GRENVILLE CALC-SILICATE, ANORTHOSITE, GABBRO, AND IRON-RICH SYENITIC ROCKS FROM THE NORTHEASTERN ADIRONDACKS

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INTRODUCTION

The Marcy anorthosite massif is delineated by a major NW-SE-trending lobe and a smaller N-S-trending lobe which coalesce to the S to form a heart-shaped outcrop pattern covering 5000km^2. (Fig. 1). In section , the major NW-trending lobe approximates a piano bench or slab 3-4.5 km thick with two legs or feeder pipes extending at least 10 km down according to the geophysical model of Simmons (1964), whereas Buddington (1969) favored an asymmetrical domical shape based on extensive field mapping and other considerations. The massif consists of a coarsely crystalline core of apparently undeformed felsic andesine anorthosite thrust over a multiply deformed roof facies consisting of gabbroic-noritic anorthosite, gabbroic anorthosite gneiss, and quartz-bearing ferrosyenite-ferromonzonite facies (Pitchoff Gneiss). Remnants of a siliceous carbonate- and quartzite-rich metasedimentary sequence and associated garnet-pyroxene-microperthite granulites form discontinuous screens and xenoliths in the roof facies. Xenoliths of any kind are very rare inside the felsic anorthosite of the core, but abound in the gabbroic anorthosite of the roof facies.

We will visit ten outcrops which include all of the major rock types (Fig. 1) of the massif, and that lie principally in its multiply deformed roof facies.

That regional metamorphism took place at high pressure, in the range of 8-10 kbar at about 800°, is indicated by the occurrence of orthoferrosilite, Fs95 + quartz, and the absence of any vestiges of fayalite in the ferrosyenite facies of the Pitchoff Gneiss (Jaffe et al., 1978). Because recent Sm147-Nd143 age dating yields 1288 M.Y. for the age of magmatic crystallization of the Marcy anorthosite (Ashwal and Wooden, 1983), and older Pb-U age dating by Silver (1969) yields about 1130 M.Y. for crystallization and about 1100-1020 for metamorphism, the Grenville orogeny may have spanned as much as 200 M.Y. and it is difficult to fix the peak of metamorphism with a specific thermal or tectonic event within this time span.

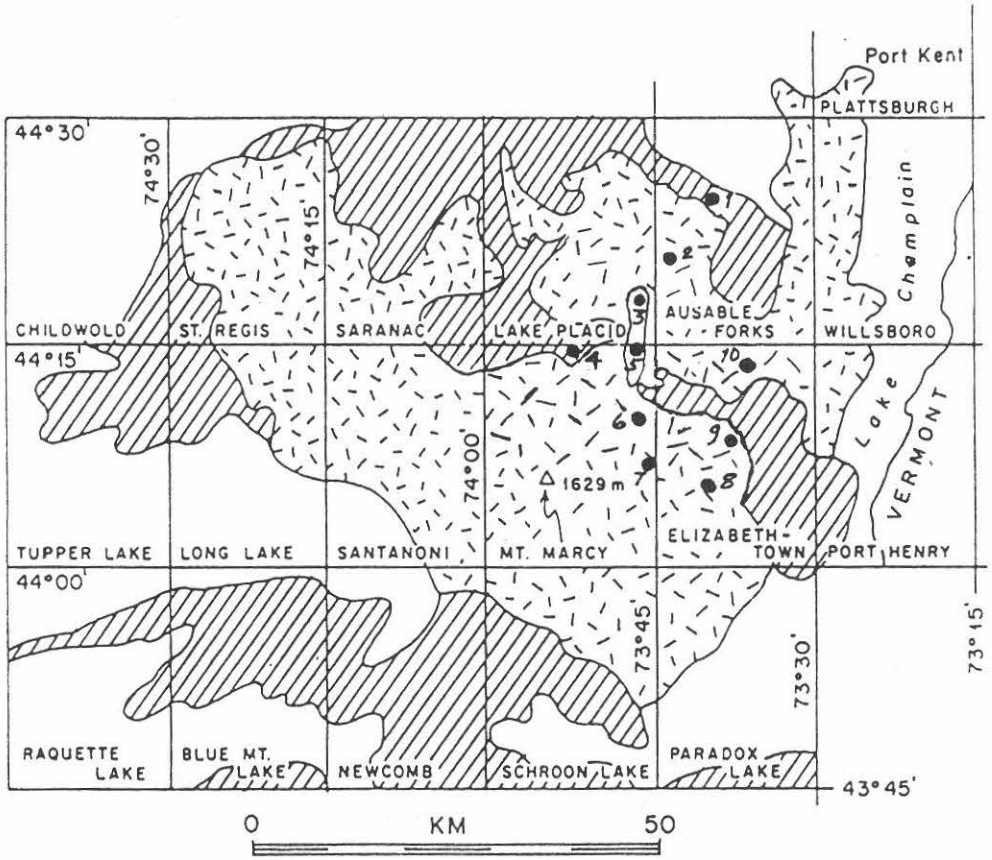


Figure 1. Generalized geologic map of the Marcy anorthosite massif and surrounding areas: anorthositic rocks ░ , ferrosyenite-ferromonzonite gneiss ▨ , and Grenville metasediments ☐ . NYSGA - 1988 field trip stops 1-10.

Stop I. FAYALITE-FERROHEDENBERGITE GRANITE, AUSABLE FORKS AREA, 15' AUSABLE FORKS QUADRANGLE, LOCALITY AF-1-A

Iron-rich granitic-syenitic-quartz monzonitic rocks, ascribed to a charnockitic gneiss series, are abundant in the northeastern and central Adirondacks, where they occur in close association with anorthositic and metasedimentary calc-silicate rocks in the Marcy Massif. Most of these contain iron-rich orthopyroxene (eulite or orthoferrosilite) with quartz, an assemblage stabilized at the high operable regional metamorphic pressure of about 8 kbar, with T = 700-770°C (Jaffe, Robinson, and Tracy, 1978: Bohlen and Boettcher, 1981). Other members of this alkali-feldspar-rich series contain fayalite and quartz in place of orthoferrosilite and quartz. From tables 1, 2, 3, 4, and Fig. 9 and Table 7 from Jaffe, Robinson and Tracy (1978), (Appendix I) it is reasonable to assume that both of these rock types were recrystallized under similar metamorphic conditions. Work by Bohlen and Essene (1978) and by Ollilla, Jaffe, and Jaffe (1988) indicate that these rocks had igneous precursors that crystallized above 900°.

