Precambrian Geology of the Popolopen Lake Quadrangle, Southeastern New York

R. T. Dodd, Jr.
Associate Professor, Department of Earth and Space Sciences,
State University of New York at Stony Brook

MAP AND CHART SERIES NUMBER 6

NEW YORK STATE MUSEUM AND SCIENCE SERVICE

The University of the State of New York/The State Education Department/Albany, 1965

M637—N64—2,000

CONTENTS

PAGE

ILLUSTRATIONS

TABLES

ABSTRACT

The Highlands metamorphic-igneous complex consists of a series of Precambrian sedimentary and, perhaps, volcanic rocks which were metamorphosed, folded, and intruded by masses of granite about 1.1 billion years ago. The metamorphic rocks are of three major types: 1) light-colored, commonly rusty-surfaced biotite-quartz-feldspar gneisses, which contain minor layers of marble and other calcareous meta-sedimentary rocks, and are thought to represent shales or graywackes; 2) dark-colored hornblende-pyroxene-plagioclase gneisses, which are interpreted as meta-morphosed basaltic volcanic rocks; and 3) light-colored quartz-plagioclase gneisses, whose parentage is uncertain. Masses of igneous granite occur as lenses and layers in all of these gneisses. The mineral assemblages in the gneisses and granites indicate that the igneous-metamorphic episode they represent took place at depths greater than 7 miles and temperatures of 700-800°C.

The complex and intricate folds shown on the geologic map indicate that the rocks were essentially plastic during deformation. Joints, some of them filled with dikes, and faults indicate a later episode or episodes of brittle deformation. The age of the joints is unknown, but the faults and dikes are probably in part related to faulting and igneous activity in the Triassic sedimentary area to the southeast.

Although radiometric dating has firmly established that the main igneous-meta-morphic episode took place about 1.1 billion years ago, conflicting results from different dating methods raise the possibility that the Precambrian rocks underwent mild reheating during one or more of the later episodes of mountain building which affected rocks to the east of the Highlands.

An iron industry, which was based on deposits of magnetite in the gneisses, is now defunct but is represented by numerous abandoned mines, furnaces, and mine roads. As most of the Highlands in the Popolopen Lake quadrangle lies on govern-ment land (Palisades Interstate Park and the U.S. Military Academy), the only resources now worked are sand and gravel, which are used locally by the State and Federal governments.

Manuscript submitted for publication April 7, 1964

I. INTRODUCTION

Setting and Physiography

Most of the Popolopen Lake quadrangle lies in the Hudson Highlands, which are part of an elongate upland of Precambrian igneous and metamorphic rocks (the Reading Prong) which extends southwestward from Connecticut, through southeastern New York and western New Jersey, into Pennsylvania. In the latitude of the Popolopen Lake quadrangle, the Highlands belt is bounded to the northwest by lower Paleozoic (Cambrian to Silurian) sedimentary rocks, to the south by red Triassic sediments (Newark group), and to the southeast by lower Paleozoic and/or Precambrian igneous and metamorphic rocks.

The topography of the Highlands is controlled primarily by structure and lithology. Longitudinal valleys and ridges (the latter reaching 1,400 feet in the Popolopen Lake quadrangle) parallel the trends of folds, while transverse valleys are controlled by joints and, less commonly, faults. The topography is modified on a small scale by glacial-erosional features (roches moutonnées and rare potholes, striations, chatter marks, and friction cracks) and glacial depositional features (filled valleys, kames, and kame terraces). Erratic material, mostly of local derivation, mantles most hills. Overall effect of glaciation has been to attenuate the topography: Maximum relief in the present area is about 750 feet.

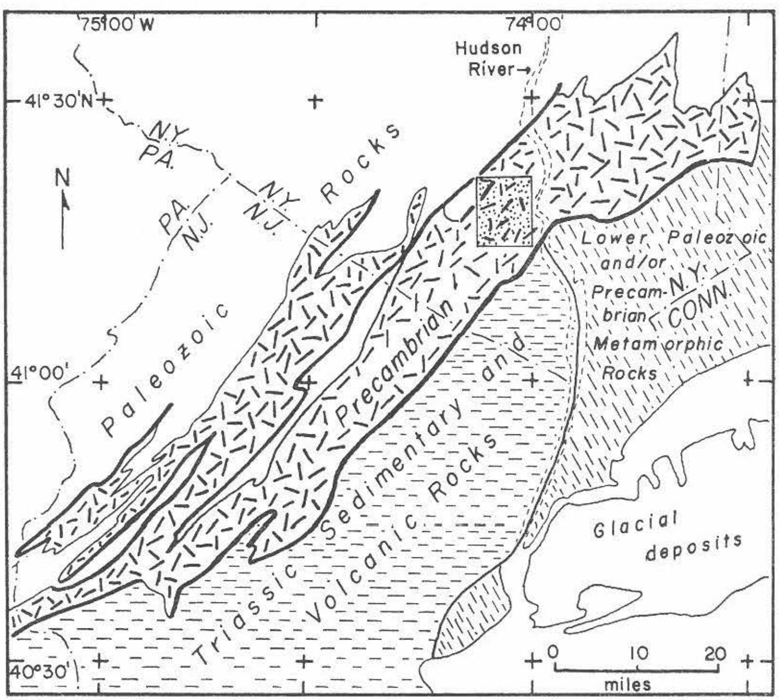


FIGURE 1. Generalized geologic map of the Hudson and New Jersey Highlands (Precambrian) and surrounding terranes. Popolopen Lake quadrangle is outlined and stippled; stratigraphic contacts are indicated by light solid lines and faults by heavy solid lines.

PREVIOUS STUDY

The geological literature on the Hudson and New Jersey Highlands has been summarized by Colony (1921) and Sims (1958). The former reference gives a detailed and interesting account of early work in the area. Several parts of the Highlands have been mapped since the publication of Sims' work: the Franklin-Sterling area, New Jersey (Hague, *et al*, 1956); the Edison District, New Jersey (Buddington and Baker, in press); and the area around Greenwood Lake, New York (Offield, unpub. dissertation, Yale University, 1961). Jaffe and Jaffe (1962) give preliminary results of a study of the area around Monroe, New York. The *Geologic Map of New York* (Fisher *et al*, 1961) incorporates a reconnaissance map of the entire Hudson Highlands, which was prepared by Offield.

Colony (1921) and Lowe (1950; 1958) studied the Popolopen Lake quadrangle in reconnaissance in connection with studies of, respectively, the Highlands magnetite deposits and the hornblende granite at Bear Mountain. The Paleozoic rocks of the northwestern corner of the quadrangle were described by Boucot (1958), and his map data are incorporated on the enclosed geologic map.

PURPOSE AND SCOPE OF THIS STUDY

This study was undertaken to extend detailed mapping of the Precambrian rocks of the Highlands, to determine the premetamorphic character of those rocks, and to reconstruct the metamorphic and igneous history of the region. The first and last of these goals have been realized, the second, only partly so.

The summers of 1959-61 and parts of the fall of 1960 and spring of 1961 were devoted to field work. Limited access precluded detailed field study of much of the Military Reservation, particularly the artillery training areas. About 300 thin sections and 20 polished sections were studied. Four chemical analyses of garnets and pyroxenes from ferruginous gneisses were secured (see Dodd, 1963).

ACKNOWLEDGMENTS

Honoraria from the New York State Museum and Science Service defrayed the field expenses of the first two summers. Princeton University provided support for the rest of the field work and for the chemical analyses.

The author is grateful to Professor J. O. K. Kalliokoski, of Princeton University, who supervised the preparation of the doctoral dissertation of which this report is a part, and to Dr. Y. W. Isachsen, of the Geological Survey, New York State Museum and Science Service, who counselled him during much of the field work. The study was an outgrowth of discussions with Professor Kurt E. Lowe, of The City College of New York. Professor Lowe provided the writer with unpublished material and the field notes of Dr. R. J. Colony.

Personnel of the Palisades Interstate Park Commission, U.S. Military Academy (West Point), Arden House (Columbia University), and the Arden Estate extended many courtesies during the field work. To these people and the many individuals who visited the field area and discussed it with him, the writer expresses his thanks.

His wife, Marya R. Dodd, assisted him in the preparation of the map. The illustrations were prepared with the assistance of the Technical Photo Branch, Air Force Cambridge Research Laboratories, Bedford, Mass.

II. PETROLOGY

Introduction

The rock types found in the Hudson Highlands of the Popolopen Lake quadrangle are summarized in table 1. They can be grouped in five general categories: 1) *Metasediments*, chiefly biotite-quartz-feldspar gneisses with minor associated marble, quartzite, pyroxene gneiss (skarn), and garnet-pyroxene gneiss; 2) *Metaigneous (?) gneisses*, amphibolites and related gneisses; 3) *Quartz-plagioclase gneisses of uncertain origin;* 4) *Syntectonic granites;* and 5) *Post-tectonic igneous rocks*, which include a granodiorite and many types of dike rocks.

As it is impossible, on the basis of present knowledge of the Highlands, to identify and correlate relict stratigraphic units, the writer follows Sims (1953; 1958) and Hotz (1953) in using descriptive terms for the rocks in preference to formation names.

Several field and petrographic characteristics of the gneisses are common to all rock types and need not be discussed for each unit. These are listed

Table 1. Highlands rocks of the Popolopen Lake quadrangle

Mode of Origin	*Lithology*	*Occurrence*	*Parentage*
METASEDIMENTARY GNEISSES	Biotite-quartz-feldspar gneisses, in part containing sillimanite, garnet, graphite, and sulfides	The predominant metasedimentary group, occurring chiefly in the southeastern half of the quadrangle	Alumino-siliceous sediments: graywackes or shales, grading to carbonaceous facies
	Marble	Very minor, occurring as layers and lenses in biotite-quartz-feldspar gneisses	Limestone, in part dolomitic
	Pyroxene gneiss (skarn)	Minor. Lenses and layers in biotite-quartz-feldspar gneisses; less commonly as boudins in other gneisses.	Metasomatically altered limestone or dolomite
	Garnet-pyroxene gneiss	Very minor. Layers in biotite-quartz-feldspar gneiss at Bear Mountain.	Ferruginous sediments
METAIGNEOUS (?) GNEISSES	Amphibolites: medium-grained (I) and coarse-grained (II)	Abundant. Layers in all other rock types, but most common in the quartz-plagioclase gneisses.	Basic volcanic flows and sills
	Biotite-hornblende-quartz-feldspar gneiss	Minor. Grades along strike to amphibolite or hypersthene-quartz-oligoclase gneiss.	Metasomatically altered amphibolite and hypersthene-quartz-oligoclase gneiss
GNEISSES OF UNCERTAIN DERIVATION	Hypersthene-quartz-oligoclase gneiss	Predominant ro k type in northwestern part of quadrangle; minor in eastern portion and absent from south-central portion	Uncertain. Perhaps potash-poor volcanic rocks.
	Quartz-plagioclase leucogneiss	Abundant in south-central portion of quadrangle; absent elsewhere	Uncertain. Perhaps potash-poor volcanic rocks.
SYNTECTONIC-INTRUSIVE IGNEOUS ROCKS	Hornblende granite, leucogranite, biotite granite, biotite-garnet granite, and related pegmatite and aplite	Concordant layers and lenses in all units. Present throughout the quadrangle. Pegmatite and aplite occur as dikes also.	Magmatic
POST-TECTONIC-INTRUSIVE IGNEOUS ROCKS	Hornblende-biotite granodiorite	Present only in extreme southeast corner of quadrangle. Relation to Highlands rocks unknown, but younger.	Magmatic
	Dikes, of many types but chiefly mafic	Present throughout quadrangle, but most abundant in southeast corner	Magmatic; perhaps in part related to the late Triassic Palisades diabase

General characteristics of the Highlands gneisses

below and mentioned subsequently only where variations occur:

1. The gneisses are typically hypidioblastic-granular: quartz and the feldspars are anhedral, the pyroxenes anhedral to subhedral, and biotite and hornblende subhedral to euhedral. Parallel orientation of the prismatic and platy minerals gives rise to a strong foliation, which typically parallels the boundaries of compositional units.
2. With rare exceptions, brown biotite and green or brownish green hornblende are typical of the gneisses throughout the quadrangle.
3. Plagioclase is typically polysynthetically twinned, with a single twin orientation per grain. The mineral is usually quite fresh, but minor amounts of sericite or paragonite occur along grain boundaries and cleavages.
4. Quartz has two habits in all of the quartz-bearing rocks. It occurs as minute, rounded grains in the feldspars and as rambling, amoeboid masses which commonly lie in the plane of foliation. Undulose extinction is characteristic.

Metasedimentary gneisses

Distribution

Metasediments, chiefly heterogeneous biotite-quartz-feldspar gneisses, are predominant in the eastern part of the quadrangle, subordinate in the south-central portion, and very minor in the northwestern portion as shown on colored geological map. The metasediments include, in addition to the biotitic gneisses, small amounts of marble, pyroxene gneiss (skarn), and garnet-pyroxene gneisses. The last of these are described in detail elsewhere (Dodd, 1963) and only summarized here.

Biotite-quartz-feldspar gneisses

The biotite-quartz-feldspar gneisses are of two distinct types: *rusty* and *gray biotite-quartz-feldspar gneisses.* The former group contains variable amounts of garnet, graphite, sillimanite, and iron sulfides; as its name suggests, it is typically rusty in outcrop because of the accessory sulfides. The latter group is gray, fresh looking, and typically migmatitic. Gneisses of this group generally lack graphite, sillimanite, and sulfides.

A third field unit, *undifferentiated biotitic gneisses*, was established as a catchall for the belt of biotitic gneisses south of West Mountain. These rocks differ from the other biotitic gneisses in locally containing varietal hypersthene and brown hornblende, and in being associated with abundant amphibolite. They are variegated and hard to characterize, and probably grade into both the rusty gneisses and hypersthene-quartz-oligoclase gneiss.

Rusty biotite-quartz-feldspar gneisses

This unit consists principally of well-foliated biotite-quartz—two feldspar gneisses which grade locally to quartzitic, biotite-rich, garnetiferous, and graphite- and sulfide-rich variants, and which are locally interlayered with small amounts of marble, pyroxene gneiss, and amphibolite.

Fresh samples of the gneisses are gray or white, fine- to medium-grained (felsic minerals 1-2 mm.; quartz up to 6 mm.), and granular. Blue-gray (graphitic) and white feldspars and gray to glassy quartz are the principal constituents, with subordinate but highly variable amounts of biotite. Pyrrhotite, pyrite, lavender or red garnet (porphyroblasts), graphite, and sillimanite (single needles or felty masses) are locally abundant and favor biotite-rich layers.

The modal analyses of table 2 illustrate some of the variations found in the gneisses. Every gradation appears between plagioclase- and microcline-rich types, but most samples contain more than 10 percent of each feldspar. The plagioclase is commonly myrmekitic and slightly antiperthitic, but otherwise typical. The potash feldspar is well twinned, slightly perthitic microcline. Brown biotite (5-25 percent) is the principal mafic mineral. Garnet appears sporadically, as equant or amoeboid masses which commonly include quartz grains. It is locally cut by or intergrown with biotite, or chlorite after biotite. Graphite occurs either as separate flakes or interleaved with biotite. Sillimanite is more common and more abundant than the modal analyses (table 2) suggest: it favors highly weathered biotitic partings which are hard to sample.

Pyrrhotite, pyrite, zircon (small, rounded, commonly overgrown grains), and apatite (subhedral to rounded) are wide-spread accessory minerals. Tourmaline, sphene, clinozoisite, and epidote occur locally, the last two as replacements of plagioclase.

Table 2. Modal analyses of rusty biotite-quartz-feldspar gneisses (1,000 points)

	002	012b	481/2	541	667	878	1,160	007	211	264
Potash feldspar	34.3	tr.	29.9	44.7	27.6	34.7	tr.	7.1	—	2.0
Quartz	38.8	35.2	39.1	37.8	42.1	0.8	17.0	77.2	74.4	55.5
Plagioclase	19.7	54.8	15.2	14.8	15.7	38.8	33.8	2.6	16.4	35.1
Biotite	—	—	6.1	2.4	3.8	7.3	21.3	7.7	6.6	5.4
Garnet	6.3	6.4	5.2	—	9.0	11.7	25.7	1.1	1.8	1.7
Sillimanite	—	2.4	—	—	—	4.9	—	2.2	—	--
Graphite	—	—	—	—	0.2	0.3	—	0.6	0.5	0.2
Zircon	tr.	tr.	0.1	tr.	tr.	0.3	—	0.3	tr.	tr.
Opaques	—	0.1	4.4	0.1	0.9	0.4	1.9	0.2	—	0.1
Others	tr.	tr.	tr.	tr.	—	0.6	0.2	—	0.1	tr.
Alteration (other than sericite)	1.0	1.0	—	0.2	0.6	—	—	—	0.1	—
Total	100.1	99.9	100.0	100.0	99.9	100.0	99.9	99.0	99.9	100.0

002. Seven Lakes Drive, east side of Bear Mountain (Peekskill quadrangle). Fresh, coarse garnet-quartz-feldspar gneiss.

012b. Seven Lakes Drive, north side, 1,700 feet west of Perkins Memorial Drive entrance, Bear Mountain. Sillimanitic garnet-quartz-plagioclase gneiss.

481/2. South end of ridge east of Forest Lake. Garnetiferous biotite-quartz-feldspar gneiss.

541. Knob just south of south end of Puddingstone Hill. Biotite-quartz-feldspar gneiss.

667. West side Lindley Mountain; layer in hypersthene-quartz-oligoclase gneiss. Garnetiferous biotite-quartz-feldspar gneiss.

878. Top of Silver Mine Ski Tow Hill. Quartz-poor garnet-biotite-feldspar gneiss. Note abundant zircon.

1,160. Knob due west of Bear Mountain, 0.5 mile northeast of Queensboro Lake. Mafic-rich biotite-garnet-quartz-plagioclase gneiss.

007. Seven Lakes Drive, south side of Bear Mountain. Biotitic quartzite.

211. Knob just southeast of south knob of West Mountain. Quartz-rich biotite-quartz-plagioclase gneiss.

264. Palisades Interstate Parkway, east side, west of Pingyp Mountain. Quartz-rich garnet-biotite-plagioclase-quartz gneiss.

The rusty gneisses commonly contain lenses, layers, and irregular, discordant masses of a gray leucogranite (fine- to medium-grained) and pegmatite, which consist of white or blue-gray (graphitic) feldspars (slightly perthitic microcline and oligoclase) and quartz in approximately eutectic proportions, with minor brown biotite, garnet, graphite, and opaques, and sparse rounded zircons, sphene, apatite, sillimanite epidote, zoisite, and muscovite. These felsic phases were mobile, as is attested by their common discordance. Their feldspars and accessories suggest that they were derived from the host gneisses by partial fusion.

Gray biotite-quartz-feldspar gneisses

Gray, commonly migmatitic, biotitic gneisses occupy several belts in this quadrangle and occur elsewhere in the Highlands. Unlike the gneisses of the previous unit, these lack rusty surfaces and rarely contain sulfides, graphite, or sillimanite. They are light to medium-gray and well foliated, with pink or white quartzofeldspathic interleaves (typically less than an inch thick) and, commonly, boudinaged layers of pink granite pegmatite.

