Ultramafic-hosted Talc-Magnesite deposits

Gilpin R. Robinson, Jr, Bradley S. Van Gosen, and Nora K. Foley

We thank Luzenac America for access to property sites and core

This presentation on the geology of ultramafic-hosted talc-magnesite deposits was given at the 42nd Forum on the Geology of Industrial Minerals, May 7-13, 2006 in Asheville, NC (USA).

Talc is a soft inert industrial mineral commodity commonly used as a component or filler in ceramic, paint, paper, plastic, roofing, and electrical applications (Lindsey, 2003; Piniazkiewicz and others, 1994). Ultramafic-hosted talc-magnesite deposits are important sources of talc (Simandl and Ogden, 1999; Harben and Kuzvart, 1997).

Luzenac America provided access to company property in the Proctorville, Vermont area and also provided site maps, drill core logs, and continuous core samples drilled in the Frostbite, Black Bear, and Kelly talc deposits in the study area.

The ultramafic (UM) rocks that host talc-magnesite deposits, typically serpentine or serpentinized peridotite, occur in metamorphic belts in lithotectonic settings commonly associated with seafloor subduction (Simandl and Ogden, 1999). Individual ultramafic rock bodies occur as fault-bounded rocks that were tectonically-transported bodies or as olistolith blocks of serpentinized seafloor deposited in an accretionary subduction complex.

Ultramafic-hosted talc-carbonate deposits occur near the contacts between ultramafic rocks and siliceous country rocks and along regional faults cutting ultramafic rocks (Piniazkiewicz and others, 1994; Simandl and Ogden, 1999). Large talc-carbonate rock bodies are structurally located in areas of least compressive stress around the larger ultramafic rock bodies. The talc (Tlc) and magnesite (Mgs) minerals formed during metamorphism of the ultramafic protolith, usually antigorite (Atg) with forsterite (Fo). Metasomatic (mass transfer) reactions accompanying metamorphism help form talc-rich deposits.

The geological, mineralogical, and geochemical features of talc deposits in the Ludlow, Vermont area will be used to illustrate the important characteristics of ultramafic-hosted talc-magnesite deposits and provide data that constrain the physical conditions and processes that form talc deposits hosted by ultramafic rocks.

Geology of Ludlow, Vermont

- UM bodies (pink) in Moretown Fm at contact between granofels (blue) and carbonaceous schist (yellow)
- Lithotectonic unit formed during Ordovician subduction
- Talc-carbonate zones (green) at UM borders and faults
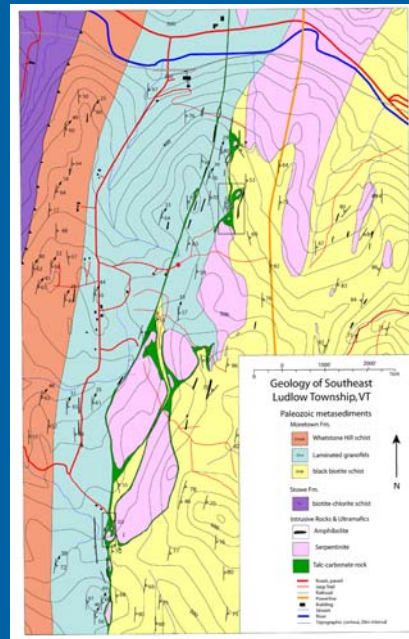
The talc deposits in Ludlow Township, Vermont, are localized within part of a north trending band of scattered ultramafic rock bodies, primarily serpentine, that transect the New England states (Larrabee, 1971). The talc deposits in this area are associated with one of the most extensive belts of ultramafic rock found in western New England and large to small masses of ultramafic rock (shown in pink color) lie scattered along a 30 kilometer zone from Proctorsville to Townshend reservoir, Vermont (Ratcliffe, 1996; Ratcliffe, Walsh, and Aleinikoff, 1997). In this area, the ultramafic rocks are interspersed in the Moretown Formation (Ratcliffe, 1996; Ratcliffe, Walsh, and Aleinikoff, 1997) at or near the contact between dark gray carbonaceous sulfidic biotite schist (Omb unit, Yellow color on map) and laminated siliceous biotite granofels (Oml unit, blue color on map). The Moretown Formation has been interpreted as a lithotectonic unit formed as an allochthonous accretionary complex produced on the upper plate of an Ordovician oceanic subduction zone (Stanley and Ratcliffe, 1985; Ratcliffe, Walsh, and Aleinikoff, 1997).

