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Stress Balance in Synthetic Serpentinized Peridotites Deformed at Subduction Zone Pressures

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26 **Abstract**

27 Weak serpentine minerals affect the mechanical behavior of serpentized peridotites at depth,
28 and may play a significant role in deformation localization within subduction zones, at local or
29 regional scale. Mixtures of olivine with 5, 10, 20 and 50 vol. % fraction of antigorite, proxies for
30 serpentized peridotites, were deformed in axial shortening geometry under high pressures (ca.
31 2 GPa to 5 GPa) and moderate temperatures (ca. 350°C), with in-situ stress and strain
32 measurements using synchrotron X-rays. We evaluate the average partitioning of stresses at the
33 grains scale within each phase (mineral) of the aggregate and compare with pure olivine
34 aggregates in the same conditions. The in-situ stress balance is different between low antigorite
35 contents up to 10 vol. %, and higher contents above 20 vol. %. Microstructure and stress levels
36 suggest the deformation mechanisms under these experimental conditions are akin to
37 (semi)brittle and frictional processes. Unlike when close to dehydration temperatures, hardening
38 of the aggregate is observed at low serpentine fractions, due to an increase in local stress
39 concentrations. Below and above the 10-20 vol. % threshold, the stress state in the aggregate
40 corresponds to friction laws already measured for pure olivine aggregates and pure antigorite
41 aggregates respectively. As expected, the behavior of the two-phase aggregate does not evolve as
42 calculated from simple iso-stress or iso-strain bounds, and calls for more advanced physical
43 models of two-phase mixtures.

44 **Plain Language Summary**

45 In subduction zones, a tectonic plate plunges beneath another one, and result in large mechanical
46 stresses. These conditions can lead to earthquakes or ground displacements observable at human
47 timescales. Measuring how viscous the rocks within subduction zones are, may help understand
48 these events. Serpentinite are rocks from subduction zones which contain a variable amount of a
49 weak minerals, including serpentine, and other stronger minerals. Using deformation
50 experiments this study seeks to measure serpentinites viscosity, as a function of the amount of
51 serpentine. At low serpentine content (at least up to 10%, but lower than 20 vol.%) and under
52 temperature relevant for cold subduction zones, we found that the rock remains as hard as the
53 strongest mineral which bears the whole load, and can even become harder because of grain-
54 scale stress concentrations. At 50% volume fraction of serpentine, the rock has the same
55 viscosity as serpentine itself. These measurements may for instance help larger scale numerical
56 models of interseismic processes that happen between earthquakes, in subduction zones.

57 **1 Introduction**

58 Understanding strain localization processes within subduction zones, from long
59 timescales (convection) to intermediate scales (slow slip events over hours or days), to short
60 events (earthquakes) has become of major importance for our global picture of subduction zones
61 dynamics. However, the strain rates and the stress balance at the interface between the slab and
62 the mantle wedge, as well as those in the inner part of the subducting slab, remain poorly
63 quantified. Rheological contrasts between different lithologies are decisive for the dynamics at
64 the interface, including the exhumation of high pressure rocks (e.g., Agard et al., 2018 for a
65 review, Schwartz et al., 2001, Federico et al., 2007), as well as seismicity (e.g. Ferrand, 2019,

66 observations in Abers et al., 2013) and mantle wedge flow (e.g. Abers et al., 2006, Wada et al.,
67 2008). Knowledge of the rheology of subduction zones lithologies is thus required in order to
68 decipher their histories and present-day processes.

69 Serpentinized rocks have long been proposed to strongly influence subduction zones
70 dynamics, through a low mechanical strength (e.g., Guillot et al., 2015 and ref. therein, Schwartz
71 et al., 2001). Serpentinization is a partial or total replacement of the most abundant silicate in
72 peridotites, olivine, and pyroxene to a lesser extent, as a result of hydration. Antigorite, the high-
73 pressure, high-temperature (above ca. 300°C) variety of serpentine (e.g., Evans, 2004; Schwartz
74 et al., 2013) is potentially widespread in the mantle above the subduction interface, where fluids
75 are released by progressive dehydration of hydrous phases in the subducting slab (e.g., Schmidt
76 and Poli, 1998).

77 The rheological behavior of fresh dunite and peridotites, or olivine aggregates under high
78 pressure - low temperatures below and up to 600°C, has been investigated for decades (e.g.,
79 Gaboriaud et al., 1981; Shimada, 1993; Raterron et al., 2004; Boettcher et al., 2007; Long et al.,
80 2011, Druiventak et al. 2011, Proietti et al 2016, Mei et al, 2010). The rheology of serpentine
81 aggregates and natural serpentinites has been studied under pressures up to 4 GPa and from
82 ambient temperature up to dehydration temperatures (e.g., Escartin et al., 1997; Hilairet et al.,
83 2007; Chernak and Hirth, 2010; Proctor and Hirth, 2016; Hirauchi et al, 2020; Shao et al, 2021,
84 Burdette and Hirth, 2022). At single-crystal scale, olivine mechanical properties have also been
85 investigated under low temperatures (e.g. Evans and Goetze, 1979; Gaboriaud et al., 1981;
86 Kranjc et al., 2016; Kumamoto et al., 2017, Idrissi et al, 2016), and more recently those of
87 antigorite (Hansen et al., 2020; Idrissi et al., 2020).

88 On the other hand, the mechanical behavior of serpentinized rocks has not been
89 systematically investigated. Experiments have been carried out mostly under pressures below 2
90 GPa on the low temperature serpentine varieties lizardite and chrysotile (e.g. Escartin et al.,
91 2001). High pressure experiments on antigorite-olivine aggregates or antigorite-rich serpentinites
92 have mostly been targeted at antigorite dehydration conditions, owing to its potential link with
93 subduction zone seismicity (e.g. Dobson et al, 2002; Jung et al, 2004; Xia et al, 2013; Chernak
94 and Hirth, 2011; Gasc et al, 2011; Gasc et al, 2017; Ferrand, 2017; Ferrand et al, 2017).

95 Olivine and serpentine have different intrinsic elastic and crystal-plastic properties.
96 Therefore the resulting elastic and plastic properties of the serpentinites may not be easily
97 predicted from the end-members (in the following, ‘plastic properties’ refers to crystal plastic
98 properties unless otherwise stated). Burnley (2013) for instance, modeled how contrasts in elastic
99 and plastic properties can lead to variable local stress states, due to stress percolation.

100 Microstructure is also expected to influence stress distribution throughout a deforming
101 two-phase aggregate. Indeed, serpentinites can be found within heterogeneously deformed shear
102 zones and tend to have strong preferred orientations (e.g., Nishii et al., 2011; Padron-Navarta et
103 al., 2012; Morales et al., 2018). Handy (1990, 1994), laid out a conceptual framework with two
104 end-members 1) the strongest phase controls the stress through a load-bearing framework 2) the
105 weakest phase controls deformation because it is spatially connected, being either abundant
106 enough to be connected prior to deformation, or becoming connected through increasing strain
107 amount. More recently Gerbi et al., (2016), underlined that beyond the simple connectivity of
108 weak phases in natural rocks, development of weak zones bridging the weak phase can control
109 the aggregate strength.

110 Analytical mixing models, ranging from simple end-member models to more complex
111 models, do exist for flow laws (e.g., Tullis et al, 1991, Takeda, 1998, Huet et al, 2014), but are
112 not easily applicable when frictional processes and semi-brittle deformation occur. A wealth of
113 numerical studies on two-phase geological aggregates is available in the literature, based one
114 way or the other on Finite Elements Models (e.g. Tullis et al, 1991, Madi et al, 2005, Jessell, et
115 al, 2009, Cook et al, 2014, Cyprych et al., 2016), sometimes combined with mean-field or
116 analytical approaches (e.g. Canova et al., 1992, Thielmann et al., 2020). These numerical models
117 remain costly computationally and need anchoring on observables and experimental work in
118 order to be relevant and well-targeted. Experimental mapping of physical (pressure, temperature,
119 strain rate, strain) and microstructural conditions for specific deformation regimes of
120 serpentinites is therefore necessary.

121 A number of studies have taken advantage of high-pressure deformation experiments
122 with in-situ synchrotron X-ray measurements in two-phase mineralogical assemblages, which
123 allow to investigate the stress partitioning between the different phases (Li et al., 2007; Wang et
124 al., 2013; Girard et al., 2016; Kaercher et al., 2016; Farla et al., 2017; Lin et al., 2019, Togle, et

125 al., 2021). We present here an experimental study of the effect of serpentine fraction within a
126 mixture of olivine+antigorite, on the mechanical behavior of the aggregate. The deformation
127 experiments were carried out under high pressure and high temperature, in axisymmetric
128 shortening (pure shear). Using *in situ* stresses and strain measurements, here we evaluate the
129 partitioning of stresses within each phase (mineral) of the aggregate. These results show two
130 distinct regimes for stress partitioning as a function of the antigorite volume fraction, with
131 different mechanisms for stress control.

132 **2 Methods**

133 The deformation experiments were carried out in the D-DIA large-volume press at ID6-
134 LVP at the European Synchrotron Radiation Facility in Grenoble, France (Guignard and
135 Crichton, 2015). A monochromatic beam with a wavelength corresponding to 33 keV was used,
136 with a beam size of ca. 1 mm wide by 0.5 mm height.

137 The samples were powders ground and mixed from natural San Carlos olivine and
138 antigorite from Corsica, used in Ferrand et al. (2017) and Ferrand (2017) with 5, 10, 20 and 50
139 vol. % antigorite. The powders were sieved for grain sizes below ca. 30 microns. Upon
140 compression under high pressure (P) and high temperature (T) (1.5 GPa, 773K), the resulting
141 aggregates display a rather homogeneous distribution of the phases (Ferrand, 2017). Antigorite is
142 distributed in patches, referred to as “clusters” in Ferrand et al. (2017), that become connected at
143 the highest antigorite fraction. In the present experiments the mixtures were hand-pressed and
144 directly loaded within the high-pressure cells.

