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1 **Ocean crust accretion along a high-temperature detachment fault in the Oman**
2 **ophiolite: a structural and petrological study of the Bahla massif.**

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12
13 **Abstract**

14 The Bahla massif exposes the lower crustal section of the Oman ophiolite located close to
15 the thrust front of the Semail nappe. It is affected by intense faulting previously attributed to
16 tectonic events that dismembered a classical ophiolitic sequence during or after the obduction.
17 Here we show that most of this complexity is primary, inherited from syn-accretion tectonics.
18 The crustal section is exposed in a 15 by 8 km tectonic enclave surrounded by mantle peridotite.
19 Its northern boundary corresponds to a major, steeply dipping normal fault striking WNW-ESE,
20 at low angle to the paleo-ridge axis. Movement along this fault was accommodated by intense
21 plastic deformation of the crustal cumulates and adjacent mantle peridotites at temperature
22 conditions $\geq 900^\circ\text{C}$. The thickness of the deformed zone reaches several hundred meters. The
23 flattening of the cumulate layering away from the fault is correlated to a decrease in the
24 deformation intensity. Undeformed olivine-gabbro dykes cross-cut this “tectonic Moho”
25 indicating that the tilting occurred before the end of the igneous activity. To the southwest, the
26 crustal enclave is bounded by a NW-SE trending transtentional shear zone that was active in
27 the amphibolite to greenschist facies and was intensely injected by syn- to post-kinematic
28 gabbro and tonalite/trondhjemite dykes and plugs. The age of one felsic sample (95.214
29 ± 0.032 Ma, high-precision U-Pb zircon dating) is within error of the age of intrusive felsic
30 intrusions into the mantle and lowermost axial crust from the length of the Oman ophiolite,
31 which slightly post-dates the mean crystallization age of the Semail crust (V1 magmatism;

32 96.1–95.6 Ma). Other contacts are low temperature features including cataclastic faults,
33 serpentine-carbonate breccias and flat-lying décollements.

34 Parent melts of the Bahla crustal cumulates were more siliceous and hydrous, i.e. more
35 andesitic, than typical mid-ocean ridge basalt (MORB) as deduced from the frequent occurrence
36 of early crystallizing orthopyroxene (opx) and late crystallizing amphibole. Some facies such
37 as cumulate harzburgite and opx-troctolite have not been documented elsewhere in the Oman
38 ophiolite and may be specific to the tectonic context in which the frontal massifs accreted. The
39 chemical composition of the lower crustal cumulates can be accounted for by the hybridization
40 in various proportions between MORB and a primitive andesite from a depleted source whose
41 origin can be looked for in melts from a nascent subduction zone or from high temperature
42 hydrothermal processes.

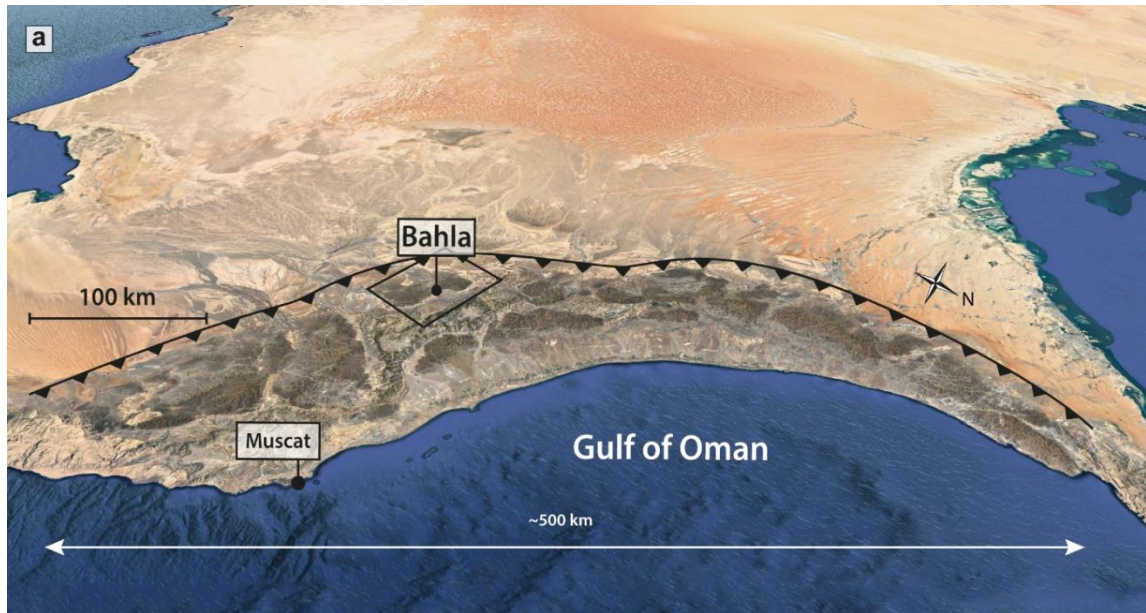
43 The structure of the Bahla lower crustal section is reminiscent of the plutonic growth faults
44 documented along present-day slow-spreading centres in both mid-ocean ridge and back arc
45 settings. The distinctive characteristics of the Moho and lower crustal section in the Bahla
46 massif are tentatively related to their position at the leading edge of the ophiolite, i.e. closer to
47 the Arabian continental margin at the time of accretion than the massifs from the internal part
48 of the ophiolite that have a more continuous and less deformed lower crust. It indicates that the
49 style of crustal accretion may have changed during the opening of the oceanic basin from which
50 the Oman ophiolite issued.

51 Keywords: Oman; ophiolite; oceanic crust; detachment faults; plutonic growth faults.

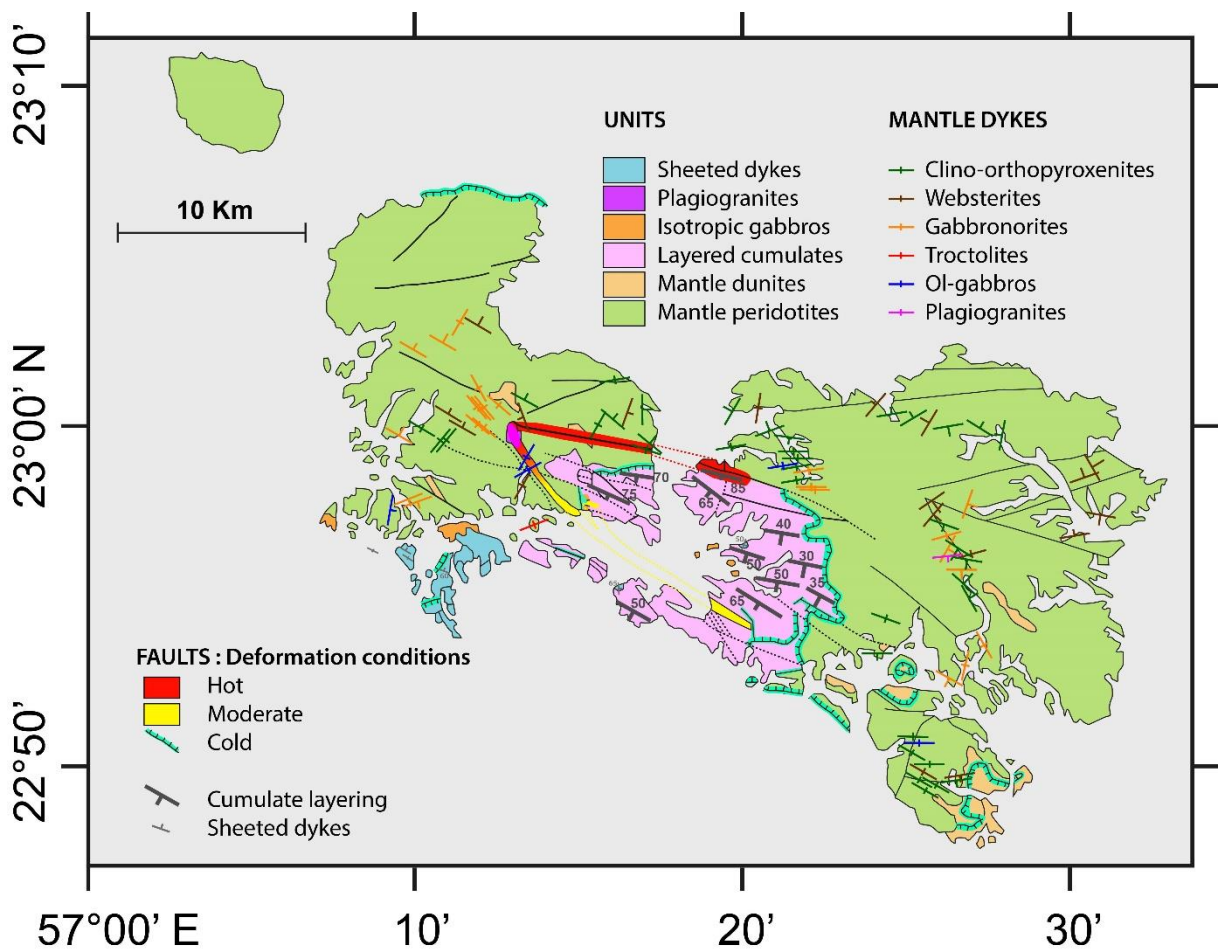
52 1. Introduction

53 The Semail ophiolite (Oman and UAE) is an upper Cretaceous remnant of the vanished
54 Tethys Ocean (Ricou, 1971; Glennie et al., 1973). It is widely considered as a fossil analog of
55 oceanic spreading centres, although its tectonic setting (mid-ocean ridge *vs.* subduction related)
56 is still debated. Our understanding of the structure and dynamics of axial magma chambers has
57 been largely nurtured by observations in its plutonic section. Surprisingly, a glance to the
58 literature reveals that the petrologic nature of this unit has been determined in a limited number
59 of spots. A bias clearly exists in favor of exposures of continuous and un-faulted sections of
60 layered cumulates. More specifically, the plutonic section remains largely unexplored where it
61 is adjacent to the thrust front of the Semail nappe. The complex structures observed there were
62 interpreted in geological maps as an imprint of thin-skin tectonics related to the obduction or

63 more recent events (Wyns et al., 1992; Béchenec et al., 1992). This situation looked
 64 unattractive to the petrologists interested by oceanic spreading centers processes. The present
 65 paper is devoted to the first combined structural, petrological and geochemical study of one of
 66 these frontal massifs, cropping out around the city of Bahla (Fig. 1a).



67



68

69 Fig. 1. (a) Location of the Bahla massif on a Google Earth image of the Northern Oman Mountains. The
70 approximate position of the thrust front of the ophiolite is shown by the black line with triangles. The
71 scale is indicative and valid only for the foreground of the image due to the oblique view. (b) Geological
72 map of the Bahla massif modified after Wyns et al. (1992) and Béchennec et al. (1992). The orientation
73 of the layering (averaged per site) is shown as grey symbols.

74

75 During the course of a systematic survey of the lower crustal cumulates of Oman, we
76 observed, in the Bahla massif, very high temperature deformation structures along the mantle-
77 crust boundary. Simple field and petrographic arguments allowed us to discard a late origin of
78 these features which left the door open to two main avenues of interpretations: (1) the imprint
79 of early intra-oceanic thrusting (that can be viewed as nascent subduction) in a near ridge
80 environment (cf. Boudier et al., 1988); (2) the trace of syn-accretion faults reminiscent of those
81 observed along present-day oceanic spreading centers (e.g. Blackman et al., 1998; Dick et al.,
82 2008; Ildfonse et al., 2007; Escartin et al., 2008; Harigane et al., 2011; Sauter et al., 2021).
83 Here we present structural evidence allowing us to decipher between these two hypotheses. We
84 also show that high temperature deformation may interfere with the petrological evolution of
85 the lower crustal cumulates of Oman and account for some of their puzzling characteristics.

86 2. Tectonic setting of the Oman ophiolite: an open question

87 The Oman ophiolite is one of the largest fragment of oceanic lithosphere exposed on land.
88 It is particularly well preserved because it is not yet affected by continental collision between
89 Arabia and Eurasia (e.g. Coleman, 1981). Igneous accretion of the ophiolite occurred in a
90 narrow time lapse (96.1 to 95.6 Ma, Rioux et al., 2013, 2021a). This event was largely
91 synchronous with the intra-oceanic thrusting of the future ophiolite. This is attested by the
92 overlap between the accretion age and the age of the metamorphic sole (Rioux et al., 2016) and
93 by structural and petrological evidence for the existence of segments of the spreading center
94 itself preserved within the ophiolite (Ceuleneer, 1991; Ceuleneer et al., 1988, 1996; MacLeod
95 and Rothery, 1992; Python and Ceuleneer, 2003). The thrusting of the oceanic lithosphere on
96 the continental margin was completed during Maestrichtian times (~70 m.y. ago) (Glennie et
97 al., 1973). Continental subduction preceded this event as witnessed by the high-pressure
98 metamorphism that affected the northeastern tip of the Oman margin ~80 m.y. ago (Goffé et
99 al., 1988; Warren et al., 2003; Gray et al., 2004, 2005; Searle et al., 2004; Yamato et al., 2007).

