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## Listvenite formation during mass transfer into the leading edge of the mantle wedge: Initial results from Oman Drilling Project Hole BT1B

Peter Kelemen, Juan Carlos de Obeso, James Leong, Marguerite Godard, Keishi Okazaki, Alissa Kotowski, Craig Manning, Eric Ellison, Manuel Menzel, Janos Urai, et al.

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1 **Listvenite formation during mass transfer**  
2 **into the leading edge of the mantle wedge:**  
3 **Initial results from Oman Drilling Project Hole BT1B**  
4

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21

22 **Abstract**

23 This paper provides an overview of research on core from Oman Drilling Project Hole BT1B and the  
24 surrounding area, plus new data and calculations, constraining processes in the Tethyan subduction  
25 zone beneath the Samail ophiolite. The area is underlain by gently dipping, broadly folded layers of  
26 allochthonous Hawasina pelagic sediments, the metamorphic sole of the Samail ophiolite, and  
27 Banded Unit peridotites at the base of the Samail mantle section. Despite reactivation of some faults  
28 during uplift of the Jebel Akdar and Saih Hatat domes, the area preserves the tectonic “stratigraphy”  
29 of the Cretaceous subduction zone. Gently dipping listvenite bands, parallel to peridotite banding and  
30 to contacts between the peridotite and the metamorphic sole, replace peridotite at and near the basal  
31 thrust. Listvenites formed at less than 200°C and (poorly constrained) depths of 25 to 40 km by  
32 reaction with CO<sub>2</sub>-rich, aqueous fluids migrating from greater depths, derived from devolatilization of  
33 subducting sediments analogous to clastic sediments in the Hawasina Formation, at 400-500°. Such  
34 processes could form important reservoirs for subducted CO<sub>2</sub>. Listvenite formation was accompanied  
35 by ductile deformation of serpentinites and listvenites – perhaps facilitated by fluid-rock reaction – in a  
36 process that could lead to aseismic subduction in some regions. Addition of H<sub>2</sub>O and CO<sub>2</sub> to the  
37 mantle wedge, forming serpentinites and listvenites, caused large increases in the solid mass and  
38 volume of the rocks. This may have been accommodated by fractures formed as a result of volume  
39 changes, mainly at a serpentinization front.  
40

41 **Plain language summary**

42 This paper reports initial results from study of core from Oman Drilling Project Hole BT1B and the  
43 surrounding area. It provides insights into subduction zone processes, including large fluxes of  
44 recycled CO<sub>2</sub> from subducting sediments into the leading edge of the mantle wedge, and surprisingly  
45 low temperature ductile deformation at less than 200°C. Recycling of CO<sub>2</sub> via carbon mineralization in  
46 the hanging wall of subduction zones may produce an important, lithospheric reservoir in the global  
47 carbon cycle. Ductile deformation of serpentinite, and during or after transformation of peridotite to  
48 listvenites (mixtures of carbonates and opal or quartz) could explain aseismic subduction atop some  
49 subduction zones.

## 1. Introduction

Oman Drilling Project (OmanDP) Hole BT1B at 23.364374°N, 58.182693°E, about 12 km southeast of the town of Fanjah in the Sultanate of Oman, sampled serpentinitized peridotites and listvenites (fully carbonated peridotites, Halls & Zhao 1995) at the base of the Samail ophiolite, the basal fault of the ophiolite, and the underlying metamorphic sole, with the intention of investigating mass transfer and deformation in the “leading edge of the mantle wedge” overlying a Tethyan subduction zone. Study of outcrops along the contact between the sole and the peridotite can illuminate processes in and above a subduction zone that are generally inaccessible to direct observation. Of particular interest are (a) the source of footwall fluids, (b) the nature and mechanism of fluid transport along the thrust fault and into the mantle wedge, (c) chemical, mineralogical and rheological modification of the hanging wall by reaction with footwall fluids, and (d) the mechanisms of subduction zone deformation.

Hole BT1B was drilled using cylindrical diamond bits and wireline core retrieval, from March 7 to March 23, 2017. Core recovery was ~ 100% throughout the Hole. Core was shipped to Japan and loaded onto Drilling Vessel Chikyu, where the OmanDP Science Team performed analyses closely following protocols established by the various incarnations of the Ocean Drilling Program (currently, the International Ocean Discovery Program, IODP). Detailed core descriptions, together with drilling history and some background information (Kelemen et al 2020b, Kelemen et al 2020c) are available online at [http://publications.iodp.org/other/Oman/VOLUME/CHAPTERS/113\\_BT1.PDF](http://publications.iodp.org/other/Oman/VOLUME/CHAPTERS/113_BT1.PDF)

This paper reports new mapping and structural observations, mineral analyses and modeling, together with a summary of prior observations. It is intended to provide interpretive context for more detailed studies of core from Hole BT1B and the geology of the surrounding region. Such studies in this Special Issue of the Journal of Geophysical Research include those focused on textural and petrologic data for listvenites (Beinlich et al 2020) and the metamorphic sole (Kotowski et al 2021), volume changes during serpentinitization (Malvoisin et al 2020), major and trace element geochemistry with relevance to subduction zone mass transfer (Godard et al 2021, Okazaki et al 2021), Mg-, Sr- and C-isotope geochemistry constraining the source of CO<sub>2</sub>-bearing fluids and the fluid-rock reaction process (de Obeso et al 2021a, de Obeso et al 2021b) and deformation of the listvenites (Menzel et al 2020, Menzel et al 2021).

Section 2 provides geological context for observations of core and surrounding outcrops. Section 3 summarizes methods used to produce results presented for the first time in this paper. Section 4 reports new geological field observations and analytical data, and reviews key results from Kelemen et al. (2020b) in context. Section 5 discusses the pressure, temperature and timing of listvenite formation, the nature and source of the fluids that transformed mantle peridotite into serpentinite and listvenite, the chemical and mechanical processes during these transformations, and deformation of altered mantle peridotite immediately above a paleo-subduction zone beneath the “leading edge of the mantle wedge”.

90

91 It is hoped that this paper, and the other papers in this Special Issue, will provide a starting point for  
92 future investigations of this unique and important site. In this context, readers should be aware that  
93 the archive half of the core is currently stored at Petroleum Development Oman where it is available  
94 for viewing, the working half of the core is stored at the American Museum of Natural History, where it  
95 can be sampled upon request to the Museum, and a huge volume of data from shipboard visual core  
96 observations and analytical data is available to anyone at  
97 <http://publications.iodp.org/other/Oman/OmanDP.html> , [https://www.icdp-](https://www.icdp-online.org/projects/world/asia/oman/)  
98 [online.org/projects/world/asia/oman/](https://www.icdp-online.org/projects/world/asia/oman/), and other sites that can be accessed from there.

99

100

## **2. Geological setting**

101

102

### *2.1 Regional geologic context*

103

104 The Samail ophiolite is composed of oceanic crust formed at a submarine spreading center above a  
105 subduction zone. The crustal thickness and composition of the ophiolite is similar to the geophysically  
106 and geologically constrained characteristics of fast-spreading, Pacific oceanic crust, with a few km of  
107 submarine lavas and sheeted dikes overlying a thicker, gabbroic lower crust (e.g., Christensen &  
108 Smewing 1981, Coleman & Hopson 1981, Nicolas et al 1996) However, the lavas have a trace  
109 element “subduction signature” (Alabaster et al 1982, Pearce et al 1981, Pearce & Peate 1995), and  
110 parental, mantle-derived magmas appear to have contained 0.2 to 2 wt% H<sub>2</sub>O, substantially more  
111 than in primitive mid-ocean ridge basalts (MacLeod et al 2013). Beneath the crustal section of the  
112 ophiolite, residual mantle peridotites and tabular dunites record polybaric decompression melting,  
113 melt extraction, and focused transport of basaltic melt upward to form the crust (Braun & Kelemen  
114 2002, Godard et al 2000, Kelemen et al 2000, Kelemen et al 1995, Monnier et al 2006).

115

116

### *2.2 Lithologies at the base of the Samail ophiolite*

117

118 Here we describe the units above and below the basal fault of the Samail ophiolite. We begin with a  
119 review of work on the metamorphic sole. Then, we describe the overlying Banded Unit at the base of  
120 the ophiolite’s mantle section. Finally, we briefly outline the nature of the sedimentary rocks beneath  
121 the metamorphic sole.

122

123 Beneath the mantle section of the ophiolite, and above allocthonous sediments of the Hawasina  
124 Formation, are discontinuously exposed lenses of a “metamorphic sole”. Peak pressures and  
125 temperatures in the sole generally record hot subduction conditions at temperatures up to 700-900°C  
126 (Cowan et al 2014, Ghent & Stout 1981, Hacker & Gnos 1997, Searle & Cox 1999, Searle & Cox  
127 2002, Searle et al 1980, Searle & Malpas 1980, Searle & Malpas 1982, Soret et al 2017) though at  
128 BT1B peak temperatures are 450-550°C (Kotowski et al 2021). Apparently – based on published data  
129 and calculations – the sole records a broad range of peak pressures from a possible lower limit of 200

130 MPa (Ghent & Stout 1981) or 800 MPa (Soret et al 2017) to a possible upper limit of 1400 MPa  
131 (Cowan et al 2014, Searle & Cox 2002). Kotowski et al. (2021) report that the sole in core from Hole  
132 BT1B records a peak pressure in the range of 800 to 1200 MPa.

133

134 The sole contains metasediments and meta-volcanic rocks – including submarine pillow lavas – with  
135 the major element compositions of mid-ocean ridge basalts (MORB) as well as alkali basalts and  
136 more evolved andesites and dacites (Alabaster et al 1982, Ernewein et al 1988, MacLeod et al 2013,  
137 Pearce et al 1981, Searle et al 1980). In core from BT1B, alkaline metabasalt compositions in the sole  
138 (Godard et al 2021, Kelemen et al 2020c) are unlike the magmas that formed the crust of the Samail  
139 ophiolite. In the ophiolite, the structurally lowest, “Geotimes” or “V1” lavas are similar to normal mid-  
140 ocean ridge basalts, though they probably were hydrous and they contain a hint of an arc trace  
141 element signature (Alabaster et al 1982, Ernewein et al 1988, MacLeod et al 2013, Pearce et al  
142 1981). Their composition, and that of dunite conduits for transport of primitive melts parental to V1  
143 through the shallow mantle, is consistent with formation of the gabbroic lower crust in the Samail and  
144 Wadi Tayin massifs of the ophiolite from primitive V1 magmas (Braun & Kelemen 2002, Kelemen et al  
145 1997, Kelemen et al 1995). The overlying “Lasail” or “V2” lavas in the ophiolite are incompatible-  
146 element-depleted, with a stronger subduction signature (Alabaster et al 1982, Ernewein et al 1988,  
147 MacLeod et al 2013, Pearce et al 1981) and include boninites (e.g., Ishikawa et al 2002) as well as  
148 tholeiitic basalts, andesites and dacites. Neither V1 nor V2 lavas are similar to the alkali basalt  
149 compositions in the sole. The present day  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in the alkali basalts in core from BT1B range  
150 from 0.704 to 0.706 (de Obeso et al 2021a), more radiogenic than MORB. Though their Sr isotope  
151 ratio may have been modified by alteration, one possibility is that the alkali basalts are remnants of  
152 subducted seamounts with elevated  $^{87}\text{Sr}/^{86}\text{Sr}$ , similar to accreted seamounts along the Cascadia  
153 margin of North America (e.g., Duncan 1982).

154

155 In addition to metabasalts, regionally the sole contains metasediments, and “exotic limestones”, all  
156 incorporated by Searle and Malpas (1980) in the “Haybi Formation”. However, in this paper we  
157 informally group the Haybi Formation into an undifferentiated metamorphic sole unit. In the sole  
158 sampled by drill core from Hole BT1B, metasediments are clearly distinguishable from the  
159 metabasalts based on texture, but some of them are compositionally similar to the metabasalts,  
160 perhaps reflecting a volcanoclastic origin, whereas others grade into somewhat odd, low-SiO<sub>2</sub>,  
161 muscovite-bearing lithologies (Godard et al 2021, Kelemen et al 2020b, Kotowski et al 2021).

162

163 Above the sole – where it is present – and elsewhere at the base of the ophiolite, the lower few km of  
164 the mantle section contains easily visible, meter to 10-meter scale, parallel bands of dunite,  
165 harzburgite and (rare) lherzolite, informally known as the Banded Unit (Godard et al 2000, Khedr et al  
166 2013, Khedr et al 2014, Linckens et al 2011, Lippard et al 1986, Prigent et al 2018a, Prigent et al  
167 2018b, Takazawa et al 2003, Yoshikawa et al 2015). The lithological contacts in this unit are sharp.  
168 They have low angle dips with respect to the paleo-seafloor, the crust-mantle transition zone, and the  
169 basal fault that juxtaposes mantle peridotite with the metamorphic sole. Mylonitic shear zones are

170 present in the Banded Unit , with textures recording deformation at 700–1,000°C (Boudier et al 1988,  
171 Herwegh et al 2016, Linckens et al 2011, Prigent et al 2018a). Thus, there is evidence for high strain  
172 ductile deformation and transposition of layering at the base of the mantle section, which might have  
173 accommodated substantial thinning (Prigent et al 2018a, Soret et al 2017). Similarly, there is evidence  
174 for thinning of the units below the ophiolite (Grobe et al 2018, Grobe et al 2019).

175

176 While some of the range in temperature and pressure estimates from the sole and the Banded Unit  
177 may be due to analytical and methodological uncertainty, or incomplete preservation and sampling of  
178 the highest-grade rocks, some may be due to temporal and spatial variability in peak metamorphic  
179 conditions. Moreover, the temperature record may be biased toward peak conditions, rather than later  
180 cooling. At the initiation of subduction near a spreading ridge, hot metamorphic rocks from the footwall  
181 may be accreted to the hot base of the newly formed mantle wedge, whereas as subduction zones  
182 grow colder and develop a steady-state thermal structure, cold dense lithologies in the footwall may  
183 be subducted (Agard et al 2016, Soret et al 2017). If so, the metamorphic sole in Oman may record  
184 the anomalously high temperatures of subduction initiation, and not the lower temperatures of  
185 evolution toward a steady-state subduction zone geotherm. The relatively low temperatures recorded  
186 by the sole in BT1B core could represent a point along this cooling path (Kotowski et al 2021).

187

188 A close correspondence between 96 to 95 Ma igneous ages in the crust, and both  $^{40}\text{Ar}/^{39}\text{Ar}$  and zircon  
189 U/Pb ages of metamorphic rocks along the basal thrust (ca. 96-94 Ma), indicates that thrusting of the  
190 Samail ophiolite over adjacent oceanic crust and nearby pelagic sedimentary units began during  
191 formation of igneous crust in the ophiolite (e.g. , Garber et al 2020, Hacker & Gnos 1997, Hacker &  
192 Mosenfelder 1996, Hacker et al 1996, Rioux et al 2012, Rioux et al 2013, Rioux et al 2016, Rioux et al  
193 2021b, Stanger 1985, Styles et al 2006, Tilton et al 1981, Warren et al 2005) or perhaps even earlier  
194 (Guilmette et al 2018).

195

196 The base of the metamorphic sole is truncated by a fault contact with autochthonous, low-grade  
197 metasediments of the Hawasina Formation, composed of pelagic clastic units interlayered with  
198 limestones (Béchenec et al 1990, Béchenec et al 1988). Relatively high, age corrected  $^{87}\text{Sr}/^{86}\text{Sr}$   
199 ratios in the clastic units suggest that they are distal sediments derived from erosion of continental  
200 crust (de Obeso et al 2021a, Weyhenmeyer 2000), while carbonate units record Sr isotope ratios  
201 similar to those of Mesozoic seawater (Weyhenmeyer 2000, Wohlwend et al 2017). These  
202 sedimentary units were thrust over Mesozoic to Proterozoic rocks of the Arabian continental margin,  
203 forming a “rumpled rug” between the autochthon and the ophiolite throughout northern Oman and the  
204 eastern United Arab Emirates.

205

#### 206 *2.4 History of the basal thrust of the Samail ophiolite*

207

208 Where the metamorphic sole is preserved, its tectonic contact with the mantle section of the ophiolite  
209 represents a paleo-subduction zone at the base of the ophiolite, which consumed several hundred

210 kilometers of Tethyan basin and then continental crust before coming to rest on the Arabian  
211 continental margin (Béchenec et al 1990, Béchenec et al 1988, Breton et al 2004, Cooper 1988,  
212 Ninkabou et al 2021, Searle & Robertson 1990, van Hinsbergen et al 2019). During this time, the  
213 overlying peridotite was “the leading edge of the mantle wedge”.

214

215 During coeval metamorphism of the sole and igneous accretion of the crust in the ophiolite, the  
216 relative locations of these two units are uncertain. Primitive V1 magmas in the ophiolite, with  
217 compositions almost indistinguishable from mid-ocean ridge basalts (MORB), crystallized to form  
218 most of the crust, particularly in the southern Wadi Tayin and Samail massifs that were the site of of  
219 the OmanDP boreholes. Like MORB worldwide, these magmas probably formed via polybaric  
220 decompression melting over a depth interval of 75 km or more (e.g., Allegre et al 1973, Asimow et al  
221 2004, Bottinga & Allegre 1973, Klein & Langmuir 1987, McKenzie & Bickle 1988). Thus, the  
222 metamorphic sole (recording peak depths less than 40 km) must not have been directly beneath the  
223 spreading center during crustal formation and metamorphism. Instead, the ophiolite section and the  
224 metamorphic sole were juxtaposed after crust formation and after peak metamorphism in the sole.

225

226 Moreover, the structural thickness of the Samail ophiolite measured perpendicular to the paleo-  
227 seafloor and/or the crust/mantle transition zone, and including both crust and mantle sections, never  
228 exceeds ~ 20 to 30 km (Boudier & Coleman 1981, Nicolas et al 2000), corresponding to a pressure  
229 less than or equal to ~ 800 MPa, beneath ~ 7 km of crust (on average, Nicolas et al 1996) and up to ~  
230 20 km of fresh mantle peridotite. Thus, the structural thickness of the ophiolite appears to be at least  
231 10 km less than the depth inferred from the high end of the pressure range recorded by the sole  
232 (1300 or 1400 MPa, ~ 40 to 45 km). In addition, there is no evidence for widespread, tectonic thinning  
233 of the crustal section of the ophiolite, either by faulting or ductile deformation.

234

235 How can these data be reconciled? One possibility is that the peak pressures inferred for the sole are  
236 imprecise, and/or that they represent tectonic “overpressures” that don’t correspond closely with  
237 depth (Garber et al 2020). In this interpretation, the metamorphism of the sole could have occurred at  
238 ~ 800 MPa, corresponding to the current structural thickness of the ophiolite. A second possibility, as  
239 noted above, is that the base of the mantle section of the ophiolite underwent tectonic thinning,  
240 perhaps via simple shear (Prigent et al 2018a, Soret et al 2017). A third alternative is that some of the  
241 lenses of the metamorphic sole – those recording the highest pressures - migrated updip to reach  
242 their current structural position, ~ 25 km below the paleo seafloor. Indeed, upward transport of  
243 buoyant footwall lithologies during subduction is recorded in many preserved collisional orogens (e.g.,  
244 Chemenda et al 2000). If so, updip migration of the sole with respect to the overlying ophiolite must  
245 have occurred after peak metamorphism but during Tethyan subduction, prior to emplacement of the  
246 ophiolite and the sole over the allochthonous Hawasina sediments. Finally, of course, it is possible  
247 that the current juxtaposition of the sole and the base of the ophiolite may be explained as the result  
248 of combinations of these three alternatives.

249

250 Subsequent events have affected the wedge, the sole, the underlying sedimentary units, and the  
251 faults between them (Grobe et al 2018, Grobe et al 2019). The end of subduction and emplacement  
252 of the ophiolite over allochthonous Hawasina sediments and the autochthonous, Arabian continental  
253 margin was followed by subaerial erosion, and then by a marine transgression marked by deposition  
254 of shallow water limestones at ~ 74 Ma (Al Khirbash 2015, Alsharan & Nasir 1996, Bailey 1981,  
255 Hansman et al 2017a, Nolan et al 1990, Schlüter et al 2008, Wyns et al 1992). Then, large scale uplift  
256 deformed all these units, forming the gigantic Jebel Akdar and Saih Hatat domes, cored by  
257 Proterozoic continental crust (e.g., Glennie et al 1973, Glennie et al 1974b). Saih Hatat uplift and  
258 cooling started at about 60 Ma, if not earlier (e.g., Grobe et al 2018, Grobe et al 2019, Hansman et al  
259 2017b). Doming reactivated and cut the basal thrust of the ophiolite in normal faults and shear zones.  
260 Some of these younger faults juxtaposed mantle peridotite from the ophiolite with the allochthonous  
261 Hawasina sedimentary rocks, and even with the autochthonous platform carbonates of the Arabian  
262 continental margin, along tectonic contacts where the metamorphic sole is no longer present.