JAFFE ET AL.: IRON-RICH PYROXENES (1978)

Table 1 Modes of pyroxene-microperthite gneiss

	Po-13	SC-6	Po-17	FFG-6	AF-1A	Po-2
Quartz	4.1	9.1	13.8	18.4	69.1	1.5
Microperthite	37.2*	46.5*	52.6*	69.2**	20.5	84.5
Plagioclase***	32.7	25.1	18.2	3.5	Trace	3.6
Augite	6.2	8.7	6.6	3.7	5.5	4.1
Orthopyroxene	3.9	2.4	1.9	None		2.4
Olivine	None	None	None	0.6	3.0	None
Hornblende	3.8	2.1	4.1	3.9	Trace	1.8
Garnet	7.1	3.6	1.7	None	None	0.8
Magnetite + Ilmenite	3.0	1.9	0.8	0.5 Trace	1.1	1.0
Zircon	0.2	0.3	0.1	0.1	0.3	Trace
Apatite	1.8	0.3	0.1	0.1	0.3	0.3
Fluorite	-	-	-	-	0.2	-
	100.0	100.0	99.9	100.0	100.0	100.0
Color Index	26	19	15	9	10	15
Mole % An*** Plagioclase	23	16	[illegible]	11	12	21
Mole % Fs Orthopyroxene	85-88† 83-85††	92 89	95 91			83-9
Mole % Fa† Olivine				99	99	

*Contains abundant exsolution lamellae of albite and is partially unmixed to microcline microperthite.

**A mesoperthite containing an oligoclase, An_{11} component.

***An values for plagioclase host grains determined by measurement of the α index of refraction in oils. For probe analyses see Table 8.

†100(Fe + Mn)/(Fe + Mn + Mg).

††100 Fe/(Ca + Fe + Mn + Mg) as used by Smith (1971a).

Table 2. Optical properties of iron-rich pyroxenes

	Po-13	SC-6	Po-17	$FeSiO_3$*
Orthopyroxenes				
γ	1.7763	1.785	1.786 Z=pale blue-green	1.789
β	1.7765	1.774	1.774 Y=pink-yellow	1.780
α	1.7560	1.764	1.765 X=pale pink	1.772
γ-α	0.0203	0.021	0.020	0.017
$2V_{calc.}$	88°,(-)	88°,(+)	79°,(+)	86°,(+)
Disp.	r<v,strong	r>v,strong	r>v,strong	
$\frac{Fe+Mn}{Fe+Mn+Mg}$	.88	.92	.95	1.00

	Po-13	SC-6	Po-17	FFG-6	Fe Augite**
Augites					
γ	1.7505	1.759	1.760	1.7645	(1.7646)
$\frac{Fe+Mn}{Fe+Mn+Mg}$	.83	.88	.93	.95	1.00

*Indices as reported by Lindsley, Davis, and MacGregor, 1964. They report 2V = 58°(+) which is inconsistent with their indices.

**The value of γ for pure Fe augite is from the equation of Jaffe et al., 1975.

(1978)

Table 3. Lattice parameters of natural and synthetic orthoferrosilite

	Po-17	Synthetic $FeSiO_3$ Burnham (1965)	 Sueno et al. (1973)
$\underline{a}$ (Å)	18.42	18.431	18.418
$\underline{b}$ (Å)	9.050	9.080	9.078
$\underline{c}$ (Å)	5.241	5.238	5.237
$\underline{V}$ (Å^3)	873.68	876.60	875.14

Table 4 Representative electron probe analyses of coexisting pyroxenes and olivine, and compositions of theoretical end members

	Po-13A	Po-13B	SC-6	Po-17	FFG-6	$CaFeSi_2O_6$
Augite						
SiO_2	47.81	47.84	48.51	48.69	47.66	48.44
Al_2O_3	1.31	1.17	1.00	1.00	.65	
TiO_2	.12	.10	.09	.14	.06	
Cr_2O_3	.05	.05	.00	.06	.03	
MgO	3.78	3.08	2.07	1.17	.91	
ZnO	.09	.07	.14	.19	.01	
FeO	25.73	26.75	27.68	29.18	29.14	28.96
MnO	.27	.38	.37	.43	.58	
CaO	19.54	19.92	19.43	19.07	20.32	22.60
BaO				.00		
Na_2O	.73	.72	.78	.72	.73	
K_2O	.00	.00	.00	.00		
Total	99.43	100.08	100.07	100.65	100.09	100.00
Augite						
Si	1.926	1.925	1.965	1.977	1.949	2.000
Al	.062	.056	.035	.023	.031	
Fe^{3+}	.012	.019			.020	
Total	2.000	2.000	2.000	2.000	2.000	2.000
Al			.013	.025		
Ti	.004	.003	.003	.004	.001	
Cr	.002	.002		.002	.000	
Fe^{3+}	.122	.124	.078	.044	.106	
Mg	.227	.185	.125	.071	.054	
Zn	.003	.002	.004	.006	.000	
Fe^{2+}	.733	.757	.860	.947	.871	1.000
Mn	.009	.013	.013	.015	.020	
Ca	.844	.859	.843	.830	.891	1.000
Na	.057	.056	.061	.057	.057	
Total	2.001	2.001	2.000	2.001	2.000	2.000

	Po-13A	Po-13B	SC-6	Po-17	FFG-6	$FeSi_2O_6$
Orthopyroxene					**Fayalite**	**$Fe_2Si_2O_6$**
SiO_2	46.15	45.90	45.65	45.50	28.62	45.54
Al_2O_3	.30	.31	.27	.36	.08	
TiO_2	.06	.08	.13	.11	.00	
Cr_2O_3	.06	.02	.05	.06	.03	
MgO	4.62	3.52	2.48	1.36	.39	
ZnO	.28	.26	.38	.37	.31	
FeO	46.36	47.60	49.28	49.81	69.51	54.46
MnO	.51	.86	.72	1.10	1.57	
CaO	.80	.75	.79	.84	.05	
BaO				.06		
Na_2O	.00	.00	.00	.03		
K_2O	.00	.01	.00	.00		
Total	99.14	99.31	99.75	99.60	100.56	100.00
Orthopyroxene					**Fayalite**	**$Fe_2Si_2O_6$**
Si	1.969	1.971	1.969	1.980	.964	2.000
Al	.015	.016	.014	.019	.003	
Fe^{3+}	.016	.013	.017	.001	.033	
Total	2.000	2.000	2.000	2.000	1.000	2.000
Ti	.002	.003	.004	.004		
Cr	.002	.001	.002	.002	0	
Fe^{3+}	.025	.023	.022	.014	.036	
Mg	.294	.225	.159	.088	.019	
Zn	.009	.008	.012	.012	.007	
Fe^{2+}	1.613	1.674	1.739	1.798	1.892	2.000
Mn	.018	.031	.026	.041	.045	
Ca	.037	.035	.037	.039	.001	
Ba				.001		
Na				.003		
K		.001				
Total	2.000	2.001	2.001	2.000	2.000	2.000

Here, at Stop 1, we will visit outcrops of the fayalite-ferrohedenbergite granite and later, at Stop 4, we will visit a eulite-ferrohedenbergite syenite gneiss on Pitchoff Mt. in the 15' Mt. Marcy quadrangle.

