GEOLOGY OF THE WILLSBORO WOLLASTONITE MINE

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INTRODUCTION

The wollastonite deposits of this region are the world's major source of of this important industrial mineral. Several occurrences of coarse wollastonite gneiss that is potential ore are known throughout the Willsboro and Ausable Forks quadrangles but to date only this and the Lewis deposit have been exploited. We have chosen this, now inactive, mine as the site for the trip because of excellent exposure of related rocktypes as well as unmatched display of structural and metamorphic features. The presently active Lewis mine is located at the other end of a fifteen kilometer long belt of metasediments that overlie the Westport anorthosite dome. Topics of particular interest are the mineralogy of the wollastonite unit, petrography of related units, mineralogical and textural relationships at contacts and the structural geology of the metasedimentary belt.

The trip will consist of a walking traverse in which we will study the lower half of the Willsboro metasedimentary belt. We begin at the lower portal of the mine and proceed north about 600 m. where we encounter the base of the "Midsection Anorthosite" a thick sill-like unit that divides the section into lower and upper parts. We will then cross the section in a westerly traverse to a point about a kilometer west of the lower portal where we will examine the wollastonite and the amphibolitic unit at the top of the Westport anorthosite dome. We then return along strike to the mine site where you can collect samples of the ore and related rocks. The entire hike is about three kilometers through wooded terrain but with one exception (a steep descent) it is not particularly difficult.

GEOLOGIC SETTING

Throughout the northeast Adirondack Mountains metasedimentary shelf type deposits are in contact with anorthosite dome-like structures. The infolded metasedimentary rocks include marble, calcsilicates of a variety of compositions, quartzite and gneisses that range from amphibolite to quartzofeldspathic in composition. Many of the latter two are thought to be of volcanic origin although some may have been intrusive. Emplaced into these units are intrusive rocks that range in composition from granite to gabbro and include anorthosite and related rocks. All of these have been subjected to granulite facies metamorphism which has altered the primary petrographic and structural features. Buddington and Whitcomb (1941) indicate the temporal sequence to begin with Grenville metasediments intruded by anorthosite, gabbro and granitic rocks all of which were deformed and metamorphosed, Our mapping indicates the metagabbro to be the younger rocktype. It occurs as dikes and sills and cuts the other three rock types. In this area we have mapped a large metagabbro sill that has intruded the metasediments above the wollastonite gneiss. We will examine its textural and contact relationships with surrounding rocks for the purpose of understanding influence it may have had on their formation.

At the Willsboro mine, foliation strikes NNW and dips N about 30 degrees. Rare lineations trend and plunge to the northwest Additional lineations have been observed at the Deerhead location about four kilometers west, where plunging folds and topography brings anorthosite to the surface beneath the axial region of a keel-like structure. From this point for about one kilometer east of Deerhead, along the belt towards Willsboro the metasediments are missing. It is interpreted that the metasedimentary belt is an isoclinal synform or keel-like structure in which plunge changes direction along strike of the belt. This results in apparent thinning and thickening ("porpoising") of the entire belt along strike.

While deformation and metamorphism associated with the Grenville orogeny has largely transformed original layering lithologic units have survived to a remarkable degree. Figure (1) indicates continuity of the thicker units along strike but in detail smaller units are discontinuous due to faulting, lensing and undoubtedly the "porpoising" noted above. Above the metasedimentary belt is found a thick a thick gabbroic anorthositic gneiss (Figure 2) indicated by Buddington and Whitcomb (1941) as strongly contaminated by metasediments that occur as "layers", "inclusions" and "schlieren" of mafic, garnet rich rock.

PETROGRAPHY AND MINERALOGY OF THE WILLSBORO MINE AREA

Structurally the lowermost unit of the mine area is the gabbroic anorthosite gneiss of the Westport dome (Figure 2). The rock generally contains large (>5 cm..) dark bluish megacrysts in a lighter bluish gray matrix. DeRudder (1962) has noted that in the mine area the anorthosite is overlain by a mafic rich gneiss that may be a few tens of meters thick. Our mapping has confirmed this but we find that at Deerhead, wollastonite is in contact with anorthosite. We will examine this contact at a point west of the mine area.

The ore consists of wollastonite, grandite garnet(Gr.10 to Gr.90) and calcium rich clinopyroxene (Di.40 to Di.70). The rocks are coarse with foliation defined by orientation of the flattened wollastonite and concentrations of the mafic minerals. The major compositional variation in this unit is the Al/Fe ratio in garnet and Mg/Fe in pyroxene. Within the wollastonite unit the mafic minerals are usually fine granular but garnet is often poikiloblastic. A second occurrence of the mafic phases is skarn-like masses along the edge or occasionally within the ore zone. These consist of grossularitic garnet and diopsidic clinopyroxene with minor quartz and albite. Shape of the skarn bodies ranges from thin (10-20 cm.) tabular masses that extend for several tens of meters along strike to thick (several meters) lenses with greater lateral extent. These are the metamorphic products of reaction between wollastonite and feldspar rich gneisses that are commonly in contact with the ore. The following reaction runs with falling temperature so the skarns are correctly considered to be retrograde.

$$\underset{An}{CaAl_2Si_2O_8} + \underset{Wo}{2CaSiO_3} \dashrightarrow \underset{Gr}{Ca_3Al_2Si_3O_{12}} + \underset{Q}{SiO_2}$$

Immediately above the wollastonite are small units of anorthositic and mafic gneisses. These in turn are overlain by calc-silicate gneisses and amphibolites, mafic and syenitic gneisses that are mixtures of metasedimentary and metaigneous rocks (Figures 2 & 3, Table 1). Major and trace elements (Table 2, Figures 4-6) as well as mineral compositions of these help distinguish the protolith and provide confidence for our field classification. In some exposures we find masses of garnetite (skarn) indicating repetition of units similar to the wollastonite found below. An interesting observation

