Trip AB-2

Precambrian Geology of the Ausable Forks Quadrangle, Northeastern Adirondacks

Philip Whitney
New York Geological Survey

and

James Olmsted
SUNY College at Plattsburgh

TRIP AB-2, PART A

PRECAMBRIAN GEOLOGY OF THE AU SABLE FORKS QUADRANGLE, NORTHEASTERN ADIRONDACKS

Philip R. Whitney
Geological Survey, New York State Museum

James F. Olmsted
Center for Earth and Environmental Sciences
State University of New York College at Plattsburgh

INTRODUCTION AND GEOLOGICAL SETTING

The Ausable Forks quadrangle (Figs. A1, A2) in the northeastern Adirondack Mountains, near the border of the Marcy anorthosite massif, contains four major rock units. All four units display mineral assemblages consistent with granulite facies metamorphism, except for local retrograde assemblages in the vicinity of late, brittle faults.

Several large, roughly domical, bodies of metanorthosite and gabbroic anorthosite gneiss are the structurally lowermost exposed rocks. Overlying the domical metanorthosites is a complex of layered metamorphic rocks several kilometers thick, which dip away from the metanorthosite domes. Foliation and compositional layering in these rocks are parallel or subparallel to the foliation in the outermost parts of the anorthosite domes. The layered complex, shown in white on Fig. A2, comprises the metasedimentary rocks, described in more detail below, as well as metaigneous rocks including granite (locally charnockitic), ferrodiorite, monzodiorite, anorthosite and gabbroic anorthosite gneisses. Larger bodies of metaigneous rocks are shown separately in Fig. A2.

The third, structurally uppermost, major unit in the quadrangle is a heterogeneous quartzofeldspathic gneiss that crops out over an area of nearly 1000 km^2 in the northeastern Adirondacks. This has been named the Lyon Mountain Granitic Gneiss by Postel (1952); we have shortened this to Lyon Mountain Gneiss (LMG) because it contains substantial amounts of rock that are not of granitic composition (cf Stops 4 & 5). This unit underlies much of the northern third of the Ausable Forks Quadrangle, and forms the core of a tight, upright, north-plunging synform (the Ausable Forks Syncline of Balk, 1931) in the central third (Fig. A2). North of the Ausable River, the LMG is host to numerous small, and a few rather large, bodies of low

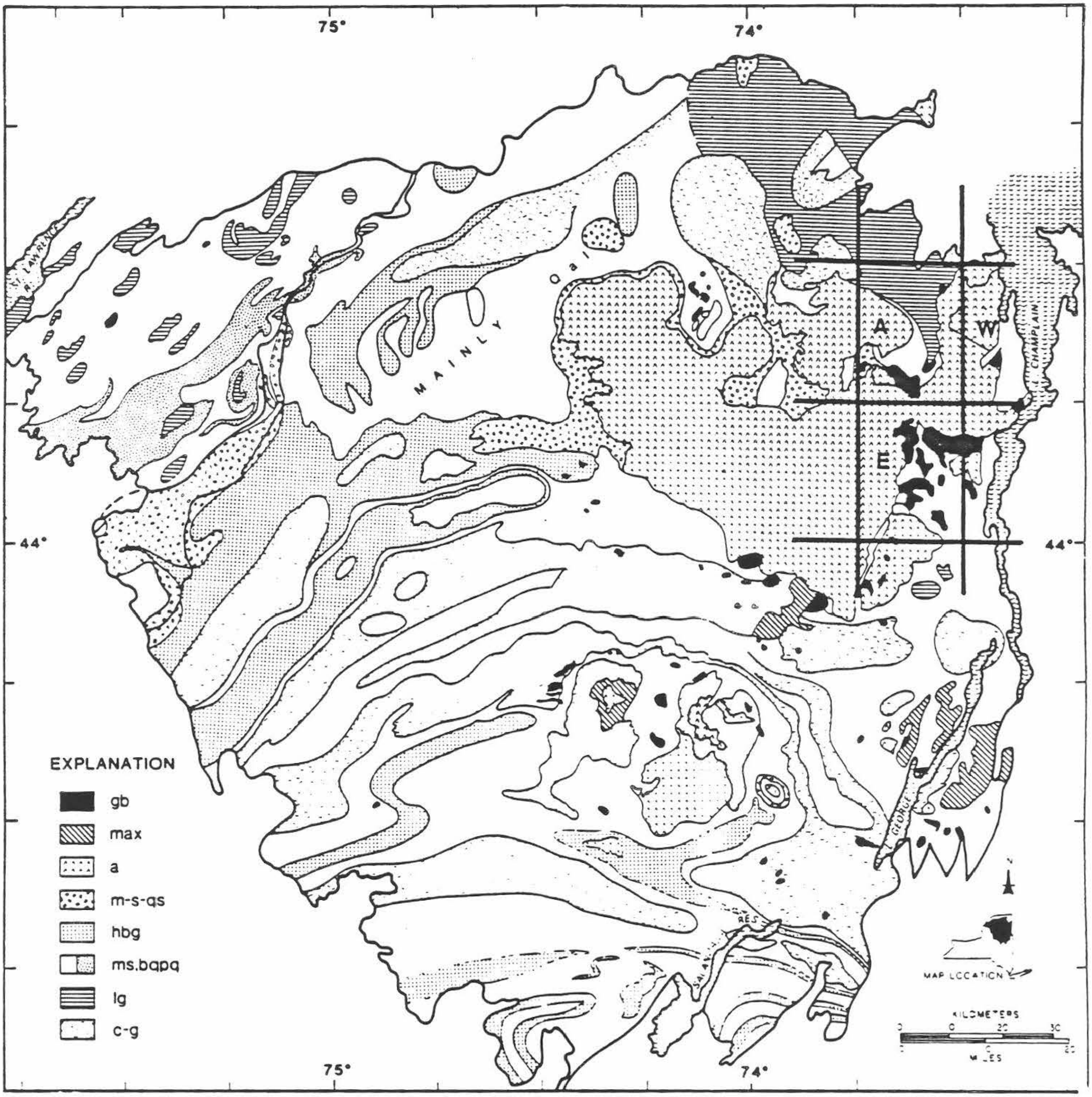

Fig A1. Generalized geologic map of the Adirondacks, after McLelland and Isachsen, 1985. Labeled quadrangles: A, Au Sable Forks; E, Elizabethtown; W, Willsboro. Legend: gb, olivine metagabbro; max, interlayered anorthositic & mangeritic rocks; a, metanorthosite; m-s-qs, mangeritic and charnockitic gneisses; hbg, hornblende granititic gneisses; ms, undifferentiated metasedimentary rocks; bqpg, biotite-quartz-plagioclase gneisses; lg, leucogneisses; c-g, charnockitic & granitic gneisses.

