summary of this short and simple talk:

no thermodynamic data for lizardite
possible “capillary flow” in chrysotile tubes
antigorite thermodynamic data render it too stable at low T, low SiO2 activity
serpentine + quartz is stable with respect to talc at low temperatures!
antigorite may be more stable than lizardite at low temperatures when aSiO2 is high
Fe substitution in serpentine seems to make it more stable at low T
   (magnetite and/or hematite in high T serpentinites “dissolve” into
    Fe³⁺ rich serpentine at lower T; papers by Klein et al., Streit et al., ...)
Fe²⁺/Fe³⁺ redox during serpentine formation from Fe²⁺ bearing phases
   helps drive fO₂ to ~10⁻⁸⁰ to 10⁻⁸⁵ bars (origin of life, abiotic H₂ and hydrocarbons,
    supergene sulfur, Ni enrichment, NiFe alloy, etc etc)
no solid solution properties for mixtures of Mg-, Fe-, Al-bearing serpentines
serpentine formation is too slow for lab studies, fast by geological standards
oxidized Fe-serpentine (hisingerite) stable on Mars surface,
   but much less abundant than oxides and, especially, Mg-carbonates
redox controlled in part by serpentine phases has a strong control on
   recycling versus deep subduction of carbon
antigorite stability, with and without minor amounts of Al (amesite) component,
   controls recycling versus deep subduction of H₂O, buoyancy of subducting mantle,
    potential for diapirs of buoyant Mg-rich, Fe-poor hydrous peridotite
low temperature viscous deformation of lizardite, opal, at and above the top of
   subducting oceanic crust may lead to aseismic subduction
   (is opal more stable than quartz at low temperature and high P(H₂O)?

Je n’ai fait celle-ci plus longue que parce que je n’ai pas eu le loisir de la faire plus courte.
Kaolinite (clay, not a serpentine mineral) \( \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \)

**\( \text{Al}_2\text{Mg}_3 \)**

- **Lizardite** \( \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \) \( \text{Mg/\text{Si}} = 1.5 \)
- **Chrysotile** \( \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \) \( \text{Mg/\text{Si}} = 1.5 \)
Kaolinite (clay, not a serpentine mineral) \[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \]

Lizardite \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \] \[ \text{Mg/Si} = 1.5 \]

Chrysotile \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \] \[ \text{Mg/Si} = 1.5 \]

peridotite, Earth’s upper mantle

gemstone name for olivine is peridot

simplify, ignoring Fe, Ca, Al, Cr, ...

Forsterite (olivine) \[ 2\text{Mg}_2\text{SiO}_4 + 3\text{H}_2\text{O} = \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 + \text{Mg(OH)}_2 \text{ brucite} \]

Enstatite (pyroxene) \[ 3\text{Mg}_2\text{Si}_2\text{O}_6 + 3\text{H}_2\text{O} = \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 + \text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 \text{ talc} \]

\( \text{Fo} + \text{En} \)

\[ 2\text{Mg}_2\text{SiO}_4 + \text{Mg}_2\text{Si}_2\text{O}_6 + 4\text{H}_2\text{O} = 2\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]
Kaolinite (clay, not a serpentine mineral) \[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \]

Lizardite \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \quad \text{Mg/Si} = 1.5 \]

Chrysotile \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \quad \text{Mg/Si} = 1.5 \]

---

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**The Serpentinite Multisystem Revisited: Chrysotile Is Metastable**

**BERNARD W. EVANS**

*Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195-1310*
chrysotile, $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$

lizardite

Mg green, Si brown, $O_a$ blue, remaining O red
reminder 100 angstroms = 10 nm

inner radius: ~ 2.55 to 5 nm
outer radius: ~ 10 to 20 nm

Fig. 1. A high-resolution TEM image of the cross-section of chrysotile asbestos.
\[ P_c = 2\sigma \cos(\theta)/r \]

\[ \sigma_{aw} = 0.0728\text{N/m} \]
\[ \theta_{aw} \text{ in glass} = 0.35 \text{ radians} \]
\[ r = 5 \text{ nm} \]

\[ h = P_c/(\rho g) \sim 14 \text{ km} \]
Mariana forearc
Oakley et al. GJI 2007

the leading edge of the mantle wedge

Oman ophiolite
Coleman 1977
listvenite = carbonated peridotite
quartz + magnesite
± chromian mica
± chrome spinel

carbonated mantle
hydrated mantle
carbonated mantle
hydrated mantle
metasediments
BT1
basal thrust
lisvenites:
carbonated
peridotite
lizardite mylonite at ~ 150°C

what is the “viscosity” of lizardite at low temperature and high P(H2O)
Cascadia intermediate depth earthquakes are almost entirely at and below the Moho in the subducting oceanic plate.  