263

264 However, despite these complexities, we reiterate that – where it is parallel to banding and foliation –  
265 the contact between the metamorphic sole and the overlying Banded Unit at the base of the Samail  
266 ophiolite mantle section represents the basal thrust of the ophiolite. In this paper, when we refer to the  
267 “basal thrust”, we are referring to contacts that preserve these characteristics. In turn, though of  
268 course there can have been imbrication and/or subduction erosion, the basal thrust of the ophiolite  
269 represents the locus of 100’s of kilometers of subduction of oceanic crust, overlying sediments and,  
270 ultimately, the Arabian continental margin.

271

272

### 2.5 Geology of MoD Mountain

273

274 Hole BT1B is on the north side of the wide Wadi Mansah, southeast of “Ministry of Defense  
275 Mountain”, (MoD Mountain), which is informally named for the military firing range on the south side of  
276 Wadi Mansah. The MoD Mountain region is close to the saddle between the northeastward plunging  
277 end of the Jebel Akdar massif, to the west, and the westward plunging Saih Hatat massif to the  
278 northeast (Figure 1).

279

280 This region preserves a gently folded, tectonic “stratigraphy” (Figures 2, 3 and 4). The lowest  
281 exposed units in this sequence, northeast of Hole BT1B, are diagenetically-altered sedimentary rocks,  
282 mostly clastic shales and slates with a few meter to 10 meter scale intercalations of limestone and  
283 minor lenses of metavolcanic rocks. These are parts of the Hawasina Formation (Béchenec et al  
284 1990, Béchenec et al 1988). Overlying the Hawasina Formation is one of the most aerially extensive  
285 outcrops of the metamorphic sole in Oman and the UAE (e.g., Figure 1 and geologic maps in Soret et  
286 al 2017, Wilde et al 2002). The outcrop area is unusually large in this region because the unit is  
287 regionally flat lying, though broadly folded.

288



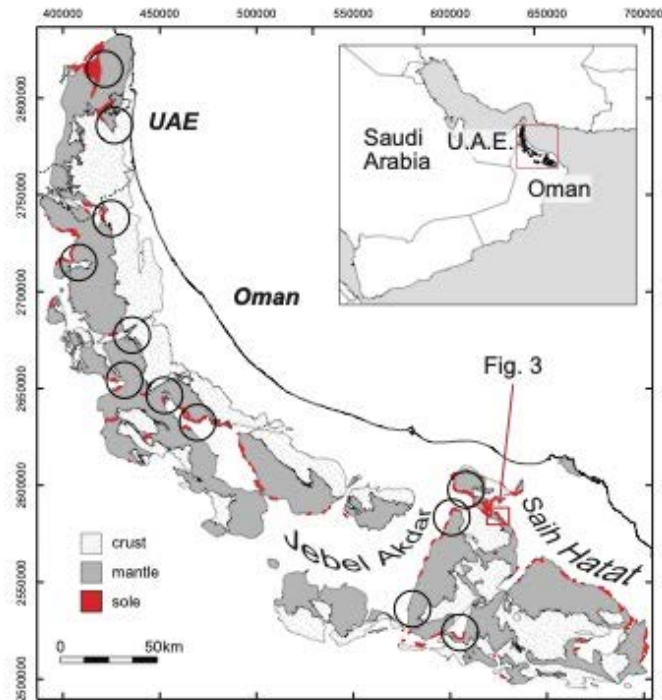


Figure 1: Outcrop area of the Samail ophiolite in Oman and the UAE, based on Nicolas et al. (2000). Metamorphic sole, in red. Black circles indicate approximate location of listvenites (Nasir et al 2007, Stanger 1985, Wilde et al 2002). Red rectangle indicates the approximate location of Figure 3, a geologic map of MoD Mtn and vicinity, which was the site of Oman DP Hole BT1B, and the focus of this paper.

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Figure 2: Photograph of the west end of the MoD Mountain ridge, from the SW, looking NE, showing bands of listvenite (rusty orange) parallel to contacts between partially serpentinized harzburgite (brown) and dunite (tan) comprising the "Banded Unit" at the base of the Samail ophiolite mantle section. Greenish metabasalts and metasediments of the metamorphic sole underlying the ophiolite are exposed along indistinct ridge in lower left. The listvenite band at top right is more than 100 m thick and extends for 1.5 kilometers along the length of the summit ridge. The listvenite band in the center of the photo is 15-20 m thick. Photo taken with a telephoto lens from ~ 23.35°N, 58.17°E, along azimuth ~ 030°.

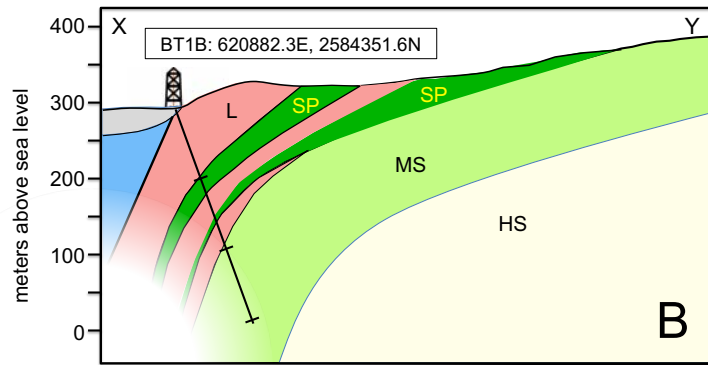
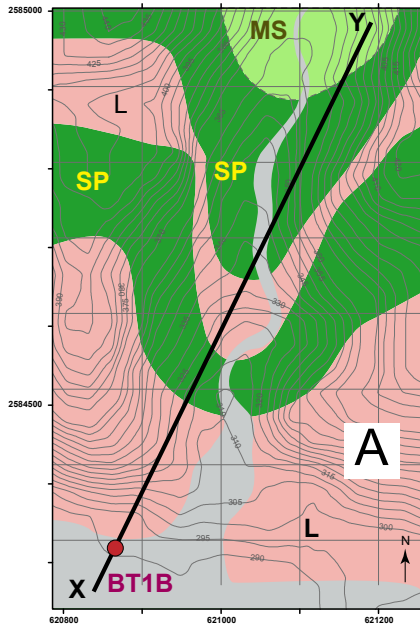


Figure 3: Map and cross section of the area NNE of Oman Drilling Project Site BT1. Yellow, HS: Hawasina sediments; light green, MS: metamorphic sole; rusty red, L: listvenite; dark green, SP: serpentinized peridotite; blue: inferred gabbro, based on outcrops south of Wadi Mansah; grey: gravels of Wadi Mansah. UTM coordinates in meters. Cross section has no vertical exaggeration. Map and cross-section modified from Figures F1 and F2 in Kelemen et al. (2020b)

300  
301

302 Above the metamorphic sole in this gently folded “stratigraphy” is partially serpentinized peridotite,  
303 composed of distinctive, banded alternations of dunite, harzburgite and lherzolite on a scale of meters  
304 to tens of meters, characteristic of the “Banded Unit” at the base of the ophiolite (Boudier et al 1988,  
305 Boudier & Coleman 1981, Lippard et al 1986, Searle & Cox 2002). Indeed, partially serpentinized  
306 mantle peridotites on MoD Mountain, northeast of Hole BT1B have compositions similar to the  
307 Banded Unit elsewhere, and distinct from shallower, residual mantle peridotites of the Samail ophiolite  
308 emantle section, as discussed in [Section 5.5](#), below. The presence of the Banded Unit overlying the  
309 metamorphic sole is another indication that MoD Mountain area exposes the basal thrust of the  
310 ophiolite – the paleo-subduction zone – together with the overlying mantle wedge.

311

312 In some localities, peridotites at the base of the Samail ophiolite mantle section have undergone  
313 100% carbonation at ~ 100-200°C to form “listvenites” (Beinlich et al 2020, Falk & Kelemen 2015,  
314 Glennie et al 1974a, Nasir et al 2007, Stanger 1985, Wilde et al 2002), in which all Mg and Ca are in  
315 carbonate minerals, and silica derived from olivine and pyroxene has formed quartz or chalcedony. In  
316 Oman, such listvenites are most abundant on and around MoD Mountain northeast of Hole BT1B,  
317 where they form part of the gently folded tectonic “stratigraphy” we are discussing here. Listvenites on  
318 the flanks of MoD Mountain form discontinuous tabular lenses with low angle dips, 10 to 200 meters  
319 thick, parallel to the basal thrust and to lithological banding in the peridotite. These lenses occur along  
320 the basal thrust – between peridotite and the sole – and enclosed within the peridotite, up to 300  
321 meters above the sole. Contacts in outcrop between listvenite and the surrounding, partially  
322 serpentinized peridotite are marked by strongly foliated, 100% serpentinized zones, 1 to > 20 m thick.

323

324 The lithological banding in the peridotite and the listvenite lenses dip gently south on the south side of  
325 MoD Mountain, north on the north slopes of the mountain, and then south again along and NE of the

326 wadi bounding MoD Mountain to the north (Falk and Kelemen 2015 and this paper, [Section 4.2](#)).  
327 Despite later faulting, these structures define a broad anticline with an axis approximately coincident  
328 with the summit ridge of MoD Mountain, and a syncline with an axis roughly coincident with the wadi  
329 northeast of MoD Mountain. Listvenites form erosion resistant dip slopes and the tops of small buttes  
330 outlining the folded stratigraphy.

331

332 Listvenites elsewhere in Oman and the UAE are found along the basal thrust, commonly juxtaposed  
333 with, or within a few km of, the metamorphic sole and/or the Banded Unit at the base of the Samail  
334 mantle section, as at MoD Mountain. In some other outcrops, listvenites form lenses within broad  
335 serpentinite mélangé zones at the base of the ophiolite (Nasir et al 2007, Stanger 1985). In contrast,  
336 listvenites are not found within the peridotite more than a few kilometers away from the basal thrust of  
337 the ophiolite.

338

339 A Rb/Sr isochron on listvenite mineral separates ( $97 \text{ Ma} \pm 29 \text{ Ma } 2\sigma$ , Falk & Kelemen 2015) is similar  
340 to the better determined, 96 to 94 Ma U/Pb ages of zircon in the metamorphic sole and igneous crust  
341 in the ophiolite. Based on the listvenite mineral isochron, there is a 67% probability that the listvenites  
342 are older than 82.5 Ma (average  $-1\sigma$ ), and a 93% probability that they are older than 75 Ma ( $1.5\sigma$ ),  
343 before the end of subduction. Thus, geological observations (summarized above and in [Section 4.2](#))  
344 together with the isochron data indicate that the listvenites formed via transfer of  $\text{CO}_2$  and other  
345 components from subducting material – probably sediments and/or altered lavas – into the leading  
346 edge of the mantle wedge during Tethyan subduction and ophiolite emplacement. New geological  
347 data supporting this are presented in 4.2. [Sections 5.6 and 5.7](#) provide thermodynamic modeling that  
348 quantifies this hypothesis.

349

350 As noted in [Section 2.4](#), Paleocene to Miocene uplift of the nearby Jebel Akdar and Saih Hatat  
351 massifs may have caused reactivation of some older faults, and definitely formed new, younger faults  
352 in the MoD area. For example, shallow-level gabbros and sheeted dikes are juxtaposed with mantle  
353 peridotite and the metamorphic sole on a steep fault parallel to Wadi Mansah, just south of Hole BT1B  
354 (Villey et al 1986, Wilde et al 2002). In another possible example, Scharf et al. (2020) report early  
355 U/Pb formation or cooling ages ( $60 \pm 16$  and  $58 \pm 6$  Ma) of calcite veins that cut listvenite, cataclasite  
356 and fault contacts between listvenite and post-emplacement, Late Cretaceous conglomerates.

357

358

### 3. Methods

359

360 Here we describe methods used for new data presented for the first time in this paper. [Supplementary](#)  
361 [Section S2](#) provides methods for data illustrated in this paper, but previously reported elsewhere.

362

363

#### 3.1 Geological mapping

364 Geological field work to produce the map and cross-section in **Figure 4** spanned short visits over  
365 about a decade. Contacts and structural measurements were located by GPS at the time of  
366 measurement. The topographic profile for the cross section was constructed using Google Earth.

367

368

### 3.2 Raman spectroscopy

369

370 Analyses of minerals in thin section and rock slabs were conducted at the Raman Microspectroscopy  
371 Laboratory, University of Colorado-Boulder with a Horiba Scientific LabRam HR Evolution Raman  
372 microscope. Measurements used a 100 mW 532 nm laser, focused through a 50x (0.75 NA)  
373 microscope objective onto a ~2  $\mu\text{m}$  spot. The laser power was modulated with neutral density filters to  
374 about 15 mW at the sample surface. Multiple (2-10) accumulations were coadded in order to filter  
375 spikes and improve signal to noise, and the acquisition time and accumulation number were adjusted  
376 to yield appropriate data quality. Data processing was performed using LabSpec 6 software (Horiba  
377 Scientific), including correction for instrumental artifacts and polynomial baseline fitting/subtraction.  
378 Raman mapping was performed using a motorized stage with 2  $\mu\text{m}$  step size, and map datasets were  
379 fit using classical least-squares fitting with endmember spectra isolated from regions within the map  
380 using LabSpec 6 after data processing.

381

382

### 3.3 Thermodynamic calculations and modeling

383

384 The speciation and chemical mass transfer code EQ3/6 (Wolery 1992) was used to predict the  
385 compositions of coexisting solid and aqueous phases that evolved during interaction between  
386 representative lithologies from the MoD Mountain area and CO<sub>2</sub>-bearing fluids. Thermodynamic data  
387 for minerals were mostly from Berman (1988). Data for pyrite and pyrrhotite were from Helgeson et al.  
388 (1978). For aqueous species, thermodynamic data used in the simulations were calculated using the  
389 Deep Earth Water (DEW) model (Huang & Sverjensky 2019, Sverjensky et al 2014) which uses  
390 recent experimental and theoretical advances (Facq et al 2016, Pan et al 2013) to expand the  
391 extended Helgeson-Kirkham-Flowers (HKF) aqueous equation of state (Shock et al 1992, Shock et al  
392 1997) to pressures up to 6.0 GPa.

393

394 The composition of 5 wt% aqueous fluid in equilibrium with a pelitic lithology from the Oman  
395 Hawasina Formation at 400 – 600°C and 0.5 to 2.0 GPa at low water/rock ratios was used.  
396 Specifically, a dilute fluid was equilibrated with the rock composition of sample OM20-17 (de Obeso et  
397 al 2021a), containing 0.06 wt% total carbon (**Supplementary Table 2**). The CaO content of OM20-17  
398 was below detection. For the model calculations it was assumed to 0.1 wt%. In addition, the S content  
399 of this sample has not been measured. For this calculation it was assumed 100 ppm. At these high  
400 temperatures and low carbon contents, carbonate minerals are unstable and all carbon in the rock will  
401 be mobilized into the fluid phase as dissolved CO<sub>2</sub>.

402

403 We calculated the outcome of cooling and decompression of the CO<sub>2</sub>-rich fluid from OM20-17, to 100  
404 – 300 °C and 0.5 to 2.0 GPa. This had no significant effect on its composition. We then calculated the  
405 products of reaction between this fluid and average Oman harzburgite (Supplementary Table 2,  
406 calculated from Godard et al 2000, Hanghoj et al 2010, Monnier et al 2006) at 100 – 300 °C and 0.5 –  
407 1.0 GPa, at water:rock ratios ranging from 100 to 1.

408

409 As a result of data limitations, solid solutions of precipitating minerals were not considered, as the  
410 Berman database lacks properties for most Fe-endmembers of minerals commonly observed in  
411 listvenites and associated rocks. Thus, for example, the model predicts co-precipitation of pure,  
412 endmember magnesite, dolomite and siderite, whereas in listvenite samples we observe Fe-bearing  
413 magnesite and dolomite. Among the serpentine polytypes, only chrysotile precipitation can be  
414 modeled. We did not include goethite. There are no thermodynamic data for a chromian muscovite  
415 component, so this was not included, despite the fact that solid solutions ranging from fuchsite to  
416 chromian muscovite are observed in MoD Mountain listvenites (e.g., Falk & Kelemen 2015).

417

418 Phase equilibrium calculations constraining the conditions for co-existing graphite ( $\pm$  amorphous  
419 carbon compounds) and hematite, and updated calculations for co-existing antigorite and quartz,  
420 used (1) Thermocalc (Powell et al 1998), (2) Perple\_X (<https://www.perplex.ethz.ch/>) (Connolly 1990,  
421 Connolly 2005, Connolly 2009), with the Holland and Powell thermodynamic data for minerals (2003,  
422 1998), and the default equations of state for H<sub>2</sub>O- CO<sub>2</sub> fluids (modified versions of Redlich-Kwong),  
423 and (3) SUPCRT (Johnson et al 1992, Zimmer et al 2016) with thermodynamic data for minerals from  
424 Helgeson et al. (Helgeson 1985, 1978) or Berman (1988, plus graphite from Helgeson et al.) and  
425 various equations of state for H<sub>2</sub>O-CO<sub>2</sub> fluids (Shock et al 1992, Shock et al 1997) modified from  
426 Helgeson et al. (1981). All of these different combinations provided consistent results, with antigorite  
427 + quartz stable with respect to talc at temperatures up to 80 to 120°C. However, calculations using  
428 the Deep Earth Water (DEW) model (Huang & Sverjensky 2019, Sverjensky et al 2014) and the  
429 extended Helgeson-Kirkham-Flowers (HKF) aqueous equation of state (Shock et al 1992, Shock et al  
430 1997) do not predict equilibrium coexistence of antigorite + quartz above 15°C.

431

### 432 3.4 (U,Th)/He ratio measurements and cooling age calculation

433

434 All (U-Th)/He analyses were completed at the UTChron facility at the University of Texas at Austin,  
435 using aliquots of zircon separates from the metamorphic sole and lower crustal gabbros, previously  
436 analyzed for U/Pb ages by Rioux et al. (in prep.), following procedures of Wolf and Stockli (2010).  
437 Individual zircon grains were morphometrically characterized to determine alpha ejection correction  
438 (Ft, Farley et al., 1996; Cooperdock et al., 2020), equivalent spherical radius (ESR), and estimated  
439 mass assuming a tetragonal prism. Single-grain zircon sample aliquots were loaded into Pt tubes for  
440 in-vacuo laser He heating for 10 min at ~1200°C by diode laser and 4He concentrations were  
441 measured by isotope dilution, using a <sup>3</sup>He tracer, on a Blazers Prisma QMS-200 quadrupole mass  
442 spectrometer, after cryogenic purification. Blanks and <sup>4</sup>He gas standards were run between unknowns

443 to monitor and quantify the procedural baseline during analytical runs. Aliquot laser reheating was  
444 repeated (2-5x) until  $4\text{He}$  gas yields dropped  $<1\%$  total extracted gas.

445

446 After degassing, individual zircon grains were removed from the Pt packets and dissolved using a  
447 two-step  $\text{HF-HNO}_3$  and  $\text{HCl}$  pressure vessel dissolution technique and measured on a Thermo  
448 Element2 HR-ICP-MS following the procedure outlined in Wolf and Stockli (2010). U-Th-Sm  
449 concentrations were calculated using isotope dilution with an isotopically enriched, mixed U-Th-Sm  
450 spike calibrated against a 1 ppb U-Th-Sm gravimetric standard solution and blank-corrected using the  
451 average of multiple procedural blanks.

452

453 Final (U-Th)/He ages were calculated using blank corrected U, Th, Sm and He measurements for  
454 each aliquot. Reported concentrations were determined using the morphometrically determined mass  
455 of each aliquot. The reported error for individual (U-Th)/He ages represents standard error (8%)  
456 based on long-term intra-laboratory reproducibility of Fish Canyon tuff zircon standard, following the  
457 approach of Farley et al. (2001). The reported mean sample ages reflect the arithmetic mean of the  
458 aliquot ages and their standard deviations.

