



Draft Manuscript for Review

Multi-stage reactive formation of troctolites in a slow-spreading oceanic lithosphere (Erro-Tobbio, Italy): a combined field and petro-chemical study.

Journal:	<i>Journal of Petrology</i>
Manuscript ID:	JPET-Jun-18-0077.R3
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	06-Feb-2019
Complete List of Authors:	Basch, Valentin; Università Degli Studi Di Genova, Dipartimento di Scienze della Terra, dell'Ambiente e della Vita (DISTAV) Rampone, Elisabetta; Università Degli Studi Di Genova, Dipartimento di Scienze della Terra, dell'Ambiente e della Vita (DISTAV) Crispini, Laura; Università Degli Studi Di Genova, Dipartimento di Scienze della Terra, dell'Ambiente e della Vita (DISTAV) Ferrando, Carlotta; CNRS, Géosciences Montpellier, Université de Montpellier; University of Lorraine, CRPG Ildefonse, Benoit; CNRS, Géosciences Montpellier, Université de Montpellier Godard, Marguerite; CNRS, Géosciences Montpellier, Université de Montpellier
Keyword:	Melt-rock interaction, Reactive crystallization, Crystallographic Preferred Orientation, Alpine-Apennine ophiolites, Troctolite, Mantle peridotite, Replacive formation

SCHOLARONE™
Manuscripts

Multi-stage reactive formation of troctolites in a slow-spreading oceanic lithosphere (Erro-Tobbio, Italy): a combined field and petrochemical study.

Basch, Valentin¹; *Rampone, Elisabetta¹; Crispini, Laura¹;

¹DISTAV, University of Genova, Corso Europa 26, I-16132 Genova, Italy

Ferrando, Carlotta^{2,3};

²Géosciences Montpellier, University of Montpellier, CNRS, Montpellier, France.

Current address: ³CRPG, University of Lorraine, Nancy, France.

Ildefonse, Benoit²; Godard, Marguerite²

²Géosciences Montpellier, University of Montpellier, CNRS, Montpellier, France.

Corresponding Author:

Elisabetta Rampone

Dipartimento di Scienze della Terra, dell'Ambiente e della Vita (DISTAV)
Università degli Studi di Genova
Corso Europa 26
I-16132 Genova (Italy)

Email: betta@dipteris.unige.it

ABSTRACT

32

Many recent studies investigated the replacive formation of troctolites from mantle-related protoliths and the compositional evolution of the percolating melt during melt-rock interaction processes. However, strong structural and geochemical constraints of a replacive origin are not yet established. The Erro-Tobbio impregnated mantle peridotites are primarily associated to a hectometre-size troctolitic body and crosscutting gabbroic dikes, providing a good field control on melt-rock interaction processes and subsequent magmatic intrusions. The troctolitic body exhibits high inner complexity, with a host troctolite (*Troctolite A*) crosscut by a second generation of troctolitic metre-size pseudo-tabular bodies (*Troctolite B*). The host *Troctolite A* is characterized by two different textural types of olivine, corroded deformed millimetre- to centimetre-size olivine and fine-grained rounded undeformed olivine, both embedded in interstitial to poikilitic plagioclase and clinopyroxene. *Troctolite A* shows melt-rock reaction microstructures indicative of replacive formation after percolation and impregnation of mantle dunites by a reactive melt. The evolution of the texture and Crystallographic Preferred Orientation of olivine are correlated and depend on the melt/rock ratio involved in the impregnation process. A low melt/rock ratio allows the preservation of the protolith structure, whereas a high melt/rock ratio leads to the disaggregation of the pre-existing matrix. The mineral compositions in the *Troctolite A* define reactive trends, indicative of the buffering of the melt composition by assimilation of olivine during impregnation. The magmatic *Troctolite B* bodies are intruded within the pre-existing *Troctolite A* and are characterized by extreme textural variations of olivine, from decimetre-size dendritic to fine-grained euhedral crystals embedded in poikilitic plagioclase. This textural variability is the result of olivine assimilation during melt-rock reaction and the correlated increase in the degree of undercooling of the percolating melt. In the late gabbroic intrusions, mineral compositions are consistent with the fractional crystallization of melts modified after the reactive crystallization of *Troctolite A* and *B*. The Erro-Tobbio troctolitic body shows a multi-stage origin, marked by the transition from reactive to fractional crystallization and diffuse to focused melt percolation and intrusion, related to progressive exhumation. During the formation of the troctolitic body, the melt composition was modified and controlled by assimilation and concomitant crystallization reactions occurring at low melt supply. Similar processes were described in ultraslow-spreading oceanic settings characterized by scarce magmatic activity.

54

55

56

57

58

59

60

61

Keywords: Alpine-Apennine ophiolites; Melt-rock interaction; Reactive crystallization; Replacive formation; Crystallographic Preferred Orientation.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67

1. INTRODUCTION

Recent studies demonstrated that melt-rock interactions can lead to extensive small-scale structural and geochemical heterogeneities within the percolated mantle peridotites at different depths (e.g., Quick, 1981, 1982; Dijkstra *et al.*, 2002, 2003; Lissenberg & Dick, 2008; Soustelle *et al.*, 2009, 2010, 2014; Collier & Kelemen, 2010; Higbie & Tommasi, 2012, 2014; Tursack & Liang, 2012; Saper & Liang, 2014; Dygert *et al.*, 2016; Paquet *et al.*, 2016; Renna *et al.*, 2016; Sanfilippo *et al.*, 2017), and can act as a rock-forming process for replacive lithotypes. In extensional settings worldwide, spinel harzburgites and spinel dunites showing decoupled bulk and mineral chemistry features have been interpreted as the replacive product of open-system reactive melt percolation at spinel-facies depth, driven by pyroxene dissolution and olivine crystallization (e.g., Takazawa *et al.*, 1992; Godard *et al.*, 1995; Kelemen *et al.*, 1995a, b, 2000, 2007; Dick *et al.*, 2008, 2010; Piccardo *et al.*, 2007; Rampone *et al.*, 2004; 2008; Rampone & Borghini, 2008; Lambart *et al.*, 2009; Liang *et al.*, 2011; Pirard *et al.*, 2013; Dygert *et al.*, 2016). On the other hand, plagioclase-rich peridotites have been ubiquitously found in ophiolitic and oceanic settings and interpreted as the replacive product of melt impregnation that occurred at shallower plagioclase facies conditions, leading to olivine dissolution and interstitial plagioclase and pyroxene crystallization (e.g., Van der Wal & Bodinier, 1996; Garrido & Bodinier, 1999; Dijkstra *et al.*, 2002, 2003; Borghini *et al.*, 2007; Rampone & Borghini, 2008; Tursack & Liang, 2012; Saper & Liang, 2014; Basch *et al.*, 2018).

Melt-rock interactions have also been increasingly invoked in the formation of the oceanic crust and described as a geochemical key process in the compositional evolution of the percolating MORB melts from several lines of evidence: (1) dissolution-precipitation microstructures and geochemical zoning in lower crustal gabbros (Lissenberg & Dick, 2008; Lissenberg *et al.*, 2013; Lissenberg & MacLeod, 2016), (2) the composition of melt inclusions in lava phenocrysts (Laubier *et al.*, 2014; Coumans *et al.*, 2016), (3) peculiarities in the compositional variations of mid-ocean ridge basalts (MORBs), not consistent with a process of fractional crystallization alone (Collier & Kelemen, 2010; Van den Bleeken *et al.*, 2011; Paquet *et al.*, 2016; Sanfilippo *et al.*, 2016a), (4) the structural and geochemical mantle inheritance inferred in olivine-rich troctolites enclosed in the lowermost oceanic crust. These olivine-rich gabbroic rocks are thought to represent the replacive product of the interaction between a dunitic matrix and a percolating tholeiitic melt in disequilibrium with its host rock (Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2009, 2010; Renna & Tribuzio, 2011; Higbie & Tommasi, 2012; Sanfilippo & Tribuzio, 2012; Sanfilippo *et al.*, 2013, 2014, 2015a, 2016b; Rampone *et al.*, 2016; Basch, 2018; Basch *et al.*, 2018; Ferrando *et al.*, 2018). However, during the dissolution-precipitation reaction, the texture of the olivine

1
2
3 100 matrix progressively evolves towards a cumulate-like poikilitic texture of the olivine-rich gabbroic
4 rock (Suhr *et al.*, 2008; Drouin *et al.*, 2010; Basch *et al.*, 2018), thus calling for the need of strong
5 structural and geochemical constraints to discriminate between a magmatic and a replacive origin of
6 the lithotype.
7
8 103
9

10 104 Previous studies have documented that the Alpine-Apennine ophiolitic peridotites record
11 various stages of melt-rock interaction occurring at different mantle depths (e.g. Rampone &
12 Borghini, 2008; Piccardo & Guarnieri, 2010; Rampone *et al.*, 2018). In the Erro-Tobbio ultramafic
13 unit (Voltri Massif, Ligurian Alps), peridotites preserve microstructures and geochemical
14 compositions indicative of a multi-stage melt-rock interaction history, related to progressive
15 exhumation of this mantle sector from spinel facies depths to shallow oceanic environments
16 (Rampone *et al.*, 2004, 2005, 2016; Borghini & Rampone, 2007; Borghini *et al.*, 2007; Piccardo &
17 Vissers, 2007; Rampone & Borghini, 2008). In places, impregnated plagioclase peridotites are
18 found in irregular contact with a hectometre-size troctolitic body, later crosscut by troctolitic and
19 gabbroic dykes. Previous studies inferred a prevalent magmatic origin for these gabbroic rocks
20 (Borghini & Rampone, 2007; Borghini *et al.*, 2007; Rampone & Borghini, 2008). In a recent study
21 on the geochemistry of olivine, Rampone *et al.* (2016) highlighted the important role of melt-rock
22 interaction in the origin of olivine-rich troctolites. The Erro-Tobbio peridotite-gabbro association
23 thus appears an ideal case study to track the structural and geochemical changes in mantle
24 peridotites progressively transforming to replacive troctolites during reactive dissolution (i.e. a
25 dissolution-precipitation process; Liang, 2003), and to identify the role of reactive versus fractional
26 crystallization in the origin of olivine-bearing gabbroic rocks. In this study, we present a detailed
27 field mapping of the internal structural complexity of the troctolitic body, coupled with Electron
28 Backscatter Diffraction (EBSD) measurements, and mineral major elements analyses (by Electron
29 Probe Micro-Analyser) of the host spinel and plagioclase peridotite, the troctolitic body, and the
30 gabbroic intrusions.
31
32 124

33 Major outcomes of this work are: (1) the documented correlation between the textural
34 evolution of the olivine matrix and the modification of the olivine Crystallographic Preferred
35 Orientation (CPO) during replacive formation of the olivine-rich troctolite, and (2) the
36 demonstrated modification of the melt composition during the melt-rock interaction history, leading
37 to peculiar mineral compositional trends in the gabbroic intrusions, shifted towards Mg-rich
38 olivines and clinopyroxenes.
39
40 131
41
42 122
43 123
44 124
45 125
46 126
47 127
48 128
49 129
50 130
51 131
52 132
53 133

2. STRUCTURAL AND PETROLOGIC BACKGROUND

1
2
3 134 The Alpine-Apennine ophiolites are predominantly constituted by mantle peridotites and represent
4 lithospheric analogues of ocean/continent transition zones and slow- to ultra-slow spreading
5 environments (Rampone *et al.*, 1997, 2004, 2008; Rampone & Piccardo, 2000; Müntener &
6 135 Piccardo, 2003; Müntener *et al.*, 2004; Piccardo *et al.*, 2004; Borghini *et al.*, 2007; Manatschal &
7 136 Müntener, 2009). They are thought to represent the lithospheric remnants of the narrow Jurassic
8 Ligurian Tethys oceanic basin, opened by passive lithosphere extension and breakup of the
9 continental lithosphere, leading to slow-spreading oceanization (Rampone & Piccardo, 2000;
10 138 Manatschal & Müntener, 2009).

