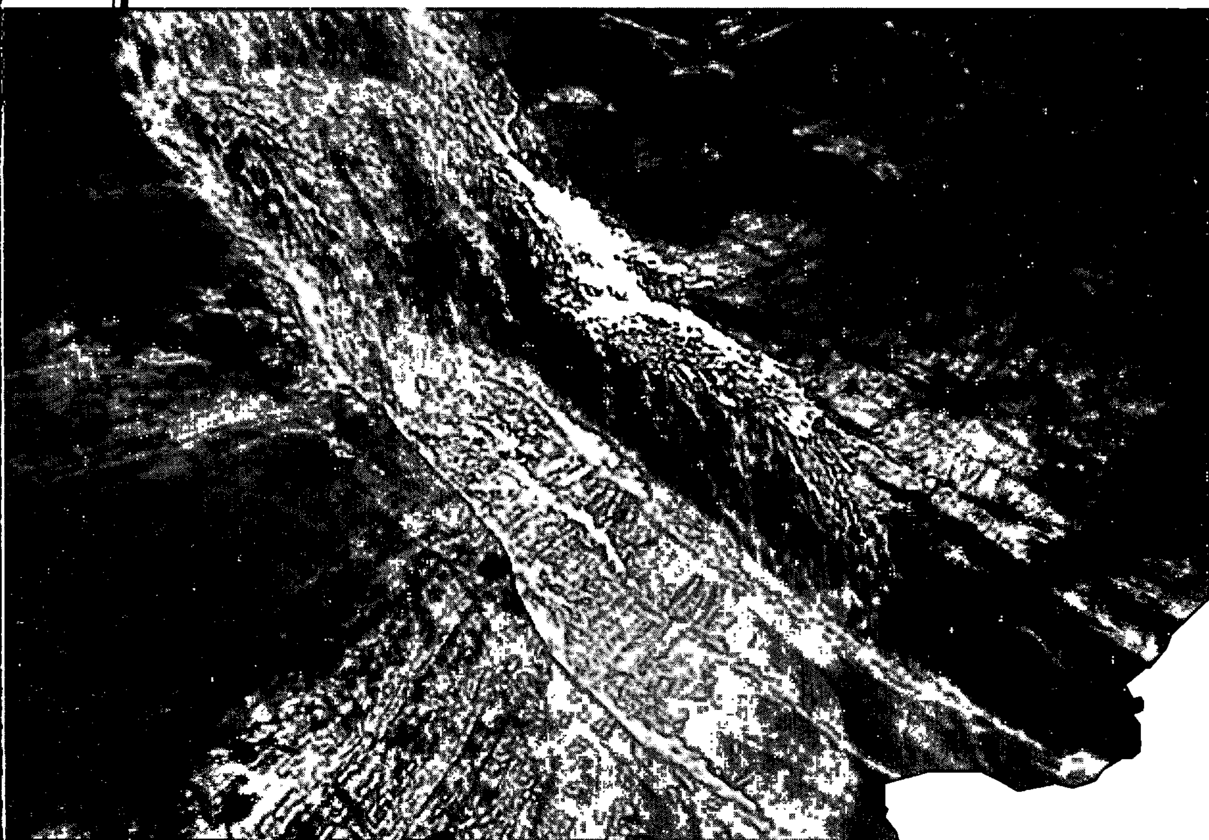
Bedrock Geology of the Au Sable Forks Quadrangle, Northeastern Adirondack Mountains, New York

by Philip R. Whitney and James F. Olmsted



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The University of the State of New York
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CONTENTS

List of Illustrations

List of Tables

ABSTRACT

The bedrock geology of the Au Sable Forks quadrangle is dominated by three domical bodies of metamorphosed anorthosite: the Jay, Westport, and Hurricane domes. These domes are the structurally lowermost rocks in the quadrangle. They are overlain by the Rocky Branch Complex, a highly tectonized unit of metasedimentary rocks interlayered with anorthositic, gabbroic, ferrodioritic, charnockitic, and granitic gneisses. The Rocky Branch Complex is overlain in turn by the Lyon Mountain Gneiss, a unit composed chiefly of granitic and trondhjemitic gneisses of probable metavolcanic origin. These rocks are all of Middle Proterozoic age and have been metamorphosed to granulite facies. Evidence of earlier contact metamorphism is locally preserved near anorthosite contacts. Foliation and compositional layering in the metasedimentary and metavolcanic rocks have been shaped by the anorthosite domes into a large, irregular synformal structure called the Au Sable Forks synform. Mineral lineations in all metamorphic rock units show a strong NNE preferred orientation.

The Lyon Mountain Gneiss north of the Ausable River contains numerous, small low-Ti magnetite ore bodies of enigmatic origin that were mined extensively during the 19th century. A unique wollastonite-garnet-pyroxene rock occurs in several locations in a zone of mixed gneisses overlying the Westport Dome in the southeastern part of the quadrangle. One of these occurrences, northwest of the village of Lewis, is currently being mined for wollastonite. Metanorthosite is quarried for building stone southwest of Au Sable Forks.

Small, unmetamorphosed mafic dikes, subvertical and with a dominant NE trend, intrude all metamorphic rocks. The dikes include late Proterozoic basaltic rocks and Mesozoic lamprophyres. Unconsolidated sandy tills and glacial lake sediments of Pleistocene (Wisconsinan) age overlie all other units.

We tentatively reconstruct the geologic history of the quadrangle and of the northeastern Adirondack Highlands as follows: (1) Deposition of sedimentary rocks in a shallow-water, locally hypersaline or saline-alkaline, environment. (2) Intrusion of voluminous igneous rocks of the anorthosite suite, olivine gabbros, charnockites, and granites, accompanied by felsic volcanism, from approximately 1,160 to 1,110 million years before present with coeval extensional deformation and contact metamorphism. The large anorthosite bodies that control the structural framework of the quadrangle were originally emplaced at this time. (3) Crustal doubling by overthrusting associated with continental collision during the final (Ottawan) stage of the Grenville orogeny, resulting in granulite facies regional metamorphism. Subsequent vertical tectonic movements may have accentuated the domical form of the large anorthosite bodies. (4) Uplift, tectonic denudation, and erosion of up to 25 km of rock by the end of Proterozoic time, with initiation of brittle deformation and intrusion of basaltic dikes during the latest Proterozoic. (5) Formation of the present landscape by renewed uplift in late Cenozoic time, followed by Pleistocene glaciation.

INTRODUCTION

The Au Sable Forks quadrangle in the Adirondack Mountains of New York State is situated at the northeastern corner of the Marcy Anorthosite Massif (Fig. 1). The quadrangle is underlain by metasedimentary and metaigneous rocks whose structure and petrology have been profoundly affected by large anorthosite domes peripheral to the massif (Plate 1). It is thus a critical area both for the study of massif anorthosites and for the interpretation of the geologic history of the Adirondacks.

The Au Sable Forks quadrangle is located between 44°15' and 44°30' north latitude and 73°30' and 73°45' west longitude (Fig. 1). Elevations range from approximately 400 feet above sea level along the Bouquet River in the southeastern corner to slightly over 3,600 feet at the summit of Saddleback Mountain. Except near the villages of Au Sable Forks, Jay, Clintonville, and Lewis, the area is heavily forested and sparsely settled. Topographic maps of the area, published by the U. S. Geological Survey, include the Lewis and Au Sable Forks 7.5' x 15' metric maps (1:25,000 scale, 1978), and the Au Sable Forks 15' sheet (1:62,500 scale, 1953). The latter, which we have found to be more accurate in detail than the more recent maps, is the base map for Plate 1 and the reference for topographic and cultural names used in this report.

Thick glacial outwash and lake sediments cover much of the areas south of the village of Jay, near Black Brook, in the Ausable River valley, and in the Bouquet River valley south of Deerhead (Cadwell and Pair, 1991). As a result, the nature of the bedrock geology in these areas remains largely conjectural. Elsewhere, Pleistocene deposits consist chiefly of sandy till of varying thickness. Thick boulder till is present in several stream valleys, including Gelina Basin on the north slope of Jay Mountain, Derby Brook east of Saddleback Mountain, and Gulf Brook near the southwestern corner of the quadrangle. Bedrock exposures are common in the mountainous topography of the southwestern and northeastern quadrants, where relief is commonly on the order of 1,000-2,000 feet, but scarce in the northwestern and southeastern quadrants.

Previously published geological work in the area includes descriptions of building stone quarries (Newland, 1916) and of graphite occurrences (Alling, 1917), as well as the bedrock map and report by Kemp and Alling (1925). Mapping in the part of the quadrangle north of the Ausable River is included in Postel's (1952) report on the Clinton County magnetite district. In addition, mapping in the Au Sable Forks quadrangle by Robert Balk during the 1920s forms part of the basis for his paper on the structural geology of the Adirondack anorthosite (Balk, 1931). Later, unpublished work by Balk is recorded in his field notebooks from the early 1940s. These notebooks are now in the Open File collection of the New York State Geological Survey (Accession No. 1m669). Some of this work is discussed in Balk (1944). The open-file collection also includes notebooks of A. F. Buddington (Accession No. 1m666), some of which include work in the Au Sable Forks quadrangle during the 1930s. Putman (1958) inventoried the wollastonite occurrences in the Au Sable Forks and Willsboro quadrangles, and provided detailed descriptions of several localities. The present report covers mapping work which occurred intermittently over two decades from 1969 to 1989, with Whitney mapping in the southern half of the quadrangle and Olmsted in the northern half.

The geological framework of the Au Sable Forks quadrangle can be broadly described in terms of three major components. Structurally lowermost are domical metanorthosite (metamorphosed anorthosite) bodies, of which we distinguish three: the Westport (Buddington, 1939), Jay, and Hurricane domes (Figures 1 and 2, and Plate 1). Of these, the largest is the Westport dome, which occupies parts of the Willsboro, Port Henry, Elizabethtown and Au Sable Forks quadrangles. It is roughly circular in plan, centered near the junction of these quadrangles. The Jay dome occupies the west-central part of the Au Sable Forks quadrangle and much of the adjacent Lake Placid quadrangle. Gravity data (Figure 3) suggests an elliptical form with elongation in a SW-NE direction from near Kilburn Mountain in the Lake Placid quadrangle to the village of Au Sable Forks. This structural unit has previously been described as the Jay-Whiteface sheet (Buddington, 1939) or nappe (Crosby, 1969). Field relationships within the Au Sable Forks quadrangle clearly show its domical character. Our mapping shows that the neck connecting the Jay and Westport domes on the map of Kemp and Alling (1925), used in the compilation of Isachsen and Fisher (1971), does not exist. The Hurricane dome is named for Hurricane Mountain in the Elizabethtown quadrangle. It occupies the southwest corner of the Au Sable Forks quadrangle and extends southward into the Elizabethtown quadrangle and the northeast corner of the Mount Marcy quadrangle. The structure in the northeastern part of the Au Sable Forks quadrangle suggests the presence of a fourth dome centered near Keeseville in the Plattsburgh quadrangle; this corresponds to Buddington's (1939) Port Kent unit.

Detailed gravity studies by Mann and Revetta (1979) show distinct negative residual gravity anomalies associated with each of the domes (Figure 3). This is consistent with the presence of deeply rooted masses of relatively low-density anorthositic rocks surrounded by higher-density metasedimentary and gabbroic rocks.

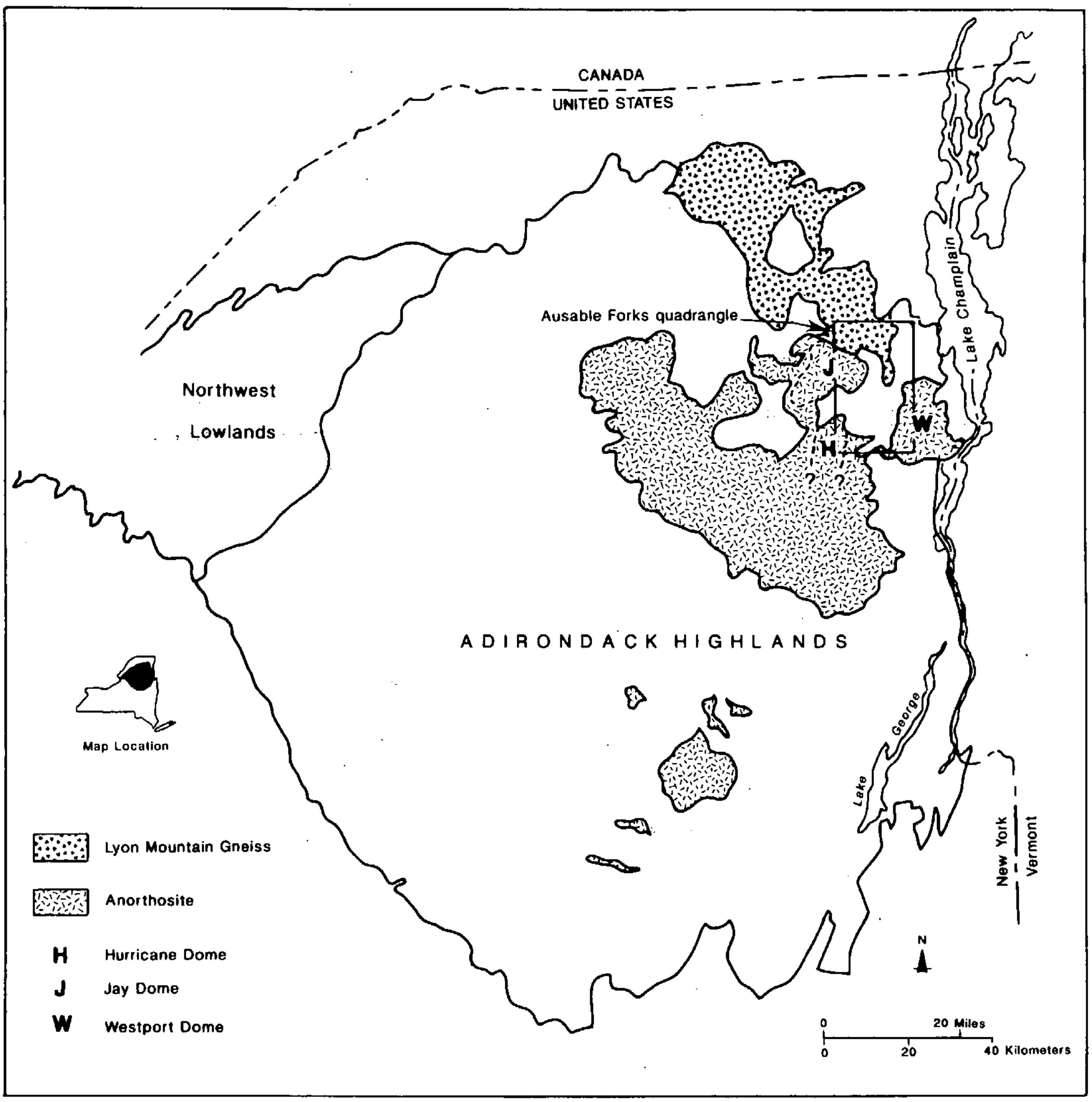


FIGURE 1. Map showing the location of the Au Sable Forks quadrangle. Domical anorthosite bodies are labeled. J: Jay Dome; W: Westport Dome; H: Hurricane Dome. Dashed lines outline thick parts of anorthosite domes as indicated by gravity (Figure 3).

The rocks overlying the anorthosite domes appear to have been shaped by them into a synformal structure named the Ausable (sic) Forks syncline by Balk (1931). This structure, henceforth the Au Sable Forks Syn*form*, is broad and open with generally shallow dips in the southwestern part of the quadrangle, but it becomes tight and slightly overturned to the west in the central region, between the Jay and Westport domes. North of Trout Pond, the structure rapidly opens again; it loses its distinct synformal character north of the Ausable River.

Directly overlying the metanorthosite domes is a complex of sedimentary rocks that have been intruded by sills and irregularly shaped bodies of anorthosite, ferrodiorite, charnockite, granite and olivine gabbro, and subsequently metamorphosed to granulite facies. We have named this heterogeneous group of metamorphic rocks the "Rocky Branch Complex" (Figure 2) for its good exposures along Rocky Branch and its tributaries in the area just north of Jay Mountain. It varies widely in the proportions and kinds of metasedimentary and metaigneous rocks present. In the vicinity of the Jay Dome and in the southwest quadrant of the map area, it is dominated by metasedimentary rocks and discrete bodies of metaigneous rocks. Around the northern and northwestern margins of the Westport dome and in the northeastern quadrant, metasedimentary rocks occur as minor components of anorthositic or granitic mixed gneisses and are

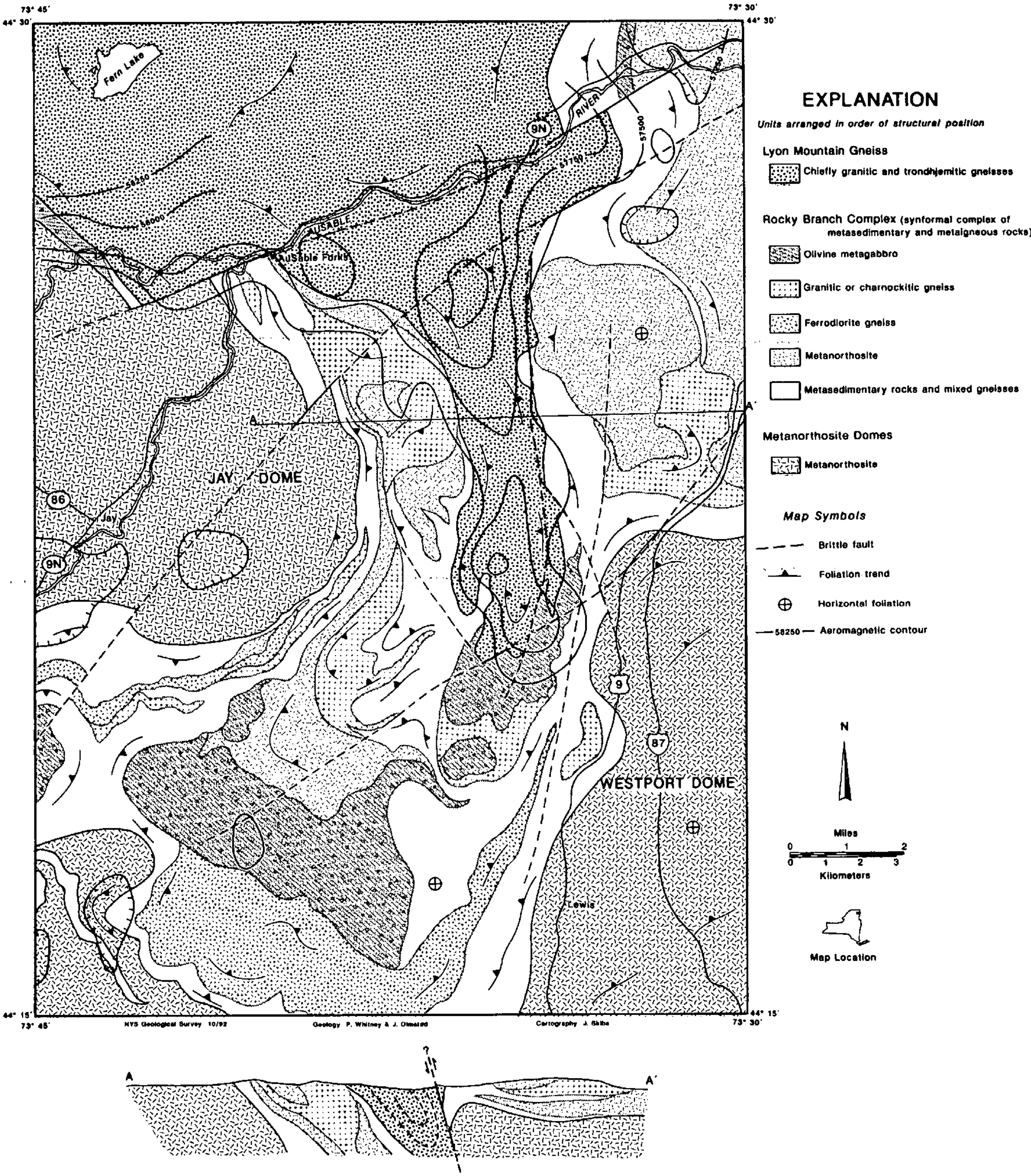


FIGURE 2. Simplified geologic map of the Au Sable Forks quadrangle showing the Jay, Westport, and Hurricane domes, Rocky Branch Complex, and Lyon Mountain Gneiss. The larger intrusive bodies within the Rocky Branch Complex are shown according to lithology, with patterns screened in order to contrast the Rocky Branch Complex (light) with the other structural units. Aeromagnetic intensity is shown by contours, interval 250 gammas (data from U.S. Geological Survey, 1978). Aeromagnetic data are missing for the northernmost part of the quadrangle. Note correspondence of high magnetic intensity with outcrop area of the Lyon Mountain Gneiss.

for the most part not separately mappable. Intense ductile deformation is characteristic of much of the Rocky Branch Complex, except for the interiors of the larger metanorthosite and metagabbro bodies.

The Rocky Branch Complex is overlain in turn by heterogeneous, stratiform, quartzofeldspathic gneisses with subordinate amphibolite and metasedimentary rocks that contain a few small olivine metagabbro bodies. Postel (1952) named this unit the "Lyon Mountain Granite Gneiss", which we have shortened herein to "Lyon Mountain Gneiss" because it includes substantial amounts of nongranitic rocks. It forms the core of the Au Sable Forks synform, and underlies most of the area north of the Ausable River.

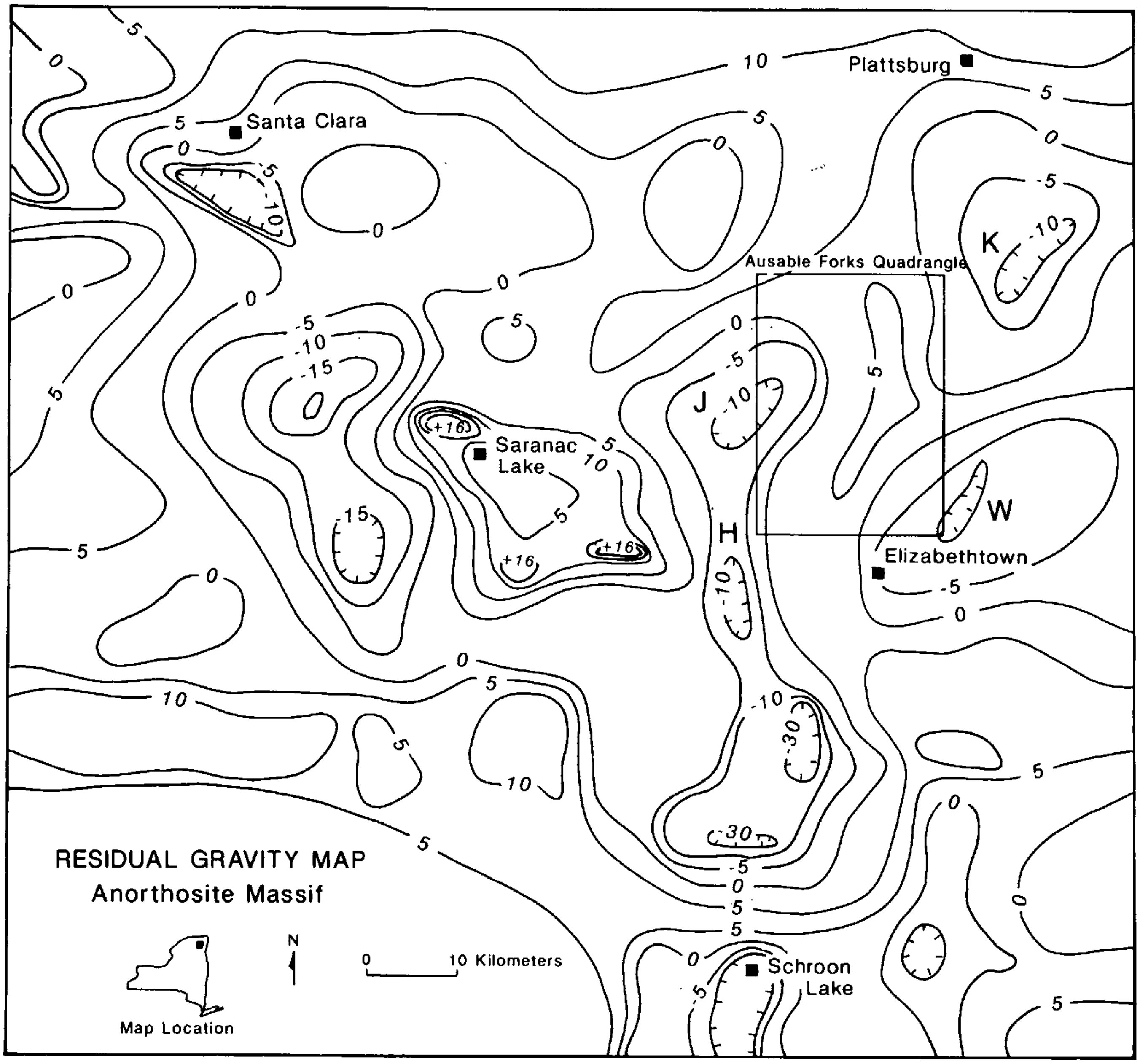


FIGURE 3. Residual gravity map of the northeastern Adirondacks (after Mann and Revetta, 1979) shows gravity lows coincident with the Jay (J), Westport (W), Keeseville (K), and Hurricane (H) anorthosite domes. Rectangular outline shows location of Au Sable Forks quadrangle.