459

460 3.5 Calibration of XRF core scanner data

461

462 XRF core scanner data were collected onboard DV Chikyu, as described in Kelemen et al. (2020b).  
463 We used the core scanner to analyze nine listvenite samples from BT1B core, and 14 gabbro  
464 samples from Hole GT1A core that had known bulk compositions based on XRF analysis at the  
465 University of St. Andrews. While onboard DV Chikyu, we used the St. Andrews data to calibrate the  
466 XRF data, as follows:  $\text{wt}\% \text{SiO}_2 = 0.89 \times (\text{scanner wt}\% \text{SiO}_2)$ ;  $\text{wt}\% \text{MgO} = 2.57 + 1.18 \times (\text{scanner wt}\% \text{MgO})$ ;  
467  $\text{wt}\% \text{FeO}^{\text{T}} = 1.048 + (\text{scanner wt}\% \text{FeO}^{\text{T}})^{0.848}$ ; and  $\text{wt}\% \text{CaO} = 0.878 \times (\text{scanner wt}\% \text{CaO})$ ,  
468 where  $\text{FeO}^{\text{T}}$  indicates all Fe is treated as FeO. Fits are illustrated in [Supplementary Figure 2](#). Okazaki  
469 et al. (2021) present a comprehensive analysis of the XRF scanner data, together with X-Ray  
470 tomography data for BT1B core.

471

472 3.6 Calculation of mineral volume proportions

473

474 Volume proportions of quartz, magnesite and dolomite were estimated from bulk rock compositions  
475 and XRF scanner data as follows. Weight fractions of  $\text{SiO}_2$ , MgO,  $\text{FeO}^{\text{T}}$  and CaO were converted to  
476 moles in 100 grams of rock using their molecular weights. (For all data reported in this paper, the sum  
477 of  $\text{wt}\% \text{SiO}_2$ , MgO,  $\text{FeO}^{\text{T}}$  and CaO was greater than 90% of the volatile free, bulk rock composition).  
478 The number of moles of dolomite were taken to be equal to moles of CaO, moles of magnesite were  
479 calculated as moles MgO – moles CaO, and moles of quartz were taken to be equal to moles of  $\text{SiO}_2$ .  
480 All Fe was inferred to be in Fe-oxides and hydroxides. If the small amounts of Fe in carbonate  
481 minerals were included in such a calculation, this would slightly increase the proportions of magnesite  
482 and dolomite, relative to quartz. Volumes of each mineral in 100 grams of rock were calculated using

483 their molar volumes. The data were “projected” from Fe oxy-hydroxides by normalizing the volumes of  
484 quartz, magnesite and dolomite to 100%.

485

486

## 4. Results

487

488

### 4.1 Drilling operations

489

490 Site BT1 is on the north side of the broad channel of Wadi Mansah, which drains mountainous  
491 regions to the east and southeast. Hole BT1A penetrated 1.90 meters of gravels in Wadi Mansah,  
492 south of listvenite outcrops flanking the Wadi. After we became concerned that a steep hole there  
493 might intersect tens of meters of gravel before reaching bedrock, and/or that the gravel might overlie a  
494 major, steep fault along Wadi Mansah that postdates ophiolite emplacement, we moved the drill and  
495 inclined the Hole. Hole BT1B is three or four meters closer to the listvenite outcrop. The well head is  
496 intact, marked and protected from floods by a concrete monument. Drilling of the fine-grained, silica-  
497 rich listvenites was challenging, because this lithology has a hardness similar to fine-grained chert or  
498 flint (~ 7 on the Mohs' scale), but with patience and expert drilling, we obtained ~ 100% recovery of all  
499 lithologies intersected by the borehole. Details of drilling operations are in Kelemen et al. (2020b).

500

501

### 4.2 Mapping and structural observations

502

503 Geological mapping of the area around MoD Mountain, together with measurement of the orientation  
504 of lithological contacts, began in 2009, and continued via brief visits through 2019. As noted in  
505 [Section 2.5](#), and reported by Falk and Kelemen (2015), the mountain is underlain by a southeast to  
506 northwest striking anticline, with its faulted hinge approximately coincident with the ridge along the  
507 summit. Exposed contacts between listvenite and serpentized harzburgite consistently dip to the  
508 southwest on the southwest side of the mountain, and to the east and northeast on the northeast side.  
509 In the valley north of the mountain, listvenite-harzburgite, listvenite-metamorphic sole, and  
510 harzburgite-sole contacts form a broad, shallow syncline. A new, detailed geological map and cross-  
511 section, incorporating our lithological and structural observations, is presented in [Figure 4](#).

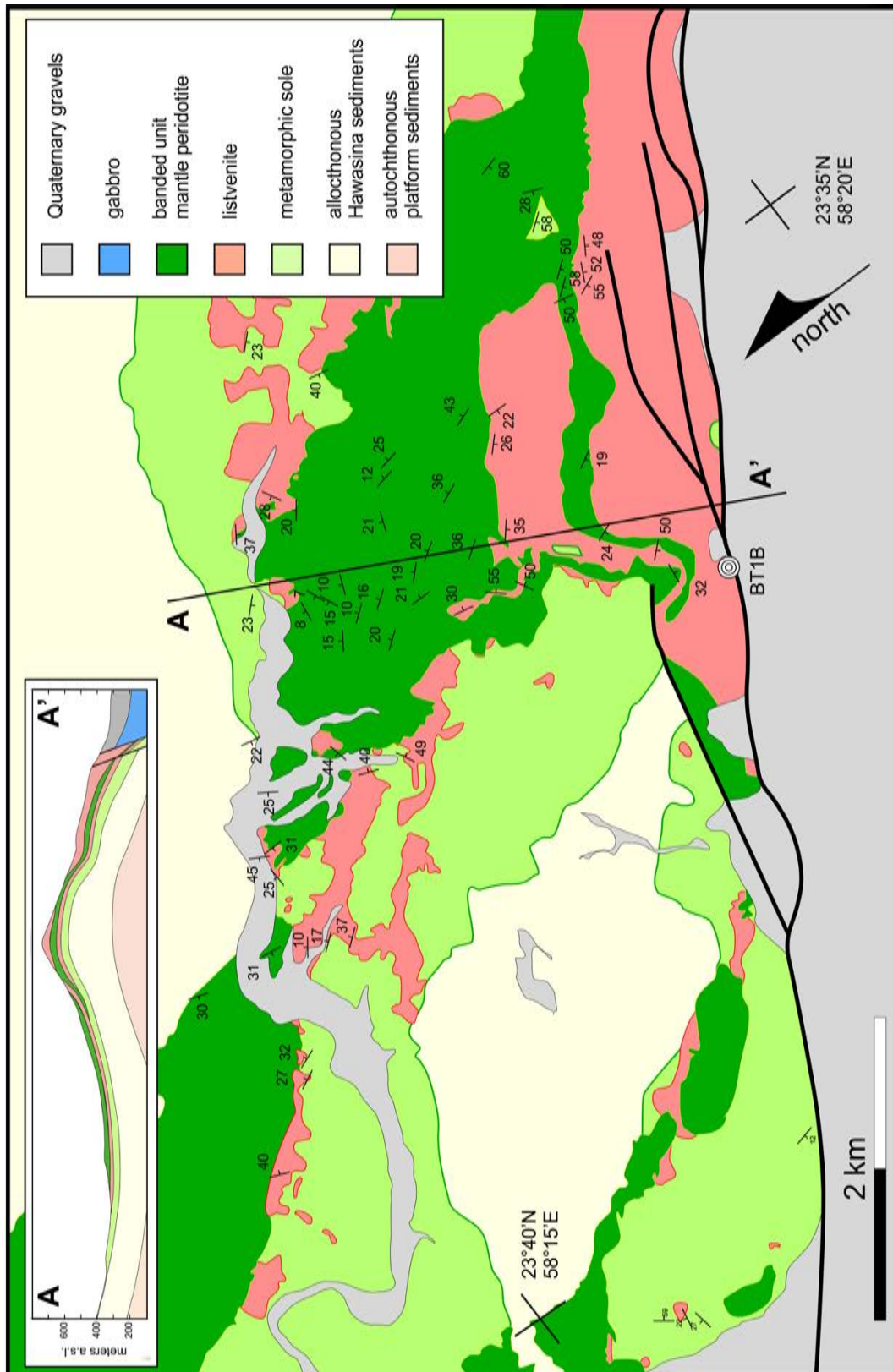
512

513 As shown on the map, in outcrops extending for more than 4 km north of Hole BT1B there is a regular  
514 tectonic “stratigraphy”, with variably altered peridotite overlying the metamorphic sole, in turn  
515 overlying Hawasina Formation sediments, all with low angle fault contacts that have been deformed  
516 by a series of gentle, broad open folds evident in the map and cross-section.

517

518 We noted normal and reverse shear sense indicators on both sides of the anticline. As a result of the  
519 folding, it is difficult to interpret the sense of shear recorded in various outcrops. Some shear sense  
520 indicators may predate the folding, while others may record deformation during or after folding.

521



522

523 *Figure 4: Geologic map and cross section of MoD Mountain and vicinity. Complex map pattern arises*  
 524 *from intersection of topography with broadly folded, gently dipping units, as is more evident in the*  
 525 *cross section (no vertical exaggeration) illustrating the antiform coinciding with MoD Mountain, and*  
 526 *the syncline to its north. Dips are all measured on lithologic contacts, including dunite/harzburgite*  
 527 *contacts within the Samail ophiolite mantle section.*



528

529 In contrast, to the northwest and southeast, outside our map area, the outcrop patterns become much  
530 more complex, the sole outcrop thins, and there are some vertical fault contacts where all of these  
531 older units are juxtaposed with Late Cretaceous Al Khod conglomerates and younger, shallow marine  
532 limestones (Stanger 1985, Villey et al 1986, Wilde et al 2002).

533

#### 534 4.3 Zircon (U,Th)/He cooling ages

535

536 Zircon (U,Th)/He cooling ages on samples from the metamorphic sole southeast of Fanjah, near MoD  
537 Mountain, are  $38.7 \pm 7.7$  and  $44.4 \pm 8.0$  Ma, cooling ages of zircons from the metamorphic sole at the  
538 base of the Wadi Tayin massif to the east are  $54.5 \pm 7.4$  and  $61.8 \pm 2.6$  Ma, and the cooling age of  
539 zircons from the lower crust of the Samail massif is  $46.4 \pm 3.9$  Ma (Supplementary Table 1 and  
540 Supplementary Figure 1).

541

542

#### 4.4 Lithology

543

544 As illustrated in Figure 5, the top of the Hole sampled ~ 200 meters of listvenite interlayered with two  
545 serpentinite bands from 80 to 100 m depth, and 181 to 185 m depth. Below 185 m, the listvenite is  
546 ubiquitously deformed, with visual core descriptions indicating a mixture of brittle and ductile  
547 deformation. At about 197 m, core was composed of a few tens of cm of soft, clay-rich fault gouge,  
548 together with a few cm of hard, aphanitic, black ultracataclasite. Beneath these fault lithologies, the  
549 core sampled ~ 102 meters of the metamorphic sole, grading from dominantly fine-grained, finely-  
550 banded, muscovite-bearing metasediments at the top (“greenschists” in Figure 5) to coarser, more  
551 massive-appearing, foliated “greenstones”, interpreted as metavolcanic rocks, at the bottom.

552

553 Serpentinite bands in the core have gradational contacts with host listvenites over 10's of centimeters  
554 to ~ 1 m thick. Serpentinities contain antitaxial veins of magnesite with a median line composed of  
555 hematite and other Fe-oxides. There are prismatic terminations of magnesite crystals away from vein  
556 centers, toward the host serpentine (Figure 6). Antitaxial veins record growth of minerals outward  
557 from the vein center. They are commonly interpreted to open due to the “pressure of crystallization”  
558 (Durney & Ramsay 1973, Urai et al 1991). However, this interpretation is less clear in the  
559 serpentinites and listvenites of Hole BT1B, where the Mg in the carbonate is derived from the host  
560 rocks. To some degree these veins may replace, rather than displace, the host.

561

562 Away from the veins, serpentinites also contain up to 10% magnesite ovoids 10 to 100 microns in  
563 diameter, unevenly dispersed within a massive serpentine matrix. These magnesite vein and ovoid  
564 textures are abundant in the listvenites as well. Thus, the Shipboard Scientific Party suggested that  
565 they are indicative of incipient replacement of serpentinite by listvenite, grading from < 10% carbonate  
566 (and no quartz) in veins and ovoids to 100% fine-grained carbonate + quartz across sharp reaction  
567 fronts (Kelemen et al 2020b). Another notable feature is that some of the serpentinites are optically

568 isotropic in thin section, probably indicative of low temperature formation of poorly ordered or  
 569 amorphous material with serpentine stoichiometry (e.g., Andreani et al 2004).  
 570

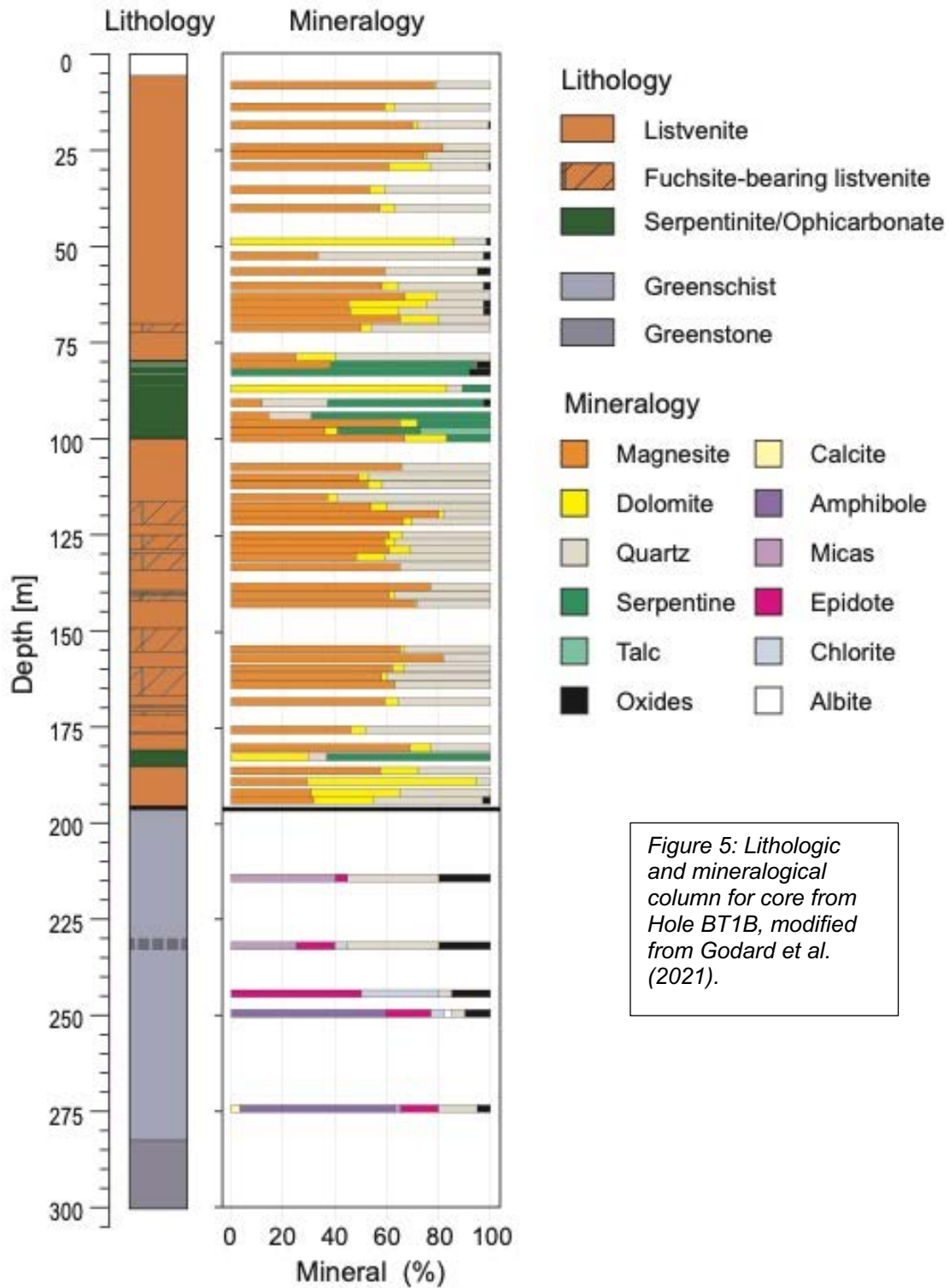
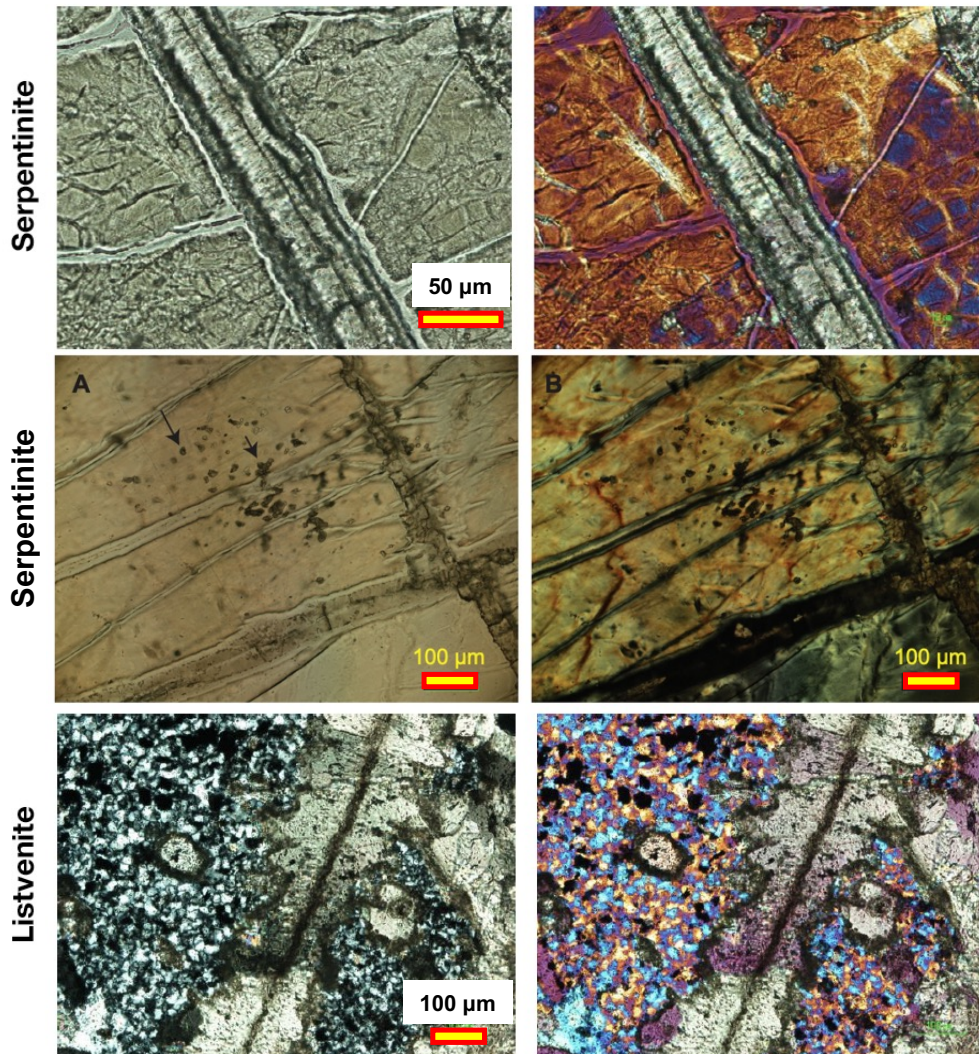


Figure 5: Lithologic and mineralogical column for core from Hole BT1B, modified from Godard et al. (2021).