11
12 139
13 140
14 141
15 142
16 143
17 144
18 145
19 146
20 147
21 148
22 149
23 150
24 151
25 152
26 153
27 154
28 155
29 156
30 157
31 158
32 159
33 151
34 152
35 153
36 154
37 155
38 156
39 157
40 158
41 159
42 160
43 161
44 162
45 163
46 164
47 165
48 166
49 167
50 168
51 169
52 170
53 171
54 172
55 173
56 174
57 175
58 176
59 177
60 178
The Erro-Tobbio ultramafic body (Voltri Massif, Ligurian Alps, Fig. 1) exposes kilometre-scale unaltered peridotites, mostly devoid of Alpine overprint (Bezzi & Piccardo, 1971; Chiesa *et al.*, 1975; Ernst & Piccardo, 1979; Ottonello *et al.*, 1979; Hoogerduijn Strating *et al.*, 1990, 1993; Piccardo *et al.*, 1990, 1992, 2004; Scambelluri *et al.*, 1991; Vissers *et al.*, 1991; Borsi *et al.*, 1996; Capponi *et al.*, 1999; Rampone *et al.*, 2004, 2005), allowing the study of the pre-Alpine structural and chemical mantle evolution. The Erro-Tobbio unit is mostly made of variably serpentized spinel-bearing lherzolites to harzburgites. Previous petrologic and structural studies documented a tectono-metamorphic decompressional evolution of these mantle rocks, from deep lithospheric settings ($P > 15\text{-}20 \text{ kbar}$) to shallow depths ($P < 5 \text{ kbar}$), with a progressive reequilibration from spinel- to plagioclase- to amphibole-facies conditions (Hoogerduijn Strating *et al.*, 1990, 1993; Vissers *et al.*, 1991; Rampone *et al.*, 2005), and the development of extensional shear zones forming spinel tectonites, plagioclase-, hornblende-, chlorite-bearing mylonites and serpentinite mylonites (Hoogerduijn Strating *et al.*, 1993). This extension-related exhumation was accompanied by multiple episodes of melt percolation and intrusion, namely: 1) a first open-system olivine-saturated reactive porous flow at spinel-facies conditions, leading to the dissolution of mantle clinopyroxene and orthopyroxene, and crystallization of olivine; 2) a melt-rock reaction at plagioclase-facies conditions ($< 8\text{-}10 \text{ kbar}$) leading to the formation of plagioclase-bearing impregnated peridotites, by dissolution of olivine and crystallization of plagioclase \pm opx \pm cpx; 3) multiple episodes of gabbroic intrusions at shallow depths ($P < 5 \text{ kbar}$) (Piccardo *et al.*, 2004; Rampone *et al.*, 2004, 2005, 2014, 2016, 2018; Borghini *et al.*, 2007; Borghini & Rampone, 2007; Piccardo & Vissers, 2007; Rampone & Borghini, 2008). Geochronological studies on gabbroic rocks from the Alpine-Apennine ophiolites indicate a large time span of gabbroic intrusions ($\sim 20 \text{ Ma}$) in the Alpine Tethys (Rampone *et al.*, 2014 and reference therein). The Erro-Tobbio gabbroic intrusions yield the oldest Sm-Nd age of the crustal gabbroic sequences within the Alpine-Apennine ophiolites with an age of $178 \pm 5 \text{ Ma}$ (Rampone *et al.*, 2014), therefore representing early melt

1
2
3 167 intrusions in thinned lithospheric mantle exhumed at ocean-continent transition domains ([Rampone](#)
4 & [Piccardo, 2000](#); [Manatschal & Müntener, 2009](#)).
5
6
7 169 In the South-Eastern part of the Erro-Tobbio peridotite, the impregnated mantle peridotites
8 170 are in irregular contact with a hectometre-size troctolitic body, previously described as a *primitive*
9 *cumulate body* ([Fig. 1](#); [Borghini & Rampone, 2008](#); [Borghini et al., 2007](#); [Rampone & Borghini,](#)
10 [2008](#); [Rampone et al., 2016](#)). Gabbroic dykes crosscut all mantle structures, as well as the troctolitic
11 body-impregnated peridotite contact ([Borghini et al., 2007](#)). [Rampone et al.](#) (2016) recently
12 demonstrated the important effect of the olivine-dissolving, plagioclase-crystallizing melt-rock
13 interaction in the Erro-Tobbio troctolitic body mineral compositions. It leads to significant
14 enrichments in specific trace elements (Zr, Hf, Ti, HREE), coupled with strong HFSE/REE
15 fractionation in olivine.
16
17 177

22 178 Previous geochemical studies documented a significant change in the melt composition
23 between the impregnation event observed in the plagioclase peridotites ([Rampone et al., 2005](#)), and
24 the late troctolite-gabbro intrusions. Impregnating melts had an orthopyroxene-saturated LREE-
25 depleted signature, consistent with single depleted melt increments produced by near-fractional
26 melting of a MORB-type asthenospheric mantle source ([Piccardo et al., 2004](#); [Borghini et al., 2007](#);
27 [Rampone & Borghini, 2008](#)). A similar origin has been inferred for other Alpine-Apennine
28 impregnated peridotites (e.g. [Rampone et al., 1997, 2008, 2018](#); [Piccardo et al., 2007](#)). On the other
29 hand, parental melts to the troctolitic body and late gabbroic discrete intrusions resemble N-MORB-
30 type aggregated melts ([Rampone et al., 1998, 2014, 2016](#); [Borghini & Rampone, 2007](#); [Borghini et](#)
31 [al., 2007](#); [Rampone & Borghini, 2008](#)). Based on available time constraints on the extensional
32 evolution of the Erro-Tobbio mantle, i.e. the Permian age of plagioclase-facies recrystallization
33 documented in impregnated peridotite mylonites ([Rampone et al., 2005](#)), and the Jurassic age of
34 gabbroic intrusions ([Rampone et al., 2014](#)), melt impregnation in the plagioclase peridotites and
35 subsequent troctolite-gabbro intrusion events were likely uncorrelated.
36
37 192
38
39
40
41
42
43
44
45
46
47
48 193

3. FIELD RELATIONSHIPS

50 194
51
52 195 The investigated area exposes a 500-metre wide ultramafic body surrounded by serpentized high-
53 pressure, low-temperature Alpine shear zones. The ultramafic body preserves a pre-Alpine mantle
54 history, displaying the association between mantle peridotites and ultramafic-mafic bodies and
55 intrusions (from plagioclase wehrlites to troctolites to olivine gabbros) ([Fig. 1](#); [Borghini &](#)
56 [Rampone, 2007](#); [Borghini et al., 2007](#); [Rampone & Borghini, 2008](#); [Rampone et al., 2016](#)). Mantle
57 peridotites are **Plagioclase-bearing Iherzolites** showing in places a weak tectonic foliation defined
58
59
60 200

1
2
3 201 by ortho- and clinopyroxene shape-preferred orientations. They are primarily associated to metre-
4 size dunitic pods and centimetre-size pyroxenite layers showing a constant NNE-SSW orientation
5 and strongly dipping to the East (Fig. 1). In the northernmost part of the ultramafic body, the
6 plagioclase lherzolites are in irregular contact with a hectometre-size troctolitic body. The contact is
7 marked by the occurrence of troctolitic and plagioclase-bearing wehrlite apophyses into the mantle
8 peridotites, crosscutting the pyroxenite banding (Borghini & Rampone, 2007; Borghini *et al.*, 2007;
9 Rampone & Borghini, 2008; Rampone *et al.*, 2016). Detailed mapping and sampling in selected
10 outcrops revealed that the inner troctolitic body is characterized by a high modal compositional
11 variability, from plagioclase wehrlite to troctolite to dunite, and a structural complexity
12 characterized by different generations of troctolites showing crosscutting relationships and highly
13 variable olivine texture. In the following, based on these structural criteria, we distinguish different
14 types of troctolites within the mafic body.
15
16
17
18
19
20
21
22
23

24 213 **Troctolite A** is in irregular contact with the mantle peridotites through a transition zone (Fig.
25 214 1) characterized by *plagioclase lherzolites* with decimetre-thick crosscutting troctolite and
26 215 plagioclase-bearing wehrlite apophyses (Fig. 2a) in which it is difficult to easily distinguish the
27 216 different lithologies (Fig. 1). *Troctolites A* show variable olivine modal contents (from 55 to 74
28 217 vol%; Table 1, Fig. 2b,c) and interstitial plagioclase ± clinopyroxene, and it includes decimetre-size
29 218 dunitic pods (Fig. 2d). The modal composition variability between olivine-rich and plagioclase-rich
30 219 troctolite forms a local sub-vertical decimetre-size layering showing a NNW-SSW orientation,
31 220 dipping to the East (Figs. 1, 2b).
32
33
34
35
36
37

38 221 **Troctolite B** is found as decimetre- to metre-size pseudo-tabular elongated bodies
39 222 crosscutting the layering of plagioclase enrichment in *Troctolite A* (Figs. 2c, 3a), and showing
40 223 irregular to sharp contacts with the host troctolite (Figs. 2c, 3a,b). *Troctolite B* bodies display
41 224 extreme olivine textural variations at the scale of a few centimetres, from millimetre-size euhedral
42 225 olivine crystals to centimetre- and decimetre-size hopper and dendritic olivine crystals (Fig. 3c,d,e).
43 226 The olivine textural layering observed in *Troctolite B*, between granular and dendritic portions of
44 227 the pseudo-tabular bodies (Fig. 3e) shows NNE-SSW strike and dips steeply to the East, similarly to
45 228 the plagioclase enrichment layering in *Troctolite A* (Fig. 1).
46
47
48
49
50
51
52

53 229 The peridotites and troctolitic bodies are both intruded by decametre-size **Gabbroic**
54 230 **intrusions**, centimetre- to metre-thick troctolitic to olivine gabbro dykes and centimetre-thick
55 231 dykelets, all striking NW-SSE, and dipping to the East (40-50°; Figs. 1, 2a; Borghini & Rampone,
56 232 2007; Borghini *et al.*, 2007) although in places dykelets occur as conjugate pairs. Dykes and
57 233 dykelets are in straight and sharp contact with the host rock and show no chilled margins. They
58 234 display a grain-size variability, from fine grains towards the margin of the intrusion (millimetre-size

1
2
3 235 crystals), to coarse grains (centimetre-size crystals) in the core of the dyke. Figure 4 summarizes the
4 field relationships mapped in the studied Erro-Tobbio ultramafic body, between *Plagioclase*
5 *lherzolites*, *Troctolite A*, *Troctolite B*, and *Gabbroic Intrusions*.
6
7 237
8 238
9
10 239 **4. SAMPLING AND ANALYTICAL METHODS**
11
12 240
13
14 241 We used samples of *Spinel Lherzolites*, *Plagioclase Lherzolites*, *Troctolites* and *Gabbroic*
15 *intrusions* collected during previous petrological investigations of the studied area (Fig. 1; Rampone
16 *et al.*, 2004, 2005, 2014, 2016; Borghini & Rampone, 2007; Borghini *et al.*, 2007), as well as newly
17 243 collected samples of *Troctolite* and *Gabbroic intrusions*. The *Spinel* and *Plagioclase Lherzolites*
18 244 have been sampled in a location nearby the troctolitic body, where the alteration is much less
19 245 developed than elsewhere within the Erro-Tobbio peridotites. These samples are used as a structural
20 246 and chemical reference of the mantle protolith, prior to the formation of the troctolitic body and
21 247 gabbroic dykes. Table 1 reports the modal composition of the 40 studied samples, namely 3 spinel
22 248 lherzolites, 4 plagioclase lherzolites, 11 troctolites A, 1 dunite pod, 5 wehrlite and troctolite
23 249 apophyses, 10 troctolite B, and 6 troctolitic to olivine gabbro intrusions. We performed structural
24 250 EBSD mapping of all samples, and mineral major (EPMA) element chemical analyses of 24
25 251 samples, namely 2 spinel lherzolites, 2 plagioclase lherzolites, 7 troctolites A, 1 dunite pod, 2
26 252 wehrlite and troctolite apophyses, 5 troctolites B, and 5 troctolitic to olivine gabbro intrusions.
27 253 Detailed methodologies for EBSD and mineral major elements analyses can be found in
28 254 Supplementary Material.
29
30
31 255 **5. PETROGRAPHY**
32
33 256
34
35 257
36 258
37
38 259 *Spinel lherzolites* show protogranular to porphyroclastic assemblages of olivine, orthopyroxene,
39 260 clinopyroxene and spinel grains. Olivine and pyroxenes (orthopyroxene + clinopyroxene) are
40 261 deformed, and display kink bands and undulatory extinctions, respectively. Clinopyroxenes and
41 262 orthopyroxenes both show thin exsolution lamellae of the complementary pyroxene. Spinel are
42 263 found as granular grains in the lherzolitic matrix and in orthopyroxene + spinel symplectites at the
43 264 rim of orthopyroxene porphyroclasts, previously described as an effect of cooling of the peridotites
44 265 and equilibration at lithospheric temperatures (970-1100°C; Rampone *et al.*, 2005; Rampone &
45 266 Borghini, 2008). The spinel lherzolites display melt-rock interaction microstructures with the
46 267 development of olivine embayments replacing mantle pyroxenes (i.e. pyroxene dissolution and
47 268 olivine crystallization). These microstructures, associated to an increase of olivine modal

1
2
3 269 compositions, have been extensively described in the Alpine-Apennine ophiolites (Piccardo *et al.*,
4 270 2004; Rampone *et al.*, 2005, 2008; Piccardo & Vissers, 2007; Rampone & Borghini, 2008; Basch *et*
5 271 *al.*, 2018) and in the Othris Massif (Dijkstra *et al.*, 2003), and were interpreted as the result of a
6 272 pyroxene-dissolving, olivine crystallizing reactive melt percolation at spinel facies.
7 273
8 274

