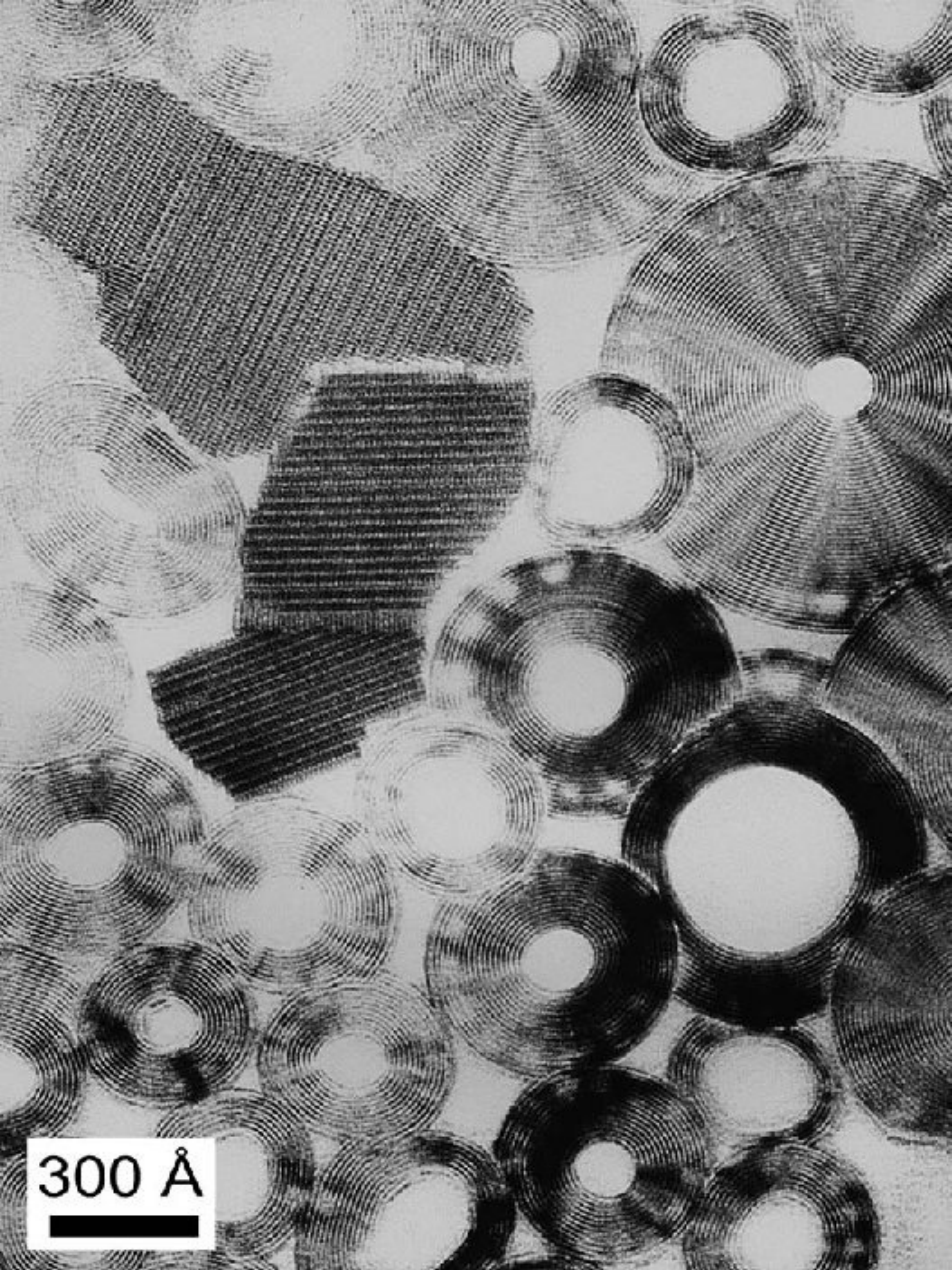
300 Å

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
        Fe^3+ rich serpentine at lower T; papers by Klein et al., Streit et al., …)
Fe^{2+}/Fe^{3+} redox during serpentine formation from Fe^2 bearing phases
    helps drive fO_2 to ~10^{-80} to 10^{-85} bars (origin of life, abiotic H_2 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) $Al_2Si_2O_5(OH)_4$

$Al_{-2}Mg_3$

Lizardite	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Chrysotile	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5

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Chrysotile	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5

peridotite, Earth's upper mantle
gemstone name for olivine is peridot
simplify, ignoring Fe, Ca, Al, Cr, ...

Forsterite (olivine)	$2Mg_2SiO_4 + 3H_2O = Mg_3(Si_2O_5)(OH)_4 + Mg(OH)_2$ brucite
Enstatite (pyroxene)	$3Mg_2Si_2O_6 + 3H_2O = Mg_3(Si_2O_5)(OH)_4 + Mg_3Si_4O_{10}(OH)_2$ talc
Fo + En	$2Mg_2SiO_4 + Mg_2Si_2O_6 + 4H_2O = 2Mg_3(Si_2O_5)(OH)_4$

Kaolinite (clay, not a serpentine mineral) $Al_2Si_2O_5(OH)_4$

Lizardite	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Chrysotile	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5

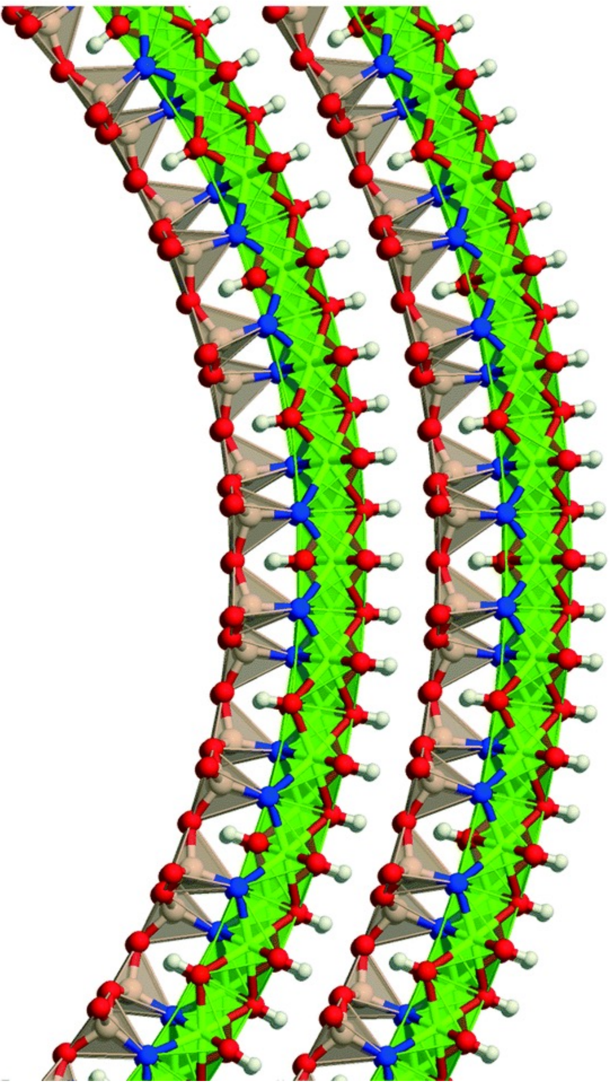
International Geology Review, Vol. 46, 2004, p. 479–506.

The Serpentinite Multisystem Revisited: Chrysotile Is Metastable

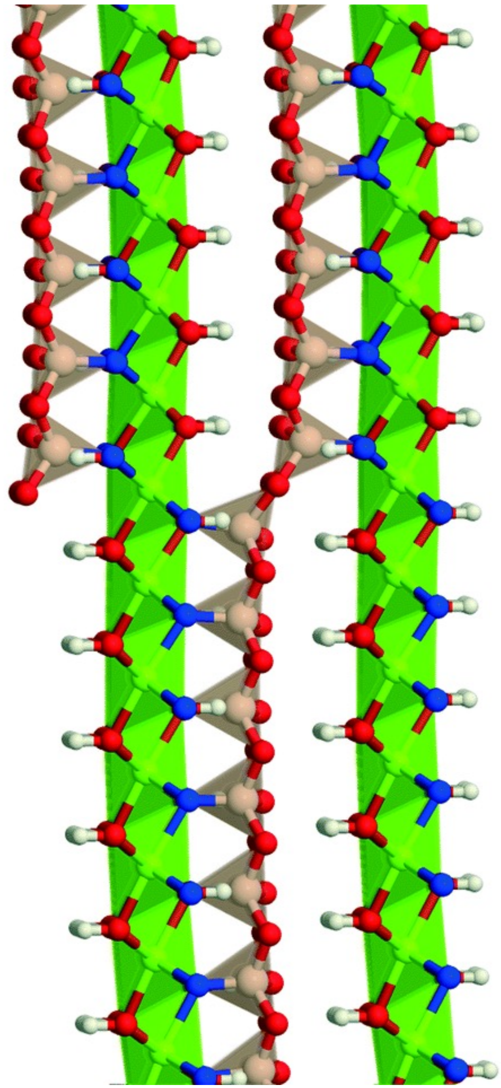
BERNARD W. EVANS

Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195-1310

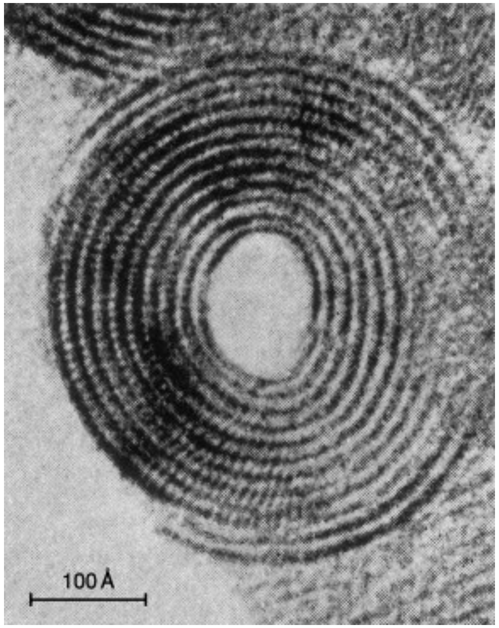
chrysotile, $Mg_3Si_2O_5(OH)_4$



lizardite



Mg green, Si brown, O_a blue, remaining O red



https://www.sciencedirect.com/topics/chemistry/chrysotile

reminder 100 angstroms = 10 nm

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

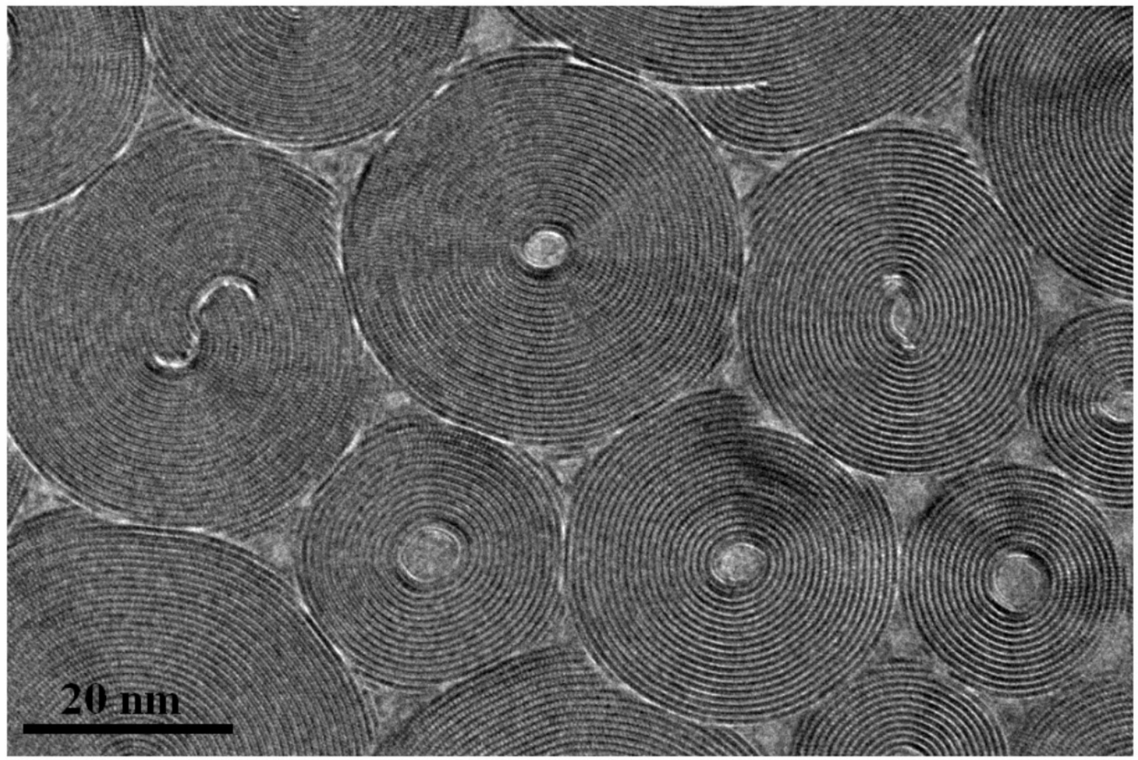
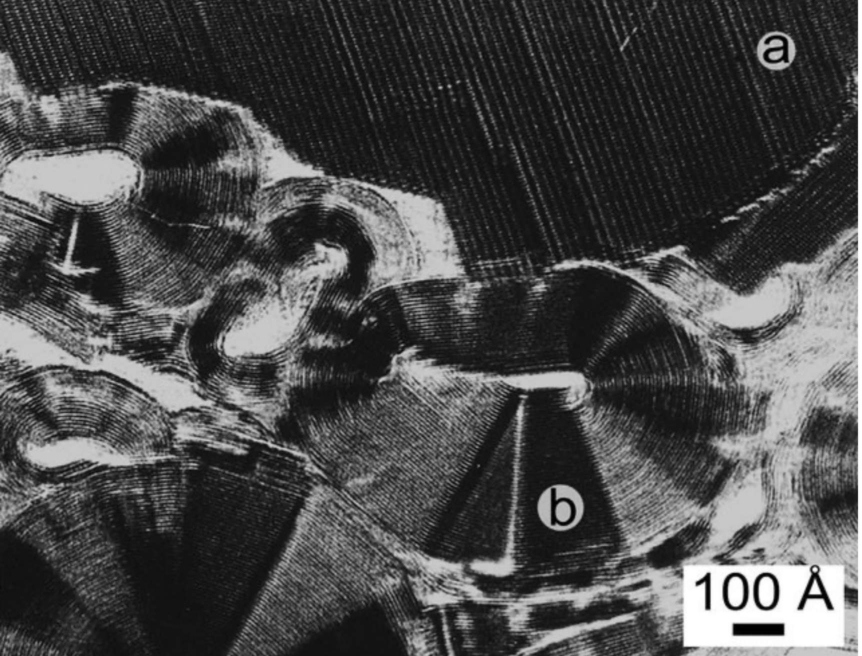
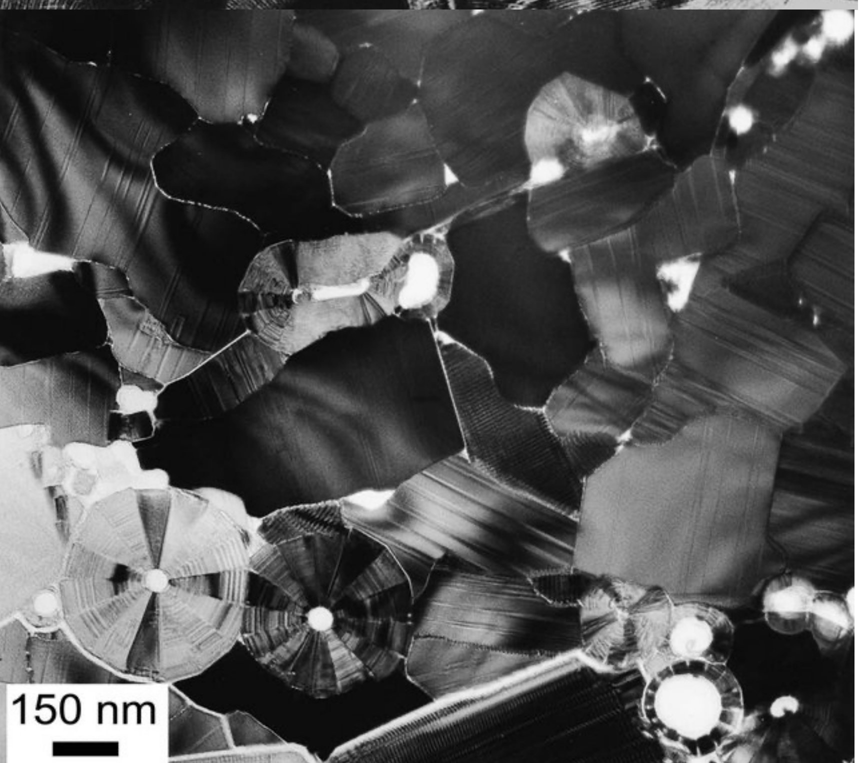
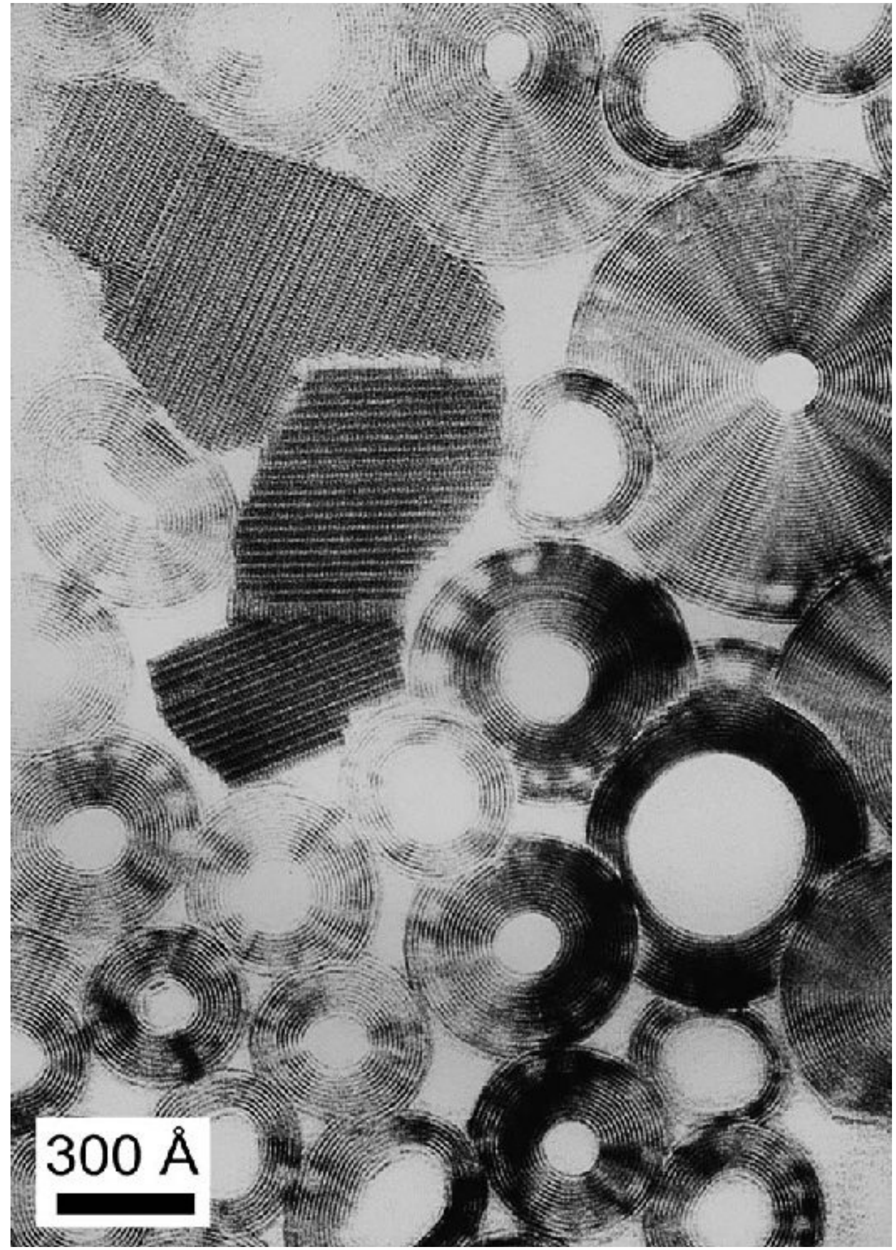


Fig. 1. A high-resolution TEM image of the cross-section of chrysotile asbestos.

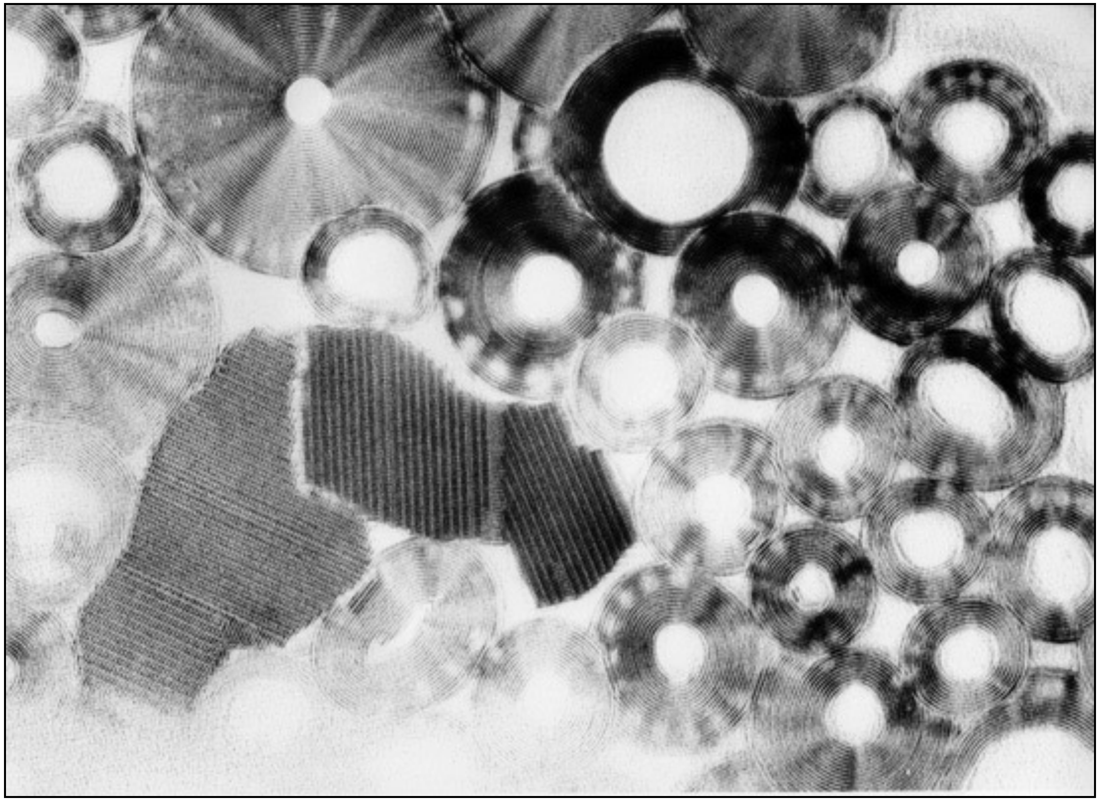
https://www.cambridge.org/core/services/aop-cambridge-core/content/view/D193D11744C5B06347D2349CC5F0CD3E/S1431927610054243a.pdf/crosssection_of_asbestos_prepared_for_temstem_with_ion_slicer.pdf

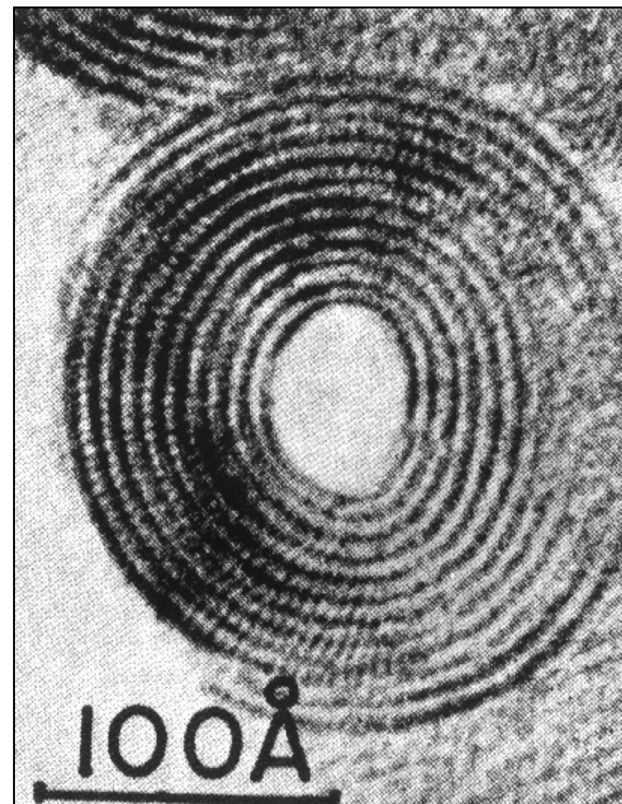






https://www.researchgate.net/publication/318295435_Crystal_
habit_of_mineral_fibres/figures?lo=1

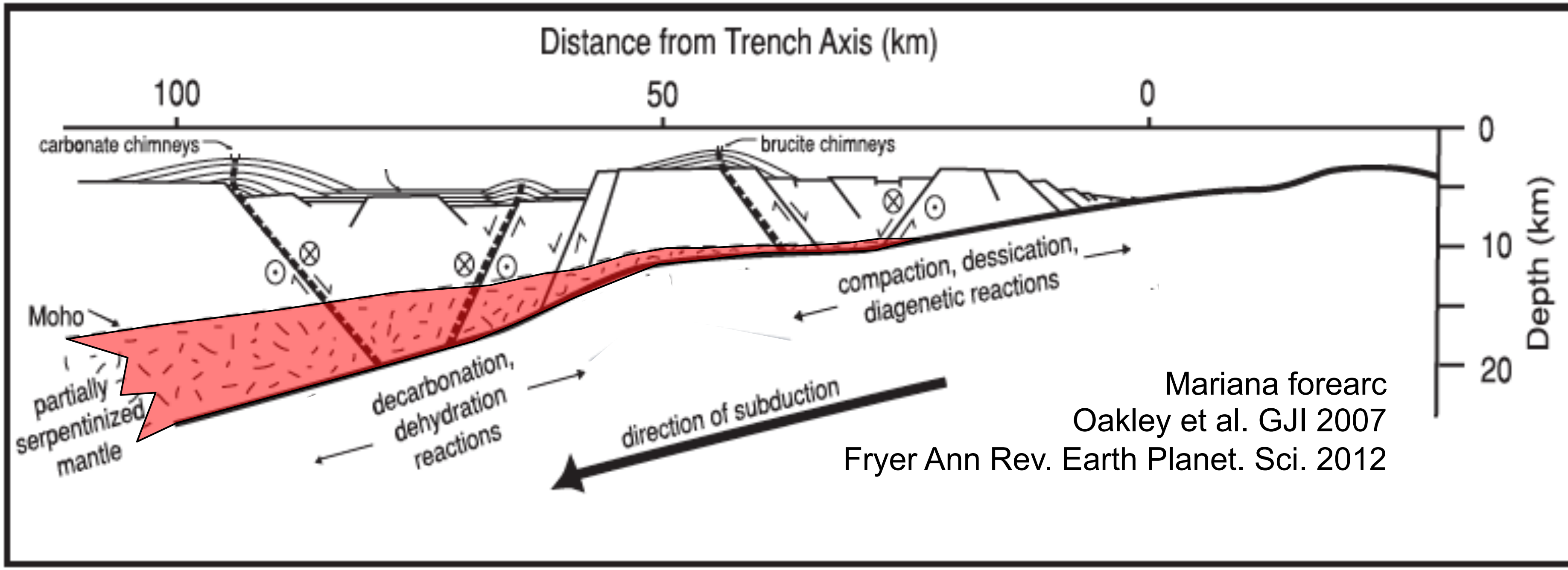




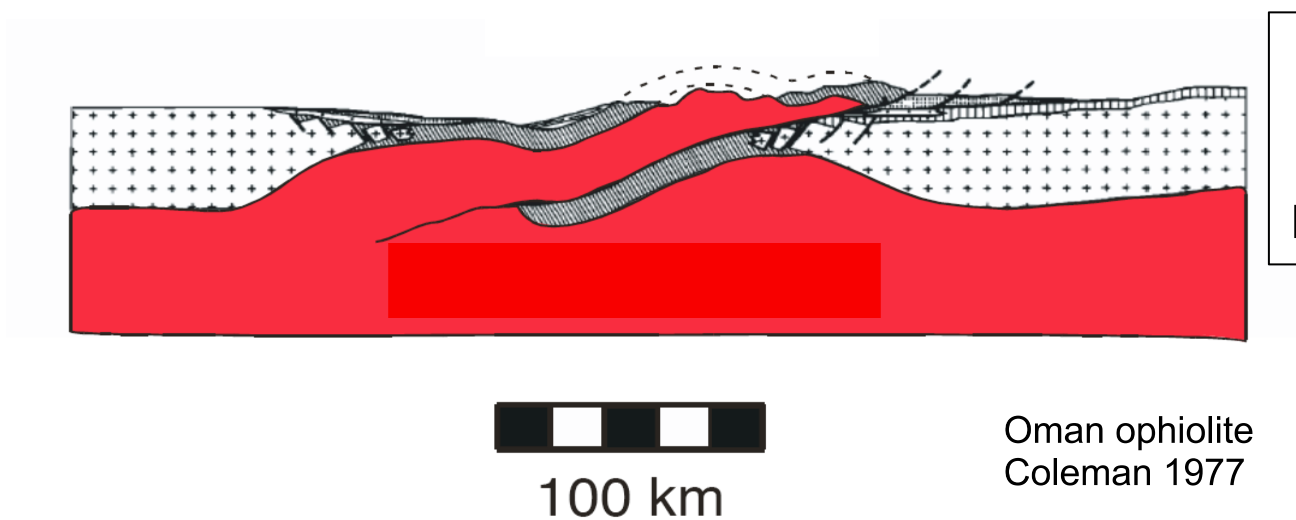
$P_c = 2\sigma \cos(\theta)/r$

$\sigma_{aw} = 0.0728 N/m$
θ_{aw} in glass = 0.35 radians
r = 5 nm

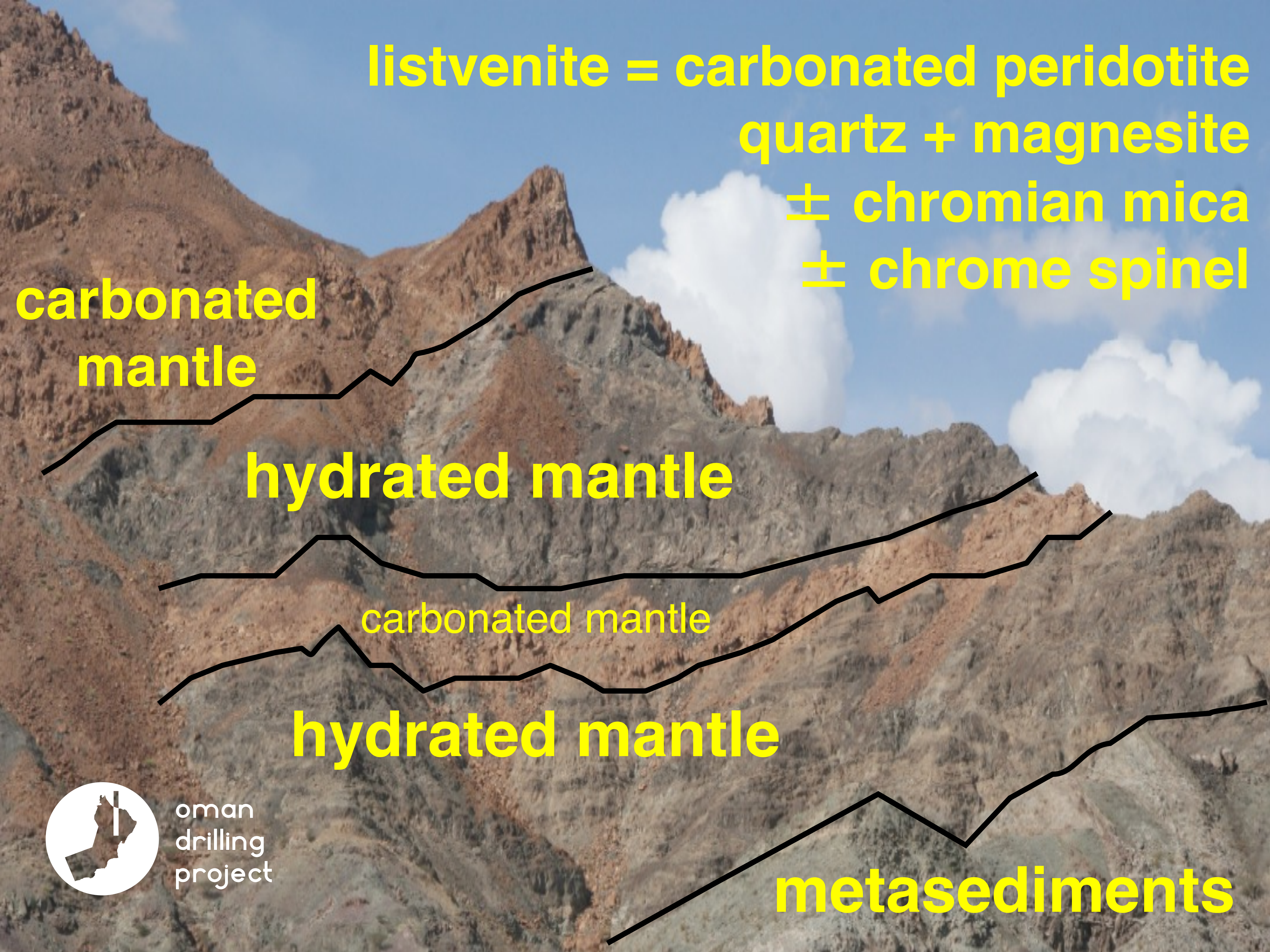
$h = P_c/(\rho g) \sim 14$ km!!!???