100 The tectonic setting (subduction-related basins vs. more open ocean ridge segments) during
101 the igneous accretion of the Oman ophiolite is a long-standing debate (e.g. Coleman, 1981;

102 Pallister and Hopson, 1981; Hopson et al., 1981; Pearce et al., 1981; Searle et al., 2004; Gray
103 et al., 2005; Ishikawa et al., 2005; Boudier and Nicolas, 2007; Warren et al., 2007, MacLeod et
104 al., 2013; Belgrano and Diamond, 2019; De Graaf et al., 2019; Agard et al., 2020). Plate tectonic
105 reconstructions, imprecise during the Cretaceous normal magnetic superchron, are of little help
106 to solve this specific problem (Granot et al., 2012). The extrusive section of the ophiolite
107 includes lavas with MORB and depleted andesitic affinities (Alabaster et al., 1982; Pearce et
108 al., 1981). Ernewein et al. (1988) introduced the notion of V1 and V2 episodes to refer
109 respectively to these two igneous series, assuming that MORB lavas are overlain by the
110 depleted andesitic lava flows, although the correlation between the geochemical signature and
111 the stratigraphic position of the lavas is not perfect (Einaudi et al., 2003; Belgrano and
112 Diamond, 2019). A similar petrological dichotomy between a MORB and a depleted andesitic
113 kindred was also found in the mantle dykes, former feeding channels of the crustal section
114 (Benoit et al., 1999; Python and Ceuleneer, 2003; Python et al., 2008) and in the layered crustal
115 cumulates themselves (Smewing, 1981; Juteau et al., 1988; Yamasaki et al., 2006; Adachi and
116 Miyashita, 2003; Clénet et al., 2010). The existence, if any, of a relative chronology (i.e. “P1
117 vs. P2”) for the emplacement and crystallization of the two plutonic series is difficult to
118 determine at the global scale, authors working on different outcrops and different lithologies
119 reaching contrasted conclusions (e.g. Benoit et al., 1999; Python and Ceuleneer, 2003; Haase
120 et al., 2016; Goodenough et al., 2014; Rospabé et al., 2017; De Graaf et al., 2019).

121 The spreading rate at the time of the igneous accretion of the Oman ophiolite is another
122 open question. This parameter is largely unconstrained. Even if the context was clearly the one
123 of high melt supply to the crust, this does not necessarily imply a high spreading rate. Structural
124 evidence like mantle flow pattern (Ceuleneer et al., 1988), the existence of a layered lower
125 crustal section and of a well-developed sheeted dyke complex (Hopson et al., 1981; Pallister
126 and Hopson, 1981; Pallister, 1981) are not definitive arguments. Recently published high
127 precision ages on plagiogranites and evolved oxide gabbro from the Wadi Tayin massif tend to
128 support fast ($\geq 5 \text{ cm.y}^{-1}$) spreading rates during the accretion of this massif located in the internal
129 and southeastern part of the ophiolite (Rioux et al., 2012).

130 The wealth of data obtained on the Oman ophiolite during the last decades reveals its
131 heterogeneity and the complexity of its igneous history that may include assimilation of
132 peridotite and/or formerly crystallized crust (e.g. Benoit et al., 1999; Koepke et al., 2009; Rioux
133 et al., 2012; Abily and Ceuleneer, 2013; Rospabé et al., 2017, 2018), ridge propagation (e.g.
134 Andronicos et al., 2008), syn-magmatic faults (Abily et al., 2011; Rospabé et al., 2019) and

135 off-axis magmatism (Jousselin and Nicolas, 2000; Rioux et al., 2013). Clearly, this diversity
136 needs to be taken into account in the interpretation of the Oman ophiolite as a whole.

137 3. Methods

138 3.1. Electron microprobe

139 Major and minor element compositions of the main magmatic phases (olivine,
140 clinopyroxene, orthopyroxene, plagioclase) were determined using the electron microprobe
141 CAMECA SX50 at Toulouse University and CAMECA SX100 at Brest University. A standard
142 analysis program with an accelerating voltage of 15 kV and a beam current of 10 to 20 nA was
143 used. Counting time was 10 s on the peak and 5 s on the background. The detection limits were
144 similar for both instruments with values of ~0.07% for Al₂O₃ and Na₂O and ~0.09% for TiO₂
145 and Cr₂O₃ for all phases analyzed.

146 3.2. LA-ICP-MS

147 Concentrations of trace elements in cpx were determined by LA-ICP-MS, at the
148 Observatoire Midi-Pyrénées (Paul Sabatier University, Toulouse). This allowed in situ analysis
149 of Cpx in 120 μm thick polished sections. The Agilent 7500 ce ICPMS apparatus was coupled
150 to a Cetac LSX-200 laser ablation module with a 266 nm frequency-quadrupled Nd-YAG laser.
151 The NIST 610 glass was used as the external standard while the NIST 612 glass was used as a
152 reference material to control the quality of measurements. Each analysis was normalized using
153 CaO values determined by electron microprobe. A beam diameter of 50-100 μm, a frequency
154 of 10 Hz and a scanning rate of 20 mm/s were used. The theoretical detection limits were
155 between 10 and 20 ppb for rare earth elements (REE), Ba, Th, U, Zr and 2 ppm for Ti. The
156 relative precision and accuracy for a laser analysis ranges from 1 to 10%. The data reduction
157 was carried out with the Glitter software (Griffin, 2008).

158 3.3. Electron Backscatter Diffraction (EBSD).

159
160 EBSD analyses have been performed on 5 samples where olivine, pyroxenes and
161 plagioclase have been analyzed. Before analyses, a mechanic-chemical polishing using a
162 Vibromet was applied for 1 h15 with a colloidal silica suspension (pH 10) to remove
163 mechanically-induced surface damage. The EBSD camera HKL Advanced Nordlys Nano
164 from Oxford Instruments is attached to a JEOL 7100 electronic microscope, located at the
165 microcharacterization centre Raimond Castaing, University Paul Sabatier, Toulouse, France.

166 The microscope working conditions include an acceleration voltage of 20 kV, a probe current
167 of 16 nA, with a stage tilt of 70°, a working distance of 16-17 mm and camera settings are
168 4x4 binning and low (0) gain. Automatic indexing was performed using AZTec software
169 (version 3.5) from Oxford Instruments, with different step size (15, 20 or 25 µm) according to
170 the grain size. Data were processed using Channel 5 package. Measurements with a mean
171 angular deviation (MAD) greater than 1.3 were removed, and grains were then calculated by
172 imposing an orientation difference smaller than 10° for any two neighboring measurements
173 belong to the same grain. Grains with a surface smaller than 10 pixels were removed to avoid
174 bias caused by potential indexing error. The maps were compared with band contrast maps to
175 ensure that the treatment did not compromise the data. The multiple uniform density (mud)
176 and the J-index, which is the measure of the fabric strength (Bunge, 1982) are reported on
177 figure 8.

178

179 4. Results

180 4.1. Structure of the Bahla massif

181 4.1.1. General structure

182 The more complete information on the general structure of the Bahla massif are reported
183 in the geological maps of the area (Wyns et al., 1992; Béchenec et al., 1992) and in the
184 synthetic maps of the high temperature structural features of the Oman ophiolite (Nicolas et al.,
185 2000). The Bahla massif is a 45 km long and 15 km wide ellipsoidal body elongated along a
186 WNW-ESE direction parallel to the local strike of the paleo-spreading ridge axis (MacLeod
187 and Rothery, 1992) (Fig. 1b). The mantle section represents the main part of the massif; it is
188 made essentially of harzburgites presenting the typical imprint of high temperature plastic flow
189 acquired at “asthenospheric” conditions (Ceuleneer et al., 1988; Nicolas et al., 1988), with
190 locally abundant dunitic and pyroxenite bands. These rocks are cut by dykes filled mostly with
191 pyroxenitic and gabbro-noritic assemblages, with rare troctolites, gabbros, diorites and
192 trondhjemites (Python and Ceuleneer, 2003).

193 The crustal section represents only one fifth of the massif area and crops out essentially in
194 its central part. The lower crust adopts the shape of a 15 km long and 8 km wide ellipse whose
195 long axis is parallel to the general elongation of the massif (Fig. 1b). To the North, West and
196 East, it is surrounded by mantle peridotites. The upper crust, including the base of the sheeted

207 dyke complex, is exposed as small scattered outcrops emerging from quaternary deposits in the
208 southern part of the massif. In geological maps some outcrops of this area are reported as mantle
209 peridotites; they are mostly ultramafic cumulates (olivine cumulates with poikilitic pyroxenes)
210 cut by diabase dykes generally striking N120°E and dipping 60° - 70° to the NE.

211 The map pattern summarized above is not an expression of topography alone. The crustal
212 section of Bahla is actually a tectonic enclave in a mantle host and not the un-eroded remnant
213 of a formerly continuous crustal layer overlying the mantle section, which is the most common
214 situation in other massifs of the Oman ophiolite. This structural specificity of the Bahla massif
215 is primarily attributable to tectonics. Here below is a description of the contrasting tectonic
216 styles we observed along these faulted mantle-crust contacts.

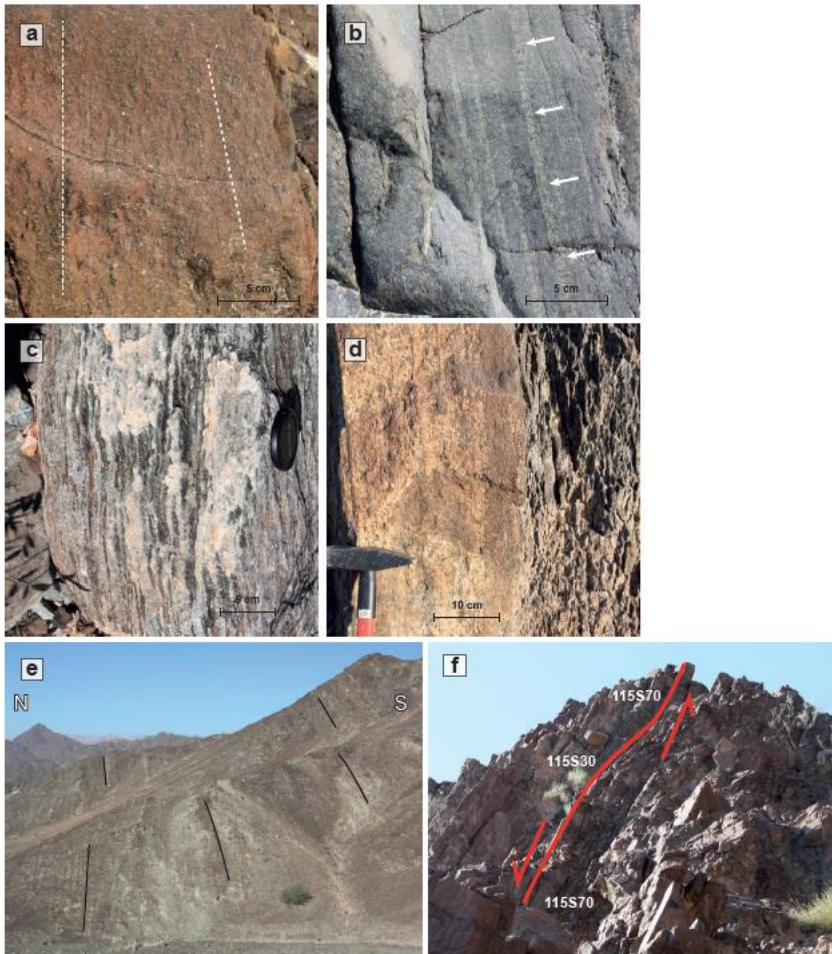
217 4.1.2. The northern contact

218 Along the northern mantle-crust boundary, the igneous textures of the layered cumulates
219 are intensely overprinted by plastic deformation. There, the mantle-crust boundary (we will call
220 the “Moho” for the sake of simplicity) is actually part of a WNW-ESE-trending sub-vertical
221 ductile shear zone (in red on Fig. 1b) penetrating to the West and to the East in the mantle
222 section. Its lateral extent reaches 15 km, being interrupted by lower temperature faults described
223 below (§4.1.3 and §4.1.4). It affects the mantle peridotites and the lower crustal cumulates on
224 both sides of the Moho on a thickness exceeding 1 km.

225 The mantle peridotites have a porphyroclastic texture and are highly foliated (Fig. 2a). This
226 intense deformation is underlined by transposed pyroxenite bands (Fig. 2b). On the crustal side,
227 mafic cumulates are intensely deformed too; they display flaser and gneissic textures (Fig. 2c)
228 with local development of a spectacular tectonic banding enhanced by centimetre-thick white
229 bands of anorthosite (Fig. 2d).

230 The primary igneous mineral assemblage is generally not modified, although locally, we
231 observe the development of hornblende rims around pyroxene porphyroclasts. The deformed
232 cumulates have medium-grained equigranular granoblastic textures with sutured grain
233 boundaries diagnostic of efficient diffusion enhancing grain boundary migration. Intra-
234 crystalline features like undulose extinction, bending and mechanical twins are present but are
235 not common, which is diagnostic of efficient recovery, and thus of high-temperature making
236 possible sub-solidus diffusion.

Fig 2



227

228 Fig. 2. Structures along the northern mantle-crust boundary affected by a high temperature normal
229 ductile shear zone. (a) Foliation in the porphyroclastic-submylonitic peridotite; (b) Highly stretched
230 pyroxenite banding in the mantle peridotite, the dashed lines showing vertical foliation planes; (c)
231 Gneissic structures in olivine gabbros from the lower crustal section, white bands rich in plagioclase
232 alternating with dark bands rich in olivine and pyroxene (N22°58'14", E57°20'10"); (d) Foliation in
233 deformed gabbroic (left) and ultramafic cumulates (right), underlined by a schistose parting in the
234 ultramafic interval (N22°58'52", E57°18'32"); (e) Progressive flattening of the cumulate layering to the
235 south, away from the mantle-crust boundary located a few hundred meters to the left of the photograph;
236 (f) Field evidence for a normal fault shear sense in the deformed lower crustal cumulates (N22°58'14",
237 E57°20'10").

238

239 The evolution of the intensity of the plastic deformation experienced by the lower crustal
240 cumulates is correlated with the dip of the layering which is sub-vertical (90°-80°S) along the
241 Moho, and tends to progressively flatten when moving south (Fig. 2e). The stretching lineation
242 is well developed and has a sub-vertical pitch (70° - 80°W to 80°E). The shear sense is normal
243 (down the dip), as revealed by macro-structural observations on the field (Fig. 2f) and

244 confirmed by a micro-structural study including lattice preferred orientation analysis (see
245 section on EBSD data).

