

**TIMING AND DEPTH OF INTRUSION OF THE MARCY ANORTHOSITE MASSIF:  
IMPLICATIONS FROM FIELD RELATIONS, GEOCHRONOLOGY, AND  
GEOCHEMISTRY AT WOOLEN MILL, JAY COVERED BRIDGE, SPLIT ROCK  
FALLS, AND THE OAK HILL WOLLASTONITE MINE**

by

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## INTRODUCTION

The depth and timing of intrusion of the Marcy anorthosite massif has critical implications for models of regional Adirondack geological development. Classic localities in the northeastern Adirondacks afford the opportunity to evaluate questions of anorthosite intrusion depth, as well as the timing and relation to granulite facies metamorphism. The first stops, at Split Rock Falls, Woolen Mill, and the Jay covered bridge, allow an examination of anorthositic to gabbroic rocks and magmatic textures and relations. The Split Rock Falls locality exposes a variety of cross cutting and block structures of anorthositic series rocks. At the Woolen Mill locality, clear cross cutting relations of anorthosite and gabbroic lithologies exist. Zircons from these rocks have been recently dated (SHRIMP II). Geochronology indicates intrusion of anorthositic rocks at ca. 1155 Ma. New  $\delta^{18}\text{O}$  data from zircons provide evidence for the magmatic contamination of the Marcy massif, causing an elevation in  $\delta^{18}\text{O}$  when compared to "normal" anorthosites worldwide. The data indicate the massif intruded as high  $\delta^{18}\text{O}$  magmas, and thus fluids did not elevate the  $\delta^{18}\text{O}$  of the anorthosite during overprinting granulite facies metamorphism. At the Jay covered bridge locality, coarse pyroxene-rich dikes cross cut anorthosite. Recent geochronology yields an age of ca. 1155 Ma for anorthosite here. The final stop, at the Oak Hill wollastonite deposit, exposes field relations of low  $\delta^{18}\text{O}$  calc-silicate lithologies to presumed marble protoliths and anorthosite. Combined stable isotope, major element chemistry, and trace element chemistry provide significant evidence for formation of the calc silicate lithologies in a complex hydrothermal skarn-forming system adjacent to shallowly intruding anorthosite. Garnet with oscillatory zonation of both major elements and  $\delta^{18}\text{O}$  from the related, nearby, Willsboro deposit further constrain skarn forming processes.

We plan to show, through field relations, geochemistry, and geochronology that the Marcy anorthosite massif intruded as a high  $\delta^{18}\text{O}$  crystal mush to depths less than 10 km in the crust at ca. 1155 Ma causing localized contact metamorphism. The anorthosite and contact metamorphic rocks were then subsequently overprinted by the regional metamorphism of the Ottawa orogeny after 1090 Ma.

This field trip guide is written in two parts. The first part includes general background information, including a brief description of anorthositic rocks in the area as well as a more detailed description of the geochemistry and petrogenesis of the Oak Hill and related wollastonite deposits. The second part includes a road log. The first three stops, anorthositic rocks at Split Rock Falls, Woolen Mill, and Jay, include detailed information about the field relations seen there, plus petrologic, geochemical, geochronologic information with interpretations. The last stop, at Oak Hill, includes detailed field descriptions of the rocks analyzed and interpreted in the first part of the guide.

## ANORTHOSITIC ROCKS OF THE NORTHEASTERN ADIRONDACKS: GEOCHRONOLOGY, STABLE ISOTOPES, AND FIELD RELATIONS

### Rock Types and Field Relations

The anorthosite massif of the Adirondacks is chiefly comprised of a coarse blue gray andesine anorthosite known as the Marcy facies. There is also the Whitface facies, chiefly found at the margins of the massif, and noted

for its smaller grain size and mortar texture (gray phenocrysts surrounded by grain size reduced plagioclase, the presence of garnet, and foliation. A variety of differentiates also may be found, ranging from gabbroic anorthosite to ferrogabbro, ferrodiorite, and oxide apatite gabbroite.

Outcrops at the stops on this trip provide a great opportunity to examine the magmatic features of the Marcy anorthosite massif and to discuss these features relative to geochronology and geochemistry. We'll see mutual cross cutting relations of different anorthositic rocks and differentiates, the different facies of anorthosite, magmatic features such as foliation, subophitic pyroxenes, and block textures. Block textures contain coarse angular blocks of anorthositic rocks ranging from cm to m scale that are interrupted and surrounded by more magmatic material, generally anorthositic. This suggests the intrusion of the anorthosite as a crystalline mush that was fractured and invaded by later differentiates of the anorthositic parent during such processes as filter pressing. Block textures have been observed in the Northeastern Adirondacks since at least Kemp and Ruedemann (1910). They were named such by Balk (1931). Blocks show magmatic foliation, subophitic textures, and gradations of foliation. The orientation of the foliation in the blocks is variable from block to block.

### Geochronology

The temporal relation of Marcy anorthosite intrusion to granulite facies metamorphism in the Adirondacks has long been a source of controversy. Geochronological studies have been conducted to place anorthosite intrusion and regional granulite facies metamorphism into a temporal framework. A general review/synthesis paper summarizing this work is by McLelland et al. (1996). McLelland et al. (1996) outline a time range of 1150-1125 Ma for anorthosite intrusion, a range determined from ages of zircons from granitic and other rocks that mutually cross-cut anorthosite, e.g. McLelland and Chiarenzelli (1990) Chiarenzelli and McLelland (1991). Age determinations based on geochronology performed directly on the anorthosite itself are rare, and have given varied results. Silver (1968) obtained zircon from pegmatitic anorthosite in the Westport dome and the Jay dome, and determined ages of  $1090 \pm 10$  and  $1070 \pm 20$ , respectively, from bulk zircon separates. Ashwal and Wooden (1983) inferred an anorthosite age as old as  $1288 \pm 36$  based on a 4 pt Sm-Nd isochron. McLelland and Chiarenzelli (1990) obtained an age of 1113 Ma from air abraded cores of zircons from anorthosite, which they considered to be a minimum age of emplacement. Recently, it has been proposed that migmatite formation found just south of the Woolen Mill locality was the result of heat from intruding anorthosite. Zircon geochronology for the migmatite indicated that partial melting event took place at ca. 1040 Ma, and was interpreted to be the time of anorthosite intrusion (Isachsen et al. 2001). New SHRIMP II geochronology on zircons from anorthositic rocks from the Woolen Mill locality provide the first high precision ages for anorthosite intrusion determined directly on anorthositic rocks, and indicate an age of intrusion ca. 1155 Ma (Clechenko et al. 2002). It is important to note that zircon textures as revealed by cathodoluminescence, calculation of Zr saturation, and the uniformity of zircon ages all indicate that the zircons are primary igneous minerals, and are not inherited xenocrysts. Additional new SHRIMP II zircon geochronology on anorthosite and related mafic rocks at many localities in the Adirondacks consistently yields the same result. The dominant events of the Ottawa orogeny have been constrained between 1090-1035 Ma (McLelland et al. 2001), and it would thus seem that the partial melting event dated by Isachsen et al. (2001) is related to regional metamorphism.

### Oxygen Isotopes

It has been known since Taylor (1968) that the Marcy anorthosite has high  $\delta^{18}\text{O}$  values compared to most normal anorthosites worldwide ( $\sim 9.5\%$  vs.  $5.8\text{-}7.6\%$ ). The Marcy anorthosite is enriched in its  $^{18}\text{O}/^{16}\text{O}$  ratio compared to anorthosite in equilibrium with a normal mantle melt. Taylor (1968) suggested that the enrichment was the result of interaction with high  $\delta^{18}\text{O}$  metamorphic fluids during regional metamorphism. Valley and O'Neil (1984) and Morrison and Valley (1988) concluded that the enrichment was a magmatic process, and that anorthosite was born of a mantle melt that had assimilated high  $\delta^{18}\text{O}$  crustal material.