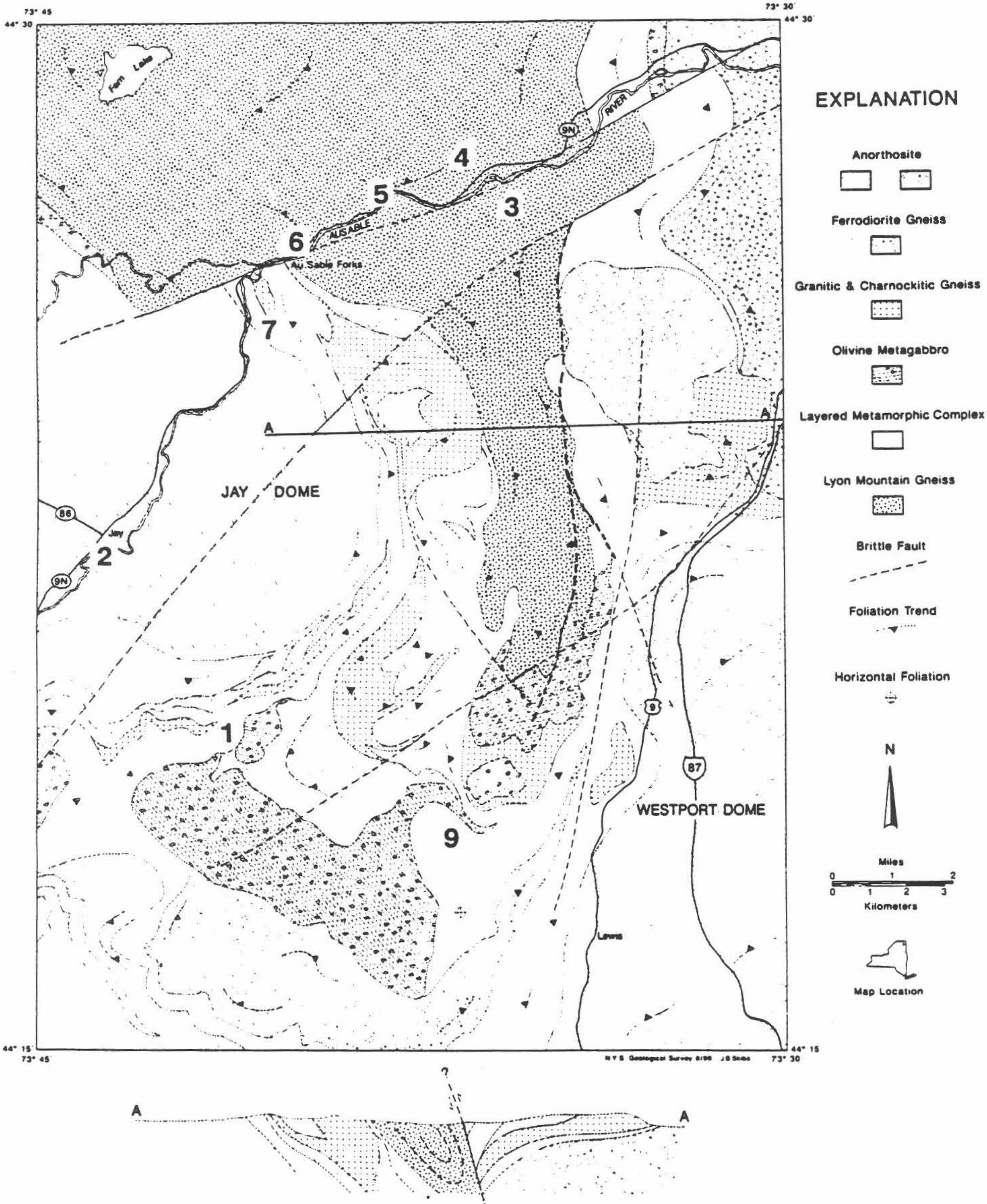

Fig. A2 Map showing the general geology of the Ausable Forks Quadrangle, after Whitney and Olmsted, 1988. Numbers show approximate stop locations. Stop 9 is the Lewis wollastonite mine, to be visted during Part B of the trip.

titanium magnetite iron ore that were worked throughout much of the nineteenth century and the first half of the twentieth (Gallagher, 1937; Postel, 1952).

The first three units are intruded by coronitic olivine metagabbro, which occurs as several large bodies in the southern half of the quadrangle, and as smaller pods and lenses in the layered rocks throughout the area. The metagabbro ordinarily retains primary igneous textures in the interiors of all but the smallest bodies, and is metamorphosed to garnet amphibolite or mafic granulite near the contacts.

On this trip we will first examine a representative section of metasedimentary rocks exposed in a stream cut (Stop 1), followed by a look at the underlying domical metanorthosite (Stop 2). Stops 3-5 are roadcut exposures of various facies of the Lyon Mountain Gneiss; Stop 6 is an unusual fayalite granite found within the Lyon Mountain but with uncertain relationship to it. Time permitting, we will return to the metasedimentary rocks at Stop 7.

DESCRIPTIONS OF MAJOR LITHOLOGIC UNITS

1. Metanorthosite

Metamorphosed anorthositic rocks underlie large areas in the central and northern Adirondacks. These rocks, together with subordinate ferrodioritic and ferrogabbroic gneisses, comprise the mafic part of the bimodal Anorthosite-Mangerite-Charnockite-Granite (AMCG) intrusive suite (McLelland and Whitney, 1990) that is found throughout the Adirondack Highlands. In the northeastern Adirondacks, including the Au Sable Forks quadrangle, metanorthosite forms large domical bodies as well as smaller, stratiform intrusions within supracrustal rocks. While Adirondack metanorthosites have in common the presence of intermediate plagioclase (An_{42-58}) as the dominant (70-98%) mineral, they are quite diverse and detailed description presents formidable complexities. Three principal variables can be distinguished:

1. Abundance of plagioclase megacrysts. Gray sodic labradorite to calcic andesine megacrysts are a prominent feature of most Adirondack anorthosites. Size of the megacrysts ranges from one or two cm to giant, 1/2 m "breadloaf" crystals and fragments. Faint to strong parallelism of the megacrysts is locally present, suggesting either cumulus texture or flow foliation. The proportion of megacrysts in the rock present ranges from nearly 100% down to nil. Where megacrysts are abundant and closely spaced in the rock, varying amounts of fine-grained, clear, recrystallized plagioclase may border the megacrysts and occupy small fractures within them. This is commonly referred to in the literature as "protoclastic" texture

(Miller, 1916; Balk, 1931; Buddington, 1939). Where megacrysts are more widely spaced, interstitial volumes are commonly occupied by a medium-to coarse grained (up to several mm) groundmass of light gray, white or buff plagioclase together with pyroxenes and oxides. This groundmass locally displays igneous textures and may have crystallized from a gabbroic anorthosite magma or crystal mush in which the megacrysts have been entrained.

2. Abundance of mafic minerals. Hypersthene, augite, titaniferous magnetite, and ilmenite or hemo-ilmenite are the chief primary mafic minerals in the anorthositic rocks. Metamorphic garnet is common, and forms reaction rims around both hypersthene and oxide minerals. Metamorphic hornblende and biotite are locally present. The color index varies from one or two percent up to as much as 30% in some anorthositic gabbros.

3. Extent of deformation. Adirondack metanorthosites range from nearly undeformed, igneous-textured varieties to anorthositic gneisses with intense foliation and well-developed lineation. As the degree of deformation increases, megacrysts change from blocky to lenticular in shape, and generally decrease in size and abundance. Rocks near the margins of metanorthosite domes and massifs ordinarily are more deformed than those in the interiors.

Large variations in all three of these factors may be present in a single outcrop, making subdivision of the anorthositic rocks for mapping purposes impractical in most locations. 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 relatively megacryst-poor and mafic rich, and also tends to be more deformed than the "Marcy". This classification is difficult to use consistently, because the three variables are at least partially independent.

Anorthositic xenoliths in anorthosite are quite common. This "block structure" sometimes consists of coarse, megacryst-rich xenoliths in a finer-grained groundmass; less commonly the xenoliths are blocks or rafts of gabbroic anorthosite or leuconorite. Individual xenoliths or megacrysts may be surrounded by a zone enriched in mafic minerals. Xenoliths of metasedimentary rocks, ranging from centimeters to several meters in size, are found in all facies of the anorthositic rocks, more commonly near the outer margins of metanorthosite bodies. Most of these inclusions are pyroxene-rich calcsilicate rocks, but quartzite and metapelite xenoliths have also been observed. The lithologic similarity of these inclusions to nearby metasedimentary rocks is evidence for intrusive nature of the anorthosites.

2. Metasedimentary Rocks

Metasedimentary rocks in the Au Sable Forks quadrangle consist principally of diopside-rich calcsilicate granulites, impure quartzites, and calcite marbles. Phlogopite and biotite schists are less common, and there is one occurrence of dolomite marble. Near the top of the layered complex, underlying the Lyon Mountain Gneiss, is a thin, graphitic, (cordierite)-sillimanite-garnet-quartz-microcline metapelite. Substantial amounts of quartzofeldspathic gneiss, amphibolite and biotite-rich mafic granulite are interlayered with the metasedimentary rocks; these rocks may be the metamorphic equivalents of felsic and mafic volcanics.

Most individual layers of metasedimentary rocks are relatively thin (less than a few tens of meters). Accurate measurement of thicknesses is prohibited by scarcity of outcrop. Layers are commonly discontinuous along strike, possibly due in part to tectonic disruption. This, plus the abundance of meta-intrusive rocks in the section and the intense deformation, have made it impossible to recognize a coherent stratigraphy.

Table 1 lists the minerals occurring in the metasedimentary rocks. The dominant phase in most of the calcsilicate rocks is diopsidic clinopyroxene, ranging from nearly colorless to dark green. The color, which depends in part on ferrous iron content, may vary widely within a few centimeters. With the clinopyroxene are variable amounts of alkali feldspar, quartz, plagioclase, calcite, scapolite, phlogopite, wollastonite, and titanite. Rocks with over 90% diopside ("diopsidites") are common, as are diopside-microcline and wollastonite-diopside ("WoDi") rocks.

The WoDi assemblage commonly includes minor feldspar, graphite, pyrrhotite, sphene, and quartz or calcite. Garnet, where present, occurs as thin grossular rims around wollastonite. The diopside is ordinarily pale green to colorless. This is in sharp contrast with the wollastonite ore deposits at Willsboro and Lewis (see description under Part B). There, the assemblage is wollastonite, dark green clinopyroxene (salite), and andraditic garnet, lacking accessory minerals.

