the slivers are shown. Fold axes plunge northeast and southwest,which suggests rotation in small circles around shallow-plunging northeast and southwest axes. However, confirmation of the later folding is not found in the poles to foliation diagram in figure 14. In addition, the correspondence in plunge is strong between the long axes of deformed quartz pebbles lying in the mylonitic foliation and those in the foliation from the synclines. Scolithus and quartz pebbles have Y to Z ratios of approximately 1:2 within the foliation, and long axes plunge N. 70° E. to S. 80° E. in both settings. The observations and the strain characteristics suggest that the synclines, the foliation, and the bordering shear zones formed in similar northeast-southwest stress fields, which are consistent with the observed shortening direction and the right-lateral component of motion on thrust faults or mylonite zones that dip steeply northwest (up-from-the-southwest sense of displacement) or dip steeply southeast (up-from-the-northeast sense of displacement).

The small faulted syncline exposed at the northern border of plate 1 east of Wiccopee Creek can be traced into the Poughquag Quartzite that mantles the northern slopes of the gneisses in the adjacent Hopewell Junction quadrangle. Coarse conglomerate unconformably rests on subvertical gneiss in excellent exposures just east of the intersection of East Mountain Road and Wiccopee Creek. The contact with the gneiss can be traced southeastward up the slope where the synclinal closure is located. In marked contrast to the fabric seen in the Canopus Lake exposures, the Poughquag Quartzite in the syncline is well bedded and only weakly foliated. The western margin of the syncline is apparently faulted by a steeply southeast-dipping, right-lateral thrust fault. Although the sense of displacement of the strata suggests a normal fault, the slip direction on the fault may plunge more steeply to the northeast than the plunge of the trace of bedding on the fault surface, which would produce the observed sense of offset. An alternative explanation is that the fault surface may dip steeply to the northwest.

Retrogressive chlorite-albite-sericite-epidote assemblages, which were altered from Proterozoic biotite and oligoclase, are extensively developed in the paragneiss units at the extreme northwestern corner of the map (pl. 1). This area of highly foliated gneiss probably formed from altered rocks developed beneath the now-eroded Poughquag Quartzite that is seen in rocks beneath the unconformity at Wiccopee Brook and at Canopus Lake.

Throughout the area of the map (pl. 1) to the northwest of the Hortonville fault system, narrow muscovite-chlorite phyllonitic shear zones are abundant. These spaced zones are difficult to trace from outcrop to outcrop but probably are much more abundant than are shown on the plate. One excellent exposure is found in a roadcut along the northern side of Route 301, 1.4 km east of Fahnestock Corners. Three narrow subvertical phyllonite zones 3 to several centimeters thick crosscut the Canada Hill Granite in northeast- to north-trending anastomosing fashion. This anastomosing composite fabric consists of a north-to-northwest sigmoidal (S) foliation that is bordered by north-northeast-striking shear, or C, fabric (figs. 15, 16). The mineralogy of these narrow zones consists of 60 to 80 percent $2M_1$ polytype muscovite, quartz, and minor chlorite. Samples were collected from the three zones for $^{40}Ar/^{39}Ar$ analyses of muscovite, but the results failed to identify plateau ages (Mick Kunk, personal commun., 1988). Sketches of the outcrop and a photomicrograph illustrating the textures and the structures present in the finest grained, most phyllonitic band are given in figures 15 and 16. Megascopic fabric data presented in figure 17

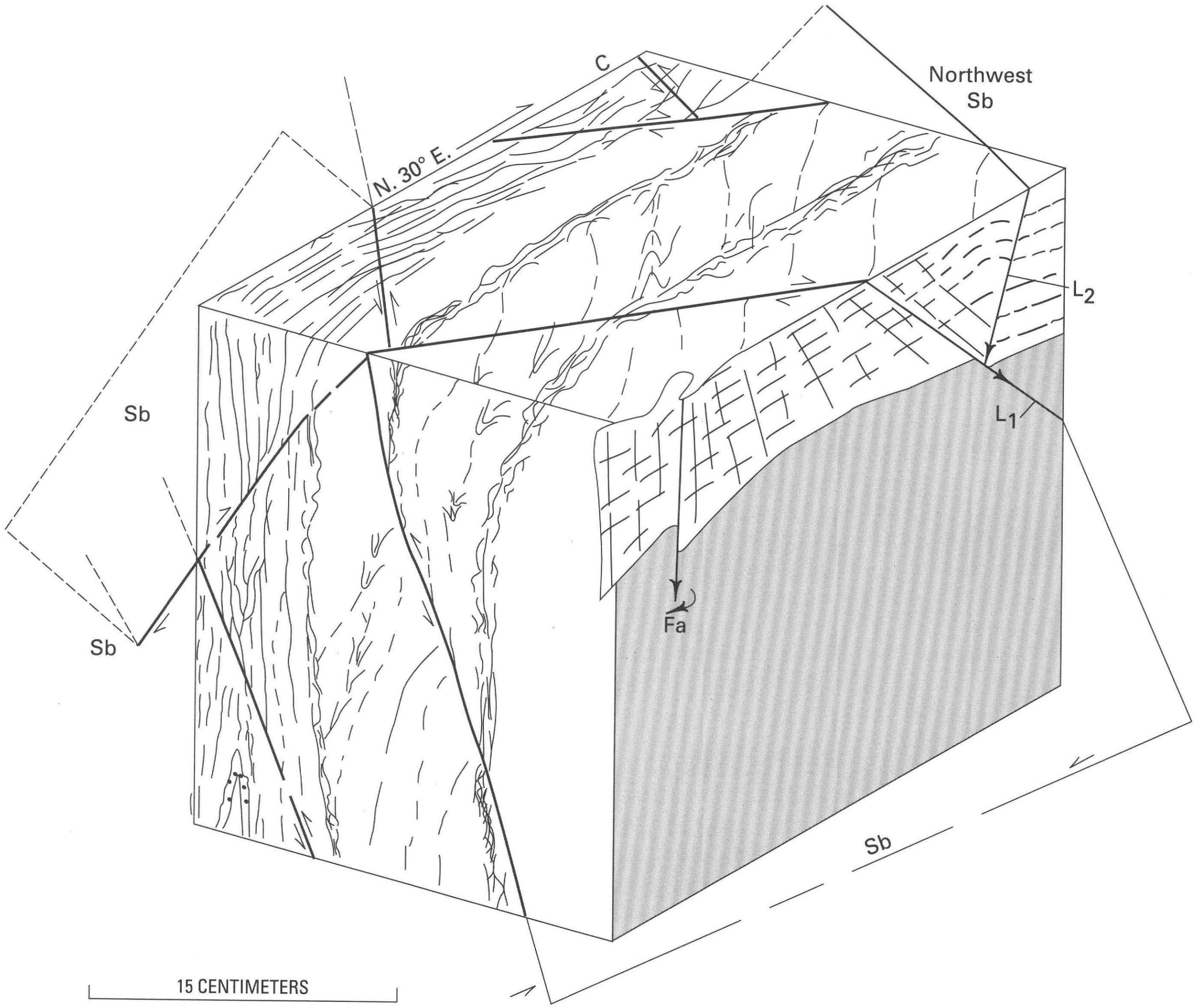



**Figure 15.** Structural elements in the central phyllonite zone in the Canada Hill Granite displayed in a roadcut on the northern side of Route 301, 1.4 km east of Fahnestock Corners. Fa, fold axis; C, mylonitic foliation; Sb, shear band; $L_1$ and $L_2$, lineations produced by intersection of two sets of shear bands that have mylonitic foliation. Arrows indicate direction of relative movement along fault.

illustrate the north-to-northwest S planes and the dominant shear surfaces (C). A prominent lineation ($L_1$) is formed by the intersection of a vertical surface with the dominant mylonite fabric.