Zircon has been shown in numerous studies to preserve its primary igneous  $\delta^{18}\text{O}$  through overprinting hydrothermal and metamorphic events. Zircons provide a robust material with which the method of elevation of anorthosite  $\delta^{18}\text{O}$  values took place. If the elevation of  $\delta^{18}\text{O}$  was a metamorphic event, zircon should preserve the primary  $\delta^{18}\text{O}$  in equilibrium with the mantle ( $5.3\%$ ). Higher zircon  $\delta^{18}\text{O}$  values would indicate that the elevation of

$\delta^{18}\text{O}$  is a magmatic event and that zircon grew in a high  $\delta^{18}\text{O}$  melt. Valley et al. (1994) report high  $\delta^{18}\text{O}$  values for zircon from one anorthosite (~8.3). Preliminary results from zircon from anorthosite at Woolen Mill (Clechenko et al. 2002) also show high zircon  $\delta^{18}\text{O}$  values ( $8.82 \pm 0.02$ ,  $n=4$ ). These initial results support the hypothesis of that the  $\delta^{18}\text{O}$  of the Marcy anorthosite was elevated during a magmatic event such as assimilation of higher  $\delta^{18}\text{O}$  crustal material (Valley and O'Neil 1984, Morrison and Valley 1988).

## WOLLASTONITE DEPOSITS OF THE NORTHEASTERN ADIRONDACKS

### Introduction

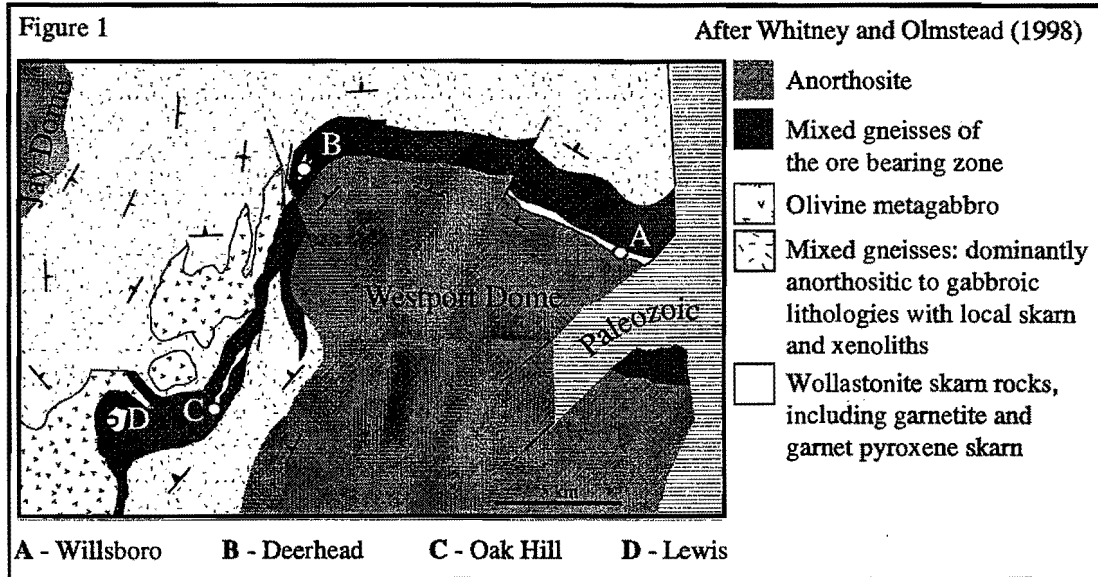
The calc silicate skarns exposed adjacent to anorthosite in the Willsboro-Lewis area of the Northeastern Adirondacks have been an important source of industrial wollastonite for 50 years. The wollastonite ore has the high variance assemblage of Wo + Gt + Cpx with no calcite or quartz, suggesting a metasomatic origin because a protolith with perfect ratios of Cc and Qtz would otherwise be needed to create the observed mineralogy in a closed system. The petrogenesis of the wollastonite deposits has been studied over the same time span, and produced a variety of theories as to the origin of the wollastonite ores. Initial debates centered on an origin involving metasomatism (Buddington and Whitcomb 1941), isochemical metamorphism of original sediments (Broughton and Burnham 1944, Putnam 1958, O'Hara 1976), or combinations of both models (Putnam 1958, DeRudder 1962). As analytical techniques and our understanding of petrologic processes progressed, a metasomatic origin has become accepted. Valley and O'Neil (1982) observed low  $\delta^{18}\text{O}$  values (as low as  $-1.3\%$ ) for wollastonite from the Willsboro deposit, as well as the high variance assemblage, and concluded that meteoric water was involved in skarn formation. The physical relation of the skarn to anorthosite led them to conclude that heat from anorthosite drove meteoric hydrothermal circulation. Valley and O'Neil (1982) concluded that it was unlikely that large volumes of hydrostatically pressured meteoric fluid could penetrate to depths greater than 10 km into the lithostatically pressured ductile regime, and thus anorthosite intrusion must have taken place at shallow crustal levels.

The important conclusions of Valley and O'Neil (1982) served in part to provide strong evidence for a poly-metamorphic model of Adirondack regional geologic development, as summarized by Bohlen et al. (1985), Valley et al. (1990), and McLelland et al. (1996). In this model, anorthosite-mangerite-charnockite-granite (AMCG) intrusion takes place between ca. 1150-1125 Ma (new data mentioned above suggests that it was nearer the older age of 1150 Ma) at shallow (<10km) levels, causing localized contact metamorphism. The intrusion of the AMCG suite was followed by regional, fluid absent, granulite facies metamorphism after ca. 1090 Ma, known as the Ottawa orogeny.

Recent studies have provided further information about the processes that formed the calc silicate skarns. Whitney and Olmstead (1998) used rare earth element (REE) analysis of wollastonite ores and related rocks to develop a two-stage model of wollastonite ore formation. The recent discovery of garnets with oscillatory zoning at Willsboro provides important new insight to the skarn forming processes. A combined oxygen isotope, major element, and trace element study of garnet from wollastonite ores and related rock, along with major element and oxygen isotope analysis of garnet with oscillatory zonation yielded further clues about the skarn petrogenesis (Clechenko 2001). These studies have also provided further evidence of a link between skarn formation and anorthosite intrusion. Any model of Adirondack geologic history that invokes deep intrusion of anorthosite must account for the huge volumes of low  $\delta^{18}\text{O}$  wollastonite ores and associated skarns, as well as geochemical indications of a link between anorthosite and the skarns. Further, phase equilibria indicates shallow origin for index minerals of contact metamorphism found at Cascade Slide, including wollastonite, monticellite, and akermanite as well as other minerals restricted to low pressure environments: cuspidine and wilkeite. This trip will visit the Oak Hill wollastonite deposit to examine some well-exposed relations of wollastonite ore, related calc-silicate skarn, marble, and igneous lithologies including anorthosite.

### Local Geology.

The Oak Hill wollastonite deposit, along with the related deposits at Willsboro, Deerhead, and Lewis, is part of a belt of metasedimentary and metaigneous rocks that is up to ~25km long and 1.5 km wide (FIG 1). The belt overlies, and forms the northern and northeastern border of, the Westport dome of the Marcy anorthosite massif.



The wollastonite deposits have significant volumes of the wollastonite ore, a granoblastic gneiss consisting of Wo (60%) + Gt + Cpx. The wollastonite ore rocks are foliated, and are compositionally layered with varying ratios of wollastonite: garnet: clinopyroxene. The wollastonite ores are deformed, showing isoclinal fold hinges, foliation, and boudinage.

A variety of other calc silicate skarn lithologies are also found associated with the wollastonite ores, chiefly garnetite and garnet pyroxene skarn. These lithologies are found interlayered with the wollastonite ores and igneous lithologies. Garnetites from Willsboro contain rare euhedral garnets with oscillatory zonation. A representative cross-section from the Oak Hill mine shows the relation of the different lithologies (FIG 2). Nearly all of these lithologies are exposed in outcrop on the surface at the mine.

#### Garnets with Oscillatory Zonation.

Massive garnetite from the Willsboro mine contains garnets with oscillatory zonation. The zoned garnets are found in clusters and aggregates and appear to be filling void spaces (FIG 3). The remaining space is filled with feldspar (or altered equivalents such as prehnite) and quartz, with occasional titanite, clinopyroxene, and calcite. Similar textures are known from the garnetite at Oak Hill, though no euhedral garnets analyzed from Oak Hill have oscillatory zonation. The growth of the zoned garnets into void spaces, as well as the involvement of meteoric water, is indicative of hydrothermal fluids and shallow depth of formation of these zoned garnets. Centimeter scale open void space could not exist at great depth (Walther and Orville 1982), and hydrostatically pressured meteoric water could not penetrate into ductile rocks.