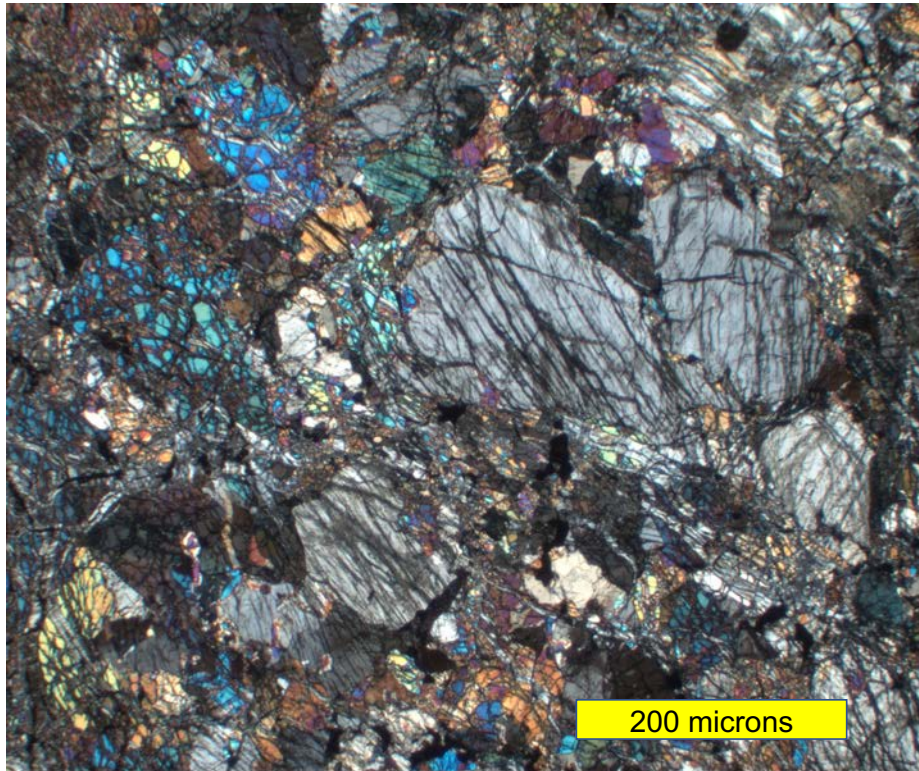
571  
 572  
 573



574  
 575 *Figure 6: Antitaxial magnesite-hematite veins, and magnesite spheroids in serpentinites and*  
 576 *listvenites in core from Hole BT1B. Top panels: plane light (left) and crossed-polarized images (right,*  
 577 *quartz plate (+1λ) inserted) of magnesite-hematite veins near the lower contact of the upper*  
 578 *serpentinite band, TS\_BT1B\_44Z-3\_9-11.5, ~100 m depth, from Figure F47 in Kelemen et al.*  
 579 *(2020b). Middle panels: tiny magnesite spheroids in serpentinite, TS\_BT1B\_44Z-3\_9-11.5, ~100 m*  
 580 *depth, from Figure F29 in Kelemen et al. (2020b). F. Bottom panels: Cross-polarized images, right*  
 581 *one with quartz plate (+1λ) inserted, of texturally similar, “antitaxial” magnesite-hematite veins and*  
 582 *magnesite ovoids in quartz-rich, listvenite matrix, TS\_BT1B\_47Z-3\_15-19 at about 110 m depth, from*  
 583 *Figure F35 in Kelemen et al. (2020b).*  
 584

585 In turn, listvenites and serpentinites recovered in drill core are hosted by more typical, partially  
 586 serpentinitized peridotites and dunites in outcrop north and northeast of Hole BT1B (Figure 7). Such  
 587 lithologies, typical of the Banded Unit at the base of the mantle section of the Samail ophiolite, are  
 588 abundant on the flanks of MoD Mountain, and are particularly well exposed west of the summit  
 589 (Figure 2) and on the broad, north facing outcrop below the summit ridge.

590



591  
592 *Figure 7: Cross-polarized image of partially-serpentinized harzburgite sample OM09-14 (Falk &*  
593 *Kelemen 2015) from ~ 10 m above lower listvenite band in [Figure 2](#). Olivine: bright interference colors*  
594 *and irregular, serpentine-filled fractures. Orthopyroxene: grey interference colors and parallel to*  
595 *orthogonal fractures. Minor calcic-pyroxene and/or hornblende are barely visible in this image.*  
596

597 A sample transect on the ridge forming the drainage divide between Wadi Mansah (site of Hole BT1B)  
598 and the parallel wadi north of MoD Mountain documented a 5-meter scale progression from listvenite  
599 to serpentinite (with intergrown quartz and antigorite) to partially serpentinized peridotite containing  
600 relict olivine and orthopyroxene (Figure 5 in Falk & Kelemen 2015). Along that watershed transect, the  
601 presence of antigorite – rather than the serpentine polytypes lizardite and chrysotile – was attributed  
602 to high SiO<sub>2</sub>-activity produced by reaction of olivine and serpentine to produce carbonate and quartz,  
603 since antigorite is more SiO<sub>2</sub>-rich than the other polytypes.

604  
605 However, the serpentinites in core from Hole BT1B are distinct from the serpentinized zone flanking  
606 listvenite on the ridge transect, and from the surrounding, partially serpentinized Banded Horizon  
607 harzburgites. Although quartz veins cut the serpentinite in the core, antigorite was not observed.  
608 Moreover, despite the presence of some orthopyroxene pseudomorphs (“bastites”) in serpentinites,  
609 and a concerted effort to find relict mantle minerals, no olivine or pyroxene were detected in drill core.  
610 Taken together, field and core observations suggest that the contact between serpentinites and  
611 partially serpentinized peridotites is gradational over a few meters at most, approximately as sharp as  
612 the contact between listvenites and serpentinites. More on this in [Sections 5.7 and 5.8](#), below.

613  
614 Essentially, two types of listvenite were recovered, magnesite + quartz + iron oxide lithologies, and  
615 volumetrically less abundant, dolomite + quartz + iron oxide rocks, previously termed magnesite-

616 listvenites and dolomite-listvenites (Falk & Kelemen 2015). Much of the core contains 0.5 to 3% relict  
617 chromian spinel, partially or fully altered to Fe-oxides. Instead or in addition, some samples contain  
618 minor amounts of Cr-rich white mica (fuchsite-muscovite solid solutions, supplementary Figure 7 in  
619 Falk & Kelemen 2015), in mm to cm scale, ovoid, microscopic intergrowths with quartz. These  
620 intergrowths are macroscopically evident in outcrop and core as cm-scale green spots, though in fact  
621 Cr-rich mica composes only a few percent of such spots, apparently has undergone alteration to clays  
622 in some samples, and was significantly damaged or removed during thin section preparation. As a  
623 result, fuchsite crystals recovered from BT1B core are not large enough for  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses. Figure  
624 5 of Nasir et al. (2007) is a photomicrograph of crystalline fuchsite from another listvenite in Oman.

625

626 Macroscopic listvenite textures are characterized by abundant veins (10 to 200 veins more than 1 mm  
627 thick per meter of core, typically  $\sim 1$  per cm) in a fine-grained matrix. In massive listvenites, the fine-  
628 grained matrix surrounding veins commonly contains ovoids of magnesite or quartz (Figure 8).  
629 Though they have similar textures, ovoids of the two different minerals are rarely adjacent to each  
630 other. Both commonly have Fe-oxides in their cores and/or in spherical zones. Microprobe analyses  
631 show that magnesite ovoids have low Fe cores, commonly rimmed with relatively Fe-rich magnesite  
632 (Beinlich et al 2020). They have sizes and shapes similar to the quartz spherulites.

633

634 Carbonate ovoids and cross-cutting magnesite-hematite veins are also observed in serpentinite  
635 bands in the core (Figure 6). Thus, the Shipboard Science Party considered it likely that many such  
636 veins initially formed within serpentinite, followed by formation of ovoids within surrounding  
637 serpentine, and then by replacement of the entire serpentinite matrix by carbonate + quartz (Kelemen  
638 et al 2020b). If so, in contrast to conventional interpretations of veins as relatively young features,  
639 “cross-cutting” their matrices, in this case the fine-grained listvenite matrix may postdate the earliest  
640 veins found within the matrix. This hypothesis is discussed further in Section 5.9

641

642 The quartz ovoids have the texture of “spherulites”, with radiating microscopic crystals producing a  
643 false, “uniaxial interference pattern” in cross-polarized light. Spherulites form during devitrification of  
644 amorphous opal as well as rhyolite glass, so Falk & Kelemen (2015) and the Shipboard Science Party  
645 (Kelemen et al 2020b) interpreted these as replacing opal, which would have been among the earliest  
646  $\text{SiO}_2$  minerals to form in many of the listvenites. Importantly, opal is commonly found in other  
647 listvenites and serpentine-magnesite associations worldwide (Abu-Jaber & Kimberley 1992, Aftabi &  
648 Zarrinkoub 2013, Akbulut et al 2006, Arisi Rota et al 1971, Barnes et al 1973, Beinlich et al 2010,  
649 Borojević Šoštarić et al 2014, Boschi et al 2009, Ece et al 2005, Jurković et al 2012, Lacinska &  
650 Styles 2013, Lapham 1961, Oskierski et al 2013a, Oskierski et al 2013b, Posukhova et al 2013,  
651 Quesnel et al 2016, Searston 1998, Ulrich et al 2014, Zarrinkoub et al 2005).

652

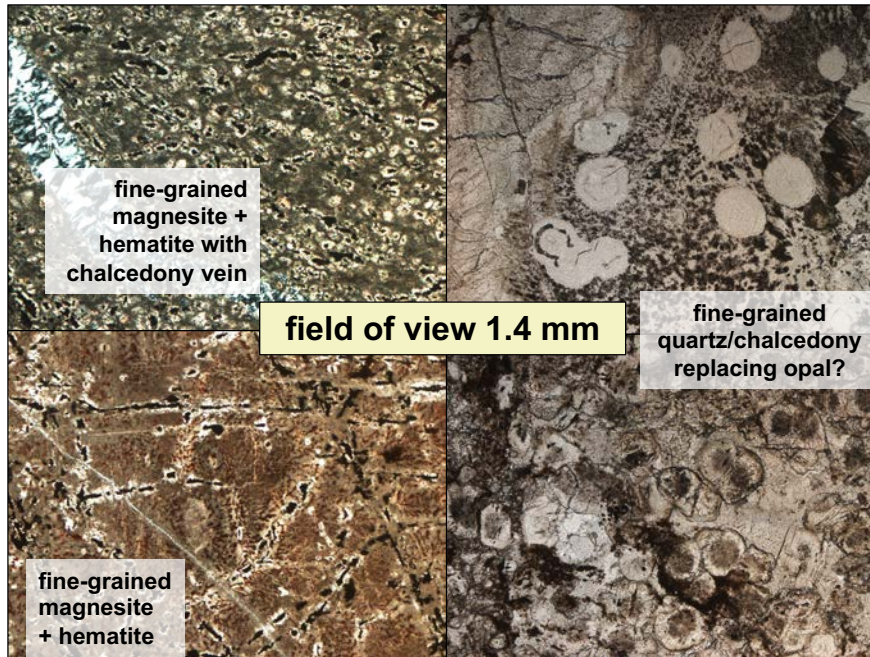
653 Vein types cutting this fine-grained matrix generally record a progression from texturally early,  
654 antitaxial magnesite veins – some with cores of hematite + other Fe-oxides (Figure 6) – and related,  
655 early Fe-oxide veins, to syntaxial dolomite veins and carbonate-quartz veins, and lastly to syntaxial

656 calcite veins. Some of the late, syntaxial veins contain vugs lined with prismatic calcite and/or  
657 dolomite. Syntaxial vein textures record inward crystallization of crystals into fractures that opened  
658 due to external, tensional stresses (Durney & Ramsay 1973, Urai et al 1991).

659

660 (A poorly exposed, weathered, fuchsite vein has been observed in outcrop 200 meters north of Site  
661 BT1B, but no such veins were sampled in BT1B core. We mention this simply to emphasize that Cr  
662 and Al were mobile at some stage during listvenite formation or later alteration.)

663

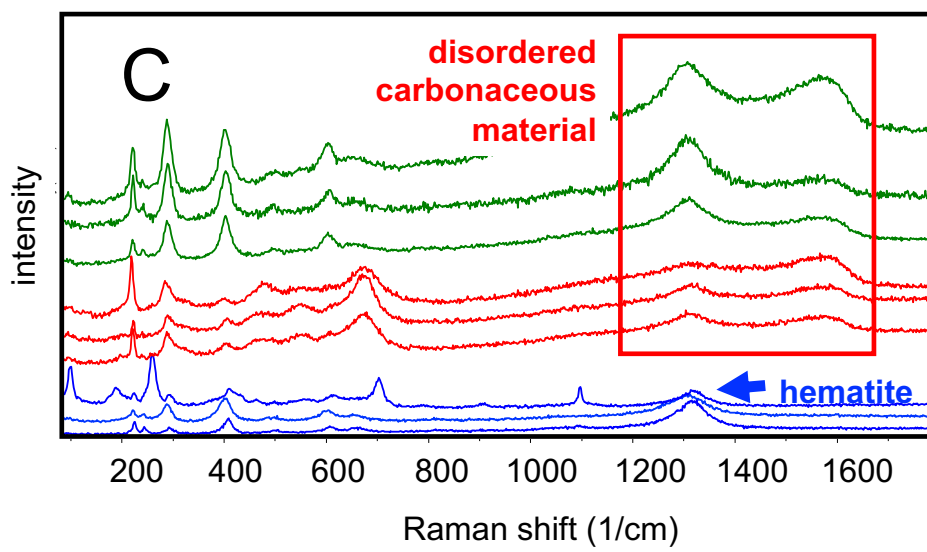
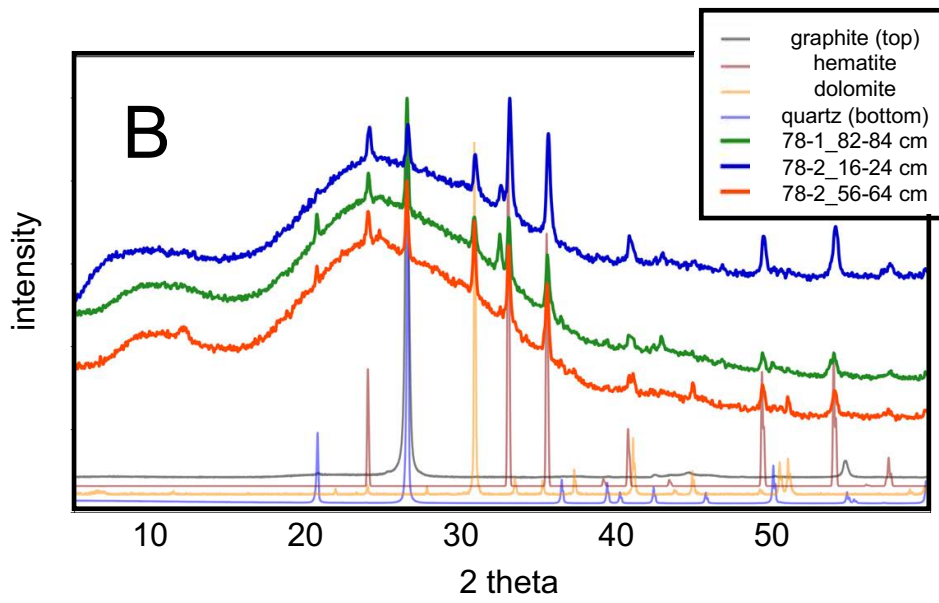


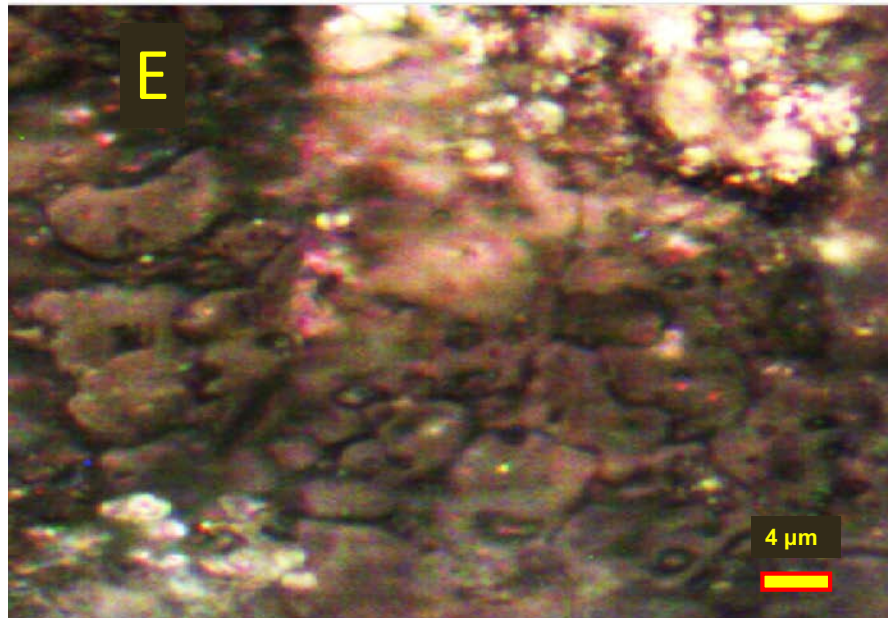
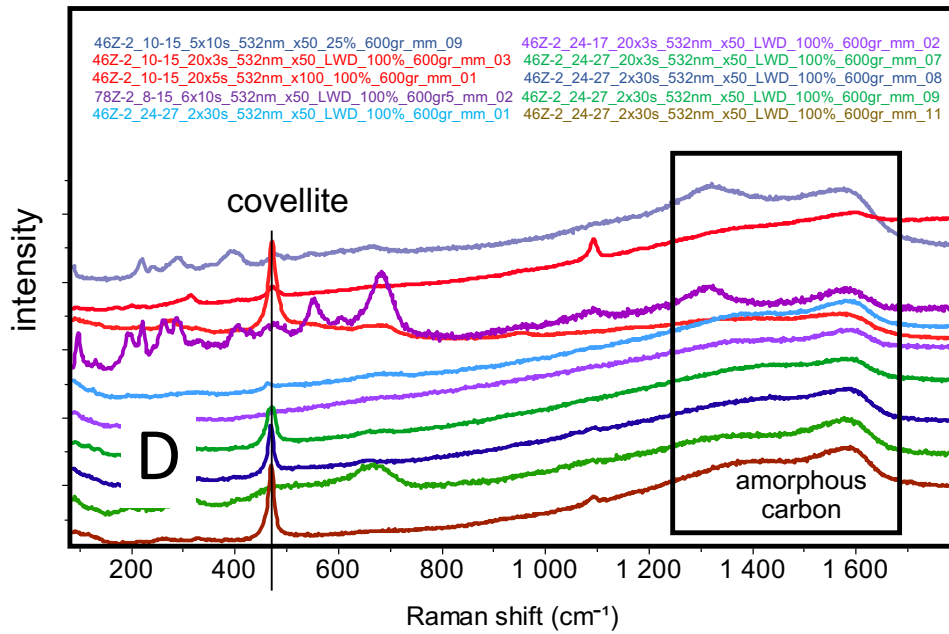
664

665 *Figure 8: Plane light photomicrographs illustrating magnesite ovoids in a matrix composed of*  
666 *magnesite, quartz, and subordinate hematite and Fe-oxyhydroxides, TS\_BT1B\_20Z-1\_42-46, ~ 40 m*  
667 *depth (left top) and TS\_BT1B\_27Z-2\_6-8.5, ~ 59 m depth (left bottom), and quartz spherulites with*  
668 *carbonate and hematite inclusions, in matrix of fine-grained quartz and hematite with subordinate,*  
669 *microscopic carbonates, TS\_BT1B\_60Z-1\_12-17, ~140 m depth (right).*