Petrographic analysis of the central 3-cm-thick phyllonite zone shows the following structural and mineralogic features as illustrated in figures 15 to 17:

- Mylonitic foliation (C).—A strongly developed mylonitic foliation, which consists of an ultrafine-grained muscovite aggregate, strikes N. 30° E. and dips steeply to the southeast and the northwest. In thin section, this foliation is seen to consist of approximately 80 percent muscovite, framboids of quartz, and minor granules of epidote.
- Schistosity (S).—Sigmoidal zones of foliated phyllite are bounded by the mylonitic zones. Minor folds that have northwest-trending (N. 8° W.) axial surface foliation mark this schistosity. Where the schistosity intersects the mylonitic foliation in horizontal and vertical section, the schistosity is tangential to the mylonite zones.
- Shear bands.—Discrete, sharply defined shear bands consist of brittle fractures in plagioclase or right-lateral, ductile- bending crosscut S and C fabrics. In vertical

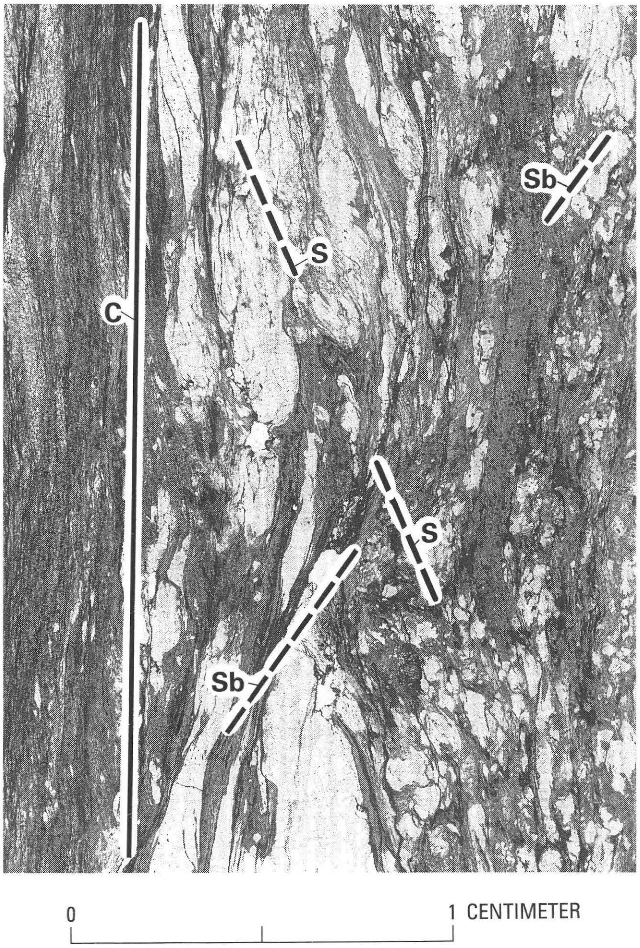



**Figure 16.** Central phyllonite zone depicted on the left side of figure 15. This horizontal section has an N. 30° E.-striking prominent mylonitic fabric (C) of muscovite-rich phyllonite at left. Shear bands (Sb) strike N. 50° E. Minor folds and intrafolial schistosity (S) strike N. 8° W. See text (p. 26) for description of features. Plane-polarized light.

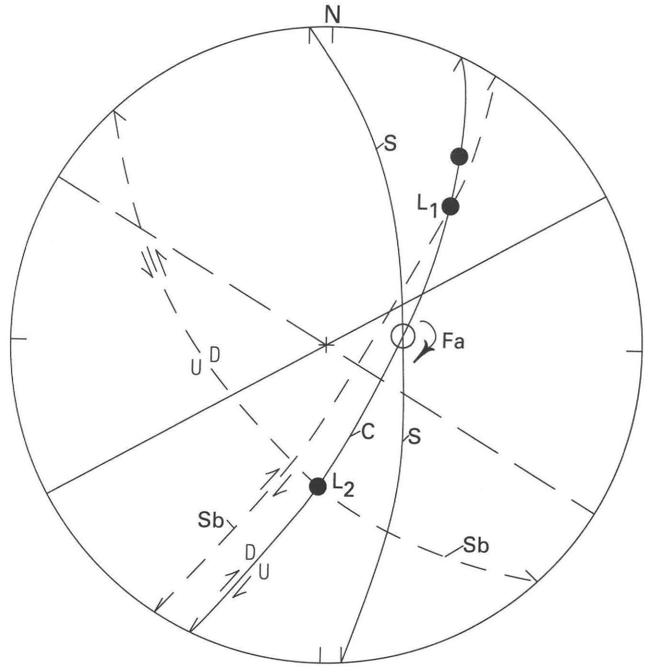



**Figure 17.** Structural elements in the central phyllonite zone illustrated in figure 15. S, schistosity; C, mylonitic foliation; Sb, shear bands; Fa, fold axis; arrows show relative horizontal motion; U and D, up and down relative motion; $L_1$ and $L_2$, lineations produced by intersection of two sets of shear bands having mylonitic foliation. Two vertical planes are brittle fractures.

section, the northeast-trending shear bands dip steeply southeast and show an up-from-the-southeast sense of displacement. A second set of shear bands strikes N. 50° W. and dips southwest showing left-lateral and an up-from-the-southwest sense of displacement of C and S.

- Minor folds.—Minor folds in schistosity show right-lateral displacement and plunge steeply down the southeast-dipping fabric.
- Shear-band, crenulation, intersection lineation.—Where the northeast-trending shear bands intersect C or S, a weakly defined lineation ($L_1$) plunges to the northeast. Where the northwest-trending, southwest-dipping shear bands or fractures cut C or S, the resulting $L_2$ lineation plunges to the southwest.
- Subvertical brittle fractures.—These fractures trend N. 60° E. and N. 60° W. (not illustrated in fig. 17).

The fabric and the petrographic data are consistent with the mineralogy and the structures that formed in a single event and that resulted from northeast-southwest compression and right-oblique faulting. The minor structures seen in this outcrop represent structures that are similar to those seen in higher grade fault zones to the east. The photomicrograph in figure 16 shows mylonitic and ductile structures in the central mylonite zone that was pictured in figure 15.

Spaced foliation and mylonitization in ductile deformation zones increase in frequency and intensity to the southeast, which is concomitant with the increase in the regional grade of Paleozoic metamorphism from lower greenschist facies to amphibolite facies in the southwestern and the eastern portions of the map (pl. 1). Many of the shear zones shown on the map are extensions of those mapped in the Poughquag quadrangle to the northeast (Ratcliffe and Burton, 1991, fig. 2); those shear zone names are retained here.

In the eastern part of the map (pl. 1) parallel to the Peekskill Hollow fault and southeast of it, all rocks contain a penetrative foliation that is subparallel to the major faults. Transposition of Proterozoic gneissic layering into Paleozoic foliation is common, and the gneisses are either strongly tectonically banded rocks or flat, which is characteristic of zones of high strain.

Mineral lineation and an elongation-shape (smear) lineation are developed in all mylonites and phyllonites. C and S mylonite fabrics, minor fault effects, shear banding, and ductile deformation indicate that the steeply dipping shear zones are oblique-thrust faults that have a slip direction of about N. 70° E. (Ratcliffe and others, 1985).

The most notable feature of the Paleozoic deformation in the Proterozoic gneissic rocks is the concentration of the strain along relatively narrow zones that have broad areas between ductile deformation zones, which are unaffected by penetrative Paleozoic deformation. This relation is well illustrated by the lack of deformation of the Late Proterozoic dikes except along the mapped ductile deformation zones.

## East Canopus and Other Faults

The East Canopus fault extends northeastward into the Hopewell Junction quadrangle where it makes a prominent bench at the elevation of 750 ft on the west-facing slopes of Hosner Mountain. A zone of retrograded biotite granite gneiss that contains pink potassium-feldspar rods occurs just above the bench. The base of the slope is marked by a 5-m-wide zone of greenish-gray phyllonite and low-grade mylonite that dips 47° to the southeast. Abundant minor folds, sheath folds, and mullions obliquely plunge northeast and east down the surface of the mylonite, N. 17° E., which strikes and dips to the southeast. Minor folds that have amplitudes of 1 to 2 mm and that have various senses of rotation are found on the darker and finer grained zones of mylonite. A slip line, which was determined from measurements of asymmetrical minor folds, yields a separation arc of 19° about N. 85° E. (fig. 18). The strong lineation, which is expressed by fine groovelike lines and by smears or rods of felsic material, plunges N. 75° to 80° E.