Suspected zoned garnets were made into polished thick sections, imaged by BSE or X-ray mapping, and quantitatively analyzed for cation concentrations on transects across zonation. Using a thin saw blade, a mm wide strip was then cut out of the thick section along the electron microprobe traverse. The strip was broken up, and the chips were analyzed for oxygen isotope ratio. One such image and the resulting transect are displayed in FIG4. The analyses reveal a correlation between  $X_{\text{Adr}}$  and  $\delta^{18}\text{O}$ . The magnitude of the fractionation is far greater (at least 10x) than that predicted between the two garnet compositions at elevated T (Kohn and Valley 1998). The garnets record variable inputs of two fluid compositions, one with high  $\delta^{18}\text{O}$  values and Fe rich (presumably magmatic (anorthositic) in source), and another with lower  $\delta^{18}\text{O}$  values, with a meteoric source.

Garnet with oscillatory zonation such as this has been reported from numerous Phanerozoic shallow contact metamorphic environments (e.g. Chamberlain and Conrad 1991, Jamtveit and Hervig 1994, Crowe et al. 2001), though the Willsboro garnets are the first known that are preserved in a granulite facies terrane. Such garnets provide a useful comparison to understanding the garnets from Willsboro with oscillatory zonation. It is important to note that the zoned garnets at Willsboro could not have formed at granulite facies conditions as indicated by their

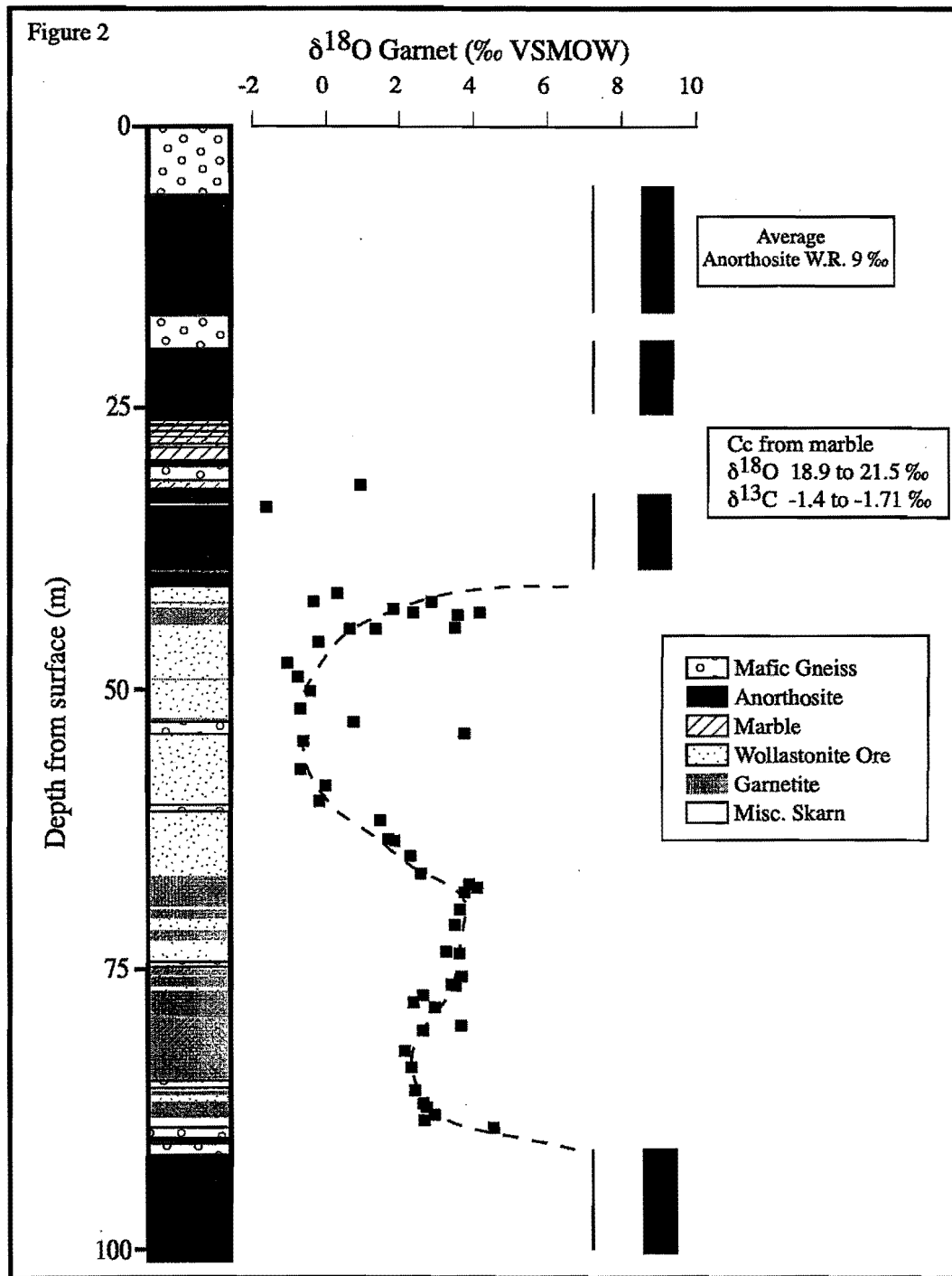


Figure 2. Lithologic and oxygen isotope transect from drill core across the Oak Hill wollastonite deposit. All data from analyses of garnet, summarized in Table 1. Note the generally higher  $\delta^{18}\text{O}$  values of garnetite compared to wollastonite ores. Calcite  $\delta^{18}\text{O}$  values suggest heterogeneity of fluid flow during skarn formation, as well as no subsequent cross-contact flow. This geometry suggests tectonic interleaving and deformation subsequent to skarn formation. Thus, the original physical relations of these lithologies during skarn formation is unclear. Black lines left of anorthosite W.R. value are fictive intermediate composition grandite garnets in isotopic equilibrium with intermediate composition plagioclase.

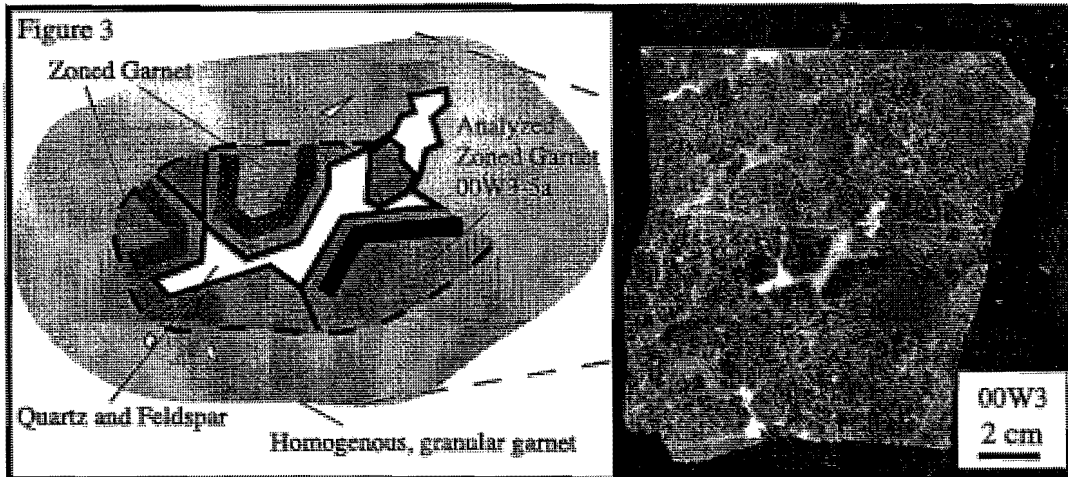


Figure 3. Image of slab of garnetite (00W3) from Willsboro wollastonite mine showing textures associated with zoned garnets. Garnets have grown filling void spaces and are surrounded by a matrix of finer grained, homogenous garnet. Cartoon interpretation included on the left. Limit of zoned garnet occurrence shown by dashed envelope in both images. Garnet zonation patterns shown with lines paralleling garnet crystal faces. The garnet analyzed is reported in Clechenko (2001), and is similar to the zoned garnet shown below in Figure 4.