9 275 **Plagioclase Iherzolites** have been previously described as the replacive product of melt
10 276 impregnation of the spinel Iherzolites (Borghini *et al.*, 2007). They show similar textures and
11 277 microstructures to the spinel facies protolith but are characterized by an enrichment in undeformed
12 278 interstitial plagioclase and orthopyroxene (Table 1), developing embayments on kinked olivine and
13 279 exsolved clinopyroxene. These melt-rock reaction microstructures are indicative of an
14 280 orthopyroxene-saturated composition of the impregnated melt, as previously described in the
15 281 Alpine-Apennine ophiolitic peridotites (Rampone *et al.*, 1997, 2005, 2008, 2016, 2018; Müntener &
16 282 Piccardo, 2003; Piccardo *et al.*, 2004; Borghini & Rampone, 2007; Borghini *et al.*, 2007; Rampone
17 283 & Borghini, 2008; Basch *et al.*, 2018) and in the Othris Massif (Dijkstra *et al.*, 2003).
18 284
19 285

20 286 **Troctolite A** shows a hypidiomorphic texture and variable grain size, from centimetre-size
21 287 anhedral to millimetre-size euhedral olivine crystals. Olivine occurs either i) as fine-grained
22 288 undeformed euhedral crystals embedded in interstitial to poikilitic plagioclase and clinopyroxene
23 289 (Fig. 5a,b), or ii) as coarse (up to centimetre-size) deformed corroded grains, displaying kink bands
24 290 (Fig. 5c,d). These two types of olivine are commonly found together, and in places fine-grained
25 291 euhedral crystals of olivine embedded in poikilitic plagioclase or clinopyroxene show the same
26 292 crystallographic orientation as a neighbouring coarsened corroded grain of olivine (Fig. 5c).
27 293
28 294

29 295 Within **Troctolite A**, the textural variability includes small dunitic domains (olivine > 90
30 296 vol%; Fig. 6a,b,c), in which interstitial plagioclase surrounds millimetre-size to centimetre-size
31 297 zones free of interstitial minerals, and plagioclase-rich domains (Fig. 6d), in which single olivines
32 298 are entirely embedded in poikilitic plagioclase ± clinopyroxene. Clinopyroxene, orthopyroxene, and
33 299 amphibole are found as thin “vermicular” crystals at the contact between olivine and poikilitic
34 300 minerals and have been previously interpreted as post-cumulus crystallization of trapped melts
35 301 (progressively evolving during late-stage closed system crystallization; Borghini & Rampone, 2007;
36 302 Borghini *et al.*, 2007). Spinel are found in the matrix both associated to olivine as millimetre-size
37 303 corroded grains (Fig. 6a,d), and associated to poikilitic plagioclase and clinopyroxene, as subhedral
38 304 to euhedral smaller grains (~100-200 µm, Fig. 6d). **Troctolite apophyses** (part of **Troctolite A**) are
39 305 very rich in coarse deformed corroded grains of olivine (Fig. 6b), and undeformed fine-grained
40 306 olivine is rare.
41 307
42 308

43 309 **Troctolite B** pseudotabular bodies crosscut the host **Troctolite A** structures. They are
44 310 characterized by lower olivine modal contents (from 45 to 60 vol%, Table 1) than the host
45 311

1
2
3 303 *Troctolite A* (from 55 vol% to 97 vol% olivine; [Table 1](#)). Moreover, *Troctolite B* shows an extreme
4 olivine textural variation, from millimetre-size euhedral crystals ([Fig. 7a](#)) to centimetre-size hopper
5 ([Fig. 7b](#)), to decimetre-size dendritic and skeletal olivine ([Figs. 3b,c,d,e, 7c,d](#)), all showing absent to
6 weak deformation ([Fig. 6e](#)). In places, this textural variability leads to the formation of a layering
7 ([Fig. 4](#)), but all olivine morphologies can also be found together at the centimetre-scale ([Fig. 6e](#)).
8
9
10 307
11
12 308 The ***Gabbroic intrusions*** (gabbroic lenses, dykes and dykelets) are mostly made of olivine
13 gabbros and minor troctolites, displaying hypidiomorphic texture and fine- to coarse-grained olivine
14 size. Subhedral plagioclase is the main rock-forming mineral (from 59 to 69 vol% modal content of
15 plagioclase, [Table 1](#)). Clinopyroxene is mostly found as large anhedral crystals including pre-
16 existing euhedral plagioclase ± olivine. Olivines (from 15 to 30 vol% modal olivine, [Table 1](#)) are
17 found both as euhedral grains included in plagioclase ± clinopyroxene, and anhedral interstitial
18 crystals in plagioclase-clinopyroxene-olivine aggregates, indicative of a eutectic crystallization of
19 the melt. These textural features in the gabbroic intrusions are indicative of an olivine – plagioclase
20 – clinopyroxene crystallization sequence.
21
22 314
23
24 315
25
26 316
27
28
29 318 **6. OLIVINE CRYSTALLOGRAPHIC PREFERRED ORIENTATIONS**
30
31 319
32
33 320 In all studied samples of *Spinel Lherzolite*, *Plagioclase Lherzolites* and *Troctolite*, a clear and
34 representative olivine CPO could be quantified, however because of large grain size of plagioclase
35 and pyroxenes ([Fig. 8](#); [Bunge, 1982](#); [Ben Ismail & Mainprice, 1998](#)), no reliable CPO of the
36 interstitial minerals could be obtained at the thin section scale. In *Gabbroic intrusions*, fine-grained
37 euhedral plagioclase crystals also allow a representative quantification of the plagioclase CPO ([Fig.](#)
38 [9](#)).
39
40 324
41
42 325
43
44 Olivines in ***Spinel Lherzolites*** (ETR2, ETR4A, ETR4B in [Table 1](#)) are characterized by an
45 axial-[100] CPO, with [100] axis showing the strongest preferred orientation in the foliation plane,
46 parallel to the lineation, [010] axis maximum oriented normal to the foliation plane, and [001]
47 maximum within the foliation plane, normal to the lineation ([Fig. 8](#)). The J-Index, representative of
48 the fabric strength (e.g., [Bunge, 1982](#); [Ben Ismail & Mainprice, 1998](#); [Mainprice *et al.*, 2014](#)),
49 ranges from 3.64 to 5.59 in spinel peridotites. Most natural peridotites show J-Index values of
50 olivine CPO between 2 and 20 ([Tommasi *et al.*, 2000](#); [Soustelle *et al.*, 2009](#)).
51
52 331
53
54 332
55
56 Olivines in ***Plagioclase Lherzolites*** (P1A, P1B in [Table 1](#)) are characterized by a strong
57 axial-[010] CPO (J-Index = 5.5-7), with the strongest axis orientation being [010] normal to the
58 foliation, and a girdle orientation of [100] and [001] within the foliation plane, showing a maximum
59 parallel and normal to the lineation, respectively ([Fig. 8](#)).
60
61

1
2
3 337 In **Troctolite A with dunitic aggregates** (Fig. 6a,b,c; MF7A1, MF7A2, MF7C1, MF96A,
4 MF96B in Table 1) and in the *Dunite* pod associated to the *Troctolite A* (MF104A in Table 1, Fig.
5 2c), all samples are characterized by a relatively weak (J-Index = 2.04-3.83) but clear axial-[100]
6 olivine CPO, with strongly oriented [100] axes within the foliation plane, [010] axes normal to the
7 foliation, and a scatter of the [001] olivine axis orientation (Fig. 8). This olivine CPO is similar to
8 that observed in the *Spinel Lherzolites* (Fig. 8). *Troctolite Apophyses* show a range of weak olivine
9 CPOs from axial-[100] to axial-[010] (J-Index = 1.86-2.1), similar to the CPO observed in *Spinel*
10 341 *Lherzolites* and *Plagioclase Lherzolites*, respectively.
11 342
12 343
13 344
14
15 345
16

17 345 In **Troctolite A without dunitic aggregates** (Fig. 6d; MF21, MF15, MF97, MF102B1 in Table
18 346 1) shows a very weak to random orientation of the [100] and [010] axes, and increased
19 347 concentrations of the [001] olivine axis (J-Index = 2.17-3.06).

20 348 In **Gabbroic intrusions** (MF20II, MF24, MF11A1, MF99 in Table 1) show very weak olivine
21 349 CPO (J-Index = 1.21-1.83) characterized by [010] and [001] showing clear maxima normal and
22 350 within the foliation plane, respectively (Fig. 9). Plagioclase shows a weak (J-Index = 1.79-4.60)
23 351 (010)[100] CPO characterized by a strong orientation of the [010] axis normal to the foliation plane
24 352 (Fig. 9).

25 353 Olivines in the granular part of **Troctolite B** (MF46A, MF94B in Table 1) are characterized
26 354 by a strong orientation of the [010] and [001] axes normal and within the foliation plane, parallel to
27 355 the lineation, respectively (Fig. 9). This (010)[001] olivine CPO is similar to that observed in the
28 356 *Gabbroic intrusions* (Benn & Allard, 1989, Jousselin *et al.*, 2012). The coarse poikilitic minerals in
29 357 Troctolite B samples do not allow a reliable characterization of the Plagioclase CPO at the thin
30 358 section scale (Fig. 9).

41 359 42 360 7. MAJOR ELEMENT MINERAL COMPOSITIONS

43 361
44
45 362 Representative major element compositions of olivine, clinopyroxene, plagioclase, orthopyroxene
46 and spinel analyzed in *Spinel lherzolites*, *Plagioclase lherzolites*, *Troctolites A*, *Dunite*, *Troctolites*
47 363 *B* and *Gabbroic intrusions* are reported in Tables 2-6 and the complete dataset is given in
48 364 Supplementary Tables S1-5. Overall our data show consistency with mineral compositions reported
49 365 in previous studies of the Erro-Tobbio peridotites and associated gabbroic rocks (troctolitic body
50 366 and gabbroic lenses and dykes) (Rampone *et al.*, 1993, 1998, 2004, 2005, 2016; Borghini &
51 367 Rampone, 2007; Borghini *et al.*, 2007).

52 368 Olivines in *Spinel lherzolites* and *Plagioclase lherzolites* show rather homogeneous high
53 369 Forsterite contents ($Fo = 89.5\text{-}90.5 \text{ mol\%}$ and $Fo = 89.6\text{-}90.3 \text{ mol\%}$, respectively; Fig. 10a) (Table
54 370

1
 2
 3 371 2). Olivines in *Troctolites A* and *B* have lower and more variable Forsterite contents ($\text{Fo} = 87.3\text{-}89.2$
 4 mol%). Within the troctolitic body, the main variations are observed between samples rather than
 5 within a single sample (Fig. 10a). No correlation is observed between the different olivine
 6 morphologies described in *Troctolite A* or *B* and Forsterite contents. Olivines within the *Dunite* pod
 7 associated to *Troctolite A* show contents of Forsterite = 88.2-89.1 mol% similar to olivines in the
 8 *Troctolite A* (Fig. 10a). The *Wehrlite Apophysis* MF47A (Table 1) has the lowest Forsterite content
 9 analyzed in *Troctolite A* ($\text{Fo} = 87.3\text{-}87.7$ mol%). *Gabbroic intrusions* show a wide range of
 10 variation of Forsterite contents in olivine from primitive compositions in the troctolitic intrusions
 11 (up to $\text{Fo} = 89.2$ mol%) to more evolved compositions in olivine gabbros ($\text{Fo} = 81.3$ mol%) (Table
 12 1; Fig. 10b).

13 377
 14 378
 15 379
 16 380
 17 381 **Clinopyroxene** cores in *Spinel Lherzolites* show high Mg-numbers ($\text{Mg\#} = 90.0\text{-}91.6$
 18 mol%), high $\text{Cr}_2\text{O}_3 = 0.82\text{-}1.33$ wt% and $\text{Al}_2\text{O}_3 = 5.2\text{-}7.4$ wt%, and low $\text{TiO}_2 = 0.30\text{-}0.58$ wt%
 19 (Table 3; Fig. 11a,b) contents. Impregnated *Plagioclase Lherzolites* show similar Mg-value ($\text{Mg\#} =$
 20 382 89.6-91.1 mol%) and $\text{TiO}_2 = 0.4\text{-}0.53$ wt% contents, higher $\text{Cr}_2\text{O}_3 = 1.02\text{-}1.40$ wt%, and lower
 21 383 $\text{Al}_2\text{O}_3 = 2.83\text{-}5.27$ wt% concentrations. *Gabbroic intrusions* exhibit clinopyroxene compositions
 22 384 consistent with olivine gabbros and troctolites from the South-West Indian Ridge (Dick *et al.*,
 23 385 2002), with a positive correlation between Mg-number ($\text{Mg\#} = 83.5\text{-}90.8$ mol%), Cr ($\text{Cr}_2\text{O}_3 = 0.18\text{-}$
 24 386 1.15 wt%), and Al ($\text{Al}_2\text{O}_3 = 2.4\text{-}3.7$ wt%), and negative correlation with Ti ($\text{TiO}_2 = 0.42\text{-}1.41$ wt%)
 25 387 (Fig. 11a,b). Clinopyroxenes in *Troctolite A* (and associated *Dunite*) and *Troctolite B* show high Cr
 26 388 ($\text{Cr}_2\text{O}_3 = 1.17\text{-}1.67$ wt%) and low Al ($\text{Al}_2\text{O}_3 = 3.1\text{-}5.0$ wt%) and Ti contents ($\text{TiO}_2 = 0.12\text{-}0.92$
 27 389 wt%) (Fig. 11a,b).