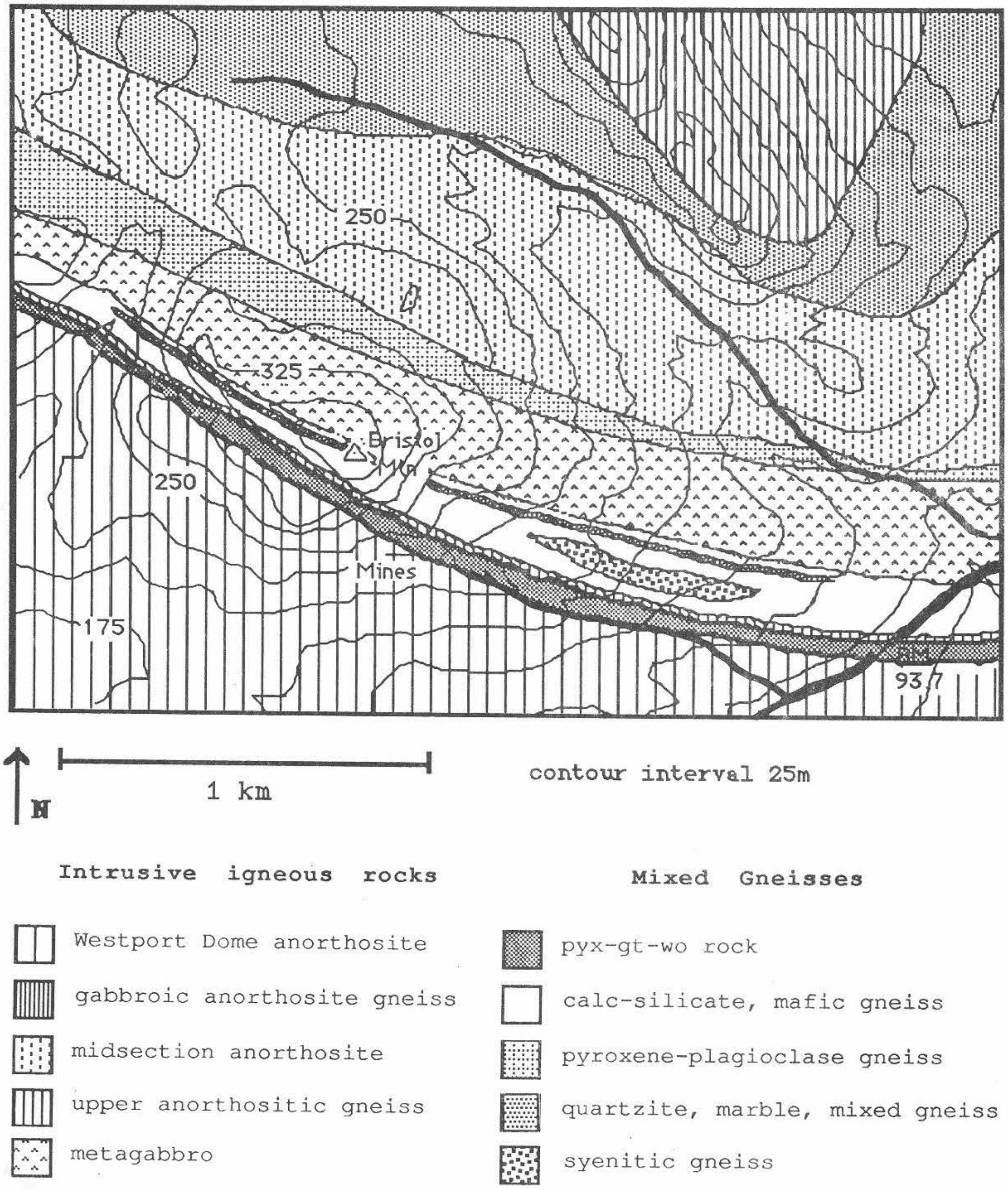
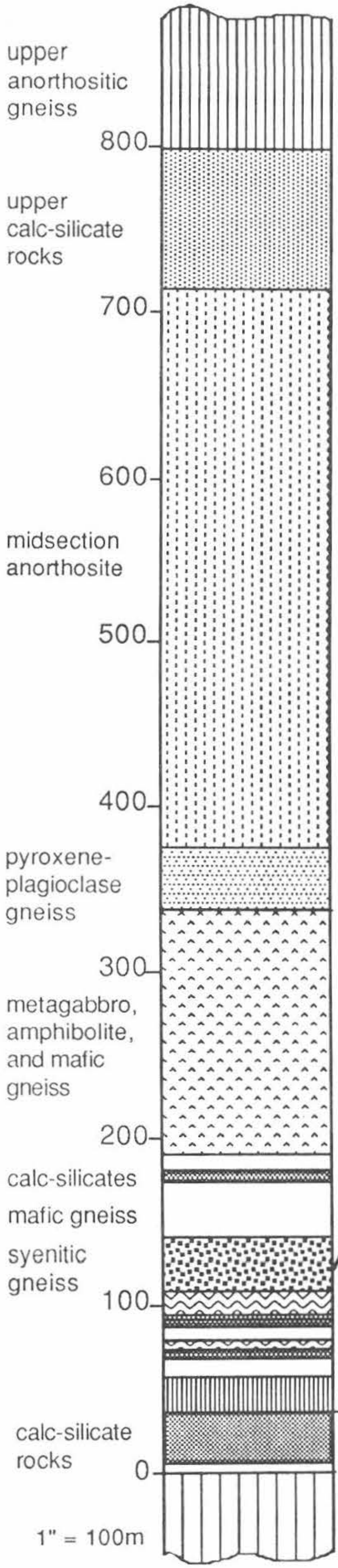


Figure 1. Geologic map of the Willsboro wollastonite deposit, Willsboro, N.Y. The map area is located in the northern part of the Willsboro 7.5 by 15 minute quadrangle approximately 4 km southwest of teh village of Willsboro.