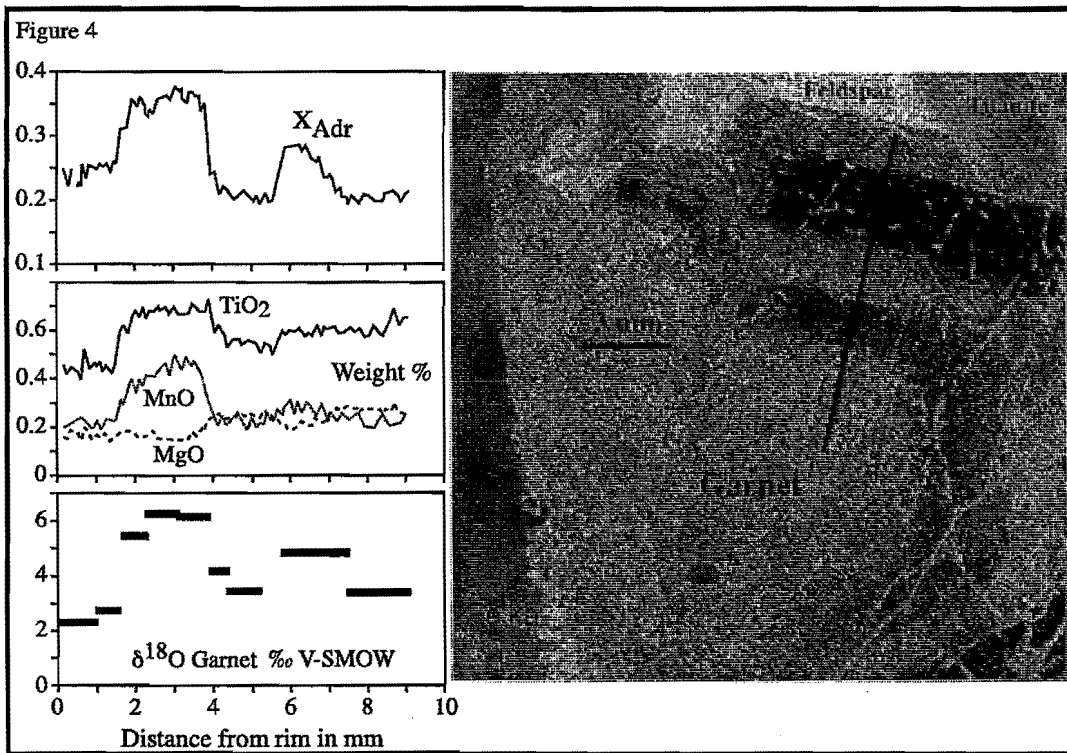


Figure 4. Fe K- $\alpha$  image of zoned garnet 94ADK11. Dark areas are more andraditic, gray areas more grossularitic. Analytical transect across garnet shown by dark line from rim to core on image to right, analytical results shown on left for cations and oxygen isotopes.

growth into void spaces and the involvement of low  $\delta^{18}\text{O}$  fluids in their growth. Preservation of zoned garnets formed prior to the regional metamorphic overprint is possible due to their large size and the slow diffusion of cations and oxygen in garnet they would be able to survive a granulite facies overprint. Additionally, the garnets survive in massive garnetite and are armored from the effects of deformation and recrystallization as boudins that are surrounded by homogenous, recrystallized garnet.

**Chemistry of Garnets from transects across deposits**

A general survey of garnet cation chemistry and oxygen isotope values was conducted from drill core and hand samples from the Oak Hill and Willsboro wollastonite mines. The original oxygen isotope transect of Valley and O'Neil (1982) showed low  $\delta^{18}\text{O}$  values of the wollastonite (to  $-1.3\text{‰}$ ), as well as large variations of  $\delta^{18}\text{O}$  over short distances of contacts between wollastonite ores and igneous rocks ( $\sim 8\text{‰}$  over 4m). The sharp nature of the variation of  $\delta^{18}\text{O}$  indicates that little cross boundary fluid flow took place during granulite facies metamorphism, assuming that the relative position of the skarn to anorthosite has not changed subsequent to granulite facies metamorphism. A similar, but more detailed, transect of garnet  $\delta^{18}\text{O}$  values from Oak Hill is shown above (FIG 2). The results are from Clechenko (2001).

Combined garnet  $\delta^{18}\text{O}$  and cation composition data from the wollastonite ores and other calc silicate assemblages at Willsboro and Oak Hill provide important new clues about the contact metamorphic/hydrothermal processes that formed the skarn. Garnet compositions in ores range from  $X_{\text{Adr}} = 0.2$  to  $0.9$ , and garnet  $\delta^{18}\text{O}$  values are positively correlated with composition, ranging from  $-1.65$  to  $2.85\text{‰}$  (FIG 5). Additionally, correlation of  $X_{\text{Adr}}$  to rare earth element (REE) patterns in whole rock (Whitney and Olmstead 1998), and a correlation of garnet REE patterns with both  $X_{\text{Adr}}$  and  $\delta^{18}\text{O}$ , (Clechenko 2001, Clechenko et al. 2001) is observed. These are most readily expressed as a ratio of light REE to heavy REE concentration (Pr/Yb) and the size of the positive Eu anomaly (Eu/Eu\*), results are shown in FIG 6. The result is a population of garnet that systematically vary from low  $X_{\text{Adr}}$ , Eu/Eu\*, Pr/Yb and high  $\delta^{18}\text{O}$  to high  $X_{\text{Adr}}$ , Eu/Eu\*, Pr/Yb, and low  $\delta^{18}\text{O}$ .

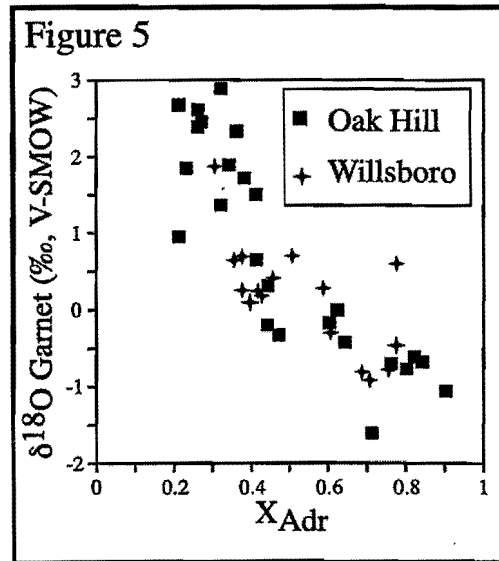


Figure 5.  $\delta^{18}\text{O}$  vs.  $X_{\text{Adr}}$  ( $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Al})$ ) of garnet from wollastonite ores from the Oak Hill and Willsboro wollastonite mines, NY.

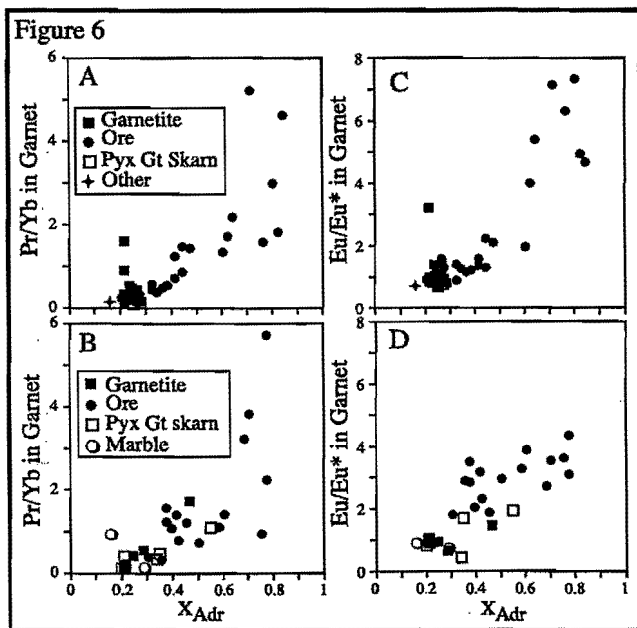


Figure 6. Pr/Yb vs.  $X_{\text{Adr}}$  ( $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Al})$ ) of garnet from the Oak Hill (A) and Willsboro (B), as well as the size of the Eu anomaly (Eu/Eu\*) vs.  $X_{\text{Adr}}$  for garnet from a variety of lithologies from Oak Hill (C) and Willsboro (D) wollastonite mines.

