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transition zone**

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► **To cite this version:**

Mathieu Rospabé, Mathieu Benoit, Georges Ceuleneer, Mary-Alix Kaczmarek, Florent Hodel. Melt hybridization and metasomatism triggered by syn-magmatic faults within the Oman ophiolite: A clue to understand the genesis of the dunitic mantle-crust transition zone. *Earth and Planetary Science Letters*, 2019, 516, pp.108-121. 10.1016/j.epsl.2019.04.004 . hal-02383757

HAL Id: hal-02383757

<https://hal.science/hal-02383757>

Submitted on 6 Dec 2019

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1 **Melt hybridization and metasomatism triggered by syn-magmatic faults**
2 **within the Oman ophiolite: a clue to understand the genesis of the dunitic**
3 **mantle-crust transition zone**

4
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12

13 **Abstract**

14 On Earth, most of the critical processes happen at the frontiers between envelopes and
15 especially at the Moho between the mantle and the crust. Beneath oceanic spreading centres,
16 the dunitic transition zone (DTZ) appears as a major interface between the upwelling and
17 partially molten peridotitic mantle and the accreting gabbroic lower crust. Better constraints
18 on the processes taking part in the DTZ allows improved understanding of the interactions
19 between silicate melts and hydrated fluids, which act competitively to generate the
20 petrological Moho. Here we combine mineral and whole rock major and trace element data
21 with a structural approach along three cross-sections up to 300 m thick above the fossil
22 Maqsad mantle diapir (Oman ophiolite) in order to understand the vertical organization of the
23 DTZ with depth. Our results highlight that most of the faults or fractures cross-cutting the
24 DTZ were ridge-related and active at an early, high temperature magmatic stage. Chemical
25 variations along the cross-sections define trends with a characteristic vertical scale of few tens

26 of meters. There is a clear correlation between the chemical variation pattern and the
27 distribution of fault zones, not only for fluid-mobile elements but also for immobile elements
28 such as REE and HFSE. Faults, despite displaying very limited displacements, enhanced both
29 melt migration and extraction up to the crust and deep hydrothermal fluids introduction down
30 to the Moho level. We propose that these faults are a vector for upwelling melt modification
31 by hybridization, with hydrothermal fluids and/or silicic hydrous melts, and crystallization.
32 Infiltration of these melts or fluids in the country rock governs part of the gradational
33 evolutions recorded in composition of both the olivine matrix and interstitial phases away
34 from faults. Finally, these faults likely control the thermal structure of the mantle-crust
35 transition as evidenced by the spatial distribution of the crystallization products from
36 percolating melts, organizing the transition zone into pure dunites to impregnated dunites
37 horizons. In this context, the DTZ appears as a reactive interface that developed by the
38 combination of three primary processes: tectonics, magmatism and deep, high temperature
39 hydrothermal circulations. Accordingly, these features fundamentally contribute to the
40 variable petrological and geochemical organization of the DTZ and possibly of the lower
41 crust below oceanic spreading centers, and may be a clue to interpret part the heterogeneity
42 observed in MORB signatures worldwide.

43

44 **Keywords**

45 Oman ophiolite, dunitic mantle-crust transition zone, syn-magmatic faulting, melt-rock
46 reactions, high temperature hydrothermalism, melt hybridization

47

48 **1. Introduction**

49 The oceanic crust is generated at spreading centers where extensive thermal and chemical
50 exchanges occur between the mantle, the crust and the external envelopes. Crustal accretion at

51 oceanic spreading centres is not a steady state process, proceeding by the cyclic succession of
52 magmatic and magma-starved episodes, whatever the spreading rate (e.g. Gente et al., 1995;
53 Sinton et al., 2002; Yeo et al., 2016). During periods of magmatic quiescence, the front of
54 hydrothermal systems can deepen significantly, a propagation likely triggered by normal
55 faulting and detachment faults. This leads to the efficient cooling and alteration of the mafic-
56 ultramafic substratum and to elements mobilization and redistribution (e.g. German et al.,
57 2016 among recent studies), and therefore impacts chemical exchanges happening along
58 oceanic spreading centers. In addition, there is accumulating evidence for magmatism-
59 hydrothermalism relationships beneath oceanic spreading centres, in temperature conditions
60 high enough to induce the re-melting of previously hydrated rocks (e.g. Amri et al, 1996;
61 Benoit et al, 1999; Koepke et al., 2005; Zhang et al., 2017 and references therein) or allowing
62 crystallizing magmas and hydrothermal fluids to interact (e.g. Abily et al., 2011; Rospabé et
63 al., 2017). The Oman ophiolite has been shown to be an excellent analogue of present-day
64 spreading centres to study deep-seated hydrothermal processes, whatever its precise tectonic
65 setting (i.e. Mid-Ocean Ridge vs. arc-related basin) (e.g. Bosch et al., 2004; Currin et al.,
66 2018; France et al., 2009, 2013; Gilgen et al., 2016; Python et al., 2007; Zihlmann et al.,
67 2018).

68
69 In the Oman ophiolite, petrological and isotopic studies have shown that the crust was
70 affected by hydrothermal circulations ranging from greenschist to upper amphibolite/granulite
71 facies (e.g. Bosch et al., 2004; Gregory and Taylor, 1981; Koepke et al., 2005; Nehlig and
72 Juteau, 1988; Currin et al., 2018). The formation of diopsidite and rodingite dikes likewise
73 involves high temperature hydrothermal fluids circulating down to the Moho and even below
74 (Akizawa et al., 2011; Python et al., 2007). Most of these alteration features post-date the
75 crystallization stage and are introduced at depth via fracture networks (Nehlig and Juteau,

76 1988; Reuber, 1988). However, when normal faults develop early and root at Moho level,
77 seawater can locally reach the incompletely crystallized lower crust (Abily et al., 2011).
78

79 The dunitic transition zone (DTZ) from the Maqsad area (Oman ophiolite), like dunites from
80 other ophiolites (e.g. Quick, 1981; Ceuleneer and Le Sueur, 2008; Sanfilippo et al., 2014;
81 2017), displays extensive petrological and geochemical variations that result from the
82 overprint of several magmatic processes: incongruent melting of harzburgite orthopyroxenes
83 (i.e. “dunitization”), chemical re-equilibration between the olivine matrix and percolating
84 melts, refertilization by variably evolved melt batches (Rospabé et al, 2018a). In addition to
85 interstitial plagioclase and clinopyroxene reflecting the fractionation from a percolating
86 MORB (Abily and Ceuleneer, 2013; Koga et al., 2001), the occurrence of orthopyroxene,
87 amphibole, diopside and garnet, both in interstitial position and - with mica - included in
88 chromite, highlights the early contribution of a more exotic, hydrated and silica-richer
89 component that variably mixed with the MORB (Rospabé et al., 2017). The composition and
90 bottom to top distribution of minerals that crystallized in response to this hybridization
91 process calls for a hydrothermal origin of the water rather than a deep, subduction-related
92 origin. Chromitites associated to minerals of high temperature hydrothermal origin are
93 ubiquitous at Moho level in the Oman ophiolite. Accordingly, it can be inferred that this
94 process affected the whole ophiolite. However, the way in which this hydrated component
95 was introduced at high temperature within the DTZ remains poorly constrained. In order (1)
96 to specify the petrological, geochemical and tectonic structuration of the DTZ beneath
97 oceanic spreading centres and (2) to decipher the enigmatic relationships between the tectonic
98 history of the DTZ and its imbricated magmatic and hydrothermal signatures, we investigated
99 a portion of the paleo-ridge axis related to the Maqsad mantle diapir. This area appears
100 densely faulted according to previous geological maps (Amri, 1995; Rabu et al., 1986). Our

101 results highlight that faults were active early at Moho level, since the magmatic stage, and
102 that they conditioned the petrological and geochemical organization of the DTZ, and probably
103 of the overlying lower crust, by exerting a strong control on the mantle harzburgite
104 dunitization and on melts migration and crystallization.

105

106 **2. Geological setting**

107 *2.1. Geology of the Oman ophiolite*

108 The Oman ophiolite is the largest (~500 × 50 km) remaining oceanic lithosphere fragment
109 from the Tethyan ocean. It formed along a (possibly fast) spreading ridge ~95-97 million
110 years ago (e.g. Boudier et al., 1988; Rioux et al., 2013 and references therein). The synoptic
111 mapping of plastic deformation structures preserved in mantle peridotites allowed
112 characterizing vertical flow patterns in several areas; they were interpreted as upwelling
113 asthenospheric diapirs beneath the former oceanic ridge axis along which the lithosphere
114 accreted (Ceuleneer et al., 1988; Jousselin et al., 1998; Nicolas et al., 1988). The paleo-ridge
115 axis orientation evolves from a N-S direction in the north of the ophiolite to NW-SE in the
116 south, although exceptions to this general tendency can be observed locally (e.g. MacLeod
117 and Rothery, 1992; Nicolas et al., 1988; Pallister, 1981). The mapping of the nature of the
118 dikes cropping out within the mantle section (Python and Ceuleneer, 2003) has evidenced a
119 MORB-like environment mainly in the SE massifs of the ophiolite, together with other
120 restricted occurrences, while a depleted calc-alkaline magmatism is observed elsewhere.

121

122 *2.2. The Sumail Massif*

123 The Sumail massif, located in the SE of the ophiolite and focus of the present study, exposes
124 the well preserved Maqsad fossil mantle diapir and its associated N130 trending paleo-
125 spreading centre (Ceuleneer, 1991; Ceuleneer et al., 1988; Jousselin et al., 1998) (Fig. 1A). It

126 fed the largest ($\sim 80 \times \sim 30$ km) MORB area of the Oman ophiolite (Python and Ceuleneer,
127 2003). The intense igneous activity related to the diapir is witnessed by abundant melt
128 migration structures cropping out in mantle harzburgites (Benoit et al., 1996; Ceuleneer et al.,
129 1996; Python and Ceuleneer, 2003), by the 300-400 m thick DTZ in between mantle and
130 crustal sequences (Abily and Ceuleneer, 2013; Boudier and Nicolas, 1995; Ceuleneer and
131 Nicolas, 1985; Jousselin et al., 1998; Rospabé, 2018), and by abundant chromitite ore bodies
132 (Ceuleneer and Nicolas, 1985). The Sumail massif was slightly tilted by post-accretion
133 tectonism, its regional dip does not exceed 10° to the SE.

134

135 Two sets of highly dipping faults confer to the Maqsad area its more salient tectonic and
136 morphologic features according to geological maps (Amri, 1995; Rabu et al., 1986): (1) One
137 strikes N130 and is parallel to the strike of the sheeted dike complex in this area, i.e. parallel
138 to the regional orientation of the inferred paleo-ridge axis (Ceuleneer, 1991; MacLeod and
139 Rothery, 1992; Pallister, 1981) (Fig. 1A). This system may reasonably be related to the
140 former spreading activity since it has been evidenced that N130-trending faults have generally
141 a normal offset and have locally disturbed crystallization sequences in the lowermost gabbroic
142 crust in this area, in association with hydrothermal fluids (Abily et al., 2011). N130 is also the
143 azimuth of the olivine gabbro dykes in the mantle section of the Maqsad area (Ceuleneer et al,
144 1996). (2) The other fault system strikes N160 to N-S, parallel to the Muqbariah high
145 temperature mylonitic shear zone (Amri et al., 1996; Ceuleneer, 1991) (Fig. 1A). Moving
146 away from the diapir, the diverging mantle flow is limited to the SW by the Muqbariah shear
147 zone, itself injected by numerous dikes from a depleted andesite kindred, contrasting with the
148 MORB signature of the dykes present in the diapir and at its immediate periphery, and to the
149 NE by an area injected by pegmatitic dikes and intrusions from the same andesitic melts
150 (Amri, 1995; Amri et al., 1996; Benoit et al., 1999). It has been proposed on the basis of

151 geological and isotopic arguments that these intrusions and dykes originated from
152 “lithospheric” melts generated by the remelting of hydrothermally altered peridotites at an
153 early stage of interaction between the lithosphere and the rising Maqsad diapir (Amri et al.,
154 1996; Benoit et al., 1999; Clénet et al., 2010). Although no detailed study was conducted yet
155 about the interplay between SW-NE spreading and shearing along N160-180 shear zones, first
156 evidence show they took place early during the Maqsad ridge development.

