WOLLASTONITE DEPOSITS OF THE NORTHEASTERN ADIRONDACKS

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INTRODUCTION

The presence of wollastonite near Willsboro in the northeastern Adirondacks (Fig. 1, 2) has been known since the early nineteenth century. The earliest reference to it in the geologic literature is by Vanuxem (1821). For over a century, the wollastonite was of little interest except as a mineralogical curiosity. Mining on a small scale began at Fox Knoll near Willsboro in 1938, with the wollastonite being used as a flux for arc welding. In 1951, the Cabot Corporation gained control, and began underground mining in 1960. Interpace Corporation took over and expanded operations in 1969. Product development resulted in uses in ceramic bodies and glazes, as a reinforcing filler in plastics and resins, and as a substitute for short-fiber asbestos. The operation, now known as NYCO, was purchased in 1979 by a subsidiary of Canadian Pacific (US), Processed Minerals Inc. Open pit mining at the Lewis (Seventy Mountain) Mine, ten miles southwest of Willsboro, began in 1980 and in 1982 the underground operation at Willsboro was closed. Both properties are now owned by NYCO Minerals, Inc., a subsidiary of Fording Coal Company of Calgary, Alberta.

The Willsboro deposit was mentioned briefly by Buddington (1939, 1950) and Buddington and Whitcomb (1941); the geology is given in more detail by Broughton and Burnham (1944). Putman (1958) described several occurrences of wollastonite in the Au Sable Forks and Willsboro quadrangles, including those at Willsboro, Deerhead, and Lewis (Figure 2). De Rudder (1962) studied the mineralogy and petrology of the Willsboro ores, and attributed them to contact metamorphism with localized alumina metasomatism. Oxygen isotope work by Valley and O'Neil (1982) demonstrated extensive metasomatism involving meteoric water.

GEOLOGIC SETTING

The Westport metanorthosite dome (Figures 1 and 2) is located east and north of the Marcy Massif. It is overlain on its north and west flanks by interlayered granulite facies metaigneous and metasedimentary gneisses, marbles, and calcsilicate rocks. The wollastonite deposits at Willsboro and Lewis, as well as two undeveloped prospects at Oak Hill and Deerhead, occur within a mappable zone up to 2000 feet thick that extends for at least 14 miles along strike (Figure 2). This ore-bearing zone (OBZ) is characterized throughout by intense foliation and locally prominent lineation. Along the northern flank of the Westport Dome from Willsboro mine to Deerhead, the OBZ directly overlies the metanorthosite of the dome, foliations dip NNE away from the dome, and lineations plunge NW. Southwestward, near Oak Hill and the Lewis mine, dips flatten and lineations become parallel with the regional NNE trend (Whitney and Olmsted, 1993). In this area the OBZ diverges from the dome, although the thickness of intervening rocks is uncertain due to poor exposure and the unknown subsurface configuration of the anorthosite.

Metaigneous rocks within the OBZ occur as sheets and lenses parallel to foliation, emplaced either as sills or as tectonic slivers. They include gabbroic and anorthositic gneisses, amphibolite, and minor charnockite. Interiors of thick gabbroic layers may display relict igneous textures. Metasedimentary rocks consist chiefly of the wollastonite ores, associated garnet-pyroxene skarn, and a diverse suite of granular-textured garnet-clinopyroxene-plagioclase rocks, with minor sphene and apatite. Calcite marble occurs locally, as do very minor amounts of quartzite and metapelite.

The ore at all four known locations occurs as tabular bodies ranging from a few feet up to as much as 80 feet thick. Multiple wollastonite-bearing horizons, separated by gabbroic or anorthositic gneisses and amphibolite, are present at Willsboro (DeRudder, 1962). The orebodies consist of wollastonite-rich ore with garnet-pyroxene skarn

In Garver, J.I., and Smith, J.A. (editors), Field Trips for the 67th annual meeting of the New York State Geological Association, Union College, Schenectady NY, 1995, p. 25-38.

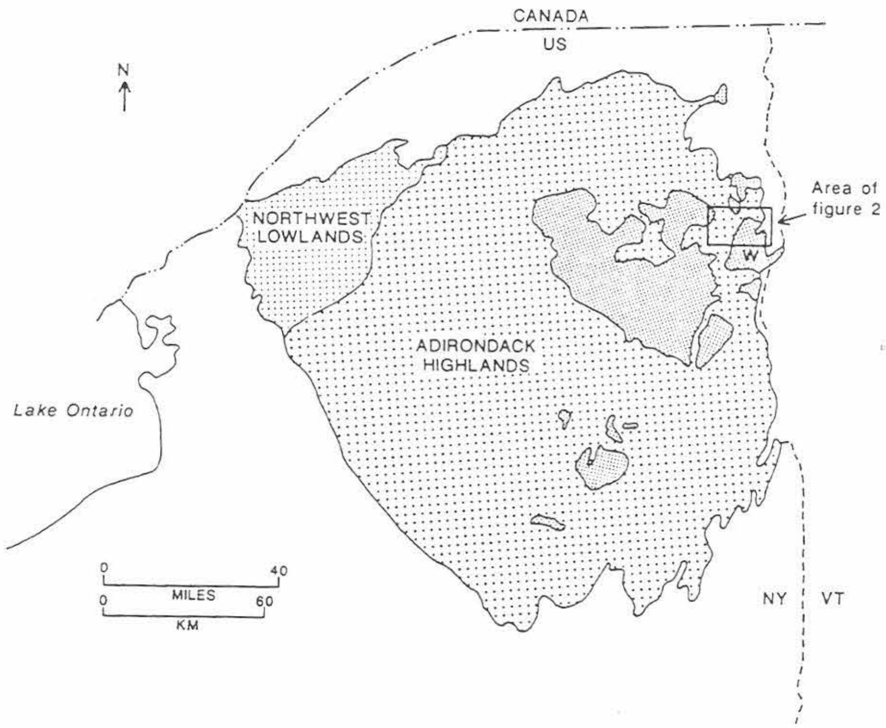

Figure 1. Location map showing the Adirondack region, with major anorthosite bodies in fine stippled pattern. W: Westport Dome. Rectangular outline: area of this trip.