The calcsilicate rocks grade into impure quartzites that are commonly tremolite-bearing and locally display centimeter-scale layering. The magnesium-rich assemblage tremolite-enstatite-diopside-(phlogopite)-quartz is present in some outcrops. Calcite marbles, usually with abundant calcsilicate minerals, occur in lenses and irregular layers. In the central part of the quadrangle west of Black Mountain, prominent marble "dikes" crosscut a stratiform body of anorthosite gneiss, illustrating the ductile behavior of the marble relative to that of

TABLE 1
MINERALOGY OF THE PRINCIPAL METASEDIMENTARY ROCKS

Calcsilicates	Quartzites	Marbles	Metapelites
*Clinopyroxene	*Quartz	*Calcite	Quartz
Microcline	K-feldspar	*Dolomite	K-feldspar
Quartz	Tremolite	*Diopside	Sillimanite
Scapolite	Diopside	#Serpentine	Garnet
Plagioclase	Phlogopite	Scapolite	Biotite
Phlogopite	Plagioclase	Forsterite	Graphite
*Garnet	Enstatite	Garnet	Pyrite
*Wollastonite	Graphite	Wollastonite	Pyrrhotite
Titanite	Pyrite	Microcline	xCordierite
Graphite		xIdocrase	
Pyrite		xChondrodite	
xEpidote		xSpinel	
xClinozoisite			
#Prehnite			
#Chlorite			

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

TABLE 2
AVERAGE MODES OF LYON MOUNTAIN GNEISS

	GG FACIES (12)			LAG FACIES (6)			MAG FACIES (11)[1]		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
PLAG[2]	11.7	0	46	64.1	51	74	65.6	33	83
KSPAR	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
CPX	1.5	0	6.1	2.7	0	13	16.7	0.3	34
AMPH	1.6	0	8.3	1.0	0	3.2	3.8	0	17
OXIDES	1.9	0.3	4.7	2.9	0.7	4.4	1.2	0	4.6
TN	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

All modes based on at least 1000 points counted

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.

anorthosite during deformation. Graphite and pyrite or pyrrhotite are common accessory minerals in all asssemblages.

Several features of these metasedimentary rocks suggest the former presence of evaporites. The preponderance of diopside-rich calcsilicate rocks, the metamorphic equivalent of silicious dolostones, is significant in that dolomite is commonly a product of hypersaline depositional environments (Friedman, 1980). The calcsilicate rocks locally contain major amounts of microcline, possibly the metamorphic equivalent of low temperature, authigenic or diagenetic microcline. Magnesium-rich metasedimentary rocks, in particular phlogopite schists and enstatite-diopside-tremolite-quartz rocks, are likely granulite facies equivalents of evaporite-related talc-tremolite-quartz schists, such as those found near Balmat in the northwest Adirondacks, in stratigraphic association with diopside-rich rocks and bedded anhydrite (Brown and Engel, 1956). Magnesite-dolomite-chlorite-quartz rocks are a possible sedimentary protolith. Granulite facies metasedimentary rocks similar to those of the Ausable Forks quadrangle occur in the Caraiba mining district of Brazil (Leake and others, 1979), and in the Oaxacan Complex of southern Mexico (Ortega-Gutierrez, 1984); in both localities anhydrite is present in the subsurface.

3. Lyon Mountain Gneiss

The Lyon Mountain Gneiss comprises three distinct facies. The most abundant facies is granitic gneiss (GG) consisting chiefly of quartz and mesoperthite with minor amounts of biotite, hornblende, clinopyroxene, or garnet and up to 5 percent magnetite. Locally present is a potassium-rich variety with microcline as the principal feldspar. Modal compositions vary widely, both with respect to the proportions of quartz and feldspar present, but also with respect to the amount and identity of the mafic minerals (Table 2). These heterogeneous rocks are common throughout the outcrop area of the LMG. A second facies, leucocratic albite gneiss (LAG), is composed of quartz and albitic plagioclase (Ab_{95}-Ab_{98}), minor clinopyroxene with up to 40 percent acmite component, and as much as 4 percent magnetite. Both the GG and LAG facies commonly appear as fine- to medium- grained granoblastic rocks, massive to weakly foliated but with locally distinct compositional layering. Colors range from white to pink, buff, or gray. Figures A3A and A3B illustrate the variability of both modal and normative quartz and feldspar.

The granitic and leucocratic albite gneisses are interlayered with lesser amounts of a third facies, mafic albite gneiss (MAG). The latter is a distinctive albite-pyroxene rock, with varying amounts of quartz and a blue-gray sodic amphibole, plus minor titanite. The pyroxenes are dark green and acmite-rich (up to 35%). Oxide minerals are uncommon; where they do occur

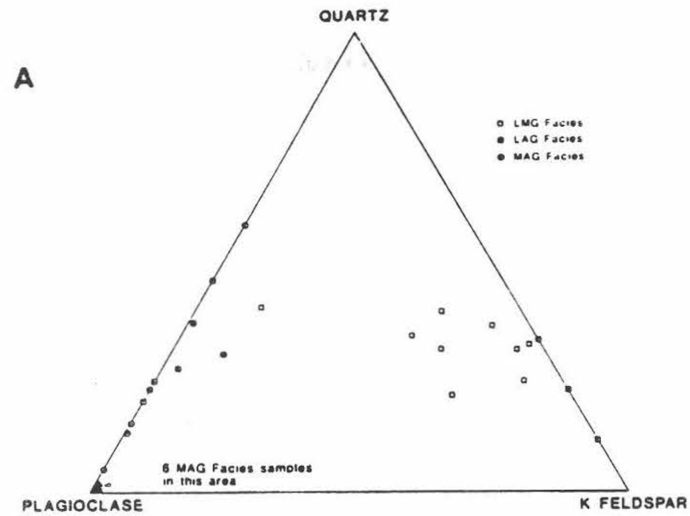

Fig. A3 A. Modal quartz, plagioclase, and K feldspar (microcline or perthite) in rocks of the Lyon Mountain Gneiss.

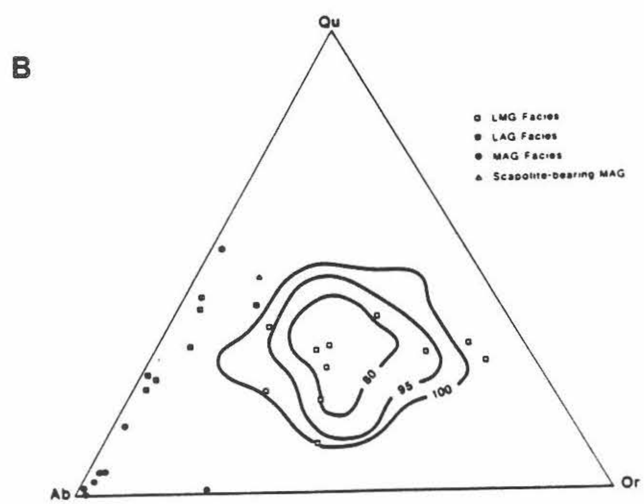

Fig. A3 B. Normative quartz, albite and orthoclase in the Lyon Mountain Gneiss. Contours show percentages of 137 analyses of Adirondack granitic rocks. After Whitney and Olmsted (1988).

they consist of laminar intergrowths of hematite and ilmenite or rutile, in contrast to the ubiquitous magnetite of the GG and LAG facies. MAG is commonly fine-grained, with a sugary granoblastic texture. In some outcrops, it displays a prominent pinstripe layering, with alternating mm-scale pyroxene-rich and albite-rich layers. Megacrysts of nearly pure albite, up to 5 cm across, are present locally. The quartz content of MAG is commonly under 5 percent, but one sample contains 45 percent, suggesting admixture of a quartz-rich sedimentary component.

Table 3 shows the average chemical composition of several facies of the Lyon Mountain Gneiss. Notice in particular the high Na_2O and low K_2O in LAG and MAG. In contrast, a microcline-bearing variant of the GG facies (MGG in Table 3) is K_2O-rich. Whitney and Olmsted (1988) attribute the heterogeneity of these rocks and the extreme alkali metal ratios to diagenetic alteration of felsic volcaniclastics in a hypersaline environment such as a playa lake. 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 rocks with diagenetic analcite (Na-rich), zeolites, or K feldspar (Surdam, 1981). A weakly metamorphosed analog of the MAG facies is present in the Damara orogen of Namibia, in the form of albite-dolomite-quartz rocks, locally with albite porphyroblasts. These late Proterozoic metasedimentary rocks also originated in a playa environment (Behr and others, 1983). Both the LAG and MAG facies are similar in mineralogy and chemistry to meta-evaporites from the Proterozoic Willyama Supergroup of South Australia (Cook and Ashley, 1992).

TABLE 3: CHEMICAL ANALYSES OF LYON MOUNTAIN GNEISS

	GG	MGG	LAG	MAG	STOP 4	STOP 6
SiO2	70.04	69.49	71.63	64.39	70.08	69.81
TiO2	0.56	0.52	0.48	0.94	0.46	0.47
Al2O3	12.96	12.89	12.71	13.17	13.11	11.97
Fe2O3	2.61	3.69	4.13	2.85	4.61	1.61
FeO	2.92	1.98	2.11	2.15	2.06	4.45
MnO	0.08	0.01	0.02	0.04	0.02	0.13
MgO	0.22	0.24	0.31	3.05	0.32	0.01
CaO	1.41	0.45	1.28	5.21	1.97	1.47
Na2O	4.27	1.34	6.81	6.98	7.48	4.07
K2O	4.44	8.79	0.48	0.68	0.25	5.15
P2O5	0.11	0.11	0.07	0.16	0.07	0.03
Rb	114	237	7	19	4	174
Sr	64	42	31	61	31	28
Ba	441	1188	55	121	27	221
Zr	844	532	1015	290	1036	1212
Y	120	59	137	55	124	117
Nb	35	19	40	18	45	41
Ce	183	113	223	68	184	141
Ga	29	18	29	18	27	30

Key: GG Granitic gneiss, average of 9
MGG Granitic Gneiss, microcline facies, average of 3
LAG Leucocratic albite gneiss, average of 6
MAG Mafic albite gneiss, average of 9
STOP 4 Leucocratic albite gneiss from Stop 4, avg. of 2.
STOP 6 Fayalite granite from stop 6

ROAD LOG, PART A

Miles	Cum	Remarks
0.0	0.0	Intersection of Routes 9N and 86 in the Village of Jay. Proceed SE on Mill Road and cross the covered bridge spanning the East Fork of the Ausable River.
0.2	0.2	Turn R at intersection at E end of covered bridge. The outcrops in the river just above the bridge are anorthosite of the Jay Dome; this will be our lunch stop.
0.7	0.9	Y intersection; continue on L fork.
0.7	1.6	Intersection of Hesseltine and Glen Roads; bear R.
0.1	1.7	Turn L on Nugent Road (unpaved).