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.



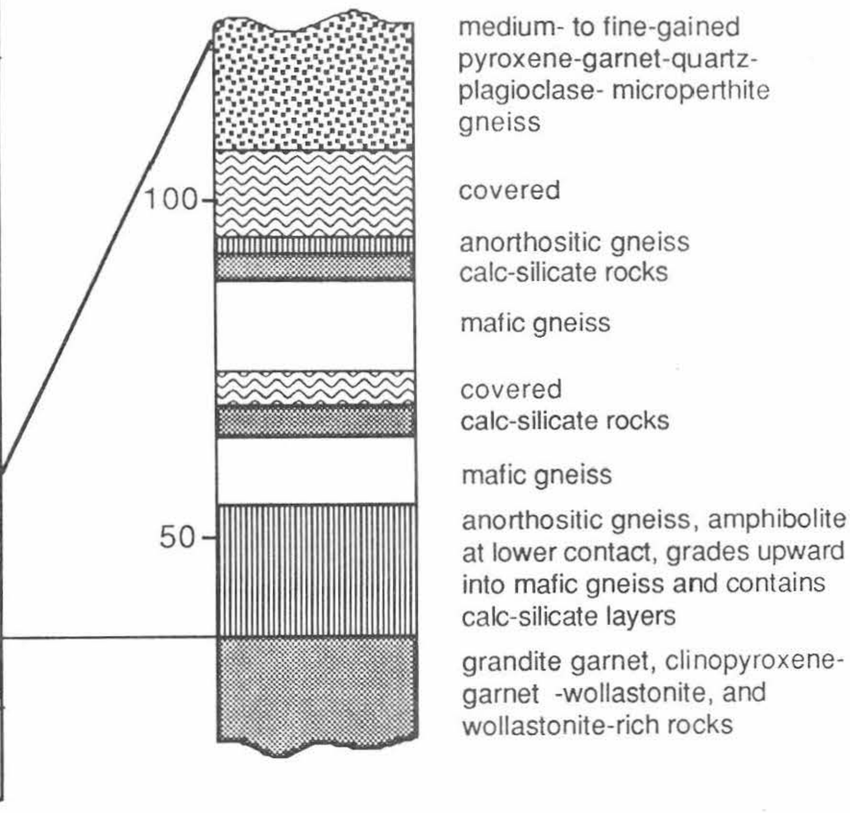


Table 1. Modes of metagabbro, mafic gneiss, and amphibolite associated with the Willsboro wollastonite deposit.

A. Metagabbro (w-27, w-86) and medium- to coarse-grained mafic gneisses that are included in the metagabbro unit shown in Figures 1 and 2.

Sample	w-27	w-86	w-27b	w-20	w-8
plagioclase	41	58	33	40	41
augite	20	4	20	36	2
orthopyroxene	6	7			
hornblende	12	16	34	13	37
biotite	0.2	2		0.6	
garnet	21	12	12	7	5
opaque		1	2	2	0.2
other		0.6	1	2	6

B. Medium- to coarse-grained amphibolites. Samples w-82,w-15, and w-12b are located north of the eastern portal of the Willsboro mine and are within the lower 200m of section shown in figure 2. Sample d138 is from drillcore 81-15.

Sample	w-82	w-15	w-12b	d138
plagioclase	25	38	32	27
augite	1.5	10	2	2
orthopyroxene			5	
hornblende	72	50	56	69
biotite		0.4		
garnet	1.5		4	
opaque			0.2	
other	0.3	0.9	0.6	1.5

C. Fine- to medium grained gneisses and granulites. Samples w-22 and w-24b are located above the middle portal at the Willsboro mine. Samples d132 and d132.5 are from drillcore 81-15. Samples w-81 amd w-78 are located above the first portal, within the lower 100m of section shown in Figure 2. Sample w-78 contains bluish-gray plagioclase augen in a fine- to medium-grained, strongly foliated matrix. Sample w-81 is weakly foliated and contains medium-grained augite in a fine grained matrix. The augite grains contain abundant orthopyroxene exsolution lamellae.

Sample	w-22	w-24b	d132	d132.5	w-81	w-78
plagioclase	47	44	46	44	35	46
augite	18	3	13		11	17
orthopyroxene	10	13	13	16	15	
hornblende		36	20	36	23	21
biotite	13	0.2	3	2	5	
garnet		4	1		10	12
opaque	4	0.6	4	2	0.6	4
other	0.4			0.3		0.2

Table 2. Chemical analyses of hornblende-augite-plagioclase gneiss (W-21), metamorphosed gabbros (W-27,W-86), amphibolite (W-82), and mafic gneisses from Willsboro, New York.

