

# Origin of the dunitic mantle-crust transition zone in the Oman ophiolite: The interplay between percolating magmas and high-temperature hydrous fluids

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1	Origin of the dunitic mantle-crust transition zone in the
2	Oman ophiolite: The interplay between percolating
3	magmas and high-temperature hydrous fluids
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11	ABSTRACT
12	Determining which petrological processes build the mantle-crust dunitic transition
13	zone (DTZ) in oceanic spreading settings has a direct impact on our understanding of
14	thermal and chemical transfers on Earth. We report on understated but widespread
15	mineral assemblages present in the DTZ at the top of a mantle diapir (Oman ophiolite),
16	including pargasite, grossular, and pyroxenes of peculiar composition. These minerals are
17	present interstitially between olivines and as inclusions in the disseminated chromite
18	grains, indicating that they are early, high-temperature features. They call for
19	hybridization between the mid-oceanic ridge basalt melts that fed the crustal section and
20	supercritical water saturated with silica. Our synoptic survey (~300 samples collected
21	along 12 cross sections) demonstrates that the DTZ was pervasively infiltrated by such
22	hybrid melts and that the abundance of their crystallization products increases upsection,

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indicates that water is involved in the reaction leading to the transformation of mantle 25 harzburgite into dunite in the DTZ. On the basis of field evidence, a hydrothermal origin 26 of the water is a reasonable guess. 27 **INTRODUCTION** 28 In ophiolites, and especially in Oman, the contact between the mantle peridotites 29 and the lower crust is underlined by a horizon as much as several hundred meters thick 30 made essentially of dunite (>95% olivine + minor chromite). The origin of this dunitic 31 transition zone (DTZ) was questioned in the pioneering studies of Moores and Vine 32 (1971) and Greenbaum (1972) and is still debated. The DTZ has been viewed as the 33 shallowest part of the mantle, i.e., a residue of reaction melting between host harzburgite 34 and a percolating melt becoming undersaturated in silica relative to orthopyroxene (Opx) 35 at low pressure (e.g., Moores and Vine, 1971; Dick, 1977; Rabinowicz et al., 1987), or as 36 the deepest part of the crust, i.e., cumulates from Mg-rich melts (e.g., Greenbaum, 1972; 37 Elthon, 1979). We have shown that the two options are not mutually exclusive and that 38 the DTZ can include both residual and cumulative horizons (Abily and Ceuleneer, 2013). 39 We have performed a systematic sampling of the DTZ in the Maqsad area and, 40 based on our sampling collection (>300 sampling sites), we realized that the DTZ 41 exposes an unexpected abundance of discreet mineral assemblages of enigmatic origin 42 (partly igneous, partly hydrous). The distribution of these mineral assemblages is not 43 random, but vertical within the DTZ. We propose that they are a clue to understand the 44 petrological processes involved in the formation of the DTZ. 45 **GEOLOGICAL SETTING AND FIELD OCCURENCE** 

46	The upper Cretaceous Oman ophiolite issued from the Tethys Ocean.
47	It is made of two contrasting magma series: one is a mid-oceanic ridge basalt (MORB)
48	type and the other has a depleted andesitic affinity attributed to subduction and/or
49	thrusting or to hydrated remelting of the shallow lithosphere during spreading (e.g.,
50	Pearce et al., 1981; Benoit et al., 1999; Python and Ceuleneer, 2003; Yamasaki et al.,
51	2006; MacLeod et al., 2013).
52	The Maqsad area (Sumail massif), the focus of our study (Fig. 1), exposes a
53	former asthenospheric diapir that contributed a large amount of melt into the crust
54	(Rabinowicz et al., 1987). It fed a ridge segment extending to the northwest and southeast
55	of the diapir for a distance of ~80 km (Python and Ceuleneer, 2003). It evolved in a
56	MORB igneous environment (Ceuleneer et al., 1996; Benoit et al., 1996; Korenaga and
57	Kelemen, 1997).
58	A few faults parallel to the paleo-ridge direction (northwest-southeast) affect the
59	DTZ. They consist of breccia with serpentine and carbonate matrix, frequently intruded
60	by gabbroic dikes altered in greenschist facies conditions. They are zones of intense fluid
61	circulation that underwent moderate normal fault movement. Away from them, dunite is
62	weakly serpentinized (<20%); this has preserved its high-temperature mineral
63	assemblages. Above the Maqsad diapir the DTZ was not transposed off axis by mantle
64	corner flow, and the massif as a whole was not affected by late tectonic events (Ceuleneer
65	et al., 1988).