246 Along rare later shear zones parallel to the high temperature foliations, the deformed
247 cumulates are partly transformed into greenschist facies minerals (epidote, chlorite, serpentine,
248 and hydrogarnets associated with rodingitisation, pointing to temperatures comprised between
249 200°C and 400°C (Bach and Klein, 2007; Python et al., 2011).

250 4.1.3. The southwestern contact

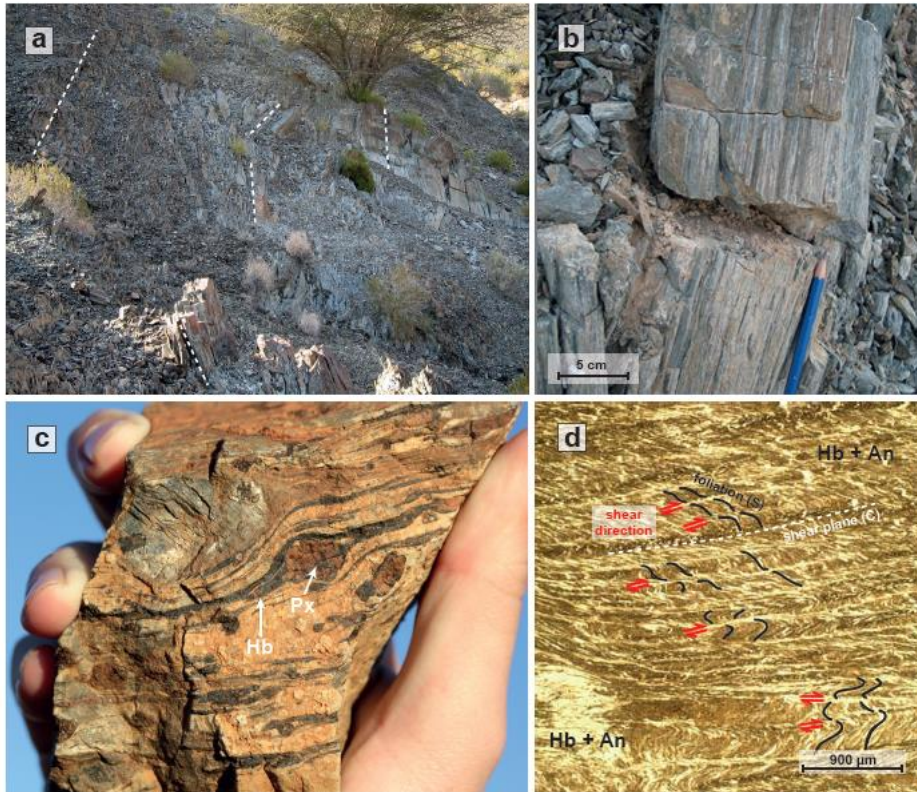
251 The southwestern border of the lower crustal section is affected by a major strike slip
252 mylonitic shear zone a few tens of meters in thickness (Fig. 3a). It has a minimum extent of 20
253 km along strike (in yellow on Fig. 1b), its central part being hidden by the quaternary deposits
254 of wadi Bahla. This shear zone presents a slight but well-defined curvature, its strike rotating
255 from NW-SE to WNW-ESE when moving from the NW to the SE. The mylonitic foliation is
256 steeply dipping to the NE. The shear sense is essentially dextral. The stretching lineation, which
257 is underlined by a well-developed pencil structure (Fig. 3b), has a moderate dip (20°-50° to the
258 SE) pointing to a normal component to the movement.

259 A metamorphic gradient is observed along the strike of this shear zone, ranging from
260 granulite-amphibolite facies at its intersection with the northern fault, at mantle depths, to
261 greenschist facies when moving upsection to the SE. Along the northwestern part of the shear
262 zone, the mantle peridotites are injected by gabbro-noritic dykes that can represent 50% of the
263 outcrop surface. Most dykes are deformed and adopt a flaser texture (Fig. 3c). Roundish
264 porphyroclasts (0.1-1cm) of orthopyroxene (opx), clinopyroxene (cpx) and plagioclase (plg)
265 are partly to completely recrystallized into a fine-grained matrix (<100 microns) with a mosaic
266 texture. Brown amphibole is abundant in the recrystallized tails around the pyroxene
267 porphyroclasts (Fig. 3c).

268 At the intersection between the northern normal fault and this shear zone, two generations
269 of foliation and lineation can be measured: a ~135N50 foliation associated with a gently dipping
270 lineation and a ~160SW70 one associated with a sub-vertical lineation. These rocks seem to
271 have recorded the deformation of both the northern normal fault and of the southwestern shear
272 zone. The detailed cross-cutting relationships between the EW fault and the NW-SE fault are
273 obscured by felsic intrusions and quaternary deposits but it is clear that the EW fault cannot be

274 followed to the W of the NW-SE fault and that, at the contrary, the NW-SE fault persists to the
275 north beyond the EW fault.

Fig 3



276

277 Fig. 3. Structures along the southwestern mantle-crust boundary affected by a mylonitic shear zone. (a)
278 General view, schistose parting and deformation orientation at local scale are highlighted by the white
279 dashed lines; (b) Detail on gabbro deformed and metamorphosed in the greenschist facies showing the
280 linear habit of the deformation (N22°59'14\", E57°13'37\"); (c) Deformed gabbro-norite dyke showing a
281 flaser structure with hornblende (Hb) recrystallization tails around pyroxene (Px) porphyroclasts; (d)
282 Crenulations in the same gabbros (thin section in transmitted light, uncrossed Nicols), An: anorthite
283 plagioclase, Hb: hornblende (N22°57'36\", E57°15'07\").

284

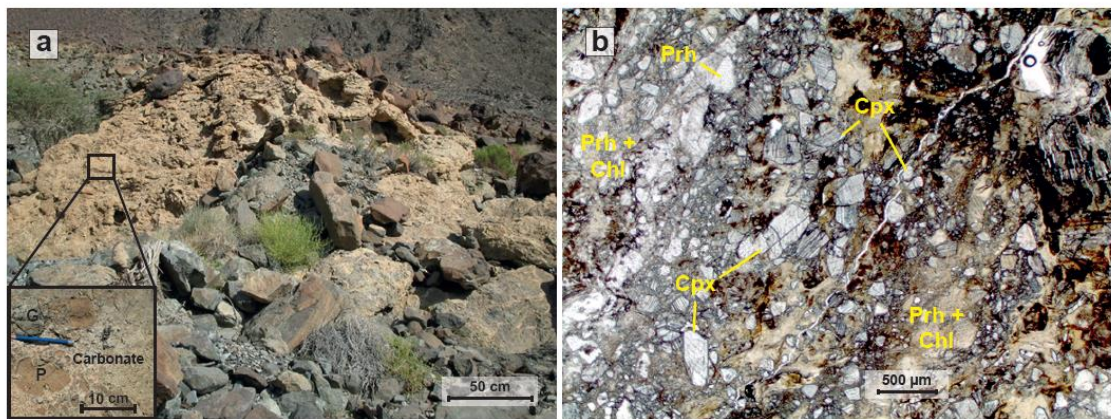
285 Moving to the SE, the gabbros are still intensely deformed into mylonites and
286 ultramylonites. Structures include extreme stretching, sheath folds and crenulation cleavages
287 (Fig. 3d). Mylonitized gabbros transformed into plagioclase + hornblende are still present but
288 the assemblage chlorite + actinolite + tremolite typical of the greenschist metamorphic facies
289 becomes the more common. Porphyroclasts preserve intense intracrystalline deformation
290 (undulose extinction, bending and rotation associated with strain shadows, C/S shear bands).
291 The transition with the undeformed rocks is gradational. At its eastern termination, deformation
292 is partitioned into a swarm of thin cataclastic shear zones.

293 All along the shear zone, the high-temperature metamorphic mineral assemblages show a
294 variable overprint of greenschist facies metamorphism with coronas of actinolite-tremolite
295 around pyroxenes and recrystallization into tremolite, actinolite, chlorite, epidote, zeolite,
296 prehnite, serpentine, talc and/or carbonate. Late veins of zeolite, carbonate, chlorite and
297 serpentine commonly cut the mylonites.

298 4.1.4. The eastern contact

299 The contact between the mantle and the crustal section in the eastern part of the massif
300 corresponds to a brecciated zone oriented NNW-SSE (in blue on Fig. 1b). Textures are
301 cataclastic with large angular clasts of peridotite and gabbros embedded in a matrix essentially
302 made of carbonate, serpentine, chlorite and prehnite (Fig. 4a and b).

Fig 4



303

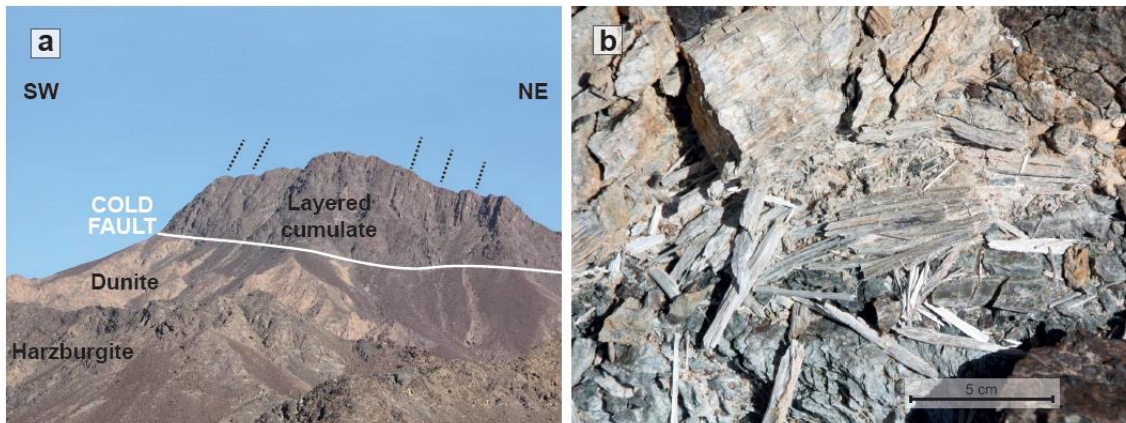
304 Fig. 4. Breccia with gabbroic clasts embedded in a carbonate-prehnite matrix typical of the eastern
305 mantle-crust boundary (N22°54'53", E57°22'09"). (a) General view, G: gabbroic clast, P: peridotite
306 clast; (b) thin section view (in transmitted light, uncrossed Nicols), Chl: chlorite, Cpx: clinopyroxene,
307 Prh: prehnite.

308

309 4.1.5. Flat-lying décollements

310 In the central part of the massif, not far from the city of Bahla, the mantle peridotites are
311 overlain by a cap of layered gabbros presenting the same intense plastic deformation and the
312 same sub-vertical orientation as the ones cropping out along the northern contact (Fig. 5a). The
313 Moho at this site actually corresponds to a knife-cut sub-horizontal décollement gently dipping
314 to the East (15°E). It is filled with fibrous chrysotile (Fig. 5b) and striated surfaces of
315 carbonates.

Fig 5



316

317 Fig. 5. Décollement (sub-horizontal “cold fault”) at the mantle-crust boundary in the central part of the
318 massif (N22°57'42”, E57°15'32”). Note the highly dipping (southward, dashed lines) deformed layered
319 gabbros at high angle to the faulted contact with the underlying transition zone dunites. (a) General
320 view; (b) Asbestos formation in the décollement.