1.7 3.4 STOP 1. Gelina Basin section of metasedimentary rocks. The road forks at this point, with the R fork leading steeply uphill. There may be a gate across the L fork. This is private property, owned by Ward Lumber Co. in Jay. If you come here on your own, get permission. We will park here and proceed on foot up the R fork (if you have a 4WD vehicle, this road can be driven). Set your altimeter for 1280 feet. After about a mile, the road ends at a hunting cabin ("Camp Pissonya") in a clearing. Walk to the R of the cabin past the outhouse, where you will find a trail that follows the top of a steep bank. Follow the trail S to about 1800 feet altitude, and work your way down the bank to the stream at the bottom. This unnamed, N-flowing stream drains a modified cirque (labeled Gelina Basin on the 15' quadrangle map) on the north flank of Jay Mountain. We will attempt to hit the stream at about 1725 feet elevation and traverse upstream over a well-exposed section of NNE-striking metasedimentary rocks.

1730-1750' (altitudes approximate) Calcsilicate rocks with diopside and wollastonite, locally rusty weathered, with quartzite layers.

1750-1760' Strongly foliated, interlayered amphibolite and calcsilicates, overlain by coarse, rusty, calcite-diopside-phlogopite-graphite marble.

1780-1820' First of three waterfalls. At the base of this falls, layered diopside-wollastonite calcsilicates (WoDi) and quartzite are exposed. The caprock is tremolite-bearing quartzite; just above this is Mg-rich enstatite (En_{95})-diopside (Di_{97})-tremolite-quartz rock.

1830′ 5′ cascade over diopsidite and diopsidic marble with thin quartzite layers.

1840-1870′ Interlayered metasedimentary rocks (diopsidites and WoDi) and thin amphibolites.

1880-1900′ Amphibolite, overlain by metasedimentary rocks, including a calcite-diopside-wollastonite-grossular-idocrase marble at the base of a second waterfall. The cap of this falls is a dark, feldspathic diopsidite with locally abundant sphene. The amphibolite here may be a sill or dike of olivine metagabbro satellitic to the larger body exposed just upstream.

1910-1960′ Third falls. The lower part of the falls is a cascade over banded WoDi rock; the upper part is olivine metagabbro locally mixed with granitic gneiss. The gabbro contact here appears to have a steep easterly dip, truncating the more gently dipping metasedimentary layers. Thin sections of the WoDi rock here show thin rims of grossularitic garnet around wollastonite, possibly a result of the reaction wollastonite + plagioclase = grossular + quartz.

From this point, we will retrace our route back to the vehicles.

0.0 3.4 Turn around and retrace route toward the Village of Jay.

3.1 6.5 STOP 2. Metanorthosite of the Jay Dome Park off road on L, just upstream from the covered bridge. Walk S up the road to the first outcrop on the R. This glacially polished and striated outcrop is relatively fine-grained anorthosite containing xenoliths of coarse, blue-gray anorthosite. One of these is surrounded by an envelope of anorthositic gabbro. This "block structure" is indicative of the complex magmatic history of the anorthosite.

The outcrops in the river are dominantly light-colored, fine grained anorthosite with scattered blue-gray andesine megacrysts and a few blocks of igneous-textured anorthositic gabbro. Small, irregular dikes of gabbro and of a mafic rock rich in pyroxene and Fe-Ti oxides cut the anorthosite and have been deformed and metamorphosed along with it.

Unmetamorphosed late Proterozoic basaltic dikes occupy fractures or faults paralleling the river. These are mildly alkaline within-plate continental basalts, possibly emplaced during extension of Grenvillian crust prior to the opening of the Proto-Atlantic Ocean (Coish and Sinton, 1992).

On the opposite side of the river (unless water levels are very low, we will have to cross the bridge to reach these outcrops) there is a textbook example of small, NE-trending faults offsetting mafic layers or dikes in the anorthosite. Also present here is a large xenolith of very fine-grained, pyroxene-rich metasedimentary rock.

We will have lunch at this stop before proceeding.

0.0 6.5 Upon leaving Stop 2, turn R onto Green Street. Do not recross the covered bridge.

3.4 9.9 Carey Road on L; continue straight.

1.1 11.0 Stickney Bridge Rd. on L; continue straight.

2.2 13.2 Grove Rd. on L; continue straight.

1.7 14.9 STOP 3 Lyon Mountain Gneiss, granitic facies. A series of large outcrops, slightly back in the woods, extends for over 0.1 miles along the N side of the road from this point. These outcrops are fairly representative of the granitic facies of the Lyon Mountain Gneiss. Notice the considerable variability in both texture and in the nature and amount of mafic minerals (hornblende, pyroxene, biotite, magnetite). A few thin amphibolite layers are present. At the eastern end of this series of outcrops, diagonally opposite the entrance to the Chesterfield Rod & Gun Club, is a roadcut of highly sheared gneiss showing two foliations on the weathered surface. The rock here lacks K feldspar, and appears to be the of the trondhjemitic (LAG) facies, although untypical.

Continue NE on Green Street

1.2 16.1 Trout Pond Road on R; continue straight.

0.6 16.7 Turn L on Dugway Road, then R on bridge over the Ausable River.

0.2 16.9 Turn L on Back St.

0.3 17.2 Turn L on Rte. 9N in Clintonville. During the height of iron mining activity in the latter part of the 19th century, Clintonville is reported to have had a population of over 10,000.

0.2 17.4 Bear R on Harkness Road.

0.8 18.2 Turn L onto old railroad grade (unpaved). Caution: do not attempt this in a vehicle with low road clearance. The thick, sandy glacial sediments here are deltaic deposits of the Lake Coveville stage.

1.5 19.7 STOP 4 Lyon Mountain Gneiss, leucocratic albite gneiss facies. Park vehicles in wide, flat area to R of road. Walk back about 1/4 mile along a series of outcrops on the N side. This is the trondhjemitic (LAG) phase of the Lyon Mountain Gneiss. The rock consists of about 70% albite (ca Ab_{95}), 20%

quartz, 5-10% dark green clinopyroxene with up to 40% acmite end member, and lesser amounts of magnetite and titanite. K feldspar is conspicuously absent; these rocks typically contain less than 0.5% K_2O (Table 3). Toward the E end of the outcrops, more mafic layers display complex folding.

A sample from this outcrop yielded a U/Pb zircon age of 1057 +/- 11 ma (McLelland et al. 1988). This age, which coincides with the age of peak granulite facies metamorphism in the Adirondacks, is interpreted by Chiarenzelli and McLelland (1991) as the age of igneous emplacement, making the Lyon Mountain Gneiss a syntectonic intrusive suite. This conflicts with the evidence cited by Whitney and Olmsted (1988) indicating a supracrustal origin. Possible resolutions of this conflict will be discussed.

Return to vehicles, turn around and return to Rte. 9N via Harkness Road.

2.4 22.1 Turn R (W) on Route 9N.

2.2 24.3 <u>STOP 5 Epidote-bearing layered gneisses.</u> The outcrops on the N side of the road are unique within the Lyon Mountain Gneiss complex. The conspicuous cm-scale layering consists of alternating layers of microcline granitic gneiss and a rock rich in quartz, epidote, and chlorite (replacing ??). Clinopyroxene, amphibole (pleochroic from blue to green), scapolite, plagioclase, and sphene are present in some layers. The delicate layering, combined with the overall felsic composition, suggests a protolith of water-laid sediments and felsic tuffs.

2.3 26.6 <u>STOP 6. Fayalite Granite.</u> Park on the N side of Route 9N near the foundation of a former restaurant, previously known as the Lima Club and the Red Bandana. The outcrops of interest are an old quarry in the woods well to the north of the road. Our approach will depend on where we can get permission from landowners. The rock is a massive to slightly foliated, dark green fayalite-ferrohedenbergite granite. In thin section, the feldspar is a magnificent flame perthite. The fayalite granite is apparently surrounded by Lyon Mountain Gneiss, although we have been unable to find an exposed contact. Interestingly, it yields an older U/Pb zircon age (1089 +/-6 ma; Chiarenzelli and McLelland 1991) than the more strongly deformed Lyon Mountain. It is also more reduced than the Lyon Mountain, with oxygen fugacity close to the fayalite-magnetite-quartz buffer.