DESCRIPTION OF ROCK TYPES

1. Westport, Jay, and Hurricane Domes.

Metanorthosite (Yand)

Metamorphosed anorthositic rocks, including the 1,500 km^2 Marcy Massif, underlie large areas in the central and northeastern Adirondacks. The metanorthosite, together with subordinate ferrodioritic gneisses, comprises the mafic part of the bimodal Anorthosite-Mangerite-Charnockite-Granite (AMCG) intrusive suite that is found throughout the Adirondack Highlands (McLelland and Whitney, 1990). In the Au Sable Forks quadrangle anorthositic rocks occur both as large domes (Yand) and as layers, lenses, and irregular bodies (Yanr) within the Rocky Branch Complex (Plate 1 and Figure 2).

Metanorthosites, gabbroic metanorthosites, and anorthositic metagabbros have in common the presence of intermediate plagioclase (An_{42-58}) as the dominant (70-98 percent) mineral. However, they are otherwise so variable that precise description and classification present formidable difficulties. Three principal variables can be distinguished:

1. Abundance of plagioclase megacrysts. Gray plagioclase megacrysts, ranging in composition from sodic labradorite to calcic andesine, are a prominent feature of many Adirondack anorthosites. Size of the megacrysts ranges from one or two centimeters in maximum dimension to giant, 1/2 meter "breadloaf" crystals and fragments. Some are visibly antiperthitic in outcrop or hand specimen; most show exsolution blebs and lamellae of potassium feldspar under the microscope. Faint to strong parallelism of the megacrysts is locally observed. The proportion of megacrysts varies from none to nearly 100 percent of the rock. Where they are abundant and closely spaced, fine-grained, clear to white, recrystallized plagioclase borders the megacrysts and occupies small fractures within them. This is commonly referred to as a "protoclastic" texture (Miller, 1916; Balk, 1931; Buddington, 1939). Where megacrysts are more widely spaced, the interstitial volumes are occupied by a medium-to coarse grained (up to several mm) groundmass

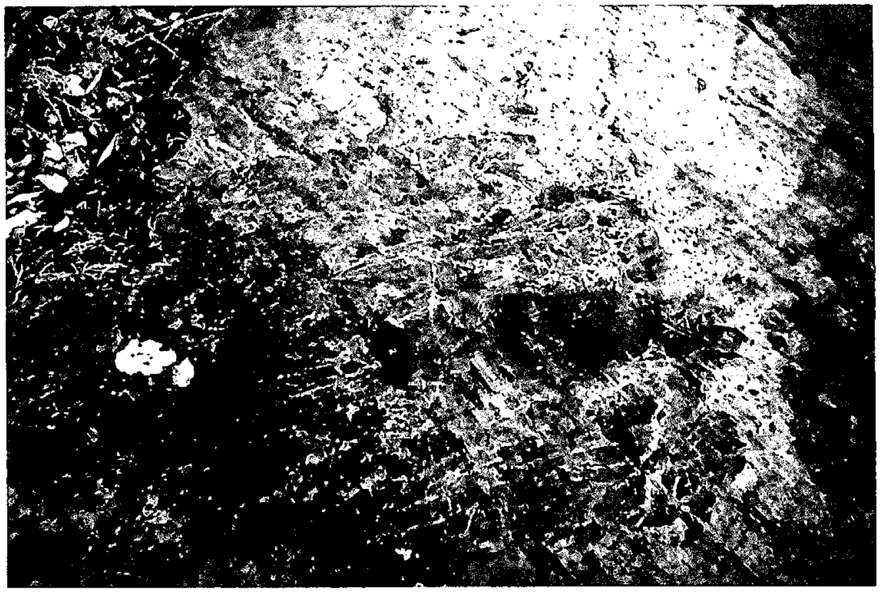
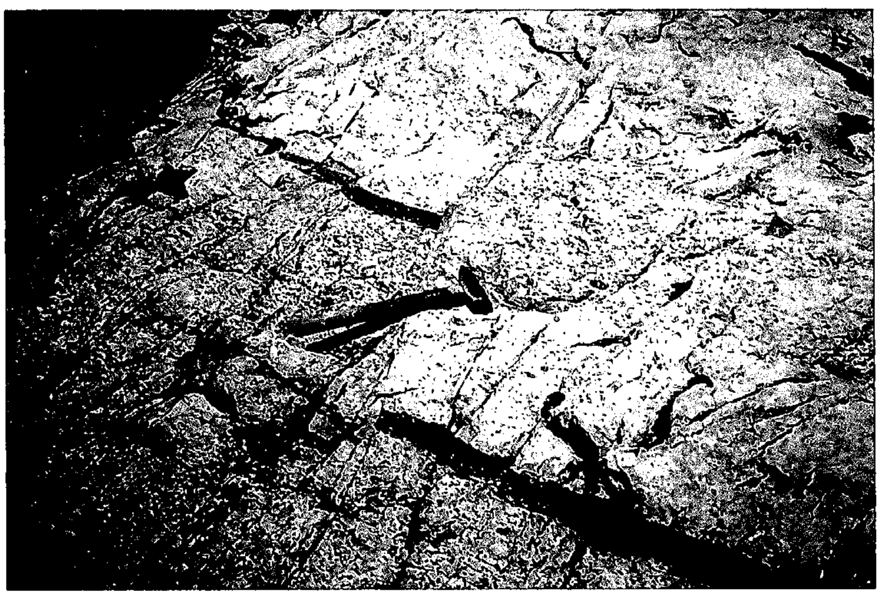


FIGURE 4. (a) Block structure in metanorthosite in a glacially polished outcrop on the west side of the road leading south from the Village of Jay, about 0.15 km south of the covered bridge. Photo, looking down onto the outcrop surface, shows a xenolith of coarse, igneous-textured anorthosite (dark) in a finer-grained, paler, anorthositic gneiss. Northeast at top of photo; pocketknife for scale. Linear features on outcrop surface are glacial striae. (b) 5-cm zone of clinopyroxene-rich mafic rock bordering a xenolith of metanorthosite (light) in gabbroic metanorthosite (dark) on the north side of the Ausable River just W of the covered bridge in Jay. Note offset of the mafic zone along a small fault.



of light gray, white or buff plagioclase together with pyroxenes and oxides. Minor (< 5 percent) quartz may also be present. This groundmass, which locally displays igneous textures, appears to have crystallized from a gabbroic anorthosite magma or crystal mush in which the megacrysts were entrained as phenocrysts or xenocrysts.

2. Abundance of mafic minerals. The color index in the anorthositic rocks varies from one or two percent in nearly pure plagioclase cumulates up to 30 percent or more in some anorthositic gabbros. Hypersthene, augite, titaniferous magnetite, and ilmenite or hemo-ilmenite are the primary mafic minerals. Common metamorphic minerals include hornblende and garnet; biotite and titanite occur locally.

3. Extent of deformation. Adirondack metanorthosites range from nearly pristine, igneous-textured varieties to anorthositic gneisses with intense foliation and lineation. As the degree of deformation increases, the megacrysts change from blocky to lenticular and decrease in size and abundance, groundmass plagioclase and mafic minerals are recrystallized, and grain size is reduced. In general, rocks near the margins of metanorthosite domes and massifs show greater deformation than those in the interiors, although shear zones with gneissic to locally mylonitic fabric are found throughout. Interpretation of these foliated and recrystallized anorthositic rocks is complicated by the difficulty in distinguishing between structures of high-temperature late- and post-magmatic origin and later tectonic deformation.

These three variables all may exhibit a considerable range on the scale of a single outcrop, and this makes subdivision of the anorthositic rocks for mapping purposes impractical in most areas. Early Adirondack workers distinguished two facies, the "Marcy" facies, which is megacryst-rich, mafic-poor and undeformed to slightly deformed, and the "Whiteface" facies, which is megacryst-poor, more mafic, and more deformed than the "Marcy". The characteristics of the two facies were summarized by Buddington (1939, p. 21). This distinction is difficult to use consistently, because the three variables used to define it are at least partially independent. There appears to be a general correlation between mafic mineral content and intensity of deformation, although this may be illusory owing to the greater visibility of foliation where mafic minerals are abundant.

Anorthositic xenoliths in anorthosite are common. This "block structure" may consist of coarse, megacryst-rich xenoliths in a finer-grained groundmass (Figure 4a); alternatively the xenoliths may be blocks or rafts of gabbroic anorthosite or leuconorite. Individual xenoliths or xenocrysts may be surrounded by a narrow zone enriched in mafic minerals (Figure 4b). Xenoliths of metasedimentary rocks, ranging from centimeters to several meters in size, are found in all varieties of metanorthosite and are common near contacts with other rocks. Most of these are calcsilicate rocks, but quartzite xenoliths also occur. One small inclusion of metapelite was found that contains the mineral assemblage plagioclase-garnet-biotite-sillimanite-corundum-spinel. The lithologic similarity of these inclusions to the adjacent metasedimentary rocks is evidence for the intrusive nature of the anorthosites.

Metanorthosite rich in plagioclase megacrysts and typical of the "Marcy facies" of Buddington (1939) is less common in the Au Sable Forks quadrangle than in the High Peaks region. It is present, however, in several locations in the interior of the Jay Dome, including Bull Hill

	AF177A	AF735	AF391B	AF241	AF23	ADK
SiO2 %	54.57	53.37	51.71	52.48	52.57	54.02
TiO2	0.55	0.34	0.80	0.75	1.26	0.71
Al2O3	23.54	24.78	20.58	24.07	23.19	24.33
Fe2O3	0.78	0.01	0.70	0.66	0.53	0.37
FeO	2.14	2.14	3.89	2.63	2.78	2.98
MnO	0.04	0.03	0.08	0.03	0.07	0.05
MgO	1.13	1.37	4.22	2.80	1.63	1.64
CaO	10.26	12.19	13.96	11.80	12.15	10.27
Na2O	4.76	4.43	3.20	4.33	4.41	4.37
K2O	0.92	0.82	0.24	0.23	0.32	0.87
P2O5	0.15	0.05	0.08	0.08	0.19	0.13
TOTAL	98.84	99.53	99.46	99.86	99.10	99.74
Rb ppm	4	6	7	2	4	6
Sr	808	681	530	649	821	685
Ba	321	203	108	76	99	246
Zr	34	35	89	49	70	56
Y	9	4	14	10	18	9
Nb	2	2	6	3	6	4
Ga	24	21	20	22	24	21
Cr	9	11	106	39	8	29
Ni	8	9	67	20	15	19
V	42	31	123	72	120	53
Ce	16	10	19	11	33	18
Qz %	0.58	0.00	0.00	0.00	0.00	0.60
Or	5.44	4.85	1.42	1.36	1.89	5.14
Ab	40.28	34.02	27.08	36.06	37.32	36.98
An	40.15	45.31	41.08	45.56	42.54	44.20
Ne	0.00	1.88	0.32	0.00	0.00	0.00
Di	8.15	12.21	22.46	10.12	13.53	4.88
Hy	2.34	0.00	3.61	0.00	0.17	5.75
Ol	0.00	0.19	1.36	4.30	0.28	0.00
Mt	0.46	0.35	0.73	0.52	0.52	0.53
Il	1.04	0.65	1.52	1.42	2.39	1.35
Ap	0.35	0.12	0.19	0.19	0.44	0.30

TABLE 1A Chemical analyses and CIPW norms of representative samples of anorthositic rocks. Major and trace analyses were done by Tariq Ahmedali of McGill University and Peter Dawson of the University of Massachusetts using X-ray fluorescence spectroscopy. Ferrous iron determinations were done by Mark Davin of the New York State Geological Survey using the modified Wilson metavanadate method. Normative minerals were calculated assuming ferric iron to be 10 percent of total iron, in order to facilitate comparison among rock types. For sample descriptions and locations see Appendix A.

	AF245	AF692	AF175D	AF76B	AF453F	AF339	AF38C	AF320	AF77	AF691	AF690
SiO2 %	50.30	50.77	50.99	51.29	51.54	52.13	52.91	53.05	53.53	55.46	56.62
TiO2	3.46	3.28	2.63	4.10	3.16	2.21	2.67	2.10	2.83	2.62	1.60
Al2O3	15.10	15.75	17.02	13.71	13.87	12.96	16.64	14.11	16.43	14.75	14.22
Fe2O3	2.41	3.35	2.08	1.85	1.38	1.23	1.69	1.41	2.58	2.62	1.79
FeO	11.00	9.65	9.51	11.14	13.15	11.98	8.51	10.91	9.00	8.65	11.03
MnO	0.18	0.16	0.17	0.18	0.19	0.21	0.14	0.19	0.15	0.15	0.19
MgO	3.01	2.75	3.11	4.32	3.51	7.75	2.42	6.07	2.34	2.15	0.94
CaO	8.45	8.46	9.05	7.81	8.39	6.90	7.87	6.72	7.77	6.91	4.96
Na2O	2.88	3.07	3.22	2.53	2.64	2.53	3.14	2.52	3.11	2.93	3.05
K2O	1.80	1.57	1.20	1.82	1.67	1.32	1.97	1.86	2.06	2.45	4.56
P2O5	1.16	1.00	0.63	0.37	0.48	0.34	0.84	0.37	0.87	0.75	0.52
TOTAL	99.75	99.81	99.61	99.12	99.98	99.56	98.80	99.31	100.67	99.44	99.48
Rb ppm	46	40	19	59	37	35	60	50	50	66	79
Sr	360	374	453	317	269	298	387	323	411	302	336
Ba	402	397	356	393	395	303	475	394	469	460	1265
Zr	209	206	231	198	204	164	237	214	219	273	705
Y	52	55	40	46	50	28	49	40	49	68	74
Nb	16	15	15	17	12	9	18	11	13	19	29
Ga	27	26	24	24	24	20	29	23	28	28	24
Cr	14	10	27	64	10	116	21	129	10	10	10
Ni	10	10	10	17	10	36	30	33	10	10	10
V	262	237	216	335	288	196	202	174	220	179	45
Ce	100	98	78	83	61	25	76	74	62	103	130
Qz %	2.88	3.17	1.82	4.68	3.68	1.73	5.50	3.62	5.57	9.22	4.98
Or	10.64	9.28	7.09	10.76	9.87	7.80	11.64	10.99	12.17	14.48	26.95
Ab	24.37	25.98	27.25	21.41	22.34	21.41	26.57	21.32	26.32	24.79	25.81
An	22.96	24.56	28.44	20.68	21.06	20.11	25.49	21.70	24.79	19.86	11.64
Di	9.65	9.23	10.40	13.05	14.77	9.80	6.82	7.64	6.86	8.11	8.37
Hy	17.80	16.81	16.21	17.80	18.88	31.60	14.07	27.18	15.59	14.35	15.41
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mt	2.12	2.04	1.83	2.06	2.32	2.11	1.62	1.96	1.82	1.77	2.04
Il	6.57	6.23	5.00	7.79	6.00	4.20	5.07	3.99	5.37	4.98	3.04
Ap	2.70	2.32	1.46	0.86	1.12	0.79	1.95	0.86	2.02	1.74	1.21

TABLE 1B. Chemical analyses and CIPW norms of representative samples of ferrodioritic and monzodioritic gneisses. Methods as in Table 1A. For sample descriptions and locations see Appendix A.

and Wainwright Mountain. It also occurs as angular to rounded inclusions, up to several meters across, in other types of metanorthosite (Figure 4a).

In the Westport and Hurricane domes, as well as much of the Jay Dome, the most common rock is metanorthosite or gabbroic metanorthosite with less than 30 percent gray megacrysts with or without a weak foliation. Most of the plagioclase is medium-to coarse-grained and white, buff, or pale gray. The subordinate gray megacrysts are blocky, broken, or rounded individual crystals or aggregates. These megacrysts appear to be fragments of a coarse, early cumulus anorthosite that was entrained in a later pulse of magma; some may be phenocrysts. In some exposures they show a measureable preferred orientation, good examples of which may be seen along the crest of the ridge between Billy and Big Spur Mountains in the northern part of the Westport Dome.

Augite is ordinarily the dominant mafic mineral and is commonly surrounded by a narrow rim of metamorphic(?) hornblende. In less-deformed rocks, the augite may form skeletal intercumulus crystals up to several cm across that subophitically enclose plagioclase. Hypersthene is common, but generally subordinate to augite. Ilmenite and titaniferous magnetite are present as accessories along with apatite. Garnet occurs as coronas around hypersthene and Fe-Ti oxides where these minerals are in proximity to one another (McLelland and Whitney, 1977).

Representative exposures of the metanorthosite domes are

	AF334	AF703	AF707	BLUFF	POKO	AF666	8568B	AF340
SiO2 %	60.68	61.13	66.37	68.65	71.45	69.81	71.51	72.11
TiO2	1.03	1.10	0.76	0.73	0.42	0.47	0.37	0.27
Al2O3	14.81	15.76	14.40	13.35	14.15	11.97	14.60	13.50
Fe2O3	1.23	1.24	0.73	1.29	1.48	1.61	0.18	0.68
FeO	6.64	6.81	5.01	3.76	1.82	4.45	2.51	2.69
MnO	0.18	0.16	0.12	0.07	0.05	0.13	0.06	0.07
MgO	0.71	1.01	0.64	0.40	0.29	0.01	0.52	0.01
CaO	3.06	3.68	2.66	2.04	1.48	1.47	1.80	1.21
Na2O	3.95	3.51	3.38	2.94	3.29	4.07	3.27	3.24
K2O	5.44	5.10	5.31	5.59	5.53	5.15	5.18	5.64
P2O5	0.35	0.39	0.19	0.14	0.13	0.03	0.09	0.06
TOTAL	98.08	99.89	99.57	98.92	100.00	99.17	100.09	99.48
Rb ppm	85	96	147	167	NA	174	188	152
Sr	130	205	185	142	NA	28	156	48
Ba	1586	1778	1069	696	NA	221	486	131
Zr	849	726	521	509	NA	1212	312	583
Y	50	57	61	66	NA	117	39	59
Nb	17	11	19	22	NA	41	15	17
Ga	18	24	27	20	NA	30	23	20
Ce	85	114	138	155	NA	141	117	243
Qz %	7.14	9.13	17.58	23.92	27.22	22.18	26.48	27.39
Or	32.15	30.14	31.38	33.04	32.68	30.44	30.61	33.33
Ab	33.43	29.70	28.60	24.88	27.84	32.90	27.67	27.42
An	6.61	12.19	8.44	6.72	6.49	0.00	8.34	5.61
Co	0.00	0.00	0.00	0.00	0.37	0.00	0.56	0.01
Ac	0.00	0.00	0.00	0.00	0.00	1.36	0.00	0.00
Di	5.47	3.04	3.05	2.15	0.00	6.33	0.00	0.00
Hy	8.74	10.90	7.57	4.64	2.24	3.36	5.26	4.09
Mt	1.78	1.80	1.06	1.87	2.15	1.65	0.26	0.99
Il	1.96	2.09	1.44	1.39	0.80	0.89	0.70	0.51
Ap	0.81	0.91	0.44	0.33	0.30	0.07	0.21	0.14

TABLE 1C Chemical analyses and CIPW norms of representative samples of granitic and charnockitic rocks. Methods as in Table 1A. NA: Not analyzed. For sample descriptions and locations see Appendix A.

	MG108	MG111	MG123	MG182	MG189	MG98	MG99A	AF686	AF751
SiO2 %	45.87	46.27	46.80	49.94	49.31	45.18	50.49	48.91	47.05
TiO2	0.80	0.57	0.58	1.11	1.01	0.36	1.18	1.39	3.33
Al2O3	15.30	17.45	21.92	16.52	18.09	15.49	16.86	9.94	14.84
Fe2O3	3.30	0.66	1.01	0.81	1.83	1.67	1.56	1.09	4.34
FeO	9.73	10.78	6.75	7.29	7.25	11.53	6.79	8.55	13.08
MnO	0.19	0.16	0.10	0.14	0.13	0.18	0.13	0.19	0.21
MgO	13.23	12.49	9.31	7.46	7.91	15.41	6.49	11.04	5.46
CaO	8.64	7.74	10.35	13.34	10.77	7.27	13.08	15.66	8.03
Na2O	1.84	2.42	2.35	2.43	2.71	1.63	2.49	1.60	2.54
K2O	0.35	0.45	0.40	0.47	0.54	0.26	0.56	0.19	1.14
P2O5	0.07	0.13	0.09	0.09	0.10	0.04	0.08	0.08	0.47
TOTAL	99.32	99.12	99.66	99.60	99.65	99.02	99.71	98.64	100.46
Rb ppm	4	8	7	6	8	3	10	3	27
Sr	233	268	326	281	306	252	312	135	243
Ba	98	119	106	154	167	85	143	50	328
Zr	31	54	36	47	57	13	67	59	237
Y	10	9	8	15	15	4	18	25	50
Nb	2	2	1	1	3	4	5	1	14
Ga	16	17	18	19	19	14	18	14	27
Cr	45	18	19	571	212	29	161	1462	86
Ni	160	155	198	66	79	202	37	92	56
V	120	59	54	203	140	41	244	347	271
Ce	13	11	13	8	17	5	25	17	52
Or %	2.07	2.66	2.36	2.78	3.19	1.54	3.31	1.12	6.74
Ab	15.57	20.48	19.89	20.56	22.93	13.79	21.07	13.54	21.49
An	32.46	35.42	48.08	32.78	35.60	34.18	33.17	19.38	25.37
Di	8.08	1.73	2.17	26.69	13.99	1.31	25.48	46.69	9.28
Hy	8.89	4.67	1.73	4.27	6.63	12.20	7.64	2.21	16.77
Ol	28.28	31.08	22.88	26.69	13.58	33.01	5.20	11.30	10.13
Mt	2.05	1.83	1.23	1.29	1.43	2.10	1.32	1.54	2.74
Il	1.52	1.08	1.10	2.11	1.92	0.68	2.24	2.64	6.32
Ap	0.16	0.30	0.21	0.21	0.23	0.09	0.19	0.19	1.09

TABLE 1D Chemical analyses and CIPW norms of representative samples of olivine metagabbros. Methods as in Table 1A. For sample descriptions and locations see Appendix A.

	AF677	AF657	AF441	AF356	AF624	AF444	AF470	AF431B
SiO2 %	62.75	65.95	68.23	69.58	71.58	73.77	74.30	74.41
TiO2	0.99	1.04	0.48	0.50	0.48	0.33	0.42	0.37
Al2O3	15.44	14.11	13.24	12.20	12.59	12.83	11.88	12.37
Fe2O3	3.44	5.06	1.77	3.85	1.71	0.17	3.54	2.31
FeO	3.38	3.22	4.05	2.83	2.69	2.69	1.69	1.24
MnO	0.12	0.04	0.13	0.09	0.07	0.05	0.04	0.04
MgO	0.77	0.40	0.19	0.09	0.32	0.08	0.06	0.06
CaO	2.02	0.95	1.38	1.86	1.48	1.01	1.27	1.28
Na2O	5.00	5.36	4.50	3.88	3.71	2.46	4.57	4.86
K2O	5.73	3.72	5.22	4.63	4.69	5.72	2.23	2.84
P2O5	0.27	0.24	0.07	0.05	0.09	0.08	0.03	0.03
TOTAL	99.91	100.09	99.26	99.56	99.41	99.19	100.03	99.81
Rb ppm	97	86	215	98	103	120	61	69
Sr	63	77	50	62	96	138	28	38
Ba	805	363	393	526	614	866	88	95
Zr	431	573	1021	1172	555	388	1229	1018
Y	69	74	228	59	95	58	200	183
Nb	17	33	49	21	23	17	53	59
Ga	22	26	38	25	25	22	33	37
Ce	108	123	375	211	147	120	241	185
Qz %	7.32	18.54	17.83	26.14	27.98	33.53	36.62	33.08
Or	33.86	21.98	30.85	27.36	27.72	33.80	13.18	16.78
Ab	42.31	45.36	38.08	32.83	31.39	20.82	38.67	41.13
An	2.76	3.15	0.51	2.20	3.85	4.49	5.32	3.35
Wo	0.00	0.00	0.00	1.34	0.00	0.00	0.16	0.91
Ac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Di	4.55	0.00	5.18	3.04	2.50	0.00	0.32	0.32
Hy	1.62	1.08	3.18	0.00	2.37	4.54	0.00	0.00
Mt	4.99	7.34	2.57	5.58	2.48	0.25	4.36	3.05
Hm	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.20
Il	1.88	1.98	0.91	0.95	0.91	0.63	0.80	0.70
Ap	0.63	0.56	0.16	0.12	0.21	0.19	0.07	0.07

TABLE 1E Chemical analyses and CIPW norms of representative samples of the granitic facies of the Lyon Mountain Gneiss. Methods as in Table 1A. DL: Below detection limit. For sample descriptions and locations see Appendix A.