28 391
 29 392 Figure 11c,d shows the correlation between the clinopyroxene composition and its
 30 393 microstructural site. As previously documented by Borghini & Rampone (2007), clinopyroxenes in
 31 394 *Troctolite A* show progressively decreasing Cr_2O_3 ($\text{Cr}_2\text{O}_3 = 0.78\text{-}1.67$ wt%) and increasing TiO_2
 32 395 ($\text{TiO}_2 = 0.12\text{-}1.24$ wt%) contents from core to rim to interstitial to vermicular microstructural sites,
 33 396 at constant Mg-number ($\text{Mg\#} = 87.7\text{-}91.0$ mol%).

34 397
 35 398 The Cr_2O_3 , Al_2O_3 and TiO_2 compositional variability in clinopyroxene is well observed in
 36 399 major elements core-rim profiles within single clinopyroxene grains (Fig. 12a-d). A progressive
 37 400 decrease in Cr_2O_3 (from 1.5 to 1.0 wt%) and Al_2O_3 (from 4 to 3 wt%), coupled with an increase in
 38 401 TiO_2 (from 0.4 to 1 wt%) is observed in the profiles, from the inner core towards the contact
 39 402 between clinopyroxene and olivine (Rampone *et al.*, 2005). As documented by Borghini *et al.*
 40 403 (2007), the strong heterogeneity of Cr_2O_3 , TiO_2 and Al_2O_3 in clinopyroxenes of *Troctolites A* (Fig.
 41 404 11c,d) is thus related to within-sample variations clearly correlated with microstructural site.

1
2
3 404 Geochemical variations in the profiles are observed from ~200 μ m to the contact with the olivine
4
5 405 (Fig. 12a-d).

6
7 406 **Plagioclases** in the *Troctolite A* (Table 4) are characterized by low and variable Anorthite
8 407 contents (An = 52.9-66.8 mol%) (Fig. 13). The same variability is observed in *Troctolites B*, with
9
10 408 Anorthite contents = 55.1-66.1 mol%. Plagioclases in *Gabbroic intrusions* show lower Anorthite =
11
12 409 51.6-62.7 mol%. In all samples of *Troctolite A* and *Troctolite B*, a correlation is observed between
13
14 410 the microstructural site and the Anorthite content of the analyzed plagioclase crystal. Thin
15
16 411 interstitial crystals and rims of large grains systematically show lower Anorthite than the
17
18 412 plagioclase cores (Fig. 13), leading to a variation of Anorthite content up to 10 mol% within a
19 413 single sample, in both *Troctolites A* and *Troctolites B*.

20 414 Again, these geochemical variations are well observed in major element profiles from core
21 415 to rim of plagioclase crystals, at the contact with olivine. A progressive decrease in Anorthite
22
23 416 content (from 66 to 56 mol%), CaO (from 14 to 12 wt%), and Al₂O₃ (from 31 to 30 wt%) is
24
25 417 observed in the profiles towards the rim and the contact with olivine (Fig. 12e-h), as previously
26
27 418 documented by Borghini & Rampone (2007). Therefore, as observed for clinopyroxene, the strong
28
29 419 compositional variation reported in single samples of *Troctolite A* and *B* (up to 10% Anorthite
30
31 420 content, Fig. 3.13) is not due to variations between different crystals but to the zonation observed at
32
33 421 the scale of a single grain (Fig. 12e-h). As documented in the clinopyroxene-olivine profiles, the
34
35 422 chemical zoning in plagioclase is observed from ~200 μ m to the contact with the olivine,
36
37 423 irrespective of its textural type (coarse deformed corroded grain or small undeformed granular
38 424 crystal).

39 425 In *Gabbroic intrusions*, no systematic zoning is observed in plagioclase, and the analyzed
40
41 426 range of Anorthite concentration is mainly observed between samples (Fig. 13), with plagioclase in
42
43 427 troctolitic dykes showing higher Anorthite contents (MF11A1, MF99, An = 53.8-62.7 mol%; Table
44
45 428 1) than plagioclases forming the olivine gabbro dykes (MF2A, MF24, An = 51.6-54.6 mol%; Table
46 429 1).

47
48 430 **Orthopyroxenes** (Table 5) analyzed in evolved *Gabbroic intrusions* show lower Mg-
49
50 431 number (Mg# = 84.53 mol%) than the homogeneous orthopyroxene compositions analyzed in
51
52 432 *Spinel* and *Plagioclase Lherzolites* (Mg# = 89.64-90.54 mol%).

53 433 **Spinels** in *Spinel Lherzolites* (Table 6) exhibit high Mg-number (Mg# = 66.9-72.8 mol%),
54
55 434 low Cr-number (Cr# = 14.2-18.6 mol%), and very low TiO₂ (0.02-0.16 wt%), similar to spinel
56
57 435 compositions in plagioclase-free peridotites from the South-West Indian Ridge (Seyler *et al.*, 2003).
58
59 436 In *Gabbroic intrusions*, spinels show low Mg-number (Mg# = 25.2-36.1 mol%), and high Cr-
60 437 number (Cr# = 63.6-69.0 mol%) and TiO₂ (1.22-1.49 wt%).

1
2
3 438 In *Troctolites A*, *Dunites* and *Troctolites B*, spinels show Mg-numbers (Mg# = 19.2-55.6
4 mol%) and Cr-numbers (Cr# = 40.5-64.5 mol%) intermediate between spinel compositions in the
5 *Spinel lherzolites* and the *Gabbroic intrusions*, and a negative correlation is observed between the
6 Mg-number and the Cr-number, consistent with spinel compositions in Troctolites from the Mid-
7 Atlantic Ridge (Miller *et al.*, 2009). Some spinels in *Troctolites A*, *Troctolites B*, and most of them
8 in *Dunites* show strong enrichments in TiO₂ (0.79-3.27 wt%), up to twice the TiO₂ concentrations
9 analyzed in *Gabbroic intrusions*. The negative correlation between Mg-number and TiO₂
10 concentrations in spinel analyzed in *Troctolites A*, associated *Dunites* and *Troctolites B* is consistent
11 with the trend reported for spinels analyzed in troctolites from the Mid-Atlantic Ridge (Miller *et al.*,
12 2009).

13 444
14 445
15 446
16 447
17 448
18 449
19 450
20 451
21 452
22 453
23 454
24 455
25 456
26 457
27 458
28 459
29 460
30 461
31 462
32 463
33 464
34 465
35 466
36 467
37 468
38 469
39 470
40 471
41 472
42 473
43 474
44 475
45 476
46 477
47 478
48 479
49 480
50 481
51 482
52 483
53 484
54 485
55 486
56 487
57 488
58 489
59 490
60 491
Figure 14a shows the Mg-Fe partitioning between olivine and clinopyroxene in all studied lithotypes. Overall, the studied samples show a positive correlation between Forsterite contents in olivine (from Fo = 81.3 mol% in *Gabbroic intrusions* to Fo = 90.5 mol% in *Spinel Lherzolite*) and Mg-value in clinopyroxene (from Mg# = 83.5 mol% in *Gabbroic intrusions* to Mg# = 91.6 mol% in *Spinel Lherzolite*). This correlation is consistent with the Mg-Fe equilibrium lines calculated between olivine and clinopyroxene by Lissenberg & Dick (2008) ($Kd_{ol/cpx}(Fe\#) = 1.30$) (Fig. 14a). Couples of olivine and clinopyroxene cores in *Troctolites A*, *Dunite*, and *Troctolites B* show compositions (Fo = 87.3-89.2 mol%, Mg# = 87.7-91 mol%) that are intermediate between the Mg-rich couples analyzed in *Spinel* and *Plagioclase Lherzolites* (Fo = 89.5-90.5 mol%, Mg# = 89.6-91.6 mol%) and the most evolved compositions in *Gabbroic intrusions* (Fo = 81.3-89.2 mol%, Mg# = 83.5-90.8 mol%).

Figure 14b shows Anorthite and Forsterite contents (mol%) in plagioclase-olivine core couples in *Troctolite A*, *Troctolite B* and *Gabbroic intrusions*. Within the troctolitic body, plagioclase-olivine couples show significant variations in Anorthite content of plagioclase cores (An = 58.4-66.8 mol%) at constant Forsterite composition in associated olivines (87.3-89.2 mol%), similar to what was reported at the easternmost South-West Indian Ridge (61-67°E) (Paquet *et al.*, 2016). By contrast, *Gabbroic intrusions* define a trend of evolution characterized by a positive correlation between Anorthite content in plagioclase cores and Forsterite content in olivine (from An_{51.6}-Fo_{81.3} to An_{62.7}-Fo_{89.2}). This trend in *Gabbroic intrusions* shows a similar slope to the compositional arrays defined by olivine gabbros in the oceanic lower crust from the South-West Indian Ridge (Hole 735B: Dick *et al.*, 2002), Mid-Atlantic Ridge (Ross & Elthon, 1997; Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2009; Miller *et al.*, 2009), and Pineto ophiolite (Sanfilippo & Tribuzio, 2012), but shifted towards higher Forsterite values of olivine (Fig. 14b).

1
2
3 471 Clinopyroxene Mg-number (mol%) shows similar correlations with plagioclase Anorthite
4 (mol%) (Fig. 14c), with relatively constant Mg-number in *Troctolite A* and *Troctolite B* (Mg# =
5 87.7-91.0 mol%) at varying Anorthite content (An = 55.1-67.0 mol%), similar to mineral
6 compositions analyzed at the easternmost South-West Indian Ridge (61-67°E) (Paquet *et al.*, 2016).
7
8 474 The *Gabbroic intrusions* show a positive correlation between Mg-number in clinopyroxene and
9 Anorthite content in plagioclase (from An_{51.6}-Mg#_{83.7} to An_{62.7}-Mg#_{90.1}). The slope defined by the
10 475 Anorthite – Mg-value (cpx) covariation in *Gabbroic intrusions* is consistent with the trends
11 documented in the oceanic gabbroic suites at the Mid-Atlantic Ridge (Ross & Elthon, 1997;
12 476 Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2009; Miller *et al.*, 2009; Ferrando *et al.*,
13 477 2018), South-West Indian Ridge (Dick *et al.*, 2002), and in the Pineto gabbroic crust (Sanfilippo &
14 478 Tribuzio, 2012), but shifted towards higher Mg-values of clinopyroxene (Fig. 14c). Also reported is
15 479 the compositional field of Alpine-Apennine troctolites, olivine gabbros and gabbros (Hébert *et al.*,
16 480 1989; Tribuzio *et al.*, 1999; Montanini *et al.*, 2008; Sanfilippo & Tribuzio, 2012), characterized by
17 481 lower Anorthite contents in plagioclase at a given Mg-value in clinopyroxene, compared to oceanic
18 482 gabbroic series (Fig. 14c; SWIR Hole 735B: Dick *et al.*, 2002; MAR Hole U1309D: Ross & Elthon,
19 483 1997; Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2009; Miller *et al.*, 2009; Ferrando
20 484 *et al.*, 2018).
21 485
22 486
23 487
24 488
25 489
26 490
27 491
28 492
29 493
30 494
31 495
32 496
33 497
34 498
35 499
36 500
37 501
38 502
39 503
40 504

8. DISCUSSION

8.1. Replacive origin of the Troctolite A

41 As documented in previous studies and herein, the Erro-Tobbio troctolitic body crosscuts the host
42 impregnated *Plagioclase lherzolites* and associated pyroxenite banding (Fig. 4; Borghini &
43 44 Rampone, 2007; Borghini *et al.*, 2007; Rampone *et al.*, 2016), includes *Dunite pods* and develops
45 46 wehrlite and troctolite apophyses into the mantle *Plagioclase Lherzolites* (Fig. 2a). The *Troctolite A*
47 48 shows a strong textural complexity with the occurrence of two distinct types of olivines within
49 50 single samples (Fig. 6a,b,c,d), i.e. millimetre-size undeformed granular olivine grains (Fig. 5a,b)
51 52 and coarse (up to centimetre-size), deformed and corroded crystals (Fig. 5c,d). As inferred in
53 54 oceanic settings during formation of olivine-rich troctolites (Suhr *et al.*, 2008; Drouin *et al.*, 2010),
55 56 Rampone *et al.* (2016) interpreted the textural complexity of the Erro-Tobbio troctolites as the
57 58 result of melt-rock interactions leading to the dissolution of the olivine matrix and crystallization of
59 60 interstitial plagioclase. Although they were not able to distinguish two olivine generations in a
61 specific troctolite sample, they inferred that the millimetre-size undeformed granular olivine grains