157

158 **3. Organization of the DTZ along the Maqsad paleo-ridge axis**

159 We report here below on the structural, petrological and geochemical characteristics of three
160 cross-sections sampled through the Maqsad DTZ. These sections were selected among twenty
161 we explored in this area (Rospabé, 2018) because they particularly well illustrate the
162 interactions between early faulting and geochemical evolution of the DTZ. They were
163 collected along the inferred paleo-ridge axis northwest to the centre of the fossil diapir (Fig.
164 1A), with from north to south the sections #1, #2 and #3 (Fig. 1B, Supplementary Table S1).
165 The sampling was performed in a W-E orientation from the wadi Mahram to the west
166 (altitude ~635 m) to the top of the DTZ to the east, exposed at an altitude of ~1070 m in this
167 area (Fig. 1B). The sampling interval ranges from 10 to 20 m vertically. We adopted this
168 strategy in order to cross the two N130 and N165-180 trending fault systems cross-cutting the
169 DTZ. Chemical evolutions along the DTZ are presented for mineral and whole rock major
170 elements as well as for whole rock trace elements for a total of 125 samples. Mineral and
171 whole rock compositions are given in Supplementary Table S2 and Supplementary Table S3
172 respectively. Analytical methods are detailed in the Electronic Supplement 1.

173

174 *3.1. Tectonic structuration of the DTZ*

175 *3.1.1. The N130 fault system*

176 The N130 faults are regularly spaced by horizontal distances of ~250 meters on average. They
177 can be followed along strike on up to 2 km and have generally a dip of 65-70° toward the NE.
178 The cross-section #2 exposes conversely two successive faults with a dip toward the SW (Fig.
179 1B). The amplitude of the displacement along N130 faults has been established in a few cases
180 where they offset plurimetric troctolites intrusions: the movement is normal and the
181 displacement is limited to a few meters at most. A troctolite lens located about 1.5 km
182 westward of the considered cross-sections developed a strong high temperature deformation
183 along a N130.70NE normal fault (Fig. 2A), similarly to what was described at the base of the
184 crustal section near Maqsad (Abily et al., 2011). The N130 fault zones display clear brittle
185 features near the top of the DTZ and appear to be progressively rooted through the DTZ
186 where they evolve to serpentine and carbonate breccias. Brecciated zones reach up to about
187 10 meters in thickness concerning major faults. The alteration halo having affected the dunitic
188 wall rock does not exceed a few meters.

189

190 *3.1.2. The N165-180 fault system*

191 The N165-180 system accommodated a transtensional movement with a clear normal and
192 more subtle dextral components. This system is represented by two main discontinuities in the
193 explored area, the western N165-180-trending one making the contact between the mantle
194 section and the DTZ, and the easternmost ~N165 being internal to the DTZ (Fig. 1B):

195 - The westernmost N165-180 major discontinuity is organized as an asymmetric
196 graben-type structure limited by two N165.85E to vertical and N180.80W faults (Fig. 1B). It
197 induced the collapse of a layered troctolite unit down to the base of the DTZ, supporting a
198 significant normal movement. This system clearly evolved during a long time scale, starting
199 with early, syn- to sub-magmatic deformations - gabbros boudins, elongated mafic intrusions
200 (Fig. 2B) -, and becoming progressively affected by increasingly brittle fracturing as well as

201 by greenschist facies alteration of surrounding rocks. The schistosity within the N165.85E
202 fault centre, making the contact between mantle harzburgites and DTZ dunites (Fig. 1B),
203 points to an intense dextral movement similar to the dominant motion recorded by the
204 Muqbariah mylonitic shear zone (Amri et al., 1996).

205 - The second system affecting the DTZ internally evolves from a N155.65NE direction
206 to the south, along the cross-section #3, to a N170 sub-vertical orientation to the north along
207 the two cross-sections #1 and #2 (Fig 1B). It accommodated a transtensional movement with
208 a normal displacement much lower than along the westernmost system in regard to the
209 absence of deformation in its centre. The strike-slip along this discontinuity is estimated to
210 about 80 m at most regarding two N130 fault segments offset, with a dextral movement, north
211 to the cross-section #1. Likewise, the geological map from Rabu et al. (1986) generally shows
212 N130 faults cross-cut and shifted by the later N165 system. However, we also observed the
213 reverse relationships in some locations with the disruption of N165-180 fractures by later
214 N130 faults, pointing out the contemporaneity of both systems.

215 Other minor N165-180 faults or fractures affecting the DTZ, few meters in width at most,
216 become more abundant upsection. They confer a shale-like parting to the dunites while
217 examination of thin section reveals no evidence of high-temperature mylonitic deformation
218 (Fig. 2C). Shear sense indicators are poorly developed and vertical offsets seem to be
219 restricted to a few meters, making of these fractures transtensional to purely extensional
220 cracks. They are mostly subvertical or with a strong dipping generally to the west. Along
221 these fractures, troctolite intrusions are affected by greenschist facies metamorphism while
222 serpentine and carbonate developed into or parallel to the fracture plans in surrounding
223 dunites. Along a companion N165.80W fault right to the west of the easternmost major
224 discontinuity, a swarm of undeformed gabbro dikes oriented according to both N125.70NE
225 and N105.60NE orientations cuts across the N165-trending schistosity, stressing on the early

226 fault development before melt percolation and fluids circulation and subsequent alteration
227 (Fig. 2C).

228

229 *3.2. Petrological sequences within the DTZ*

230 Previous studies described a highly variable mineralogical content within the Maqsad DTZ,
231 with dunites evolving from “pure”, containing only olivine together with a few percent of
232 scattered chromite grains and rare, small clinopyroxene, to strongly impregnated (up to 30%
233 of interstitial minerals) (e.g. Abily and Ceuleneer, 2013; Boudier and Nicolas, 1995; Koga et
234 al., 2001). Impregnated dunites contain one or more interstitial mineral phases among
235 clinopyroxene, plagioclase, orthopyroxene, amphibole and other accessory minerals (e.g.
236 hydrothermal diopside, grossular garnet) (Rospabé et al., 2017). Hence, dunites from the
237 Maqsad DTZ are classified in the present study as pure dunites, cpx-bearing dunites, pl/cpx-
238 bearing dunites, opx/pl/cpx-bearing dunites and amph-bearing dunites (\pm opx/pl/cpx)
239 (Rospabé et al., 2018a).

240

241 The contacts between the main units composing the ophiolite are frequently faulted within the
242 studied area. Mantle harzburgites were not observed along the wadi Mahram except to the
243 west of the major westernmost N165 tectonic accident (Fig. 1B). The three sampled cross-
244 sections are entirely made of variably impregnated dunites and contain a high abundance of
245 troctolite intrusions upsection (Fig. 3). These intrusions, plurimetric in size and cumulative in
246 texture, display clear intrusive relationships at the contact with surrounding dunites showing
247 they were injected within the near-solidified DTZ. The cross-sections #1 and #3 present a
248 similar lithological succession, with a lower half part made of pure dunites and an upper part
249 widely impregnated. The transition from pure to impregnated portions corresponds to the
250 major easternmost \sim N165 discontinuity. The pure dunitic lower units regularly contain small

251 size (100 μm at most) clinopyroxene or hybrid diopside (i.e. hybrid between igneous
252 clinopyroxene and hydrothermal diopside; Rospabé et al., 2017) in interstitial position along
253 olivine grain boundaries (Fig. 4A). We observed locally, approaching fault zones, a higher
254 amount of chromite, occurring as schlierens and more rarely as massive dikes (Fig. 4B).
255 Along the cross-section #1, clinopyroxene and a scarce amount of plagioclase progressively
256 appear just above the major eastern N170 fault (Fig. 3). They become much more abundant
257 together with the appearance of orthopyroxene and amphibole twenty meters above, in the
258 uppermost section part, beyond a N130.60NE fault. Along the cross-section #3,
259 clinopyroxene, plagioclase, orthopyroxene and amphibole appear all together above the N155
260 segment, directly in the southward continuity of the eastern \sim N165 major discontinuity (Fig.
261 3). These mineral phases are observed all along the impregnated upper part. Plagioclase is
262 slightly more abundant than clinopyroxene until a N175 fault zone, while clinopyroxene and
263 orthopyroxene are more frequently observed above (Fig. 4C). Amphibole is unequally
264 distributed along the section.

265

266 The cross-section #2, located midway from sections #1 and #3, does not respect this
267 dichotomous structuration (Fig. 3). Interstitial amphibole, plagioclase and clinopyroxene are
268 more frequent all along this section (Figs. 4D and E) while pure dunites are quite uncommon.
269 Despite this erratic mineral distribution, amphibole appears more abundant in specific
270 subsections, limited by both N130 and N165-N180 faults zones, while orthopyroxene is
271 restricted to the uppermost level above a N130.55SW fault.

272

273 *3.3. DTZ geochemical patterns*

274 The olivine chemical content is highly variable in dunites collected along the Maqsad DTZ,
275 with Fo and NiO contents varying from 93.2 to 85.7 and from 0.16 to 0.45 wt.% respectively.

276 The olivine composition does not correlate with the presence/abundance of other minerals
277 (Fig. 5A).

278 Pure dunites are characterized by U- or V-shaped REE patterns ($La_{CN}/Sm_{CN} = 0.60-3.8$;
279 $Gd_{CN}/Yb_{CN} = 0.05-0.27$) and by enrichment in LILE and positive Pb, Sr and Ti anomalies in
280 regard to REE in their extended trace element patterns (Fig. 6B). Impregnated samples
281 containing clinopyroxene, plagioclase, orthopyroxene and/or amphibole interstitially between
282 olivine grains generally show convex-upward REE patterns characterized by HREE to LREE
283 depletion ($La_{CN}/Yb_{CN} = 0.02-0.42$) (Fig. 6B).

284 Mineral and whole rock compositions as a function of the sampling altitude are shown in
285 figures 6 and 7 (see also the Electronic Supplement 2). The regional N130 and N165-180
286 faults are reported at the altitude they cut across each section respectively (see Figure 3 for
287 their dipping). Chemical variations are not randomly distributed from one sampling point to
288 another: they display progressive and successive increasing or decreasing evolutions
289 (depending on the regarded element) with inversions from a trend to another every hundred
290 meters approximately. In the following we propose to show how the different chemical trends
291 are related (1) to the samples modal composition, (2) to their position relative to fault zones,
292 or (3) if they are essentially cryptic (i.e. unrelated to lithological or structural features).

293

294 *3.3.1. Chemical trends related to lithological facies*

295 Mineral and whole rock chemical compositions are highly variable in the Maqsad DTZ
296 dunites (Rospabé et al., 2018a). Whole rock vertical composition evolutions are partly
297 controlled by the modal composition of the samples. High amount of interstitial phases
298 (essentially plagioclase and pyroxene), likely related to impregnation (Fig. 4), leads to an
299 increase in CaO and Li contents, in the Gd_{CN}/Yb_{CN} ratio and the concavity of REE patterns
300 ($\sqrt{(Sm_{CN} \times Gd_{CN})/\sqrt{(Ce_{CN} \times Yb_{CN}) - 1}}$), and to a decrease in La_{CN}/Sm_{CN} and Nb/Ta ratios (Fig.

301 7 and Electronic Supplement 2). The Cr content directly reflects the few percent of
302 disseminated chromite in dunites, which also seems to control the whole rock Zr/Hf ratio
303 (Electronic Supplement 2).

304

305 The most impressive mineral composition variations along the three cross-sections are
306 observed in pure dunites or more generally at the base of each section below the N155-170
307 fault (Fig. 6). They are unpredictable as they are not related to the samples modal
308 composition. Conversely, Fo in olivine ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}_{\text{total}})$), XCr in chromite
309 ($100 \times \text{molar Cr}/(\text{Cr} + \text{Al})$) (Fig. 6) and Mg# in whole rock ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}_{\text{total}})$)
310 (Fig. 7) are much less variable in impregnated dunites, whatever the nature of interstitial
311 minerals.

312

313 *3.3.2. Chemical trends related to fault zones*

314 In some cases, especially in pure dunites, the vertical evolution of chemical signatures along
315 the cross-sections define patterns that appear to be influenced by the distribution of major
316 fault zones, whatever their orientation. In details, the Fo in olivine, XCr in chromite and Mg#
317 in whole rock decrease down to values of about 88 or below, ~45 and ~87 respectively
318 approaching faults (e.g. the interval ~700-725 m in the three sections; Figs. 5 and 6). NiO in
319 olivine and Ni in whole rock follow the same tendency as well as the Mg# ($100 \times \text{molar}$
320 $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$) in clinopyroxene, orthopyroxene and amphibole, both when they are
321 interstitial between olivine grains or as inclusions in chromite (Electronic Supplement 2). The
322 $\text{La}_{\text{CN}}/\text{Sm}_{\text{CN}}$ and U/Th ratios in pure dunites also decrease until 1 and below 0.75 respectively
323 (toward 700 m and 775 m in altitude in the cross-section #1, 725 m and 850 m in the cross-
324 section #3; Fig. 7). These variations are correlated with an increase of the CaO content in
325 olivine in pure dunites (until ~0.3 wt.%), TiO₂ content in pyroxenes (up to 0.5 wt.%) (Fig. 6

326 and Electronic Supplement 2). Similarly, Gd_{CN}/Yb_{CN} (and thus the concavity of the REE
327 patterns) and Nb/Ta ratios in whole rocks increase in pure dunites toward most of the fault
328 zones (Fig. 7 and Electronic Supplement 2).