670

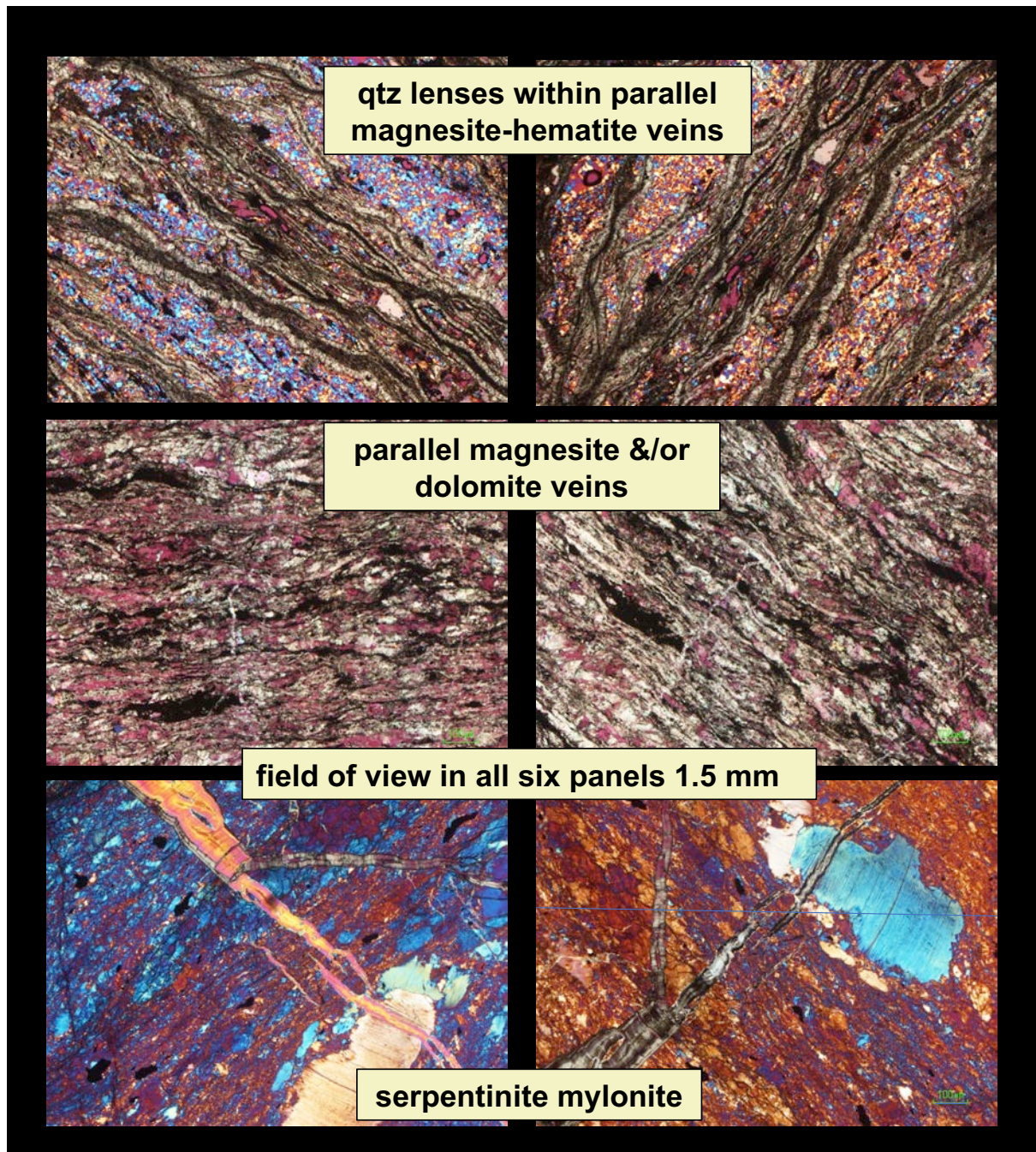
671 Among the Fe-oxide veins, some contain minor sulfide – generally not detected during core  
672 description – and amorphous, organic carbon compounds. The carbon compounds were first  
673 identified in core at the drill site, in the lowest listvenite band, as elongate lenses within transposed  
674 hematite veins parallel to the penetrative foliation, where they were described as “graphite”. Soft  
675 organic carbon compounds in these features appear to have been largely lost from sample surfaces  
676 during washing and handling of the core prior to shipboard observations and analyses, and again  
677 during fabrication of thin sections. However, Raman spectroscopy of small, armored relicts, in oxide  
678 veins and also in isolated, dark red spots that resemble relict spinel on the core face and rock slabs,  
679 reveals the presence of disordered, thermally immature carbonaceous material (Figure 9), some of  
680 which may retain a more ordered organic molecular structure. The carbonaceous materials we can  
681 still find, on freshly cut surfaces from the core interior, are commonly on the margins of microscopic  
682 chalcocite and covellite crystals, in one case also associated with copper sulfate (chalcantite)





684  
 685 *Figure 9: Carbonaceous material in drill core. A: Drill site photo of 1 to 2 mm vein of shiny, grey, soft*  
 686 *material described as graphite on the drill site, in a vein rimmed with hematite. Field of view 5 cm*  
 687 *wide, core 74Z-01, ~ 195 m depth. B: Shipboard XRD spectra of soft “graphite” powder extracted from*  
 688 *veins with “graphite” + hematite, replacing Figure F43 in Kelemen et al. (2020b). Interpretation of*  
 689 *these data is complicated by the similarity of the quartz and graphite peaks at ~ 26° 2θ, but quartz*  
 690 *also has a prominent peak at ~ 21° 2θ which is absent from the blue spectrum for 78Z-02\_16-24. C:*  
 691 *Raman spectra of black material in samples BT1B\_77Z-03\_30-38 (blue), 78Z-02\_8-15 (red) and 78Z-*  
 692 *02\_50-56 (green, ~ 192-198 m depth). Broad double peaks at wavenumbers of ~1350/cm and*  
 693 *1600/cm are indicative of disordered carbon compounds; no Raman spectra diagnostic of graphite*  
 694 *were obtained. Many microscopic, soft, black domains contained hematite, with a single broad peak*  
 695 *at ~1350/cm, instead of, or in addition to, disordered carbon compounds. D: Raman spectra of black*  
 696 *material in samples BT1\_44Z-02\_10-15, BT1\_78Z-02\_8-15, and BT1\_44Z-02\_24-27, showing broad,*  
 697 *double peaks indicative of disordered carbon compounds, some associated with covellite. Core 44Z ~*  
 698 *98 m depth. E: dark grey copper sulfate “cow pies”, spatially associated with brightly reflecting*  
 699 *covellite, near amorphous carbon material, field of view ~ 100 microns, sample BT1\_44Z-02\_24-27.*  
 700 *Data and images from core 44Z are from a 1 mm diameter black spot with a red rim in the interior of*  
 701 *the core, exposed by the rock saw during sample preparation.*





702

703 *Figure 10: Examples of crystallographic preferred orientation (CPO) in localized zones in core from*  
 704 *Hole BT1B. All images in cross-polarized light with quartz plate inserted. Images on right are of the*  
 705 *same area as on left, but rotated 90° with respect to the polarizers. Areas showing optical continuity*  
 706 *have a crystallographic preferred orientation. Top, TS\_BT1B\_31Z-4\_12-14, ~ 65 m depth, quartz*  
 707 *lenses within sub-parallel, anastomosing magnesite-hematite veins. Middle, TS\_BT1B\_78Z-2\_34-38,*  
 708 *~ 195 m, thin section composed almost entirely of parallel magnesite and/or dolomite veins, with a*  
 709 *CPO in the carbonates. Bottom, TS\_BT1B\_74Z-1\_59-62, ~ 183 m, serpentinite mylonite, with a*  
 710 *strong CPO in the fine-grained matrix, and visible, internal deformation in serpentine porphyroclasts.*  
 711

712

#### 4.5 Crystallographic preferred orientation of minerals

713

714 An overall preferred orientation of veins is not evident from structural data on the core scale, possibly  
 715 due to differential rotation of core pieces. And, systematic measurements have not been made on the

716 outcrop scale. However, at the meter scale many core intervals contain textures indicative of ductile  
717 deformation (Figure 10). Some samples show a strong macroscopic foliation, defined by parallel  
718 (possibly transposed) veins enclosing elongate lenses of the fine-grained matrix, in textures  
719 commonly interpreted to form via boudinage during ductile deformation. In samples with a strong  
720 foliation defined by dozens of subparallel, early magnesite veins per 10 mm<sup>2</sup>, intervening patches of  
721 fine-grained quartz commonly have a crystallographic preferred orientation (CPO). Some samples  
722 with a strong foliation defined by abundant, subparallel (tectonically transposed?) carbonate veins  
723 also have an optically evident, crystallographic preferred orientation in magnesite and/or dolomite.  
724 Similarly, some shear zones in serpentinite have an optically evident, strong shape- and  
725 crystallographic-preferred orientation of lizardite crystals, and contain deformed serpentine  
726 porphyroclasts.

727

#### 728 *4.6 Brittle deformation textures*

729

730 A broad range of different breccias and cataclasites are observed in listvenites and in the  
731 metamorphic sole, in outcrop and in core. In turn these are cut by sharp faults – some associated with  
732 planar bands and branching veins of aphanitic ultracataclasite and/or pseudotachylite – and by late  
733 calcite veins. The nature and interpretation of cataclasites and faults observed in core from Hole  
734 BT1B are discussed in detail by Menzel et al. (2020).

735

#### 736 *4.7 Geochemical data*

737

738 The bulk composition of core samples was measured in five different ways: (1) Major and minor  
739 element compositions of nine samples were measured by XRF at St. Andrews University. (2) Major  
740 and minor element compositions of 74 samples, including those previously analyzed at St. Andrews,  
741 were measured via XRF (both fusion and pressed pellets) onboard the Drilling Vessel Chikyu. (3)  
742 Major element compositions of the cut face of selected core sections were analyzed onboard using an  
743 XRF core scanner. (4) Trace element compositions of a few samples were analyzed onboard via ICP-  
744 MS. (5) Trace element compositions of 61 samples were analyzed via ICP-MS at the Université de  
745 Montpellier. These data, and subsequent analyses, are tabulated and described in Kelemen et al.  
746 (2020b) and Godard et al. (2021), so for brevity we simply refer readers to those other publications.

747

### 748 **5. Discussion**

749

#### 750 **5.1 Subduction zone setting of listvenite formation**

751

752 On the basis of their structural observations west and northwest of the MoD Mountain area, and U/Pb  
753 formation or cooling ages from cross-cutting calcite veins, (60 ± 16 and 58 ± 6 Ma) Scharf et al.  
754 (2020) infer that listvenites in the Fanjah area postdate ophiolite emplacement, echoing the qualitative  
755 ideas of Stanger (1985) and Wilde et al. (2002). As noted in Sections 2.5 and 4.2, our

756 geochronological and field observations are inconsistent with this interpretation. The listvenite mineral  
757 isochron age of  $97 \pm 29$  Ma ( $2\sigma$ ) (Falk & Kelemen 2015) yields a 93% chance ( $1.5\sigma$ ) that the  
758 listvenites formed before 75 Ma, while subduction beneath the ophiolite was still active, and a 97%  
759 chance that the listvenites formed before 68 Ma. Thus, the isochron data support listvenite formation  
760 during subduction, and show that the calcite veins cutting listvenite, dated by Scharf et al., postdate  
761 listvenite formation.

762

763 In this paper, our mapping and structural observations indicate an intact tectonic “stratigraphy” around  
764 the basal thrust of the ophiolite, encompassing the allocthanous Hawasina metasediments, overlain  
765 by the metamorphic sole, in turn overlain by Banded Unit dunites and harzburgites of the Samail  
766 ophiolite mantle section, with essentially horizontal lithologic contacts extending for kilometers. This is  
767 the stratigraphy created during subduction beneath the ophiolite, and – together with the isochron – it  
768 indicates that these units were juxtaposed during low angle thrusting along the subduction zone. In  
769 turn, all the listvenites in the MoD Mountain area are less than a kilometer away from the basal thrust,  
770 and have contacts with surrounding mantle peridotites and the metamorphic sole that are parallel to  
771 the basal thrust. All these data, taken together, indicate that the listvenites formed along and above  
772 the basal thrust of the ophiolite during subduction.

773

## 774 5.2 Faulting, deformation and veining after listvenite formation

775

776 (U,Th)/He cooling ages (Section 4.3) indicate that the region around MoD Mountain remained above  
777 the closure temperature for He diffusion in zircon,  $\sim 180^\circ\text{C}$  (Reiners et al 2004), or were reheated  
778 above this temperature, during 30 to 60 million years after formation of the igneous crust in the  
779 ophiolite and peak metamorphism of the sole. Based on textural observations, it is clear that the  
780 breccias and cataclasites sampled in BT1B drill core postdate listvenite formation (Menzel et al 2020).  
781 Some may postdate ophiolite emplacement, and may be broadly related to Paleocene to Miocene  
782 uplift and extension during formation of the nearby Jebel Akdar and Saih Hatat domes. On the other  
783 hand, some could be related to deformation during subduction beneath the ophiolite. The long term  
784 persistence of temperatures above  $180^\circ\text{C}$  in this region renders it difficult to distinguish formation from  
785 cooling ages using (U,Th)/He data.

786

787

## 787 5.3 Temperature of listvenite formation

788

789 The temperatures of listvenite formation have been previously constrained using metamorphic phase  
790 equilibria, conventional oxygen isotope thermometry, and clumped isotope analyses. Falk & Kelemen  
791 (2015) noted the presence of intergrown antigorite (serpentine) + quartz. in the reaction zone between  
792 listvenite and serpentinite on the west ridge of MoD Mountain (Figure 2). In some cases, these  
793 samples also contain talc. They used Thermocalc (Powell et al 1998), with thermodynamic data from  
794 Holland and Powell (2003, 1998), and similar methods using the thermodynamic data of Gottschalk  
795 (1997), to estimate that equilibrium coexistence of antigorite, quartz and talc occurs at 80 to  $120^\circ\text{C}$ ,

796 depending on the choice and uncertainty of thermodynamic parameters for the minerals, and the  
797 (poorly known) pressure at which these assemblages crystallized. For this paper, we obtained similar  
798 using Perple\_X (<https://www.perplex.ethz.ch/>) (Connolly 1990, Connolly 2005, Connolly 2009) and  
799 mineral properties from Holland and Powell.

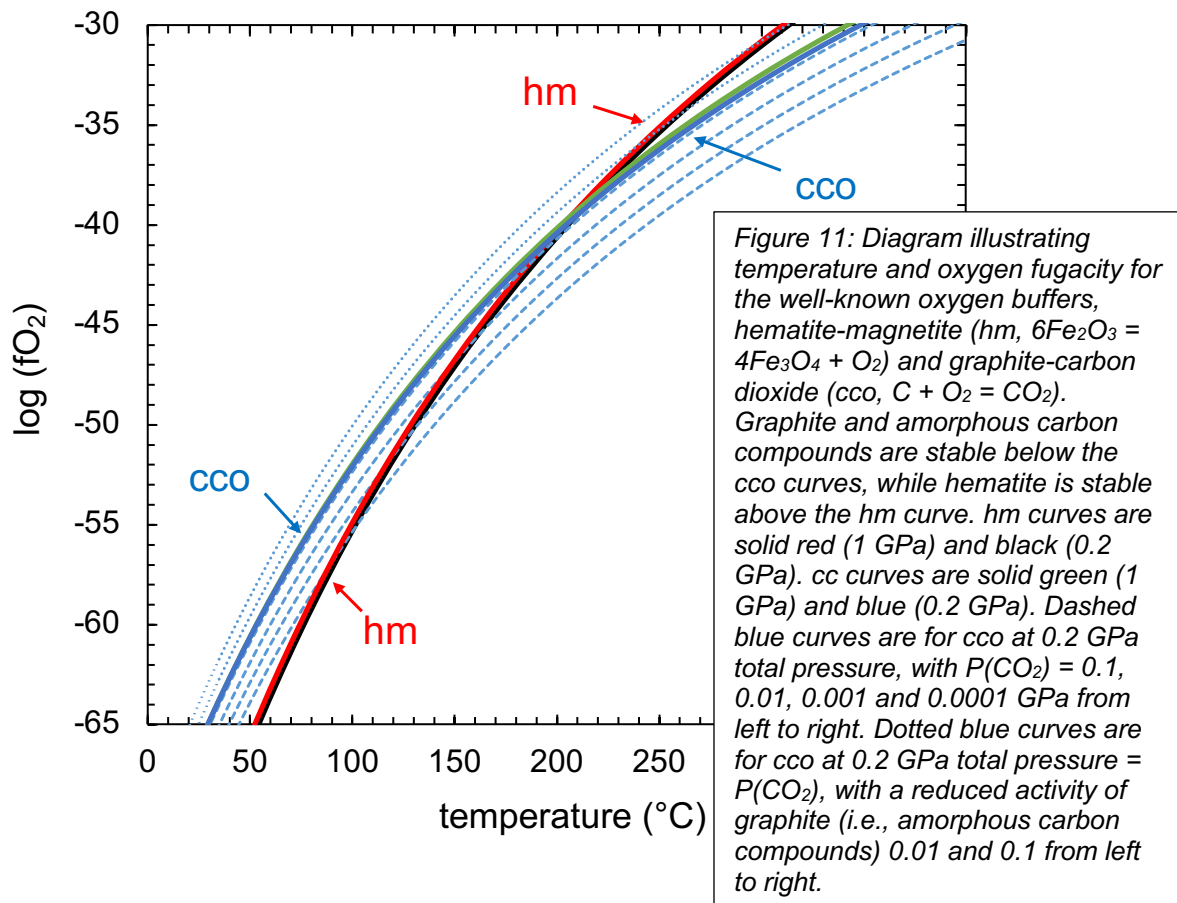
800

801 In contrast, calculations using the Deep Earth Water (DEW) model (Huang & Sverjensky 2019,  
802 Sverjensky et al 2014) and the extended Helgeson-Kirkham-Flowers (HKF) aqueous equation of state  
803 (Shock et al 1992, Shock et al 1997) do not predict equilibrium coexistence of antigorite + quartz  
804 above 15°C. Since antigorite-quartz intergrowths indicate coeval crystallization of both phases, in  
805 rocks that formed at > 80°C, we presume that these latter results stem from incorrect extrapolation of  
806 thermodynamic data to low temperature.

807

808 Leaving the DEW results aside, the other temperature estimates based on co-existing antigorite +  
809 quartz are broadly consistent with temperature estimates based on  $\delta^{18}\text{O}$  in quartz and carbonate  
810 minerals in the listvenite, assuming that fluid  $\delta^{18}\text{O}$  was similar to seawater, and with clumped isotope  
811 analyses of magnesite and dolomite yielding temperatures of 80 to 130°C for listvenite samples (Falk  
812 & Kelemen 2015). Observation of quartz spherulites in listvenite, possibly reflecting devitrification of  
813 opal, also suggests that listvenite formation occurred in this “low temperature” regime, at ~ 150°C or  
814 less, in the presence of aqueous fluid.

815



816

817

818

819 Here we show that veins of intergrown amorphous carbon compounds and hematite sampled in the  
820 core also must have formed below  $\sim 200^\circ\text{C}$  (Figure 11). The observation of “reduced” hydrocarbon  
821 species intergrown with oxidized iron minerals in veins may seem surprising at first, but they are  
822 mutually stable at low temperature due to the stronger temperature dependence of the iron oxidation  
823 state, compared to the carbon oxidation state. Above  $\sim 200^\circ\text{C}$ , reduced, organic carbon compounds  
824 and oxidized iron minerals such as hematite cannot coexist at the same oxygen fugacity, but they can  
825 crystallize together at moderate oxygen fugacities below  $\sim 200^\circ\text{C}$ . We’ve found that this result is  
826 robust across all available sets of internally consistent thermodynamic data, and in the pressure range  
827 from 0.2 to 1.0 GPa.

828

829 Fourteen more recent clumped isotope analyses for listvenites and carbonate-bearing serpentinites  
830 from BT1B core yield an average temperature of  $147\pm 58^\circ\text{C}$  ( $1\sigma$ ). Ten of the 14 temperature estimates  
831 lie within the  $1\sigma$  range, whereas two are lower ( $45\pm 5$  and  $52\pm 8^\circ\text{C}$ ) and the two least precise estimates  
832 are higher ( $227\pm 52$  and  $247\pm 52^\circ\text{C}$ ) (Beinlich et al 2020). Though a few MoD Mtn listvenites might  
833 have formed at temperatures greater than  $200^\circ\text{C}$ , such temperatures are too high for crystallization of  
834 intergrown amorphous carbon + hematite, they are too high for crystallization of intergrown antigorite  
835 + quartz, and they are too high for crystallization of opal. Also, carbonation of peridotite above  $\sim 150^\circ\text{C}$   
836 would form abundant talc + magnesite, whereas talc is absent in most MoD Mountain listvenites, and  
837 rare in serpentinite-listvenite contact zones that are gradational over a few meters (Falk & Kelemen  
838 2015, Kelemen et al 2020b).

839

840 The range in temperature estimates based on phase equilibrium and clumped isotope ratios from the  
841 MoD Mountain listvenites may indicate that mineral assemblages in the listvenites and surrounding  
842 serpentinites formed gradually over a range of times and temperatures. In addition, some of the  
843 clumped isotope data may record closure temperatures during cooling, rather than the peak  
844 temperature at which the MoD Mountain listvenites first crystallized, as proposed for clumped isotope  
845 data from fine-grained 10-meter scale magnesite veins in California (Garcia del Real et al 2016).  
846 Alternatively, since the highest clumped isotope temperatures from Beinlich et al. are also the most  
847 imprecise estimates, perhaps they result from analytical uncertainties or disequilibrium effects. When  
848 the 14 clumped isotope temperatures from Beinlich et al. are combined with the 31 older clumped  
849 isotope temperatures from Falk and Kelemen, the full data set yields an average of  $100 \pm 46^\circ\text{C}$  ( $1\sigma$ ),  
850 with the highest temperatures from Beinlich et al. falling outside the  $2.5\sigma$  (99% probability) range.