In Vermont, talc-rich parts of the ultramafic rock bodies are generally located along the periphery of the serpentine bodies where they are in contact with schist and siliceous granofels and along regional faults that have cut the serpentine bodies. The largest talc-magnesite lenses in the Proctorville, Vermont area are localized along the north and south margins of individual serpentine bodies, elongated parallel to the trend of regional foliation and faults (shown as talc-carbonate rock (green color on map)).
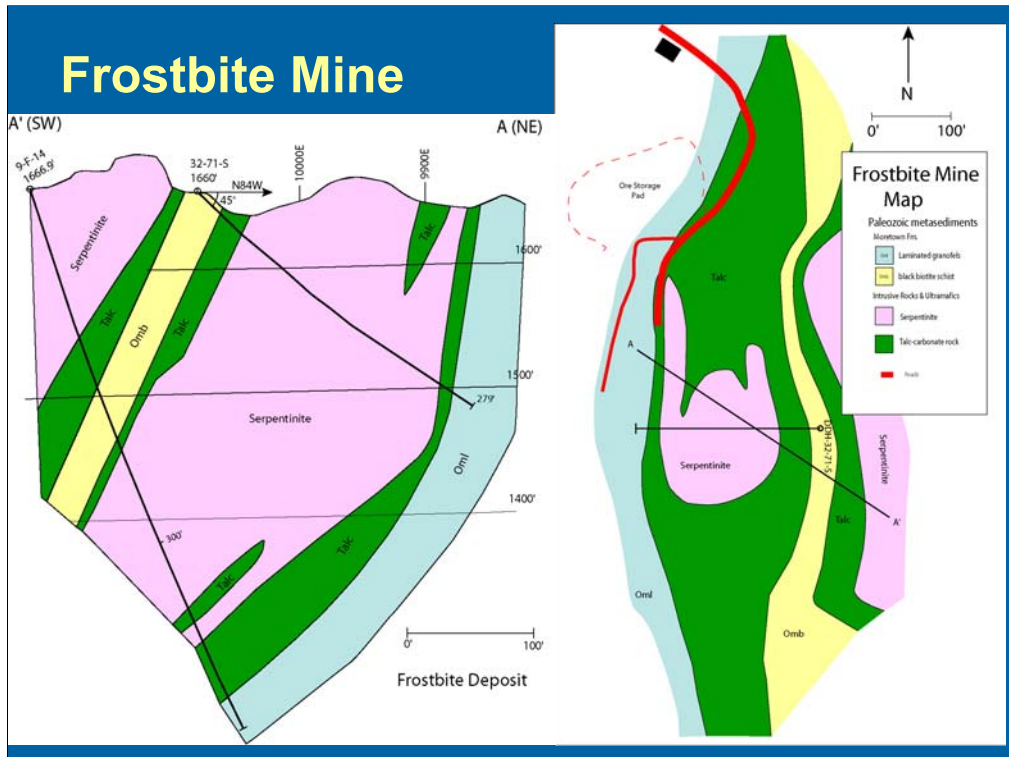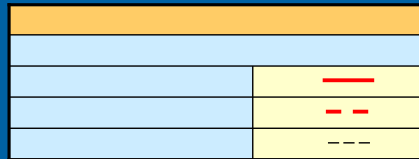
The geology of the Frostbite mine area is shown in cross section (left figure) and map (right figure) views. The cross section occurs along line A-A' of the map view and is based on surface geology and rock relations observed in drill core.