(GPS) layers and lenses ranging from less than an inch to several feet thick. This compositional layering is ordinarily straight and sharply defined; it is probably not an original sedimentary feature but rather a result of tectonically induced metamorphic differentiation during or subsequent to ore formation. More diffuse compositional layering and foliation within the ore locally exhibits complex folding. Where layering is less prominent, garnet and pyroxene may occur in clusters or lenses up to 2 inches across.

MINERALOGY

The ore layers contain the high-variance assemblage wollastonite-grandite garnet-clinopyroxene. Traces of retrograde calcite occur as thin films replacing wollastonite along fractures and grain boundaries. GPS layers within the ore consist chiefly of garnet and clinopyroxene with or without minor wollastonite. Another type of GPS, containing up to several percent of sphene and apatite, occurs at contacts between ore and metaigneous gneisses or amphibolites and, less commonly, as sill- or dike-like bodies within the ore. Minor and trace minerals occurring very locally in GPS include scapolite, plagioclase, clinozoisite, idocrase, and zircon. Discontinuous layers up to several feet thick of nearly pure garnet, or garnet with minor plagioclase and quartz are present at some ore/gneiss contacts. These "garnetites" pinch and swell along strike or form detached lenses that resemble boudins.

Compositions of garnets and pyroxenes in ore and GPS were determined by electron microprobe. Standard polished thin sections were used for these analyses where possible; where the ore was too friable, grain mounts were prepared from hand specimens or 2-4 inch segments of drill core. The pyroxenes lie close to the diopside-hedenbergite join, containing >93% (Di + Hd), with acmite (up to 3.2%) as the most common minor component. The garnets are grossular-andradite mixtures, with > 92% (Gr + Ad); almandite (up to 4.9%) and schorlomite (up to 3.1%) are the dominant impurities. Figure 3 shows the range of compositions for the ore and GPS. Compositional variation among grains within a sample can be as great as 20% Ad and 10% Hd for garnet and pyroxene respectively, but individual grains lack detectable internal zoning.

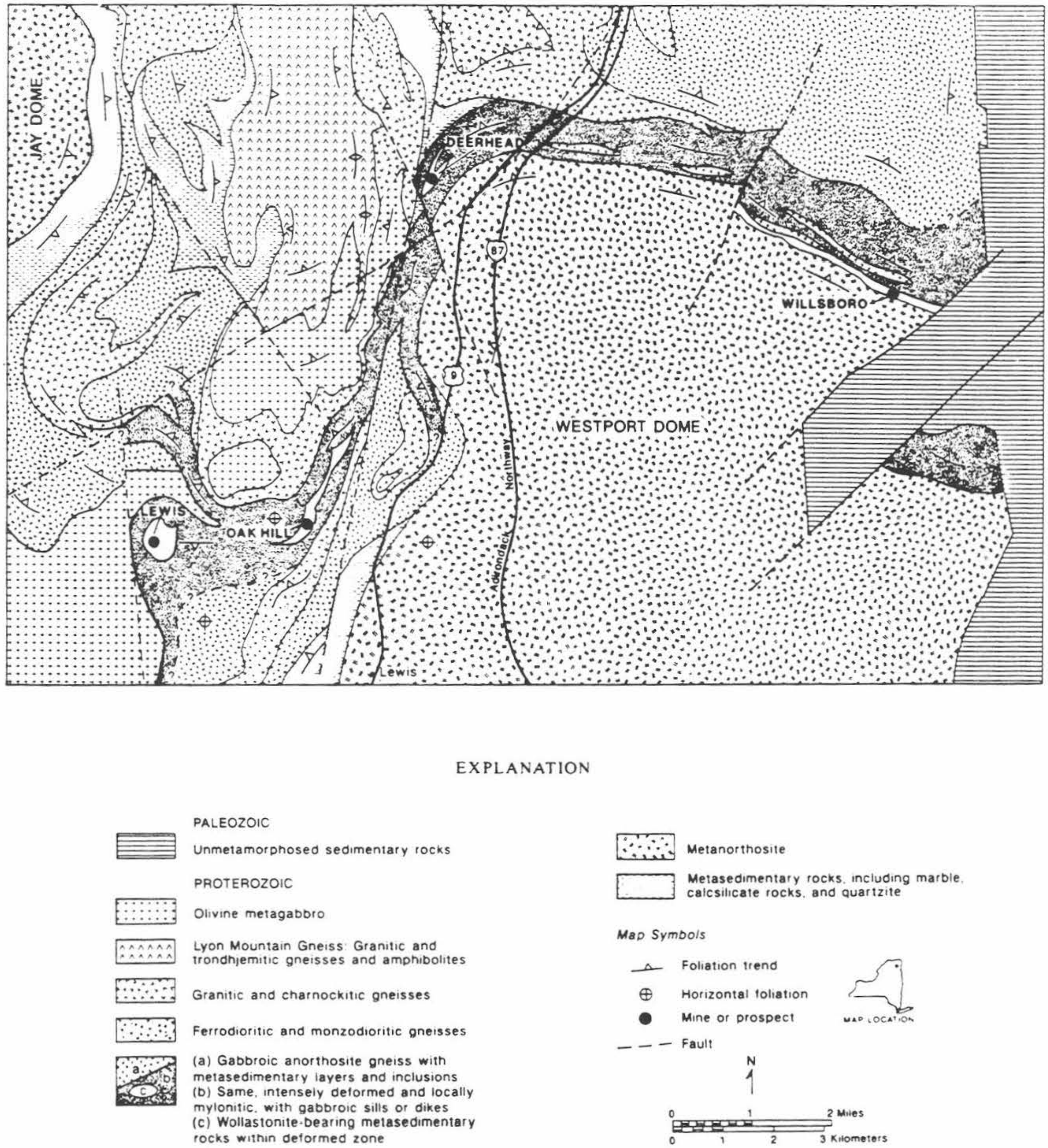

Figure 2. Simplified geological map of the northeastern Adirondack wollastonite district, after Buddington and Whitcomb (1941) and Whitney and Olmsted (1993). The heavy stippled pattern designates the zone of strongly foliated and lineated rocks containing the wollastonite mines and prospects (OBZ). Areas of predominantly metasedimentary rocks within the zone are blank.