Thin sections cut parallel to this lineation show strongly asymmetric fabrics, which indicate an up-from-the-northeast sense of motion (fig. 19). Large, fish-scalelike, shimmer aggregates of muscovite form right-sigmoidal clots up to 6 mm long that are bounded by the mylonitic foliation (C). Fine-grained (0.02-mm) quartz forms elongated subgrains intergrown with chlorite and muscovite to form a strongly banded mylonitic layering 0.5 mm thick. Alternating light and dark layers result from varying proportions of muscovite and relict biotite. Isolated rounded to ellipsoidal porphyroclasts of plagioclase are spaced throughout the rock. Ellipsoidal grains are oriented at various angles to the foliation. No fragments of potassium-feldspar from the original rock remain. Tiny granules of epidote and sphene form trails in the mylonitic paste. Locally, 25° to 30° southeast-dipping shear bands that have an up-from-the-east sense of motion offset the mylonitic fabric. Steeply dipping, 3-mm-wide extension

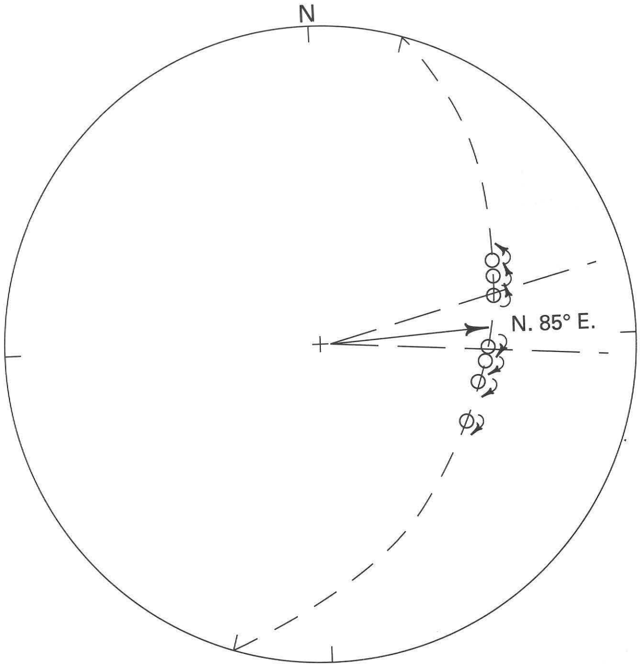



**Figure 18.** Plunge of minor folds (open circles) in the mylonite zone in the East Canopus fault along the western slopes of Hosner Mountain in the Hopewell Junction quadrangle. Small arrows show the rotation sense of folds used for the slip line determination. Separation arc, 19°; slip line direction, N. 85° E. Lower hemispheric projection.

veins cut some of the more felsic mylonitic layers and dip 70° to 80° in blocks between shear bands. Small brown plates of stilpnomelane that have their (001) cleavage oriented subparallel to the mylonitic fabric outside the cracks have grown across the veins. Evidence of multiple growth stages is seen. These fractures appear to have formed as internal accommodation veins in response to simple shear on right-lateral bounding shears. Deformed veins, which are found chiefly in the more micaceous mylonite layers, have right-sigmoidal forms within later deformation zones. Undeformed veins are approximately normal to the extension direction. Chlorite-rich pressure shadows are developed on the larger porphyroclasts. The fabrics, the textures, and the mineralogy indicate that the mylonite zone marking the East Canopus fault at Hosner Mountain is a right-oblique thrust fault developed during low-grade muscovite-chlorite-albite-quartz subfacies conditions.

Paleozoic deformation along the Dicktown fault is especially intense in the zone of consolidated motion that extends northeast from the Taconic State Parkway. Black to dull-greenish-gray bands of biotite-rich mylonite that are up to 2 m thick crosscut the quartzofeldspathic gneiss. Where deformation zones affect garnet-bearing leucogneiss (Ygt), an elongated sheath of biotite forms around the garnet in the prominent lineation. Abundant textural data from oriented

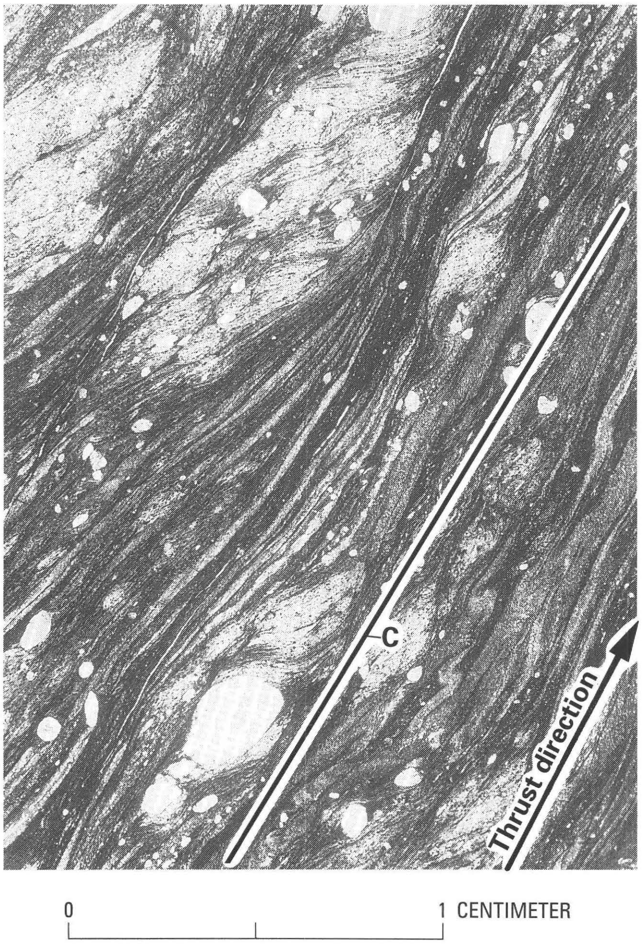



**Figure 19.** Mylonitic hornblende granite gneiss from Hosner Mountain along the East Canopus fault 0.5 km north of the quadrangle boundary at the slip line locality referred to in figure 18. The section is cut parallel to slip line direction and normal to the mylonitic fabric (C), which dips to the northeast. See text (p. 28) for discussion of features. Plane-polarized light.

thin sections show that biotite, actinolite (locally), epidote, and muscovite grew syntectonically in the shear zones. Fabrics indicate a right-lateral, high-angle, up-from-the-northeast sense of motion on specimens cut parallel to the prominent east-plunging lineation. The dip of the sheared zone passes through the vertical; locally, it dips 80° to the northwest. At these localities, oriented thin sections show a distinct right-lateral, up-from-the-southwest, sense of motion. The variation from an up-from-the-northeast sense of motion on southeast-dipping segments to an up-from-the-west-southwest sense of motion on northwest-dipping segments indicates that the fabrics within the zones are composite but have consistent and proper senses of motion for primary attitudes rather than folded faults. This geometry is consistent with the anastomosing pattern of the shear zones seen in vertical section in the field. In all cases, right-lateral deformation dominates in horizontally cut thin sections.

The California Hill fault and ancillary splays dip steeply northwest, vertically, and steeply southeast. Splay faults in the north show minor displacement of Proterozoic strata and Late Proterozoic dikes. Textural data and analysis of thin sections support right-lateral deformation. The belt of Proterozoic rocks between the California Hill fault and the Peekskill Hollow fault system is strongly deformed and has intense Proterozoic mylonitic fabric. Throughout this zone, thin and larger masses of pegmatites intrude blastomylonitic zones in the gneiss, and dikes of granite are intruded parallel to the limbs of tight folds. Intense deformation of Middle Proterozoic age has affected the eastern limb of the clockwise-deformed zone near the Wiccopee pluton. Zones of blastomylonite expressed by seams of coarse biotite and parallel stringers of granite mark these features. Locally, these same zones have been reactivated as Paleozoic shear zones.

Syntectonic minerals from retrograde (Paleozoic) deformational zones along the California Hill fault include biotite, which replaces garnet, muscovite; epidote; and actinolite. Green hornblende has grown syntectonically at one locality near the northern edge of the map (pl.1). Biotite and plagioclase have grown within blastomylonitic rocks associated with the California Hill fault, and the minerals are markedly coarser grained and have better forms than in zones to the west. Coarse-grained lepidoblastic biotite (fig. 20) from the California Hill fault zone on California Hill yielded an $^{40}Ar/^{39}Ar$ plateau age of 436±3 Ma (John Sutter, USGS, written commun., 1985).