Sample	W-27	W-27B	W-21	W-86	W-78	W-81	W-82	W-15
SiO2	48.07	46.04	49.20	47.98	47.65	48.15	44.56	48.73
TiO2	0.72	2.13	1.02	0.61	2.51	1.95	2.28	1.38
Al2O3	18.33	16.47	9.59	21.55	18.20	15.60	15.64	17.98
Fe2O3	11.56	13.93	10.21	8.7	12.77	13.66	14.81	11.48
MnO	0.15	0.17	0.15	0.11	0.2	0.18	0.18	0.16
MgO	8.86	6.62	10.54	8.02	3.84	7.68	7.98	6.59
CaO	9.79	11.29	17.85	10.33	10.77	8.83	10.86	9.39
Na2O	2.61	2.87	1.53	2.52	3.54	3.08	2.8	3.47
K2O	0.42	0.49	0.13	0.41	0.6	1.09	1.03	0.75
P2O5	0.02	0.02	0.01	0.07	0.43	0.30	0.27	0.21
Total	100.53	100.01	100.21	100.30	100.51	100.53	100.39	100.15
Trace elements (ppm)								
V	108	285	599	63	201	204	269	143
Cr	126	77	252	16	58	80	123	73
Ni	131	86	35	115	27	98	89	86
Zn	98	138	54	71	123	127	113	111
Sr	331	491	169	374	421	279	374	329
Zr	14	28	22	33	158	133	98	103
Nb	0.4	0.8	0.4	1.2	6.6	5	5	3.7
Ba	165	221	22	123	169	329	183	224
La	0	0.4	0	2.9	16	12	5.5	8.5
Ce	1.8	7.4	7.4	9.9	40	34	31	25

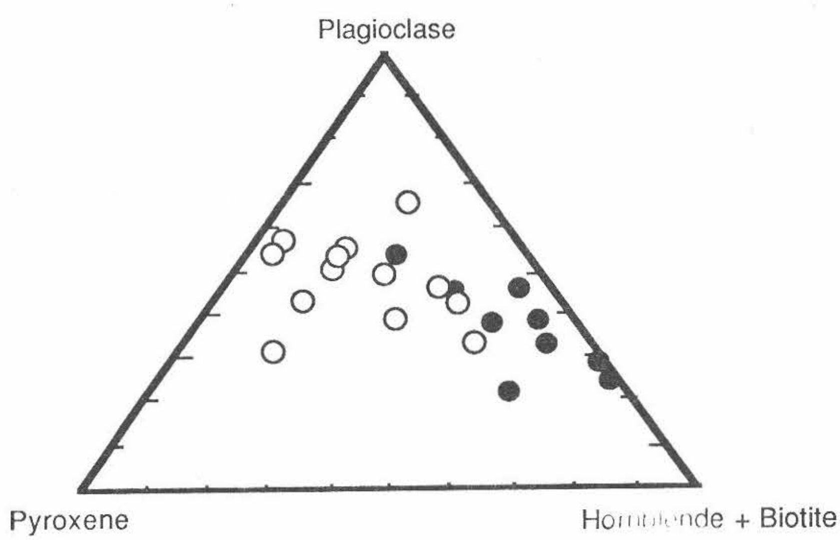


Figure 3. Modes of mafic gneisses and amphibolites from Willsboro, NY plotted on the triangle plagioclase-pyroxene- hornblende + biotite. The samples plotted in black were collected within approximately one meter of a contact with calc-silicate rocks. Other samples were collected at greater distances from contacts with calc-silcate rocks.

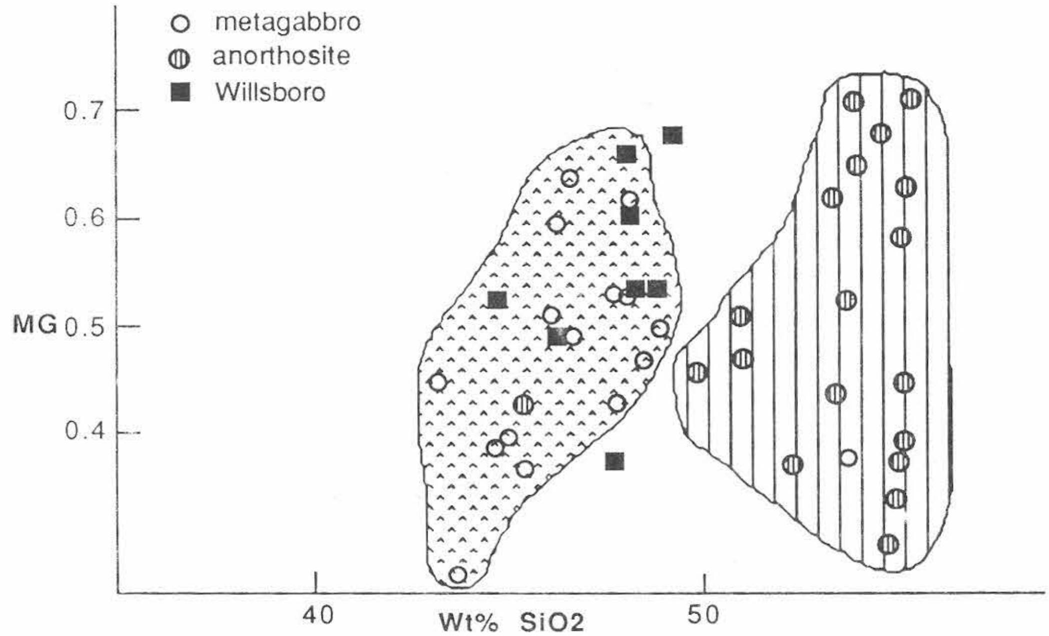


Figure 4. MG (100 Mg/Mg+Fe) versus wt.% SiO2 for spinel bearing metagabbros, gabbroic anorthosites, and mafic gneisses from Willsboro. The lined pattern on the right encloses 15 of 16 gabbroic and noritic anorthosite analyses from Buddington (1939), Clough (1987), and unpublished analyses from Ollila. The pattern on the left encloses 15 of 16 metagabbro analyses from Buddington (1939), and Gasparik (1980). Analyses of spinel-bearing metagabbros are shown, however, other metagabbros and amphibolites show a similar pattern. Spinel was chosen as a discrimant because it is rare in anorthosite related rocks. Note that six of the eight analyses from Willsboro fall within the metagabbro field. The two analyses that are outside the field are w-78, which contains plagioclase augen and is thought to be anorthosite related and w-21, a calc-silicate gneiss.