**Formation of the Willsboro-Lewis wollastonite ores**

A synthesis of existing knowledge of the origin of the Willsboro-Lewis wollastonite ores is presented here. Whitney and Olmstead (1998), based on observed whole rock REE patterns, indicated a two-stage model of skarn formation involving contact metamorphism of a carbonate followed by massive metasomatism involving meteoric water. Much additional data from the study of Clechenko (2001) allows an even more detailed understanding of the hydrothermal system that formed the Willsboro-Lewis skarn. We propose that intrusion of anorthosite took place at shallow crustal levels at ca. 1155 Ma causing contact metamorphism of siliceous carbonates to form silicate marbles. Garnet in such a marble would have been relatively high  $\delta^{18}\text{O}$ , HREE enriched, lack an Eu anomaly, and be low  $X_{\text{Adr}}$ . Magmatic fluids were released periodically by hydrofracturing from the intruding anorthosite as it crystallized, as described by Hanson (1996) for skarns in the Sierra Nevada of California. Late during crystallization, meteoric water started to penetrate the system. The resulting episodic mixing of these fluids in varying amounts gave rise to the localized growth of garnets with oscillatory zonation. The zonation records the relative input of a high  $\delta^{18}\text{O}$ , Fe enriched fluid (magmatic) varying with a low  $\delta^{18}\text{O}$ , relatively Fe poor fluid (meteoric) over the time of garnet growth. Subsequently, after exhaustion of magmatic fluid, the system became dominated by massive amounts of meteoric water heated by the still hot anorthosite. Metamorphic volatiles evolved via contact metamorphism were either channeled away from the system, or diluted by large volumes of the heated meteoric water. Hot, low  $\delta^{18}\text{O}$  meteoric waters became enriched in Si, Fe, and Eu by interaction with anorthositic rocks, and caused the growth of more silicates (Wo + Gt + Cpx) in the marble, transforming it to skarn. The second stage of wollastonite ore formation just described was postulated by Whitney and Olmstead (1998) based on REE patterns of whole rock. The garnet that precipitated from this fluid was low  $\delta^{18}\text{O}$ , LREE, had large Eu anomalies, and high  $X_{\text{Adr}}$ . Subsequent fluid-absent granulite facies metamorphism and deformation after 1090 Ma during the Ottawa orogeny caused the homogenization of the skarn minerals (with the exception of the rare large garnets with oscillatory zoning, protected in massive garnetite) and inter-mineral oxygen isotope equilibration. The granulite facies metamorphism inter-mineral equilibration also reset U-Pb and Sm-Nd ages (1035 Ma by both methods, from K. Burton (pers. comm. to JWV) and Basu et al. 1988, respectively). The deformation recrystallized or homogenized many of the original zoned minerals and destroyed much of the original spatial relation of the skarn and fluid flow system.

**SUMMARY**

The combined geochronologic, field, stable isotope, and petrologic study of the Marcy anorthosite and associated contact metamorphic rocks constrains a detailed geologic understanding of anorthositic magmatism in the Adirondacks. New SHRIMP II zircon geochronology from anorthosites and anorthositic rocks indicates anorthosite intrusion took place at ca. 1155 Ma. The intruding anorthosite was a partially solidified crystal mush that underwent brittle fracture into blocks, magmatic foliation formation, and filter pressing and magmatic evolution. The Marcy anorthosite began as a normal  $\delta^{18}\text{O}$  mantle melt, the high  $\delta^{18}\text{O}$  presumably the result of assimilation of crustal material into the mantle melt when it was ponded at the base of the crust. The anorthosite intruded the crust at shallow levels (<10km) as shown by the formation of low  $\delta^{18}\text{O}$  skarns adjacent to anorthosite. Calc silicate skarn formation was due to a complex hydrothermal system involving multiple stages and fluids from different reservoirs, one of which was meteoric. The Ottawa orogeny, after 1090 Ma, was a mostly fluid absent granulite facies event that largely overprints the anorthosite and the contact metamorphic rocks. The anorthosite behaved as a dry rigid body, and thus was not significantly deformed during regional metamorphism, preserving the igneous features observed in the field. The contact metamorphic rocks had their original geometry destroyed, but much of their chemistry was not significantly altered, allowing a significant understanding of the skarn forming processes.

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## ROAD LOG

### Mileage

From Lake George Village, take I-87 north to Exit 30.

- 0.0 Exit 30, start odometer at end of off ramp. Take a left onto Rts. 9 and 73.
- 2.3 Right onto Rt. 9 north toward Elizabethtown.
- 4.6 After crossing bridge, pull into parking area on right side of road.

**STOP 1. SPLIT ROCK FALLS LOCALITY.** (OPTIONAL) The roadcut across from the parking area provides evidence for multiple intrusions of anorthositic and gabbroic rock. The dominant rock type is gabbroic anorthosite that encloses altered xenoliths. Subophitic textures are preserved in the more gabbroic xenoliths. Garnetiferous gabbro truncates foliation in some xenoliths and has, itself, a different foliation. Some small xenoliths of anorthosite are elongated and are deformed parallel to the foliation in the gabbroic facies suggesting coeval magmatism. All of the above facies, including the garnetiferous anorthositic gabbro, are disrupted by a more mafic facies similar to Woolen Mill gabbro. Late mafic dikes (Phanerozoic?) with well developed slickensides cut all other lithologies.

The outcrop not only gives good evidence for the composite nature of the Marcy anorthosite massif, but it also demonstrates the manner in which these rocks can acquire foliation during magmatism and without the need for regional strain. Numerous other localities exist in which different members of the anorthosite suite locally develop foliations that are crosscut by other anorthosite facies. The fact that these rocks involved are clearly contemporaneous, and that the fabrics are strictly local, provide compelling evidence that the foliations developed during composite magmatism when semi-consolidated blocks and magmas underwent differential movement.

Turn right out of parking area, continue north on 9N

- 12.6 Left onto Rt. 9N in Elizabethtown
- 13.6 Right into turnout on side of road, opposite tall roadcut. Bridge and Lord Rd. on right are just beyond parking area.

**STOP 2. WOOLEN MILL LOCALITY.** The outcrops exposed in road cuts along Rt. 9N and in the stream at the site of the former Woolen Mill afford an excellent opportunity to examine field relations of cross-cutting anorthosite series rocks. A sketch map is included here as FIG 7. Recent SHRIMP II geochronology has been undertaken on zircons from the different rock types exposed here to constrain the age of emplacement of the Marcy anorthosite massif and related mafic rocks (Clechenko et al. 2002). New oxygen isotope data have provided further evidence for the magmatic enrichment of the anorthosite in  $^{18}\text{O}/^{16}\text{O}$  compared to “normal” magmatic anorthosite, as opposed to enrichment by metamorphic fluids during subsequent metamorphism (Clechenko et al. 2002).

The roadcut on the south side of Rt. 9N shows anorthosite (east end) intruded by a dark, fine-grained rock, first described by Kemp and Ruedemann (1910) as the “Woolen Mill Gabbro”. The Woolen Mill Gabbro is a fine to medium grained clinopyroxene-garnet-oligoclase granulite with magnetite-ilmenite, apatite, and minor K-spar and quartz. The gabbro also contains a population of cm scale andesine xenocrysts that have their apparent source from the anorthosite. These may be easily seen as one walks west along the outcrop from the anorthosite contact. The rock is clearly metamorphosed, as indicated by the presence of significant garnet, but lacks significant deformation

features. Zircons obtained from the Woolen Mill Gabbro along the road had cores that exhibited oscillatory zonation, interpreted to be magmatic in origin, and yielded an age of  $1154 \pm 9$  Ma. Thick, structureless, U poor overgrowths imprecisely date a metamorphic zircon growth episode at  $1008 \pm 32$  Ma.

