

ORIGIN OF THE LEWIS WOLLASTONITE DEPOSIT

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INTRODUCTION

The Willsboro-Lewis mining district is a world-class wollastonite (CaSiO_3) producer in the eastern Adirondack Mountains, where wollastonite skarn is associated with Mesoproterozoic anorthosite. This district has estimated reserves of about 6 million short tons (St) from the Lewis open pit, Fox Knoll (the underground mine), and Oak Hill, half of which are represented by the currently operating Lewis mine. NYCO's Willsboro, NY plant produced 58,000 St of finished product in 2007. Combined with another 60,000 St produced at its Mexican operations, NYCO supplies approximately $\frac{1}{4}$ of the world's wollastonite. Wollastonite and its association with clinopyroxene and garnet was first described from the mining district by Vanuxem (1822), and his chemical analysis may be the first of a mineral from the Adirondacks (Buddington 1977). Fieldwork by A.F. Buddington in 1936 and 1937 led to the recognition that wollastonite skarns formed between anorthosite plutons and carbonate country rocks (Buddington and Whitcomb 1941). Oxygen isotope studies (Valley and O'Neil 1982; Valley et al. 1990; Clechenko and Valley 2003) reveal the importance of heated meteoric water during anorthosite emplacement and formation of the wollastonite-clinopyroxene-garnet ores.

Mining in the Willsboro-Lewis mining district is ongoing at the Lewis mine, which has been in operation since 1983. Mining in the area was intermittent until the early 1953, when Cabot Corporation began wollastonite mining operations at the Willsboro mine for use as a ceramic base and filler (Olmsted et al. 1992; Whitney and Olmsted 1995). Underground mining at Willsboro began in 1960 and ended in 1982. Currently at Oak Hill, NYCO is in contract with Graymont Materials of Lewis to crush the caprock for aggregate applications, thus lowering the overall strip ratio. Wollastonite mining will commence in approximately six years, with an overlap in supply to the plant in Willsboro from both the Lewis and Oak Hill mines. At this time the Deerhead deposit has been deemed uneconomical for mining. Wollastonite from Lewis and NYCO's operation in Sonora, Mexico is primarily used for applications such as plastics & elastomers, paints & coatings, construction materials, friction and metallurgical products, and finally for conductive/anti-static purposes.

GEOLOGIC OVERVIEW

Wollastonite ores in the Willsboro-Lewis area are associated with the contact zone of the Westport dome of the Marcy anorthosite massif (Fig. 1). The Marcy anorthosite and associated granitic rocks intruded at ca. 1155 Ma (McLelland et al., 2004). This AMCG (Anorthosite-Mangerite-Charnockite-Granite) suite dominates the Adirondack Highlands, and is contemporaneous with the Morin and Lac St. Jean anorthosite suites in Quebec (Doig 1991; Higgins and van Breemen 1996). In the Adirondack Highlands, anorthosite-suite rocks were emplaced into crust made up of 1300–1250 Ma arc-related tonalities and metasediments metamorphosed during the ca. 1210–1160 Ma Shawinigan orogeny (Heumann et al. 2006). Anorthosite-suite plutons and country rocks are overprinted by ca. 1080-1050 Ma granulite-facies mineral assemblages of the Ottawa orogeny (McLelland et al., 2001).

The Willsboro, Lewis, Oak Hill, and Deerhead wollastonite deposits are located in a ca. 25 km long, 1.5 km thick belt of metasedimentary and metaigneous rocks that border the Westport anorthosite dome on the north and west (Fig 1b; Buddington and Whitcomb 1941; Whitney and Olmsted 1993). Anorthositic rocks of the Westport dome are primarily made up of gray intermediate plagioclase megacrysts surrounded by finer-grained (often recrystallized) white or pale gray plagioclase, pyroxenes, Fe-Ti oxides, hornblende, garnet, and sulfides. Deformation of anorthositic rocks is shown in apparent igneous flow-alignment of plagioclase megacrysts and foliation (with or without gneissic banding) that could be related to emplacement and subsequent metamorphism.