**Abers et al.**  
*Geology* 2009,  
*EPSL* 2013  

What is the “viscosity” of lizardite at low temperature and high P(H2O)?
what is the “viscosity” of lizardite at low temperature and high $P(H_2O)$

SW Japan intermediate depth earthquakes are almost entirely at and below the Moho in the subducting oceanic plate.
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Mg/Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$</td>
<td></td>
</tr>
<tr>
<td>Lizardite</td>
<td>$\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td>1.5</td>
</tr>
<tr>
<td>Chrysotile</td>
<td>$\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td>1.5</td>
</tr>
<tr>
<td>Antigorite</td>
<td>$\text{Mg}<em>{48}(\text{Si}</em>{34}\text{O}<em>{85})(\text{OH})</em>{62}$</td>
<td>1.41, 16x lizardite + 2SiO$_2$ – H$_2$O</td>
</tr>
</tbody>
</table>

Lizardite contains 1.5 Mg/Si atoms. Chrysotile also has Mg/Si = 1.5 atoms. Antigorite has Mg/Si ~ 1.41, 16x lizardite + 2SiO$_2$ – H$_2$O.
chrysotile, $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$

lizardite

antigorite

Mg green, Si brown, $\text{O}_a$ blue, remaining O red
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Formula</th>
<th>Mg/Si Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lizardite</td>
<td>Mg$_3$(Si$_2$O$_5$)(OH)$_4$</td>
<td>1.5</td>
</tr>
<tr>
<td>Chrysotile</td>
<td>Mg$_3$(Si$_2$O$_5$)(OH)$_4$</td>
<td>1.5</td>
</tr>
<tr>
<td>Antigorite</td>
<td>Mg$<em>{48}$(Si$</em>{34}$O$<em>{85}$)(OH)$</em>{62}$</td>
<td>1.41, 16x lizardite + 2SiO$_2$ – H$_2$O</td>
</tr>
</tbody>
</table>

**Evans 2004:**

Antigorite alone, according to the data of Berman (1988), is stable with respect to talc + chrysotile down to below 25°C. To the writer’s knowledge, such very low grade antigorite has never been reported.
Kaolinite (clay, not a serpentine mineral)  \[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \]

Lizardite  \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]  \[ \text{Mg}/\text{Si} = 1.5 \]

Chrysotile  \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]  \[ \text{Mg}/\text{Si} = 1.5 \]

Antigorite  \[ \text{Mg}_{48}(\text{Si}_{34}\text{O}_{85})(\text{OH})_{62} \]  \[ \text{Mg}/\text{Si} \sim 1.41, 16x \text{lizardite} + 2\text{SiO}_2 - \text{H}_2\text{O} \]

\[
\text{lizardite} + 2\text{ quartz} = \text{talc} \text{Mg}_3(\text{Si}_4\text{O}_{10})(\text{OH})_2 \\
\sim 25^\circ\text{C}, \text{ Streit et al. Contrib. Mineral Petrol. 2012}
\]

\[
\text{antigorite} + 2\text{ quartz}\text{ SiO}_2 = \text{talc} \text{Mg}_3(\text{Si}_4\text{O}_{10})(\text{OH})_2 \\
\sim 100^\circ\text{C} \text{ Streit Falk & Kelemen Geochim. Cosmochim. Acta 2015}
\]
Streit et al. 2012

chrysotile & lizardite + quartz formed during weathering in $^{14}$C-bearing (young) carbonate alteration assemblages
Fig. 6 $T$–$X$ diagram of the phase relations between pure (activity = 1) Mg-end-member magnesite (mgs), chrysotile (chr), talc (ta), and quartz (q) at 5 bar.
Falk & Kelemen 2015

antigorite + quartz
at < 150°C
talc + H₂O
antigorite + quartz
Kaolinite (clay, not a serpentine mineral) \[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \]

Lizardite \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \quad \text{Mg}/\text{Si} = 1.5 \]
Chrysotile \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \quad \text{Mg}/\text{Si} = 1.5 \]
Antigorite \[ \text{Mg}_{48}(\text{Si}_{34}\text{O}_{85})(\text{OH})_{62} \quad \text{Mg}/\text{Si} \sim 1.41, 16x \text{lizardite} + 2\text{SiO}_2 \rightarrow \text{H}_2\text{O} \]
Greenalite \[ \text{Fe}^{2+}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]
Hisingerite \[ \text{Fe}^{3+}_2\square(\text{Si}_2\text{O}_5)(\text{OH})_4 \]
Cronstedtite \[ \text{Fe}^{2+}_2\text{Fe}^{3+}_2(\text{Fe}^{3+}\text{Si}_5\text{O}_5)(\text{OH})_4 \]
Mg-cronstedtite \[ \text{Mg}_2\text{Fe}^{3+}_3(\text{Fe}^{3+}\text{Si}_5\text{O}_5)(\text{OH})_4 \]

\textit{tschermak’s substitution, Mg}_{-1}\text{Si}_{-1}\text{AlAl}
Kaolinite (clay, not a serpentine mineral) \[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \]

Lizardite \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \quad \text{Mg}/\text{Si} = 1.5 \]

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Antigorite \[ \text{Mg}_{48}(\text{Si}_{34}\text{O}_{85})(\text{OH})_{62} \quad \text{Mg}/\text{Si} \sim 1.41, 16\times \text{lizardite} + 2\text{SiO}_2 - \text{H}_2\text{O} \]

Greenalite \[ \text{Fe}^{2+}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]

Hisingerite \[ \text{Fe}^{3+}_2\square(\text{Si}_2\text{O}_5)(\text{OH})_4 \]