329

330 *3.3.3. Chemical trends unrelated to lithological or structural features*

331 Beyond variations related to the amount of interstitial phases (local-scale) or approaching
332 fault zones (tens of meter-scale), we can observe chemical evolutions depending on the
333 altitude along the whole DTZ. In this frame, Mg# and Ni content in both whole rock and
334 minerals generally decrease in the uppermost part of the DTZ. In the same time TiO_2 content
335 in ortho- and clinopyroxene and Na_2O content in amphibole increase whatever their mode of
336 occurrence (i.e. interstitial between olivine grains or included in chromite). This suggests that
337 DTZ dunites recorded the cumulate effect of several processes involved in their formation.
338 Concerning few chemical proxies, such as Co in whole rock or YFe^{3+} in chromite, their
339 vertical evolution is partly correlated to the presence of fault zones but without clear
340 systematic increasing or decreasing trend (Electronic Supplement 2). This leads to the
341 alternation of positive and negative correlations between Ni and Co in some horizons like at
342 the base of the cross-section #1.

343

344 *3.3.4. Focus on clinopyroxene major element zoning*

345 It was shown in previous studies that chemical zonings in interstitial minerals in deeply
346 impregnated mantle-derived rocks probably reflect melt/rock reactions (e.g. Drouin et al.,
347 2009; Sanfilippo et al., 2015). Among the studied impregnated samples, twenty chemical
348 profiles were performed across single grains of clinopyroxene in order to investigate the
349 pattern of possible zoning in their major element composition as it was already reported (even
350 if not systematic) in some cases (Koga et al., 2001; Rospabé et al., 2018a). This was made for

351 clinopyroxene of various sizes in 11 samples displaying various interstitial minerals in
352 variable amount. Half of the analyzed clinopyroxene shows an increase in Mg# (up to 92.5),
353 and in SiO₂ and TiO₂ contents (up to 53.8 wt.% and 0.33 wt.% respectively), associated to a
354 decrease of Al₂O₃ and Cr₂O₃ contents (down to 2.8 wt.% and 1.2 wt.% respectively), from
355 core to rims (Fig. 8A). The other half does not show zoning in Mg# and SiO₂, and show
356 normal zoning in Al₂O₃ and Cr₂O₃ in some cases only (Fig. 8B). It appears that both the
357 chemical content of and the presence/absence of zoning in clinopyroxene are independent of
358 the paragenetic assemblage, neither with the degree of impregnation nor with the size of the
359 considered clinopyroxene crystal. However, well-defined zonings are systematically observed
360 in samples collected close to fault zones. Oppositely, chemically weakly zoned
361 clinopyroxenes are observed in samples located everywhere in the DTZ, independently from
362 any fault location.

363

364 **4. Interpretations and discussion**

365 *4.1. Early syn-magmatic faulting at Moho level*

366 The faults located between the distinctive main units of the Sumail massif were originally
367 attributed to later tectonic events postdating the oceanic lithosphere accretion, potentially
368 related to the emplacement of the ophiolitic nappe onto the Arabian margin (Amri, 1995;
369 Glennie et al., 1974; Rabu et al., 1986). Other studies interpreted the development of the both
370 N130 and N165 tectonic systems as synchronous with magmatism, these features being
371 responsible for the deformation and disturbed crystallization in the lower crustal, layered
372 gabbros along N130 faults (Abily et al., 2011; Jousselin et al., 1998), and of the genesis of
373 plagiogranitic and andesitic intrusions within the N165-trending Muqbariah regional shear
374 zone system (Amri et al., 1996; Benoit et al., 1999).

375

376 We observed that the DTZ was also affected by the both N130 and N165-180 systems (Fig.
377 1B), which led to a stronger serpentinization and carbonation of surrounding dunites. In spite
378 of these ubiquitous witnesses of low temperature hydrothermal circulations, some outcrops
379 preserved strong evidence of a high temperature deformation of the magmatic products along
380 the both fault systems (Figs. 2A and B). Excepting the two main N165-180 discontinuities,
381 which accommodated a significant strike-slip displacement (i.e. estimated to 80 m
382 horizontally concerning the easternmost one), other faults are better described as cracks with a
383 movement restricted to a few meters at most. The N130-trending faults may reasonably be
384 related to the ridge accretion, the strike of the sheeted dike complex displaying the same
385 orientation in this area (MacLeod and Rothery, 1992; Pallister, 1981). The slight normal
386 displacement on fault planes, generally measured with a dip of 50 to 70° at a regional scale,
387 locally induced the syn-magmatic deformation and the disturbance of crystallization
388 sequences in layered troctolites and gabbros at the transition between the crustal section and
389 the DTZ (Fig. 2A; see also Abily and Ceuleneer, 2011). The two areas affected by N130
390 faults with an opposite dipping toward the SW (along the cross-section #2) define local
391 graben-type structures accommodating the general extensional frame (Fig. 1B). We observed
392 that N130 oriented mafic dikes, viewed as cumulates after the last basaltic melt batches
393 discharged from the Maqsad diapir (Ceuleneer et al., 1996), cut across the tectonic
394 lineaments, especially the transtensional N165 ones (Fig. 2C). This supports that most of the
395 N130 and N165 tectonic events on one hand and the magmatic activity on the other hand
396 developed then ceased contemporaneously.

397

398 Otherwise, chemical variations observed vertically along the DTZ constitute an independent
399 and indirect argument supporting syn-magmatic fluid circulation along faults that experienced
400 moderate displacement. The minerals (both olivine and impregnating phases) and bulk-rock

401 display evolutions of their composition over tens of meters vertically toward the fault zones,
402 including for immobile elements or element ratios, expected to be related to magmatic
403 processes only (e.g. XCr in chromite, TiO₂ in impregnant minerals or REE and HFSE in bulk-
404 samples; Figs. 5 and 6, Electronic Supplement 2). Such continuous evolutions suggest that
405 faults played an important role in the DTZ genesis and are consistent with a moderate
406 amplitude of the displacements along fault planes: major offsets post-dating the DTZ
407 formation would have partly erased the systematic chemical trends observed approaching the
408 faults. It is worth mentioning that common vertical chemical evolutions are observed both in
409 minerals composing dunites as well as in silicate inclusions, supposed to be isolated early by
410 their host chromite. Consequently, all these observations allow us to interpret both N130 and
411 N165 oriented faults as structures developed early at a high temperature, syn-magmatic stage.
412 They strongly influenced the petrological and geochemical organization of the DTZ, although
413 they continued to be main vectors for hydrothermal fluids at lower temperature, following the
414 cessation of any magmatic activity.

415

416 *4.2. Relationships between faulting and melt-rock reactions*

417 *4.2.1. Faulting and percolating melts characteristics*

418 The relationship between fault zones and minerals/whole rock compositions designs several
419 similar chemical evolutions along the three cross-sections - especially between cross-sections
420 #1 and #3 that also display a similar petrological sequence (Fig. 3). Fault zones partly
421 condition the chemical patterns recorded in the dunitic matrix as revealed by olivine and pure
422 dunites whole rock compositions. The decrease of Fo in olivine and La_{CN}/Sm_{CN} ratio
423 associated to an increase of the CaO content in olivine and Gd_{CN}/Yb_{CN} ratio in pure dunites
424 (Figs. 6 and 7) was previously attributed to the percolation of MORB and subsequent
425 reequilibration with the surrounding olivine (Abily and Ceuleneer, 2013; Rospabé et al.,

426 2018a). This implies the overprint of a MORB signature over a prior enriched signature
427 potentially related to the genesis of small melt batches enriched in H₂O, silica and
428 incompatible trace elements during the early dunitization (Rospabé et al., 2018a). This
429 interpretation is also supported by the fractionation of U/Th and Nb/Ta ratios from the dunitic
430 horizons toward fault zones (decrease of U/Th and increase of Nb/Ta toward faults with few
431 exceptions; Fig. 7), considering that U is known to be a fluid/hydrous melt mobile element
432 and Ta is likewise expected to be much more easily mobilized by hydrous fluids or melts than
433 by dry (or slightly hydrated) melt - MORB in our case - relative to Nb (Green, 1995).
434 Evolutions of the chemical composition of the dunitic matrix, as well as of impregnant
435 minerals (chromite, clinopyroxene, orthopyroxene and amphibole) at the approach of fault
436 zones indicates that syn-magmatic faults conditioned the nature of the melt that circulated
437 through the DTZ. A reasonable way to account for these observations is to envision a
438 hybridization process between different melt batches within fault zones, which hence leads to
439 an evolving reequilibration signature within the host olivine matrix, i.e. starting from faults
440 and propagating into the surrounding dunitic horizons.

441

442 The introduction of hydrous fluids into the DTZ from above at an early magmatic stage is
443 strongly supported by the petrological sequences along both cross-sections #1 and #3:
444 interstitial orthopyroxene and amphibole appear in the shallowest levels of the DTZ, just
445 above fault zones (N130 in the case of cross-section #1, N155 in the case of cross-section #3).
446 This observation was previously attributed to the hybridization of upwelling MORB with
447 downwelling hydrothermal fluids and/or hydrated silica-rich melts issued from the hydrous
448 melting of surrounding rocks, with an increase of the hydrothermal component upsection
449 (Rospabé et al., 2017). The correlation between syn-magmatic faults (see paragraph 4.1) and
450 the appearance of minerals indicative of a hydrated magmatic environment supports that the

451 DTZ was continuously hydrated all along its development thanks to fracturing, from the prior
452 dunitization stage until the later stage when more and more percolating melts invaded the
453 DTZ. Finally, along fault zones occurs the hybridization between (1) the first interstitial H₂O-
454 and silica-rich melts batches, (2) MORB issued from the deeper mantle partial melting and
455 drained along faults through the DTZ, and (3) possibly continuous supply of hydrothermal
456 fluids. The low Nb/Ta ratios within pure dunitic horizons (Fig. 7) may reflect melt-rock
457 reaction at low melt/rock ratio (see Kelemen et al. (1993) concerning arc magmas generation
458 and evolution, and Rospabé et al. (2018) concerning the present Maqsad DTZ), and/or that the
459 early hydrated, enriched melt has fractionated a small amount of hydrous and Ti-rich minerals
460 such as amphibole or mica (Bodinier et al., 1996; Green, 1995) prior to the reequilibration
461 with the surrounding dunitic matrix. This later hypothesis is in accordance with (1) the
462 assumption that this exotic melt was involved in the transport and the widespread
463 fractionation of chromite at Moho level, chromite that entrapped inclusions of amphibole and
464 mica (Rospabé et al., 2017; 2018), and (2) the observation of an increasing amount of
465 chromite, especially as schlierens, approaching the faults (Figs. 3 and 4B; see also the vertical
466 evolution of Cr in whole rock in the Electronic Supplement 2). It is worth noting that pure
467 dunites that present a quite high Nb/Ta ratio while being located few tens of meters far from
468 fault zones, chiefly at the base of the cross-section #1 (Fig. 7), generally correspond to
469 samples containing schlierens of chromite (see the correspondence between the whole rock Cr
470 content and HFSE ratios in the Electronic Supplement 2) that contain Ti-rich mineral
471 inclusions. At a much larger scale, chromitite deposits were regularly observed along major
472 shear zones within the DTZ and the uppermost part of the mantle section of the Oman
473 ophiolite (Boudier and Al-Rajhi, 2014; Zagrtednov et al., 2018).

474

475 *4.2.2. Faulting and refertilization*

476 Accordingly, the fact that the cross-section #2, in intermediate location between sections #1
477 and #3 (Figs. 1B and 3), is more impregnated all the way up may be related to its peculiar
478 structural situation. A large part of this section is enclosed in a graben structure, bordered by
479 N130 fault zones with an opposite dip. Accordingly, we interpret this location as a main
480 avenue for melt percolation, issued from the mantle partial melting, and for hydrothermal
481 fluids circulation, introduced along fault zones. This led to strong fluid-melt-rock reactions
482 and to the refertilization of the dunitic matrix, potentially linked to a temperature decrease
483 within the graben structure. Contrariwise, pure dunitic horizons in sections 1 and 3 were
484 compacted at higher temperature before massive crystallization from interstitial melts.

485

486 Clinopyroxene grains from samples collected few meters from faults preserve a chemical
487 zoning while zoning is uncommon at larger distance (Fig. 8A). The occurrence or absence of
488 zoning is unrelated to the modal composition of the rock and from the grain size and seems to
489 depend only on the vicinity of a fault. Such chemical zonings in strongly impregnated
490 peridotites (frequently described as “olivine-rich troctolites”) collected along detachment
491 faults in present-day ridges and in ophiolites were previously interpreted as the result of
492 reactive crystallization (e.g. Drouin et al., 2009; Sanfilippo et al., 2015 and references
493 therein), i.e. mineral fractionation associated to harzburgite orthopyroxene or dunite olivine
494 assimilation (Collier and Kelemen, 2010). The importance of reactive crystallization relative
495 to fractional crystallization was previously considered as limited in the case of the Maqsad
496 DTZ (Rospabé et al., 2018a). Nonetheless, our results allow us to consider that, even if the
497 refertilization process was dominated by fractional crystallization from percolating melts, the
498 development of syn-magmatic fault zones during the DTZ formation reinforced local (fluid-
499)melt-rock reactions triggering reactive crystallization. Therefore, we propose that strong
500 relationships between the structural environment and mantle refertilization may be the key to

501 decipher the origin of hybrid olivine-rich troctolites along oceanic core complex (Sanfilippo
502 et al., 2015 and references therein).