	AF370	AF665	AF664	AF667	AF678	AF673	AF671	AF364B	AF658	AF442	AF676
SiO2 %	68.45	69.09	71.07	72.09	74.02	59.24	61.45	61.65	62.25	65.34	78.24
TiO2	0.62	0.44	0.48	0.50	0.44	0.87	1.01	1.08	1.01	1.16	0.63
Al2O3	13.49	13.10	13.13	13.10	11.93	16.46	14.29	13.58	13.37	12.75	8.01
Fe2O3	4.36	5.48	3.73	2.90	4.33	4.72	4.01	1.83	2.04	3.53	1.36
FeO	2.86	2.47	1.65	1.80	2.01	1.97	2.44	2.31	2.76	2.16	1.58
MnO	0.02	0.01	0.03	0.02	0.01	0.03	0.02	0.02	0.05	0.03	0.03
MgO	0.45	0.29	0.34	0.36	0.17	3.69	2.93	3.48	2.89	2.29	3.56
CaO	1.17	1.37	2.57	0.96	1.16	3.49	2.82	7.66	7.29	4.19	2.69
Na2O	7.76	7.31	7.63	6.57	5.54	6.25	8.69	8.09	7.89	8.01	4.46
K2O	0.28	0.38	0.11	0.99	0.54	2.99	0.49	0.15	0.21	0.26	0.29
P2O5	0.13	0.07	0.07	0.08	0.03	0.17	0.21	0.21	0.07	0.21	0.12
TOTAL	99.59	100.01	100.81	99.37	100.18	99.88	98.36	100.06	99.83	99.93	100.97
Rb ppm	9	6	2	12	4	80	4	2	3	3	4
Sr	33	37	25	42	33	153	47	61	36	43	28
Ba	64	27	27	101	53	161	47	10	27	62	40
Zr	901	988	1084	653	1320	230	307	283	315	292	385
Y	105	126	121	75	182	46	47	80	85	45	34
Nb	43	45	38	18	48	18	14	21	17	23	10
Ga	33	27	27	24	31	25	19	20	18	14	10
Cr	DL	DL	DL	DL	DL	37	49	57	91	57	23
Ni	DL	DL	DL	DL	DL	42	32	23	27	12	17
V	DL	DL	DL	DL	DL	94	69	108	67	89	38
Ce	75	184	233	154	338	58	72	103	86	66	53
Qz %	19.95	22.92	22.83	27.86	37.07	0.71	2.46	0.41	2.61	10.93	42.59
Or	1.65	2.25	0.65	5.85	3.19	17.67	2.90	0.89	1.24	1.54	1.71
Ab	65.67	61.86	64.57	55.60	46.88	52.89	70.78	68.46	66.77	64.14	37.74
An	1.15	1.81	1.25	3.33	5.56	8.03	0.00	0.30	0.45	0.00	0.98
Wo	0.00	1.06	3.63	0.00	0.00	0.00	0.00	4.28	4.81	1.41	0.00
Ac	0.00	0.00	0.00	0.00	0.00	0.00	2.43	0.00	0.00	3.21	0.00
Di	3.10	1.56	1.83	0.72	0.00	6.36	9.85	20.54	18.92	12.49	9.09
Hy	0.00	0.00	0.00	0.00	0.00	6.24	2.94	0.00	0.00	0.00	5.39
Mt	6.32	6.72	4.02	4.20	5.24	3.93	4.60	2.65	2.96	3.51	1.97
Hm	0.00	0.85	0.95	0.00	0.72	2.01	0.00	0.00	0.00	0.00	0.00
Il	1.18	0.84	0.91	0.95	0.84	1.65	1.92	2.05	1.92	2.20	1.20
Ap	0.30	0.16	0.16	0.19	0.07	0.40	0.49	0.49	0.16	0.49	0.28

TABLE 1F Chemical analyses and CIPW norms of representative samples of the albite gneisses from the Lyon Mountain Gneiss. Leucocratic albite gneiss, samples AF370, AF665, AF664, AF667, AF678. Mafic albite gneiss, samples AF673, AF671, AF364B, AF658, AF442, AF676. Methods as in Table 1A. DL: Below detection limit. For sample descriptions and locations see Appendix A.

Calcsilicate rocks

* Clinopyroxene $Ca(Mg,Fe)Si_2O_6$	Quartz SiO_2
* Garnet $Ca_3(Fe,Al)_2Si_3O_{12}$	Titanite $CaTiSiO_5$
* Wollastonite $CaSiO_3$	Pyrite FeS_2
Plagioclase $Na_{1-x}Ca_xAl_{1+x}Si_{3-x}O_8$	Pyrrhotite $Fe_{1-x}S$
Microcline $(K,Na)AlSi_3O_8$	Graphite C
Phlogopite $KMg_3AlSi_3O_{10}(OH,F)_2$	
Biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$	
Scapolite $(Ca,Na)_4[(Al,Si)_4O_8]_3(CO_3,Cl,SO_4)$	
x Epidote $Ca_2(Al,Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$	
x Clinozoisite $Ca_2Al_3O(SiO_4)(Si_2O_7)(OH)$	
# Prehnite $Ca_2Al(AlSi_3O_{10})(OH)_2$	
# Chlorite $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2.(Mg,Fe)_3(OH)_6$	

Marbles

* Calcite $CaCO_3$	Quartz SiO_2
* Dolomite $CaMg(CO_3)_2$	Microcline $(K,Na)AlSi_3O_8$
Diopside $CaMgSi_2O_6$	Forsterite Mg_2SiO_4
Phlogopite $KMg_3AlSi_3O_{10}(OH,F)_2$	Titanite $CaTiSiO_5$
Plagioclase $Na_{1-x}Ca_xAl_{1+x}Si_{3-x}O_8$	Apatite $Ca_5(PO_4)_3(F,Cl,OH)$
Grossular $Ca_3Al_2Si_3O_{12}$	Pyrite FeS_2
Wollastonite $CaSiO_3$	Pyrrhotite $Fe_{1-x}S$
x Chondrodite $Mg_5(SiO_4)_2(F,OH)_2$	Graphite C
x Spinel $(Mg,Fe)Al_2O_4$	
x Idocrase $Ca_{10}(Mg,Fe)_2Al_4(SiO_4)_5(Si_2O_7)_2(OH)_4$	
# Serpentine $Mg_3Si_2O_5(OH)_4$	

Quartzites

* Quartz SiO_2	Diopside $CaMgSi_2O_6$
Alkali feldspar $(K,Na)AlSi_3O_8$	Tremolite $Ca_2Mg_5Si_8O_{22}(OH,F)_2$
Plagioclase $Na_{1-x}Ca_xAl_{1+x}Si_{3-x}O_8$	Enstatite $MgSiO_3$
Biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$	Pyrite FeS_2
Phlogopite $KMg_3AlSi_3O_{10}(OH,F)_2$	Graphite C

Metapelites

Alkali feldspar $(K,Na)AlSi_3O_8$	Quartz SiO_2
Plagioclase $Na_{1-x}Ca_xAl_{1+x}Si_{3-x}O_8$	Graphite C
Biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$	Pyrrhotite $Fe_{1-x}S$
Garnet $(Fe,Mg,Mn,Ca)_3Al_2Si_3O_{12}$	Pyrite FeS_2
Sillimanite Al_2SiO_5	
x Cordierite $(Mg,Fe)_2Al_4Si_5O_{18}.nH_2O$	
# Chlorite $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2.(Mg,Fe)_3(OH)_6$	

* May form nearly monomineralic rock
x Local occurrence only
Alteration products

Table 2. Mineral species occurring in the principal metasedimentary rocks of the Au Sable Forks Quadrangle, with generalized chemical formulae.

TABLE 2 Mineralogy of the principal metasedimentary rocks of the Au Sable Forks quadrangle, with approximate chemical formulae.

FIGURE 5. (a) Gently dipping wollastonite-diopside-andradite rock at the Lewis wollastonite mine. Photo, looking NW, was taken in 1983 shortly after removal of overburden. Note the karst surface, resulting from the solution of wollastonite, one of the few silicate minerals that are appreciably soluble in water. (b) Steeply dipping, thinly layered metasedimentary rocks at elevation 2400, N60E of the summit of Black Ash Mountain. Thicker, light layers are quartzite; thin layers which are weathered back from the surface and appear darker contain the assemblage quartz-diopside-tremolite-enstatite-phlogopite. Photo looking SW.

found in roadcuts along the Adirondack Northway (I-87) where it crosses the Westport Dome, along the Ausable River upstream from the covered bridge near Jay (Jay Dome), and on Big Crow Mountain and the south-facing slopes southwest of Lost Pond (Hurricane Dome). Chemical analyses of typical metanorthosites of the domes are presented in Table 1A (analyses AF177 and AF735).

Metamorphic foliation is more evident near the outer margins of the domes, and plagioclase megacrysts become less abundant, smaller, and more rounded than in the interiors. In the strongly foliated anorthositic gneisses close to the contacts and in local zones of high strain within the domes, megacrysts are rare and usually consist of a few small augen with gray cores surrounded by rims of white, recrystallized plagioclase. Minor quartz and potassium feldspar are usually present. Metamorphic hornblende is common and biotite appears locally. Garnet occurs as discrete porphyroblasts, commonly undeformed, as well as coronas. Streaks of mafic minerals including pyroxene, hornblende, and granular garnet may define a lineation. Anorthositic gneisses are well exposed on Mount Discovery and on the western spur of Hickory Mountain.

2. Rocky Branch Complex

(a) Metasedimentary rocks (Yms)

The metasedimentary rocks of the Au Sable Forks quadrangle occur as relatively thin (at most a few tens of meters thick), discontinuous layers in the Rocky Branch Complex and locally in the Lyon Mountain Gneiss. Interlayered with the metasedimentary rocks are substantial amounts of quartzofeldspathic gneiss with variable quartz content, along with lesser amounts of amphibolite and fine-grained two pyroxene-biotite-plagioclase granulite. Metanorthosite, olivine metagabbro, and ferrodioritic, charnockitic and granitic gneisses occur as layers, lenses, and irregular bodies within the metasedimentary rocks. These metaigneous rocks have been mapped separately where they are sufficiently thick. Because of insufficient outcrop, discontinuity of individual layers along strike, and abundant interlayered metaigneous rocks, we are unable either to demonstrate a coherent stratigraphic sequence for the metasedimentary rocks or to obtain an estimate of total thickness of the section.

The best exposures of metasedimentary rocks in the southern part of the quadrangle are in the streams that drain Gelina Basin and Kelly Basin north of Jay Mountain, along Rocky Branch northeast of Arnold Mountain, and on the northern and western slopes of Big Lawler Mountain. Further north, good exposures are found near the west end of The Gulf and on the west slopes of Long Tom and Black Mountains.

The dominant metasedimentary rocks are calcsilicate granulites, impure quartzites, and calcite marbles. Table 2 summarizes the minerals that occur in these rocks. The principal mineral in most of the calcsilicate rocks is a clinopyroxene that ranges from colorless or pale green, nearly pure diopside to dark green to nearly black, hedenbergite-rich varieties. The color of clinopyroxene may vary significantly on the scale of a hand specimen. Nearly monomineralic diopsidites are present locally; more commonly the clinopyroxene is associated with microcline (or mesoperthite), plagioclase, quartz, wollastonite, grossular-andradite garnet, tremolite, scapolite, phlogopite, enstatite, or titanite.

Wollastonite is common as an accessory mineral in, and locally as a major constituent of, calcsilicate granulites and siliceous marbles. Of particular interest is a wollastonite-grandite garnet-green clinopyroxene rock that forms layers and lenses in the metasedimentary rocks in proximity to anorthosite and olivine metagabbro contacts. Zones of this unusual rock up to 25 m thick are found approximately 1.5 km NNW of Deerhead and at the Lewis Mine 1.5 km SW of Mt. Fay (Figure 5a). The latter occurrence is currently being mined for wollastonite (see section on Economic Geology). Wollastonite also occurs in a rusty-weathering wollastonite-pale diopside rock that is locally present throughout the Rocky Branch Complex. This latter rock normally contains quartz, pyrite, and graphite, in contrast to the wollastonite-diopside-andradite ores, which lack these minerals.

The calcsilicate rocks grade into impure quartzites in which tremolite and diopside are the dominant calcsilicate minerals. The Mg-rich assemblage tremolite-enstatite-diopside-(phlogopite)-quartz is locally present. Some quartzites display centimeter-scale layering, in which layers of nearly pure quartz alternate with layers rich in tremolite or diopside (Fig. 5b); elsewhere the quartzites are massive. Calcite marbles, usually with abundant calcsilicate minerals, occur in lenses and irregular layers. In the central part of the quadrangle near the west end of The Gulf, prominent marble "dikes" crosscut a strati-form metanorthosite body, illustrating the ductile behavior of marble during deformation. This is one of the localities that led Emmons (1842) to conclude that the marble ("primitive limestone") is an intrusive igneous rock. Dolomite marble is exposed northwest of Lawson Pond and in the bed of Hale Brook northwest of Sunset Hill.

Subordinate metapelitic rocks include thin, rusty-weathering biotite or phlogopite schist interlayered with the calcsilicate rocks, and quartz-microcline-sillimanite-garnet-graphite-(biotite) gneiss. The latter occurs locally in association with marble and as a thin, discontinuous layer at the contact of the Rocky Branch Complex with the overlying Lyon Mountain Gneiss. Outcrops of this metapelite in Doyle Brook north of Lawson Pond contain cordierite, together with coarse poikiloblastic sillimanite, pale brown biotite, pyrrhotite, and minor garnet. The presence of cordierite is notable because this mineral has not previously been reported in the northeastern Adirondacks and is known at only two other localities in the Adirondack Highlands (Seal, 1986).

(b) Metanorthosite (Yanr)

Most of the metanorthosite occurring within the Rocky Branch Complex is similar to that of the metanorthosite domes, except that it is, in general, more gabbroic, more deformed, and poorer in plagioclase megacrysts. One type, however, is confined to the Rocky Branch Complex and has not been found in the domes. This variety is found principally in conformable layers within the metasedimentary rocks and mixed gneisses. It is characterized by white, fine-to-medium grained granoblastic plagioclase and lacks megacrysts. Clinopyroxene, pale green and slightly pleochroic in thin section, and hornblende dominate the mafic assemblage. Garnet, where present, forms discrete granules or large poikiloblasts up to several centimeters across. Orthopyroxene and opaque oxide minerals are scarce to absent; the dominant accessory is usually titanite. Quartz is generally absent, and chemical analyses (samples AF23, AF241, and AF391B, Table 1A) show that these rocks, unlike typical Adirondack anorthosites, are slightly olivine normative. Distinct compositional layering is common, with individual layers ranging from nearly pure metanorthosite to metagabbro, amphibolite, or garnet hornblendite. This variety of metanorthosite characterizes the large, sill-like body that extends from Ragged Mountain south and east to the notch west of Mount Fay. It is well exposed along the NW-trending ridge of Jay Mountain between the two summits (3,600 and 3,540 feet), as well as near the western end of a deep east-west fault valley called The Gulf, south of Ellis Mountain.

Zones of hybrid rocks containing major amounts of clinopyroxene locally accompanied by grossular-andradite garnet, titanite, or scapolite, are present in some granofelsic and gneissic metanorthosites. These hybrids, which are similar to those described by Buddington and Whitcomb (1941) in the northwestern part of the Willsboro quadrangle, appear to have formed by contamination of anorthositic or gabbroic anorthosite magma with calcareous metasedimentary rocks. With increasing amounts of pyroxene, the hybrid metanorthosite grades into calcsilicate granulite.

(c) Ferrodiorite and monzodiorite gneisses (Yfd)

These rocks, which are part of the AMCG intrusive suite, occur locally as layers, lenses, and dikes within metanorthosite, but the principal occurrence in the Au Sable Forks quadrangle is a large, gently dipping sheet. This body overlies metanorthosite and metasedimentary rocks and is exposed over an area of nearly 25 km^2 in the southwestern part of the quadrangle. It has a maximum thickness in excess of 250 meters. Representative exposures are found on the northern slope of Yard Hill. A thinner layer of monzodiorite gneiss that appears to be an extension of the same body crops out along the east limb of the Au Sable Forks Synform. A separate layer of this rock occurs on Little Lawler Mountain and Round Hill. Ferrodiorite gneisses are also present in the band of mixed gneisses that crosses the Soda Range NNE of Big Crow Mountain. A small lens within strongly deformed metanorthosite is well exposed in a roadcut on the northbound exit ramp of the Adirondack Northway at Exit 32 near the village of Lewis.

The ferrodiorite gneisses are garnet-orthopyroxene-clinopyroxene-plagioclase rocks with minor hornblende, quartz, potassium feldspar, ilmenite and magnetite. The plagioclase is relatively fine grained and ranges from sodic andesine to calcic oligoclase. In most samples, gray andesine augen megacrysts in various stages of grain size reduction are also present; one xenolith of anorthosite has been found. A strong gneissic fabric is typical; no relict igneous textures have been observed. Compositional layering is present in many exposures in the form of relatively coarse grained and feldspathic layers that alternate with finer-grained, more mafic layers. Locally, biotite is a major phase and garnet is absent. With increasing amounts of potassium feldspar, the ferrodiorite grades into monzodiorite and quartz mangerite gneisses. All varieties of ferrodiorite gneiss are veined or streaked with quartzofeldpathic material, and xenoliths of metasedimentary rocks are common.

Chemical analyses of several ferrodioritic gneisses are listed in Table 1B. These rocks are relatively enriched in iron, titanium, and phosphorus; most samples are quartz normative. They are geochemically distinct from the olivine metagabbros (Table 1D), which are strongly olivine normative and have higher Al, Ni, and Mg/Fe and lower Ti, K, Rb, and Ba.

(d) Granitic and charnockitic gneisses (Ycg)

Irregular layers and lenses of medium- to coarse-grained granitic gneisses are common throughout the Rocky Branch Complex. Some are up to several hundred meters thick (e.g., near Pokamoonshine, Long Tom, and Bluff Mountains). They contain mesoperthite or microcline, quartz, and hornblende, plus minor Fe-Ti oxides and traces of apatite and zircon. Plagioclase is present in most samples, but is subordinate to alkali feldspar. Biotite occurs locally in the most felsic varieties; more mafic granitic gneisses grade into clino- and orthopyroxene-bearing charnockites. In the latter, mafic silicates and Fe-Ti oxides may be rimmed by garnet. The charnockites are green to olive-gray on fresh surfaces, whereas the hornblende granitic gneisses are ordinarily pink or white. A quartz mangeritic facies is well exposed in several small abandoned quarries near the west end of Ragged Mountain.

Foliation is nearly ubiquitous in the granitic and charnockitic gneisses. Where foliation is strong, phacoidal or flaser textures are developed locally, and quartz-blade lineations are common. The strongest foliation and lineation are found where the gneisses are thin and near contacts with rocks of contrasting mechanical properties. In most exposures, the charnockitic and granitic rocks are migmatites, with coarse quartzofeldspathic leucosomes that form thin, foliation-parallel layers, irregular patches, and occasional cross-cutting veins.

Amphibolites of varying thickness are common in some of the granitic bodies. In the cliff on the east face of Pokamoonshine Mountain, amphibolite layers up to 10 meters in thickness are present and may be sills or transposed dikes of metagabbro (Figure 6). Decreasing grain size toward the contacts suggests a relict chilled margin. These amphibolites have a composition similar to olivine metagabbro (Table 1D, column 9).

Contacts between granitic gneisses and metanorthosite, rarely exposed, are likewise parallel to foliation. One occurrence of xenoliths of metanorthosite in granitic gneiss has been found in a large pavement outcrop on the west side of rise 1380, 3.1 km WNW of Lewis.

Chemical analyses of representative granitic rocks are shown in Table 1C. These are A-type granitoids (Whalen and others, 1987), with slight enrichment in large-ion lithophile elements (K, Rb, Ba) and considerable enrichment in high field strength elements (Y, Nb, Zr). They bear a strong geochemical and petrographic resemblance to charnockitic and hornblende granitic gneisses of the AMCG suite elsewhere in the Adirondack Highlands (McLelland and Whitney, 1990; Whitney, 1992).

(e) Olivine metagabbros (Yog)

Layers, lenses, and irregularly shaped bodies of olivine metagabbro are found within all other lithologic units in the quadrangle, with the exception (possibly fortuitous) of the ferrodiorite gneisses. Most are located within the Rocky Branch Complex, although several small metagabbros are found within the Lyon Mountain Gneiss. All of the large metagabbro bodies occur in the southern half of the quadrangle. The largest under-

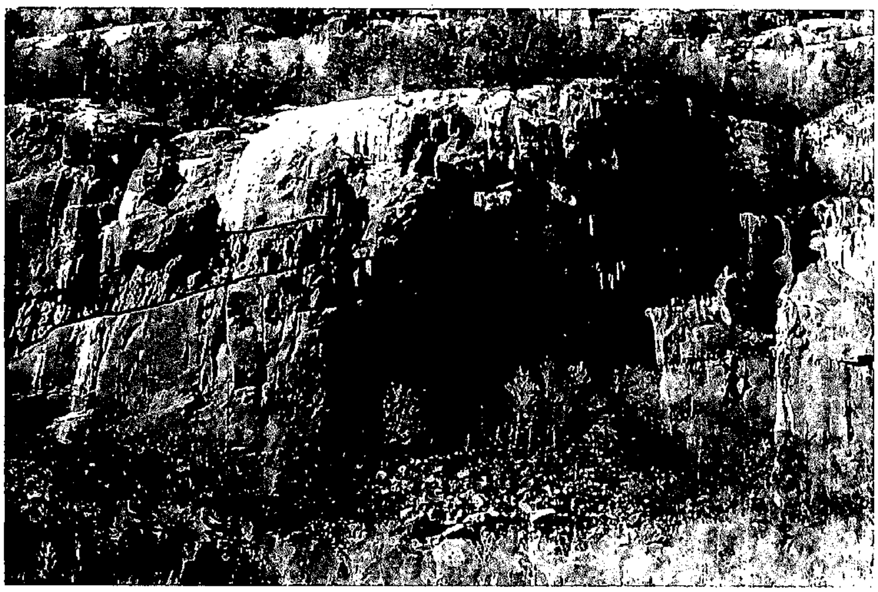


FIGURE 6. View, looking west, of the east face of Pokamoonshine Mountain. Note the prominent (10-20 m thick) sill of mafic granulite (outlined in ink) in granitic gneiss. The sill is offset along small fault just to left-of-center. Chemical analyses show that the sill is probably a fine grained equivalent of the olivine metagabbro.

FIGURE 7. (a) Dike of olivine metagabbro cutting anorthosite, just east of rise 3450 on west ridge of Jay Mountain. Photo taken looking down. North at top of photo; hammer for scale. (b) Xenoliths of foliated anorthosite (light) in olivine metagabbro (dark), 900' elevation, 0.3 km S55°E of Spear Mountain. Photo taken looking north with notebook (22 cm long) for scale; dappled appearance of the metagabbro surface on right is due to leaf shadows. (c) Xenolith of olivine metagabbro in granitic gneiss, elevation 1900' on stream draining Gelina Basin north of Jay Mountain. Photo taken looking down. South at top of photo; pocketknife for scale.

FIGURE 8. (a) Layering in olivine metagabbro of the Jay Mountain body. Elevation 3420' NNW of summit of Saddleback Mountain, looking east. Hammer for scale. Plagioclase-rich layers (indented) weather more rapidly than olivine-rich layers that contain abundant metamorphic garnet. (b) Layering in olivine-free metagabbro zone within the Jay Mountain body, elevation about 3400' on east side of Saddleback Mountain, looking west. Hammer for scale. Plagioclase-rich layers (in which the plagioclase lacks the spinel clouding that characterizes the olivine metagabbros) appear white; pyroxene-rich layers are dark. (c) Ultramafic (olivine-clinopyroxene) layer (under hammer) in olivine metagabbro, top of hill 3320, NNW of Saddleback Mountain, looking west.

lies Jay and Saddleback Mountains, and somewhat smaller bodies occur on or near Clements Mountain, Mount Fay, and Spear Mountain.

Dikes of metagabbro crosscut the foliation in stratiform metanorthosite on Jay Mountain (Figure 7A), and a foliated xenolith of metanorthosite occurs in metagabbro on Spear Mountain (Figure 7B). Metagabbro with relict igneous texture in the interior and a distinctly fine-grained marginal facies 1-2 m thick cuts foliated granitic gneiss at a high angle to the foliation at a location 1.1 km N37E from the summit of Lesperance Mountain. Such crosscutting relationships are unusual, however, and most metagabbro-granite gneiss contacts are parallel to foliation. One instance of an apparent xenolith of metagabbro in granitic gneiss is found close to the contact of the Jay Mountain metagabbro body in Gelina Basin (Figure 7C).