145 Anvils with 6 mm truncation were used, made of tungsten carbide on the upstream side
146 and sintered diamond (SD) on the downstream side, for recovering full angular dispersive
147 diffraction patterns. 9 mm edge cubic cells were used (figure S1), with amorphous B+epoxy as
148 pressure medium, a graphite furnace, porous alumina pistons, and zirconia plugs for thermal
149 insulation. In each run, two samples were stacked in the cell: ca. 1.5 mm height, pure olivine
150 powder, and ca. 1.5 mm height, two-phase powder (antigorite + olivine). The pure olivine
151 powder is used as a reference in the same P and T conditions as each two-phase aggregate, in
152 order to compare runs between themselves. All samples were separated from one another and
153 from the pistons by 20 microns-thick gold foils.

154

155 The samples were compressed at a target load of 30 bars, intended to reach hydrostatic P
156 ca. 3 GPa (not always reached, see table 1). The temperature was imposed by a current
157 circulating through a graphite furnace and estimated from an off-line calibration, between 395
158 and 420°C at the beginning. The shortening of the assembly during deformation in the D-DIA
159 can induce changes in the T gradient (Raterron et al., 2013). Based on their results (at 1673 K,
160 much higher than the present study) and the total length of our samples, here a temperature of
161 300 to 350°C is assumed. The stresses built-up during compression were relaxed at the run T for
162 about 1 hour prior to deformation. The samples were then shortened up to the final strain,
163 quenched and decompressed, and finally recovered for SEM analysis.

164 Sample axial strains were measured using X-ray radiography. Due to the x-ray beam
165 height of 0.5 mm, the samples stacks were scanned in the vertical direction to take a series of 12
166 or more images, and the full image was reconstructed. One full image was typically acquired
167 over a few seconds, which remains very short with respect to the speed of deformation. The
168 strain is defined as $\varepsilon = \ln(l/l_0)$, l being the sample length and l_0 the reference length taken at the
169 beginning of the deformation (start of differential rams). The experiments were carried out at
170 strain rates around 10^{-5} s^{-1} and total strains up to ca. 30% (Table 1).

171 2D X-ray diffraction (XRD) patterns were collected on a rotating linear 1-D detector (see
172 Guignard and Crichton, 2015, for details), with a typical acquisition time of the order of 1 minute
173 for a 360° full azimuthal acquisition. The detector tilt and rotation relative to the incident beam
174 were calibrated with a LaB₆ standard using Fit2D (Hammersley, 2016). The 2D diffractions
175 allowed recovering stresses within phases in the single-phase and two-phase samples for each
176 run. The full framework for these analyses has been widely presented in the literature (e.g.,
177 Uchida et al., 1996; Singh et al., 1998). For a polycrystal under differential stress, departure of
178 the powder diffraction pattern from ideal rings can be used as a proxy for the supported
179 differential stress. This departure is referred to as “lattice strain”, noted $Q(hkl)$ for the hkl
180 diffraction line. The isotropic component of the stress tensor (the mean stress), hereafter called
181 either pressure (P) or mean stress, can also be recovered. The analysis was carried out using the
182 Multifit – Polydefix software available online at <http://merkel.zoneo.net/Multifit-Polydefix/>
183 (Merkel and Hilairet, 2015).

184 P was calculated using a thermal equation of state for San Carlos olivine (Guyot et al.,
185 1996) in the reference sample and in the two-phase sample. Both were fairly consistent (table 1).
186 Antigorite d-spacings were not converted to pressures because only one diffraction plane with
187 robust information was available.

188 Converting lattice strains into macroscopic stresses is not straightforward (see Chen et
189 al, 2006, Burnley and Zhang, 2008, Merkel et al, 2009 for a full discussion, and Hilairet et al,
190 2011 on olivine specifically). Lattice strains from the 021, 101, 130, 131 and 112 diffraction
191 lines (pbnm setting is used throughout the manuscript) were recovered for olivine in both the
192 single-phase aggregates and in the two-phase aggregates. The stresses were calculated from
193 different $Q(hkl)$ using elastic stiffness tensors (C_{ij}) at the relevant P and T (Isaak, 1992; Zha et
194 al., 1996) assuming a constant stress hypothesis (Uchida et al., 1996; Singh et al., 1998). This
195 leads to a spread of stresses calculated from different crystallographic planes, which are then
196 averaged to represent the aggregate stress. This averaging represents the main limitation of *in*
197 *situ* stress measurements based on XRD, as it has no theoretical grounds and does not take into
198 account plastic relaxation occurring within the sample. As of today, there is no satisfactory way to
199 obtain the stress uncertainty. Elasto-Visco-Plastic Self-Consistent (EVPSC) modeling of the data
200 has been proposed as an answer to this pitfall (Burnley and Zhang, 2008; Burnley, 2015). The
201 implementation of relevant mechanisms for olivine deformation into these codes, however, is
202 still incomplete (Hilairet et al., 2011; Burnley, 2015). We believe some precautions ensure that
203 relative comparisons can still be made out of these measurements. First, the deformation curves
204 for the four runs display the same relative evolutions for the different planes (not shown), and we
205 compare here averages from the same lattice strains. Second, the texture of the olivine in the
206 aggregates is weak and the diffraction lines include many more crystal orientations than in a
207 strongly textured case. The planes (021), (101), (130), (131) and (112) cover the three main
208 lattice directions in olivine, hence the average is not biased by underrepresented directions of the
209 unit cell.

210 For antigorite, we recovered lattice strains for the 001 diffraction lines for all two-phase
211 samples. Only pressure dependencies of C_{ij} for antigorite are available (Bezacier et al., 2010).
212 The expected effect of increasing T would be opposite effect to that of P. Therefore C_{ij} at
213 ambient P and T were used. This also allows to keep consistency with previous results on
214 antigorite aggregates (Hilairet et al., 2007). Using C_{ij} at 3 GPa and ambient T increases the

215 calculated $t(hkl)$ stresses by about 15%, which provides an upper bound for the interpretation of
 216 the results.

217 **3 Results**

218 The main results from in-situ measurements are summarized in table 1. Olivine and
 219 antigorite are referred to as ‘ol’ and ‘atg’ in the table and figures.

220 **Table 1.** Summary of experimental runs conditions.

run #	atg vol. % in two phase aggr.	Strain rate ref.	final strain ref.	Strain rate two- phase aggr.	final strain two- phase s aggr.	σ_{ol} ref. (GPa) ^a	P ref. (GPa) ^b	σ_{ol} two- phase aggr. (GPa) ^a	P two- phase aggr. (GPa) ^b	σ_{atg} (001) (GPa)	peak $\sigma_{atg(001)}$ (GPa)
serp6	0.05	-1.99E-05	-0.23	-1.58E-05	-0.20	3.78	4.86	3.69	4.91	1.06	2.18
serp7	0.1	-1.43E-05	-0.25	-1.66E-05	-0.29	3.73	4.00	3.49	4.00	1.68	2.58
serp9	0.2	-1.17E-05	-0.14	-4.52E-05	-0.27	3.23	1.89	3.02	1.78	2.84	2.84
serp10	0.5	-1.77E-05	-0.19	-3.61E-05	-0.34	3.25	3.18	2.67	3.17	2.64	2.64

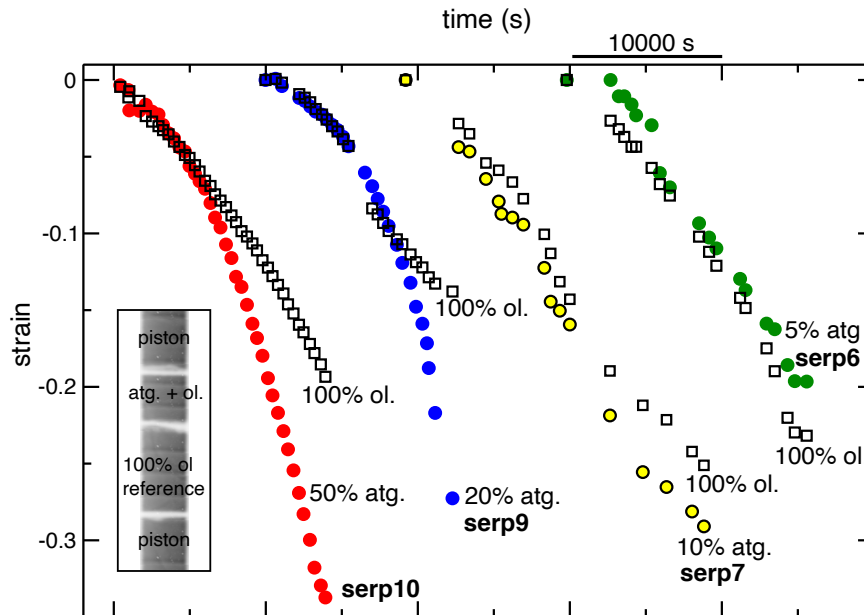
^a stress calculated from olivine diffraction planes

^b P measured from olivine diffraction, given here at the final strain

221

222 3.1 *In-situ* strain rate

223 The strain rates of the two-phase aggregate with 5 and 10 vol. % and their respective
 224 reference aggregates are similar (fig. 1).