Mineral and chemical zones in and surrounding the ultramafic rock bodies with their characteristic mineral assemblages and modal abundances are shown above.
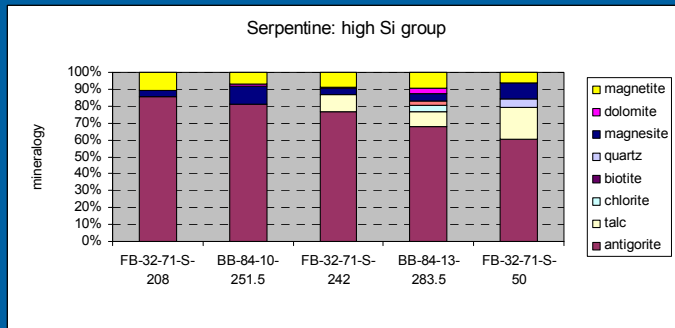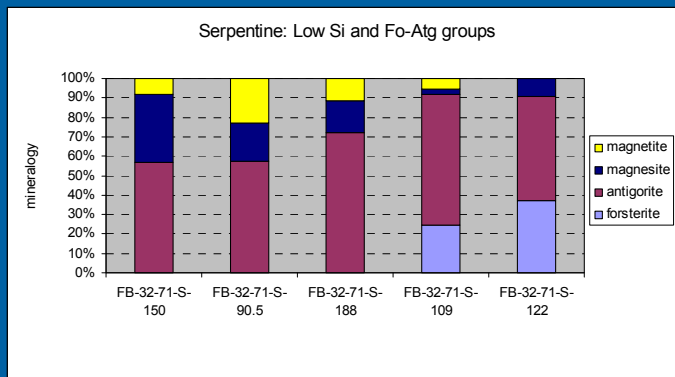
The interior serpentine core zone consists of silicate-carbonate mineral assemblages of antigorite+forsterite+/-magnesite (Fo-Atg Group). Samples FB-32-71-S-109 and 122 shown in the upper figure illustrate the mineralogy of the interior serpentine core zone (Atg-Fo Serpentine Zone). Low Silica Serpentine that surrounds the core zone contains antigorite+magnesite assemblages. High silica serpentine (lower figure) contains antigorite+magnesite±talc assemblages.

The serpentine rocks generally contain magnetite-spinel minerals, whereas the talc-carbonate rocks generally lack magnetite.
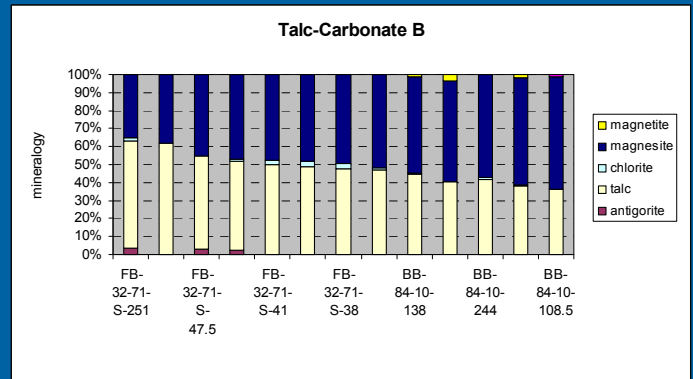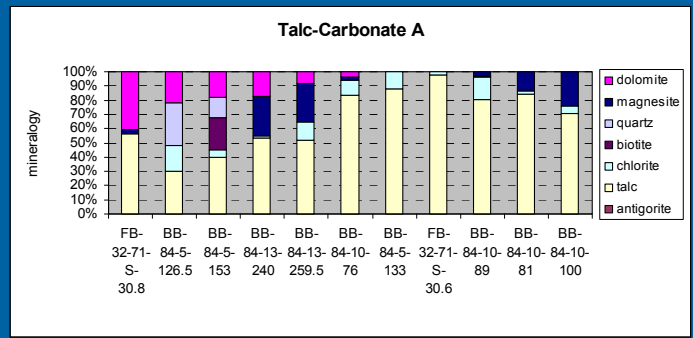
Serpentine rocks transition, commonly abruptly, into talc-carbonate rocks: 1) talc+magnesite assemblages (Talc-Carbonate B) and 2) talc±magnesite±dolomite assemblages (Talc-Carbonate A) near the periphery of the serpentine bodies and along shear and fault zones. The carbonate minerals, magnesite and dolomite, incorporate the iron formerly hosted by magnetite in the serpentine rocks.

The rocks in Talc-Carbonate B Zone contain talc and magnesite in roughly equal proportions by weight. The rocks in Talc-Carbonate A Zone have a higher weight proportion of talc to magnesite and frequently contain dolomite and minor amounts of chlorite. The Talc-Carbonate A Zone rocks are usually localized near lithologic contacts with siliceous metamorphic rocks and the calcium and aluminum components required to form dolomite and chlorite, respectively, are likely derived from these surrounding country rocks.