A circular outcrop area, about 1 km in radius from the center of Ausable Forks village, was mapped by Kemp and Alling (1925) as an olivine-bearing quartz nordmarkite. They located several quarries within this outcrop area. On a fresh break, the rock shows the greenish cast typical of the ferrosyenites and charnockitic rocks of the northeastern and central Adirondack region. It is a medium-grained (1-5mm) hypersolvus granite, in places gneissic, with a color index of 5-15. Similar fayalite-bearing granitic rocks were described by Buddington and Leonard (1962) from the Cranberry Lake quadrangle, near Wanakena, from the St. Lawrence Co. magnetite district of the central Adirondacks. At Wanakena, and very likely at Ausable Forks, eulite- or orthoferrosilite-ferrohedenbergite granitic-quartz-monzonitic gneiss is closely associated with the fayalite-ferrohedenbergite granitic rock. Fayalite and ferrosilite, together with quartz, have not thus far been found in the same specimen; if they were it would provide a precise geobarometric value for the pressure of regional metamorphism. From Fig. 9 and Table 7, Jaffe, Robinson and Tracy, (1978) (see Appendix I) it will be seen that the assemblage orthoferrosilite + quartz gives a minimum P, whereas fayalite + quartz gives a maximum P. A range of 7-9 kbar at 600° or 10-12 kbar at 800° outlines the extremes of the metamorphic P-T conditions. Recent work by Ollila, Jaffe and Jaffe (1988) indicates that the orthoferrosilite in Pitchoff Mt. syenite gneiss is actually an inverted pigeonite crystallized from a magma above 9 kbar and 900°c, conditions in excess of those accepted for the regional metamorphic peak.

In the Ausable Forks area, fayalite-ferrohedenbergite granite contains only trace amounts of hornblende: in outcrops where hornblende becomes abundant, fayalite is pseudomorphously altered to a brown fibrous serpentine or talc. The granitic rocks are cut by dikes of hornblende granite pegmatite and diabase.

The fayalite-ferrohedenbergite granite differs from the orthoferrosilite-ferrohedenbergite granitic-syenitic gneisses in several important aspects;

1) the fayalite granite is massive to poorly foliated, while the ferrosilite granitic gneiss is well foliated.

2) the fayalite granite is hypersolvus, carrying only a "strip" or "striped" microperthite that is slightly unmixed to sodic plagioclase and orthoclase, whereas the ferrosilite granitic gneiss is subsolvus, containing blebby and patchy microperthite more unmixed to sodic plagioclase and partly inverted to microcline, and this microcline microperthite coexists with an intermediate plagioclase,

3) the fayalite granite does not contain garnet because of the absence of intermediate plagioclase, whereas the ferrosilite granitic gneiss always carries garnet.

All of this suggests that the fayalite granite might be younger than the ferrosilite granitic gneiss. We concur with Buddington and Leonard (1962) who suggested that the fayalite granite could have originated from the fractional remelting at depth of the pyroxene granitic gneisses, with its intrusion occurring during the waning stages of deformation.

Stop 2. ANORTHOSITE NEAR COVERED BRIDGE AT JAY, 15' AUSABLE FORKS QUADRANGLE

Outcrops just beyond a covered bridge about 0.32 km E of Ausable Forks center show the characteristic textures of anorthositic rocks along the margins of the Marcy Massif. In the roadcut, anorthositic block structure shows up to 2m blocks of coarse, cumulate-textured andesine anorthosite, and coarse hypersthene (to 25 x 15cm) enclosed in a gabbroic anorthosite. Dark layers, up to 2.5cm thick, occur within the country rock. Outcrops in the East Branch of the Ausable River are principally of coarse andesine anorthosite with a megacryst index of about 20-30 and a color index of only 1. Numerous shear veinlets crisscross the anorthosite, trending N40E and N10W for the most part.

Stop 3. GRENVILLE-ANORTHOSITE HYBRID GNEISS 3.4 KM S OF UPPER JAY ON RTE 9N IN THE 15' LAKE PLACID QUADRANGLE

We are located in a 6.4 x 1.6 km north-trending section of Grenville strata consisting largely of calc-silicate-amphibolite-marble assemblages. Graphitic marbles occur across the Ausable River to the W of this roadcut. All these have been intruded and pervaded by sills of gabbroic anorthositic composition, resulting in the formation of Grenville-anorthosite-hybrid gneisses. Subsequently these were intruded by a sill of gabbro that forms the center of the E side of the large road cut on Rte. 9N (Fig. 2).

The section may be divided into three parts:

1) a lower unit consists principally of a mottled granular black and white sphene-augite-andesine calc-silicate gneiss discontinuously interlayered with black hornblendite-amphibolite lenses presumably of volcanic origin. The granular mottled host rock consists of white andesine, An32-39, black augite, and 5-10% of red-brown to yellow-brown sphene. The black amphibolitic layers contain mostly brown hornblende along with white plagioclase now altered to prehnite and calcite.

2) a central unit is a biotite-hornblende-hypersthene-augite-garnet-plagioclase metagabbro sill. The abundance of garnet, 20%, suggests that the gabbro sill may have been olivine-rich. The sill shows sharp contacts above and below with the anorthosite-calc-silicate-hybrid gneiss.

Figure 2. Grenville calc-silicate anorthosite hybrid.

3) above the upper contact of the gabbro sill, the rock is augite-andesine An39-40 gabbroic anorthosite gneiss intercalated with dark amphibolite and calc-silicate layers.

Sporadic large garnets up to 6 cm in diameter occur along contacts of anorthositic and mafic layers.

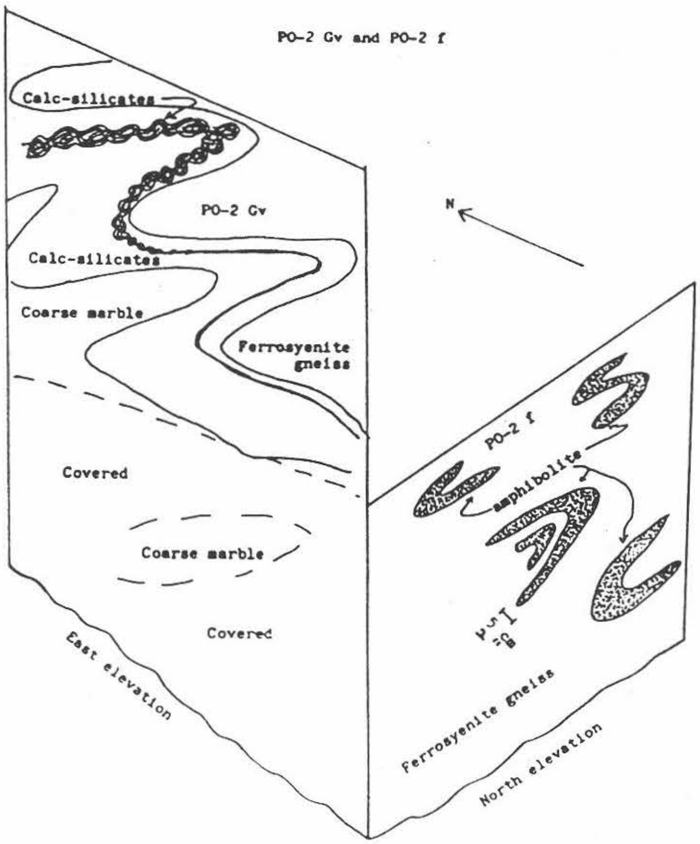
The outcrop on the W side of the road shows a well-developed high strain pencil lineation, oriented N25E.