321

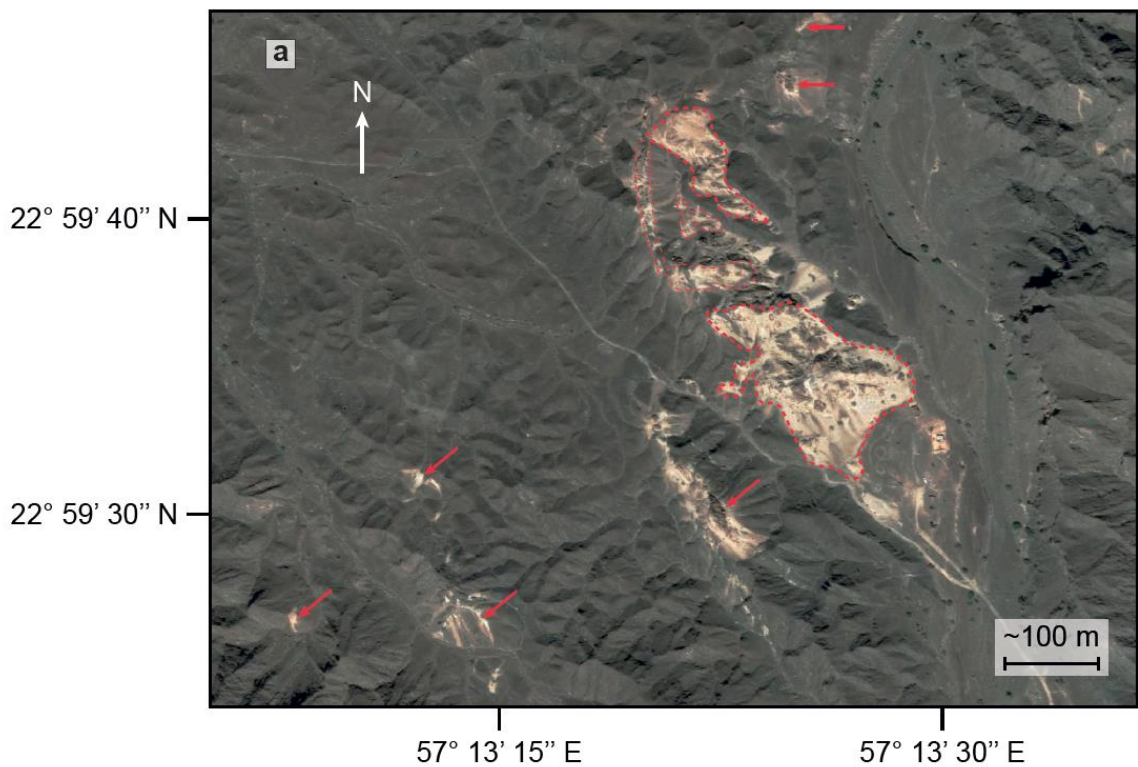
322 4.2 Magmatic intrusions

323 4.2.1. Plagiogranite plugs and dykes

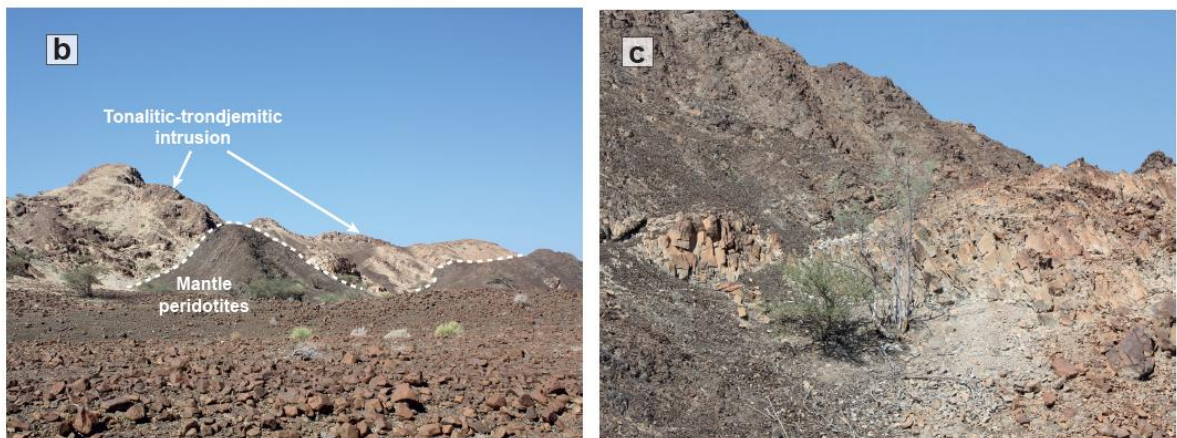
324 A few tonalite and trondhjemitic intrusions elongated along the NNW-SSE direction and
325 up to several hundred meters in length intrude mantle harzburgites close to the intersection
326 between the northern normal fault and the southwestern shear zone (Figs. 1b and 6a, b). They
327 are made of plagioclase, quartz, and rare micas, (altered into chlorite) and amphibole. They are
328 intensely sheared with the development of boudinage (Fig. 6c) and of gneissic textures along
329 their margins with the NNW-SSE mylonitic shear zone while the internal part of the intrusions
330 is undeformed (coarse grained texture with no apparent mineral preferred orientation). This
331 deformation gradient is correlated with a mineralogical evolution: the felsic intrusions are more
332 tonalitic (i.e. richer in ferromagnesian minerals), with calcic plagioclase (An60-80) at the
333 contact with mylonitic peridotites while they are purely trondhjemitic (i.e. almost devoid of
334 ferro-magnesian minerals) with albitic plagioclase (An < 30) in the internal part of the
335 intrusions. Trondhjemitic dykes up to one meter in thickness inject the peridotites hosting the
336 major intrusions; some of them are affected by boudinage (Fig. 6b). One sample of trondhjemitic
337 with a strong lineation from the intrusion pictured in figure 6a has been dated (U-Pb on zircon)
338 at 95.20114 ± 0.032 Ma (13211M02; Rioux et al., 2021a). This sample has an $\epsilon_{Nd}(t) = -4.86$
339 (Rioux et al., 2021b).

340

Fig 6



341



342

343 Fig. 6. Tonalitic-trondhjemitic intrusions (whitish outcrops) in mantle peridotite (brownish outcrops)
344 along the southwestern mylonitic shear zone. (a) Google Earth image showing the extent and the general
345 orientation (NW-SE to NNW-SSE) of these intrusions. The main outcrops of the largest intrusion are
346 highlighted by the red dashed lines, and smaller occurrences are shown by red arrows; (b) Outcrop view
347 on the main undeformed plug; (c) Deformed felsic dyke showing boudinage.

348

349

350 4.2.2. Post-tectonic olivine gabbro dykes

351 Along the northern contact, the deformed and tilted layered gabbros are intruded by a
352 swarm of undeformed, discordant dykes a few decimeters in thickness (Fig. 7). They have a
353 WNW-ESE direction and dip from 30° to 75° to the North, sharing a similar azimuth but having
354 a different dip than the southward dipping deformed layered gabbros. They lack of chilled
355 margins; some dykes show the development of coarse-grained margins (crescumulate textures).
356 They are fine-grained olivine-gabbros having the composition of moderately evolved
357 cumulates. Olivine has a Fo content ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}_{\text{total}})$) of about 77 mol% and a
358 NiO content around 0.20 wt%, clinopyroxene an average XMg ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}_{\text{total}})$)
359 of 83 mol% and average Cr₂O₃, Al₂O₃ and TiO₂ contents of 0.45 wt%, 2.4 wt% and 0.40 wt%
360 respectively, and plagioclase an average An content of 87 mol%. The assemblage contains also
361 minor amount of ferrichromite with an average XCr ($100 \times \text{molar Cr}/(\text{Cr} + \text{Al})$) of 55 mol%,
362 YFe³⁺ ($100 \times \text{molar Fe}^{3+}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$) of 43 mol% and an average TiO₂ content of 2.2 wt%.
363 No orthopyroxene or igneous amphibole are present in these olivine-gabbro dykes.

Fig 7



364

365 Fig. 7. Post-tectonic olivine gabbro dykes cross-cutting the deformed and tilted layered gabbros near the
366 northern ductile fault.

367

368 4.3. Petrography of the layered cumulates

369 Our exhaustive sampling (210 samples) of the Bahla deformed and undeformed layered
370 cumulates reveals an important lithological diversity in this unit. The layering of the crustal
371 section results from the alternation of layers centimetric to pluricentimetric in thickness with
372 different mineral proportions. The contrast between mafic and ultramafic layers is the more
373 spectacular in the field, but microscope observations reveal more subtle variations in the modal
374 content and textures. Following the classification of Irvine (1982) combining modal proportions
375 and, when preserved, textural criteria for the crystallization order, seven main lithological
376 groups can be defined in the layered cumulates of Bahla: troctolites, gabbros, opx-troctolites
377 and gabbroonorites for the mafic layers, dunites-wehrlites, clinopyroxenites and cumulate
378 harzburgites for the ultramafic intervals.

379 It is worth mentioning that the so-called “wehrlite *intrusions*” invading the layered
380 cumulates and present in most massifs of Oman (e.g. Juteau et al., 1988), are quite uncommon
381 in Bahla and are thus not included in the present study.

382 • The **troctolites** (6% of the samples) are essentially adcumulate to mesocumulate cpx-
383 troctolites; “pure” troctolites devoid of clinopyroxene (cpx) are uncommon. They essentially
384 consist of euhedral to subhedral plagioclase (plg), subhedral olivine and interstitial to poikilitic
385 cpx. The modal proportions are highly variable: the olivine content ranges from 5% to 70% and
386 the cpx content from 0% to 20%. The modal proportion of plagioclase varies accordingly. A
387 few troctolites also include traces ($\leq 1\%$) of interstitial orthopyroxene (opx) and/or magmatic
388 amphiboles. Chromian spinel is ubiquitous but generally not abundant ($\leq 1\%$), reaching
389 exceptionally 10%. Magnetite and sulfides can be present.

390 • The **gabbros** are the most common (61% of the samples) and principally consist of
391 olivine-gabbros with variable modal proportions. They have the same petrographic
392 characteristics and minor minerals as the troctolites, the difference between the two groups
393 being the higher modal abundance of cpx and its subhedral to interstitial habit in the gabbros.
394 Gabbros devoid of olivine (cpx and plg only) and anorthosites ($>90\%$ plg) do exist but are
395 uncommon.

396 • The **opx-troctolites** (Fig. 8a) (12% of the samples) are characterized by the
397 crystallization of opx and cpx slightly after plg and olivine. This is expressed by subhedral to

398 anhedral, sometimes poikilitic, pyroxenes (up to 37% of opx and 15% of cpx) associated with
399 euhedral to subhedral plg (24% - 87%) and subhedral olivine (5% - 49%). They have ad- to
400 orthocumulate textures (> 25% of post-cumulus material). The main opaque mineral phase is
401 magnetite, which is not abundant ($\leq 2\%$) and is rarely associated with sulfides and chromian
402 spinel. Magmatic amphiboles are common in these troctolites; they are mostly interstitial with
403 modal proportions of less than 3%. This, together with the paucity of chromian spinel, contrasts
404 with the troctolites and olivine-gabbros.

405 • The **gabbronorites** (5% of the samples) occur as layers alternating with other mafic
406 lithologies in the layered cumulates. They are medium-grained adcumulates characterized by
407 the early crystallization of opx (cumulus phase). They present euhedral to subhedral crystals of
408 opx (10% - 47%) and plg (30% - 75%) and always subhedral cpx (5% - 25%). When olivine is
409 present (olivine-gabbronorite), it is subhedral to anhedral and variably abundant (2% - 25%).
410 Only a few samples contain opaque minerals (<1% of chromian spinel and/or magnetite).

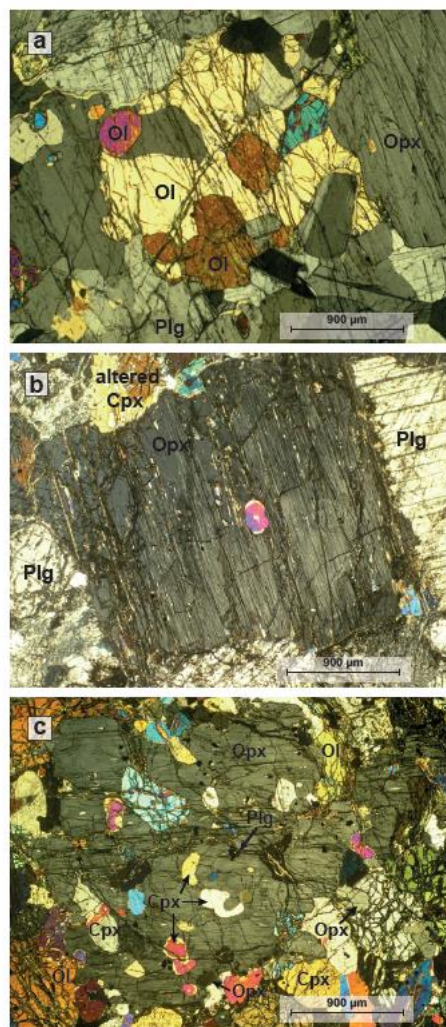
411 • The **clinopyroxenites** (2% of the samples), alternating with mafic layers, are coarse-
412 grained mesocumulates and orthocumulates characterized by abundant (60% - 92%) euhedral
413 to subhedral cpx and interstitial post-cumulus olivine, plg and/or opx; no “pure”
414 clinopyroxenite is observed. Olivine is the most abundant post-cumulus phase (7% - 38%) while
415 plg and opx have modal proportions ranging from 1% to 8%. Chromian spinel is observed in
416 some clinopyroxenites.

417 • The **dunites-wehrlites** (13% of the samples) appear as layers alternating with gabbros.
418 They are medium to coarse-grained adcumulates and mesocumulates. Dunites are essentially
419 composed of euhedral to subhedral olivine ($\geq 85\%$) and usually present poikilitic plg. Chromian
420 spinel is present in the rare “pure” dunites only and can be abundant (up to 10%). Wehrlites are
421 made of olivine (32% - 92%) and cpx (2% - 42%). Olivine is a euhedral to subhedral cumulus
422 phase. Cpx is a post-cumulus, often poikilitic, phase. Post-cumulus plg and opx are common as
423 interstitial or poikilitic crystals and can be relatively abundant with modal proportions varying
424 from 5% to 33% for plg and from 6% to 22% for opx. Opaque minerals include chromian spinel,
425 magnetite and minor sulfides. Their abundance varies from 0.5% to 6%.

426 • The **harzburgites** (Fig. 8b) (1% of the samples) are medium-grained orthocumulates
427 characterized by rounded or subhedral cumulus olivine (38% - 48%) and post-cumulus opx,
428 cpx and plg. Opx is abundant (15% - 32%) and appears generally as large (2-5mm) subhedral
429 poikilitic crystals including numerous rounded olivine. Poikilitic plg and cpx constitute the rest

430 of the mineral assemblage. Cpx is present as both small ($\leq 1\text{mm}$) subhedral to anhedral grains
431 and larger poikilitic crystals. This texture indicates that opx crystallized slightly before cpx and
432 that plg was the last phase to crystallize. Minor ($\leq 1\%$) subhedral chromian spinel and pleonaste
433 are common. It is worth mentioning that cumulate harzburgites, cropping out as weathered low
434 hills on the southern border of the Bahla massif, are mapped as mantle peridotites in geological
435 maps. We realized lately that these rocks adopted a cumulate texture and were actually part of
436 the crustal section. Accordingly, the abundance of cumulus harzburgite is certainly much higher
437 than the 1% estimate based on our sample proportions.

Fig 8



438

439 Fig. 8. Igneous facies in the undeformed lower crustal cumulates. (a) Opx-troctolite (sample 08BA8Fb
440 ZII); (b) Subhedral opx crystal in an opx-troctolite (sample 09BA14 ZI; N22°54'26", E57°19'50"); (c)
441 Cumulate cpx-harzburgite with poikilitic opx (sample 09BA14 ZI).