A complex anastomosing fault zone extends along Peekskill Hollow north to Boyd Corners Reservoir. Closely spaced mylonite zones expressed by biotite, muscovite, and recrystallized feldspar and quartz are present on slopes east and west of Peekskill Hollow. Infolded and faulted slivers of the Poughquag Quartzite are present. In addition, coarse-grained, magnetite-bearing granite and pegmatite crosscut or intrude other Proterozoic faults northeast of Tomkins Corners.

Intense folding accompanies shearing in zones that extend up to 100 m from fault traces. Within these ductilely deformed zones, complex recrystallization of biotite, plagioclase, and quartz and growth of sprays of new postdeformational hornblende are common. Along the northeastern side of Boyd Corners Reservoir, excellent exposures in hornblende-plagioclase gniess (Ywh) exhibit these folds and minor thrust faults along the lower limbs of stacked asymmetrical folds (figs. 21, 22).

The Poughquag Quartzite on the slopes south of Kent Cliffs is not sheared near its northern termination and, although the exposures are poor, appears to rest unconformably on gneiss. To the southwest, the southeastern and the southwestern margins of the Poughquag are faulted and intensely mylonitic. The amount of displacement on the


**Figure 20.** Biotite-rich mylonite from the California Hill fault. This is a horizontal section; northeast is at top. Large oligoclase porphyroblasts are set in matrix of biotite, muscovite, and dynamically recrystallized quartz and oligoclase. Biotite from this rock yielded an $^{40}Ar/^{39}Ar$ biotite plateau age of 436±3 Ma (John Sutter, USGS, written commun., 1985). Plane-polarized light.

Peekskill Hollow fault is uncertain. Carbonate rocks of the Wappinger Group possibly extend into the quadrangle from the south, but no outcrops or well data are known to support this interpretation.

Paleozoic deformation is much greater east of the Peekskill Hollow fault. Narrow zones of biotite-rich mylonite and mylonite gneiss are spaced every 10 to 15 m in exposures on Bryant Hill along the Taconic Parkway. These zones dip southeast at 60° to 80°, commonly are strongly lineated, and are associated with tight folds. Deformation zones like those seen in the Bryant Hill roadcuts must penetrate all rocks on Bryant Hill and zones to the east, but exposures are very limited, and shear zones could not be mapped except where large exposures exist.

Coarse-grained, brown biotite; muscovite; and recrystallized, broadly twinned plagioclase are crystallized in shear zones. Plagioclase contains opaque dust but lacks epidote; this suggests that the albite-epidote-sericite replacement textures seen in plagioclase to the west are replaced by thoroughly recrystallized, new (Paleozoic), prograde plagioclase. Ribbon quartz and phacoidal feldspars are entirely recrystallized. Metamorphic grade is hard to judge, but assemblages that are present in aluminous cover rocks to the southwest and in retrograded Proterozoic rocks of aluminous composition to the northeast indicate that rocks east of the Peekskill Hollow fault range in grade from upper garnet zone to staurolite kyanite.

## Mesozoic Structures

Mesozoic normal faults are well developed outside the quadrangle to the south and the southwest, where the northern end of the Newark basin and Mesozoic rocks are exposed. The major border faults of the Newark basin, the Ramapo and the Thiells faults (Ratcliffe, 1971), strike into the Canopus fault zone. Mesozoic faults commonly strike N. 25° to 50° E. and dip steeply southeast or northwest. Movement on the faults is almost always oblique slip, such that a component of right-normal slip is present on southeast-dipping surfaces and that left-normal slip is present on northwest-dipping surfaces. Brittle fractures associated with Mesozoic faulting have been mapped throughout the Reading Prong from Pennsylvania to the Poughquag quadrangle (Ratcliffe, 1980, fig. 1). Prominent zones of Mesozoic faulting are identified in Ratcliffe and Burton (1991, fig. 2).

Gouge zones, greenish or gray zones of microbreccia, silicified zones, and hematite-calcite-chlorite-zeolite-coated joints are common near Mesozoic faults. The increase in fracture density generally is a good indication of proximity to such a fault.

Within this quadrangle, distinct faults of Mesozoic age are not mappable. A drill core from the Canopus fault zone 2 km south of the quadrangle boundary near Annsville, N.Y., contains prominent zones of brittle reactivation of the Canopus phyllonite zone at depths of 580–700 ft below the surface. Exposures of the Canopus fault in the Peekskill quadrangle show right-oblique normal fault reactivation of the contact between the Annsville Phyllite of Lowe (1947) and mylonite of the Canopus fault. These data suggest that Mesozoic faulting also extends northeastward along this zone into the Oscawana Lake quadrangle. Although isolated outcrops along the Canopus zone in this quadrangle locally show features characteristic of Mesozoic faulting, continuous zones could not be mapped, and only the brittle fracture data are shown on the map (pl. 1).

Locally, brittle fractures coincide with older faults in the northwestern corner of the Oscawana Lake quadrangle and with the walls of some of the Late Proterozoic dikes. Isolated brittle faults that have minor displacement are present in the California Hill area and in the area extending north to the Dicktown fault. Although brittle faults tend to

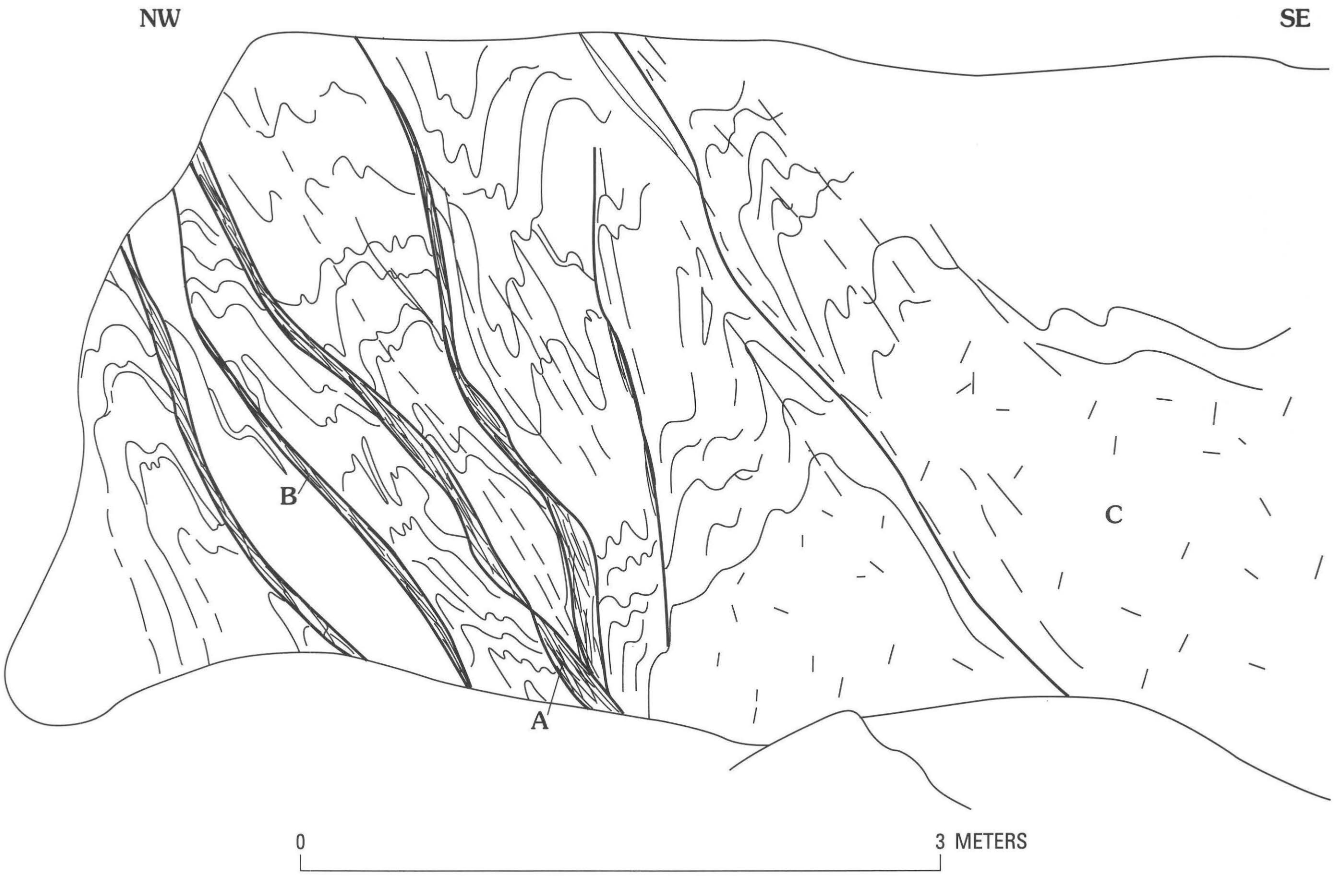



**Figure 21.** Stacked fold-thrust folds and ductile shear zones in Ywh on the north shore of Boyd Corners Reservoir showing characteristic Paleozoic deformation along or near the Peekskill Hollow fault. A, B, and C refer to samples used for the $^{40}Ar/^{39}Ar$ studies on hornblende and biotite (John Sutter, USGS , written commun., 1985) discussed in text (p. 33). A and B are fine-grained shear zone rocks that consist of recrystallized biotite, hornblende, plagioclase, and epidote. C, is a equigranular hornblende-biotite plagioclase gneiss that has the relict Middle Proterozoic hornblende habit illustrated in figure 11.

follow the grain of the older faults, such reactivated faults are hard to recognize in areas of poor exposures and without fresh roadcuts.