Stop 4. THE PITCHOFF GNEISS - FERROSYENITE FACIES, PO-2

Turn right (north) on Route 73, and go through Keene Village, where Route 73 turns west. Follow it about 4.5 miles (7.2 km) to the foot of Lower Cascade Lake. Park at the lakeside in the second parking area on the left, just past a sign FALLEN ROCK 1 1/2 MILE. Be very careful cutting across traffic: this is a busy high-speed highway. Recross the road on foot, again with great caution. Walk back toward the FALLEN ROCK sign, to a rough trail up the talus just short of the sign. The talus and cliff are both steep and full of loose rocks: be considerate of those below and behind.

The prominent, southeast-facing cliff we are climbing to is a ferrosyenite gneiss that crystallized from a melt prior to its metamorphism. It is one of a group of quartz-poor, alkali-feldspar- and ferroan-pyroxene-rich igneous rocks that acquired their gneissic fabric during an episode of isoclinal and recumbent folding associated with the Grenville orogeny at about 1100 M.Y. The persistent proximity and intimate intercalation of these gneisses with "Grenville" supracrustal rocks suggests that they may have initially been iron-rich felsic volcanics, or perhaps sills, interlayered with siliceous dolomites, calcareous quartzites, marls and basaltic flows comprising a Proterozoic series of rocks deposited about 1350 M.Y. This Grenville age is estimated from Ashwal's (1983) recent Sm^{147}-Nd^{143} date of 1288 M.Y. believed to represent the age of crystallization of the Marcy anorthosite massif-core facies. Following the model of McLelland and Isachsen (1980) for the southern Adirondacks, we suggest that, in the High Peaks Region of the northeastern Adirondacks, a "typical" Grenville supracrustal sequence correlative with rocks of the Central Metasedimentary Belt (Wynne-Edwards, 1972) was buried in a plate-tectonic event or events to a depth of about 70 km (42 mi), that of a doubly thickened crust. Following Emslie (1977), we envisage the birth of an anorthositic magma from the fractionation of copious amounts of orthopyroxene from an already-fractionated Al-rich gabbroic magma. Under these deep-seated conditions, the high pressures and temperatures plus the availability of Grenville-strata-derived $C0_2$-rich fluids initiated the formation of potassium- and iron-rich, relatively quartz-poor, melts of syenitic to monzonitic composition (Wendlandt, 1981). Ascent, intrusion, and emplacement of the syenitic melt at levels on the order of 25-35 km (15-21 mi) and temperatures of 800-900^{o} induced deep contact metamorphism of appropriate Grenville rock types. Here, at the easternmost part of the PO-2 outcrop, designated PO-2Gv (Fig. 3), a calc-silicate sequence infolded with the ferrosyenite contains the assemblage: wollastonite-diopside-grossular-quartz. Because anorthosite is absent, the contact-metamorphic origin of the wollastonite must be attributed to the intrusion of syenitic melt. Further, because the ferrosyenite contains relict inverted pigeonite, which now consists of host orthoferrosilite, 100Fe/(Fe+Mg)=85-92, the melt must have crystallized at temperatures of 850-900^{0} (Lindsley, 1983 and Ollila, Jaffe and Jaffe, 1988). Alternatively, shallow emplacement with

Figure 3. PO-2gv. Folded amphibolite, marble, and wollastonite-bearing calc-silicate rock in ferrosyenite gneiss. Pitchoff Mt. cliff, above north end of Lower Cascade Lake. Mt. Marcy quadrangle.



crystallization of fayalite and quartz, later deeply buried and converted to orthoferrosilite and quartz, is conceivable, yet unlikely, because no relict olivine, whatsoever, has been observed by Jaffe or by Ollila in quartz-bearing syenitic rocks of the Mt. Marcy and the Santanoni quadrangles. Fayalite (Fa_{95}) plus quartz, but with orthopyroxene absent, has been described from quartz-syenitic rocks in the Cranberry Lake quadrangle to the west (Buddington and Leonard, 1962, Jaffe et al. 1978) and in the Ausable Forks quadrangle to the northeast (Kemp and Alling, 1925 and Jaffe et al, 1978). A deep emplacement with high pressure crystallization is consistent with field observations and experimental data for all of these rocks.

At the PO-2 outcrop, we will split into several smaller groups: the footing can be a bit tricky. Remember not to step back for a better look at the outcrops. The first or westernmost cliff consists of strongly foliated ferrosyenite gneiss, N45E30W, with a large inclusion of shonkinite granulite (Fig. 4, Table 5). The foliation continues through the inclusion. The southwest end of the inclusion is sharply cut off by the gneiss but the northeast end fingers out. The inclusion is cut by a discordant vertical tongue of gneiss which becomes a subhorizontal pegmatite vein. At the northeast end of this cliff, the ferrosyenite gneiss is cut by an unfoliated aplite dike. Small amphibolite inclusions can be seen in the gneiss.

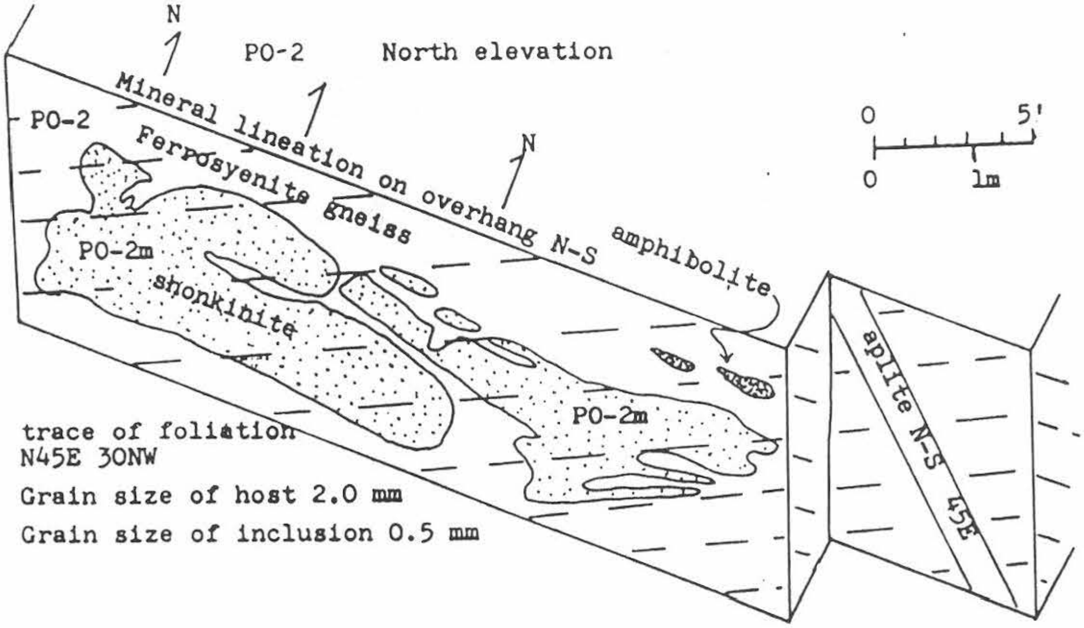


Figure 4. Xenolith of folded shonkinite layer PO-2m and amphibolite remnant in quartz ferrosyenite gneiss PO-2. Aplite dike cuts syenite gneiss. Pitchoff Mt. cliff above north end of Lower Cascade Lake, Mt. Marcy quadrangle.