Serpentine & Talc-Carbonate rocks

- **Molar ratio diagram shows alteration path and characteristic mineral assemblages**

Serpentine-Talc-Carbonate rocks

Mgs

molar C/MF

1.0
0.8
0.6
0.4
0.2
0.0

Mgt   Fo   Atg   Tlc

0.0   0.5   1.0   1.5

molar Si/MF

- ♦ Atg-Fo Serpentine
- ■ Atg-Mgs Serpentine
- ▲ Talc-Carbonate B
- ✕ Talc-carbonate A
- ● minerals

USGS
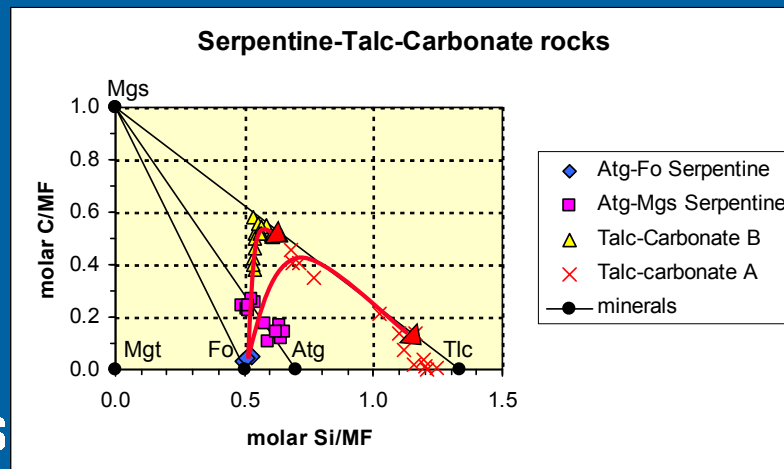
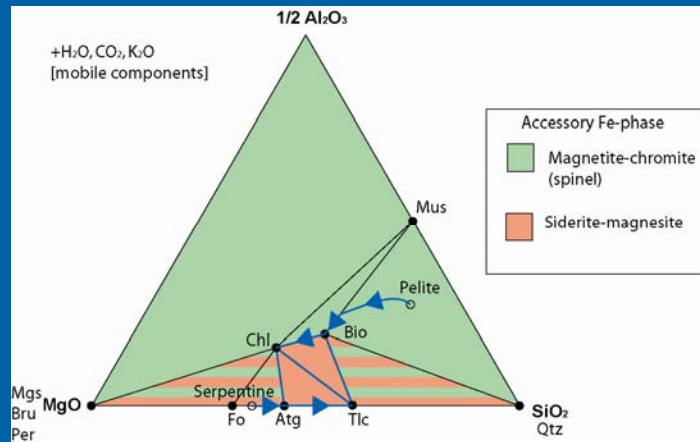Geochemical relations between the ultramafic rock groups are illustrated in the above figure, that portrays the relative concentrations of magnesia, iron, silica, and carbonate, in terms of molar ratios, in the rock groups. Using molar ratios of $Si/(Mg + Fe)$, shown as Si/MF, and $C/(Mg + Fe)$, shown as C/MF, as graph variables allows both rock and mineral compositions to be shown in a way that illustrates the dominant mineralogy of the rock groups and the relative differences in silica, magnesia + iron, and carbonate compositions between the rock groups.

The least altered serpentine rock in the cores of larger ultramafic rock bodies are the Atg-Fo (antigorite-forsterite) Serpentine group rocks. These rocks have a Si/MF value near 0.5, which is the composition expected from a dunite (olivine-rich) ultramafic rock protolith. Serpentinization by hydration of the precursor dunite oxidizes iron in the olivine forming antigorite-magnetite assemblages. Carbonation of the ultramafic rock protolith (increasing C/MF) forms rocks in the Ant-Mgs serpentine group; however two clusters of Atg-Mgs serpentine rocks can be seen in the figure above. The cluster with Si/MF values near 0.5 can be formed dominantly by carbonate addition, but the cluster with Si/MF values near 0.6 require carbonation accompanied by a relative gain in silica and/or relative loss in magnesia.