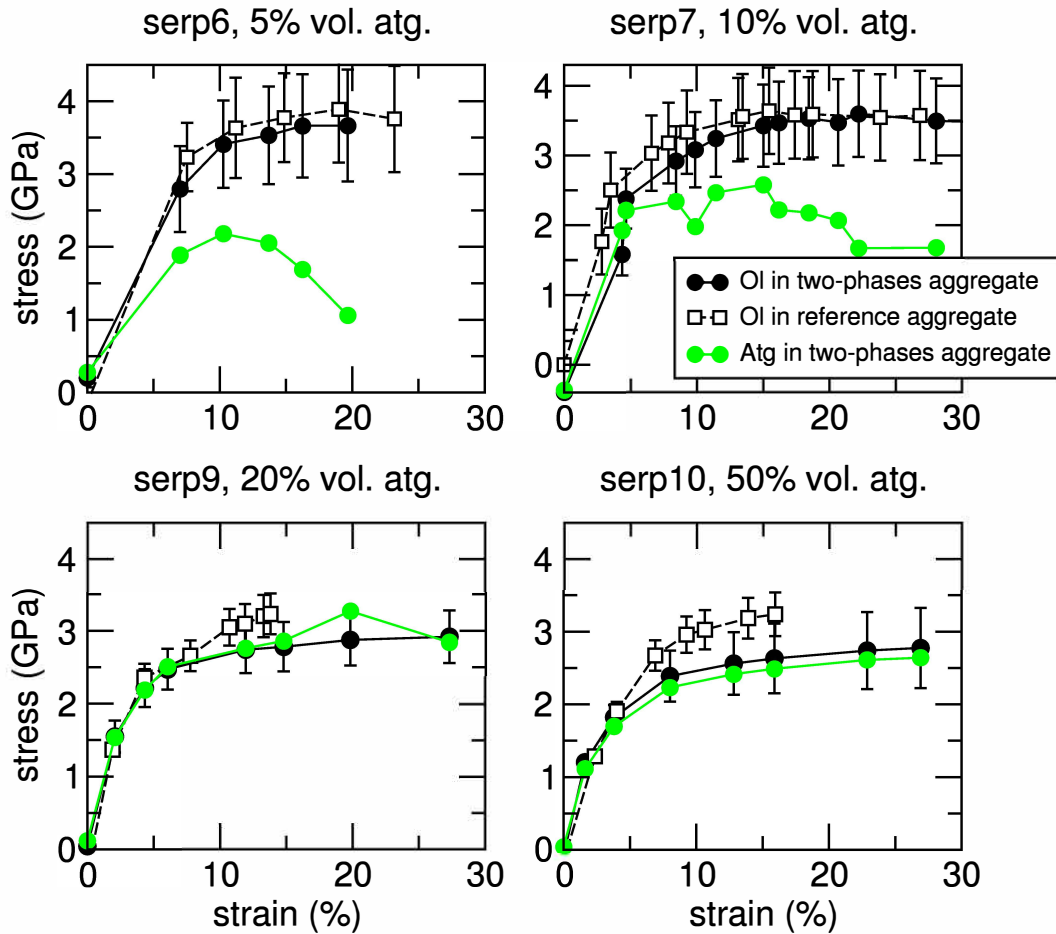


225 **Figure 1.** Strain evolution with time for the two-phase aggregates (filled symbols) and for the reference (100 vol. % olivine
 226 aggregate, empty squares). Each run (serp6, 7, 9, 10) had a reference aggregate in the column stack, as shown in the inset. The
 227 curves have been shifted one run from another on the time axis, for visibility. The scatter on runs serp6 and serp7 is due to the
 228 image analysis process, which was improved for runs serp 9 and serp10. The jump and change of slope seen on serp9 is real.
 229

230 With 20 and 50 vol. % antigorite, the two-phase aggregates deformed faster than the
 231 reference aggregate. The speed of the differential rams was identical in all experiments
 232 (175 $\mu\text{m}/\text{hour}$). The scatter in runs serp6 and serp7 (two-phase and reference aggregate) is due to
 233 difficulties in reconstructing an image of the full sample column, from the series of images taken
 234 while scanning the column. However, the jump in strain in run serp9 on the olivine reference
 235 aggregate is real, and very likely related a failure in the reference aggregate. This is further
 236 examined in the discussion.

237 3.2 *In-situ* partitioning of stresses

238 The diffraction allows us to obtain stress information in each of the two minerals of the
 239 two-phase aggregates, which are reported in fig. 2 as stress-strain curves.



240
 241 **Figure 2.** Stress partitioning as a function of strain measured in the olivine (ol, solid black circles) and antigorite (atg, green) of the
 242 two-phase aggregates, compared to stress - strain curve measured on the olivine single-phase reference aggregate (empty black
 243 squares) for each experiment. Stress was not measured for each strain step shown in fig. 1, therefore the final strain shown here
 244 can be different. For olivine the stress is calculated from averaging the stress measured on different crystallographic planes. The
 245 error from the diffraction fitting is typically the size of the symbols, the bars represent the standard deviation for the average
 246 stress (not an actual error on stress, see further information in the methods section). For antigorite, only one plane could be
 247 confidently analyzed.

248 Olivine (*hkl*) planes stresses calculated from available lattice strains $Q(hkl)$ are averaged
 249 for clarity. Since the same diffraction planes are considered, and since $Q(hkl)$ relative amplitudes
 250 remain similar, the averaged stresses from the two-phase and the reference aggregates can be
 251 compared (also see methods section for stress uncertainty). For the antigorite bearing aggregates,
 252 only the basal 001 diffraction peak of antigorite could be confidently fitted. In the 5 vol. %

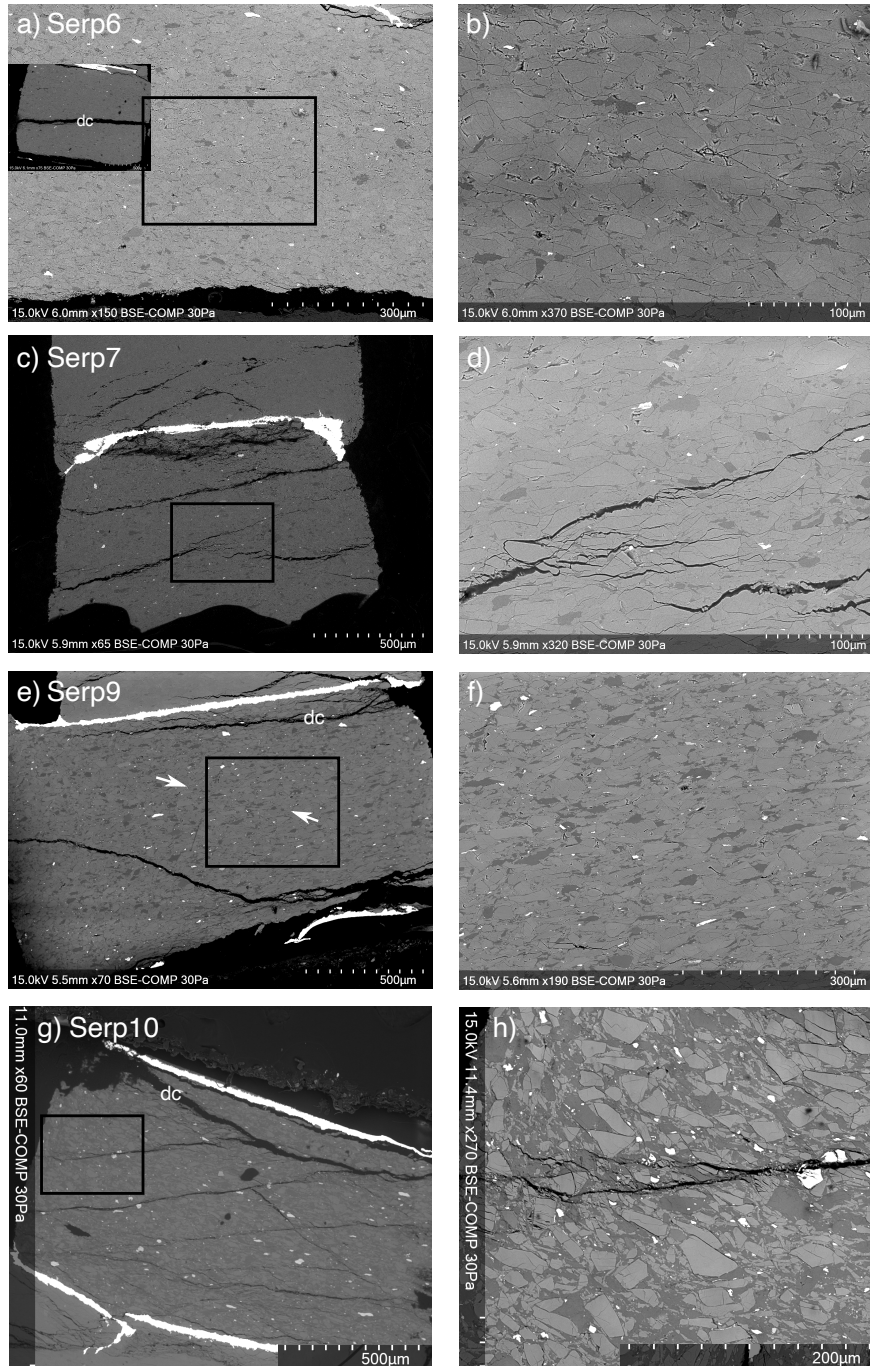
253 sample, as deformation proceeded the signal on this 001 diffraction line broadened and became
254 too faint to be analyzed.

255 The 5 and 10 vol. % antigorite aggregates on one side, and the 20 and 50 vol. %
256 antigorite aggregates on the other side, show a different behavior of the (001) plane. The stress
257 on (001) becomes similar to the olivine mean stress when the amount of serpentine is 20% or
258 more. For antigorite-poor aggregates, the stress reaches a maximum and then decreases (fig. 2).
259 The 001 peak then disappears for 5 vol. % antigorite sample, while with the 10 vol. % antigorite,
260 it remains present and reaches a plateau.

261 3.3 Microstructures

262 In recovered samples, a wide range of brittle features are observed, from micro-cracking,
263 to diffuse or single fracturation at sample scale, sometimes overprinted with unloading cracks.
264 These features are present in single-phase and two-phase aggregates. See figure S2 for
265 micrographs of recovered samples. Note the initial angle of any brittle feature generated under
266 high pressure and high temperature may have been altered by the decompression stage, carried
267 out under ambient temperature.

268 Back-scattered electron images (BSE) were obtained on the recovered samples. This
269 work was carried out at the electron microscopy facility of the Advanced Characterization
270 Platform of the Chevreul Institute, using a FLEXSEM 1000 scanning electron microscope
271 (SEM): (fig. 3), a Hitachi SU 5000 under low-vacuum conditions (Fig. 4), and a JEOL JSM-
272 7800F (Fig. S2). Olivine grain sizes in recovered samples range from less than a micron to an
273 apparent equivalent diameter ca. 25-50 μm . BSE images in fig. 3 show the antigorite distribution
274 relative to olivine grains.