The gneisses are fine- to medium-grained (felsic minerals 1-2 mm. in diameter, with discoidal quartz grains up to 5 mm. or more) and consist chiefly of white feldspars, gray quartz, and variable amounts of brown biotite. The proportions of the major minerals vary widely across strike; potash feldspar (microcline-microperthite; locally untwinned microperthite) is enriched in the felsic layers. Red, diablastic garnet favors the margins of the felsic layers (figure 2). Accessory minerals include opaque oxides and rounded grains of apatite and zircon. Sphene, epidote, and sillimanite are uncommon. Although the gneisses are typically unaltered, chlorite partly or, rarely, wholly replaces biotite in some samples.

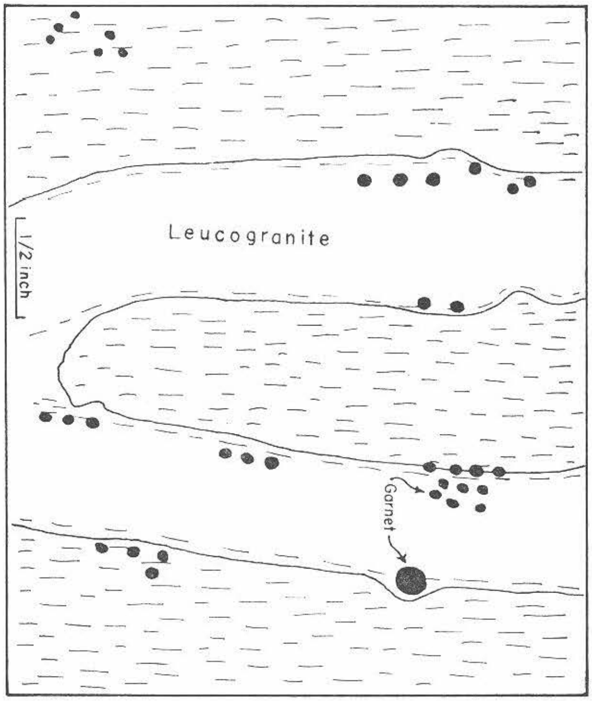


FIGURE 2. Relationship between garnet and felsic layers in gray biotite-quartz-feldspar gneiss, just south of Turkey Hill Pond

Undifferentiated biotitic gneisses

A sequence of gneisses, which lies south of West Mountain, defies simple description or meaningful division. Most of the rocks of this sequence are biotite-quartz-feldspar gneisses, but they differ from either of the preceding units in lacking sulfides, garnet, and sillimanite and containing minor amounts of *brown* hornblende, hypersthene, and/or clinopyroxene, all of which are commonly partly chloritized. Amphibolite and layers and irregular masses of hornblende granite are also present in the sequence.

The biotitic gneisses are typically gray to white in outcrop and greenish gray where fresh. They display a strong foliation which is contorted locally in a chaos of small folds. A curious feature of these folds is the harmonious deformation of intercalated amphibolites. Elsewhere (see below) folded amphibolite layers are boudinaged and fractured and appear to have been more competent than the associated quartzofeldspathic gneisses.

Like the other biotitic gneisses, these consist chiefly of quartz, plagioclase, and microcline or microcline-microperthite in all proportions, with variable amounts of biotite. In addition to the other mafic minerals noted above, they contain apatite, graphite, rounded zircons, and rare sphene as accessories. In addition to chlorite, secondary minerals include minor epidote, zoisite (?), and muscovite, the last of these locally replacing biotite.

Marble

Marble is a very minor component of the gneisses of the Popolopen Lake quadrangle. It occurs in discontinuous lenses and layers up to about 50 feet thick, which are most commonly associated with rusty biotite-quartz-feldspar gneisses and pyroxene gneisses. Most exposures are too small to be shown to scale in figure 1 and are indicated by the letter "M."

Marble is well exposed at the south ends of Popolopen and Lower Twin Lakes, in Bradley Mine, and on the southwest side of Bear Mountain. In the first two occurrences (see also Lowe, 1958, p. 50), the marble consists of gray calcite (locally pink at Twin Lakes), with abundant chondrodite, spinel, and sphene. The marble in Bradley Mine appears to grade to a garnet-pyroxene skarn which is exposed in the east wall and ceiling of the main mine opening. The Bear Mountain material, which is typical of that found in the biotitic gneisses, is graphitic and contains occasional inch-scale layers of green clinopyroxene.

In view of the small extent and poor preservation of marble in this quadrangle, petrographic study was not attempted.

Pyroxene gneisses

Rocks which consist chiefly of olive green, or, less commonly, pale green clinopyroxene are minor but widespread in the gneisses. They occur as lenses and layers a few inches to a few feet thick in rusty biotitic gneisses and as boudins in quartz-plagioclase leucogneiss. These gneisses are equivalent to skarns in the terminology of Hotz (1953) and Sims (1953; 1958).

Although the pyroxene gneisses are typically nearly monomineralic and structureless, a layer on the southwest side of West Mountain contains biotite, platy quartz, and graphite, and is strongly foliated. Graphite occurs elsewhere in this rock type, and quartz is very abundant in a body of the gneiss in the valley north of Surebridge Swamp.

Garnet-pyroxene gneisses

Iron-rich gneisses which consist principally of garnet and pyroxenes occur as layers in the rusty biotite-quartz-feldspar gneisses on the southwest side of Bear Mountain, throughout a stratigraphic interval of about 100 feet. They were described first by Lowe (1950, p. 142) and, more recently, by Dodd (1963).

Two subtypes are recognized: a garnet-quartz-eulite rock (garnet-othopyroxene gneiss) and a garnet-magnetite-ferroaugite rock (garnet-clinopyroxene gneiss). The first occurs in a 15-foot layer at the bottom of the Bear Mountain sequence. It is dark green beneath a thin rind of limonite, a consists of a coarse intergrowth of thumb-si eulite crystals (En_{17}), within which poikilobl of garnet (Alm_{55} Sp_{23} And_{13} Gr_5 Pyr_4) are d tributed in layers about ¼-½ inch thick. Coa scales of graphite occur in pyroxene cleavages a along grain boundaries. The rock is modally va able, but consists of roughly 50-75 percent eul (with minor ferroaugite in some samples), 20 percent garnet, 0-30 percent quartz, 1 percent gra ite, 1 percent apatite, and minor calcite, sphene, a magnetite. The microscopic texture is shown figure 3.

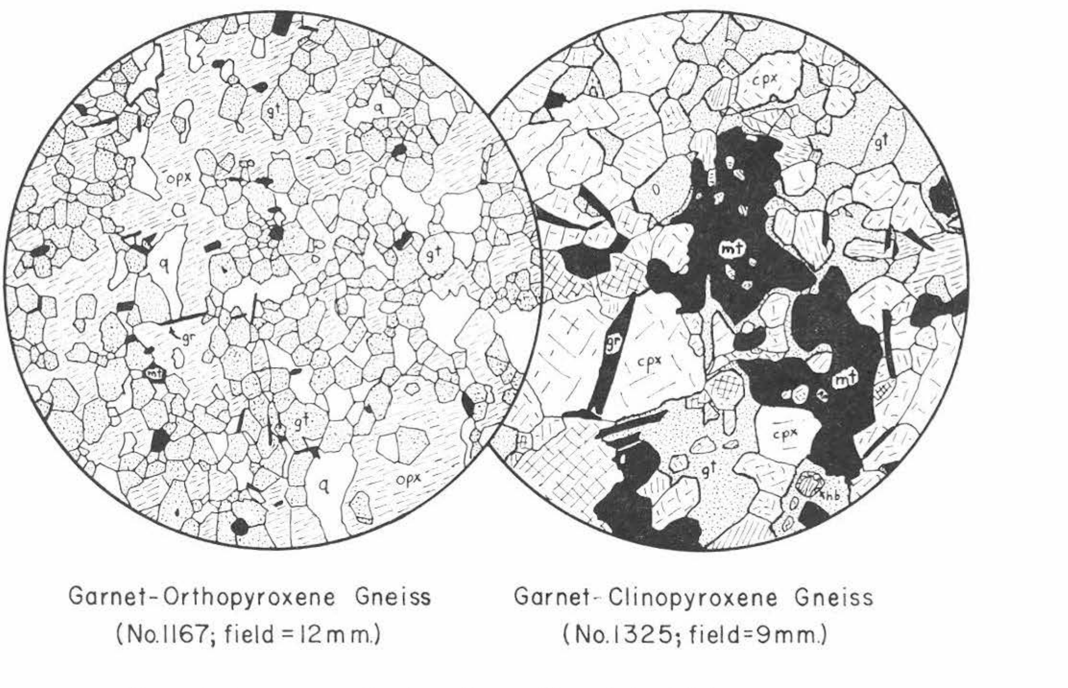


FIGURE 3. Microtextures of garnet-pyroxene gneisses. Literal symbols: *opx* orthopyroxene; *cpx* clinopyroxene; *gt* garnet; *q* quartz; *hb* hornblende; *mt* magnetite; *gr* graphite

Garnet-clinopyroxene gneiss occurs in several layers above the previous subunit. It forms dark green, vuggy, granular outcrops. The gneiss is medium-grained and indistinctly layered. Its texture, which contrasts strongly with that of garnet-orthopyroxene gneiss, is shown in figure 3. The approximate modal composition is: Ferroaugite (Fe_{37} Mg_{15} Ca_{48}) 70 percent, garnet (Alm_{45} G And_{12} Sp_9 Pyr_4) 10-15 percent, and magnetite (w minor exsolved ilmenite) 10-15 percent, with acc sory amounts of graphite, green hornblende, apati and zircon.

Chemical analyses and mineral norms for t pyroxenes and garnets are given in Dodd (1963).

Origin and parentage of the metasediments

A metasedimentary origin for the rusty biotite-quartz-feldspar gneisses is suggested by their rounded, commonly overgrown zircons, and by disseminated graphite and iron sulfides. In addition, they grade to and contain rock types of clearly sedimentary parentage: quartzites (sandstones or cherts); graphitic and sulfide-rich gneisses (dark, carbonaceous shales); marbles and pyroxene gneisses (limestones and/or dolomites); and garnet-pyroxene gneisses (ferruginous chert-carbonate sediments). This assemblage of gneisses probably represents argillaceous sediments, shales or graywackes, in which clastic deposition gave way locally to formation of carbonates and dark shales.

The gray biotite-quartz-feldspar gneisses are also interpreted as metasediments, on the basis of their heterogeneity and their content of rounded, probably detrital zircons. The pegmatite layers, which become more abundant near granite contacts, suggest that the metasediments have been affected by the injection of granitic material. This suggestion is corroborated by the local gradation of this unit to hornblende granite through a zone of biotite granite (see geologic map, specifically the west side of Letterrock Mountain).

The strike relations of the undifferentiated biotitic gneisses suggest that they are in part related to rusty biotite-quartz-feldspar gneiss and in part to hypersthene-quartz-oligoclase gneiss. The first of these is a metasediment; the second is regarded, with strong reservations, as a metavolcanic rock. Rounded zircons, modal variability, and minor accessory graphite in the present unit suggest that it is chiefly a metasediment. Its differences from the other biotitic gneisses may be due to slight differences in metamorphic history. This point is discussed further in the section on metamorphism.

Metaigneous (?) gneisses

Types and distribution

Three rock types in the Popolopen Lake quadrangle are tentatively interpreted as metamorphosed mafic volcanic rocks. Two of these are amphibolites and are distinguished here as "Amphibolite I" and "Amphibolite II." The third gneiss differs from amphibolite in containing abundant quartz and potash feldspar and is called "biotite-hornblende-quartz-feldspar gneiss."

The medium-grained Amphibolite I is very abundant and occurs throughout the quadrangle in various associations. Amphibolite II, a coarse-grained type, is abundant only on the east side of Fingerboard Mountain and east of Arden House (figure 1). Biotite-hornblende-quartz-feldspar gneiss is essentially restricted to Cranberry and Long Mountains and their southward extensions, although a small amount appears south of Lake Tiorati.

Amphibolite I

Amphibolite I typically occurs as concordant layers, a few inches to several feet thick, in other rock types. It is usually associated with the quartz-plagioclase gneisses, but also occurs in biotite-quartz-feldspar gneisses, as inclusions in hornblende granite, and, less commonly, with marble or pyroxene gneisses. Although the amphibolite layers are typically sharply defined, they are boudinaged and streaked out into schlieren in zones of intense folding as discussed in the section "Structure."

Amphibolite I is dark gray to black on both fresh and weathered surfaces. Pyroxene-rich varieties tend to be lighter-colored and greenish. The gneiss is hypidioblastic, medium-grained (roughly ½-2 mm.), and nearly equigranular, with a strong biotite foliation and pronounced linear parallelism of hornblende and, rarely, apatite.

Although the gneiss is modally variable (table 3), it consists chiefly of andesine (30-60 percent; N_x of 1.545-1.549 $\pm$ 0.001 for six specimens indicates a range of $An_{32\text{-}41}$ according to the curves of Hess, 1960), green hornblende (25-60 percent; *X* yellow-tan, *Y* and *Z* dark green or brownish green; $2V_x$ = 52-76 degrees; $Z \wedge c$ = 16-19 degrees), salite-augite (0-20 percent; see optical data in table 4), and brown biotite (0-12 percent). Hornblende and clinopyroxene show a rough inverse variation (table 3). Orthopyroxene (slightly pleochroic from pale green or gray to pink, with fine diopside lamellae parallel to (100)) is locally present in minor amounts. Both pyroxenes are typically slightly serpentinized.

Opaque oxides (0-3 percent) and apatite (0-1.5 percent) are usually present. Rare accessories include zircon (rounded, slightly elongate grains), sphene, allanite, and a carbonate.

Table 3. Modal analyses of metaigneous (?) gneisses

Rock type	*Amphibolite I*						*Amphibolite II*				*Biotite-hornblende-quartz-feldspar gneiss*	
Specimen No.	018	181	247a	447/1	487	1,021	1,330	1,331	1,332	250a	1,334	1,339
Plagioclase	48.6	61.1	28.6	36.2	27.6	60.5	47.8	41.2	57.6	53.2	23.9	32.9
Hornblende	45.6	26.6	64.0	42.4	58.9	26.0	42.9	48.5	34.4	34.7	11.9	10.8
Clinopyroxene	1.6	4.7	1.8	19.1	—	12.0	9.2	5.3	5.7	11.8	—	—
Orthopyroxene	—	2.5	0.8	0.7	—	—	—	—	—	—	1.5	—
Biotite	4.0	2.1	1.2	—	12.1	—	—	tr.	—	—	3.4	8.6
Quartz	0.1	—	—	—	—	—	—	—	—	—	23.2	23.5
Alk. Feldspar	—	—	—	—	—	—	—	—	—	—	29.6	22.6
Opaques	—	0.9	2.5	0.1	1.1	1.0	tr.	1.4	0.9	0.1	1.1	0.9
Apatite	0.1	1.3	0.4	—	0.3	0.2	tr.	0.2	0.1	0.1	0.3	0.6
Zircon	tr.	—	tr.	—	tr.	tr.	—	tr.	—	—	0.1	—
Alteration	—	0.7	0.8	1.5	—	0.2	0.1	3.0	1.3	0.1	—	—
Sphene	—	—	—	—	—	—	—	—	—	—	tr.	tr.
Others	—	0.1	—	—	—	0.2	—	—	—	—	—	—
Total Percent	100.0	100.0	100.1	100.0	100.0	100.1	100.0	99.6	100.0	100.0	100.0	99.9
Points	1,000	1,000	1,000	1,000	1,000	1,000	2,000	2,000	2,000	2,000	1,000	1,000

Amphibolite I

018. Northeast end of Cranberry Hill, south side of Route 6. Amphibolite with concordant leaves of granite pegmatite.

208. North end of ridge west of Palisades Interstate Parkway, just west of Anthony Wayne. Medium-coarse amphibolite.

247a. Route 293, small knob just north of Mine Lake Brook. Amphibolite interleaved with hypersthene-quartz-oligoclase gneiss.

447/1. South end of Stockbridge Mountain. Pyroxene-rich amphibolite, included in granite pegmatite.

487. North end of ridge just east of Forest Lake. Amphibolite, included in leucogranite.

1,021. Northeast side Black Mountain, near bottom. Medium-course, pyroxene-rich amphibolite.

Amphibolite II

1,330. Southwest side Fingerboard Mountain, near eastern contact of this unit

1,331. 100 feet below western contact of this unit; location as above

1,332. 10-20 feet from western contact of this unit; location as above

250a. Road cut, west side Lake Tiorati, on Seven Lakes Drive. "Smeared" facies of this unit.

Biotite-hornblende-quartz-feldspar gneiss

1,334. Small knob just due west of northwesternmost part of Cranberry Pond

1,339. Cranberry Mountain

Table 4. Optical data for clinopyroxenes from amphibolite I

Specimen No. 1021: $N_\gamma = 1.6851 \pm 0.001$

$2V_z = 54.7°$

Pleochroism: X pale gray-green
Y pale gray-green
Z pale pink

Composition (Hess, 1949):
$Ca_{45.5}\,Mg_{44}\,Fe_{10.5}$
(Salite-augite)

Specimen No. 447/1: $N_\gamma = 1.6907 \pm 0.001$

$2V_z = 54.2°$

Pleochroism: X pale green
Y pale green
Z pale pink

Composition (Hess, 1949):
$Ca_{45}\,Mg_{40}\,Fe_{15}$
(Salite-augite)

Remarks: 1) Sample locations are given in table 3.
2) Exsolution lamellae are typically absent, but are represented locally by a fine-grained mixture of serpentine and opaques.

Amphibolite II

Coarse-grained amphibolite occurs in a concordant sheet several hundred feet thick and at least $2\frac{1}{2}$ miles long on the east side of Fingerboard Mountain (Lowe, 1950, p. 143), in narrower sheets east of Arden House and south of Lake Tiorati, and in isolated nodules in the gneissic hornblende granite on Bradley Mountain. The writer is unaware of similar material elsewhere in the Highlands, but some of the diorite mentioned by Colony (1921) may be similar.

Modally (table 3) and in the character and paragenesis of its minerals (chiefly green hornblende, andesine, and diopsidic clinopyroxene), Amphibolite 2 closely resembles Amphibolite 1. It differs chiefly in grain size (hornblende and plagioclase 1-5 mm.; pyroxene < 1-3 mm.), and in a pronounced tendency toward clumping of the mafic minerals, with pyroxene mantled by crystals of hornblende. The latter mineral is in turn commonly rimmed by grains of opaque oxides, especially between adjacent hornblende crystals.