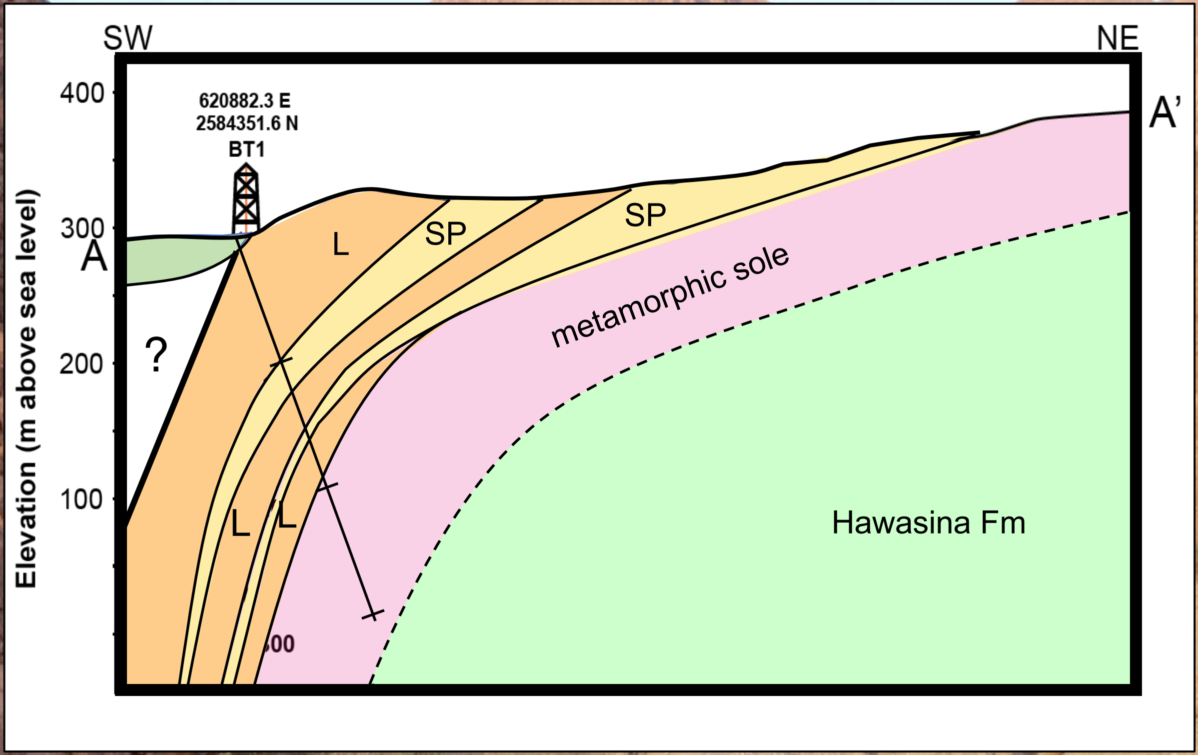
the leading edge of the mantle wedge



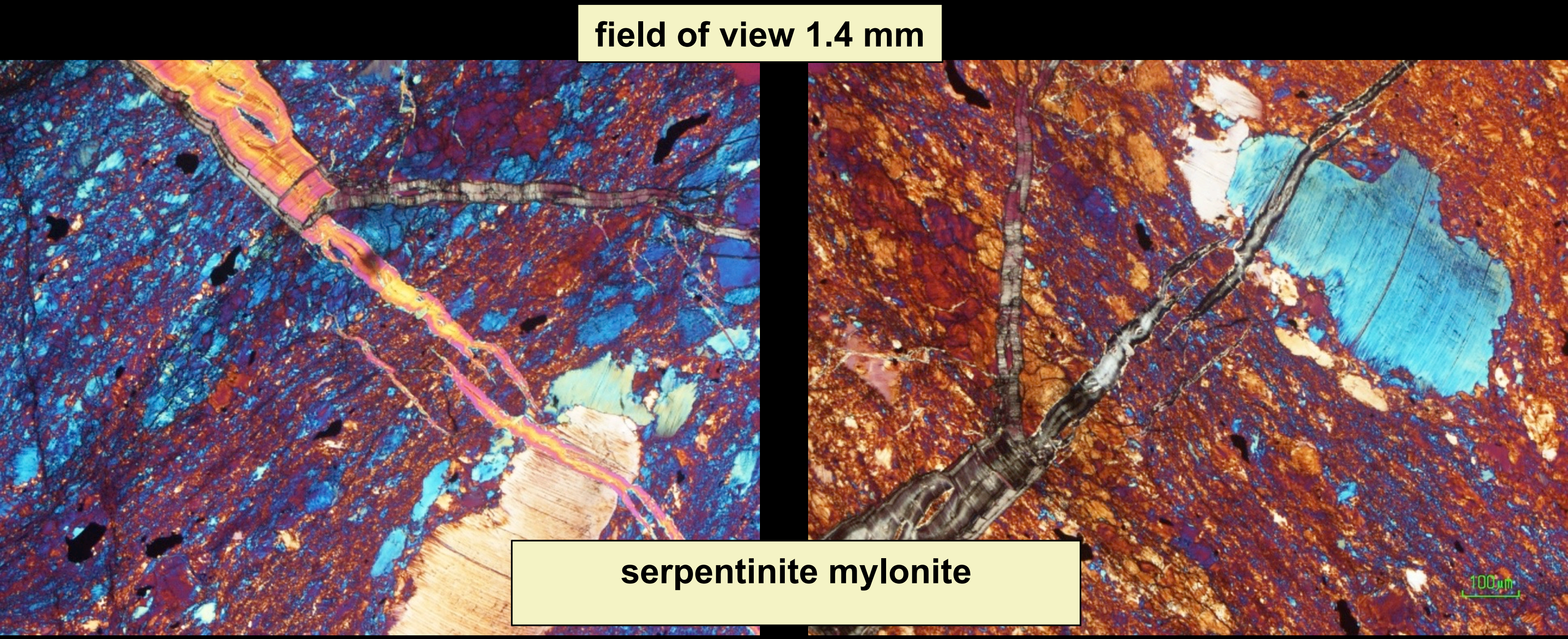
Oman ophiolite
Coleman 1977


listvenite = carbonated peridotite
quartz + magnesite
± chromian mica
± chrome spinel
carbonated mantle
hydrated mantle
carbonated mantle
hydrated mantle
metasediments
oman drilling project

BT1
basal thrust lisvenites:
carbonated peridotite



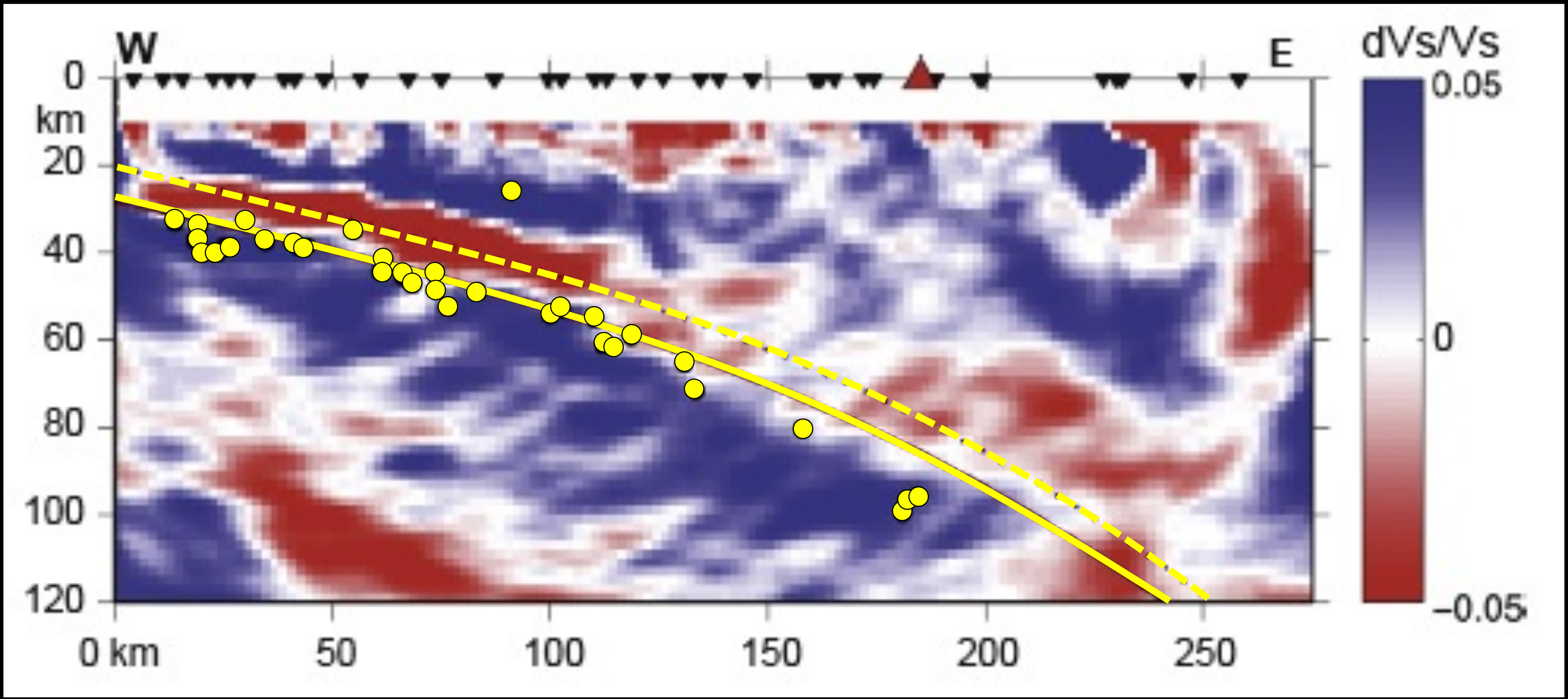
oman drilling project



lizardite mylonite at ~ 150°C

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(H2O)

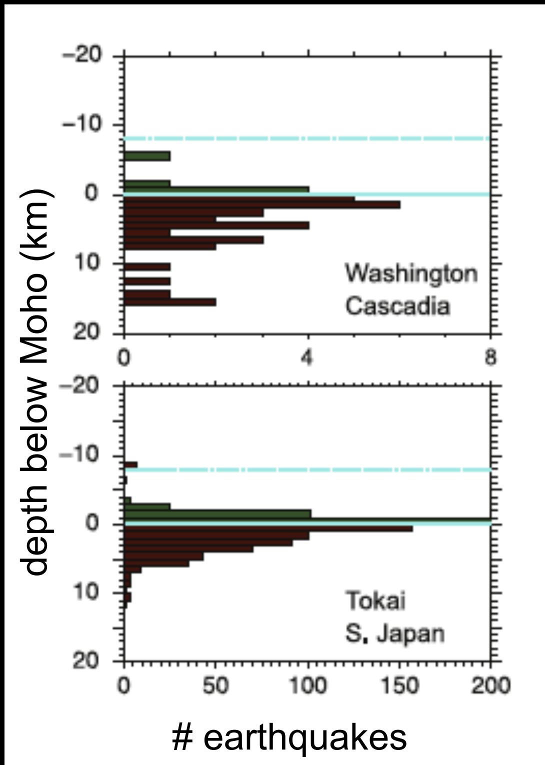


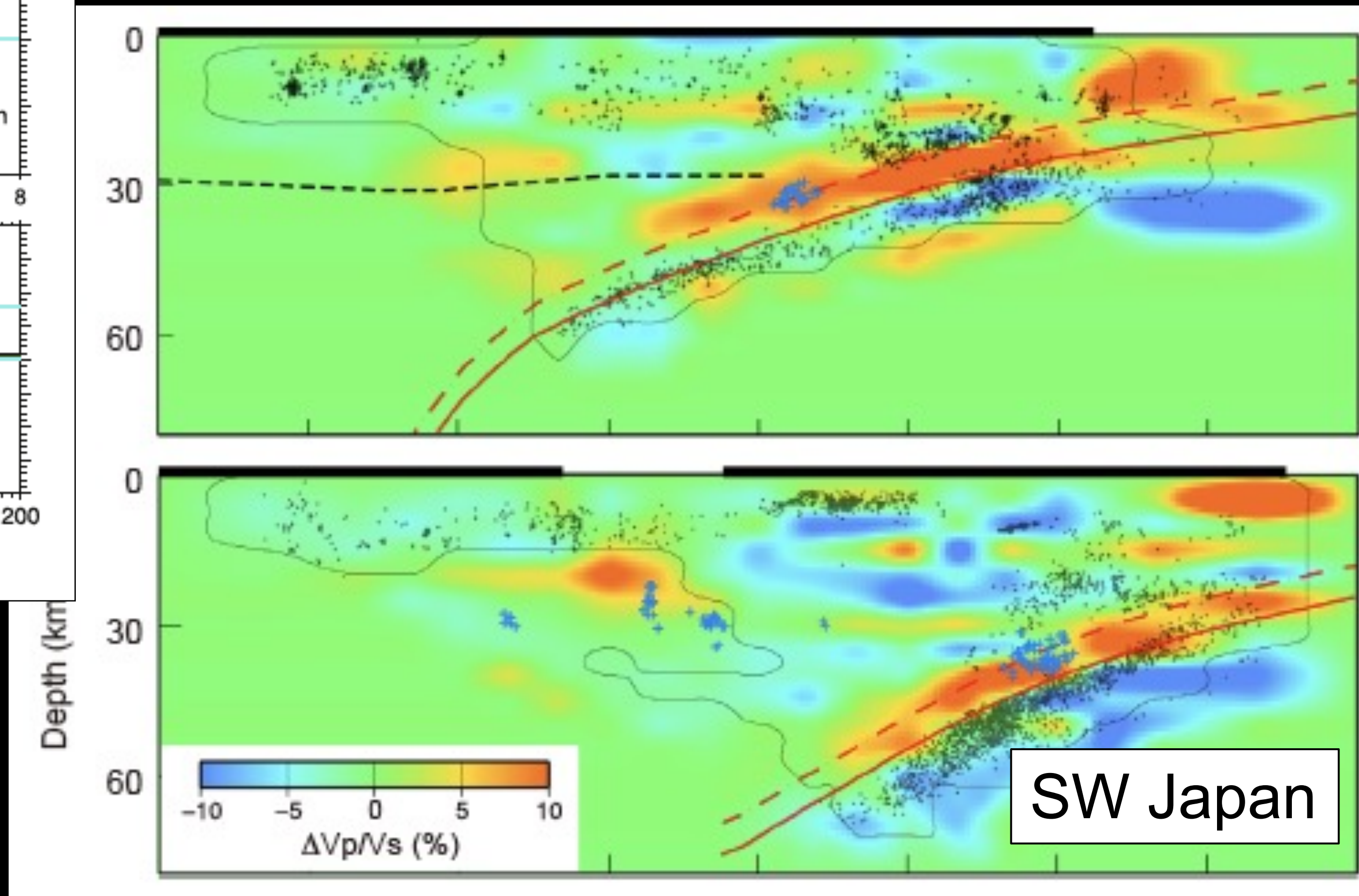
top of subducting oceanic plate
Moho in subducting plate

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

Abers et al. Geology 2009, EPSL 2013

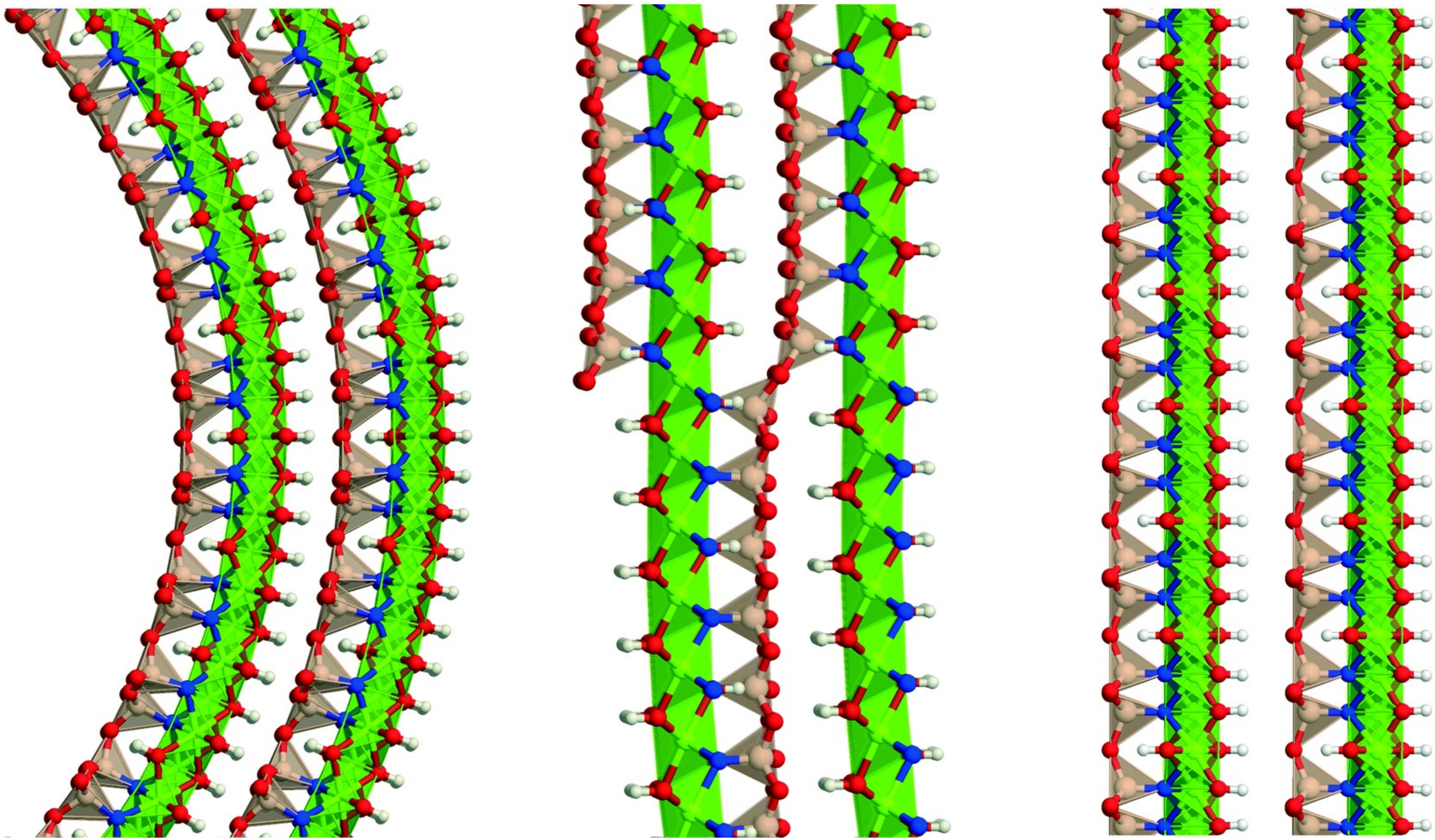
what is the "viscosity" of lizardite at low temperature and high P(H2O)





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

Kaolinite (clay, not a serpentine mineral)	$Al_2Si_2O_5(OH)_4$	
Lizardite	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Chrysotile	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Antigorite	$Mg_{48}(Si_{34}O_{85})(OH)_{62}$	**Mg/Si ~ 1.41, 16x lizardite + $2SiO_2$ – H_2O**



Mg green, Si brown, O_a blue, remaining O red

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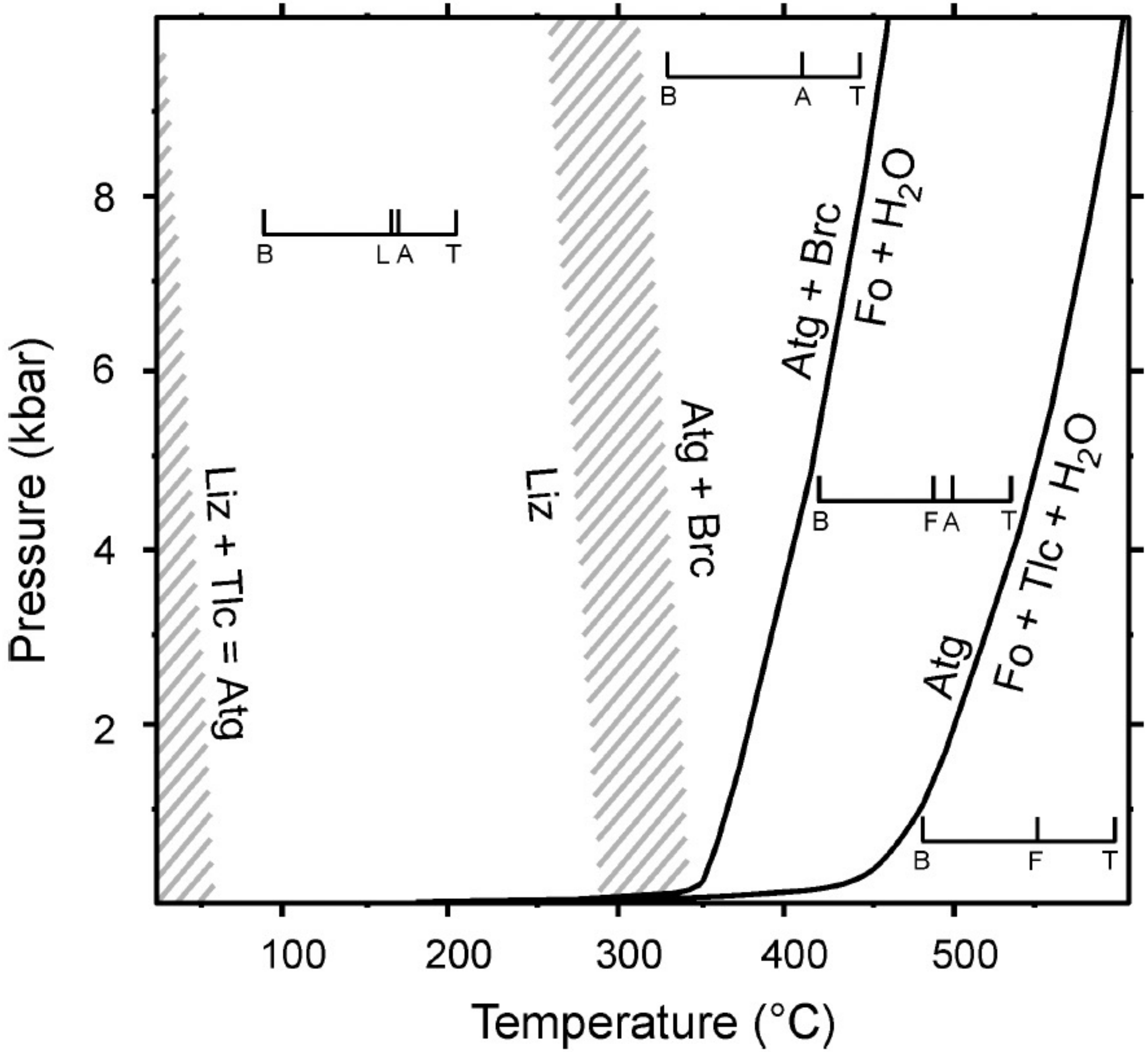
Evans 2004:

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.


Pressure (kbar)
Temperature (°C)
100
200
300
400
500
2
4
6
8
Liz + Tlc = Atg
Liz
Atg + Brc
Atg + Brc
Fo + H2O
Atg
Fo + Tlc + H2O
B
L A
T
B
A
T
B
F A
T
B
F
T

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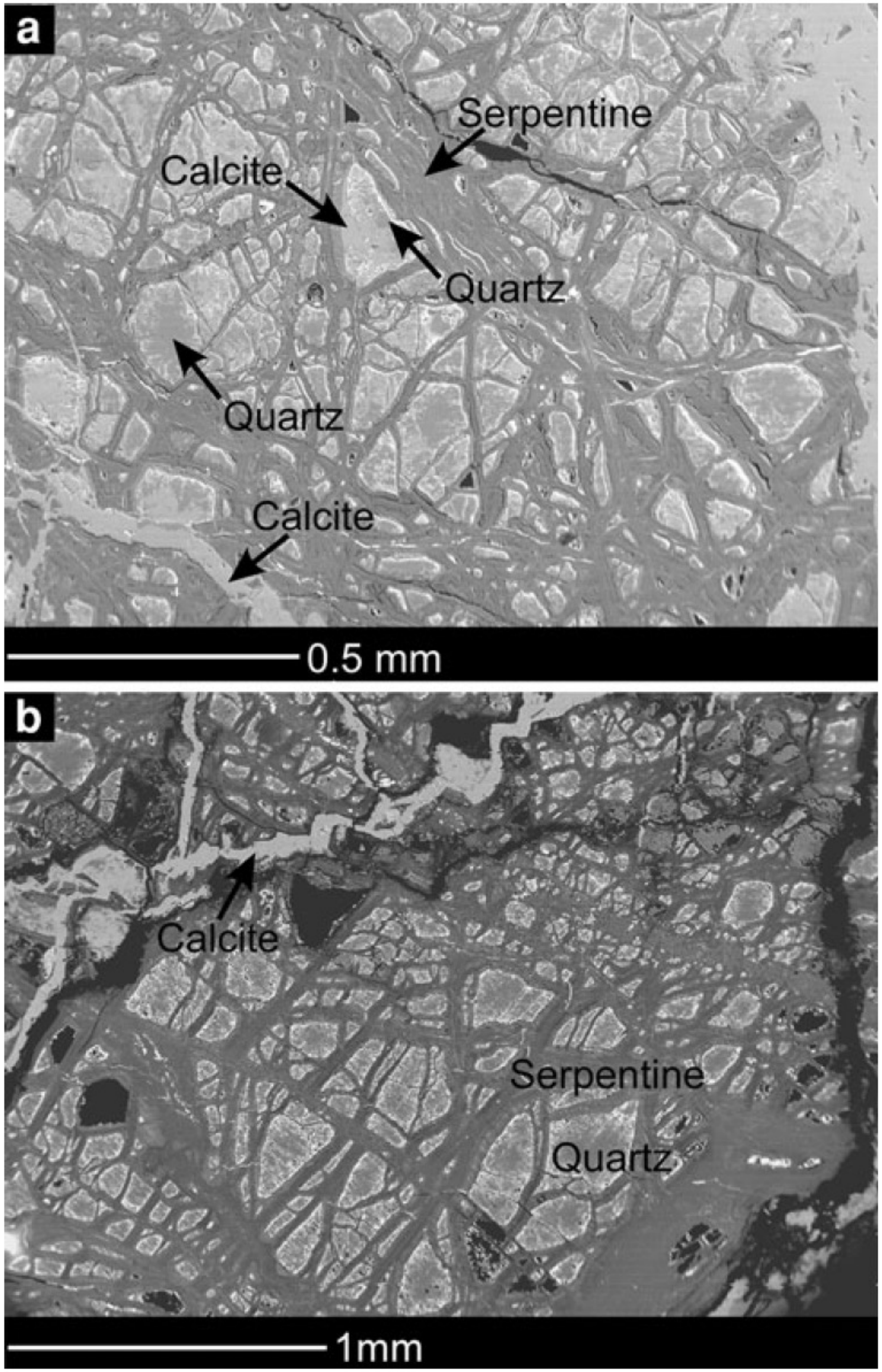
lizardite + 2 quartz = talc $Mg_3(Si_4O_{10})(OH)_2$
~ 25°C, Streit et al. Contrib. Mineral Petrol. 2012

antigorite + 2 quartz SiO_2 = talc $Mg_3(Si_4O_{10})(OH)_2$
~ 100°C 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

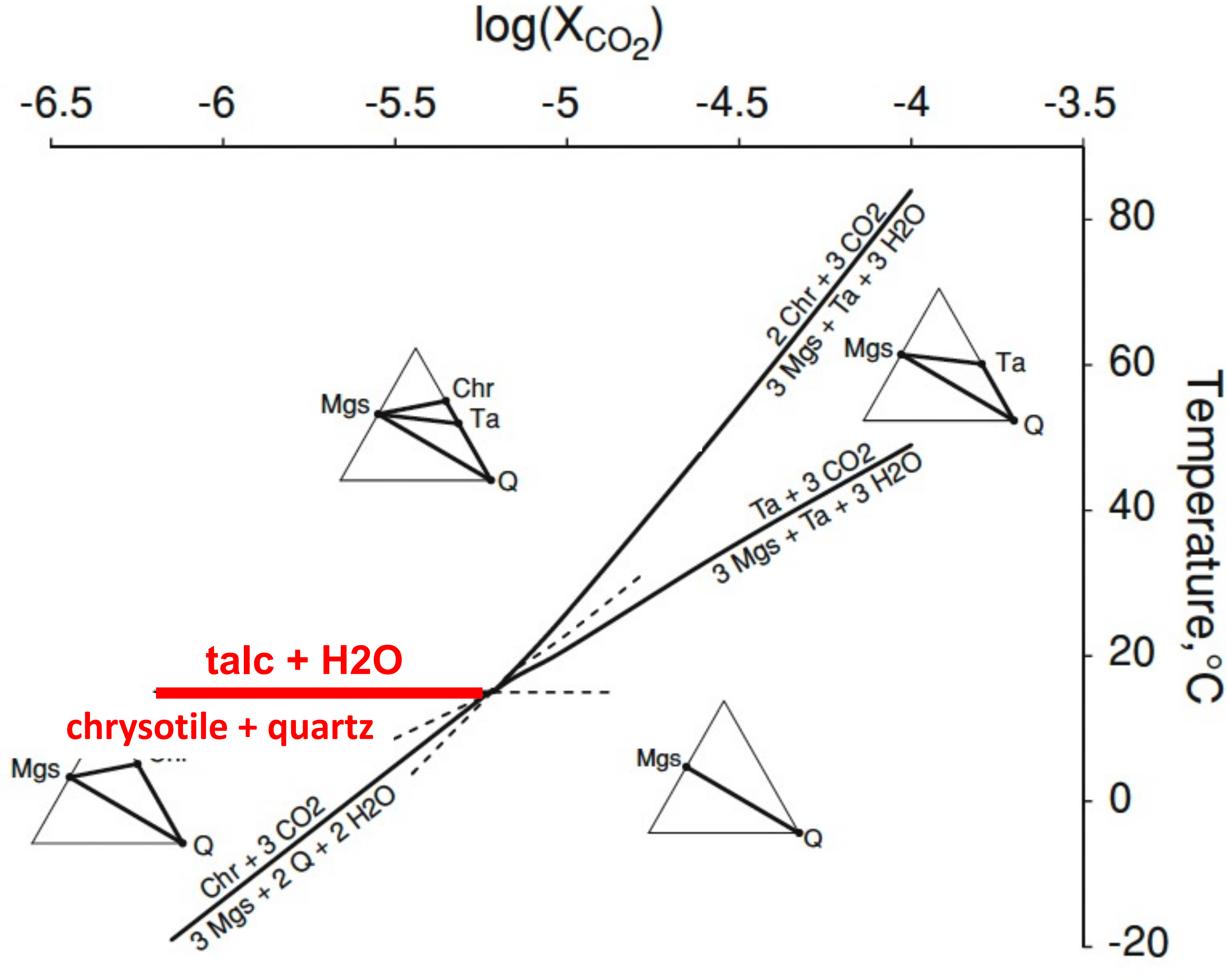
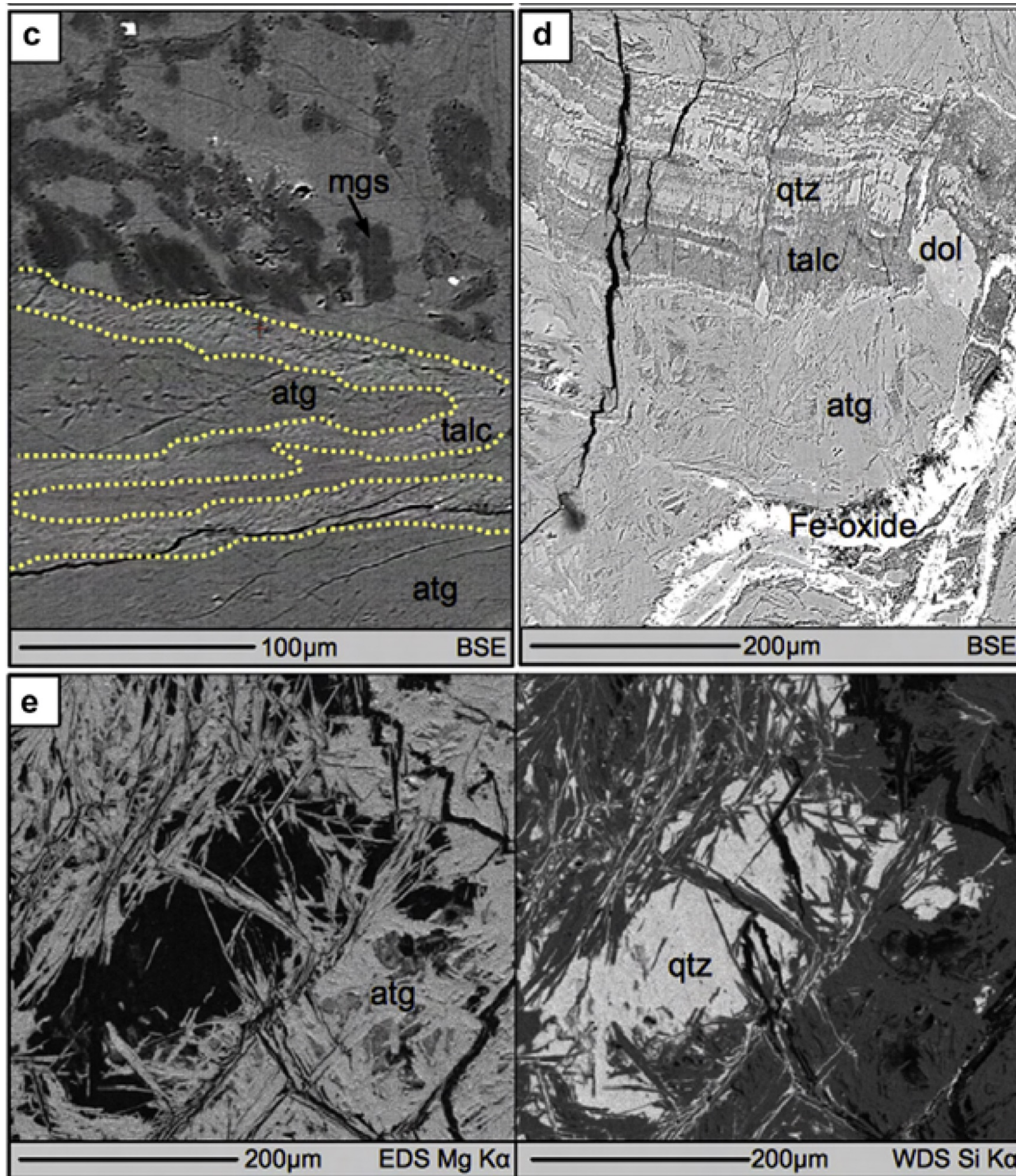


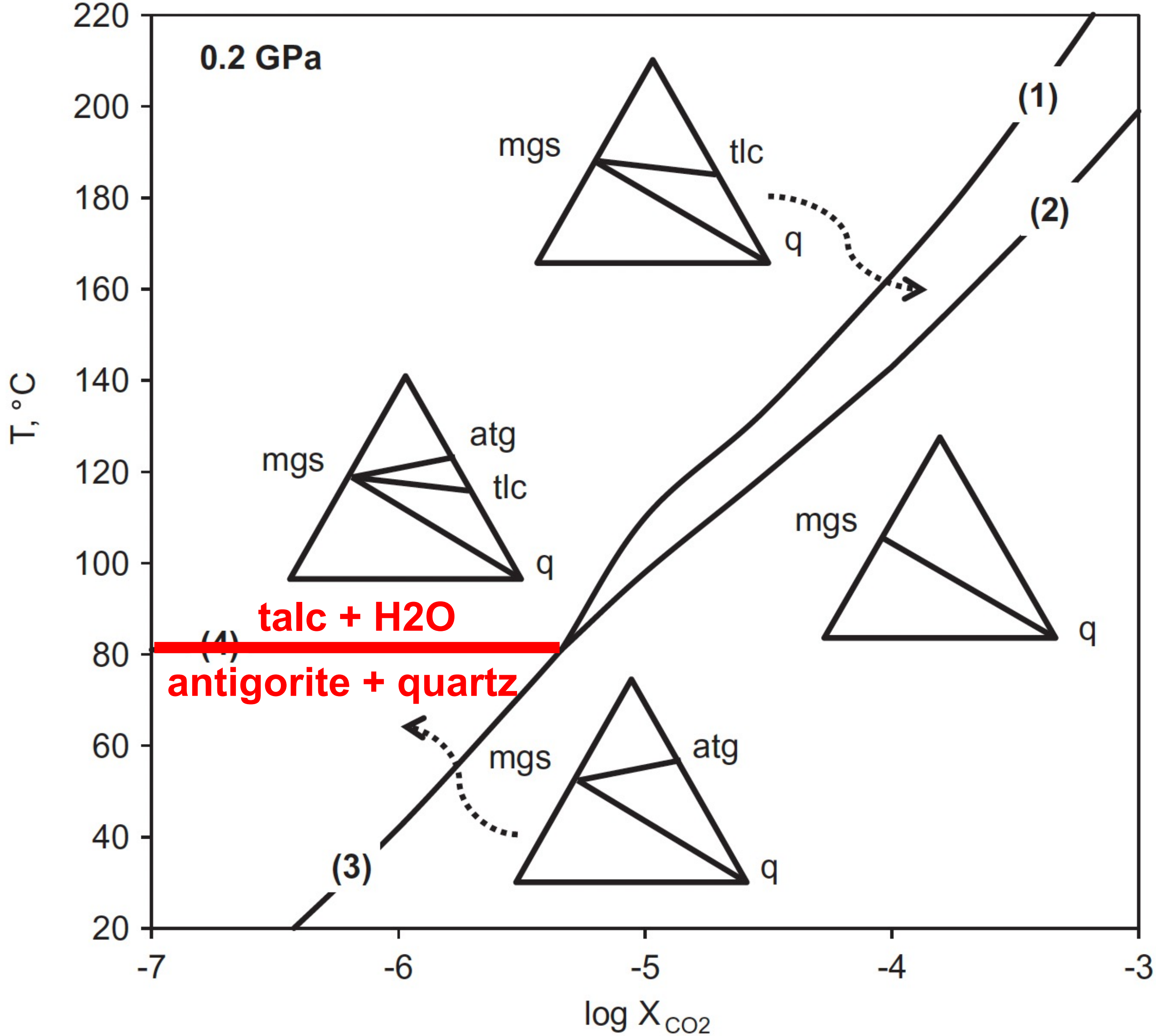
Fig. 6 *T–X* diagram of the phase relations between pure (activity = 1) Mg-end-member magnesite (mgs), chrysotile (chr), talc (ta), and quartz (q) at 5 bar

Falk & Kelemen 2015

antigorite + quartz at < 150°C



E.S. Falk, P.B. Kelemen / Geochimica et Cosmochimica Acta 160 (2015) 70–90



Streit Falk & Kelemen 2015

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Greenalite	$\mathbf{Fe^{2+}_3}(Si_2O_5)(OH)_4$	
Hisingerite	$\mathbf{Fe^{3+}_2}\square(Si_2O_5)(OH)_4$	
Cronstedtite	$\mathbf{Fe^{2+}_2Fe^{3+}}(\mathbf{Fe^{3+}}SiO_5)(OH)_4$	
Mg-cronstedtite	$Mg_2\mathbf{Fe^{3+}}(\mathbf{Fe^{3+}}SiO_5)(OH)_4$	

tschermak’s substitition, $Mg_{-1}Si_{-1}AlAl$

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Cronstedtite	$\mathbf{Fe^{2+}_2Fe^{3+}}$ $(\mathbf{Fe^{3+}}SiO_5)(OH)_4$	
Mg-cronstedtite	$Mg_2\mathbf{Fe^{3+}}$ $(\mathbf{Fe^{3+}}SiO_5)(OH)_4$	

tschermak's substitition, $Mg_{-1}Si_{-1}AlAl$

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]

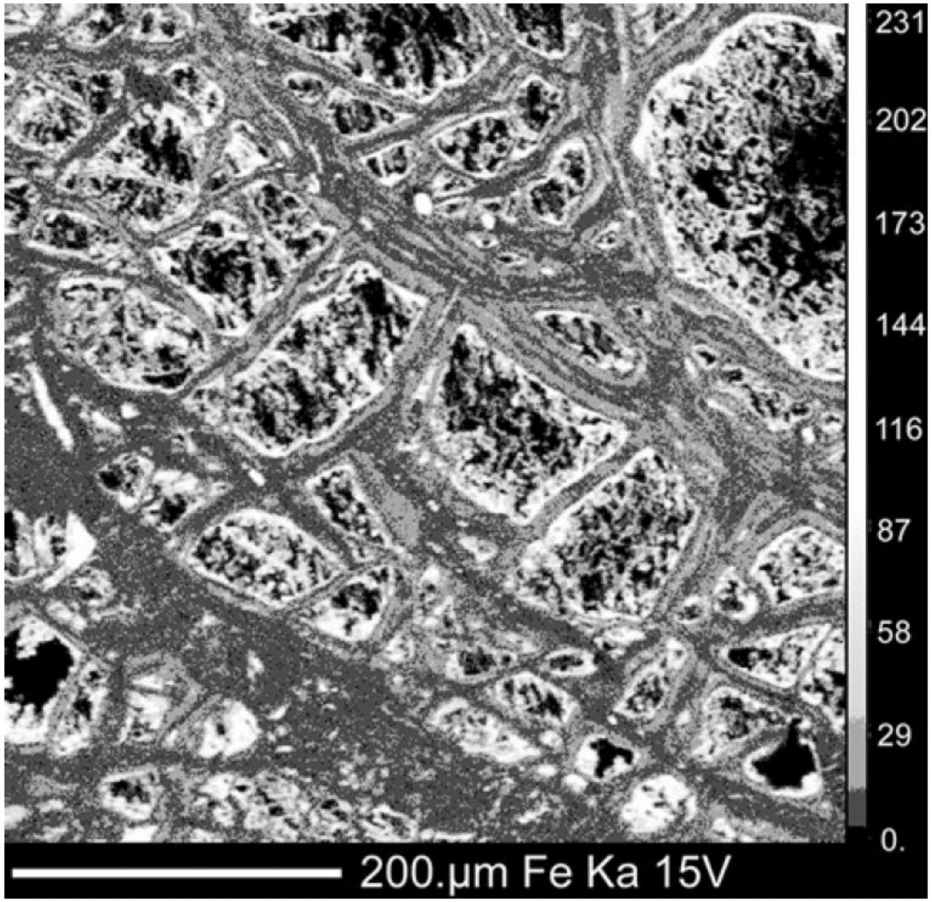
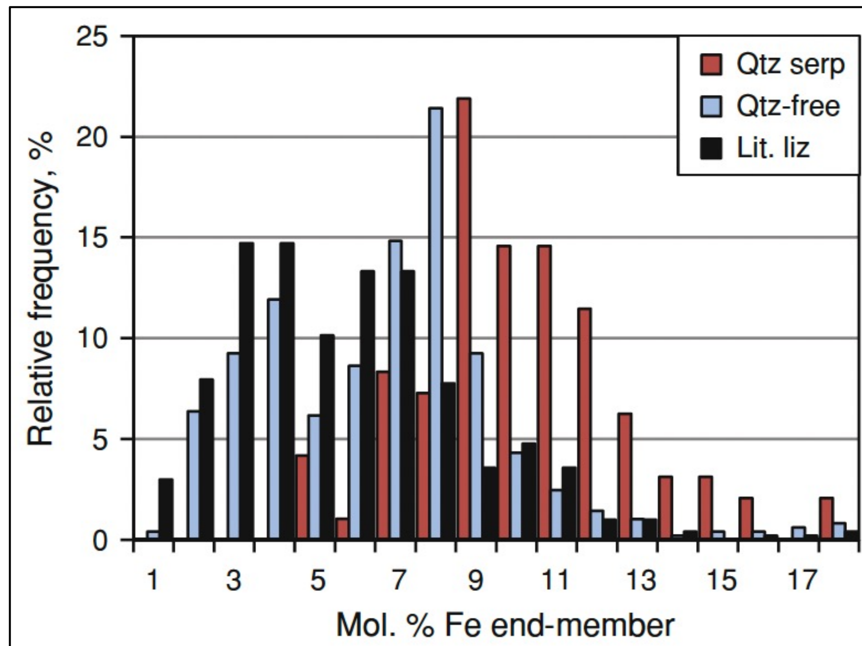
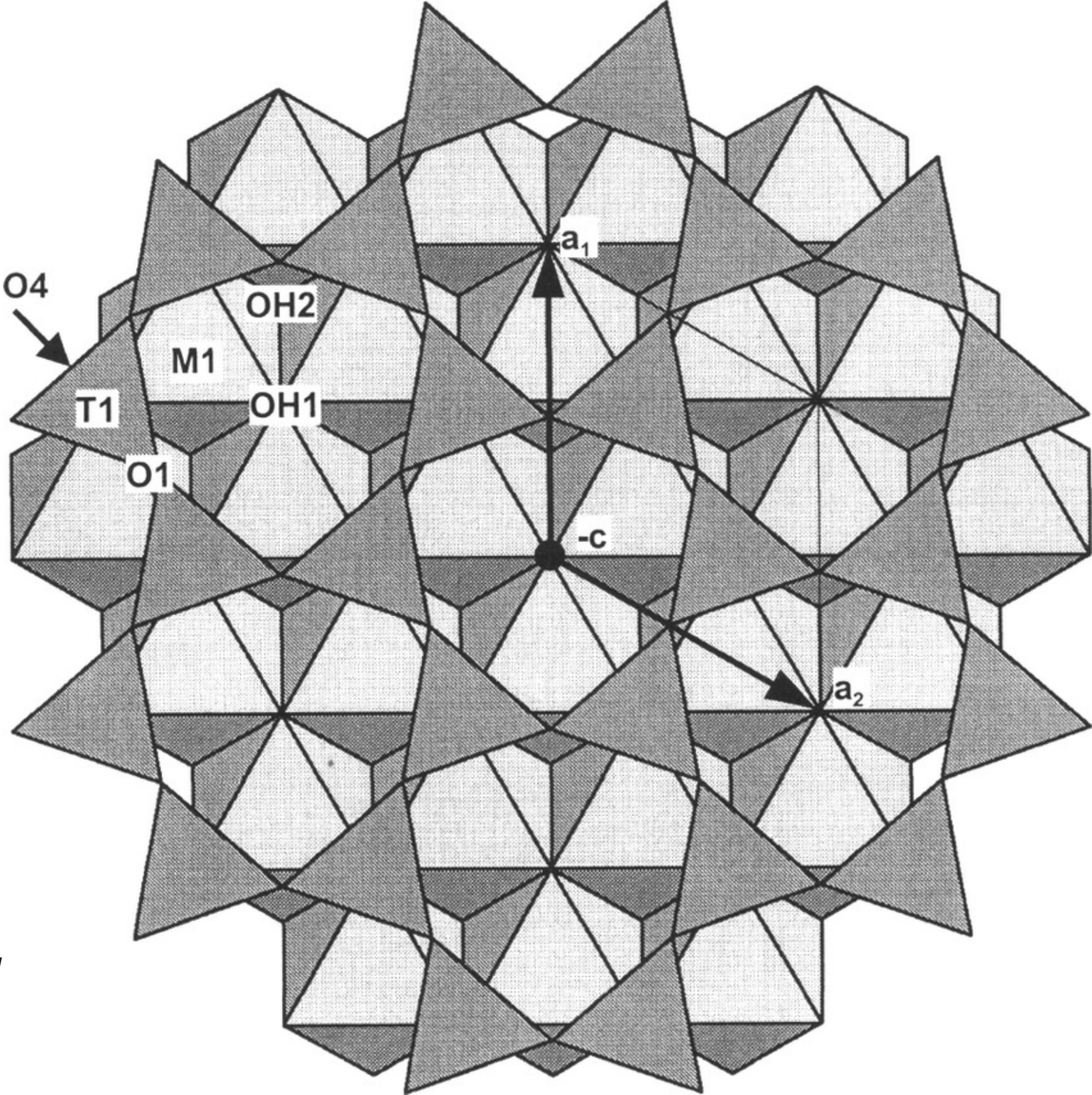


Fig. 4 WDS element map of Fe content in coexisting serpentine + quartz in sample OM08-206D. Strands of Fe-rich material (very *light gray* and *white*) are distributed within the quartz regions (*black*), concentrated at the edge of the quartz "mesh centers."