Clearly, any major Mesozoic fault at an angle to the prominent metamorphic structures can be ruled out by the map data (pl. 1). Conversely, significant Mesozoic movement along the older faults *cannot* be ruled out and indeed is likely. Excellent exposures in a roadcut along Route 301 in the Lake Carmel quadrangle 300 m east of the map area (pl. 1) contain biotite-rich mylonitic zones that show reactivation as normal faults (fig. 23). Although significant reactivation of old faults cannot be proven throughout the area, it can be shown that reactivation has occurred locally.

## METAMORPHISM AND GEOCHRONOLOGY

Basement rocks of the Oscawana Lake quadrangle contain relict mineral assemblages indicative of hornblende-granulite-facies metamorphism. West of the Dennytown fault, Middle Proterozoic minerals including sillimanite; brown hornblende; titanium-rich, red-brown biotite; clinopyroxene; microcline perthite; and antiperthite are locally present. Quartzofeldspathic rocks contain garnet and perthite. Calcium silicate rocks contain augite, hornblende, and, locally, chondrodite. These and other minerals formed during a series of poorly understood events that coincided with the formation of the $YF_1$, $YF_2$, and $YF_3$ structures. U-Pb zircon ages (Grauch and Aleinikoff, 1985; Aleinikoff and Grauch, 1990) indicate that regional metamorphism, plutonism, and final pegmatite formation in the $YF_1$ to $YF_3$ events spanned a time period from 1.15 to 0.96 Ga. On the basis of textural evidence cited herein, hornblende-granulite-facies assemblages (Dallmeyer, 1972a,b, 1974) appear to have reached maximum temperature and pressure conditions before the formation of the Canada Hill Granite, which is dated at approximately 1.01 Ga according to U-Pb zircon studies (Aleinikoff and Grauch, 1990). Reports of a much older granulite-facies metamorphism that affected paragneiss units at 1.23 Ga (Grauch and Aleinikoff, 1985)

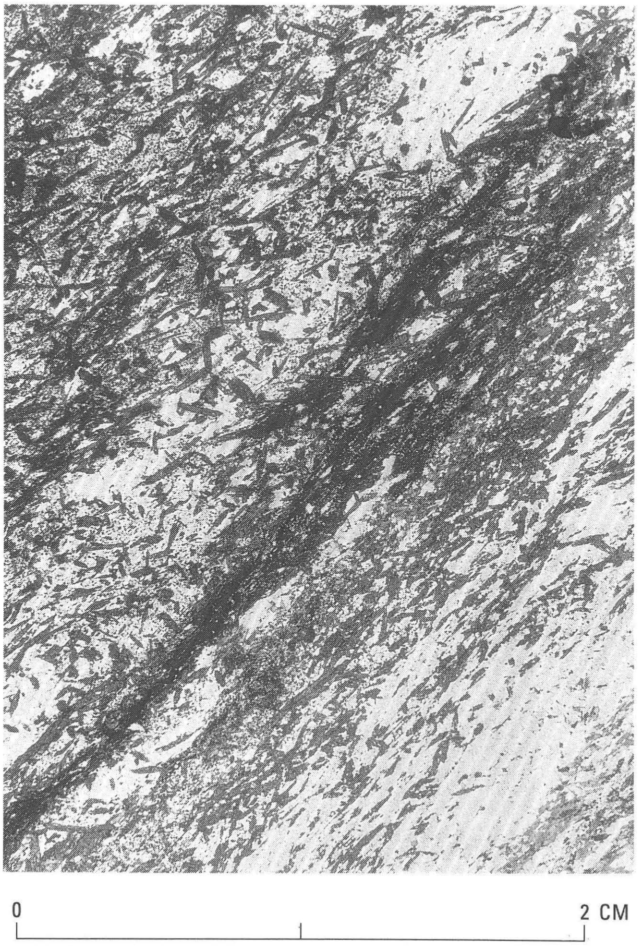



**Figure 22.** Mylonitically banded shear zone rock on the limb of a fold at locality A in figure 21. This is a vertical section cut parallel to a northeast-plunging extension lineation and normal to foliation. Lepidoblastic muscovite, biotite, and hornblende define darker layers. Prismatic-green hornblende has grown oriented in the mylonitic layering, as well as across it. Plane-polarized light.

are now discounted on the basis of recognition of detrital cores in zircons from the paragneiss with inheritance of U-Pb from source rocks formed at least by 1.46 Ga (Aleinikoff and Grauch, 1990). Formation of the Canada Hill Granite by partial melting of aluminous paragneiss appears to reflect a high-heat-flow event at 1,010 Ma, approximately 120 m.y. later than the intrusion of the Storm King Granite at about 1,130 Ma (Aleinikoff and Grauch, 1990).

High-grade hornblende-granulite facies metamorphism predated intrusion of the Canada Hill Granite and the Canopus pluton and ferrodiorite-to-ferromonzonite-associated dikes [probably (Ynd) of this report] dated at 1,020 Ma on the basis of U-Pb zircon ages from the Canopus pluton (John Aleinikoff, USGS, written commun., 1989). Metamorphic zircon from amphibolite in the Peekskill quadrangle appears to have crystallized at 1,090 Ma (Grauch and Aleinikoff, 1985), which is consistent with the assignment of $YF_2$ to a pre-Canopus event (Ratcliffe and others, 1972).

Few estimates of the peak temperature and pressure conditions that developed during Proterozoic metamorphism in the basement rocks of the Hudson Highlands exist; more importantly, of these, none can be specifically assigned to any stage of $YF_1$, $YF_2$, or $YF_3$ deformation. On the basis of the textural evidence that $YF_2$ structures are expressed by hornblende and sillimanite lineations, nearly complete transposition of older structures, and migmatitic structures, the preserved mineral assemblages are probably no older than the $YF_2$ event. However, the long history of granite plutonism and intrusion of late granite pegmatite in post-$YF_3$ time suggests that relations should be interpreted with caution.

Dallmeyer and Dodd (1971) reported the coexistence of cordierite and garnet in biotite-quartz-sillimanite paragneiss from the Popolopen Lake and the Monroe quadrangles. Their data suggest that metamorphic temperatures of 700 to 750 °C and pressures of 3.0 to 5.5 kilobars corresponded to a lithotectonic load of only 15 km at the time of equilibration. Labotka (1982) reported microprobe analyses of ferromagnesian phases in quartz-plagioclase gneiss, calc-silicate granofels, and biotite, two-feldspar gneisses on Iona Island in the Peekskill quadrangle. Titanium-rich biotite, pargasite to potassium hastingsite, augite (Fe:Mg equals from 0.3 to 0.7), orthopyroxene, and complexly variable garnet compositions are present in the gneisses. Fe-Mg partitioning between garnets and biotite suggests temperatures of between 682 and 825 °C (Labotka, 1982).

Final equilibration of the U-Pb systems in monazite and xenotime from about 946 to 950 Ma and late pegmatites that intruded at about 965 Ma mark the last phases of activity in the Middle Proterozoic (Grauch and Aleinikoff, 1985; Aleinikoff and Grauch, 1990). $^{40}Ar/^{39}Ar$ closure ages for biotite and hornblende in the northern Reading Prong of from 780 to 800 Ma and 940 Ma, respectively, mark the passage of these minerals through their retention temperatures of 350 and 550 °C following Middle Proterozoic metamorphism (Dallmeyer and Sutter, 1976).