0.4 27.0 The small outcrops on the R are the leucocratic albite gneiss facies of the Lyon Mountain, here with conspicuous thin mafic layers.

0.6 27.6 Route 9N turns sharply to L in the village of Au Sable Forks.

0.3 27.9 Route 9N turns R; continue straight ahead across bridge and turn R on Sheldrake Road.

1.4 29.3 STOP 7 The Snake No hammers, please! Small outcrops on the E (left) side of the road show intricately folded marble, calcsilicates, amphibolite and granitic gneiss of the Rocky Branch Complex on the west limb of the Au Sable Forks synform, not far from the contact of the Jay Dome to the West. This very photogenic outcrop, informally known as "The Snake", has now been partially obscured by debris from construction upslope.

Turn around and return to Route 9N in Au Sable Forks.

1.5 30.8 Cross bridge and turn L on Route 9N.

1.8 32.6 Stickney Bridge. On the hill to the R (W) is a large quarry in massive anorthosite of the Jay Dome. This quarry, and another just E of the river but not visible from the road, are operated by the Lake Placid Granite Co., and are the only active quarries in the Adirondacks producing anorthosite as dimension stone.

3.6 36.2 Intersection of Routes 9N and 86 in Jay.

END OF PART A.

TRIP AB-2, PART B
GEOLOGY OF THE WILLSBORO-LEWIS WOLLASTONITE ORES

James F. Olmsted[1], Philip R. Whitney[2]
and Paul W. Ollila[3]

1. S.U.N.Y. Plattsburgh, Plattsburgh, NY 12901
2. N.Y.S. Geological Survey, Albany, NY 12230
3. 7 Newton St., Shrewsbury, MA 01545

INTRODUCTION

The presence of wollastonite near Willsboro in the northeastern Adirondacks has been known since the early nineteenth century (Buddington, 1977). Without an obvious use, the occurrence was of little interest except as a mineralogical curiosity until the early 1950's when the Cabot Corporation began mining it for use as a filler and ceramic base. Product development resulted in such uses as a tempering agent in ceramics, flux in welding rods, an alloying agent, an extender in plastics and, recently, as a substitute for short fiber asbestos. With the opening of the large open pit mine in Lewis, ten miles SW of Willsboro, in 1980, the original Willsboro mine was closed. Both properties are now owned by NYCO Minerals, Inc.

GEOLOGIC SETTING

Both the Willsboro and Lewis deposits lie in a zone of interlayered, granulite facies, metasedimentary and metaigneous rocks immediately overlying the anorthosite of the Westport Dome (Figs. A2, B1, B2). This zone, mappable for 22 km along strike, also contains two undeveloped wollastonite prospects near Deerhead and Oak Hill on the Au Sable Forks quadrangle. It occupies the same structural position as the lower part of the layered metamorphic complex of the Au Sable Forks quadrangle (Fig. A2), and is continuous with it. In addition to the ore, the metasedimentary rocks include pyroxene-rich calcsilicate granulites and local marbles. The metaigneous rocks include stratiform metanorthosite, amphibolite, metagabbro, and, locally, charnockite.

Structurally, the lowest unit in the Willsboro mine area is the anorthositic gneiss of the Westport dome (Figs B1 & B2). This rock contains large (>5cm) dark bluish megacrysts embedded in a lighter gray granular plagioclase matrix. The contact between the anorthositic rocks and the overlying wollastonite ore is nowhere exposed. De Rudder (1962) reports a mafic gneiss up to a few tens of meters thick between this anorthosite and the ore. One exposure of this rock may be seen at the middle portal; our

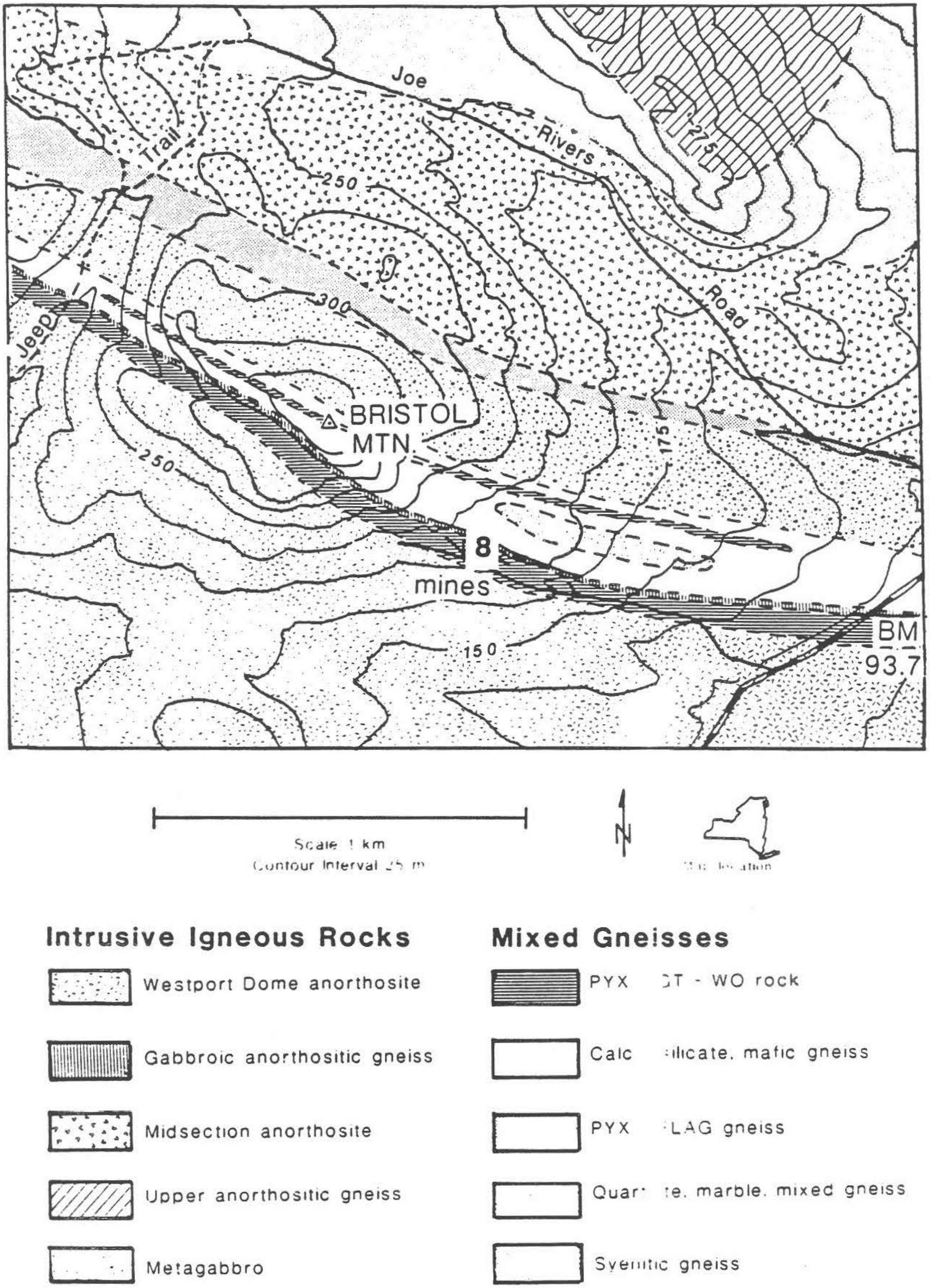

Fig. B1 Geologic map of the vicinity of the Willsboro wollastonite mine. Geology by J. F. Olmsted and P. W. Ollila.