# 66 PETROLOGY AND MINERAL CHEMISTRY

67 We sampled the Maqsad DTZ with a vertical step of 10–20 m along 12 cross
68 sections extending from the mantle harzburgites to the layered cumulates (Fig. 1C). All

69	samples (~300) as well as ~400 silicate inclusions enclosed in chromite grains were
70	analyzed with the electron microprobe.
71	The Maqsad DTZ, 200–350 m thick, is made of alternating metric to decametric
72	horizons of pure dunites and dunites containing variable amounts of interstitial
73	clinopyroxene (Cpx) and plagioclase (Fig. 2). The abundance of these interstitial
74	minerals, witnesses of melt percolation, and the degree of differentiation increase upward
75	in most sections, e.g., lower Mg# ( $100 \times Mg/[Mg + Fe_{Total}]$ ) in olivine and Cpx, lower
76	NiO in olivine, and higher $TiO_2$ in chromite.
77	In addition to large (millimeter to centimeter) interstitial and poikilitic Cpx
78	compositions (Cr, Al, and Ti rich) consistent with an igneous origin, tiny (tens to
79	hundreds of microns) Cpx crystals underline olivine grain rims (Fig. 3A).
80	They display high Mg# (93 < Mg# < 99) and CaO (>25 wt%) and low Al <sub>2</sub> O <sub>3</sub> , Cr <sub>2</sub> O <sub>3</sub> , and
81	$TiO_2$ contents (see the GSA Data Repository <sup>1</sup> ). These compositions are spread between
82	two end members, the igneous Cpx and the diopsides found in hydrothermal diopsidite
83	veins (Python et al., 2011) (Fig. 4A). They are observed in two-thirds of the samples,
84	distributed across the DTZ and particularly abundant at the top of the diapir. Inclusions of
85	Cpx in chromite exhibit the same range of compositions.
86	Among the other exotic [[SU: should not be in quotes. "exotic" has specific
87	geological meaning (i.e., foreign or introduced); is meaning here "unusual" or
88	similar?]] interstitial phases, we observed grossular garnet (37 samples; Fig. 3B),
89	amphibole (pargasites and magnesio-hornblendes) (41 samples; Fig. 3C), and enstatite
90	(Opx, 19 samples; Fig. 3D). Almost all occurrences of amphibole and garnet are in the
91	upper half of the DTZ (>~150 m above its base), and Opx is restricted to its upper part

92	(>~250 m) (Fig. 2). The vertical distribution of each mineral phase in inclusions in
93	chromite grains perfectly mimics their distribution in the olivine matrix.
94	Interstitial calcic amphiboles (Fig. 3C) have a lower $TiO_2$ content (mostly <0.2
95	wt%) than those in inclusions in chromite (0.2–0.9 wt%) (Fig. 4B). This can be attributed
96	to chemical exchange with the host chromites. All amphiboles (both interstitial and
97	enclosed in chromite) display a common evolution of $(Na^+K)_A$ element concentration
98	from 0.4 to 1. DTZ Opx forms oikocrysts with lobate contacts with olivine, in obvious
99	contrast to their porphyroclastic texture in mantle harzburgite (Fig. 3D). The composition
100	of the two kinds of Opx is also contrasted (Fig. 4C): DTZ Opx (both oikocrysts and
101	inclusions in chromite) have a much higher $TiO_2$ content for similar Mg#, reaching 0.37
102	wt% (average = $0.2 \text{ wt\%}$ ). Among the ~400 analyzed inclusions in chromite (Figs. 3E,
103	3F), 40% = amphibole (mostly pargasite), 39% = igneous Cpx, 7% = hybrid diopside, 7%
104	= olivine, $3\%$ = mica (Na-rich aspidolite and K-rich phlogopite), $3\%$ = Opx, and $1\%$ =
105	plagioclase and garnet.
106	INVOLVMENT OF A HYDROUS MELT IN THE GENESIS OF THE DTZ
107	Variations in the distribution of the interstitial minerals evoke crystallization from
108	a percolating melt in response to compaction (Rabinowicz et al., 1987). In previous
109	studies, the origin of the DTZ has been discussed in a dry igneous system. Interstitial,
110	igneous, Ti-rich Cpx indicates that a MORB melt percolated through the Maqsad DTZ
111	(Abily and Ceuleneer, 2013; this study). This is also evidenced by the composition of the
112	feeding melt channels entrapped in the underlying mantle harzburgite (Kelemen et al.,
113	1995; Ceuleneer et al., 1996; Benoit et al., 1996) and by the composition of the
114	troctolitic-gabbroic sills inside the DTZ (Korenaga and Kelemen, 1997). However, the