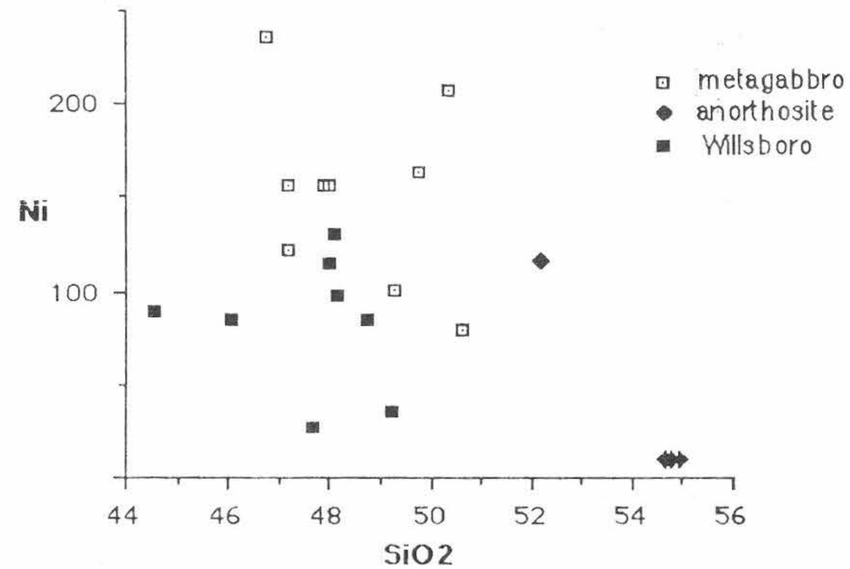


Figure 5. Metagabbro (Buddington,1939; Clough,1987), gabbroic anorthosite (Clough, 1987), and mafic gneisses from Willsboro plotted on Ni (ppm) versus wt.% SiO2. The two Willsboro samples that have low Ni contents are samples w-78 and sample w-21. The other mafic gneisses and amphibolites have Ni contents more typical of metagabbro.