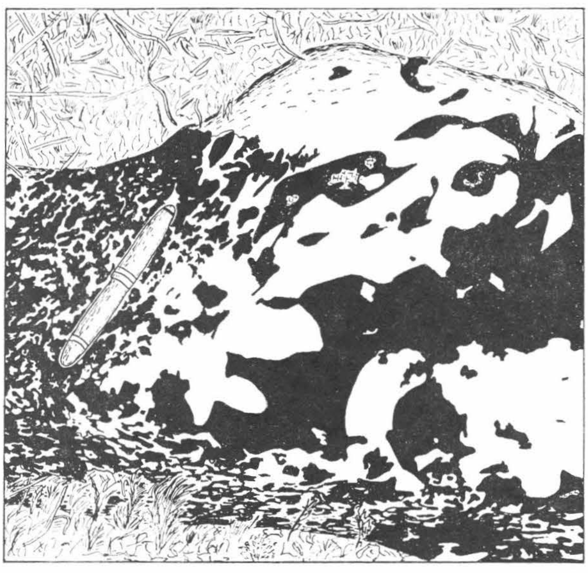


FIGURE 4. Amphibolite II, west side of Seven Lakes Drive, west side of Lake Tiorati.
The "smeared" facies occurs at the bottom of the figure. The coronitic relationship of hornblende (black) to pyroxene (hatched) is also apparent in thin sections. Plagioclase is white in the tracing.
Drawn from photograph

The coronitic habit of hornblende around pyroxene is particularly striking in a facies of the gneiss that occurs along Seven Lakes Drive west of Lake Tiorati. Here, inch-scale clots of mafic minerals are smeared out in a manner suggestive of plastic flowage. The "normal" and "smeared" facies are shown in figure 2.

Biotite-hornblende-quartz-feldspar gneiss

In the field, this unit resembles gneissic hornblende granite with an unusually high percentage of mafic minerals (15-25 percent, vs. 0-12 percent for the granite). It is gray or pinkish gray in outcrop, well foliated and subtly layered, and contains boudinaged layers of granite pegmatite and, commonly, Amphibolite 1. The gneiss appears along strike from and is evidently gradational into Amphibolite 1 and hypersthene-quartz-oligoclase gneiss (figure 1). Its external contacts are concordant. At Long Mountain, it grades within a few feet to the overlying hornblende granite.

Biotite-hornblende-quartz-feldspar gneiss is medium-grained (essential minerals $\frac{1}{2}$-2 mm. across) and hypidioblastic-granular. The mafic minerals typically occur together, with biotite locally cutting or replacing hornblende. The principal minerals (table 3) are plagioclase (28-45 percent; commonly myrmekitic and slightly antiperthitic, microcline-microperthite (10-30 percent; rarely with albite rims), quartz (15-30 percent), brown biotite (0-15 percent), and green, highly pleochroic hornblende (10-15 percent). Where the gneiss is on strike with hypersthene-quartz-oligoclase gneiss, it contains minor hypersthene and clinopyroxene. Opaque oxides and subhedral to rounded apatite are constant accessories. Sphene, zircon (rounded, locally overgrown), pyrite, and pyrrhotite are minor and rare.

Origin of the hornblende-plagioclase gneisses

Amphibolites are abundant in the Highlands and other high-grade gneiss terranes. They have been variously interpreted as metamorphosed 1) limestone (Adams, 1909), 2) marly clays (Hietanen, 1947), 3) limy shale, 4) graywacke (Hewitt, 1955), 5) mafic volcanics (Hewitt, 1955; Parras, 1958; Hague, *et al*, 1956), 6) mafic dikes and sills (Hewitt, 1954; Budding, 1955; Parras, 1958; Francis, 1958), and 7) plutonic igneous rocks (Buddington, 1939; Hewitt, 1954). An origin in metamorphic segregation has also been suggested, either by differential movement of alkalies (Orville, 1963; Engel and Engel, 1962) or through partial fusion (Yoder and Tilley, 1956). The many interpretations of amphibolites reflect the general opinion that such rocks can be produced from many starting materials, and that the parentage of a given amphibolite is rarely demonstrable (see Engel and Engel, 1962, p. 75).

There is, likewise, no consensus on the origin of the Highlands amphibolites. In the older reports (Berkey and Rice, 1919; Colony, 1921), they were interpreted as intrusive diorites (the Pochuck diorite). Hotz (1953) and Sims (1953; 1958) interpret them as metamorphosed calcareous sediments, while Hague, *et al* (1956) favor a metavolcanic interpretation on the strength of possible relict pillows in some layers.

In the absence of relict igneous or sedimentary textures, the amphibolites of the present area cannot be interpreted with certainty. The writer favors a metavolcanic interpretation, on the basis of the following field arguments:

1. Amphibolite I does not transect other units, as one would expect it to if it were of intrusive origin. The argument that the concordant relations of amphibolite are secondary (see Engel, 1949) is not valid here, as concordance is found in fold noses as well as on flanks.

2. The association of Amphibolite I with all other rock types requires a parent which was compatible with many associates. Volcanics meet this requirement.

3. Layers of amphibolite are sharply defined, despite gradational fluctuations in the associated rocks. This suggests either an abrupt change in sedimentation or influx of volcanic material to produce the parent of amphibolite. The latter is more likely.

4. The occurrence, though rare, of sharply defined layers of amphibolite in marble militates against derivation of amphibolite from carbonate rocks. Where partial replacement of marble by silicates is evident, the product is a skarn, not amphibolite.

5. Metamorphic differentiation is attractive where amphibolite is interlayered with a uniform, less mafic gneiss (e.g. quartz-plagioclase leucogneiss), but this association of complementary rock types is not general.

Amphibolite II is also regarded as metaigneous. The greater grain size may in part reflect an initial difference in the parents of the two amphibolites: Amphibolite II may represent basic sills rather than flows.

The field relations and petrographic character of biotite-hornblende-quartz-feldspar gneiss suggest that it grades in one direction to amphibolite and hypersthene-quartz-oligoclase gneiss and in the other direction to hornblende granite. It is tempting to interpret the gneiss as the result of potash and silica metasomatism of the two potash-poor gneisses, and to identify hornblende granite as the source of solutions. However, as Engel and Engel have shown (1962, pp. 59-60), the opposite interpretation is also possible, viz., that the intermediate gneiss represents a granitic rock from which part of the potash and silica have been removed and which is thus approaching amphibolite. A final decision between these hypotheses is impossible with the evidence at hand.

Quartz—plagioclase gneisses of uncertain origin

Definition and distribution

Two gneisses, both of which consist chiefly of quartz and sodic plagioclase and are typically interlayered with amphibolite, are very abundant in the quadrangle. Their origin is a crucial question in Highlands petrology.

The more abundant of the gneisses, a hypersthene-quartz-oligoclase rock, makes up most of the northwestern portion of the quadrangle and is also abundant south of Bear Mountain. The less abundant type, a mafic- poor quartz-sodic plagioclase gneiss, is restricted to the south-central part of the quadrangle. These two rock types are described separately, but their origins are considered together as they raise similar problems of interpretation.

Hypersthene-quartz-oligoclase gneiss

Rocks similar to this unit occur throughout the Highlands. They include Hotz's quartz-oligoclase gneiss (1953), Sims' quartz-diorite (1953; 1958), and the hypersthene-quartz-oligoclase gneiss of Buddington and Baker (in press). Bayley, *et al* (1914) included such rocks in the Losee gneiss. Equivalents in the older terminology of the Hudson Highlands are unknown.

Hypersthene-quartz-oligoclase gneiss is white to light gray on weathered surfaces, green or greenish-buff where fresh. A fair to strong foliation is due to parallel orientation of biotite, hornblende, and, locally, discoidal quartz grains. The foliation is typically paralleled by layers, blocks, boudins, and schlieren of amphibolite or, rarely, pyroxene gneiss.

The gneiss is usually concordant with other units, but granite pegmatite layers intrude it slightly.

The gneiss on the eastern side of the quadrangle shows two distinctive features which are not present elsewhere. At Bear Mountain, it contains concordant or slightly discordant layers, less than an inch to a few inches thick, of a white alaskite (the "pseudo-alaskite" of Lowe, 1950, p. 144; see also Hotz, 1954, p. 210). Along the Palisades Interstate Parkway, just north of Anthony Wayne Recreation Area, the gneiss carries lenses of granite pegmatite (pink feldspar, quartz, hornblende) a few inches in diameter. Neither of these phenomena has been studied in any detail.

Table 5. Modal analyses of hypersthene-quartz-oligoclase gneiss

Specimen Number	366	491	554	715	786	841	857	215	1,144	1,163/1	1,173/1
Plagioclase (including antiperthite)	64.5	58.5	59.8	68.4	64.8	66.7	74.0	60.0	64.4	68.6	60.3
(per. ent anorthite)		(29)	(27.5)		(29)	(29)		(27)	(29)	(25)	(27)
Potash feldspar:											
Free grains	tr.	0.7	0.5	—	—	—	—	3.6	1.4	0.4	0.3
(percent anorthite)	1.04	0.86	1.54	(tr.)	—	0.49	1.24	0.75	6.5	4.5	tr.
Quartz	11.2	33.2	18.6	21.3	22.5	0.9	9.9	21.1	19.6	5.0	23.8
Hornblende	16.5	—	14.7	—	2.4	tr.	0.4	—	—	—	—
Biotite	—	1.8	—	6.3	5.3	—	—	13.0	10.5	3.7	5.3
Clinopyroxene	—	—	—	—	—	2.2	6.1	0.3	—	—	1.0
Orthopyroxene	6.6	4.7	5.6	3.0	4.9	26.4	8.0	1.7	3.9	19.3	5.7
(percent enstatite)		(59)	(57)		(60)	(62)			(53)	(59)	(57)
Opaques	0.9	0.9	0.7	0.9	0.1	2.9	1.7	0.4	—	2.2	0.1
Apatite	tr.	tr.	0.2	tr.	tr.	0.7	—	tr.	0.2	0.8	0.2
Sphene	—	tr.	tr.	—	tr.	—	—	tr.	—	—	—
Zircon	—	—	—	—	tr.	—	tr.	tr.	tr.	tr.	tr.
Alteration	—	—	—	—	—	—	—	—	—	—	2.2
Total percent	99.7	99.8	100.1	99.9	100.0	99.8	100.1	100.1	100.0	100.0	98.9
Points counted	1,042	1,000	1,092	1,000	1,600	1,500	1,086	1,566	1,000	1,000	1,000

Samples from northwestern portion of quadrangle:

366. West side of Fingerboard Mountain. Gneiss layer in terrane of hornblende granite.

491. Knob 0.5 mile due noth of Bradley Mountain

554. 0.5 mile due west of Summit Lake. Schlieren of amphibolite abundant.

715. East side of Echo Mountain. Massive, unusually poorly foliated.

786. 0.25 mile north-northeast of cove on Summit Lake

841. East of first major summit west of Long Mountain, 0.75 mile northeast of Route 6. Poorly foliated but with abundant amphibolite schlieren.

857. 2,500 feet due east of north end of Lake Te-Ata, north of Route 6. Medium-grained, massive gneiss. A sample of pyroxenes from this gneiss has been dated (Hart and Dodd, 1962).

Samples from eastern portion of quadrangle:

215. East side of Palisades Interstate Parkway, opposite gas station. Strongly foliated.

1,144. Just northeast of No. 215

1,163/1. Palisades Interstate Parkway, west side of Bear Mountain

1,173/1. Palisades Interstate Parkway, east side, southwest side of Bear Mountain

Remarks:

1. The abundance of potash feldspar in antiperthite was determined by counting 300 point modes on the plagioclases (stained for potash feldspar).
2. The anorthite content of plagioclase was determined from N_X and the enstatite content of orthopyroxene from $2V_X$.

Hypersthene-quartz-oligoclase gneiss is medium-grained (essential minerals 1-2 mm.) and hypidioblastic. It consists chiefly of calcic oligoclase (60-75 percent; slightly antiperthitic and myrmekitic; An_{25-29} on the basis of N_x of 1.541-1.543 ± 0.001 for nine samples) and quartz (1-35 percent) (table 5). Free microcline is typically insignificant, but it appears locally in optical continuity with antiperthitic lamellae in plagioclase. The only characteristic mafic constituent is hypersthene (1.7-26.4 percent, typically 5-10 percent; pleochroic from pale green to pale pink, and containing fine diopside lamellae parallel to (100); slightly serpentinized; En_{53-62} on the basis of $2V_x$ of 47-53 degrees). It is accompanied by any or all of the following: pale green, slightly pleochroic clinopyroxene (0-6.1 percent), brown biotite (0-13 percent), and green hornblende (0-16.5 percent). Biotite commonly crosscuts or is intergrown with the other mafic minerals. Opaque oxides and apatite occur in all samples. Minor accessories include zircon (rounded, locally subhedral; see Eckelmann, 1963), sphene, and rare epidote and graphite. Garnet is uncommon in this unit but appears locally where the gneiss is in contact with garnetiferous rusty biotite-quartz-feldspar gneiss and, rarely, where it is cut by granite pegmatite.

Quartz-plagioclase leucogneiss

Rocks which consist almost wholly of quartz and albite-oligoclase are abundant in the Highlands and include Sims' albite-oligoclase granite (1958), Buddington's albite-oligoclase alaskite (1958), and a facies of Hotz's quartz-oligoclase gneiss (1953). The relation of the present unit to older Highlands terminology is uncertain, though study of Colony's field notes (loaned to the writer by K. E. Lowe) suggests that he identified it with the Pochuck granite (see also Colony, 1921).

In the present quadrangle, leucogneiss occurs in sharply defined layers, a few inches to tens of feet thick, which are interlayered with amphibolite or, rarely, biotite-plagioclase gneiss. The structural relations of these rocks are as described for the previous unit (see also the section of this report on "Structure"). Contacts between leucogneiss and other rock types are usually concordant and sharp, but the gneiss on Letterrock Mountain grades into hornblende granite over an interval of a few feet.

Table 6. Modal analyses of quartz-plagioclase leucogneiss

Specimen Number	043	113	883	922/2	990	115	178b	234	991
Plagioclase (including antiperthite)	52.8	67.3	51.5	62.6	39.9	55.8	34.9	68.2	69.0
Anorthite content	(7.5)		(15.0)	(10.5)	(12.5)				
Potash feldspar: Free grains	2.5	1.6	7.8	2.1	18.2*	—	27.2	7.0	4.1
In antiperthite	—	10.8	—	5.6		23.1	—	5.6	5.5
Quartz	37.6	30.5	38.6	29.5	40.8	31.0	34.4	12.2	22.0
Hornblende	—	—	—	—	—	6.5	0.1	9.1	3.4
Biotite	—	0.1	—	0.1	—	0.1	—	1.3	—
Opaques	3.6	0.2	1.5	4.7	0.8	1.7	2.9	0.3	0.9
Zircon	tr.	0.1	—	0.3	tr.	tr.	tr.	tr.	tr.
Sphene	—	—	—	—	—	0.2	0.1	—	—
Apatite	0.2	0.1	—	—	—	0.1	—	0.4	—
Alteration (except sericite)	3.3	—	0.6	0.7	0.3	4.3	0.4	0.5	0.6
Others	—	0.1	—	—	tr.	0.3	tr.	1.0	—
Total percent	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Points	1,000	1,000	1,000	1,000	1,500	1,000	1,000	1,000	1,000

* Includes both free and exsolved potash feldspar. For other slides, separate 300-point modes were prepared for plagioclase to determine the amount of potash feldspar present.

043. North knob Letterrock Mountain, near contact with hornblende granite
113. Due south of Lake Tiorati, just south of entrance road to Camp Thendara. Fine- to medium-grained, nearly mafic-free gneiss.
883. Southern projection of Silver Mine Ski Tow Hill, overlooking Bockey Swamp Brook. Fine-grained leucogneiss from a thick sheet interlayered with amphibolite.
922/2. East side, south end of Letterrock Mountain
115. Northwest side Flaggy Meadow Mountain. Potash feldspar occurs in patch antiperthite.
178b. North of Black Mountain. Interlayered with amphibolite.
234. Summit of first major ridge due east of Lake Tiorati. Amphibolite predominates here.
991. North end Letterrock Mountain, near major tributary to Stillwater Brook. Leucogneiss occurs as layers in a migmatitic biotite-hornblende-plagioclase gneiss.

Leucogneiss is chalk-white or very pale pink in outcrop and white or reddish in hand specimens. It is medium-grained (essential minerals 1-2 mm. across; quartz plates may exceed 5 mm.) and xenoblastic. Foliation appears locally because of parallel orientation of sparse hornblende and biotite crystals and large quartz plates. Albite-oligoclase (35-60 percent; An_{7-18} on the basis of four N_x measurements of 1.532-1.538 ± 0.001; antiperthitic and myrmekitic) and quartz (12-40 percent) are the principal minerals (table 6). Microcline (2.5-27.2 percent) occurs chiefly in antiperthite lamellae, but is locally abundant as free grains. The reddish cast of hand specimens is due to minute, reddish brown inclusions in the plagioclase. They are too small for identification here, but Sims (1958, p. 31) found similar inclusions to be hematite.

Magnetite and ilmenite (0.2-4.7 percent), in both separate grains and intergrowths, are the most abundant mafic minerals. Brown biotite, green hornblende, and clinopyroxene occur locally. Zircon (rounded, locally subhedral) and apatite (rounded, rarely subhedral) are widespread accessory minerals. Sphene, epidote, clinozoisite, and muscovite are rare.

Origin of the quartz-plagioclase gneisses

Characteristics of the quartz-plagioclase gneisses which must be considered in their interpretation are: (1) their chemical compositions, in particular their high soda/potash ratios (table 7); (2) their restricted ranges of modal composition (less true of leucogneiss than of hypersthene-quartz-oligoclase gneiss); (3) their great areal extent; and (4) their intimate association with amphibolite. We may consider three hypotheses of origin for the gneisses: (1) intrusion as melts; (2) isochemical metamorphism of sediments or volcanic rocks; (3) diagenetic or metamorphic alteration of existing rocks. The first and second hypotheses are shown below to be improbable; the third wins a none-too-convincing victory by default.

Table 7. Calculated abundances of CaO, Na_2O, and K_2O in the quartz-plagioclase gneisses (Wt. percent)*

Oxide	Hypersthene-quartz-oligoclase gneiss	Quartz-Plagioclase leucogneiss
CaO	6.4	1.4
Na_2O	8.4	5.2
K_2O	0.8	2.2
Total	15.6	8.8
Na_2O/K_2O	10.5	2.4

* Oxides were calculated from average modes for each rock type, using the average composition of plagioclase. Clinopyroxene was assumed to be pure diopside, biotite 50 percent phlogopite and 50 percent annite, and hornblende was assumed to be the average of Adirondack hornblendes as given by Buddington and Leonard, 1953. The results, though hardly quantitative, adequately express the general chemical relationships.