503

504 *4.3. Implications for the development of the DTZ and melt migration beneath spreading*
505 *centres*

506 The progressive chemical evolution vertically along the DTZ, starting from a enriched melt
507 and acquiring progressively a MORB signature, reflects that the hybridization between
508 different melt batches is enhanced in fault zones that are avenues for both melt and fluids
509 circulations. The syn-magmatic faults affecting the DTZ, whatever their orientation but with a
510 dipping frequently higher than 60°, may have assisted the MORB extraction from the Maqsad
511 diapir. In this way, the most salient MORB signature is markedly recorded in dunites located
512 close to N165-N180 fault zones (e.g. higher CaO values; Fig. 6), the percolation having
513 potentially been facilitated by the transtensional feature. Moreover, troctolite intrusions
514 observed in the highest levels of the DTZ might represent the last extracted melt batches,
515 which suffered fractional crystallization due to cooling. In other words, it appears that the
516 DTZ recorded the switch between different melt extraction modes, starting with pervasive
517 porous flow within the host dunite (strongest MORB-reequilibrated signature at the approach
518 of faults), then followed in time when temperature decreases by melt discharges focused
519 along fault zones (cumulate troctolite intrusions). In Figure 9 we propose a synthetic scenario
520 for the DTZ formation above the Maqsad diapir:

521 - Stage A: Fault zones (important dipping, slight displacement) affect the DTZ early.
522 They allow the introduction of fluids at Moho level that potentially assist the orthopyroxene
523 melting out, leading to the mantle harzburgite transformation into dunite (Rospabé et al.,
524 2017), and to the early generation of small volume of H₂O-, SiO₂ and incompatible trace
525 elements enriched melts (Rospabé et al., 2018a).

526 - Stages B and C: Subsequently, fault zones focus the percolation of MORB issued
527 from the continuous partial melting of mantle peridotites, allowing (1) to a more or less strong
528 chemical reequilibration with host dunite, (2) to their hybridization with prior enriched melt
529 which has a direct influence on the Cr redistribution at Moho level, (3) to their accumulation
530 at certain levels, and (4) to the refertilization of the host dunite, mainly to the top of the DTZ,
531 with anhydrous or hydrated minerals fractionation interstitially (fractional or reactive
532 crystallization).

533 -Stage D: In addition to their strong influence on fluid-melt-rock reactions at Moho
534 level, fault zones drain residual melts from the DTZ to the lower crust. Plurimetric intrusions
535 of cumulate troctolites, becoming more and more abundant in the uppermost DTZ, are
536 witnesses of these melt discharges before/during the magmatic activity cessation.

537

538 Beyond the structural control on the magmatic processes that occur within the oceanic Moho,
539 fault zones continued to focus fluid circulation at lower temperature after the cessation of the
540 magmatic activity. In addition to the Cr transport at high temperature and its massive
541 fractionation as chromitite ore bodies that may have occurred preferentially along fault zones
542 (Boudier and Al Rajhi, 2014; Zagrtdenov et al., 2018), later hydrothermal circulations along
543 long-standing fractures should have led to strong chemical exchanges during low temperature
544 alteration of the lower crust (Zihlmann et al., 2018) and serpentinization and carbonation at
545 Moho level.

546

547 **5. Conclusion**

548 The fluid-melt-rocks reactions occurring at the mantle-crust transition below oceanic
549 spreading centers are expected to significantly influence the nature of the melts that feed the
550 crust and the chemical exchanges between the deep lithosphere and superficial envelopes. Our

551 combined structural, petrological and geochemical study of the DTZ in the Sumail massif
552 reveals that syn-magmatic tectonic lineaments primarily control these reactions. The Maqsad
553 DTZ evolved in a transtensional environment induced by two N130 and N165-180 fault
554 systems related to the complex (asymmetric) oceanic accretion geometry. Surprisingly, both
555 systems seem to have influenced the petrological and geochemical organization of the DTZ,
556 supporting their contemporaneity as formulated on the basis of field evidence. They both
557 govern:

558 (1) the vertical chemical evolutions recorded in the olivine matrix and the interstitial minerals
559 over tens of meters approaching faults zones, concerning elements considered immobile in
560 fluids or during alteration such as REE, HFSE or Th (i.e. reflecting the overprint of several
561 processes: the prior dunitization process, the focused migration of interstitial melts and/or
562 fluids through the dunitic matrix along fault zones, and the modification of the percolating
563 melt chemistry by hybridization);

564 (2) the petrological organization of the DTZ (i.e. the succession of pure and impregnated
565 horizons, that reflects the spatial distribution of melt crystallization products).

566 In this frame, the fact that faults affect syn-magmatically the mantle-crust transition zone may
567 be considered as the missing link between high temperature magmatic-related chemical
568 imprints in DTZ dunites, the evident involvement of a hydrous component, the migration and
569 extraction of percolating melts, and the mobilization and precipitation of a high amount of Cr
570 within this interface. Moreover, the successive melt discharges from the DTZ to the crust,
571 following different extraction modes, may have potentially contributed to the heterogeneity
572 observed in the Oman ophiolite crust (Jansen et al., 2018) and along oceanic spreading centers
573 worldwide.

574 Finally, syn-magmatic faults may have a great effect on the thermal and rheological structure
575 of the oceanic lithosphere while they also apparently strongly influence chemical

576 geodynamics (metals, sulfur and carbon cycles and so on) in oceanic ridges environment since
577 fluids are introduced continuously along fault zones, from (more or less hydrated) magmatic
578 stage to later, low temperature serpentinization and carbonation related to solely seawater-
579 derived hydrothermal circulations. These findings may contribute to better understand the
580 connection between the petrological, chemical and alteration reactions at Moho level and
581 within the lower oceanic crust, and the thermal, tectonic and rheological structure of the
582 whole oceanic lithosphere.

583

584 **Acknowledgments**

585 We would like to thank F. de Parseval, J.-F. Ména and L. Menjot for thin sections preparation
586 and, for technical assistance during sample preparation and data acquisition, M. Henry and
587 Jonathan Prunier (cleanroom lab), S. Gouy, J. Langlade and Ph. de Parseval (microprobe
588 analysis), F. Candaudap (HR-ICP-MS for whole rock trace elements analysis) and D.
589 Roggero (LA-ICP-MS for clinopyroxene trace elements analysis). We are grateful to H. Al
590 Azri for its hospitality, as well as to M. Al Araithi, M. Al Batashi, A. Al-Rajhi, S.
591 Almusharrafi and other colleagues from the Ministry of Commerce and Industry, Sultanate of
592 Oman, for their kind support. We greatly thank A. Sanfilippo and an anonymous reviewer for
593 their constructive comments, as well as T. A. Mather for editorial handling and comments,
594 which helped to improve this manuscript. This work has benefited from a financial support
595 provided by the Centre National de la Recherche Scientifique-Institut National des Sciences
596 de l'Univers (CNRS-INSU).

597

598 **Figure 1.** (A) Simplified geological map of the Sumail massif (modified after Béchenec et
599 al. (1992) and Wyns et al. (1992)). The massif exposes a N130-oriented paleo-ridge spreading
600 centre. It is centred on a mantle paleo-diapir structure defined by the vertical mantle flow

601 structure observed in the Maqsad area (Ceuleneer et al., 1988; Jousselin et al., 1998). The
602 dunitic transition zone is well exposed along the ridge axis and to the SW between the ridge
603 axis and the N165 ductile Muqbariah fault system. The white rectangle highlights our study
604 area. (B) Detailed geological map of the studied area (modified after Rabu et al. (1986)). The
605 dunitic transition zone (DTZ) is more than 300 m thick along the ridge axis. The three studied
606 cross-sections (cross-sections #1, #2 and #3 from north to south) were sampled from the wadi
607 Mahram to the west to the higher levels of the DTZ to the east. The sampling density we
608 adopted (step of 10 to 20 meters of elevation) has been previously shown to be optimal to the
609 description of the vertical petrological and geochemical variability through the DTZ (Abily
610 and Ceuleneer, 2013; Rospabé, 2018), particularly in the Sumail massif where the paleo-
611 Moho is sub-horizontal with a weak ESE regional dip (i.e. current absolute altitudes
612 correspond closely to paleo-depth). Structural measurements completed during our field
613 exploration are also reported on this sketch, especially the dipping and the dipping direction
614 along the two N130 and N165-N180 main fault systems identified in this area. The along
615 strike extent of the main faults exceeds several kilometers.

616

617 **Figure 2.** Three examples of relationships between deformed magmatic features and N130
618 (A) or N165-180 (B and C) fault zones affecting the DTZ in the studied area. A) A layered
619 troctolite lens is offset by about few meters along a N130.70NE normal fault making the
620 contact with surrounding dunite (left). These mafic cumulates recorded a strong deformation
621 near the fault plane (centre) while plagioclases show a remarkable elongation within the
622 groundmass (right). B) Deformation of magmatic products in the tectonic corridor located at
623 the base of the studied cross-sections and separating the DTZ from the harzburgite mantle
624 section (Fig. 1B). Among others, we observed an elongated gabbroic boudin (top) or flames
625 structures displayed by gabbros laminated within the host dunite (centre) along the N180.80W

626 fault, as well as aligned and elongated plagioclase impregnations in dunites (bottom) along
627 the N165.85E major fault. C) A N165.80W fault zone cross-cutting the cross-section #1 is
628 characterized by a well organized schistose parting in dunites (left) with no evidence of
629 mylonitic deformation (right top). An undeformed amphibole-bearing gabbroic dike, oriented
630 N125.70NE, cross-cut the schistosity of the N165.80W fault zone (right bottom).

631

632 **Figure 3.** Petrological and structural logs of the three studied cross-sections: from north to
633 south the section #1 (293 m), the section #2 (343 m) and the section #3 (371 m). Regardless
634 of the petrological sequences of the DTZ - a lower pure dunitic half surmounted by an
635 impregnated half (cross-sections #1 and #3), or more extensively impregnated (cross-section
636 #2) -, the transition from a lithological facies to another generally corresponds to the presence
637 of a fault zone. There is no systematics between the direction of the fault, N130 or N165-180,
638 and the minerals distribution.

639

640 **Figure 4.** Photomicrographs showing the different mineral contents characterizing the DTZ
641 dunites in the Maqsad area, with A) a “pure dunite”, almost made of olivine and chromite
642 only and containing a very few amount (<0.5%) of small (few hundreds microns at most)
643 clinopyroxene rims between two olivine grains or located at 120° olivine grains triple
644 junctions (16OM07A - cross-section #3), B) a dunite containing chromite organized as
645 schlierens (16OM24A - cross-section #3), C) an orthopyroxene oikocryst in an opx/pl/cpx-
646 bearing dunite (16OM29 - cross-section #3), D) a part of a clinopyroxene oikocryst up to 5
647 mm in a strongly impregnated pl/cpx-bearing dunite (16OM49 - cross-section #2), and E)
648 interstitial amphibole in an amph-bearing dunite (\pm opx/pl/cpx) (16OM74B - cross-section
649 #2).

650

651 **Figure 5.** Chemical variations along cross-sections 1, 2 and 3 in the Maqsad dunitic transition
652 zone (data for cross-section 1 are from Rospabé et al. (2018), data for cross-sections 2 and 3
653 are newly presented here). A) NiO content as a function of Fo in olivine, B) whole rock
654 chondrite-normalized REE and Primitive Mantle-normalized multi-elements patterns of pure
655 dunites (in the middle) and impregnated dunites (at the bottom). The precision is better than
656 10% for LILE, REE, Pb, Th and U, and better than 20% for HFSE (see also Rospabé et al.,
657 2018b). Grey fields represent the entire variation ranges described in Rospabé et al. (2018).
658 Analytical methods used to acquire the data are detailed in the Electronic Supplement 1.
659 Chondrite and Primitive Mantle normalizing values are from Barrat et al. (2012) and Sun and
660 McDonough (1989) respectively.