The olivine metagabbros ordinarily retain relict igneous textures except within a few meters of their contacts, where they are recrystallized and amphibolitized. The dominant mineral in the typical metagabbro is plagioclase (An_{30}-An_{45}) with a dark grayish-green color owing to the presence of small (<10 μ) spinel inclusions of metamorphic origin (Whitney 1972). The plagioclase ordinarily occurs as rectangular laths, which display parallelism of cumulus origin. Olivine (Fo_{55}-Fo_{75}) is present in smaller amounts in anhedral, round to amoeboid grains. Where olivine is in contact with plagioclase, it is invariably surrounded by metamorphic reaction coronas of pyroxenes and garnet. Augitic clinopyroxene is commonly present as skeletal intercumulus crystals that subophitically enclose plagioclase laths and/or round olivine grains. Many of the olivine metagabbros, however, contain little or no igneous pyroxene and are more correctly called metatroctolites. Minor primary phases include ilmenite, locally intergrown with green spinel, and apatite. Ilmenite is separated from plagioclase by metamorphic reaction coronas of biotite, amphibole, and garnet.

Most of the large metagabbro body on Jay and Saddleback Mountains consists of olivine metagabbro or metatroctolite, with locally distinct modal layering (Figure 8A). However, it also contains zones of olivine-free metagabbro up to several tens of meters thick. Primary minerals in the latter include clear plagioclase (An_{55}-An_{65}) with few or no spinel inclusions, cumulus augite, and minor ilmenite and apatite. These olivine-free metagabbros commonly display centimeter-scale layering with alternating plagioclase- and pyroxene-rich layers (Figure 8B). Also present in the Jay Mountain body are a few ultramafic layers (dunite and wehrlite) up to 0.5 m thick (Figure 8C), as well as thin (<10 cm) anorthositic layers. The latter display a very strong alignment of tabular plagioclase crystals that defines an igneous foliation parallel to the layering.

Chemical analyses of representaive olivine metagabbros are shown in Table 1D.

(f) Mixed gneisses (Ymga, Ymgb)

Two types of mixed gneisses are distinguished on the map. The more abundant type, "A" on Plate 1, consists principally of anorthositic gneisses and metanorthosite-metasedimentary rock hybrids with subordinate layers of metasedimentary rocks, amphibolite (Figure 9), ferrodiorite gneiss, and granitic gneiss. The individual layers are too small to show at map scale. Ferrodiorite gneiss, where present, contains xenoliths of both metasedimentary rocks and metanorthosite. This variety of mixed gneisses is similar to the gabbroic anorthosite gneiss with layers and shreds of "skarn" mapped by Buddington and Whitcomb (1941) in the structural saddle between Sugarloaf and Bigelow Mountains in the northwestern part of the Willsboro quadrangle. In the northeastern corner of the quadrangle, and in the vicinity of the Westport Dome, Mixed Gneiss A is largely metanorthosite. In the latter location, it grades into the metanorthosite of the dome itself and the location of the contact on Plate 1 is somewhat arbitrary. The other type of mixed gneisses ("B" on Plate 1) comprises granitic gneisses with subordinate metasedimentary rocks and gabbroic anorthosite gneiss. It is exposed primarily in the northeastern corner of the quadrangle in the area near Fordway Mountain.

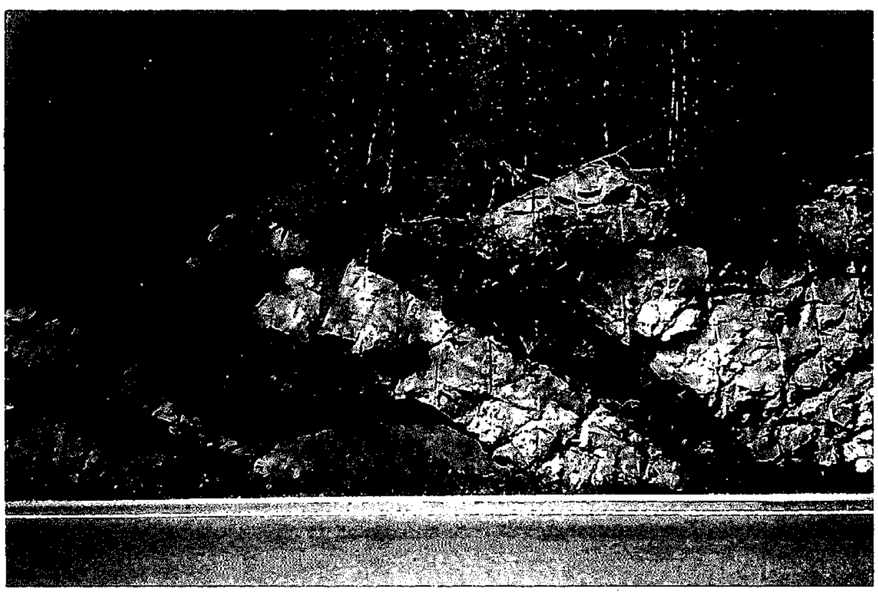


FIGURE 9. NW-dipping layers of amphibolite in anorthositic gneiss of the mixed gneiss A unit, roadcut on west side of southbound lane of Adirondack Northway, WNW of Dry Mountain, looking west.

3. Lyon Mountain Gneiss

(a) Granitic gneisses and albite gneisses with metasedimentary interlayers (Ylm)

Postel (1952) provided a detailed description of the Lyon Mountain Gneiss on the basis of drill

	GRANITIC GNEISSES (12)			LEUCOCRATIC ALBITE GNEISSES (6)			MAFIC ALBITE GNEISSES (11)[1]		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
PLAGIOCLASE[2]	11.7	0	46	64.1	51	74	65.6	33	83
ALKALI FELDSPAR	53.5	11	78	0.7	0	2.6	0.6	0	0.6
QUARTZ	27.5	10	38	27.2	18	43	8.9	0	45
CLINOPYROXENE	1.5	0	6.1	2.7	0	13	16.7	0.3	34
AMPHIBOLE	1.6	0	8.3	1.0	0	3.2	3.8	0	17
OPAQUE OXIDES	1.9	0.3	4.7	2.9	0.7	4.4	1.2	0	4.6
TITANITE	0.2	0	1.3	0.5	0	1.3	1.7	0	2.7
OTHER[3]	2.0	0	6.7	0.8	0	2.9	1.5	0	13

1 Excludes one sample with 30% scapolite
2 Includes antiperthite
3 Includes biotite, zircon, apatite, garnet (in two sections), fayalite (in one section), fluorite, and low-T alteration.

TABLE 3 Average modes of the Lyon Mountain Gneiss. All modes are based on at least 1000 points counted in one or more thin sections.

cores and surface exposures in the mining district of Clinton County, which includes the Au Sable Forks quadrangle north of the Ausable River. For the purposes of this report, we have divided these rocks into two major types: granitic gneiss, which includes the microperthite and microcline types of Postel (1952), and leucocratic albite gneiss, which is trondhjemitic in composition and includes Postel's plagioclase and microantiperthite types. Also present in the Lyon Mountain Gneiss are subordinate layers of amphibolite and mafic albite gneiss, the latter being a distinctive albite-pyroxene rock of probable sedimentary origin. The mafic albite gneiss may correspond in part to the rocks described by Postel (1952, p. 10) as pyroxene granite gneiss, contaminated granite gneiss, and granitized skarn. Mafic albite gneiss and amphibolite in the Lyon Mountain Gneiss are most common in the tightly folded central part of the Au Sable Forks Synform. As the synform opens northwards in the area north of Trout Pond, the mafic rocks become less abundant. At Keeton Mountain near Clintonville, and near Perkett Mountain west-northwest of Deerhead, small olivine metagabbro bodies are present within the Lyon Mountain Gneiss (Plate 1). Although unequivocal contact relationships are lacking, the metagabbros appear to be intrusive; this indicates that the protolith of the Lyon Mountain Gneiss predates intrusion of the olivine gabbros.

Both the granitic and leucocratic albite gneiss facies are fine- to medium-grained granoblastic rocks that are massive to weakly foliated but with pronounced compositional layering in most exposures. Their colors range from pink to buff or white, but mafic varieties are locally gray. Modal compositions are widely variable, even at outcrop scale, with respect to the relative proportions of quartz, plagioclase and potassium feldspar (Figure 10A) and to the amount and identity of mafic minerals (Table 3). This heterogeneity is also evident from the chemical analyses (Tables 1E and 1F) and from the variable proportions of quartz, albite, and orthoclase in the norm (Figure 10B). The granitic gneisses consist chiefly of microperthite and quartz with minor amounts of plagioclase, magnetite, biotite, hornblende, clinopyroxene, and, less commonly, garnet. Leucocratic albite gneisses contain albite (Ab_{95}-Ab_{98}) and quartz with lesser amounts of clinopyroxene, deep green and pleochroic in thin section, that contains up to 40 percent of the acmite end member (Table 4A). Both granitic and leucocratic albite gneisses contain up to 3 percent magnetite, which is the only ferromagnesian mineral present at many locations. The magnetite gives rise to a distinctive aeromagnetic signature for the Lyon Mountain Gneiss that closely correlates with the map pattern (Figure 2). Titanite and apatite are common accessories.

Mafic albite gneiss is a pink to gray, fine-grained rock with sugary granoblastic texture; it consists chiefly of albite (around Ab_{95}) and clinopyroxene (Table 3). The pyroxene is deep green and acmite-rich (Table 4A); in some samples it is accompanied by a blue-gray amphibole (silicic edenite or magnesio-kataphorite, Table 4B). Quartz content is ordinarily less than 5 percent, but locally as high as 45 percent; this suggests the presence of a quartz-rich sedimentary component in the protolith. Thirty percent scapolite is present in one specimen. Oxide minerals are less abundant than in the granitic and trondhjemitic facies and consist of lamellar intergrowths of hematite and ilmenite or rutile with little or no magnetite. Minor titanite is characteristically present. In some outcrops, the mafic albite gneiss displays a prominent mm-scale layering or foliation with alternating albite- and pyroxene-rich layers. This layering may be planar (Figure 11A), folded (Figure 11B), or chaotic. Both massive and layered varieties locally contain pink megacrysts of albite up to 5 cm across. Trains of small pyroxene grains parallel to the layering in the rock cross these megacrysts, some of which consist of numerous subgrains with slightly differing optical orientations.

The geochemistry of the Lyon Mountain Gneiss has been described in detail by Whitney and Olmsted (1988). Table 1E

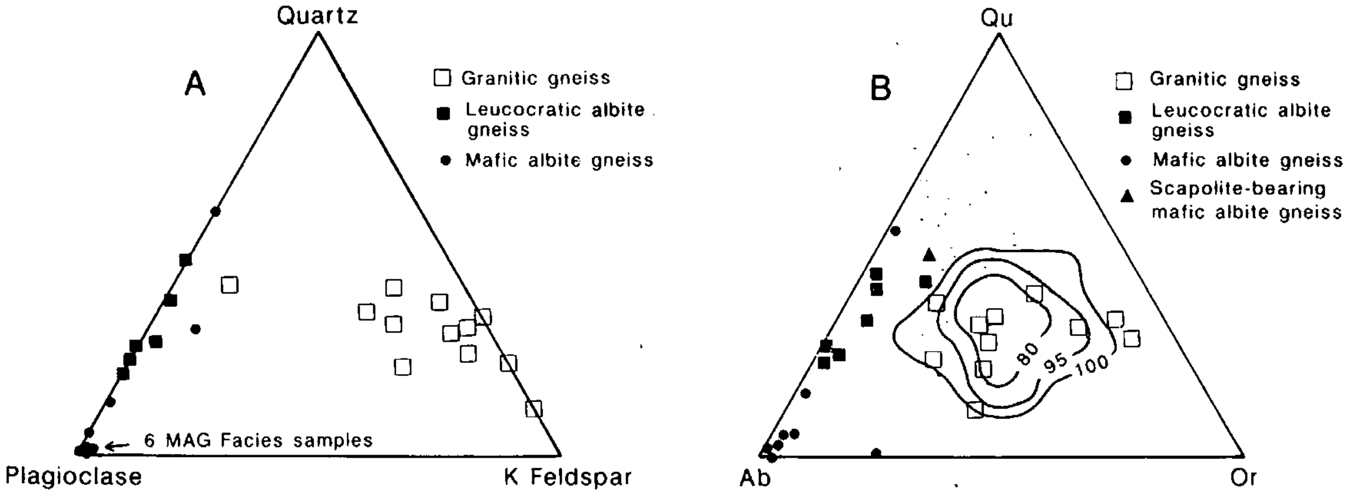


FIGURE 10. (a) Triangular diagram showing modal quartz, plagioclase, and K-feldspar (microcline and/or perthite) in thin sections of the Lyon Mountain Gneiss. (b) Triangular diagram showing CIPW-normative quartz, albite, and orthoclase in the Lyon Mountain Gneiss. Note, here and in Figure 10a, the scatter of points that reflect the great variability of these rocks. Contours show percentage of analyses of 137 Adirondack granitic rocks.

shows representative analyses for the granitic facies; Table 1F contains analyses of the albite gneisses. The granitic gneiss has the geochemical signature of an A-type granite, similar to that of typical Adirondack granitic and charnockitic gneisses (Figure 12). Relatively immobile elements, such as Ce, Y, Nb, and Zr show a nearly identical pattern in the leucocratic albite gneiss (Figure 12), but K, Rb, and Ba are strongly depleted, and Na is enriched relative to the granitic facies.

The felsic nature of the granitic and trondhjemitic rocks, combined with their striking lithologic and geochemical heterogeneity, suggests a protolith of rhyolitic volcanic rocks, possibly ash-flow or ash-fall tuffs, that have undergone extensive postde-

	GRANITIC GNEISSES		LEUCOCRATIC ALBITE GNEISSES			MAFIC ALBITE GNEISSES		
	AF431B	AF441	AF664	AF665	AF8533	AF442	AF545B	AF632
SiO_2	48.39	48.78	49.14	51.15	50.19	51.94	52.58	52.81
TiO_2	.24	.28	.21	.31	.14	.34	.28	.37
Al_2O_3	1.68	.81	1.82	1.50	2.08	1.36	1.19	1.36
Fe_2O_3	6.17	4.43	16.57	12.39	13.94	10.93	6.71	6.83
FeO	18.86	25.11	12.25	7.02	13.76	3.57	5.00	9.23
MnO	.79	1.03	.38	.01	.17	.07	.00	.15
MgO	2.84	1.54	2.11	7.18	2.20	10.50	12.07	9.08
CaO	18.94	16.27	13.99	16.20	14.10	17.44	20.29	18.08
Na_2O	1.96	1.90	5.31	4.50	5.22	3.82	2.29	3.18
Total	99.87	100.13	101.78	100.25	101.82	99.98	100.41	101.09
Cations per 6 oxygens								
Si	1.94	1.98	1.91	1.95	1.94	1.95	1.96	1.98
Al^{IV}	.06	.02	.08	.05	.06	.06	.05	.02
Al^{VI}	.02	.02	.00	.01	.04	.01	.01	.04
Ti	.01	.01	.01	.01	.00	.01	.01	.01
Fe^{+++}	.19	.14	.49	.36	.41	.31	.19	.19
Fe^{++}	.63	.85	.40	.22	.45	.11	.16	.29
Mn	.03	.04	.01	.00	.01	.00	.00	.01
Mg	.17	.09	.12	.41	.13	.59	.67	.51
Ca	.81	.71	.58	.66	.58	.70	.81	.73
Na	.15	.15	.40	.33	.39	.28	.17	.23

TABLE 4A Electron microprobe analyses of pyroxenes in the Lyon Mountain Gneiss. Ferric iron computed using the method of Robinson (1980).

positional alteration. The interlayered amphibolites may represent the mafic component of a bimodal volcanic suite. On a local scale, more homogeneous volumes of felsic rocks may be either intrusions contemporaneous with the deposition of the volcanic pile, or later intrusive rocks. In Hale Brook south-southeast of McCray Mountain, fragments of mafic albite gneiss occur in a relatively homogeneous matrix of granitic gneiss, strongly suggestive of an intrusive relationship.

(b) Fayalite granite gneiss (Yfg)

A dark, olive-gray granitic gneiss containing very Fe-rich clinopyroxene (ferrohedenbergite) and minor amounts of fayalitic olivine is exposed in several outcrops and abandoned quarries at Bailey Mountain, ENE of the village of Au Sable Forks. The feldspar is a coarse flame perthite, in contrast to the fine microperthites characteristic of much of the Lyon Mountain gneiss. Fluorite is present locally. This rock, described by Buddington (1939, p. 126), is relatively homogeneous and massive to faintly foliated. Its contacts are not exposed, which leaves its relationship to the surrounding Lyon Mountain Gneiss conjectural. Leucocratic albite gneiss is exposed near the southwestern corner of Bailey Mountain, and in the area between what appear to be two separate bodies of the fayalite granite gneiss. The albite gneiss in these outcrops is well foliated, whereas the foliation seen locally within the fayalite granite gneiss is poorly developed; this suggests that the latter rock may be younger and intrusive into the Lyon Mountain Gneiss.

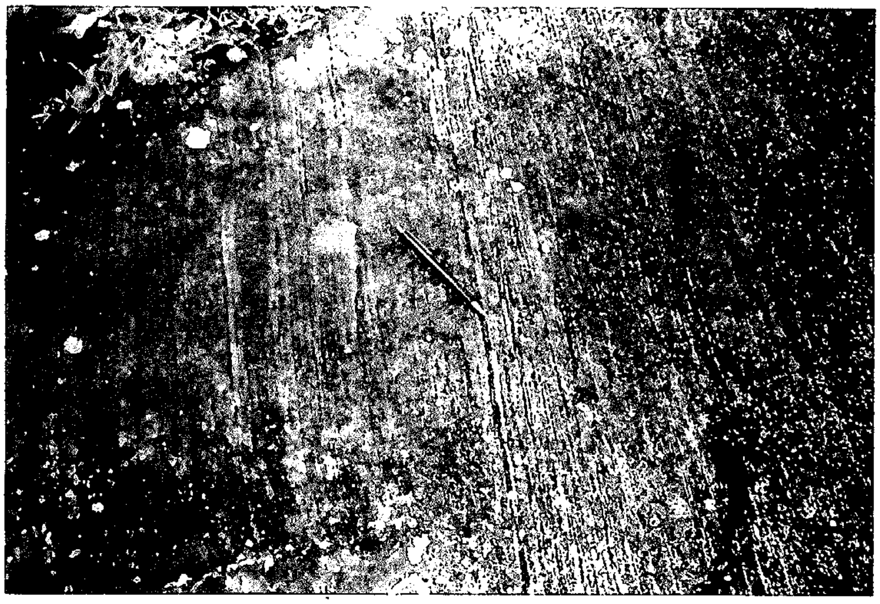
Despite mineralogical differences, the fayalite granite gneiss (sample AF666, Table 1C) is geochemically similar to the granitic facies of the Lyon Mountain Gneiss (Table 1E). It may be either a later intrusive, or a reduced facies of the Lyon Mountain Gneiss itself. The coexistence of quartz, magnetite, and fayalite indicate that oxygen fugacity during metamorphism was close to the fayalite-magnetite-quartz buffer. The fayalite granite gneiss is thus significantly more reduced than typical Lyon Mountain Gneiss. The latter probably was metamorphosed at an oxygen fugacity near the hematite-magnetite-quartz buffer, in view of the common partial replacement of magnetite by martite (Postel, 1952).

4. Unmetamorphosed dikes

Numerous small (commonly <1 meter wide), unmetamorphosed mafic dikes intrude all other rock types (Plate 1). Their

	GRANITIC GNEISSES		LEUCOCRATIC ALBITE GNEISSES		MAFIC ALBITE GNEISSES			
	AF441	AF624	AF370	AF674	AF371B	AF442	AF545B	AF671
SiO_2	40.82	39.04	48.81	47.90	50.32	52.26	49.65	50.66
TiO_2	1.80	2.36	.44	.84	1.29	.58	.43	.55
Al_2O_3	7.15	10.33	4.62	7.44	6.81	3.36	4.94	3.58
Fe_2O_3	9.95	5.45	9.22	5.17	5.33	5.83	5.00	5.94
FeO	24.14	24.02	6.70	4.71	5.82	6.03	9.62	6.84
MnO	.66	.51	.16	.11	.06	.04	.00	.13
MgO	1.77	2.41	14.77	16.79	16.69	17.04	14.89	16.37
CaO	8.29	9.61	9.45	11.06	11.07	9.14	11.12	8.63
Na_2O	2.67	1.99	2.93	2.09	2.14	3.51	2.07	4.14
K_2O	1.69	2.02	.62	1.09	.62	.52	.61	.86
Total	98.94	97.74	97.72	97.20	100.15	98.31	98.33	97.71
Cations per 23 oxygens								
Si	6.51	6.25	7.11	6.90	7.02	7.42	7.19	7.32
Al^{IV}	1.34	1.75	.79	1.10	.98	.56	.81	.61
Al^{VI}	.00	.20	.00	.16	.14	.00	.05	.00
Ti	.22	.28	.05	.09	.14	.06	.05	.06
Fe^{+++}	1.19	.66	1.01	.56	.56	.62	.54	.65
Fe^{++}	3.22	3.22	.82	.57	.68	.72	1.16	.83
Mn	.09	.07	.02	.01	.01	.00	.00	.02
Mg	.42	.57	3.20	3.60	3.47	3.61	3.21	3.52
Ca	1.41	1.65	1.47	1.71	1.66	1.39	1.72	1.34
Na	.83	.62	.83	.58	.58	.97	.58	1.16
K	.34	.41	.12	.20	.11	.09	.11	.16

TABLE 4B Electron microprobe analyses of amphiboles in the Lyon Mountain Gneiss. Ferric iron estimated assuming stoichiometry.



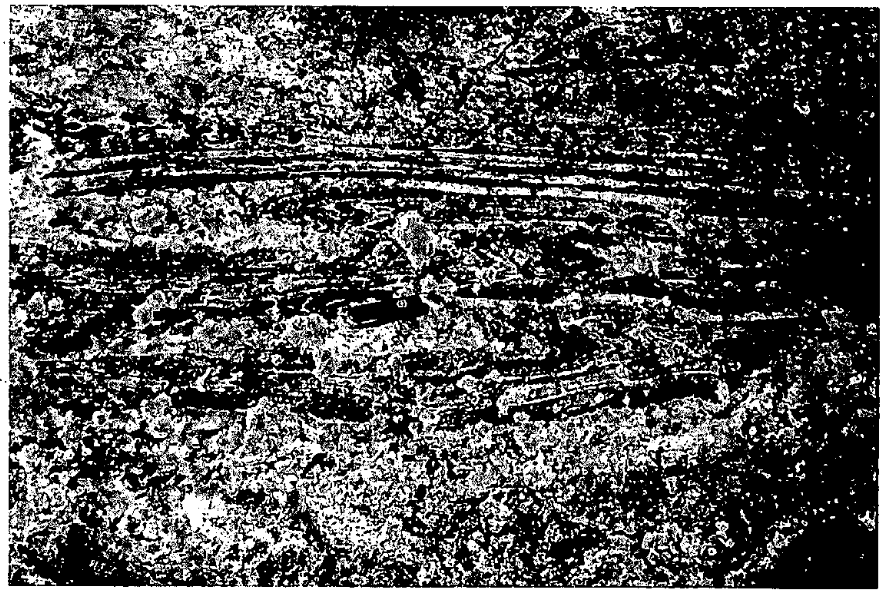


FIGURE 11. (a) Millimeter-scale layering in mafic albite gneiss, summit of McCray Mountain, looking down at pavement outcrop. North at top of photo; pencil for scale. Light layers are rich in albite, dark layers in pyroxene. The origin of the layering is uncertain; it may either be tectonic or a relict sedimentary feature. (b) Mafic albite gneiss with isoclinal folding, summit of Schoolhouse Mountain, looking down. West at top of photo. Pocketknife for scale.

textures range from aphanitic to diabasic. Most appear to be basaltic; a few are lamprophyric. The latter correspond to the "camptonites" of Kemp and Alling (1925). Many of the finer-grained basaltic dikes bear plagioclase phenocrysts, while the lamprophyres have clinopyroxene or hornblende phenocrysts. Similar dikes are found thoughout the northeastern Adirondack region; they are described in detail by Kemp and Alling (1925) and Isachsen et al. (1988). A few larger dikes are present. One NE-trending dike with a minimum width, where exposed, of several meters crops out on the northeastern slope of Big Lawler Mountain between the elevations of 2,400 and 2,200 feet. It is a coarse olivine diabase with plagioclase laths up to 1 cm in length. A three meter wide dike of lamprophyre with hornblende phenocrysts trends N70W and occupies a prominent notch in the east face of Pokamoonshine Mountain just SW of the state park. The unmetamorphosed dikes are never wide enough and rarely long enough to be visible at 1:62500 scale, hence they are represented on Plate 1 by symbols that exaggerate their size.