GEOCHEMISTRY

Rare Earth Elements (REE)

Thirty-three samples of ore and 20 of GPS from the Willsboro and Lewis deposits were analyzed for rare earth elements (REE) by inductively coupled plasma mass spectrometry (ICPMS). REE were also determined in several metaigneous rocks within and near the ore zone, and in 8 marbles from the northeastern Adirondack area. The analyses reveal a variety of REE distributions in ore and GPS. Three general types can be distinguished; curves A-C in Figure 4a are the averages for these types. All but three of the 30 wollastonite-rich ores display the A pattern; those three have flat or slightly negative Eu anomalies. A similar distribution (A') is found in concordant GPS layers in the ore. A-type REE patterns are associated with relatively andradite-rich garnet (Table 1). The B pattern is typical of sphene and apatite- bearing GPS. Type C distributions occur in a few samples of both lean ore (<50% wollastonite) and sphene-free GPS. Both B and C patterns are correlated with andradite-poor garnet (Table 1).

TABLE 1: MINERAL COMPOSITIONS AND REE DISTRIBUTION

REE pattern	A		A'		B		C	
	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE
Garnet (% Ad)	51	25-93	58	35-83	23	14-41	27	22-33
Pyroxene (% Hd)	43	30-56	38	32-52	30	15-46	40	34-42
n	19		4		6		4	

Major and trace elements

X-ray fluorescence was used to determine the major- and trace- element chemistry of the ores and GPS. Twenty-one samples of ore and 18 of GPS from the Willsboro and Lewis deposits were analyzed. Table 2 shows the average compositions of samples from the four groups defined by REE patterns.

TABLE 2: MAJOR AND TRACE ELEMENTS

REE pattern	TYPE A	TYPE A'	TYPE B	TYPE C
n	18	5	9	7
SiO2	47.85	40.85	42.84	44.38
TiO2	0.18	0.43	1.94	0.45
Al2O3	2.45	6.86	9.22	9.69
Fe2O3(Tot)	6.74	16.06	9.05	8.39
MnO	0.17	0.17	0.21	0.28
MgO	1.33	2.24	3.76	2.41
CaO	40.68	32.92	31.61	33.94
Na2O	0.14	0.21	0.22	0.09
K2O	0.00	0.01	0.01	0.00
P2O5	0.01	0.04	0.97	0.05
Rb (ppm)	< 1	< 1	< 1	< 1
Sr	41	10	45	24
Ba	2	2	2	4
Zr	43	108	319	73
Y	7	13	61	79
Nb	2	3	13	2
Ga	8	20	15	15

ORIGIN OF THE ORES

Metasomatism

Wollastonite ordinarily occurs as a contact metamorphic mineral formed by reaction of calcite and quartz. However, the Willsboro-Lewis ores show metasomatism on a large scale. The evidence is outlined in the following four sections.

Mineral assemblages and compositions. If the wollastonite ore had been formed by isochemical contact metamorphism, the absence of either quartz or primary calcite would imply a protolith with precisely the right balance of quartz and calcite. This highly improbable requirement, together with the high variance of the ore mineral assemblage, indicates that metasomatism has occurred (Valley and O'Neil, 1982).

Metasomatic wollastonite, grandite garnet, and pyroxene are commonly observed in hydrothermal skarn deposits (e. g. Einaudi et al., 1981). Zoning is a common feature of hydrothermal garnets (Meagher, 1982), and may arise from variations in pressure and temperature, or changes in fluid composition (Lee and Atkinson, 1985). Varying proportions of andradite and grossular in originally zoned grains may account for much of the variability of garnet compositions in the Willsboro-Lewis ores and GPS (Figure 3). If early, contact metamorphic grossular was present, it is likely that hydrothermal garnet would nucleate on it to form composite crystals. The present lack of zoning in either garnet or pyroxene grains can be attributed to internal homogenization during subsequent granulite-facies metamorphism.

Oxygen isotopes. Valley and O'Neil (1982) determined oxygen isotopes in both the Willsboro and Lewis deposits. They found $\delta^{18}O_{SMOW}$ in the wollastonite ore from -1.3 to 7.0‰; as much as 25‰ lower than typical Adirondack marbles. Sharp gradients occur between ore and wall rocks. They (Valley and O'Neil, 1982) showed that the $\delta^{18}O$ data could not be explained by isotopic fractionation during devolatilization reactions, but required exchange with large volumes of heated meteoric waters at the time of anorthosite intrusion. Valley (pers. comm. 1992) analyzed four of our samples. Three ore samples yielded $\delta^{18}O$ values of +0.7, +0.7, and +1.3‰, and a GPS sample measured +2.9‰, in agreement with the results of Valley and O'Neil (1982). Eight ore samples from their work were included in this study and yielded type A REE patterns.

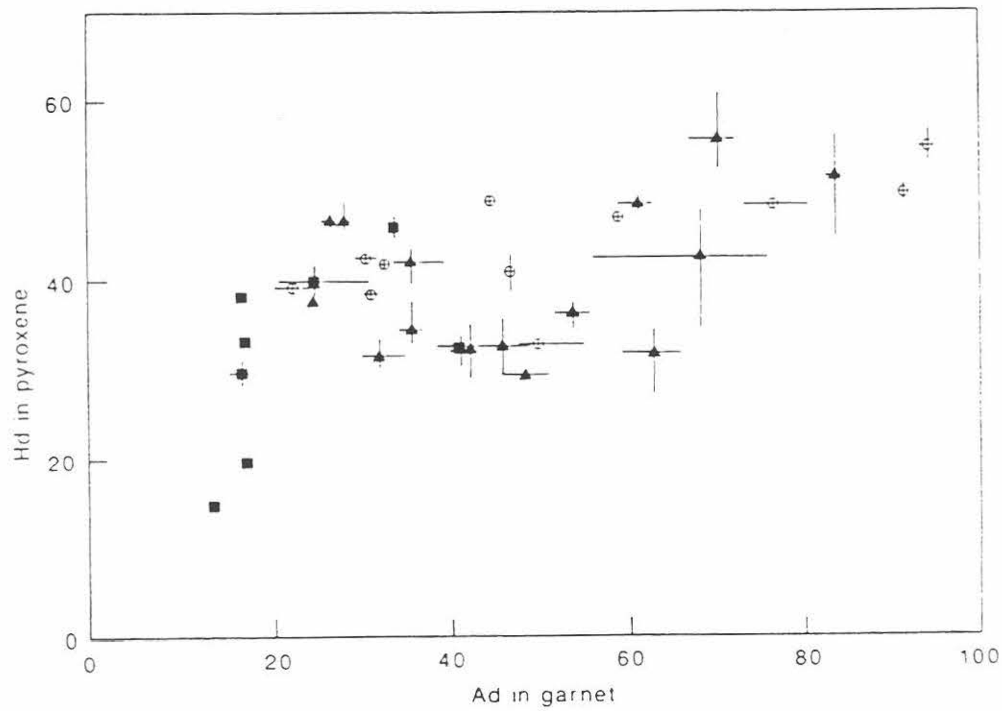

Figure 3. Garnet and pyroxene compositions in wollastonite ores and garnet-pyroxene skarns (GPS) as determined by electron microprobe. Bars show the range of mineral compositions within a thin section or 2-4 inch section of core; individual garnet and pyroxene grains are unzoned. Triangles: Willsboro ore. Open circles: Lewis ore. Filled squares: GPS.