Streit et al. 2012

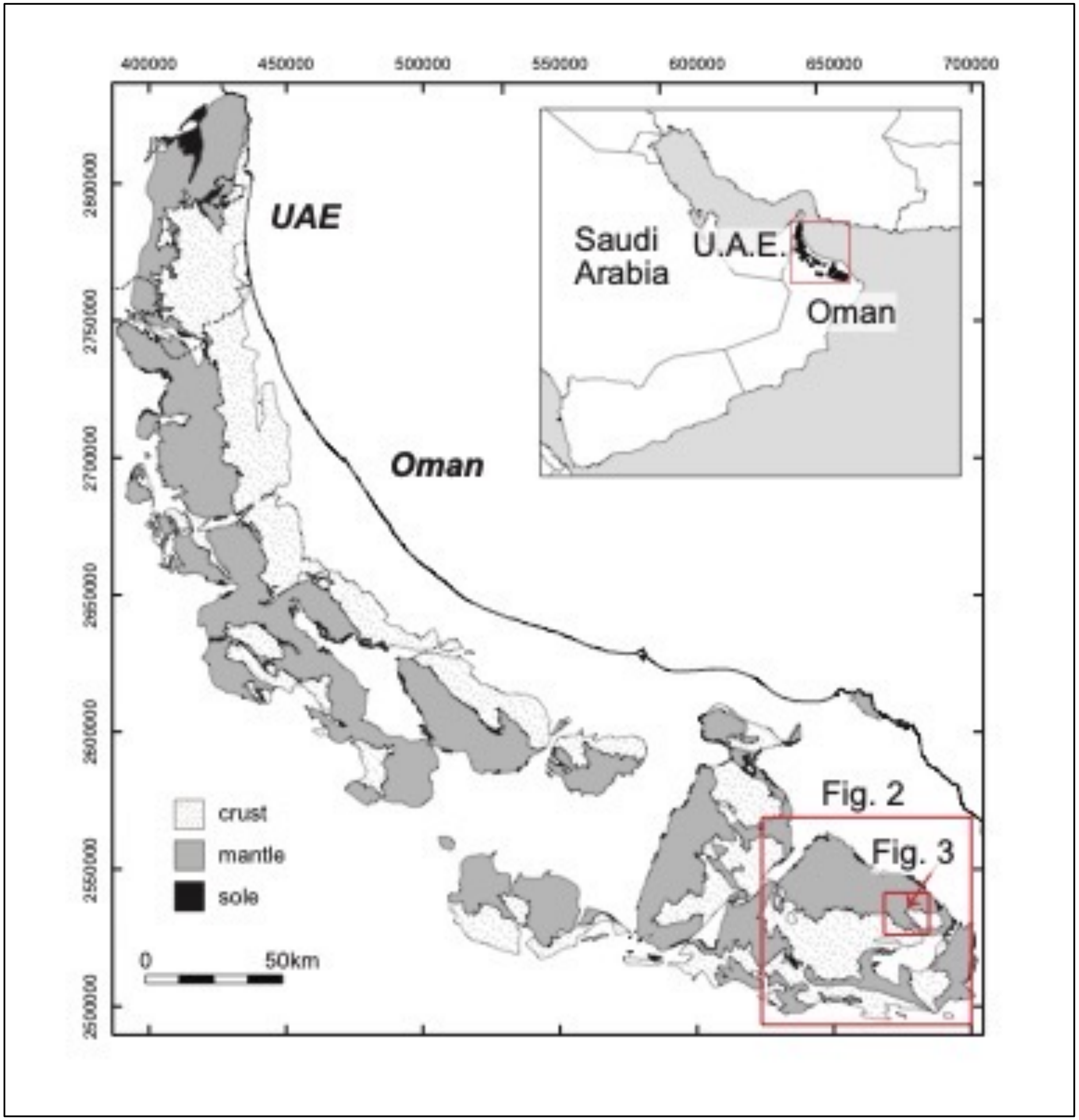
lizardite + quartz
formed during weathering
in ^{14}C-bearing (young)
carbonate alteration assemblages

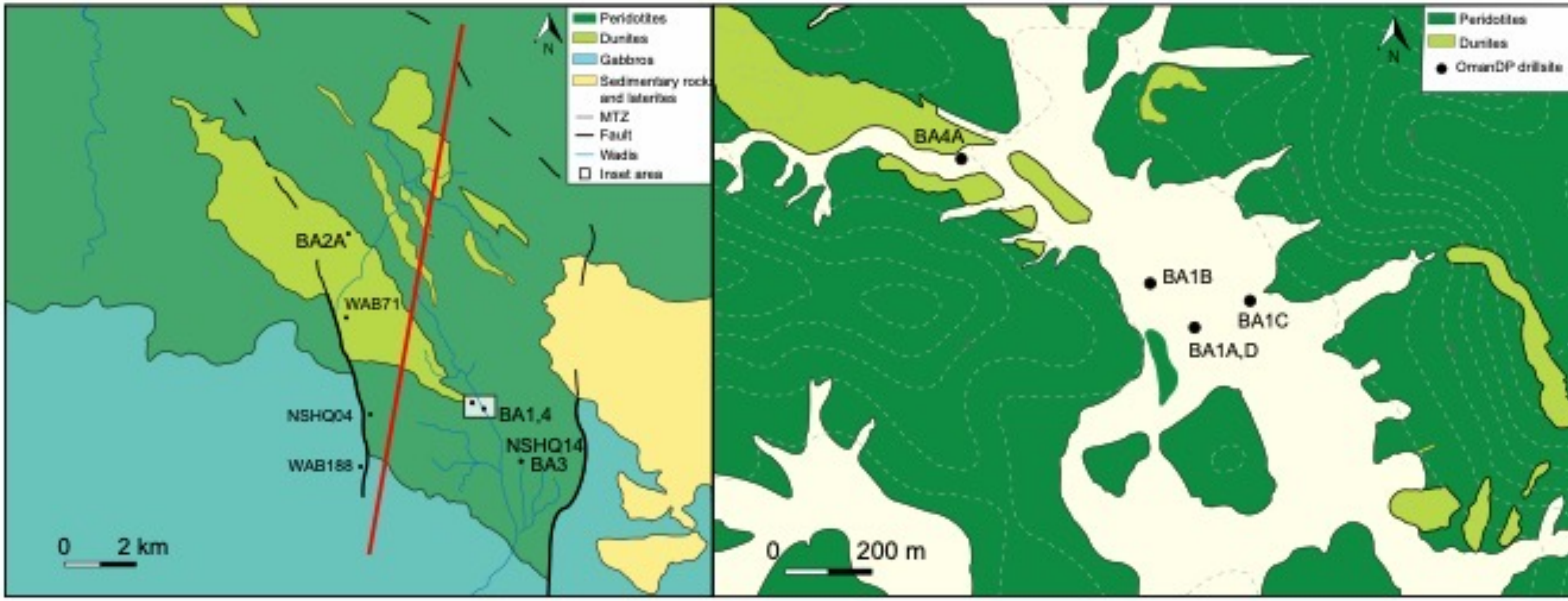


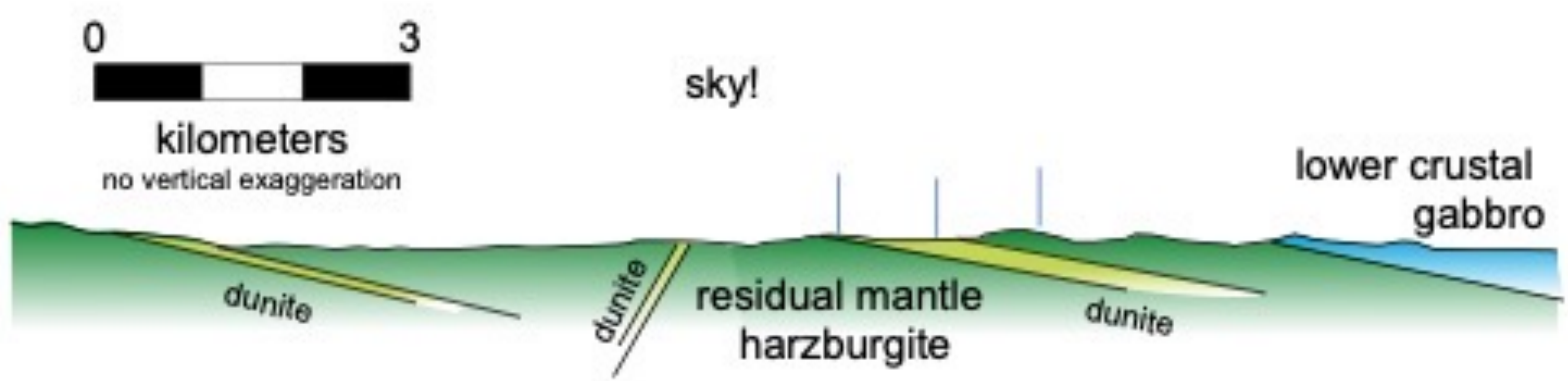


Hybler, J., Petříček, V., Ďurovič, S. and Smrčok, Ĺ., 2000. Refinement of the crystal structure of cronstedtite-1T. *Clays and Clay Minerals*, *48*(3), pp.331-338.

https://www.mindat.org/min-1158.html

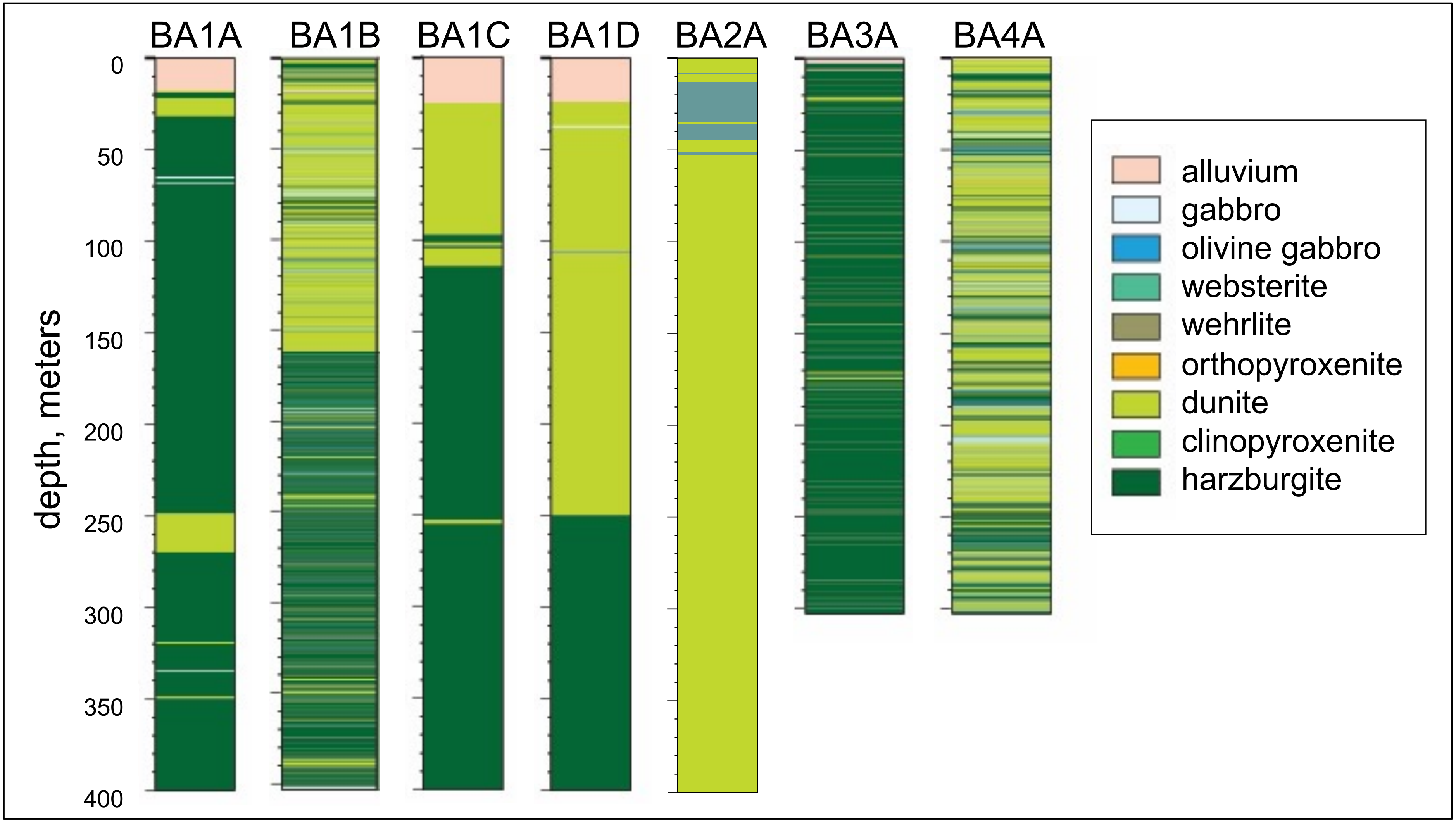

400000
450000
500000
550000
600000
650000
700000
2800000
2750000
2700000
2650000
2600000
2550000
2500000
UAE
Oman
Saudi Arabia
U.A.E.
Oman
Fig. 2
Fig. 3
crust
mantle
sole
0
50km



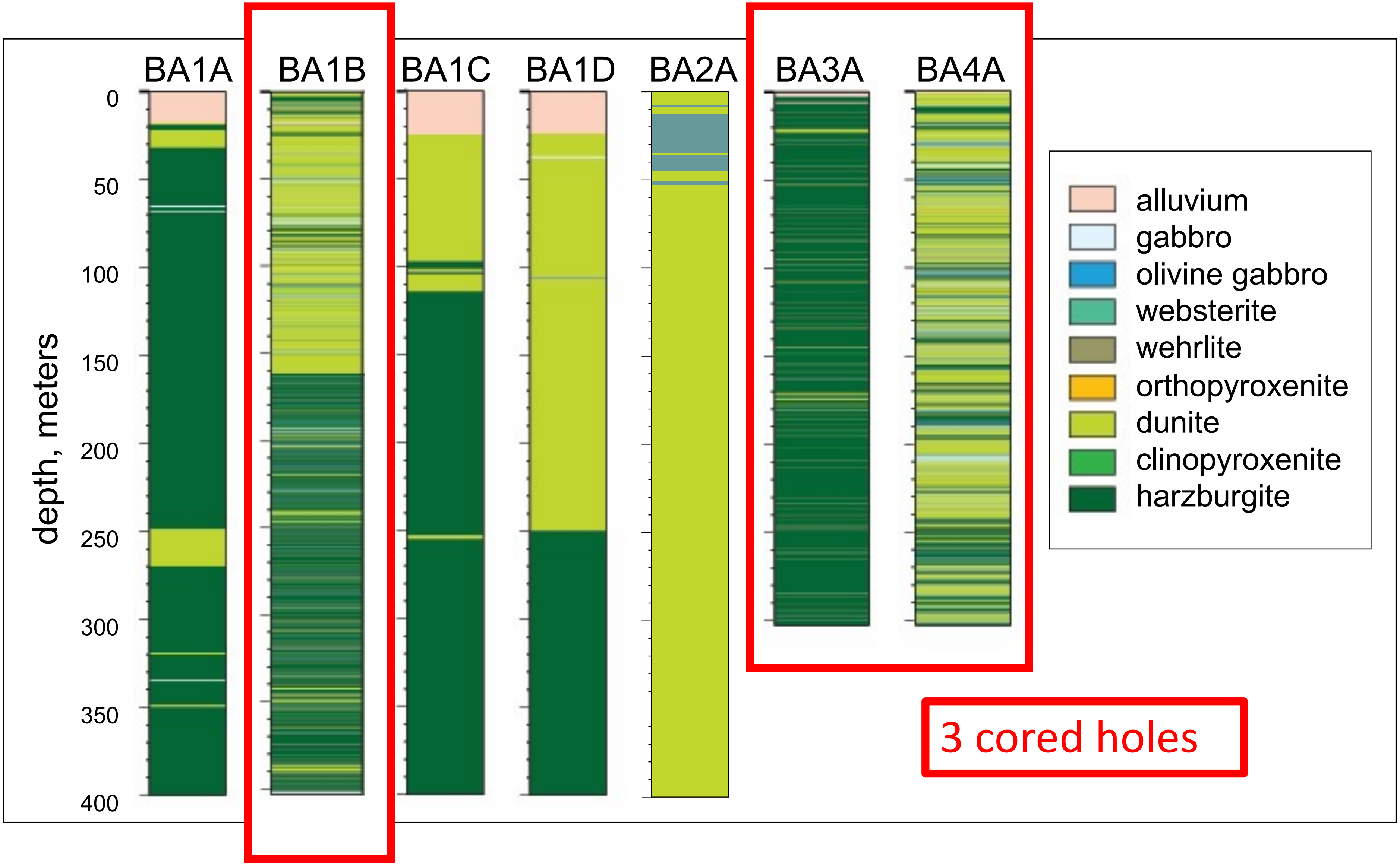


peridotite approx 3 km thick
overlying allocthanous Hawasina nappes
overlying autocthanous Mesozoic to Proterozoic Arabian continental margin

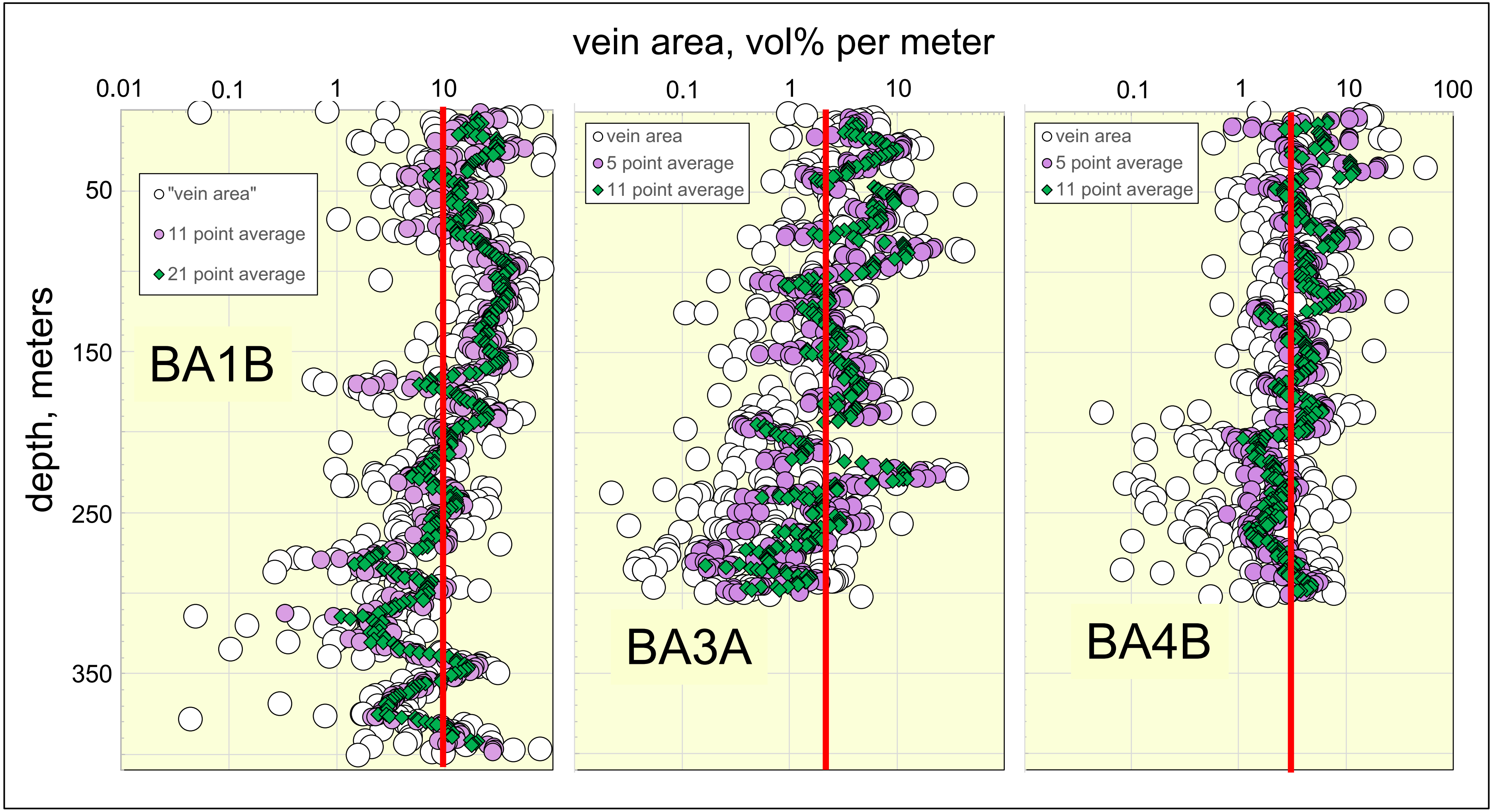
Kelemen et al J Geophys Res 2021



Kelemen et al J Geophys Res 2021



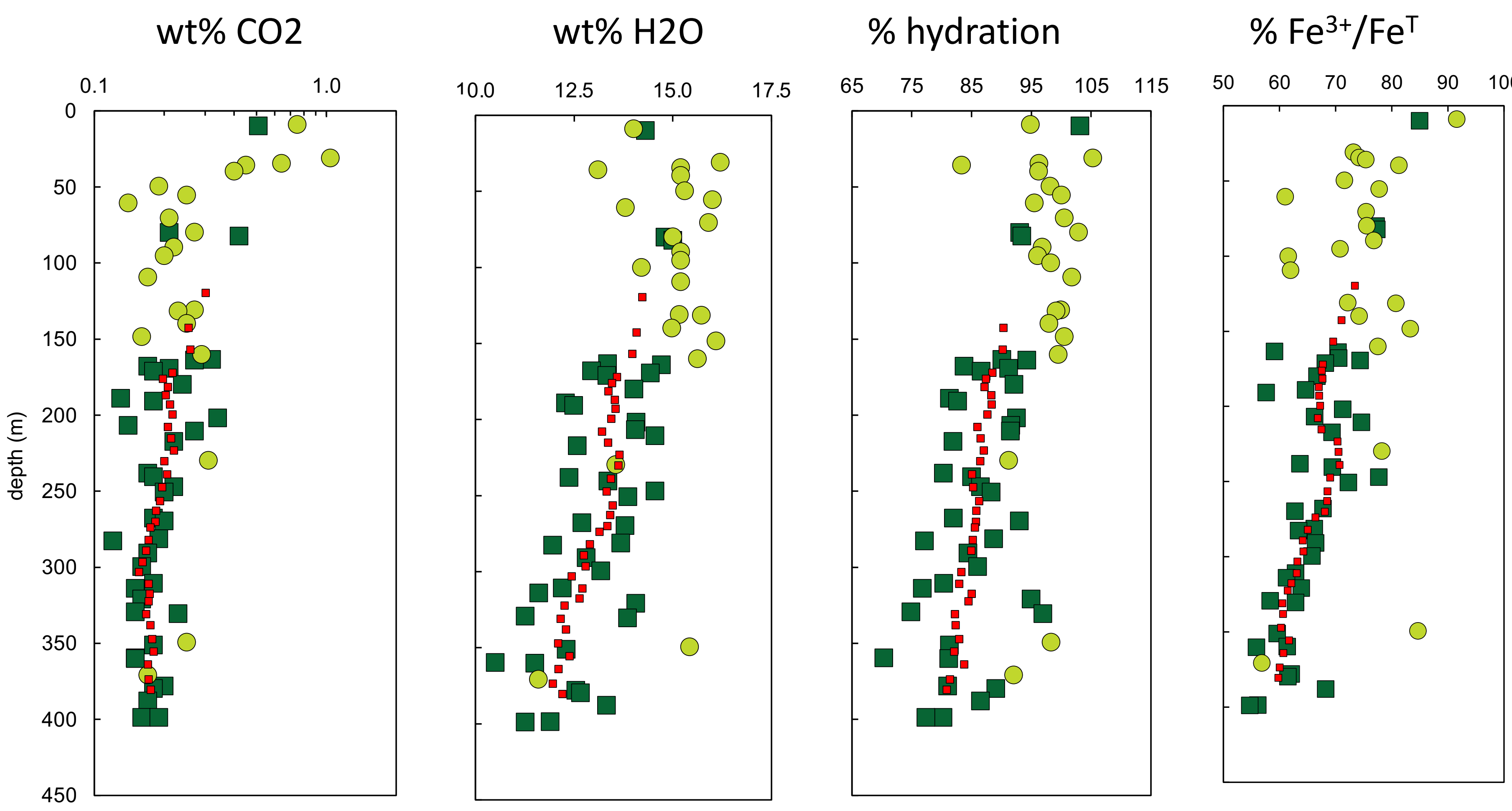
working half of core is stored at AMNH
available for sampling



volume proportion of veins decreases with depth

1 decreasing alteration with depth

Kelemen et al J Geophys Res 2021

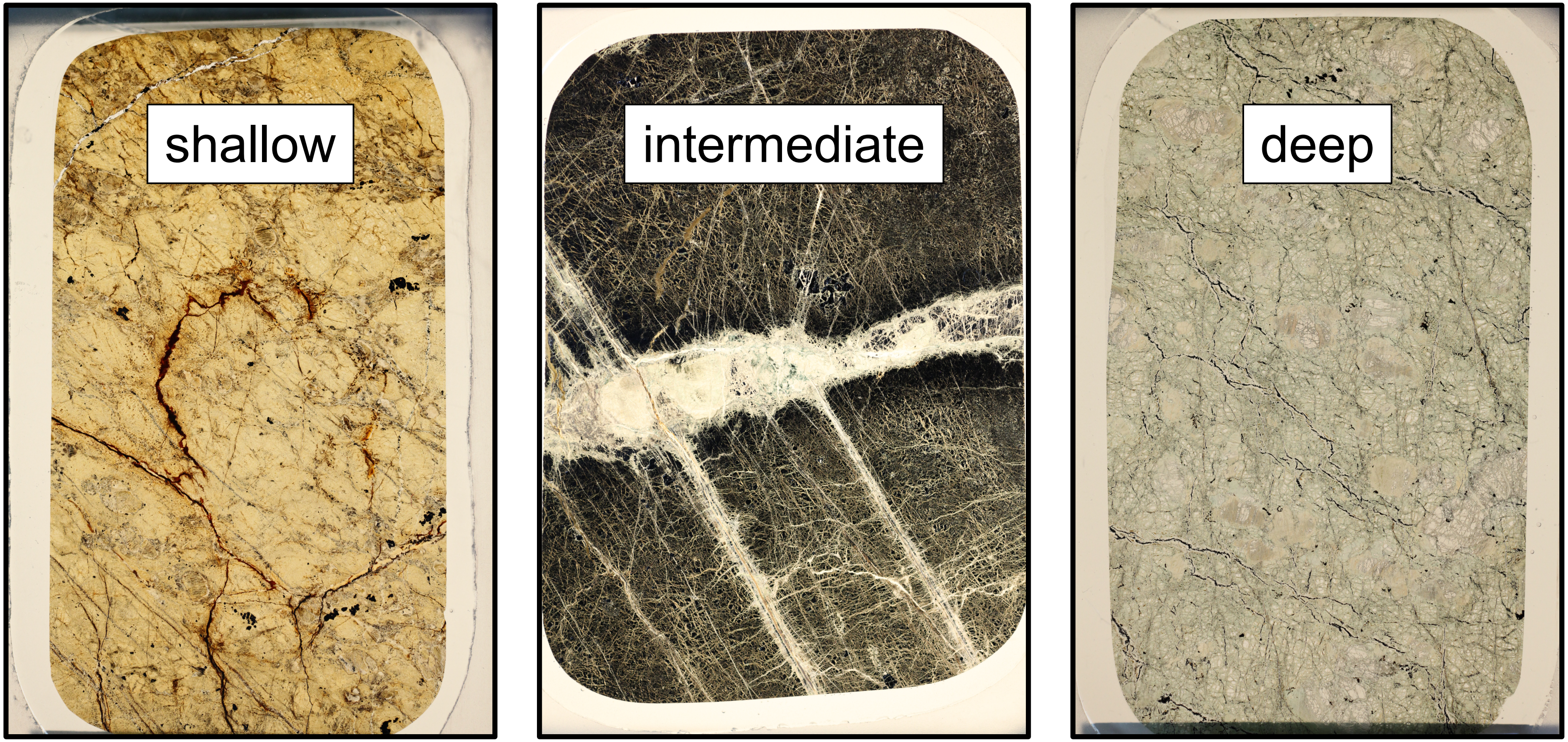


Hole BA1B

1 decreasing alteration with depth

Kelemen et al J Geophys Res 2021

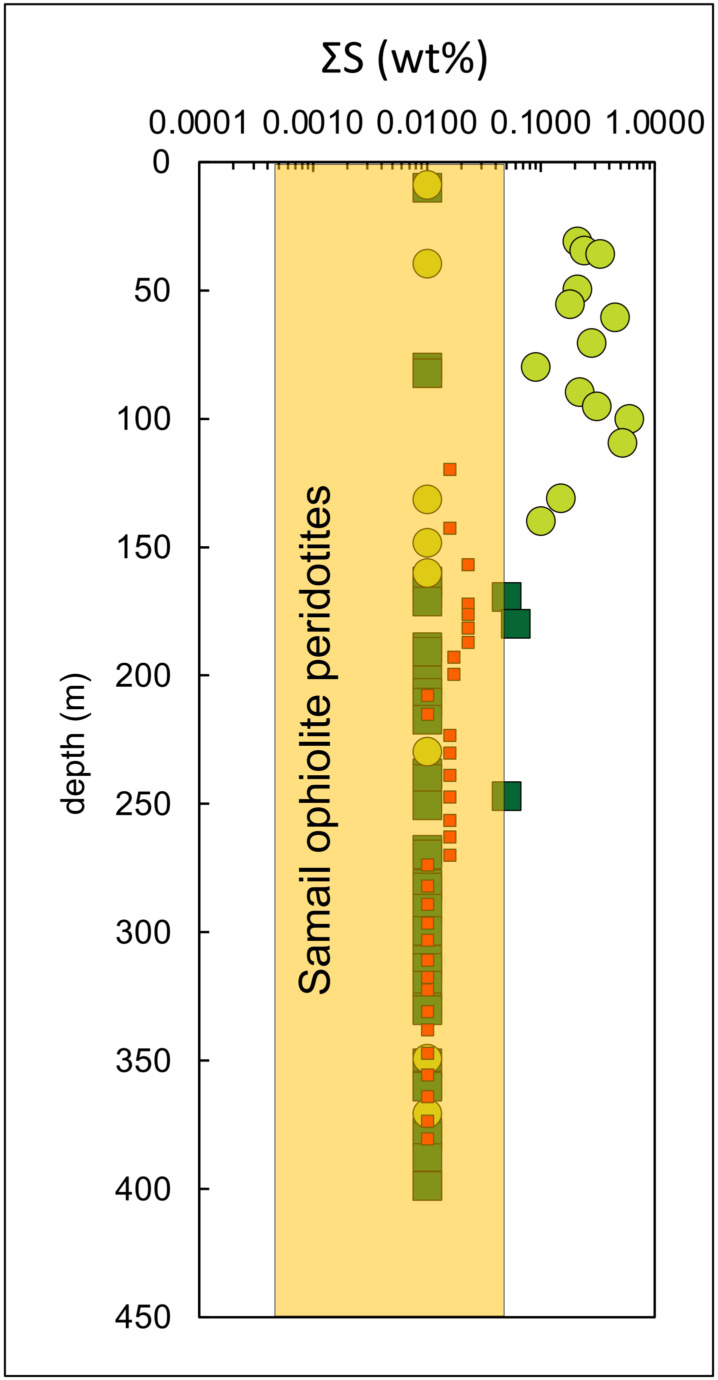
Hole BA1B



full thin section photos, PPL

2 supergene enrichment

Kelemen et al J Geophys Res 2021



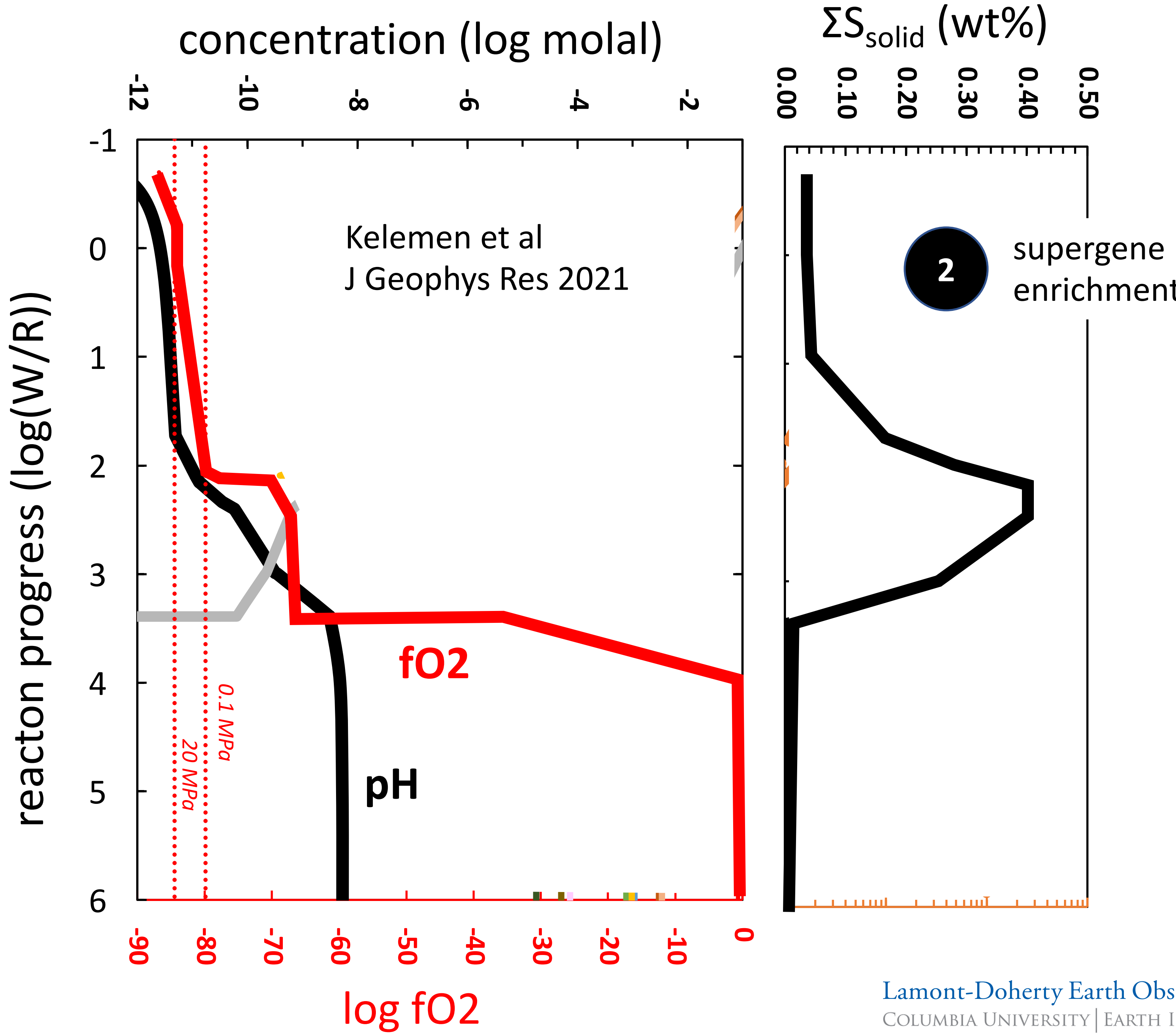
2 supergene enrichment

sulfur enrichment
from 30 to 150 m

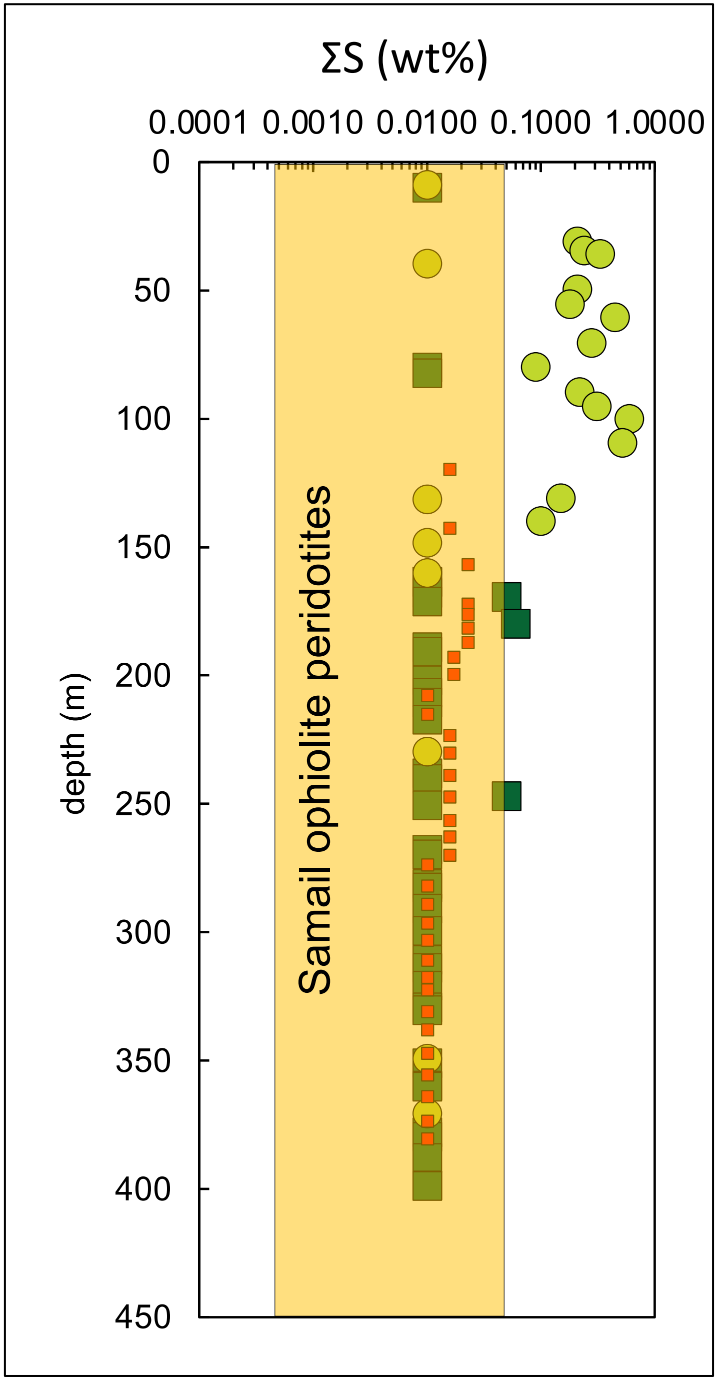
Hole BA1B

Kelemen et al J Geophys Res 2021

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute



concentration (log molal)
-12
-10
-8
-6
-4
-2
ΣS solid (wt%)
0.00
0.10
0.20
0.30
0.40
0.50
-1
0
1
2
3
4
5
6
reacton progress (log(W/R))
Kelemen et al
J Geophys Res 2021
2
supergene
enrichment
fO2
pH
0.1 MPa
20 MPa
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
log fO2