851

852

#### 5.4 Depth of listvenite formation

853

854 The depth of listvenite formation is difficult to constrain. As noted in Section 2.4, published work on  
855 the metamorphic sole beneath the Samail ophiolite reports peak temperatures up to 700 to  $900^\circ\text{C}$  at  
856 pressures ranging from 200 to 1400 MPa, indicative of anomalously hot subduction zone conditions.  
857 Common peak pressure estimates,  $\sim 1200$  MPa, indicate depths exceeding the structural thickness of

858 the ophiolite. Thus, either (1) the published range of pressure estimates for the metamorphic sole is  
859 the result of uncertainty rather than true variation in depth, and/or (2) the lower few km of the ophiolite  
860 mantle section has undergone thinning in some places, and/or (3) the lenses of the metamorphic sole  
861 recording the highest pressures migrated upward with respect to the overlying peridotite, and/or (4)  
862 some mineral equilibria record tectonic overpressures rather than lithostatic loads. Also, we infer from  
863 Sr isotope data that the fluids that formed the listvenites were not derived from the metamorphic sole  
864 (Section 5.6, below, and de Obeso et al 2021a). For all these reasons, it is unclear whether the  
865 metamorphic pressures inferred for the sole constrain the depth of listvenite formation. However,  
866 temperatures and pressures recorded by the sole do provide a window into the thermal evolution of  
867 subduction beneath the ophiolite before and during listvenite formation.

868  
869 Initiation of subduction, during formation of the metamorphic sole, involved thrusting of a hot mantle  
870 wedge over newly formed, hot basaltic crust. Over time, subduction of progressively older oceanic  
871 crust and – eventually – the pelagic sediments of the Hawasina Formation would have caused cooling  
872 of the subduction zone as it evolved toward a steady state geotherm. A few clumped isotope analyses  
873 on calcite in sediments beneath the ophiolite and the metamorphic sole on MoD Mountain yield  
874 temperatures of 150 to 200°C (Falk & Kelemen 2015). It is possible that these were peak  
875 temperatures during diagenesis of the sediments along a late, steady state subduction geotherm at  
876 the pressure and depth recorded by the metamorphic sole in core from Hole BT1B, 800 -1200 MPa,  
877 or about 25 to 40 km.

878  
879 In turn, even lower temperatures for most listvenite samples may record continued, isobaric cooling of  
880 rocks flanking the subduction zone. Temperatures of 100 to 200°C at depths of 25 to 40 km are  
881 inferred for fore-arc regions above subduction zones from heat flow data (reviewed in Peacock 1996)  
882 predicted for steady state, oceanic subduction geotherms in numerical models (e.g., Peacock 1996,  
883 Peacock et al 2005, Syracuse et al 2010), including those recently modeled by Van Keken et al.  
884 (2019), and lie within the cold end of the range of PT conditions recorded by subduction-related  
885 metamorphic rocks (Hacker 1996, Hacker 2006, Penniston-Dorland et al 2015). Such low  
886 temperatures at 25 to 40 km are rare or absent in other tectonic environments.

887  
888 To summarize, it is possible that the sediments and the overlying mantle peridotites at the base of the  
889 ophiolite were juxtaposed by subduction at the leading edge of the mantle wedge, at a depth of 25 to  
890 40 km, and that the MoD Mountain listvenites formed at these depths along a cold, steady state  
891 subduction geotherm. Alternatively, if the metamorphic sole has migrated updip with respect to the  
892 overlying peridotites, then the listvenites could have formed at lower pressures and shallower depths.

893

#### 894 *5.5 Composition of listvenite protolith and geochemical fluid additions*

895

896 Given the abundance and variety of mineralogically simple veins, many of which are monomineralic,  
897 there is substantial compositional variation in listvenites at the millimeter to meter scale. This

898 variability extends to larger scales in some parts of the core. Nevertheless, remarkably enough,  
899 average MgO/SiO<sub>2</sub>/FeO\* (all Fe as FeO) ratios in the listvenites are very similar to those in average  
900 residual peridotites from the ophiolite (Figure 12), as discussed further by Okazaki et al. (Okazaki et al  
901 2021). These oxides comprise more than 90% of the volatile-free bulk composition of the rock. These  
902 data suggest that there was little dissolution and export of major elements from the rocks during  
903 transformation of peridotite to serpentinite and then to listvenite as discussed further in Section 5.9.

904

905 On the other hand, serpentinites and listvenites record addition of tens of weight percent H<sub>2</sub>O and  
906 CO<sub>2</sub> to the original bulk composition of mantle peridotite protoliths. In addition to CO<sub>2</sub>, dolomite  
907 listvenites clearly record substantial addition of CaO, and – since CaO and Sr concentrations are  
908 strongly correlated – of Sr as well.

909

910 Although the shipboard data do not reveal systematic variation in the abundance of magnesite vs  
911 dolomite listvenites downhole, there is a clear change in the abundance of both Al and K, together  
912 with many other highly incompatible trace elements. Concentrations of these elements are relatively  
913 low above the serpentinite band at 80-100 m depth, and much higher below that band (Godard et al  
914 2021, Kelemen et al 2020b).

915

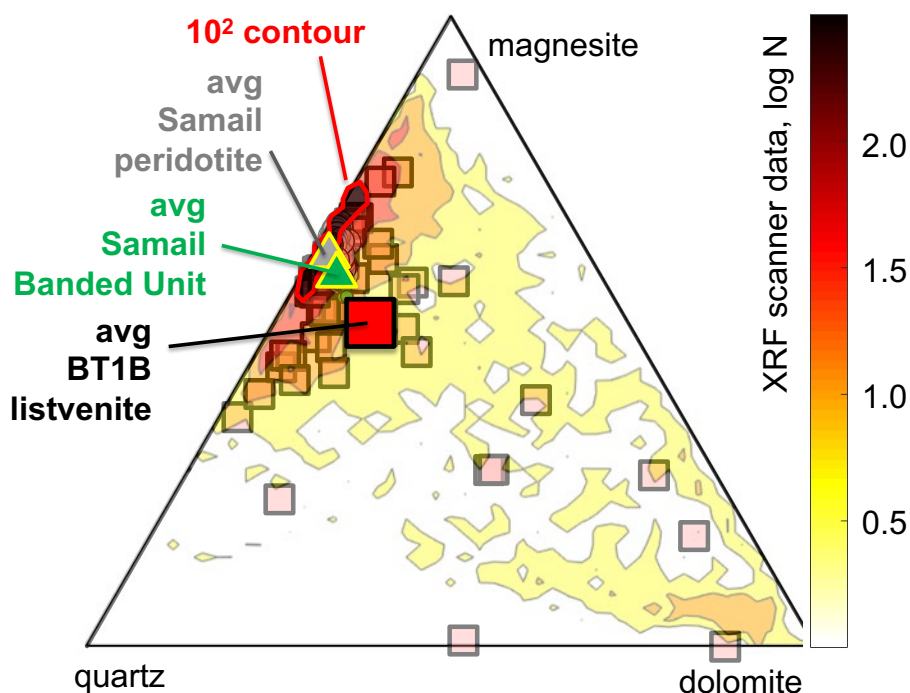
916 Understanding the source for enrichment in these elements is complicated by uncertainty about their  
917 concentration in the peridotite protolith. As noted in Sections 2.3, 2.5 and 4.4, a “Banded Unit” of  
918 alternating dunite, harzburgite and lherzolite characterizes the base of the ophiolite mantle section in  
919 many regions. Some Banded Unit peridotites record high temperature geochemical “refertilization” by  
920 reaction of residual mantle peridotites with infiltrating melt or fluid at > 800°C, with addition of calcic  
921 pyroxene and Mg-rich hornblende. This produced enrichment in CaO and Al<sub>2</sub>O<sub>3</sub> to levels well above  
922 those in typical residual mantle peridotites in the Samail ophiolite (Godard et al 2000, Hanghoj et al  
923 2010, Monnier et al 2006). Indeed, four out of six harzburgite samples from the Banded Unit on MoD  
924 Mountain have Ca and Al contents outside the 1σ range of variability in residual mantle peridotite in  
925 the ophiolite (Falk & Kelemen 2015, Godard et al 2021, Kelemen et al 2020c).

926

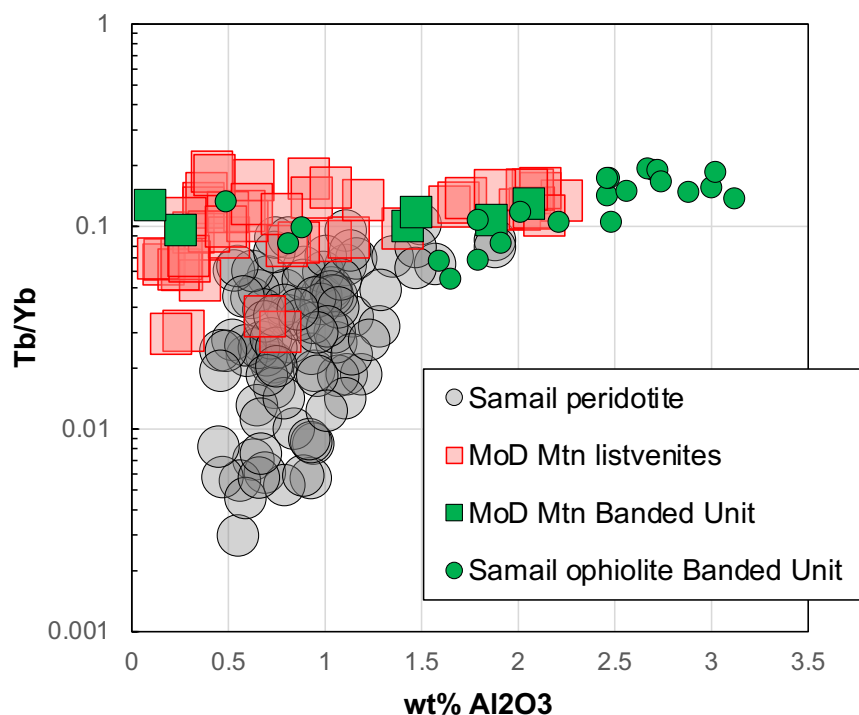
927 The listvenites below 100 meters depth in core from Hole BT1B have trace element ratios that are  
928 distinct from typical peridotites, but characteristic of the Banded Unit (Figure 12 and Godard et al  
929 2021), as shown in Figure 13. In particular, middle to heavy rare earth element ratios in the Banded  
930 Unit, and in the listvenites, are high compared to typical Samail peridotites. Such enrichment in middle  
931 rare earth elements is commonly associated with the presence of igneous hornblende in peridotites.  
932 Thus, the listvenites probably inherited these characteristics from the enriched, Banded Unit protolith.

933

934 On the other hand, it is clear that most listvenites have higher Sr concentrations than typical Samail  
935 ophiolite peridotites *and* the Banded Unit (de Obeso et al 2021a). Instead, Sr and Ca were added  
936 during low temperature alteration, along with H<sub>2</sub>O and CO<sub>2</sub>. These topics are discussed further by  
937 Godard et al. (2021).



938  
 939 *Figure 12: Ternary diagram illustrating volume proportions of quartz, magnesite and dolomite,*  
 940 *projected from hematite, calculated from whole rock compositions, for Samail mantle peridotites*  
 941 *(average in grey triangle, data as large, grey open circles, barely visible beneath the averages and*  
 942 *the 10<sup>2</sup> contour area, Godard et al. 2000; Monnier et al. 2006; Hanghoj et al. 2010}, Banded Unit*  
 943 *peridotites near the base of the Samail ophiolite mantle section (small, green open circles, barely*  
 944 *visible, Falk & Kelemen 2015, Khedr et al 2013, Khedr et al 2014, Takazawa et al 2003), and*  
 945 *listvenites from Hole BT1B and MoD Mtn (open squares, Falk & Kelemen 2015, Kelemen et al*  
 946 *2020b), superimposed on contoured histogram of mineral proportions from shipboard XRF scanner*  
 947 *data. Contour interval 10<sup>2</sup>. Okazaki et al. (2021) provide more thorough interpretation of shipboard*  
 948 *XRF scanner data plus X-Ray Computed Tomography data on the whole core. Average listvenite,*  
 949 *Banded Unit and Samail mantle peridotite compositions are provided in Supplementary Table 2.*



*Figure 13: Wt% Al<sub>2</sub>O<sub>3</sub> versus Tb/Yb ratios in bulk rock compositions of MoD Mtn listvenites (open squares, Falk & Kelemen 2015, Godard et al 2021, Kelemen et al 2020b), and MoD Mountain peridotites that host listvenites (green squares, Falk & Kelemen 2015, Godard et al 2021), compared to typical Samail mantle peridotites (grey open circles, Godard et al 2000, Hanghoj et al 2010, Monnier et al 2006), and Banded Unit peridotites from the base of the ophiolite (Khedr et al 2013, Khedr et al 2014, Takazawa et al 2003).*



## 5.6 Source of fluid for listvenite formation

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Present day Sr isotope ratios in listvenites and serpentinites from MoD Mtn range from ~ 0.708 to 0.715 (de Obeso et al 2021a, Falk & Kelemen 2015). Using current Rb/Sr contents in these samples, age corrected  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios at 96 Ma range from ~ 0.708 to 0.714, much higher than the range of Sr ratios in Samail ophiolite peridotites (0.703 to 0.707, Benoit et al 1999, Gerbert-Gaillard 2002, Gregory & Taylor Jr 1981, Lanphere et al 1981, McCulloch et al 1980, McCulloch et al 1981), the range in Late Cretaceous to modern seawater (~ 0.7075 to 0.7081), or the range in peridotite-hosted ground water in the Samail ophiolite (~0.7065 to 0.7092, Weyhenmeyer 2000). Thus, the Sr-, Ca- and CO<sub>2</sub>-rich fluid(s) that modified the mantle overlying the basal thrust of the ophiolite had relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios compared to fresh, residual mantle peridotites.

Initially, we expected that the metamorphic sole, as sampled by core from Hole BT1B, might be the source of fluids that formed listvenites in overlying peridotites, or at least might be analogous to the source of these fluids. However, this is not consistent with the Sr isotope data on the sole in core from Hole BT1B. Measured and age-corrected Sr isotope ratios in the metamorphic sole are consistently lower than corresponding ratios in the listvenites (de Obeso et al 2021a).

Instead, pelagic, clastic units of the underlying Hawasina sedimentary rocks have measured and age-corrected Sr isotope ratios that span the same range as those in the listvenites (de Obeso et al 2021a). Thus, these sedimentary units in the Hawasina may be analogous to subducted sedimentary rocks that produced CO<sub>2</sub>-bearing fluids which, in turn, formed the MoD Mountain listvenites. This is likely, despite the presence of C- and Sr-rich limestone and dolomite units with lower Sr isotope ratios in the Hawasina Formation, because devolatilization of clay and mica bearing, clastic metasediments produces abundant, CO<sub>2</sub>-rich aqueous fluids, while limestone and marble remain relatively refractory at low to moderate temperature, subduction zone conditions (e.g., Kerrick & Connolly 2001, Stewart & Ague 2020).

Indeed, there is evidence for a deeply subducted component with terrigenous isotope characteristics – like those of the Hawasina clastic sedimentary rocks – elsewhere in the Samail ophiolite. A series of felsic intrusions in the sole, mantle and lower crust along the length of the ophiolite have low, age-corrected  $^{143}\text{Nd}/^{144}\text{Nd}$  (and thus, presumably, high  $^{87}\text{Sr}/^{86}\text{Sr}(t)$ ), attributed to melting of high-grade metasediment in the subduction zone below the ophiolite (Amri et al 2007, Briquet et al 1991, Cox et al 1999, Haase et al 2016, Haase et al 2015, Lippard et al 1986, Rioux et al 2021a, Rioux et al 2013, Rioux et al 2021b, Rollinson 2015, Spencer et al 2017).

A complication is that the clastic units in the Hawasina formation have  $\delta^{13}\text{C}$  less than -4 per mil, whereas listvenites have  $\delta^{13}\text{C} > -3$  per mil. These differences in carbon isotope ratios can be understood as the result of temperature dependent carbon isotope fractionation. As discussed in more detail in de Obeso et al. (2021a), at temperatures greater than ~ 300°C, dissolved CO<sub>2</sub> in

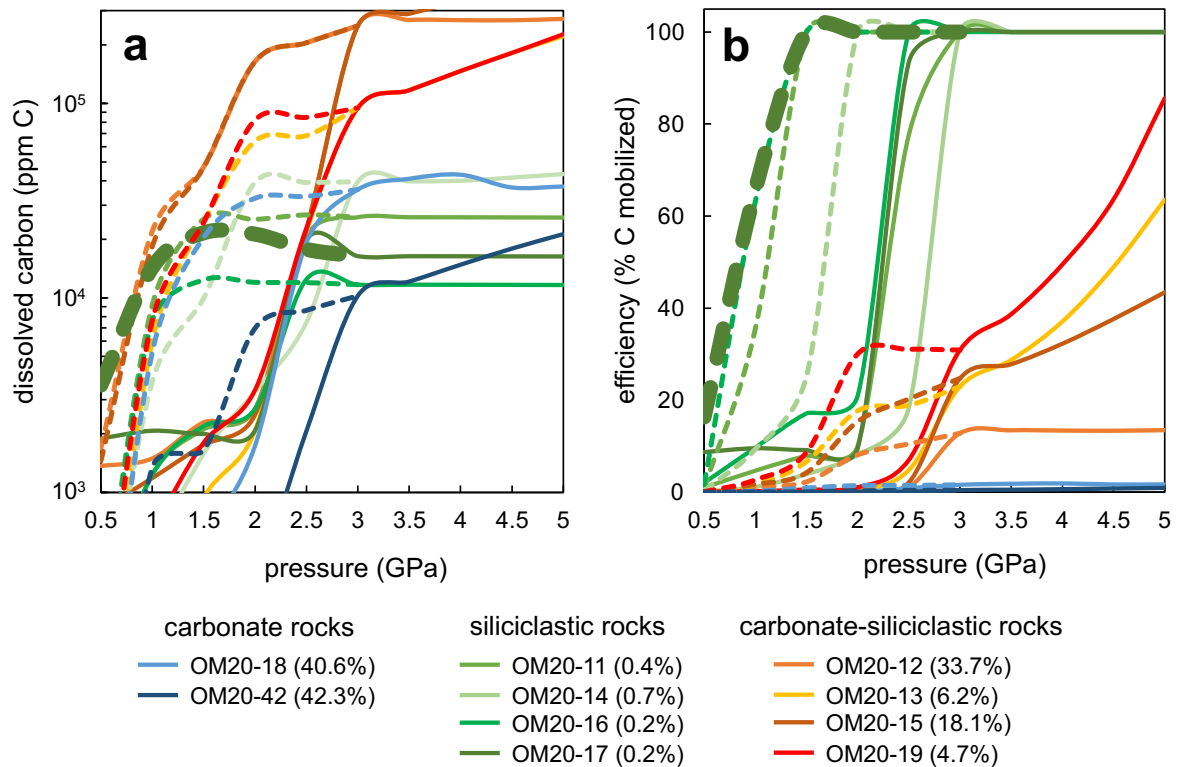
991 aqueous fluids has  $\delta^{13}\text{C}$  higher than co-existing calcite and dolomite (Deines 2002, Horita 2014). At  
992 lower temperatures, calcite and dolomite have  $\delta^{13}\text{C}$  higher than co-existing fluids. Dolomite and  
993 magnesite crystallized at relatively low temperature, from aqueous fluids that acquired their carbon  
994 isotope ratios during higher temperature devolatilization of Hawasina clastic sediment compositions,  
995 would have  $\delta^{13}\text{C}$  in the range of 1.0 to -3.0‰, as observed in the MoD Mountain listvenites. In  
996 addition, low carbon solubilities in low temperature, low pressure aqueous fluids saturated in  
997 carbonate minerals in mineral assemblages similar to those in the Hawasina clastic sedimentary  
998 rocks (Figure 22 and associated text in Chapter 4, Falk 2014, Kelemen & Manning 2015) may be  
999 insufficient to produce the MoD Mountain listvenites (Falk & Kelemen 2015)de Obeso, 2021 #300}.