East of the Dennytown fault system, Paleozoic retrogression of Middle Proterozoic assemblages is extensive. From this point eastward, calcic plagioclase is retrograded to a mixture of epidote, albite, and sericite; pyroxene and (or) hornblende are fringed or replaced by actinolite, and complex veining by epidote and salmon-colored potassium-feldspar is common. Proterozoic garnet is retrograded to iron-rich chlorite or is overgrown with biotite. Alteration is spatially associated with sheared zones where $2M_1$-polytype muscovite, quartz, and epidote form finely foliated phyllonite. Reequilibration of low-temperature assemblages in sheared zones and ductile faults gives rise to prograde assemblages that increase to staurolite-kyanite grade in the southeastern part of the map area (pl. 1). Locally, biotite, hornblende, garnet, and muscovite have grown syntectonically in the California Hill fault and in higher grade shear zones to the southeast. Outside the quadrangle, Ratcliffe and others (1985) documented staurolite-kyanite and sillimanite plus muscovite from shear zones in the Lake Carmel quadrangle.

Long and Kulp (1962) reported seven K-Ar biotite ages from the Oscawana Lake quadrangle (pl. 1). These biotite ages unsystematically range from 810 to 390 Ma. Generally, Paleozoic age values were obtained for rocks from the southeastern part of the mapped area, whereas other samples in or near shear zones yielded highly variable results. Long and Kulp's sample L–437, which was taken from mylonitic biotite-quartz-plagioclase gneiss (Ybg) in the Dennytown fault, yielded an apparent age of 425 Ma. A photomicrograph (fig. 24) of this rock shows highly shredded biotite in a ductilely deformed phyllonitic matrix.

Three $^{40}Ar/^{39}Ar$ ages reported by Dallmeyer and Sutter (1976) are available for the Oscawana Lake area. Their sample site 8, which is located in the Indian Lake shear zone, yielded a disturbed Ar release spectrum characteristic of an altered but nonequilibrated biotite. Their sample 10 of hornblende-biotite-plagioclase gneiss (Ywh) from the Wiccopee pluton yielded a hornblende plateau age of 913 Ma and a slightly disturbed biotite spectrum that has a plateau age of 710 Ma. These data are interpretable as cooling ages from Middle Proterozoic events. Their locality 10 contains excellent $YF_2$ structures and a coarse hornblende lineation parallel to fold hinges of reclined $YF_2$ folds. This area between the Dicktown and the California Hill faults preserves Middle Proterozoic fabric, minerals, and structure.

Coarse lepidoblastic crystals of biotite, which were collected from the California Hill fault (fig. 20), are intergrown with plagioclase in the mylonitic fabric of the fault. An $^{40}Ar/^{39}Ar$ plateau age of 436 Ma is best interpreted as a cooling age and, therefore, a minimum age for mylonite formation (John Sutter, USGS, written commun., 1983). Biotite from a ductile shear zone in the hornblende-plagioclase diorite gneiss (Ywh) on the northern shore of Boyd Corners Reservoir yields a total gas age of 426 Ma (John Sutter, USGS, written commun., 1983); a sketch of the deformation zones sampled is shown in figure 21. Fine needles of hornblende (fig. 22) overgrow the shear-zone fabric in these rocks, whereas hornblende outside the shear zones contains chunky cores. Hornblende from this outcrop produced a disturbed $^{40}Ar/^{39}Ar$ release spectrum that is characteristic of partially altered Proterozoic hornblende. The acicular hornblende is difficult to purify, and $^{40}Ar/^{39}Ar$ studies have not been conducted on this material. Because the hornblende has formed in the shear zones and this marks its first occurrence in shear zones, an $^{40}Ar/^{39}Ar$ age might be expected to closely approximate the time of formation. On the basis of the information now available, the mylonitic zones that were mapped within the Oscawana Lake quadrangle are 436 Ma or older and thus are Taconian (Ratcliffe and others, 1985).

## EARTHQUAKES AND GEOLOGIC STRUCTURE

The Oscawana Lake area lies along the northeast-trending tectonic grain of the Ramapo and ancestral fault systems (Ratcliffe, 1971). Low-magnitude earthquakes have been detected in this area by a seismograph network, which has been operated since 1973 by the Lamont-Doherty Geological Observatory (Palisades, N.Y.) and more recently by Woodward-Clyde Consultants (Woodbridge, N.J.). In general, recorded seismic activity occurs in a band approximately 40 km wide and approximately centered over the Ramapo fault (Yang and Aggarwal, 1981; Kafka and others, 1985). Another belt of seismicity is located to the east of this band and extends southwest from New York City into north-central New Jersey. The largest instrumentally detected events in the New York City area [Love wave magnitudes ($m_{bLg}$) of 3.9, 4.0, and 3.7] occurred as a swarm during a 4-h period on August 23, 1938, that was centered in New Jersey 5.0 km south of New York City and one $m_{bLg}$ = 3.8 event occurred about 50 km north of New York City on the same day. The center of the error ellipse for this single event is roughly positioned in the Oscawana Lake area (Dewey and Gordon, 1984; Kafka and others, 1985, fig. 5).

One well-located $m_{bLg}$ = 2.1 event (Kafka and others, 1985, table 2) occurred in the Oscawana Lake quadrangle on June 19, 1975, at a depth of approximately $3\pm1.3$ km. The epicenter (pl. 1) is coincident with the California Hill fault. However, because the California Hill and other nearby faults are steeply dipping, the earthquake could have occurred on any one of them. No fault-plane solution is available for this event, but it lies in the same belt as the Whaley Lake event in the Poughquag quadrangle, which could have occurred on one of the steep faults in the Poughquag quadrangle (Ratcliffe and Burton, 1991).

The Oscawana Lake event is located on a northeast-southwest trend that connects the Whaley Lake event with a zone of abundant activity near Annsville, N.Y., and with activity to the southwest along the Ramapo fault (Kafka and others, 1985, fig. 8). Analysis of recent seismic activity at Annsville and Verplank, N.Y., areas 20 and 25 km, respectively, southwest of the Oscawana Lake event, has produced data that suggest faulting in both areas at depths of 5–10 km is taking place on the northwest-striking fault rather than on the northeast-striking fault (Seborowski and others, 1982; Quittmeyer and others, 1985). These results contradict earlier fault-plane solutions of Aggarwal and Sykes (1978) and Yang and Aggarwal (1981), which indicated thrust faulting on northeast-trending faults in the Ramapo seismic zone.