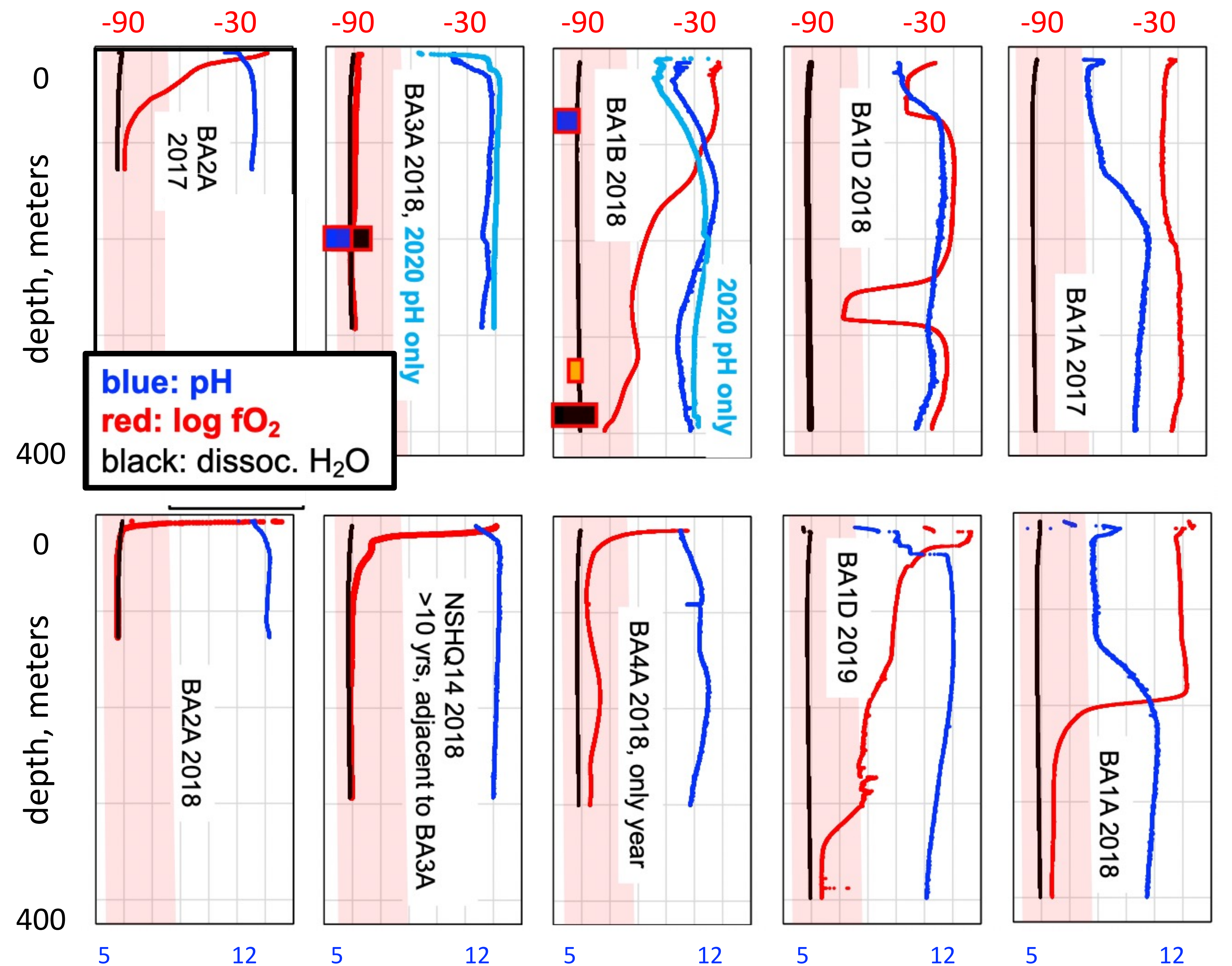


2 supergene enrichment

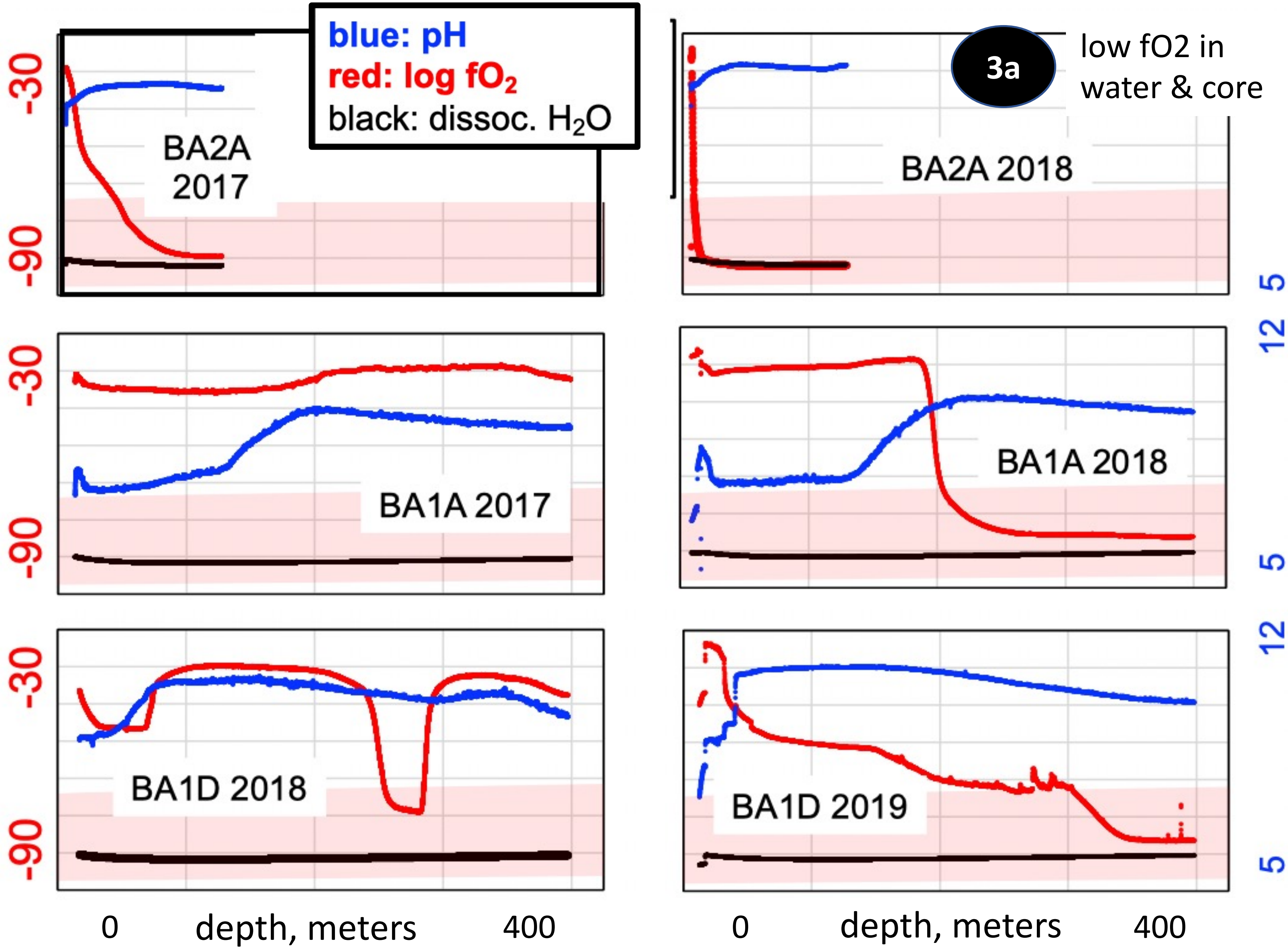
sulfur enrichment
from 30 to 150 m
cannot be mass balanced
by depletion in overlying
serpentinites

some derived from
serpentinites that have
since eroded away

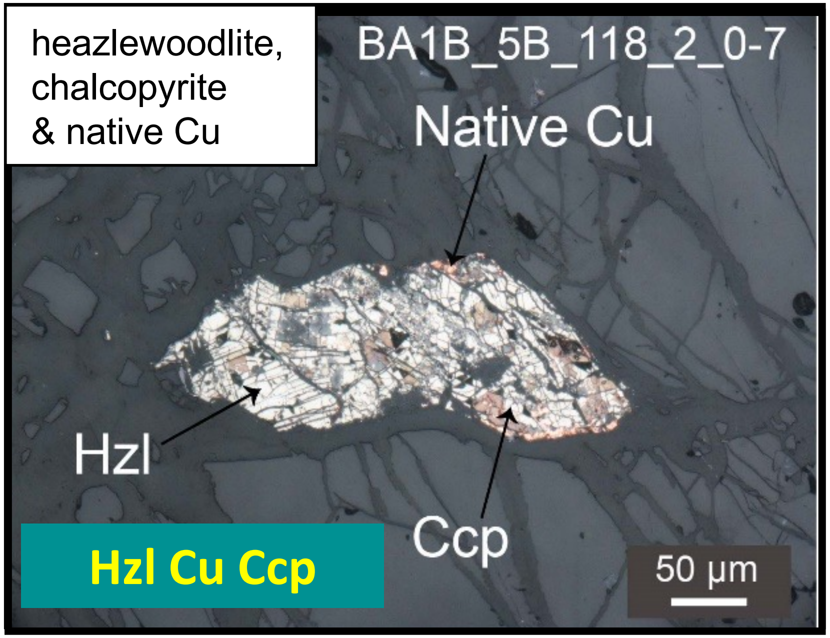
Kelemen et al J Geophys Res 2021

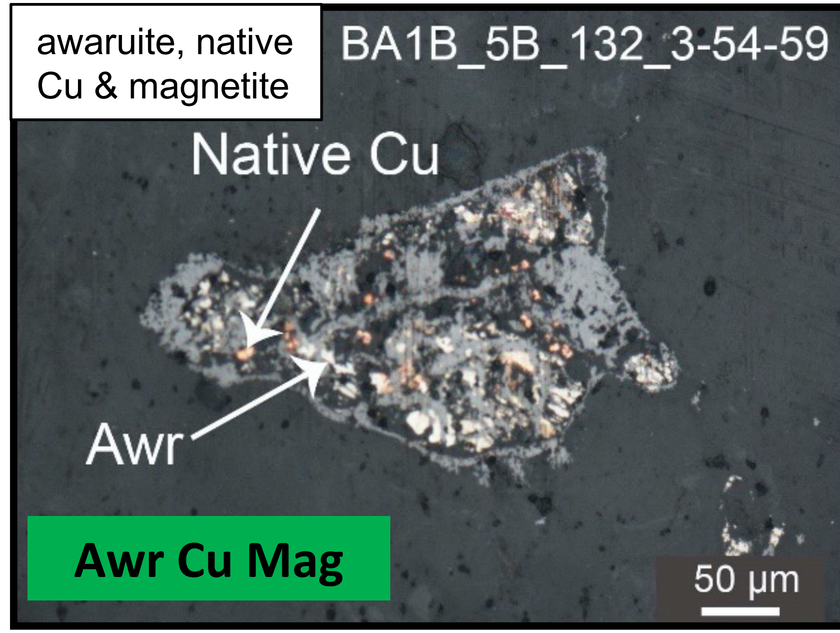


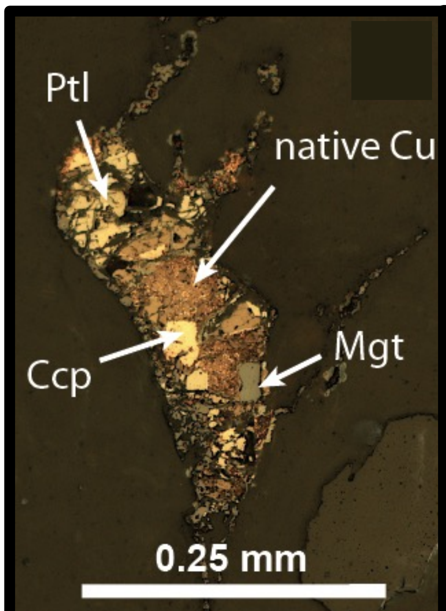
-90
-30
0
400
depth, meters
BA2A 2017
BA3A 2018, 2020 pH only
BA1B 2018
2020 pH only
BA1D 2018
BA1A 2017
blue: pH
red: log fO2
black: dissoc. H2O
BA2A 2018
NSHQ14 2018 >10 yrs, adjacent to BA3A
BA4A 2018, only year
BA1D 2019
BA1A 2018
5
12



Kelemen et al J Geophys Res 2021







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

Mag Cu Pn

3a low fO2 in water & core

very low fO2
sulfide + alloy
assemblages

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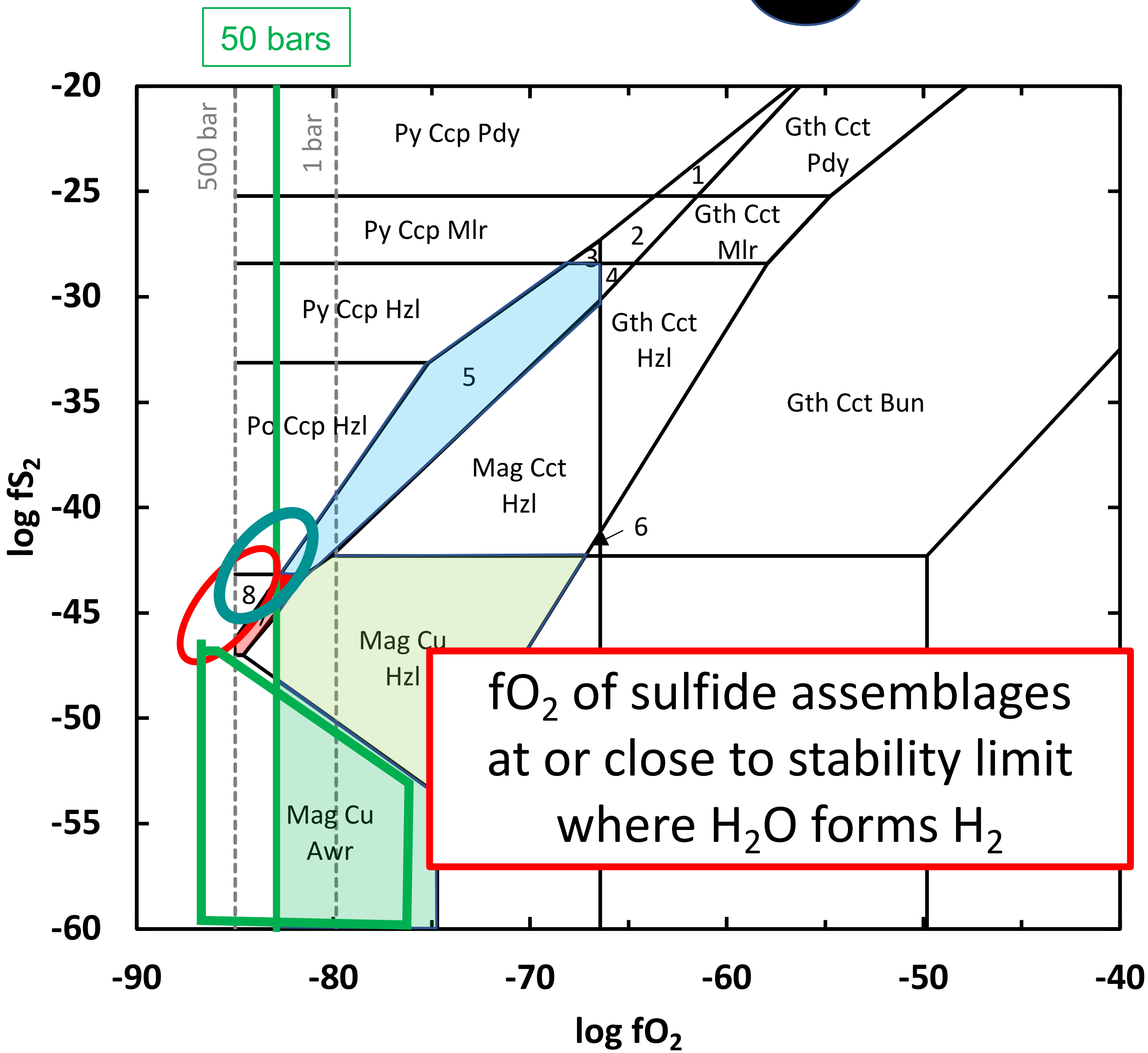
3a low fO2 in water & core



1 – Gth Ccp Pdy
2 – Gth Ccp Mlr
3 – Mag Ccp Mlr
4 – Gth Ccp Hzl
5 – Mag Ccp Hzl
6 – Mag Cct Bun
7 – Mag Cu Pn
8 – Po Cu Pn

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

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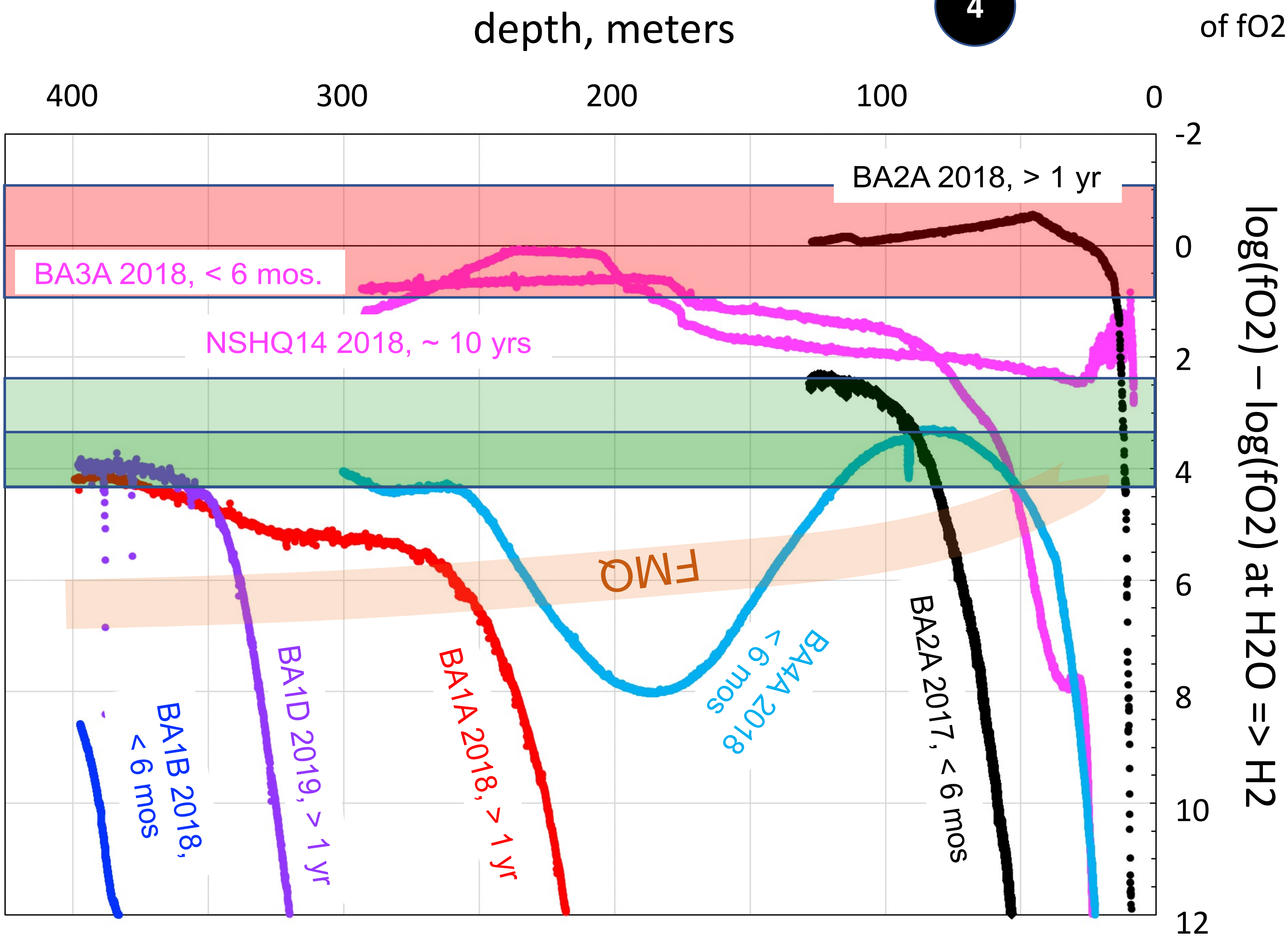

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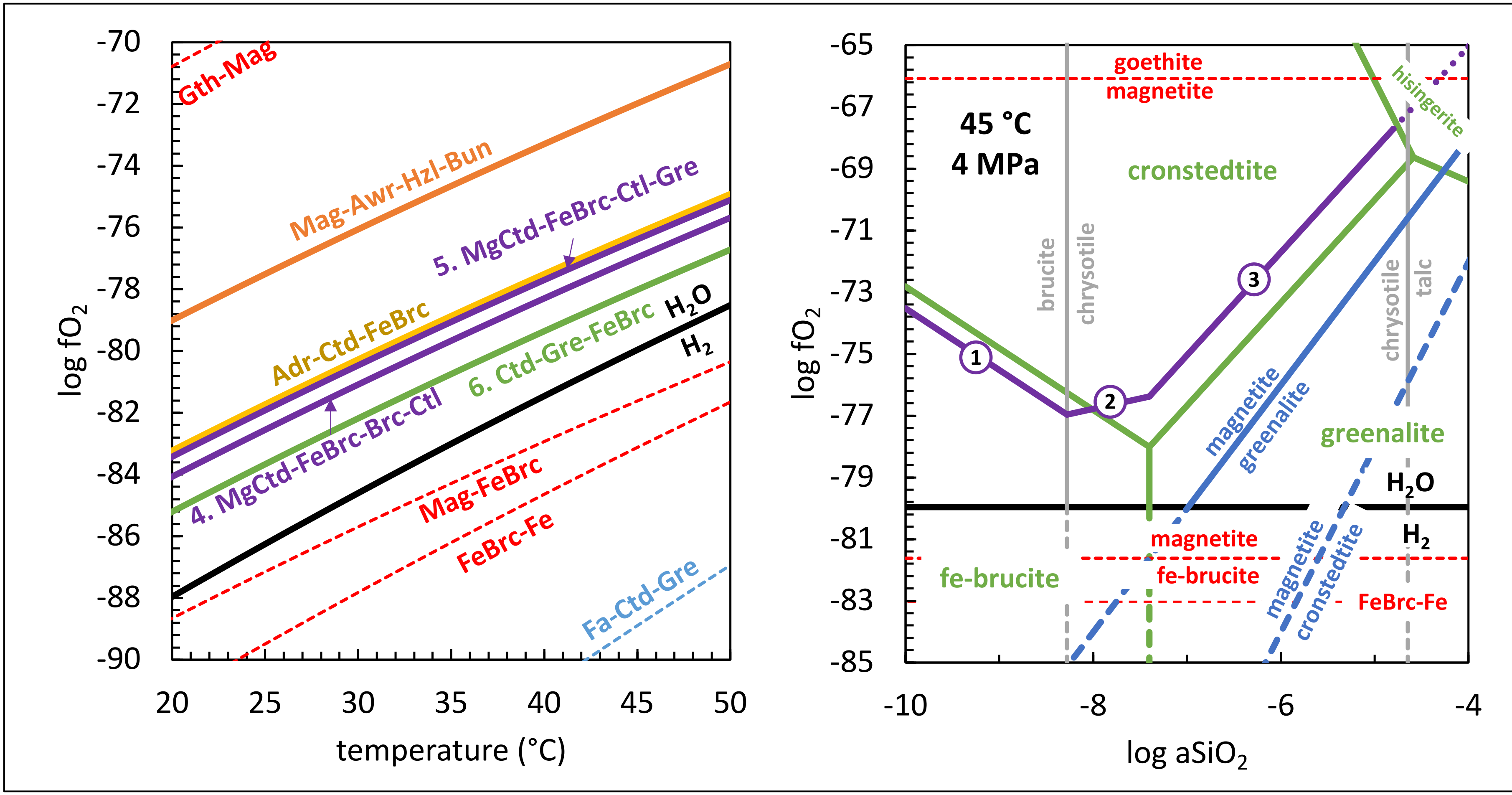

Ctl	chrysotile	Gre	greenalite
MgCtd	Mg-cronst	Ctd	cronstedtite
Brc	brucite	FeBrc	Fe brucite
Adr	andradite	Gth	goethite
Mag	magnetite	Fe	iron
Fa	fayalite	Awr	awaruite

4 mineral controls of fO2

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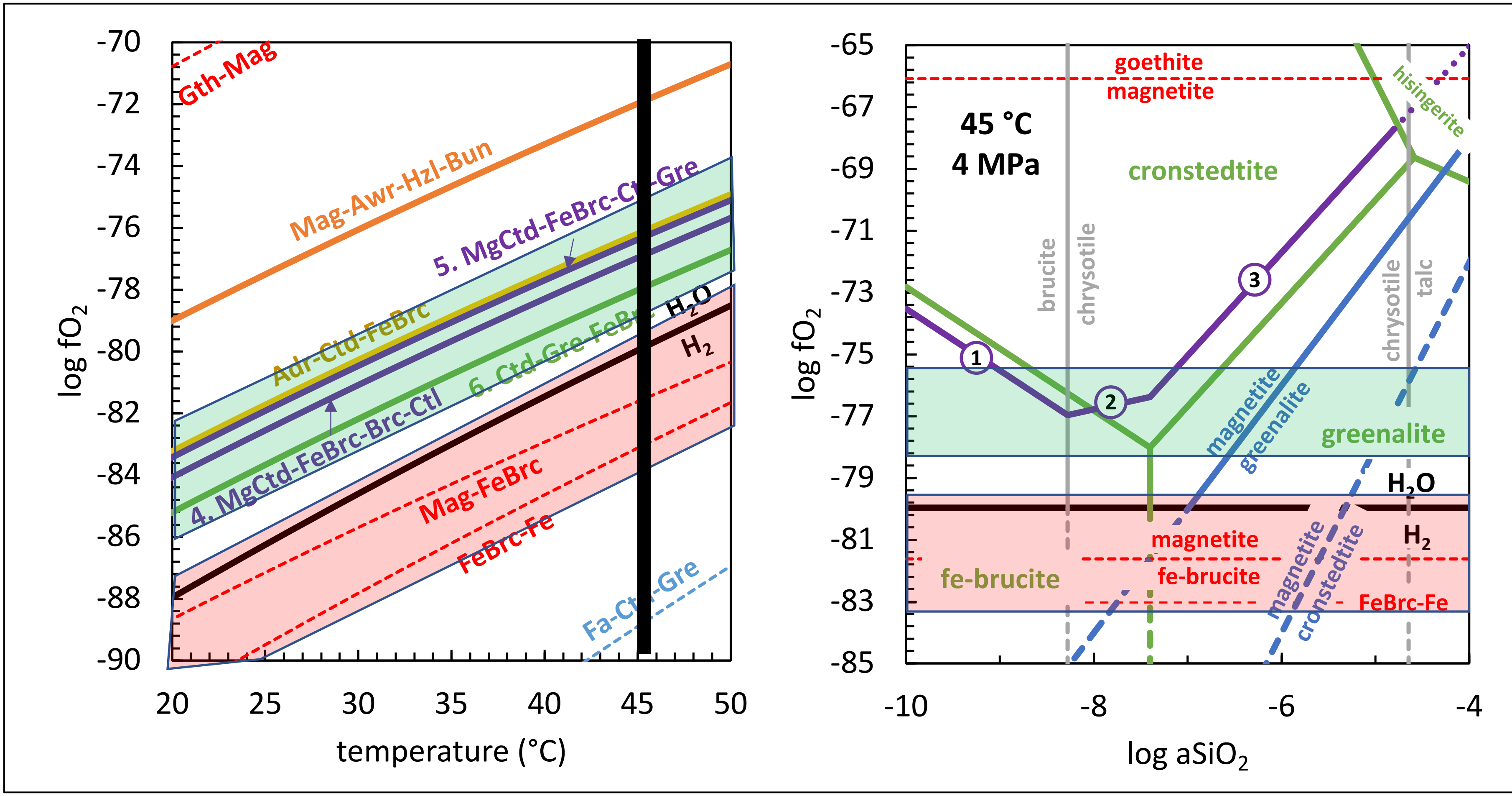

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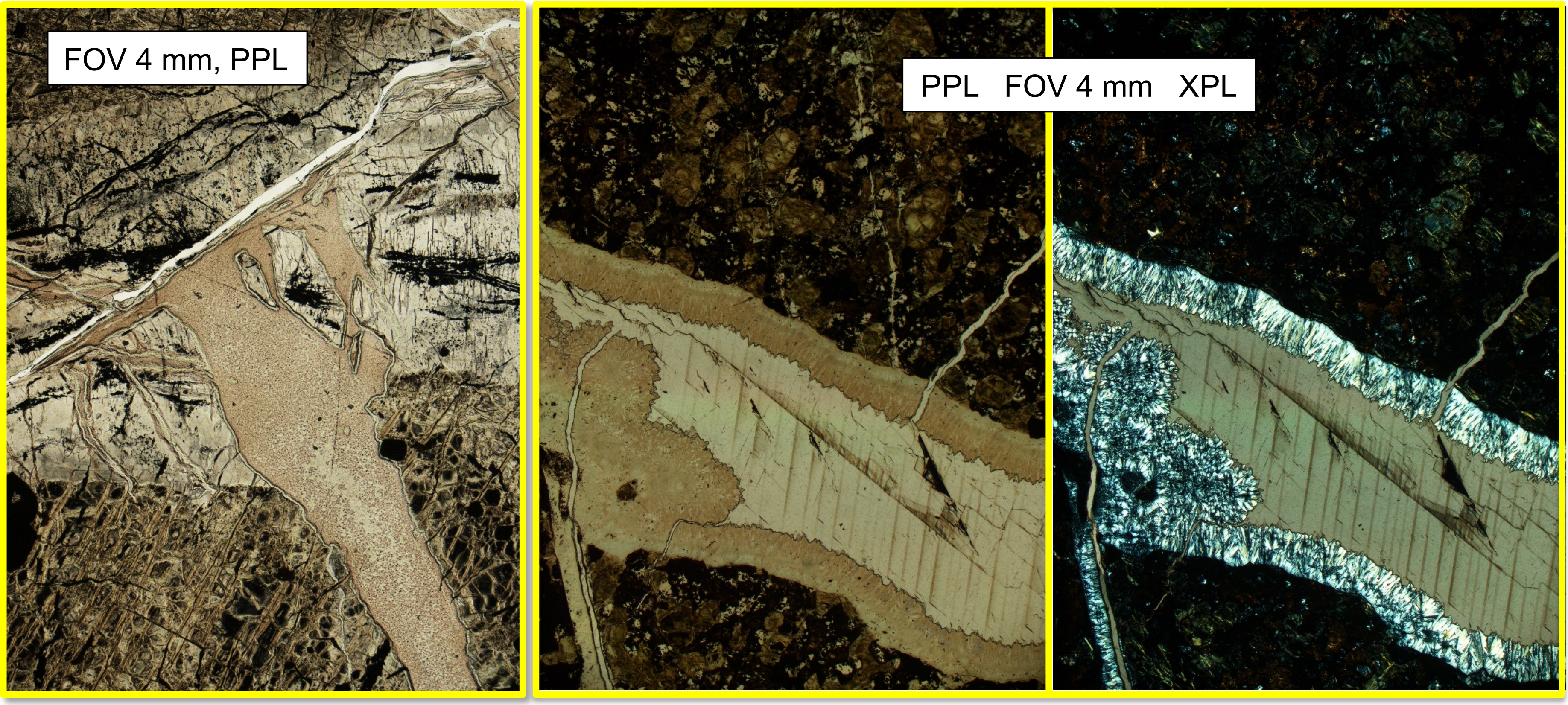
Brc	brucite	FeBrc	Fe brucite
Adr	andradite	Gth	goethite
Mag	magnetite	Fe	iron
Fa	fayalite	Awr	awaruite

4 **mineral controls of fO2**

green: serpentines, brucite, andradite

red: H_2O, magnetite, Fe-brucite, Fe^0



^{14}C "ages" of acid-leached carbonate veins, 1000's of years

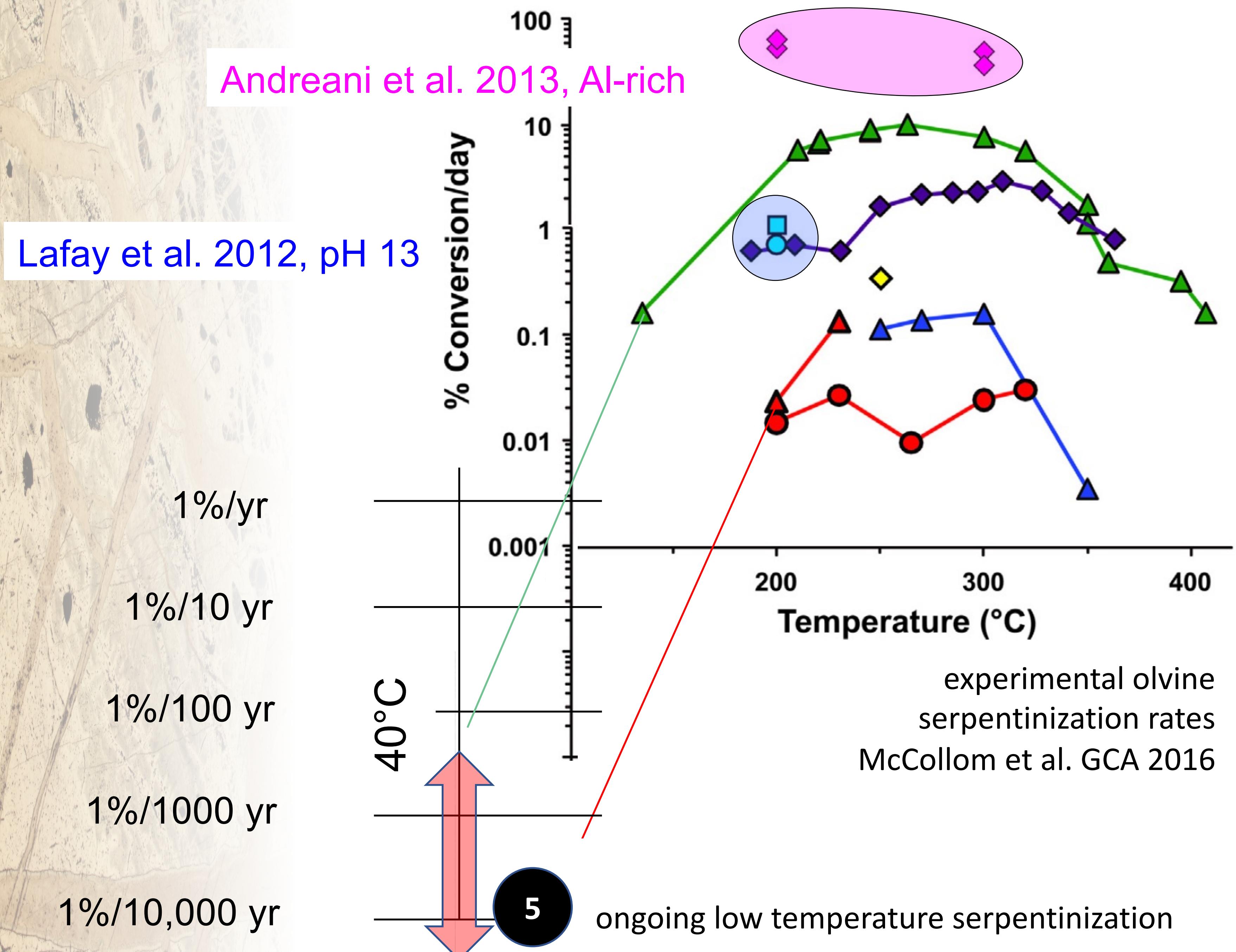
BA3A: 20, 23, 33, 36, 45 (% modern 8, 6, 2, 1, 0.4)

BA4A: 31, 33, 35, 36, 41, 43, 45, 48 + 4>52 (2, 2, 1,1, 0.6, 0.5, 0.4, 0.2, 4x<0.1)

BA1B: 29, 41, 44, 3x45, 50, 52 + 3>46 & 5>52 (3, 0.6, 4x0.4, 2x0.2, 8x<0.2)

5 ongoing low temperature serpentinization

Kelemen et al J Geophys Res 2021



experimental olvine serpentinization rates McCollom et al. GCA 2016

ongoing low temperature serpentinization

Orbital Identification of Carbonate-Bearing Rocks on Mars

Bethany L. Ehlmann,[1] John F. Mustard,[1] Scott L. Murchie,[2] Francois Poulet,[3] Janice L. Bishop,[4] Adrian J. Brown,[4] Wendy M. Calvin,[5] Roger N. Clark,[6] David J. Des Marais,[7] Ralph E. Milliken,[8] Leah H. Roach,[1] Ted L. Roush,[7] Gregg A. Swayze,[6] James J. Wray[9]

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.