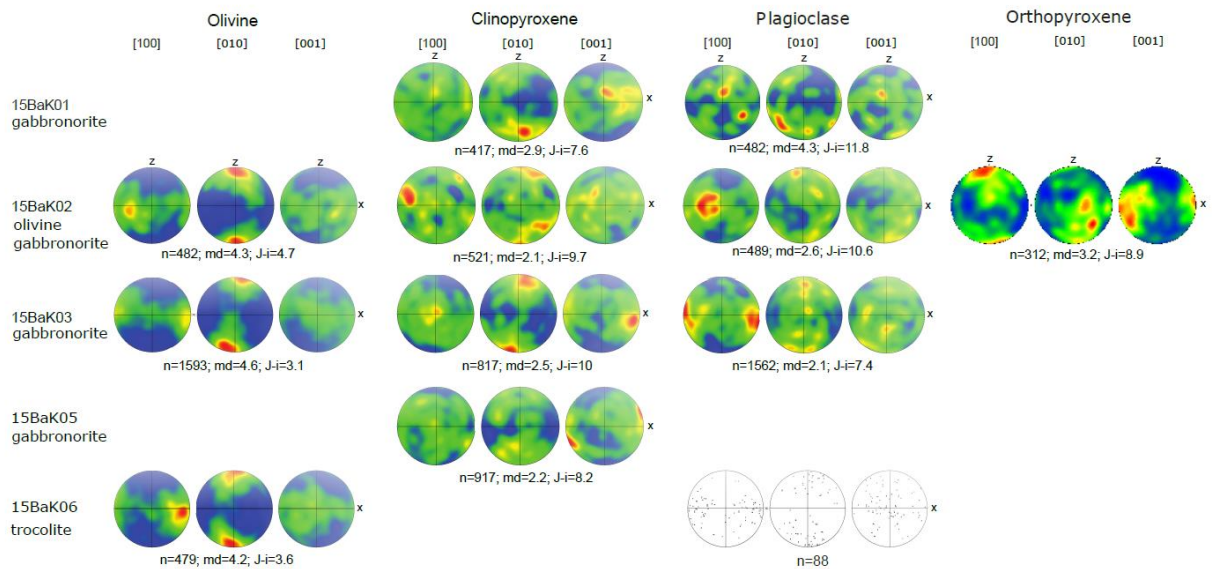
442

443

444 4.4. Microstructure and mineral fabric of deformed cumulates

445 Crystallographic preferred orientation (CPO) of olivine, pyroxenes, and plagioclase have
 446 been measured using Electron Backscatter Secondary Diffraction (EBSD) in 5 samples from
 447 the northern contact including 1 troctolite, 3 gabbronorites, 1 olivine-gabbronorite (Fig. 9).

448 Where olivine is present, its [100] axes are at low angle to X and [010] are sub-
 449 perpendicular to the foliation plane (XY) suggesting the activation of the classical [100](010)
 450 A-type slip-system (X and XY are respectively the lineation and foliation deduced from the
 451 mineral flattening and elongation and from the shape preferred orientation). The A-type slip
 452 system is usually interpreted to be formed at high temperature, low stress and dry conditions
 453 (Nicolas et al., 1971; Ben Ismail and Mainprice, 1998; Karato, 2008).



454
 455 Fig. 9. Crystallographic preferred orientation of olivine, clinopyroxene, plagioclase and orthopyroxene
 456 from five samples. Poles figures represent one point per grain on a lower-hemisphere, equal area
 457 stereographic projection; N is the number of grains, md is the multiple of uniform distribution, which is
 458 calculated for pole figures with more than 110 grains. The strength of the crystallographic preferred
 459 orientation (CPO) was estimated using the J-index (Bunge, 1982).

460
 461 Clinopyroxene shows [001] or [100] axes sub-parallel to the lineation and parallel to
 462 olivine [100] axes, and [010] axes sub-perpendicular to the foliation plane.

463 Plagioclase presents CPO patterns where [100] axes show a point concentration sub-
 464 parallel to X, and weak concentration of [010] axes sub-parallel to Z, suggesting the possible

465 activation of the [100](010) slip system which is the dominant activated slip system in
466 plagioclase (Marshall and McLarent, 1977; Olsen and Kohlstedt, 1984) at temperature higher
467 than 700°C (e.g., Diaz Aspiroz et al. 2011, Kruse et al. 2001).

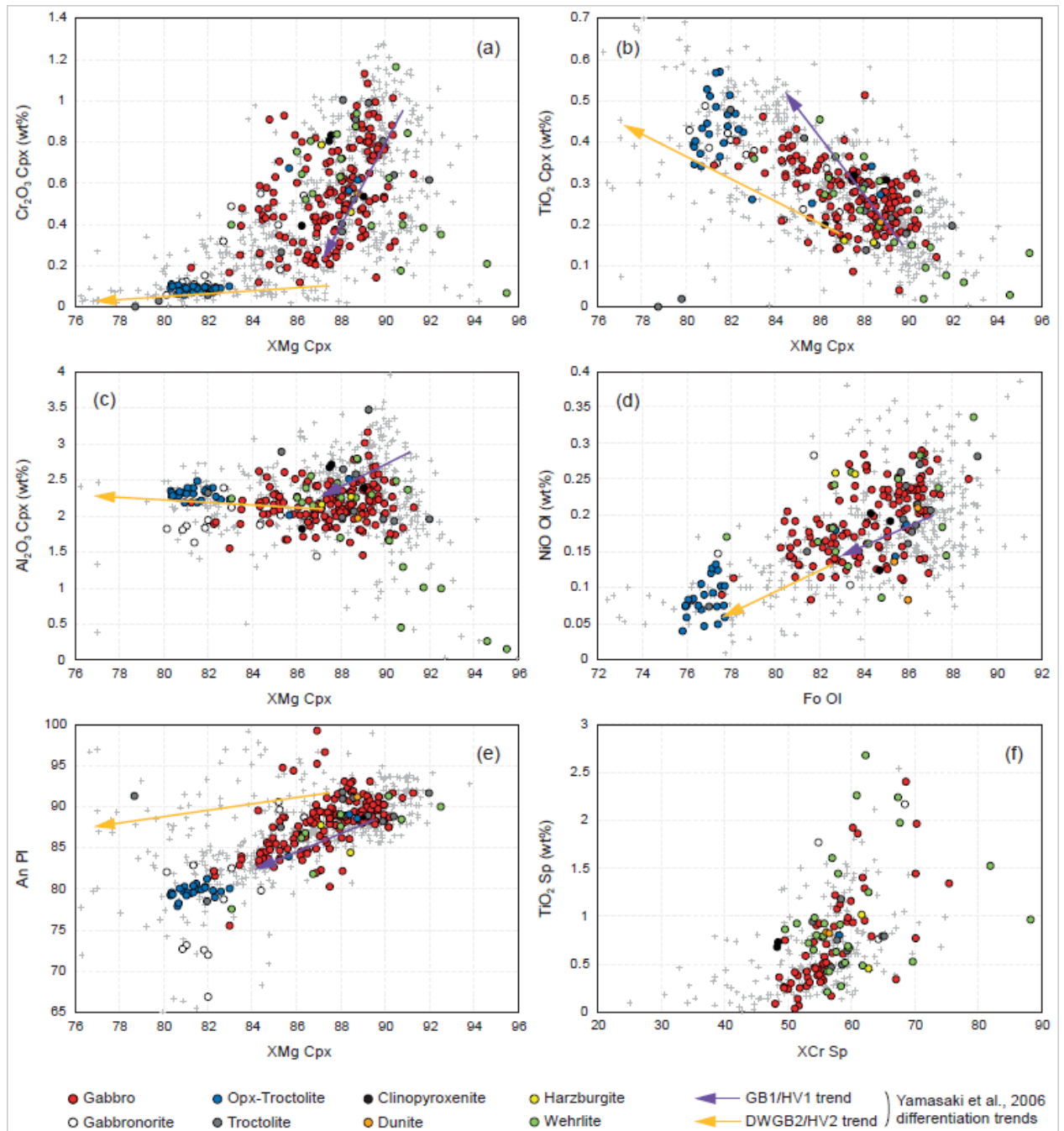
468 Orthopyroxene has been observed in one sample (15BaK02). The pattern displays point
469 concentrations of [001] axes sub-parallel to X and of [100] axes sub-parallel to Z, suggesting
470 the activation of [001](100) slip system, known to be activated at high temperature (e.g. Ross
471 and Nielsen, 1978).

472 The alignment of olivine [100] axes, clinopyroxene [001] or [100] axes, plagioclase [100]
473 axes, and orthopyroxene [001] axes sub-parallel to the stretching lineation (X) suggests coeval
474 deformation of these minerals. In detail, these crystallographic axes display a small angle to the
475 stretching lineation which, combined with the orientation of the foliation (sub-vertical to high
476 southward dip bearing a vertical lineation), (where X represents the top of the outcrop) confirm
477 the normal shear sense determined on the basis of macroscopic field criteria.

478 4.5. Mineral chemistry of the layered cumulates

479 4.5.1. Major and minor elements (Supplementary Table 1)

480 Pyroxenes from the lower crustal cumulates are diopsides ($Wo_{45-52}En_{44-51}Fs_{2-10}$),
481 magnesium-rich augites ($Wo_{41-45}En_{46-53}Fs_{5-10}$) and enstatites ($Wo_{0-5}En_{73-90}Fs_{9-24}$), and are
482 characterized by low-aluminium contents (average $Al_2O_3 \approx 2.1$ wt% in cpx and 1.2 wt% in
483 opx). Their XMg (calculated with total iron) vary from 80 to 95 mol% for cpx and from 76 to
484 89 mol% for opx. Similarly, the forsterite (Fo) content of olivine and the anorthite (An) content
485 of plg present wide compositional ranges varying from 76 to 89 mol% and from 67 to 99 mol%
486 respectively.



487

488

489 Fig. 10. Major and minor elements content determined on minerals with the electron microprobe.
 490 Crosses: data on lower crustal cumulates from other massifs of the Oman ophiolite (Abily, 2011,
 491 Korenaga and Kelemen, 1997; Müller, 2015; Yamasaki et al., 2006). Each dot and cross represents the
 492 average values for one sample.

493

494

495 In terms of classical differentiation indexes (Fo and Ni in olivine, An in plagioclase, XMg,
496 Cr₂O₃ and TiO₂ in pyroxenes), the mafic and ultramafic cumulates of Bahla range from
497 primitive to moderately evolved and plot in the field of other Oman ophiolite lower crustal
498 cumulates (Fig. 10a, b, c). Relatively evolved compositions (XMg_{cpx} < 83 mol%, XMg_{opx} < 79
499 mol%, Fo < 78 mol%, An < 82 mol%) are observed in opx-troctolites and in gabbronorites.
500 These relatively evolved cumulates are also characterized by high titanium contents in cpx
501 (TiO₂ > 0.80 wt%), low chromium contents in pyroxenes and low NiO contents in olivine, close
502 or below the detection limits.

503 In other terms, most opx-troctolites, part of gabbronorites and rare gabbros, one troctolite
504 and one wehrlite, define a distinct group at the most evolved end of the general trend. This is
505 particularly evident in the composition of olivine which shows a clear compositional gap in Fo
506 between between 80 and 78 mol%, perfectly correlated with its NiO content (Fig. 10d). This
507 hiatus is likely not an artefact of sampling as (1) the number of samples is statistically
508 significant (> 200 samples), (2) they cover a large lithological diversity, i.e. it is unlikely that
509 we missed some facies corresponding precisely to this differentiation index, and (3) we sampled
510 the different parts of the massif and different stratigraphic levels. This dichotomy is also
511 reflected in both cpx and opx compositions (Fig. 10a, b, c) and in the plagioclase composition
512 (Fig. 10e). The Al content of pyroxenes does not show any correlation with lithology, apart
513 from a few dunites and wehrlite showing a “abnormally” low Al content (and to a lesser extent
514 in Cr) in pyroxenes (Fig. 10c) given their high XMg. This likely reflects the impact of high
515 temperature hydrothermal processes (cf. Python et al., 2007, 2011; Rospabé et al., 2017).

516 Within the most primitive group, Fe-Mg phases and plg in gabbros have globally the same
517 range of composition for major (XMg, Fo, An) and minor (TiO₂, Cr₂O₃, NiO) elements than
518 those in the dunites-wehrlites (Fig. 10). However, the high-XMg cpx (XMg > 92 mol%)
519 crystallized preferentially in dunites-wehrlites while the high-calcium plg (An > 94 mol%) are
520 only observed in gabbroic cumulates. Troctolites, harzburgites and clinopyroxenites plot in the
521 same compositional field as the one of dunites-wehrlites and gabbros. However, troctolites have
522 generally more primitive compositions (XMg_{cpx} ≈ 89 mol%, Fo ≈ 86 mol%, An ≈ 90 mol%)
523 than those of cumulate harzburgites and clinopyroxenites (XMg_{cpx} ≈ 88 mol%, Fo ≈ 84 mol%,
524 An ≈ 88 mol%).

525 Yamasaki et al. (2006) identified two suites in the Oman layered crust based on distinct
526 trends in their clinopyroxene composition: GB1/HV1 which has composition consistent with a

527 MOR-related setting, and DWGB2/HV2 that was attributed to a SSZ setting. In comparison,
528 we can see that the Bahla cumulates follow a trend closer to the GB1 suite (e.g. An vs. XMg
529 cpx) or intermediate between those two trends (e.g. TiO₂ vs. XMg cpx).

530 The XCr in Cr-spinel ranges from 50 to 70 mol% with a few outliers toward high Cr. Their
531 TiO₂ content presents huge variations, from virtually zero to almost 3 wt% (Fig. 10f). No
532 correlation is observed between the Cr-spinel composition and the lithology, although Cr-spinel
533 is absent from the most evolved cumulates in which the main opaque mineral is usually
534 magnetite.