Cronstedtite \[ \text{Fe}^{2+}_2\text{Fe}^{3+}_3(\text{Fe}^{3+}\text{Si}_2\text{O}_5)(\text{OH})_4 \]

Mg-cronstedtite \[ \text{Mg}_2\text{Fe}^{3+}_3(\text{Fe}^{3+}\text{Si}_2\text{O}_5)(\text{OH})_4 \]

tschermak’s substitution, \( \text{Mg}_{-1}\text{Si}_{-1}\text{AlAl} \)

*American Mineralogist, Volume 97, pages 184–196, 2012*

Implications of ferrous and ferric iron in antigorite

**BERNARD W. EVANS,**¹ **M. DARBY DYAR,**²,**,* and **SCOTT M. KUEHNER**¹

*American Mineralogist, Volume 94, pages 1731–1734, 2009*

LETTER

Magnetite-free, yellow lizardite serpentinization of olivine websterite, Canyon Mountain complex, N.E. Oregon

**BERNARD W. EVANS,**¹,**,* **SCOTT M. KUEHNER,**¹ **AND ANASTASIA CHOPELAS**²
lizardite + quartz formed during weathering in $^{14}$C-bearing (young) carbonate alteration assemblages

Fig. 4 WDS element map of Fe content in coexisting serpentine + quartz in sample OM08-206D. Strands of Fe-rich material (very light gray and white) are distributed within the quartz regions (black), concentrated at the edge of the quartz “mesh centers.”
peridotite approx 3 km thick
overlying allochthonous Hawasina nappes
overlying autochthonous Mesozoic to Proterozoic Arabian continental margin
working half of core is stored at AMNH available for sampling
volume proportion of veins decreases with depth

Kelemen et al J Geophys Res 2021
Hole BA1B

1 decreasing alteration with depth

Kelemen et al J Geophys Res 2021
Hole BA1B

shallow

intermediate

deep

full thin section photos, PPL

2 supergene enrichment

Kelemen et al J Geophys Res 2021
sulfur enrichment from 30 to 150 m

Hole BA1B

Kelemen et al J Geophys Res 2021
sulfur enrichment from 30 to 150 m cannot be mass balanced by depletion in overlying serpentinites

some derived from serpentinites that have since eroded away

Kelemen et al J Geophys Res 2021
Kelemen et al. J. Geophys. Res. 2021
awaruite, native Cu & magnetite

native Cu, bornite & covellite

BA1B_5B_118_2_0-7

Native Cu

Heazlewoodlite, chalcopyrite & native Cu

50 μm

Hzl Cu Ccp

BA1B_5B_132_3-54-59

Native Cu

Awarite Cu Mag

50 μm

Very low fO2 sulfide + alloy assemblages

BA3A_79-2-36-41 intergrown native Cu, pentlandite, chalcopyrite & magnetite

Mag Cu Pn

0.25 mm

3a low fO2 in water & core

Kelemen et al. J Geophys Res 2021

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute
fO$_2$ of sulfide assemblages at or close to stability limit where H$_2$O forms H$_2$

Kelemen et al J Geophys Res 2021

Abbreviations
Py – pyrite
Ccp – chalcopyrite
Pdy – polydymite
Mlr – millerite
Hzl – heazlewoodite
Po – pyrrhotite
Pn – pentlandite
Mag – magnetite
Gth – goethite
Awr – awaruite
Cu – copper
Cct – chalcocite
Cpr – cuprite
Bun - bunsenite

hematite, bornite and cubanite suppressed
Kelemen et al. J. Geophys. Res. 2021

**mineral controls of fO2**

![Graph showing depth, meters vs. log(fO2) - log(fO2) at H2O => H2](image)

- **BA1A 2018, > 1 yr**
- **BA1B 2018, < 6 mos.**
- **BA1D 2018, > 1 yr**
- **BA1D 2019, > 1 yr**
- **BA2A 2017, < 6 mos.**
- **BA2A 2018, > 1 yr**
- **BA3A 2018, < 6 mos.**
- **BA3A 2020**
- **BA4A 2018, < 6 mos.**
- **NSHQ14 2018, ~ 10 yrs**

**Additional Details**

- Log(fO2) scale
- Depth in meters
- Various markers indicating different time periods and events.
Kelemen et al. J. Geophys. Res. 2021

The diagram illustrates the mineral controls of $fO_2$ as a function of temperature and $aSiO_2$. The temperatures range from 20°C to 50°C, and the $log fO_2$ range is from -72 to -85. Key minerals are labeled, including chrysotile, greenalite, cronstedtite, magnetite, goethite, and talc. The mineral assemblage changes with temperature and $aSiO_2$.