Science 2008

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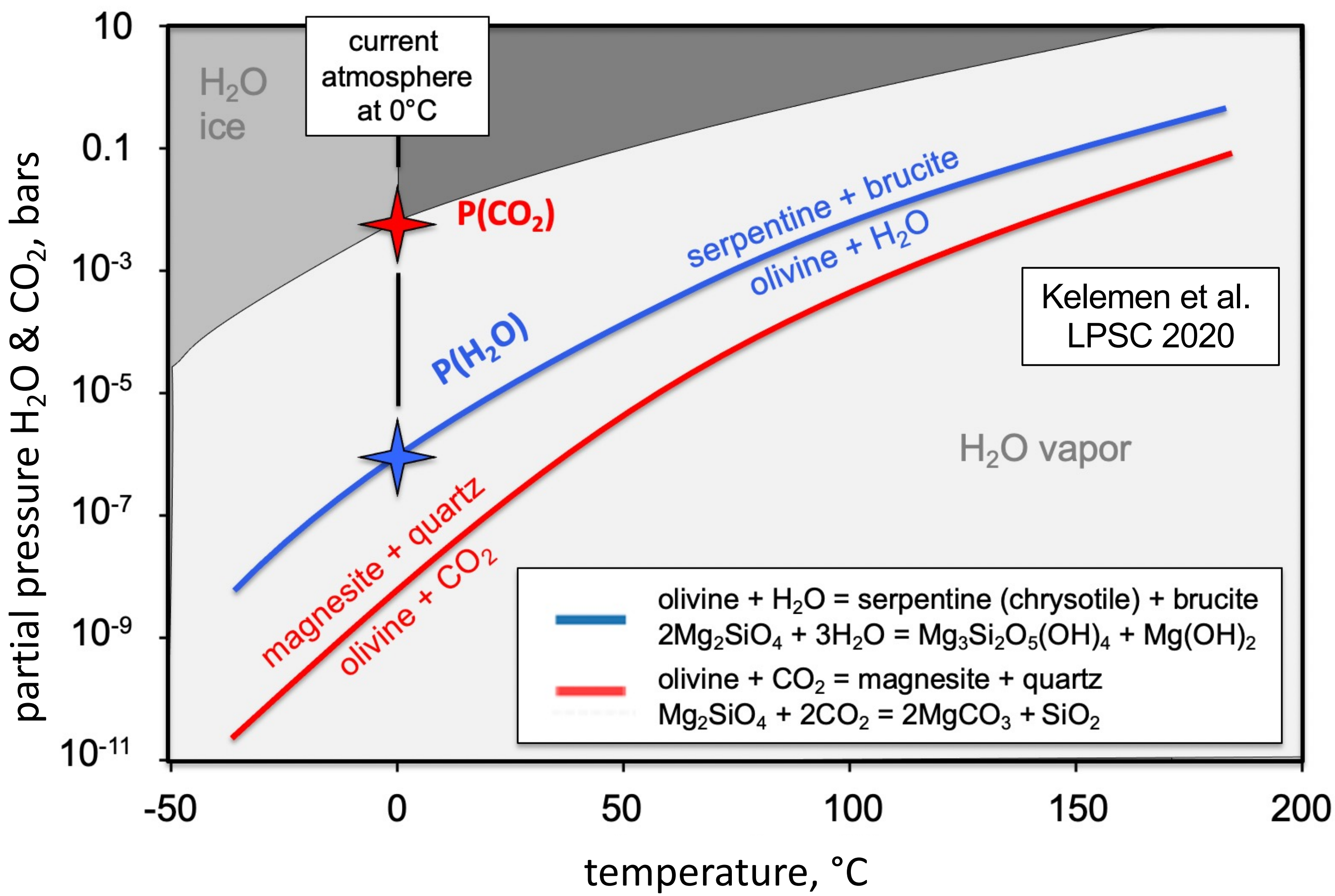
??? via ambient weathering in an atmosphere similar to the present Martian atmosphere over billions of years ???

Science 2008



Fe-free olivine

forsterite Mg_2SiO_4

unstable with respect to magnesite + quartz

marginally stable withrespect to serpentine + brucite

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute

Kelemen et al LPSC 2020

Modern Mars Atmosphere

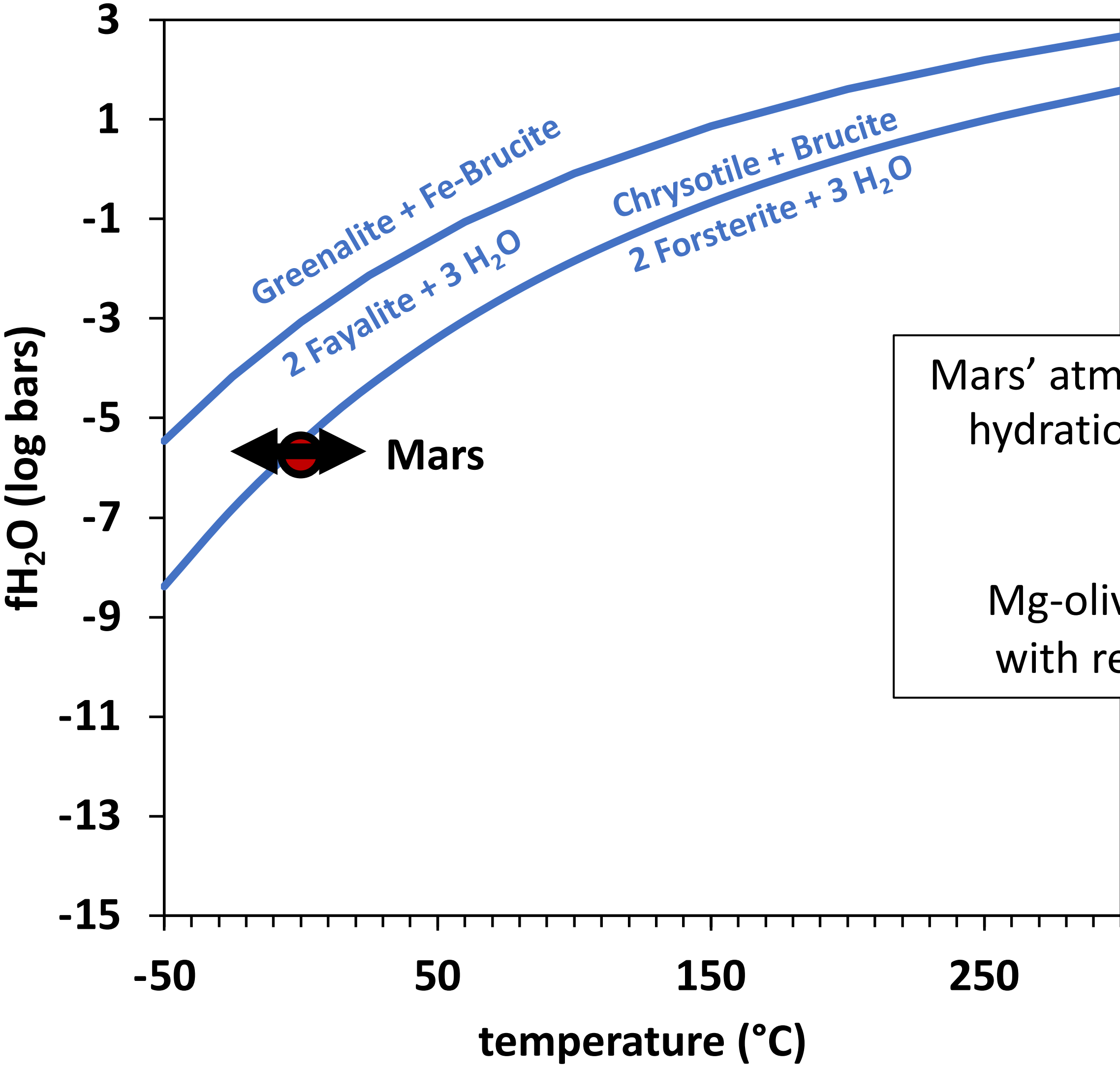
(Gale Crater, Franz et al. 2017)

Gas	vol %	
CO_2	95	→ carbonation
O_2	0.17	→ oxidation
H_2O	0.03	→ hydration
N_2	2.8	
Ar	2	
CO	0.07	

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute

Leong et al GSA & AGU presentations, 2022

OLIVINE HYDRATION

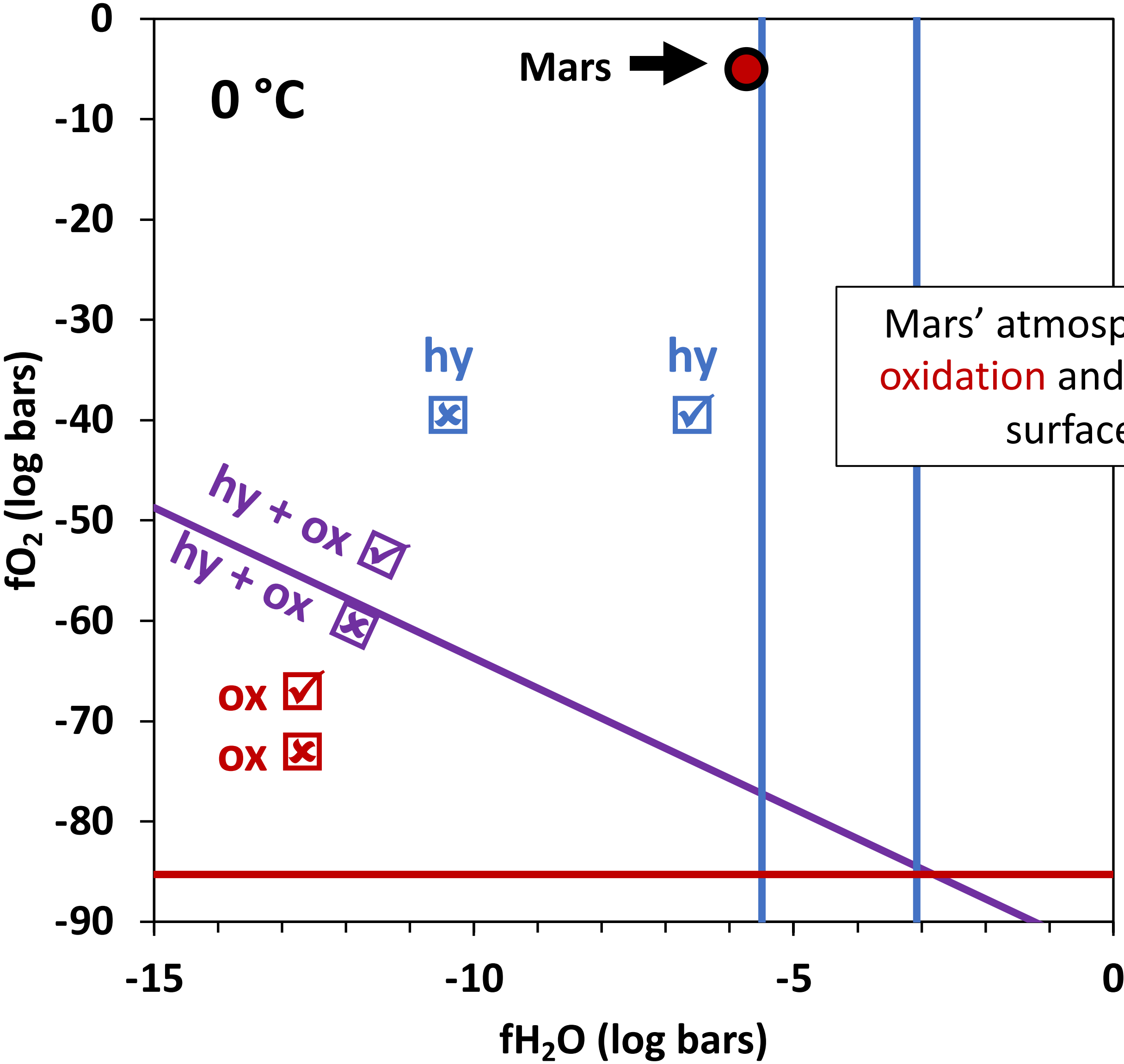


Mars' atmosphere is unfavorable for hydration of surface olivine with appreciable Fe

Mg-olivine is marginally stable with respect to serp + brucite

Leong et al GSA & AGU presentations, 2022

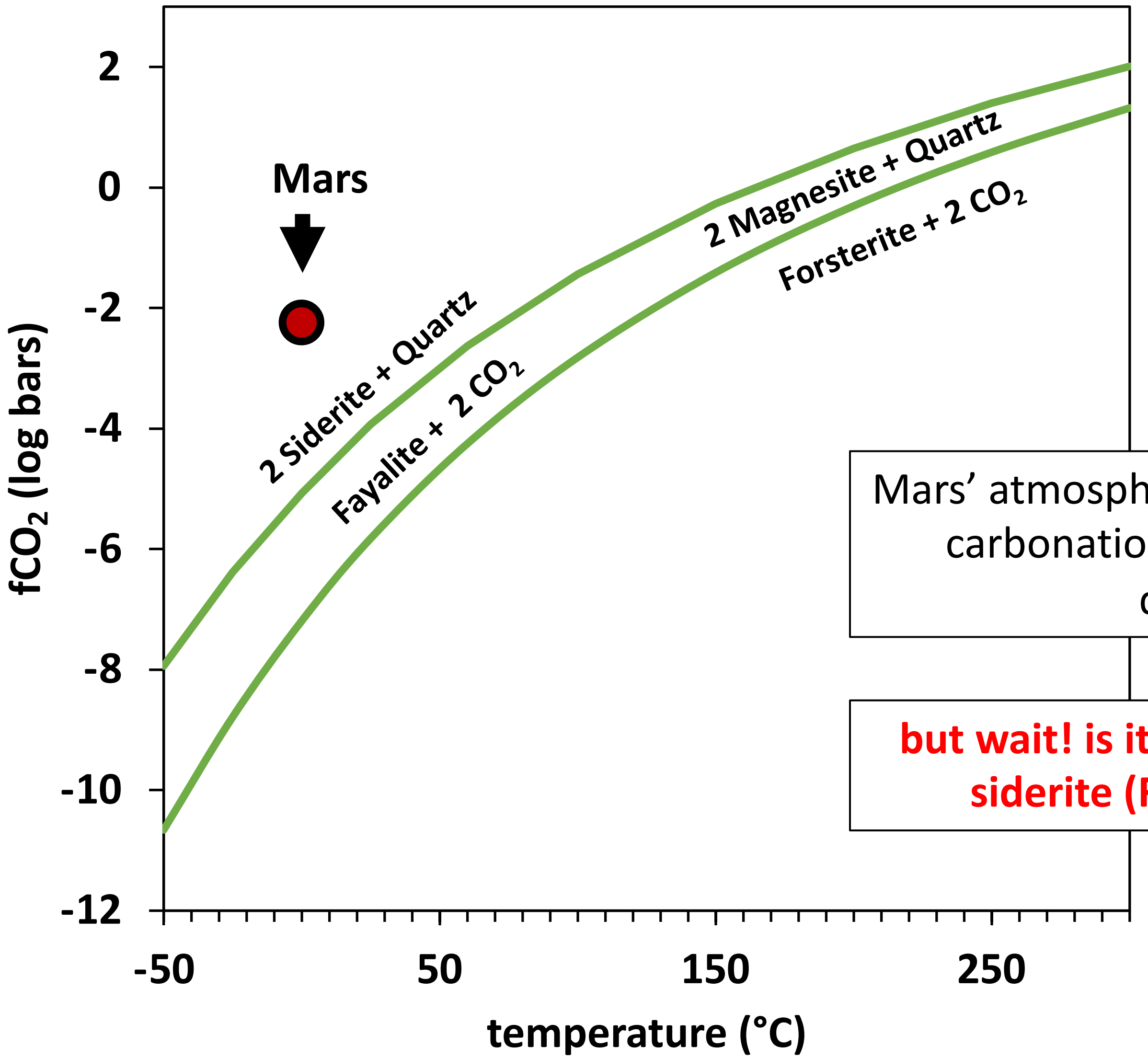
OLIVINE HYDRATION + OXIDATION



Mars’ atmosphere is favorable for the oxidation and hydration + oxidation of surface olivine deposits.

Leong et al GSA & AGU presentations, 2022

OLIVINE CARBONATION

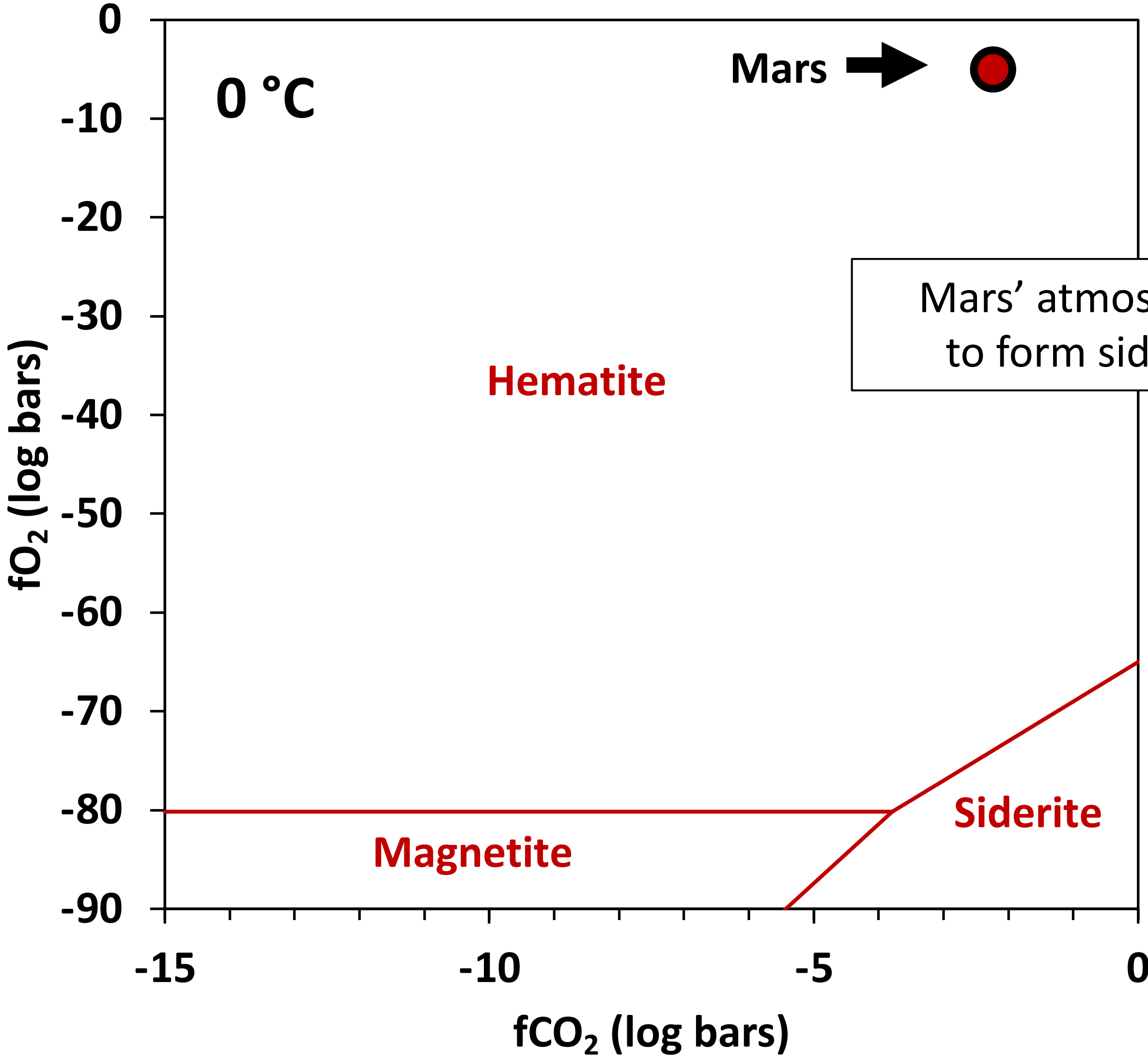


Mars' atmosphere is favorable for the carbonation of surface olivine deposits.

but wait! is it too oxidized to form siderite (Fe(II)-carbonate)?

Leong et al GSA & AGU presentations, 2022

OLIVINE CARBONATION + OXIDATION



Mars' atmosphere is far too oxidized to form siderite (Fe(II)-carbonate)

Leong et al GSA & AGU presentations, 2022

EQUILIBRIUM ASSEMBLAGES AT MARS SURFACE
(AFTER OLIVINE Fo_{50})

(RXN 1) **hydration** + **oxidation** + **carbonation**

$$4(Mg_{0.5}Fe_{0.5})_2SiO_{4(olivine)} + 4H_2O + O_2 + 4CO_2 = 4MgCO_{3(magnesite)} + 2Fe_2Si_2O5(OH)_{4(hisingerite)}$$

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

WITH EXCESS H_2O

SECONDARY MINERALS

Mineral	Mass (kg)	% Mass
Serpentine	8.7	65
Carbonate	4.6	35
Total	13.4	100

Solid Solution	Mole Fraction
Serpentine	
Chrysotile	0.004
Greenalite	5.90E-20
Cronstedtite	1.10E-13
Hisingerite	0.996
Carbonate	
Magnesite	1.000
Siderite	5.30E-18

Leong et al GSA & AGU presentations, 2022

EQUILIBRIUM ASSEMBLAGES AT MARS SURFACE (AFTER OLIVINE Fo_{50})

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$$4(Mg_{0.5}Fe_{0.5})_2SiO_{4(olivine)} + 4H_2O + O_2 + 4CO_2 = 4MgCO_{3(magnesite)} + 2Fe_2Si_2O5(OH)_{4(hisingerite)}$$

UNTIL ALL (LIMITED!) H_2O CONSUMED
THEN

(RXN 2) **oxidation** *(from excess O_2)*

$$2Fe_2SiO_{4(fayalite)} + O_2 = 2Fe_2O_{3(hematite)} + 2SiO_{2\ (quartz)}$$

USES ALL (LIMITED!) O_2
AND THEN

(RXN 3) **carbonation** *(from excess CO_2)*

$$Mg_2SiO_{4(forsterite)} + 2CO_2 = 2MgCO_{3(magnesite)} + SiO_{2\ (quartz)}$$

CONSUIMING ABUNDANT O_2

Leong et al GSA & AGU presentations, 2022

WEATHERING THICKNESS PER KM^3 ATMOSPHERE PER KM^2 SURFACE (AFTER OLIVINE Fo_{50})

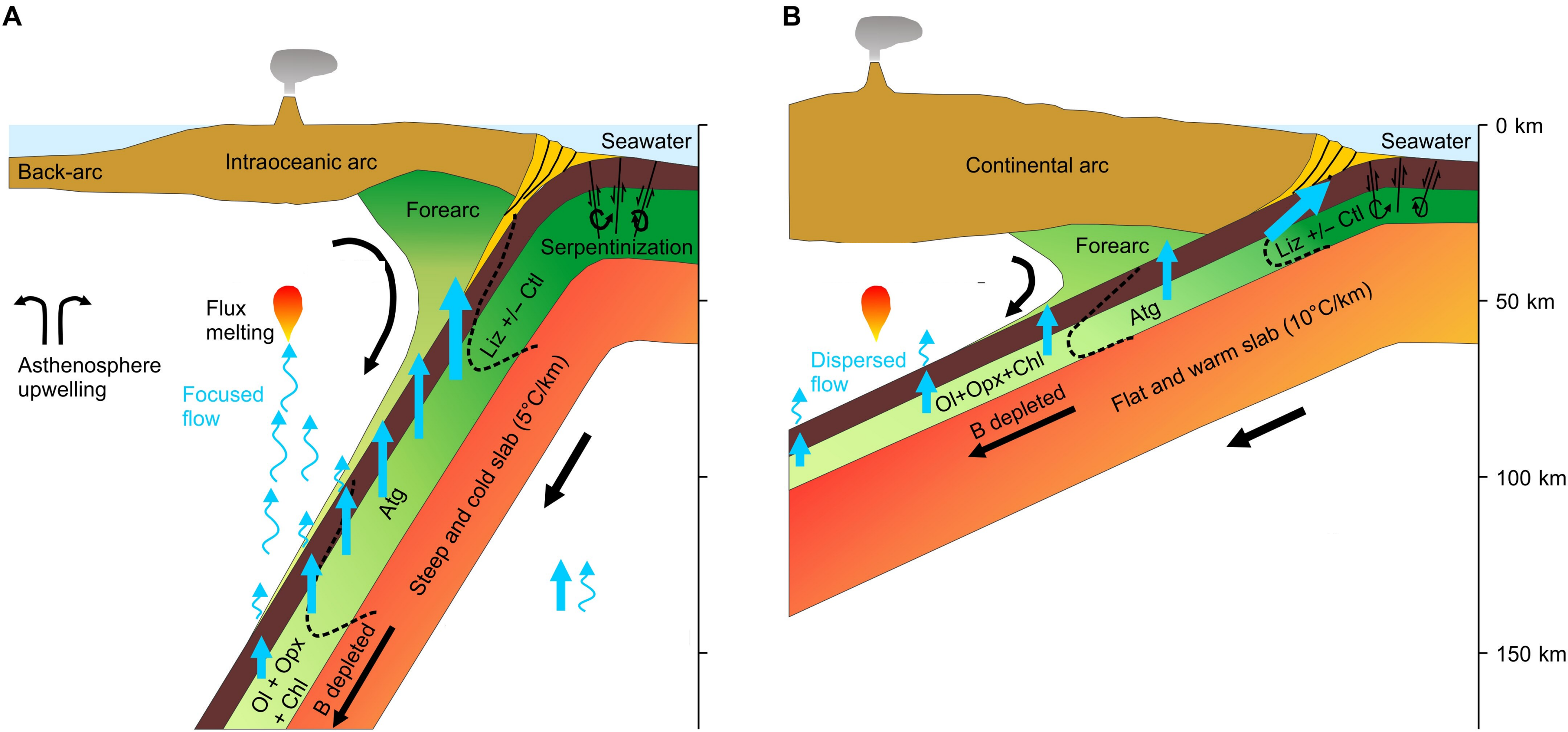
(assuming similar H_2O, O_2, and CO_2 supply rate or residence time)

WEATHERING PROFILE
mm/(km^3 atmosphere)/(km^2 surface)

MINERAL	RXN 1	RXN 2	RXN 3	Total	vol%
magnesite	0.002		4.97	**4.97**	**63.09**
quartz		0.03	2.86	**2.88**	**36.52**
hematite		0.02		**0.03**	**0.34**
serpentine (hisingerite)	0.004			**0.004**	**0.05**

bulk of weathered mass forms via RXN (3), as Mars' atmosphere is very rich in CO_2 relative to O_2 and H_2O

Leong et al GSA & AGU presentations, 2022



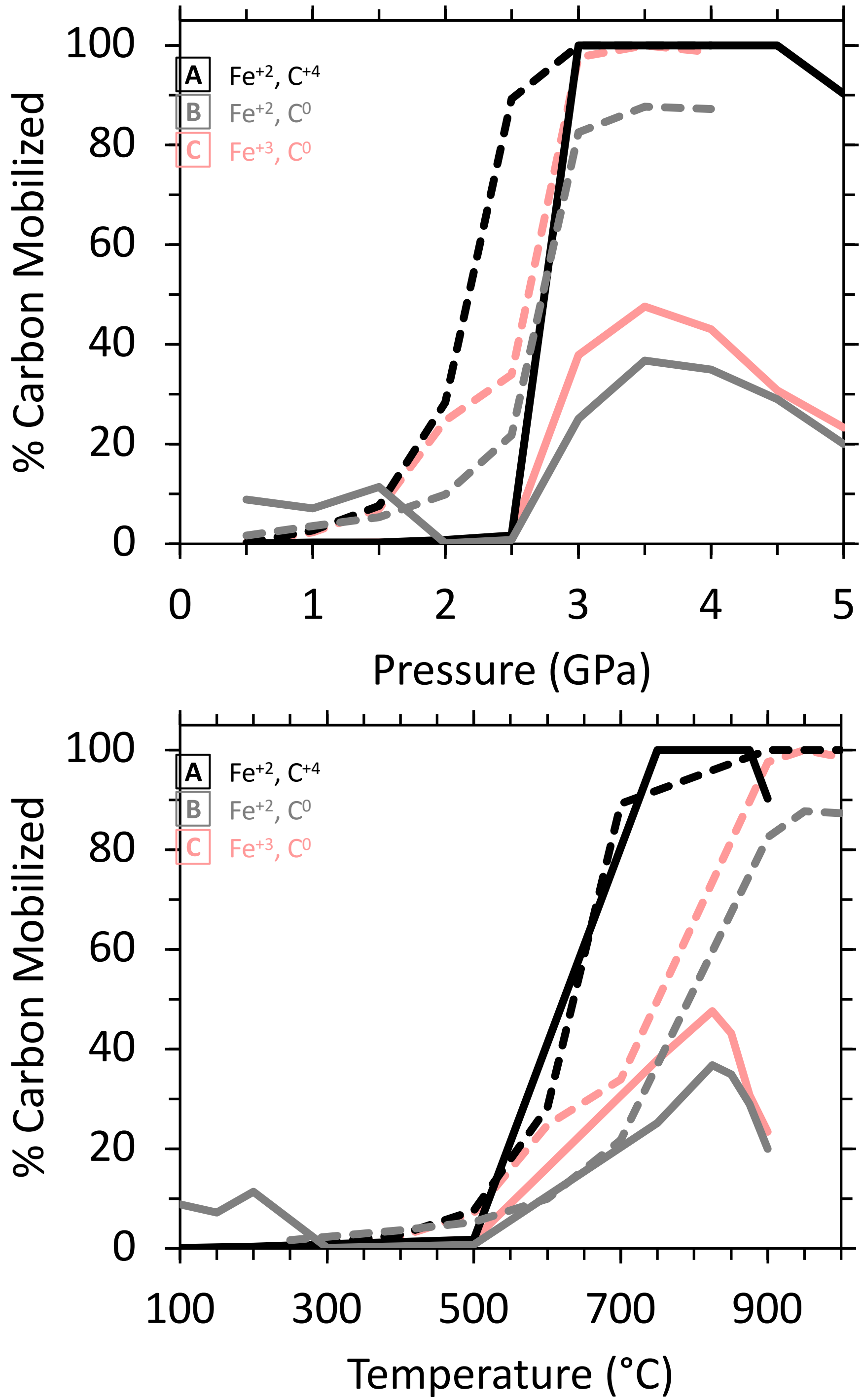
https://www.science.org/doi/10.1126/sciadv.abj2515

“GLOSS”

global average subducting sediment

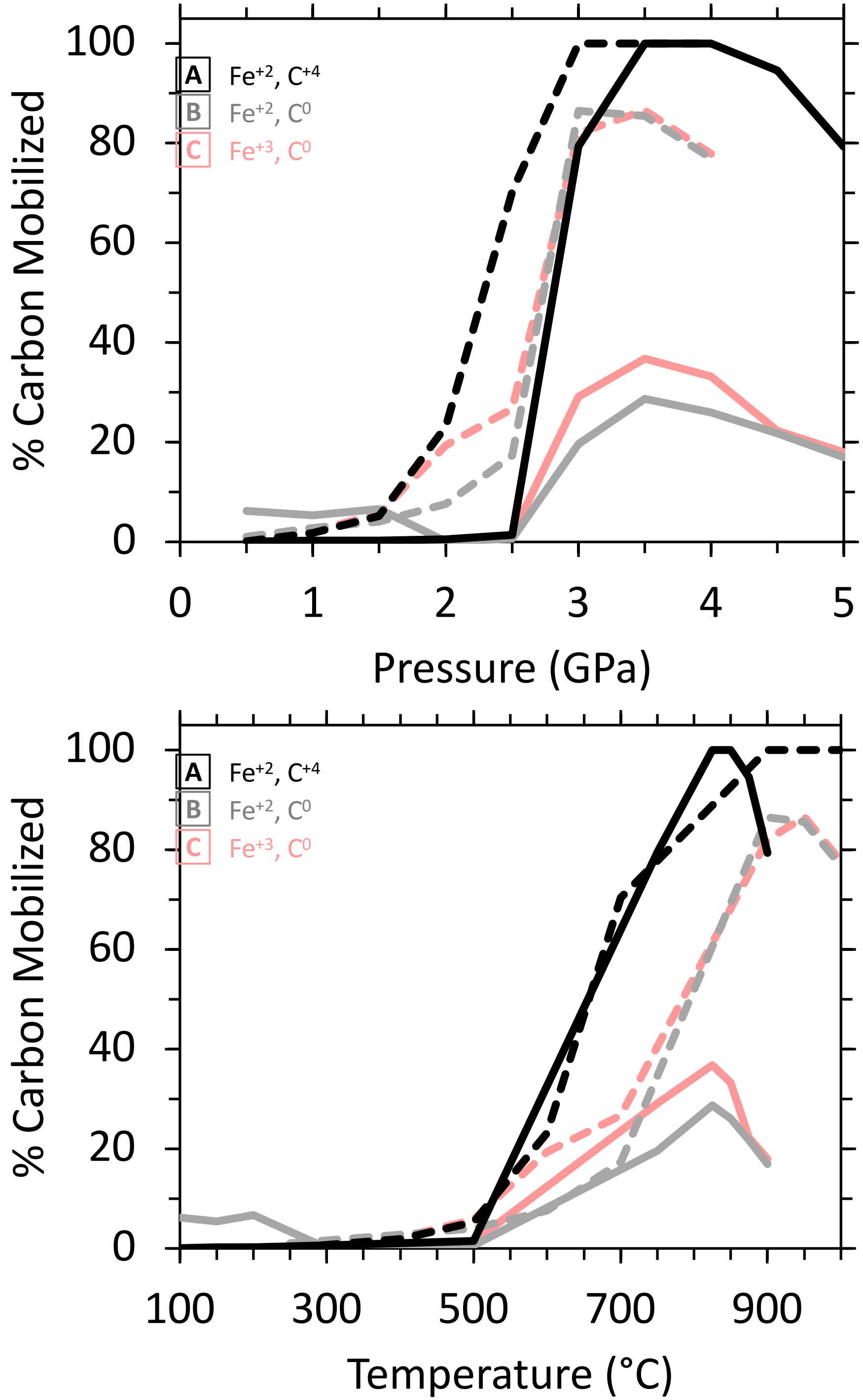
solid lines = cold subduction

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

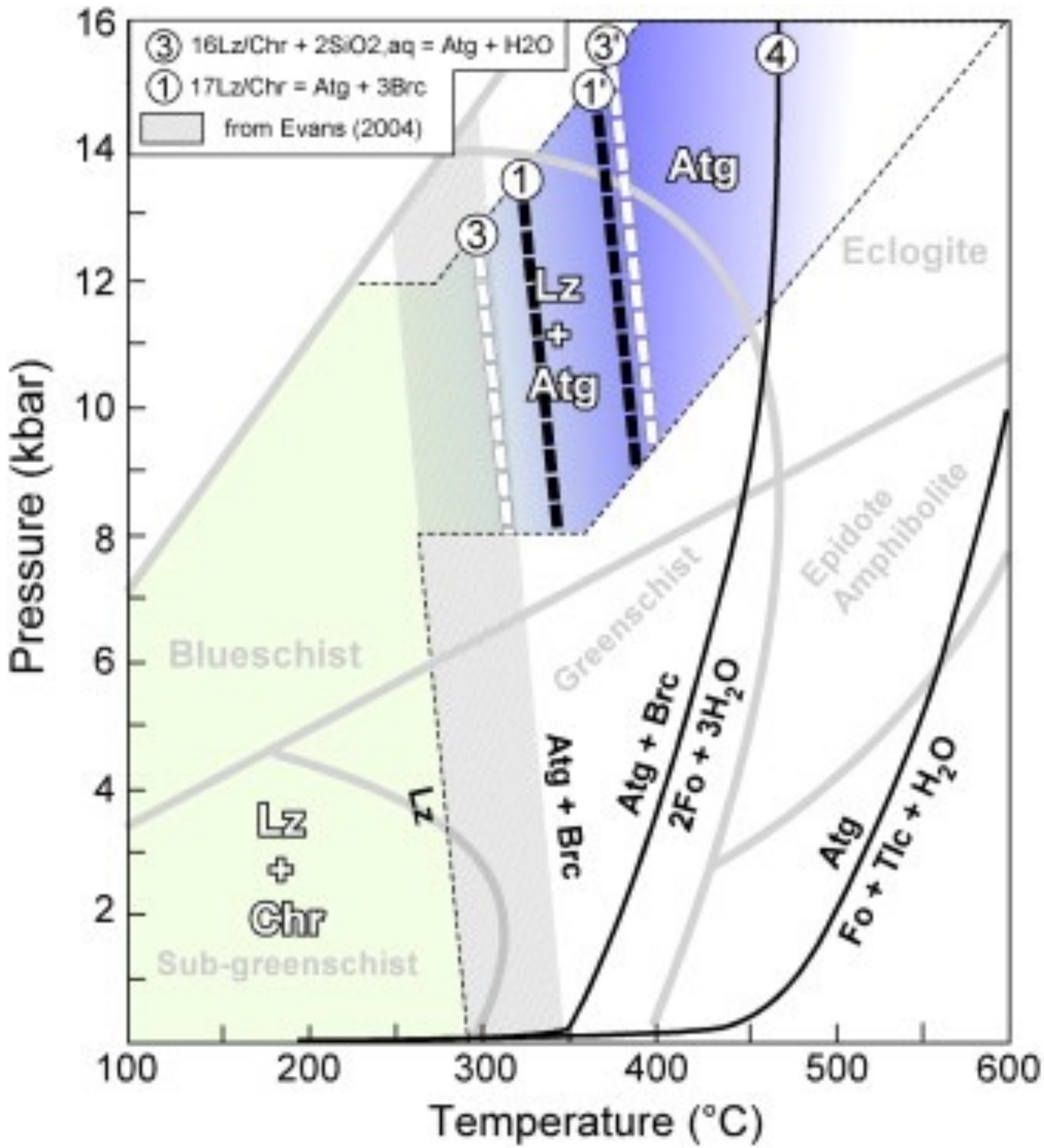


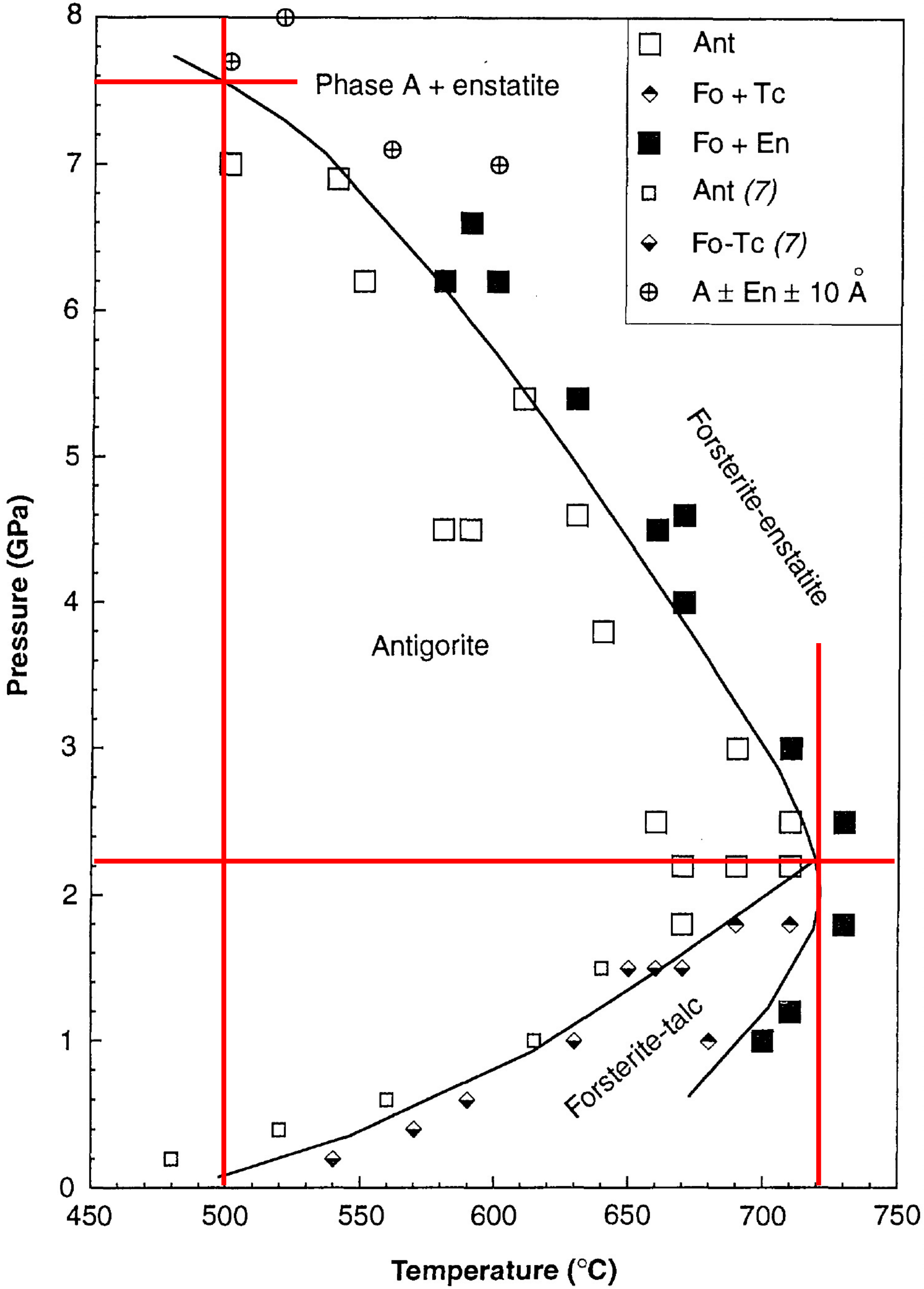
https://www.sciencedirect.com/science/article/pii/S0024493712004781