275

276

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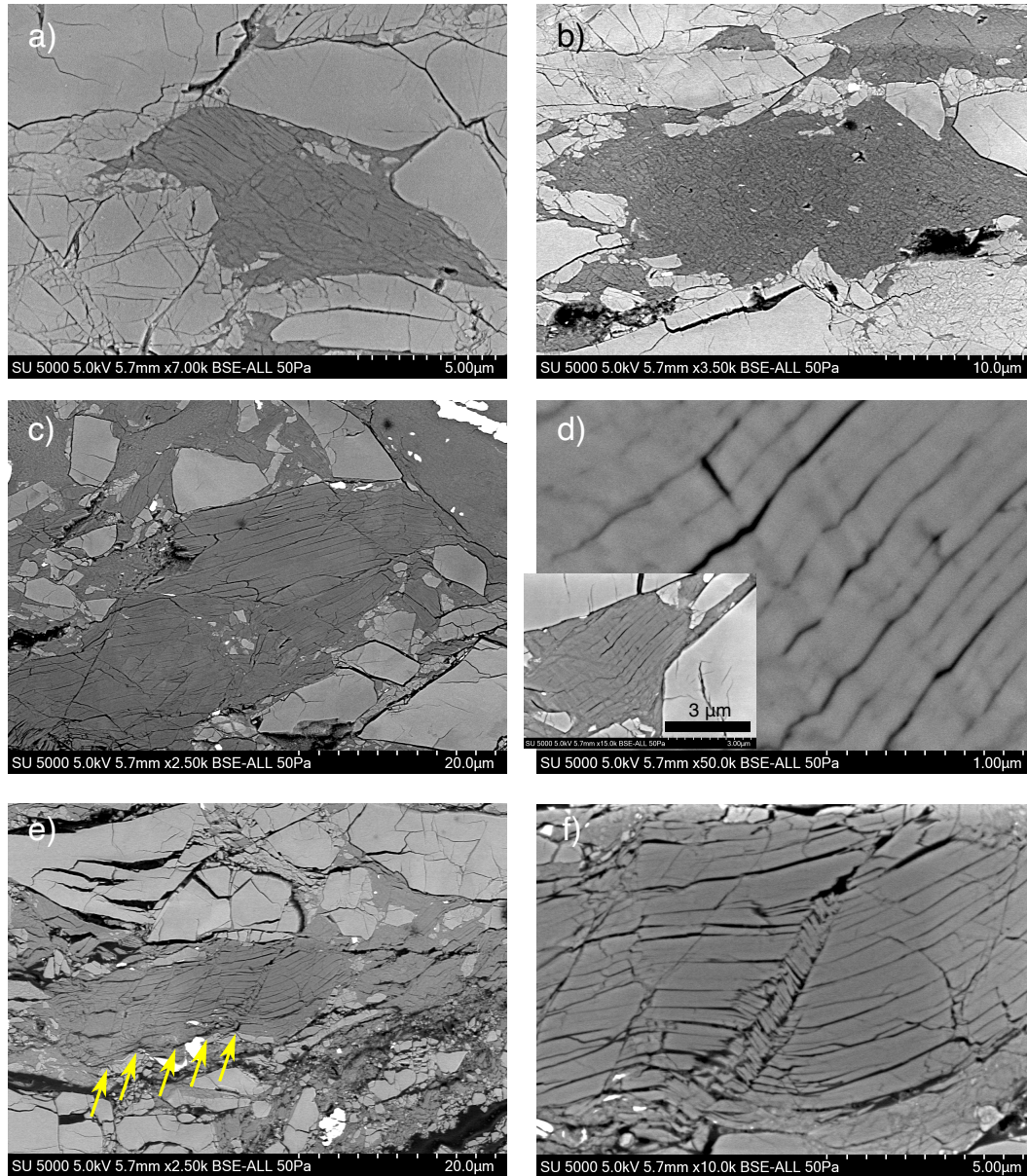
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281

Figure 3. Electron microscopy (Back Scattered Electrons) images of the recovered two-phase aggregates. The rectangles on the left column show the location of the smaller scale images on the right. Antigorite is dark grey on all images and olivine is light grey. The bright materials are the gold sheets used as strain markers, and iron oxides naturally present in the starting powders. The bottom of Serp7 in c) is covered with conductive paste. dc = decompression crack. The white arrows in e) show an echelon distribution of clusters, which may play a major role in obtaining a stress controlled by antigorite without having an interconnected network.



282

283 **Figure 4.** BSE images of deformation features in antigorite clusters, for 20% (a and b, serp9) and 50% (c, d, e, f, serp10) antigorite

284 fraction samples. Antigorite is dark grey, olivine light grey and the bright phases are oxides. The maximum stress direction is

285 vertical. In serp9 : a) antigorite crystal preserved with grain size reduction next to an olivine grain size reduction area and b)

286 intense grain size reduction area. In serp10: c) large antigorite crystal preserved with an area of grain size reduction in the upper

287 left part, d) kink bands at the 100-nm scale in response to local strain field imposed by the olivine crystals (inset), e) crystal

288 deformed by a series of fractures and kinks with the same orientation (arrows) and bending, f) close up of the kink-band with loss

289 of cohesion between sheets. Further images for 5 and 10% vol. antigorite, see figure S2.

290 Serp6 sample with 5 vol. % antigorite shows no obvious microcracking at the *aggregate*
291 scale. Serp7 sample with 10 vol. % antigorite shows three oblique cracks which seem conjugated
292 and could be related to deformation, without obvious displacements. Openings at grain
293 boundaries, due to the decompression at the end of the run, highlight the cracks. At *crystal* scale
294 olivine presents microcracking in both Serp6 and Serp7 (supplementary figure S3). Antigorite is
295 distributed as isolated clusters throughout the sample. In these aggregates with 5 and 10% vol.
296 antigorite (serp6, serp7), these clusters tend to have lower aspect ratio than those in the 20 vol. %
297 antigorite sample (figures 3b, 3d).

298 Serp 9 with 20 vol. % antigorite, shows only one large crack, not conjugated and with no
299 visible motion, and which geometry is ambiguous to interpret. The distribution of antigorite
300 within the olivine matrix shows clusters of antigorite generally up to 90-100 μm of apparent
301 length on the 2D section, at high angles or perpendicular to the maximum compression axis. One
302 cluster up to 200 μm is observed. The deformation is heterogeneous with some clusters much
303 less deformed in the upper left part of the sample on fig. 3e. As first glance they do not seem to
304 be fully connected across the sample. However, a suite of an-echelon clusters, ca. 500 microns
305 long, is observed in the central part (fig. 3e). The deformation style of antigorite clusters thus
306 evolves with increasing antigorite fraction. The antigorite in the clusters themselves is preserved
307 as crystals of a few microns, with grain size reduction often close to olivine grains (fig. 4a).
308 Some regions with grain size reduction are observed in both in olivine and antigorite (fig. 4b).

309 Finally, in Serp10 with 50% antigorite, major brittle features allowed a homogeneously
310 distributed (semi-)brittle deformation of the sample. They consist of a regular network of
311 conjugated micro-fractures with a similar apparent angle from the maximum compression axis.
312 At grain scale, the olivine crystals are angular, distributed within an antigorite matrix. Large
313 crystals of antigorite can be preserved, and although grain size reduction is observed, it seems
314 less developed than in serp9. The antigorite clusters deform by grain boundary slip,
315 delamination, kink bands, fracturation, bending (fig. 4 d, e, f), in response to the local
316 surroundings (relation with olivine crystals fig. 4e).

317 Reference aggregates in runs serp7 and serp9 display some regions with very small grain
318 sizes (olivine), similar to those observed by Ferrand et al. (2017). Their cause, grain size

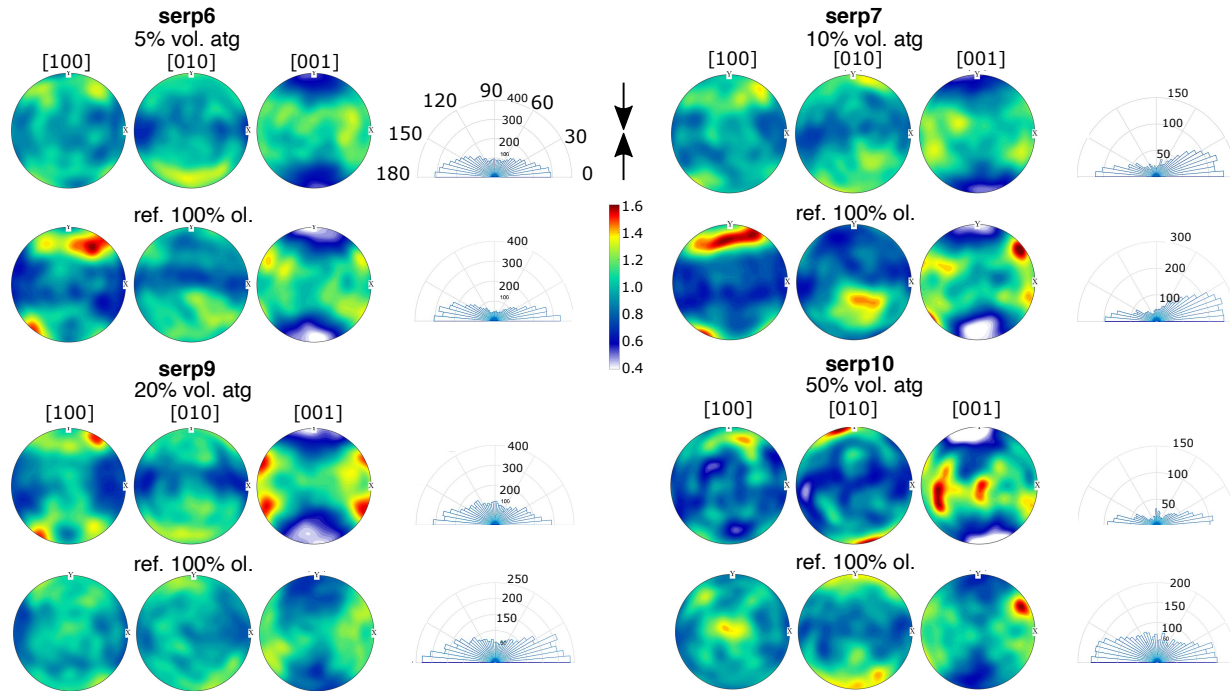
319 reduction during deformation or presence from the beginning of the run, is unclear. They are
320 found in olivine reference aggregates only.

321 The samples have also been investigated by Electron Back-Scattered Diffraction (EBSD)
322 – Scanning Electron Microscopy at the University of Montpellier, on the French CNRS-INSU
323 National EBSD Facility (CamScan Crystal probe). Regions, typically 400 by 500 μm , were
324 mapped for the reference and the two-phase aggregate for each run. Unfortunately, despite
325 several attempts, the EBSD signal on antigorite crystals could not be investigated. This is partly
326 due to the difficulty in polishing the surfaces with such a hardness contrast and with grain sizes
327 approaching the micron - a suitable way of preparing the samples remains to be found. Other
328 likely factors are the deformation mechanisms of antigorite (see discussion). Qualitatively, in situ
329 X-ray diffractions during deformation (not shown) show a lattice preferred orientation for
330 antigorite, with the normals to the basal planes 001 mostly parallel to the maximum compression
331 direction. This texture is stronger at the end of the deformation.