661

662 **Figure 6.** Vertical evolution of the mineral chemical composition along the studied cross-
663 sections, plotted as a function of the altitude. The colours of the dots represent the different
664 lithological facies, with pure dunites in blue, cpx-bearing dunites in red, pl/cpx-bearing in
665 orange, opx/pl/cpx-bearing dunite in purple and amph-bearing dunites in green. Red dashed
666 lines are faults, each being localized where they respectively cut across each section. The grey
667 gradient highlights the vertical increasing or decreasing characteristic of each element or
668 element ratio, in some case related to the presence of fault zones. Are represented the Fo (100
669 \times molar $Mg/(Mg + Fe_{total})$) and the CaO content (wt.%) in olivine, the XCr ($100 \times$ molar
670 $Cr/(Cr + Al)$) in chromite and the TiO_2 content (wt.%) in clinopyroxene. Mineral
671 compositions for samples from the cross-section #1 are issued from Rospabé et al. (2018),
672 corresponding to the “Buri cross-section”. The amount of impregnation is also reported to the
673 left as a function of the altitude. The modal content, available in Supplementary Table 1, was
674 calculated using the MINSQ least squares method (Herrmann and Berry, 2002) based on
675 whole rock and minerals major element compositions.

676

677 **Figure 7.** Vertical evolution of the whole rock chemical composition along the studied cross-
678 sections, plotted as a function of the altitude. The colours of the dots represent the different
679 lithological facies, with pure dunites in blue, cpx-bearing dunites in red, pl/cpx-bearing in
680 orange, opx/pl/cpx-bearing dunite in purple and amph-bearing dunites in green. Red dashed
681 lines are faults, each being localized where they respectively cut across each section. The grey
682 gradient highlights the vertical increasing or decreasing characteristic of each element or
683 element ratio, in some case related to the presence of fault zones. Are represented the Mg#
684 ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}_{\text{total}})$), $\text{La}_{\text{CN}}/\text{Sm}_{\text{CN}}$, Nb/Ta and U/Th ratios. Chondrite normalizing
685 values used to calculate the $\text{La}_{\text{CN}}/\text{Sm}_{\text{CN}}$ ratio are from Barrat et al. (2012). Whole rock
686 compositions for samples from the cross-section #1 are issued from Rospabé et al. (2018),
687 corresponding to the “Buri cross-section”. The amount of impregnation is also reported to the
688 left as a function of the altitude. The modal content, available in Supplementary Table 1, was
689 calculated using the MINSQ least squares method (Herrmann and Berry, 2002) based on
690 whole rock and minerals major element compositions.

691

692 **Figure 8.** Magnesium number ($\text{Mg\#} = 100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}^{2+})$) and SiO_2 , Al_2O_3 , Cr_2O_3
693 and TiO_2 concentration profile across two clinopyroxenes from opx/pl/cpx-bearing dunites
694 (15OM03A to the left, 16OM26 to the right). A) The first one to the left shows a well-defined
695 composition zoning with an increase of Mg# and SiO_2 and TiO_2 contents, together with the
696 decrease of Al_2O_3 and Cr_2O_3 , from core to rims. This pattern is similar to what is observed in
697 the case of reactive crystallization in abyssal olivine-rich troctolites, when the surrounding
698 peridotite is partly assimilated during fractional crystallization (Sanfilippo et al., 2015 and
699 reference therein). B) The second one to the right exhibits patterns more random in Mg#,
700 flattest in SiO_2 and TiO_2 , and similar to the first one in Al_2O_3 and Cr_2O_3 with the same

701 decrease toward grain rims.

702

703 **Figure 9.** Synthetic model for the DTZ vertical structuration in the Maqsad area. Stage A:
704 Introduction of fluids at Moho level along fault zones which potentially assist the upper
705 mantle dunitization (Rospabé et al., 2017) and, consequently, leads to the generation of small
706 melts batches enriched in H₂O-, SiO₂ and incompatible trace elements (Rospabé et al.,
707 2018a). Stage B: Ascending MORB percolation focused along fault zones, hybridization
708 between MORB and the early interstitial enriched melt, reequilibration with the surrounding
709 dunitic matrix, melt accumulation and interstitial mineral crystallization in the upper levels of
710 the DTZ (fractional or reactive crystallization depending on the distance to faults). Stage C:
711 Fractionation of hydrous minerals, or anhydrous minerals witnessing of hydrous melts
712 percolation, following the continuous hybridization between MORB and other exotic melts
713 through the DTZ. This hybrid melt is involved in the mobilization and precipitation of Cr.
714 Note that stages B and C may be contemporaneous since it has been evidenced that exotic
715 H₂O- and SiO₂-rich melt were involved as early as the dunitization itself (Rospabé et al.,
716 2017; 2018). The two stages were here decoupled to make easier the understanding of the
717 structural, petrological and geochemical organization of the DTZ. Stage D: Residual melts
718 extraction from the DTZ to the crust, with the formation of entrapment zones represented by
719 cumulate troctolite intrusions at the top of the DTZ. Subsequent alteration (serpentinization,
720 carbonation) of the DTZ dunites, especially along faults and fractures, follows the magmatic
721 activity cessation.

722

723 **References**

724 Abily, B., Ceuleneer, G., 2013. The dunitic mantle-crust transition zone in the Oman
725 ophiolite: Residue of melt-rock interaction, cumulates from high-MgO melts, or both?

- 726 Geology 41, 67-70. doi:10.1130/G33351.1
- 727 Abily, B., Ceuleneer, G., Launeau, P., 2011. Synmagmatic normal faulting in the lower
728 oceanic crust: Evidence from the Oman ophiolite. *Geology* 39, 391-394.
729 doi:10.1130/G31652.1
- 730 Akizawa, N., Arai, S., Tamura, A., Uesugi, J., Python, M., 2011. Crustal diopsidites from the
731 northern Oman ophiolite: Evidence for hydrothermal circulation through suboceanic
732 Moho. *J. Mineral. Petrol. Sci.* 106, 261-266. doi:10.2465/jmps.110621b
- 733 Amri, I., 1995. Etude pétrologique et structurale d'une dorsale océanique fossile, Massif de
734 Sumail (ophiolite d'Oman). Implications pour les mécanismes d'accrétion océanique.
735 Université Paul Sabatier, Toulouse III.
- 736 Amri, I., Benoit, M., Ceuleneer, G., 1996. Tectonic setting for the genesis of oceanic
737 plagiogranites: evidence from a paleo-spreading structure in the Oman ophiolite. *Earth*
738 *Planet. Sci. Lett.* 139, 177-194. doi:10.1016/0012-821X(95)00233-3
- 739 Barrat, J.-A., Zanda, B., Moynier, F., Bollinger, C., Liorzou, C., Bayon, G., 2012.
740 Geochemistry of CI chondrites: Major and trace elements, and Cu and Zn Isotopes.
741 *Geochim. Cosmochim. Acta* 83, 79-92. doi:10.1016/j.gca.2011.12.011
- 742 Béchenec, F., Roger, J., Le Métour, J., Wyns, R., 1992. Geological Map of Seeb: Sheet NF
743 40-03, Scale: 1:250,000. Explanatory Notes. Dir. Gen. Miner. Oman Minist. Pet. Miner.
- 744 Benoit, M., Ceuleneer, G., Polvé, M., 1999. The remelting of hydrothermally altered
745 peridotite at mid-ocean ridges by intruding mantle diapirs. *Nature* 402, 514-518.
746 doi:10.1038/990073
- 747 Benoit, M., Polvé, M., Ceuleneer, G., 1996. Trace element and isotopic characterization of
748 mafic cumulates in a fossil mantle diapir (Oman ophiolite). *Chem. Geol.* 134, 199-214.
749 doi:10.1016/S0009-2541(96)00087-3
- 750 Bodinier, J.L., Merlet, C., Bedini, R.M., Simien, F., Remaidi, M., Garrido, C.J., 1996.

751 Distribution of niobium, tantalum, and other highly incompatible trace elements in the
752 lithospheric mantle: The spinel paradox. *Geochim. Cosmochim. Acta* 60, 545-550.
753 doi:10.1016/0016-7037(95)00431-9

754 Bosch, D., Jamais, M., Boudier, F., Nicolas, A., Dautria, J.M., Agrinier, P., 2004. Deep and
755 high-temperature hydrothermal circulation in the Oman ophiolite-petrological and
756 isotopic evidence. *J. Petrol.* 45, 1181-1208. doi:10.1093/petrology/egh010

757 Boudier, F., Al-Rajhi, A., 2014. Structural control on chromitite deposits in ophiolites: the
758 Oman case. *Geol. Soc. London, Spec. Publ.* 392, 263-277. doi:10.1144/SP392.14

759 Boudier, F., Ceuleneer, G., Nicolas, A., 1988. Shear zones, thrusts and related magmatism in
760 the Oman ophiolite: Initiation of thrusting on an oceanic ridge. *Tectonophysics* 151, 275-
761 296. doi:10.1016/0040-1951(88)90249-1

762 Boudier, F., Nicolas, A., 1995. Nature of the moho transition zone in the Oman ophiolite. *J.*
763 *Petrol.* 36, 777-796. doi:10.1093/petrology/36.3.777

764 Ceuleneer, G., 1991. Evidence for a Paleo-Spreading Center in the Oman Ophiolite: Mantle
765 Structures in the Maqsad Area. Springer Netherlands, pp. 147-173. doi:10.1007/978-94-
766 011-3358-6_9

767 Ceuleneer, G., Le Sueur, E., 2008. The Trinity ophiolite (California): the strange association
768 of fertile mantle peridotite with ultra-depleted crustal cumulates. *Bull. Soc. Géol. Fr.*
769 179, 503-518. doi:10.2113/gssgfbull.179.5.503

770 Ceuleneer, G., Monnereau, M., Amri, I., 1996. Thermal structure of a fossil mantle diapir
771 inferred from the distribution of mafic cumulates. *Nature* 379, 149-153.
772 doi:10.1038/379149a0

773 Ceuleneer, G., Nicolas, A., 1985. Structures in podiform chromite from the Maqsad district
774 (Sumail ophiolite, Oman). *Miner. Depos.* 20, 177-184. doi:10.1007/BF00204562

775 Ceuleneer, G., Nicolas, A., Boudier, F., 1988. Mantle flow pattern at an oceanic spreading

776 centre: the Oman peridotite record. *Tectonophysics* 151, 1-26. doi:10.1016/0040-
777 1951(88)90238-7

778 Clénet, H., Ceuleneer, G., Pinet, P., Abily, B., Daydou, Y., Harris, E., Amri, I., Dantas, C.,
779 2010. Thick sections of layered ultramafic cumulates in the Oman ophiolite revealed by
780 an airborne hyperspectral survey: Petrogenesis and relationship to mantle diapirism.
781 *Lithos* 114, 265-281. doi:10.1016/j.lithos.2009.09.002

782 Collier, M. L., Kelemen, P. B., 2010. The case for reactive crystallization at mid-ocean ridges.
783 *J. Petrol.* 51, 1913-1940. doi:10.1093/petrology/egq043

784 Currin, A., Wolff, P. E., Koepke, J., Almeev, R. R., Zhang, C., Zihlmann, B., Ildefonse, B.,
785 Teagle, D. A., 2018. Chlorine-rich amphibole in deep layered gabbros as evidence for
786 brine/rock interaction in the lower oceanic crust: A case study from the Wadi Wariyah,
787 Samail Ophiolite, Sultanate of Oman. *Lithos* 323, 125-136.
788 doi:10.1016/j.lithos.2018.09.015

789 Drouin, M., Godard, M., Ildefonse, B., Bruguier, O., Garrido, C.J., 2009. Geochemical and
790 petrographic evidence for magmatic impregnation in the oceanic lithosphere at Atlantis
791 Massif, Mid-Atlantic Ridge (IODP Hole U1309D, 30°N). *Chem. Geol.* 264, 71-88.
792 doi:10.1016/j.chemgeo.2009.02.013

793 France L., Ildefonse B., Koepke J., 2013. Hydrous magmatism triggered by assimilation of
794 hydrothermally altered rocks in fossil oceanic crust (northern Oman ophiolite).
795 *Geochem. Geophys. Geosyst.*, 14, 2598-2614. doi:10.1002/ggge.20137

796 France L., Ildefonse B., Koepke J., 2009. Interactions between magma and hydrothermal
797 system in Oman ophiolite and in IODP Hole 1256D: fossilization of a dynamic melt lens
798 at fast spreading ridges. *Geochem. Geophys. Geosyst.*, 10, Q10019. doi:
799 10.1029/2009GC002652

800 Gente, P., Pockalny, R. A., Durand, C., Deplus, C., Maia, M., Ceuleneer, G., Mével, C,

801 Cannat, M, Laverne, C., 1995. Characteristics and evolution of the segmentation of the
802 Mid-Atlantic Ridge between 20°N and 24°N during the last 10 million years. *Earth*
803 *Planet. Sci. Lett.* 129, 55-71. doi:10.1016/0012-821X(94)00233-O

804 German, C.R., Petersen, S., Hannington, M.D., 2016. Hydrothermal exploration of mid-ocean
805 ridges: Where might the largest sulfide deposits be forming? *Chem. Geol.* 420, 114-126.
806 doi:10.1016/j.chemgeo.2015.11.006

807 Gilgen S.A., Diamond L.W., Mercolli I., 2016. Sub-seafloor alteration: Timing, depth and
808 stratigraphic distribution in the Semail ophiolite, Oman. *Lithos*, 260, 191-210. doi:
809 10.1016/j.lithos.2016.05.014

810 Glennie, K.W., Boeuf, M.G.A., Hughes Clarke, M.W., Moody-Stuart, M., Pilaar, W.F.H.,
811 Reinhardt, B.M., 1974. *Geology of the Oman Mountains*. Verh. van het K. Ned. Geol.
812 Mijnbouwk. Genoot. 31, 423 pp.