TABLE 5. Modes of rocks at Stop 4 , locality PO-2

	Ferrosyenite gneiss		Shonkinite	Amphibolite	Aplite
	PO-2	host rock	PO-2m inclusion	Inclusion	PO-2d dike
Q	1.5	2.0	-	-	23.0
Mp	84.5	84.0	50.0	-	60.0
Plag	3.6	4.0	13.0	30.0	16.0
Aug	4.1	4.0	12.7	-	-
Hy	2.4	2.0	16.6	-	-
Hb	1.8	2.0	4.1	58.0	0.9
Ore	1.0	1.0	2.6	+	0.1
Gt	0.8	1.0	+	-	0.0
Ap	0.3	+	1.0	2.0	tr
Zr	+	+	+	-	-
Bio	-	-	+	10.0	-
	100.0	100.0	100.0	100.0	100.0
An	21		21		
Fs(opx)	83-89		75		
CI	15		40	88	1

Mineral assemblages infolded in ferrosyenite gneiss host rock at locality PO-2Gv.

Amphibolite: hornblende and altered plagioclase.

Calc-silicate: hedenbergite-plagioclase-quartz

hedenbergite-plagioclase-quartz-scapolite-sphene

diopside-grossular-quartz-sphene

wollastonite-diopside-grossular-quartz

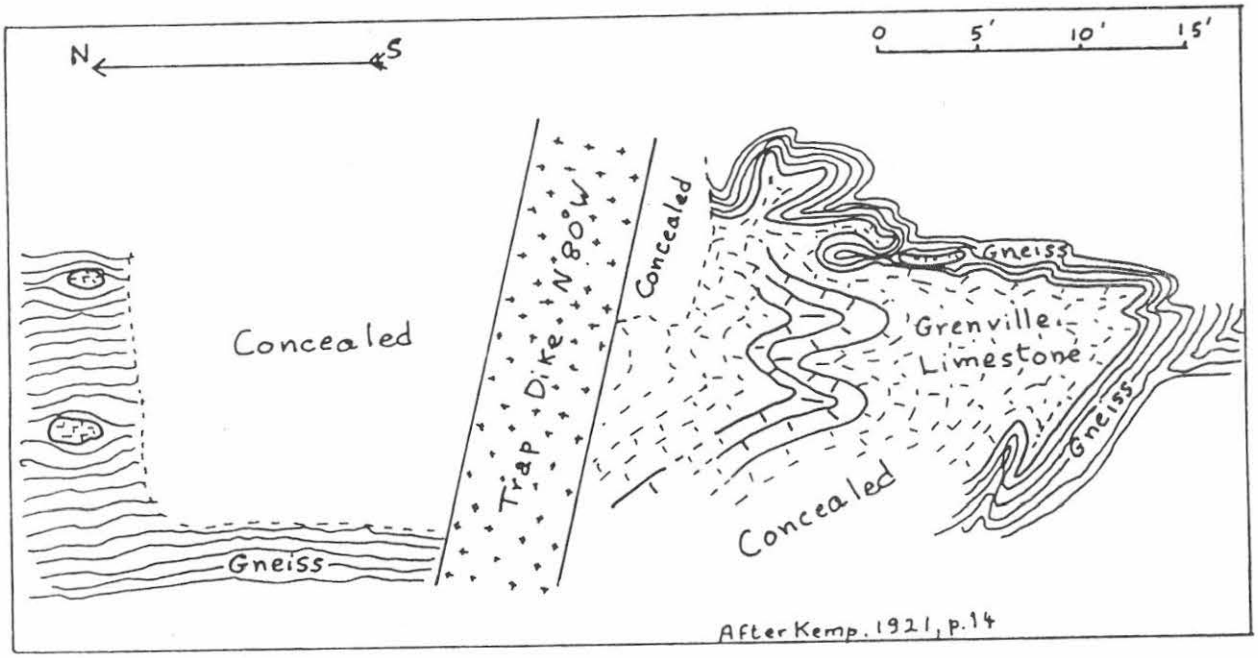
wollastonite-calcite-prehnite

diopside-calcite

We will proceed cautiously about 300' (91.5 m) along the base of the cliff to the northeast, across a stream and a gully. Here we see several larger folded amphibolite inclusions in the ferrosyenite gneiss (Fig. 3). The axial planes of these folds are approximately parallel to the pervasive foliation. We will now crawl a few feet up the gully: in its east wall are exposed marbles and calc-silicates intimately infolded in the ferrosyenite gneiss. Wollastonite occurs in these calc-silicate beds (Fig. 3). If we make allowance for the plasticity of the marble, these folds are also approximately parallel to the pervasive foliation. There is a cave in the marble a little higher up this gully. On the opposite side of Lower Cascade Lake, in the anorthosite, another cave can be found a few hundred feet higher up. Caves are common in New York State, but these two must be among the few in Precambrian rocks.

Stop 5. GRENVILLE MARBLE-SYENITE-ANORTHOSITE SECTION SOUTH OF KEENE

Drive five miles (8 km) northeast on Route 73 to the first right turn after a Gulf gasoline station and almost into Keene village center. Turn right (south) on the westernmost of two small roads that parallel both sides of the East Branch of the Ausable River. Drive about 0.75 (1.2 km) miles south on this western side of Hulls Falls Road and park judiciously along the edge of this little travelled road. Descend about 25' (7.6 m) to the bank of the river watching out to avoid standing or sitting in <u>Rhus</u> <u>toxicodendron</u> which commonly grows in Grenville marble terrain. A fine river outcrop of folded Grenville marble consists of calcite (white), diopside (green), fluopargasite (black), and minor glistening flakes of phlogopite (brown) along with less abundant graphite. Pink quartz leucosyenite and black-streaked gray-white gabbroic anorthosite gneiss have been dragged into highly contorted syntectonic folds enhanced by the plasticity of the marble and the probable molten state of the quartz syenite and gabbroic anorthosite (Fig. 5). Occasional tongues of gabbroic anorthosite cross-cut the syenitic rocks. A major vertical fracture zone, the Keene Fault Zone runs parallel to the river in a N-S direction, and is well exposed about one-half mile (0.8 km) south in a granulated anorthosite outcrop. The Keene Fault has dragged the preexisting, gently north dipping, isoclinally folded strata into fairly steeply plunging folds at this locality. A late, brittle stage of movement on the same fault has granulated and retrograded all of the brittle rock types. Feldspar in syenite is sericitized, intermediate plagioclase in gabbroic anorthosite has been albitized and veined by calcite, grossular-diopside calc-silicate rocks have been prehnitized and chloritized, but marble merely goes along for the glide.



