

The genetic variability of trass deposits can be shown by reference to Western Europe: The deposit Andernach at Laacher See, Eifel, Germany originated in the late Pleistocene during the giant eruption of a maar volcano (Schmincke *et al.* 1999). Hot phonolitic pumiceous ash was deposited in a shallow lake. The material consists of analcite, phillipsite and SiO₂ glass phases (Liebig & Althaus 1998). The bed has a thickness of ~9 m and covers an area of 8 by 2.5 km. Trass is also exploited in the Miocene impact structure Nördlinger Ries in southern Germany. This material is derived from suevite, a polymict impact breccia containing sedimentary and crystalline lithic fragments, and glassy impact-melt shards in montmorillonite matrix (Liebig & Althaus 1998). Suevite was pervasively altered by alkaline hydrothermal fluids that produced montmorillonite, saponite, illite, analcite, erionite and clinoptilolite (Osinski 2005). In Austria, trass is extracted from the flank of a Miocene trachyandesite volcano near Gossendorf. Pyroclastic rocks were strongly altered by acidic hydrothermal fluids (Klammer 1997). This material consists essentially of alunite, kaolinite and opal-C/CT phases.

As reported above, only pumice and perlite are considered in international statistics. Volcanic rocks used in the building industry or in manufacturing cement are part of the giant mass of crushed rock that is briefly quantified in the description of "Quartz Sand and Gravel" in Section 3.22.

3.26 WOLLASTONITE

Wollastonite	CaSiO ₃	Density 2.8–3.0 g/cm ³
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Calcium in wollastonite may be substituted by several percent of Fe and Mn, and lesser Mg or Al. This can reduce the value of the product, either by lowering whiteness, or by causing less desirable electric, physical and chemical properties. Frequent gangue minerals of wollastonite are diopside-hedenbergite, tremolite (beware of asbestiform varieties), vesuvianite, grossular-andradite, graphite, quartz, plagioclase and calcite.

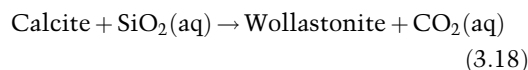
Exploitable wollastonite ore has a minimum content of ~30% CaSiO₃. Saleable by-products (e.g. garnet sand, calcite) allow mining lower grades.

Usually, wollastonite occurs in coarse, bladed masses, but after crushing and grinding the mineral is acicular to fibrous. The needles have a high strength that is the key to many uses of wollastonite. It is applied as a component or filler in the production of ceramics (especially tiles), plastics and rubber, paints, adhesives, isolating material, in ceramic abrasives and building elements. Fibrous wollastonite substitutes for asbestos, as in paint, refractory materials and in welding rods. The most important properties of processed wollastonite are: i) percentage and shape of fibres (length/thickness); and ii) reflectivity and whiteness. Depending on the intended use, very low chemical reactivity and weight/volume loss due to heating, and the mineral's alkaline reaction in emulsified state (pH 9.9 in 10% water slurry) may play a role.

3.26.1 Wollastonite deposit formation

Wollastonite is a product of contact-metasomatism (skarn-formation) of limestone and calcite marble. Isochemical regional metamorphism of siliceous limestone does not form sufficiently high grades of wollastonite. Although it is theoretically possible that the silica in skarn is derived from impurities in the original calcite rock, investigations show that it is commonly introduced by magmatic-hydrothermal fluids (Grammatikopoulos & Clark 2006). Exotic elements in the skarn, such as W, Cu and Au; serve as monitors for the passage of magmatic fluids. Wollastonite forms according to reaction 3.18, at T ~500 to >700°C and P at 100–500 MPa (1–5 kbar); corresponding to highest-temperature hornblende hornfels and pyroxene hornfels facies.

Contact-metasomatic formation of wollastonite:



CO₂ must leave the system, as otherwise the reaction would stall. In a closed system, quartz and calcite can coexist stably side by side, even under conditions of the granulite facies. Therefore, mass transformation requires an open system. For wollastonite formation, the fluid phase must be

mainly aqueous with a low CO_2 -content ($X_{\text{CO}_2} < 0.3$). High fluid/rock ratios are needed in order to dilute and export the CO_2 generated by the reaction. This prerequisite for the formation of a wollastonite orebody is achieved by a considerable mass flow of magmatic water outwards through the nascent wollastonite zone. Because during the prograde stage of contact metamorphism, decarbonation reactions and high X_{CO_2} prevail, conditions of wollastonite formation are mainly realized during the retrograde path (Nabelek 2007).