Figure 7

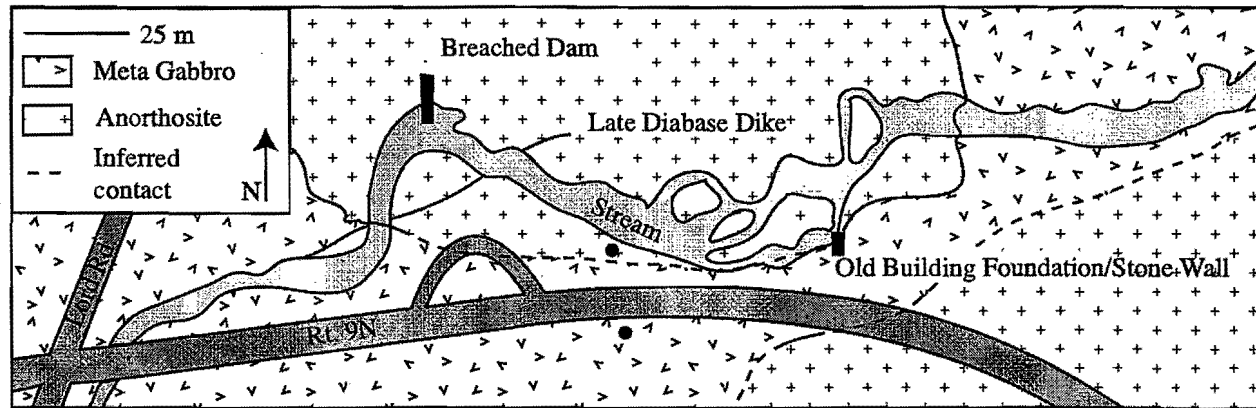


Figure 7. Sketch map of the Woolen Mill area, 1 mile west of Elizabethtown, NY on Rt. 9N. Map is after Kemp and Reudemann (1910). Best exposed cross cutting relations and block texture all found near stream bed within 25 m of turnout off of Rt. 9N and breached dam. Black dots represent approximate location of geochronology samples discussed in text. Dot on south side of road is location of metagabbro sample, dot under word stream location of pegmatitic anorthosites.

Cross the road to examine the exposures in the streambed. Starting from the west, where the stream flows out from under the Rt. 9N bridge, on the north shore of the stream, more Woolen Mill Gabbro is exposed, and as one walks east (downstream) on the north side of the stream, it may be seen becoming apparently finer grained near the contact. A weak apparent foliation also exists, defined by plagioclase lathes, and is best seen on the weathered surfaces in the streambed. Plagioclase xenocrysts and small anorthosite xenoliths are found in the gabbro in a number of spots near the contact. At the contact, the gabbro is clearly seen cross cutting anorthosite. The contact is irregular, and cuts across a variety of different anorthositic lithologies, including a coarse, pyroxene rich facies. At some points along the contact, anorthosite has broken off and floats in the gabbro. Dikes and veins of the gabbro extend into the anorthosite at a number of areas near the contact, and may also be seen as one moves further downstream away from the contact. Also apparent are a number of light colored, cm scale thick dikes that originate at the contact and extend into the gabbro. These appear anorthositic, as they contain plagioclase that has the blue gray appearance of plagioclase in the anorthosite, but contain significant quartz. These may be mixed lithologies, of the transitional "Keene Gneiss" type of Miller (1919).

Crossing the stream to south bank immediately below the parking turnout and across the stream from the breached dam, the outcrops are of anorthosite. The anorthosite here has a clearly developed "block structure" where several different types of anorthosite have been undergone brittle fracture and been intruded by a variety of mafic (anorthositic to gabbro) and felsic material. The angular blocks vary in size from 10's of cm to meter scale. The blocks are generally of a coarse anorthosite with large plagioclase phenocrysts and megacrysts. One block at the top of the outcrops has "deformed" anorthosite transitional to "undeformed" anorthosite. The occurrence in a block with a preserved transition indicates a magmatic origin of the foliation. Sub-ophitic pyroxene textures of a magmatic origin are also developed in a number of places in the anorthosite.

Some intruding material is equivalent to the Woolen Mill Gabbro, as mentioned above. This material is found as veining throughout the outcrop. In one location at the western edge of the outcrop and near the streambed, intruding Woolen Mill gabbro cuts across a plagioclase megacryst. At another location near the top of the outcrop, just adjacent to the foliated anorthosite block described above, gabbro intrudes the anorthosite in the shape of a reversed "7" when viewed looking to the south. Blocks of the gabbro are broken, forming a series trailing away from the main vein. Much of the intruding material is of an anorthositic gabbro composition. More than one

“generation” of such gabbroic anorthosite material is found, varying in both mafic content and crystal size. Some of the dikes or veins are granitic in nature.

Anorthosite throughout the outcrops contains the characteristic post-metamorphic alteration assemblages of calcite  $\pm$  chlorite  $\pm$  sericite that are commonly seen as late-stage, hairline vein fillings or as alteration products of Fe-Mg silicates throughout the Adirondacks (Buddington 1939; Morrison and Valley 1988). Average values of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  for calcite are 12.6 and  $-2.2$  permil, respectively, which suggests that alteration fluids were deep seated in origin and exchanged with igneous as well as metasedimentary rocks. These veins are related to the formation of at least some high density,  $\text{CO}_2$ -rich fluid inclusions and the temperatures of alteration are estimated at 300-500° C (Valley et al. 1990).

The retrograde fluids that have infiltrated the anorthosite to precipitate calcite have not significantly altered its oxygen isotopic composition. Values of  $\Delta_{(\text{Cc}-\text{Plg})}$  range from 0.9 to 6.6, indicating that the isotopic composition of the alteration minerals was controlled primarily by the hydrothermal fluid and that the  $\delta^{18}\text{O}$  of the host rock remains largely unchanged due to low fluid/rock ratios.

Values of  $\delta^{18}\text{O}$  (plag) for the blocks and their host anorthosite at this outcrop range from 8.5 to 9.3‰. In general, the metanorthosites in the NE part of the Marcy massif are somewhat more isotopically heterogeneous than those in the northwestern part of the massif, but they show the same roughly 2.5 permil enrichment in the  $\delta^{18}\text{O}$  relative to normal anorthosites worldwide (Morrison and Valley 1988).

Travelling further downstream, the blocking texture becomes less pronounced. Populations of zircons were obtained from coarse-grained anorthositic pegmatites between the dam and the foundations downstream, as well as from gabbroic anorthosite taken from the outcrop at the dam. Prismatic zircons with sector and oscillatory zoning (interpreted to be igneous) from one of the anorthositic pegmatites yielded an age of  $1151 \pm 6$  Ma. A subordinate population of zircons from the pegmatitic anorthosite have structureless (in CL) rims that give an age of metamorphic growth at  $1012 \pm 5$  Ma. Upon reaching the foundations of the old mill buildings above some falls, more metagabbro is exposed, and below the falls, the rocks in the streambed and on the banks are nearly all Woolen Mill gabbro.

When all relations exposed here are taken in total, they suggest the intrusion of a plagioclase rich cumulate that was fractured and intruded by more mafic differentiates, as well as a small amount of granitic material. This event took place at ca. 1155 Ma, as determined from igneous zircons from both anorthosite and the metagabbro at this locality. These ages are in agreement with new ages determined from zircons separated from Marcy anorthosite at a number of localities across the Adirondacks, and are also in general agreement with ages determined from zircons from granitic rocks that cross cut anorthosite at a number of localities (Chiarenzelli and McLelland 1991). The ages lend no credence to assertions of anorthosite intrusion in this area at ca. 1040 Ma (Isachsen et al. 2001).

Turn right out of parking area, heading westward on 9N (toward Keene).

- 23.1 Right onto Rts. 9N and 73 toward Keene.
- 25.0 Right at intersection in Keene, remains Rt 9N, toward Jay
- 31.2 Remain on Rt. 9N (effectively a right turn) in Upper Jay, still heading toward Jay.
- 35.0 Right on to Mill Rd. (north edge of the small park) in Jay. Go down hill, bear right over bridge, bear right after bridge.
- 35.3 Right into turnouts on side of road and park.