The ultramafic rocks in Talc-Carbonate B Zone indicate increased carbonation relative to the serpentine rocks (increasing C/MF) accompanied by small gains in silica relative to magnesia from the ultramafic rock protolith. Talc-carbonate rocks in zone A lie along the talc-magnesite join and exhibit moderate to large gains in silica relative to magnesia to form from the ultramafic rock protolith.

Metasomatic reaction paths

- **Metasomatic reactions create bi- and mono-mineralic rock zone sequences.**

- **Mgt→Sid**

1/2 Al_2O_3

+H_2O, CO_2, K_2O
[mobile components]

Accessory Fe-phase
- Magnetite-chromite (spinel)
- Siderite-magnesite

Mus

Pelite

Chl   Bio

Mgs
Bru MgO   Serpentine   SiO₂
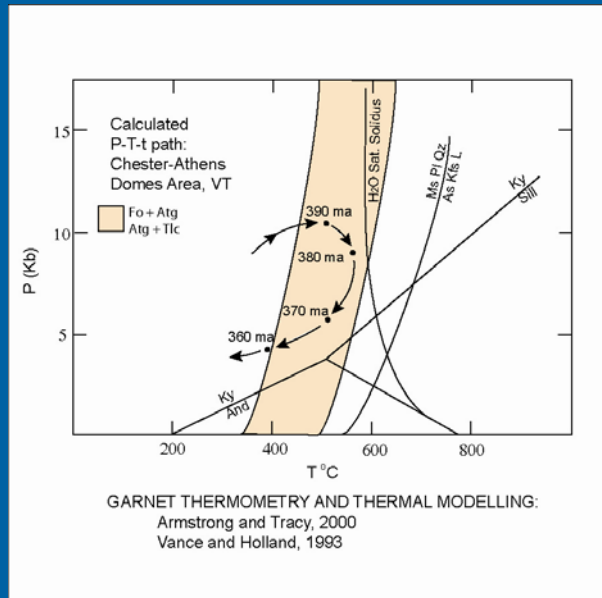Per   Fo Atg Tlc   Qtz

≈USGS

The mineralogy and bulk composition of the ultramafic rock groups tend to lie along binary silicate-carbonate mineral joins. The small number of minerals present in these rock zones, the scale of the talc occurrences, and the significant and consistent mineral and chemical zoning developed between the ultramafic rock bodies and their enclosing metamorphic host rocks suggest that a fluid flow system driving metasomatic (mass transfer) alteration led to the formation of the talc deposits (Korzhinskii, 1970). The metasomatic reaction paths experienced by the ultramafic rocks and their enclosing siliciclastic metamorphic rocks are shown as blue lines in the above figure. The metasedimentary rocks, shown as the "pelite" composition lose silica and gain magnesia during metasomatism to form biotite and chlorite-rich alteration zones bordering the ultramafic rocks.

Chemical zonation patterns in the metamorphic rocks surrounding the ultramafic rock bodies indicate that silica, magnesium, potassium, carbon, sulfur, arsenic, and water were all mobile components, to varying degrees, during metasomatism (Sanford, 1982). In addition to providing the silica needed to form talc from antigorite, the carbonation reactions in the talc-carbonate zones progressively destroy magnetite in the altering serpentine, forming ferroan magnesite.

Metamorphic History, Ludlow, VT

- **Clockwise P-T-t path**
- **Decompression in Atg field – MSH system**
- **Least hydrated state: ~5-7 Kb**

GARNET THERMOMETRY AND THERMAL MODELLING:
Armstrong and Tracy, 2000
Vance and Holland, 1993