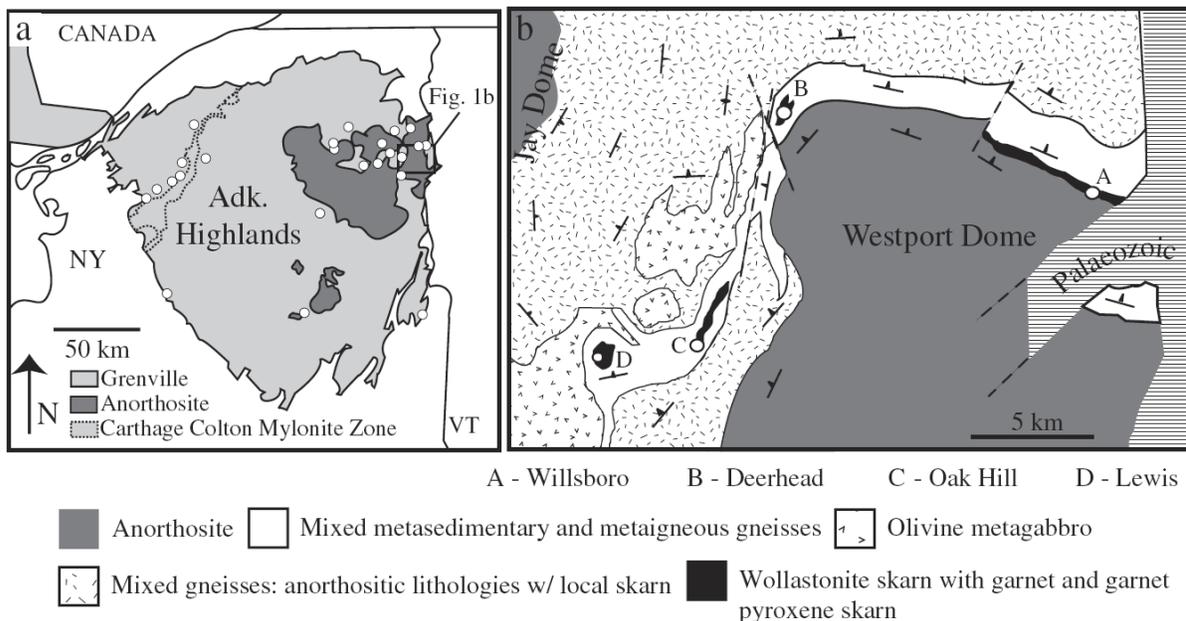


Figure 1. (a) Regional map showing Grenville-aged exposure of the Adirondack Highlands. Open circles are wollastonite occurrences from Valley et al. (1990). (b) Geology of the Willsboro-Lewis mining district, after Whitney and Olmsted (1998). Maps from Clechenko and Valley (2003).

Metamorphic clinopyroxene, clinopyroxene, and garnet, often showing coronitic textures with igneous minerals, formed during the Ottawa orogeny at ca. 850-800°C to 650°C and 6.5 to 8 kbar (Bohlen et al., 1985; Spear and Markussen, 1997). Compositions of relict igneous pyroxenes suggest emplacement temperatures of $\geq 1000-1200^{\circ}\text{C}$ (Bohlen and Essene 1978). A depth of emplacement for the anorthosite massif of $< 10\text{ km}$ is constrained by the infiltration of meteoric water into the contact aureole during skarn formation (Valley and O'Neil 1982), consistent with the aluminum contents of igneous clinopyroxenes (Spear and Markussen, 1997).