115	nature and abundance of the exotic minerals call for pervasive percolation of another
116	water- and silica-rich melt throughout the DTZ that occurred early, as demonstrated by
117	the entrapment of these minerals in the chromite grains. This leads us to formulate the
118	hypothesis that the hydrous melt percolation did not occur after dunite formation, but that
119	it contributed to the process that built the DTZ.
120	The possibility of a hydrous origin of dunites at a temperature significantly lower
121	than the liquidus of dry basaltic melts was stressed in the seminal work of Bowen and
122	Tuttle (1949). Addition of water to the system triggers the incongruent melting of
123	enstatite into olivine and silica melt. Dunite will form, and excess silica produced by this
124	reaction is exported from the system. Opx will eventually crystallize where this silica-
125	enriched melt accumulates and cools. The absence of Opx in the lower part of the DTZ
126	and its crystallization at its top is elegantly accounted for in this frame.
127	ORIGIN OF WATER
128	A water-saturated melt can have different origins: (1) a mantle source hydrated in
129	a subduction setting (e.g., MacLeod et al., 2013), (2) a shallow lithospheric source
130	hydrated by hydrothermal fluids and undergoing remelting in response to the rise of a
131	mantle diapir (Benoit et al., 1999), (3) an extreme degree of fractional crystallization of a
132	dry (actually water poor) MORB, and (4) hybridization of a MORB with hydrothermal
133	fluids.
134	In the first two hypotheses, the mantle source is depleted in incompatible
135	elements, including Ti. Primitive cumulates rich in Opx are widespread in the ophiolite
136	but crystallized from highly depleted melts (Benoit et al., 1999; Python and Ceuleneer,
137	2003; Akizawa and Arai, 2009). High Mg# in interstitial Opx in dunite seems to

138	contradict MORB involvement (e.g., Wang et al., 2016) but not the high Ti content.
139	Moreover, the successive occurrences of garnet, amphibole, and then Opx upsection (Fig.
140	2) are not in accordance with a deep-water source, which should have delivered hydrated
141	melt across the DTZ. The third hypothesis is difficult to reconcile with the high Mg# of
142	Opx and the abundance of amphibole: even if we consider that the Mg# is partly buffered
143	by high-forsterite olivine, the degree of fractional crystallization necessary to reach water
144	saturation should be far too high (Gillis and Meyer, 2001).
145	This led us to explore the fourth hypothesis. The percolation of high-temperature
146	hydrothermal fluids in the Oman lower oceanic crust is well documented (e.g., Coogan,
147	2003; Bosch et al., 2004; Akizawa et al., 2011; Koepke et al., 2014). The distribution of
148	hydrous minerals in the DTZ is consistent with the involvement of hydrothermal water.
149	The fact that Cpx composition spreads between igneous and hydrothermal end members
150	(Fig. 4A) is strong evidence for hybridization. We propose that the hybrid melt is a blend
151	between supercritical hydrothermal fluids rich in silica, i.e., trondhjemitic melt issued
152	from hydrous melting of the country rocks (Amri et al., 1996), and variably evolved
153	MORB.
154	Synmagmatic faults are present at the base of the Maqsad lower crust and were
155	main avenues for seawater penetration down to the Moho (Abily et al., 2011). The brittle

156 features affecting the DTZ may be the late expressions of faults that were active earlier.

157 They mainly affect the top of the DTZ and are, with the hydrous mineral distribution

158 (Fig. 2), consistent with a water supply from above. The presence of Opx and amphibole

159 in layered gabbroic cumulates in present-day oceanic lower crust was also explained by

160 the involvement of hydrothermal fluids (Gillis and Meyer, 2001) and by the extraction

161 from the mantle of heterogeneous batches of slightly evolved and unmixed melt (Gillis et

162 al., 2014).