1
2
3 could represent a second generation of “*olivine 2*”, whether of magmatic origin or representing
4 disrupted coarse olivine grains. Detailed EBSD analysis (size, shape, misorientation; Fig. 6) allows
5 us to interpret the coarse deformed and corroded olivine as the pre-existing, possibly mantle relict
6 “*olivine 1*”. The occurrence of coarse corroded grains almost disrupted into several granular
7 olivines (Fig. 5c) suggests that most of the small undeformed olivine grains are formed after
8 extensive corrosion and disruption of the coarsened pre-existing olivines. This process of textural
9 evolution of the olivine matrix during progressive melt-rock interaction and replacive formation of
10 olivine-rich troctolites has been previously inferred in oceanic settings (Suhr *et al.*, 2008; Drouin *et*
11 *al.*, 2010; Ferrando *et al.*, 2018) and recently demonstrated in ophiolitic settings at the Mt.Maggiore
12 peridotitic body (Basch *et al.*, 2018).
13
14

15 At the scale of the sample, the *Troctolite A* is also characterized by variations in the texture
16 of the olivine matrix (taken as a whole, *olivines 1 + olivines 2*), between samples characterized by
17 plagioclase-free dunitic aggregates surrounded by interstitial phases (Fig. 6a,b,c), and disaggregated
18 samples where single olivines are completely embedded in poikilitic plagioclase (Fig. 6d). This
19 textural variability is well correlated with a change in olivine CPO. The olivine matrix of *Troctolite A*
20 characterized by plagioclase-free dunitic aggregates shows an axial-[100] fabric (Fig. 8), similar
21 to the *Spinel lherzolites* and *Dunite pods*. This axial-[100] CPO is typically reported in natural
22 peridotites deformed under asthenospheric conditions (e.g., Tommasi *et al.*, 2000; Le Roux *et al.*,
23 2008; Soustelle *et al.*, 2009), and indicates that plastic deformation was related to dislocation creep
24 with joint activation of (010)[100] and (001)[100] slip systems, the most easily activated at high
25 temperature conditions (1100-1200°C) (Ben Ismail & Mainprice, 1998; Tommasi *et al.*, 2000;
26 Karato *et al.*, 2008; Drouin *et al.*, 2010; Higbie & Tommasi, 2012). The samples characterized by a
27 disaggregated olivine matrix, embedded in poikilitic plagioclase, show scattered orientations of
28 [100] and [010] olivine axes, and a stronger concentration of the [001] axis (Fig. 8). Such olivine
29 CPOs have been previously reported in zones of melt accumulation in the Oman Moho Transition
30 Zone (Ceuleneer & Rabinowicz, 1992; Boudier & Nicolas, 1995; Jousselin *et al.*, 1998; Dijkstra *et*
31 *al.*, 2002; Higbie & Tommasi, 2012) and during the replacive formation of olivine-rich troctolites at
32 the Atlantis Massif (Drouin *et al.*, 2010). It has been interpreted as a loss of cohesion of the solid
33 matrix during impregnation at high melt/rock ratios (20-40% melt fraction; Rosenberg & Handy,
34 2005). Melt-rock interaction microstructures, indicating the corrosion of the pre-existing olivine
35 matrix, together with the preservation of dunitic pods within the host *Troctolite A* (Figs. 2d, 4) and
36 the correlation between the observed texture of the olivine matrix and its CPO (Fig. 8), suggest a
37 replacive formation of *Troctolites A*. We infer that they formed from a mantle *Dunite* protolith
38 (itself preserving the mantle precursor axial-[100] CPO), after reactive percolation of a MORB-type
39
40

1
2
3 539 melt at variable melt/rock ratios (Fig. 15). The disaggregation of the olivine matrix associated to the
4 loss of the olivine axial-[100] CPO are indicative of high instantaneous melt-rock ratios (>20-40%;
5 Rosenberg & Handy, 2005), whereas the samples preserving the mantle olivine CPO indicate a
6 reactive percolation at lower melt/rock ratios (Fig. 15). Texture and CPO analyses, together with the
7 occurrence of preserved dunitic pods within the *Troctolite A* thus indicate that *Troctolites A* are
8 likely the replacive product of reactive percolation and impregnation of a pristine dunitic matrix by
9 melts crystallizing plagioclase and minor clinopyroxene.
10 543
11 544
12 545
13
14 546

15 546 Peculiar geochemical compositional trends of the rock-forming minerals, not consistent with
16 a simple fractional crystallization process, support the replacive origin of the *Troctolites A*. Despite
17 547 strong variations in olivine modal compositions (from 55 vol% in troctolites to 97 vol% in dunitic
18 548 pods), olivines and clinopyroxenes in the *Dunite* and the *Troctolite A* show a narrow range of
19 549 composition ($Fo = 88.2\text{-}89.1 \text{ mol\%}$; Figs. 10a, 14b; $Mg\# = 89\text{-}91 \text{ mol\%}$; Fig. 14c). These constant
20 550 compositions of the mafic minerals (Forsterite in olivine and Mg-value in clinopyroxene) are
21 551 coupled with significant within-sample variations in plagioclase Anorthite contents ($An = 52.9\text{-}66.8$
22 552 mol%; Fig. 14a,b), and therefore do not follow the compositional trends of fractional crystallization
23 553 defined by the oceanic gabbroic sequences (South-West Indian Ridge, Dick *et al.*, 2002; Mid-
24 554 Atlantic Ridge, Ross & Elthon, 1997; Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*,
25 555 2009; Miller *et al.*, 2009). These peculiar compositional trends (Fig. 14a,b) are indicative of the
26 556 buffering of the melt Mg-value by olivine-dissolving reactive porous flow percolation (e.g. Collier
27 557 & Kelemen, 2010; Sanfilippo *et al.*, 2016b; Borghini *et al.*, 2018). Mineral compositions in
28 558 *Troctolite A* are similar to those documented in the amagmatic easternmost South-West Indian
29 559 Ridge troctolites and olivine gabbros (61-67°E; Paquet *et al.*, 2016). These peculiar mineral
30 560 chemistry co-variations were attributed to melt-rock interaction processes involving olivine and
31 561 orthopyroxene dissolution by a percolating Na-rich basic melt, and subsequent crystallization of
32 562 plagioclase and clinopyroxene.
33 563
34 564
35
36 558

48 565 8.2. Thermodynamic model of olivine-consuming reactive crystallization 49 50 566

51 567 To better constrain and quantify the role of reactive crystallization in the formation of the peculiar
52 568 An-Fo and An-Mg# compositional trends in the Erro-Tobbio troctolitic body (Fig. 14a,b), we
53 569 performed an assimilation – fractional crystallization (AFC) geochemical modeling assuming
54 570 variable dissolved mass of olivine and concomitant melt crystallization, using the *pMELTS*
55 571 thermodynamic program (Ghiorso *et al.*, 2002). This model aims at reproducing the diffuse reactive
56 572 percolation of a high-temperature melt (1270°C) into the shallow lithospheric mantle. Based on

1
2
3 573 mineral-mineral partitioning, [Rampone et al. \(2016\)](#) documented high temperature of equilibration
4 (> 1100-1200°C) in both troctolites and host peridotites. The interaction process thus occurred at
5 574 relatively high mantle temperatures.
6 575
7 576

8 576 The Erro-Tobbio ultramafic body does not include any basaltic intrusion, precluding direct
9 information on the *Troctolite A* parental melt composition. However, few unaltered primitive
10 577 basaltic intrusions (LOI < 2%; Mg# > 70 mol%) have been documented in the Alpine-Apennine
11 ophiolites. The initial melt composition used is a primitive MORB-type basalt (Mg# = 70.75 mol%)
12 578 associated to the Pineto gabbroic suite ([Saccani et al., 2008](#); Alpine ophiolite), which composition
13 579 is given in [Table 7](#). This primitive melt is characterized by a relatively low Ca/Na ratio (Ca# =
14 580 61.54 mol%), most likely as the result of low degrees of mantle melting ([Klein & Langmuir, 1987](#);
15 581 [Montanini et al., 2008](#); [Saccani et al., 2008](#); [Renna et al., 2018](#)), similarly to what was described at
16 582 the easternmost South-West Indian Ridge (Ca# = 55-60 mol%; [Paquet et al., 2016](#)). Such a Na-rich
17 583 parental melt composition is consistent with the Alpine-Apennine compositional field of gabbroic
18 584 rocks ([Fig. 14c](#); [Hébert et al., 1989](#); [Tribuzio et al., 1999](#); [Montanini et al., 2008](#); [Sanfilippo &](#)
19 585 [Tribuzio, 2012](#)), showing more Na-rich plagioclase compositions (at given Mg-value in
20 586 clinopyroxene) than the oceanic gabbroic series at the South-West Indian Ridge and Mid-Atlantic
21 587 Ridge ([Fig. 14c](#)).
22 588
23 589

24 590 We modelled isobaric (P = 4 kbar) reactive fractional crystallization of the primitive MORB
25 591 melt, cooling at steps of 5°C while dissolving a fixed mass of olivine (0g, 1g, 2g, 3g per 100g of
26 592 melt) per 1°C of cooling ([Fig. 16](#)). Similar models of reactive crystallization using the *pMELTS*
27 593 thermodynamic program ([Ghiorso et al., 2002](#)) have been previously performed by [Collier &](#)
28 594 [Kelemen \(2010\)](#) and [Sanfilippo et al. \(2016\)](#), involving the assimilation of mantle lherzolites at 6
29 595 kbar. In the Erro-Tobbio, the *Troctolite A* includes decimetre-size dunitic pods ([Fig. 2d](#)) preserved
30 596 from melt impregnation and no mantle pyroxene relict is found in any dunite or troctolite sample.
31 597 This suggests that the protolith of the Erro-Tobbio troctolite was a *Dunite*. Microstructures in
32 598 *Troctolite A* indicate the late crystallization of poikilitic clinopyroxene in minor proportions ([Table](#)
33 599 [1](#); [Fig. 5b](#)), therefore suggesting relatively low crystallization pressures (<7kbar), leading to the late
34 600 saturation of clinopyroxene on a MORB-type melt liquid line of descent ([Husen et al., 2016](#)). Based
35 601 on field, microstructural observations, and previous geobarometric estimates within the *Troctolite A*
36 602 (3-5 kbar; [Borghini et al., 2007](#)), we decided to model the dissolution of 100% olivine Fo₈₉ (olivine
37 603 composition in the *Dunite* pods) at variable assimilation rates (see below) during a reactive
38 604 fractional crystallization process occurring at 4 kbar. Recent experimental work ([Borghini et al.,](#)
39 605 [2018](#); [Francombe, 2018](#)) demonstrated the possible replacive formation of an olivine-rich troctolite
40 606 from a dunite protolith and the efficient buffer of the melt composition towards high Mg-values by

1
2
3 607 olivine assimilation. They also demonstrated that the reactivity of a melt saturated in olivine (AH6;
4 Husen *et al.*, 2016) with a dunitic matrix Fo₉₀ is driven by the chemical disequilibrium between the
5 olivine forming the dunitic matrix (more forsteritic) and the olivine in equilibrium with the melt
6 (see also Liang, 2003). The partial dissolution of the dunitic matrix is thus associated with the
7 precipitation of an olivine of different composition that is in equilibrium with the modified melt.
8
9 611
10 612
11

12 612 Figure 16 shows the computed crystal line of descent of olivine, plagioclase and
13 613 clinopyroxene and Table S6 reports the evolution of the melt and mineral compositions during
14 614 fractional and reactive crystallization. The computed crystallization order is [olivine-plagioclase-
15 615 clinopyroxene], as expected from the crystallization of a MORB melt at low pressures (<7 kbar;
16 Bender *et al.*, 1978; Husen *et al.*, 2016). The starting melt composition is in equilibrium with an
17 616 olivine Fo = 87 mol%, but at increasing dissolution rates (from 0g/°C to 3g/°C of cooling), the
18 617 equilibrium Forsterite content in olivine and the Mg-value in clinopyroxene are progressively
19 618 buffered by the composition of the dissolved olivine (Fo = 89 mol%). It is worth noting that this
20 619 extensive olivine dissolution implies the crystallization of new olivine crystals and/or
21 620 recrystallization of the olivine matrix all along the reactive percolation process (Table S6; Liang,
22 621 2003). Table S6 shows that even at high dissolution rates (3g/°C of cooling), the early stages of
23 622 reactive crystallization (1270-1260°C) characterized by crystallization of olivine only, do not
24 623 involve a significant variation in melt mass (olivine dissolved/olivine crystallized = 0.88-1.12). This
25 624 supports the dissolution-reprecipitation of the pre-existing dunitic matrix. Moreover, given that in
26 625 the Troctolite A, most small undeformed olivine crystals embedded in poikilitic plagioclase and
27 626 clinopyroxene are the result of extensive corrosion and disruption of large olivine grains (and
28 627 therefore do not represent newly formed magmatic olivines; see previous Discussion 8.1), it is
29 628 likely that olivine precipitation mostly consisted in the recrystallization of the pre-existing olivine
30 629 rims (Liang, 2003; Morgan & Liang, 2005). However, no compositional variation was found
31 630 between the olivine cores (possibly relict) and rims (possibly recrystallized) (Fig. 12i-l). This is
32 631 presumably due to similar composition of the pre-existing (Fo = 89 mol%; Table 2) and
33 632 recrystallized olivine (Fo ≈ 88 mol%; Table S6), and to the fast Mg-Fe diffusion rates of olivine at
34 633 magmatic temperatures ($t_{\text{equ}} < 200$ years for 3 mm radius; Dohmen & Chakraborty, 2007; Ferrando
35 634 et al., 2018).