813 Green, T.H., 1995. Significance of Nb/Ta as an indicator of geochemical processes in the
814 crust-mantle system. *Chem. Geol.* 120, 347-359. doi:10.1016/0009-2541(94)00145-X

815 Gregory, R.T., Taylor, H.P., 1981. An oxygen isotope profile in a section of Cretaceous
816 oceanic crust, Semail Ophiolite, Oman: Evidence for $\delta^{18}\text{O}$ buffering of the oceans by
817 deep (>5 km) seawater-hydrothermal circulation at mid-ocean ridges. *J. Geophys. Res.*
818 *Solid Earth* 86, 2737-2755. doi:10.1029/JB086iB04p02737

819 Herrmann, W., Berry, R. F., 2002. MINSQ - a least squares spreadsheet method for
820 calculating mineral proportions from whole rock major element analyses. *Geochemistry*
821 *Explor. Environ. Anal.* 2, 361-368. doi:10.1144/1467-787302-010

822 Jansen, M. N., Lissenberg, C. J., Klaver, M., de Graaff, S. J., Koornneef, J. M., Smeets, R. J.,
823 MacLeod, C.J., Davies, G. R. 2018. Isotopic variation in Semail Ophiolite lower crust
824 reveals crustal-level melt aggregation. *Geochem. Persp. Lett.* 8, 37-42.
825 doi:10.7185/geochemlet.1827

826 Jousselin, D., Nicolas, A., Boudier, F., 1998. Detailed mapping of a mantle diapir below a
827 paleo-spreading center in the Oman ophiolite. *J. Geophys. Res. Solid Earth* 103, 18153-
828 18170. doi:10.1029/98JB01493

829 Kelemen, P.B., Shimizu, N., Dunn, T., 1993. Relative depletion of niobium in some arc
830 magmas and the continental crust: partitioning of K, Nb, La and Ce during melt/rock
831 reaction in the upper mantle. *Earth Planet. Sci. Lett.* 120, 111-134. doi:10.1016/0012-
832 821X(93)90234-Z

833 Koepke, J., Feig, S. T., Snow, J, 2005. Hydrous partial melting within the lower oceanic crust.
834 *Terra Nova* 17, 286-291. doi:10.1111/j.1365-3121.2005.00613.x

835 Koga, K.T., Kelemen, P.B., Shimizu, N., 2001. Petrogenesis of the crust-mantle transition
836 zone and the origin of lower crustal wehrlite in the Oman ophiolite. *Geochemistry,*
837 *Geophys. Geosystems* 2. doi:10.1029/2000GC000132

838 MacLeod, C.J., Rothery, D.A., 1992. Ridge axial segmentation in the Oman ophiolite:
839 Evidence from along-strike variations in the sheeted dyke complex. *Ophiolites Their*
840 *Mod. Ocean. Analog.* 60, 39-63. doi:10.1144/GSL.SP.1992.060.01.03

841 Nehlig, P., Juteau, T., 1988. Deep crustal seawater penetration and circulation at ocean ridges:
842 Evidence from the Oman ophiolite. *Mar. Geol.* 84, 209-228. doi:10.1016/0025-
843 3227(88)90102-8

844 Nicolas, A., Ceuleneer, G., Boudier, F., Misseri, M., 1988. Structural mapping in the Oman
845 ophiolites: Mantle diapirism along an oceanic ridge. *Tectonophysics* 151, 27-56.
846 doi:10.1016/0040-1951(88)90239-9

847 Pallister, J.S., 1981. Structure of the sheeted dike complex of the Samail Ophiolite near Ibra,
848 Oman. *J. Geophys. Res. Solid Earth* 86, 2661-2672. doi:10.1029/JB086iB04p02661

849 Python, M., Ceuleneer, G., 2003. Nature and distribution of dykes and related melt migration
850 structures in the mantle section of the Oman ophiolite. *Geochemistry, Geophys.*

851 Geosystems 4. doi:10.1029/2002GC000354

852 Python, M., Ceuleneer, G., Ishida, Y., Barrat, J.-A., Arai, S., 2007. Oman diopsidites: a new
853 lithology diagnostic of very high temperature hydrothermal circulation in mantle
854 peridotite below oceanic spreading centres. *Earth Planet. Sci. Lett.* 255, 289-305.
855 doi:10.1016/j.epsl.2006.12.030

856 Quick, J. E., 1981. The origin and significance of large, tabular dunite bodies in the Trinity
857 peridotite, northern California. *Contrib. Mineral. Petrol.* 78, 413-422.
858 doi:10.1007/BF00375203

859 Rabu, D., Béchenec, F., Beurrier, M., Hutin, M., 1986. Geological Map of Nakhil: Sheet NF
860 40-3E, Scale: 1:100,000. Explanatory Notes. Dir. Gen. Miner. Oman Minist. Pet. Miner.

861 Reuber, I., 1988. Complexity of the crustal sequence in the northern Oman ophiolite (Fizh
862 and southern Aswad blocks): The effect of early slicing? *Tectonophysics* 151, 137-165.
863 doi:10.1016/0040-1951(88)90244-2

864 Rioux, M., Bowring, S., Kelemen, P., Gordon, S., Miller, R., Dudás, F., 2013. Tectonic
865 development of the Samail ophiolite: High-precision U-Pb zircon geochronology and
866 Sm-Nd isotopic constraints on crustal growth and emplacement. *J. Geophys. Res. Solid
867 Earth* 118, 2085-2101. doi:10.1002/jgrb.50139

868 Rospabé, M., 2018. Etude pétrologique, géochimique et structurale de la zone de transition
869 dunitique dans l'ophiolite d'Oman : Identification des processus pétrogénétiques à
870 l'interface manteau/croûte. Université Paul Sabatier, Toulouse III.

871 Rospabé, M., Benoit, M., Ceuleneer, G., Hodel, F., & Kaczmarek, M. A., 2018a. Extreme
872 geochemical variability through the dunitic transition zone of the Oman ophiolite:
873 Implications for melt/fluid-rock reactions at Moho level beneath oceanic spreading
874 centers. *Geochim. Cosmochim. Acta* 234, 1-23. doi:10.1016/j.gca.2018.05.012

875 Rospabé, M., Benoit, M., Candaudap, F., 2018b. Determination of Trace Element Mass

876 Fractions in Ultramafic Rocks by HR-ICP-MS: A Combined Approach Using a Direct
877 Digestion/Dilution Method and Preconcentration by Coprecipitation. *Geostand.*
878 *Geoanalytical Res.* 42, 115–129. doi:10.1111/ggr.12181

879 Rospabé, M., Ceuleneer, G., Benoit, M., Abily, B., Pinet, P., 2017. Origin of the dunitic
880 mantle-crust transition zone in the Oman ophiolite: The interplay between percolating
881 magmas and high-temperature hydrous fluids. *Geology* 45, 471-474.
882 doi:10.1130/G38778.1

883 Sanfilippo, A., Tribuzio, R., Ottolini, L., Hamada, M., 2017. Water, lithium and trace element
884 compositions of olivine from Lanzo South replacive mantle dunites (Western Alps):
885 New constraints into melt migration processes at cold thermal regimes. *Geochim.*
886 *Cosmochim. Acta* 214, 51-72. doi:10.1016/j.gca.2017.07.034

887 Sanfilippo, A., Morishita, T., Kumagai, H., Nakamura, K., Okino, K., Hara, K., Tamura, A.,
888 Arai, S., 2015. Hybrid troctolites from mid-ocean ridges: Inherited mantle in the lower
889 crust. *Lithos* 232, 124-130. doi:10.1016/j.lithos.2015.06.025

890 Sanfilippo, A., Tribuzio, R., Tiepolo, M., 2014. Mantle-crust interactions in the oceanic
891 lithosphere: Constraints from minor and trace elements in olivine. *Geochim.*
892 *Cosmochim. Acta* 141, 423-439. doi:10.1016/j.gca.2014.06.012

893 Sinton, J., Bergmanis, E., Rubin, K., Batiza, R., Gregg, T.K.P., Gronvold, K., Macdonald,
894 K.C., White, S.M., 2002. Volcanic eruptions on mid-ocean ridges: New evidence from
895 the superfast spreading East Pacific Rise, 17 degrees-19 degrees S. *J. Geophys. Res.*
896 *Solid Earth* 107. doi:10.1029/2000JB000090

897 Sun S.-S. and McDonough W. F., 1989. Chemical and isotopic systematics of oceanic basalts:
898 implications for mantle composition and processes. *Geol. Soc. Lond., Spec. Publ.* 42,
899 313-345. doi:10.1144/GSL.SP.1989.042.01.19

900 Wyns, R., Béchenec, F., Chevrel, S., Le Métour, J., Roger, J., 1992. Geological Map of

901 Nazwa: Sheet NF 40-07, Scale: 1:250,000. Explanatory Notes. Dir. Gen. Miner. Oman
902 Minist. Pet. Miner.

903 Yeo, I.A., Devey, C.W., LeBas, T.P., Augustin, N., Steinführer, A., 2016. Segment-scale
904 volcanic episodocity: Evidence from the North Kolbeinsey Ridge, Atlantic. *Earth Planet.*
905 *Sci. Lett.* 439, 81-87. doi:10.1016/j.epsl.2016.01.029

906 Zagrtdenov, N. R., Ceuleneer, G., Rospabé, M., Borisova, A. Y., Toplis, M. J., Benoit, M., &
907 Abily, B., 2018. Anatomy of a chromitite dyke in the mantle/crust transition zone of the
908 Oman ophiolite. *Lithos*, 312, 343-357. doi:10.1016/j.lithos.2018.05.012

909 Zhang, C., Koepke, J., France, L., Godard, M., 2017. Felsic Plutonic Rocks from IODP Hole
910 1256D, Eastern Pacific: Implications for the Nature of the Axial Melt Lens at Fast-
911 Spreading Mid-Ocean Ridges. *J. Petrol.* 58, 1535-1565. doi:10.1093/petrology/egx064

912 Zihlmann, B., Müller, S., Coggon, R.M., Koepke, J., Garbe-Schönberg, D., Teagle, D.A.,
913 2018. Hydrothermal fault zones in the lower oceanic crust: An example from Wadi
914 Gideah, Samail ophiolite, Oman. *Lithos* 323, 103-124. doi:10.1016/j.lithos.2018.09.008

Figure 1

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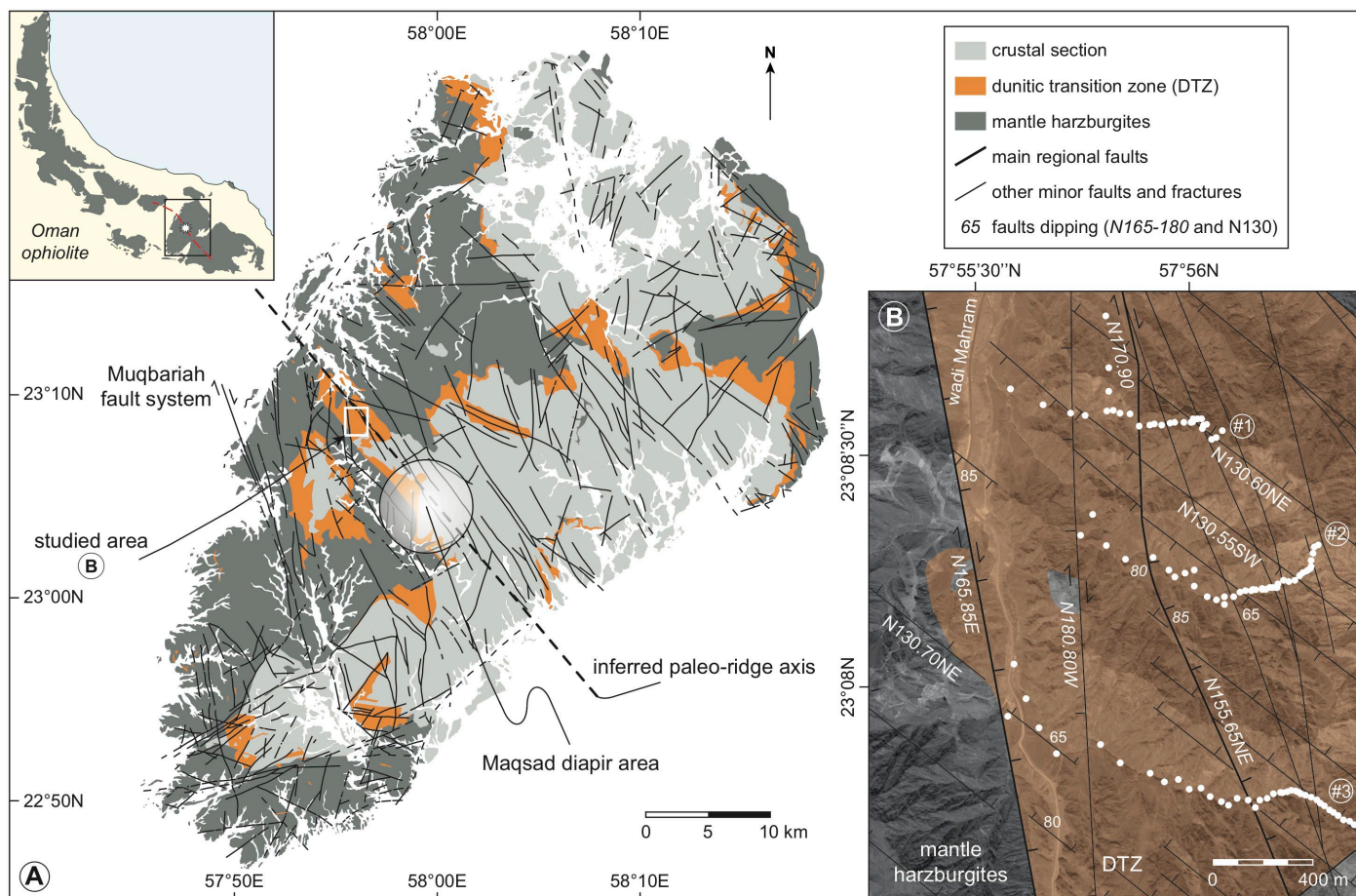