GEOLOGY AND GEOCHEMISTRY OF WOLLASTONITE ORE DEPOSITS

The ore zone in the Willsboro-Lewis district is a mixed zone made up of mafic (anorthositic to gabbroic) gneiss, granitic gneiss, amphibolite, quartzite, pelite, calc-silicate, marble, and skarn (Whitney and Olmsted 1995; Olmsted et al. 1992). Skarn lithologies include garnetite, garnet-pyroxene rocks, and wollastonite-garnet-clinopyroxene ores. Individual lenses of foliated metaigneous and metasedimentary rock in the ore zone range from meters to over a hundred meters in thickness. Some metaigneous bodies are observed to intrude metasediments and thicker gabbroic layers display relict igneous textures (Whitney and Olmsted 1995). Both 1070-1050 Ma Ottawa deformation and deformation predating ca. 1155 Ma skarn formation is evident in the ore zone. Large euhedral skarn garnets formed during anorthosite emplacement are locally preserved in zones of low strain, but most garnet was recrystallized during Ottawa deformation (Clechenko and Valley 2003). Skarn-converted dikes that cut pre-existing foliation are also preserved (Whitney and Olmsted 1998), and demonstrate that some of the observed fabrics are older than ca. 1155 Ma.

Wollastonite ore bodies are discontinuous, range up to 30 meters thick, and are composed of wollastonite + garnet + clinopyroxene. The general lack of excess reactants (calcite or quartz) in these rocks has led most workers to attribute wollastonite formation to voluminous circulation of fluids in the contact zone between the Westport anorthosite dome and carbonate country rocks (e.g. Valley and O'Neil 1982). Trace element and mineralogical composition are consistent with that majority of ore being formed from metasomatized carbonate rocks, with some rocks forming from altered anorthosite-suite rocks (i.e. endoskarn). Skarns with igneous protoliths can contain up to several percent apatite and titanite with accessory scapolite, plagioclase, clinozoisite, idocrase, and zircon (Whitney and Olmsted 1998).

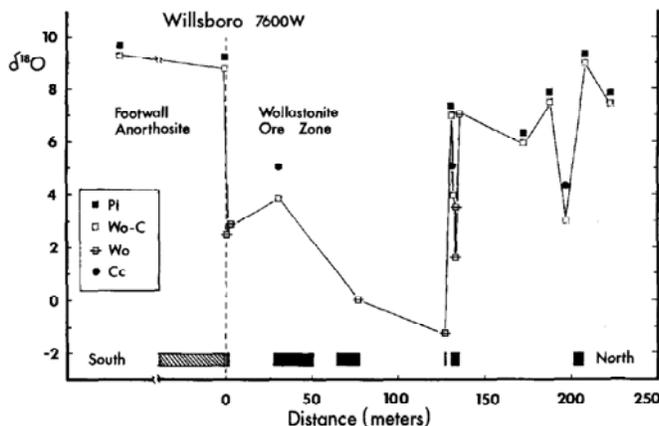
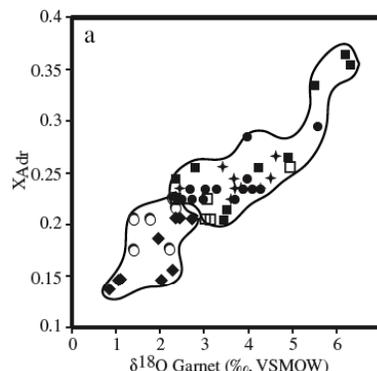


Figure 2. Oxygen isotope ratios of minerals from a traverse of Willsboro ore zone in drillcore. Low $\delta^{18}\text{O}$ values in skarn ores are caused by interaction with heated meteoric water during anorthosite emplacement. Sharp gradients in $\delta^{18}\text{O}$ between different lithologies are preserved through Ottawa granulite facies metamorphism, showing limited post-intrusion modification by fluids. Figure from Valley et al. (1990).