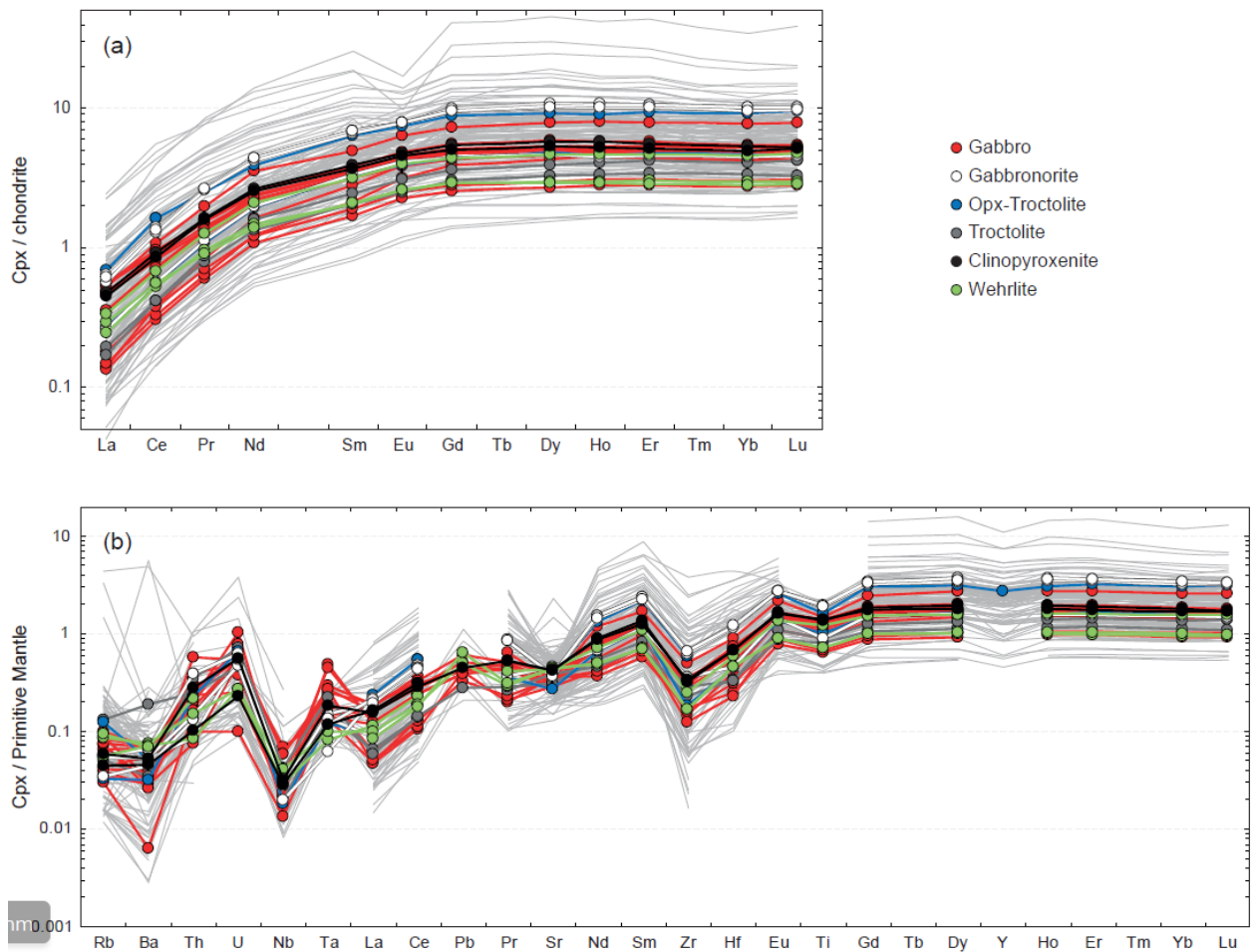
535 The most evolved cumulates (XMg_{cpx} < 85 mol%) crop out essentially in the east and in
536 the southeast of the main crustal section and belongs to both layered and overlying more
537 “massive” (i.e. with no ultramafic layers making the layering evident in the field) cumulate
538 units. The most primitive cumulates (XMg_{cpx} > 89 mol%) are principally observed along or
539 close to both the high-temperature and the low-temperature faults. The “massive” cumulate unit
540 is mainly composed of relatively evolved cumulates.

541 4.5.2. Trace elements in cpx (Supplementary Table 2)

542 Cpx in cumulates of all lithological groups have similar shape of chondrite-normalized
543 Rare Earth Elements (REE) patterns (Fig. 11a), characterized by a depletion in Light Rare Earth
544 Elements (LREE) compared to Middle and Heavy REE (MREE-HREE; nearly flat segment
545 from Gd to Lu) and by the lack of Eu anomaly. Their chondrite-normalized La/Yb ratios vary
546 from 0.03 to 0.11. The REE contents of cpx range from 10⁻¹ (LREE) to 10 times (HREE) the
547 chondritic values. The most enriched cpx are essentially observed in in opx-troctolites and
548 gabbronorites, one opx-troctolite and one ol-gabbro while the most depleted cpx are
549 preferentially observed in some (ol-)gabbros, troctolites and dunites-wehrlites, which is
550 consistent with variations in incompatible minor elements.

551 Primitive mantle-normalized extended trace elements patterns of cpx in all lithological
552 groups (Fig. 11b) are characterized by depletion in the most incompatible elements. For more
553 compatible elements (Nd - Lu segment), all patterns have a similar shape characterized by a
554 strong negative anomaly in Zr (Zr/Sm_{PMN} = 0.15-0.35) and Hf and a less pronounced negative
555 anomaly in Ti (Ti/Gd_{PMN} = 0.53-0.80) relative to neighbouring REE. The amplitude of Ti
556 anomaly (i.e. more variable Ti/Gd_{PMN}) is slightly higher in cpx of gabbronorites and in one opx-
557 troctolite and one ol-gabbro (Ti/Gd_{PMN} < 0.6). Conversely, for most other incompatible trace

558 elements (Rb - Sr segment), patterns are quite intricate and overlap each other. A clear negative
 559 Sr anomaly is observed in most samples and its amplitude generally increases with the increase
 560 in the Ti content (i.e. stronger anomalies in some gabbro, opx-troctolites and gabbros,
 561 with Sr/Nd ratios mostly < 0.4). However, in some trace element patterns, this negative Sr
 562 anomaly is weaker (samples with the lowest REE and Ti contents); cpx in all dunites-wehrlites
 563 and troctolites present this characteristic. Similarly, a clear negative Nb anomaly of varying
 564 amplitude is observed in most patterns, with stronger anomalies in patterns displaying the
 565 stronger negative Ti anomalies. Apart for these light tendencies, the presence and the amplitude
 566 of all trace element anomalies are largely independent of the lithological group with large
 567 variabilities even in a single lithological group (especially the (ol-)gabbros).



568

569 Fig. 11. Trace elements content of clinopyroxene determined with LA-ICP-MS. Grey lines: data on
 570 lower crustal cumulates from other massif of the Oman ophiolite (Abily, 2011, Korenaga and Kelemen,
 571 1997; Müller, 2015; Yamasaki et al., 2006). Each pattern represents the average values for one sample.
 572 Symbols as in Figure 10.

573

574

575 5. Discussion

576 5.1. Structural specificity of the Bahla massif.

577 Our survey has revealed that several structural features of the Bahla massif contrast with
578 common views concerning the Oman ophiolite. Among these paradigms, the lower crustal
579 section of Semail is generally described as a laterally continuous unit and the layering of the
580 basal cumulates is considered as parallel or at low angle to the mantle-crust boundary, equated
581 with the paleo-horizontal plane (cf. Pallister and Hopson, 1981). Clearly, the Bahla massif is an
582 exception to the rule for these aspects. The present general shape and size of its plutonic section
583 - a 15 by 8 km ellipsoid in map view - is clearly not attributable to the erosion of a former
584 laterally continuous crustal unit conformably resting on the underlying mantle peridotites. It is,
585 at least partly, a more pristine characteristic of this massif inherited from the interplay of a few
586 major fault zones that recorded different kinematics and were active over a wide temperature
587 range, during the accretion of the ophiolite and the early stages of intra-oceanic thrusting or
588 nascent subduction.

589 On the geological maps and associated structural sketches of the area, the apparently
590 dismembered aspect of the Bahla massif is attributed to the same tectonic events responsible
591 for the regional faulting and folding of the nearby autochthonous and allochthonous
592 sedimentary formations (Wyns et al., 1992; Béchenec et al., 1992). While we cannot exclude
593 *a priori* that the late décollements and cataclastic breccia correspond to such late tectonism, the
594 high temperature ductile faults we described above were active much earlier. As a matter of
595 fact, in this external part of the Northern Oman Mountains, the sedimentary formations escaped
596 any high temperature history, apart from a moderate, very low temperature imprint of upper
597 anchizone metamorphism (Breton et al., 2004). On the other hand, the seemingly synclinal-like
598 geometry of the Bahla massif was, among other arguments deduced from the occurrence of the
599 mantle section along both the northern and the southern contacts with the crustal section. We
600 realized that, to the south, the peridotites were mostly ultramafic cumulates, part of the crustal
601 section and cannot be used as an evidence of general folding of the Bahla massif.

602 5.2. The Moho at Bahla: a major syn-magmatic normal fault.

603 The highest temperature tectonic contact between the mantle and crustal sections we
604 identified in Bahla is a ductile normal fault of lateral extent exceeding 15 km and striking
605 WNW-ESE, at low angle to the direction of the former ridge axis. It is interrupted to the west
606 by a lower temperature shear zone and to the east by a brittle fault. The deformation textures

607 and the lattice fabrics, together with the preservation of the magmatic igneous mineral
608 assemblage - apart from the local and partial transformation of the pyroxenes into metamorphic
609 amphibole - point to very high temperature conditions during deformation, close to the gabbro
610 solidus.

611 High temperature conditions during deformation is attested by the activation of the high
612 temperature slip systems in olivine and pyroxenes. It is confirmed by thermometric
613 determinations (Supplementary Table 3). Temperatures have been estimated for orthopyroxene
614 and clinopyroxene using Brey and Köhler (1990) thermometer (Op_{XBK90}) based on Ca contents
615 in opx, and two-pyroxenes Brey and Köhler (1990) thermometer ($2Pr_{XBK90}$) based on Fe–Mg
616 exchange (see table in supplementary material). These thermometers have been applied at a
617 pressure assumed to be 0.2 GPa, implying equilibration in the plagioclase stability field. Both
618 thermometers have been applied on all types of gabbro, which have been classified for these
619 calculations by the apparition of orthopyroxene during the crystallization sequence. The first
620 group concerns gabbro with early crystallization of orthopyroxene (5 samples), the second
621 group where orthopyroxene and clinopyroxene crystallized simultaneously (8 samples), and the
622 third group where the orthopyroxene is late in the crystallization sequence (12 samples). For all
623 groups, the estimated temperatures are similar giving an average temperature of 984 ± 44 °C
624 and 920 ± 47 °C using Op_{XBK90} and $2Pr_{XBK90}$ thermometers respectively. The two pyroxenes
625 thermometer is always slightly lower in temperature but within the range of Op_{XBK90} . In details,
626 there is no temperature difference within the three identified groups of orthopyroxenes.

627 Almost monomineralic thin bands of anorthosites are common features in these deformed
628 gabbroic cumulates. They can reflect segregation processes during deformation of a crystal
629 mush (e.g. Abily et al., 2011) and would be evidence of incomplete crystallization of the lower
630 crust when the shearing initiated. They could also represent metamorphic segregations at high
631 temperature in the solid state. The good preservation of the igneous layering, i.e. the alternation
632 of decimetres-thick mafic and ultramafic cumulate layers, in spite of the intensity of the
633 deformation, could be inherited from the initial strain partitioning in the layers richer in
634 interstitial melt. The formation of the layering itself may be contemporaneous with the early
635 stage of deformation. Once fully crystallized, the sub-solidus plastic deformation affected the
636 cumulates and adjacent mantle peridotites in a more homogeneous way, but the initial focusing
637 of the ductile normal fault at Moho level is inherited from and earlier, probably syn-magmatic
638 stage.

639 Field observations and oblique lattice fabrics relative to the foliation and lineation point to
640 simple shear deformation. It allows us to determine a shear sense and to confirm the down the
641 dip displacement of the crustal section relative to the mantle section, primarily deduced from
642 field arguments. A normal fault sense is also consistent with the polarity of the rotation of the
643 gabbro layering away from the fault, i.e. flattening to the south. The important steepening of
644 the layering of the cumulates as the fault is approached was clearly induced by the same tectonic
645 event as the one that imprinted the plastic deformation, given the correlation between the dip
646 of the layering and the deformation intensity.

647 This “tectonic Moho” is presently sub-vertical. However, the Bahla massif presents a
648 general tilt of about 20° southward, induced by the post-obduction doming of the nearby Jebel
649 Akhdar; it is reflected, among other, in the dip of the cumulate layering away from the fault.
650 Accordingly, it seems reasonable to infer that the original dip of the northern fault at the time
651 it formed at the spreading centre was closer to about 70°S. Here again, this reconstruction is
652 consistent with a normal fault leading to the downward displacement of the layered gabbro
653 relative to the mantle peridotites. This displacement was likely substantial, even if impossible
654 to quantify, given the deformation intensity and the thickness of the zone of affected by plastic
655 deformation.

656 The activity of the fault ceased before cooling below the brittle–ductile transition of the
657 cumulates, as attested by the moderate imprint of low temperature deformation, limited to some
658 serpentine shear zones focused mainly in the ultramafic cumulate layers and preserving the
659 flaser structure of the gabbros. Moreover, there is clear evidence that the tilt of the gabbro, and
660 thus the normal fault activity, is prior to the end of the igneous activity in the Bahla massif, as
661 attested by the occurrence of dykes cross-cutting the deformed cumulates. These dykes are
662 parallel to the azimuth of the former ridge axis and filled with a mineral assemblage (olivine
663 gabbro) consistent with derivation from a moderately evolved MORB-like tholeiite. The
664 presence of crescumulate textures on the inner walls of several of these dykes together with the
665 absence of chilled margins indicate that the cumulates slightly, but not extensively cooled down
666 at the time of injection ($T^{\circ} \gg 400^{\circ}\text{C}$).

667 5.3. The southwestern shear zone as a high temperature trans-tensional ductile fault.