The regional geologic setting of the serpentine bodies and the pressure-temperature-time evolution of regional metamorphic conditions are important controls on the formation of large high-grade talc deposits associated with ultramafic rocks. These metamorphic constraints can be used as guides for talc exploration. Peak metamorphic conditions need to occur in the stability zone of forsterite+antigorite and antigorite+talc assemblages, and the stability field for these mineral assemblages (Bucher and Frey, 1994) in the MgO-SiO_2-H_2O (MSH) system are shown in the above figure in relation to metamorphic conditions estimated for rocks in the nearby Chester-Athens Domes area of Vermont (Vance and Holland, 1993; Armstrong and Tracy, 2000). Metamorphic rocks in the Proctorville area equilibrated at slightly lower temperature and pressure conditions than the Chester-Athens Domes areas (Ratcliffe, Armstrong, and Aleinikoff, 1997, Figure 9), but are within the stability zone for antigorite+talc assemblages ranging from about 450 to 550 C at 5 to 10 kilobars pressure. The metamorphic pressure-temperature-time conditions modeled for the Chester-Athens Domes area (Armstrong and Tracy, 2000), adjusted to the slightly lower pressure-temperature conditions most likely in the Proctorville area, indicate that metamorphic fluids related to dehydration reactions (Bucher and Frey, 1994) in the metapelitic rocks surrounding the ultramafic rock bodies are likely to be present during the metamorphic temperature-pressure-time path under conditions exceeding about 450 C and 5 kilobars.

T-X$_{CO_2}$ relations at 5 Kbar

- **Atg + Mgs and Tlc + Do assemblages at 5 Kb :
  T < 490 C and
  X$_{CO_2}$ < 1.5 wt%.**
- **↑ P at T shifts reactions to ↓ CO$_2$.**
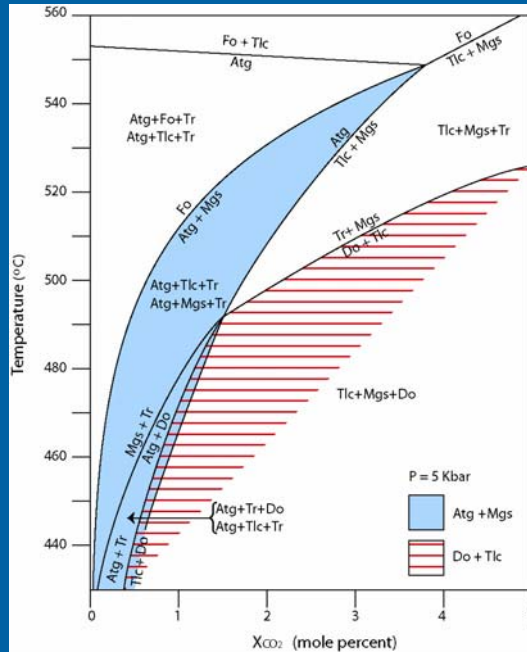
Mineral assemblage relationships as a function of fluid composition in the MgO-CaO-SiO$_2$-H$_2$O-CO$_2$ system at 5 kilobars pressure are shown in the above figure, calculated using the thermodynamic data and TWQ program of Berman (1988; 1991), provide a framework to interpret the relative temperature and fluid composition relationships of the mineral reactions.

At 5 kilobars (and higher pressures), antigorite is stable only with metamorphic fluids with very low concentrations of CO$_2$ and antigorite-magnesite assemblages coexist with talc-dolomite assemblages only at temperatures below about 490 C with fluid compositions between 0.5 and 1.5 mole percent CO$_2$ (figure above). At temperatures below 490 C, antigorite-forsterite-magnesite assemblages are stable at very low concentrations of CO$_2$ (less than 0.4 mole percent).

The high-grade massive talc-magnesite assemblages typically exhibit patchy textures and discontinuous zones of intersecting carbonate veins. The mineral reaction and mass balance relationships in the talc-carbonate alteration zones imply a negligible to small volume increase should develop in the Talc-Carbonate B zone rocks and a larger volume increase should occur in the Talc-Carbonate A zone rocks. The preferential development of the largest talc-carbonate alteration zones in areas of least compressive stress around ultramafic bodies is consistent with the structural setting expected to result from rock volume increase and associated fracture permeability caused by mass gain during metasomatism. The metasomatic alteration processes tend to concentrate talc in the outer part of the alteration zone where silica is likely to be more available from siliceous country rocks. Enrichments in arsenic, nickel, and sulfur also occur in the outer parts of the talc-magnesite alteration zones in the form of trace pyrite, nickel arsenide minerals, and nickel arsenate films on weathered fracture surfaces. Arsenic concentrations in talc and process waters need to be monitored during mineral processing and waste disposal.