#### 163 THERMAL AND CHEMICAL GEODYNAMIC IMPLICATIONS

164 Interstitial hydrous minerals described in this study crystallized early, as shown 165 by similar phases enclosed in chromite grains. Purely hydrothermal alteration followed 166 the magmatic activity, as indicated by Cpx and amphibole alteration products (Fig. 4B) 167 and the presence of hydrogrossular and serpentine (see also Gregory and Taylor, 1981), 168 but obviously did not totally overprint the high-temperature features. This suggests a high 169 cooling rate of the DTZ, consistent with previous geothermometric studies of the base of 170 the Oman lower crust (VanTongeren et al., 2008) and uppermost mantle section (Dygert 171 and Liang, 2015). 172 Below a 5–6-km-thick crust, the stability field for Opx and amphibole after 173 fractionation from a primitive (virtually dry) to a highly evolved (water-saturated) 174 MORB may imply temperature decrease to ~950 °C (pressure of 0.2 GPa) (Berndt et al., 175 2005). High-temperature conditions of crystallization of diopside from hybrid melts are 176 supported both by their entrapment in chromite and their coexistence with igneous Cpx. 177 Regarding the composition range pointing toward igneous Cpx, the crystallization 178 temperature of diopside seems to be higher than the 600–800  $^{\circ}$ C previously estimated for 179 a pure hydrothermal frame (Python et al., 2007; Arai and Akizawa, 2014). Although the 180 garnet stability field is variable (300-800 °C) (e.g., Bach and Klein, 2009; Newton and 181 Manning, 2007), inclusions of andradite and grossular in chromites show that they also 182 fractionated at a high temperature. Considering that a dry MORB injected at Moho level

183 during the rise of the Maqsad diapir reached 1230 °C (Ceuleneer et al., 1996), the

184	mineralogical distribution through the DTZ (Fig. 2) points toward a thermal gradient of
185	about few hundreds degrees in only few hundred meters, making the Moho a clear
186	rheological transition between the hot ductile mantle above the diapir and the lower crust.
187	CONCLUSIONS
188	We propose that the formation of the DTZ bears witness to transient processes
189	attributable to the meeting, at Moho level, of an ascending front of mantle partial melts
190	and a descending front of hydrothermal fluids. This specific context triggers the
191	formation of hybrid melts out of equilibrium with their country rocks, which contribute to
192	deeply modify the mineralogical and geochemical composition of the shallow mantle and
193	deep crust. Furthermore, hydrous melts are well known to be particularly efficient in
194	mobilizing metals, such as Cr, in the formation of chromitite ore bodies (Borisova et al.,
195	2012). Our results suggest that the DTZ is among the most reactive interfaces on Earth.
196	Its formation may be a major factor in the global chemical transfer and redistribution
197	between the mantle, the crust, and the ocean, and can condition the cycle of carbon,
198	halogens, and gases such as hydrogen and methane.
199	Our views, although challenging, do not fully contradict previous models for the
200	genesis of the DTZ, but reconcile different pieces of evidence in a more general scenario.
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## 206 **REFERENCES CITED**

- Abily, B., and Ceuleneer, G., 2013, The dunitic mantle-crust transition zone in the Oman
- 208 ophiolite: Residue of melt-rock interaction, cumulates from high-MgO melts, or
- 209 both?: Geology, v. 41, p. 67–70, doi:10.1130/G33351.1.
- Abily, B., Ceuleneer, G., and Launeau, P., 2011, Synmagmatic normal faulting in the
- 211 lower oceanic crust: Evidence from the Oman ophiolite: Geology, v. 39, p. 391–394,
- doi:10.1130/G31652.1.
- 213 Akizawa, N., and Arai, S., 2009, Petrologic profile of peridotite layers under a possible
- 214 Moho in the northern Oman ophiolite: An example from Wadi Fizh: Journal of
- 215 Mineralogical and Petrological Sciences, v. 104, p. 389–394,
- 216 doi:10.2465/jmps.090622a.
- 217 Akizawa, N., Arai, S., Tamura, A., Uesugi, J., and Python, M., 2011, Crustal diopsidites
- 218 from the northern Oman ophiolite: Evidence for hydrothermal circulation through
- suboceanic Moho: Journal of Mineralogical and Petrological Sciences, v. 106,
- 220 p. 261–266, doi:10.2465/jmps.110621b.
- Amri, I., Benoit, M., and Ceuleneer, G., 1996, Tectonic setting for the genesis of oceanic
- 222 plagiogranites: Evidence from a paleo-spreading structure in the Oman ophiolite:
- 223 Earth and Planetary Science Letters, v. 139, p. 177–194, doi:10.1016/0012-
- 224 821X(95)00233-3.
- Arai, S., and Akizawa, N., 2014, Precipitation and dissolution of chromite by
- 226 hydrothermal solutions in the Oman ophiolite: New behavior of Cr and chromite:
- 227 American Mineralogist, v. 99, p. 28–34, doi:10.2138/am.2014.4473.