In theory, potash-poor magmas can arise in several ways: through contamination of granitic magma by limestone (Dietrich, 1957, p. 82) or amphibolite (Buddington, 1939, p. 170); by extraction of early-crystallized biotite from a wet diorite magma (Goldschmidt, 1922, p. 6-8); by partial fusion of basalt, andesite, or tonalite (Bass, 1956; Yoder and Tilley, 1956), or biotite-quartz-plagioclase gneiss (Buddington, 1939, p. 170 and 1948, p. 38; Sims, 1958, p. 39); and by unmixing of a sodic melt from a granitic melt (Sundius, 1925, p. 35). Although only the last of these mechanisms can be ruled out on the basis of theory and experiment (Bowen, 1928, p. 12), all of the others require conditions which are not indicated in the exposed Highlands. There is too little marble to account for the gneisses by Dietrich's mechanism, and amphibolite appears in clearly defined, unresorbed xenoliths in the Highlands granites. Biotite-rich residues are not in evidence as predicted by Goldschmidt's hypothesis, nor are the basic residues to be expected from partial fusion of volcanic rocks or gneisses. All of these difficulties can, of course, be circumvented by invoking more favorable conditions at greater depths.

There are arguments which militate against the intrusive hypothesis regardless of the magma source: the absence of intrusive relations with other gneisses (Sims, 1958, p. 39, describes a discordant quartz-albite pegmatite which may be related to the present units; a red quartz-albite pegmatite found with fragments of ore from the Forest of Dean mine may be similar, but its field relations are unknown); the improbability of migration of potash-poor magma through potash-bearing gneisses without substantial contamination; and the improbability of the close relations between the quartz-plagioclase gneisses and amphibolites if the former are intrusives.

Isochemical metamorphism is scarcely more attractive, as the high soda/potash ratios in the gneisses (table 7) are hard to match with possible parent rocks. No sediments known to the writer show a ratio as high as that in hypersthene-quartz-oligoclase gneiss (roughly 10:1). Even in soda-rich graywackes, Na_2O/K_2O seldom exceeds unity (Pettijohn and Bastron, 1959, p. 596), though Reed (1957, p. 13) records a ratio of about 5:1 for a single New Zealand sample. Some of the cobalt argillites have ratios up to 3:1, but contain less lime than does hypersthene-quartz-oligoclase gneiss (Pettijohn and Bastron, 1959, p. 595). The soda/

potash ratio of leucogneiss (variable, but about 2:1) can be satisfied by either graywackes or argillites, but its extremely low mafic content cannot.

The chemical compositions of the gneisses also rule out most volcanic rocks, in which high soda/potash ratios are accompanied by high contents of Ca, Fe, and Mg (Nockolds, 1954). A possible exception is the quartz-keratophyres (Turner and Verhoogen, 1960, p. 262), which resemble leucogneiss in their K-Na-Ca relations. However, the paucity of potash in these rocks is itself a petrogenetic problem. In summary, there appears to be no sedimentary or volcanic parent which could produce either of the quartz-plagioclase gneisses by isochemical metamorphism.

It seems necessary to assume that the parents of the quartz-plagioclase gneisses have been chemically altered during either diagenesis or metamorphism. Engel and Engel (1953, pp. 1,080-1,090) suggest that the Major Paragneiss of the Adirondacks represents a reworked sodic tuff to which soda was added during diagenesis. Dickinson (1962, p. 260) has suggested an opposite mechanism—loss of potash during diagenesis—for the development of quartz keratophyres. Dickinson's mechanism is preferable in the present case, as the chemical problem is a deficiency of potash rather than an excess of soda. The possibility that the quartz-plagioclase gneisses lost potash during metamorphism (Ramberg, 1948) is hard to reconcile with the abundance of potash in the other gneisses and sharp contacts between potassic and potash-poor gneisses.

In conclusion, the writer prefers an hypothesis which invokes pairs of diagenetically altered volcanic parents for the intercalated quartz-plagioclase gneisses (quartz-keratophyres?) and amphibolites (spilites?), but in the absence of stronger evidence at present, the gneisses remain of uncertain origin.

Petrology of the Igneous Rocks

Introduction

The igneous rocks of the Popolopen Lake quadrangle include several granites, a granodiorite of uncertain affinity, and many types of dike rocks. The granites are interpreted as the products of a single magmatic episode which accompanied and slightly outlasted metamorphism and deformation, and which was accompanied by partial fusion of the gneisses. The granodiorite and the dike rocks are regarded as posttectonic in view of their chilled contacts and the absence of tectonite fabrics. They are younger than the granites and were emplaced at shallower depths, but their stratigraphic and absolute ages are unknown.

Syntectonic intrusive rocks: hornblende granite and related granites

Types and distribution

Four types of granite can be distinguished in this area on the basis of the types and abundances of varietal minerals. In order of decreasing abundance, these are: (1) hornblende granite, (2) leucogranite and pegmatite, (3) biotite granite, and (4) biotite-garnet granite. As all but the last of these occur together and intergrade, they are assumed to be the products of a single magmatic episode. Biotite-garnet granite is of very restricted occurrence and cannot be tied to the other granites by field evidence.

Granites similar to those reported here occur elsewhere in the Highlands. They include the Storm King granite (Berkey and Rice, 1919; Colony, 1921; Lowe, 1950), some types of Byram gneiss (Spencer, *et al*, 1908; Hague, *et al*, 1956) and the "hornblende granite and related facies" of Sims (1953; 1958) and Hotz (1953).

The chief granite type, hornblende granite, is described in detail below. The other types are then discussed briefly, and the origin of all the granites is taken up in a concluding section.

Hornblende granite

Field relations

Hornblende granite is dark, bronzy green in road cuts and buff or pink in fresh exposures elsewhere. It weathers to pink, rounded surfaces which commonly display sheeting (e.g. at the summit of Bear Mountain). Zones of intensely weathered granite occur on the north side of Bear Mountain (south side of Palisades Interstate Parkway) and on the south side (along Perkins Memorial Drive—see also Lowe, 1950, pp. 141-142), but in general the rock is very resistant and forms many summits in the quadrangle.

Sheets and lenses of the granite, which are from a few to hundreds of feet thick and which tend to thicken in fold noses, occur throughout the quadrangle in all types of host rocks. These masses are concordant at map scale and possess a foliation which parallels that in the host rocks. However, the granite is commonly transgressive in detail (figure 5) and it locally fingers out into the gneisses along strike. The only rocks which cut granite are granite pegmatite dikes, quartz veins, and posttectonic dikes. The last include an aplite which resembles the granite but is finer grained and nearly free of mafic minerals. (The location of this aplite and a modal analysis are given in table 9; Lowe, 1950, p. 147, describes similar material).

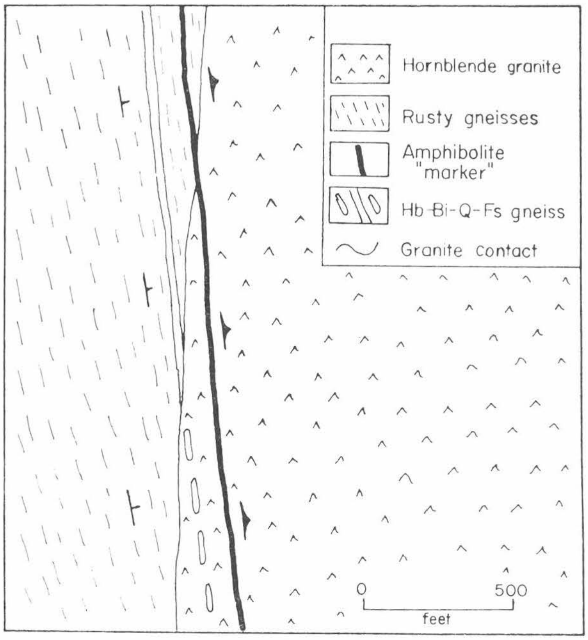


FIGURE 5. Contact relations of hornblende granite, west side of West Mountain

A strong linear alignment of single crystals and clots of hornblende is visible in most outcrops. This grades locally to a foliation in which platy masses of quartz also take part. Foliation is typically most pronounced near the borders of large granite masses and in the limbs of tightly folded sheets, but this correlation of fabric and position is imperfect

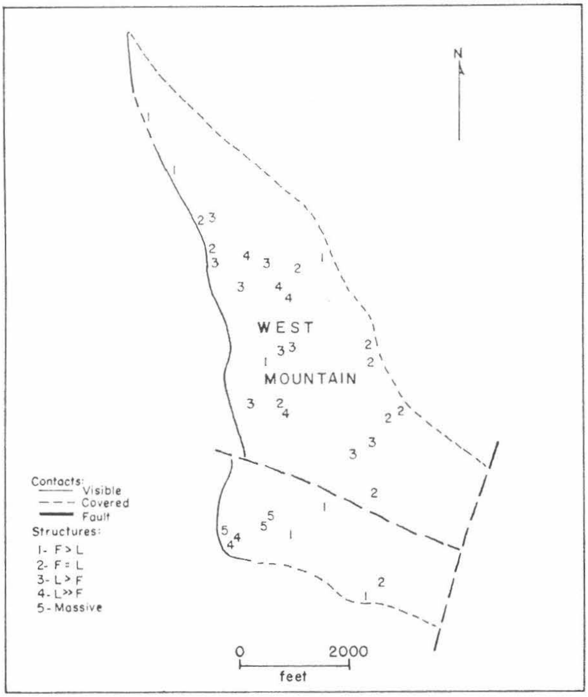


FIGURE 6. Relation of foliation (F) to lineation (L) in hornblende granite at West Mountain

(figure 6). The few inclusions which occur in the granite (mainly Amphibolite I) are nearly always aligned with the foliation.

Petrography and mineralogy

Most of the major granite masses and many small sheets were sampled, but extended study was restricted to the Bear and West Mountain plutons. Sampling is inadequate for more than a survey of the granites. The modal analyses in table 8 are from the entire quadrangle. They are grouped according to structural position, and discussed below.

The granite is medium- to coarse-grained (essential minerals typically 1½ to 2½ mm. in diameter, ranging to 6 mm. or more at Bear and West Mountains) and hypidiomorphic-granular. Microcline-microperthite (26-65 percent, commonly with albite or, rarely, microcline, rims; locally accompanied by free microcline), oligoclase (3-30 percent, usually myrmekitic; rarely slightly antiperthitic), and quartz (15-38 percent) are the essential minerals. Hornblende (0-13 percent; *X* tan, *Y* and *Z* dark green or brownish green), brown biotite (0-3 percent, locally intergrown with hornblende), and clinopyroxene (0-1 percent) are the varietal minerals, the last practically restricted to Bear Mountain and West Mountain. Hornblende and biotite are locally chloritized, while the pyroxene is typically partly or wholly serpentinized. Magnetite and ilmenite, as separate grains and in intergrowths, are the most abundant accessories. Rounded to subhedral apatite grains and euhedral or slightly rounded zircons (see Eckelmann, 1963) are also typically present. Sphene, tourmaline, allanite, and epidote are rare accessories, the last appearing near shear zones. Garnet and graphite are present in the granite near garnetiferous or graphitic host rocks.

The modal data in figure 8 show both a general similarity among granite samples and some minor but apparently significant differences in mineralogy. In the three large sheets represented in the table, biotite and hornblende increase near contacts (see also Lowe, 1950, p. 145) while potash feldspar decreases. The small concordant granite sheets are modally variable, but most samples from this setting show a greater ratio of plagioclase to potash feldspar than is found in the granites from large masses, and in some cases plagioclase predominates.

It should be noted that the modes in tables 8 and 9 present two sets of figures for plagioclase and potash feldspar. In the first set ("Alkali feldspar," "Free plagioclase"), perthites are counted as alkali feldspar; in the second set, a correction is made for the plagioclase content of perthites (see the footnote to table 8 for method) to arrive at a better estimate of the plagioclase: potash feldspar ratios. A comparison of uncorrected and corrected modal data for samples from Bear and West Mountains (respectively figures 7a and 7b) shows that contact samples in these granite masses show a higher proportion of free plagioclase than do interior samples (see Hague, *et al*, 1956, pp. 453 and 458-459 for similar results), but that the plagioclase: potash feldspar ratios are nearly the same in interior and contact samples. (It should also be noted that a comparison of figures 7a and 7b suggests that the West Mountain granites have, in general, somewhat less quartz than the Bear Mountain samples. This distinction is unexplained but could signify a difference in water vapor pressure for the two masses, as suggested by the Ab-Or-Q diagram in figure 10.) Figure 8, which presents similar data for the granites from small sheets, shows that these granites display a more thorough separation of the two feldspars than do the large masses. As the small sheets occur chiefly in tight folds and are strongly foliated, the feldspar data appear to support Chayes' contention (1952, p. 293) that stress promotes exsolution in perthites.

Table 8. Modal analyses of hornblende granites

	1	2	3	4	5	6	7	8	9	10	11	12	13
Alkali feldspar	63.6	59.8	49.3	57.9	49.0	35.8	28.4	47.8	29.6	32.7	37.3	26.6	41.5
Free plagioclase	6.4	3.4	17.9	14.5	12.6	28.4	28.4	20.1	26.7	29.2	21.7	28.3	18.0
Quartz	23.0	31.8	22.9	15.3	32.5	19.1	34.1	27.6	37.8	26.8	35.3	34.6	28.0
Hornblende	5.5	2.5	8.0	7.9	4.7	8.9	5.1	1.1	2.3	9.7	2.2	9.0	9.1
Clinopyroxene	—	0.7	—	0.1	tr.	—	0.9	—	—	—	—	—	—
Biotite	—	0.4	0.1	—	0.6	—	—	—	1.0	—	1.9	—	—
Fe-Ti oxides	0.8	0.5	0.9	0.8	—	4.8	0.7	1.0	1.2	0.8	1.2	1.0	1.6
Apatite	0.1	0.1	0.2	0.3	tr.	0.2	0.5	0.1	0.3	—	—	0.2	0.3
Zircon	tr.	tr.	0.1	0.1	tr.	0.1	tr.	—	—	—	—	tr.	0.1
Alteration (except sericite)	0.6	0.6	0.6	3.0	0.4	2.6	1.6	0.7	1.1	0.8	0.6	0.2	1.4
Others	—	0.2	—	0.1	0.5	—	0.1	1.5	—	—	—	—	—
Total	100.0	100.0	100.0	100.0	100.3	99.9	99.8	99.9	100.0	100.0	100.2	99.9	100.0
K-feldspar*	40.1	37.4	41.7	39.4	32.5	33.8	27.2	45.1	26.6	27.9	34.7	25.6	37.5
Plagioclase*	29.9	25.8	25.5	33.0	29.1	30.4	29.6	22.8	29.7	34.0	24.3	29.3	22.0

* These figures are adjusted feldspar values based on 300-point modes of perthites. (X ray study of perthites from the granites, using the method of Tuttle and Bowen (1958), indicates that little or no potash feldspar resides in plagioclase and vice versa; the modes thus approach true abundances closely.) The main modes are 1,000 to 2,000 points per sample.

Granites from the interiors of major masses

1. Average of five samples from the interior of West Mountain
2. Average of two samples from the interior of Bear Mountain
3. Average of two samples from the interior of Letterrock Mountain

Granites from near contacts of major masses

4. Average of four samples from near contacts of West Mountain
5. Average of four samples from near contacts of Bear Mountain
6. Single sample from near contact of Letterrock Mountain

Granites from small, concordant sheets

7. Sample No. 077: North side of Tiorati-Cohasset Road, north of Cohasset Lake
8. Sample No. 432: South end of Bradley Mountain, near contact ("Others" = 1.5 percent garnet)
9. Sample No. 530: Route 6, south side, north end of Stockbridge Mountain
10. Sample No. 629: East of Summit, Cranberry Hill
11. Sample No. 732: Just north of Surebridge Swamp
12. Sample No. 1042: West side of Palisades Interstate Parkway, east-northeast of Owl Lake
13. Sample No. 1669+: Southeast flank of Long Mountain

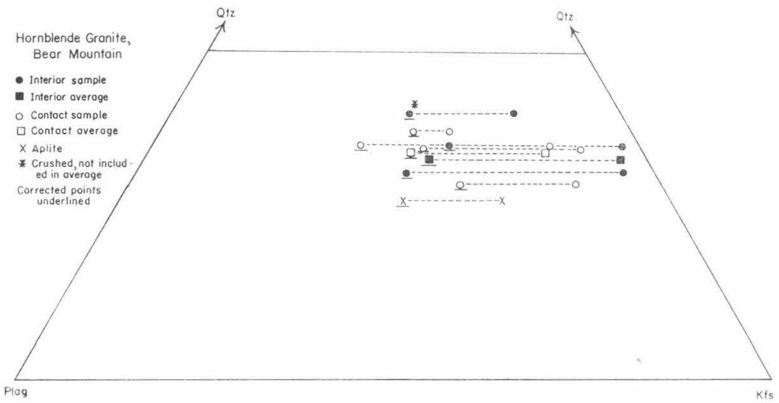


FIGURE 7a. Orthoclase:plagioclase:quartz relations in samples of hornblende granite from Bear Mountain (based on modal analyses).

For each sample, the point to the right is uncorrected for plagioclase contained in perthites; that to the left represents total potash feldspar and total plagioclase.

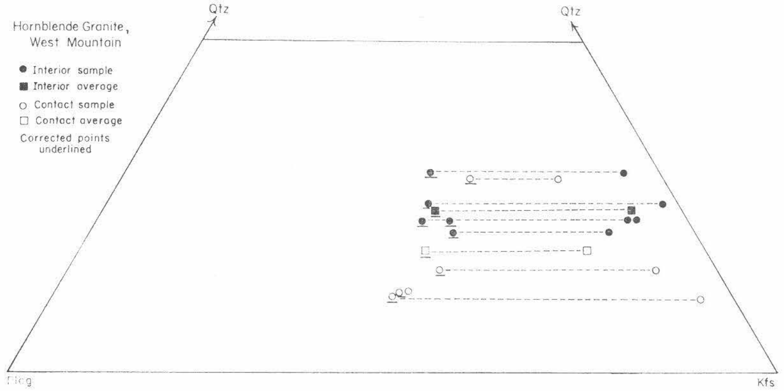


FIGURE 7b. Orthoclase:plagioclase: quartz relations in samples of hornblende granite from West Mountain. Significance of points is as in figure 7a.

Note that the West Mountain samples are somewhat poorer in quartz than those from Bear Mountain.

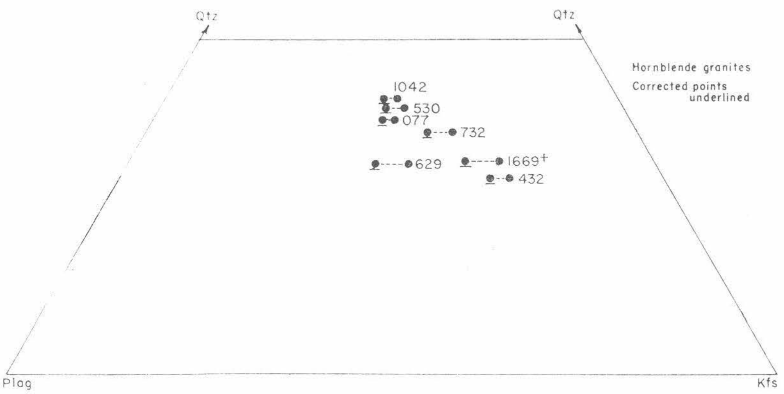


FIGURE 8. Orthoclase:plagioclase: quartz ratios in seven hornblende granites from thin, concordant sheets in isoclinal folds. Representation as in figure 7a. Sample locations given in table 8.