668 The style and geometry of the southwestern NW-SE fault contrasts markedly with the one
669 of the northern fault: its thickness is much less (tens of meters compared to hundreds of meters);

670 the deformation conditions do not exceed amphibolite facies; mylonitic textures are the rule;
671 the overprint of greenschist facies and cataclastic deformation is more widespread.

672 The kinematics is the one of a dextral strike-slip shear zone with a moderate down the dip
673 component. The deformation fabric is very linear, with a well-defined stretching lineation.
674 Consistently, the dip of the foliation is quite variable, ranging from high to moderate northward.
675 If we consider the 20°S general tilt of the massif, it can be inferred that the average original dip
676 of the fault plane was closer to 45°N toward the axis. Combined with the moderate dip of the
677 lineation southward and with the dextral shear sense, this geometry is consistent with that of a
678 transtensional ductile fault.

679 In contrast to the northern fault where the deformation plane is parallel to the igneous
680 structures, this mylonitic shear zone cross-cuts the bedding of the gabbros. The observed
681 metamorphic gradient from high temperature at the NW termination of the fault, where it roots
682 in the mantle section, to colder conditions to the SE, likely results from the fact that shallower
683 levels of the crust are progressively encountered when moving to the SE. Accordingly, it would
684 not reflect a real along strike metamorphic gradient at a constant depth.

685 This shear zone was active during and after intense magmatic injection. The lithological
686 nature of these intrusions contrasts with those of the bulk of the crust: these are essentially
687 pegmatitic gabbronorites and tonalite/trondhjemite dykes and plugs. Most of the dykes are
688 intensely deformed, including the felsic ones. The largest felsic plug is located where the
689 northern fault is interrupted by the mylonitic shear zone. It is free of shearing except along its
690 margins. This is consistent with the transtensional nature of the movement which made room
691 for the emplacement of the plug. These structural observations together with the age ($95.201 \pm$
692 0.032 Ma) confirms the fact that the emplacement of felsic melts at near Moho depth, and thus
693 the faults activity, occurred early and was nearly contemporaneous with the average accretion
694 age of the Semail ophiolite determined at the global scale. The $\epsilon_{Nd}(t)$ of -4.86 determined for
695 this plug reveals a sedimentary component in its source (Rioux et al., 2021b) suggesting that
696 this final magmatic episode and the late activity of the mylonitic faults were contemporaneous
697 with the intraoceanic thrusting. The position of the Semail basin close to the continental margin
698 could account for the presence of sediments in an environment of ocean crust generation.

699 5.4. Low temperature, but maybe not late décollements and breccias.

700 In restricted parts of the Bahla massif, the peridotite-gabbro contact adopts a sub-horizontal
701 attitude but this is clearly a consequence of a low temperature décollement. The high angle
702 between the deformed gabbros layering and the contact contrasts with the situation in most
703 other massifs of Oman. Elsewhere a sub-horizontal paleo-Moho, parallel to the bedding of the
704 lower crustal cumulates, is the rule and evidently a pristine feature (e.g. Boudier and Nicolas,
705 1995), although locally affected to some degree by faulting over a wide temperature range
706 (Glennie et al., 1973; Abily et al., 2011; Zihlmann et al., 2018; Rospabé et al., 2019). In Bahla,
707 these contacts are underlain by rodingites and diopsidites, together with the presence of
708 chrysotile, indicative of temperatures exceeding the regional upper anchizone metamorphic
709 conditions affecting the sedimentary formations near Bahla (Breton et al., 2014). Breccias with
710 gabbroic elements embedded in a matrix of prehnite and carbonates are definitely lower
711 temperature features but their occurrence is frequent in fault zones affecting the lower crust and
712 the mantle along present-day mid-ocean spreading centres (e.g. MacLeod et al., 2002; Gillis et
713 al., 2014) and arc related basins (e.g. Harigane et al., 2011) . Accordingly, although it cannot
714 be strictly demonstrated, the fact that these relatively low temperature brittle faults predate the
715 obduction and belong to the same tectonic episode than the high temperature faults of Bahla is
716 in the field of possibilities. The preservation of greenschist facies and higher temperature
717 alteration minerals in these breccias in spite of lower temperature overprint is, however, a good
718 indication that they developed early.

719 5.5. Petrological specificity of the Bahla lower crustal layered cumulates.

720 Our exhaustive sampling of the lower crustal cumulates of the Bahla massif has revealed
721 the important lithological diversity of this unit. It includes most rock types described up to now
722 in other massifs of Oman and, in addition, lithologies that, as far as we know, seem more
723 specific to this frontal part of the ophiolite i.e. the cumulate harzburgites and the opx-troctolites.

724 Orthopyroxene appears more abundant and ubiquitous in the lower crustal cumulates at
725 Bahla than elsewhere in Oman, at the massif scale at least: 41% of our samples present post-
726 cumulus opx and 17% early crystallizing opx (cumulus or early post-cumulus). These are
727 minimum values as we under-sampled the cumulate harzburgites. Early crystallizing
728 orthopyroxene is virtually absent from the lower crustal cumulates of entire massifs, especially
729 in the southern part of the ophiolite (e.g. Pallister and Hopson, 1981; Kelemen et al., 1997) and
730 present but more occasional than in Bahla in some sections of other massifs, mostly in the
731 central and northern part of the ophiolite (e.g. Smewing, 1981; Browning, 1990; Yamasaki et

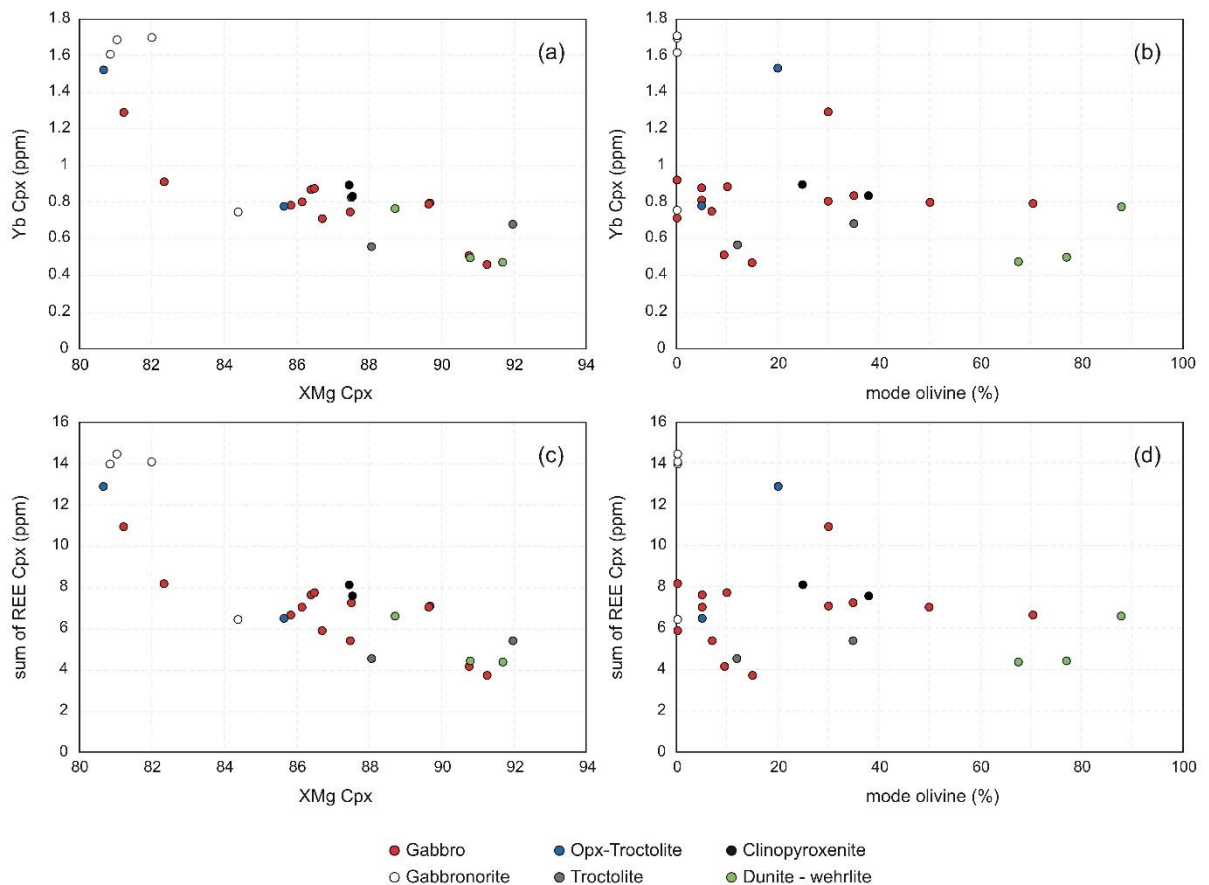
732 al., 2006; Abily, 2011). This abundance in early crystallizing orthopyroxene is thus another
733 distinctive characteristic of the Bahla massif that might be shared with the nearby Wuqbah
734 massif cropping out also at the front of the ophiolite (Abily, 2011).

735 A simple way to account for the early crystallization of orthopyroxene in an ocean
736 spreading context is to invoke a parent melt with a silica content a few percent higher than in
737 MORB, i.e. with a more andesitic composition, or an increase of the partial pressure of water
738 and/or the oxygen fugacity in the melt, the two hypotheses being not mutually exclusive. The
739 origin of the water or of the water-rich melts can be looked for in the subduction factory (e.g.
740 MacLeod et al., 2013; Belgrano and Diamond, 2019; Koepke et al., this volume) or in deep-
741 seated episodic hydrothermal processes in a spreading ridge context (e.g. Benoit et al., 1999;
742 Boudier et al., 2000; Nonnotte et al., 2005; Rospabé et al., 2017).

743 Primitive or moderately evolved opx-rich lithologies (pyroxenites and gabbronorites) are
744 the dominant facies in the dykes cross-cutting the mantle section of Bahla showing that, at a
745 certain stage, it was percolated by andesitic, hydrous melts (Fig. 1b and Python and Ceuleneer,
746 2003). We can guess that these melts contributed to feed the crustal magma chamber. This
747 would be consistent with the high proportion of opx-rich cumulates at Bahla. It is worth
748 mentioning that, in the Oman plutonic section, orthopyroxene can be abundant in highly
749 evolved cumulates but, in these cases, it has a low XMg and generally co-crystallizes with Fe-
750 Ti oxides, amphibole and, occasionally, sulfides. This was observed along some sections of the
751 Oman crust where it was attributed to extreme degrees of fractional crystallization made
752 possible by the specific context of the leading edge of a magma chamber (Lachize et al., 1996;
753 Boudier et al., 2000; Adachi and Miyashita, 2003). This mechanism of differentiation cannot
754 account alone for the early crystallizing opx present in the Bahla lower crust.

755 Considering the mineral major and minor element compositions, the global decrease in Cr
756 in pyroxenes, Ni in olivine and An of plagioclase, and the increase of Ti in pyroxenes with the
757 decrease in XMg (Fig. 10) indicate that fractional crystallization actually contributed to some
758 extent to the evolution of the parent melts of all the cumulates of Bahla. The opx-bearing
759 lithologies also have clinopyroxene with higher trace incompatible element concentrations,
760 especially in REE (Fig. 11). However, (1) the incompatible minor and trace elements
761 concentrations show a significant variability for a given XMg, *even in a single lithological*
762 *group*, and (2) there is a general lack of consistency between the modal composition and the
763 chemical indexes of differentiation (Fig. 12). These are not characteristics unique to Bahla (cf.

764 Abily, 2011) but they are particularly evident in the case of this massif. This suggests that
 765 fractional crystallization from a common parent melt cannot solely account for this chemical
 766 variability and does not explain the relationships between the various lithologies. Among
 767 others, many cumulate harzburgites, dunites, wehrlites and pyroxenites, that would be
 768 considered as primitive on mineralogical grounds, may present quite evolved mineral
 769 compositions (Fig. 10), which is counter intuitive in the frame of cumulates issued from a single
 770 parent melt. The opx-troctolites constitute, apart from a few exceptions, a quite homogeneous
 771 group at the most evolved end of the chemical trends, especially in major elements. From a
 772 chemical perspective, the opx-troctolites share some characteristics with the most evolved
 773 samples from the gabbronorite group but the abundance of early crystallizing olivine and
 774 plagioclase is puzzling.



775

776 Fig. 12. Yb and sum of REE in clinopyroxene reported as a function of XMg of clinopyroxene and of
 777 modal content of olivine.

778

779 It is tempting to group the seven lithological groups identified in the Bahla lower crust in
780 two main series as we did for the mantle dykes (Python and Ceuleneer, 2003): one whose
781 mineralogical assemblage and crystallization order fit with an olivine tholeiite, MORB-like,
782 parent melt (i.e. the troctolites, the olivine gabbros and the evolved gabbronorites) and another
783 one including all the lithologies that do not fit a tholeiitic parent melt, i.e. most ultramafic
784 cumulates (cumulate harzburgites, wehrlites, pyroxenites) and the opx-troctolites. The problem
785 is that, contrasting with the mantle dykes, the geochemical composition of Bahla cumulates do
786 not define two contrasted trends that would be diagnostic of a melt produced from a MORB
787 mantle source on one hand and from a highly depleted mantle source on the other hand. As a
788 matter of fact, the geochemical compositions of our different lithologies largely overlap.

789 In detail, the total REE content of cpx in the second group, except the opx-troctolites, is in
790 the lower part of the variation field of Bahla cumulates and, more generally, of the lower crustal
791 cumulates of Oman. However, the different lithologies do not contrast markedly in the shape
792 of their REE patterns, showing that they did not crystallize from melts that are issued from a
793 dramatically different degree of partial melting of the mantle source. The ultramafic cumulates
794 and opx-rich gabbro display a less pronounced negative Sr anomaly in their extended trace
795 element patterns than the troctolites and olivine gabbros. It results from a similar to lower Nd
796 content but also from a slightly higher Sr content (higher than 9 $\mu\text{g/g}$ while below 8 $\mu\text{g/g}$ for
797 other lithologies). This could be an effect of Sr depletion from the melt related to early
798 plagioclase crystallization in troctolites and olivine gabbros, but it is not reflected in the Eu
799 anomalies, which are mostly absent in all lithologies. The other difference between the two
800 series is higher Ni (> 200 $\mu\text{g/g}$) and Cr (> 4000 $\mu\text{g/g}$) contents in clinopyroxene from the
801 ultramafic lithologies (dunites and pyroxenites).