332 The EBSD data on olivine were analysed using the Matlab MTEX toolbox (Bachmann et
333 al., 2010). Fig. 5 shows the pole figures in the two-phase aggregates compared with pole figures
334 for their respective reference aggregate with 100% olivine (pbnm setting).

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338 **Figure 5.** Olivine pole figures and grains long axis orientations in two-phase and reference aggregates, relative to the maximum
 339 compression direction, as obtained from EBSD on recovered samples. Color scale bar in mrd (multiples of random deviation); the
 340 maximum compression axis is vertical, indicated by the black arrows (90° on the rose diagrams).

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The Crystal Preferred Orientations (CPO) on deformed samples are overall weak and are characterized by minima of [001] parallel to the maximum compression direction. The [100] axes define maxima slightly tilted from the maximum compression direction (or weak girdles around this direction). The [010] distribution relative to the maximum compression axis is more diffuse except on the serp10 sample. All two-phase samples showing maximum close to the compression direction.

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To deconvolute the final CPO from the one resulting from the loading stage, the lattice preferred orientation (LPO) prior deformation have been analysed for two-phase aggregates using their in situ X-ray diffractions, under high pressure and high temperature (see figure S4 and text). Comparison with the starting textures shows that deformation induced, in all two-phase samples, rotation of the b axes and a axes closer to the maximum compression direction.

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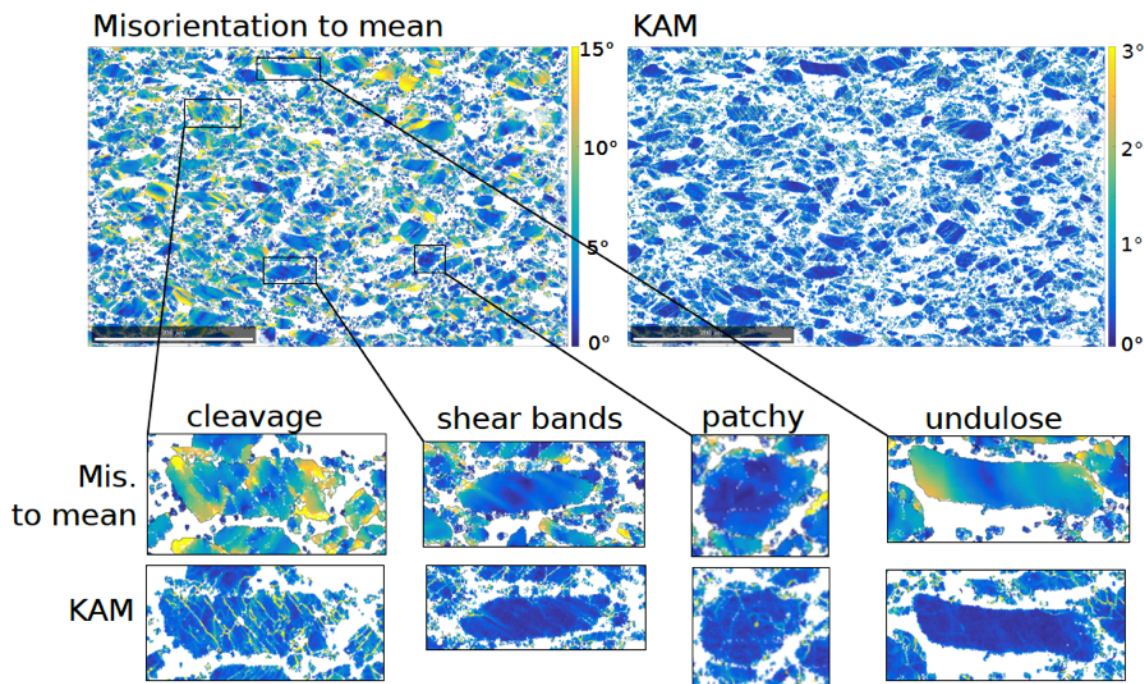
In order to characterise the strength of the CPO we use the J-index (Bunge, 1982), which is 1 for a uniform distribution and infinite for a single orientation. The J-index for all samples is shown in figure S5. Overall, the CPO intensity slightly increases with increasing total strain from

355 1.07 for the lowest strains to 1.22 for the highest antigorite fraction (50%) and large strain (-
356 23.6%) in the two-phase aggregates. The reference olivine aggregates also show a trend with low
357 J-index of 1.06, for the lowest strains (-12.9%), up to a J-index of 1.2 for the highest strains (-
358 23.6%).

359 The crystal long axis orientations relative to the compression axis are shown on rose
360 diagrams in fig. 5 for the two-phase and reference aggregates. This long axis is mostly oriented
361 normal to the compression axis, which evidences a Shape Preferred Orientation (SPO).

362 The local misorientation within olivine grains gives information on the global strain
363 gradient in the grain and the spatial distribution of this gradient. The Kernel Average
364 Misorientation (KAM; angle, within a grain, between a pixel orientation and the mean
365 orientation of its 4 neighbours) reveals local strain gradients within the grains while
366 misorientations to the mean grain orientation (“Mis2Mean”) reflects the strain gradient at the
367 grain scale. Maps of KAM and Mis2mean highlight deformation styles of olivine that range
368 between brittle to crystal-plastic end-members (fig. 6).

369



370
 371 **Figure 6.** Misorientation to mean grain orientation and kernel average misorientation (KAM) maps on serp9 recovered two-phase
 372 aggregate (20 vol. % antigorite). Only olivine was analysed; the white is serpentine and non-indexed regions. The different
 373 deformation styles of olivine crystals are highlighted. The scale bar on large maps is 200 μm .

374 Crystals, especially large ones, show multiple intragranular microcracks, sometimes akin
 375 to cleavage. For some, deformation occurs mostly by microcracking and there is only limited
 376 misorientation relative to the mean grain orientation. In other cases, the crystals (small or large)
 377 show few or no microcracks and undulose to patchy orientation sectors developed within grains.
 378 For large grains, KAM maps also highlight a number of impingement microcracks, ie. crack
 379 radiating out of the contact sites with other grains (Passchier and Trouw, ed. 2005). Grain
 380 microcracks tend to follow diagonal directions, and overall the deformation style is rather
 381 cataclastic. We also obtained inverse pole figures showing the rotation axis orientation for low-
 382 angle boundaries ($2\text{-}10^\circ$) which are presented in the supplementary material (fig. S6).

383 **4 Discussion**

384 4.1 Deformation mechanisms

385 4.1.1 Antigorite

386 The loss of definition of the antigorite peaks on the X-ray diffraction as deformation
387 proceeded, especially on the 5 vol. % atg sample, can indicate one or all of the following
388 processes in this sample: delamination, grain size reduction (comminution), loss of order in the
389 layers stack, large scale crystal defects, and/or amorphisation of antigorite crystals. These
390 mechanisms, except for the stacking disorder, can create new weak zones and cause a decrease in
391 measured stress. After about 18% strain, no peak could be seen anymore on the diffraction for
392 the 5 vol. % atg sample.

393 We were unable to observe antigorite deformation mechanisms using EBSD. The
394 difficulty in obtaining a signal suitable from EBSD was expected for the aggregates with low
395 antigorite content, because the in-situ XRD indicated some state akin to loss of crystal structure
396 ordering or comminution. However, it was unexpected for the aggregates with highest antigorite
397 content. The small grain sizes lead to crystals being very easily scraped off the surface during
398 preparation, which could have prevented obtaining a good enough polish on antigorite grains.
399 Another possibility is a large number of defects or distortion in antigorite, too large for the
400 crystals to provide an EBSD signal.

401 4.1.2 Olivine

402 The analysis for the intracrystalline deformation mechanisms in olivine requires caution.
403 The CPO are very weak, and the effect of dislocation glide is likely convoluted with crystal
404 shape effects, ie. the SPO. The rose diagrams show a clear correlation between crystal shapes
405 and orientations relative to the shortening axis, hence a well-defined SPO (fig. 5). For olivine
406 reference aggregates (serp6 and 7, table 1) the SPO is slightly stronger in the more deformed
407 aggregates. This relationship is not clear for two-phase aggregates (fig. 5).

408 The CPO of reference aggregates in serp 6, serp7 and 20 vol. % atg aggregate in serp9
409 have a majority of [100] close to the maximum compression axis and a girdle of [001]
410 perpendicular to the compression axis, which would be consistent with the (100)[001] slip
411 system. The misorientation analysis fig. S6 (supplementary material) gives further information

412 about the dislocations locally accommodating the plastic deformation of olivine crystals, which are
413 consistent with the suggested slip system.

414 We examined possible trends of deformation at the crystal scale with respect to the total
415 sample strain, fraction of antigorite, and aggregate stress. Together with the KAM for local
416 misorientation gradients, the grain orientation spread (GOS; average of Mis2Mean for each
417 grain) was considered, which quantifies the global gradient of orientation existing in the grain.
418 Statistics of the KAM and GOS are presented in fig. S7. The reference olivine aggregates tend to
419 show increased median KAM and median GOS (fig. S7), i.e., to be more damaged with
420 increasing stress and strain. Meanwhile, in the olivine within the two-phase aggregates, the
421 median GOS shows a slight tendency to decrease with antigorite fraction (or with decreasing
422 stress) even at larger strains.

423 These observations are consistent with Wallis et al, 2011, who reported natural
424 microstructures for antigorite free and antigorite bearing dunites of ca. 10, 21 and 42% modal
425 fraction of antigorite, derived from mantle wedge conditions in the Higashi-Akaishi body, NE
426 Japan. They observed weakening of the olivine CPO with increasing antigorite fraction, due to
427 phase boundary slip and rigid rotation of olivine grains.

428 4.1.3 Deformation mechanisms of the aggregate

429 The SEM observations, CPO and SPO all point to 1) intracrystalline plasticity in olivine,
430 which gradually generates the crystal lattice bending and undulose or patchy orientation domains
431 in crystals, for accommodating local strain incompatibilities, and 2) a shortening mainly
432 accommodated by crushing/cleaving of crystals, and by rigid rotation of olivine crystals according
433 to their shape.