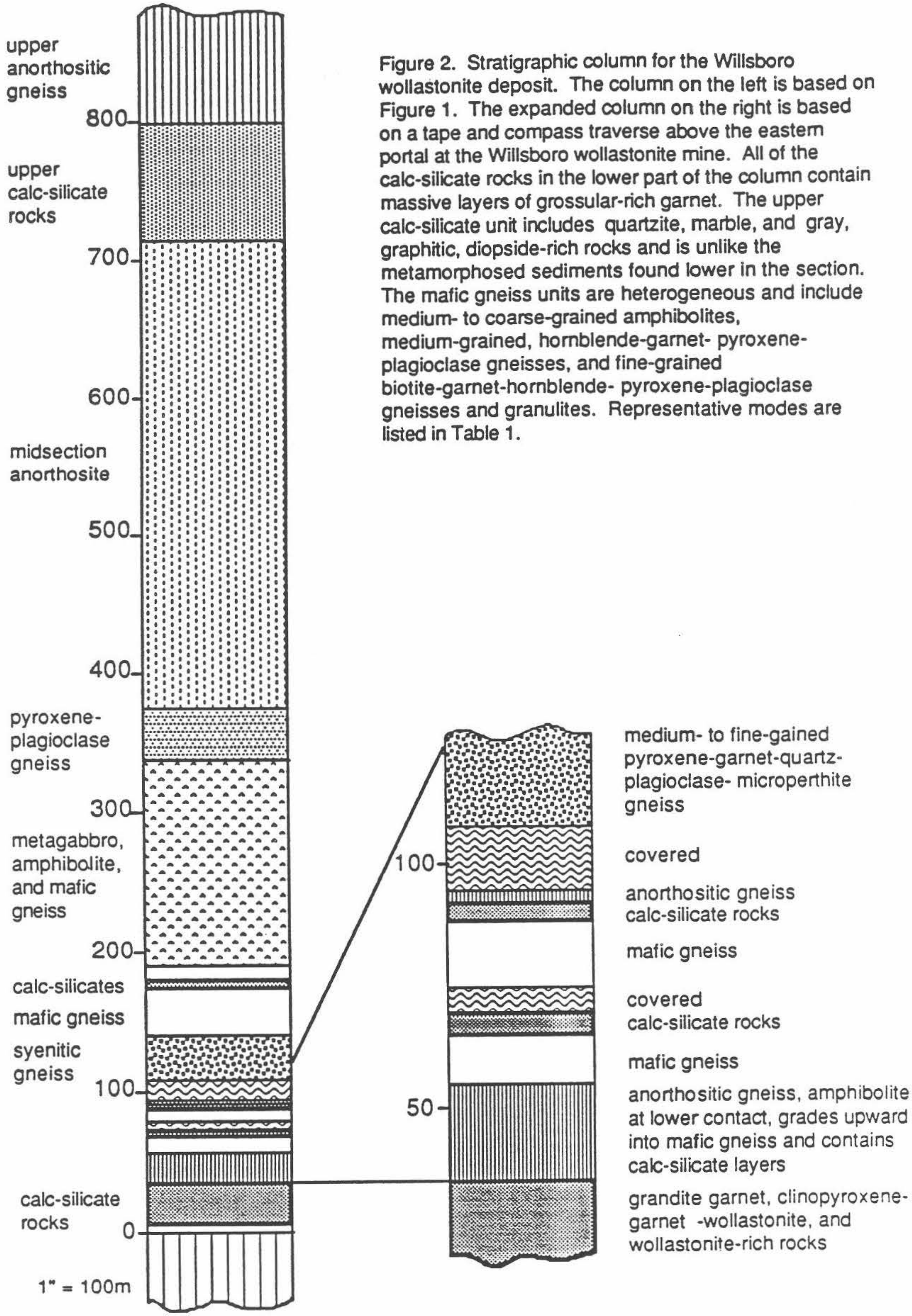

Figure 2. Stratigraphic column for the Willsboro wollastonite deposit. The column on the left is based on Figure 1. The expanded column on the right is based on a tape and compass traverse above the eastern portal at the Willsboro wollastonite mine. All of the calc-silicate rocks in the lower part of the column contain massive layers of grossular-rich garnet. The upper calc-silicate unit includes quartzite, marble, and gray, graphitic, diopside-rich rocks and is unlike the metamorphosed sediments found lower in the section. The mafic gneiss units are heterogeneous and include medium- to coarse-grained amphibolites, medium-grained, hornblende-garnet- pyroxene-plagioclase gneisses, and fine-grained biotite-garnet-hornblende- pyroxene-plagioclase gneisses and granulites. Representative modes are listed in Table 1.

mapping suggests that its thickness is highly variable. Immediately above the wollastonite are units, of varying thickness, of anorthositic and mafic gneiss. These in turn are overlain by lenses and layers of calcsilicate gneisses, amphibolite, plagioclase-pyroxene +/- garnet (mafic) gneiss and syenitic gneiss all of which may be various mixtures of former igneous and sedimentary rocks, intruded by a large sill-like body of metagabbro. Other stratiform metaigneous bodies including the "midsection anorthosite" (Fig. B2) also intrude the metasedimentary belt and may have played a role in the development of the ores. Thinner layers of metagabbro and metanorthosite, which may be either sills or tectonic slivers, are locally present in the ore zone itself. Contacts between ore and anorthositic or gabbroic layers are commonly marked by zones of nearly monomineralic, grossularitic garnet from a few cm up to a meter or more in thickness. Because of the soluble nature of wollastonite, this "garnetite" may be the only indicator at the surface of the presence of ore. The metasedimentary belt as a whole is overlain by a thick upper anorthositic gneiss unit (Figs. B1 & B2), extensively contaminated by layers, inclusions, and schlieren of metasediments and mafic, garnet-rich rock (Buddington and Whitcomb, 1941; Buddington, 1977)

In the vicinity of the Willsboro mine compositional layering and foliation strike WNW with moderate northerly dips. Lineations and small fold closures trend northwesterly, nearly parallel to the strike of the foliation, and plunge at shallow angles. Lineations at the Deerhead prospect four km to the west plunge more steeply to the west suggesting that fold axes there are more steeply inclined. Between the two areas in the vicinity of the Adirondack Northway the metasedimentary rocks in the upper part of the section are found only as inclusions in anorthosite, and the wollastonite ore horizon appears to be absent. We interpret the metasedimentary belt as a keel-like structure in which plunge changes direction along strike of the belt. This results in apparent thinning or thickening ("porpoising") of the belt along strike. Mapping in the Willsboro quadrangle to the west of the mine area also suggests that the lower part of the section is beveled by the midsection anorthosite sheet and the upper units. Consistent with this, it is reported by the mine management that the ore body at Willsboro thins greatly down dip, so that in the lowermost part of the mine it is only a few meters thick. The irregular keel-like structure of the metasedimentary belt combined with the beveling of units within it leads to the observed absence of the wollastonite ore horizon along much of the belt.

MINERALOGY, PETROLOGY, AND ORIGIN OF THE ORE

Typical occurrences of wollastonite in metasedimentary rocks in the northeastern Adirondacks, such as those at Stop 1 of Part A of this trip, contain wollastonite in association with diopside and several of the following: feldspar (microcline and/or plagioclase), scapolite, quartz and/or calcite, grossularitic garnet (usually as reaction rims), graphite, and pyrrhotite or pyrite. In striking contrast, the Willsboro-Lewis ores commonly contain only the high-variance assemblage wollastonite-clinopyroxene-garnet.

The mineral composition of the wollastonite ore zone is quite variable. A specific norm calculation of four analyses of ore by DeRudder (1962) average almost 80% wollastonite, but the average mine average for a nine month period in 1960-61 was 64 percent wollastonite. Extreme compositions include garnet- and pyroxene-rich layers of varying thickness that contain minor titanite, apatite, and zircon. Locally, these appear to crosscut foliation in the ore at a small angle. We will examine some of them at the lower and middle portals of the Willsboro mine.

Electron microprobe studies of the garnet and pyroxene in the ores show an extreme range in composition. In 22 samples from Willsboro, clinopyroxene ranges from Hd_4 (diopside) to Hd_{58} (salite) and garnet from Ad_7 to Ad_{72}. In 3 samples from Lewis, the ranges are Hd_{38}-Hd_{49} and Ad_{21}-Ad_{93} respectively. Garnet compositions may vary by as much as 15% Ad within a 5 cm piece of drill core, and by several percent within a standard thin section. The garnet in the ore is commonly andradite-rich, though highly variable, while that in the garnet-pyroxene layers is more grossularitic. There is no consistent correlation between garnet and pyroxene compositions. In hand specimen, the grossularitic garnets have a light brownish orange color while the andradite-rich garnets are a deep reddish brown. The pyroxenes range from pale green (diopside) to nearly black (salite).

Wollastonite is ordinarily formed by the reaction:

Calcite + Quartz = Wollastonite + CO_2 (1)

under contact metamorphic conditions. The evidence for meta-evaporites in the northeastern Adirondacks suggests

Anhydrite + Quartz = Wollastonite + (sulfur species) + Oxygen (2)

as a possible alternative. Experimental work by Luhr (1990) has shown that reduction of anhydrite can take place under geologically reasonable conditions of temperature, pressure, and oxygen fugacity. Oxidation reactions coupled with reaction (2) provide one explanation for the conspicuous absence of graphite and sulfide minerals in the ores. The abundance of ferric iron, present in andraditic garnet, also suggests oxidizing conditions. The andradite-hedenbergite thermometer/oxygen barometer of Zhang and Saxena (1991), applied to a sample from Lewis with exceptionally andradite-rich garnet, indicates oxygen fugacities well above the fayalite-magnetite-quartz buffer (Fig. B3).

Valley and O'Neil (1982, 1984) and Valley (1985) report oxygen isotopic data for both the Willsboro and Lewis deposits. They find anomalously low $\delta^{18}O$ values (-1.3 to 3.1; up to 20 permil lower than typical Adirondack marbles) in the wollastonite ore, as well as extremely sharp gradients between ore and wall rocks. Valley (1985) argues that such extreme $\delta^{18}O$ values cannot be explained solely by devolatilization reactions and probably result from deep circulation of heated meteoric waters 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 depths of less than 10 km, shallow relative to the subsequent 7-8 kbar granulite facies metamorphism (Bohlen et al, 1985). If the wollastonite was a product of contact metamorphism at the time of anorthosite intrusion, as its spatial relationship to anorthosite suggests, it follows that anorthosite intrusion also occurred at relatively shallow depths.