**Table of Minerals**:
- **Ctl**: chrysotile
- **MgCtd**: Mg-cronst
- **Brc**: brucite
- **Adr**: andradite
- **Mag**: magnetite
- **Fa**: fayalite
- **Gre**: greenalite
- **Ctd**: cronstedtite
- **FeBrc**: Fe brucite
- **Awr**: awaruite

**Graph Notes**:
1. **Adr-Ctd-FeBrc**
2. **Mag-Awr-Hzl-Bun**
3. **Gre-FeBrc**
4. **Mag-FeBrc**
5. **MgCtd-FeBrc-Ctl-Gre**
6. **Ctd-FeBrc**

**Temperatures and Pressures**:
- **45 °C, 4 MPa**

**Legend**:
- **Gth-Mag**
- **H_2O**
- **H_2**
- **FeBrc-Fe**
- **Fa-Ctd-Gre**
- **Mag-Awr-Hzl-Bun**
- **Adr-Ctd-FeBrc**
- **Mag-Awr-Hzl-Bun**
- **Gre-FeBrc**
- **Mag-FeBrc**
- **MgCtd-FeBrc-Ctl-Gre**
- **Ctd-FeBrc**

**Mineral Assemblages**:
- **1**
- **2**
- **3**
- **Mg-FeBrc**
- **Ctd-FeBrc**
- **Ctl-Gre**

**Important Minerals**:
- **FeBrc-Fe**
- **Fe-brucite**
- **magnetite**
- **goethite**
- **greenalite**
- **cronstedtite**
- **hisingerite**
- **talc**

**Note**: The diagram shows how mineral assemblages change with varying $fO_2$, temperature, and $aSiO_2$.
Kelemen et al J Geophys Res 2021

Mineral controls of fO2

- **Green**: serpentines, brucite, andradite
- **Red**: H₂O, magnetite, Fe-brucite, Fe⁰

4. MgCtd-FeBrc-Ctd-Gre
5. MgCtd-FeBrc-Ctd-Gre
6. Ctd-Gre-FeBrc-H₂O

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Mineral</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ctl</td>
<td>chrysotile</td>
<td></td>
</tr>
<tr>
<td>MgCtd</td>
<td>Mg-cronst</td>
<td>cronstedtite</td>
</tr>
<tr>
<td>Brc</td>
<td>brucite</td>
<td>FeBrc</td>
</tr>
<tr>
<td>Adr</td>
<td>andradite</td>
<td>Fe</td>
</tr>
<tr>
<td>Mag</td>
<td>magnetite</td>
<td>iron</td>
</tr>
<tr>
<td>Fa</td>
<td>fayalite</td>
<td>awaruite</td>
</tr>
</tbody>
</table>

Temperature (°C) vs. log fO₂ and log aSiO₂ graph.
14C “ages” of acid-leached carbonate veins, 1000’s of years

BA3A: 20, 23, 33, 36, 45
BA4A: 31, 33, 35, 36, 41, 43, 45, 48 + 4>52
BA1B: 29, 41, 44, 3x45, 50, 52 + 3>46 & 5>52

(% modern 8, 6, 2, 1, 0.4)
(2, 2, 1, 1, 0.6, 0.5, 0.4, 0.2, 4x<0.1)
(3, 0.6, 4x0.4, 2x0.2, 8x<0.2)

ongoing low temperature serpentinization

Kelemen et al J Geophys Res 2021
Andreani et al. 2013, Al-rich

Lafay et al. 2012, pH 13

1%/yr
1%/10 yr
1%/100 yr
1%/1000 yr
1%/10,000 yr

实验橄榄石蛇纹化速率
McCollom et al. GCA 2016

正在进行低温蛇纹化
Mars Reconnaissance Orbiter mapping reveals a regional rock layer with near-infrared spectral characteristics that are consistent with the presence of magnesium carbonate in the Nili Fossae region. The carbonate is closely associated with both phyllosilicate-bearing and olivine-rich rock units, and probably formed ... from the alteration of olivine by either hydrothermal fluids or near-surface water.
Mars Reconnaissance Orbiter mapping reveals a regional rock layer with near-infrared spectral characteristics that are consistent with the presence of magnesium carbonate in the Nili Fossae region. The carbonate is closely associated with both phyllosilicate-bearing and olivine-rich rock unites, and probably formed ... from the alteration of olivine by either hydrothermal fluids or near-surface water via ambient weathering in an atmosphere similar to the present Martian atmosphere over billions of years.
Fe-free olivine

forsterite Mg$_2$SiO$_4$

unstable with respect to magnesite + quartz

marginally stable with respect to serpentine + brucite

Kelemen et al. LPSC 2020
### Modern Mars Atmosphere

(Gale Crater, Franz et al. 2017)

<table>
<thead>
<tr>
<th>Gas</th>
<th>vol %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>95</td>
</tr>
<tr>
<td>O₂</td>
<td>0.17</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.03</td>
</tr>
<tr>
<td>N₂</td>
<td>2.8</td>
</tr>
<tr>
<td>Ar</td>
<td>2</td>
</tr>
<tr>
<td>CO</td>
<td>0.07</td>
</tr>
</tbody>
</table>

- **carbonation**
- **oxidation**
- **hydration**
Mars’ atmosphere is unfavorable for hydration of surface olivine with appreciable Fe.