Exploitable wollastonite concentrations are not common. The first mines were established in 1943, in the Willsboro district of the Adirondack Mountains in New York State. Until today, this district is a globally significant producer. The deposits occur in the Mesoproterozoic Grenville Orogen (Tollo *et al.* 2004):

Many of the wollastonite deposits in the Adirondacks occur near the contact of anorthosite with calcite marble. The Valentine deposit and many smaller occurrences are the product of a quartz-syenitic intrusion into granulite-facies metasediments (Gerdes & Valley 1994). At the contact, calcite marbles were transformed into a skarn shell 60m wide, that contains coarsely crystalline wollastonite and minor amounts of calcite, diopside and secondary prehnite. Reserves are $>7\text{Mt}$ ore. Megascopic boundaries between the wollastonite skarn and calcite marble are irregular in shape but sharp. Oxygen isotope ratios in calcite marble remain unchanged right up to the skarn boundary. As there is hardly any silica in the marbles the SiO_2 must have been delivered by hydrothermal fluids.

An important wollastonite deposit is exploited near Lapeenranta in southern Finland, not far from calcite marble deposits at Ihalainen. At Lapeenranta, a large body of calcite marble with bands of fine-grained quartzofeldspathic metavolcanic rock ("leptite") floats in a giant intrusion of Mesoproterozoic Rapakivi granite. The marbles are traversed by swarms of granitic, pegmatitic and mafic dykes. The whole assemblage experienced strong thermal metamorphism that provoked the formation of wollastonite orebodies (with a gangue of quartz, grossular, diopside and serpentinite). The average wollastonite grade is 25–30%; grinding and flotation are employed to produce a concentrate of $>90\%$ wollastonite with very little iron. Resources are estimated to $>30\text{Mt}$.

Wollastonite production continues to increase. In 2008, processed wollastonite world output was $\sim 600,000\text{t}$. China was the leading producer (70%), followed by India, USA, Mexico, Spain and Finland. Spain has several potential deposits (Galan & Caliani 1997; Figure 3.35). Prospecting is based on geological models. It is advisable to carry out processing tests early in investigations, because many occurrences do not yield a product of sufficient quality (Gracia *et al.* 1999). Considerable tonnages of wollastonite are produced synthetically from quicklime and quartz sand ("cyclo-, pseudo-, or β -wollastonite", a high-temperature phase).

3.27 ZEOLITES

		Density g/cm^3
Analcime (analcite)	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$	2.3
Chabazite	$\text{Ca}(\text{K}, \text{Na}, \text{Sr})\text{Al}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$	2.1
Clinoptilolite	$(\text{Na}, \text{K}, \text{Ca})_{2-3}(\text{Al}, \text{Si})_{18}\text{O}_{36} \cdot 11\text{H}_2\text{O}$	2.1
Erionite	$(\text{Ca}, \text{K}_2\text{Na}_2)_2(\text{Al}_4\text{Si}_{14}\text{O}_{36}) \cdot 15\text{H}_2\text{O}$	2.0
Ferrierite	$(\text{K}, \text{Na}, \text{Mg})_{4.4}(\text{Si}, \text{Al})_{36}\text{O}_{72} \cdot 20\text{H}_2\text{O}$	2.2
Mordenite	$(\text{Na}_2\text{Ca}, \text{K}_2)\text{Al}_2\text{Si}_{10}\text{O}_{24} \cdot 7\text{H}_2\text{O}$	2.1
Phillipsite	$(\text{K}, \text{Ca}, \text{Na})_2(\text{Si}, \text{Al})\text{O}_{16} \cdot 6\text{H}_2\text{O}$	2.2

This list includes the few economically prominent zeolites from more than 70 zeolite minerals in nature (Bish & Ming 2001). Note that cation ratios may vary so that formulas and specific densities provided are only indicative. Zeolites are crystalline hydrated aluminosilicates of alkali and alkaline earth elements with a zeolite structure and with the capability of cation exchange and reversible dehydration. The zeolite structure is a three-dimensional framework of anionic tetrahedra (AlO_4 and SiO_4) similar to feldspar, with interconnected micropores, which contain water and exchangeable cations. When heated, many zeolites fuse readily and display marked swelling, giving