After Kemp. 1921, p.14

Figure 5. Contorted folding in diopside-calcite-pargasite-calcite marble, quartz leucosyenite gneiss, and anorthosite gneiss in the West Branch of the Ausable River south of Keene, N.Y. A camptonite dike cuts the marble-gneiss section. After Kemp, 1921. Mt. Marcy quadrangle.

At the northernmost end of the outcrop, the diopsidic marble and the quartz syenite are transected by a 4' (1.2 m) wide N80W90 trending lamprophyre dike (Fig. 5) which displays good chilled margins. It is a classic lamprophyre: a dark, dense, porphyritic dike rock in which the ferromagnesian minerals occur in two generations and in which only the dark minerals form the phenocrysts. It consists of 1-5 mm diameter phenocrysts of partially serpentinized magnesian olivine, and zoned clinopyroxene with augite cores and titanaugite rims, which display spectacular zoning, intense anomalous interference colors and dispersion, and hourglass structure. The groundmass contains a second generation of microphenocrysts of titanaugite, kaersutite, titanian biotite and abundant very thin needles of apatite in a quasi-isotropic base that has too high an index of refraction to be analcime or leucite; it has a mean index of refraction = 1.525 and is either untwinned anorthoclase or a zeolite. The dike may be classified as either a camptonite or a monchiquite, but exactly conforms to neither.

Notes:

Stop 6 THE 1063 MYLONITE

On the west side of Route 73, 1.3 miles (2.1 km) south of the village of Keene Valley at BM 1063 and opposite the Beer Bridge across the Ausable River, the anorthosite is cut by a well-developed mylonitic zone about 2' (0.6 m) wide which trends N55E35NW. Park on the west shoulder of the road south of the outcrop and walk back. The anorthosite here appears to be the normal gabbroic type; however, the mafic minerals occur in clots and aggregates of augite+apatite, many of which are bent into mini- and microfolds. These clots and the sparse megacrysts of labradorite form a foliation which trends N70W70SW. The coarse grained contaminated felsic anorthosite and the mafic clots of partially assimilated augite+apatite represent either remnants of a Grenville phosphate-rich calc-silicate rock, or a mafic cumulate segregated from a gabbroic anorthosite melt. The iron content of the augite, 100Fe/(Fe+Mg) = 47, while too high for felsic anorthosite, is representative for anorthositic gabbro. Further, the profusion of "100" and "001" metamorphic pigeonite exsolution lamellae in the host augite (Jaffe et al., 1975) suggest that the clots may derive from anorthositic gabbro, where such are common, rather than from a Grenville calc-silicate lithology, where they are rare. Labradorite megacrysts in this rock are nevertheless higher in anorthite than felsic anorthosites of the Marcy region, and show $An_{50.5-54.5}$ rather than the typical An_{46-48}, suggesting a probable assimilation of calcium from the augite-apatite-rich clots of xenoliths. For this reason we classify such rocks as a percalcic subfacies of the gabbroic anorthosite facies.

Just north of a small waterfall, the outcrop changes dramatically: the rough foliation gives way to fine layering along which the dark minerals occur as streaks and schlieren, though occasional megacrysts have escaped granulation and appear as flaser. The mylonite is focused in a 2' (0.6 m) zone which dies out gradually to the north after about 20' (6 m) giving way again to percalcic anorthosite. Just beyond a covered interval, the north end of the outcrop contains a mafic rock, in rudely vertical attitude, but somewhat bent about a sub-horizontal axis, perhaps earlier than the mylonitization. It has been named "aproxite" by one of the authors, in allusion to its bimineralic apatite + pyroxene composition, which is identical with that comprising the mafic clots in anorthosite host rock at the south end of the outcrop. The mineralogy thus suggests that the "aproxite" is a folded layer in anorthosite rather than a mafic dike.

The mylonitic zone does not retain any of its primary magmatic or high grade metamorphic mineralogy but is totally retrograded to a fine-grained mixture of albite, prehnite, sericite, quartz, chlorite, pumpellyite, epidote, and calcite. Labradorite is altered by the following probable retrograde reaction:

$$4[Na_{0.5}Ca_{0.5}Al_{1.5}Si_{2.5}0_8] + KAlSi_30_8 + 2H_20$$

$$\text{4 Lab} \quad + \quad \text{Or} \quad + \text{Water}$$

$$= 2[NaAlSi_30_8] + Ca_2Al[AlSi_30_{10}](OH)_2 + KAl_2[AlSi_30_{10}](OH)_2 + Si0_2$$

$$= \text{2 Ab} \quad + \quad \text{Prehnite} \quad + \text{Sericite} \quad + \text{Qz}$$

Augites have been drawn out into elongate lenses, spindles, and schlieren, and totally retrograded to a mixture of fibrous, isotropic chlorite and pumpellyite with a little calcite. Apatite, alone, remains unaltered, appearing as microflaser in the mylonitized base (Fig. 6).

Figure 6. The mylonite zone in gabbroic anorthosite on N.Y. Rte 73 S of Keene Valley Stop 6. W elevation.

This wet assemblage is inconsistent with deep, ductile shear and suggests that the mylonitized zone originated by brittle shear or cataclasis in a wet, relatively shallow crustal setting.

That the shear zone was initially a deep, ductile mylonite, later retrograded, remains a possibility.

Stop 7. CHAPEL POND ANORTHOSITE, EAST CENTRAL MARGIN OF 15' MT. MARCY QUADRANGLE

Outcrops on the E side of Rte. 73 consist of andesine anorthosite containing shear zones of scapolite gneiss and a garnetiferous aplite dike (Fig. 7). For a detailed description of these outcrops, see Kelly (1974).

Most of the rock here is Marcy facies andesine anorthosite.

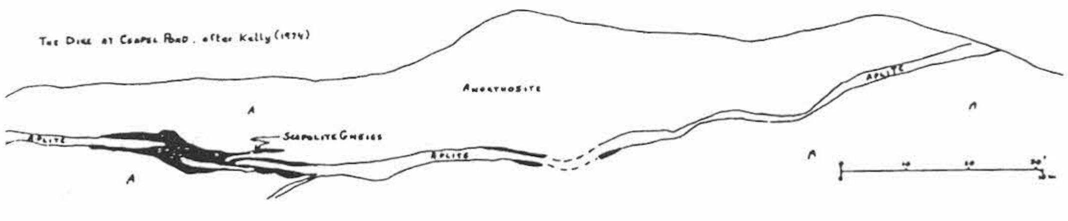


Figure 7. The dike at Chapel Pond, after Kelly (1974).

It consists of 30-40% dark blue-gray megacrysts of calcic andesine, An45-49, set in a matrix of white andesine, hypersthene, augite, and a little hornblende. Plagioclase makes up about 90% of the rock. A fine-grained aplite dike, up to 1 m thick, trends roughly parallel to the road where it may be seen to crosscut the foliation marked by aligned megacrysts of plagioclase in the anorthosite. The aplite contains about 60% microperthite, 25% quartz, 10% altered plagioclase, 3% magnetite, and 1% each of garnet and altered ferromagnesian silicates.