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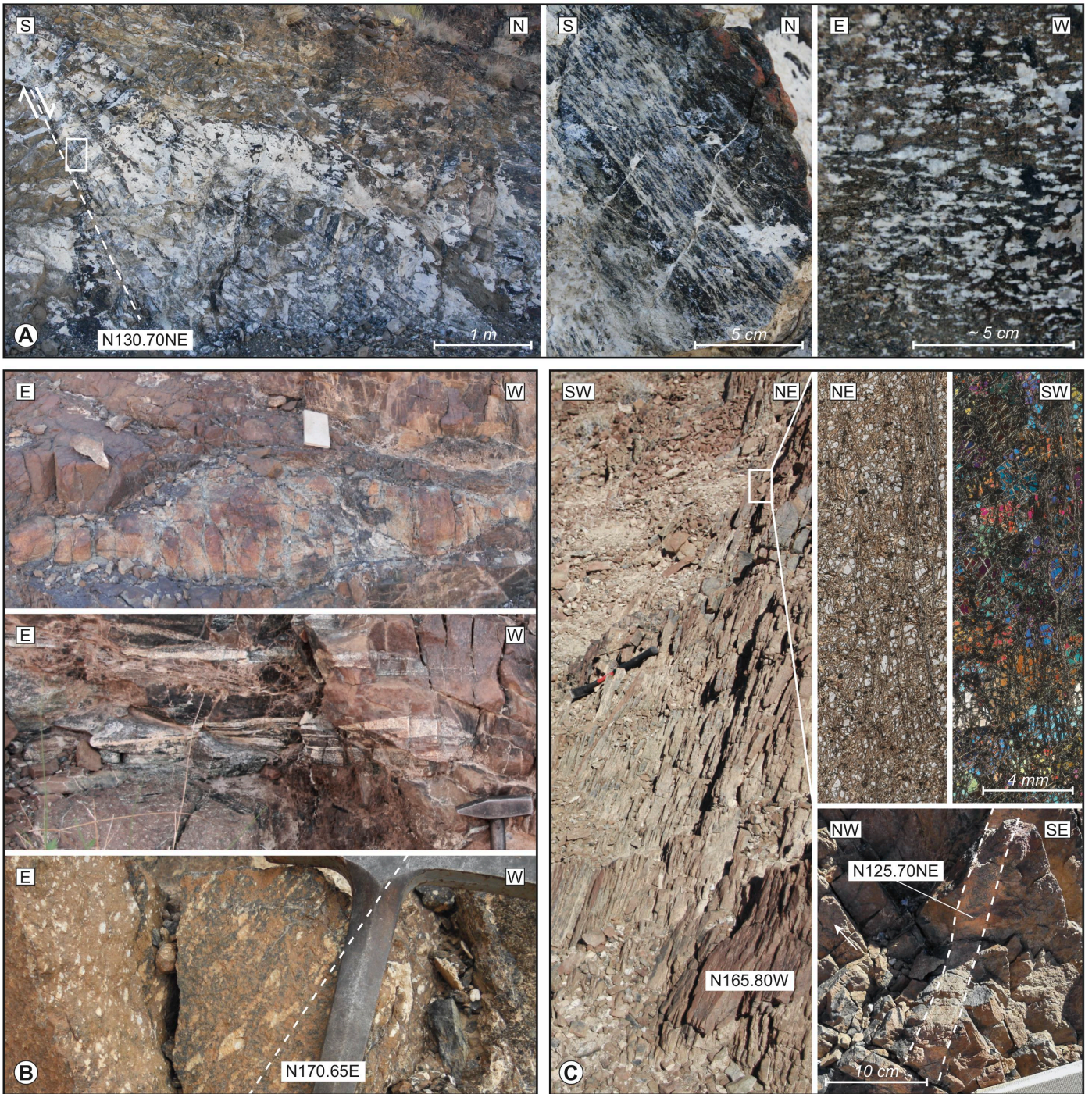


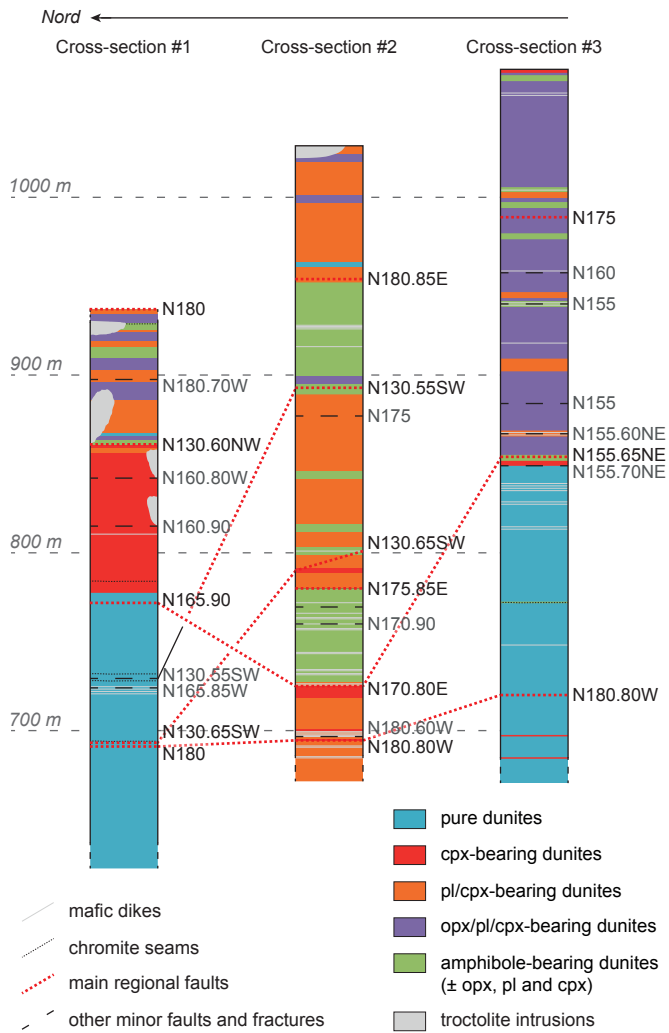
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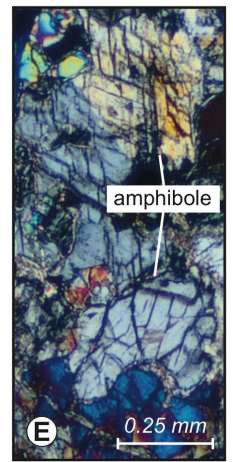
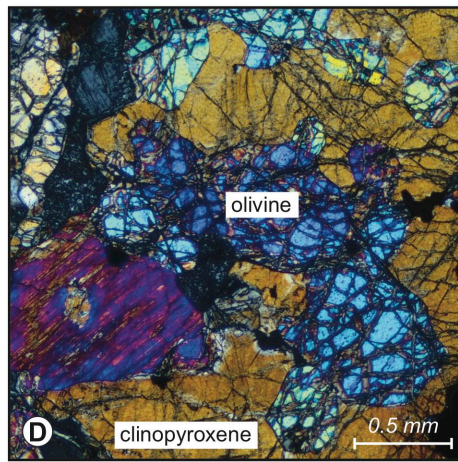
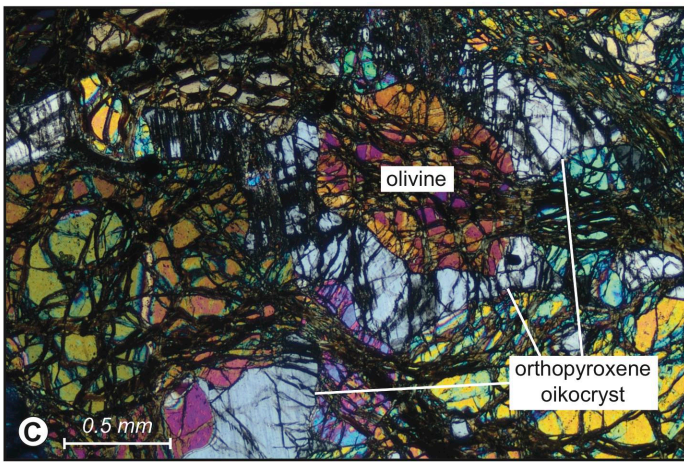
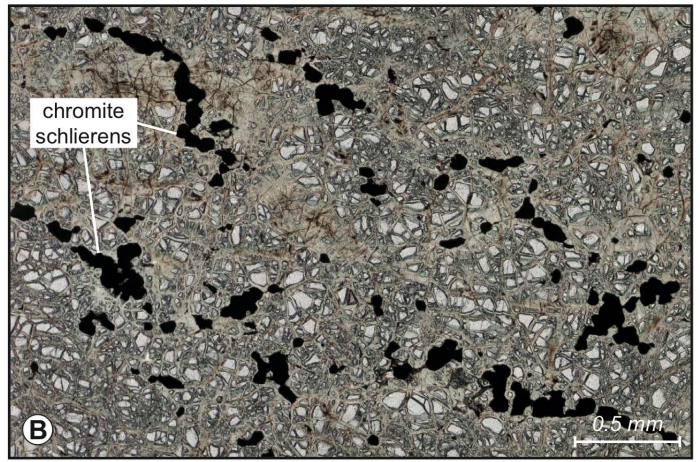
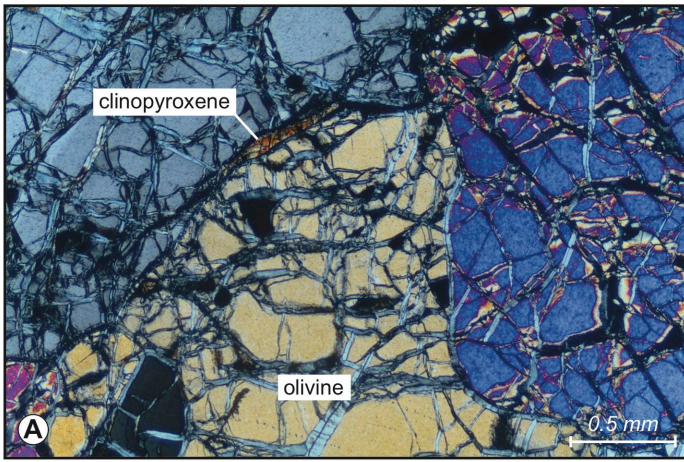