Leucogranite

Leucogranite and coarser but otherwise similar granite pegmatite occur as concordant and cross-cutting layers in other units and, locally, as thick, independent sheets. In some places (e.g. the east side of Stockbridge Mountain), they grade into hornblende granite along strike.

Leucogranite forms pink, rounded exposures which typically lack linear structures and show only a weakly defined quartz foliation. The rock is pink or buff in fresh cuts, medium-grained to pegmatitic, and composed almost entirely of salmon, buff, or white feldspars and gray or glassy quartz, with very minor magnetite, biotite, or (in pegmatite) hornblende.

Major sheets of leucogranite have contact relations similar to those described for hornblende granite. Some of the discordant dikes have straight, undeformed walls, while others are boudinaged or folded. The emplacement of leucogranite and pegmatite evidently occurred both during and after deformation of the gneisses.

Texturally, the leucogranites differ from hornblende granite chiefly in lacking a conspicuous oriented fabric. Mineralogically, they differ in the abundance and types of mafic minerals (less than 2 percent, chiefly opaque oxides and biotite, both slightly altered), in a slightly greater abundance of quartz (25-35 percent vs. 15-30 percent in hornblende granite; see table 9), and in a greater tendency toward separation of the two feldspars (figure 9). The last distinction may be misleading, however, as most of the leucogranite samples are from tight folds, in which the hornblende granite too shows unusually complete separation of the feldspars. The accessory minerals are as described for hornblende granite.

Table 9. Modal analyses of leucogranites and biotite granite

	683	567	768	826	437/2	1,038	apl	928	954	934
Alkali feldspar	42.3	48.8	58.3	60.4	53.7	41.4	49.9	55.3	56.8	41.5
Free plagioclase	19.6	18.2	5.4	3.2	15.9	31.4	22.2	6.3	2.7	4.7
Quartz	34.2	30.3	34.0	35.9	30.2	26.2	27.7	24.5	23.5	48.0
Biotite	—	1.4	0.6	0.4	—	tr.	—	12.4	6.6	3.1
Pyroxene	—	0.4	—	—	—	—	—	—	—	—
Fe-Ti oxides	2.1	0.4	1.1	0.1	0.2	tr.	0.2	1.0	2.4	1.0
Apatite	tr.	tr.	—	—	tr.	—	—	—	tr.	—
Zircon	tr.	0.1	tr.	tr.	tr.	—	tr.	tr.	tr.	0.1
Sphene	—	—	tr.	—	—	—	—	tr.	—	—
Alteration (except sericite)	1.4	0.4	0.6	—	tr.	1.2	—	0.1	8.0	1.6
Others	—	—	—	—	—	—	—	0.4	tr.	tr.
Total	99.6	100.0	100.0	100.0	100.0	100.2	100.0	100.0	100.0	100.0
K-feldspar*	39.6	44.8	46.3	47.6	49.2	32.9	36.9	28.2	32.9	22.2
Plagioclase*	22.3	22.2	17.4	16.0	20.4	39.9	35.2	33.4	35.6	24.0

* Corrected values based on subtraction of the plagioclase component from perthite. The abundances of plagioclase and potash feldspar in perthite were determined with separate 300-point modal analyses of perthite; the other modes all consist of 1,000 points each.

Leucogranites:

683. Leucogranite associated with granite pegmatite. Knob just southwest of the south end of Cranberry Lake.

567. Fine- to medium-grained leucogranite. Ridge immediately east of Summit Lake. Both ortho- and clinopyroxene are present.

768. Fine- to medium-grained, homophanous leucogranite. Just west of the north end of Lake Te-Ata.

826. Typical leucogranite, medium-grained. 0.3 miles east of Lake Massawippa dam.

437/2. Leucogranite, medium-grained, occurring as a layer in gneissic hornblende granite. West side of Bradley Mountain.

1,038. Medium-coarse-grained leucogranite, grading to pegmatite. Just west of gas station on the Palisades Interstate Parkway.

Aplite:

apl. Underformed dike cutting hornblende granite. South side of Palisades Interstate Parkway on the north side of Bear Mountain.

Biotite granite:

928. Valley between south knobs of Letterrock and Goshen Mountains

954. Northwest side of Letterrock Mountain, near the contact of this unit with hornblende granite

934. East side, south end, of Letterrock Mountain

Biotite granite

Biotite granite is restricted to the northwest side of Letterrock Mountain, where it grades upward to migmatitic biotite-quartz-feldspar gneiss and downward to hornblende granite (plate 1). It is evidently a border facies of the hornblende granite, from which it differs in containing abundant biotite and no hornblende, in containing slightly more plagioclase (and less free plagioclase) (tables 8 and 9; figure 9), and in showing only rounded or, rarely, subhedral zircons. The other accessories are as described for hornblende granite.

A minor textural distinction of possible genetic significance is the presence in this unit of considerable patch perthite in addition to mesoperthite; the patch texture is rare in the other granites.

Biotite-garnet granite

Thin sheets, a few to a few tens of feet thick, of garnetiferous biotite granite gneiss occur in hypersthene-quartz-oligoclase gneiss near Twin Lakes. The gneiss resembles leucogranite in outcrop but has a good biotite foliation, which is enhanced by the presence of layers rich in porphyroblastic red garnet. The rock is similar to the other granites in thin section, but contains about 5 percent each of brown biotite, garnet, and opaque iron-titanium oxides. Most of the plagioclase occurs as lamellae in mesoperthite.

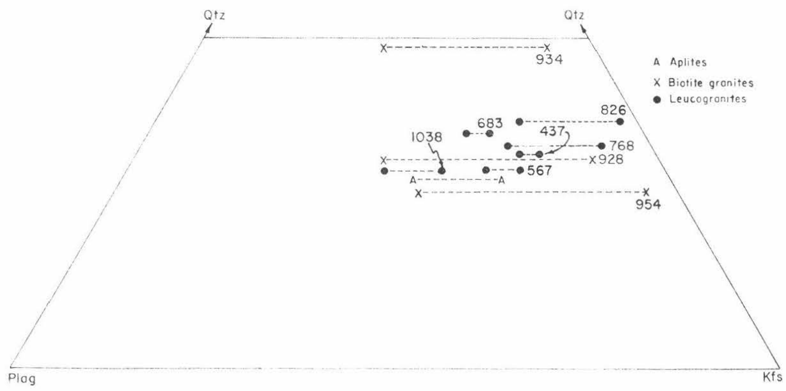


FIGURE 9. Orthoclase:plagioclase: quartz ratios for leucogranites, aplite and biotite granites. Representation as in figure 7a. Sample locations given in table 9.

Origin of hornblende granite and related rocks

The granites of this quadrangle are typical syntectonic, catazonal granites (Buddington, 1959, pp. 714-15): They have generally concordant contacts which lack both chilled facies within the granite and contact metamorphic aureoles in the host. They are locally migmatitic. They carry inclusions which are typically, but not invariably, aligned with foliation. Finally, they are associated with plastically deformed gneisses of high metamorphic grade. The sporadic occurrence of undeformed, discordant granite pegmatite and aplite dikes suggests that the granite-forming episode, though chiefly syntectonic, slightly outlasted deformation.

The structural relations listed above fit either a magmatic or a metasomatic interpretation of the granites. Uniformity of composition, and the approximate coincidence of this composition with the ternary eutectic in the system albite-orthoclase-quartz (figure 10; see also Bowen and Tuttle, 1958, p. 75) favor the magmatic interpretation, but Orville (1962) has shown that a granitic composition can also be reached by nonmagmatic alkali transfer in a chloride-rich vapor. The compositional evidence is persuasive but not compelling.

However, several lines of evidence suggest that most of the granite in this quadrangle is magmatic: (1) the tendency for large granite masses (e.g. Bear and West Mountains, plate 1) to thicken in fold noses while the surrounding gneisses remain of nearly constant thickness; (2) the tendency for foliation to be strongest near the contacts in large granite masses (Balk, 1937); and (3) the presence of euhedral, zoned zircons in the granite at Bear Mountain (Eckelmann, 1963, and personal communication) and of rounded zircons in the other gneisses.

Metasomatism appears to have played a minor role near some contacts, as is suggested by: (1) the contact relations on the west side of West Mountain (figure 5); (2) gradations between biotite-hornblende-quartz-feldspar gneiss and amphi-

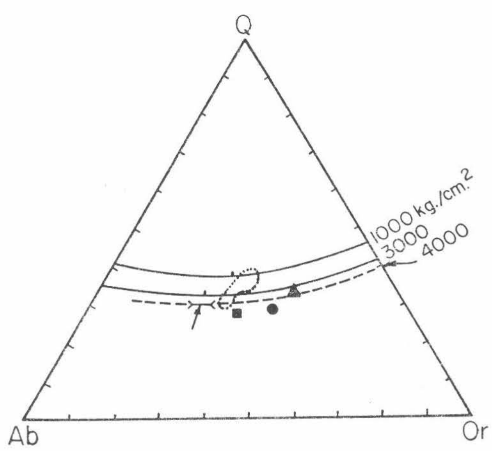


FIGURE 10. Average albite-orthoclase-quartz ratios from modes of 27 hornblende granites (circle), 6 leucogranites (triangle), and 2 biotite granites (square), plotted against isobaric minima in the experimental system at various pressures of water vapor (Tuttle and Bowen, 1958, p. 75). The dotted line outlines the maximum for a plot of all rocks from Washington's Tables which contain more than 80 percent normative AB, OR, and Q.

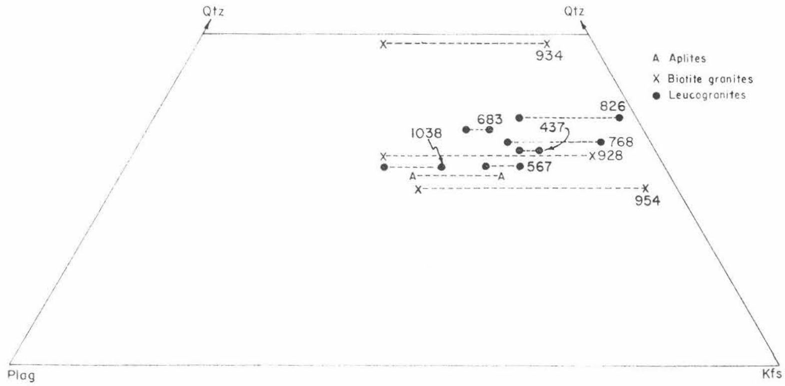


FIGURE 9. Orthoclase:plagioclase: quartz ratios for leucogranites, aplite and biotite granites. Representation as in figure 7a. Sample locations given in table 9.

Origin of hornblende granite and related rocks

The granites of this quadrangle are typical syntectonic, catazonal granites (Buddington, 1959, pp. 714-15): They have generally concordant contacts which lack both chilled facies within the granite and contact metamorphic aureoles in the host. They are locally migmatitic. They carry inclusions which are typically, but not invariably, aligned with foliation. Finally, they are associated with plastically deformed gneisses of high metamorphic grade. The sporadic occurrence of undeformed, discordant granite pegmatite and aplite dikes suggests that the granite-forming episode, though chiefly syntectonic, slightly outlasted deformation.

The structural relations listed above fit either a magmatic or a metasomatic interpretation of the granites. Uniformity of composition, and the approximate coincidence of this composition with the ternary eutectic in the system albite-orthoclase-quartz (figure 10; see also Bowen and Tuttle, 1958, p. 75) favor the magmatic interpretation, but Orville (1962) has shown that a granitic composition can also be reached by nonmagmatic alkali transfer in a chloride-rich vapor. The compositional evidence is persuasive but not compelling.

However, several lines of evidence suggest that most of the granite in this quadrangle is magmatic: (1) the tendency for large granite masses (e.g. Bear and West Mountains, plate 1) to thicken in fold noses while the surrounding gneisses remain of nearly constant thickness; (2) the tendency for foliation to be strongest near the contacts in large granite masses (Balk, 1937); and (3) the presence of euhedral, zoned zircons in the granite at Bear Mountain (Eckelmann, 1963, and personal communication) and of rounded zircons in the other gneisses.

Metasomatism appears to have played a minor role near some contacts, as is suggested by: (1) the contact relations on the west side of West Mountain (figure 5); (2) gradations between biotite-hornblende-quartz-feldspar gneiss and amphi-

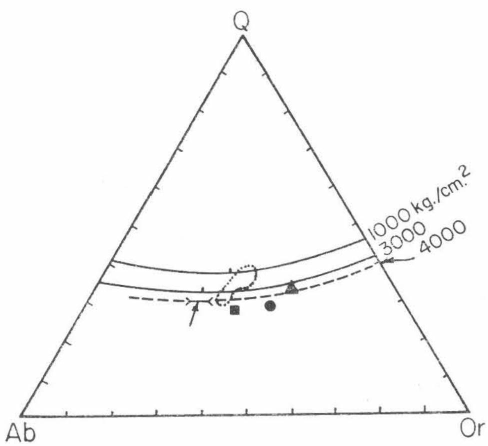


FIGURE 10. Average albite-orthoclase-quartz ratios from modes of 27 hornblende granites (circle), 6 leucogranites (triangle), and 2 biotite granites (square), plotted against isobaric minima in the experimental system at various pressures of water vapor (Tuttle and Bowen, 1958, p. 75). The dotted line outlines the maximum for a plot of all rocks from Washington's Tables which contain more than 80 percent normative AB, OR, and Q.

bolite or hypersthene-quartz-oligoclase gneiss (as noted above, this does not certainly indicate addition of potash and silica to the first rock type; it may represent extraction of these oxides from the second and third); and (3), the presence of rounded (rather than euhedral) zircons, patch perthites (Andersen, 1928), and, in one case, excess quartz in biotite granite.

In summary, the writer interprets the granites of this area as magmatic rocks, which were emplaced during and just after a period of deformation, and which effected minor metasomatic alteration of the host gneisses.

Post-tectonic intrusive igneous rocks

Hornblende-biotite granodiorite

A granodiorite of unknown age and extent occurs in the extreme southeast corner of this quadrangle and in adjacent portions of the Thiells and Haverstraw quadrangles. Its texture and field relations differ from those of the other Highlands rocks and indicate that it is magmatic and posttectonic.

Like much of the hornblende granite, the granodiorite is pink, both on weathered surfaces and in hand specimens. It differs from the granite in lacking an oriented fabric and in having chilled contacts against inclusions of fine-grained, biotitic amphibolite (figure 11). The writer has not seen border contacts between the granidiorite and the Highlands rocks.

The granodiorite is medium-grained (feldspars 1-6 mm., quartz up to 3 mm., mafics up to 2½ mm. but typically 1 mm.) and seriate-inequigranular. The mafic minerals are subhedral to anhedral, the felsic minerals anhedral and interlocked (plate 4). The rock shows neither foliation nor lineation.

The mineral proportions vary somewhat with distance from inclusions. Far from inclusions, the rock consists of about 50 percent plagioclase (*zoned*, with polysynthetic twinning; locally highly sericitized), 15-25 percent potash feldspar (microcline, locally slightly perthitic and with albite rims), about 15 percent quartz, and about 15 percent highly pleochroic green hornblende and brown biotite, which are commonly intergrown. The hornblende is of particular interest, as it occurs as prisms with as much as a tenfold elongation, which contrast strikingly with the stubby laths in the other Highlands rocks. Accessories include magnetite, zircon (slender euhedra up to 0.5 mm. long and with as much as eight-fold elongation), and euhedral apatite.

Near inclusions, the potash feldspar content rises to about 80 percent while the abundances of quartz, plagioclase, and the mafic minerals diminish.

The granodiorite is imperfectly known at all levels of study. It deserves further attention.

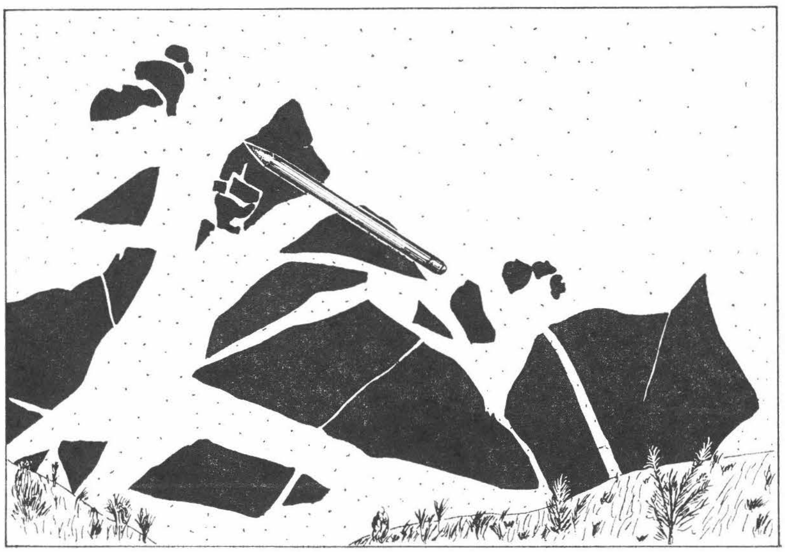


FIGURE 11. Angular inclusions of amphibolite (black) in hornblende-biotite granodiorite (lightly stippled) at Camp Bullowa, extreme northwest corner of the Haverstraw quadrangle.
The absence of foliation and the presence of chilled contacts against inclusions are unique to this unit and set it apart from the Highlands granites.
Drawn from a photograph.

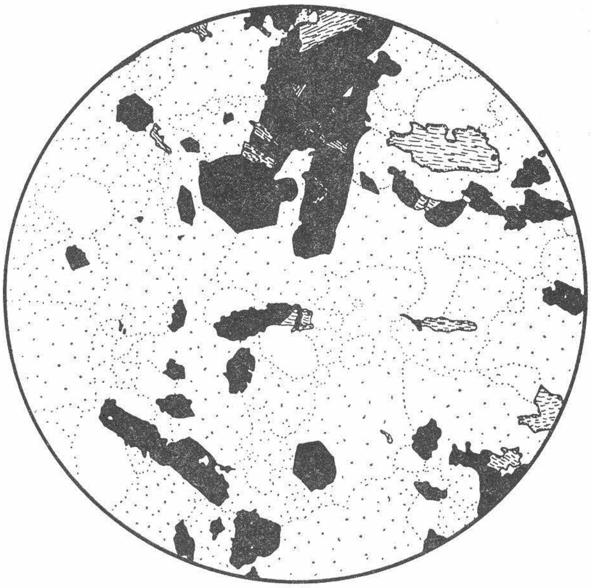


FIGURE 12. Thin section of hornblende-biotite granodiorite (location as for figure 11). Field diameter 10 mm.
The constituents are hornblende (black), biotite (dashed pattern), feldspars (lightly stippled), and quartz (white). Note the prismatic habit of hornblende and its random orientation.
Drawn from a photograph.