- Bach, W., and Klein, F., 2009, The petrology of seafloor rodingites: Insights from
- 229 geochemical reaction path modeling: Lithos, v. 112, p. 103–117,
- 230 doi:10.1016/j.lithos.2008.10.022.
- 231 Benoit, M., Polvé, M., and Ceuleneer, G., 1996, Trace element and isotopic
- characterization of mafic cumulates in a fossil mantle diapir (Oman ophiolite):
- 233 Chemical Geology, v. 134, p. 199–214, doi:10.1016/S0009-2541(96)00087-3.
- Benoit, M., Ceuleneer, G., and Polvé, M., 1999, The remelting of hydrothermally altered
- peridotite at mid-ocean ridges by intruding mantle diapirs: Nature, v. 402, p. 514–
- 236 518, doi:10.1038/990073.
- 237 Berndt, J., Koepke, J., and Holtz, F., 2005, An experimental investigation of the influence
- of water and oxygen fugacity on differentiation of MORB at 200 MPa: Journal of
- 239 Petrology, v. 46, p. 135–167, doi:10.1093/petrology/egh066.
- 240 Borisova, A.Y., et al., 2012, A new view on the petrogenesis of the Oman ophiolite
- 241 chromitites from microanalyses of chromite-hosted inclusions: Journal of Petrology,
- 242 v. 53, p. 2411–2440, doi:10.1093/petrology/egs054.
- 243 Bosch, D., Jamais, M., Boudier, F., Nicolas, A., Dautria, J.M., and Agrinier, P., 2004,
- 244 Deep and high-temperature hydrothermal circulation in the Oman ophiolite—
- 245 Petrological and isotopic evidence: Journal of Petrology, v. 45, p. 1181–1208,
- 246 doi:10.1093/petrology/egh010.
- 247 Bowen, N.L., and Tuttle, O.F., 1949, The system MgO-SiO<sub>2</sub>-H<sub>2</sub>O: Geological Society of
- 248 America Bulletin, v. 60, p. 439–460, doi:10.1130/0016-
- 249 7606(1949)60[439:TSM]2.0.CO;2.

Ceuleneer, G., Nicolas, A., and Boudier, F., 1988, Mantle flow patterns at an oceanic

- spreading centre: The Oman peridotites record: Tectonophysics, v. 151, p. 1–26,
  doi:10.1016/0040-1951(88)90238-7.
  Ceuleneer, G., Monnereau, M., and Amri, I., 1996, Thermal structure of a fossil mantle
  diapir inferred from the distribution of mafic cumulates: Nature, v. 379, p. 149–153,
  doi:10.1038/379149a0.
  Coogan, L.A., 2003, Contaminating the lower crust in the Oman ophiolite: Geology,
- 257 v. 31, p. 1065–1068, doi:10.1130/G20129.1.