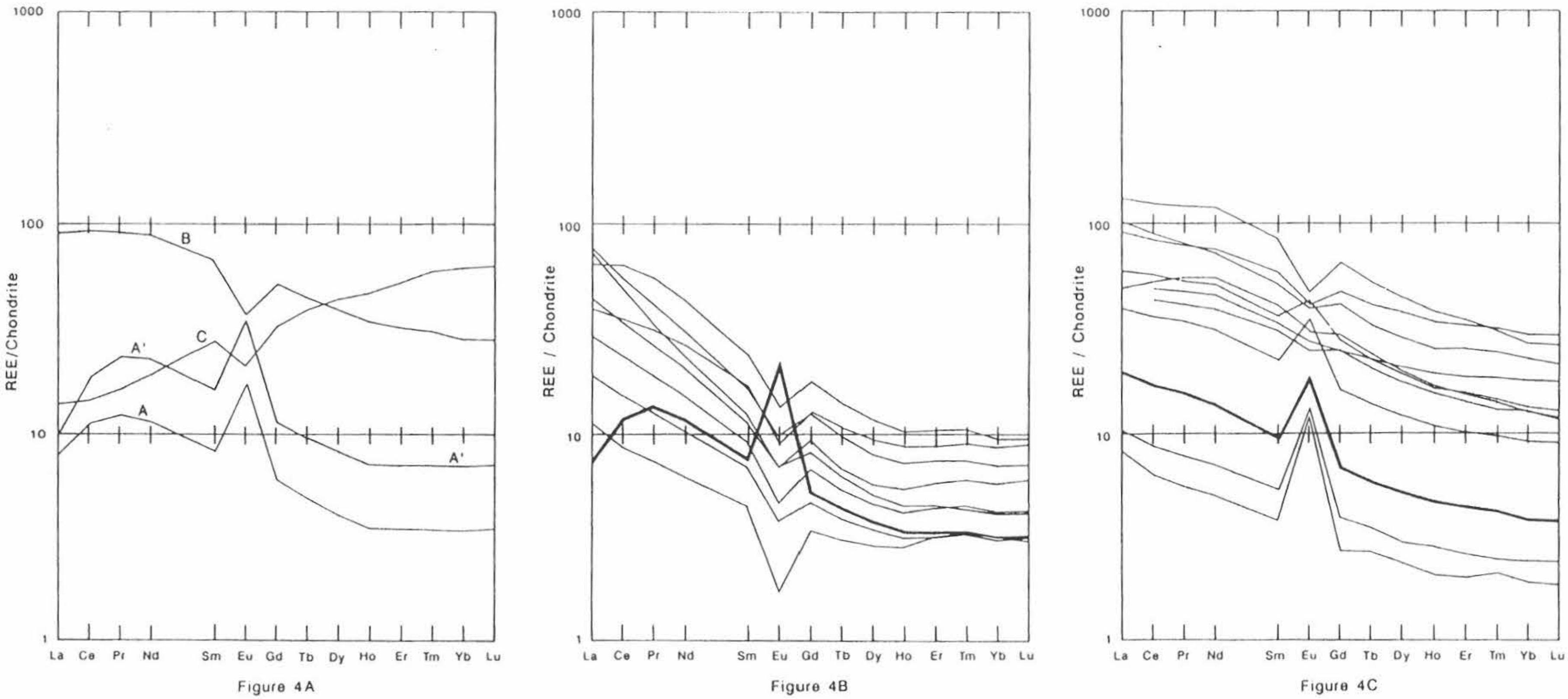

Figure 4. (a) Chondrite-normalized REE distribution in ore and (GPS). A: Average of 30 wollastonite-rich ores. A': Average of 6 conformable, sphene-free, high-andradite GPS layers in ore. B: Average of 10 sphene-bearing GPS. C: Average of 7 lean ores and sphene-free, low-andradite GPS. Letters correspond to the REE patterns discussed in text.

(b) REE distribution in northeastern Adirondack marbles and siliceous marbles. Heavy line: average wollastonite ore.

(c) REE distribution in metaigneous rocks in and near the OBZ. Upper lines are gabbros, amphibolites, and gabbroic anorthosites; lower lines are anorthosite; lowermost line is Westport Dome anorthosite approximately 10 m below the contact with the ore zone at Willsboro. Heavy line: average of 24 anorthosites and gabbroic anorthosites of the Marcy Massif.

The isotopic requirement for fluids of **meteoric** origin is consistent with the absence of nearby felsic or intermediate intrusive rocks to provide a source of magmatic fluids. Anorthosite and gabbro, both of which have anhydrous primary mineral assemblages, are unlikely to have been the source of large volumes of fluids. In addition, the andradite-rich garnet in the ores and the absence of the graphite and iron sulfides commonly present in Adirondack marbles indicate relatively oxidizing conditions, also consistent with meteoric fluids.

Depletion of Na, K, Rb, Ba, and Sr. Only those elements that can be accomodated in the structures of wollastonite, garnet, and pyroxene are present in significant concentrations in the ores and GPS (Table 2). This is particularly clear for the large-ion lithophile elements (LILE) K, Rb, and Ba, which are present in only negligible amounts. Comparison with Adirondack marbles shows levels of LILE in the ores significantly depleted from a hypothetical marble protolith (Table 3), suggesting metasomatic removal. Strontium is also depleted in the ores relative to marbles, although to a lesser extent. Some of the Sr in the ores is present in secondary calcite and may have been introduced subsequent to ore formation. LILE, Na, and Sr are also depleted by one or more orders of magnitude relative to the levels present in the host gneisses and amphibolites.