36 636 During the reactive fractional crystallization process, the Anorthite contents in plagioclase
37 637 evolve freely towards lower values along the crystal line of descent (Fig. 16), leading to the reactive
38 638 crystallization trends of variation previously described by Collier & Kelemen (2010) and Sanfilippo
39 639 et al. (2016) (decreasing Anorthite contents in plagioclase at constant Forsterite contents in olivine
40 640 and Mg-value in clinopyroxene). Crystal lines of descent at high rates of olivine dissolution during

1
2
3 641 reactive crystallization (from 2g/°C to 3g/°C of cooling) fit well the analyzed peculiar trends of
4 mineral covariation in the Erro-Tobbio troctolites and confirms the strong implication of olivine-
5 dissolving reactive porous flow processes in the formation of the *host Troctolite A* from a pre-
6 existing dunite (Figs. 15, 16).
7
8 644

9
10 645 Clinopyroxene cores from the *Troctolite A* show high Cr₂O₃ contents (Fig. 11a,c), similar to
11 those described in oceanic gabbroic rocks analyzed at the Mid-Atlantic Ridge (Lissenberg & Dick,
12 646 2008; Lissenberg & MacLeod, 2016; Ferrando *et al.*, 2018), easternmost South-West Indian Ridge
13 647 (Paquet *et al.*, 2016) and Godzilla Megamullion (Sanfilippo *et al.*, 2016b), and in olivine-rich
14 648 troctolites from the Internal Liguride ophiolite (Renna & Tribuzio, 2011; Renna *et al.*, 2016).
15 649 Although *pMELTS* (Ghiorso *et al.*, 2002) does not allow the Cr₂O₃ compositional modeling of
16 650 clinopyroxene, the process of partial dissolution and recrystallization of a dunite (olivine + spinel)
17 651 described above could well explain the Cr₂O₃ enrichments observed in the clinopyroxene cores
18 652 (Fig. 11a,c). Within *Troctolite A*, interstitial minerals often develop embayments on corroded relict
19 653 of spinel grains. This indicates partial dissolution of Cr-rich spinel (Cr# = 55-65 in the dunite; Table
20 654 6) together with the olivine during the reactive melt percolation process, as was previously
21 655 described in oceanic settings and in the Internal Liguride ophiolites during replacive formation of
22 656 olivine-rich gabbroic rocks (Lissenberg & Dick, 2008; Renna & Tribuzio, 2011; Lissenberg &
23 657 MacLeod, 2016; Paquet *et al.*, 2016; Renna *et al.*, 2016; Sanfilippo *et al.*, 2016b; Ferrando *et al.*,
24 658 2018). The corrosion of spinel leads to Cr₂O₃ enrichments in the reacting melt, therefore explaining
25 659 the Cr-rich compositions of clinopyroxenes crystallized from the percolating modified melt (Fig.
26 660 11a). The corrosion of spinel during impregnation of the dunite and the Cr-rich character of the melt
27 661 is also suggested within *Troctolite A* by the crystallization of numerous fine-grained euhedral
28 662 spinels associated with the poikilitic plagioclase (Fig. 6d).
29
30 663
31 664
32 665
33 666
34 667
35 668
36 669
37 670
38 671
39 672
40 673
41 674

44 665 8.3. Magmatic origin of Troctolite B

45 666
46 667
47 668
48 669
49 670
50 671
51 672
52 673
53 674
54 675
55 676
56 677
57 678
58 679
59 680
60 681
61 682
62 683
63 684
64 685
65 686
66 687
67 688
68 689
69 690
70 691
71 692
72 693
73 694
74 695
75 696
76 697
77 698
78 699
79 700
80 701
81 702
82 703
83 704
84 705
85 706
86 707
87 708
88 709
89 710
90 711
91 712
92 713
93 714
94 715
95 716
96 717
97 718
98 719
99 720
100 721
101 722
102 723
103 724
104 725
105 726
106 727
107 728
108 729
109 730
110 731
111 732
112 733
113 734
114 735
115 736
116 737
117 738
118 739
119 740
120 741
121 742
122 743
123 744
124 745
125 746
126 747
127 748
128 749
129 750
130 751
131 752
132 753
133 754
134 755
135 756
136 757
137 758
138 759
139 760
140 761
141 762
142 763
143 764
144 765
145 766
146 767
147 768
148 769
149 770
150 771
151 772
152 773
153 774
154 775
155 776
156 777
157 778
158 779
159 780
160 781
161 782
162 783
163 784
164 785
165 786
166 787
167 788
168 789
169 790
170 791
171 792
172 793
173 794
174 795
175 796
176 797
177 798
178 799
179 800
180 801
181 802
182 803
183 804
184 805
185 806
186 807
187 808
188 809
189 810
190 811
191 812
192 813
193 814
194 815
195 816
196 817
197 818
198 819
199 820
200 821
201 822
202 823
203 824
204 825
205 826
206 827
207 828
208 829
209 830
210 831
211 832
212 833
213 834
214 835
215 836
216 837
217 838
218 839
219 840
220 841
221 842
222 843
223 844
224 845
225 846
226 847
227 848
228 849
229 850
230 851
231 852
232 853
233 854
234 855
235 856
236 857
237 858
238 859
239 860
240 861
241 862
242 863
243 864
244 865
245 866
246 867
247 868
248 869
249 870
250 871
251 872
252 873
253 874
254 875
255 876
256 877
257 878
258 879
259 880
260 881
261 882
262 883
263 884
264 885
265 886
266 887
267 888
268 889
269 890
270 891
271 892
272 893
273 894
274 895
275 896
276 897
277 898
278 899
279 900
280 901
281 902
282 903
283 904
284 905
285 906
286 907
287 908
288 909
289 910
290 911
291 912
292 913
293 914
294 915
295 916
296 917
297 918
298 919
299 920
300 921
301 922
302 923
303 924
304 925
305 926
306 927
307 928
308 929
309 930
310 931
311 932
312 933
313 934
314 935
315 936
316 937
317 938
318 939
319 940
320 941
321 942
322 943
323 944
324 945
325 946
326 947
327 948
328 949
329 950
330 951
331 952
332 953
333 954
334 955
335 956
336 957
337 958
338 959
339 960
340 961
341 962
342 963
343 964
344 965
345 966
346 967
347 968
348 969
349 970
350 971
351 972
352 973
353 974
354 975
355 976
356 977
357 978
358 979
359 980
360 981
361 982
362 983
363 984
364 985
365 986
366 987
367 988
368 989
369 990
370 991
371 992
372 993
373 994
374 995
375 996
376 997
377 998
378 999
379 999
380 999
381 999
382 999
383 999
384 999
385 999
386 999
387 999
388 999
389 999
390 999
391 999
392 999
393 999
394 999
395 999
396 999
397 999
398 999
399 999
400 999
401 999
402 999
403 999
404 999
405 999
406 999
407 999
408 999
409 999
410 999
411 999
412 999
413 999
414 999
415 999
416 999
417 999
418 999
419 999
420 999
421 999
422 999
423 999
424 999
425 999
426 999
427 999
428 999
429 999
430 999
431 999
432 999
433 999
434 999
435 999
436 999
437 999
438 999
439 999
440 999
441 999
442 999
443 999
444 999
445 999
446 999
447 999
448 999
449 999
450 999
451 999
452 999
453 999
454 999
455 999
456 999
457 999
458 999
459 999
460 999
461 999
462 999
463 999
464 999
465 999
466 999
467 999
468 999
469 999
470 999
471 999
472 999
473 999
474 999
475 999
476 999
477 999
478 999
479 999
480 999
481 999
482 999
483 999
484 999
485 999
486 999
487 999
488 999
489 999
490 999
491 999
492 999
493 999
494 999
495 999
496 999
497 999
498 999
499 999
500 999
501 999
502 999
503 999
504 999
505 999
506 999
507 999
508 999
509 999
510 999
511 999
512 999
513 999
514 999
515 999
516 999
517 999
518 999
519 999
520 999
521 999
522 999
523 999
524 999
525 999
526 999
527 999
528 999
529 999
530 999
531 999
532 999
533 999
534 999
535 999
536 999
537 999
538 999
539 999
540 999
541 999
542 999
543 999
544 999
545 999
546 999
547 999
548 999
549 999
550 999
551 999
552 999
553 999
554 999
555 999
556 999
557 999
558 999
559 999
560 999
561 999
562 999
563 999
564 999
565 999
566 999
567 999
568 999
569 999
570 999
571 999
572 999
573 999
574 999
575 999
576 999
577 999
578 999
579 999
580 999
581 999
582 999
583 999
584 999
585 999
586 999
587 999
588 999
589 999
590 999
591 999
592 999
593 999
594 999
595 999
596 999
597 999
598 999
599 999
600 999
601 999
602 999
603 999
604 999
605 999
606 999
607 999
608 999
609 999
610 999
611 999
612 999
613 999
614 999
615 999
616 999
617 999
618 999
619 999
620 999
621 999
622 999
623 999
624 999
625 999
626 999
627 999
628 999
629 999
630 999
631 999
632 999
633 999
634 999
635 999
636 999
637 999
638 999
639 999
640 999
641 999
642 999
643 999
644 999
645 999
646 999
647 999
648 999
649 999
650 999
651 999
652 999
653 999
654 999
655 999
656 999
657 999
658 999
659 999
660 999
661 999
662 999
663 999
664 999
665 999
666 999
667 999
668 999
669 999
670 999
671 999
672 999
673 999
674 999
675 999
676 999
677 999
678 999
679 999
680 999
681 999
682 999
683 999
684 999
685 999
686 999
687 999
688 999
689 999
690 999
691 999
692 999
693 999
694 999
695 999
696 999
697 999
698 999
699 999
700 999
701 999
702 999
703 999
704 999
705 999
706 999
707 999
708 999
709 999
710 999
711 999
712 999
713 999
714 999
715 999
716 999
717 999
718 999
719 999
720 999
721 999
722 999
723 999
724 999
725 999
726 999
727 999
728 999
729 999
730 999
731 999
732 999
733 999
734 999
735 999
736 999
737 999
738 999
739 999
740 999
741 999
742 999
743 999
744 999
745 999
746 999
747 999
748 999
749 999
750 999
751 999
752 999
753 999
754 999
755 999
756 999
757 999
758 999
759 999
760 999
761 999
762 999
763 999
764 999
765 999
766 999
767 999
768 999
769 999
770 999
771 999
772 999
773 999
774 999
775 999
776 999
777 999
778 999
779 999
780 999
781 999
782 999
783 999
784 999
785 999
786 999
787 999
788 999
789 999
790 999
791 999
792 999
793 999
794 999
795 999
796 999
797 999
798 999
799 999
800 999
801 999
802 999
803 999
804 999
805 999
806 999
807 999
808 999
809 999
810 999
811 999
812 999
813 999
814 999
815 999
816 999
817 999
818 999
819 999
820 999
821 999
822 999
823 999
824 999
825 999
826 999
827 999
828 999
829 999
830 999
831 999
832 999
833 999
834 999
835 999
836 999
837 999
838 999
839 999
840 999
841 999
842 999
843 999
844 999
845 999
846 999
847 999
848 999
849 999
850 999
851 999
852 999
853 999
854 999
855 999
856 999
857 999
858 999
859 999
860 999
861 999
862 999
863 999
864 999
865 999
866 999
867 999
868 999
869 999
870 999
871 999
872 999
873 999
874 999
875 999
876 999
877 999
878 999
879 999
880 999
881 999
882 999
883 999
884 999
885 999
886 999
887 999
888 999
889 999
890 999
891 999
892 999
893 999
894 999
895 999
896 999
897 999
898 999
899 999
900 999
901 999
902 999
903 999
904 999
905 999
906 999
907 999
908 999
909 999
910 999
911 999
912 999
913 999
914 999
915 999
916 999
917 999
918 999
919 999
920 999
921 999
922 999
923 999
924 999
925 999
926 999
927 999
928 999
929 999
930 999
931 999
932 999
933 999
934 999
935 999
936 999
937 999
938 999
939 999
940 999
941 999
942 999
943 999
944 999
945 999
946 999
947 999
948 999
949 999
950 999
951 999
952 999
953 999
954 999
955 999
956 999
957 999
958 999
959 999
960 999
961 999
962 999
963 999
964 999
965 999
966 999
967 999
968 999
969 999
970 999
971 999
972 999
973 999
974 999
975 999
976 999
977 999
978 999
979 999
980 999
981 999
982 999
983 999
984 999
985 999
986 999
987 999
988 999
989 999
990 999
991 999
992 999
993 999
994 999
995 999
996 999
997 999
998 999
999 999
1000 999
1001 999
1002 999
1003 999
1004 999
1005 999
1006 999
1007 999
1008 999
1009 999
1010 999
1011 999
1012 999
1013 999
1014 999
1015 999
1016 999
1017 999
1018 999
1019 999
1020 999
1021 999
1022 999
1023 999
1024 999
1025 999
1026 999
1027 999
1028 999
1029 999
1030 999
1031 999
1032 999
1033 999
1034 999
1035 999
1036 999
1037 999
1038 999
1039 999
1040 999
1041 999
1042 999
1043 999
1044 999
1045 999
1046 999
1047 999
1048 999
1049 999
1050 999
1051 999
1052 999
1053 999
1054 999
1055 999
1056 999
1057 999
1058 999
1059 999
1060 999
1061 999
1062 999
1063 999
1064 999
1065 999
1066 999
1067 999
1068 999
1069 999
1070 999
1071 999
1072 999
1073 999
1074 999
1075 999
1076 999
1077 999
1078 999
1079 999
1080 999
1081 999
1082 999
1083 999
1084 999
1085 999
1086 999
1087 999
1088 999
1089 999
1090 999
1091 999
1092 999
1093 999
1094 999
1095 999
1096 999
1097 999
1098 999
1099 999
1100 999
1101 999
1102 999
1103 999
1104 999
1105 999
1106 999
1107 999
1108 999
1109 999
1110 999
1111 999
1112 999
1113 999
1114 999
1115 999
1116 999
1117 999
1118 999
1119 999
1120 999
1121 999
1122 999
1123 999
1124 999
1125 999
1126 999
1127 999
1128 999
1129 999
1130 999
1131 999
1132 999
1133 999
1134 999
1135 999
1136 999<br