Mg-olivine is marginally stable with respect to serp + brucite.
Mars’ atmosphere is favorable for the oxidation and hydration + oxidation of surface olivine deposits.
Mars’ atmosphere is favorable for the carbonation of surface olivine deposits. But wait! Is it too oxidized to form siderite (Fe(II)-carbonate)?
Mars’ atmosphere is far too oxidized to form siderite (Fe(II)-carbonate).
EQUILIBRIUM ASSEMBLAGES AT MARS SURFACE  
(AFTER OLIVINE Fo$_{50}$)

(RXN 1) hydration + oxidation + carbonation

$$4(Mg_{0.5}Fe_{0.5})_2SiO_4(\text{olivine}) + 4H_2O + O_2 + 4CO_2 = 4MgCO_3(\text{magnesite}) + 2Fe_2Si_2O_5(OH)_4(\text{hisingerite})$$

**REACTANTS:**
1 kg (55.5 moles) of water vapor
9.5 kg (55.5 moles) of Fo$_{50}$-olivine

**PRODUCTS:**
13.4 kg of secondary phases

**SECONDARY MINERALS**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Mass (kg)</th>
<th>% Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serpentine</td>
<td>8.7</td>
<td>65</td>
</tr>
<tr>
<td>Carbonate</td>
<td>4.6</td>
<td>35</td>
</tr>
<tr>
<td>Total</td>
<td>13.4</td>
<td>100</td>
</tr>
</tbody>
</table>

**Solid Solution Mole Fraction**

<table>
<thead>
<tr>
<th>Solid Solution</th>
<th>Mole Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serpentine</td>
<td>0.004</td>
</tr>
<tr>
<td>Chrysotile</td>
<td>5.90E-20</td>
</tr>
<tr>
<td>Greenalite</td>
<td>1.10E-13</td>
</tr>
<tr>
<td>Cronstedtite</td>
<td>0.996</td>
</tr>
<tr>
<td>Hisingerite</td>
<td>1.000</td>
</tr>
<tr>
<td>Carbonate</td>
<td>5.30E-18</td>
</tr>
<tr>
<td>Magnesite</td>
<td>1.000</td>
</tr>
<tr>
<td>Siderite</td>
<td></td>
</tr>
</tbody>
</table>

WITH EXCESS H$_2$O

Leong et al GSA & AGU presentations, 2022
EQUILIBRIUM ASSEMBLAGES AT MARS SURFACE
(AFTER OLIVINE FeO_{50})

(RXN 1) hydration + oxidation + carbonation

\[ 4(Mg_{0.5}Fe_{0.5})_2SiO_4(\text{olivine}) + 4H_2O + O_2 + 4CO_2 = 4MgCO_3(\text{magnesite}) + 2Fe_2Si_2O_5(OH)_4(\text{hisingerite}) \]

UNTIL ALL (LIMITED!) H\textsubscript{2}O CONSUMED

THEN

(RXN 2) oxidation (from excess O\textsubscript{2})

\[ 2Fe_2SiO_4(\text{fayalite}) + O_2 = 2Fe_2O_3(\text{hematite}) + 2SiO_2 \text{ (quartz)} \]

USES ALL (LIMITED!) O\textsubscript{2}

AND THEN

(RXN 3) carbonation (from excess CO\textsubscript{2})

\[ Mg_2SiO_4(\text{forsterite}) + 2CO_2 = 2MgCO_3(\text{magnesite}) + SiO_2 \text{ (quartz)} \]

CONSUMING ABUNDANT O\textsubscript{2}

Leong et al GSA & AGU presentations, 2022
**WEATHERING THICKNESS PER KM$^3$ ATMOSPHERE PER KM$^2$ SURFACE (AFTER OLIVINE $\text{Fo}_{50}$)**

*(assuming similar $\text{H}_2\text{O}$, $\text{O}_2$, and $\text{CO}_2$ supply rate or residence time)*

**WEATHERING PROFILE**

$\text{mm}/(\text{km}^3 \text{ atmosphere})/(\text{km}^2 \text{ surface})$

<table>
<thead>
<tr>
<th>MINERAL</th>
<th>RXN 1</th>
<th>RXN 2</th>
<th>RXN 3</th>
<th>Total</th>
<th>vol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnesite</td>
<td>0.002</td>
<td></td>
<td>4.97</td>
<td>4.97</td>
<td>63.09</td>
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<tr>
<td>quartz</td>
<td>0.03</td>
<td>2.86</td>
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<td>2.88</td>
<td>36.52</td>
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<tr>
<td>hematite</td>
<td>0.02</td>
<td></td>
<td>0.03</td>
<td>0.03</td>
<td>0.34</td>
</tr>
<tr>
<td>serpentine (hisingerite)</td>
<td>0.004</td>
<td></td>
<td></td>
<td>0.004</td>
<td>0.05</td>
</tr>
</tbody>
</table>

bulk of weathered mass forms via RXN (3), as Mars’ atmosphere is very rich in $\text{CO}_2$ relative to $\text{O}_2$ and $\text{H}_2\text{O}$

Leong et al GSA & AGU presentations, 2022
“GLOSS”

global average subducting sediment

solid lines = cold subduction
dashed lines = hot subduction

oxygen partial pressure, controlled in part by redox involving Fe-serpentine polytypes, will have a large effect on the solubility of carbon in fluids released by serpentine dehydration that react with overlying, subducting, carbon-bearing sediments.
Vanuatu subducting clay formed from volcanic ash
Pressure–temperature estimates of the lizardite/antigorite transition in high pressure serpentinites