250

- 258 Dick, H.J.B., 1977, Evidence of partial melting in the Josephine Peridotite, *in* Dick,
- 259 H.J.B., ed., Magma Genesis 1977: Proceedings of the American Geophysical Union
- 260 Chapman Conference on Partial Melting in the Earth's Upper Mantle: State of
- 261 Oregon Department of Geology and Mineral Industries, p. 59–62.
- 262 Dygert, N., and Liang, Y., 2015, Temperatures and cooling rates recorded in REE in
- 263 coexisting pyroxenes in ophiolitic and abyssal peridotites: Earth and Planetary
- 264 Science Letters, v. 420, p. 151–161, doi:10.1016/j.epsl.2015.02.042.
- 265 Elthon, D., 1979, High magnesia liquids as the parental magma for ocean floor basalts:
- 266 Nature, v. 278, p. 514–518, doi:10.1038/278514a0.
- 267 Gillis, K.M., and Meyer, P.S., 2001, Metasomatism of oceanic gabbros by late stage
- 268 melts and hydrothermal fluids: Evidence from the rare earth element composition of
- amphiboles: Geochemistry, Geophysics, Geosystems, v. 2, 1012,
- 270 doi:10.1029/2000GC000087.
- 271 Gillis, K.M., et al., 2014, Primitive layered gabbros from fast-spreading lower oceanic
- 272 crust: Nature, v. 505, p. 204–207, doi:10.1038/nature12778.

- 273 Greenbaum, D., 1972, Magmatic processes at ocean ridges: Evidence from Troodos
- 274 massif, Cyprus: Nature, v. 238, p. 18–21, doi:10.1038/physci238018a0.
- 275 Gregory, R.T., and Taylor, H.P., 1981, An oxygen isotope profile in a section of
- 276 Cretaceous oceanic crust, Samail Ophiolite, Oman: Evidence for  $\delta^{18}$ O buffering of
- 277 the oceans by deep (>5 km) seawater-hydrothermal circulation at mid-ocean ridges:
- Journal of Geophysical Research, v. 86, p. 2737–2755,
- doi:10.1029/JB086iB04p02737.
- 280 Kelemen, P.B., Shimizu, N., and Saltersi, V.J., 1995, Extraction of mid-ocean-ridge
- basalt from the upwelling mantle by focused flow of melt in dunite channels: Nature,
- 282 v. 375, p. 747–753, doi:10.1038/375747a0.
- 283 Koepke, J., Berndt, J., Horn, I., Fahle, J., and Wolff, P.E., 2014, Partial melting of
- 284 oceanic gabbro triggered by migrating water-rich fluids: A prime example from
- the Oman Ophiolite, *in* Rollinson, H.R., et al., eds., Tectonic evolution of the
- 286 Oman Mountains: Geological Society of London Special Publication 392, p. 195–
- 287 212, doi:10.1144/SP392.10.
- Korenaga, J., and Kelemen, P.B., 1997, Origin of gabbro sills in the Moho transition zone
- of the Oman ophiolite: Implications for magma transport in the oceanic lower crust:
- 290 Journal of Geophysical Research, v. 102, p. 27,729–27,749, doi:10.1029/97JB02604.
- 291 MacLeod, C.J., Lissenberg, C.J., and Bibby, L.E., 2013, "Moist MORB" axial
- 292 magmatism in the Oman ophiolite: The evidence against a mid-ocean ridge origin:
- 293 Geology, v. 41, p. 459–462, doi:10.1130/G33904.1.

- 294 Moores, E.M., and Vine, F.J., 1971, The Troodos massif, Cyprus and other ophiolites as
- 295 oceanic crust—Evaluation and implications: Royal Society of London Philosophical
- 296 Transactions, ser. A, v. 268, p. 443–467, doi:10.1098/rsta.1971.0006.
- 297 Newton, R.C., and Manning, C.E., 2007, Solubility of grossular, Ca<sub>3</sub>Al<sub>2</sub> Si<sub>3</sub>O<sub>12</sub>, in H<sub>2</sub>O-
- 298 NaCl solutions at 800° C and 10kbar, and the stability of garnet in the system
- 299 CaSiO<sub>3</sub>-Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O-NaCl: Geochimica et Cosmochimica Acta, v. 71, p. 5191–5202,
- doi:10.1016/j.gca.2007.08.021.
- 301 Pearce, J.A., Alabaster, T., Shelton, A.W., and Searle, M.P., 1981, The Oman ophiolite as
- 302 a Cretaceous arc-basin complex: Evidence and implications: Royal Society of
- 303 London Philosophical Transactions, ser. A, v. 300, p. 299–317,
- doi:10.1098/rsta.1981.0066.
- 305 Python, M., and Ceuleneer, G., 2003, Nature and distribution of dykes and related melt
- 306 migration structures in the mantle section of the Oman ophiolite: Geochemistry,
- 307 Geophysics, Geosystems, v. 4, 8612, doi:10.1029/2002GC000354.
- 308 Python, M., Ceuleneer, G., Ishida, Y., Barrat, J.A., and Arai, S., 2007, Oman diopsidites:
- 309 A new lithology diagnostic of very high temperature hydrothermal circulation in
- 310 mantle peridotite below oceanic spreading centres: Earth and Planetary Science
- 311 Letters, v. 255, p. 289–305, doi:10.1016/j.epsl.2006.12.030.
- 312 Python, M., Yoshikawa, M., Shibata, T., and Arai, S.,
- 313 2011, Diopsidites and rodingites: Serpentinisation and Ca-metasomatism in the
- 314 Oman Ophiolite mantle, *in* Srivastava, R.K., ed., Dyke swarms: Keys for
- 315 geodynamic interpretation: Berlin, Springer-Verlag,
- doi:10.1007/978-3-642-12496-9\_23.