434 The rigid rotations imply grain boundary slip in olivine or between olivine and antigorite
435 in a diffusionless sense (at this experimental timescale, because T is low and in the absence of
436 fluid). Olivine crystal rotation can also be purely accommodated by strain in neighbouring
437 antigorite, in the samples with higher antigorite fractions (e.g. serp10, Figure 3h).

438 The deformation style of antigorite clusters evolves with increasing antigorite fraction
439 and is consistent with the stress analysis : the low stress in antigorite, for low antigorite fractions
440 (serp6 and 7) is due to the olivine matrix controlling the strain. Hence, antigorite clusters in this

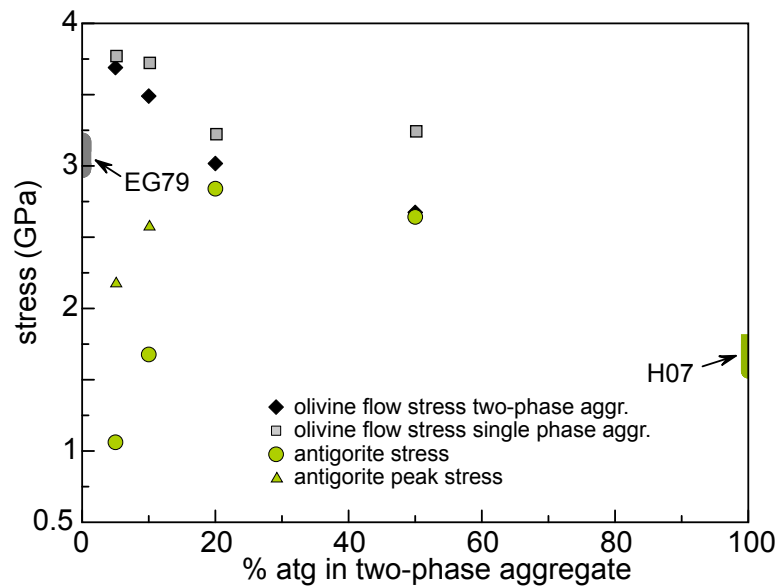
441 case (figures 3b and d) are weakly deformed. At 20 vol. % antigorite, the strain is no longer
442 controlled by olivine only, and the antigorite clusters are sheared (figure 3f). The antigorite
443 clusters have maximum length scales around 200 microns and more typically are about 100
444 microns, and therefore are not connected in 2D over the aggregate length scale. We propose that
445 the en-echelon organization of these clusters forms a weak zone in the aggregate at the scale of
446 the group, even if the clusters are not connected. As proposed for instance by Gerbi et al., (2016),
447 fine-grained olivine can form bridges between antigorite clusters and could also constitute weak
448 zones (not obvious on our 2D images). More likely here, glide on bridging grain boundaries
449 could also play a similar role.

450 The semi-brittle/brittle components of the aggregates' deformation in our experiments are
451 further examined in the light of the available literature in section 4.3.

452 4.2 *In situ* stresses from X-ray data and interpretation

453 Figure 7 compares the stresses within olivine and antigorite in the aggregates as a
454 function of the serpentine fraction in the two-phase aggregate. The stress in the reference
455 aggregate of each run is also reported.

456 Run serp9 showed macroscopic fracturing and a jump in strain for the olivine reference
457 aggregate so comparison of its microstresses with the other runs presented here deserves to be
458 justified. The stress curves in serp9 do not indicate a stress drop simultaneously with the strain
459 jump. In previous works where high-pressure failure took place (e.g., Ferrand et al., 2017; Incel
460 et al., 2017), the stress was measured on a small portion of the sample (200 x 200 μm for a 3 x 2
461 mm sample). In contrast, here the stress was measured on a larger sample area (ca. 1 mm wide x
462 0.5 mm height) centered over ca. 1.3 mm height aggregates, which means we were less likely to
463 miss a major stress drop in the fractured region. We infer that fracturation is only evidenced in
464 the strain data because the volume of crystals in which stress was « unloaded » by this
465 fracturation remained small. Thus, we also consider the stress balance between the two phases in
466 this experiment can be compared with our three other experiments.



467
 468 **Figure 7.** Stresses measured within olivine and antigorite in two-phase aggregates. The stresses for olivine (black) and for
 469 antigorite (green) are taken when the stresses have reached a « plateau » on the stress-strain curve (Table 1). For antigorite, the
 470 stress is measured only on the (001) plane, see discussion for its significance; the peak stress before the plateau, if any, is
 471 indicated by a light green triangle. Stresses in olivine reference aggregates (same run) are in grey. The range of expected stresses
 472 under the strain rate, T and P of the four experiments using flow laws by Evans and Goetze (1979) [EG79] and Hilairet et al.
 473 (2007) [H07] were calculated for single phase olivine and antigorite aggregates respectively. Note these experimental stresses
 474 are not normalized to same strain rate, pressure and temperature. Doing so has a modest effect on stress values and does not
 475 change the conclusions here.

476 In antigorite-poor aggregates (5 and 10 vol. %), the antigorite stress first increases above
 477 the stress expected for deformation of pure antigorite aggregates. The olivine framework
 478 imposes this transient overshoot in stress, since the overshoot is not observed in pure antigorite
 479 aggregates (e.g. Hilairet et al., 2007, Hirauchi et al., 2020). We postulate the antigorite is
 480 confined within the olivine matrix and first undergoes elastic compression leading to the peak in
 481 stress, because unable to deform freely (strain incompatibilities). After the transient, for 5 vol. %
 482 antigorite, the stress decreases below that expected for a pure antigorite aggregate. At that time,
 483 the stress in antigorite crystals could be shielded by olivine. Alternatively these low stresses
 484 could be due to deformation of very fine grained or partly amorphized antigorite. In the 10 vol.
 485 % antigorite aggregate, the stress given by antigorite after the transient stage is consistent with
 486 the flow stress expected for a pure antigorite aggregate. Thus the local strain rate imposed to the

487 antigorite patches may be close to that of the aggregate at this time. The deformation at the
488 aggregate scale is buffered by the stress percolating within the framework of olivine crystals.

489 For the 20 and 50 vol. % antigorite aggregates, the stress balance is different from that
490 with lower atg fraction. No transient regime is observed. Antigorite indicates higher stresses than
491 expected from its flow law in these P, T and strain rate conditions, and similar to those of olivine
492 (fig. 7). The explanation can reside in microstructural factors and/or come from different
493 deformation mechanisms than those corresponding to the flow law in Hilairet et al (2007). As for
494 microstructural factors: with a weak CPO and five measured diffraction planes (which thus cover
495 many different orientations in the olivine unit cell), the olivine stress is calculated from a
496 population of diffracting grains that sample a large orientation range. The situation is quite
497 different for serpentine, which becomes strongly textured in our experiments. The population of
498 diffracting grains for the only measured diffraction plane (the basal plane (001)) is in vast
499 majority made of grains oriented orthogonal to the beam when the stress plateau is reached. If
500 deformation can occur in antigorite by a mechanism (as yet unclear), which end-result is glide
501 more or less parallel to the (001) planes, most grains oriented perpendicular to the maximum
502 stress direction are therefore not able to accommodate deformation anymore. Amiguet et al. (2012)
503 investigated lizardite aggregate deformation, and referred to such population as having a
504 « locked geometry ». Our lattice strain $Q(001)$ is calculated from a full angular dispersive
505 diffraction line, and therefore includes grains in « unlocked » orientations. However, the stronger
506 the texture, the less unlocked grains can contribute, and the higher may become the influence of
507 the locked grains on the stress as calculated from the lattice strains $Q(hkl)$. Thus, for our 20 and
508 50 vol. % antigorite samples, these locked grains are in an isostress state with the olivine
509 crystals. The second factor that can explain this discrepancy is a mix of deformation mechanisms
510 that are different than those occurring in Hilairet et al. (2007), specifically a larger part of brittle
511 like mechanisms. This is examined in the next section.

512 4.3 Comparison with antigorite and olivine deformation experiments from the literature.

513 In our experiments the deformation mechanisms are more akin to frictional processes
514 *sensu lato* (diffusionless sliding on grain boundaries and cracks, microcracking and
515 delamination) than purely (intra)crystalline defects-controlled processes, because of the high
516 strain rates, low temperature, high stress level and the absence of fluids.

517 From X-ray diffraction, the ‘hydrostatic’ pressure P (mean stress) and the differential
 518 stress σ_d are measured *in situ*. Taking compressive stresses as positive, σ_1 and σ_3 as the
 519 maximum and the minimum compressive stress respectively, assuming the transversal isotropy
 520 of stresses $\sigma_2 = \sigma_3$ because of the cylindrical geometry of the sample and compression, we have
 521 $P = \frac{1}{3}(\sigma_1 + 2\sigma_3)$ and $\sigma_d = \sigma_1 - \sigma_3$. Therefore σ_1 and σ_3 are straightforwardly obtained from
 522 $\sigma_1 = P + \frac{2}{3}\sigma_d$ and $\sigma_3 = P - \frac{1}{3}\sigma_d$. From this, the state of stress on any given plane within the
 523 aggregate can be characterized and plotted as a Mohr circle.

524 The tangential stress τ on a plane reads:

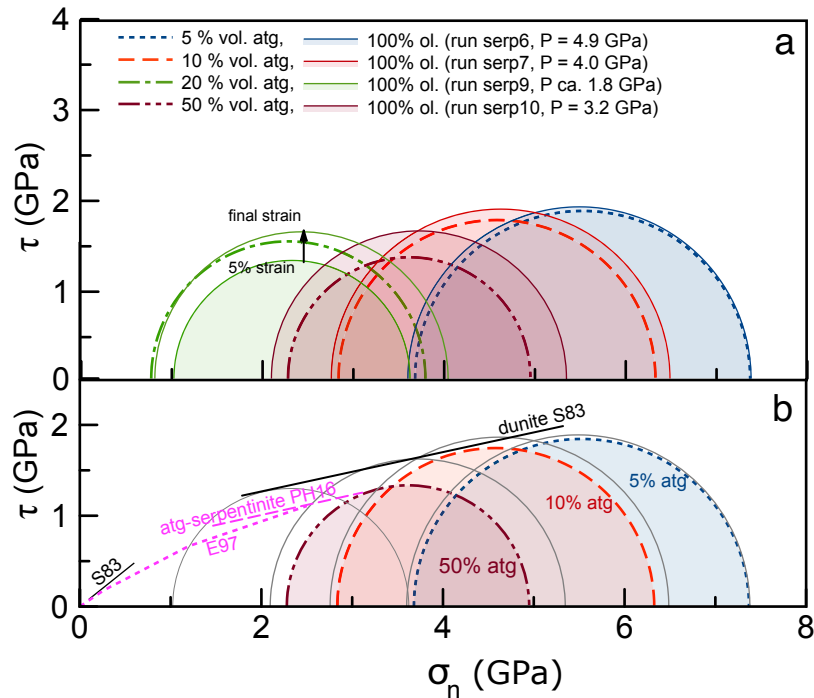
$$525 \quad \tau = \frac{1}{2}\sigma_d \sin 2\alpha$$

526 where α is the angle between the plane normal and the minimum compressive stress (α is
 527 used to avoid confusion with θ already defined as the diffraction angle).