1
2
3 675 Ligurian ophiolites (Renna *et al.*, 2016) and in crystallization experiments (Donaldson, 1976, 1977;
4 676 Faure *et al.*, 2003, 2007) as resulting from a rapid disequilibrium crystallization of an undercooled
5 677 melt (driven by a difference between the liquidus temperature of the melt and the melt temperature).
6 678
7 679 Olivine CPO in the granular portion of the *Troctolite B* shows random orientations of the
8 680 [100] axis, strong concentrations of the [010] axis normal to the foliation, and [001] axis being the
9 681 strongest axis concentration within the foliation plane (Fig. 9). In *Gabbroic intrusions*, similar
10 682 olivine CPOs are observed, correlated with strong orientations of plagioclase [010] axis normal to
11 683 the foliation plane (parallel to the [010] axis of olivine) (Fig. 9). Benn & Allard (1989) and
12 684 Jousselin *et al.* (2012) previously described such CPOs of olivine in the Oman lower crustal layered
13 685 gabbros and interpreted these orientations as the shape-related physical orientation of the crystals
14 686 during magmatic flow.
15 687
16 688

17 689 Based on the crosscutting relationships between *Troctolite B* and the *host Troctolite A* (Figs.
18 690 2b, 3a,c), the textural variability of olivine (Figs. 3b,c,d,e, 6e), and the CPO indicative of magmatic
19 691 flow within the granular part of the *Troctolite B* (Fig. 9), we infer that the *Troctolite B* originated as
20 692 a magmatic segregation within the hot pre-existing *Troctolite A* during focused percolation of the
21 693 melt modified after the diffuse reactive percolation forming the *Troctolite A* (see the modeling
22 694 below). The irregular contacts between the *Troctolite B* intrusions and the host *Troctolite A* indicate
23 695 a brittle-ductile rheological behaviour, thus suggesting a minor temperature difference (<50°C)
24 696 between the system and the intruding melt. The rheological evolution from diffuse percolation
25 697 (forming *Troctolite A*) to focused percolation (related to a slight decrease in the temperature of the
26 698 system) allowed higher quantities of melt to segregate and to form a magmatic flow (Fig. 9),
27 699 leading to the crystallization of the *Troctolite B*.
28 700
29 701

30 702 The mineral major elements compositions of olivine, plagioclase and clinopyroxene in
31 703 *Troctolite B* are less variable than in *Troctolite A*. The Forsterite contents in olivine ($Fo = 87.3\text{--}89.2$;
32 704 Figs. 10a, 14b,c), the Mg-values ($Mg\# = 88.2\text{--}91$; Figs. 11, 14a,c) and Cr_2O_3 contents in
33 705 clinopyroxene (up to $Cr_2O_3 = 1.55$ wt%; Fig. 11a,c), and the Anorthite contents in plagioclase ($An = 55.1\text{--}66.1$; Fig. 14) are in the same range of composition as previously described in *Troctolite A*.
34 706 The geochemical model (using *pMELTs*; Ghiorso *et al.*, 2002) of reactive fractional crystallization
35 707 developed for the *host Troctolite A* (Fig. 16) also fits the major element compositions of the
36 708 *Troctolite B* mineral couples, showing constant Forsterite contents in olivine and Mg-values in
37 709 clinopyroxene at decreasing Anorthite contents in plagioclase (Figs. 14b,c, 16). This indicates that
38 710 the magmatic *Troctolite B* crystallized from the melt modified after the diffuse reactive percolation
39 711 originating the *Troctolite A*. Table 7 reports the initial melt composition and liquidus temperature of
40 712 the Pineto primitive MORB melt used in the thermodynamic model of fractional and reactive
41 713

1
2
3 709 crystallization (see **Discussion 8.2**), and the modified melt composition and liquidus temperature
4 computed using *pMELTs* (Ghiorso *et al.*, 2002), after dissolution of 5, 10, and 15 grams of olivine
5 (corresponding to a 5°C step of cooling for the modelled 1g/°C, 2g/°C and 3g/°C; **Fig. 16**). It should
6 be noted that the modified compositions reported in **Table 7** consider only the dissolution of the
7 olivine matrix during a 5°C cooling step, and not the subsequent precipitation of olivine from the
8 melt. This approach allows to compute the maximum increase in liquidus temperature driven by
9 olivine assimilation (**Table 7**) in the modified melts, and therefore to assess the maximum degree of
10 undercooling developed prior to olivine reprecipitation. The dissolution of olivine leads to a local
11 increase of the Mg-value of the melt, resulting in an increase of the liquidus temperature of the melt
12 up to 83°C (relative to the liquidus temperature of the initial melt), for the assimilation of 15 grams
13 of olivine during one 5°C step of cooling (3g/°C of cooling; Ghiorso *et al.*, 2002; **Table 7**). Hence,
14 the described process of partial dissolution of the olivine matrix is able to rapidly develop a
15 significant degree of undercooling of the melt, by increasing its liquidus temperature at almost
16 constant melt temperature. We infer that the textural variability of olivine observed within the
17 magmatic *Troctolite B* is the result of local changes in the degree of undercooling of the segregated
18 melt, as was previously described in the Rum layered intrusion (Donaldson, 1974, 1976, 1977,
19 1982; O'Driscoll *et al.*, 2007). Crystallization experiments of mafic/ultramafic melts performed
20 over a range of degrees of undercooling and cooling rates (Donaldson, 1976, 1977, Donaldson *et*
21 *al.*, 1975; Faure *et al.*, 2003, 2007) highlighted the possible development of hopper and dendritic
22 olivine morphologies at degrees of undercooling as low as 10-20°C. Olivine dissolution involved in
23 the reactive formation of *Troctolite A* is therefore a very good candidate to explain the skeletal and
24 dendritic morphologies of magmatic olivine crystallized in *Troctolite B*.
25
26

41 731 The lack of significant geochemical variation between the different olivine morphologies
42 (granular, hopper and skeletal) precludes the identification of a clear scenario for their formation
43 sequence. However, slightly more evolved major elements composition of olivine (Fo = 87.5-88,
44 Fig. 10), plagioclase (An = 60-62, Fig. 13) and clinopyroxene (Mg# = 88.7-89.5) in the granular
45 part of *Troctolite B* (MF46A, **Table 1**) possibly implies a late crystallization, after the rapid growth
46 of skeletal dendritic olivines. Moreover, O'Driscoll *et al.* (2007) previously proposed for the Rum
47 layered intrusion that the absence of initial suspended olivine in the primitive magmatic flow may
48 favour the development of a melt undercooling. These arguments point to a model of formation of
49 *Troctolite B* where dendritic olivines rapidly formed in the undercooled melt, prior to its evolution
50 and crystallization of the granular olivines (Fig. 17).
51
52

53 739 **8.4. Intrusion of the modified melt – Formation of the Gabbroic intrusions**
54
55 740
56
57 741
58
59
60 742

1
2
3 743
4
5 744 *Gabbroic intrusions* crosscut both the troctolitic body and the associated impregnated *Plagioclase*
6 *Iherzolites* and show straight contacts with their host rock (Borghini & Rampone, 2007; Borghini *et*
7 *al.*, 2007; Rampone *et al.*, 2016). Olivines and plagioclases from *Gabbroic intrusions* show CPO
8 consistent with the shape-related orientation of the crystals in a magmatic flow (Benn & Allard,
9 1989; Jousselin *et al.*, 2012). Major elements compositions of the rock-forming minerals (Forsterite
10 747 content in olivine, Anorthite content in plagioclase and Mg-value in clinopyroxene) show a positive
11 748 correlation and an evolution following a fractional crystallization trend, parallel to the
12 749 compositional trends reported for oceanic gabbroic series at the Mid-Atlantic Ridge (Fig. 14b,c)
13 750 (Ross & Elthon, 1997; Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2009; Miller *et*
14 751 *al.*, 2009; Ferrando *et al.*, 2018) and the South-West Indian Ridge (Dick *et al.*, 2002). However,
15 752 although showing similar mineral geochemical trends of evolution to the oceanic gabbroic series,
16 753 their compositions are shifted towards higher Forsterite contents in olivine and Mg-value in
17 754 clinopyroxene at a given Anorthite content in plagioclase (Fig. 14b,c). The most primitive *Gabbroic*
18 755 *intrusions* show mineral major element compositions similar to those analyzed in *Troctolite B*, thus
19 756 indicating a common parental melt. Accordingly, we infer that *Gabbroic intrusions* formed by
20 757 fractional crystallization of the melt modified after the reactive fractional crystallization that formed
21 758 *Troctolites A* and *B* (Fig. 16), at lower temperatures allowing for brittle behaviour and emplacement
22 759 of the melt in fractures (Borghini *et al.*, 2007; Rampone & Borghini, 2008).
23 760
24 761
25 762
26 763
27 764
28 765
29 766
30 767
31 768
32 769
33 770
34 771
35 772
36 773
37 774
38 775
39 776

In order to test this hypothesis, we performed a geochemical modelling of fractional crystallization (using *pMELTS*; Ghiorso *et al.*, 2002) using as a starting melt the output modified melt composition after previous reactive fractional crystallization (Fig. 18, Table 7). As shown in Figure 18, the fractional crystallization of the modified melt reproduces the chemical covariation arrays observed in *Gabbroic intrusions*, almost parallel to the trends defined by oceanic gabbroic suites but shifted towards Mg-rich mineral compositions of olivine (Forsterite content) and clinopyroxene (Mg-value). This confirms that the *Gabbroic intrusions* parental melt corresponds to the melt modified after formation of *Troctolites A* and *B*, and that no further melt-rock interaction was involved in the fractional crystallization process.

53 772 8.5. Constraints on the geodynamic context and melt-rock interaction processes

54 773
55 774 Geochronological data on the Erro-Tobbio gabbroic intrusions (Sm-Nd, 178 ± 5 Ma; Rampone *et*
56 775 *al.*, 2014), together with gabbroic rocks in the External Liguride units (170-179 Ma Northern
57 776 Apennines; Tribuzio *et al.*, 2004), yield the oldest ages available for the gabbroic crust of the

1
2
3 777 Ligurian Tethys ocean. These ages are older than the continental break-up and onset of oceanization
4 of the Ligurian Tethys (164-166 Ma; [Manatschal & Müntener, 2009](#)). Also, they indicate a ~10 Ma
5 time gap between the early emplacement of the Erro-Tobbio and External Liguride gabbros, and the
6 main magmatic activity of the Ligurian Tethys (155-165 Ma; [Rampone et al., 2014](#) and references
7 therein). Accordingly, the Erro-Tobbio gabbroic intrusions have been interpreted as an early
8 magmatism in thinned lithospheric mantle exhumed at ocean-continent transition settings during the
9 onset of the Jurassic lithospheric extension ([Fig. 19a; Manatschal & Müntener, 2009; Rampone et](#)
10 [al., 2014](#)). The scarcity of gabbroic and basaltic bodies found in the Alpine-Apennine ophiolites
11 (e.g. [Marroni et al., 1998; Tribuzio et al., 2000, 2004; Montanini et al., 2008; Saccani et al., 2008](#)),
12 and the Na-rich composition of the basaltic parental melts ([Fig. 14c; Saccani et al., 2008](#); see
13 **Discussion 8.2**) are consistent with low degree of melting of the upwelling mantle in a slow- to
14 ultra-slow spreading environment ([Klein & Langmuir, 1987; Montanini et al., 2008; Saccani et al.,](#)
15 [2008; Renna et al., 2018; Fig. 19a](#)).