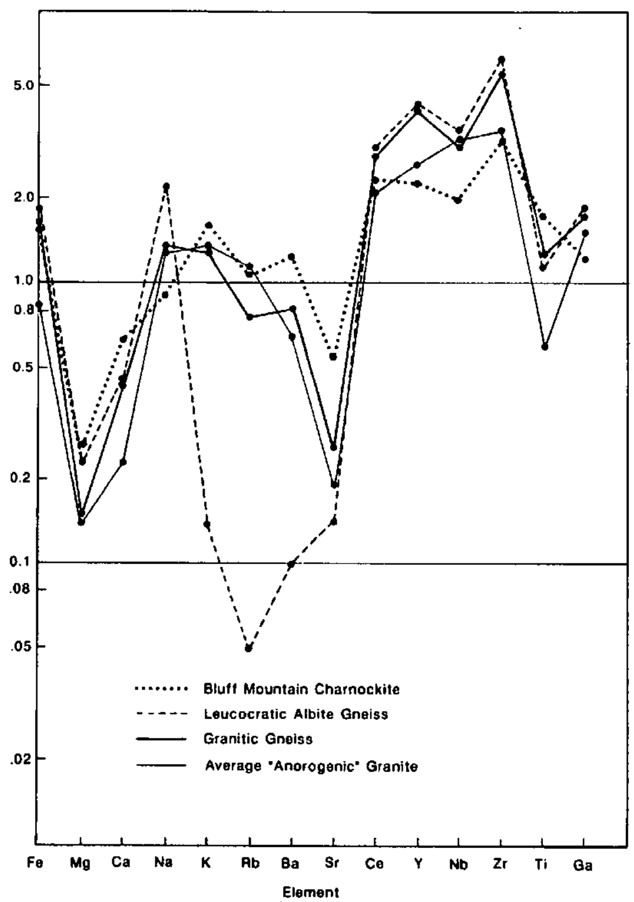


FIGURE 12. Diagram showing average concentrations of selected major and trace elements normalized to average I-type granite, the common granite of orogenic regions (Whalen et al., 1987). A: average A-type (anorogenic or post-tectonic) granite of Whalen et al. (1987). Note the similarity of enrichment/depletion patterns in the granitic gneisses of the Lyon Mountain Gneiss to both the Bluff Mountain charnockites and to average A-type granite. The strong depletion of K, Rb, and Ba, and enrichment of Na in the leucocratic albite gneiss results from diagenetic or metasomatic alteration of initially granitic or rhyolitic rocks.

STRUCTURAL GEOLOGY

1. Major structures

The large-scale structural framework of the Au Sable Forks quadrangle, consisting of the Jay, Westport, and Hurricane anorthosite domes and the Au Sable Forks Synform, has been described in the introduction.

2. Foliation and minor folds

Foliations along the margins of the anorthosite domes are subparallel to those in the overlying mantle. Within the domes, foliation, where present, is commonly faint and difficult to measure. No consistent foliation pattern is present except in a throughgoing shear zone that transsects the Westport Dome between Mount Discovery and Hickory Mountain.

The Rocky Branch Complex as a whole consists of well foliated, layered metasedimentary and mixed gneisses that surround less deformed lenses and irregular bodies of metanorthosite, olivine metagabbro, and charnockite. The latter range from a few m up to several km in length. Foliation in the metasedimentary and mixed rocks is nearly everywhere coincident with compositional layering and wraps around the larger bodies of metaigneous rocks. Most metanorthosite and metagabbro bodies show penetrative foliation only near their contacts; foliation in the interiors of these bodies is ordinarily confined to localized shear zones no more than a few m thick. Granitic and charnockitic bodies, such as those at Bluff and Pokamoonshine Mountains, are foliated throughout, as is the large body of ferrodiorite near the southern edge of the quadrangle. The foliation in these metaigneous rocks is subparallel both to their contacts and to foliation in the surrounding rocks.

Poles to foliations in the Rocky Branch Complex in the southern half of the quadrangle are shown in Figure 13a. The slight N-S elongation of the maximum reflects the concentration of measurements in well-exposed rocks in the soutwestern part of the quadrangle, where the axis of the Au Sable Forks Synform trends nearly E-W between the Hurricane Dome to the south and the Jay Dome to the north (Plate 1). In the northern half of the quadrangle, foliations in the Rocky Branch Complex form a rough girdle (Figure 13B), attributable to the Ausable Forks Synform which there trends N-S between the Jay and Westport domes. The Lyon Mountain Gneiss, which contains fewer metaigneous inclusions, tends to show better defined foliation patterns. South of a line from Ragged Mountain to Hogback Mountain, where the Lyon Mountain Gneiss forms the core of the Au Sable Forks synform, most of the foliation and compositional layering strikes nearly due N with steep dips (Figure 13C). The position of the maximum in Figure 13C results from the fact that the synform is slightly overturned to the west. The structure as a whole plunges gently N. Foliation trends north of the Ragged Mountain-Hogback Mountain line (Fig. 13D) suggest the presence of north-plunging folds in that area as well, although the Au Sable Forks Synform is less well defined there. This is consistent with the north- to northeast-plunging folds described by Postel (1952, p. 27) in the Dannemora and Lyon Mountain quadrangles.

The lack of laterally continuous, recognizeable marker beds within the Rocky Branch Complex and the Lyon Mountain Gneiss precludes systematic mapping of minor structures. Outcrop-scale minor folds are uncommon. They occur principally in two situations. One is in thin calcsilicate or quartzite layers in marble; these tend to be poorly defined, asymmetric, and rootless. Rarely are they as well developed as the fold shown in Figure 14. The other is within granitic and charnockitic gneisses where small amphibolites with thicknesses on the order of a few centimeters may be isoclinally folded with limbs parallel to foliation. Foliation in the amphibolite is visibly folded in the fold hinges, but an axial planar foliation may also be present. The origin of these small amphibolites is not known, but their size and lack of lateral continuity suggest intensely deformed xenolithic inclusions or small transposed and dismembered dikes. Orientations of hinge lines of both types of minor folds are scattered (Figure 13E), but several lie approximately within a NS vertical plane, that is roughly coincident with the axial plane of the Au Sable Forks Synform.

3. Lineation

Lineations show a strong preferred orientation throughout the quadrangle (Figure 13E), in contrast to foliations, which are highly variable and, to a significant extent, determined both by the shape of the metanorthosite domes and by metaigneous bodies within the layered rocks. The lineations are defined by quartz ribbons or blades in granitic and metasedimentary rocks and by streaks of mafic minerals in gabbroic and anorthositic rocks (Figure 15). The dominant lineation trends about N21°E with an average plunge of about 11° N (Figure 13E). This is roughly coincident with the regional trend of lineations reported by Balk

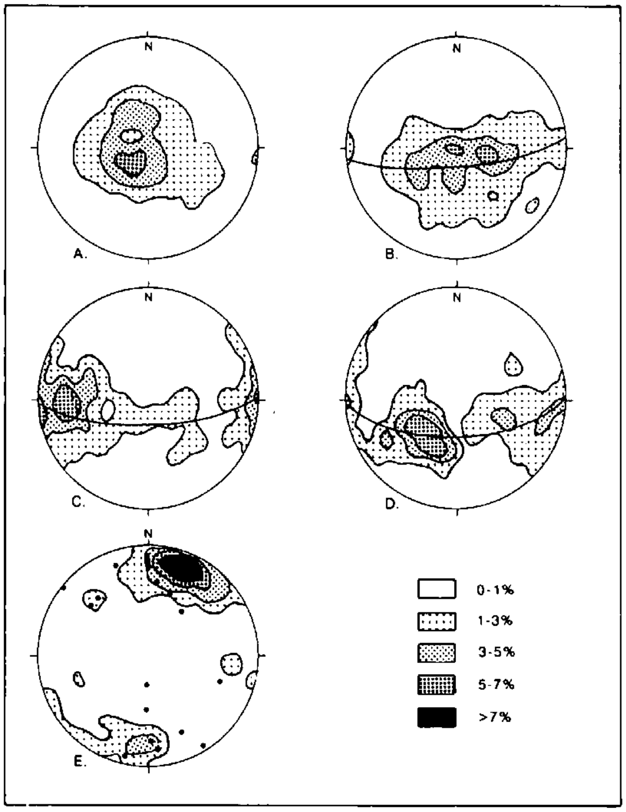


FIGURE 13. Equal-area, lower hemisphere stereonet diagrams. Contoured using the computer program Stereo-PC (Rockware Inc., Wheatridge, CO). (a) Poles to foliation in the Rocky Branch Complex, southern half of the Au Sable Forks quadrangle (829 measurements). The slight north-south elongation of the maximum reflects numerous measurements in the southwestern part of the quadrangle, where the axis of the Au Sable Forks Synform trends nearly E-W between the north flank of the Hurricane Dome and the south flank of the Jay dome. (b) Poles to foliation, with best-fit great circle, in the Rocky Branch Complex, northern half of the Au Sable Forks quadrangle (216 measurements). Here, and in Figure 11c, most of the data are from the constricted central part of the Au Sable Forks Synform, where the axis trends nearly N-S. Pole to great circle has azimuth of 355° and plunge of 13° N. (c) Poles to foliation, with best-fit great circle, in the Lyon Mountain Gneiss south of a line between Ragged and Hogback Mountains (167 measurements). Here, as in Figure 11b, data are from the central part of the Au Sable Forks Synform. Pole to great circle has azimuth of 359° and plunge of 18° N. (d) Poles to foliation, with best-fit great circle, in the Lyon Mountain Gneiss north of a line between Ragged and Hogback Mountains (110 measurements). These data are from the northern 1/3 of the quadrangle, where the Au Sable Forks Synform opens and becomes less distinct. Pole to great circle has azimuth of 358° and plunge of 27° N. (e) Mineral lineations (contoured) and minor fold axes (filled circles), entire quadrangle (115 measurements). Note the strong maximum with azimuth 21° and plunge 11° NE. This is the regional lineation trend in much of the northeastern Adirondack highlands.

(1931) and with the most of the lineations and minor fold axes mapped in the Lyon Mountain Gneiss of the Dannemora, Lyon Mountain, and Churubusco quadrangles by Postel (1952). It forms an angle of about 20-25° with the axis of the Au Sable Forks Synform. A much less prominent set of lineations in the Au Sable Forks Quadrangle trends WNW. The latter are developed in the rocks surrounding and underlying the rootless McGuire Mountain metanorthosite body (east of Trout Pond in the northeastern part of the quadrangle) and locally elsewhere. Although the azimuth of the dominant NNE lineations is consistent throughout the area, the plunge is variable and controlled by the domical metanorthosite bodies. On the south flanks of metanorthosite domes, lineations plunge south, whereas on the north flanks they plunge north. This suggests that the lineations predate at least the most recent vertical movements of the domes.

4. High strain zones

In addition to the foliation described above, relatively thin, laterally extensive zones of exceptionally strongly developed foliation and lineation are also present. Some of these can be traced for several kilometers despite discontinuous outcrop. Mylonites occur locally within these zones. The high strain zones are subparallel to compositional layering and foliation in the rocks, and may be localized by such structurally weak units as marbles or quartzofeldspathic gneisses. Although some may be ductile faults that mark tectonic discontinuities in the layered rocks, it has not been possible to determine the extent of displacement along them. Dips of foliation within the zones commonly have a northward component, and lineations plunge north to northeast parallel to the regional trend. These zones are folded by and appear to predate the Au Sable Forks Synform. We interpret these to be the locus of extensional movement (see section on geologic history). The most prominent of the zones are shown on Plate 1.

Evidence of intense ductile deformation is also found at contacts between rocks with contrasting high-temperature mechanical properties. Quartz-bearing rocks such as granitic gneisses tend to show strong deformation near contacts with quartz-free rocks; contacts of granitic gneiss with metanorthosite or olivine metagabbro are noteworthy in this respect. Several metagabbro bodies, with only slight internal evidence of deformation, occupy local structural basins within strongly foliated rocks that dip under the metagabbro. This relationship, observed by Balk (1931) in numerous other localities in the eastern Adirondack highlands, is well displayed at Clements Mountain south of Jay, around the western end of the large Jay Mountain gabbro, and on the western slope of Mount Fay.

5. Brittle deformation: faults, fracture zones, lineaments, and joints

Numerous brittle faults and fracture zones are present in the Au Sable Forks quadrangle, although rarely exposed. Most of

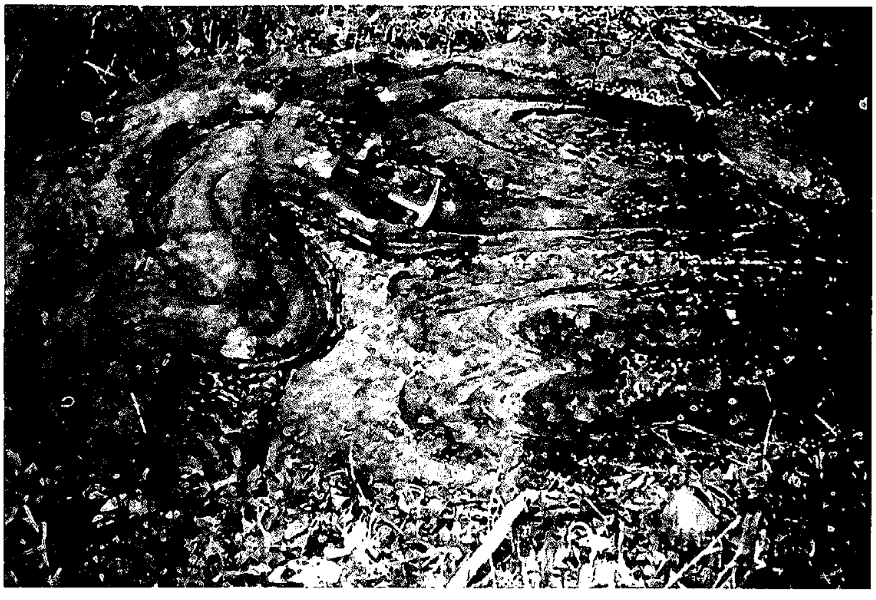


FIGURE 14. Folds in marble (light) and calcsilicate granulite (dark); small outcrop on east side of Sheldrake Road 1.5 km south of Au Sable Forks, south-southwest of Ragged Mountain. Looking east; hammer for scale. Folds plunge NNE at a shallow angle.

the faults shown on Plate 1 have been inferred from apparent offsets of mapping units or interpolated between scarce exposures by the use of airphoto lineaments. The strike of the majority of the faults and fracture zones is from NE to ENE, although a few strike north or northwest. Where exposed, fracture orientations suggest that most of these features are nearly vertical. The overall pattern of faulting is consistent with that described by Quinn (1933) for the Champlain Valley region and fits the regional pattern of brittle deformation for the Adirondacks as a whole (Isachsen and McKendree, 1977).

A major fault, poorly located due to lack of outcrop control, strikes ENE along the Ausable River. Although the actual fault plane is nowhere exposed, a sinistral strike-slip separation of up to 2 km is suggested by the map pattern. Just south of the village of Clintonville, outcrops of Lyon Mountain Gneiss in the bed of the Ausable River and close to the projected trace of the fault are extensively shattered. Some of the fractures are filled by small (< 1m) unmetamorphosed mafic dikes that strike ENE parallel to the presumed fault.

Another major fault, subparallel to the Ausable River fault, can be traced from south of Fordway and Curren Mountains southwestward across Gagnon Ridge. It passes south of Sheep Mountain and Green Street and leaves the quadrangle along the NW flank of Clements Mountain, where a scarp of olivine metagabbro marks the fault trace. Apparent movement on this fault, as estimated by offsets of the Rocky Branch Complex near Green Street and Ellis Mountain, was largely vertical, north side down. Parallel to this fault and further to the south, the prominent steep-walled valley called The Gulf probably marks another fault, but no offset is observed.

An ENE-trending fracture zone that crosses the entire quadrangle appears in the soutwestern corner as a photolineament that follows Jones Brook, crosses Oak Ridge and passes through the notch between Jay and Saddleback Mountains. From there, it follows the headwaters of Hale Brook, where it is marked by outcrops of shattered and altered anorthositic and gabbroic rocks. It appears in outcrop again in a zone of strongly fractured rock, locally chloritized and slickensided, just west of Ore Bed Pond. From there, it passes south of Beech Hill and curves northward to parallel U.S. Route 9. Outcrops of breccia are seen in roadcuts on the W side of Route 9 south of Pokamoonshine Mountain (Figure 16). No offsets related to this feature can be mapped.

A fault striking roughly N to N10E is marked at its northern end by a photolinear at Noon Notch northwest of Barber Mountain. Southward, it passes east of Forge Mountain and through a small notch northwest of Taylor Mountain. The latter contains outcrops of shattered rock with numerous subvertical fractures. Slickensides on the fractures indicate vertical movement without a strike-slip component at this location. This fault is directly on strike with, and is probably a northward extension of, a major fault zone that roughly parallels the Bouquet River south of Elizabethtown in the Elizabethtown quadrangle.

Figure 17A is a rose diagram of orientations of 286 joints and

FIGURE 15. Mafic mineral lineation in gabbroic anorthosite gneiss overlying wollastonite ore at the Deerhead wollastonite occurrence. Lineation here plunges 46° on an azimuth of N 66° W. Photo looking NW and up at lower surface; hammer for scale.

FIGURE 16. Fault breccia in mixed gneisses, west side of Route 9, near benchmark 879 southeast of Pokamoonshine Mountain. Looking west; sledgehammer for scale.

includes data both from our work and from unpublished notebooks of Robert Balk (New York State Geological Survey Open File No. 1 m 669). The joint data are not fully representative because they are principally derived from the southern half of the quadrangle and because joints were recorded in the field only where unusually prominent or closely spaced. A maximum occurs at approximately N 70° E, and a smaller maximum at roughly N 50° W. Figure 17B shows the orientations of 146 unmetamorphosed mafic dikes, again combining our data (shown on Plate 1) and the unpublished work of Balk. The dike orientations show a broad maximum in the vicinity of N 60° E, with a much smaller cluster just E of due N.

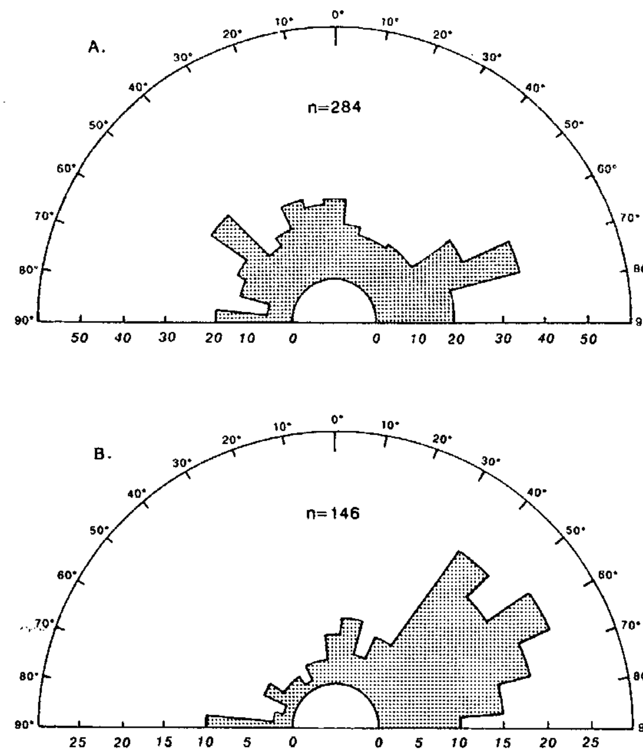


FIGURE 17. Rose diagrams showing orientation of: (a) 284 joint and fracture sets. (b) 146 unmetamorphosed dikes. Data from this work and from unpublished notebooks of Robert Balk in the New York State Geological Survey Open File collection, Accession # 1 m 669

METAMORPHISM

The rocks of the Au Sable Forks quadrangle contain granulite facies mineral assemblages, with the exception of unmetamorphosed dikes and local zones of retrograde alteration. Temperatures of 700-750^{o}C and pressures of 7-8 kbar are indicated by the data of Bohlen et al. (1985).

The quartz-rich metasedimentary rocks contain several mineral assemblages that are potentially useful in constraining the metamorphic conditions. Either tremolite or (enstatite + diopside) is present in many quartzites; locally all three minerals coexist in apparent textural equilibrium. This suggests that pressure, temperature, and activity of water are close to equilibium values for the reaction:

Tremolite = 2 Diopside + 3 Enstatite + Quartz + H_2O (1)

(Boyd, 1959; Valley et al., 1983; Lamb and Valley, 1988). If the metamorphic pressures and temperatures were close to those reported by Bohlen et al. (1985), this indicates relatively low but locally variable water activities.

Phlogopite is common in quartz-bearing rocks in the Rocky Branch Complex, but the assemblage enstatite-K feldspar is not observed. This indicates that conditions were on the low-temperature side of the reaction:

Phlogopite + 3 quartz = K feldspar + 3 enstatite + H_2O (2)

(Lamb and Valley, 1988). With precise determinations of mineral compositions, this reaction could be used to determine either an upper limit for the metamorphic temperature or a lower limit for water activity.

In many of the calcsilcate granulites, grossular-rich garnet occurs either as discrete grains or as reaction rims around various minerals. Some of these rims surround diopside or scapolite; more commonly, the cores of these coronas contain low-temperature alteration products such as prehnite, and in such cases it has not been possible to determine the original reactant minerals. Grossular reaction rims in similar rocks have been reported by Warren et al. (1987) from Australia and Antarctica and attributed by them to reactions between meionitic scapolite and calcite or wollastonite. In hybrid gneisses from the hanging wall of the Lewis wollastonite orebody, coronas of grossular and quartz occur around wollastonite grains in contact with plagioclase, indicating the reaction:

Plagioclase + Wollastonite =
Grossular + Quartz + more sodic Plagioclase (3)

The coexistence of grossularitic garnet and quartz limits metamorphic temperature to less than 815 ^{o}C at a pressure of 8 kbar (Valley, 1985; Valley et al., 1990); determination of plagioclase and garnet compositions in this rock could be used to further constrain the pressure-temperature conditions of the metamorphism.

The common presence of wollastonite in calcsilicate rocks and marbles close to the anorthosite and its absence or scarcity at greater distances suggest an origin as a contact metamorphic mineral formed at the time of anorthosite intrusion. Two lines of evidence point to shallow origin for this contact metamorphism. Valley and O'Neil (1982, 1984) and Valley (1985) report anomalous oxygen isotopic compositions (δ ^{18}O as low as -1.3 permil, which is up to 20 permil lower than typical Adirondack marbles) at both the Lewis and Willsboro wollastonite deposits. In addition, they find extremely sharp δ ^{18}O gradients between the wollastonite ore and surrounding rocks. Valley (1986) concluded that the isotopic anomalies cannot be explained solely by devolatilization reactions and probably result from deep circulation of heated meteoric waters along fractures at the time of anorthosite intrusion. Because such fluids would be at hydrostatic pressure, they could not penetrate a ductile metamorphic environment where fluids are at lithostatic pressure. This suggests that ore formation took place at shallow depths (<10 km) relative to the subsequent granulite facies metamorphism. The origin of the sharp gradients is enigmatic, but their preservation indicates that there was no significant fluid movement across strike subsequent to wollastonite ore formation.

The occurrence of monticellite and akermanite with wollastonite in a marble xenolith in anorthosite at Cascade Slide in the Mount Marcy quadrangle (Tracy et al., 1978; Valley, 1985) requires either an unreasonably high magmatic temperature for the anorthosite or a very low partial pressure of CO_2. In the absence of evidence for massive dilution of CO_2 by water or other fluids at this location (Valley et al., 1990), the most likely explanation of the assemblage is low total pressure associated with a shallow depth of intrusion (Valley, 1985). Preservation of wollastonite through the subsequent 7-8 kbar Grenville metamorphism requires low CO_2 activities at that time as well. The combined low activities of water and carbon dioxide are consistent with fluid-absent metamorphic conditions, as has been demonstrated for the Adirondacks in general by Valley et al. (1990).