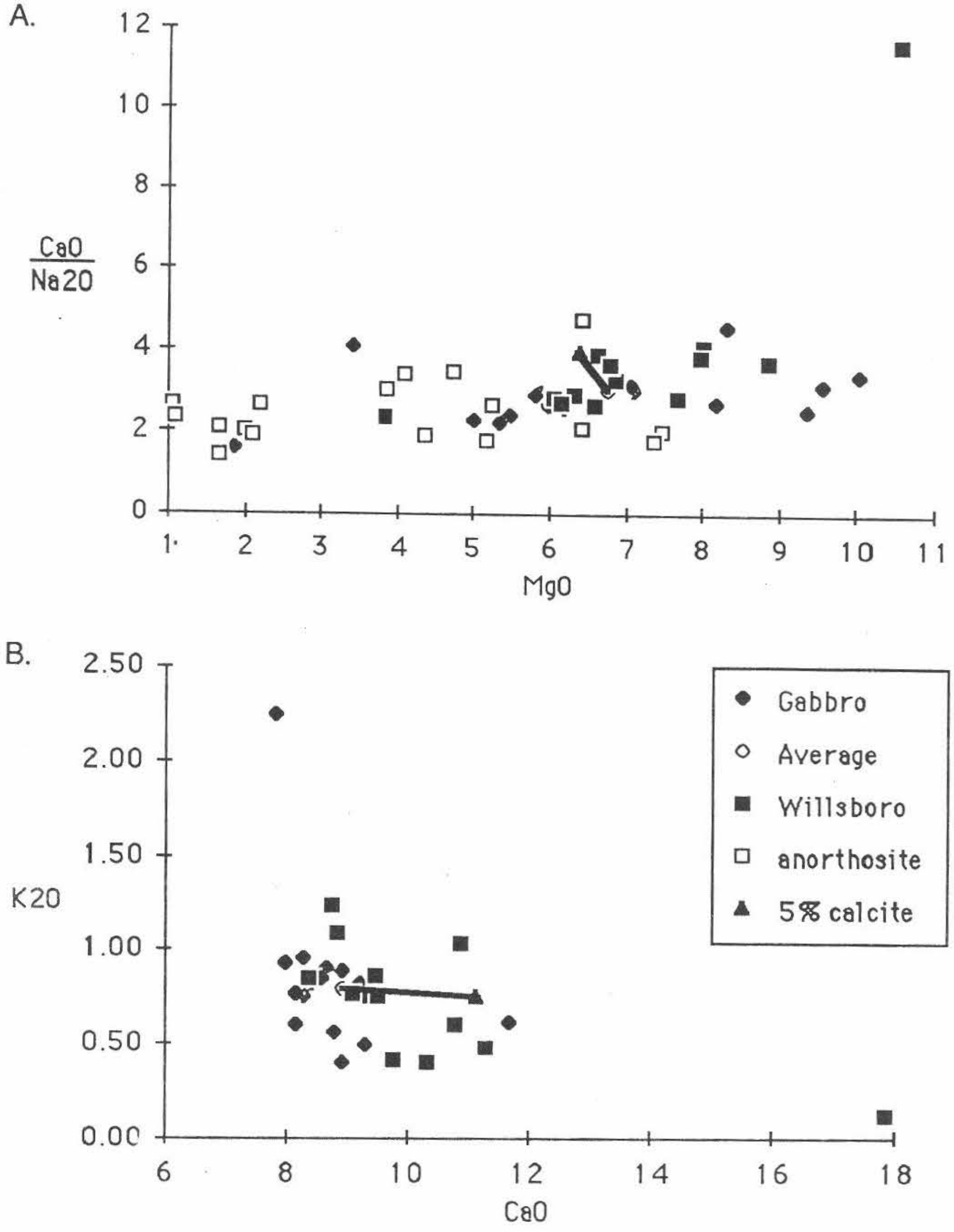


Figure 6. Chemical analyses of rocks from Willsboro, NY. plotted on the diagram CaO/Na2O vs. MgO and K2O vs. CaO (adapted from Hollocher,1985). Gabbroic and noritic anorthosite analyses (n=16) were selected from Buddington (1939), Clough (1987), and unpublished analyses from Ollila. Spinel bearing metagabbro analyses (n=16) are from Buddington (1939) and Gasparik (1980). The average of the16 metagabbro analyses and a composition determined by adding 5% calcite to the average composition are shown connected by a line. Note that the Willsboro samples either have compositions that closely resemble those of igneous metagabbros, or have compositions that can be explained by the assimilation of only modest amounts of calcite (or wollastonite). The CaO-rich sample in each plot is w-21, a calc-silicate gneiss.

that can be used locally as an exploration tool for wollastonite is that it weathers readily leaving topographic depressions and virtually no outcrop where it occurs near the surface. As a result we are left with these garnetite skarns as sole clues to the presence of wollastonite. Higher in the section we find a metagabbro unit that has been mapped over five kilometers along strike (figures 1 & 2). This unit preserves fine examples of relict igneous texture but grades to amphibolite at lower and upper contacts with metasediments (Figure 3). This supports the notion that a fluid phase was present during the metamorphism of the metagabbro.

The uppermost unit that we will examine is a thick sill-like body of gabbroic anorthosite gneiss. This extends the entire length of the Willsboro belt and is readily distinguished from the massif anorthosite in both composition and texture. This represents either a contaminated anorthosite intrusive or an unusual intermediate magma composition. Its most distinguishing feature relative to the massif anorthosite is the absence of the blue megacrysts that are so typical of rocks closely related to the massif anorthosite. Its texture is granoblastic with an occasional large almandine poikiloblast. Another interesting feature of this unit is its striking similarity to a sill-like body that occurs in the metasedimentary section surrounding the Jay dome anorthosite some fifteen kilometers west of the present site.

OXYGEN ISOTOPES

Valley and O'Neil (1982) suggested, on the basis of exceptionally low ^{18}O values, that the Willsboro wollastonite deposit formed at relatively shallow levels (<10 km.). They interpret the wollastonite to be a contact metasomatic deposit produced at the margin of an anorthosite intrusion and, because the low ^{18}O values require involvement of meteoric water, have provided a powerful argument in favor of the shallow intrusion of anorthosite. There are, however, a number of problems associated with the shallow intrusion hypothesis. These have been summarized by Bohlen et al. (1985) and by Ollila et al. (1988). One of the main purposes of this study was to see if other explanations for the low ^{18}O rocks are possible.

The details of Valley and O'Neil's study open a number of interesting questions. In particular, the high ^{18}O gradients within the ore zone and the lack of low ^{18}O plagioclase in anorthositic rocks both here and in highly contaminated anorthositic rocks that overlie the wollastonite deposit (Valley and O'Neil,1982; Morrison, 1987) seem at odds with the model that Valley and O'Neil have presented.

Initially, Ollila et al. (1987) thought that the low ^{18}O values could be explained by a model involving exchange with metamorphic fluids and then further oxygen exchange with late-stage, lower-temperature fluids. The basis for this was the pervasive occurrence of low temperature alteration in associated calc-silicate rocks, the near absence of such alteration in mafic gneisses and anorthostic rocks, and the fact that coexisting minerals analyzed by Valley and O'Neil yielded temperatures of 73°C (Wo-Cpx) and 240°C (Gt-Cpx) according to the thermometers of Mathews et al. (1983) and Bottinga and Javoy (1975). These temperatures are outside the calibrated range of the geothermometers and the uncertainties are extremely large. Consequently, they do not indicate the temperature at which the deposit last equilibrated but do leave open the possibility of low temperature exchange. Kinetic arguments, however, make the model presented above seem unlikely because oxygen isotopic ratios would have to be lowered during the initial metamorphic event to values below what might reasonably be expected during regional metamorphism.