802 Magma mingling/mixing between the two contrasting melts identified in the mantle dykes
803 of Oman is among the possible processes of the petrological characteristics of the Bahla lower
804 crust. Although it is far from being a unique explanation, it is a simple way to account for the
805 departure from simple fractional crystallization trends and for the poor contrast of the
806 geochemical signatures between the various lithologies. Another avenue of explanations is
807 variable input of water from a subducted slab (Koepke et al., this issue).

808 At the massif scale, we do not observe a geographical partitioning of the different types of
809 cumulates. Several lithologies coexist in adjacent layers showing that the mixing was
810 sufficiently incomplete to preserve the contrast in modal composition down to the outcrop scale.

811 We propose that deformation related to the first stages of activity of the high temperature
812 ductile faults might have induced the mingling and the compaction of the crystal mush. In this
813 model, interstitial melts, more or less hydrous and in variable stage of differentiation, were
814 expelled and partially mixed at a local scale. Rapid crystallization, possibly triggered by the
815 circulation of hydrothermal or subduction-derived fluids along the faults, made possible the
816 preservation of contrasted lithological facies and of a certain heterogeneity in the chemical
817 compositions. Mixing of the melts from both series identified in the mantle dyke population
818 may have contributed to attenuate the contrast in incompatible elements signatures between the
819 two series. The peculiar opx-troctolite lithology could be issued from an evolved tholeiitic melt
820 relatively enriched in Ti and total REE due to fractional crystallization, whose cotectic
821 trajectories has been modified by late mixing with a silica and Mg richer andesitic melt. Higher
822 water concentration, whatever its origin, may have also contributed to its genesis as attested the
823 presence of igneous amphibole in this facies. Such special conditions and petrological processes
824 might also account for the compositional gap in the Fo of olivine which remains mysterious.

825 The origin of the MORB parent melt is not a real issue in the oceanic spreading setting that
826 led to the accretion of the ophiolite. They can be formed at both mid-ocean ridges and in back-
827 arc basins (although the absence of a mature arc along the northern margin of Arabia makes
828 this late interpretation difficult). The genesis of the primitive andesite parent melt is also an
829 open question in the specific context of the Oman ophiolite. Most authors working in Oman
830 attribute such melts to mantle melting in the context of subduction. A challenging hypothesis
831 is to consider that the genesis of opx-rich cumulates and of their parent melts is a natural
832 consequence of the interaction between the mantle and lower crustal rocks and deep-seated
833 hydrothermal fluids in a spreading setting, made possibly by the cyclic nature of the accretion
834 process and triggered by faulting (Benoit et al., 1999; Clénet et al., 2010; Abily et al., 2011;
835 Koepke et al., 2014; Rospabé et al., 2019). The formation of primitive gabbro-dykes in
836 response to the hydrated re-melting of the mantle along detachment faults is not unique to the
837 Oman ophiolite (cf. Liu et al., 2014). Opx-rich, or at least bearing, primitive cumulates have
838 been sampled along present-day mid-ocean ridges (both low and fast spreading) where the
839 influence of subduction can be excluded in both slow-spreading (Nonnotte et al., 2005) and
840 fast-spreading contexts (Gillis et al., 2014). In spite of their discrete occurrences, and different
841 textures in the case of fast spreading ridges, these lithologies exist in “open” mid-ocean settings
842 and nurture discussions about their use to constrain the tectonic setting of ophiolites.

843 Although the present study is far from bringing definitive arguments allowing us to
844 decipher between these hypotheses, it contributes to illustrate one among many tectonic
845 contexts leading to the interaction and crystallization of two magmatic series that contributed
846 to the building and igneous evolution of the Oman ophiolite.

847 5.6. Possible tectonic context of accretion of the Bahla massif.

848 The intense deformation experienced by the layered cumulates of Bahla occurred in very
849 high temperature conditions and records a normal fault movement. This kinematic calls for
850 extensional tectonics and is more consistent with a syn-accretion event rather than with the
851 compressive context that prevailed during the early intra-oceanic thrusting or nascent
852 subduction of the ophiolite that precluded the obduction.

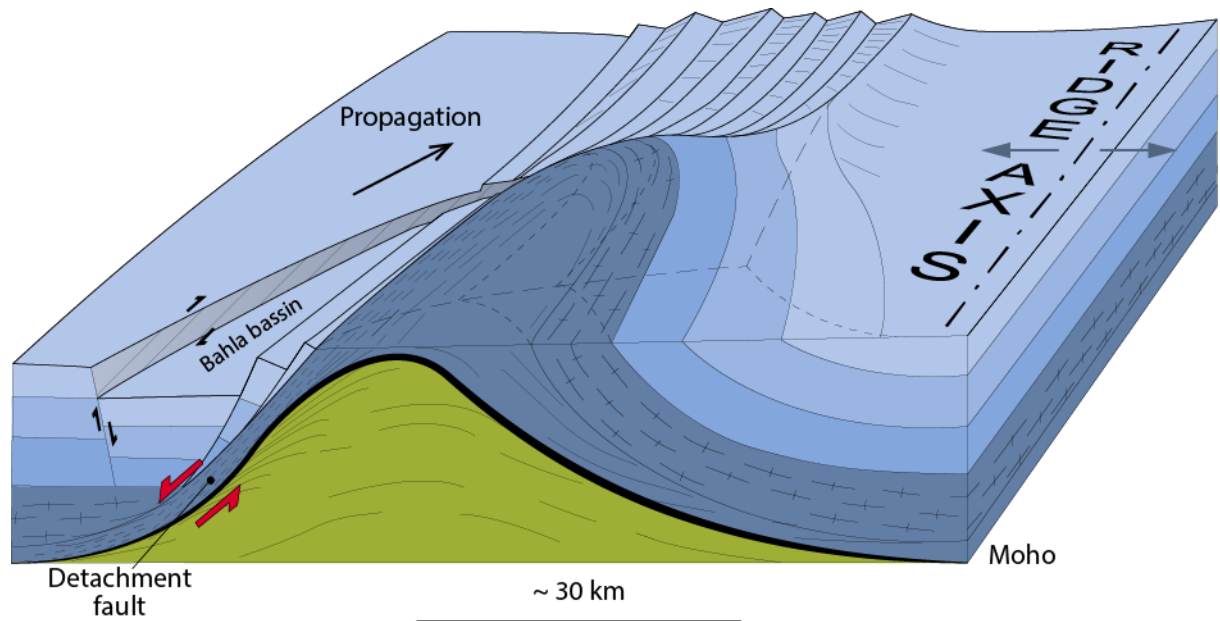
853 It is tempting to see in the Bahla massif an analogue of the oceanic core complexes mapped
854 along present-day slow-spreading ridges (e.g. Blackman et al., 1998) and in arc-related basins
855 (e.g. Harigane et al., 2011). However, the great variability of present-day core complexes in
856 terms of size, deformation structures, lithologies and, mostly, the fact that the pristine
857 morphology and seafloor rock exposure of the Bahla massif at the time of accretion is not
858 preserved due to erosion make a detailed comparison difficult. It remains that some
859 characteristics of the Bahla massif may support this working hypothesis. Among others, the
860 lithological diversity of the Bahla crustal section is strikingly reminiscent of the rocks sampled
861 in this context of intense normal faulting, including ultramafic, troctolitic, gabbroic and
862 gabbro-noritic cumulates, trondhjemites and post-deformation gabbro dykes (e.g. Cannat and
863 Casey; 1995; Cannat et al., 1997; Dick et al., 2008 and 2010).

864 The intersection between a spreading ridge and a transform fault is a setting where oceanic
865 core complexes commonly develop. Among such so-called “intersection massifs”, those to the
866 south of the Kane Fracture zone (Dick et al., 2008 and 2010) were particularly well surveyed.
867 There, the concept of “plutonic growth faults” was introduced to account for addition of magma
868 directly to the lower crust with minor counterparts in the erupted lavas. This context is
869 favourable to the deformation and rotation of the lower crustal cumulates at an early stage of
870 crystallization. This tectonic imprint pre-dates the last magmatic pulses as attested by the
871 frequent occurrence of cross-cutting dykes (gabbro, diorite and diabase) in the dredged samples
872 (Dick et al., 2010) and by the local imprint of very high temperature ductile deformation
873 recording normal faults kinematic as observed in the cores sampled during the ODP Leg 153,
874 Holes 921-923 (Cannat et al., 1997; Fletcher et al., 1997).

875 The detachment faults along present-day core complexes have variable extents along strike,
876 ranging from a minimum of about 15 km to several tens of kilometres. They are interrupted
877 longitudinally by faults sub-perpendicular to the spreading axis. In the context of intersection
878 massifs, high and low temperature mylonites develop along one edge in response to the strike-
879 slip tectonics induced by the transform fault (Dick et al., 2010). Brittle faults (breccias and
880 cataclasites) are the rule at the other end of the detachment fault. This is remarkably close to
881 the situation observed at Bahla. According to recent scenarios of formation and evolution of
882 oceanic core complexes (e.g. Brun et al., 2018), the sense of rotation of the gabbro layering
883 approaching the northern fault is consistent with a spreading ridge located to the ENE of Bahla.
884 In this case, the Bahla massif would have formed along the WSW flank of the spreading center.
885 This is in agreement with the fact that a paleo-ridge segment, witness of the last spreading
886 activity recorded by the Oman ophiolite, has been frozen about 30 km to the NE of the Bahla
887 massif, in a more internal part of the ophiolite (Ceuleneer, 1991; Ceuleneer et al., 1996; Nicolas
888 et al., 2000; Python and Ceuleneer 2003). To invoke ridge jumps is another possibility. In this
889 case, the accretion could have stopped along the internal paleo-ridge segments before the
890 accretion of the Bahla massif, in reaction to the complex changes in stress field that likely
891 precluded the inversion from divergence to convergence.

892 A major difference with the present-day core complexes is the non-cylindrical geometry at
893 Bahla where the strike slip mylonitic fault is oriented at about 45° from the main detachment
894 and has a significant normal fault component. This fault pattern evokes a context of a pull apart
895 basin developing in response to north-westward ridge propagation and oblique extension. Ridge
896 propagation has been invoked to account for complex structuration in the Oman ophiolite, in
897 particular the cross-cutting relationships in the gabbroic section and in the sheeted dyke
898 complex (e.g. Reuber, 1988; MacLeod and Rothery, 1992). It has been related to the
899 reorganization of the plate motion that characterizes upper Cretaceous times (e.g. Stampfli and
900 Borel, 2002) and that eventually resulted in the major episode of ophiolite emplacement on the
901 Arabian margin (Ceuleneer, 1986; Agard et al., 2007). The accretion of the Oman ophiolite
902 occurred during the regional inversion of extension to convergence, the main evidence being
903 provided by the overlap between the crystallization ages of the evolved crustal lithologies dated
904 so far and the ages of amphibolites from the metamorphic sole. The stress field in which the
905 future ophiolite accreted was likely already partly impacted by this major reorganization which
906 favoured the opening of pull-apart basins, ridge propagation and/or ridge jumps.

907



908

909 Fig. 13. A simplistic sketch illustrating a possible tectonic context for the formation of the Bahla
 910 massif (propagation is to the NW). Modified from Brun et al. (2018).

911 Accordingly, we tentatively interpret the Bahla massif as a witness of the opening of small
 912 pull-apart oceanic basins in a context of northward ridge propagation along the Oman
 913 continental margin (Fig. 13). The age of the plagiogranite (95.2 Ma) provides a minimum
 914 estimate of the age of accretion. It formed during the late stages of activity of the Bahla syn-
 915 accretion faults and early stages of intra-oceanic thrusting or nascent subduction. While the
 916 deformation along the main normal fault stopped early, permitting the preservation of high
 917 temperature structures with very minor overprint of low temperature deformation and alteration,
 918 the mylonitic strike slip fault was likely active a bit longer, up to the emplacement of the
 919 plagiogranite plug whose source was contaminated by melts or fluids from the nascent
 920 metamorphic sole.

921 In the present-day setting, the life time of plutonic growth faults and of related igneous
 922 activity (including the last dyke injection events in off-axis position) is rather well constrained
 923 by magnetic data and rock sampling in present-day setting; it is of the order of 1 to 2 million
 924 years (Dick et al., 2008). Accordingly, we can guess that igneous accretion started at Bahla 96
 925 to 97 million years ago. As plutonic growth faults are common features at slow spreading
 926 centres, the opening of the Semail basin may have started in slow spreading conditions before
 927 evolving, for a short period of time, into fast spreading before the death of the system prelude
 928 the compressive movements. Alternately, plutonic growth faults might exist in fast spreading

929 settings where they are hidden below lava flow due to higher extrusive rates (e.g. Sauter et al.,
930 2021).

931 6. Conclusion

932 Early faulting and its consequences are not included in oceanic accretion models inspired
933 by studies in Oman. The local impact of syn-magmatic faults was initially revealed by field and
934 petrological studies in the Maqsad area (Abily et al., 2011; Rospabé et al., 2019). Evidence
935 from the Bahla massif indicate that former plutonic growth faults can condition the general
936 structure and influence the petrological evolution of entire massifs, i.e. at a much larger scale.

937 The data presented in this paper led us to reconsider some common views about the tectonic
938 setting of the Oman ophiolite, and to speculate about its possible evolution. The Oman ophiolite
939 is a complex heterogeneous geological object. Clearly, the paradigm of viewing the Oman
940 ophiolite *as a whole* as the archetype for fast-spreading oceanic crust accretion (whether mid-
941 ocean ridge or subduction related) should be nuanced.

942

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952

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