The abundance of wollastonite in these rocks, coupled with the complete absence of both quartz and calcite (or anhydrite) 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 played a significant role in the ore-forming process. This is consistent with the high variance of the mineral assemblages in the ore, but inconsistent with the sharp gradients observed in mineral compositions over distances on the order of centimeters. An alternative explanation, preferred by your trip leaders, is that leftover reactants have been removed in solution, most probably by the heated meteoric waters that gave the ore its oxygen isotope signature. The fact that anhydrite (and/or gypsum) are more soluble than either calcite or quartz is another piece of circumstantial evidence favoring an evaporite protolith. Moreover, the presence of readily soluble minerals would provide favorable channelways for aqueous solutions.

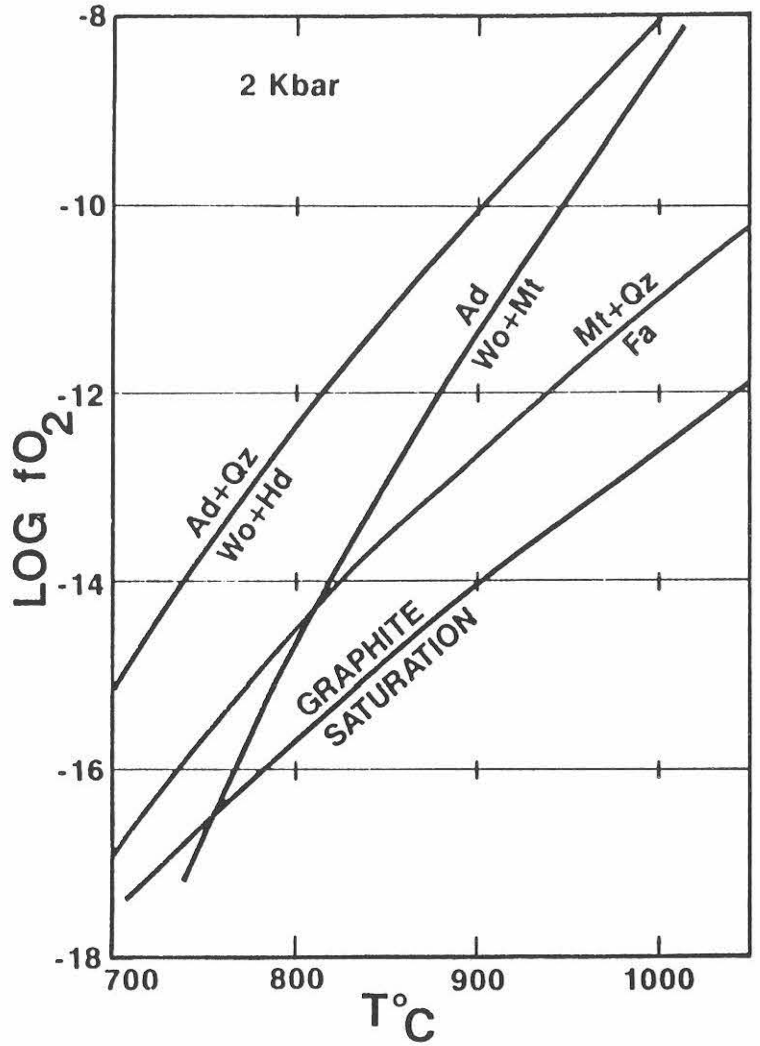

Fig. B3. Log fO_2 vs. T diagram for Lewis wollastonite ore, based on the reactions 4Hd + 2Wo +O_2 = 2Ad + 4 Qz and 18Wo + 4Mt + O_2 = 6Ad (Zhang and Saxena, 1991); calculated for a sample with garnet Ad93 and pyroxene Hd49 and an assumed pressure of 2 kbars. For the ore assemblage wollastonite-garnet-pyroxene without quartz or magnetite, fO_2 must lie between the two upper curves. Less Fe-rich garnet and higher metamorphic pressure move the second reaction to substantially lower fO_2.

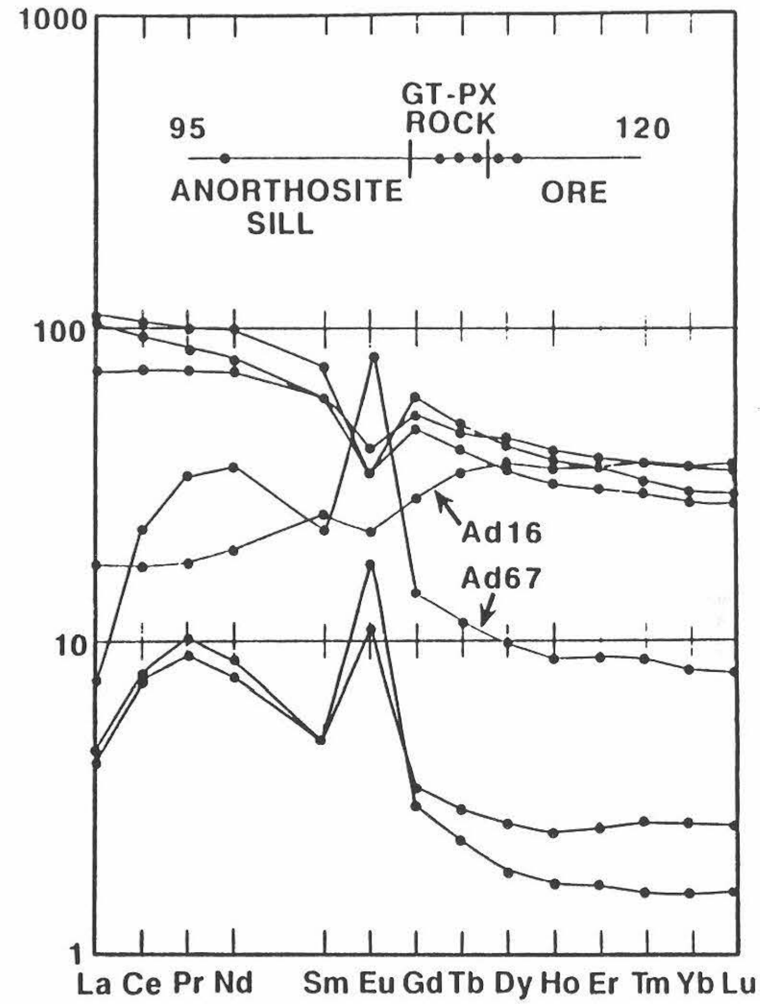

Fig. B4 Chondrite-normalized REE distributions for samples spaced one foot apart in drill core. Lower two curves are wollastonite ore; upper three curves are garnet-pyroxene rock. Curves Ad67 and Ad16 are for garnet separates from ore and Gt/Px rock, respectively; the labels are the garnet compositions as determined by electron microprobe.

Whether the protolith consisted of carbonates plus quartz or evaporites plus quartz, the presence of subordinate amounts of, e.g., dolomite and chlorite could account for the garnet and pyroxene in the ore. The grossularitic "garnetite" zones at the contacts between ore and plagioclase-rich rocks may result from a later (Grenville?), higher pressure metamorphic reaction such as:

Wollastonite + Plagioclase =
Garnet + Quartz + more sodic plagioclase (3)

We are currently studying the distribution of rare earth elements (REE) in the wollastonite ores. Figure B4 shows results representative of the more than 30 samples analyzed to date. It shows chondrite-normalized REE distributions in five samples taken at one foot intervals in a drill core at the Willsboro mine, and hand-picked garnet separates from two of them. The lower two curves are typical wollastonite ore, with strong positive Eu anomalies and a general enrichment in the light REE (LREE) combined with relative depletion in La and Ce. The curve labeled Ad67 is the garnet (67% andradite) from one of them; it is enriched in all REE relative to the whole rock, but shows the same general distribution. The upper three curves are for garnet-pyroxene (titanite, apatite, zircon) rock in a layer adjacent to the ore. Compared to the ore samples, all show less LREE enrichment with no depletion in La and Ce; moreover they have <u>negative</u> Eu anomalies. The garnet (Ad16) from one of these shows modest heavy REE enrichment and a slight negative Eu anomaly. The bulk of the LREE in this sample is contained in titanite and apatite.

At this stage of our work we do not clearly understand the significance of the REE data. The abrupt gradients in <u>mineral</u> REE content confirm the disequilibrium already inferred from the electron microprobe data. The overall REE distribution in the ores, including the strong positive Eu anomaly, is remarkably similar to that in Adirondack anorthosites (Ashwal and Siefert, 1980), and may reflect hydrothermal (?) exchange with the subjacent Westport Dome anorthosite at the time of ore formation. Marbles in the metasedimentary section show LREE enrichment similar to that in the ore, but they are not depleted in La and have distinct negative Eu anomalies. Even more speculatively, the La and Ce depletion in the ore may result from removal in solution of massive amounts of a relatively LREE-enriched soluble phase (anhydrite?). The distinctly different REE patterns in the garnet-pyroxene layers, which locally appear to crosscut foliation in the ore, may result from REE exchange combined with solution and removal of wollastonite along fractures during a later (and unrelated ?) hydrothermal event.

ROAD LOG (PART B)

Because there are only two stops on this part of the trip, an abbreviated road log will be used beginning at the intersection of NY routes 9 & 22 at exit 33 if the Adirondack Northway (I-87).