Dike rocks

Several types of dike rocks occur in the Highlands of the Popolopen Lake quadrangle. All have crosscutting relations with the Highlands rocks, and most have chilled border facies. They appear to be younger than both the granites and the post-granite faults, but their ages are unknown. There is a tendency for dikes to be more numerous toward the southeast, suggesting a relationship with the Palisades diabase (Late Triassic), although Jaffe and Jaffe (1962, p. B-3) have found post-Ordovician, possible pre-Triassic dikes in the Monroe quadrangle to the west.

The dike rocks were not studied in thin section, but they were divided in the field into three categories:

1) Mafic-rich, dark greenish-gray to black, fine-grained rocks, which consist principally of pyroxenes, plagioclase, and, locally, hornblende. This is the most abundant type (47 out of 71 observed dikes) and includes equigranular rocks (34) and porphyritic rocks (13), the latter carrying phenocrysts of pyroxene, plagioclase, and/or hornblende.

2) Medium-gray, fine-grained to aphanitic rocks, which consist (where minerals can be identified) of gray or white feldspars, quartz, and less than 30 percent of biotite and/or hornblende. Five of these dikes are equigranular; 10 carry phenocrysts of pink feldspar, hornblende, and/or quartz (?).

3) Pinkish to greenish-gray, aphanitic, mafic-poor rocks. Nine of the observed dikes are of this type.

Metamorphism

Metamorphic facies

As a background for discussion, it is useful to quote Turner's statement (in Fyfe, *et al*, 1958, p. 232) on the definition and subdivisions of the granulite facies:

> "Eskola's (1939, p. 360) granulite facies was proposed to cover an association of regionally metamorphosed rocks characterized by the pair kyanite- (or sillimanite-) garnet in place of micas, and diopside-hypersthene in place of amphiboles. The garnet is almandine-pyrope, typically with notable substitution of Ca^{+2} for Fe^{+2}, much as in the garnets of eclogites. Cordierite is said to be absent from true granulites, and rutile is a highly characteristic minor constituent. For rocks conforming strictly to these specifications the new pyroxene-granulite subfacies is now proposed. They are to be distinguished from an association of hornblende-, biotite-, and cordierite-bearing granulites (in some respects similar to the almandine amphibolite facies) which is so extensively developed in some terranes as to warrant independent status. This is here termed the hornblende granulite subfacies."

The principal mineral assemblages of the gneisses in the Popolopen Lake quadrangle (table 10) meet Turner's requirements for assignment to the hornblende granulite subfacies. The first assemblage in table 10 is also appropriate to the almandine amphibolite facies, but in view of its close field association with the other assemblages, it probably formed under the same conditions and is assigned to the same facies.

Although there are no recognizable changes of metamorphic grade within the quadrangle, there is a suggestion that the undifferentiated biotitic gneisses of the southeast corner of the area experienced slightly higher temperatures than did the other gneisses: They locally contain brown hornblende, which is absent elsewhere and has been interpreted as indicative of high temperatures (Barnes, 1930), and the associated amphibolites are more intricately puckered than those in other parts of the quadrangle, suggesting unusually high plasticity for this rock type.

Table 10. Major mineral assemblages in the Popolopen Lake quadrangle, compared with those of Turner (Fyfe, *et al*, 1958)

Popolopen Lake quadrangle	*Turner*	*Remarks*
1. Quartz-microcline-plagioclase- biotite- (garnet, sillimanite, graphite). *Biotite-quartz-feldspar gneisses.*	Quartz-microcline-sillimanite-almandine- (plagioclase, biotite). Almandine amphibolite facies and hornblende granulite subfacies.	Appropriate to both the almandine amphibolite facies and the hornblende granulite subfacies (Turner, 1958, p. 235).
2. Plagioclase-hornblende-diopside- (biotite, hypersthene). *Amphibolites I and II.*	Plagioclase-hornblende-diopside-hypersthene. Pyroxene granulite subfacies.	Hypersthene not appropriate to the almandine amphibolite facies; biotite not expected in the pyroxene granulite subfacies.
3. Plagioclase-hypersthene-quartz- (diopside, biotite, hornblende). *Hypersthene-quartz-oligoclase gneiss.*	Plagioclase-hypersthene-diopside- (quartz, orthoclase). Pyroxene granulite subfacies.	The present gneisses show biotite and hornblende in a granulite facies assemblage; the sparse potash feldspar is microcline, not orthoclase.

Slight retrograde metamorphism is suggested by the sporadic occurrence of epidote and chlorite (partly replacing, respectively, plagioclase and mafic minerals) and the more general occurrence of sericite (paragonite?) partly replacing plagioclase. Chlorite and epidote are typically found in the gneisses near faults and are thought to be largely or wholly related to mineralization along the faults. The sericite is not restricted to a particular setting and probably reflects a more widespread process, either retrograde metamorphism during the late stages of the principal metamorphism, or reheating during one or more of the Paleozoic orogenies which are represented in the rocks east of the Highlands.

Conditions of metamorphism

The temperature, pressure, and water vapor pressure of metamorphism are hard to assess quantitatively. The data available for the present area permit only a general definition of these parameters.

Most of the gneisses in the quadrangle contain microcline-microperthite, which indicates that metamorphic temperatures exceeded the feldspar solvus, whose crest is at 660°C. for the albite-orthoclase system at 1,000 bars total pressure (Tuttle and Bowen, 1958, p. 40) and is raised by higher pressures with the addition of anorthite to the system (Yoder, Stewart, and Smith, 1957, p. 213). As the microperthites in this area are potash-rich, they lie off the crest of the solvus and can only be said to represent temperatures of greater than about 500°C.

Other data suggest that the minimum temperature indicated by the perthites is at least 200° too low. Apparently anatectic granites in the biotitic gneisses suggest temperatures of about 700°C., if P_{H_2O} was of the order of 2,000 bars (Winkler and von Platen, 1960, p. 57). The development of sillimanite from biotite in the rusty biotitic gneisses suggests temperatures of 700-800°C. (Miyashiro, 1961, pp. 285-286), and this range coincides with that proposed by Turner and Verhoogen (1960, p. 557) for the granulite facies.

The total and water vapor pressures of metamorphism are harder to assess. The absence of cordierite has been interpreted as due to high pressures (Turner and Verhoogen, 1960, p. 557), but can be explained in other ways (Ramberg, 1952, p. 61; Yoder, 1952, p. 623; Winkler and von Platen, 1960, p. 56). The albite: orthoclase: quartz ratios of the Highlands granites (figure 10) suggest crystallization under water vapor pressures of the order of 3,500-5,000 bars (Bowen and Tuttle, 1958, p. 75), although neglect of the effect of lime on the eutectic introduces much uncertainty into this conclusion. If we assume that 4,000 bars is of the right order, and that the total pressure was equal to or greater than this vapor pressure, then the depth of emplacement was 7 miles or more. This result, though far from authoritative, agrees well with the depths of 7-12 miles suggested by Buddington 1959, pp. 714-722) for the catazone, and with Miyashiro's estimate of a pressure of 4,500 bars for the development of granulite facies assemblages at a temperature of 700°C. (1961, p. 285).

III. STRUCTURAL GEOLOGY

Introduction

The structures of the Highlands rocks of the Popolopen Lake quadrangle represent catazonal plastic deformation followed by jointing and faulting at much shallower depths. There is no evidence of premetamorphic structures, nor of more than one episode of folding. In the following sections, the structures are grouped as (1) those of the catazonal phase, and (2) those formed by brittle deformation.

Structures of the Catazonal Phase

The geological map shows a complex pattern of folds, all of which plunge gently to moderately northeastward, and all of which have vertical or eastward-dipping axial planes. The consistency of plunge direction, true, with rare exceptions, throughout the Highlands (Buddington, 1956, p. 117), has not been explained.

The folded structure of the gneisses is best-displayed in the south-central portion of the quadrangle (geologic map; also Lowe, 1950, p. 153). A major synform in the vicinity of Lake Tiorati (plate 1) is typical of folds in this area: It is an approximately cylindrical (figures 13, 14), parallel fold, in which foliation almost invariably parallels lithological contacts and lineation is closely parallel to the fold axis (*b*-lineation).

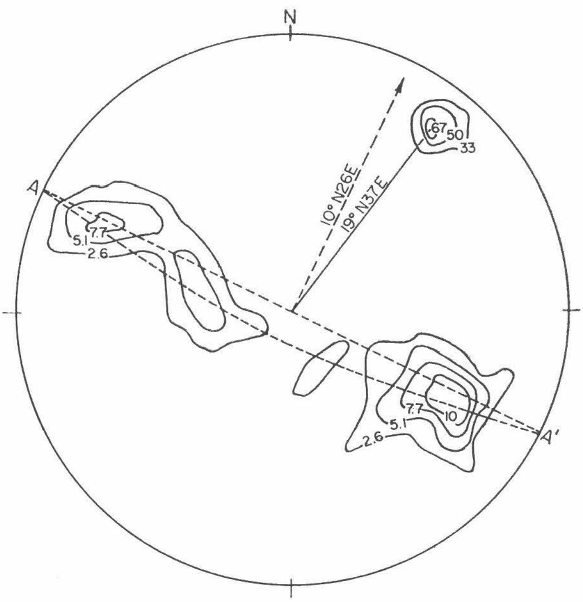


FIGURE 13. Equal area projection (lower hemisphere) of 78 poles to foliation from the Tiorati syncline. Isopleths in percent.

A great circle (A-A′) through the foliation maxima indicates that the fold is essentially cylindrical and plunges 10° N26E. The plunge indicated by twelve lineations is also shown.

This plot determines the general fold form (cylindrical) and plunge used in the construction of figure 14. A similar plot (not shown) was used in the construction of figure 17.

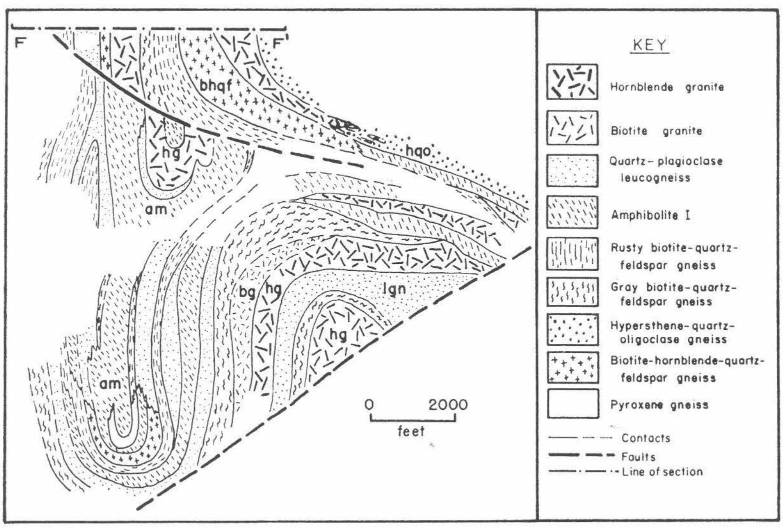


FIGURE 14. Right-normal section (normal to plunge) of the Lake Tiorati-Letterrock Mountain area. Data for the construction are from figure 13.

In the northwestern portion of the quadrangle, and in very tight folds elsewhere, the parallelism between foliation and lithological contacts breaks down because of discordant folding of rock types of different competences (figure 15; an excellent example can also be seen behind the men's bath house at the Anthony Wayne Recreation Area). Such discordances and the absence of distinctive marker lithologies in the large areas of hypersthene-quartz-oligoclase gneiss (geologic map) make elucidation of folds in the northwestern section of the quadrangle difficult.

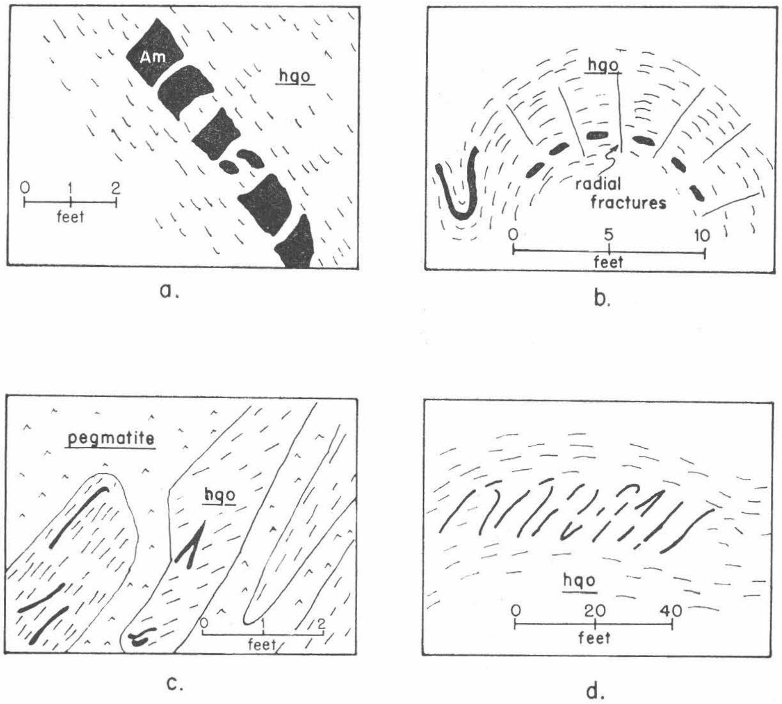


FIGURE 15. Examples of boudinage and discordant folding of amphibolite in hypersthene-quartz-oligoclase gneiss at:
a. Boudinage north side, east end of Mine Lake.
b. Boudinage west side, north end of Blackcap Mountain.
c. East side of valley just east of Surebridge Fire Tower, southeast corner of Monroe quadrangle.
d. North side of summit of Long Pond Mountain.

The map pattern of the eastern part of the quadrangle suggests open folds, but this is probably an illusion. In right-normal section (figure 16, 17; see Stockwell, 1950), the Bear Mountain synform is seen to be a recumbent, isoclinal fold, with a gently warped axial surface which has localized the Bear Mountain granite mass. Attitudes of foliation in the nose (figure 16), flow folds in the nose (some of which contain weak axial plane foliation parallel to that of the major structure) (Lowe, 1950, p. 157), and the sporadic presence of *a*-lineation (figure 16; also Lowe, 1950, plate 5) agree with this interpretation.

The lensoid shape of the West Mountain granite mass suggests that it too was localized by a broad, secondary downwarp. The Bear Mountain and West Mountain structures may be parts of the same major synform. A northward pinching out of the rusty biotite-quartz-feldspar gneisses which lie west of Bear Mountain (geologic map; figure 17) suggests an antiform complementary to the (isoclinal) Bear Mountain synform, but the area in which the nose should occur (northwest of the Torne) is completely obscured by glacial drift.

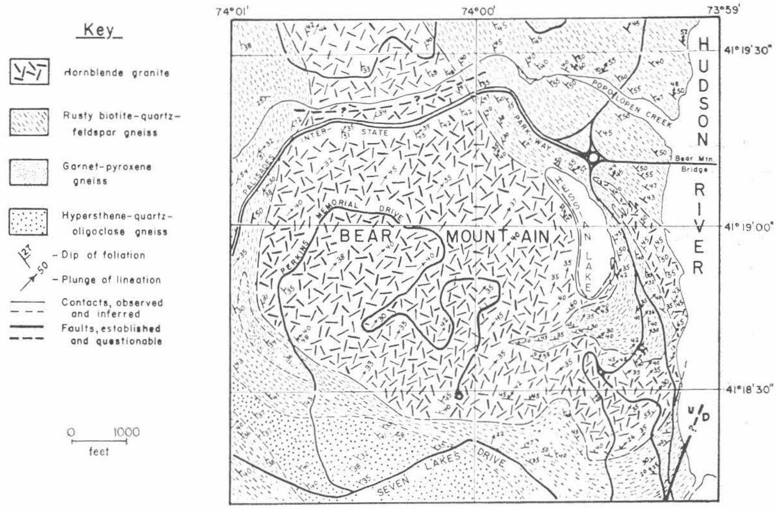


FIGURE 16. Geological map of Bear Mountain area, in part after Lowe, 1950.

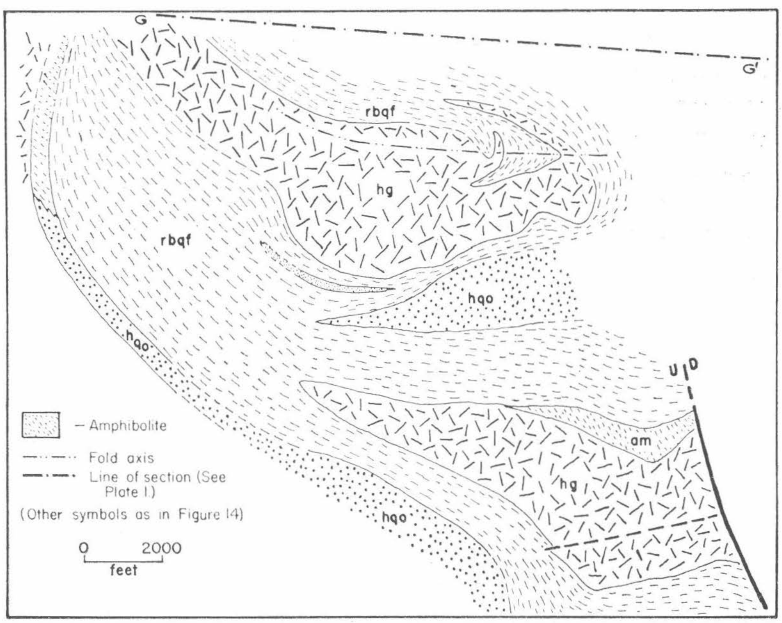


FIGURE 17. Right-normal section of Bear Mountain and vicinity. Plunge used in construction is 40° N45E.

Significance of foliation

The relation of foliation in the gneisses to primary layering or bedding varies and appears to be governed by the intensity of deformation. Open folds show nearly complete parallelism of foliation and lithological contacts; here, foliation evidently mimics primary structures. In tight folds, however, the bedding-foliation relationship deteriorates and competent lithologies appear as disoriented blocks and boudins (figure 15). It is possible, using boundinage relationships, to arrange the major rock types in a rough scale of descending competence, as follows:

a. Pyroxene gneisses
b. Granite pegmatite; leucogranitic layers in biotitic gneisses
c. Amphibolites
d. Leucogneiss; hypersthene-quartz-oligoclase gneiss; biotite-quartz-feldspar gneisses
e. Marble

If one regards the pyroxene gneisses as metasomatized carbonate rocks, the high position of these gneisses on this scale indicates that their deformation took place after they were reconstituted.

Lineation

Lineation in the gneisses, whether produced by mineral orientation, minor fold axes, crenulations on foliation surfaces, or major axes of boudins, invariably plunges northeastward (figure 18) and is subparallel to major fold axes. Even the weakly developed *a*-lineation east of Bear Mountain (Lowe, 1950, plate 5) is accompanied by a much stronger *b*-lineation. There is a slight, but evidently systematic, variation in the attitude of *b*-lineation across the quadrangle, from N25-45E, 10-20°, in the northwestern portion to N40-60E, 20-45°, in the eastern portion. This is reflected in the dispersion shown by the lineation diagrams (figures 18 and 19), which also show the parallelism between lineations in the gneisses and granites.