Along anorthosite-dike contacts, fracture zones in the anorthosite contain clear andesine, An44-47, abundant scapolite, Me36-47, dark olive hornblende, and a little hypersthene. Fluids carrying Cl and CO2 apparently migrated into fractures in the anorthosite to convert plagioclase into scapolite.

The abundance of the plagioclase megacrysts here and the overall texture of the rock is typical of the anorthosite that forms the core of the Adirondack high peaks to the west.

Stop 8. GABBROIC ANORTHOSITE PROTOMYLONITIC GNEISS, SOUTH CENTRAL ELIZABETHTOWN QUADRANGLE

The prominent outcrop on the W side of Rte. 9 is a gabbroic anorthosite protomylonite or straight gneiss located in one of the prominent northeast-trending fault zones that abound in the NE Adirondacks. Note that the size reduction and mylonitization of this gabbroic anorthosite are not so intense as that seen at Stop 6, the 1063 mylonite.

The rock consists of very fine crenulations and streaks of hornblende, garnet, ilmenite, and augite in a fine matrix of white andesine, An32, and anorthoclase. Recrystallization took place under dry conditions, and all minerals are fresh.

The high strain nature of the gabbroic anorthosite gneiss is evident, and is illustrated by the total granulation and virtual absence of plagioclase megacrysts. An occasional block or xenolith of felsic anorthosite is present. Punky grey veins of finely altered rock occur in fracture zones.

Notes:

Stop 9. MULTIPLY DEFORMED LAYERED GABBROIC ANORTHOSITE GNEISS, RTE. 9, 2 KM S OF ELIZABETHTOWN

The prominent cliff on the W side of Rte. 9 is a hydrothermally altered layered gabbroic anorthosite or leucogabbro located in one of the prominent northeast-trending fault zones that abound in the NE Adirondacks.

Figure 8. Refolded layered gabbroic anorthosite neiss.

The rock contains kaolinitized andesine, titanian brown hornblende, augite, and garnet, with a little ilmenite and apatite. Compositional layering is marked, with more mafic layers rich in augite and garnet, and more felsic layers richer in altered andesine and hornblende and without garnet. Many thin veinlets of white prehnite, calcite, and chlorite crosscut the gneiss. The layered gneiss was subsequently intruded by one or more aplite dikes, composed of altered albitic plagioclase, potassium feldspar, and quartz, along with garnet, and small amounts of apatite. Garnet is altered to chlorite. The rock is sliced on a mm scale, and slickensided, fracture surfaces often being coated with bright green pistacite.

The gneiss was recumbently folded under a high strain rate and then subjected to open folding (Fig. 8). Do the conspicuous open folds delineated by the pink aplite represent:

1) refolding of the recumbently folded gneiss?

2) a sheath fold squeezed or squirted up inside the gneiss?

3) are there one or two aplite dikes, and does the aplite layer close into a fold hinge beneath the road?

Just across Rte. 9 on the E side, the rock has a completely different texture. About half the rock consists of 0.5-5cm green, euhedral kaolinite pseudormorphs after plagioclase phenocrysts lying in a foliated matrix of brown hornblende, quartz, anorthoclase, augite, magnetite, and apatite. The fine black matrix is unaltered, in contrast to the large plagioclase phenocrysts. The green kaolinite pseudomorphs show good albite and Carlsbad twinning, but under the microscope only trace amounts of unaltered plagioclase remain. Compositionally, the rock is a quartz gabbro or quartz diorite. However, it may represent a porphyritic gabbro with its groundmass recrystallized to a metamorphic assemblage.

Stop 10. THE WOOLEN MILL GABBRO AND ANORTHOSITE, RTE. 9N, 15' ELIZABETHTOWN QUADRANGLE

On Rte. 9N about 1.6 km W of the intersection of Rtes. 9 and 9N at the golf course on the southern edge of Elizabethtown are outcrops of gabbro and anorthosite at the site of an old, long disused broken dam. Recent reconstruction of the dam and installation of a penstock along the Branch River just N of the road may limit our examination of a fine exposure of anorthosite block structure along the river.

On the S side of the road, a prominent cliff exposes the very irregular contact of a garnet- and magnetite-rich gabbro with a white gabbroic anorthosite in which almost all of the plagioclase megacrysts have been granulated. A rude foliation may be observed in both rocks. Modes of the gabbro and optically determined compositions of plagioclase, augite and hypersthene from the gabbro and anorthosite are given in Table 6. The contrast in Fs content of coexisting clino- and orthopyroxene in gabbro and anorthosite is marked. Note that the iron-rich gabbro has abundant garnet, while the relatively iron-poor anorthosite has none. The presence in the gabbro of isolated blue-gray, well-twinned (Carlsbad and albite) labradorite xenocrysts and occasional xenoliths, as well as contact relations, suggests that the gabbro has intruded the anorthosite before regional deformation. Toward the center of the roadcut, a pink aplite dike has intruded both the anorthosite and the gabbro.

The complexity of the contact relations here has led different geologists to different interpretations. Kemp and Ruedemann (1910) and Kemp (1921) reported that river outcrops showed "anorthosite tonguing in to the dark supposed gabbro"

Table 6. MODES AND MINERAL COMPOSITION OF GABBRO AND ANORTHOSITE FROM THE WOOLEN MILL LOCALITY, RTE 9N,1.6 KM W OF ELIZABETHTOWN

Mineral	metamorphosed gabbro % by volume		anorthosite
orthoclase	0.5-------0.5		tr
andesine	43.0------50.1	An$_{33,5}$ 1/	andesine An$_{44.5}$ 2/
augite	12.9------16.4	Fs$_{48}$ 3/	augite Fs$_{29}$ 4/
hypersthene	4.5-------4.1	Fs$_{60}$ 5/	hypersthene Fs$_{40.5}$ 6/
almandine	9.9------10.2		none
ilmenite	8.2-------2.7		tr
magnetite	15.0------10.0		none
apatite	6.0-------6.0		none
	100.0 100.0		

1/ mol % An from optical meas., α = 1.546

2/ " " " " " " α = 1.5520

3/ mol % Fs, Fe/(Fe+Mg) from meas. of γ =1.730

4/ " " " " " " " " γ = 1.717

5/ " " " " " " " " γ = 1.740

6/ " " " " " " " " γ = 1.715

A plagioclase xenocryst in gabbro has α = 1.555, An$_{50.5}$

For optical composition curves, see Jaffe, Robinson, Tracy and Ross (1975). Amer. Mineral. 60, 9-28.

and suggested that the gabbros might represent "surviving inclusions of Grenville sedimentary gneisses impregnated with matter from the anorthosites." They suggested that the Woolen Mill gabbro was thus an old Grenville rock hybridized by later intrusion of anorthosite. Commenting on this interpretation, Miller (1919) assigned these plagioclase-megacryst-bearing gabbros to the Keene gneiss, which he believed to be a syenitic magma containing assimilated anorthosite! Buddington (1962) described the Woolen Mill gabbro as a typical olivine gabbro intrusive into anorthosite, in which olivine was extensively converted to garnet during regional metamorphic recrystallization. No evidence of relict olivine could be found under the microscope.