317	Rabinowicz, M., Ceuleneer, G., and Nicolas, A., 1987, Melt segregation and flow in
318	mantle diapirs below spreading centers: evidence from the Oman ophiolite: Journal
319	of Geophysical Research, v. 92, p. 3475–3486, doi:10.1029/JB092iB05p03475.
320	VanTongeren, J.A., Kelemen, P.B., and Hanghøj, K., 2008, Cooling rates in the lower
321	crust of the Oman ophiolite: Ca in olivine, revisited: Earth and Planetary Science
322	Letters, v. 267, p. 69-82, doi:10.1016/j.epsl.2007.11.034.
323	Wang, C., Liang, Y., Dygert, N., and Xu, W., 2016, Formation of orthopyroxenite by
324	reaction between peridotite and hydrous basaltic melt: An experimental study:
325	Contributions to Mineralogy and Petrology, v. 171, 77, doi:10.1007/s00410-016-
326	1287-z.
327	Yamasaki, T., Maeda, J., and Mizuta, T., 2006, Geochemical evidence in clinopyroxenes
328	from gabbroic sequence for two distinct magmatisms in the Oman ophiolite: Earth
329	and Planetary Science Letters, v. 251, p. 52-65, doi:10.1016/j.epsl.2006.08.027.
330	FIGURE CAPTIONS
331	Figure 1. A: Location of the Oman ophiolite. B: Geological map of the southeast massifs
332	of the Oman ophiolite showing the Maqsad paleo-ridge segment (red outline) and the
333	inferred position of the paleo-spreading axis (red dotted line) (Python and Ceuleneer,
334	2003). C: Enlargement of the Maqsad diapir area; orange lines indicate the positions of
335	our cross sections.
336	
337	Figure 2. Synthetic lithological log showing the vertical distribution of the mineral
338	assemblages along the dunitic transition zone (DTZ) in the vicinity of the Maqsad diapir,
339	Oman. Pl—plagioclase; Ol—olivine.

340	
341	Figure 3. Photomicrographs showing the texture of the various minerals constituting the
342	dunitic transition zone dunites and phases enclosed as inclusions in chromite grains. A:
343	500 $\mu$ m clinopyroxene (tiny diopside) underlying olivine grains. B: Interstitial grossular
344	garnet (sporadically associated with hydrogrossular and andradite; see the Data
345	Repository; see footnote 1). C: Interstitial pargasite (frequently associated with
346	magnesiohornblendes and rare magnesio-hastingsites). D: Oikocrystic orthopyroxene in
347	dunite showing lobate contacts with olivine. E, F: Inclusions of garnet, clinopyroxene,
348	hybrid diopside, orthopyroxene, and amphibole in chromite.
349	
350	Figure 4. Major element compositions of clinopyroxene (cpx), amphibole (amph), and
351	orthopyroxene (opx) observed interstitially in dunite and in inclusion in chromites. A:
352	$Al_2O_3$ and $TiO_2$ versus Mg# in clinopyroxene. B: $TiO_2$ versus $Al_2O_3$ and $(Na^+K)_A$ versus
353	Al <sub>IV</sub> in amphiboles. C: TiO <sub>2</sub> versus Mg# in orthopyroxene.
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356	<sup>1</sup> GSA Data Repository item 2017xxx
357	, is available online at
358	http://www.geosociety.org/datarepository/2017/ or on request from
359	editing@geosociety.org.