TABLE 3: INCOMPATIBLE ELEMENTS IN ORES AND MARBLES

	Marbles NW Adirondacks[1]	Marbles NE Adirondacks	Wo ores
K (ppm)	1594	-------	59
Ba (ppm)	227	170	2
Sr (ppm)	356	-------	41

[1] Data from K. Hauer, (Pers. Comm., 1993)

REE distribution. Assuming a carbonate protolith for the ore, comparison of the REE distributions in ore and GPS (Fig. 4a) with those of northeastern Adirondack marbles (Fig. 4b), confirm substantial metasomatic redistribution of REE. The REE patterns may be influenced by numerous factors including mineral compositions and modal abundance, protolith composition, fluid composition, fluid-rock ratios, and kinetics. Analyses of mineral separates suggest that Type A and A' patterns are largely controlled by the composition of garnet, which contains most of the REE in the ores. Both the size of the Eu anomaly and the Ce/Yb ratio are highly correlated with the andradite content of garnet, probably because the relatively large Eu^{+2} and light rare earth ($LREE^{+3}$) ions are more readily accomodated in the larger X sites of andradite relative to grossular (Novak and Gibbs, 1971). Interaction of the metasomatizing fluids with strongly Eu-positive anorthosite (Fig. 4c) may also have contributed to the Eu anomaly. The largest REE ions, La and Ce, tend to be excluded even from andradite, resulting in their depletion relative to Pr and Nd. Concentration of garnet from the ore into conformable GPS layers by tectonically induced metamorphic differentiation produces the similar A' pattern.

The very different REE distribution (Type B) found in sphene- and apatite-bearing GPS probably resulted from localized metasomatism of mafic igneous rocks in contact with ore; compare the B pattern in Figure 4a with the REE distribution in mafic metaigneous gneisses in the ore zone (Fig. 4c). In these rocks, LREE are retained in sphene and apatite while the heavy rare earths (HREE) remain in the relatively grossularitic garnet. The third major type of REE distribution (C) may originate from contact metamorphic calcsilicates and siliceous marbles containing abundant grossularitic garnet. The garnet retains the HREE and negative Eu anomaly of the protolith; subsequent overgrowths of metasomatic andradite from REE-poor hydrothermal fluids are insufficient to obscure the earlier pattern.

Sequence of ore-forming events

Origin of the ores by hydrothermal metasomatism requires a heat source to provide the minimum temperatures (ca. 450^{o}C) for formation of wollastonite and to drive the hydrothermal circulation. This requirement, and the close spatial association between the ores and the Westport Dome (Fig. 2) strongly indicate that the ore is coeval with emplacement of the anorthosite, in agreement with the conclusions of earlier workers (Buddington 1939, 1950; Broughton and Burnham 1944, DeRudder 1962). Moreover, access of large volumes of dominantly meteoric fluids implies a relatively shallow depth of emplacement (Valley and O'Neil 1982, Valley 1985). Access of fluids would also be facilitated in an extensional tectonic setting. Massif anorthosites are widely believed to be associated with extensional tectonics (Ashwal, 1993). Whitney and Olmsted (1993) and Fakundiny and Muller (1993) have argued that the Adirondack anorthosites were emplaced in an extensional setting that included large listric or detachment faults. We speculate that the present OBZ was the locus of one or more such faults. A similar association of extensional faulting with magmatic doming has been proposed by Lister and Baldwin (1993) for some metamorphic core complexes. Major low-angle extensional faults can provide channels for circulating hydrothermal fluids (Reynolds and Lister, 1987; Kerrich and Rehrig, 1987). When the Westport Dome was emplaced, hydrothermal circulation driven by heat from the intrusive may have followed the low-angle faults, fed from the surface by meteoric water penetrating along associated high-angle normal faults (Figure 5). Where the faults intersected or followed reactive carbonate units, infiltration metasomatism produced wollastonite and andraditic garnet, accompanied by exchange of REE and oxygen isotopes.

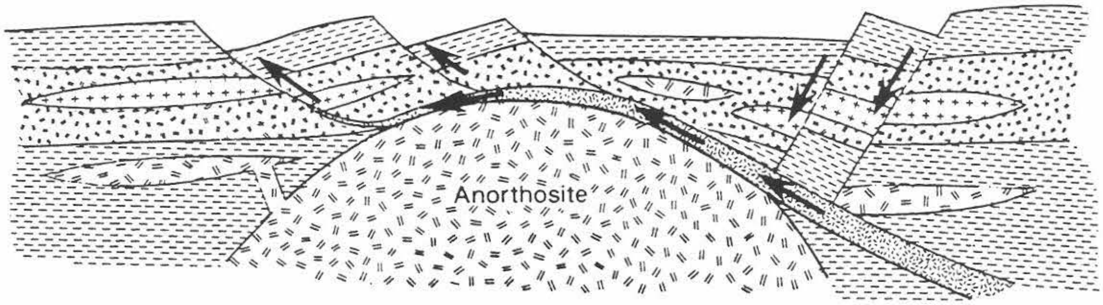

Figure 5. Cartoon illustrating the hydrothermal system inferred to be responsible for the wollastonite ores. Low-angle extensional faults developed coincident with anorthosite intrusion, and coalesced to form a zone along the flanks of the anorthosite dome. Surface-fed hydrothermal circulation (heavy arrows) in the fault zone, driven by heat from the intrusion, formed ore by infiltration metasomatism where the zone intersected or followed carbonate units.

Continuing or subsequent deformation produced the foliation in the ore and concentrated garnet and pyroxene into conformable GPS layers and lenses by mechanical metamorphic differentiation. Garnetite endoskarns (Einaudi et al., 1981), at contacts of the ore with sills or tectonic slivers of igneous rock, were boudinaged and disrupted. Subsequently, tabular bodies of mafic rocks, some of which crosscut foliation in the ore, were intruded during a second period of igneous activity. Where these were in contact with wollastonite ore, localized metasomatic reactions have replaced them with a second generation of GPS having Type B REE signatures inherited from the igneous protolith. The timing of this second metasomatism is unknown; it may have occurred as late as the subsequent granulite facies metamorphism in the Adirondack highlands (Bohlen et al, 1985), which postdates the anorthosite by as much as 50-80 ma (McLelland and Chiarenzelli, 1990a, b).

REFERENCES

Ashwal, L. D., 1993, Anorthosites: Springer Verlag, New York, 422 p.