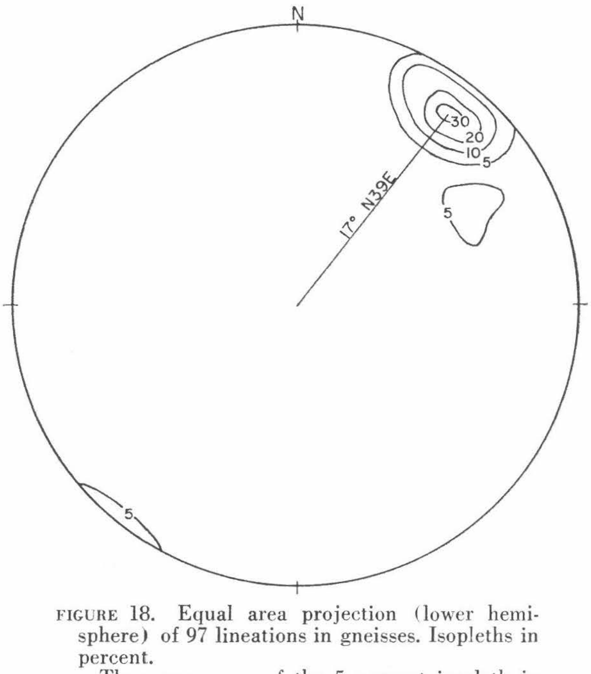


FIGURE 18. Equal area projection (lower hemisphere) of 97 lineations in gneisses. Isopleths in percent.
The appearance of the 5 percent isopleth in the southwest corner of the diagram is due to the method of construction. No southwest plunges were found.

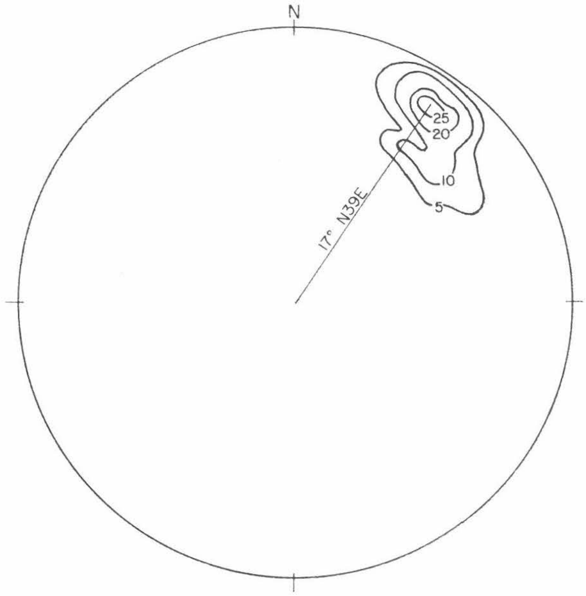


FIGURE 19. Equal area projection (lower hemisphere) of 72 lineations in hornblende granite. Isopleths in percent.

Mode and conditions of deformation

The characteristics of the open folds in this area —parallel fold style (figure 14), strong predominance of *b*-lineation, and parallelism between foliation and bedding—indicate that the folds developed in the catazone, where high temperature and high confining pressure favored flexure folding and inhibited the transportation of material normal to *b* and parallel to the axial planes. Competent layers in the gneisses controlled the forms of the rising folds.

Where folding was more intense (in isoclinal folds and in the cores of more open folds), the competent layers were unable to yield by flexing. They were boudinaged and fractured, and the fragments were rotated to positions athwart the foliation of less competent units. In effect, flexure folding gave way, in tight folds, to flowage folding.

In the absence of evidence of repeated folding (e.g. split maxima on lineation diagrams, crossed foliation directions, cross folds), the writer interprets the folds of this area as due to a single episode of plastic deformation. Even the complex Bear Mountain fold lacks lineations or foliations indicative of more than one deformation (Lowe, 1950, p. 168), though the possibilities of two or more deformations along the same lines, or complete obliteration of an earlier structure pattern by a later one, cannot be excluded.

Structures formed during brittle deformation

Joints

Detailed study of the joints in this area was not undertaken. The measurements compiled in figure 20, largely from the southeastern half of the quadrangle, indicate predominant transverse (striking northwest, essentially vertical) and subordinate longitudinal (striking northeast, dipping 65-80° northwest) sets. All joints are typically straight, smooth-surfaced, and spaced from a few inches to a few feet apart. They are undeformed and hence postdate folding. They are interpreted as tension fractures related to uplift of the Highlands block.

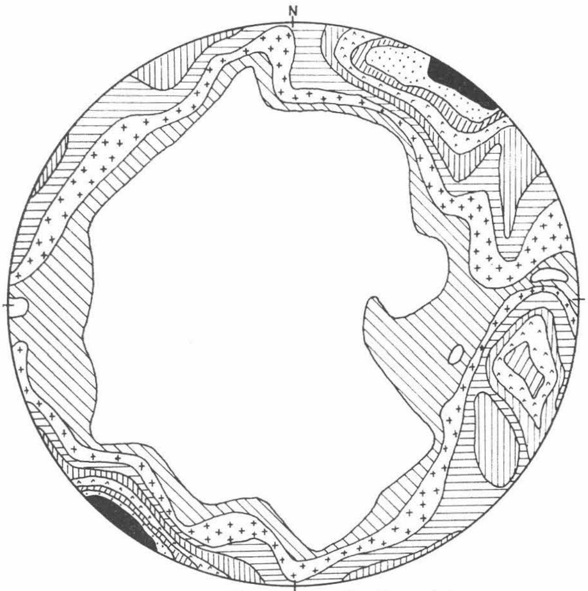


Figure 20. Equal area projection (lower hemisphere) of poles to 457 joints

>4% >2½% >1½% >3½ >2 >1 >3 >½

Dikes occupy both joint sets but appear to favor the transverse set (compare figures 20 and 21). Chlorite, epidote, and hematite locally fill joints of both sets.

Faults

Few of the faults in this quadrangle show mappable displacements, and only in the case of the border faults can the amount and direction of movement be estimated certainly. Hence, no effort is made to describe individual faults here. The discussion is restricted to a brief summary of the general character of faults in the area and comments on their age.

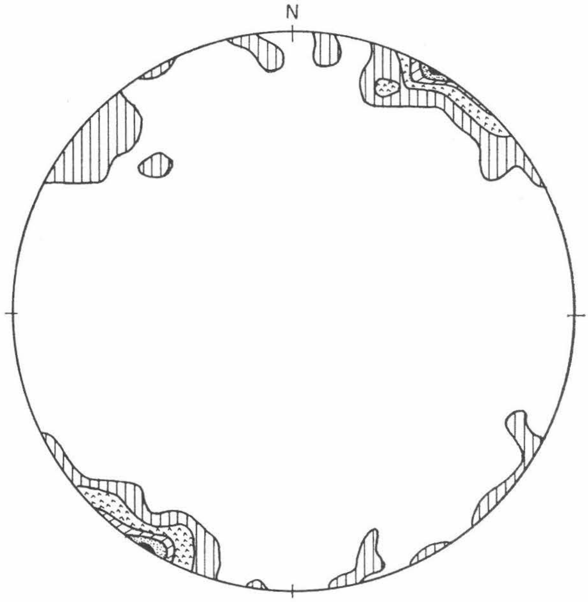


Figure 21. Equal area projection (lower hemisphere) of poles to 68 dikes

>18% >10% >6% >14% >2%

Most of the faults in the quadrangle dip steeply or are vertical. Slickenside striae also dip steeply, indicating that the last movement was chiefly vertical. No transcurrent faults have been recognized.

Several characteristics of the fault zones suggest that faulting occurred at shallow depths: (1) The faults lack any systematic geometrical relation to the catazonal structures; (2) rocks in the fault zones are brecciated rather than mylonitized; and (3) the fault zones contain abundant chlorite and epidote, accompanied locally by zeolites, carbonates, and/or hematite.

The faults within the Highlands block can only be dated as younger than the granites (which they cut) and older than the dikes (which they do not cut). The faults along the northwest border of the Highlands block separate the block from Silurian sediments and are thus Silurian or younger. The system of faults in the southeastern corner of the quadrangle (including the Timp Pass-Hudson River fault of Lowe, 1950, plate 1 and p. 172) approximately parallels the border fault between the Precambrian and the Triassic Newark group sediments (figure 1). It appears from stratigraphic evidence (figure 22) that the eastern blocks in this system have moved downward relative to the western blocks, suggesting a genetic relationship to the border fault along which the movement sense has been the same. This interpretation is in contrast to that of Lowe (1950, p. 172), who interpreted these faults as Precambrian high-angle reverse faults with the east sides up.

In summary, the faults in this quadrangle are the results of vertical movements which postdated granite emplacement, preceded dike formation, and probably took place, at least in part, late in the Triassic period.

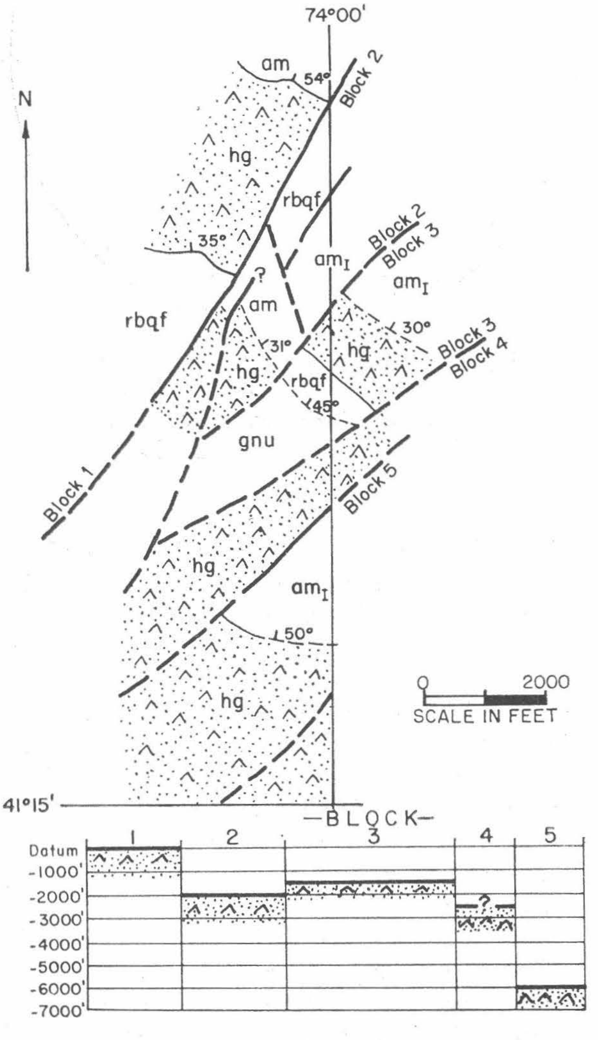


FIGURE 22. Map of the Timp Pass-West Mountain area and estimates of movement on faults in this area.

The reference datum is the upper contact of the hornblende granite (hg—stippled) and amphibolite (am_I). Movement is assumed to be vertical on the basis of slickensides.

Block 2 has been simplified in the lower part of the diagram to facilitate presentation.

IV. GEOLOGICAL HISTORY

Radioactive Dates

The available radioactive dates from the Popolopen Lake quadrangle have been summarized by Long and Kulp (1962) and are tabulated in table 11, with new data by Hart (Hart and Dodd, 1962).

Table 11. Radioactive dates from the Popolopen Lake quadrangle

Unit and Location	*Mineral*	*Age (m.y.)*						
		U^{238}/Pb^{206}	U^{235}/Pb^{207}	Pb^{207}/Pb^{206}	Th^{232}/Pb^{208}	K^{40}/Ar^{40}	Rb^{87}*$/Sr^{87}$	Pb-α
Hornblende granite, Bear Mountain	Zircon	960[4]	990[4]	1060[4]	850[4]	—	—	1140[1]
	Biotite	—	—	—	—	850[5] 840[5]	875[3]	—
	Hornblende	—	—	—	—	930[2]	900[2]	—
Hypersthene-quartz-oligoclase gneiss, Bear Mountain ("Canada Hill")	Zircon	1140[4]	1150[4]	1170[4]	1030[4]	—	—	—
	Biotite	—	—	—	—	870[3] 780[5]	820[3] 835[3]	—
Pegmatite, west side of Lake Tiorati	Biotite	—	—	—	—	765[3]	—	—
Hypersthene-quartz-oligoclase gneiss, north of Route 6, between Lake Massawippa and Long Mountain	Pyroxenes	—	—	—	—	1500[6]	—	—
Amphibolite, north side Black Mountain	Hornblende	—	—	—	—	1000[6]	—	—
Amphibolite, east side Route 293, near Camp Buckner	Hornblende	—	—	—	—	900[6]	—	—

* Data from literature recalculated by Long and Kulp (1962) using $\lambda\beta = 1.47 \times 10^{-11}$ yr.$^{-1}$

Sources:

1) Stern and Rose, 1961
2) Hart, 1961
3) Long and Kulp, 1962
4) Tilton and Davis, 1959
5) Tilton and others, 1960
6) Hart and Dodd, 1962

Concordant zircon ages from hypersthene-quartz-oligoclase gneiss ("Canada Hill") at Bear Mountain date the metamorphism of that gneiss at about 1,150 m.y. ago. The zircon ages for the granite at Bear Mountain are slightly discordant and have a lead-loss pattern which suggests that the 1,060 m.y. Pb^{207}-Pb^{206} age of the granite is a minimum (Long and Kulp, 1962, p. 986). These data are not inconsistent with field and petrographic evidence that the granite was syntectonic.

The significance of the potassium-argon dates is less certain. Long and Kulp (1962, p. 986) suggest that the low biotite ages are due to either Precambrian reheating about 835 m.y. ago or mild reheating by the Paleozoic metamorphisms recorded in the Manhattan Prong. They favor the first interpretation. A third interpretation of the data is that the 835 m.y. ages date the time at which the temperature of the gneisses became low enough to permit complete retention of argon in biotite. The hornblende ages are nearer to the zircon ages than are the biotite results, suggesting that hornblende is less prone to argon loss than biotite (Hart, 1961).

Two pyroxene ages were secured by Hart, but the results—1,500 m.y. and 10.4 b.y.—are probably (in the latter case, certainly) anomalous and due to excess argon (Hart and Dodd, 1962).

In summary, a major igneous-metamorphic event at about 1,150 m.y. has been established by a variety of radioactive dating techniques. Petrographic evidence suggests that this is the only metamorphism of detectable intensity which has affected this part of the Highlands, though the discrepant results on biotite and hornblende and the sporadic appearance of retrograde metamorphic minerals may be due to mild reheating.

Summary of geological history

In spite of the diversity of rock types and structures found in the Highlands rocks of the Popolopen Lake quadrangle, it appears that they fit a relatively simple history. A sequence of chiefly argillaceous sediments and potash-poor volcanic (?) rocks was folded, metamorphosed to the hornblende granulite subfacies, and intruded by several types of granite about 1,150 million years ago. These events were essentially simultaneous and took place at depths in excess of 7 miles and under temperatures of about 700-800°C. After folding and a decline of temperature and pressure, the area was elevated with the formation of joints and faults. Faulting took place at shallow depths and was followed by the emplacement of several types of dikes and a granodiorite of uncertain affinity. The ages of these post-tectonic features are not known, but some of the faults and dikes are thought to be Triassic.

The discovery of metasedimentary cores in zircons from the granite at Bear Mountain (Eckelmann, 1963) raises the hope that, in time, this sequence of events will be extended backward. Studies of individual rock types, particularly the amphibolites and quartz-plagioclase gneisses, will elucidate the premetamorphic makeup of the Highlands, while study of discrepant radiometric dates should provide more details on the events which followed the main metamorphism. For the moment, the writer's conception of the history of this area extends only to 1,150 m.y. ago. It appears that the major petrographic features of the Popolopen Lake quadrangle were developed at that time and but slightly modified thereafter.

V. ECONOMIC GEOLOGY

Magnetite

Abandoned mines, furnaces, and coke ovens which are scattered throughout the Highlands are reminders of a small iron industry which was in operation in 1710, reached a peak in the late 19th Century, and declined thereafter (Buddington, 1957, p. 7). Today, only one of the Highlands iron mines is active, namely the Scrub Oaks mine near Dover, New Jersey (Sims, 1958, pp. 116-124). All of the mines in the Popolopen Lake quadrangle (see map for locations) are closed, and most of them are flooded, or have been filled for public safety.

Although many workers have studied the Highlands magnetites (see summaries in Sims, 1958 and Colony, 1921), only one of the deposits in the present quadrangle has been mapped, namely the Forest of Dean orebody. The geology of this body was summarized by Newland (1919; includes a cross-section) and Colony (1921). The deposit occupies the nose of a small, tight syncline and occurs in "biotite gneiss" (Newland, 1919, p. 120; from the location of the mine, this rock is probably the hypersthene-quartz-oligoclase gneiss of the present report). The ore is cut by stringers of a "coarse, reddish granite" (Newland, 1919), in fact a quartz-sodic plagioclase pegmatite, which Colony (1921) regarded as a late differentiate of his Pochuck diorite magma. Although the mine has been buried, fragments of the ore and pegmatite can still be found nearby. The pegmatite may be related to the quartz-plagioclase leucogneiss of this paper, but its field relations are, of course, unknown.

The writer did not study the iron mines in detail, nor did he examine ore samples. Routine observations of the mines and dumps indicate, however, that most of the deposits occur in amphibolite or, less commonly, pyroxene gneiss or marble (Bradley Mine), and that most occur in tight folds. The tendency for magnetite to be associated with amphibolites has been noted elsewhere in the Highlands, though it is by no means restricted to this rock type (Buddington, 1957, pp. 7-8).

The more recent students of the Highlands magnetites (Colony, 1921; Hotz 1953 and 1954; Sims 1953, 1958; Buddington and Baker, in press; Hagner and others, 1963) interpret the deposits as metasomatic replacements. Colony relates the mineralization to an inferred dioritic magma (Pochuck); Hotz, Sims, Buddington and Baker relate it to the syntectonic granites, and Hagner's group thinks the iron was released from mafic minerals in the amphibolite host rock during regional metamorphism. All modern studies have rejected earlier suggestions (Kitchell, 1857; Cook, 1868; Smock, 1873) that the ores were derived from ferruginous sediments, on the grounds that: (1) the ores are not restricted to a single host, (2) replacement textures are abundant in the deposits, and (3) the inferred metasedimentary parents have not been recognized. The present study adds nothing to the argument, though it should be noted that at least one ferruginous metasediment—garnet-pyroxene gneiss—occurs in the Popolopen Lake quadrangle, and that similar gneisses could easily be mistaken for metasomatized marble (skarn).

Phlogopite

A deposit of phlogopite was mined just south of the present Anthony Wayne Recreation Area. The deposit lies in rusty biotite-quartz-feldspar gneiss, but its nature is unknown, as the mine has been filled.

Sand and gravel

The only mineral resources which are now extracted in the Popolopen Lake quadrangle are sand and gravel, which occur in kames, kame terraces, and glacial lake deposits in several valleys. The Park Commission and the Military Academy work deposits north of Tiorati Circle, just northwest of the Torne, and west of Barnes Lake.