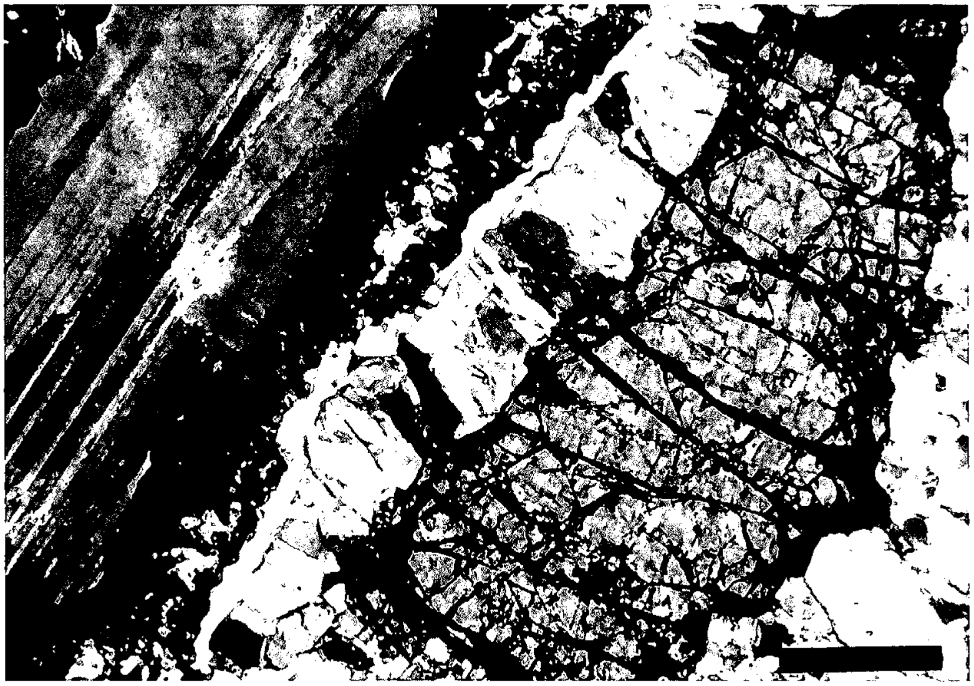
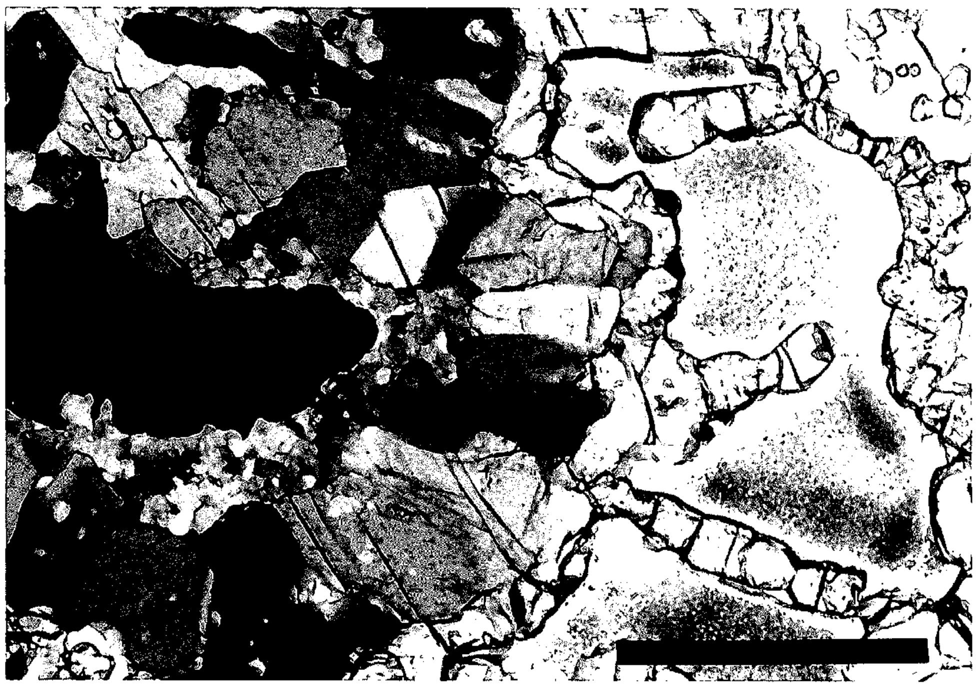


FIGURE 18. Photomicrographs of corona structures in olivine metagabbros. (a) Olivine (large grain with prominent fracture, on right), surrounded by shells of (right to left) ortho- and clinopyroxene, clear plagioclase (narrow, bright), and garnet (black) with inclusions of clinopyroxene. Plagioclase (left, with twinning) is clouded with minute inclusions of green spinel. Crossed polars. Scale bar (lower R) is 0.2 mm. Sample from 1.2 km east of summit of Saddleback Mountain. (b) Ilmenite (black) surrounded in sequence by biotite (fine-grained gray aggregate), hornblende (coarse gray aggregate), garnet (clear, high relief), and spinel-clouded plagioclase. Plane light. Scale bar (lower R) is 0.2 mm. Sample from peak of Mount Fay.



In metapelites, garnet that encloses fine needles of sillimanite occurs in apparent textural equilibrium with coarse sillimanite. This suggests two distinct generations of sillimanite in metapelites. At the Doyle Brook cordierite locality, the garnet is $Alm_{28}Pyr_{46}Sps_{21}Gro_5$. This unusually Fe-poor composition and the anomalous presence of cordierite may result from the sequestering of most of the iron in pyrrhotite.

Metamorphic effects in the interiors of olivine metagabbro bosies are largely confined to the development of reaction coronas. Two types of coronas are commonly present. The first (Figure 18A) occurs at contacts between olivine and plagioclase, and usually consists of two major zones. Adjacent to olivine is an aggregate of small pyroxene grains, either clinopyroxene or a mixture of clino- and orthopyroxene. In some well-developed coronas, the pyroxene zone includes two distinct subzones with orthopyroxene adjacent to olivine and clinopyroxene rimming the orthopyroxene. The outer zone is ordinarily garnet with inclusions of clinopyroxene, hornblende, or plagioclase. The inclusions tend to be concentrated near the middle of the garnet zone. In a few coronas, the outer zone comprises a vermicular intergrowth of garnet and clinopyroxene. Rarely, the garnet appears to replace a fine mixture or vermicular intergrowth of clinopyroxene and spinel. The inner (pyroxene) and outer (garnet) zone may be separated by a narrow moat of clear plagioclase (An_{30}-An_{35}). Much less commonly, spinel-free plagioclase replaces most or all of the pyroxene zone. The outer edge of the garnet zone may abut directly on spinel-clouded plagioclase, or there may be a zone of clear plagioclase between the garnet and the clouded feldspar.

The origin of the olivine-plagioclase coronas has been discussed in detail by Whitney and McLelland (1973) and McLelland and Whitney (1980a,b). In brief, the coronas form in a two-stage reaction between olivine and plagioclase:

Olivine + Plagioclase =
Clinopyroxene(I) + Orthopyroxene + Spinel + more sodic Plagioclase (4)

Orthopyroxene + Clinopyroxene(I) + Spinel + Plagioclase =
Garnet + Clinopyroxene(II) + more sodic Plagioclase (5)

During the course of these reactions, the partial reaction

Plagioclase + Na^{+} +$(Mg,Fe)^{++}$ =
Ca^{++} + Spinel + more sodic Plagioclase (6)

produces the spinel clouding in the primary plagioclase.

The second type of reaction occurs between ilmenite and plagioclase. An inner zone of amphibole and/or biotite occurs in contact with the ilmenite. This inner zone commonly comprises two subzones: red titanian biotite in contact with ilmenite and surrounded by reddish-brown kaersutitic hornblende (Figure 18B). The outer zone, locally incomplete or absent, consists of garnet, which is ordinarily clear but may carry inclusions or vermicular intergrowths of clinopyroxene. This second corona type was described in detail by Whitney and McLelland (1983); it also forms in a two-stage reaction linked by exchange of components with the olivine-plagioclase reaction:

Plagioclase + Fe-Ti Oxides + Olivine + water =
Hornblende + Spinel + Orthopyroxene + Biotite
+ more sodic plagioclase (7)

Hornblende + Orthopyroxene + Spinel + Plagioclase =
Garnet + Clinopyroxene + more sodic Plagioclase (8)

Near contacts with the surrounding rocks, and in internal shear zones, olivine metagabbros are metamorphosed to amphibolite. Plagioclase is totally recrystallized, clear, and free of spinel inclusions. Garnet occurs as discrete grains and forms porphyroblasts up to 10 cm in diameter. The remaining clinopyroxene is recrystallized, and no orthopyroxene is present. Biotite is locally abundant in the most strongly deformed rocks. Some of these garnet amphibolites resemble the garnet ore at the Barton Mine at Gore Mountain in the Thirteenth Lake quadrangle (Bartholeme, 1960), which is also a border facies of olivine metagabbro.

Metamorphic effects in the olivine-free gabbros are generally limited to the local occurrence of thin rims of hornblende around primary clinopyroxene and poorly developed coronas of biotite and hornblende around ilmenite where adjacent to plagioclase. Garnet is much less common than in the olivine-bearing rocks, but is found in a few samples as coronas around ilmenite or clusters of recrystallized pyroxene.

Metamorphism is inconspicuous in the less-deformed facies of the metanorthosite. Garnet occurs locally as coronas around orthopyroxene and oxides, and hornblende may rim or replace some of the pyroxene. The garnet is formed by a reaction between plagioclase, orthopyroxene, oxides, and quartz to yield garnet and clinopyroxene (McLelland and Whitney, 1977):

Plagioclase + Orthopyroxene + Fe-Ti Oxides + Quartz =
Garnet + Clinopyroxene + more sodic Plagioclase (9)

In more strongly deformed and recrystallized anorthositic gneisses, garnet occurs as discrete rounded grains and porphyroblasts, and hornblende is more extensively developed.

Garnet in the metaigneous rocks is, in general, almanditic but contains up to 45 percent pyrope in Mg-rich facies of the olivine metagabbros, and 15-20 percent grossular in both metanorthosites and gabbros (Whitney and McLelland, 1973, 1983; McLelland and Whitney, 1977, Johnson and Essene, 1982). Almanditic garnets also occur locally in the charnockitic and granitic gneisses, both as porphyroblasts and as coronas surrounding orthopyroxene and oxides.

Most of the granitic gneisses and charnockites, and some of the ferrodiorite gneisses, are migmatites. This is not always noticeable on fresh outcrop surfaces, but it is usually apparent on weathered or glacially scoured surfaces. Quartzofeldspathic leucosomes that are coarser than the host gneiss form: (1) irregular, discontinuous layers up to several cm thick parallel to foliation; (2) poorly defined networks (nebulites); or (3) less commonly, crosscutting veins. This pervasive migmatization indicates that some anatectic melting accompanied the granulite facies metamorphism.

ECONOMIC GEOLOGY

1. Iron ores

The area north of the Ausable River was an important center for iron mining during the nineteenth century. Twelve mines near Palmer Hill, Arnold Hill, and Cook Mountain, as well as two near Black Brook, were active at various times between 1806 and 1906. Total production from the district, principally from the Arnold Hill and Palmer Hill mines, has been estimated by Newland (1908) as being in excess of 2 million tons of magnetite concentrates.

Much of this ore was processed locally at smelting and fabricating facilities in Clintonville, Au Sable Forks, Jay, and Black Brook (Dawson et al., 1988). Charcoal used in the smelting operation was an important local industry, as reflected in such geographic names as Kiln Brook, Coal Dirt Hill, and Seven Kiln in the southern part of the quadrangle (USGS 15' topographic map, 1953 edition). Some of the "limestone" used at the forges was quarried locally from calcite marbles within the metasedimentary rocks (Kemp and Alling, 1925). The iron mines are now inacessible due to caving and flooding, and the following discussion is based upon descriptions of the geology by Newland (1908), Kemp and Alling (1925), and Postel (1952).

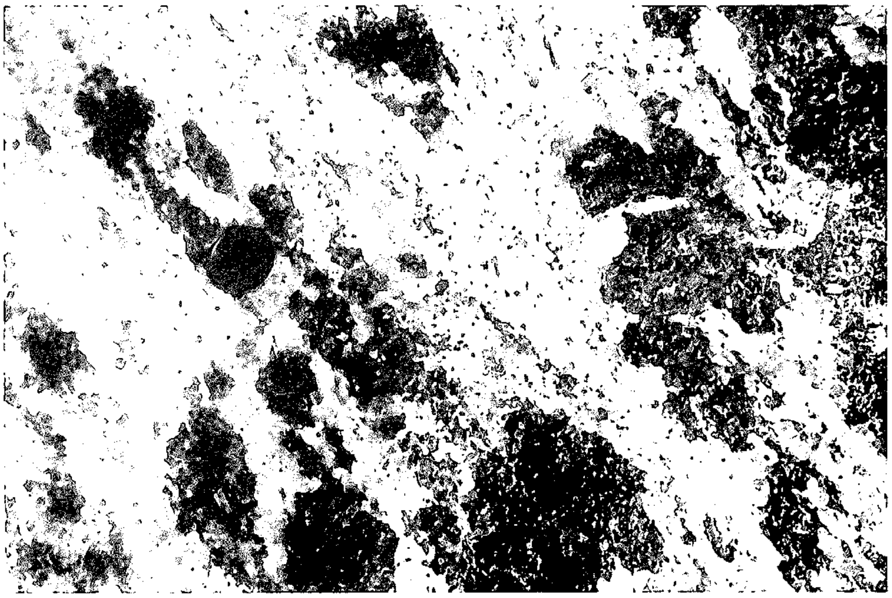
The host rock for the ore in all the mines is the Lyon Mountain Gneiss or interlayered metasedimentary rocks. Amphibolites and pyroxene-rich skarns are also reported in the vicinity of some of the ore zones. A consistent association between ore and any particular facies of the Lyon Mountain Gneiss is not evident, although Alling (1939) observed a general association of ore with pyroxene-rich rocks. Postel (1952) noted the occurrence of ore within zones of cataclastic deformation. The ore occurs as relatively thin (up to 6 m) layers and lenses that are conformable with foliation and compositional layering in the host rock or as "shoots" parallel to the regional N to NE lineation. Crosscutting pegmatite and quartz veins are commonly noted. Up to 1 percent fluorite is present in the granitic phase of the gneiss near the Palmer Hill deposits.

The principal ore mineral is magnetite, commonly partially replaced by martite. Locally, the replacement by martite is nearly complete, as in the "blue vein" ore at Arnold Hill (Newland, 1908). Trace ilmenite occurs both as exsolution lamellae in magnetite and as separate grains. The ores range from nearly pure iron oxides to mixtures with varying amounts of gangue minerals that include quartz, feldspars, clinopyroxene, and biotite. Titanite is a common accessory that occurs as discrete grains and, in lean ore, as rims on magnetite grains. Variable, but minor, amounts of apatite are usually present. Pyrite is uncommon. Ore textures suggest that several generations of magnetite may be present (Kemp and Alling, 1925; Postel 1952).

Numerous workers have discussed the origin of the low-Ti iron ores of the northern and eastern Adirondacks. Several (Alling 1925, 1939; Gallagher 1937; Postel 1952; Buddington 1966) advocate variations of the hypothesis of selective replacement of the host rock by late, iron-bearing fluids derived from differentiation of granitic magma. Miller (1919) likewise appealed to late-magmatic fluids but derived the iron from preexisting mafic rocks intruded by the granite. Nason (1922), noting the stratabound nature of the ores, proposed a metasedimentary origin. Hagner and Collins (1967) proposed that iron derived from breakdown of mafic silicates in the host rocks had migrated into shear zones and structural openings during regional deformation and metamorphism. McLelland (1986) argued for exhalative deposits produced by subaqueous precipitation of iron oxides and carbonates during felsic volcanism. One of us (PRW) speculates that the ores may have originated as iron oxide magmas that erupted at the surface or were intruded in a subvolcanic setting, and were later modified during metamorphism by halogen-rich fluids from evaporites in the metasedimentary rocks. Further research is hindered by lack of access to the mine workings.

2. Wollastonite

The presence of wollastonite in the northeastern Adirondacks has been known since about 1810 (Broughton and Burnham, 1944). Without an obvious use, the occurrence was of little interest except as a mineralogical curiosity. In 1952, the Cabot Corporation opened a mine near Willsboro in the Willsboro quadrangle and sold wollastonite for use as a filler and ceramic base. Subsequent product development has resulted in such uses as a tempering agent in ceramics, flux for welding rods, an alloying agent, an extender in plastics, and a substitute for short-fiber asbestos. In 1980, production was shifted from the underground mine at Willsboro to an open pit operation in the Au Sable Forks quadrangle 5 km NW of the village of Lewis and 1.5 km SW of Mount Fay. The latter mine is currently operated by the NYCO division of Process Minerals, Inc. Both the Willsboro and Lewis deposits lie within a 22-km zone of highly tectonized mixed intrusive and metasedimentary rocks (Mixed Gneiss "A", Plate



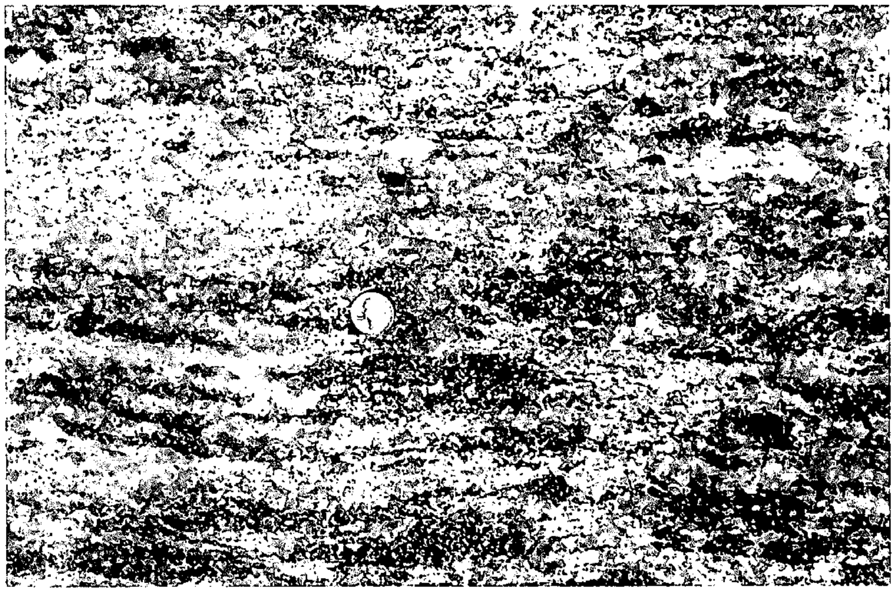
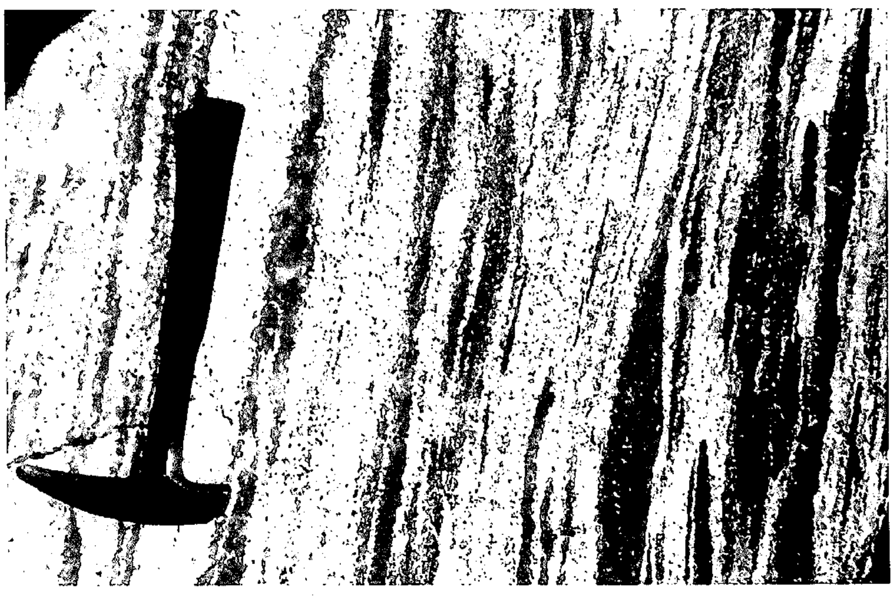
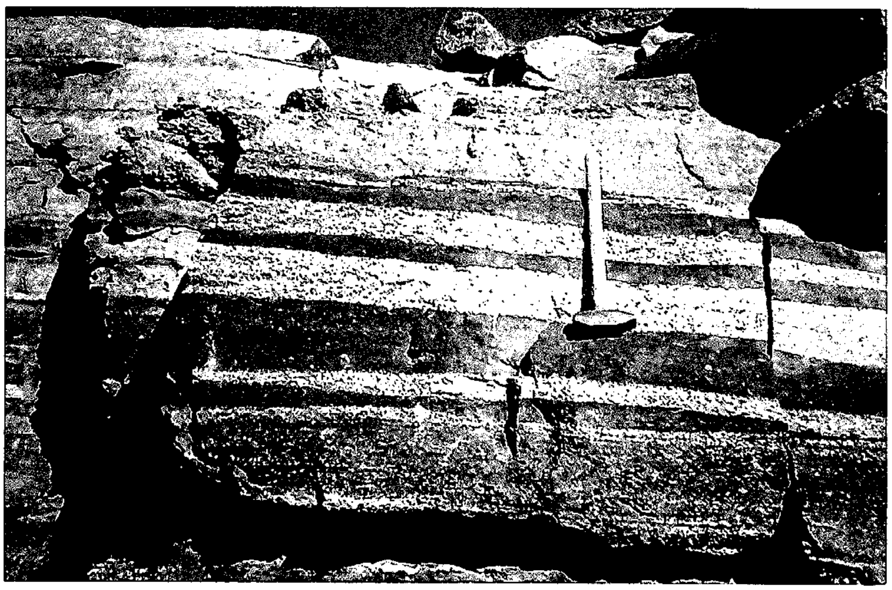


FIGURE 19. Textures of wollastonite ore in the Lewis open pit mine. Dark minerals are garnet and clinopyroxene; white is wollastonite. (a) Ore with slight foliation and clots of pyroxene and garnet up to 10 cm. Quarter for scale. (b) Well-foliated ore with diffuse streaks of garnet and pyroxene. Quarter for scale (c) Strongly foliated ore with sharply defined streaks and lenses of dark minerals. Hammer for scale.





(d) Lean ore with thin layering of probable tectonic origin; white spots in layer under hammer handle are porphyroclasts of coarse wollastonite. (e) Ore with thick tectonic (?) layering. The strongly layered ore tends to occur close to the hanging wall of the orebody.

1) close to the base of the Rocky Branch Complex where it overlies metanorthosite of the Westport Dome. Smaller prospects occur within the same zone about 1.5 km NNW of Deerhead and near the 1000 foot elevation ESE of the summit of Oak Hill (the southernmost of four "Oak Hills" on the Au Sable Forks 15' topographic sheet). The widespread occurrence of calcsilicate-rich metamorphic rocks in proximity to anorthositic and gabbroic intrusives throughout much of the southern two-thirds of the Au Sable Forks quadrangle suggests the potential for additional economic wollastonite deposits.

The geology of the Willsboro deposit and has been described in considerable detail (Putman, 1958; DeRudder, 1962; Olmsted and Olilla, 1988). By contrast, the immediate geologic setting of the Lewis deposit, as it is commonly called, is poorly known due to lack of exposures. On the west side of the open pit where the ore zone is close to 25 m thick, it is overlain by charnockitic gneiss; while to the north and east, anorthositic gneiss is exposed above the ore. On the basis of temporary exposures within the mine and drill core data, the footwall appears to be gabbroic anorthosite gneiss. All units strike approximately E-W with a average dip of 10-15^{o} S or SW, approximately parallel to the topographic surface. An unusually thick (4-6m), vertical diabase dike striking N68E cuts the ore in the pit and shows narrow chilled margins against it.

The mineralogy of the Lewis ore, like that at Willsboro, Deerhead, and Oak Hill, is simple and consists almost exclusively of the "skarn" assemblage of wollastonite, garnet, and clinopyroxene. Electron probe microanalysis shows that the pyroxene compositions are close to the diopside-hedenbergite join and range from Hd_{20} to Hd_{50}. The garnets are grossular-andradite solid solutions ranging from Ad_{17} to Ad_{93}. Garnet compositions may vary by as much as 15 percent Ad within a 5 cm piece of drill core, and by several percent within a standard thin section. The garnet in wollastonite-rich ore is commonly andraditic, though highly variable, while that in the garnet-pyroxene layers is more grossularitic. The grossularitic garnets are light brownish orange while the andradite-rich garnets are a deep reddish brown to almost black. Pyroxenes range from pale green (diopside) to nearly black (salite). Titanite and apatite occur in minor amounts in some garnet- and pyroxene-rich layers. Grossular-rich garnet (Ad_{16} in one sample) occurs near contacts with metanorthosite and other plagioclase-bearing rocks and locally forms "garnetite" with minor quartz and albite in zones and lenses up to a meter thick.

The texture of the ore is gneissic with varying intensity of foliation (Figure 19). Centimeter-to decimeter-scale modal layering is locally prominent within the orebody, with nearly monomineralic wollastonite layers alternating with garnet-pyroxene layers containing little or no wollastonite (Figures 19C-19E). This layering, which we believe to be of tectonic origin, is most pronounced in the vicinity of the hanging wall of the orebody.