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.

Broughton, J. G., and Burnham, K. D., 1944, Occurrence and uses of wollastonite from Willsboro, New York: American Institute Of Mining and Metallurgical Engineers, Technical Publication 1737, 8 p.

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

Buddington, A. F., 1950, Composition and genesis of pyroxene and garnet related to Adirondack anorthosite and anorthosite-marble contact zones: American Mineralogist, v. 35, p. 659-670.

Buddington, A.F. and Whitcomb, L., 1941, Geology of the Willsboro quadrangle: New York State Museum Bulletin, no. 325, p. 1-137.

DeRudder, R. D., 1962, Mineralogy, petrology, and genesis of the Willsboro wollastonite deposit, Willsboro quadrangle, New York: PhD dissertation, Indiana University.

Einaudi, M. T., Meinert, L. D., and Newberry, R. J., 1981, Skarn deposits: in: B. J. Skinner, (ed.), Econ. Geol. 75th Anniv. Volume, Economic Geology Publishing Co., p. 317-391.

Fakundiny, R. H., and Muller, P. D., 1993, Middle Proterozoic emplacement and deformation of metanorthosite and related rocks in the northeastern Marcy Massif, Adirondack Mountains, NY: Geological Society of America Abstracts with Programs, v. 25, p. 14.

Isachsen, Y. W., Kelly, W. M., Sinton, C., Coish, R. A., and Heisler, M. T., 1988, Dikes of the northeast Adirondack region: their distribution, orientation, mineralogy, chronology, chemistry, and mystery: In: Olmsted, J. F., (ed.), New York State Geological Association Field Trip Guidebook, no. 60, p. 215-243.

Kerrich, R., and Rehrig, W., 1987, Fluid motion associated with Tertiary mylonitization and detachment faulting: $^{18}O/^{16}O$ evidence from the Pichaco metamorphic core complex, Arizona: Geology, v. 15, p. 58-62.

Lee, C. G., and Atkinson, W. W. Jr., 1985, Geochemistry of zoned garnets from the San Pedro mine, Santa Fe County, New Mexico: New Mexico Geology, v. 7, p. 69-74.

Lister, G. S., and Baldwin, S. L., 1993, Plutonism and the origin of metamorphic core complexes: Geology, v. 21, p. 607-610.

McLelland, J. M., and J. Chiarenzelli, 1990a, Geochronological studies in the Adirondack Mountains and the implications of a middle Proterozoic tonalitic suite: in: Gower, C., Ryan, B., and Rivers, T., (eds.), Proterozoic geology of the southwestern margin of Laurentia and Baltica, Geological Association of Canada Special Paper 38, p. 175-179.

McLelland, J. M., and J. Chiarenzelli, 1990b, Constraints on emplacement age of anorthositic rocks, Adirondack Mountains, New York: Journal of Geology, v. 98, p. 19-42.

Meagher, E. P., 1982, Silicate Garnets: in: Ribbe, P. H., (ed.), Orthosilicates: Mineralogical Society of America Reviews in Mineralogy, v. 5, 2nd Ed., p. 25-66.

Novak, G. A., and Gibbs, G. V., 1971, The crystal chemistry of the silicate garnets: American Mineralogist, v. 56, p. 791-825.

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, no. 60, p. 263-276.

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

Reynolds, S. J., and Lister, G. S., 1987, Structural aspects of fluid-rock interactions in detachment zones: Geology, v. 15, p. 362-366.

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

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

Vanuxem, L., 1821, Description and analysis of the table spar from the vicinity of Willsborough, Lake Champlain: Jour. Acad. Nat. Sci. Phil., v. 2, pt. 1, p. 182-185.

Whitney, P. R., and Olmsted, J. F., 1993, Bedrock Geology of the Au Sable Forks Quadrangle, northeastern Adirondack Mountains, New York: New York State Museum Map & Chart Series 43, 48 p.

ROAD LOG

The route of the trip and the locations of the six planned stops is shown in Figure 6.

At Exit 31 of the Adirondack Northway (I87), turn right (E) on Route 9N and go 0.2 miles; park on right opposite large roadcut.

STOP 1: METANORTHOSITE OF THE WESTPORT DOME

Massif anorthosites are plagioclase-rich igneous rocks. Their origin is controversial; the debate is summarized in Ashwal (1993). Most current models involve variations on this theme: Large volumes of mantle-derived basaltic magma fractionate in the upper mantle or lower crust toward an aluminum-rich residuum. Appreciable contamination may take place from partially melted lower crust. As the magma rises through the crust, plagioclase crystallizes to produce a crystal-rich magma or mush which is emplaced in the middle or upper crust. Further fractionation may follow emplacement; iron-enriched residual liquids may sink or be expelled by filter pressing.

In the Adirondack anorthosites, plagioclase occurs in two forms: dark-gray megacrysts and smaller, light-gray to white interstial grains. Compositions range from An_{42} to An_{60}, most commonly An_{48} to An_{55}. Antiperthitic megacrysts are locally common. The interstitial feldspar, which may include some K feldspar, consists of varying proportions of crushed megacryst ("protoclastic") plagioclase and feldspar crystallized from residual liquid. In addition to plagioclase, the principal minerals of igneous origin are orthopyroxene, clinopyroxene, and iron-titanium oxides. Metamorphic minerals include garnet (in the more iron-rich varieties), hornblende, and biotite.

The Westport Dome is the largest anorthosite body in the Adirondacks outside the Marcy Massif. This exposure, near the southern end of the dome, illustrates the outcrop-scale lithologic variability common in Adirondack anorthosites. Gabbroic anorthosite is present in the eastern third of the cut; anorthosite in the remainder; textures and abundance of megacrysts vary widely. Note the vertical, ENE-trending ductile shear zone and the small, deeply weathered fault near the middle of the cut.

Turn around and go right onto the northbound entrance ramp for the Northway. At approximately 5.5 miles, turn right into rest area and park.

STOP 2: ANORTHOSITIC GNEISS

Cuts along the E side of the parking area expose strongly foliated anorthositic gneiss. The foliation here ranges from nearly horizontal to gently north-dipping; a NNE-trending lineation, common throughout the northeastern Adirondacks, is visible on some surfaces. Intense ductile deformation is common along the margins of the dome but is also present in the interior in zones such as this one. The timing of this deformation is unclear save that it postdates consolidation of the anorthosite. Walk north 0.1 miles along the road. On the left, blasted outcrops of anorthositic gneiss contain an irregular, tabular body of garnet-two pyroxene-plagioclase gneiss with minor K feldspar. "Jotunites" such as this one may be residual liquids from the anorthosite.