References Cited

Adams, F. D.
1909. On the origin of the amphibolites of the Laurentian area of Canada. Jour. Geol., 17:1–18

Andersen, O.
1928. The genesis of some types of feldspar from granite pegmatites. Norsk. Geol. Tids. 10

Balk, Robert
1937. Structural behavior of igneous rocks. Geol. Soc. Amer. Mem. 5

Barnes, V. E.
1930. Changes in hornblende at about 800° C. Amer. Mineral. 15:393–417

Bass, M. N.
1956. An interpretation of the geological history of part of the Timiskaming Subprovince, Canada. Ph.D. thesis. Princeton University

Bayley, W. S., Salisbury, R. D. & Kümmel, H. B.
1914. U. S. Geol. Surv. Geol. Atlas, Raritan folio, No. 191

Berkey, C. P. & Rice, Marion
1919. Geology of the West Point quadrangle. N. Y. State Mus. Bull. 225–226

Boucot, A. J.
1959. Brachiopods of the Lower Devonian rocks at Highland Mills, New York. Jour. Paleontology 33:727–769

Bowen, N. L.
1928. The evolution of the igneous rocks. Princeton Univ. Press

Budding, A. J.
1955. The geology of the Settee Lake area, east half. Saskatchewan Dept. of Mineral Resources, Rept. 17

Buddington, A. F.
1939. Adirondack igneous rocks and their metamorphism. Geol. Soc. Amer. Mem. 7

———
1948. Origin of granitic rocks of the northwest Adirondacks. In Gilluly, J., ed., Origin of granite. Geol. Soc. Amer. Mem. 28: 21–43

———
1956. Correlation of rigid units, types of folds, and lineation in a Grenville belt. In Thompson, J. E., ed., The Grenville Problem. Royal Soc. Can. Spec. Pub. 99–118

———
1958. The geologic section at Hibernia Mine. In Sims, P. K., Geology and magnetite deposits of the Dover District, Morris County, New Jersey. U. S. Geol. Survey Prof. Paper 287

———
1959. Granite emplacement with special reference to North America. Geol. Soc. Amer. Bull. 70: 671–747

——— & Baker, D. R.
In press. Geology and magnetite deposits of the Franklin and part of the Hamburg quadrangles, New Jersey

——— & Leonard, B. F.
1953. Chemical petrology and mineralogy of hornblende in northwest Adirondack granitic rocks. Amer. Mineral. 38: 891–902

Chayes, Felix
1952. On the association of perthitic microcline with highly undulant or granular quartz in some calc-alkaline granites. Amer. Jour. Sci. 250: 281–296

Colony, R. J.
1921. The magnetite iron deposits of southeastern New York. N. Y. State Mus. Bull. 249–250

Dickinson, W. R.
1962. Metasomatic quartz-keratophyre in central Oregon. Amer. Jour. Sci. 260: 249–266

Dietrich, R. V.
1954. Fish Creek phacolith, northwestern New York. Amer. Jour. Sci. 252: 513–531

Dodd, R. T., Jr.
1963. Garnet-pyroxene gneisses at Bear Mountain, New York. Amer. Mineral. 48:811–820

Eckelmann, F. D.
1963. Precambrian events recorded in zircon populations of the Storm King granite and Canada Hill gneiss, Bear Mountain, New York. Program of the 44th Annual Meeting of the Amer. Geophys. Union: 120 (Abs.)

Engel, A. E. J.
1949. Studies of cleavage in the metasedimentary rocks of the northwest Adirondack Mountains, New York. Amer. Geophys. Union Trans. 30: 767–784

——— & Engel, C. G.
1953. Grenville series in the northwest Adirondack Mountains, part II: Origin and metamorphism of the Major Paragneiss. Geol. Soc. Amer. Bull. 64: 1049–1098

———
1962. Progressive metamorphism of amphibolite, northwest Adirondack Mountains, New York. In Engel, A. E. J., James, Harold L. & Leonard, B. F., editors, Petrologic studies: A volume in honor of A. F. Buddington: 37–82. Published by the Geological Society of America

Eskola, Pentti
1939. Die metamorphen Gesteine. In Barth, T. F. W., Correns, C. W. and Eskola, P., Die Entstehung der Gesteine. Berlin, Springer.

Fisher, D. W., Isachsen, Y. W., Rickard, L. V., Broughton, J. G. & Offield, T. W.
1962. Geologic map of New York, 1961. N. Y. State Mus. & Sci. Serv., Geol. Survey Map and Chart Series 5

Francis, G. H.
1958. The amphibolite of Doir 'a' Chatha (Durcha), Sutherland. Geol. Mag. 95:25–39

Fyfe, W. S., Turner, F. J. & Verhoogen, J.
1958. Metamorphic reactions and metamorphic facies. Geol. Soc. Amer. Mem. 73

Goldschmidt, V. M.
1922. Stammestypen der Eruptivgesteine. Vidensk. selsk., Kristiania Skrifter, I. Kl., No. 10

Hagner, A. F., Collins, L. G. & Clemency, C. V.
1963. Host rock as a source of magnetite ore, Scott Mine, Sterling Lake, N. Y. Econ. Geol. 58:730–768

Hague, J. M., Baum, J. L., Herrmann, L. A. & Pickering, R. J.
1956. Geology and structure of the Franklin-Sterling area, New Jersey. Geol. Soc. Amer. Bull. 67:435–474

Hart, S. R.
1961. The use of hornblendes and pyroxenes for K-Ar dating. Jour. Geophys. Research 66:2995–3001

——— & Dodd, R. T., Jr.
1962. Excess radiogenic argon in pyroxenes. Jour. Geophys. Research 67:2998–2999

Hess, H. H.
1949. Chemical composition and optical properties of clinopyroxenes, part I. Amer. Mineral. 34:621–666

——————
1960. Stillwater igneous complex. Geol. Soc. Amer. Mem. 80

Hewitt, D. F.
1953. Geology of the Brudenell-Raglan area, Ontario. Ontario Dept. of Mines Ann. Rept. 62, part 5

——————
1955. Geology of Monteagle and Carlow Townships. Ontario Dept. of Mines Ann. Rept. 63, part 6

Hietanen, A.
1947. Archaean geology of the Turku district. Geol. Soc. Amer. Bull. 58: 1019–1084

Hotz, P. E.
1953. Magnetite deposits of the Sterling Lake, New York —Ringwood, New Jersey area. U. S. Geol. Surv. Bull. 982-F 1954. Some magnetite deposits in New Jersey. U. S. Geol. Surv. Bull. 995-F

Jaffe, H. W. & Jaffe, E. B.
1962. Geology of the Precambrian crystalline rocks, Cambro-Ordovician sediments, and dikes of the southern part of the Monroe quadrangle. Field Guidebook for the 34th Ann. Meeting of the N. Y. State Geol. Assoc.: B-1 to B-10

Long, L. E. & Kulp, J. L.
1962. Isotopic age study of the metamorphic history of the Manhattan and Reading Prongs. Geol. Soc. Amer. Bull. 73: 969–996

Lowe, K. E.
1950. Storm King granite at Bear Mountain, New York. Geol. Soc. Amer. Bull. 61: 137–190

——————
1958. Precambrian and Paleozoic geology of the Hudson Highlands. In Lowe, Kurt E., editor, Field Guidebook to the 30th Ann. Meeting of the N. Y. State Geol. Assoc.: 41–47

Miyashiro, Akiho
1961. Evolution of metamorphic belts. Jour. Petrology 2:277–311 Nockolds, S. R.

Nockolds, S.R.
1954. Average chemical compositions of some igneous rocks. Geol. Soc. Amer. Bull. 65: 1007–1032

Offield, T. W.
1961. Bedrock geology of the Goshen and Greenwood Lake quadrangles, New York. Ph.D. thesis. Yale University

Orville, P. M.
1960. Alkali feldspar- alkali chloride hydrothermal ion exchange: Ann. Report Dir. Geophys. Lab. for 1959–60: 104–108

——————
1963. Alkali ion exchange between vapor and feldspar phases. Amer. Jour. Sci. 261: 201–237

Parras, Kauko
1958. On the charnockites in the light of a highly metamorphic rock complex in southwestern Finland. Bull. Geol. Comm. de Finlande 181

Pettijohn, F. J. & Bastron, Harry
1959. Chemical composition of argillites of the Cobalt series (Precambrian) and the problem of soda-rich sediments. Geol. Soc. Amer. Bull. 70: 593–600

Ramberg, Hans
1948. On the petrogenesis of the gneiss complex between Sukkertoppen and Christianshaab, west Greenland. Medd. Dansk Geol. Foren. 11: 312–327

——————
1952. The origin of metamorphic and metasomatic rocks. University of Chicago Press

Reed, J. J.
1957. Petrology of the lower Mesozoic rocks of the Wellington district. New Zealand Geol. Surv. Bull. 57

Sims, P. K.
1953. Geology of the Dover magnetite district, Morris County, New Jersey. U. S. Geol. Surv. Bull. 982-G

——————
1958. Geology and magnetite deposits of the Dover District, Morris County, New Jersey. U. S. Geol. Surv. Prof. Pap. 287

Spencer, A. C., Kümmel, H. B., Wolff, J. E., Salisbury, R.D. & Palache, C.
1908. U. S. Geol. Surv. Atlas, Franklin Furnace folio, No. 161

Stern, T. W. & Rose, H. J., Jr.
1961. New results from lead-alpha age measurements. Amer. Mineral. 46:608

Stockwell, C. H.
1950. The use of plunge in the construction of cross-sections of folds. Proceedings of the Geol. Soc. of Can. 3: 97–121

Sundius, N.
1925. On the differentiation of the alkalies in aplites and aplitic granites. Sveriges geol. undersökning, Ser. Ca, No. 2, Arsbok 19

Tilton, G. R. & Davis, G. L.
1959. Geochronology. In Abelson, P. H., ed., Researches in geochemistry. New York. John Wiley and Sons

Tilton, G. R., Wetherill, G. W., Davis, G. L. & Bass, M. N.
1960. 1000-million-year-old minerals from the eastern United States and Canada. Jour. Geophys. Research 65: 4173–4179

Turner, F. J. & Verhoogen, J.
1960. Igneous and metamorphic petrology. New York. McGraw

Tuttle, O. F. & Bowen, N. L.
1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8 - KAlSi_3O_8 - SiO_2 - H_2O$. Geol. Soc. Amer. Mem. 74

Winkler, H. G. F. & von Platen, H.
1960. Experimentelle Gesteinsmetamorphose—III. Anatektische ultrametamorphose kalkhaltiger Tone. Geochim. et Cosmochim. Acta 18: 294–316

Yoder, H. S., Jr.
1952. The $MgO - Al_2O_3 - SiO_2 - H_2O$ system and the related metamorphic facies. Amer. Jour. Sci., Bowen Volume: 569–627

—————— & Tilley, C. E.
1956. Annual Rept. of Dir. of Geophys. Lab. for 1955: 169–171

Glossary

Glossary of those terms not defined in Webster's Third New International Dictionary

catazone, catazonal—pertaining to the deepest zone of regional metamorphism, and hence characterized by high temperatures and pressures

coronitic—a textural term referring to the peripheral growth of one mineral around another

diablastic—a textural term applied to a sieve-like intergrowth of two or more minerals

hypidioblastic—a textural term applied to granular metamorphic rocks in which few of the constituent minerals are bound by crystal faces

isochemical—a term generally applied to metamorphism to emphasize that the metamorphic recrystallization was not accompanied by any significant addition or subtraction of material

leucogranite—a light colored granite, one virtually lacking in dark minerals

mesoperthite—a microscopic intergrowth of approximately equal amounts of K-feldspar and plagioclase

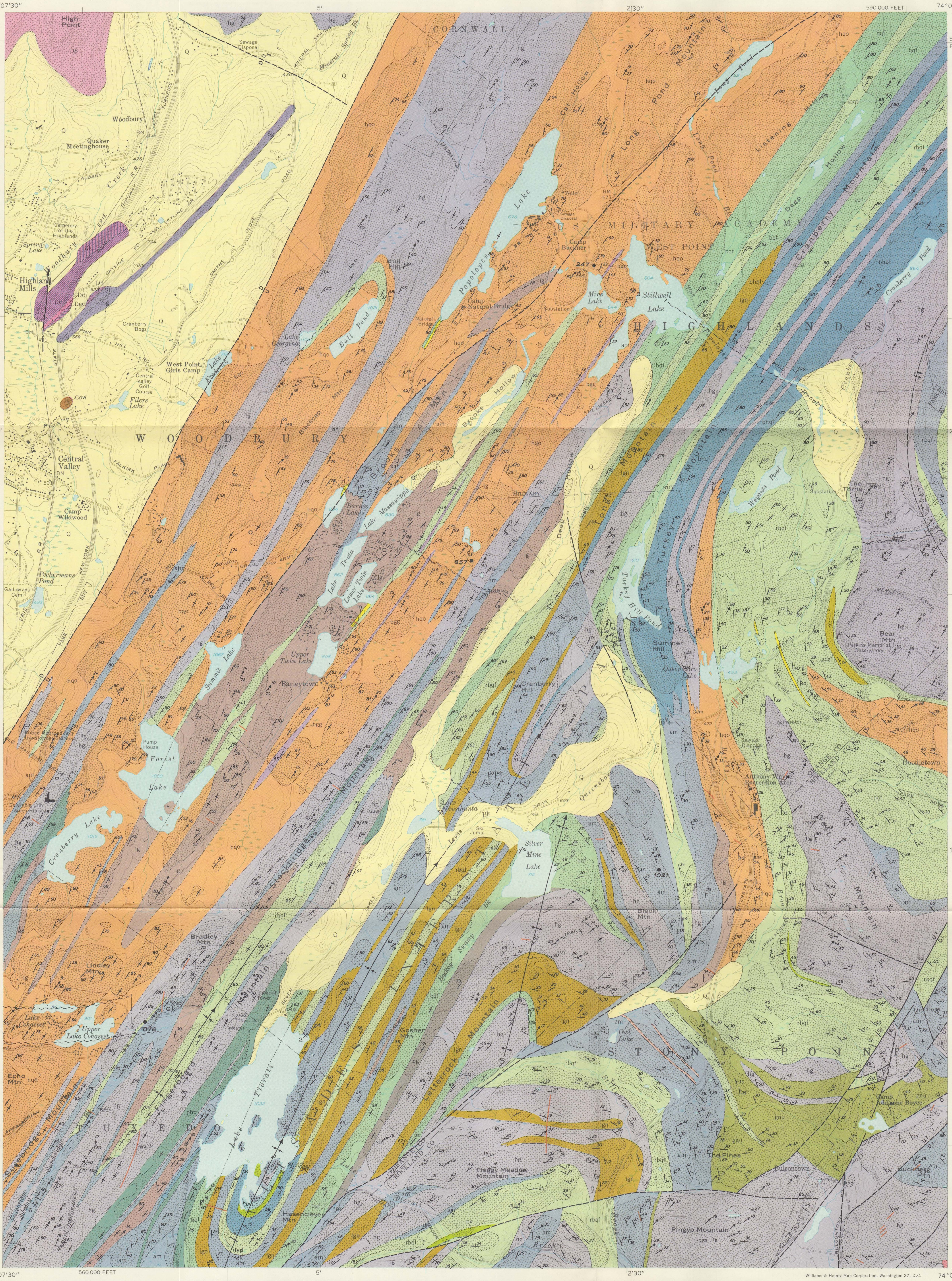
modal analysis—a microscopic determination of the relative percentages of constituent minerals in a rock

syntectonic—contemporaneous with the major episode of deformation or tectonism

NEW YORK STATE MUSEUM AND SCIENCE SERVICE
WILLIAM N. FENTON, ASSISTANT COMMISSIONER

THE UNIVERSITY OF THE STATE OF NEW YORK
THE STATE EDUCATION DEPARTMENT

GEOLOGICAL SURVEY
JOHN G. BROUGHTON, STATE GEOLOGIST



EXPLANATION

Q — Quaternary
Deposits too extensive to permit contact extrapolation.

IGNEOUS ROCKS: POST-TECTONIC

TRIASSIC: Dikes

?: gd — Hornblende-biotite granodiorite

SEDIMENTARY ROCKS (FROM BOUCOT, 1959)

PALEOZOIC

Db — Middle Devonian
Bellvalle Sandstone

Dk, De, Dc, Dec, Dh — Lower Devonian
Dk, Kanouse Sandstone; De, Esopus Formation; Dc, Connelly Conglomerate; Dec, Central Valley Sandstone; Dh, Limestone of Early Helderberg age

Sl, Sg — Silurian
Sl, Longwood Shale; Sg, Green Pond Conglomerate

Cow — Cambrian or Ordovician
Wappinger Dolomite

IGNEOUS ROCKS: SYNTECTONIC

PRECAMBRIAN

hg — Hornblende granite

lg — Leucogranite

bg — Biotite granite

bgg — Biotite-garnet granite

METASEDIMENTARY ROCKS

rbqf — Rusty biotite-quartz-feldspar gneiss

bqf — Gray biotite-quartz-feldspar gneiss

m — Marble
o; *Masses too small to map*

px — Pyroxene gneiss

gpx — Garnet-pyroxene gneiss

gnu — Undifferentiated biotite gneiss

META-IGNEOUS (?) GNEISSES

am — Amphibolite I

php — Amphibolite II (pyroxene-hornblende-plagioclase gneiss)

bhqf — Biotite-hornblende-quartz-feldspar gneiss

GNEISSES OF UNCERTAIN DERIVATION

hqo — Hypersthene-quartz-oligoclase gneiss

lgn — Quartz plagioclase leucogneiss

Contact, exposed
Contact, readily inferred
Contact, hypothetical
Outline of exposure
U/D — Fault showing relative movement (dashed where approximate)
Shear zone, lacking evidence of displacement
40 — Strike and dip of foliation
60 — Bearing and plunge of lineation
Synform: trace of axial plane
Synform: overturned
Antiform
Antiform overturned
1021 — Location and sample number of radiometrically dated specimen (Hart & Dodd; 1962)
A — A' Line of right normal section

MINES
IRON:
1. Bradley
2. Caldwell
3. Forest of Dean
4. Cranberry
5. Hasenclever
6. Surebridge
MICA:
7. Beechy Bottom

PROSPECTS

Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS
Topography from aerial photographs by photogrammetric methods
Aerial photographs taken 1955 and 1956. Field check 1957
Polyconic projection. 1927 North American datum
10,000-foot grid based on New York coordinate system,

New York State Museum and Science Service
Geological Survey, Map and Chart Series: No. 6
(1964)

M655.064-2,000

PLATE 1. GEOLOGIC MAP OF THE POPOLOPEN LAKE QUADRANGLE, NEW YORK

By R. T. Dodd, Jr.

MN
12°

SCALE 1:24 000
1 ½ 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

NEW YORK
QUADRANGLE LOCATION

POPOLOPEN LAKE, N.Y.
SE/4 SCHUNEMUNK 15' QUADRANGLE
N4115—W7400/7.5
1957