Graphite-H$_2$O phase equilibria

- **Graphite buffered fluids are H$_2$O-rich with little CO$_2$**
  - $\downarrow$ P = $\uparrow$ CO$_2$.
- **Carbonation and dehydration reactions drive fluid from graphite saturation.**
- **Carbonation reactions reduce fluid**
 - Mgt $\rightarrow$ Sid
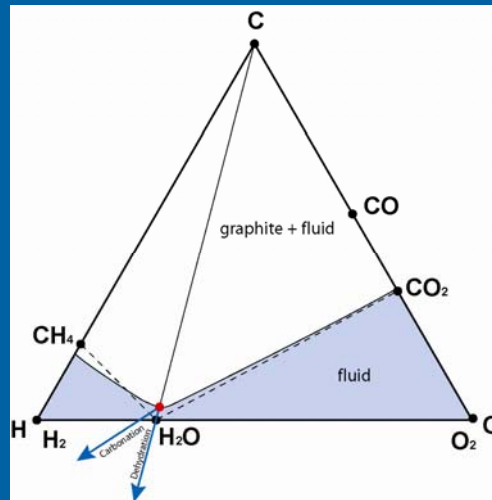
The mineral buffers controlling, and relative timing of changes in, carbonate activity in the fluid phase during the metamorphic cycle influence the texture and abundance of talc in the alteration assemblage. In Vermont, the talc deposits occur in serpentine bodies bordering or enclosed in reduced (graphite-bearing) siliciclastic metamorphic host rocks that lack carbonate minerals. In these settings, the activity of CO$_2$ in metamorphic fluids is controlled by graphite-water equilibria.

Graphite-buffered metamorphic fluids in prograde siliciclastic rocks are H$_2$O-rich with little CO$_2$. Fluid compositions lie along the C-H$_2$O tieline. Decreasing pressure increases the CO$_2$ concentration in the graphite buffered fluid. Carbonation of antigorite to form magnesite removes CO$_2$ and adds H$_2$O to the fluid, moving off graphite saturation toward highly reduced H$_2$O-CH$_4$-H$_2$ fluids, that replace magnetite with a siderite component in magnesite.

P-T-t-X_{CO_2} & Talc deposits

- ↓P ↑ CO_2 in graphite-buffered H_2O fluid
- Clockwise P-T-t path = early Silica metasomatism followed by carbonation
- Talc formation shown in green

≈USGS
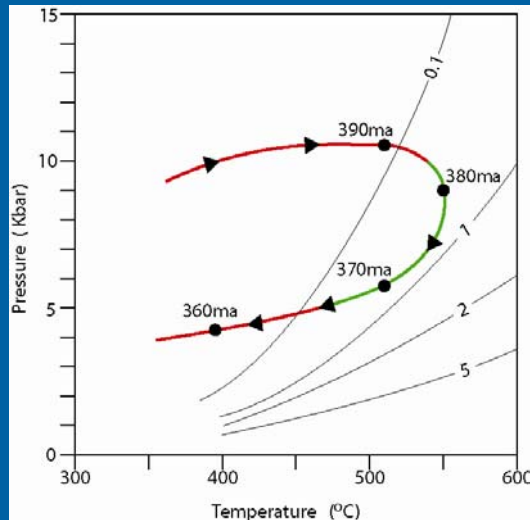
This figure shows the pressure-temperature-time (PTt) path of the Ludlow, Vermont rocks (red and green lines with arrows) in relation to the CO_2 concentration in fluids buffered by graphite-water equilibria (Connolly and Cesare, 1993) as a function of pressure and temperature (black contours labeled in weight percent CO_2). CO_2 concentrations increase with increasing temperature and decreasing pressure. The area where talc- forming reactions are likely in Serpentine during the metamorphic temperature-pressure-time path of the Vermont rocks is shown in green.

Serpentine bodies localized in siliclastic metamorphic rocks containing carbonate minerals tend to have higher activities of CO_2 in metamorphic fluids, with the result that serpentine reacts early in the metamorphic cycle to form listwanite (magnesite-quartz-talc rocks) or a fine-grained soapstone containing less than 50% of talc by weight. These rock types generally do not contain recoverable talc resources. The optimal metamorphic pressure-temperature-time path for the generation of high-grade talc deposits occurs where the early phase of prograde metamorphism occurs at high pressure and temperature conditions where the activity of CO_2 is very low, fostering silica metasomatism during the early phase of serpentine alteration. This metamorphic phase is followed by a high temperature decompression trend that fosters gradual carbonation of the alteration assemblage in response to the increasing activity of CO_2 in fluids buffered by the graphite-water system as pressure is reduced.