MILES	CUMULATIVE	
0.0	0.0	Leave the intersection of Rts.9 & 22 heading southeast on Route 22 toward Willsboro.
6.7	6.7	Turn right on Fish and Game Club Road just after sign indicating the Willsboro village limit.
0.3	7.0	Bear right.
0.7	7.7	Road left, continue straight.
0.5	8.2	Bear right on Mtn. View Road at YIELD sign.
0.5	8.7	Joe Rivers Road to right. Continue on Mtn. View Road.
0.4	9.1	Turn R on unpaved road and proceed about 0.1 miles up hill to gate. Park on side of road and continue on foot to the lower portal of the abandoned Willsboro mine.

STOP 8. WILLSBORO MINE This will be a long stop during which we will examine relationships at surface exposures near the middle and lower portals, and then proceed northward across the overlying units about 600 m where we encounter the "midsection" anorthosite unit (see figs B1 and B2). We will then return to the mine via a slightly more westerly traverse to see additional exposures of the units overlying the ore, including a fine example of coronitic metagabbro.

CAUTION: Please do not under any circumstances go underground. NYCO has graciously given us permission to visit these mines, but this privilege will be withdrawn in the event of an accident to any of our visitors. If you wish to follow this trip on your own, first get permission at the NYCO offices in Willsboro.

0.2	9.3	Upon returning to paved road, turn R (West) towards Lewis.
2.3	11.6	Turn R onto Reber Road.
1.0	12.6	Turn R at T intersection in hamlet of Reber.
0.1	12.7	Turn L (still on Reber Road).

2.7 15.4 Bridge over Northway.

0.3 15.7 Cross Bouquet River.

0.7 16.4 Turn L onto Route 9.

3.9 20.3 Turn R on Wells Road.

2.8 23.1 End of paved road. The gate to the Lewis Mine is on the L. Get permission; then proceed up gravel road to the mine.

STOP 9. LEWIS MINE While the immediate geologic setting of the Willsboro deposit is well known (Putman, 1958; DeRudder, 1962; Olmsted and Ollila, 1988), that of the Lewis deposit is less clear due to lack of natural exposures in the immediate vicinity. The orebody strikes roughly E-W and dips, on the average, gently south, approximately parallel to the topographic surface. On the west side of the open pit, where the ore is close to 25 m thick, it is overlain by charnockitic gneiss, whereas north and east of the pit the overlying rock is mainly anorthositic. Based on drilling data and temporary exposures within the mine, the footwall appears to be amphibolite and gabbroic anorthosite gneiss.

REFERENCES

Ashwal, L. D., and Seifert, K. E., 1980, Rare earth element geochemistry of anorthosite and related rocks from the Adirondacks, New York, and other massif-type complexes: Geological Society of America Bulletin, v. 91, part II, p. 659-684.

Balk, R., 1931, Structural geology of the Adirondack anorthosite: Min. Pet. Mitt., v. 41, p. 308-434.

Behr, H-J., Arendt, H., Martin, H., Porada, H., Rohrs, J., and Weber, K., 1983, Sedimentology and mineralogy of upper Proterozoic playa-lake deposits in the Damara orogen, In Martin, H., and Eder, F.W., eds., Intracontinental fold belts. New York, Springer Verlag, p. 577-610.

Bohlen, S. R., Valley, J. W., and Essene, E. J., 1985, Metamorphism in the Adirondacks: I. Petrology, Pressure, and Temperature: Journal of Petrology, v. 26, p.971-992.

Brown, J.S., and Engel, A.E.J., 1956, Revision of Grenville stratigraphy and structure in the Balmat-Edwards district, northwest Adirondacks, New York: Geol. Soc. Amer. Bull., v. 67, p. 1599-1622.

Buddington, A. F., 1939, Adirondack igneous rocks and their metamorphism: Geological Society of America Memoir, no. 15, p. 1-354.

Buddington, A. F., 1977, Guidebook for field trips, petrology and mineral deposits, northwestern and northern Adirondack area. Unpublished.

Buddington, A.F. and Whitcomb, L. (1941) Geology of the Willsboro quadrangle, New York. New York State Museum Bulletin, 325, 137p.

Chiarenzelli, J. R., and McLelland, J. M., 1991, Age and regional relationships of granitoid rocks of the Adirondack Highlands: Journal of Geology, v. 99, p. 571-590.

Coish, R. A., and Sinton, C. W., 1992, Geochemistry of mafic dikes in the Adirondack Mountains: implications for late Proterozoic continental rifting: Contrib. Mineral. Petrol., v. 110, p. 500-514.

Cook, N. D. J., and Ashley, P. M., 1992, Meta-evaporite sequences, exhalative chemical sediments, and associated rocks in the Proterozoic Willyama Supergroup, South Australia: implications for metallogenesis: Precambrian Research, v. 56, p. 211-226.

DeRudder, R.D., 1962, Petrology and genesis of the Willsboro wollastonite deposit, Willsboro, New York. PhD thesis, Indiana University, 156 p.

Friedman, G.M., 1980, Dolomite is an evaporite mineral: evidence from the rock record and sea-marginal ponds of the Red Sea. In Zenger, D.H., Dunham, J.B., and Etherington, R.L., eds., Concepts and models of dolomitization: SEPM Special Publication 28, p. 69-80.

Gallagher, D., 1937, Origin of the magnetite deposits at Lyon Mountain, New York. New York State Museum Bull. 311, 85 p.

Leake, B.E., Farrow, C.M., and Townend, R., 1979, A pre-2000 myr-old granulite facies metamorphic evaporite from Caraiba, Brazil?: Nature v. 277, p. 49-51.

Luhr, J. F., 1990, Experimental phase relations of water- and sulfur- saturated arc magmas and the 1982 eruption of El Chichon volcano: Journal of Petrology, v. 31, p. 1071-1114.

McLelland, J.M.; Chiarenzelli, J.; Whitney, P.R., and Isachsen, Y.W., 1988, U-Pb zircon geochronology of the Adirondack Mountains and implications for their geologic evolution: Geology, v. 16, p. 920-924.

McLelland, J. M., and Isachsen, Y. W., 1985, Geological evolution of the Adirondack Mountains: a review: in Tobi, A. C., and Touet, J. L. R., eds., The deep Proterozoic crust of the North Altlantic provinces: Reidel, Dordrecht, p. 175-215.

McLelland, J. M., and Whitney, P. R., 1990, Anorogenic, bimodal emplacement of anorthositic, charnockitic and related rocks in the Adirondack Mountains, New York: in Stein, H.J. and Hannah, J.L., eds., Ore-bearing granite systems: petrogenesis and mineralization processes. Geological Society of America, Special Paper 246, p. 301-316.

Miller, W. J., 1916, Origin of foliation in the Precambrian rocks of northern New York: Journal of Geology, v. 24, p. 587-619.

Olmsted, J. F., and Ollila, P. W., 1988, Geology of the Willsboro wollastonite mine: in Olmsted, J. F., ed., New York State Geological Association Field Trip Guidebook, v. 60, p. 263-276.

Ortega-Gutierrez. F., 1984, Evidence of Precambrian evaporites in the Oaxacan granulite complex of southern Mexico: Precambrian Research, v. 23, p. 377-393.

Postel, A.W., 1952, Geology of the Clinton County magnetite district, New York. U.S. Geol. Surv. Prof. Paper 237, 88 p.

Putman, G. W., 1958, The geology of some wollastonite deposits in the eastern Adirondacks, New York: MS thesis, Pennsylvania State University.

Surdam, R.C., 1981, Zeolites in closed hydrologic systems: In Mumpton, F.A., ed., Mineralogy and geology of natural zeolites. Mineral. Soc. Amer. Reviews in Mineralogy, v. 4, p. 65-91.

Valley, J. W., 1985, Polymetamorphism in the Adirondacks: wollastonite at contacts of shallowly intruded anorthosite: In: Tobi, A. C., and Touret, J. L. R., The deep Proterozoic crust of the North Atlantic Provinces, Riedel, Dordrecht, p. 217-235.

Valley, J. W., Bohlen, S. R., Essene, E. J., and Lamb, W., 1990, Metamorphism in the Adirondacks: II, The role of fluids: Journal of Petrology, v. 31, p. 555-597.

Valley, J. W., and O'Neil, J. R., 1982, Oxygen isotope evidence for shallow emplacement of Adirondack anorthosite: Nature, v. 300, p. 497-500.

Valley, J. W., and O'Neil, J. R., 1984, Fluid heterogeneity during granulite facies metamorphism in the Adirondacks: stable isotope evidence: Contributions to Mineralogy and Petrology, v. 85, p. 158-173.

Whitney, P.R. and Olmsted, J.F., 1988, Geochemistry and origin of albite gneisses, northeastern Adirondack Mountains, New York: Contrib. Mineral. Petrol., v. 99, p. 476-484.

Zhang, Z., and Saxena, S. K., 1991, Thermodynamic properties of andradite and application to skarn with coexisting andradite and hedenbergite: Contrib. Mineral. Petrol., v. 107, p. 255-263.