Pressure–temperature estimates of the lizardite/antigorite transition in high pressure serpentinites

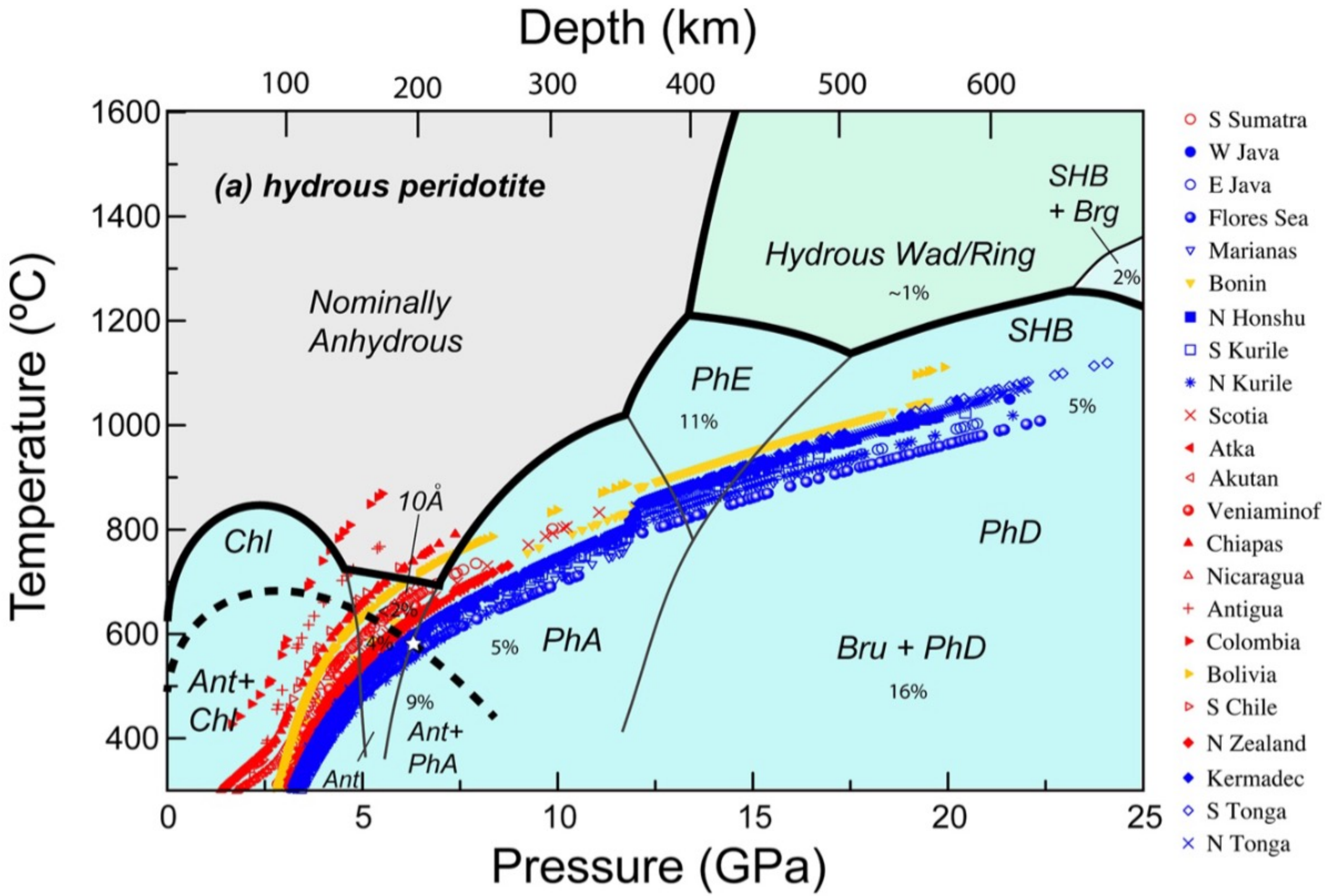
Stéphane Schwartz, Stéphane Guillot, BrunoReynard, Romain Lafay, Baptiste Debret, Christian Nicollet, Pierre Lanari, Anne Line Auzende

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 SiO_2 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.



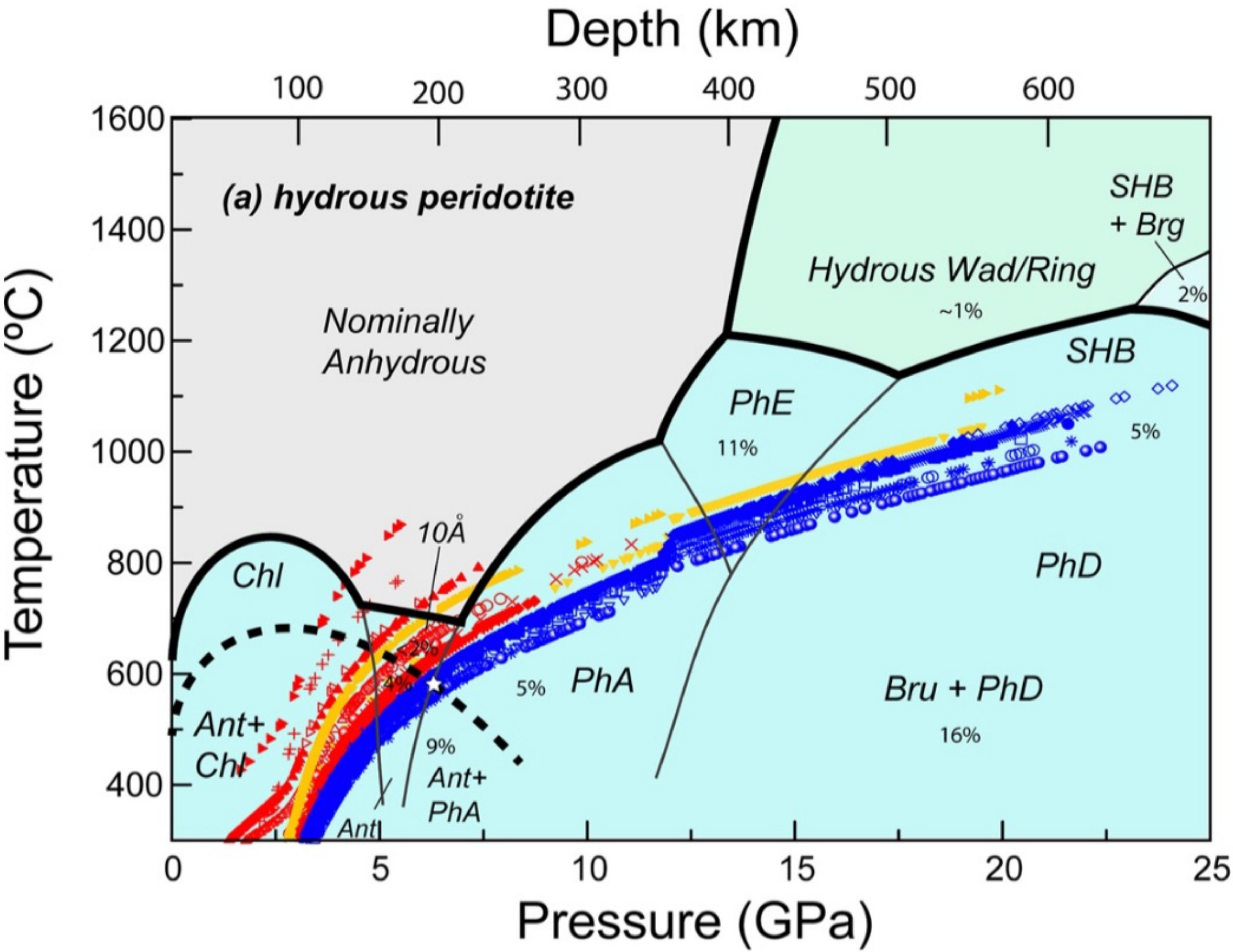


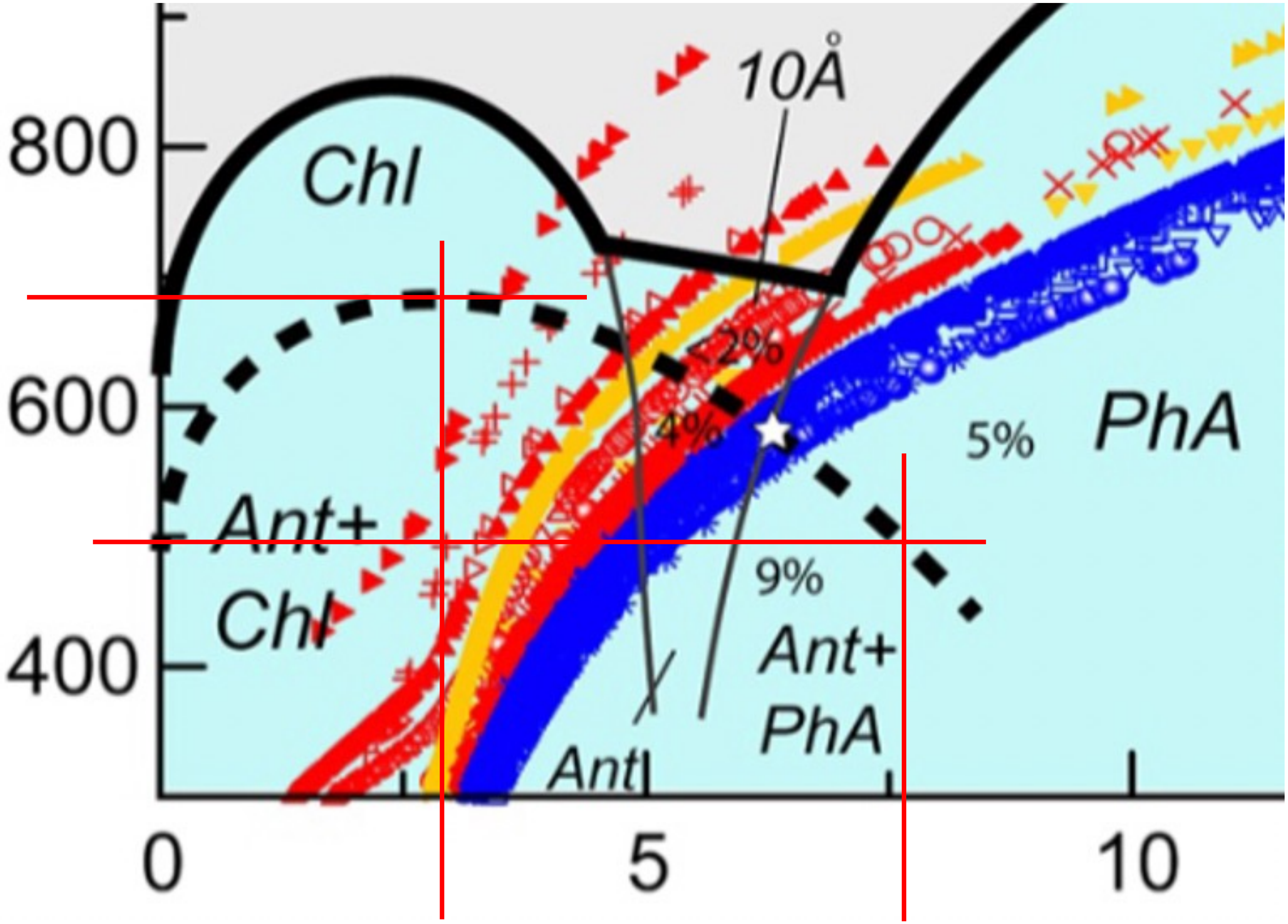
Ulmer & Trommsdorf 1995



The white star shows an estimate of the maximum temperature at which antigorite-bearingperidotite 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)

(19) (PDF) Slab Transport of Fluids to Deep Focus Earthquake Depths—Thermal Modeling Constraints and Evidence From Diamonds. Available from: https://www.researchgate.net/publication/351895714_Slab_Transport_of_Fluids_to_Deep_Focus_Earthquake_Depths-Thermal_Modeling_Constraints_and_Evidence_From_Diamonds [accessed Oct 30 2022].


Depth (km)
100
200
300
400
500
600
(a) hydrous peridotite
Nominally Anhydrous
Hydrous Wad/Ring
~1%
SHB + Brg
2%
SHB
PhE
11%
5%
Chl
10Å
2%
4%
5%
PhA
PhD
Bru + PhD
16%
Ant+ Chl
9%
Ant+ PhA
Ant
Temperature (ºC)
1600
1400
1200
1000
800
600
400
0
5
10
15
20
25
Pressure (GPa)



800
600
400
0
5
10
Chl
10Å
<2%
4%
5%
PhA
Ant+
Chl
9%
Ant+
PhA
Ant

Kaolinite (clay, not a serpentine mineral) $Al_2Si_2O_5(OH)_4$

Lizardite	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Chrysotile	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Antigorite	$Mg_{48}(Si_{34}O_{85})(OH)_{62}$	Mg/Si ~ 1.41, 16x lizardite + $2SiO_2$ – H_2O
Greenalite	$Fe^{2+}{}_3(Si_2O_5)(OH)_4$	
Hisingerite	$Fe^{3+}{}_2(Si_2O_5)(OH)_4$	

Clinochlore (chlorite group, not a serpentine mineral)	$Mg_5Al(AlSi_3O_{10})(OH)_8$
chromian chlorite	$Mg_5Cr(CrSi_3O_{10})(OH)_8$
ferric iron chlorite?	$Fe^{2+}{}_5Fe^{3+}(Fe^{3+}Si_3O_{10})(OH)_8$?

Amesite	$\mathbf{Mg_2Al(AlSiO_5)(OH)_4}$	+ $Mg_3(Si_2O_5)(OH)_4$ = clinochlore
chromian serp?	$Mg_2Cr(CrSiO_5)(OH)_4$???	+ $Mg_3(Si_2O_5)(OH)_4$ = chromian chl
Cronstedtite	$\mathbf{Fe^{2+}{}_2Fe^{3+}(Fe^{3+}SiO_5)(OH)_4}$	+ $Fe^{2+}{}_3(Si_2O_5)(OH)_4$ = Fe-chlorite?
Mg-cronstedtite	$\mathbf{Mg_2Fe^{3+}(Fe^{3+}SiO_5)(OH)_4}$	

Kaolinite (clay, not a serpentine mineral) $Al_2Si_2O_5(OH)_4$

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Greenalite	$Fe^{2+}{}_3(Si_2O_5)(OH)_4$	
Hisingerite	$Fe^{3+}{}_2(Si_2O_5)(OH)_4$	

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chromian chlorite	$Mg_5Cr(CrSi_3O_{10})(OH)_8$
ferric iron chlorite?	$Fe^{2+}{}_5Fe^{3+}(Fe^{3+}Si_3O_{10})(OH)_8$?

tschermak's substitition, $Mg_{-1}Si_{-1}AlAl$

Amesite	$Mg_2\mathbf{Al}(\mathbf{Al}SiO_5)(OH)_4$	+ $Mg_3(Si_2O_5)(OH)_4$ = clinochlore
chromian serp?	$Mg_2\mathbf{Cr}(\mathbf{Cr}SiO_5)(OH)_4$???	+ $Mg_3(Si_2O_5)(OH)_4$ = chromian chl
Cronstedtite	$\mathbf{Fe^{2+}{}_2Fe^{3+}(Fe^{3+}SiO_5)(OH)_4}$	+ $Fe^{2+}{}_3(Si_2O_5)(OH)_4$ = Fe-chlorite?
Mg-cronstedtite	$\mathbf{Mg_2Fe^{3+}(Fe^{3+}SiO_5)(OH)_4}$	

Lithos 178 (2013) 186–196

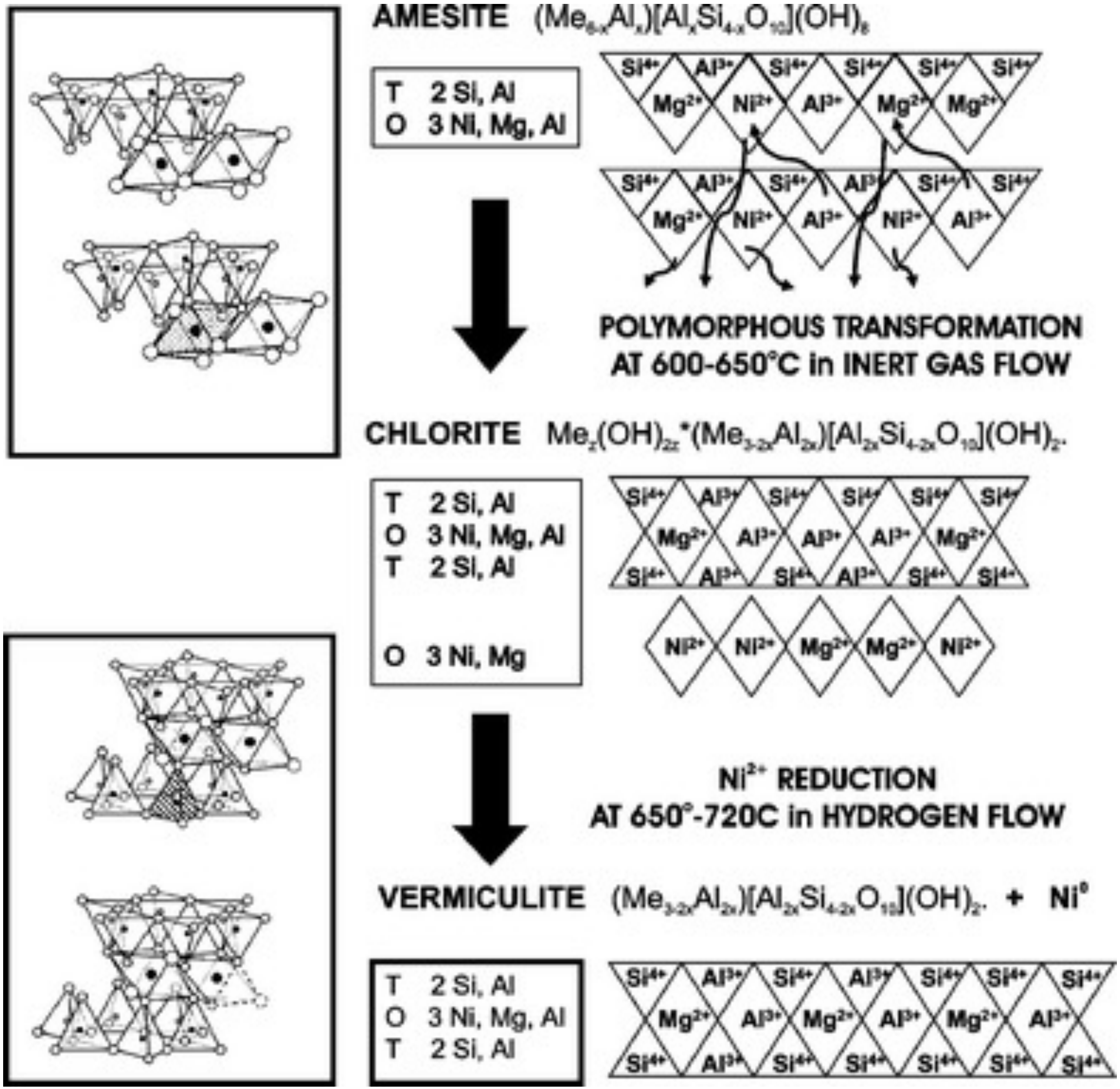
Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

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 [e], Carlos J. Garrido [d], María Teresa Gómez-Pugnaire [d,f], Claudio Marchesi [d]



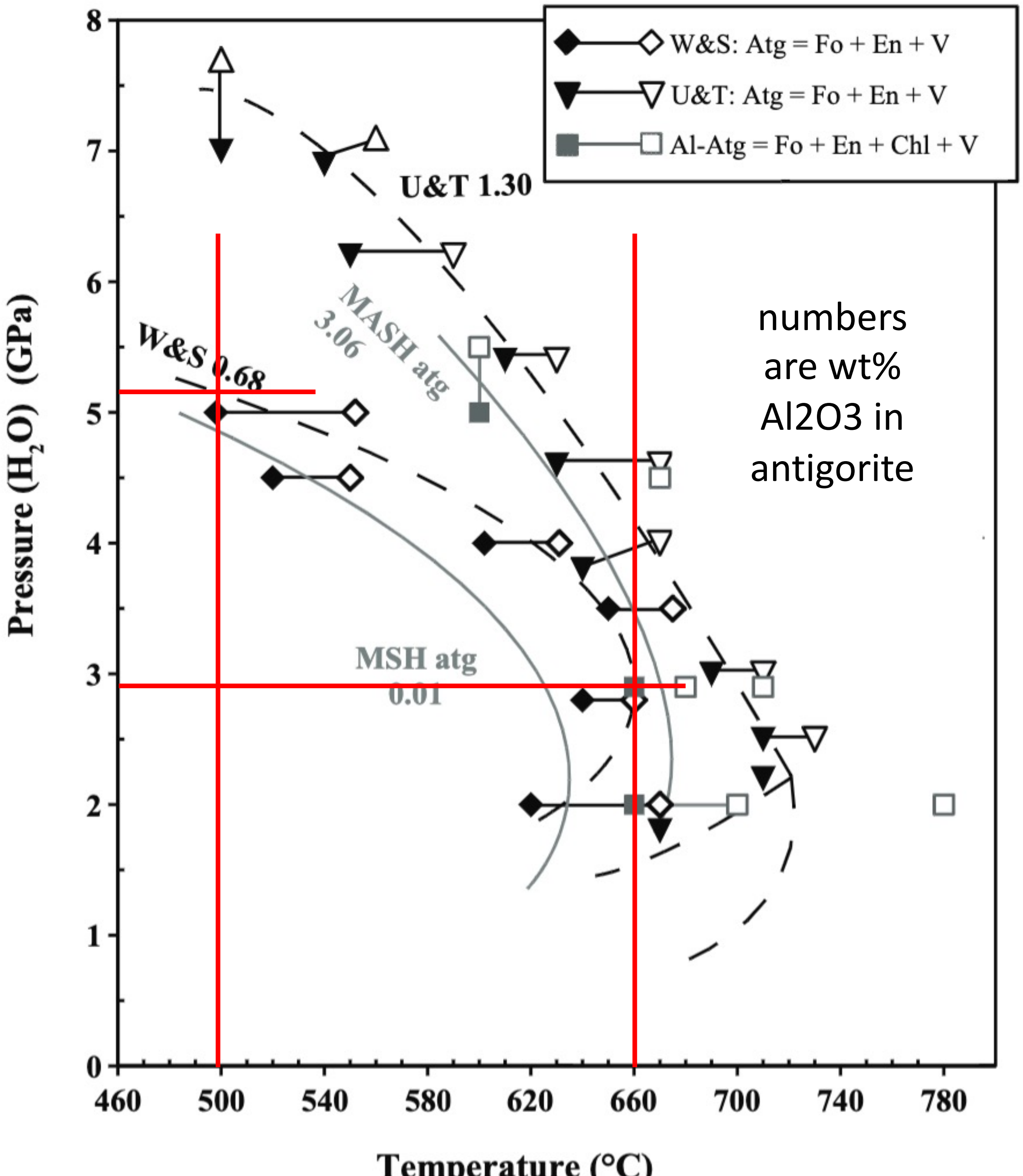
Khassin, A.A., Yurieva, T.M., Demeshkina, M.P., Kustova, G.N., Itenberg, I.S., Kaichev, V.V., Plyasova, L.M., Anufrienko, V.F., Molina, I.Y., Larina, T.V. and Baronskaya, N.A., 2003. Characterization of the nickel-amesite-chlorite-vermiculite system. Part I. Silicon binding in Ni–Mg–Al phylloaluminosilicates. *Physical Chemistry Chemical Physics*, *5*(18), pp.4025-4031.

Bromley & Pawley 2003

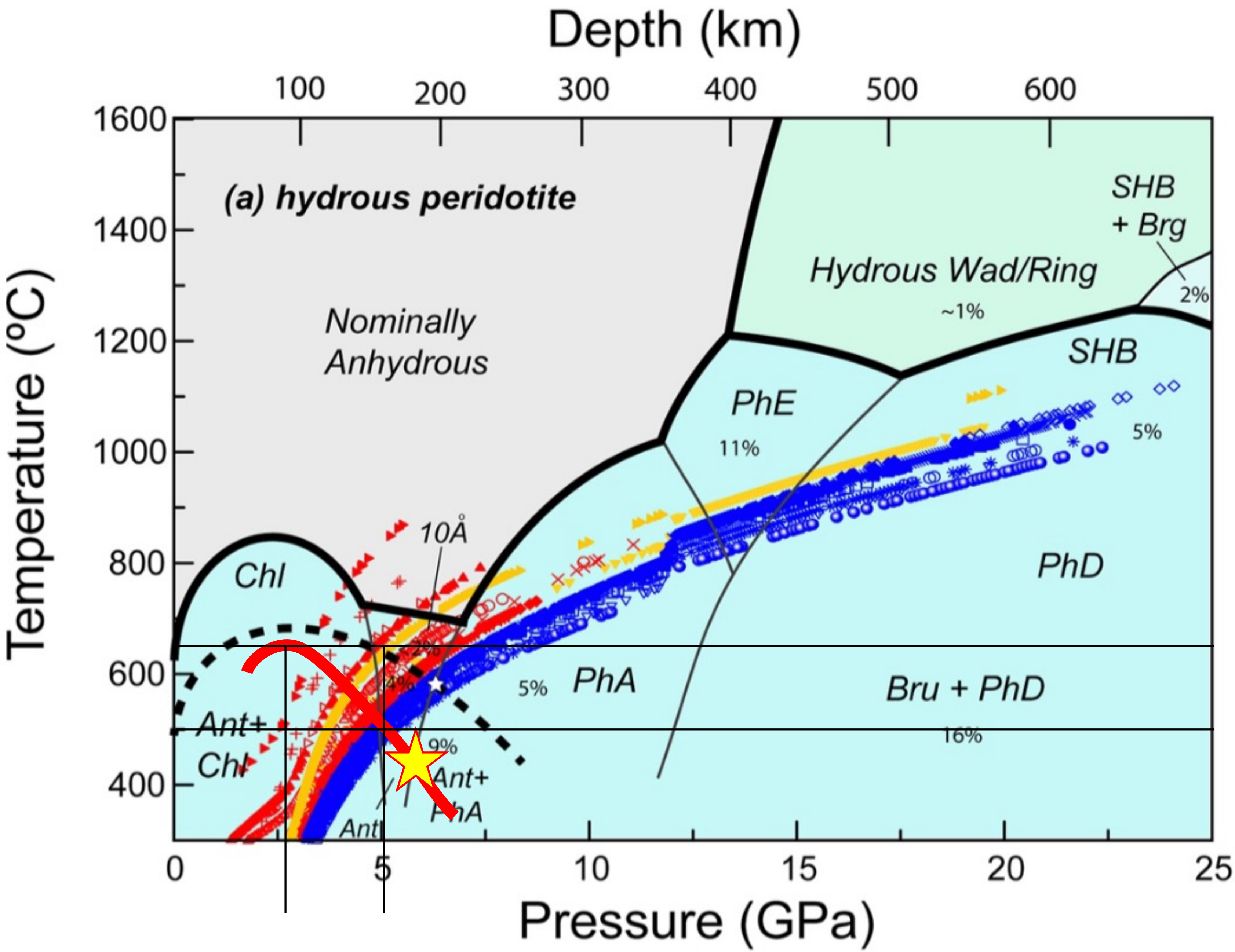
average depleted peridotite (harzburgite) contains ~1 wt% Al2O3

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

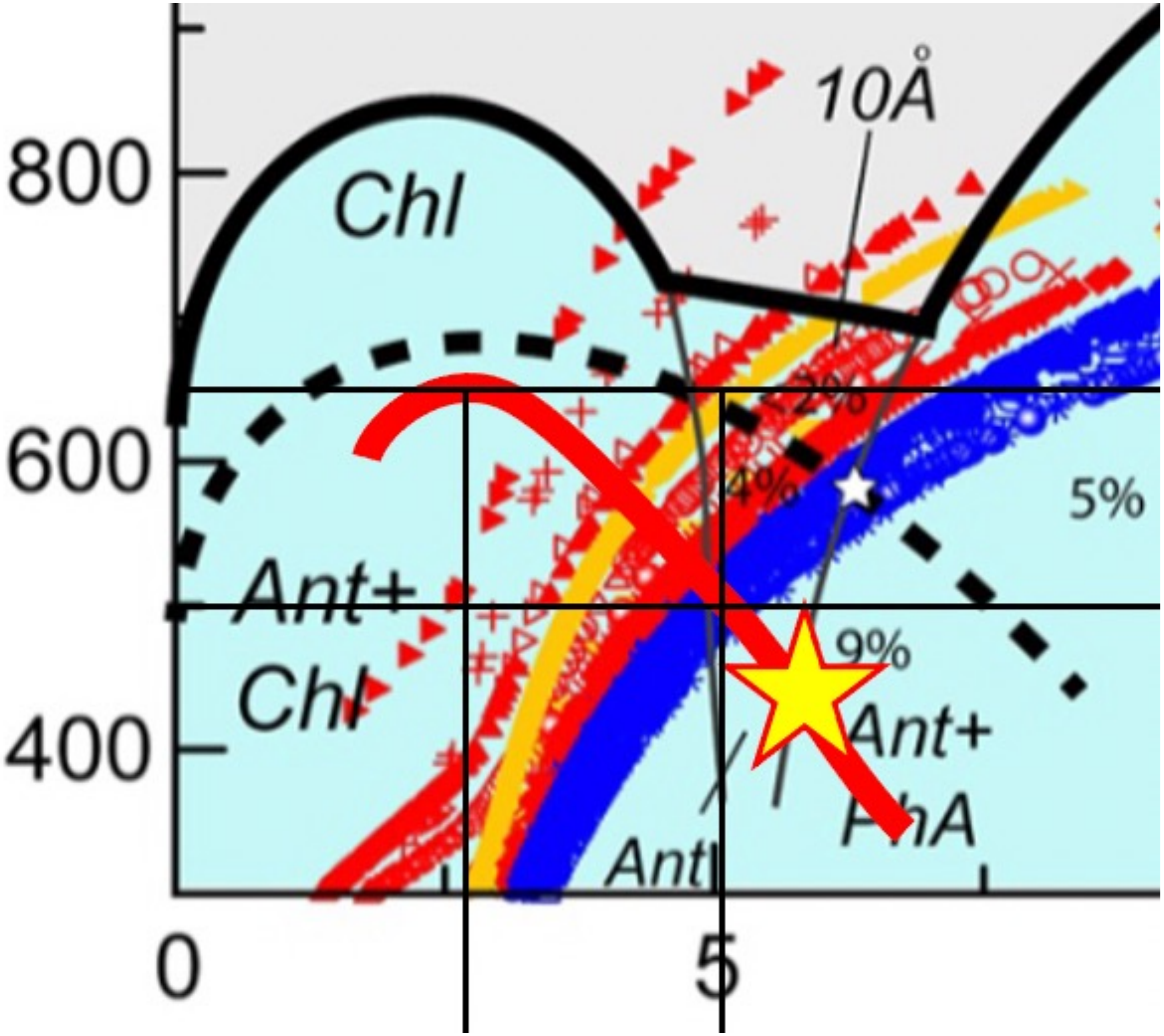
similar to W&S

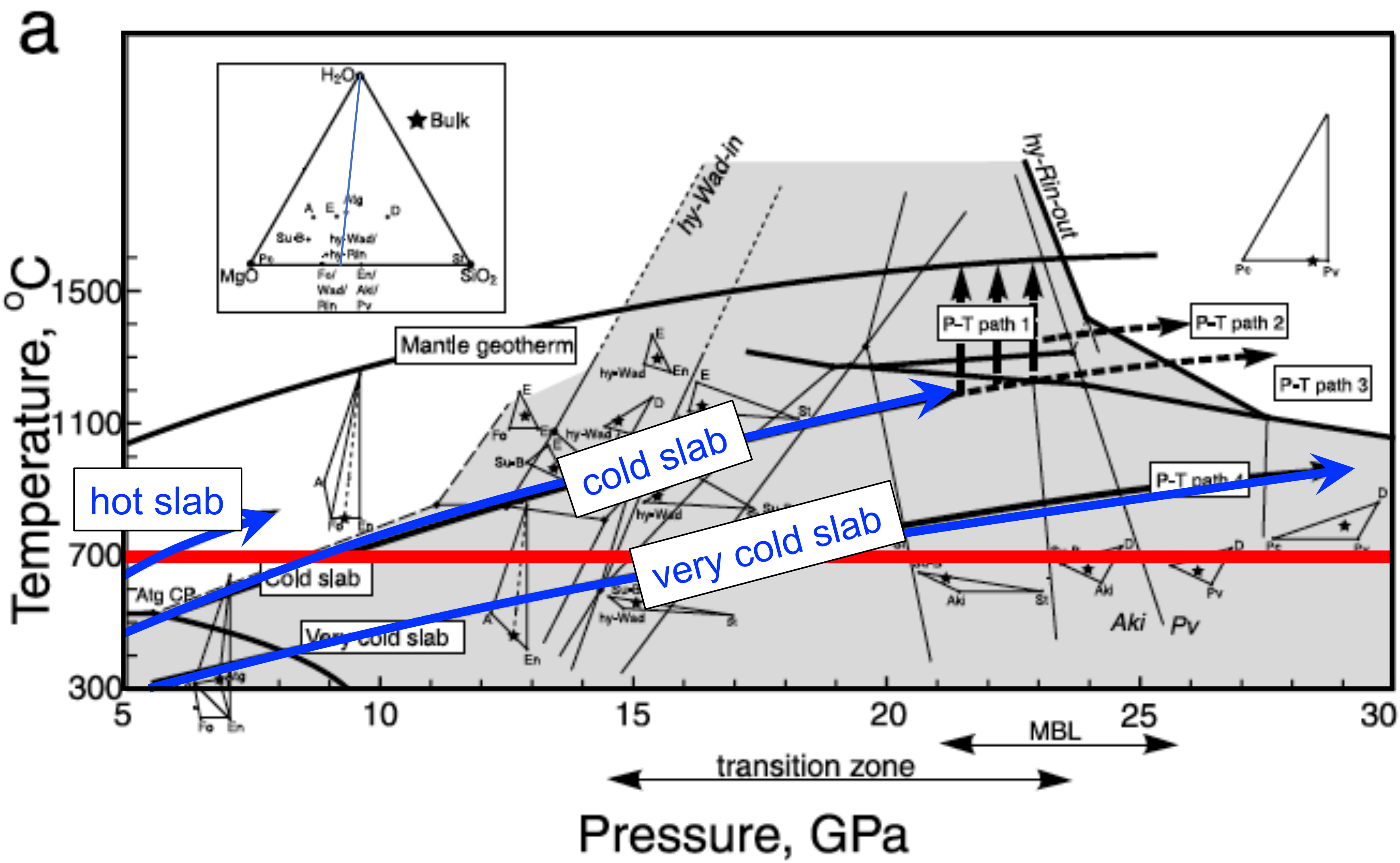


numbers are wt% Al2O3 in antigorite



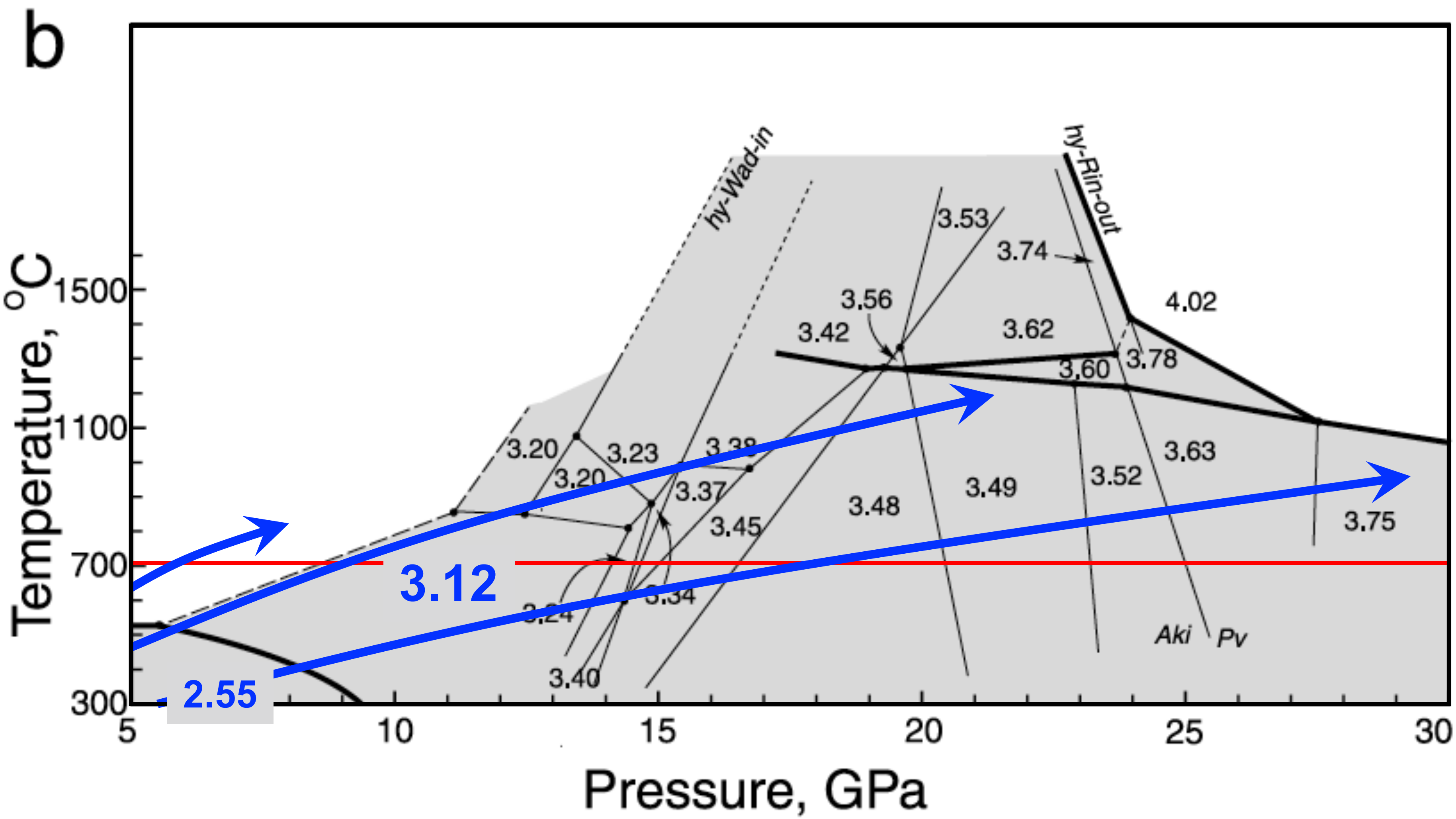
Depth (km)
100
200
300
400
500
600
1600
1400
1200
1000
800
600
400
Temperature (ºC)
(a) hydrous peridotite
Nominally Anhydrous
Hydrous Wad/Ring
~1%
SHB + Brg
2%
SHB
PhE
11%
5%
10Å
Chl
2%
4%
5%
PhA
Bru + PhD
PhD
Ant+ Chl
9%
16%
Ant+ PhA
Ant
0
5
10
15
20
25
Pressure (GPa)