Black Bear Mine, Proctorsville, Vt

References

Armstrong, T.R. and Tracy, R.J., 2000, One-dimensional thermal modeling of Acadian metamorphism in southern Vermont, USA: J. Metamorphic Geol., v. 18:6, p. 625-638.

Berman, R. G., 1988, Internally-consistent thermodynamic data for minerals in the system Na2O-K2O-CaO-MgO-Al2O3-SiO2-TiO2-H2O-CO2. Journal of Petrology, v. 29, p. 445-522.

Berman, R. G., 1991, Thermobarometry using multi-equilibrium calculations: A new technique with petrological applications: Can. Mineralogist., v. 29, p. 384-392.

Bucher, K. and Frey, M., 1994, Petrogenesis of metamorphic rocks: Springer-Verlag, Berlin, 318 p.

Connolly, J.A.D. and Cesare, B., 1993, C-O-H-S fluid composition and oxygen fugacity in graphitic metapelites: J. Metamorphic Geol., v. 11, p. 379-388.

Harben, P.W. and Kuzvart, M., 1997, Industrial minerals: A global geology. Industrial Minerals Information Ltd., Metal Bulletin PLC, London, p. 407-417.

Korzhinskii, D.S., 1970, Theory of metasomatic zoning. Oxford University Press, London, 162 p.

Larrabee, D.M., 1971, Map showing distribution of ultramafic and intrusive mafic rocks from New York to Maine: U.S. Geological Survey Miscellaneous Investigations series Map I-676, scale 1:500,000.

Lindsey, T., 2003, Smooth operator – Talc gets specialized for growth: Industrial Minerals, v. 428, May, 2003, p. 24-33.

Piniazkiewicz, J., McCarthy, E.F., and Genco, N.A., 1994, Talc, in Carr, D.D. (ed.), Industrial Minerals and Rocks, 6th Edition: Society for Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado, p. 1049-1069.

Ratcliffe, N.M., 1996, Digital bedrock geologic map of the Andover quadrangle, Vermont: U.S. Geological Survey Open-File Report 96-31, scale 1:24,000.

Ratcliffe, N.M., Armstrong, T.R., and Aleinikoff, J.N., 1997, Stratigraphy, geochronology, and tectonic evolution of the basement and cover rocks of the Chester and Athens Domes, in Grover, T.W., Mango, H.N., and Hasenohr, E.J. (eds.), Guidebook to fieldtrips in Vermont and adjacent New Hampshire and New York: New England Intercollegiate Geological Conference, 89th Annual meeting, Killington-Pico region, Vermont, September 19-21, 1997, trip B6, p. 1-55.

Ratcliffe, N.M., Walsh, G.J., and Aleinikoff, J.N., 1997, Basement, metasedimentary, and tectonic cover of the Green Mountain massif and western flank of the Chester Dome, in Grover, T.W., Mango, H.N., and Hasenohr, E.J. (eds.), Guidebook to fieldtrips in Vermont and adjacent New Hampshire and New York: New England Intercollegiate Geological Conference, 89th Annual meeting, Killington-Pico region, Vermont, September 19-21, 1997, trip c6, p. 1-54.

Sanford, R.S., 1982, Growth of ultramafic reaction zones in greenschist to amphibolite facies metamorphism: Am. J. Sci., v. 282, p. 543–616.

Simandl, G.J. and Ogden, D., 1999, Ultramafic-hosted talc-magnesite, in Simandl, G.J., Hora, Z.D., and Lefebure, D.V. (eds.), Selected British Columbia mineral deposit profiles, V. 3, Industrial Minerals: British Columbia Ministry of Energy and Mines.

Stanley, R.S. and Ratcliffe, N.M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, p. 1227-1250.

Vance, D. and Holland, T., 1993, A detailed isotopic and petrological study of a single garnet from the Gassetts Schist, Vermont: Cont. Min. Pet., v. 114:1, p. 101-118.