1000

1001 Based on the data and reasoning described in the previous paragraph, we hypothesize that  
1002 subduction zone devolatilization at 400 to 600°C produced CO<sub>2</sub>-rich aqueous fluids that then cooled  
1003 and decompressed by flow up the subduction zone, and reacted with peridotite at less than 200°C to  
1004 produce the MoD Mountain listvenites. To quantify this hypothesis, we made thermodynamic  
1005 calculations with the compositions of solid reactants given in **Supplementary Table 2**, methods  
1006 described in **Section 3**, and results outlined in **Figures 14 and 15**. As the source of fluid, we chose  
1007 sample OM20-17, a pelitic end-member from among the Hawasina clastic sedimentary rocks  
1008 analyzed by Falk & Kelemen (2015) and de Obeso et al. (2021a). As the peridotite reactant, we used  
1009 an average Samail harzburgite composition calculated from published studies (Godard et al 2000,  
1010 Hanghoj et al 2010, Monnier et al 2006).

1011

1012 Devolatilization of clastic Hawasina sediments, including OM20-17, is predicted to produce fluids with  
1013 ~ 20,000 ppm dissolved C at ~ 400°C to ~ 600°C along subduction zone geotherms (Figure 14).  
1014 Closed system decompression and cooling of fluid produced from OM20-17 to 100 to 300°C, and 0.5  
1015 to 1 GPa produced no significant change in the composition of this modeled fluid. (Modeling open  
1016 system, reactive transport of this fluid, updip along a subduction zone geotherm, is beyond the scope  
1017 of this paper, as is modeling the fate of subduction zone fluids that have more than 10 wt% CO<sub>2</sub> –  
1018 predicted for mixed siliciclastic-carbonate rocks (Figure 14) – as they cool and decompress).



1019  
 1020 *Figure 14: Calculated dissolved carbon concentrations at a water/rock ratio of 5% (a) and extent of*  
 1021 *carbon removal (b) for samples of Hawasina sediments in the MoD Mountain area (Supplementary*  
 1022 *Table 2 in de Obeso et al 2021a), evolving along cold (550°C at 2.5 GPa) and hot (500°C at 1.5 GPa)*  
 1023 *subduction geotherms. Solid curves are results for the average (“cold”) subduction zone geotherm*  
 1024 *from Syracuse et al. (2010). Dashed curves follow a hot geotherm suggested by Penniston-Dorland*  
 1025 *et al. (2015). The initial carbon contents of the rocks (wt%, all carbon as CO<sub>2</sub>) are given in the legend.*  
 1026

### 1027 5.7 Listvenite formation

1028  
 1029 Reaction of the model fluid from OM20-17 with peridotite at 100-300°C and 0.5 to 1.0 GPa is  
 1030 predicted to produce mineral assemblages similar to those modeled by Klein and Garrido (2011): (1)  
 1031 Small masses of “birbirite” (silicified peridotite) at high water/rock ratios and/or low temperatures,  
 1032 through (2) moderate masses of listvenite and soapstone (talc-carbonate rocks) at moderate  
 1033 water/rock and temperature, to (3) relatively large masses of carbonate-bearing serpentinite at low  
 1034 water/rock ratios and/or high temperature (Figure 15). Predicted magnesite and quartz proportions  
 1035 correspond closely to observed proportions in MoD Mtn listvenites (Figure 12). Most of the PT  
 1036 conditions we modeled produced small amounts of hematite coexisting with magnesite and quartz, as  
 1037 observed. Predicted magnesite and siderite proportions correspond to a solid solution with ~ 8 wt%  
 1038 FeO, which is a few wt% higher than observed in MoD Mtn listvenites. Most modeled conditions  
 1039 produced dolomite in listvenite assemblages at water/rock ratios at water/rock ratios less than 10 (log  
 1040 water/rock = 1), consistent with the presence of relatively late, cross-cutting dolomite-bearing veins in  
 1041 the listvenites. Most model runs produce small amounts of kaolinite, and very limited proportions of  
 1042 muscovite, in listvenite mineral assemblages, consistent with the widespread presence of minor  
 1043 amounts of chromian white mica in MoD Mtn listvenites, and in listvenites worldwide. It is possible that  
 1044 addition of a thermodynamic model for fuchsite would yield stable white mica, rather than kaolinite,

1045 over a wider range of temperature and water/rock ratios. Alternatively, perhaps some of the green  
1046 sheet silicates in listvenites are chrome-bearing clays rather than true micas.

1047

1048 Thus, thermodynamic modeling suggests that the CO<sub>2</sub>-bearing aqueous fluids that formed the MoD  
1049 Mountain listvenites formed by metamorphic devolatilization in a subduction zone at > 400°C. These  
1050 fluids then migrated updip to react with peridotite at the leading edge of the mantle wedge, probably at  
1051 a depth less than 40 km. However, this is just a forward model, and there may be other possibilities.

1052

1053 Subhorizontal lenses of listvenite at MoD Mountain contain a cumulative mass of about 2 billion tons  
1054 of CO<sub>2</sub> over a strike length of 2 km NS, and 5 km EW, corresponding to 1 million to 400,000 tons of  
1055 CO<sub>2</sub> per m along strike. The allochthonous sedimentary units below the ophiolite are about 3 km thick.  
1056 Within these, clastic units comprise at least half the section, and contain about 2300 ppm C, or 0.84  
1057 wt% CO<sub>2</sub> on average (de Obeso et al 2021a), yielding a total of about 35 tons CO<sub>2</sub> per m along strike,  
1058 per m subducted. (As noted above, rocks composed mainly of calcite and/or dolomite in the  
1059 subducting sedimentary section would be unlikely to contribute significant amounts of CO<sub>2</sub> to  
1060 subduction fluids at temperatures less than 800°C). At subduction velocities of 0.05 to 0.1 m/year,  
1061 90% decarbonation of the clastic units in the Hawasina Formations with a density of 2.75 tons/m<sup>3</sup>, at ~  
1062 400-500°C would produce at least 1.7 to 3.5 tons of CO<sub>2</sub> per year per m of strike length. If most of this  
1063 CO<sub>2</sub> reacted with peridotite at the depth and temperature of MoD Mtn listvenite formation, this could  
1064 supply the observed mass of CO<sub>2</sub> at MoD Mountain in less than 600,000 years.

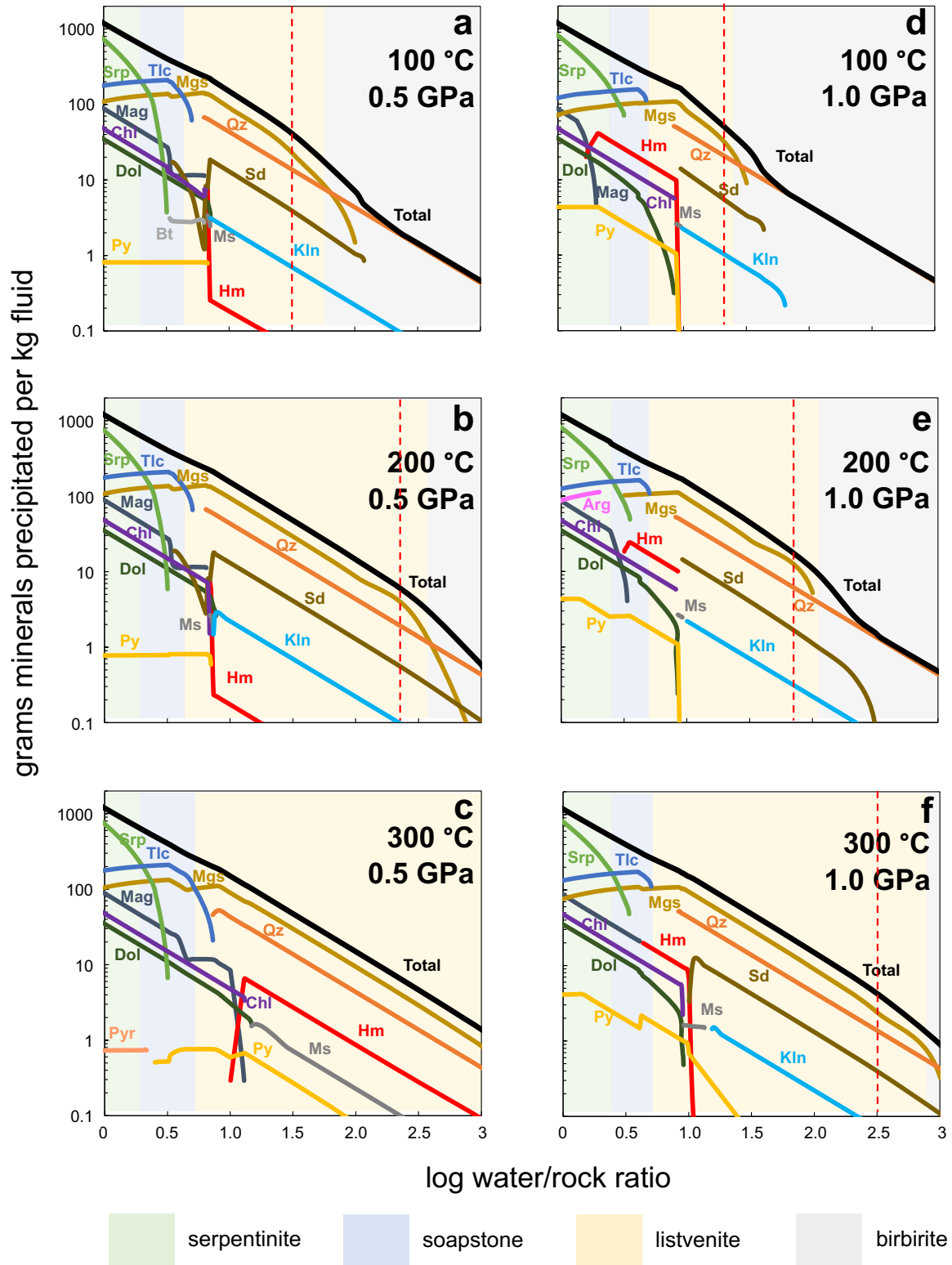
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1066 Most of the model results at different conditions predict precipitation of a few weight percent  
1067 magnesite (and some dolomite) in the serpentinization domain. This is consistent with observation of  
1068 carbonate veins in serpentinites from Hole BT1B, and with the hypothesis that formation of carbonate  
1069 veins in the serpentinite zone preceded transformation of the serpentinite host rocks to listvenite (also  
1070 see [Figure 6](#) and associated text in [Section 4.4](#),

1071

1072 The fluid temperatures, compositions and fluxes used in these calculations are different from the  
1073 constraints used in some calculations by Falk & Kelemen (2015). In that previous work, we explored  
1074 the possibility that CO<sub>2</sub> to form the listvenites was supplied over tens of millions of years, carried in  
1075 100 to 200°C fluids containing a few hundred ppm dissolved carbon, derived from pore fluids and/or  
1076 dewatering of opal and clay minerals, from the Hawasina sedimentary rocks immediately below the  
1077 site of listvenite formation at MoD Mountain. However, one of us (Falk!) insisted on mentioning the  
1078 possibility that the CO<sub>2</sub> to form listvenites was derived from fluids formed deeper in the subduction  
1079 zone, that migrated updip. We now prefer this latter hypothesis, for the reasons outlined above.

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Figure 15: Results of thermodynamic reaction path models of reaction between fluids derived from devolatilization of Hawasina pelitic sedimentary rock sample OM20-17 (Section 5.6) and average Oman harzburgite. Mineral end-member abbreviations Qz quartz, Sd siderite, Mgs magnesite, Klin kaolinite, Ms muscovite, Dol dolomite, Chl chlorite, Py pyrite, Tlc talc, Srp serpentine (chrysotile), Pyr pyrrhotite. Red, vertical dashed line indicates where magnesite/quartz molar and volume proportions are ~ 2:1, as observed in magnesite listvenites from MoD Mtn (e.g., Figure 12).

1089 Updip migration of fluids in a subduction zone has been predicted in some simplified dynamic models  
1090 of fluid flow in a viscously deforming subduction zone with high permeability (Wilson et al 2014).  
1091 However, the tendency of fluid buoyancy to drive vertical fluid flow may often dominate subduction  
1092 zone fluid fluxes. Thus, formation of relatively shallow listvenites, like those at MoD Mountain, may be  
1093 localized and unusual. Elsewhere, CO<sub>2</sub>-bearing fluids may migrate vertically into overlying mantle  
1094 peridotite at greater depth (e.g., Kelemen & Manning 2015). It is interesting to ponder how subduction  
1095 zone CO<sub>2</sub> fluxes may be partitioned between these different transport and mineralization processes.

### 1097 *5.8 Multiple reaction fronts*

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1099 The thermodynamic models presented in Sections 5.6 and 5.7 provide a starting point for  
1100 understanding “chromatographic effects” during transformation of peridotite to serpentinite. As can be  
1101 seen in Figure 15, our reaction path models predict sharp fronts where serpentinite is replaced by  
1102 soapstone, and then by listvenite. Talc-bearing, soapstone assemblages are predicted to crystallize in  
1103 a limited range of conditions, consistent with the fact that talc is rare in core from Hole BT1B, and in  
1104 hand specimens from MoD Mtn, where it is almost entirely restricted to narrow (~ 1 m scale) transition  
1105 zones between listvenite and serpentinite. If we were to use different thermodynamic data, talc might  
1106 be even less abundant, or absent in models at 100°C, because talc is predicted to be unstable below  
1107 ~ 100°C with respect to antigorite + quartz when using mineral data from Holland and Powell or  
1108 Gottschalk, together with the Redlich-Kwong equation of state for H<sub>2</sub>O- CO<sub>2</sub> fluids as modified by  
1109 Kerrick and Jacobs (1981) and by Holland and Powell (2003).

1110  
1111 In the model results presented in Figure 15, with reaction progress increasing from high fluid/rock  
1112 ratios on the right to low fluid/rock ratios on the left, magnesite + quartz and magnesite + talc become  
1113 unstable with respect to serpentine as dissolved carbon in the fluid is exhausted. Because carbon is a  
1114 minor constituent of aqueous fluid, but a major component of the listvenite assemblage, exhaustion of  
1115 dissolved carbon is predicted to occur at a fluid/rock ratio much greater than 1 (log fluid/rock > 0). Of  
1116 course, because aqueous fluid is composed mainly of H<sub>2</sub>O, the potential for serpentinization of  
1117 peridotite continues to much lower fluid/rock ratios.

1118  
1119 Although we cannot model it, we can also predict that – in the presence of pervasive fluid flow on the  
1120 grain scale – there could also be a sharp front where serpentine replaces olivine at water/rock ratios  
1121 less than one. Thermodynamic calculations for simplified olivine serpentinization by Kelemen et al.  
1122 (2020a) indicate that olivine + H<sub>2</sub>O would be stable with respect to serpentine at 100°C and a partial  
1123 pressure of ~ 10<sup>-2</sup> bars, and at 200°C and P(H<sub>2</sub>O) ~ 1 bar. While these conditions cannot be modeled  
1124 using EQ3/6, we can anticipate that low partial pressures of H<sub>2</sub>O – much lower than lithostatic  
1125 pressures – are produced along grain boundaries and near the tips of incipient fractures and veins,  
1126 especially where fluid has been almost completely consumed by peridotite hydration reactions. Under  
1127 these conditions, there could be a sharp front where serpentine (at higher fluid pressures) becomes  
1128 stable relative to olivine (at lower fluid pressure).

1129

1130 Throughout the mantle section of the Samail ophiolite, residual mantle peridotites commonly contain  
1131 about 50 to 80% serpentine, as inferred from the fact that bulk rock analyses yield loss on ignition  
1132 (mostly, H<sub>2</sub>O) of 8 to 10 wt% as compared to 13 to 16 wt% H<sub>2</sub>O in completely serpentinized, Mg end-  
1133 member harzburgite and dunites. These partially serpentinized peridotites commonly show a “mesh  
1134 texture”, with relict olivine and pyroxene “cores” transected by a “mesh” of cross-cutting serpentine  
1135 veins – typically 10 to 100 microns apart (Francis 1956, Green 1961, Green 1964, Raleigh & Paterson  
1136 1965). In some regions within the Samail ophiolite, particularly areas of relatively subdued topography  
1137 that have undergone extensive, penetrative weathering, relict mantle minerals in the mesh cores are  
1138 completely replaced by serpentine (e.g., OmanDP Sites BA1, BA2, BA3 and BA4, Kelemen et al  
1139 2021, Kelemen et al 2020c). However, along the steep canyons and narrow ridges that are typical of  
1140 outcrops in the mantle section of the ophiolite, subject to relatively rapid erosion, the pervasive  
1141 presence of the serpentine vein mesh surrounding relict mantle minerals attests to relatively rapid  
1142 fluid transport in fractures and veins, compared to slow transport of H<sub>2</sub>O into the mesh cores by  
1143 diffusion and/or imbibition.

1144

1145 In contrast, as noted above, the serpentinites sampled in core from Hole BT1B contain no relict olivine  
1146 or orthopyroxene, though pyroxene pseudomorphs (“bastites”) are evident. A zone of 100%  
1147 serpentinized peridotites a few meters thick was sampled by Falk & Kelemen (2015) in a transect  
1148 across a listvenite-peridotite contact on the watershed ridge east of the summit MoD Mountain.  
1149 Outside this zone, samples of peridotite had compositions and textures typical of partially  
1150 serpentinized residual mantle peridotites throughout the ophiolite. Based on these observations, we  
1151 infer that there is a 100% serpentinite zone a few meters thick, with sharp fronts – less than a meter  
1152 thick, between serpentinite and listvenite on one side, and between partially and completely  
1153 serpentinized peridotite on the other side.

1154

1155

### 5.9 Volume change during listvenite formation

1156

1157 The likely volume change during fluid-rock reactions has long been debated. Whereas Coleman &  
1158 Keith (1971) proposed that serpentinization involved simple addition of H<sub>2</sub>O to peridotite, with no  
1159 significant change in the volatile-free solid composition, Carmichael (1987), Nahon & Merino (1987),  
1160 and Fletcher & Merino (2001) argued that such reactions take place at nearly constant volume, with  
1161 addition of some components balanced by dissolution and export of others. Fletcher & Merino  
1162 provided quantitative calculations to support this hypothesis. Where a fluid that is super-saturated in a  
1163 new mineral phase, A, starts to crystallize A within a host mineral B that is initially in equilibrium with  
1164 fluid, expansion of B around A leads to an increase in local effective stress. In turn, because chemical  
1165 potential is proportional to the mean stress, this reduces supersaturation in A and leads to  
1166 undersaturation in B. This process continues, with very small volume changes, until the rate of  
1167 crystallization of A becomes equal to the rate of dissolution of B, at a steady state stress.

1168

1169 Using the methodology of Fletcher and Merino (2001) and a saturation index of 2 (as they did),  
1170 Kelemen and Hirth (2012) calculated that the steady state, effective stress during replacement of  
1171 olivine with serpentine is ~ 40 MPa. However, because olivine is very far from equilibrium with water  
1172 at low temperature, the saturation index for water reacting with olivine to form serpentine at 50 to  
1173 250°C and  $P(\text{H}_2\text{O}) > 1$  bar is close to  $10^7$ , and the steady state, effective stress estimated using the  
1174 method of Fletcher and Merino is ~ 800 MPa (Kelemen & Hirth 2012). Clearly, such a large differential  
1175 stress cannot be sustained within most rocks, which will deform at a lower stress, before the steady  
1176 state can be reached, either via ductile mechanisms (if reactions are slow and temperatures are high)  
1177 or via fracture and frictional deformation (if reactions are fast and temperatures are low). The latter  
1178 outcome is sometimes termed “reaction-induced cracking” (Jamtveit et al 2009, Rudge et al 2010) or  
1179 “reaction-driven cracking” (Kelemen & Hirth 2012). Thus, while some workers still disagree over the  
1180 extent of volume change in specific replacement processes, the approach of Fletcher and Merino  
1181 nicely explains a continuum between nearly constant volume replacement of one mineral by another  
1182 at high temperature, close-to-equilibrium conditions, and large volume changes accommodated by  
1183 fractures and frictional sliding at low temperature, far-from-equilibrium conditions.