Begin road log at this point (mile 0.0). Caution: road signs may not correspond to the road names shown on the topographic maps.

0.0 **0.0** Return to the vehicles and drive N out of the rest area onto the ramp at Exit 32.

0.3 **0.3** Turn right on Essex County Route 12 (Jersey Street).

0.95 **1.25** Outcrops on left are moderately deformed anorthosite containing lenticular dark patches rich in pyroxene that may be the remnants of large pyroxene oikocrysts.

2.35 **3.60** Crest of small rise overlooking the Champlain Valley with Lake Champlain and the Green Mountains of Vermont visible in the distance.

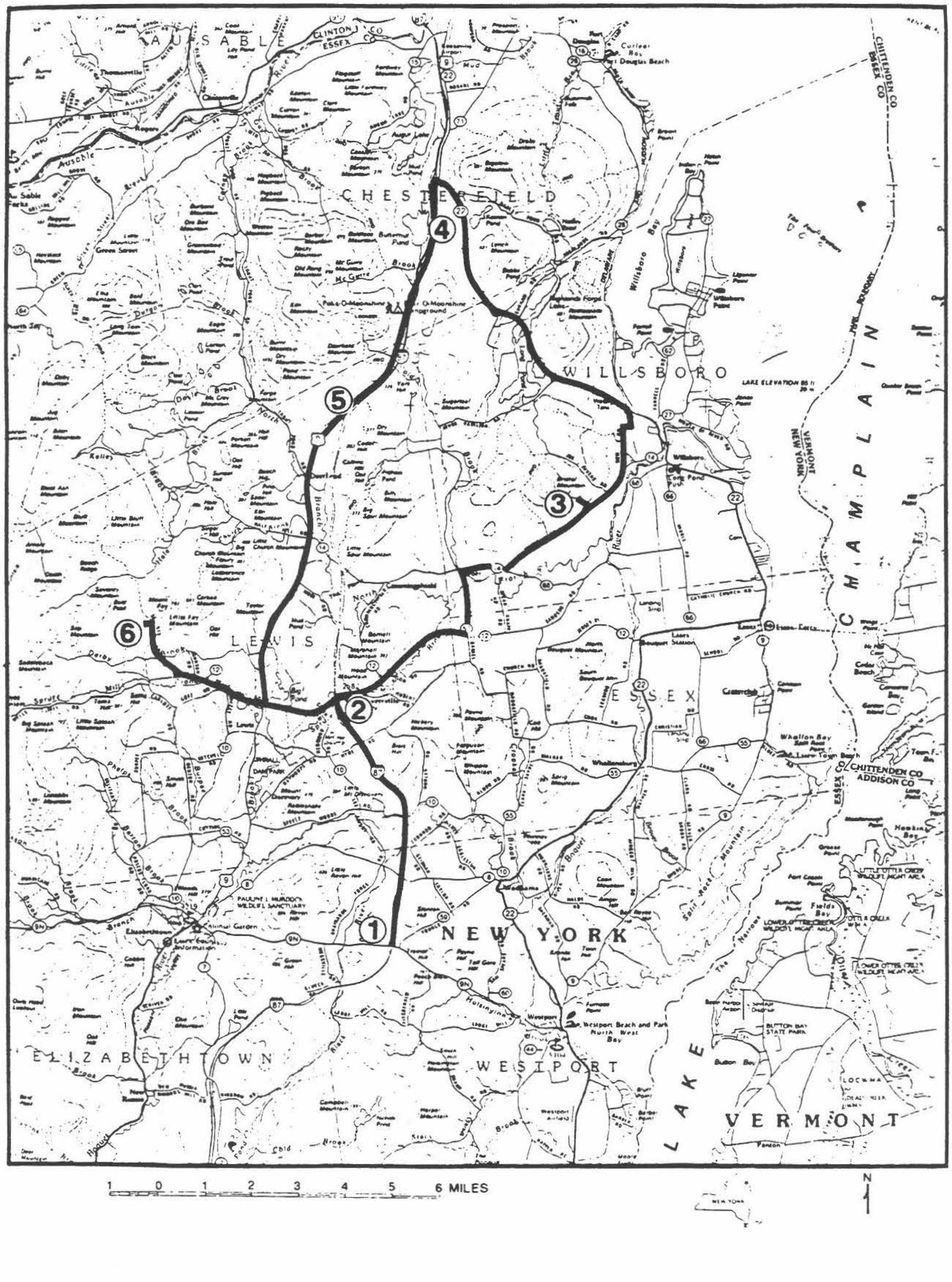

Figure 6. Map of parts of the Willsboro, Au Sable Forks, Elizabethtown and Port Henry 15' quadrangles showing the route of this field trip. Scale: 1:150,000.

0.05 3.65 Turn left (N) on Reber Valley Road.

1.40 5.05 Turn righton Mountain View Road.

1.05 6.1 Turn left at intersection; this is still Mountain View Road.

0.3 6.4 To the right, a fine view of the Green Mountains, from Mt. Mansfield (L) to Camel's Hump (R).

2.1 8.5 Willsboro Mine road (unpaved) on left. This is private property; be sure to obtain permission from NYCO before entering. Proceed through the gate and about 0.4 miles up this road to the lower portal of the Willsboro Mine.

STOP 3: WILLSBORO MINE

The Willsboro deposit is located near the base of the ore-bearing zone (OBZ), separated from the underlying metanorthosite by, at most, several tens of feet of amphibolite. Average strike of foliation and compositional layering within the OBZ is N 60^{o}-65^{o} W with considerable local variation; dips range from 15^{o}-35^{o} north. DeRudder (1962) cites drill core evidence for as many as seven ore layers, with maximum thickness of the principal ore horizon on the order of 50 feet. Numerous small brittle faults and unmetamorphosed mafic dikes (Isachsen et al., 1988) cut the ore.