Oxygen isotope ratios of minerals in wollastonite ores demonstrate the importance of surface waters in skarn formation (Fig. 2). Ore rocks from the Willsboro, Lewis, Oak Hill, and Deerhead deposits have low $\delta^{18}\text{O}$ values (as low as -1.3‰ SMOW), which is indicative of interaction with heated meteoric water (Valley and O'Neil 1982; Clechenko 2001; Clechenko and Valley 2003). Major and trace elements and oxygen isotope chemistry in ore-zone garnets shows early formation of contact metamorphic garnet (HREE enriched, high $\delta^{18}\text{O}$, low Fe, higher Mn, Ti, Mg, Zr, negative Eu anomaly) and later formation of hydrothermal garnet (LREE enriched, low $\delta^{18}\text{O}$, high Fe, low Ti, Mn, Mg, and Zr, positive Eu anomaly) in meteoric fluids with some igneous component (Whitney and Olmsted 1998; Clechenko 2001). Interestingly, at the Willsboro mine, relict skarn garnets in garnetite preserve zoning that reveals details of a different hydrothermal circulation system or event (Fig. 3). Zoning in garnetite ranges from grossular-rich garnet with low $\delta^{18}\text{O}$ to andradite-rich garnet with higher $\delta^{18}\text{O}$ values. This is interpreted to be the result of low $\delta^{18}\text{O}$, Mg-rich meteoric fluids and high $\delta^{18}\text{O}$, Fe-, Mn-, and Ti-rich magmatic fluids both being involved in garnetite genesis (Clechenko and Valley 2003).

Figure 3. Oxygen isotope ratios and mole fraction andradite in garnets from Willsboro mine garnetite. Low $\delta^{18}\text{O}$ and low iron contents are attributed to meteoric fluids which mixed in the skarn zone with high $\delta^{18}\text{O}$, higher iron igneous fluids. Different symbols are different individual garnets. Figure from Clechenko and Valley (2003).



The presence of meteoric water during anorthosite intrusion places important constraints on the depth of emplacement of the Marcy anorthosite. Low $\delta^{18}\text{O}$ values caused by hydrothermal alteration by meteoric fluids are not limited to the Westport Dome, for example anorthosites in the southern Marcy massif have $\delta^{18}\text{O}$ values as low as 3.0‰ (Morrison and Valley, 1988). Large volumes of surface water during contact metamorphism is strong evidence of shallow (<10 km) anorthosite emplacement, and is an important line of evidence for contact metamorphism not being the heat source for regional granulite-facies metamorphism (Valley and O'Neil 1982). In contrast, skarns associated with coterminous Morin anorthosite suite do not show isotopic evidence for meteoric water (Peck 1996; Peck et al. 2005), nor do wollastonite-bearing rocks elsewhere in the Adirondacks (Valley et al. 1990), including the ca. 1155 Ma Valentine wollastonite deposit near Harrisville in the NW Adirondacks (Gerdes and Valley 1994) or the ca. 1155 Ma Canton Saint-Onge wollastonite deposit from the Lac St. Jean anorthosite (Higgins et al. 2001). This may indicate deeper emplacement in the crust or differences in hydrothermal flow conditions for these intrusive suites.

FIELD TRIP TO THE LEWIS OPEN PIT

The geology of the Lewis deposit is described by Whitney and Olmsted (1993), and Figure 4 shows the current open pit workings. The footwall to the ore zone is gabbroic anorthosite gneiss. The ore zone, which is on average 8-10 meters thick, is gneissic with alternating wollastonite and garnet+pyroxene layers. Garnetite is locally abundant near the contacts with plagioclase-bearing rocks, such as anorthosite. The ore zone and adjacent units strike E-W and dip 10-15° S or SW (Whitney and Olmsted 1993). Historically, the Lewis deposit was one continuous ore section that was up to 21 meters thick in some areas of the mine. As mining proceeded southward, the ore fingers out with layers of “interburden” amid the ore. The interburden zones can range from 0.3 meters to 9.0 meters thick which create a challenge to mining operations.