800
600
400
0
5
Chl
10Å
2%
4%
5%
Ant+
Chl
9%
Ant+
PhA
Ant

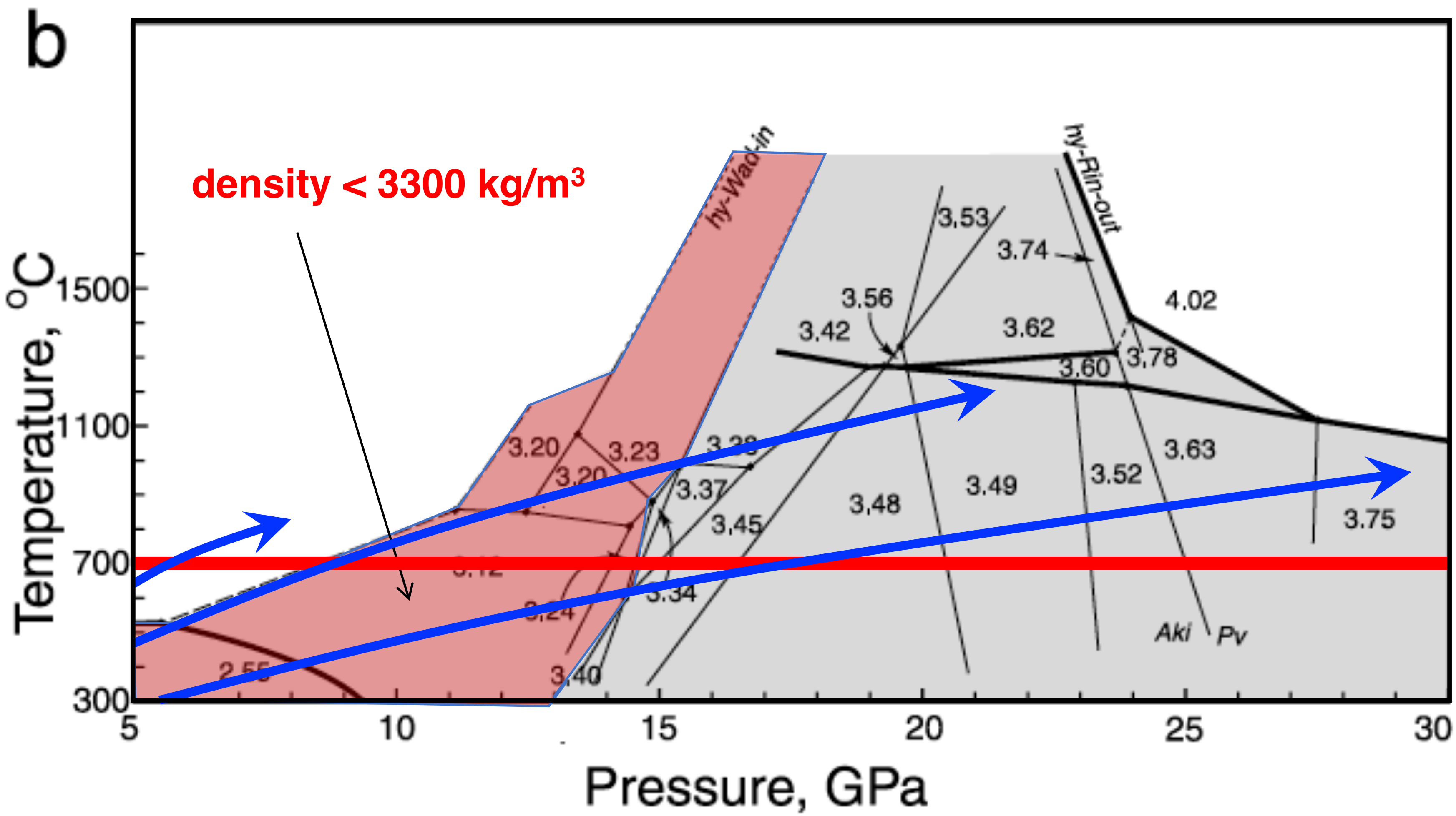


Komabayashi et al. JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, B03206, doi:10.1029/2003JB002651, 2004

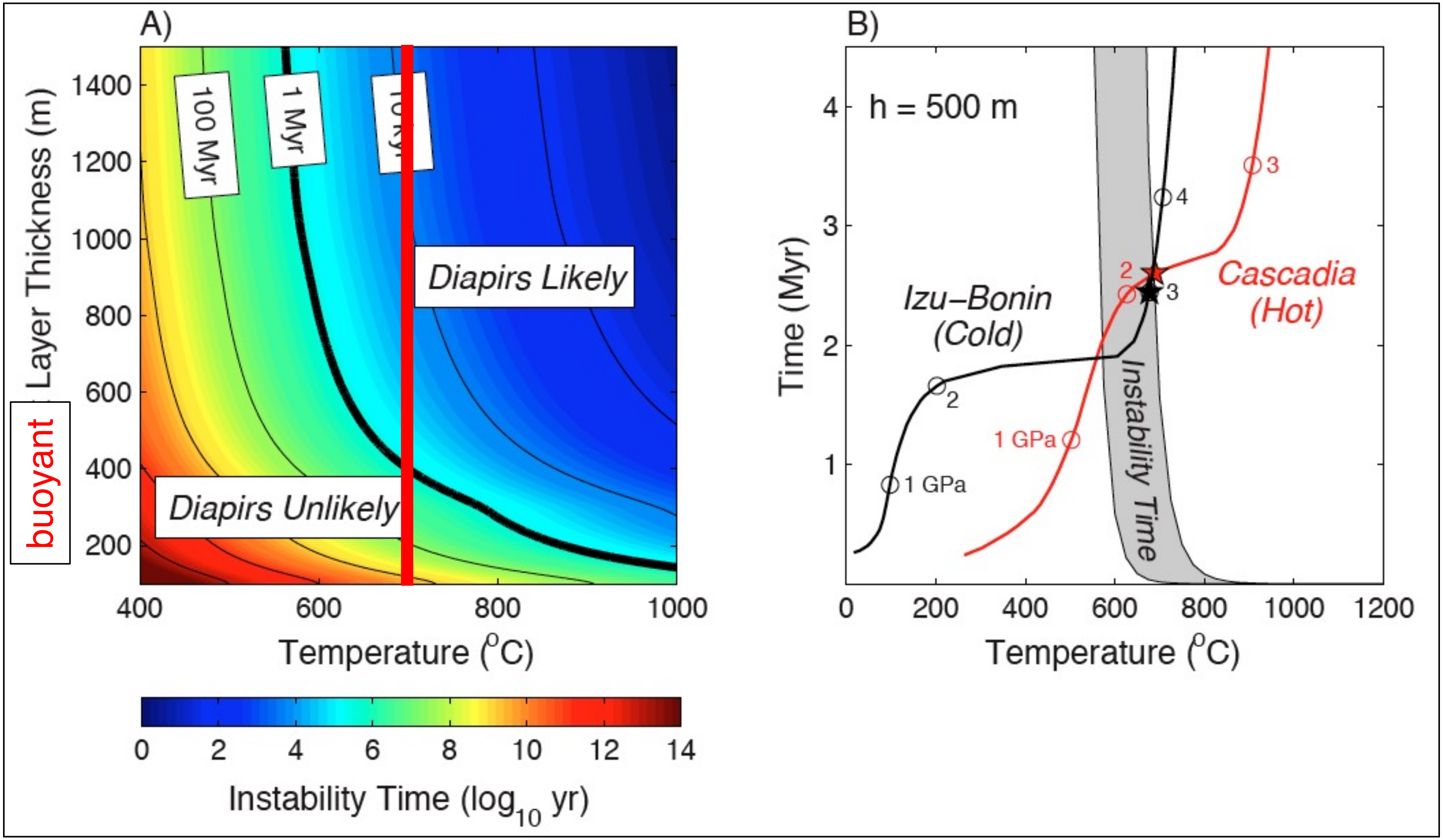
densities, tons/m^3



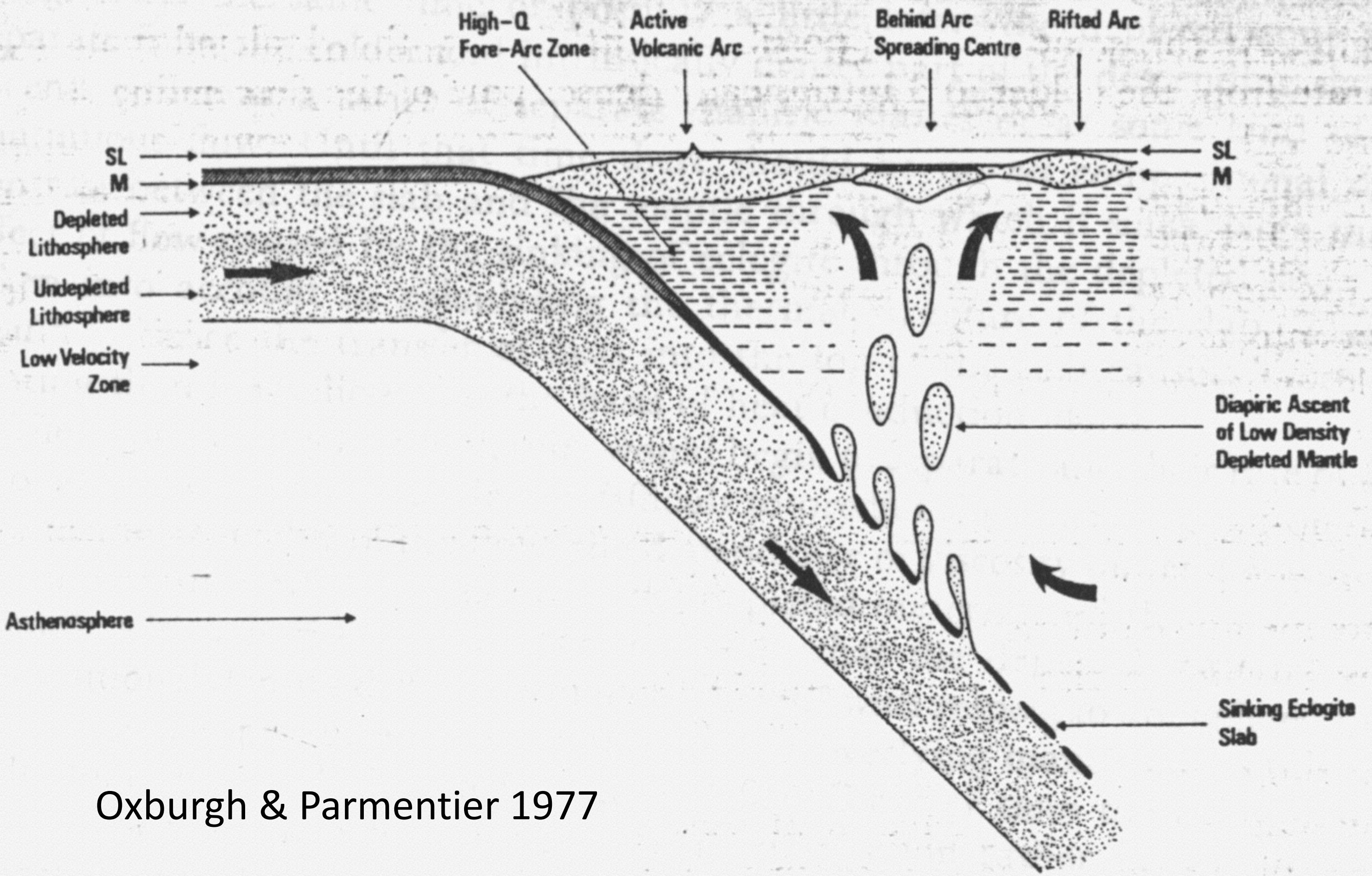
Komabayashi et al. JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, B03206, doi:10.1029/2003JB002651, 2004



Komabayashi et al. JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, B03206, doi:10.1029/2003JB002651, 2004



Behn et al., Nature Geoscience 2011



Oxburgh & Parmentier 1977

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.

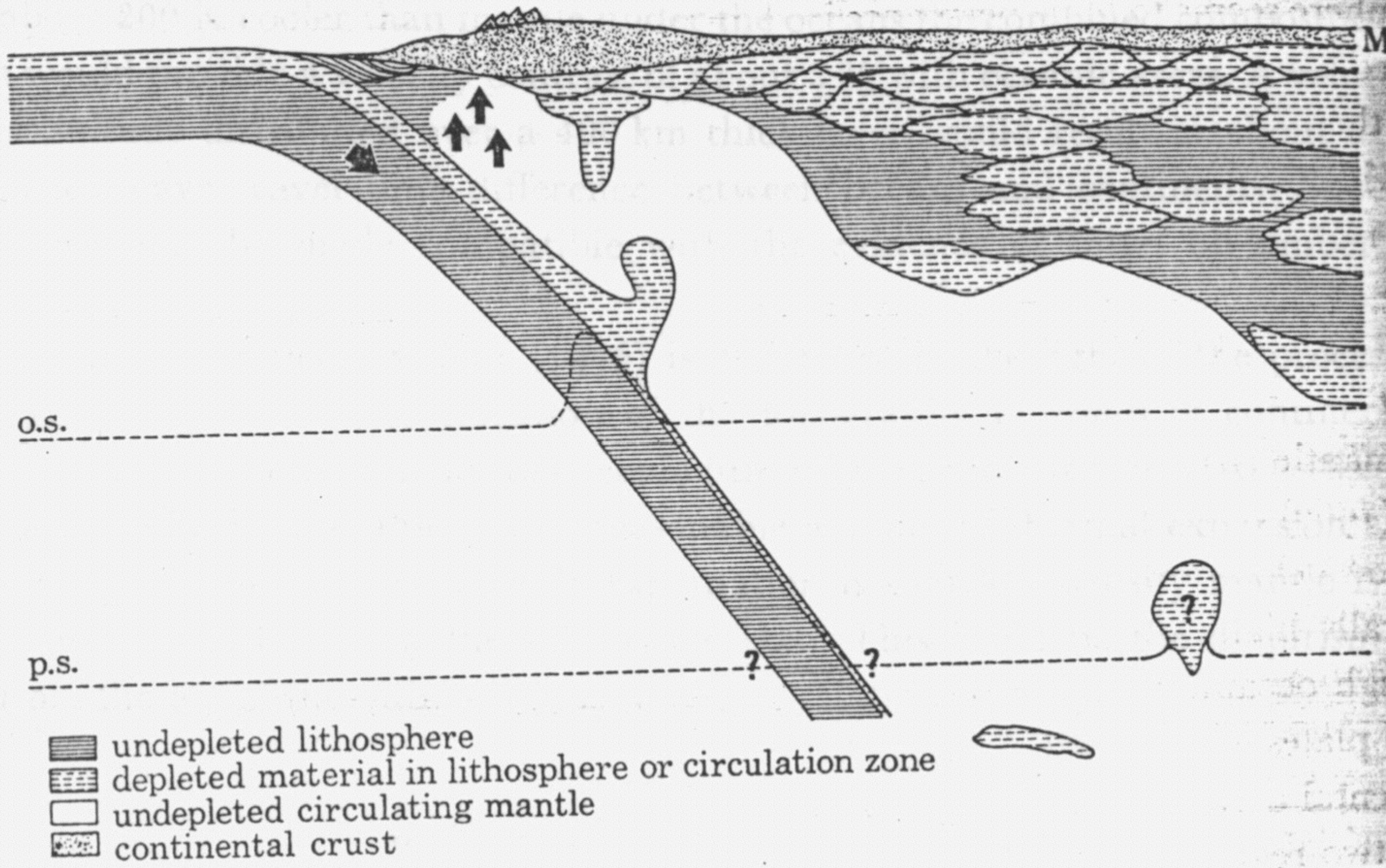


FIGURE 6. Subduction of a lithospheric slab with a depleted top and undepleted base (oceanic crust om a continental margin; vertical arrows indicate rise of magmas. A diapir is shown about to separate top of the slab: o.s., olivine–spinel phase change; p.s., post-spinel phase change.

Oxburgh & Parmentier 1978

Kaolinite (clay, not a serpentine mineral) $Al_2Si_2O_5(OH)_4$

Lizardite	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Chrysotile	$Mg_3(Si_2O_5)(OH)_4$	Mg/Si = 1.5
Antigorite	$Mg_{48}(Si_{34}O_{85})(OH)_{62}$	Mg/Si ~ 1.41, 16x lizardite + $2SiO_2 - H_2O$
Greenalite	$Fe^{2+}{}_3(Si_2O_5)(OH)_4$	
Hisingerite	$Fe^{3+}{}_2(Si_2O_5)(OH)_4$	

Clinochlore (chlorite group, not a serpentine mineral)	$Mg_5Al(AlSi_3O_{10})(OH)_8$
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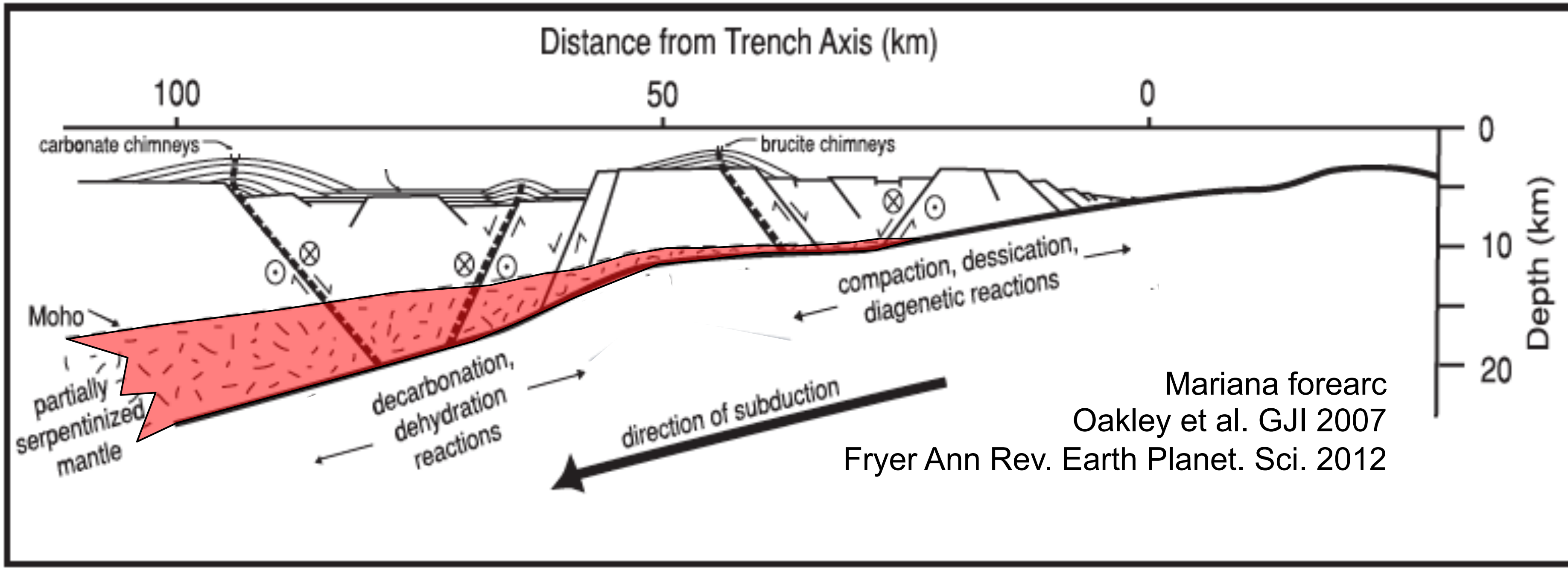
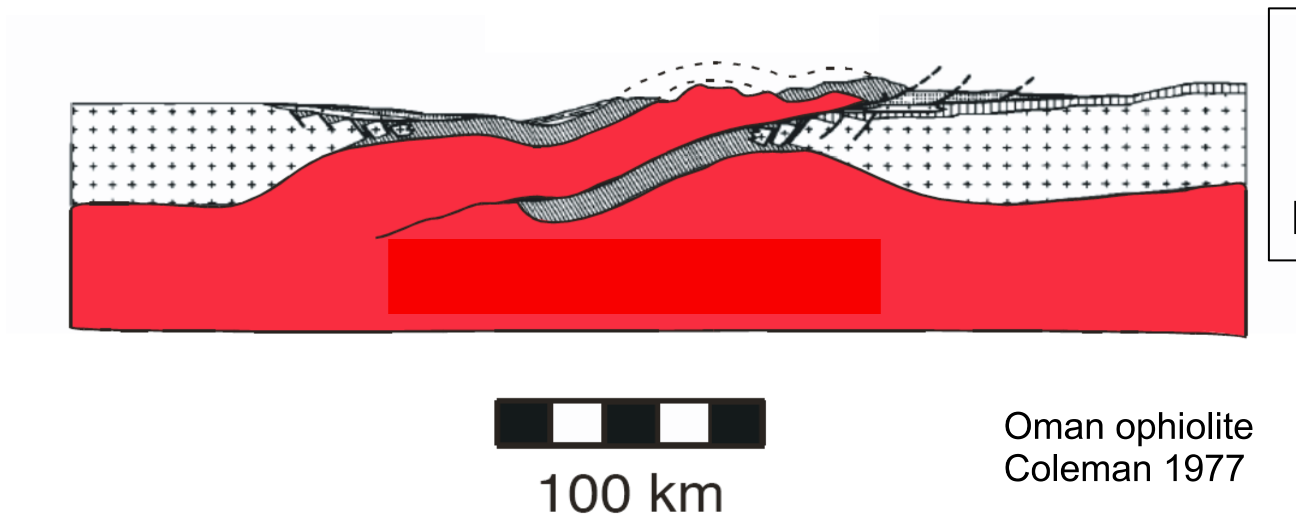
Amesite	$Mg_2Al(AlSiO_5)(OH)_4$	+ $Mg_3(Si_2O_5)(OH)_4$ = clinochlore
chromian serp?	$Mg_2Cr(CrSiO_5)(OH)_4$???	+ $Mg_3(Si_2O_5)(OH)_4$ = chromian chl
Cronstedtite	$Fe^{2+}{}_2Fe^{3+}(Fe^{3+}SiO_5)(OH)_4$	+ $Fe^{2+}{}_3(Si_2O_5)(OH)_4$ = Fe-chlorite?

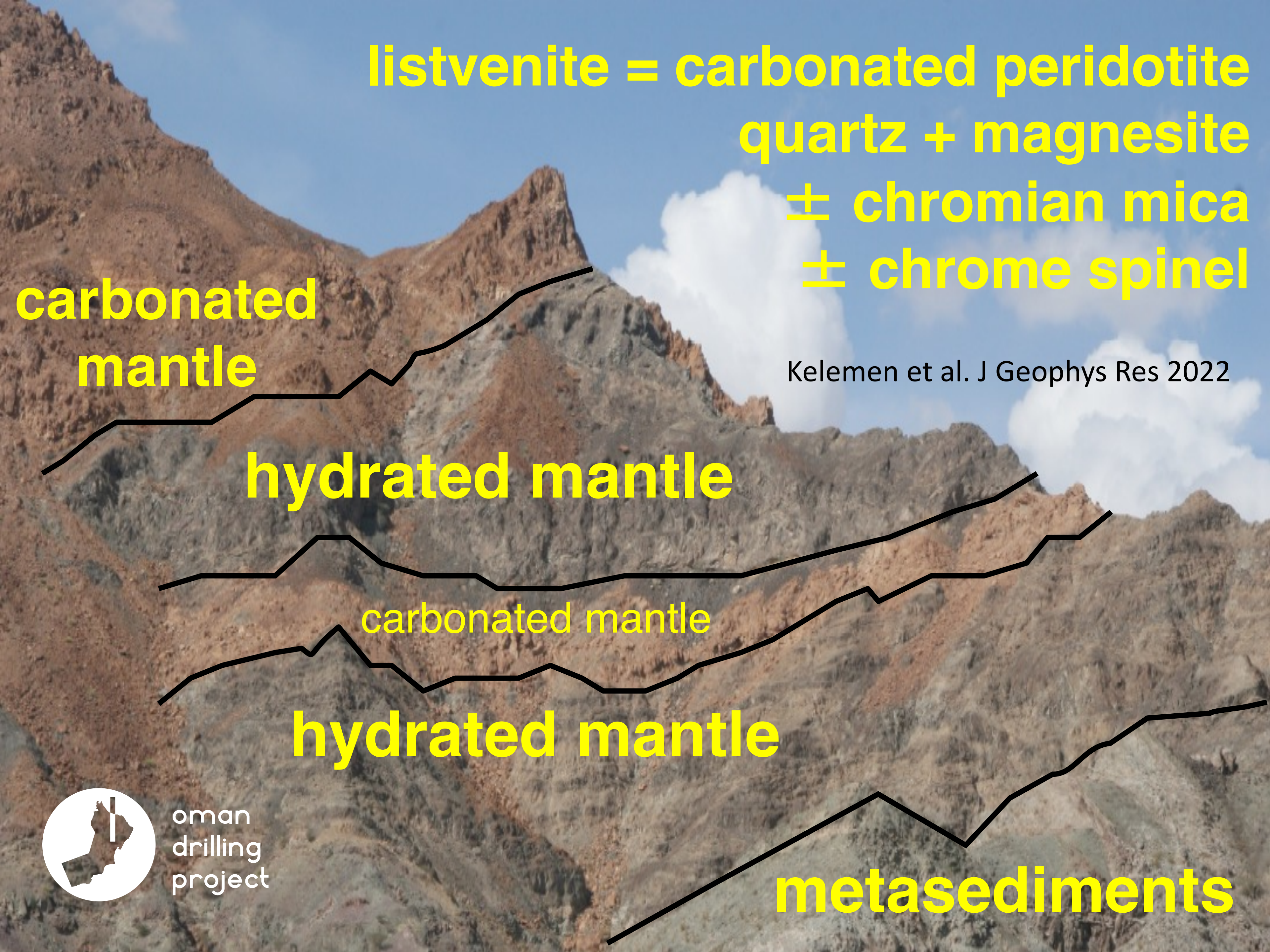
Pecoraite	$\mathbf{Ni_3(Si_2O_5)(OH)_4}$
Népouite	$\mathbf{(Ni,Mg)_3(Si_2O_5)(OH)_4}$

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
carbonated
mantle
hydrated mantle
carbonated mantle
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metasediments
oman
drilling
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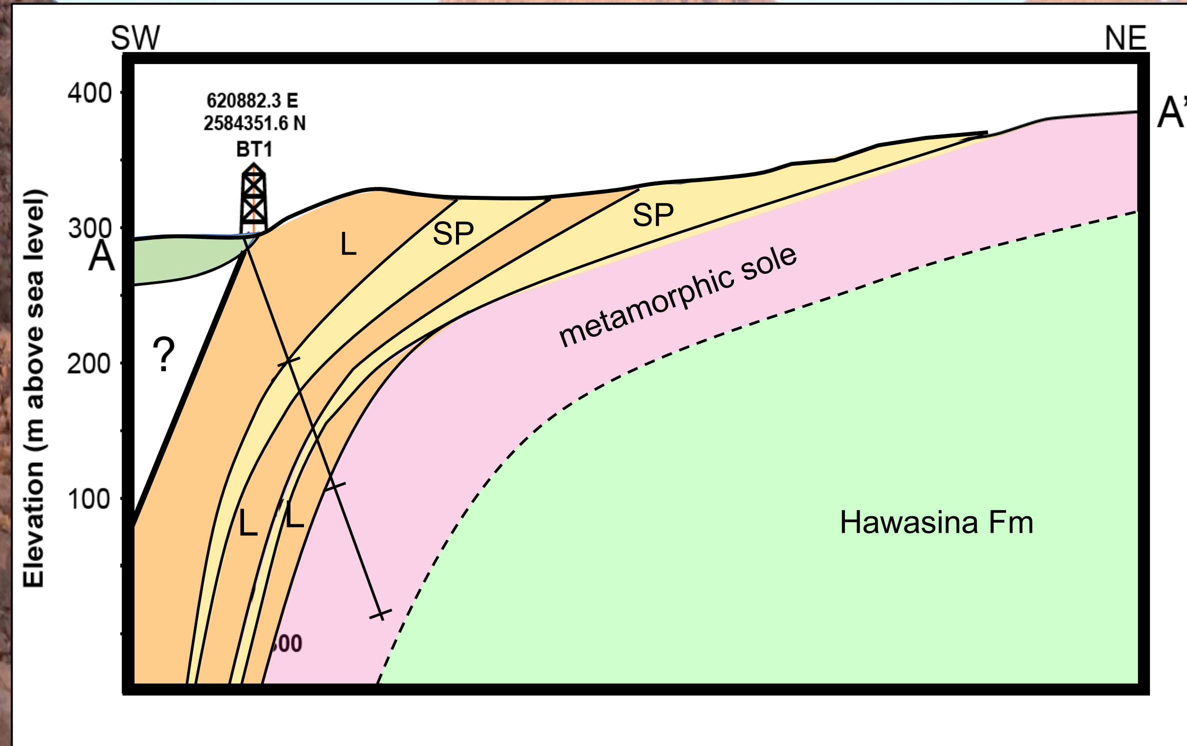
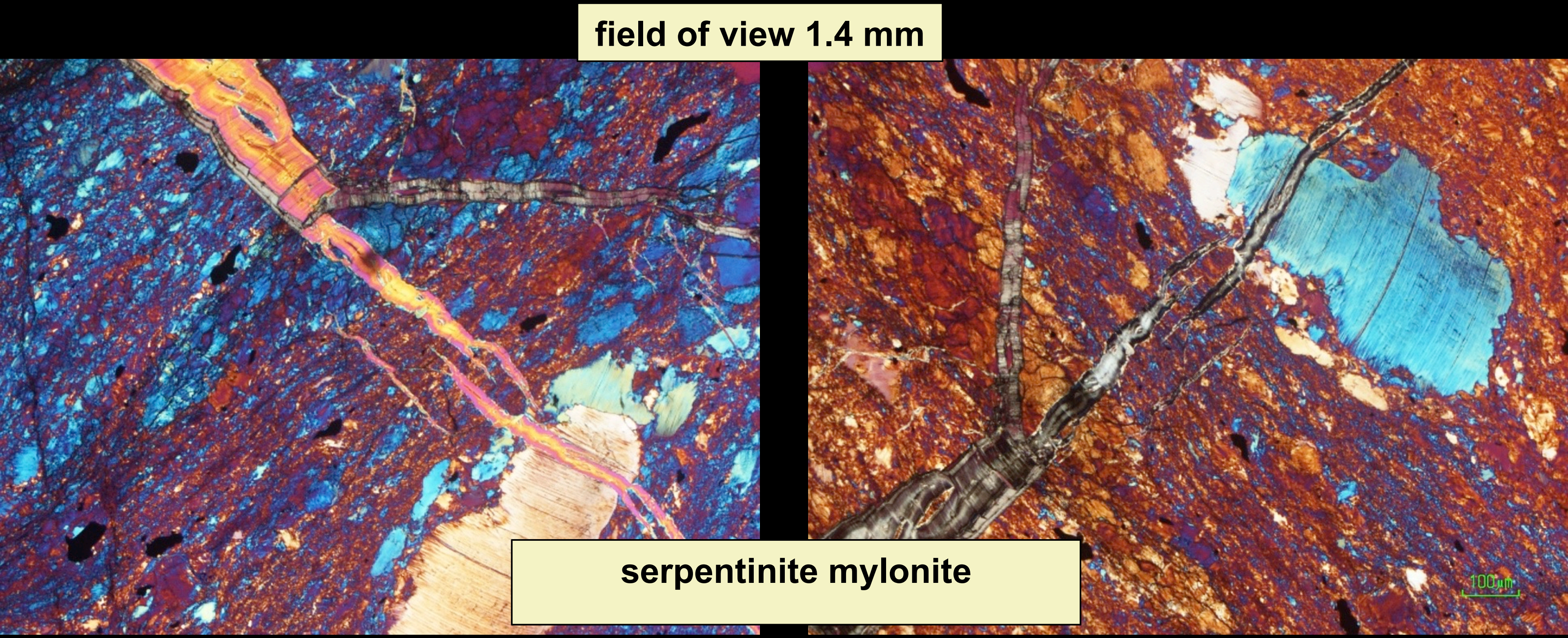
BT1
basal thrust lisvenites:
carbonated peridotite