We will examine exposures at both the lower and middle portals of the now-abandoned underground mine. The area around the middle portal was formerly operated as an open pit. Observe the straight, sharply defined garnet-pyroxene rock (GPS) layers in the ore as well as diffuse compositional layering within the ore; the latter shows complex folding in a few places. One GPS layer appears to crosscut foliation and compositional layering at a low angle. At contacts of the ore with gabbroic anorthosite or amphibolite, discontinuous layers and lenses (boudins?) of pale orange-brown garnet rock ("garnetite") are locally present. If time permits, we will traverse part of the OBZ overlying the ore, to examine a complex section of interlayered rocks including garnetite, amphibolite, gabbroic anorthosite gneiss, mafic calcsilicate rocks, and olivine metagabbro.

Return to the gate and resume road log (8.5 miles)

1.0 9.5 Turn left (N) on Fish and Game Road. Outcrops of unmetamorphosed carbonates in the woods just east of this intersection attest to the presence of a N-S normal fault, mapped by Buddington and Whitcomb (1941), that separates the Precambrian and Paleozoic rocks in this area. Going North on Fish and Game Road, the outcrops on the left are Precambrian marbles and gneisses.

1.6 11.1 Turn left on Route 22.

2.4 13.5 Long Pond on the left. The outcrops along this road are gabbroic and anorthositic gneisses with some interlayered metasedimentary rocks, occupying a structural saddle between the Westport dome to the south and the Port Kent dome to the north.

4.7 18.2 Turn left (S) onto US Route 9.

1.0 19.2 Park on right shoulder.

STOP 4: MARBLE XENOLITH IN JOTUNITE

Climb the bank on the right side of the road. At the top, climb over the fence and examine the rocks at the top of a large roadcut on the northbound lane of I-87. **Please exercise great caution near the edge of the cut cliff facing the Northway. Also, please do not climb down to road level, as it greatly distresses the State Police.**

The white rock is a large xenolith of calcite marble surrounded by mafic gneiss. The marble contains varying amounts of phlogopite, diopside, chondrodite, grossular, graphite, and sulfides. Phlogopite also occurs in clots a few centimeters across. A few lens-like masses of amphibolite are folded in a manner that suggests the "fishhook" forms commonly found in other intensely deformed marbles. Diopside-plagioclase rock with very calcic plagioclase occurs near contacts with the host rock; identical rocks are found in the OBZ upsection from the Willsboro Mine.

The host rock is strongly foliated and lineated garnet-pyroxene-K feldspar-plagioclase gneiss, similar to the jotunites at Stop 2. This is one of many locations where carbonates in contact with rocks of the anorthosite suite have not developed large amounts of wollastonite. The outcrops on both sides of Route 9 at this location are also jotunites; those on the east side contain a layer or lens of garnet-rich gabbroic anorthosite gneiss, as well as masses of quartz (quartzite xenoliths?).

Continue south on Route 9.

1.2 20.4 Roadcuts beneath and to the south of the I-87 overpass are strongly foliated gabbroic anorthosite gneiss with garnet- and pyroxene-rich zones.

0.3 20.7 The cliffs on the right, on the east face of Pokomoonshine Mountain, are granitic gneiss; the outcrops at road level are gabbroic anorthosite gneiss.

0.4 21.1 Entrance to Pokomoonshine State Park on right. Continue South on Route 9.

0.5 21.6 Outcrops of fault breccia on right. A NNE-trending brittle fault roughly follows the road here.

1.6 23.2 **Alternate stop if time permits**. Park on the left, just North of a small outcrop of gabbroic anorthosite gneiss. Cross a narrow strip of woods to the southbound lane of the Northway. The roadcuts here are anorthositic gneisses with marble inclusions. Again, **please remain on the top of the outcrop, and do not cross the road.**

0.6 23.8 Park on right shoulder.

STOP 5: GABBROIC AND ANORTHOSITIC GNEISSES

Two fault-shattered outcrops on the West side of the road and one on the East contain very stongly foliated gabbroic and anorthositic gneisses. We map these as part of the OBZ, at the NW corner of the Westport Dome. The gabbroic gneisses contain millimeter-scale layers of garnet-pyroxene rock. Marble is present at the base of the outcrop on the East side. The more northerly outcrop on the West contains an undeformed hornblende-quartz-feldspar pegmatite. If wollastonite-rich layers are present in this section of the OBZ, they are not exposed.

1.6 25.4 Trout Pond Road on right. Continue on Route 9.

5.1 30.5 Turn right onto Wells Hill Road.

2.0 32.5 Bear right on Seventy Road.

0.9 33.4 Gate to Lewis Mine. **Get permission from NYCO before proceeding.** The large open pit of this operating mine is a short distance up the gravel road.

STOP 6: 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 gently south, approximately parallel to the topographic surface, on the south limb of an open, E-W trending anticlinal crossfold. On the west side of the open pit, where the ore is close to 80 feet thick, it is overlain by strongly foliated charnockite; to the east the overlying rock, where exposed, is mainly anorthositic gneiss. Throughout much of the present mine area, the ore was exposed at the erosion surface. When the overburden was removed to begin mining, a karst-like surface was present, owing to the fact that wollastonite is one of the few silicate minerals that are appreciably water-soluble. Based on drilling data and temporary exposures within the mine, the footwall appears to be amphibolite and gabbroic anorthosite gneiss.

The hills north of the mine are gently N-dipping gabbroic anorthositic gneiss, underlain by deformed olivine metagabbro of the Jay Mountain body; both of these units are structurally above the ore-bearing horizon. Unlike Willsboro, where the ore is at most a few tens of meters above the anorthosite of the Westport Dome, our mapping suggests that the ore at Lewis is underlain by a considerable thickness of mixed gneisses and metasedimentary rocks. At one point during mining, a 4-6 m wide unmetamorphosed diabase dike was exposed.

Throughout much of the Lewis orebody, ore is interlayered with straight, sharply defined, discontinuous GPS layers parallel to foliation in the ore. We interpret this as tectonic layering. The regional NNE lineation can be seen locally on foliation surfaces in the ore here and at the Oak Hill prospect two miles to the east. A few thin, discontinous layers of pyroxene-plagioclase-sphene granulite, rimmed by garnet-rich GPS, are present locally within the ore. Toward the north end of the present pit, layering and foliation are less prominent and the ore is leaner, rich in pyroxene and grossularitic garnet. At the northwest corner, a folded dike of GPS clearly crosscuts foliation.

After leaving the mine, return to the intersection of Wells Hill Road and Route 9. Cross Route 9 and continue east 1.6 miles to Exit 32 of the Northway (I-87).

END OF TRIP