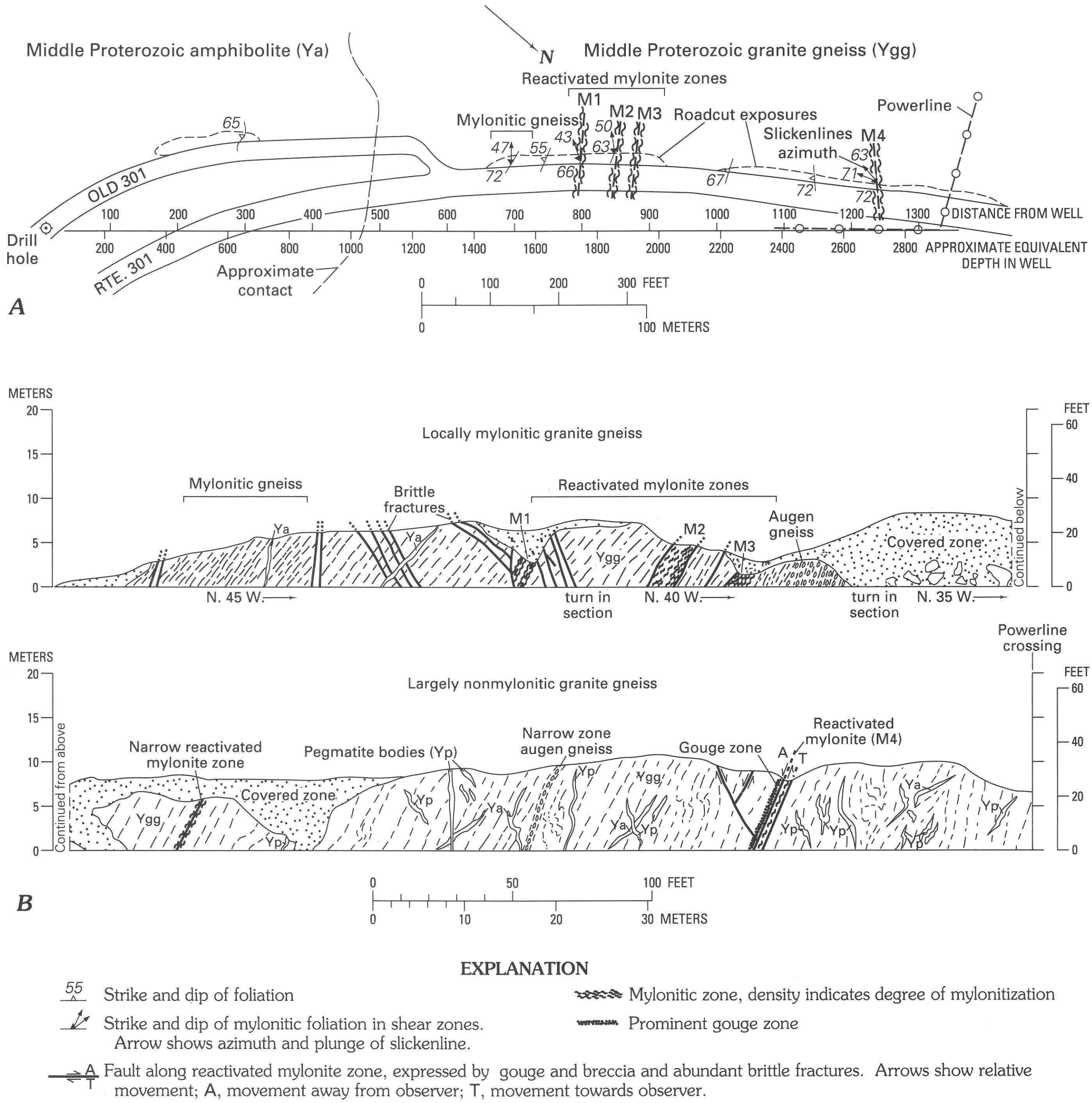



**Figure 23.** Faults in the Lake Carmel quadrangle area. *A*, Road cuts in the Reservoir Gneiss along Route 301 east of the drill site. Four mylonitic zones, labeled M1 through M4, show reactivation of Paleozoic shear zones as brittle faults of probable Mesozoic age. *B*, Enlarged cross section of the road cuts shown in *A*. From Ratcliffe and others (1985). *C*, Well log of the drill hole used for hydrofracture and borehole breakout studies of the stress field.

A 1-km-deep corehole located on Route 301, 300 m southeast of the Oscawana Lake quadrangle border, was used for hydrofracture experiments in 1984 (fig. 23). On the basis of the results of the in situ hydrofracture and borehole-breakout studies, the principal horizontal compressive stress is oriented approximately N. 55° E. (Zoback and others, 1985). These data appear to confirm the interpretation of Quittmeyer and others (1985) in support of a northeast-southwest compressive stress field. If this interpretation is correct, then northeast-striking faults, such as the major faults in the Oscawana Lake quadrangle, could be reactivated as strike-slip faults rather than as thrust faults.

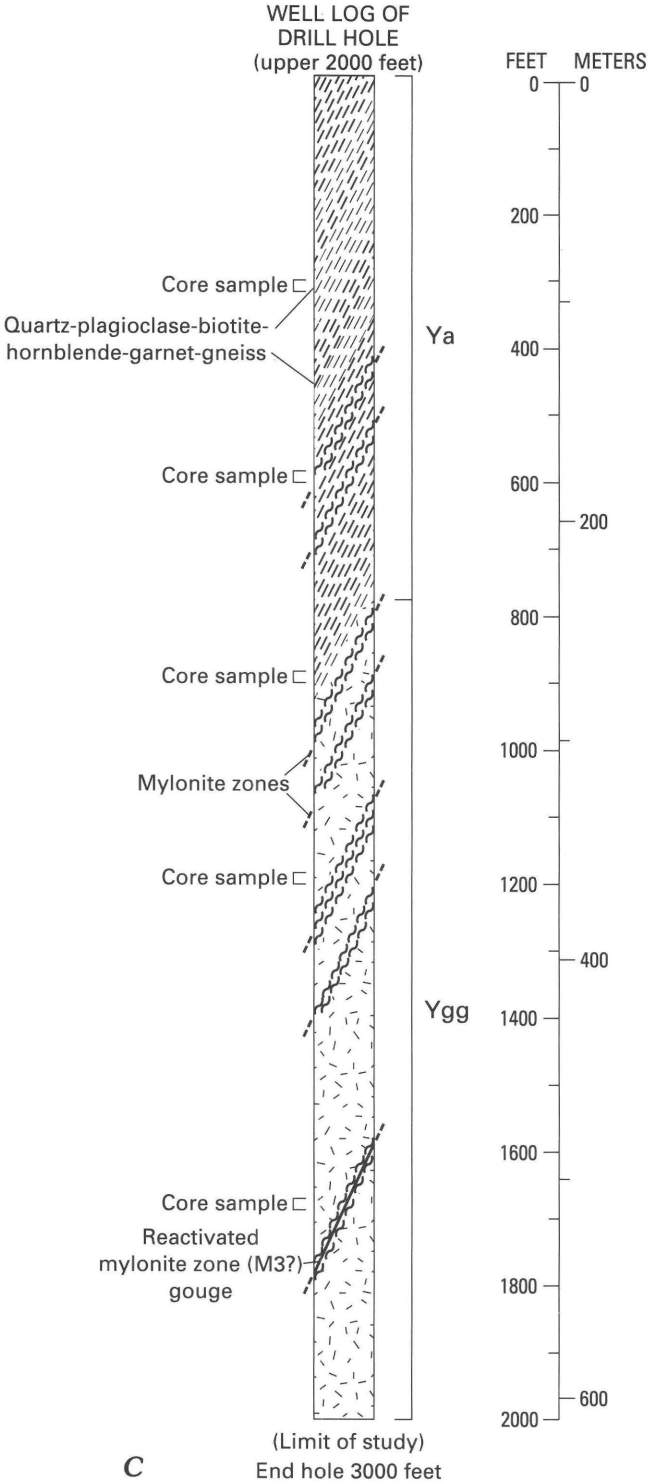



**Figure 23.** Continued.

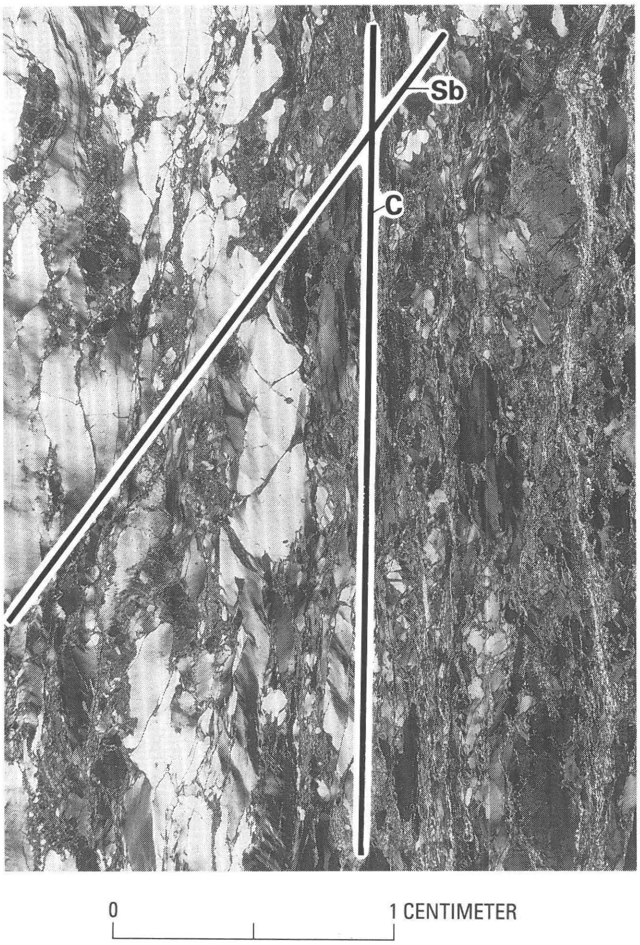



**Figure 24.** Phyllonitic biotite-quartz-plagioclase leucogneiss (Ybqp) near the Dennytown fault 1 km southeast of Fahnestock Corners near the K-Ar biotite sample site of Long and Kulp (1962). This is a horizontal section (map view). Strike of prominent mylonitic fabric (C) is N. 20° E., and shear bands (Sb) are oriented more to the northeast. The fine-grained matrix consists of sericite and epidote; ribbon quartz and chlorite-rich tails on shredded biotite define the mylonitic foliation. Crossed nichols.