**STOP 3. COVERED BRIDGE AT JAY** (note: covered bridge no longer crosses river, and is set on side of road). Walk a few tens of feet farther south along the paved road from the parking turnouts. At the sharp bend in the road there is a low, polished outcrop that exposes two exceptional examples of rafts of coarse, blue-gray andesine anorthosite of the Marcy facies. The more southerly of these is enveloped in medium grained gabbro similar to a xenolith bearing, gabbroic facies found on Giant Mtn. The gabbro is, in turn, surrounded by a fine grained anorthosite. The northern raft of Marcy anorthosite lacks the rim of gabbro and is directly surrounded by the white, fine-grained anorthosite. The northern raft also contains giant pyroxene whose edges show subophitic relates with plagioclase.

Within the river there occurs a wide area of water-swept exposures of white, fine grained, and highly altered anorthosite containing a few remnant blue-gray andesines as well as a few blocks of subophitic gabbro. The exposures are disrupted by two types of dikes: 1) late unmetamorphosed (Phanerozoic?) diabase paralleling the river, and 2) irregular, pyroxene-rich dikes and veins that trend mainly N-S and E-W but show other orientations and right angle turns, as well. Some of the dikes are 15-20 cm wide but most fall into the 2-5 cm range. Both sharp and gradational contacts exist. Several of the dikes intrude along zones of mafic mylonite that may be of the same composition as the dikes themselves.

Mineralogically, the dikes consist of coarse, emerald green clinopyroxene and Fe, Ti-oxide. Some dikes also contain small quantities of plagioclase, garnet, apatite and titanite. The apatite-free dikes contain very Mg rich clinopyroxene ( $X_{Mg} \sim 0.80$ ) while the apatite bearing dikes have less magnesian clinopyroxene ( $X_{Mg} \sim 0.65$ ). The key to understanding these dikes is to note that some exhibit comb structure defined by pyroxene and plagioclase crystals growing perpendicular to the dike walls. The texture is diagnostic of growth from a fluid and provides compelling evidence that the dikes were intruded as liquid rich magma. Preliminary experimental work by D. Lindsley (pers. comm. to J.M.) indicates that representative dike material reaches its liquidus at 1200°C (max).

It is suggested that the pyroxene-rich, and sometimes apatite bearing, dikes represent immiscible silicate fractions complementary to magnetite-ilmenite deposits. Emplacements may have occurred when jostling about of essentially congealed plagioclase cumulates resulted in fracturing and the development of large blocks whose shifting provided passageways along which pyroxene-oxide magmas could be filter pressed. Depending on the batch of magma tapped, the intruding material would vary from Mg rich to Fe rich with apatite. Some dikes may have been cumulate-rich.

Dikes of the sort exposed in the river at Jay are common throughout the Marcy anorthosite massif, and their presence indicates a substantial, but small, amount of mafic material – and possibly mafic cumulate – in the massif. Invariably these dikes consist of green clinopyroxene and Fe, Ti-oxide, and it is common to find the silicate and oxide phases physically separated within the same vein. It is possible that, where this occurs, it reflects liquid immiscibility operating on late-stage interstitial fractions that are filter-pressed into veins.

Zircons from the clinopyroxene-plagioclase dike contain very low concentrations of uranium and therefore yielded a poorly constrained SHRIMP II age of  $1139 \pm 89$  Ma. Because the zircons show no inherited cores, it is planned to re-date them by single grain TIMS procedures. A pegmatitic gabbroic anorthosite occupying a ductile shear zone in the riverbed yielded abundant zircons that gave a well constrained SHRIMP II age of  $1155 \pm 13$  Ma. This age is consistent with ca. 1155 Ma SHRIMP II ages obtained from six other anorthosite samples from across the Marcy massif, including those described at Woolen Mill. These results make it clear that attempts to argue for a young age of ca. 1040 Ma (Isachsen et al. 2001) for the Marcy anorthosite are without merit and are wrong.

Retrace route to Elizabethtown.

58.0 Jct. of Rts 9 and 9N in Elizabethtown. Left turn (heading north toward Lewis) on Rt. 9.

64.9 Left onto Pulsifer Rd. View of Oak Hill deposit on hillside ahead. Follow around sharp bend to north. Gate to mine located on left side of road at transition from pavement to dirt. Depending on conditions, we will either park here and walk in, or drive up unimproved road to mine.

**STOP 4. OAK HILL WOLLASTONITE DEPOSIT.** (Private property, seek permission at NYCO offices in Willsboro if coming on your own) The Oak Hill wollastonite deposit provides excellent exposures of interlayered calc silicate skarn and anorthositic lithologies, typical of the low  $\delta^{18}O$  wollastonite skarns found between Lewis and Willsboro in a belt of rocks that form the northern and northwestern border of the Westport anorthosite dome. The rocks are exposed on an east-facing hillside of Oak Hill, cleared of trees and overburden within the past few years. The rocks occur in nearly parallel layers, dipping into the hillside, as known from drill core (FIG 2) and outcrop. The lowest units known are anorthositic rocks of varying composition. Overlying this are the calc silicate skarns of the wollastonite ore horizon, and above that, interlayered igneous and marble lithologies. This portion of the trip will entail a short walking transect across lithologies exposed on the hillside and in test pits at Oak Hill. This transect is the surface exposure of the drill core cross section shown previously in this field guide (FIG 2) as well as in Clechenko (2001). A sketch map is included (FIG 8) showing the position of features described in this road log.

Future mining activity at the Oak Hill deposit may alter the appearance of the area, and the features described below and shown on the map may be altered or simply not exist in the future.

Figure 8

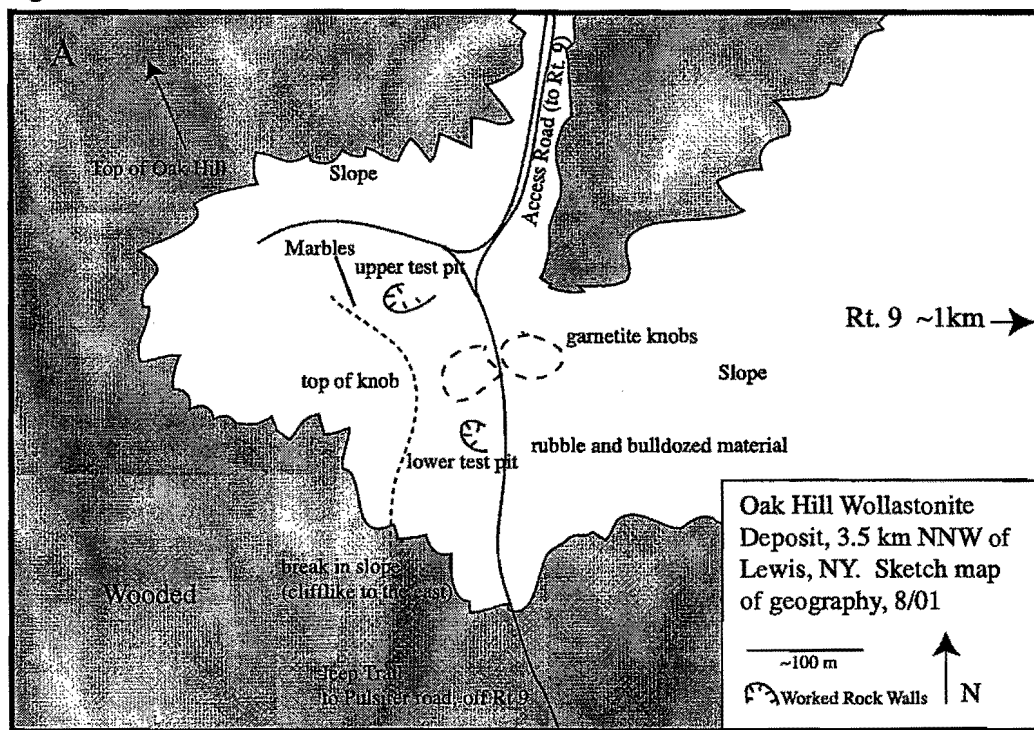


Figure 8. Sketch map of the Oak Hill deposit showing relative location of features described in text.