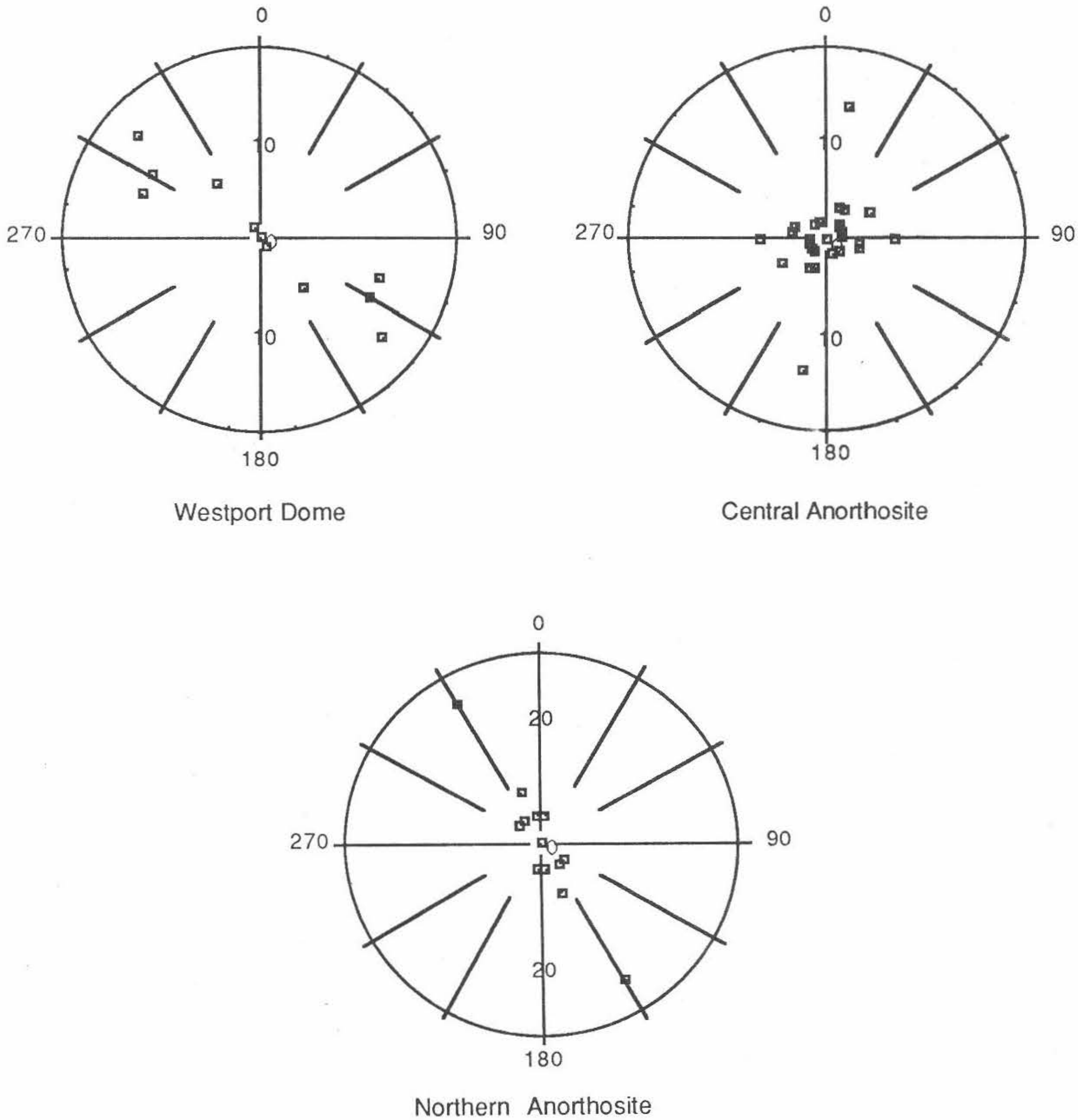


Figure 7. Strikes of metagabbro dikes shown on the geologic mapof the Willsboro quadrangle (Buddington and Whitcomb, 1945). Frequency % on 10 degree intervals.

An alternate hypothesis is that hydrothermal convection systems involving meteoric water were driven by metagabbro intrusions. This hypothesis is based on the following observations:

1) The majority of the mafic gneisses at Willsboro appear to have chemistries more appropriate to metagabbro than anorthosite (Figures 4-6).

2) Isotopic data presented by Valley and O'Neil (1982) shows that the only rocks at Willsboro with plagioclase ^{18}O lower than typical for Adirondack igneous rocks are amphibolites that are interlayered with wollastonite ores.

3) Modal data (Figure 3) suggests that the calc-silicate rocks acted as conduits for fluids because metaigneous rocks near contacts with calc-silicate rocks are more hydrated. Furthermore the observed low temperature alteration in the calc-silicate rocks demonstrates that they are effective channels for fluids in brittle environments.

5) There is a strong correlation between low ^{18}O plagioclase elsewhere in the Marcy anorthosite massif and the occurrence of metagabbro (Taylor,1969; Morrison,1987).

An important unanswered question is the circumstances and timing of the intrusion of the metagabbros. Lochead and McLelland (1987) provided evidence that certain metagabbros in the Adirondacks were intruded after a high grade regional metamorphism and that this intrusive event was followed by another metamorphic event.

Metagabbro is far less deformed than anorthosite and metagabbro dikes cut anorthosite and locally anorthositic gneiss. Metagabbro dikes exhibit northwest trends in both the Willsboro quadrangle (Figure 7) and in the Mt. Marcy quadrangle (Adinolfi,1974) . This indicates that the anorthosite was rigid enough to fracture at the time when metagabbro was intruded and suggests that the region experienced NE-SW extension during this time period. Elsewhere, however, anorthositic gneisses and metagabbros are strongly foliated, are concordant, and are deformed together in upright folds. This sort of relationship can be seen in road cuts at the Willsboro exit of the Adirondack Northway (I-87). Ambiguous relationships such as these were also described by Buddington and Whitcomb (1941). These relationships can be explained by intrusion of metagabbro between two metamorphic events or by metagabbros cutting a protoclastic foliation in anorthosite. More field work is necessary to answer this question.

If the metagabbros were intruded at relatively shallow levels after other rocks, including anorthosite, were metamorphosed, the model presented above can provide answers as to why high ^{18}O gradients exist at Willsboro, why anorthositic rocks do not contain low ^{18}O plagioclase, and can explain the spotty occurrence of low ^{18}O plagioclase elsewhere in the Marcy anorthosite massif. While it seems quite possible that low ^{18}O rocks can be explained by the intrusion of metagabbro, the significance of this finding in terms of the intrusion history of anorthositic rocks awaits more knowledge of the temporal relationship between anorthosite and metagabbro.