How would you interpret the outcrop relations?

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ROADLOG AND TIMETABLE--H.W. & E.B. Jaffe Adirondack High Peaks Trip.

MILES	CUMUL		TIME
0.00	0.0	**STOP 0**.Arby parking lot, Plattsburgh,R	8:30
0.3		on Rt.3W to 187S,turn L	
14.25	14.55	to Ex.34,Ausable Forks turn L on Rt.9N	8:45
10.6	25.15	**STOP 1**.Rt.9N 1.3 miles E of Ausable Fks.	9;05-9:35
1.3	26.45	Turn L at blinker in Ausable Fks. with Rte.9N	
6.1	32.55	Turn L off Rte.9N in Jay, cross covered bridge, park R	
0.2	33.15	**STOP 2**.Outcrop in river,on bank.	9:50-10:20
0.2	33.25	Continue W on 9N through Jay to Upper	
6.6	39.85	Jay, where we turn L(S) with 9N	
3.9	43.75	**STOP 3**.Rock cut S of Upper Jay	10:35-11:05
		Go S on Rt.9N to Rt.73 in Keene,turn R	
2.3	46.05	(W) on Rte.73	
4.5	50.55	**STOP 4**.Park on L at Cascade Lks., cross Rt.73 cautiously,follow path up to cliff	11:20-12:05
4.4	54.95	Turn E on Rte.73, return to Keene Turn R(S) on small road before bridge	
0.75	55.70	**STOP 5**.Park,E side of road, scramble down to river,see outcrop, lunch	12:15-12:55
1.8	57.50	Proceed S on small road to Rte 73,	
4.0	61.50	go S through Keene Valley.	
		STOP 6.Roadside,Rte.73	13:07-13:37
3.0	64.50	Continue S on Rte 73 to Chapel Pond.	
		STOP 7.Walk N to E side outcrop.	13:43-14:13
		Continue S to Rte.9 intersection.	
4.1	68.60	turn L on Rte 9	
2.3	70.90	**STOP 8**.Park R, cross to outcrop	13:26-14:56
		Continue N on 9 through New Russia	
6.4	77.30	**STOP 9**.Park on right	15:26-15:56
1.3	78.60	At Rt. 9N, turn L	
1.0	79.60	**STOP 10**.Park on right,Rte.9N	16:00-16:20
1.0	80.60	Return E on Rt 9N to Rt 9, turn L	

Return via I-87 to Plattsburgh by either 9N to exit 31(5 mi),or 9 to exits 32(6mi),33(10mi) or 34(20 mi). Exit 37 in Plattsburgh returns you to the Arby parking lot where you started, in about an hour.

APPENDIX I.

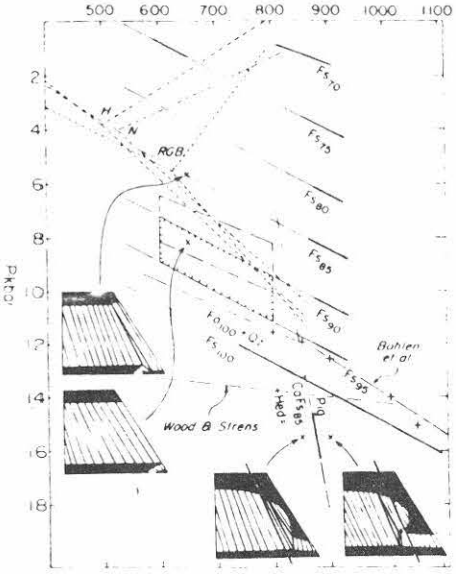

Fig. 9. *P–T* diagram with isopleths showing the compositions of orthopyroxene in equilibrium with olivine and quartz, based on experimental work of Lindsley (1965) and Smith (1971b) in the system $MgSiO_3$–$FeSiO_3$. Determination of Fs_{100} isopleth by Bohlen *et al.* (1978) and a calculation of its position by Wood and Strens (1971) are also shown, the former with an inflection consistent with the high–low quartz inversion. Also shown are the low temperature stability of pigeonite on the join hedenbergite$_{85}$–ferrosilite$_{85}$ as determined by Smith (1972) and the stabilities of the Al_2SiO_5 polymorphs based on Richardson *et al.* (1969), Newton (1966), and Holdaway (1971). Outlined areas indicate brackets for minimum pressure estimates for metamorphism of Mt. Marcy orthoferrosilite according to data of Smith (hachures) or of Bohlen *et al.* (long dashed). See text for detailed interpretation.

In order to estimate pressures for the Adirondacks, the calculated ferrosilite contents of orthopyroxenes have been applied to the isopleths of Smith (1971b) on Figure 9. The Smith calibration was used rather than the Wood and Strens calibration because the Fs_{100} curve of Smith is in reasonable agreement with the Fs_{100} curve of Bohlen *et al.* (1978), especially considering Smith's suggestion that his pressures are probably slightly high due to the mechanical behavior of the solid-media apparatus.

The ferrosilite content of the most iron-rich orthopyroxene of this study, Po-17, is calculated to be Fs 95 and Fs 90 respectively, using the two extreme calculation methods. If equilibration occurred at 800°C, then *minimum* pressure was 9 kbar and could have been as high as 11 kbar. Equilibration at 600°C implies *minimum* pressure of 7 kbar to 9 kbar (Table 9). These limiting minimum pressure values based on experimental data of Smith (1971b) are outlined on Figure 9, together with adjusted values estimated from the Fs_{100} experiments of Bohlen *et al.* (1978). Similar reasoning based on optical data for the eulite-bearing (Fs 88) specimen FFG-2 from near Wanakena, Cranberry Lake quadrangle, yields the minimum pressure estimates given in Table 9.

On the other hand, composition of olivine in the

Table 7. Estimates of pressure of metamorphism of selected Adirondack rocks*

Estimates of __minimum pressure__ (kbar) based on orthopyroxene composition in olivine-free assemblage.

	"Fs"	600°C	800°C
Po-17, Mt. Marcy quad., probe analyses			
Fe/(Fe + Mg)	.95	9	11
$Fe^{2+}/2.00$	.90	7	9
FFG-2, Cranberry Lake quad., optical estimates			
Fe/(Fe + Mg)	.88	6.5	9
$Fe^{2+}/2.00$	.84	4.5	7

Estimates of __maximum pressure__ (kbar) based on olivine-augite assemblage where "hypothetical orthopyroxene" composition has been estimated.

	"Fs"	600°C	800°C
FFG-6, Cranberry Lake quad., probe analyses			
Fe/(Fe + Mg)	.97	9.5	12
$Fe^{2+}/2.00$	.91	7.5	10
AF-1A, Ausable Forks quad., optical estimates			
Fe/(Fe + Mg)	.97	9.5	12
$Fe^{2+}/2.00$	.91	7.5	10

*To accord with the experiments of Bohlen et al. (1978) these values should be adjusted approximately -0.8 kbar at 600°C and -1.5 kbar at 800°C.