Stéphane Schwartz, Stéphane Guillot, Bruno Reynard, Romain Lafay, Baptiste Debret, Christian Nicollet, Pierre Lanari, Anne Line Auzende

below 300 °C, lizardite and locally chrysotile are the dominant species in the mesh texture. Between 320 and 390 °C, lizardite is progressively replaced by antigorite at the grain boundaries through dissolution–precipitation processes in the presence of SiO₂ enriched fluids and in the cores of the lizardite mesh. Above 390 °C, under high-grade blueschist to eclogite facies conditions, antigorite is the sole stable serpentine mineral until the onset of secondary olivine crystallization at 460 °C.
Ulmer & Trommsdorf 1995
The white star shows an estimate of the maximum temperature at which antigorite-bearing peridotite can transform to phase A-bearing peridotite without loss of bulk water. Phase labels designate generalized regions of stable hydrous magnesiansilicates: Ant, antigorite; Chl, chlorite; 10Å, 10 angstrom phase; PhA, phase A; PhE, phase E; Bru, brucite; PhD, phase D; SHB, superhydrous phase B; Wad, wadsleyite; Ring, ringwoodite; Brg, bridgmanite. Estimated storage capacities for hydrous peridotite are shown as H2O wt% (after Iwamori, 2004; Komabayashi & Omori, 2006).

Kaolinite (clay, not a serpentine mineral) \( \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \)

Lizardite \( \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \) \( \text{Mg}/\text{Si} = 1.5 \)
Chrysotile \( \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \) \( \text{Mg}/\text{Si} = 1.5 \)
Antigorite \( \text{Mg}_{48}(\text{Si}_{34}\text{O}_{85})(\text{OH})_{62} \) \( \text{Mg}/\text{Si} \sim 1.41, 16\times \text{lizardite} + 2\text{SiO}_2 - \text{H}_2\text{O} \)
Greenalite \( \text{Fe}^{2+}_2(\text{Si}_2\text{O}_5)(\text{OH})_4 \)
Hisingerite \( \text{Fe}^{3+}_2(\text{Si}_2\text{O}_5)(\text{OH})_4 \)

Clinochlore (chlorite group, not a serpentine mineral) \( \text{Mg}_5\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_8 \)
chlorium chlorite
ferric iron chlorite?

Amesite \( \text{Mg}_2\text{Al}(\text{AlSi}_3\text{O}_5)(\text{OH})_4 \) + \( \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \) = clinochlore
chromian serp? \( \text{Mg}_2\text{Cr}(\text{CrSiO}_5)(\text{OH})_4 \) ???
Cronstedtite \( \text{Fe}^{2+}_2\text{Fe}^{3+}(\text{Fe}^{3+}\text{SiO}_5)(\text{OH})_4 \) + \( \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \) = chromian chl
Mg-cronstedtite \( \text{Mg}_2\text{Fe}^{3+}(\text{Fe}^{3+}\text{SiO}_5)(\text{OH})_4 \) + \( \text{Fe}^{2+}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \) = Fe-chlorite?
Kaolinite (clay, not a serpentine mineral)  \[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \]

Lizardite  \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]  \hspace{1cm} \text{Mg}/\text{Si} = 1.5
Chrysotile  \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]  \hspace{1cm} \text{Mg}/\text{Si} = 1.5
Antigorite  \[ \text{Mg}_{48}(\text{Si}_{34}\text{O}_{85})(\text{OH})_{62} \]  \hspace{1cm} \text{Mg}/\text{Si} \sim 1.41, 16\times \text{lizardite} + 2\text{SiO}_2 - \text{H}_2\text{O}
Greenalite  \[ \text{Fe}^{2+}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]
Hisingerite  \[ \text{Fe}^{3+}_2(\text{Si}_2\text{O}_5)(\text{OH})_4 \]

Clinochlore (chlorite group, not a serpentine mineral)  \[ \text{Mg}_5\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_8 \]
chromian chlorite  \[ \text{Mg}_5\text{Cr}(\text{CrSi}_3\text{O}_{10})(\text{OH})_8 \]
ferric iron chlorite?  \[ \text{Fe}^{2+}_5\text{Fe}^{3+}(\text{Fe}^{3+}\text{Si}_3\text{O}_{10})(\text{OH})_8 \]?

tschermak’s substitution, Mg\text{-}1Si\text{-}1AlAl

Amesite  \[ \text{Mg}_2\text{Al}(\text{AlSi}_5\text{O}_5)(\text{OH})_4 \]  \hspace{1cm} + \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 = \text{clinochlore}
chromian serp?  \[ \text{Mg}_2\text{Cr}(\text{CrSi}_5\text{O}_5)(\text{OH})_4 \] ???  \hspace{1cm} + \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 = \text{chromian chl}
Cronstedtite  \[ \text{Fe}^{2+}_2\text{Fe}^{3+} (\text{Fe}^{3+}\text{Si}_5\text{O}_5)(\text{OH})_4 \]  \hspace{1cm} + \text{Fe}^{2+}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 = \text{Fe-chlorite}?
Mg-cronstedtite  \[ \text{Mg}_2\text{Fe}^{3+} (\text{Fe}^{3+}\text{Si}_5\text{O}_5)(\text{OH})_4 \]

---

Tschermak's substitution in antigorite and consequences for phase relations and water liberation in high-grade serpentinites