ECONOMIC GEOLOGY

Coarse potentially recoverable wollastonite has been discovered at four sites along the perimeter of the Westport dome. In all of these the wollastonite is found in contact, or nearly so, with anorthosite. At present only two of these have proven to be economic but its many uses as an industrial mineral make it an attractive target for exploration. Poor exposure due to its solubility and lack of any strong geophysical contrasts make exploration difficult with the result that the major methods of discovery are field mapping and luck.

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ROAD LOG

Because there is only one stop on this trip an abbreviated road log will be used beginning at the intersection of NY routes 9 & 22 at exit 33 of the Adirondack Northway (I-87).

Miles	Cumulative	
0.0	0.0	Leaving the intersection head east (south) on NY 22 towards Willsboro.
6.7	6.7	Turn right on Fish and Game Road just after sign indicating 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 right on unpaved (white mine tailings) road up hill to mine. Park on right if gate is closed or continue up road to first portal.

From the east end of the lower portal of the mine we will climb up over the exposed bedrock, carefully examining the rocktypes as we climb. In the immediate area of the mine they include; wollastonite ore, garnetite, gabbroic anorthosite gneiss, syenitic gneiss and a very mafic appearing calc silicate gneiss. We will point out several structural features as we move up the hill. Higher in the woods we will see evidence of repetition of the wollastonite rock in the form of another garnetite unit. The northernmost extent of the traverse will be indicated by an anorthositic unit that forms a prominent ridge. At this point we turn southwesterly back across the valley where we encounter more mafic calcsilicates, then up the hill to a large exposure of metagabbro. We will continue southwesterly over Bristol Mountain and down into the next valley where we will examine among other things, the base of the wollastonite unit, it upper contact and the underlying rocks of the Westport Dome. We will then walk easterly along strike of the wollastonite unit past the mine area where you may collect ore samples to your heart's content and back to the cars.

Optional stops may include the westward extension of the Willsboro belt where it crosses the Adirondack Northway and the Deerhead location which is another similar wollastonite occurrence that can provide additional structural insight as well as opportunity to examine other rocktypes in the section.

The following is an abstract of the address by Professor McLelland at the banquet of the Sixtieth annual meeting of the New York State Geological Association, October 8, 1988.

U-Pb Zircon Geochronology of the Adirondack Mts. and Tectonic Implications

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Zircons from metatonalites in the southern and eastern Adirondacks give Pb-Pb age of 1301 Ma, interpreted as their minimum emplacement age. Metatonalite from the eastern Adirondacks yields an upper intercept age of 1321 ±60 Ma. It is inferred that these, and intervening metatonalite (1318 ±20 Ma) northwest of Saratoga Springs, represent a broad zone of ~1300 Ma calcalkaline magmatism. Associated with these units are granodioritic masses (batholiths?) yielding ages of 1235 Ma. Compositionally the metatonalite are similar to the Elzevirian plutons of the Central Metasedimentary Belt (CMB), and it is suggested that both are the result of arc-related magmatism associated with the collision of microplate fragments derived from an early (1800-1600?) supercontinent disrupted during 1450-1350 Ma anorogenic magmatism. This event is believed related to 1415 ±6 Ma leucogranitic gneiss exposed in the Frontenac Arch. These leucogranitic gneisses crosscut quartzites (zircon ages: 1600-1910 Ma) which must be older than any rock yet recognized in the CMB or Adirondacks and suggest that the Frontenac Terrane has a different history than neighboring terranes.

Marginally calcalkaline leucogranitic gneiss in the Adirondack Lowlands yield U-Pb zircon ages of 1230-1290 Ma and may represent a second Adirondack magmatic arc. Abrupt termination of the leucogranitic gneiss at the Highland-Lowland boundary suggests that the boundary may represent a cryptic suture. Late (~950 Ma) collapse of the orogen probably cropped the Lowlands down to the northwest along this same zone.

Foliated garnet-sillimanite xenoliths in olivine metagabbros dated by U-Pb zircon at 1144 ±7 Ma may record ~1200-1300 Ma metamorphism accompanying docking associated with the microplates and magmatic arcs described above. The olivine metagabbros appear to belong to the anorogenic, or rift-related, anorthosite-mangerite-charnockite (AMC) magmatism that disrupted eastern portions (Fennoscandia?) of the newly assembled continent at ~1160-1130 Ma. Subsequent closure along S.E. dipping subduction zones resulted in the ~1100-1000 Ottawan phase of the Grenville orogenic cycle. In the Adirondacks this event was accompanied by extreme deformation, doubling of crustal thickness, granulite facies metamorphism, and granitic plutonism at ~1100-1060 Ma. The granites fall into an 1100-1090 Ma suite of hornblende granitic gneiss and magnetite-bearing alaskitic rocks that yield ages of 1070-1060 Ma. These granitic rocks may have supplied substantial heat for the granulite facies metamorphism.

Careful dating of baddeleyite and air abraded zircons from the Marcy anorthosite clearly demonstrate that its emplacement age is somewhat greater than 1110 Ma. A maximum age of the anorthosite is fixed by the crosscutting relationships of sheets of Whiteface type anorthositic gneiss relative to hornblende granitic gneiss dated at 1135 ±5 Ma. It is concluded that Adirondack anorthosites were emplaced coevally with mangeritic and charnockitic rocks dated at 1130-1160 Ma. The mafic and granitoid suites do not appear to be comagmatic.

This work has been undertaken with the N.Y. Geological Survey and with Jeff Chiarenzelli who performed the age determinations.