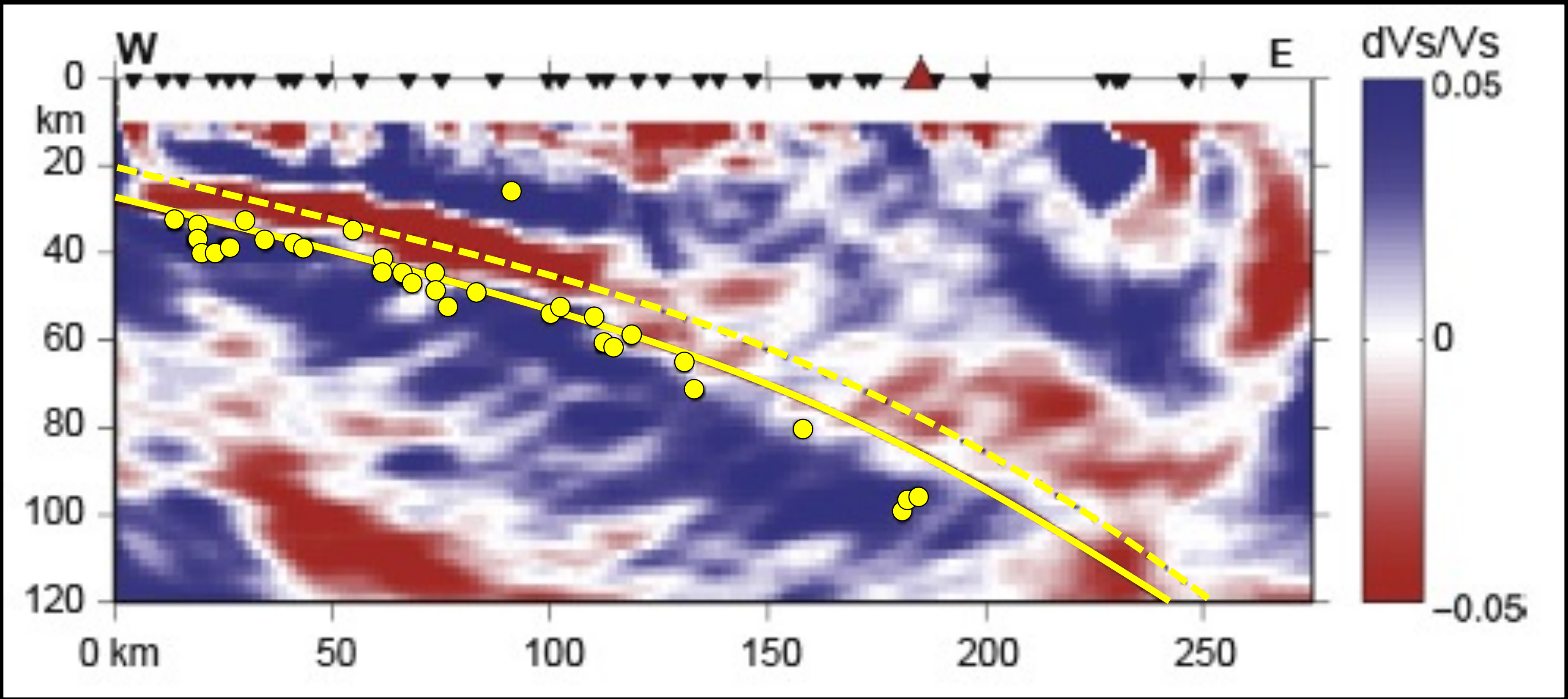


lizardite mylonite at ~ 150°C

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

Kelemen et al. J Geophys Res 2022

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

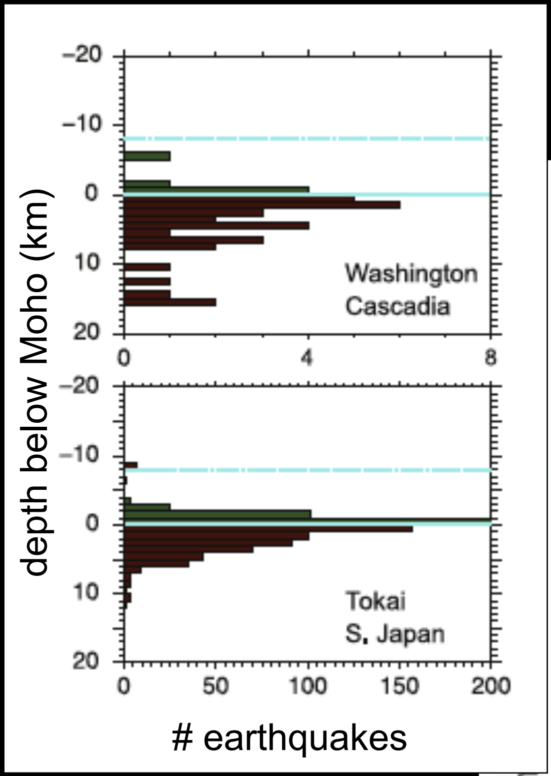


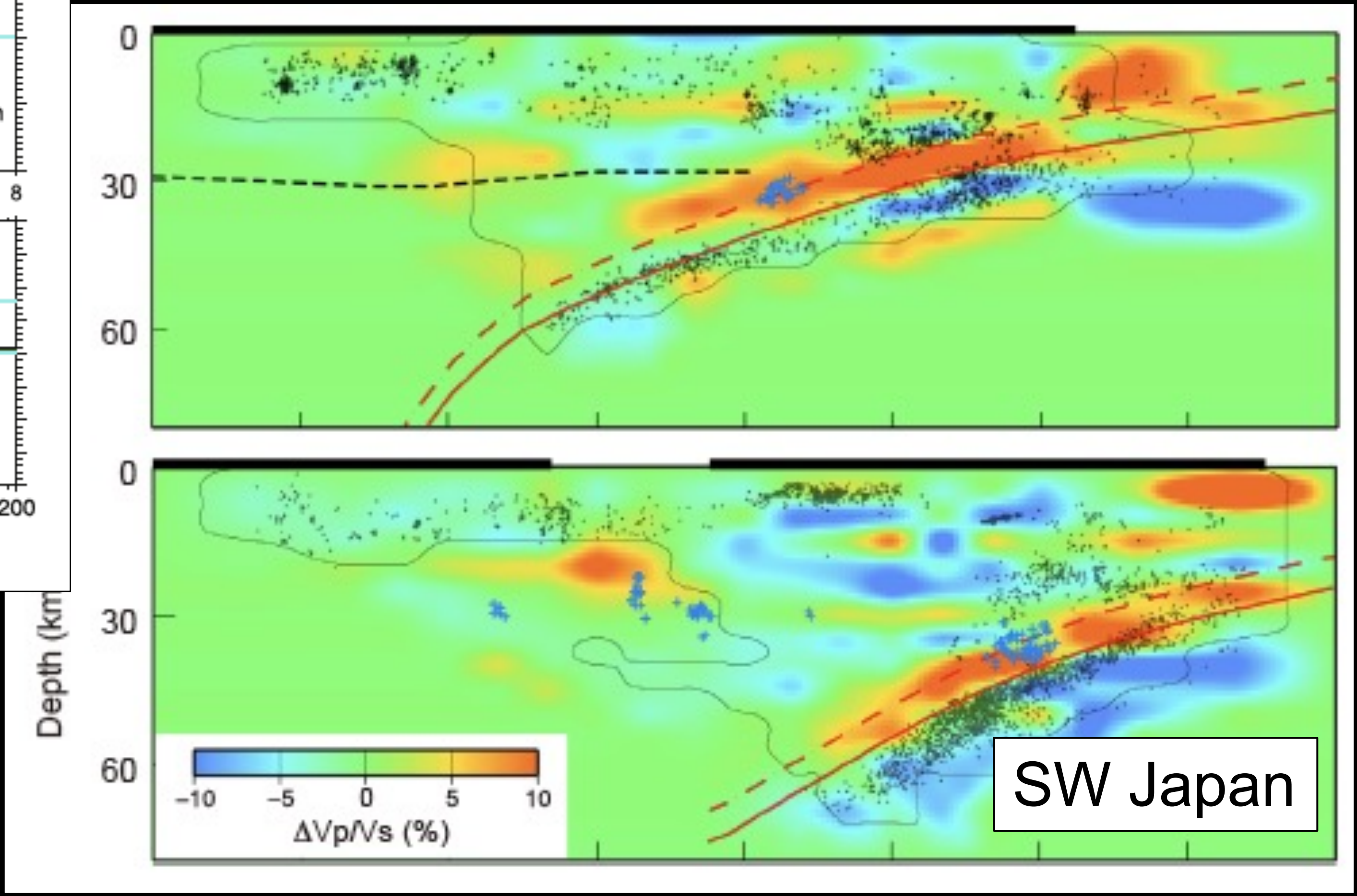
top of subducting oceanic plate
Moho in subducting plate

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

Abers et al. Geology 2009, EPSL 2013

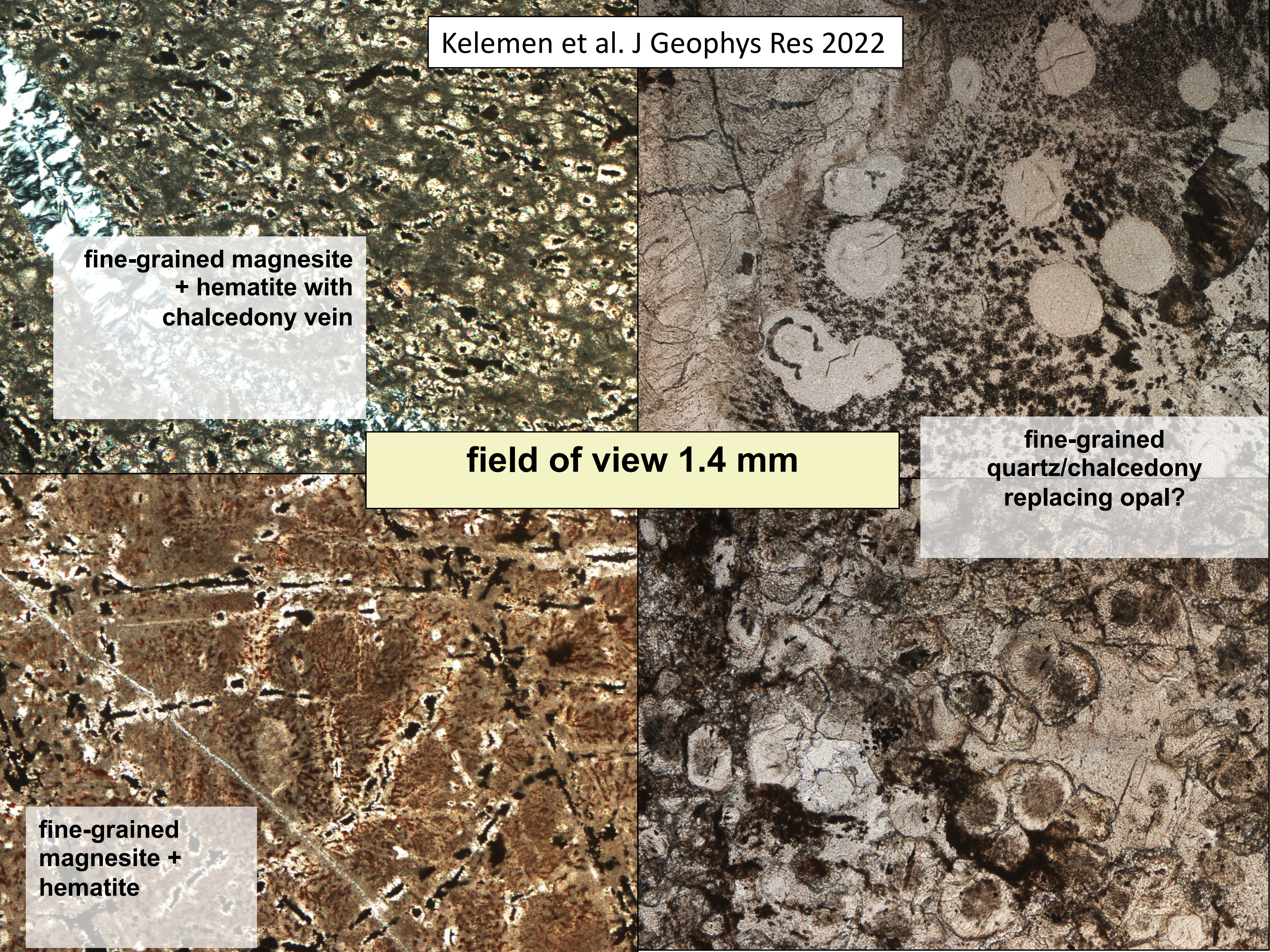
what is the “viscosity” of lizardite at low temperature and high P(H2O)

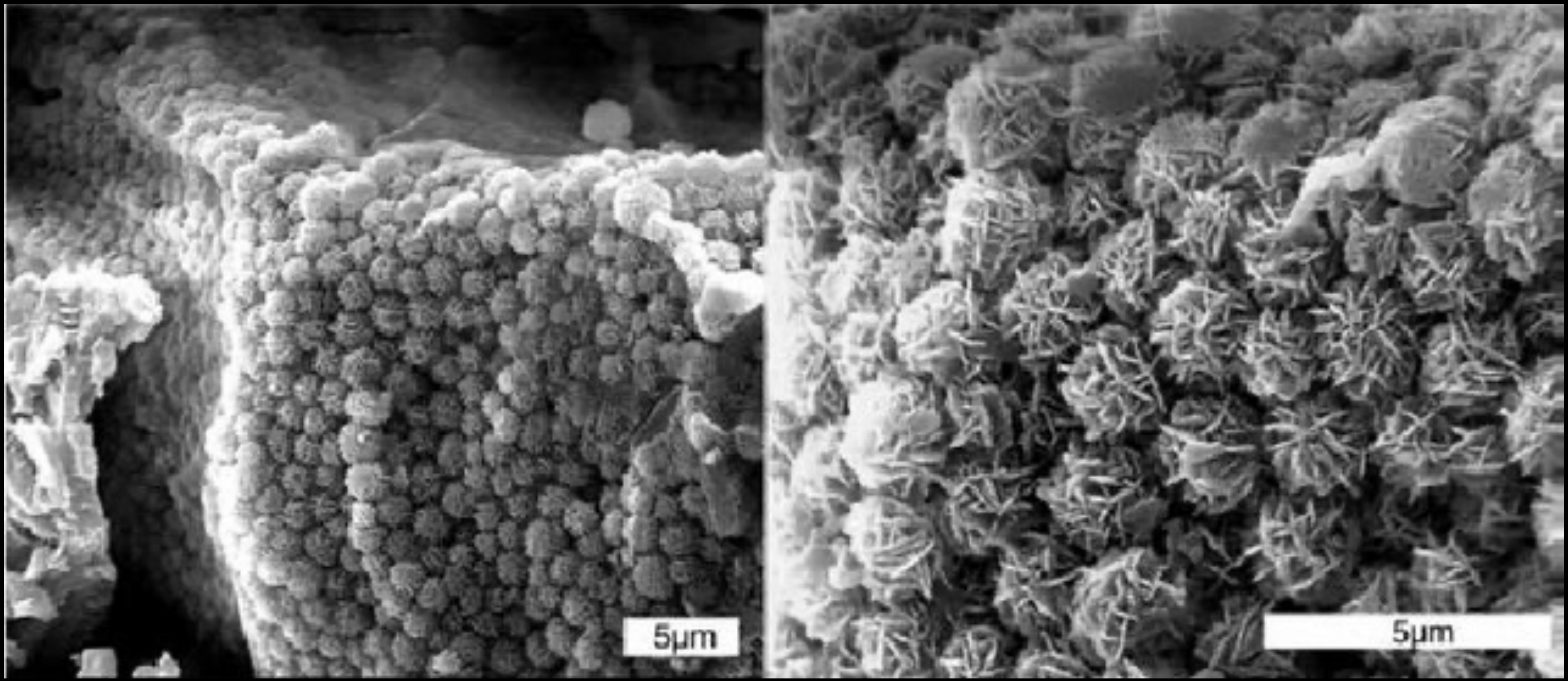




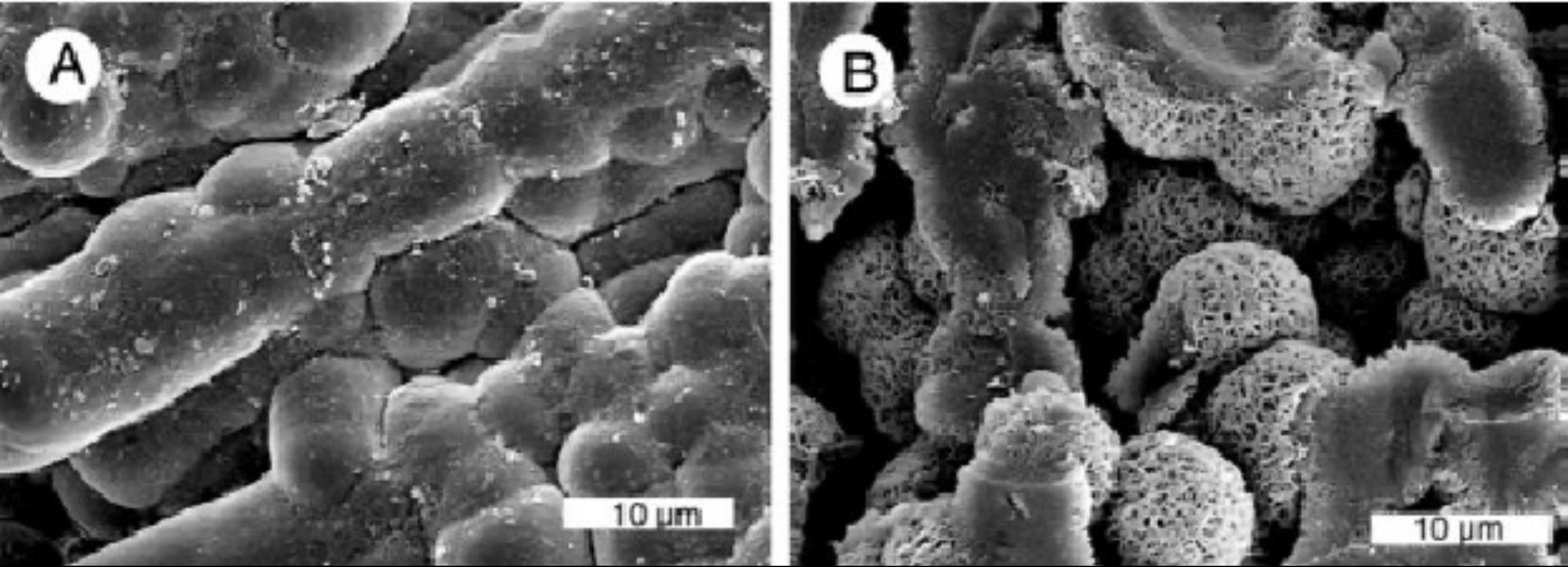
SW Japan intermediate depth earthquakes
are almost entirely at and below the Moho
in the subducting oceanic plate

Abers et al.
EPSL 2013


Kelemen et al. J Geophys Res 2022
fine-grained magnesite + hematite with chalcedony vein
field of view 1.4 mm
fine-grained quartz/chalcedony replacing opal?
fine-grained magnesite + hematite



https://www.researchgate.net/publication/282851612_Late_Tertiary_Petrified_Wood_from_Nevada_USA_Evidence_of_Multiple_Silicification_Pathways



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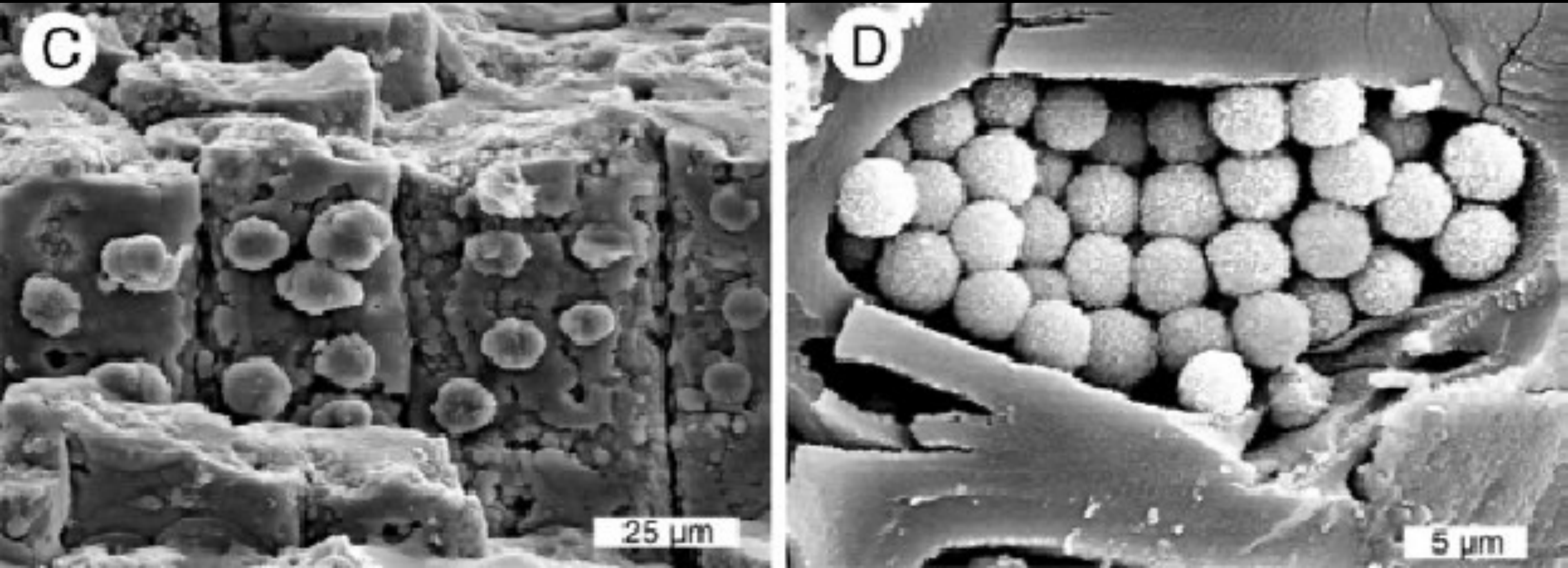
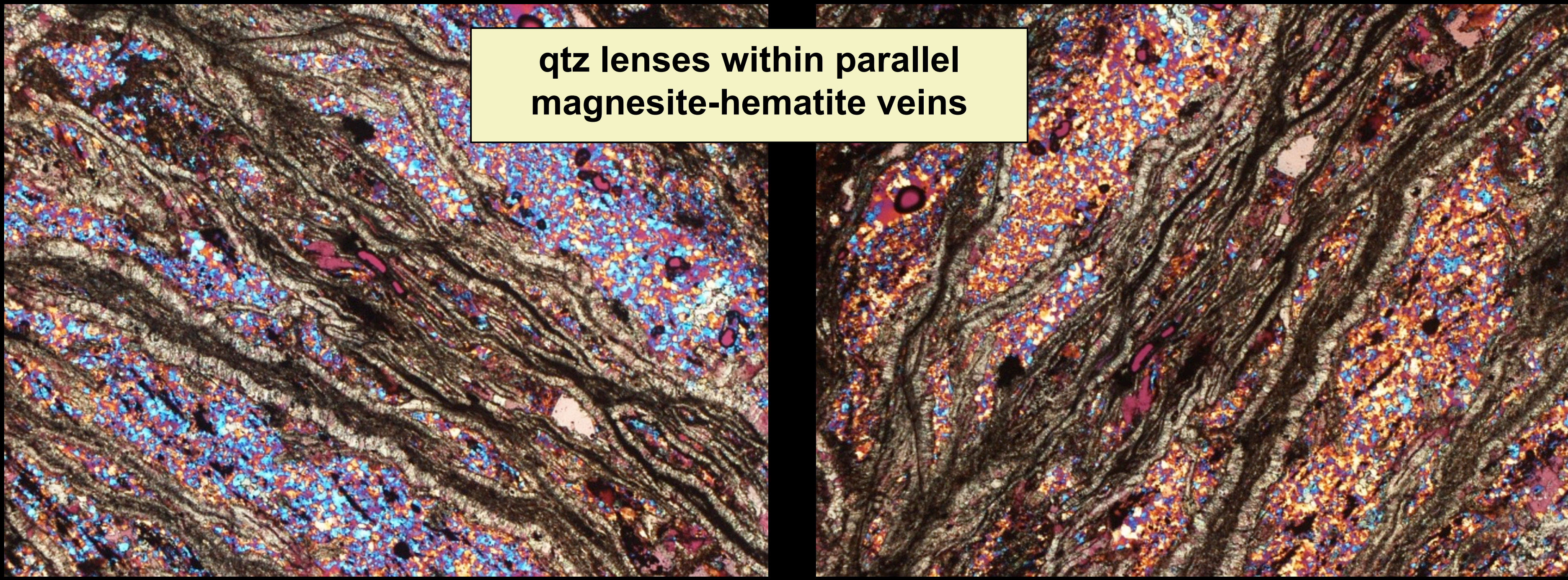
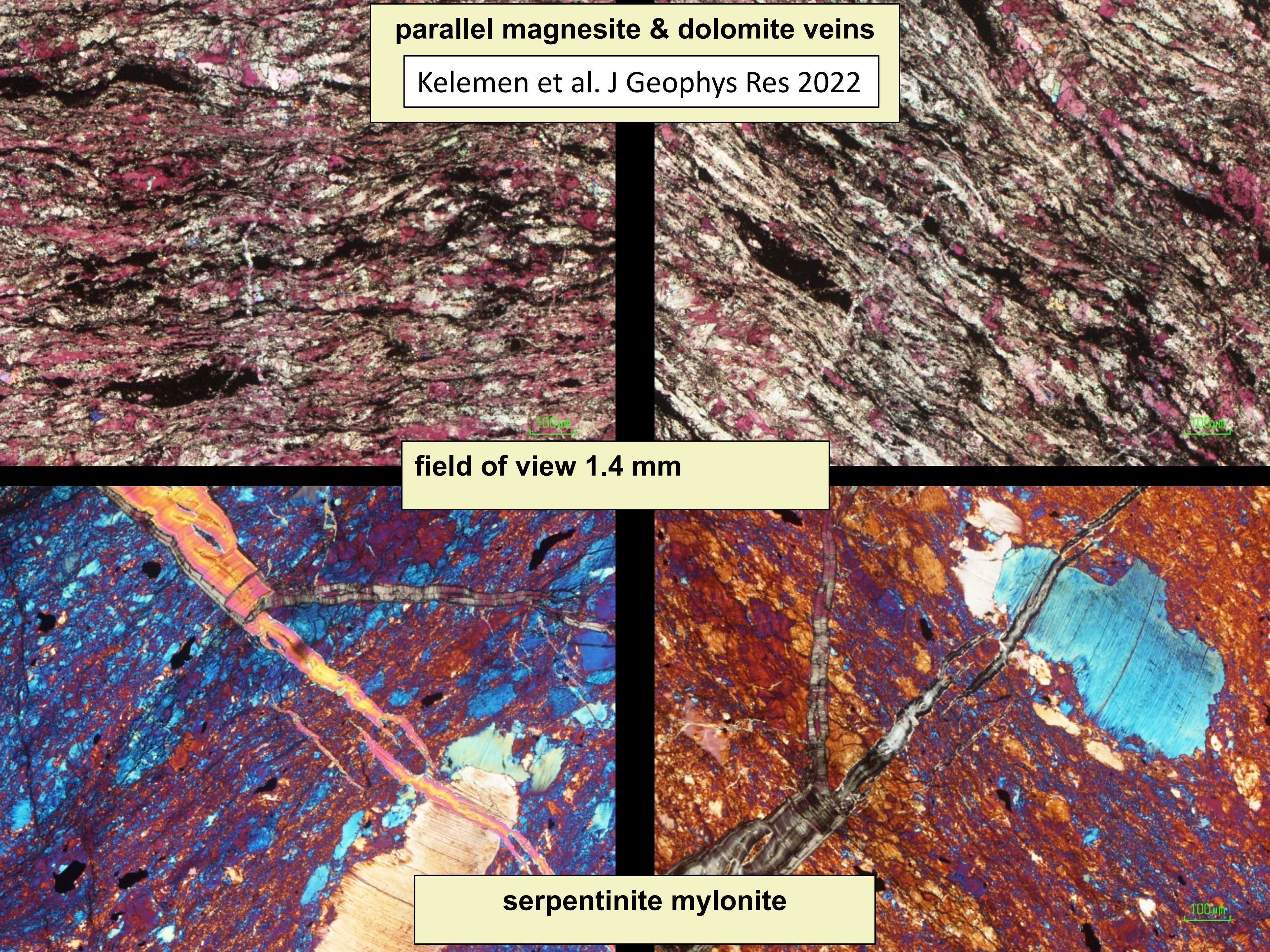


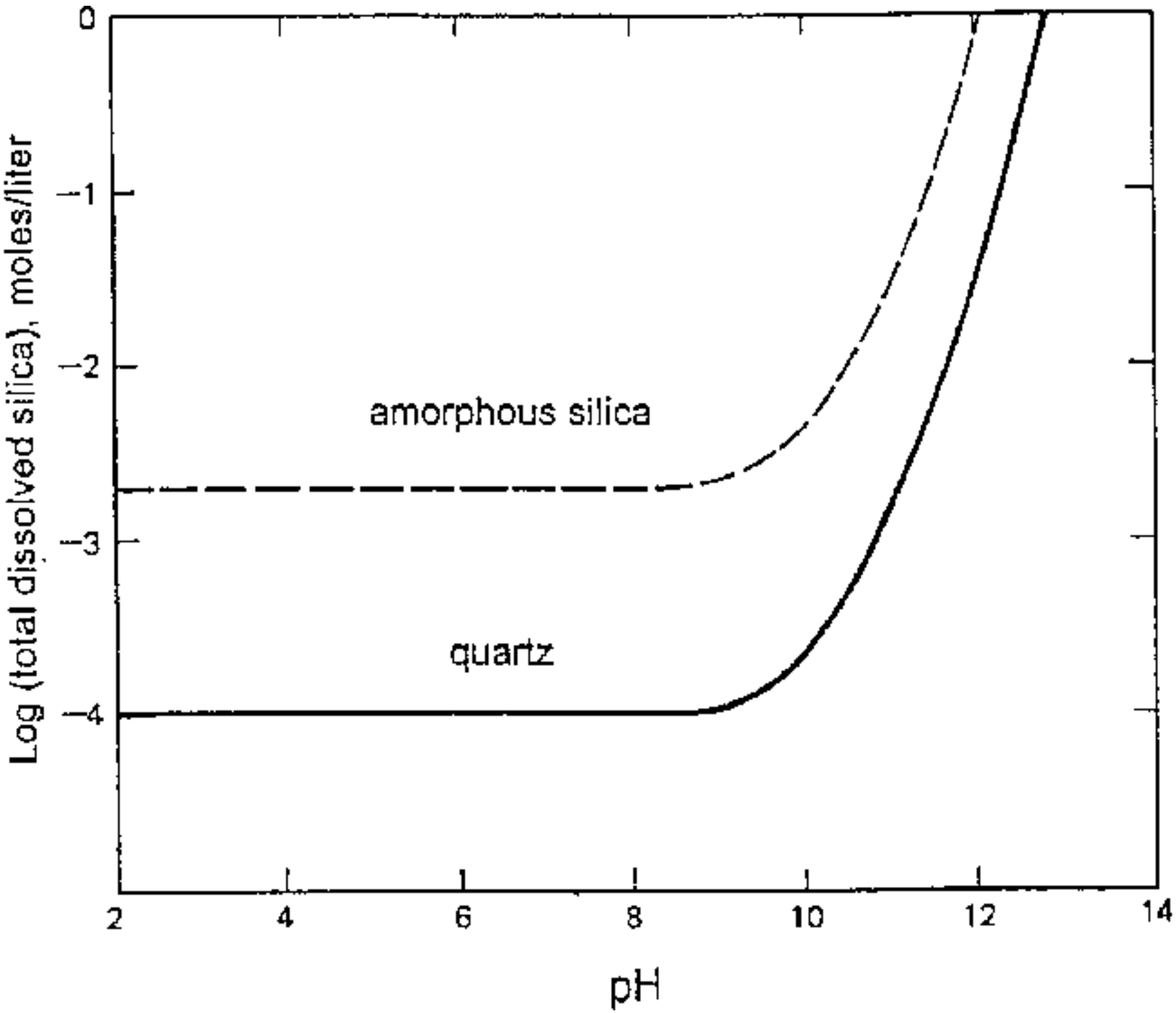


oman drilling project

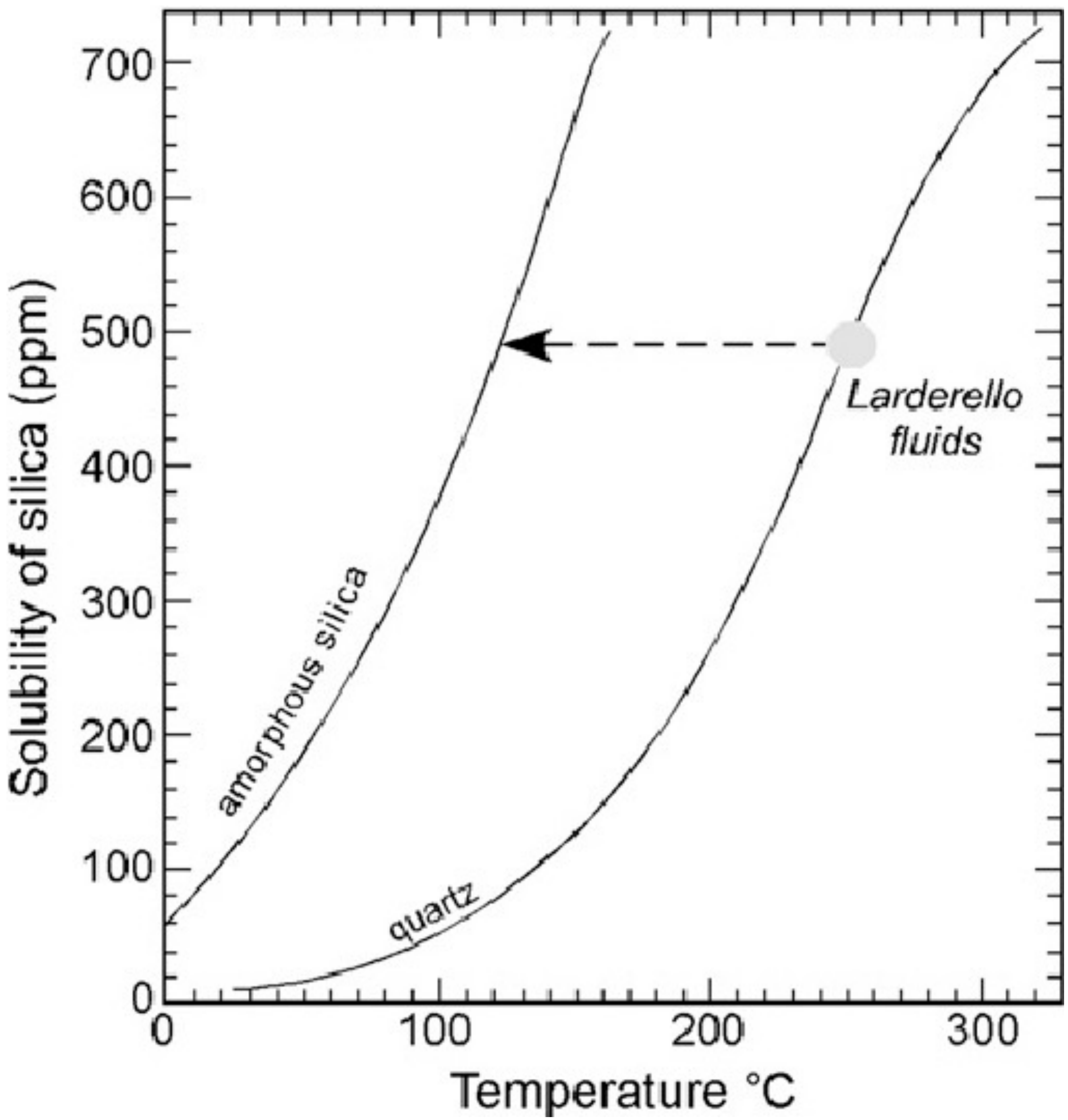
Kelemen et al. J Geophys Res 2022



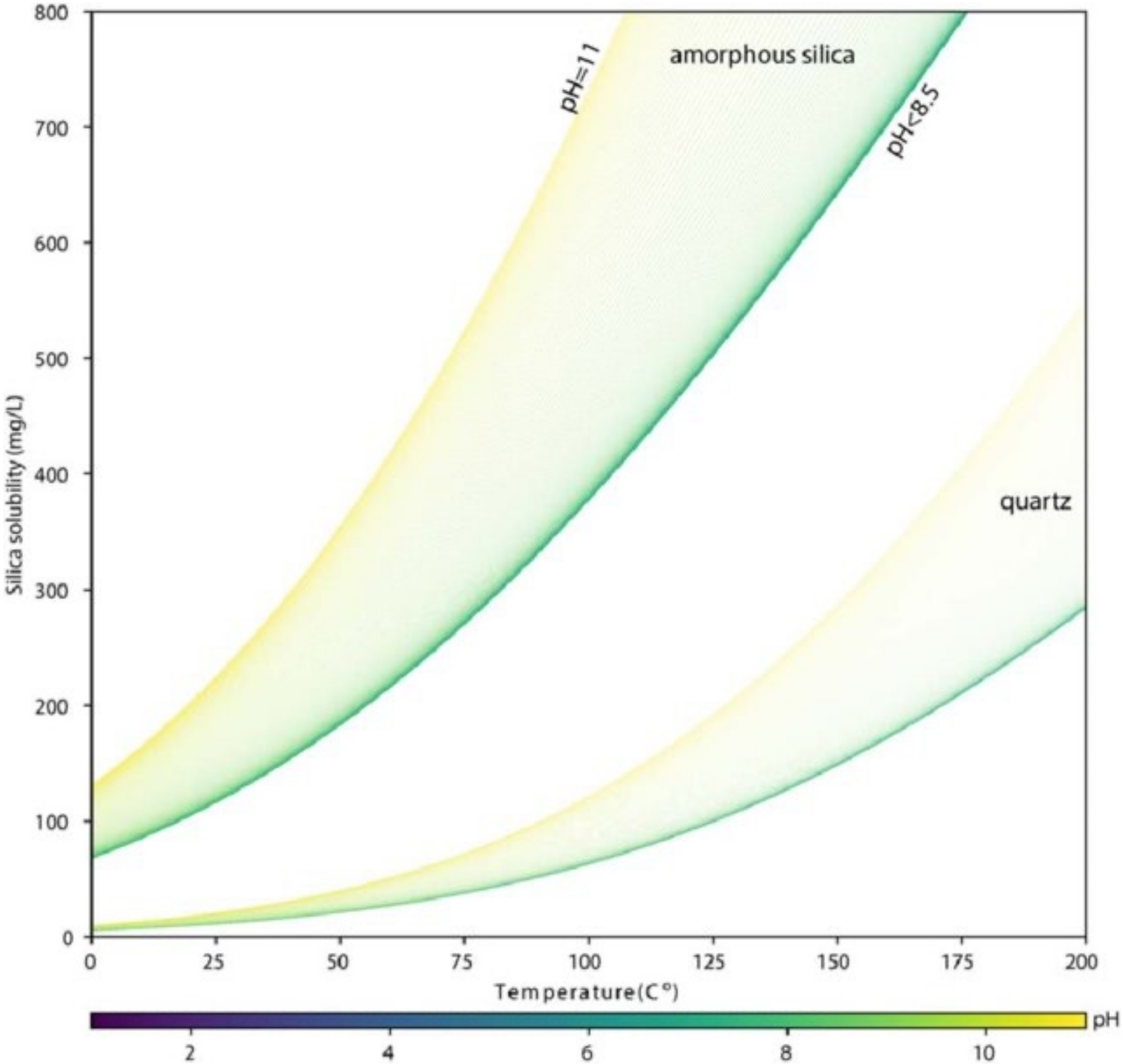
parallel magnesite & dolomite veins
Kelemen et al. J Geophys Res 2022
field of view 1.4 mm
serpentinite mylonite



https://www.researchgate.net/publication/313514282_Geochemistry_of_capillary_seepage_in_Mammoth_Cave



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
        Fe^3+ rich serpentine at lower T; papers by Klein et al., Streit et al., …)
Fe^{2+}/Fe^{3+} redox during serpentine formation from Fe^2 bearing phases
    helps drive fO_2 to ~10^{-80} to 10^{-85} bars (origin of life, abiotic H_2 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.


300 Å
thank you
for your
attention

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Forsterite (olivine) $2Mg_2SiO_4 + 3H_2O = Mg_3(Si_2O_5)(OH)_4 + Mg(OH)_2$ brucite
Enstatite (pyroxene) $3Mg_2Si_2O_6 + 3H_2O = Mg_3(Si_2O_5)(OH)_4 + Mg_3Si_4O_{10}(OH)_2$ talc
Fo + En $2Mg_2SiO_4 + Mg_2Si_2O_6 + 4H_2O = 2Mg_3(Si_2O_5)(OH)_4$