The footwall of the layered sequence is anorthosite of the Westport dome. These are not seen in outcrop, but are known from drill core. The anorthosite varies in appearance, generally based on the amount of mafic minerals and also quartz, but is typically of the "Whiteface facies" of foliated white anorthosite with crushed and recrystallized plagioclase. Some samples contain noticeable quartz. Minor garnet is found in these anorthosites.

The structurally lowest outcrop exposures in the section are massive garnetites consisting almost entirely of grandite garnet, and are exposed as knobs on either side of one of the southern access road. The garnetites overlie anorthositic rocks at this locality as known from drill core. Garnet from the massive garnetite has a generally restricted compositional range (when compared to garnet from wollastonite ore) that is grossular rich. The garnetite has a range of textures. Some areas are comprised of small, equant sized garnet grains, while other areas are comprised of large (cm scale) euhedral crystals surrounded by feldspar and quartz. This texture is also observed in garnetite from the Willsboro mine (FIG 3), where some of the euhedral garnets have oscillatory zonation. The texture is interpreted to be growth of euhedral garnets into open void spaces. The clusters of large euhedral garnet behaved as rigid boudins during Ottawa metamorphism and deformation, while surrounding garnets could have been recrystallized and chemically homogenized. The low  $\delta^{18}\text{O}$  nature of the zoned garnet and the demonstrated chemical link between anorthosite and the oscillatory zonation of the garnet indicate that anorthosite intrusion took place at shallow crustal levels. Additional accessory minerals include titanite and clinopyroxene. On the west-side of the western knob, the garnetite is intruded in places by gabbroic anorthosite. Presumably, this represents a late stage anorthositic series magma that intruded the garnetite. The intrusive relation has been armored by garnetite during the major metasomatic wollastonite ore formation event and subsequent deformation.

Structurally overlying the garnetite, and exposed in two pits (one south of the garnetite, one uphill and west), are the low  $\delta^{18}\text{O}$  (garnet as low as  $-2\%$ ) wollastonite skarn rocks ( $\text{Wo} + \text{Gt} + \text{Cpx}$ ), along with related lithologies, including garnetite ( $\text{Gt} \pm \text{Qtz} \pm \text{Fsp}$ ) and garnet pyroxene skarn ( $\text{Gt} + \text{Cpx} \pm \text{Ttn} \pm \text{Ap}$ ). As a general rule, the wollastonite skarn rocks (the wollastonite ore) do not contain primary quartz or calcite, indicating their high

variance and formation in an open system. The wollastonite skarn runs approximately at 50-70% wollastonite, though that is variable on the order of 10's of centimeters. Garnet from wollastonite ores have a range of composition  $X_{\text{Adr}} = 0.1$  to 0.9. Color is a general indicator of garnet composition, with darker garnets containing more Fe, and redder garnets more Al. Garnet  $\delta^{18}\text{O}$  varies with composition, higher  $X_{\text{Adr}}$  correlates to lower  $\delta^{18}\text{O}$ . The walls of the test pits and numerous blocks lying about afford an excellent opportunity to examine the nature of the wollastonite ores. The ores are a coarse granoblastic combination of wollastonite, grandite garnet, and clinopyroxene. The ore has a weak foliation defined by the tabular wollastonite grains, and a gneissic habit defined by compositional layering of varying modal percentages of wollastonite and the mafic minerals. In the lower test pit (south of the garnetite knobs), typical wollastonite ore may be found, as well as blocks of garnet pyroxene titanite apatite skarn. In the upper test pit (just above the garnetite knob to the west), additional wollastonite ore rocks may be found, as well as a meter thick layer of garnet pyroxene skarn that pinches and swells along the boundary between the wollastonite ores and the overlying anorthosite (Whiteface facies). The anorthosite is typical "Whiteface facies" and is further exposed as one proceeds west above the test pit.

A number of interlayered lithologies, including anorthosite and anorthosite series rocks such as gabbro, marble, and rocks of granitic composition overlie the wollastonite ores. Generally, the interlayering is on the order of 10's of centimeter to meter scale. The anorthositic rocks here are generally similar in appearance to those in the footwall of the deposit that are known from drill core. In places they are more typical Whiteface facies, with occasional plagioclase megacrysts and garnet. Included in one marble layer exposed at the base of the hillside immediately above the upper wollastonite test pit are complexly folded granulite calc-silicate layers. In some places the calc silicates folds and layers are weathering out of the marble, resulting in pieces of rock lying about that give the appearance of dirty dishrags (FIG 9). The complex folding is the result of the contrast in physical properties between the calc silicate layers and the marble. Marbles contain clinopyroxene, titanite, and graphite, and have a measured calcite  $\delta^{18}\text{O}$  of  $-20\text{‰}$  for three different samples.

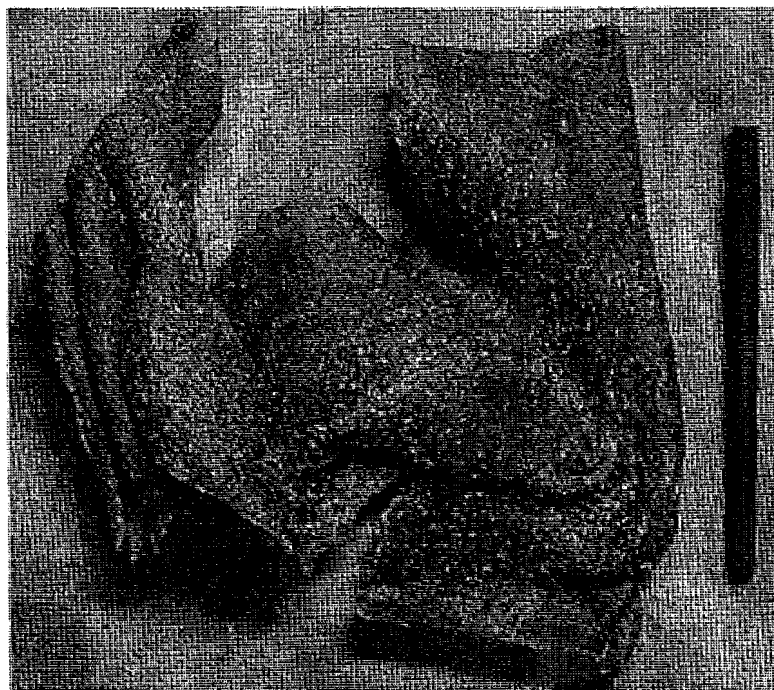


Figure 9. Calc silicate fold ("dishrag") weathered out of marble from Oak Hill wollastonite mine, sample collected from marble layer at base of cliff above wollastonite ore horizon.

The overall given by the exposures and field relations at Oak Hill are as follows. (1) Skarn formation predates the major deformation and recrystallization event. Low  $\delta^{18}\text{O}$  skarn lithologies are deformed, they exhibit foliation and gneissic layering, and the whole of the deposit is drawn into parallelism with the other lithologies and in accord with the regional grain. These relations are well preserved in the quarry faces at Willsboro. (2) Deformation has

served to obscure the original geometry and spatial relations of the hydrothermal system that formed the skarn. (3) The skarns are intimately related to anorthosite. This is true at Oak Hill and throughout the belt surrounding the Westport dome. (4) The fluid flow system that created the skarns was channelized, as marbles near the skarns have not been affected by infiltration of fluids and turned to calc silicates.

When field relations and textures are combined with geochemical analysis, our understanding of the Willsboro-Lewis skarn belt formation is significantly advanced. All results point to formation at shallow crustal levels adjacent to anorthosite (at ca. 1155 Ma) in a complex hydrothermal system, followed by regional deformation and granulite facies metamorphism at temperatures of  $\sim 750^{\circ}\text{C}$  and pressures of  $\sim 7$  kb. The metamorphism was fluid-absent, most likely by partitioning of water into small amounts of anatectic melt. Garnet U-Pb ages of  $\sim 1035$  Ma from skarns indicate closure of U diffusion and end of recrystallization at that time.

End of Day.

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