José Alberto Padrón-Navarta a,b,*; Vicente López Sánchez-Vizcaíno c; Joerg Hermann b; James A.D. Connolly c; Carlos J. Garrido d; María Teresa Gómez-Pugnaire e;f; Claudio Marchesi h
average depleted peridotite (harzburgite) contains
~1 wt% Al$_2$O$_3$

about 0.3 wt% is in Cr-Al spinel
leaving about 0.7 wt% for serpentine ± chlorite minerals

similar to W&S

numbers are wt% Al$_2$O$_3$ in antigorite
duplicates, tons/m$^3$
density < 3300 kg/m$^3$
Fig. 4. Compositionally stratified descending lithosphere. Eclogite layer (black) sinks through less dense depleted mantle (light stipple) as the top of lithosphere is warmed. Depleted material continues to rise through the overlying mantle providing a mechanism for behind-arc spreading. See text for further discussion.
Figure 6. Subduction of a lithospheric slab with a depleted top and undepleted base (oceanic crust on a continental margin; vertical arrows indicate rise of magmas. A diapir is shown about to separate the top of the slab: o.s., olivine-spinel phase change; p.s., post-spinel phase change.
Kaolinite (clay, not a serpentine mineral)  \[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \]

Lizardite  \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \quad \text{Mg/Si} = 1.5 \]
Chrysotile  \[ \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \quad \text{Mg/Si} = 1.5 \]
Antigorite  \[ \text{Mg}_{48}(\text{Si}_{34}\text{O}_{85})(\text{OH})_{62} \quad \text{Mg/Si} \sim 1.41, 16\times \text{lizardite} + 2\text{SiO}_2 - \text{H}_2\text{O} \]
Greenalite  \[ \text{Fe}^{2+}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]
Hisingerite  \[ \text{Fe}^{3+}_2(\text{Si}_2\text{O}_5)(\text{OH})_4 \]

Clinochlore (chlorite group, not a serpentine mineral)  \[ \text{Mg}_5\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_8 \]
Chromian chlorite  \[ \text{Mg}_5\text{Cr}((\text{CrSi}_3\text{O}_{10})(\text{OH})_8 \]
Ferric iron chlorite?  \[ \text{Fe}^{2+}_5\text{Fe}^{3+}(\text{Fe}^{3+}\text{Si}_3\text{O}_{10})(\text{OH})_8? \]

Amesite  \[ \text{Mg}_2\text{Al}(\text{AlSi}_5\text{O}_5)(\text{OH})_4 \]
Chromian serp?  \[ \text{Mg}_2\text{Cr}(\text{CrSi}_5\text{O}_5)(\text{OH})_4 \quad ??? \]
Cronstedtite  \[ \text{Fe}^{2+}_2\text{Fe}^{3+}(\text{Fe}^{3+}\text{Si}_5\text{O}_5)(\text{OH})_4 \]

\[ \text{Ni}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]
\[ (\text{Ni,Mg})_3(\text{Si}_2\text{O}_5)(\text{OH})_4 \]

Ni FOR BATTERIES
the leading edge of the mantle wedge
listvenite = carbonated peridotite quartz + magnesite ± chromian mica ± chrome spinel

Kelemen et al. J Geophys Res 2022
BT1
basal thrust
lisvenites:
carbonated peridotite

metamorphic sole
Hawasina Fm
lizardite mylonite at ~ 150°C

what is the “viscosity” of lizardite at low temperature and high P(H2O)

Kelemen et al. J Geophys Res 2022
Cascadia intermediate depth earthquakes are almost entirely at and below the Moho in the subducting oceanic plate. What is the “viscosity” of lizardite at low temperature and high P(H2O)?

---

top of subducting oceanic plate
Moho in subducting plate

Cascadia intermediate depth earthquakes are almost entirely at and below the Moho in the subducting oceanic plate.

Abers et al. Geology 2009, EPSL 2013
what is the “viscosity” of lizardite at low temperature and high P(H2O)?

SW Japan intermediate depth earthquakes are almost entirely at and below the Moho in the subducting oceanic plate

Abers et al. EPSL 2013
Kelemen et al. J Geophys Res 2022

Field of view 1.4 mm

Fine-grained magnesite + hematite with chalcedony vein

Fine-grained quartz/chalcedony replacing opal?
https://www.researchgate.net/publication/282851612_Late_Tertiary_Petrified_Wood_from_Nevada_USA_Evidence_of_Multiple_Silicification_Pathways
qtz lenses within parallel magnesite-hematite veins

Kelemen et al. J Geophys Res 2022
parallel magnesite & dolomite veins

Kelemen et al. J Geophys Res 2022

field of view 1.4 mm

serpentinite mylonite
https://www.researchgate.net/publication/221720128_Enhanced_CO2-mineral_sequestration_by_cyclic_hydraulic_fracturing_and_Si-rich_fluid_infiltration_into_serpentinites_at_Malentrata_Tuscany_Italy
https://www.researchgate.net/publication/351335960_Voluminous_Silica_Precipitated_from_Martian_Waters_during_Late-stage_Aqueous_Alteration
summary of this short and simple talk:

no thermodynamic data for lizardite
possible “capillary flow” in chrysotile tubes
antigorite thermodynamic data render it too stable at low T, low SiO2 activity
serpentine + quartz is stable with respect to talc at low temperatures!
antigorite may be more stable than lizardite at low temperatures when aSiO2 is high
Fe substitution in serpentine seems to make it more stable at low T
   (magnetite and/or hematite in high T serpentinites “dissolve” into
   Fe3+ rich serpentine at lower T; papers by Klein et al., Streit et al., ...)
Fe2+/Fe3+ redox during serpentine formation from Fe2 bearing phases
   helps drive fO2 to ~10^-80 to 10^-85 bars (origin of life, abiotic H2 and hydrocarbons,
   supergene sulfur, Ni enrichment, NiFe alloy, etc etc
no solid solution properties for mixtures of Mg-, Fe-, Al-bearing serpentines
serpentine formation is too slow for lab studies, fast by geological standards
oxidized Fe-serpentine (hisingerite) stable on Mars surface,
   but much less abundant than oxides and, especially, Mg-carbonates
redox controlled in part by serpentine phases has a strong control on
   recycling versus deep subduction of carbon
antigorite stability, with and without minor amounts of Al (amesite) component,
   controls recycling versus deep subduction of H2O, buoyancy of subducting mantle,
   potential for diapirs of buoyant Mg-rich, Fe-poor hydrous peridotite
low temperature viscous deformation of lizardite, opal, at and above the top of
   subducting oceanic crust may lead to aseismic subduction
   (is opal more stable than quartz at low temperature and high P(H2O)?

Je n’ai fait celle-ci plus longue que parce que je n’ai pas eu le loisir de la faire plus courte.
thank you for your attention
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Mg/Si Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kaolinite</strong></td>
<td>$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$</td>
<td></td>
</tr>
<tr>
<td><strong>Lizardite</strong></td>
<td>$\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td>Mg/Si = 1.5</td>
</tr>
<tr>
<td><strong>Chrysotile</strong></td>
<td>$\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td>Mg/Si = 1.5</td>
</tr>
<tr>
<td><strong>Antigorite</strong></td>
<td>$\text{Mg}<em>{48}(\text{Si}</em>{34}\text{O}<em>{85})(\text{OH})</em>{62}$</td>
<td>Mg/Si ~ 1.41, 16x lizardite + 2SiO$_2$ – H$_2$O</td>
</tr>
<tr>
<td><strong>Greenalite</strong></td>
<td>$\text{Fe}^{2+3}(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td></td>
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<tr>
<td><strong>Hisingerite</strong></td>
<td>$\text{Fe}^{3+2}(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td></td>
</tr>
<tr>
<td><strong>Clinochlore</strong></td>
<td>$\text{Mg}_5\text{Al(AlSi}<em>3\text{O}</em>{10})(\text{OH})_8$</td>
<td></td>
</tr>
<tr>
<td><strong>Chromian chlorite</strong></td>
<td>$\text{Mg}_5\text{Cr(CrSi}<em>3\text{O}</em>{10})(\text{OH})_8$</td>
<td></td>
</tr>
<tr>
<td><strong>Ferric iron chlorite?</strong></td>
<td>$\text{Fe}^{2+5}\text{Fe}^{3+}(\text{Fe}^{3+}\text{Si}<em>3\text{O}</em>{10})(\text{OH})_8$?</td>
<td></td>
</tr>
<tr>
<td><strong>Amesite</strong></td>
<td>$\text{Mg}_2\text{Al(AlSiO}_5)(\text{OH})_4$</td>
<td>+ $\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$ = clinochlore</td>
</tr>
<tr>
<td><strong>Chromian serp?</strong></td>
<td>$\text{Mg}_2\text{Cr(CrSiO}_5)(\text{OH})_4$ ???</td>
<td>+ $\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$ = chromian chl</td>
</tr>
<tr>
<td><strong>Cronstedtite</strong></td>
<td>$\text{Fe}^{2+2}\text{Fe}^{3+}(\text{Fe}^{3+}\text{SiO}_5)(\text{OH})_4$</td>
<td>+ $\text{Fe}^{2+3}(\text{Si}_2\text{O}_5)(\text{OH})_4$ = Fe-chlorite?</td>
</tr>
<tr>
<td><strong>Pecoraite</strong></td>
<td>$\text{Ni}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td></td>
</tr>
<tr>
<td><strong>Népouite</strong></td>
<td>$(\text{Ni,Mg})_3(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td></td>
</tr>
<tr>
<td><strong>Forsterite (olivine)</strong></td>
<td>$2\text{Mg}_2\text{SiO}_4 + 3\text{H}_2\text{O} = \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 + \text{Mg(OH)}_2$ brucite</td>
<td></td>
</tr>
<tr>
<td><strong>Enstatite (pyroxene)</strong></td>
<td>$3\text{Mg}_2\text{Si}_2\text{O}_6 + 3\text{H}_2\text{O} = \text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4 + \text{Mg}_3\text{Si}<em>4\text{O}</em>{10}(\text{OH})_2$ talc</td>
<td></td>
</tr>
<tr>
<td><strong>Fo + En</strong></td>
<td>$2\text{Mg}_2\text{SiO}_4 + \text{Mg}_2\text{Si}_2\text{O}_6 + 4\text{H}_2\text{O} = 2\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$</td>
<td></td>
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</tbody>
</table>