The abundance of wollastonite in these rocks, coupled with the complete absence of both quartz and calcite raises an interesting problem. If this were a simple contact metamorphic deposit, it would be necessary to postulate a protolith with precisely the right balance of reactant minerals to produce wollastonite with no leftovers. Given the variability of sedimentary processes, such a balance throughout large orebodies such as those at Willsboro and Lewis is enormously improbable. This observation led De Rudder (1962) and Buddington (1977) to suggest that metasomatism may have had a significant role in the ore-forming process.

We propose (pg. 37, below) that emplacement of the anorthosite took place at relatively shallow depths in an extensional tectonic environment that may have included large scale listric normal faults or detachment faults (Fakundiny and Muller, 1993). We propose that these faults and their associated shear zones provided channels for circulating hydrothermal fluids, driven by heat from the anorthosite. Dissolved silica and iron in the fluids produced the ore mineralization by infiltration metasomatism where the fault planes followed or intersected carbonate units. If the aqueous fluids were largely of meteoric origin, the same process could account for the anomalous oxygen isotope signature of the ore (Valley and O'Neil, 1982, 1984).

Such a mechanism is consistent with the high variance of the mineral assemblage in the ore, but apparently inconsistent with the sharp gradients observed in mineral compositions over distances on the order of centimeters. Grandite garnets in many skarn deposits show strong compositional zoning. Such zoned crystals can have substantially different average compositions even though the rims deposited at any given time may have been in equilibrium with each other and with hydrothermal fluids. In the Adirondack deposits, zoned garnets with different average compositions may have been juxtaposed during syn- or post-ore deformation and internally homogenized during subsequent granulite-facies metamorphism. Since the latter metamorphism probably took place under fluid-absent conditions (Valley et al., 1990) equilibration between grains more than a few cm apart may not have occurred, leading to the observed variations in composition over short distances.

Although the primary mineralization occurred at the time of anorthosite intrusion, we speculate that the grossularitic "garnetite" zones at the contacts of the orebody originated during the granulite facies metamorphism by local metasomatic reactions similar to reaction (3) above (page 28).

3. Graphite

Economic concentrations of graphite in metasedimentary rocks have been reported by Alling (1917) and Kemp and Alling (1925) southeast of Trout Pond, where some mining occurred, and at the eastern end of The Gulf. Although considerable graphite is present in the rocks in these areas, we have been unable to relocate the actual mines and prospect pits. Prospect pits, presumably for graphite, are present in graphitic marbles east of Coonrod Pond.

4. Dimension stone

Quarrying of stone for building and monument use has been carried on sporadically in the Au Sable Forks quadrangle. A number of small quarries in the northern part of the quadrangle are described by Newland (1916). Six of these are in rock described by Newland (1916) as green syenite and by Kemp and Alling (1925) as quartz nordmarkite. Three of the quarries are in the Bailey Mountain fayalite granite, just north of U. S. Route 9N and roughly 1.6 km east of the village of Au Sable Forks. Two are in green quartz mangerite and quartz syenite at the western end of Ragged Mountain about 0.9 km south of Au Sable Forks, while the fifth is roughly due west of these in a small exposure of the same rock on the opposite side of the river west of Route 9N. All of these are now abandoned. Small amounts of red, magnetite rich "granite" (Lyon Mountain Gneiss) were quarried in a now-abandoned operation near the road about 3 km east of Au Sable Forks.

Metanorthosite quarries about 0.9 km southeast of Stickney Bridge, near the west end of Augur Lake, and "west of Keeseville" are described by Newland (1916). It is uncertain whether Keeseville quarry, which we have not seen, is within the Au Sable Forks quadrangle. In 1959, the Cold Spring Granite Company opened the Lake Placid Granite (sic) Quarries in the anorthositic gneiss near the northern margin of the Jay Dome, roughly 3 km south of Au Sable Forks. Of these two quarries, one is at or near the site of the former Stickney Bridge quarry and the other is on the eastern slope of hill 961, west of the East Branch of the Ausable River. These are the only dimension stone quarries now operating in the quadrangle. At present (1990) the company is producing about 90,000 cubic feet of stone per year and has an annual payroll of close to $600,000 for about 30 employees. The anorthositic rock is quite variable in color and ranges from light bluish gray to many hues of greenish gray. It is quarried by drill-and-blasting methods combined with the "drive in" system of removal with loaders. The stone is used principally for paving, fascia, and monuments. Excellent "exposures" of this rock are found in floors and steps of the Empire State Plaza in Albany.

5. Sulfide mineralization

Small, noneconomic concentrations of sulfide minerals occur locally within the Jay Mountain gabbro body. The most notable of these is exposed in the notch between Tom's Hill and Seth's Hill, near a concealed contact between metagabbro and metasedimentary rocks. At this location, a small prospect pit has been excavated in metagabbro mineralized with disseminated pyrrhotite and minor pyrite, chalcopyrite, and pentlandite. Grab samples from the most strongly mineralized zones contain up to 1,700 parts per million nickel and 1,200 parts per million copper. The mineralization appears to be very localized. Other small zones of disseminated sulfides occur in the notch between Big Slash and Little Slash mountains and in the narrow band of gabbroic rocks that crosses Derby Brook south-southwest of Little Fay Mountain.

INTERPRETATION AND GEOLOGIC HISTORY

1. Sedimentation and magmatism

The metasedimentary rocks of the Rocky Branch Complex probably represent the oldest rocks exposed in the area. No rocks identifiable as an earlier "basement" have been found. Although the metasedimentary rocks rest with apparent conformity upon the domical metanorthosites in the present structural configuration (deWaard and Walton, 1967), the numerous xenoliths of metasedimentary rocks in metanorthosite and the sill-like bodies of metanorthosite within metasedimentary rocks show that the metanorthosites are younger.

Several features of the metasedimentary rocks suggest a protolith that included evaporites. The preponderance of diopside-rich calcsilicate rocks, the metamorphic equivalent of siliceous dolostones, is significant in that dolomite is commonly a product of hypersaline environments (Friedman, 1980). The diopside-rich rocks locally contain major amounts of potassium feldspar, possibly the metamorphic equivalent of low-temperature, authigenic or diagenetic microcline. The latter, in part pseudomorphous after evaporite minerals, has been reported from late Proterozoic, evaporite-bearing dolomitic rocks in South Australia (Rowlands et al., 1980) and in the Damara orogen in Namibia (Behr et al., 1983). Magnesium-rich metasedimentary rocks, in particular phlogopite schists and tremolite-enstatite-diopside-(phlogopite)-quartz rocks, are probable granulite facies equivalents of evaporite-related talc-tremolite-anthophyllite-quartz schists, such as those found in the northwest Adirondacks near Balmat (Brown and Engel, 1956; Valley et al., 1983). There, they occur in stratigraphic association with diopside-rich rocks and bedded anhydrite. The common presence of scapolite in both marbles and calcsilicate rocks is another possible indicator of an evaporite origin (Serdyuchenko, 1975).

The dominance of calcsilicates, quartzites, and carbonate rocks, with numerous features indicating the former presence of evaporites, suggests a shallow, hypersaline to saline-alkaline depositional environment. The protolith may have been dolomitic sandstones and mudstones, quartz sandstones, dolostone, and anhydrite or gypsum. Magnesite- and chlorite-bearing sediments are likely precursors of the Mg-rich facies. Authigenic K-feldspar, albite, and/or scapolite in dolomites and dolomitic sandstones provided the feldspar components of the present feldspathic calcsilicate rocks. Diopside-bearing phlogopite schists may represent evaporitic marls (Moine et al., 1981). The irregular cm-scale layering, locally present in quartzites (Fig. 5b), suggests a protolith of laminated cherts. Unmetamorphosed or weakly metamorphosed Proterozoic sedimentary rocks resembling these hypothetical precursors are found, for example, in the Adelaidian of South Australia (Rutland et al., 1980; Rowlands et al., 1980) and in the Damara Basin of Namibia (Behr et al., 1983). Granulite facies metasedimentary rocks similar to those of the Au Sable Forks quadrangle occur in the Caraiba mining district of Brazil (Leake et al., 1979) and in the Oaxacan Complex of southern Mexico (Ortega-Gutierrez, 1984); in both localities anhydrite is present in the subsurface. Quartzofeldspathic rocks interlayered with the metasedimentary rocks may be the metamorphic equivalent either of arkosic sandstones or of felsic volcanics and shallow intrusives. Amphibolites may correspond to the mafic component of a bimodal volcanic suite; alternatively they may be transposed dikes related to the ferrodiorites or the olivine metagabbros.

The Lyon Mountain Gneiss, which overlies the metasedimentary rocks with apparent conformity, appears to be a bimodal, dominantly felsic volcanic suite with metasedimentary interlayers and local comagmatic, subvolcanic intrusives. The extreme variations in K/Na ratios within these rocks, previously noted by Buddington (1966), indicate diagenetic or metasomatic alteration. We suggest that the protolith of the Na-enriched, K-depleted trondhjemitic facies was a felsic volcaniclastic rock diagenetically altered in a hypersaline environment such as a playa lake (Whitney and Olmsted, 1988). Possible unmetamorphosed analogs of these rocks are found in several areas in the southwestern United States, where rhyolitic tuffs of Pliocene to Recent age have been altered in a playa setting to produce diagenetic analcite (Na-rich), zeolites, or K-feldspar (Surdam, 1981). Similar rocks have also been described from the Miocene of Samos Island, Greece (Stamatakis, 1989). K-rich, Na-depleted microcline gneisses, corresponding to the diagenetic K-feldspar facies (Surdam, 1981), are also found in the Lyon Mountain Gneiss (Postel, 1952; Whitney and Olmsted 1988) although they are not well exposed in the Au Sable Forks quadrangle. Possible Proterozoic analogs of the Na- and K-enriched facies of the Lyon Mountain Gneiss are described from the Willyama Supergroup, New South Wales, Australia, by Cook and Ashley (1992).

No igneous rocks analogous to the mafic albite gneiss facies are known. Weakly metamorphosed albite-dolomite-quartz rocks, locally with albite porphyroblasts, have been described in a series of late Proterozoic sedimentary rocks in the Damara orogen of Namibia by Behr et al. (1983), and attributed by them to sedimentation in a playa environment. Since the corresponding granulite facies mineral assemblage would be albite-clinopyroxene, such rocks are a possible protolith for the mafic albite gneiss.

The evaporite-related metasedimentary rocks and overlying felsic metavolcanics are consistent with deposition in a cratonic basin or a failed intracontinental rift. In either situation, an anorogenic (noncompressional) tectonic environment is indicated.

The origin of rocks of the anorthosite suite has been attributed to intrusion of voluminous mafic magmas at or near the base of the continental crust (Emslie 1978, 1985; Morse 1982). Fractionation by separation of olivine and pyroxene drives the magma toward an aluminum-rich composition and, at the same time, increases the Fe/Mg ratio. The remaining gabbroic anorthosite or leuconorite liquid is intruded to higher crustal levels where plagioclase begins to crystallize. The resulting rocks include (1) plagioclase cumulates (anorthosites) with minor, largely intercumulus, pyroxenes and oxides; (2) gabbroic anorthosites crystallized directly from the magma or from plagioclase-rich crystal mush; and (3) ferrodiorite or ferrogabbro, which crystallize from the residual liquid.

Most known massif anorthosites are considered to be anorogenic (Morse, 1982). No direct evidence links them to rifting (Emslie, 1985), but a failed-rift setting is not excluded. Evidence for the anorogenic origin of the Adirondack anorthosites includes their 1113-1138 Ma age (McLelland and Chiarenzelli, 1990a), which lies between an early orogenic event at about 1240 Ma (McLelland and Chiarenzelli, 1990b) and the final (Ottawan) phase of the Grenville orogeny between 1100 and 1030 Ma (Emslie and Hunt, 1990; McLelland and Chiarenzelli, 1990a). Simmons (1964) deduced from gravity data that the shape of the main anorthosite massif is roughly that of a 5 km thick sheet with at least two deeper roots. More detailed gravity data from the northeastern part of the massif obtained by Mann and Revetta (1979) (Figure 3) suggest that the sheet in this area consists of multiple coalescing domes, in agreement with field data from the Au Sable Forks quadrangle. Such a laterally extensive, relatively thin configuration is difficult to reconcile with a compressional setting. In addition, the large volume (ca. 7,500 km^3) of anorthositic rocks presents a formidable "space problem" in a compressional environment, whereas for a relatively shallow intrusion in an anorogenic or extensional setting, the intrusive rocks could be accomodated by uplift of the overlying material.

The ferrodioritic and monzodioritic rocks that occur in close spatial relationship to the anorthosite have a geochemical character that is consistent with their derivation by fractionation of a gabbroic anorthosite magma. Least squares mixing model calculations (Bryan et al., 1969), starting with a liquid of average gabbroic anorthosite composition, show that crystallization of plagioclase and minor pyroxene yields about 80-85 percent of anorthositic cumulate (90-93 percent plagioclase around An_{52}, 7-10 percent pyroxene) and leaves a residual liquid with a composition closely approximating that of the ferrodiorites in both major and trace elements. This modeling and the close spatial association of anorthositic and ferrodioritic rocks support a comagmatic origin, in agreement with Buddington (1972), Ashwal (1978), Morse (1982), and Emslie (1985). The andesine megacrysts in the ferrodioritic gneisses probably are xenocrysts derived from partially consolidated anorthosite. Convincing evidence for the intrusion of ferrodioritic rocks (the "Woolen Mill Gabbro" of Buddington, 1939) into partially consolidated anorthosite is present at the Woolen Mill locality in the Elizabethtown Quadrangle (Whitney et al., 1989).

The accumulation of voluminous mafic magmas at the base of the crust and the subsequent intrusion of aluminum-rich derivatives into the crust to produce the anorthosite suite would inevitably cause substantial heating and partial melting of the lower crust. Partial melting of source rocks containing hydrous minerals can give rise to large volumes of granitic magma (Clemens and Vielzeuf, 1987). This provides a mechanism for the origin of the granitic and charnockitic gneisses within the layered sequence. Their A-type geochemical signature (Figure 12), characteristic of both anorogenic (Collins et al., 1982) and post-collisional (Sylvester 1989) granites, is nearly identical to that of granitic and charnockitic gneisses elsewhere in the Adirondack Highlands (McLelland and Whitney, 1990; Whitney, 1992). This composition suggests that the source of the magmas may be intermediate igneous rocks from an earlier orogenic cycle (Whalen et al., 1987; Sylvester 1989). The local presence of anorthosite xenoliths in the granitic gneisses does not necessarily imply a significantly younger age, since the melting range of the granitic rocks is at considerably lower temperatures than that of the anorthosite. We believe that the granitic rocks are essentially coeval, although not comagmatic, with the anorthosite. The geochemical similarity of the felsic metavolcanic rocks of the Lyon Mountain Gneiss to the granitic gneisses suggests that the former may be the extrusive equivalent of the latter.

As in the case of the anorthosites, the "space problem" associated with the origin of the granitic rocks is simplified if they were emplaced in an anorogenic or extensional setting. Granitic magmatism synchronous with ductile shearing at relatively shallow levels in an extensional zone has been described by Hutton et al. (1990) in Greenland, where it produced granitic bodies roughly similar in size and shape to those of the Au Sable Forks quadrangle.

The olivine gabbros may have been emplaced late during the same magmatic event. They are, in general, geochemically less evolved than the presumed anorthositic magmas, having a higher Mg/(Mg+Fe) ratio, higher Ni and Cr, and less Al enrichment (Table 1D). They may represent direct tapping of a replenished subcrustal magma reservoir during continued crustal extension. The metagabbros in the Au Sable Forks quadrangle do not have a significant preferred orientation, but Balk (1944) describes dikes of similar metagabbro in anorthosite at Trembleau Mountain near Port Kent (Plattsburgh Quadrangle) that are statistically oriented NW-SE, suggesting that extension in a NE-SW direction occurred at the time of gabbro intrusion. Another large (30 m) gabbro dike, also with NW-SE orientation, is exposed on Mt. Colden in the Mount Marcy quadrangle (Jaffe, 1946).

Deformed marginal regions of the olivine metagabbro bodies share the same NNE-trending stretching lineation that is developed in the metasedimentary, anorthositic, and granitic rocks. We speculate that this resulted from extensional collapse of magmatically thickened upper crust, with a SW-over-NE sense of movement (i.e., away from the largest anorthosite intrusions). Unambiguous kinematic indicators have not, however, been found in the rocks. This interpretation, if correct, implies that extensional collapse occurred synchronously with the later stages of magmatism, giving rise to the deformation of both the metagabbro and of the rocks it intrudes. Although original horizontality cannot be confidently assumed for igneous layering, the southwestward dip of the layering in the Jay Mountain gabbro body is at least consistent with rotation during NE-verging listric normal faulting associated with crustal extension. Mapping in the Elizabethtown quadrangle by Fakundiny and Muller (1993) has produced evidence of at least two episodes of anorthosite intrusion, separated in time by extensional shearing, with the younger anorthosite postdating the gabbro.

U/Pb zircon geochronology for rocks of the AMCG suite in the Adirondack Highlands indicates that most of the intrusive activity occurred between 1160 and 1110 Ma (Silver, 1969; Grant et al., 1986; McLelland et al., 1988; McLelland and Chiarenzelli, 1990a; Chiarenzelli and McLelland, 1991). Two olivine metagabbros have been dated; one near the eastern edge of the Adirondack Highlands gives a U/Pb zircon age of 1144+7 Ma (McLelland and Chiarenzelli, 1989); another, which cuts the main anorthosite massif near Schroon Lake, gives a minimum U/Pb baddeleyite age of 1109 Ma (McLelland and Chiarenzelli, 1990a). These data provide an approximate minimum age for the metasedimentary rocks, which are extensively intruded by both the AMCG suite and olivine metagabbro, and for the Lyon Mountain Gneiss, which contains bodies of olivine metagabbro. The question of the age of the Lyon Mountain is complicated by zircon ages of 1073 and 1057 Ma reported for these rocks by Chiarenzelli and McLelland (1991). We think, however, that these are metamorphic ages (see discussion under "Suggestions for Future Work", below). Direct evidence for the age of the metasedimentary rocks is lacking. If the Lyon Mountain Gneiss is the extrusive equivalent of the granitic and charnockitic gneisses, the presence of metasedimentary layers within it suggests that sedimentation and magmatic activity overlapped in time.

The voluminous magmatism at this time in the Adirondack Highlands probably caused widespread contact metamorphism. However, the only clear evidence that has survived the subsequent regional metamorphism is the distribution of wollastonite, the local occurrence of monticellite and akermanite, and the skarn mineralogy and anomalous oxygen isotopic composition of the wollastonite ores.

2. Thrusting and regional metamorphism

The granulite facies metamorphism that has affected all the rocks with the exception of the small, unmetamorphosed dikes probably occurred during the Ottawan phase of the Grenville orogeny (1100-1030 Ma), possibly as much as 50-100 Ma after the peak magmatic activity (Emslie and Hunt, 1990). At this time, large-scale thrusting associated with a collisional event to the southeast gave rise to a doubly-thickened crust in the Adirondack Highlands. This thrusting, although still largely conjectural, provides the most plausible mechanism for burying supracrustal rocks and shallow intrusives to depths of 25-30 km, which corresponds to the 7-8 kbar pressure for peak granulite metamorphism (Bohlen et al., 1985). Widespread development of W- to WNW-oriented ribbon lineation and sheath folds in the southeastern and south-central Adirondack highlands (McLelland, 1984) suggests WNW-directed thrusting associated with the Grenville tectonic thickening (Whitney 1983, McLelland and Isachsen 1985, Whitney et al., 1989). These features are not strongly developed in the Au Sable Forks quadrangle, possibly due to the buttressing effect of the large anorthosite bodies. Alternatively, the rocks now exposed in the northeastern Adirondacks may have been at greater depths relative to the zone of thrusting than the rocks further south. Some W- to NW-oriented lineations are observed, however, and they may record movement associated with the thrusting event. The northwesterly lineation is best developed near the base of the rootless McGuire Mountain anorthosite body (E of Trout Pond, Plate 1), which may have been tectonically emplaced at that time.

Later stages of magmatism may have overlapped in time with the initiation of collisional tectonics, and provided a source of heat for the granulite facies metamorphism. It is possible that the thermal peak of the metamorphic event preceded the maximum pressures (Emslie and Hunt, 1990); this is consistent with the counterclockwise pressure-temperature-time path deduced for the Adirondack Highlands by Bohlen (1987).

Metamorphism probably occurred or continued after cessation of deformation. Deformed garnet is scarce or absent in most rocks of the quadrangle. Together with the ubiquitous occurrence of garnet as delicate reaction coronas around other minerals, this suggests that either (a) the garnet was formed relatively late in the Grenville tectonic cycle and postdates most or all of the deformation, or (b) most of the observed deformational features originated during the earlier extensional tectonic regime.

3. Vertical Tectonics

The NNE-directed lineations (Fig. 13E) show reversals of plunge across the anorthosite domes and suggest post-lineation doming. One explanation, suggested by Fakundiny and Muller (1993), is that domical intrusion of a second generation of anorthosite occurred late in the magmatic cycle, after most or all of the extensional deformation. Alternatively, during and after the granulite facies metamorphism and following relaxation of the compressive stresses associated with thrusting, the large, low density anorthosite bodies may have become gravitationally unstable and moved upward through thermally softened cover rocks (Whitney, 1983). In either situation, as the domes rose, the overlying gneisses were swept into pseudoconformity with the anorthosite contact. This relationship, present in many areas of the Adirondack Highlands, led deWaard and Walton (1967) to conclude that the anorthosite was part of a preexisting basement complex on which the sedimentary rocks were deposited.

In the central and southern parts of the quadrangle, the overall configuration of the cover rocks closely follows the contours of the anorthosite domes. We believe that most of the large-scale structure in this area, including the constricted central part of the Au Sable Forks synform, is a consequence of vertical tectonic movements, with the cover rocks being downfolded between rising anorthosite domes. However, the open, irregular, north-trending folds in the Lyon Mountain gneiss near and to the north of the Ausable River are less readily explained by this hypothesis, and may be the result of compressional forces during the Ottawan deformation.

4. Post-Grenville events

Uplift, cooling, and unloading took place over an undetermined interval of time after the Grenville orogeny. Erosion to near present levels by Middle Cambrian time is indicated by exposures along the eastern margin of the Adirondack Highlands of the Upper Cambrian Potsdam Sandstone that rests unconformably on Proterozoic rocks. Some brittle deformation must have commenced prior to the beginning of the Cambrian, based on the fact that NE-trending fractures and fault zones are commonly occupied by diabasic dikes similar to those at Rand Hill in the Plattsburgh quadrangle. These dikes have been dated by Isachsen et al. (1988) in the range 588-542 Ma (uppermost Proterozoic). The initial faulting and dike intrusion may be related to the opening of the Iapetus Ocean (Isachsen et al., 1988). Brittle deformation continued well into the Paleozoic, however, since the N- and NE-trending faults displace Lower Paleozoic rocks (through Middle Ordovician) in the Champlain Valley (Quinn, 1933; Buddington and Whitcomb, 1941). Later lamprophyre and trachyte dikes that occupy ENE- to ESE-trending fractures (Kemp and Alling, 1925) are considerably younger, probably early Cretaceous (Isachsen et al., 1988).

Exposure, or reexposure, of the Precambrian rocks now at the surface probably occurred relatively recently, as a result of late Cenozoic doming of the entire Adirondack region. This uplift, which may have involved reactivation of some of the major NE-trending faults, continues into the present (Isachsen, 1975).

SUGGESTIONS FOR FUTURE WORK

1. Detailed mapping of the metanorthosite domes. During this study, the interior regions of the metanorthosite domes were mapped in reconaissance fashion only. No attempt was made to map systematically either variations in mineralogy and texture, or the orientations of minor shear zones. Neither preferred orientations of plagioclase megacrysts nor metamorphic foliations were recorded unless they were quite distinct. In those parts of the domes where sufficient exposure is present, detailed mapping may yield useful information relevant to the origin, emplacement, and deformation of the anorthosite.

2. Petrology and geochemistry of metanorthosite. Fakundiny and Muller (1993) have distinguished two generations of anorthosite in the Elizabethtown quadrangle, directly south of the map area. This was based on field criteria including intensity of deformation. A search should be made for systematic petrologic, geochemical, and textural differences that could be used to distinguish between these groups in doubtful cases. In the Au Sable Forks quadrangle, a petrologic and geochemical comparison among the three metanorthosite domes and between the domes and the smaller metanorthosites within the Rocky Branch Complex could test whether more than one suite of anorthosites is present there also, and provide a basis for correlation with other areas.

3. Detailed structural studies. Our present understanding of the deformational history of the northeastern Adirondack area is very inadequate, and further work on the structural geology of the area is needed. One place to start would be a careful search within the highly strained rocks for kinematic indicators, on both mesoscopic and microscopic scales, to determine the sense of tectonic transport. Structural studies should also focus on questions relating to the timing of deformation, including whether the major shear zones were, as we believe, related to pre-Ottawan extensional movements or whether they are, later, syn- or post-regional metamorphic features. The approach to this problem should combine structural petrology and geochronology. If the results confirm an early date for the major deformation, the question of whether structural effects of unequivocally Ottawan age are present needs to be addressed.