528 The normal stress σ_n reads:

$$529 \quad \sigma_n = \left(\frac{\sigma_1 + \sigma_3}{2}\right) - \left(\frac{\sigma_1 - \sigma_3}{2}\right) \cos 2\alpha.$$

530 Fig. 8a shows this stress state as Mohr-Coulomb circles for pure olivine and two-phase
 531 aggregates in this study. For the run serp10, the stress state actually used for the figure in the
 532 reference aggregate is taken at 13 % shortening, while for the two-phase aggregate the total
 533 strain is above 20%. Since in the latter, the stress does not vary between 13% and 20% strain
 534 (fig. 2 lower right) they can still be compared here. For the same reason, the stress states of the
 535 other runs are also those at the final strain even if these differ (table 1).



536

537 **Figure 8.** Strength of two-phase aggregates and comparison with friction laws for antigorite and olivine. a) Mohr circles
 538 representing the stress state in two-phase and reference single-phase aggregates in this study, as calculated from in-situ
 539 measurements of differential stress and pressure (mean stress). The stress values at final strain were considered as
 540 representative. For run serp9, stress state on the reference aggregate is plotted at ca. 5% (before strain jump ; cf. fig. 1) and at
 541 final strain. b) Data from this study compared with friction laws from literature : Escartin et al., (1997) [E97], Proctor and Hirth
 542 (2016) [PH16], for antigorite, and Shimada (1983) [S83] for dunite. Serp9 two-phase aggregate stress state is not reported for
 543 clarity (in a), dashed green circle).

544 In fig. 8b, we compare these data with friction laws and fracture envelopes from the
 545 literature, i.e., the so-called Byerlee law defined by a compilation of rock mechanical data
 546 (friction) up to 2 GPa for σ_n (Byerlee, 1978), and the fracture envelope reported for the Horoman
 547 dunite by Shimada (1983). The results on olivine aggregates by Boettcher et al. (2007) are not
 548 included because less relevant (with fluid, up to 300 MPa effective pressure only, and
 549 temperatures from 600°C to 1000°C). For antigorite aggregates, the Mohr envelope obtained by
 550 Escartin et al. (1997) and Proctor and Hirth (2016) at higher pressures are shown.

551 For reference aggregates (100% olivine) in serp6, serp7 and serp10, the stress states on
 552 fig. 8 do correspond to the fracture envelope determined on the Horoman dunite by Shimada
 553 (1983). For the two-phase aggregates, when antigorite fraction is low (5 vol. % atg), the olivine

554 indicates a state of stress similar to the pure olivine aggregate. Meanwhile, for high antigorite
555 content (50 vol. %), the stress state in olivine is much lower than in the reference, and can be
556 interpreted as buffered by the antigorite frictional properties measured by Escartin et al., (1997)
557 and Proctor and Hirth (2016). In this case, olivine crystals likely behave as rigid inclusions.
558 Antigorite indeed controls the deformation above 20 vol. % antigorite, and mechanisms akin to
559 frictional processes, such as those reported at lower pressure, control the stress in antigorite.

560 In run serp9 the state of stress in the reference aggregate at the final strain is above the
561 envelope defined by Shimada et al (1983). When the stress state is taken at 5% strain, where a
562 strain jump occurs (fig. 1) likely due to a sample fracture, the Mohr circle actually fits the
563 fracture envelope by Shimada 1983 (fig. 8, circle marked 5% strain). Further increase in stress
564 may be an indication of the fracture being locked and/or of sample hardening due to
565 intracrystalline defects multiplication. For the antigorite+olivine aggregate in this run the stress
566 state is also well above the fracture envelope for dunite, and the friction law defined for pure
567 antigorite aggregates in Proctor and Hirth (2016) (similar to its reference olivine aggregate). The
568 stress state is however, in this run, measured from the olivine crystals and a subpopulation of
569 antigorite crystals in locked orientations. The actual stress under which the two-phase aggregate
570 deforms (ie. force over surface), may be lower than the one measured in these olivine and
571 antigorite crystals, in the case of deformation localization. The en-echelon organization seen in
572 figure 3e is a candidate region in this sample. Hardening may be invoked in other regions of the
573 sample.

574 Note that Shimada's experiments had a larger grain size (0.1 to 0.9 mm compared to 1-40
575 microns here) and were conducted at ambient T, while our experiments are at 300 to 350°C .
576 Therefore the dependence of fracturation/frictional properties of olivine on grain size or T of
577 aggregates cannot be discussed here. We also provide in fig. S8 a comparison with data available
578 for deformation of olivine or antigorite under low T at similar or higher confining pressures that
579 plot close to or above the Goetze criterion, together with a short discussion.

580 In summary, our data at low temperature are consistent with previously determined
581 friction laws in olivine and antigorite aggregates, and suggest their continuity for T up to ca
582 350°C, even at these high pressures up to 4-5 GPa. Experiments under low temperature below
583 ca. 900 K, and high pressures above ca. 2 GPa, are commonly fitted using an exponential flow

584 law – which implies a deformation controlled by dislocation glide under high stresses. It is yet
585 unclear to us whether one of these frameworks represents best our data. This calls for a better
586 understanding of how to describe deformation mechanisms within antigorite aggregates, which
587 do not obey simple dislocation glide-based mechanisms (Idrissi et al., 2020, Hansen et al., 2020).

588 4.4 Antigorite fraction: threshold for changes in mechanical control

589 The differences in strain rates and in-situ stresses recorded by the 5 and 10 vol. %
590 antigorite aggregates on one side, and the 20 and 50 vol. % antigorite aggregates on the other
591 side, highlight a change in the aggregate mechanical behavior between 10 and 20 vol. %
592 antigorite. This value is also reflected in the change in local olivine crystal plasticity as
593 previously discussed (see olivine deformation mechanisms, section 1.2). This threshold does
594 correspond to the usual values for stress percolation problems of a weak phase within the
595 framework of a stronger phase (e.g., Karato, 2008).

596 This threshold is somewhat different from that obtained in experiments at ambient T by
597 (Escartin et al., 2001) in which about 5 -10 vol. % lizardite and chrysotile serpentine decreased
598 the overall strength of serpentinized peridotites by a factor of 2-3. This difference is easily
599 explained by the crystallographic structure of antigorite (e.g. Escartin et al., 2001; Amiguet et al.,
600 2012) which is more compact than lizardite. As a result, lizardite (and chrysotile) have internal
601 friction coefficients much lower than antigorite (Escartin et al., 1997). A second explanation
602 resides in the microstructure : while our samples are synthetic aggregates with patches or grains
603 of antigorite within a matrix of olivine, the rock used by Escartin et al. (2001) was a peridotite in
604 which former olivine grain boundaries were lined up by lizardite and chrysotile, interconnected
605 despite a low volume content. As proposed by Handy (1990), this comparison illustrates that
606 microstructure is crucial in controlling and modifying the mechanical behavior of an aggregate
607 even at modest strains.

608 Ferrand et al. (2017) and Ferrand (2017) used the same starting material than in this
609 study, with varying antigorite contents (0, 5, 20 and 50 vol. %) for investigation of the link
610 between intermediate-depth earthquakes and serpentine dehydration, in similar conditions of
611 strain, pressure, similar microstructure, and higher temperature (ca. 500°C) and strain rates ($5 \cdot 10^{-5}$
612 to 10^{-4} s^{-1}). In Ferrand et al. (2017), aggregates containing as little as 5 vol. % antigorite showed
613 already lower olivine stresses than pure olivine aggregates in the same conditions, suggesting

614 that temperature or strain rate modify the elastic and crystal-plastic interactions between olivine
615 and antigorite.

616 Given the microstructural observations, the single-crystal strength of olivine is expected
617 to have a major role in controlling deformation of the reference aggregates or antigorite-poor
618 aggregates. However, the stresses obtained for the 100% olivine reference aggregate and two-
619 phase aggregates at the highest pressures, are higher than single-crystal hardness measured by
620 Evans and Goetze (1979) using an indentation technique. Those at lower pressures are consistent
621 with Evans and Goetze (1979). The higher stresses seen in the highest pressure experiments thus
622 could be due to the pressure effect on the deformation mechanisms, not taken into account in the
623 flow law by Evans and Goetze (1979).