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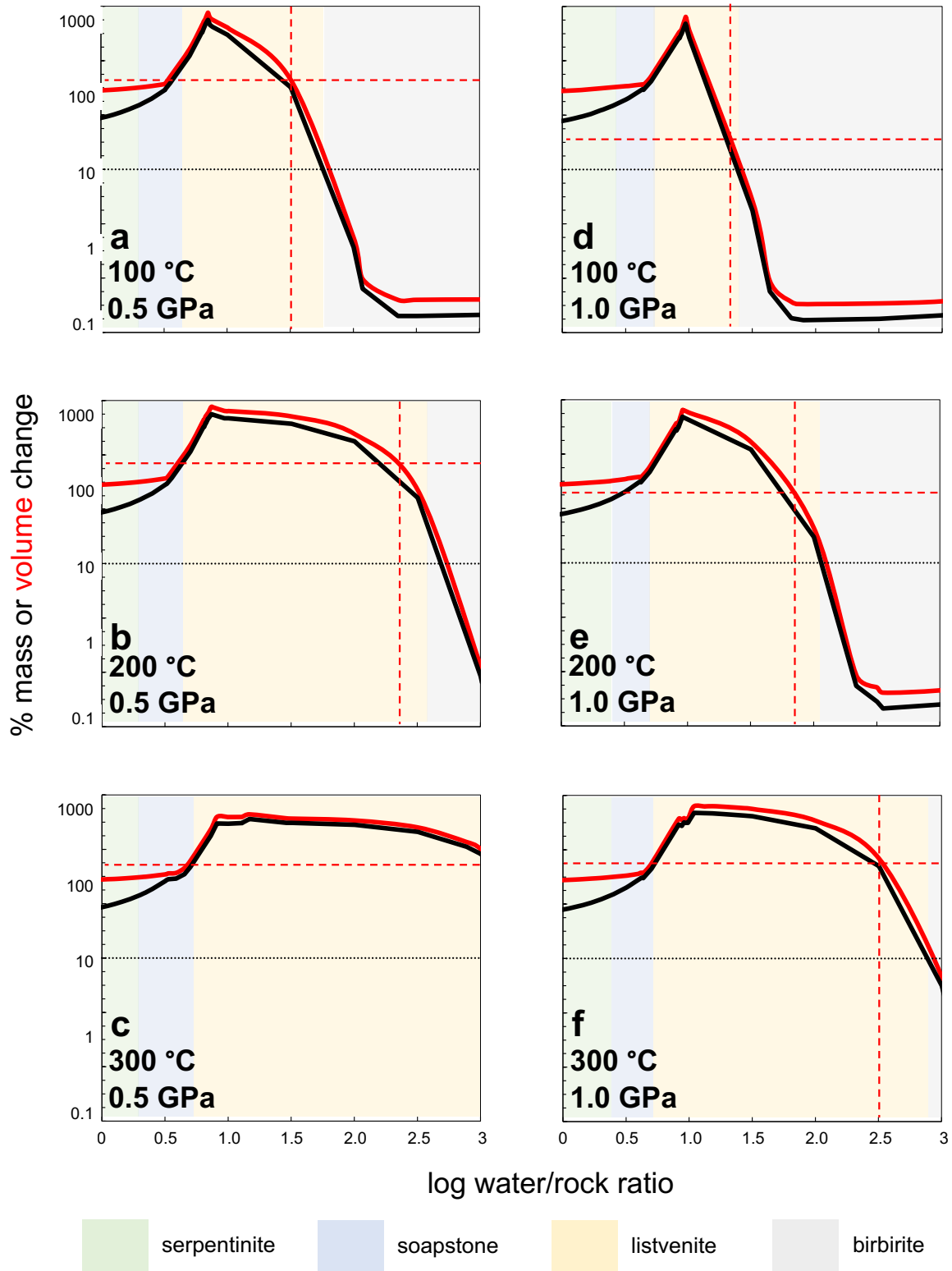
1185 As noted in [Section 5.5](#), despite dramatic, local variability, the average major element composition of  
1186 listvenites from MoD Mountain – in drill core and surface samples – is strikingly similar to the average  
1187 composition of residual mantle harzburgites in the Samail ophiolite. Together, the concentrations of  
1188 MgO, SiO<sub>2</sub> and FeO\* (all Fe as FeO) account for more than 90% of the volatile-free bulk composition  
1189 of listvenite samples. Thus, the fact that average Mg/Si/Fe ratios in the listvenites are almost identical  
1190 to those in Samail peridotites suggests that either (1) large scale dissolution of the peridotite protoliths  
1191 was nearly congruent, exporting dissolved, major elements in approximately their initial proportions, or  
1192 (2) there was little dissolution and export of major elements in the protolith during addition of CO<sub>2</sub> to  
1193 form listvenites, and addition of H<sub>2</sub>O to form serpentinites.

1194

1195 Thermodynamic models, experimental data, and observations of natural rock samples strongly favor  
1196 the second of these hypotheses. The solubility of silicate and Fe-oxide minerals in rock-buffered  
1197 aqueous fluids at low temperature is too low to allow for large scale dissolution and export of major  
1198 elements in open system, fluid-rock reactions. In turn, models of addition of CO<sub>2</sub> and/or H<sub>2</sub>O to  
1199 peridotites, predict very little removal of other species, together with large increases in the mass and  
1200 volume of the solid products of reaction. Birbirite formation may involve net volume and mass loss  
1201 due to extensive dissolution of peridotite reactants at water/rock ratios greater than ~ 100. However,  
1202 the models of listvenite formation illustrated in [Figure 15](#) yield predicted mass and volume increases  
1203 of 10 to 55 percent relative to an anhydrous, peridotite reactant, as illustrated in [Figure 16](#). Similar  
1204 results have been produced by thermodynamic models of serpentinitization (volume increase of 40-  
1205 60%, de Obeso & Kelemen 2018, Malvoisin 2015), experimental observation of closed system  
1206 serpentinitization (30-60%, Klein & Le Roux 2020) and analysis of microstructures in partially  
1207 serpentinitized peridotites formed in an open system (59±30 to 74±36%, Malvoisin et al 2020).

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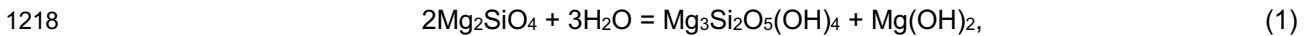




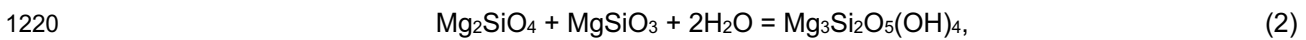
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Figure 16: Calculated mass and volume change relative to an anhydrous peridotite, for the reaction path models illustrated in Figure 15. Dashed, vertical red lines indicate where molar and volume proportions of magnesite/quartz reach 2:1, as observed in MoD Mtn listvenites (e.g., Figure 12). Dashed, horizontal line highlights the minimum increase in solid volume calculated for listvenite formation.

1216 These modeled and observed volume changes approximate those resulting from simplified, Fe-free,  
 1217 stoichiometric reactions. Thus, hydration of olivine to form serpentine and brucite,



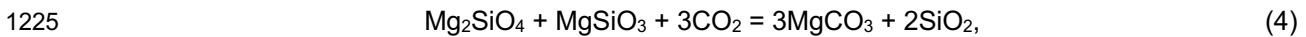
1219 and hydration of olivine + orthopyroxene to form serpentine,



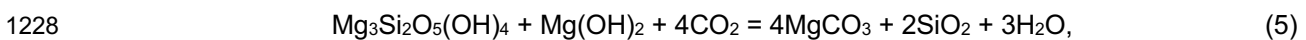
1221 can produce 52 and 63% increases in the solid volume, respectively. (Volume change calculated as  
 1222 100% (product volume -reactant volume)/(reactant volume)). Direct carbonation of olivine



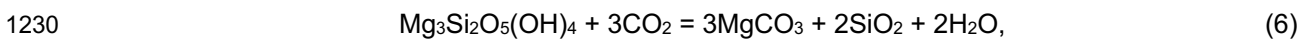
1224 and olivine + orthopyroxene,



1226 can lead to 85% and 74% increases in the solid volume, respectively. And, carbonation of serpentine  
 1227 plus brucite

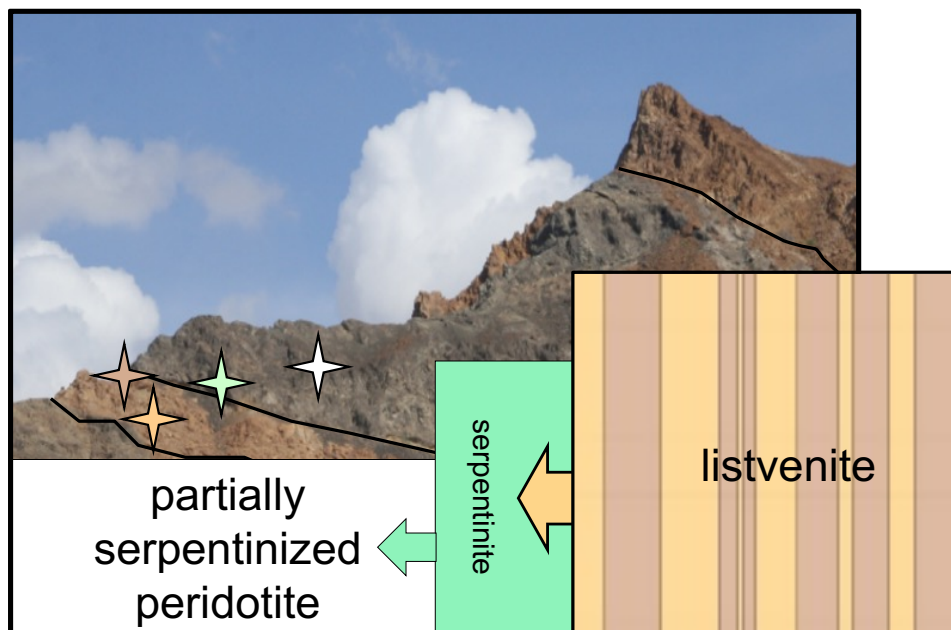


1229 and serpentine alone



1231 both produce solid volume increases ~ 22%.

1232



1233 *Figure 17: Schematic illustration of sequential volume changes during replacement of partially*  
 1234 *serpentinized peridotite by serpentinites and then replacement of serpentinites by listvenites. The*  
 1235 *height of the rectangles corresponds to the relative volumes, produced by reaction of CO<sub>2</sub>-bearing*  
 1236 *fluid with an initial, anhydrous peridotite. The tan and brown stripes in the “listvenite” represent*  
 1237 *alternations of different listvenite compositional bands. Stars on photo of the SW side of MoD Mtn*  
 1238 *illustrate position of listvenite, serpentine and partially serpentinized peridotite samples (Falk &*  
 1239 *Kelemen 2015).*

1240

1242 Because porosities in peridotite, serpentine and listvenite rarely if ever exceed 5%, all of these solid  
 1243 volume changes must be accommodated mainly by expansion of the entire rock volume. It is  
 1244 interesting to speculate how much uplift – and/or lateral expansion – in forearc regions is caused by

1245 hydration and carbonation of the mantle wedge. However, at the plate tectonic scale, the rates of  
1246 reactions similar to those outlined in equations (1-6) are unknown. It is likely that the strains due to  
1247 reaction are comparable to, or smaller than, other rates of deformation at convergent plate  
1248 boundaries, rendering the effect of solid volume expansion difficult to detect at the regional scale.

1249

1250 Based on the considerations outlined in this section, it is likely that large increases in the solid volume  
1251 occurred during formation of the MoD Mountain listvenites, and were accommodated mainly by  
1252 reaction-driven cracking, frictional sliding along existing fractures, and/or reaction-assisted granular  
1253 flow (Menzel et al 2021). The presence of abundant, antitaxial magnesite, magnesite-hematite, and  
1254 Fe-oxide veins in both serpentinites and listvenites is qualitatively consistent with a reaction-driven  
1255 cracking process. However, we have not identified any obvious strain markers that would allow a  
1256 quantitative evaluation of this hypothesis using rock textures.

1257

1258 Building upon an idea from Hansen et al. (2005), the Shipboard Scientific Party developed the  
1259 hypothesis that large volume increases due to hydration of olivine and pyroxene (reactions 1 & 2) may  
1260 have initially formed fractures at (and beyond) a serpentinization front – not observed in drill core, but  
1261 traversed by Falk & Kelemen (2015) – and these fractures were conduits for fluid flow and sites of  
1262 localized deformation during the smaller volume changes due to carbonation of serpentinites  
1263 (reactions 5 and 6) as schematically illustrated in [Figure 17](#).

1264

#### 1265 *5.10 Low temperature ductile deformation in subduction zones*

1266

1267 As noted above, the listvenites at MoD Mountain may have formed at depths of 25 to 40 km, at  
1268 temperatures less 200°C, yielding low temperature “geotherms” of 5 to 8°C/km depth. Such small  
1269 increases of temperature with depth are characteristic of the forearc above subduction zones  
1270 (Peacock 1996). High fluid pressures at these depths may account for the somewhat surprising  
1271 indications of low temperature, ductile deformation in core samples from Hole BT1B, based on the  
1272 observed crystallographic preferred orientation (CPO) in quartz, magnesite and serpentine in core  
1273 samples ([Section 4.4, Figure 10](#)).

1274

1275 Some of the fabrics illustrated in [Figure 10](#) could be inherited. For example, in early formed,  
1276 magnesite-hematite veins, magnesite forms parallel crystals, perpendicular to vein margins, with  
1277 small misorientations between adjacent crystals. When these veins are parallel (because they form  
1278 that way, or after they are transposed), this imparts a CPO to the sample, and may also give the  
1279 impression that sub-grain boundaries are present, even if there was no deformation of magnesite  
1280 crystals via dislocation creep. Similarly, quartz replacing opal may inherit a CPO, or a CPO may arise  
1281 due to anisotropic stress during recrystallization, without substantial strain.

1282

1283 On the other hand, the serpentine mylonite illustrated in [Figure 10](#) almost certainly records large  
1284 strains due to distributed deformation along grain boundaries. Moreover, clear examples of ductile

1285 deformation and shear zones with classical indicators of substantial strain indicate that ductile  
1286 deformation was active during the initial stages of listvenite formation, perhaps assisted by positive  
1287 feedback between weakening, due to reaction-induced recrystallization, and porosity enhancement  
1288 due to deformation, as discussed by Menzel et al. (2021). An important role for ductile deformation in  
1289 reaction zones at the top of subducting oceanic crust may help to explain why, in the relatively hot  
1290 Cascadia and SW Japan subduction zones, there are very few earthquakes at the top of the  
1291 subducting crust (Abers et al 2009, Abers et al 2013, Hirose et al 2008).

1292

1293

## 6. Conclusions

1294

1295 Observations of drill core of listvenite (completely carbonated peridotite), serpentinite, and  
1296 subduction-related metamorphic rocks from OmanDP Hole BT1B provide constraints on temperature,  
1297 depth, and deformation during mass transfer of H<sub>2</sub>O and CO<sub>2</sub> from subducted sediments into  
1298 overlying mantle peridotites at the leading edge of the mantle wedge. Listvenites, and a surrounding  
1299 zone of serpentinite, formed at temperatures less than ~ 200°C and poorly constrained depths of 25  
1300 to 40 km. Serpentinization and carbonation involved reaction of partially serpentinized, residual  
1301 mantle peridotite with CO<sub>2</sub>-rich, aqueous fluids produced by devolatilization of subducting, clastic  
1302 sediments analogous to the Hawasina formation, probably at 400 to 600°C. These fluids cooled as  
1303 they were transported up the subduction zone to the site of listvenite formation.

1304

1305 Such processes could play a significant role in the global carbon cycle. Not all listvenites form above  
1306 subduction zones. However, listvenites are found at and near the basal thrust in other ophiolites,  
1307 worldwide (Akbulut et al 2006, Borojević Šoštarić et al 2014, Escayola et al 2009, Menzel et al 2018,  
1308 Quesnel et al 2016, Quesnel et al 2013, Scarsi et al 2018, Sofiya et al 2017, Ulrich et al 2014). The  
1309 leading edge of the mantle wedge – and subduction modified mantle that has later been incorporated  
1310 into the continental mantle lithosphere – may be a globally important reservoir for carbon (Foley &  
1311 Fischer 2017, Kelemen & Manning 2015, Li et al 2017, Scambelluri et al 2016)

1312

1313 During BT1B listvenite formation, total solid volume increased by tens of percent due to hydration  
1314 followed by carbonation. While core and surface samples provide few direct constraints on the  
1315 mechanism that accommodated this expansion, one hypothesis is that large volume changes during  
1316 hydration of olivine and pyroxene along a serpentinization front caused large stresses and fractures  
1317 that accommodated expansion via frictional sliding, and provided secondary porosity for the CO<sub>2</sub>-rich  
1318 fluids that transformed serpentinites to listvenites.

1319

1320 Based on observed crystallographic preferred orientation in quartz, magnesite and serpentine in  
1321 macroscopically identified shear zones, it is inferred that ductile deformation of listvenite and  
1322 serpentinite occurred under low temperature conditions at the base of the mantle wedge during  
1323 subduction. Low temperature ductile deformation, coeval with serpentinization and listvenite  
1324 formation, may have been facilitated by recrystallization associated with the hydration and carbon

1325 mineralization processes, as discussed in more detail by Menzel et al. (Menzel et al 2021). Such a  
1326 process could be active in subduction zones where the interface between subducting oceanic crust,  
1327 sediments, and hanging wall peridotites is aseismic.

1328

1329

## 6. Author contributions

1330

1331 Kelemen and de Obeso conducted field mapping at MoD Mountain. de Obeso made new Sr and C  
1332 isotopic analyses of listvenites, the metamorphic sole and the underlying sedimentary rocks, updating  
1333 work by Falk & Kelemen (2015). Stockli carried out the reconnaissance (U,Th)/He analyses of zircons  
1334 from the metamorphic sole and lower crust, using zircon separates samples provided by Rioux.  
1335 Godard expertly led the BT1B geochemistry team onboard Drilling Vessel Chikyu, and then heroically  
1336 continued with analyses at the Université de Montpellier on behalf of the Shipboard Scientific Party.  
1337 Okazaki labored with Kelemen on the triangular histogram of shipboard XRF scanner data. Leong and  
1338 de Obeso conducted the EQ3/6 thermodynamic modeling, in consultation with Kelemen. Working with  
1339 his computer in 46°C weather on the drill site, Manning provided key insights into conditions for  
1340 coexisting hematite and organic carbon compounds. Ellison supervised Kelemen's Raman  
1341 spectroscopy analyses at the University of Colorado, Boulder, and offered essential advice and data  
1342 interpretation. Kotowski led analysis of core from the metamorphic sole and shared her results. Urai  
1343 led the structural geology team during core description onboard DV Chikyu, and is now advising  
1344 Menzel, who is leading analysis and interpretation of microstructures. Hirth offered insights into  
1345 potential mechanisms of low temperature, ductile deformation in subduction zones. Lafay and Beinlich  
1346 provided valuable input on the drill site and as members of the Shipboard Scientific Party. Coggon  
1347 (Project Manager) supervised drilling, core curation and logistics for this and all other OmanDP  
1348 boreholes, together with Nehal Warsi (Site Geologist). Matter (Project Director), Teagle (ICDP Lead  
1349 Investigator) and Sulaimani (Country Manager) worked tirelessly to ensure the success of the Oman  
1350 Drilling Project. Harris, Kelemen, Michibayashi, and Takazawa served as Co-Chief Scientists onboard  
1351 DV Chikyu during description of core from Hole BT1B. Kelemen (Chief Scientist) helped lead the  
1352 project, had a few ideas, and took the lead in writing this manuscript.

1353

1354

1355

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1390  
1391 **Data Availability:** Samples in [Supplementary Table 1](#) have IGSN numbers and locations. Data in  
1392 [Supplementary Table 1](#) are in the process of being archived in the Geochron database  
1393 ([www.geochron.org](http://www.geochron.org)). [Figures 4, and 6](#) are compilations of images that are published at  
1394 <http://publications.iodp.org/other/Oman/OmanDP.html>, where they are freely available, with more  
1395 detailed references provided in the figure captions. [Figures 1, 2, 5, and 7-17, Supplementary Figures](#)  
1396 [1 and 2, and Supplementary Tables 1 and 2](#) constitute data that are original with this paper. When  
1397 this manuscript is accepted, the tabulated data will be uploaded to the Zenodo repository  
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1399

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