4. Age of the Lyon Mountain Gneiss. We have concluded (1) that the Lyon Mountain Gneiss originated as dominantly felsic volcanic rocks with minor interlayered sediments that have undergone extensive diagenetic alteration or low-temperature metasomatism; and (2) that it is the extrusive equivalent of the granitic rocks of the AMCG intrusive suite and, thus, approximately coeval with them. These conclusions are based on the heterogeneous, stratified nature of the Lyon Mountain Gneiss including the interlayered metasedimentary rocks, its similarity in composition to the AMCG granitic rocks, the extremely variable alkali metal ratios, and the presence within it of bodies of olivine metagabbro of probable intrusive origin.
However, Chiarenzelli and McLelland (1991) have obtained U-Pb zircon ages for two samples from the Lyon Mountain Gneiss that would suggest a younger age. A sample of leucocratic albite gneiss from 3 km west of Clintonville in the Au Sable Forks quadrangle yielded an age of 1057±10 Ma, and a sample of exceptionally K-rich granitic gneiss from the large roadcut on N. Y. Route 374 about 2 km northwest of Dannemora, Dannemora quadrangle, gave an age of 1073±6 Ma. The former sample is from the same outcrop as sample AF664 (Table 2E) and the latter from the same roadcut as sample DAS01 of Whitney and Olmsted (1988). Both rocks show extreme K/Na ratios that are unlikely to reflect original igneous compositions. Chiarenzelli and McLelland (1991) interpret the ages as igneous and argue that the Lyon Mountain Gneiss consists of syntectonic intrusive rocks emplaced during the Ottawan orogeny. We suggest that the ages may be metamorphic, and that the original zircons in the rock were either destroyed by diagenetic or metasomatic alteration, or recrystallized in the presence of alkali- or halogen-rich fluids at the time of granulite facies metamorphism and anatexis. The apparent discrepancy between radiometric ages and field relationships clearly warrants further investigation. In particular, ages should be obtained from samples of the Lyon Mountain Gneiss that are of approximately granitic composition and, thus, less likely to have undergone severe diagenetic or metasomatic alteration.

5. Origin of the low-Ti magnetite ores. There is to date no agreement in the literature on the origin of these rocks and their relationship to the host Lyon Mountain Gneiss, although numerous models have been proposed (see section on Economic Geology, above). Unfortunately, the mine workings are now inaccessable, and few surface exposures of the ore are known. Geochemical studies using existing museum specimens and drill core should be done in order compare trace element suites with those in magnetite ore deposits of known origin.

6. Origin of the wollastonite ores. Work is currently in progress by the authors on the petrology and geochemistry of the wollastonite ores from the Willsboro-Lewis district. This includes studies of mineral chemistry using electron microprobe

methods and determination of the rare earth element distribution in the ores and their constituent minerals, in order to obtain a better understanding of the protolith and the ore-forming process.

7. Search for additional wollastonite deposits. A broad area south and east of the present Lewis mine is underlain by nearly horizontal mixed gneisses of the same type as those which contain the Lewis, Oak Hill, and Deerhead wollastonite occurrences. Much of the area in question is covered by glacial deposits. We recommend a search for possible additional economic wollastonite by utilizing the characteristic association of the ore with orange-red grandite garnet. Stream sediments and glacial till in the southeastern part of the quadrangle between the Westport Dome and the Jay Mountain metagabbro body should be sampled in order to determine the amount of this easily recognizeable garnet in the heavy mineral fraction. Areas yielding anomalously high percentages of garnet should then be explored further.

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APPENDIX A. LOCATIONS OF ANALYZED SAMPLES

Anorthositic rocks (Table 1A)

AF177A	Gabbroic anorthosite, Lost Pond	44°15'22"N	73°43'11"W
AF735	Gabbroic anorthosite, Stickney Bridge	44°24'36"N	73°40'52"W
AF391B	Gabbroic anorthosite, US Mountain	44°19'00"N	73°40'22"W
AF241	Gabbroic anorthosite, Arnold Mountain	44°19'47"N	73°39'42"W
AF23	Gabbroic anorthosite, Slip Mountain	44°18'18"N	73°38'33"W
ADK	Average of 24 Adirondack anorthositic rocks		

Ferrodiorite and monzodiorite gneisses (Table 1B)

AF245	Ferrodiorite Gneiss, Yard Hill	44°16'45"N	73°41'12"W
AF692	Ferrodiorite Gneiss, Limekiln Mountain	44°15'01"N	73°38'42"W
AF175D	Ferrodiorite Gneiss, South of Lost Pond	44°15'15"N	73°42'47"W
AF76B	Ferrodiorite Gneiss, Ausable No. 4	44°15'23"N	73°40'41"W
AF453F	Ferrodiorite Gneiss, Northway Exit 32	44°17'08"N	73°31'49"W
AF339	Ferrodiorite Gneiss, E of Round Hill	44°19'45"N	73°43'10"W
AF38C	Ferrodiorite Gneiss, Yard Hill	44°16'53"N	73°41'40"W
AF320	Ferrodiorite Gneiss, Ausable No. 4	44°15'51"N	73°40'02"W
AF77	Ferrodiorite Gneiss, Limekiln Mountain	44°15'12"N	73°39'20"W
AF691	Monzodiorite, Limekiln Mountain	44°15'05"N	73°38'28"W
AF690	Ferromonzonite, Limekiln Mountain	44°15'10"N	73°38'02"W

Granitic and charnockitic gneisses (Table 1C)

AF334	Quartz syenite gneiss, Little Lawler Mtn.	44°19'40"N	73°41'45"W
AF703	Quartz syenite gneiss, Quartz syenite gneiss,	44°25'59"N	73°40'40"W
AF707	Charnockite, Quartz syenite gneiss,	44°25'59"N	73°40'40"W
BLUFF	Charnockite, average (3), Bluff Mountain	44°20'10"N	73°38'10"W
POKO	Hb gran. gneiss, av.(6), Pokamoonshine Mtn.	44°24'15"N	73°30'15"W
AF666	Fayalite Granite, Bailey Hill	44°27'46"N	73°39'40"W
8568B	Hb granitic gneiss, S of Ausable Forks	44°25'42"N	73°41'20"W
AF340	Leucogranitic gneiss, S of Round Hill	44°19'15"N	73°43'29"W

Olivine metagabbros (Table 1D)

MG108	Olivine metagabbro, Saddleback Mountain	44°17'38"N	73°40'03"W
MG111	Metatroctolite, Saddleback Mountain	44°18'06"N	73°40'07"W
MG123	Olivine metagabbro, Saddleback Mountain	44°17'40"N	73°41'31"W
MG182	Olivine-free metagabbro, Jay Mountain	44°18'19"N	73°41'45"W
MG189	Olivine-free metagabbro, Jay Mountain	44°18'15"W	73°40'31"W
MG98	Metatroctolite, Jay Mountain	44°18'49"N	73°41'04"W
MG99A	Olivine-free metagabbro, Saddleback Mtn.	44°17'16"N	73°39'51"W
AF686	Clinopyroxene-plag. cumulate, Saddleback Mtn.	44°18'00"N	73°40'29"W
AF751	Composite of 5 samples of mafic dike in granitic gneiss, Pokamoonshine Mountain,	44°24'15"N	73°30'15"W

Lyon Mountain Gneiss
Granitic gneisses (Table 1E)

AF677	Quartz syenite gneiss, Eagle Mountain	44°23'41"N	73°35'22"W
AF657	Biotite granite gneiss, S of Lawson Pond	44°21'56"N	73°35'40"W
AF441	Ferrohastingsite granite gneiss, Perkett Mtn.	44°21'47"N	73°34'40"W
AF356	Magnetite granite gneiss, Sunset Hill	44°21'09"N	73°35'08"W
AF624	Biotite granite gneiss, Hall Hill	44°21'55"N	73°34'06"W
AF444	Garnet granite gneiss, Perkett Mountain	44°21'35"N	73°35'10"W
AF470	Magnetite gran. gneiss, S of Schoolhouse Mtn.	44°21'50"N	73°35'49"W
AF431B	Magnetite gran. gneiss , Oak Hill	44°21'08"N	73°34'42"W

Lyon Mountain Gneiss, leucocratic albite gneisses (Table 1F)

AF370	Albite gneiss, Hale Brook S of McCray Mtn.	44°22'16"N	73°34'38"W
AF665	Albite gneiss, SW of Dry Bridge	44°27'48"N	73°36'39"W
AF664	Albite gneiss, SW of Dry Bridge	44°27'48"N	73°36'39"W
AF667	Albite gneiss, Clintonville	44°28'00"N	73°34'49"W
AF679	Albite gneiss, S of Lockart Pond	44°23'31"N	73°35'31"W

Lyon Mountain Gneiss, mafic albite gneisses (Table 1F)

AF673	Mafic albite gneiss with biotite, Oak Hill	44°21'20"N	73°34'49"W
AF671	Mafic Albite Gneiss, Perkett Mountain	44°21'44"N	73°34'51"W
AF364B	Mafic Albite Gneiss, Schoolhouse Mountain	44°22'15"N	73°35'45"W
AF658	Mafic Albite Gneiss, Schoolhouse Mountain	44°22'15"N	73°35'45"W
AF442	Mafic Albite Gneiss, Perkett Mountain	44°21'44"N	73°34'51"W
8545	Mafic Albite Gneiss, with scapolite, Burnt Hill	44°28'28"N	73°39'37"W
AF676	Mafic Albite Gneiss, quartz rich, Eagle Mtn.	44°23'40"N	73°34'49"W

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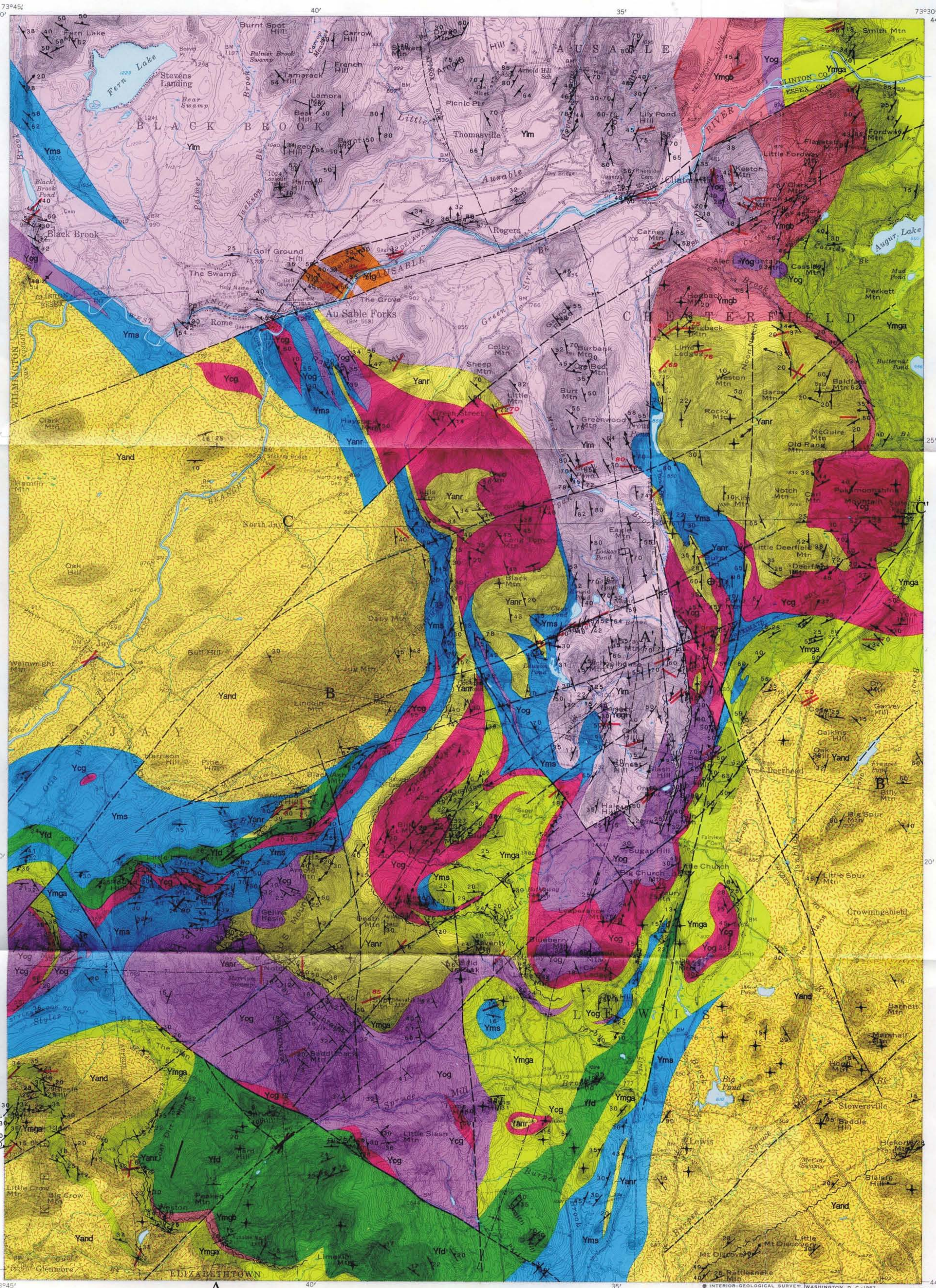

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Aerial photographs taken 1942, 1947, and 1952. Field check 1953
Polyconic projection. 1927 North American datum

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SCALE 1:62500

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

Map and Chart Series 43
Geological Survey-New York State Museum

LITHOLOGIC KEY

Late Proterozoic and Phanerozoic

UNMETAMORPHOSED DIKES
Fine- to medium-grained mafic dikes up to several meters in width, intruding all other lithologies. Most are of basaltic composition and late Proterozoic age; a few are of lamprophyric composition and probable Cretaceous age.

Middle Proterozoic

UNITS ARRANGED IN ORDER OF STRUCTURAL POSITION

LYON MOUNTAIN GNEISS

Varied quartz-feldspar gneisses of probable metavolcanic origin, with some intrusive granitic rocks. Includes subordinate layered amphibolite and metasedimentary rocks, and a few small olivine metagabbro (Yog) bodies.

Yfg — **FAYALITE GRANITE GNEISS**
Weakly foliated to massive, green to olive-gray, fayalite-ferrohedenbergite-quartz-mesoperthite gneisses. Found only in vicinity of Au Sable Forks.

Ylm — **GRANITIC AND TRONDHJEMITIC (ALBITE) GNEISSES**
Heterogeneous, commonly leucocratic, magnetite-quartz-feldspar gneisses with variable, generally minor amounts of clinopyroxene, amphibole, biotite, and titanite. The principal feldspar may be microcline, mesoperthite, or mesoperthite + plagioclase (granitic facies) or albite (leucocratic albite gneiss facies). Includes subordinate amounts of albite-pyroxene granulite (mafic albite gneiss) and amphibolite. Abundant vein quartz is commonly present in albite-rich zones; magnetite ore bodies occur locally in these rocks north of the Au Sable River

ROCKY BRANCH COMPLEX

Metasedimentary and metavolcanic rocks containing numerous large bodies of olivine metagabbro, metanorthosite, ferrodiorite gneiss, charnockite, and granitic gneiss. The Rocky Branch Complex structurally overlies the metanorthosite domes and underlies the Lyon Mountain Gneiss.

METAIGNEOUS ROCKS

Yog — **OLIVINE METAGABBRO**
Clinopyroxene-olivine-plagioclase metagabbros and metatroctolites with varying amounts of garnet, orthopyroxene, hornblende, ilmenite and biotite. Large bodies includes minor amounts of olivine-free gabbro and thin (<1 m.) layers of dunite, wehrlite, and anorthosite. Foliated amphibolite and garnet amphibolite are developed near contacts with other rocks. Mappable olivine metagabbro bodies are found principally within the Rocky Branch Complex but a few smaller bodies occur within the Lyon Mountain Gneiss. *Parallel lines within the large metagabbro body on section A-A' show approximate orientation of igneous layering.

Ycg — **GRANITIC AND CHARNOCKITIC GNEISS**
Hornblende-quartz-mesoperthite (microcline) gneisses with minor plagioclase, biotite, pyroxene, or garnet commonly present. Includes granitic, charnockitic and quartz syenitic facies. Amphibolite, mafic granulite, metasedimentary rocks, anorthositic gneiss, and olivine metagabbro are locally present as layers, sills, xenoliths, or shreds.

Yfd — **FERRODIORITE AND MONZODIORITE GNEISS**
Garnet-two pyroxene-plagioclase gneisses with minor quartz, ilmenite, magnetite and apatite and varying amounts of mesoperthite, hornblende, or biotite. Biotite-rich facies may lack garnet. Xenoliths of quartzite, calcsilicate granulite, or anorthosite, and xenocrysts of andesine are common. These rocks grade locally into anorthositic, monzodioritic, or quartz monzonitic gneisses.

Yanr — **METANORTHOSITE AND GABBROIC METANORTHOSITE**
Tabular to irregular bodies of metanorthosite similar to Yand but usually more mafic, with fewer plagioclase megacrysts, and more strongly deformed. Includes granoblastic (garnet)-(hornblende)-titanite-clinopyroxene-plagioclase gneisses with locally pronounced compositional layering.

METASEDIMENTARY ROCKS AND MIXED GNEISSES

Ymgb — **MIXED GNEISSES (B)**
Quartzofeldspathic gneisses of uncertain origin interlayered with metasedimentary rocks, amphibolite, and subordinate gabbroic anorthosite gneiss.

Ymga — **MIXED GNEISSES (A)**
Anorthosite and gabbroic anorthosite gneiss with interlayered metasedimentary rocks, ferrodiorite gneiss, amphibolite, and subordinate quartzofeldspathic gneisses. Hybrid anorthosite-calcsilicate rocks occur locally. Grades into metanorthosite at margins of domes. A thick layer or "screen" of mixed gneisses occurs within the Hurricane Dome in the Soda Range north and east of Big Crow Mountain.

Yms — **METASEDIMENTARY ROCKS**
Calcsilicate granulite and quartzite with subordinate calcite marble, and minor dolomite marble, mafic granulite, biotite schist and garnet-sillimanite metapelite. Locally includes layers of quartzofeldspathic gneiss and amphibolite.

METANORTHOSITE DOMES

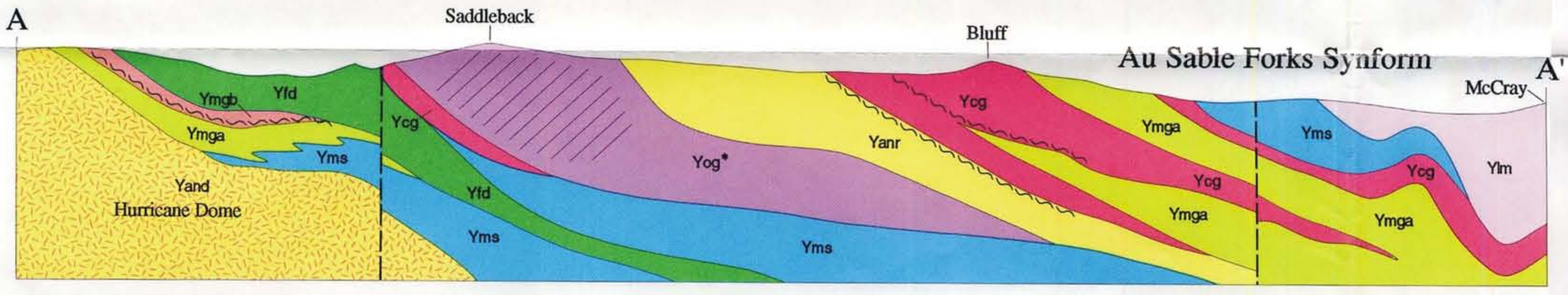
Large, roughly domical bodies composed chiefly of rocks of the anorthosite suite:

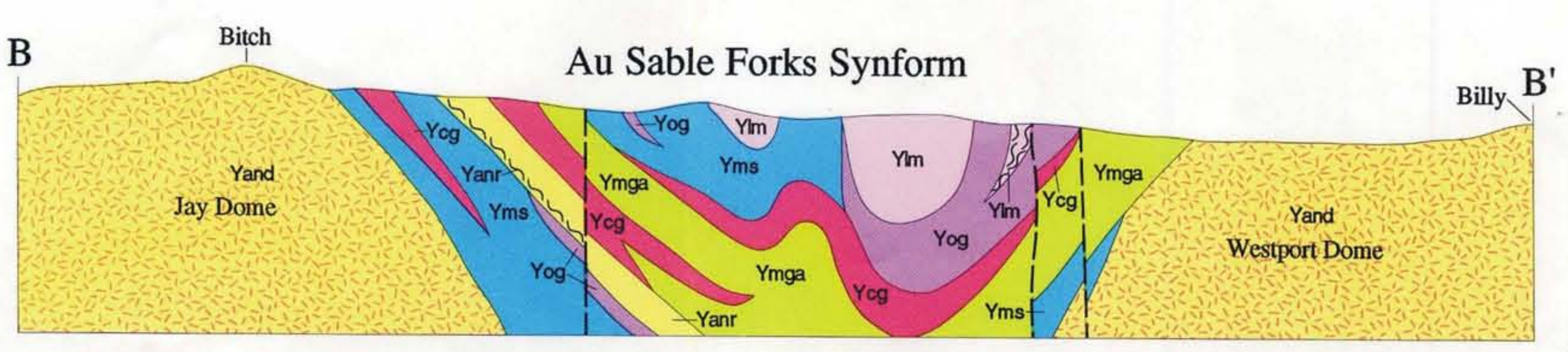
Yand — **METANORTHOSITE AND GABBROIC METANORTHOSITE**
Plagioclase-rich rocks that typically contain varying amounts of gray-blue andesine or labradorite megacrysts, in a finer-grained plagioclase groundmass with minor augite and/or hypersthene. Garnet, hornblende, biotite, magnetite, ilmenite, titanite, quartz and alkali feldspar are common minor minerals. Massive to well-foliated. Gneissic varieties occur most commonly near contacts and shear zones, and are ordinarily richer in mafic minerals and contain fewer, smaller plagioclase megacrysts than the less deformed rocks in the interiors of the domes. Locally includes thin layers or dikes of ferrodiorite or granitic gneiss, and xenoliths of metasedimentary rocks and mixed gneisses.

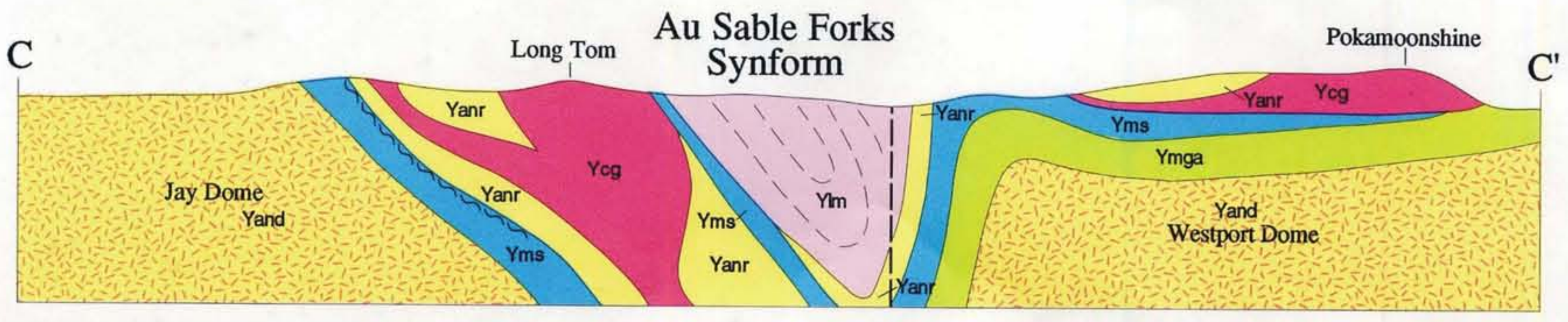
STRUCTURAL SYMBOLS

- Exposed Contact.
- Approximately located contact.
- Inferred contact.
- Exposed fault or major fracture zone.
- Inferred fault or major fracture zone.
- Approximate location of major shear zone, showing dip where known. Actual zone may be wider than symbol
  - Dip 45° or less
  - Dip greater than 45°
  - Vertical or subvertical
- Approximate trace of axial plane of major fold.
- Strike and dip of foliation or compositional layering in deformed rocks.
- Lineation, with plunge.
- Strike and dip of igneous layering in undeformed metagabbro, or megacryst orientation in metanorthosite.
- Shaded areas show location of outcrops or of areas where outcrops are relatively abundant.

CROSS SECTIONS







BEDROCK GEOLOGY OF THE AU SABLE FORKS QUADRANGLE, NORTHEASTERN ADIRONDACK MOUNTAINS, NEW YORK

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