Figure 5
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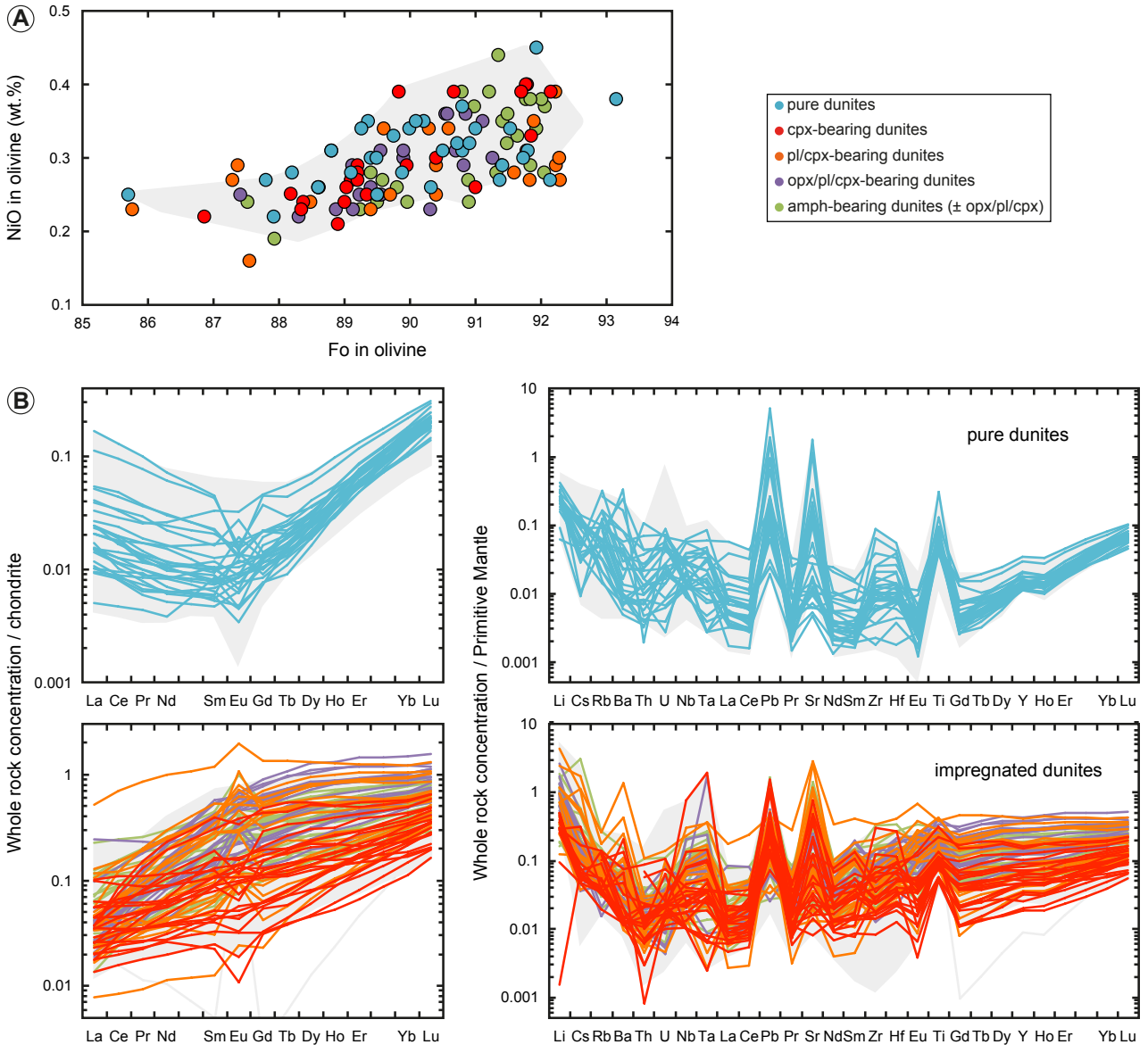


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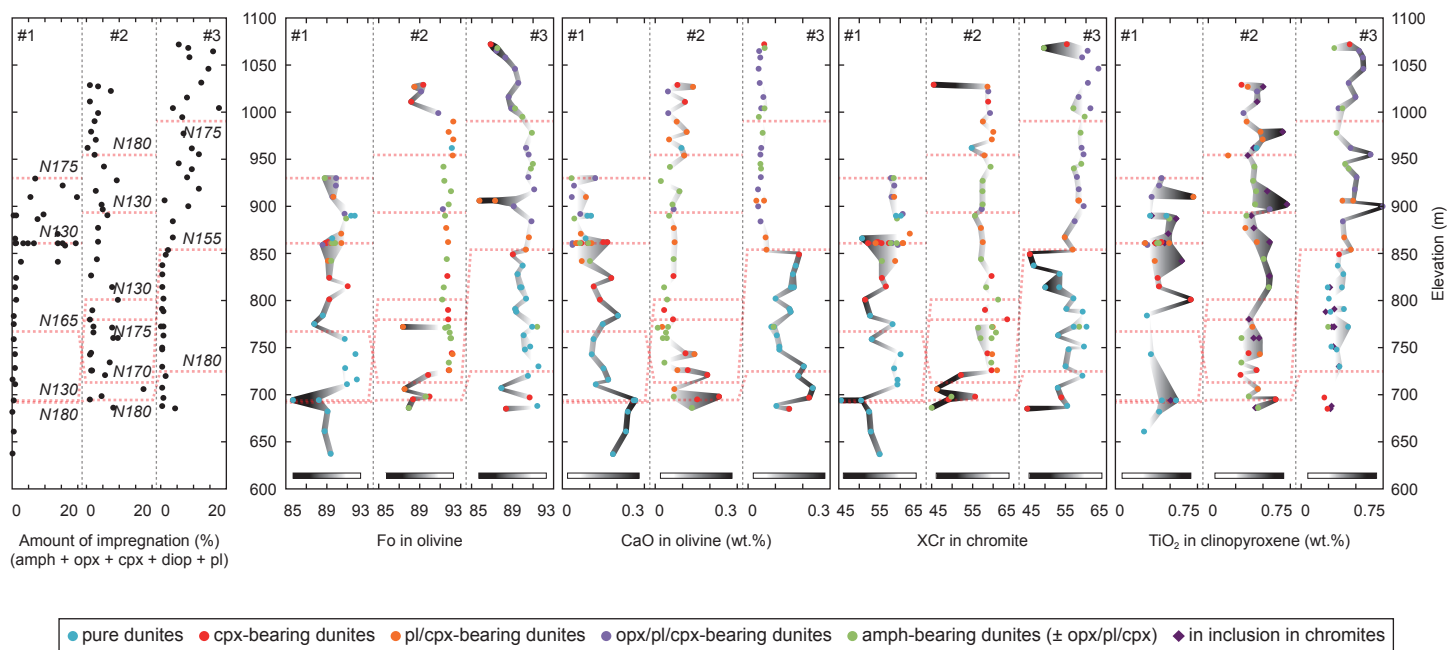
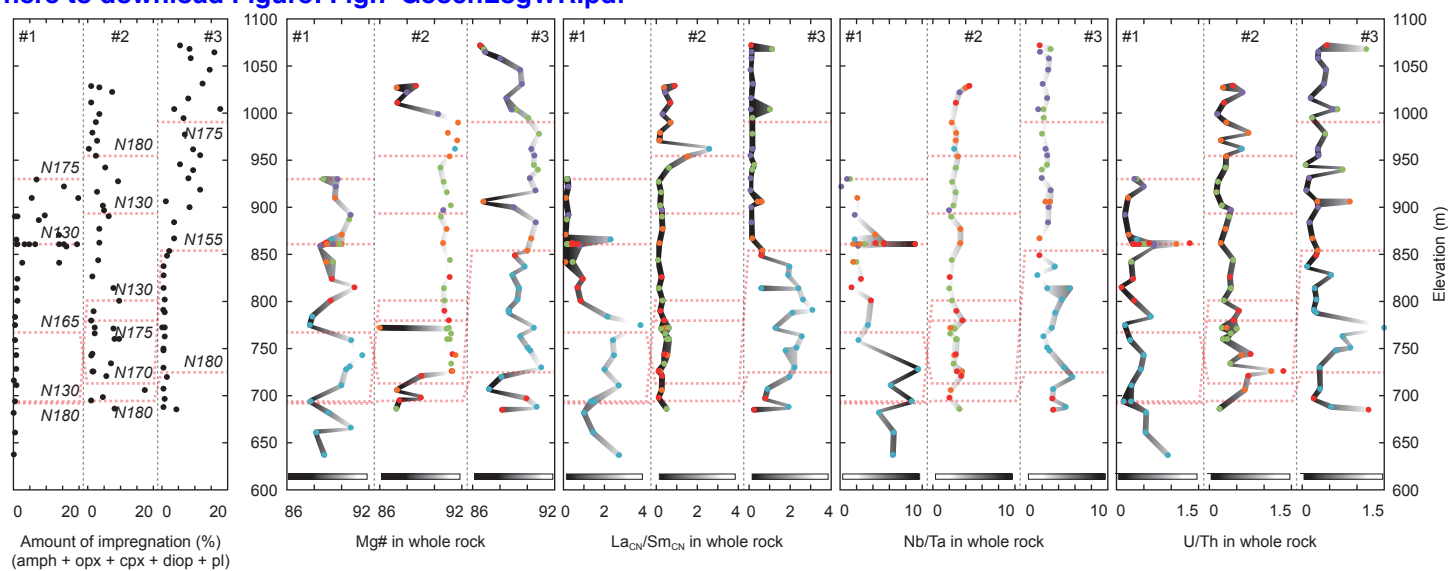


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● pure dunites ● cpx-bearing dunites ● pl/cpx-bearing dunites ● opx/pl/cpx-bearing dunites ● amph-bearing dunites (\pm opx/pl/cpx)

Figure 8

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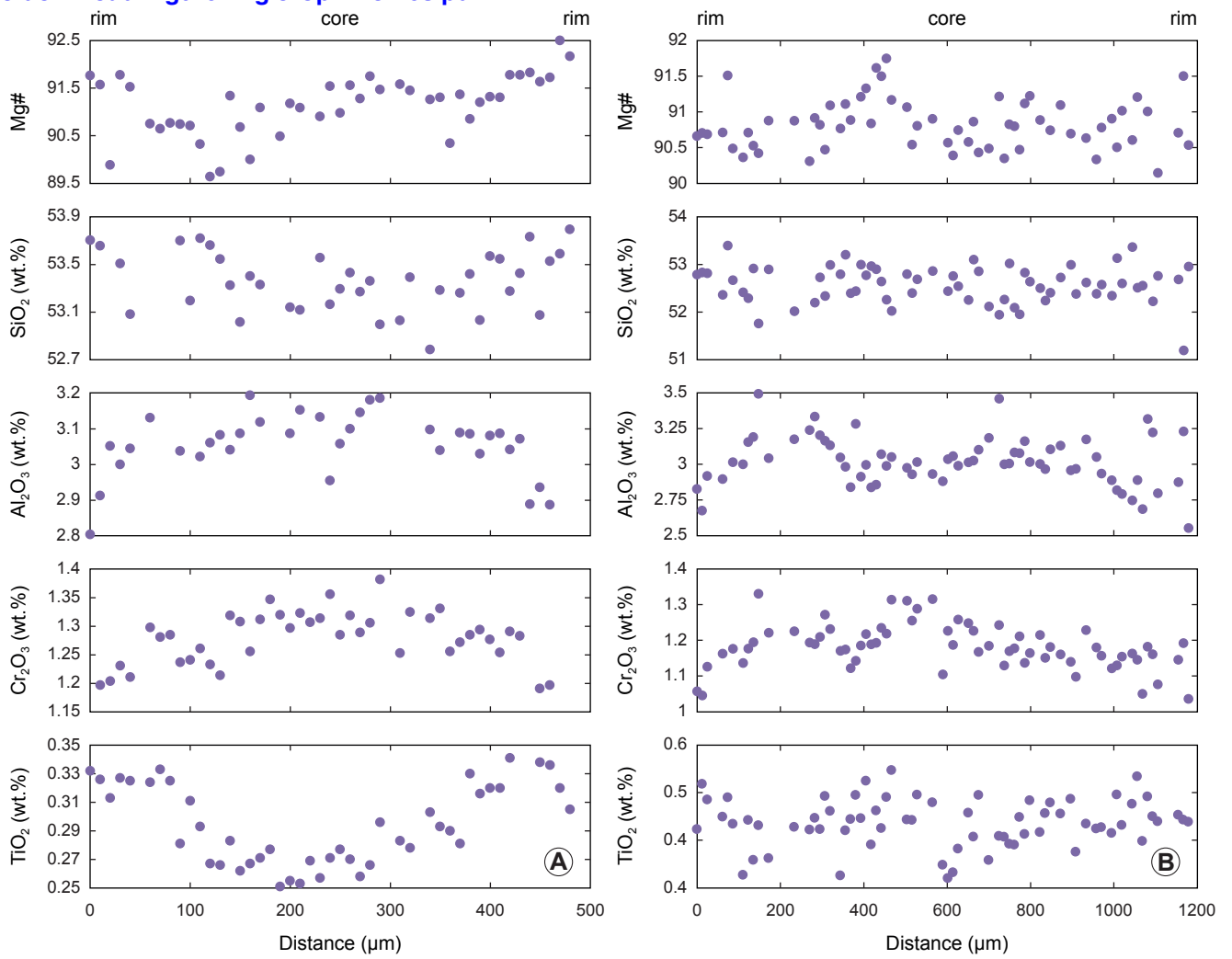


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