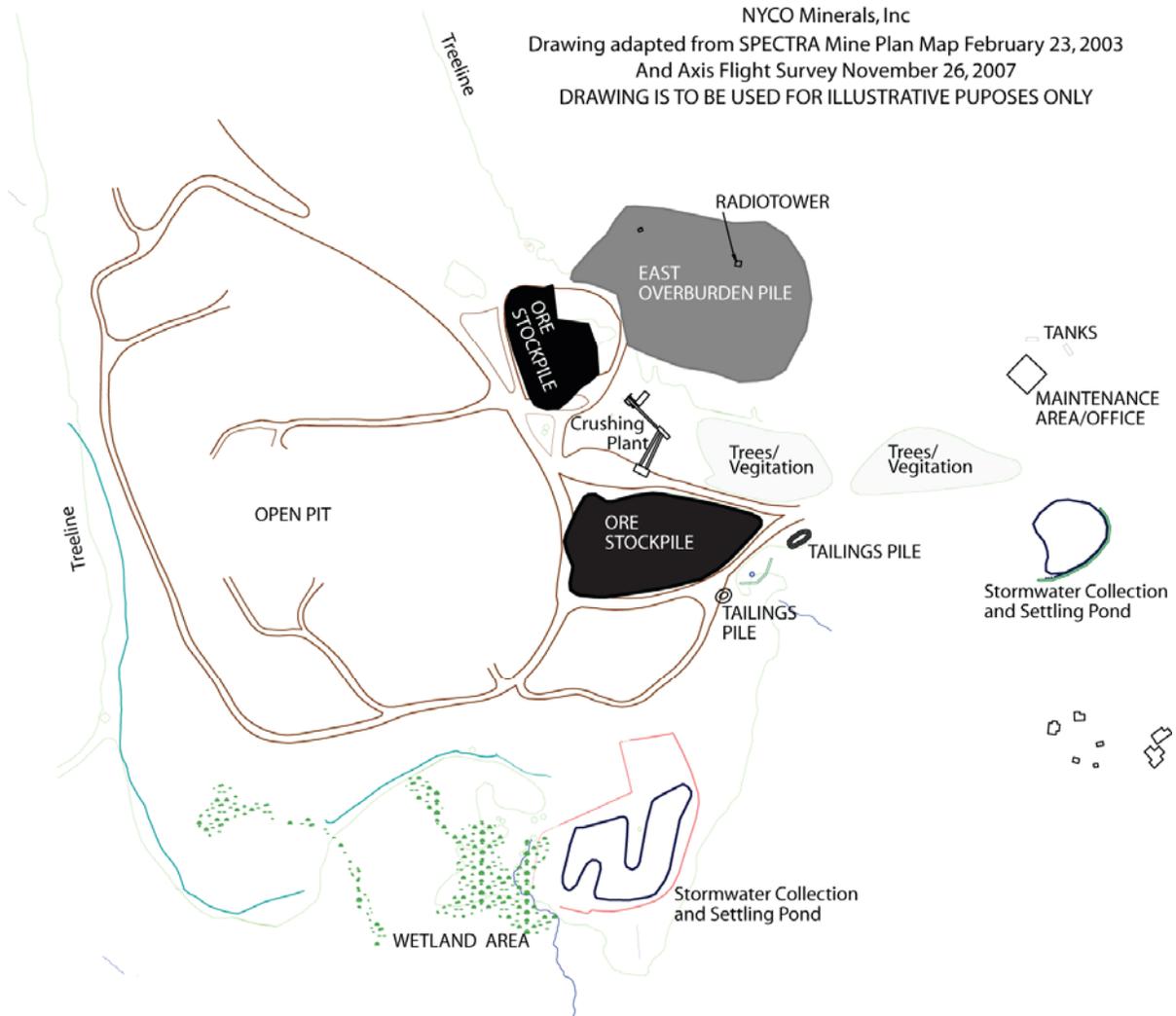


Figure 4. Simplified drawing of the Lewis open pit and area.

ACKNOWLEDGEMENTS

This summary of the geology of wollastonite deposits around the Westport Dome draws heavily on the work of Phil Whitney, Jim Olmsted, John Valley, and Cory Clechenko. The authors would like to thank John Valley and Cory Clechenko for stimulating and fun field trips to Adirondack wollastonite deposits and discussions about their geology. John Valley is also thanked for his comments on this manuscript and Bruce Selleck is thanked for his patient editorial guidance.

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