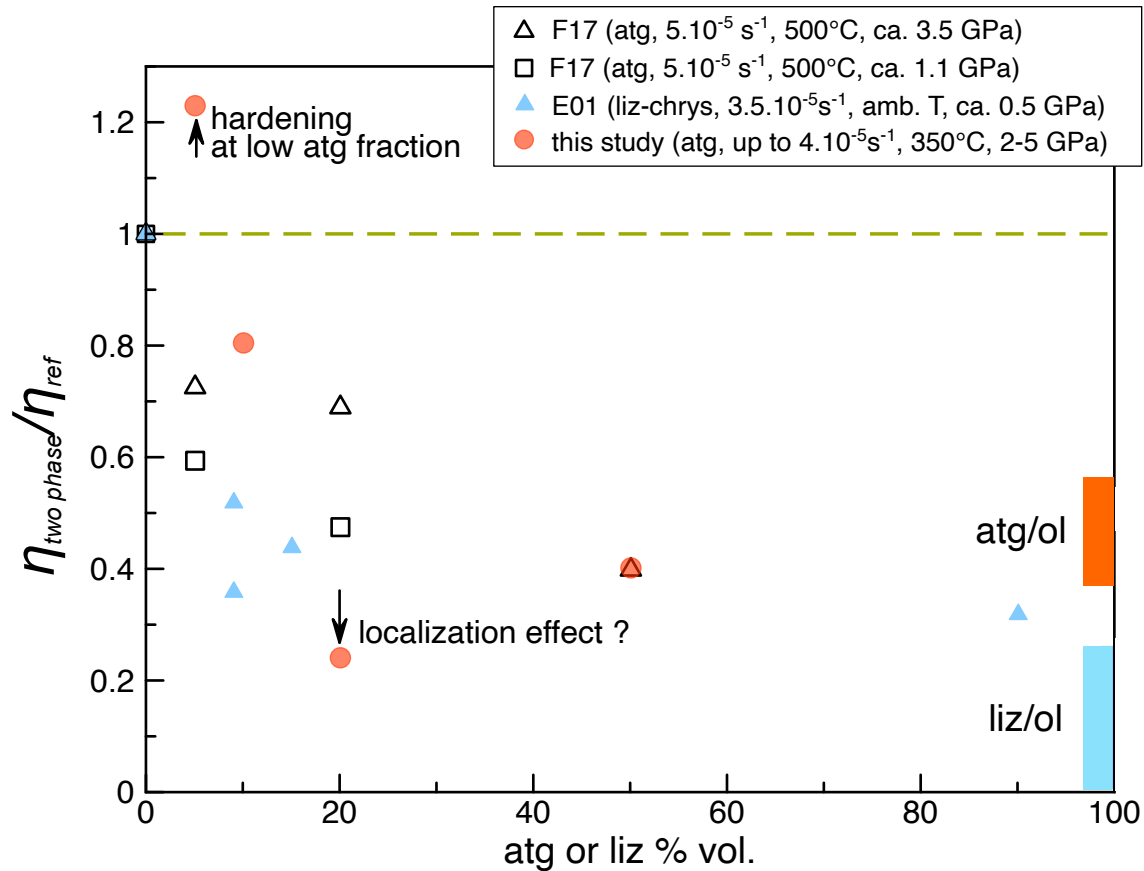
624 In addition to these pressures differences, the strain rates at which the single-phase
625 aggregates and two-phase aggregates deform here differ, up to a factor of almost 4. We attempt
626 here to make a comparison “free” from strain rate and pressures variations, ~~and compare with the~~
627 ~~literature~~, by defining for the two-phase and reference aggregates in each experiment :

$$628 \quad \eta_{two\ phase} = \frac{\sigma_{two\ phase}}{\dot{\epsilon}_{two\ phase}} \quad \text{and} \quad \eta_{ref} = \frac{\sigma_{ref}}{\dot{\epsilon}_{ref}} .$$

629 Figure 9 shows the evolution of the ratio $\frac{\eta_{two\ phase}}{\eta_{ref}}$ as a function of antigorite content, and a
630 comparison with literature data. Studies at higher temperatures are not included for the sake of
631 clarity, but can be found in Ferrand (2017). Contrasts expected for monomineralic antigorite or
632 lizardite (chrysotile) rocks with respect to dunite, are calculated from published flow laws
633 (Hilaireret et al., 2007, Amiguet et al., 2012, Evans and Goetze, 1979). The flow laws calculated
634 contrasts are consistent with the shear strain contrasts between pure antigorite, lizardite
635 (chrysotile) and olivine aggregates found by Hirauchi and Katayama (2013) at 300°C under 1
636 GPa confining pressure. Note the use of these flow laws for pure end members implies a
637 deformation by dislocation-motion controlled processes, while our data seem (also) consistent
638 with friction-like controlled behavior.

639 At moderate temperatures, our aggregate with 5 vol. % antigorite has a higher $\frac{\sigma}{\dot{\epsilon}}$ than its
640 single-phase counterpart in the same run, with similar stresses in both aggregates. The lower
641 strain rate of the two-phase aggregate is what causes this apparent higher “viscosity”, and could
642 be interpreted as a result of local hardening of olivine at low serpentine fractions. Handy (1990)

643 for instance (his fig. 1) suggest a hardening effect at low amounts of weak phase in such
 644 aggregates. Comparing with Ferrand et al (2017), we infer this hardening vanishes closer to
 645 dehydration temperatures because intracrystalline deformation processes are more active. Figure
 646 9 is further discussed in the next section.



647

648 **Figure 9.** Contrast in $\eta = \frac{\sigma}{\dot{\epsilon}}$ between serpentine+olivine aggregates and pure olivine aggregates, from this study and the
 649 literature. The aggregate strengths in this study are normalized by the strain rates (all different from one aggregate to another),
 650 the two phase aggregates compared against the reference aggregate for each run. Data from Ferrand et al, 2017 (F17) were
 651 normalized using their 100% olivine aggregates runs at 3.5 and 1.1 GPa. Lizardite-serpentinites data from Escartin et al, 2001
 652 (E01) were normalized using their unaltered Horoman Dunite data with the pressure (mean stress) calculated from the confining
 653 pressure (σ_3) and the differential stress. The contrast for antigorite or lizardite rocks compared to dunite ([atg/ol] and [liz/ol]
 654 respectively) is calculated from published flow laws which implies theoretically deformation controlled by dislocation motion
 655 processes. Hilairet et al, (2007) is used for antigorite, Amiguet et al, (2012) for lizardite, and Evans and Goetze (1979) for olivine
 656 with strain rate $2.10^{-5} s^{-1}$, P between 1 and 3 GPa, T at 400°C. See sections 4.4 and 4.5 for discussion.

657 4.5 Applicability to subduction zone dynamics

658 Our aggregates with varied antigorite contents can be considered as a proxy for dunite
659 with different serpentinization degrees, and our olivine aggregates as a proxy for a mantle
660 unaltered dunite. Fig. 9 thus shows estimates of the strength or viscosity contrast between these
661 two rocks at our experimental strain rates, ie., for timescales ranging from hours to days.

662 At high pressures corresponding to depths of 90 km, our results suggest the viscosity
663 could be inverted at very low serpentine (5%) fractions because of the local concentration of
664 stresses. The viscosity contrast could remain on the order of 0.7 or higher for a serpentine
665 amount of 10 vol. %, and around 0.4 to 0.5 for 50% serpentinization or more. The viscosity
666 contrast for 20 vol. % antigorite, lower than 0.3, may be due to the proposed strain localization
667 along the en-echelon antigorite clusters. Further experiments would be needed to clarify the role
668 of mean stress here.

669 The viscosity contrast becomes larger for a lower serpentine amount, in the lower
670 pressure, higher temperature series in the antigorite-bearing samples in Ferrand et al. (2017, 1.1
671 GPa series), and for the lizardite-chrysotile serpentinites deformed under a mean stress ca. 0.5
672 GPa and at ambient T in Escartin et al., (2001). The difference between our results and those of
673 Ferrand et al. (2017) at low antigorite contents, is likely the balance of controlling deformation
674 mechanisms for olivine. Frictional processes *s.l.* occur in our experiments at low T, while
675 intracrystalline olivine plasticity can be expected more active at higher T in Ferrand et al. (2017)
676 (e.g. results by Raterron et al, 2004). This may however be mitigated by an increased strain rate.

677 For a large serpentine content (50% and more) at first order the strength contrast between
678 a serpentinized rock and an olivine rock does not seem to depend on the T or the mix in
679 deformation mechanisms (brittle-like vs. intracrystalline): this contrast is similar and around 0.4
680 to 0.5, whether it is taken at high T (Ferrand et al. 2017), in our aggregates at lower T, or if
681 calculated from a flow law in a pure antigorite rock with a different mix of these deformation
682 mechanisms.

683 The hardening of the aggregate with the lowest serpentine fraction (5%) relative to pure
684 olivine aggregate, and the shielding of stress within antigorite for 5 and 10 vol. % serpentine
685 aggregates, can be related to the creation of load-bearing networks (e.g. Handy, 1990, 1994) or
686 force chains (a concept widely known in granular mechanics, e.g. Peters et al., 2005) through the

687 harder olivine grains, in contact with each other. The relevance of this hardening for a natural
688 serpentized peridotite and for different microstructures remains to be demonstrated. Recently,
689 Burnley (2013), and Beall, Fagereng and Ellis (2019a, b), studied numerically the development
690 of force chains in deforming aggregates, and shear zones at cm to m scale, respectively. These
691 studies, the results by Ferrand et al., (2017) on dehydrating antigorite+olivine aggregates,
692 Ferrand (2019), and the present study, suggest that when the weak component is between 0 and
693 20 vol. %, understanding the modalities of load-bearing networks appearance, and characterizing
694 them at several scales, is essential in describing the rheology of polymineralic and matrix/clast
695 mélanges.

696 Our dataset remains limited, with several parameters at play that have opposite effects
697 (temperature, pressure, strain rate, plastic properties of crystals, and microstructure).
698 Extrapolation to the natural context and background strain rates must be made with caution.
699 First, the displacement and stress geometry on shear zones, and the resulting microstructure, may
700 be best represented by simple shear experiments. Lower strain rates may lead to different plastic
701 relaxation interactions between antigorite and olivine. Fluids circulate at least episodically in
702 shear zones, in subduction settings, and these fluids promote very different deformation
703 mechanisms in serpentinites such as pressure solution (e.g., Auzende et al., 2015), especially
704 when considering long timescales.

705 The results here, nonetheless, provide clues on the stress distribution in, and strength
706 contrasts between, rocks when subject to relatively high stresses and high strain rates which may
707 arise in subduction zones. They could be relevant to ductile deformation of serpentized zones
708 (or shear zones reactivation) upon stress transfer from loaded parts of the subduction zones (e.g.
709 models by Montesi and Hirth, 2003, Regenauer-Lieb and Yuen, 2008, Montesi, 2013, Goswami
710 and Barbot, 2018, observations by Hirauchi et al., 2021), where high stresses/fast strain rates
711 may transiently be achieved, and to events that occur on timescales of hours to days, such as
712 slow slip events. Because carried out under high pressures (> GPa) and at a temperature close to
713 350°C, our results could be particularly relevant for the rheology of the so-called stable sliding
714 zone of the interface between the slab and mantle, for the transition between stable sliding and
715 seismic zones, and for understanding the stress state(s) within cold subducting slabs.

716

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737 **Open Research**

738 Availability statement: The stress and strain data from this study are available in a .csv
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