Another possibility is that new, unrecognized faults, which would trend northwest and dip moderately northeast or southwest, are responsible for the earthquakes.

Careful examination of glacially polished and striated pavement exposures in the Oscawana Lake area and the Hudson Highlands as a whole uncovered no examples of faulted Pleistocene bedrock pavement. Such features may represent evidence of post-Pleistocene faulting at the Earth's surface and thus possibly evidence for paleoearthquakes. Numerous examples of offset glacial pavement were discovered in the slates of the Hudson River Valley in the Hopewell Junction quadrangle to the north. After studying all known faulted Pleistocene pavement exposures in the Hudson River Valley, Ratcliffe (1982) concluded that these faulted exposures, which are commonly attributed to tectonic faulting (Oliver and others, 1970), are more readily explained by ice wedging that acted on irregular structural features in the slates. These features include crenulated foliation and acutely intersecting slip cleavage and foliation. Because the deformation structures suitable for frost wedging are localized near brittle faults, there is only an apparent association of young faults and the supposed post-Pleistocene faults. Present-day seismicity in the Ramapo area and on the Hudson Highlands is not readily attributed to movement on major northeast-striking faults.

## SUMMARY AND CONCLUSIONS

Middle Proterozoic bedrock units of the Hudson Highlands east of the Hudson River in the vicinity of the Oscawana Lake quadrangle closely resemble similar units in the Hudson Highlands near West Point, N.Y., previously mapped by Dodd (1965), Helenek (1971), and Helenek and Mose (1984). Within the Oscawana Lake quadrangle, rocks east of the Canopus fault have abundant intrusive biotite granite gneiss and migmatitic gneiss of the Reservoir Gneiss rock type that are largely absent to the west.

The presumed lower parts of the stratigraphic section, the biotite-quartz-oligoclase gneiss (Ycl) and the biotite-quartz-plagioclase leucogneiss (Ybqp), closely resemble similar rocks in the central Hudson Highlands and of the Losee Metamorphic Suite of the Reading Prong (Drake, 1984). Minor mafic plutonic rocks (Ywp, Ywh, Ywu, Ywd) of the Wiccopee pluton, certain amphibolitic gneisses (Ya), and the garnet-rich leucogneiss (Ygt) enclaves in the Reservoir Gneiss within the older sequence may collectively represent a calc-alkaline volcanic and volcanoclastic sequence that contains hypabyssal plutonic rocks.This metavolcanic sequence is overlain by a fairly persistent paragneiss sequence that generally consists of rusty sillimanitic paragneiss, magnetite quartzite, calcium silicate granofels and marble, hornblende pyroxene gneiss, epidotitic quartzite, and well-layered, garnetiferous, biotitic, two-feldspar and biotite-quartz-plagioclase gneisses.

Felsic intrusive rocks and migmatite intruded or formed in place throughout the sequence. The oldest granites, a hornblende-biotite granite (Yhgr) and the Reservoir Gneiss (Ygg), may be approximately equivalent in age because they were affected by the strong $YF_2$ deformation. Minor ferrodioritic dikes and sill-like masses (Yd) postdate the $YF_2$ deformation and may be equivalent in age to the ferrodiorite and the quartz-monzonites of the Canopus pluton.

The Canada Hill Granite formed late in the tectonic evolution as an anatectic rock derived from rusty sillimanitic paragneisses with which it is intimately associated. Chemistry of the Canada Hill Granite is highly variable, but variations in normative An-Ab-Or and Ab-Or-Q contents suggest incomplete to extensive partial melting to produce the observed rocks. Late pegmatites crosscut the Canada Hill Granite and all older units and commonly were intruded along the latest ($YF_3$) Middle Proterozoic structures. A suite of northeast- to north-trending metadiabase dikes of probable Late Proterozoic age crosscut all Middle Proterozoic rocks and structures but are offset along Paleozoic faults and are strongly foliated near shear zones.

Following complex deformation, hornblende-granulite facies metamorphism, and intrusion of Late Proterozoic dikes, the basement rocks were exposed to erosion in Early Cambrian time. Quartz sand and conglomerate of the Poughquag Quartzite were deposited unconformably on the basement rocks, thus forming the base of the transgressive Lower Cambrian through Lower Ordovician shelf sequence that is exposed northwest of the area in the Hudson River Valley and to the southeast in the Manhattan Prong.

During the Middle to the Late Ordovician, Taconian deformation and metamorphism affected the basement and the cover rocks and produced a series of tightly folded and faulted synclines of the Poughquag Quartzite. Numerous steeply dipping, ductile shear zones formed the principal zones of strain accumulation in the basement rocks. Between these shear zones, little deformation developed in the basement rocks. Mineral assemblages within the ductile deformation zones increase from lower greenschist facies in the northwest to staurolite-kyanite grade in the southeast. Analysis of microscopic fabrics and megascopic features indicates that the ductile deformation zones experienced a significant component of right slip. The slip direction on faults striking N. 20° to 45° E. is approximately N. 75° E. $^{40}Ar/^{39}Ar$ biotite ages from mylonites suggest that the shear zones are older than the 436-Ma biotite cooling age obtained from mylonite in the California Hill fault. This cooling age is equivalent to biotite ages in the northwestern Manhattan Prong near the Cortlandt complex and is consistent with slow regional cooling of high-grade metamorphic rocks from a metamorphic event at about 460 Ma (Dallmeyer and Sutter, 1976).

The age of tectonic activity following the Taconic orogeny into Acadian and Alleghenian is not well delineated. No mineral ages or metamorphic fabrics attributable to the Acadian orogeny of Early Devonian age or to the Alleghenian orogeny of Permian age are known. Brittle faults of probable Mesozoic age are present and probably are more important than had been previously recognized. Reactivation of northeast-trending Middle Proterozoic and Ordovician faults is likely and locally can be proven.

Current seismicity within and adjacent to the Oscawana Lake quadrangle could be controlled by movement on the major, northeast-striking tectonic features in the gneisses, but no evidence of post-Pleistocene faulting has been discovered. In place stress determinations near the eastern border of the map (pl. 1) and recent fault-plane solutions for events near Annsville, N.Y., suggest that the present principal horizontal compressive stress may be oriented at N. 55° E. These data suggest that the steeply dipping, ductile deformation zones in the quadrangle could be reactivated at present as right-slip faults. An alternate possibility is that minor, undetected northwest-trending faults, such as those inferred from analyses of microseismicity at Annsville and Verplank, N.Y., by Seborowski and others (1982) and Quittmeyer and others (1985), may be actively growing thrust faults at 2–10 km beneath the land surface. Geologic mapping has ruled out the possibility of any major, northwest-trending, continuous faults in the exposed basement rocks of the Oscawana Lake quadrangle. The major tectonic features, however, such as axial traces of folds, strike of Middle Proterozoic units, and Proterozoic and Paleozoic fault zones, trend N. 20° to 40° E. across the quadrangle. Narrowly spaced ductile shear zones that consist of ultrafine-grained quartz and abundant phyllosilicates extend to depths of 10 km or more and define zones of potential stress-induced creep at these depths. Present-day seismic release on short, geologically undetectable faults may be forming within blocks in response to internal stresses induced by a seismic creep along the block boundaries. Although evidence of this hypothetical creep in a right-lateral or other sense has not been discerned, the geologic evidence is very clear—once mylonite zones are established, these zones are repeatedly reactivated through geologic time in widely different stress fields. This observation suggests, but does not prove, that present-day seismic activity is related to strain accumulation along shallow (0–10 km deep), ductile, shear zones in basement rocks. Geologic data indicate that the structural fabric of the seismogenic source area for current activity, which is in the range of 0–10 km deep, is probably similar to that exposed at the surface in the Oscawana Lake area.

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