16 Our structural data, showing the partial preservation of the protolith axial-[100] olivine CPO
17 during replacive formation of the *Troctolite A* ([Fig. 8](#)), point to a percolation process occurring at
18 variable instantaneous melt/rock ratios, in an overall low melt supply regime ([Fig. 15](#); see
19 **Discussion 8.1**). Also, our thermodynamic models show that extensive dissolution-precipitation
20 reactions are needed during the multi-stage formation of *Troctolite A* and *Troctolite B* to explain
21 their peculiar compositional trends ([Figs. 16, 19b](#); see **Discussion 8.2, 8.3**). As demonstrated by
22 several mass balance and Assimilation Fractional Crystallization models ([Lissenberg & Dick, 2008;](#)
23 [Sanfilippo et al., 2015b; Paquet et al., 2016; Rampone et al., 2016](#)), modifications of the melt
24 composition during melt-rock interactions are only possible at low melt supply conditions.
25 Chemical core-rim profiles in interstitial phases from *Troctolite A* (plagioclase and clinopyroxene,
26 [Fig. 12a-h](#)) show decreasing Cr_2O_3 and Al_2O_3 , and increasing TiO_2 concentrations in clinopyroxene
27 towards the rim (<200 μm from the contact with olivine), and decreasing Anorthite content, CaO
28 and Al_2O_3 concentrations towards the plagioclase rim. These core-rim chemical zonations in
29 interstitial clinopyroxene and plagioclase suggest an *in-situ* evolution of the melt composition
30 during reactive crystallization at decreasing melt mass ([Borghini & Rampone, 2007; Borghini et al.,](#)
31 [2007; Rampone & Borghini, 2008](#)). This indicates that the process forming the replacive *Troctolite*
32 *A* is not characterized by constant replenishment and efficient extraction of the melt ([Fig. 19b](#)), but
33 rather by sparse melt injections which chemical composition were dominated by the dissolution-
34 precipitation processes.

35 Mineral reactive compositional trends (constant Mg# of olivine and clinopyroxene at
36 variable An content in plagioclase), similar to those observed in the Erro Tobbio troctolitic body,
37

1
2
3 811 have been documented in olivine-rich troctolites from slow-spreading oceanic environments at the
4 easternmost South-West Indian Ridge (Fig. 16; Paquet *et al.*, 2016) and at the Godzilla
5 Megamullion (Fig. 16; Sanfilippo *et al.*, 2016b). Both these settings are characterized by scarce
6 basaltic and gabbroic intrusions in kilometres of exhumed mantle peridotites. In these troctolites,
7 peculiar compositional trends in minerals were interpreted as the result of extensive melt-rock
8 interaction processes involving low magma supplies and melt/rock ratios (Paquet *et al.*, 2016;
9 Sanfilippo *et al.*, 2016b).
10 816
11 817
12 818
13 819
14 820
15 821
16 822
17 823
18 824
19 825
20 826
21 827
22 828
23 829
24 830
25 831
26 832
27 833
28 834
29 835
30 836
31 837
32 838
33 839
34 840
35 841
36 842
37 843
38 844

Replacive olivine-rich troctolites were also described at the Atlantis Massif (IODP Hole U1309D; Blackman *et al.*, 2006; Suhr *et al.*, 2008; Drouin *et al.*, 2009, 2010; Ferrando *et al.*, 2018), associated to a 1415-metre-long crustal section (>90% gabbroic rocks; Blackman *et al.*, 2006). Interestingly, the mineral compositions of these olivine-rich troctolites and associated gabbroic crust follow a trend of fractional crystallization at ~2kbar (Miller *et al.*, 2009). This indicates that the global composition of the percolating MORB melt was not modified during the melt-rock interaction processes and formation of replacive olivine-rich troctolites (Ferrando *et al.*, 2018). Consistently, structural data of the olivine CPO within olivine-rich troctolites from Atlantis Massif suggest high melt supply and melt/rock ratios involved in the melt percolation and dissolution-precipitation reactions (Drouin *et al.*, 2010; Ferrando *et al.*, 2018). This further confirms that low melt/rock ratios are necessary to drive a significant modification of the melt composition during melt-rock interaction processes.

The context of formation of the Erro-Tobbio troctolitic body and associated gabbroic intrusions is therefore representative of a slow- to ultraslow-spreading system characterized by very low melt supply, and therefore allowing the percolating melt composition to be controlled and buffered by the melt-rock interaction processes.

43 834 44 835 9. SUMMARY AND CONCLUSIONS 45 836 46 837 47 838

In the studied field, the Erro-Tobbio peridotites, troctolites and gabbroic intrusions record a multi-stage structural and geochemical evolution involving extensive dissolution-precipitation reactions. It can be summarized as follows: i) The formation of the replacive *Troctolite A* is related to diffuse reactive melt percolation in a pre-existing dunitic matrix (Fig. 19b). Mineral compositions in *Troctolite A* and thermodynamic models indicate a melt-rock interaction-dominated process (Fig. 16), which involves olivine dissolution and crystallization of plagioclase and minor clinopyroxene; ii) Subsequently, the focussing of melts modified after reactive percolation leads to the formation of pseudo-tabular *Troctolite B* magmatic bodies (Fig. 19b). High degrees of undercooling in the

modified melt result in hopper to dendritic olivine morphologies during crystallization of *Troctolite B* (Fig. 17); iii) The late gabbroic dykes, crosscutting the association between the impregnated plagioclase peridotites and *Troctolite A* and *B*, represent the product of fractional crystallization of the same modified melts (Fig. 19b).

The evolution from diffuse reactive percolation to focused reactive percolation, followed by intrusion and fractional crystallization of the *Gabbroic intrusions*, is driven by the decreasing temperature of the exhuming system (Fig. 19a), ruling the rheology of the host rock and the ability of the melt to segregate into magmatic intrusions. The geochemical similarities observed between *Troctolite B* and the most primitive *Gabbroic intrusions* indicate a common modified parental melt, which allows to link the focused percolation and intrusion events. Thus, the multi-stage formation of the troctolitic body and associated gabbroic intrusions (Fig. 19b) are related to a single thermal evolution of the ultramafic body, during the onset of opening of the Ligurian Tethys (Fig. 19a).

This study provides field-controlled constraints on the structural and geochemical modifications induced by melt-rock interaction processes, as a function of the involved melt/rock ratio. At low melt supply and melt/rock ratios, the structure of the protolith is preserved during reactive crystallization, while the melt composition can be easily controlled by the ongoing dissolution-precipitation reactions. This leads to the observed buffer of the melt composition towards high Mg-values in the troctolitic body. In contrast, melt percolation involving high melt supply and melt/rock ratios leads to the loss of cohesion of the solid matrix and pre-existing structure. In such circumstances, the global melt composition cannot be modified during melt-rock interactions and the crystallized minerals follow a fractional crystallization trend, as documented at the Atlantis Massif.

Acknowledgements:

We would like to thank Prof. Joerg Hermann, Dr. Alessio Sanfilippo and an anonymous reviewer for their constructive comments and the increase of the quality of the manuscript. We also thank Paolo Campanella and Alessandra Gavoglio, Christophe Nevado and Doriane Delmas for realisation of the thin section and high-quality polishing, as well as Fabrice Barou for assistance with the EBSD analyses, Andrea Risplendente for assistance with the EPMA analyses, Marco Scarsi and Nicola Campomenosi for assistance with field work, and Giulio Borghini for stimulating discussions. This project has been supported by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA-Grant Agreement No. 608001, "ABYSS", and by the Italian Ministry of Education, University and Research (MIUR)

- 1
2
3 878 [PRIN-2015C5LN35] “Melt-rock reaction and melt migration in the MORB mantle through
4
5 879 combined natural and experimental studies”.
6
7 880
8 881 **References**
9
10 882
11
12 883 Basch, V. (2018) Melt-rock interactions in the oceanic lithosphere: microstructural and
13 petro-geochemical constraints from ophiolites. *PhD thesis, IRIS (Institutional Research Information*
14 *System)*, doi: 10.15167/basch-valentin_phd2018-05-10.
15
16 885
17 886
18
19 887 Basch, V., Rampone, E., Crispini, L., Ferrando, C., Ildefonse, B. & Godard, M. (2018).
20 From mantle peridotites to hybrid troctolites: textural and chemical evolution during melt-rock
21 888 interaction history (Mt.Maggiore, Corsica, France). *Lithos*, doi: 10.1016/j.lithos.2018.02.025.
22 889
23
24 890
25
26 891 Bender, J. F., Hodges, F. N. & Bence, A. E. (1978). Petrogenesis of basalts from the project
27 FAMOUS area: experimental study from 0 to 15 kbars. *Earth and Planetary Science Letters*, **41**,
28 892 277-302, doi: 10.1016/0012-821X(78)90184-X.
29 893
30
31 894
32
33 895 Ben Ismail, W. & Mainprice, D. (1998). An olivine fabric database: an overview of upper
34 mantles fabrics and seismic anisotropy. *Tectonophysics*, **296**, 145-157, doi: 10.1016/S0040-
35 896 1951(98)00141-3.
36 897
37
38 898
39
40 899 Benn, K. & Allard, B. (1989). Preferred mineral orientations related to magmatic flow in
41 ophiolite layered gabbros. *Journal of Petrology*, **30**, 925-946, doi: 10.1093/petrology/30.4.925.
42
43 901
44
45 902 Bezzi, A. & Piccardo, G. B. (1971). Structural features of the Ligurian ophiolites: Petrologic
46 evidence for the ‘oceanic’ floor of the Northern Apennines geosyncline: A contribution to the
47 903 problem of the alpine-type gabbro-peridotite associations. *Memorie della Società Geologica*
48 904 *Italiana*, **10**, 53–63.
49
50 905
51
52 906
53 907 Blackman, D. K., Ildefonse, B., John, B. E., Ohara, Y., Miller, D. J., MacLeod, C. J. &
54
55 908 Expedition 304/305 Scientists (2006). Expedition 304/305. *Proceedings of the Integrated Ocean*
56
57 909 *Drilling Program*, **304/305**, doi: 10.2204/iodp.proc.304305.101.2006.
58
59 910
60

1
2
3 911 Borghini, G. & Rampone, E. (2007). Postcumulus processes in oceanic-type olivine-rich
4 cumulates: the role of trapped melt crystallization versus melt-rock interaction. *Contributions to*
5
6 912 *Mineralogy and Petrology* **154**, 619-633, doi: 10.1007/s00410-007-0217-5.
7
8 913
9
10 914
11
12 915 Borghini, G., Rampone, E., Crispini, L., De Ferrari, R. & Godard, M. (2007). Origin and
13 emplacement of ultramafic–mafic intrusions in the Erro-Tobbio mantle peridotite (Ligurian Alps,
14 Italy), *Lithos*. **94**, 210-229. doi: 10.1016/j.lithos.2006.06.014.
15
16 918
17 919
18 920
19 921
20 922
21 923
22 924
23 925
24 926
25 927
26 928
27 929
28 930
29 931
30 932
31 933
32 934
33 935
34 936
35 937
36 938
37 939
38 940
39 941
40 942
41 943
42 944
43 945
44 946
45 947
46 948
47 949
48 950
49 951
50 952
51 953
52 954
53 955
54 956
55 957
56 958
57 959
58 960
59 961
60 962

10 915 Borghini, G., Rampone, E., Crispini, L., De Ferrari, R. & Godard, M. (2007). Origin and
11 emplacement of ultramafic–mafic intrusions in the Erro-Tobbio mantle peridotite (Ligurian Alps,
12 Italy), *Lithos*. **94**, 210-229. doi: 10.1016/j.lithos.2006.06.014.
13
14 916
15 917
16
17 918
18 919
19 920
20 921
21 922
22 923
23 924
24 925
25 926
26 927
27 928
28 929
29 930
30 931
31 932
32 933
33 934
34 935
35 936
36 937
37 938
38 939
39 940
40 941
41 942
42 943
43 944
44 945
45 946
46 947
47 948
48 949
49 950
50 951
51 952
52 953
53 954
54 955
55 956
56 957
57 958
58 959
59 960
60 961

17 919 Borghini, G., Francombe, J. E. & Fumagalli, P. (2018). Melt-dunite interactions at 0.5 and
18 920 0.7GPa: experimental constraints on the origin of olivine-rich troctolites. *Lithos*, doi:
19 921 10.1016/j.lithos.2018.09.022.
20
21 922
22 923
23 924
24 925
25 926
26 927
27 928
28 929
29 930
30 931
31 932
32 933
33 934
34 935
35 936
36 937
37 938
38 939
39 940
40 941
41 942
42 943
43 944
44 945
45 946
46 947
47 948
48 949
49 950
50 951
51 952
52 953
53 954
54 955
55 956
56 957
57 958
58 959
59 960
60 961

24 923 Borsi, L., Scharer, U., Gaggero, L. & Crispini, L. (1996). Age, origin and geodynamic
25 924 significance of plagiogranites in Iherzolites and gabbros of the Piedmont-Ligurian ocean basin.
26 925 *Earth and Planetary Science Letters*, **140**, 227-241, doi: 10.1016/0012-821X(96)00034-9.
27
28 926
29 927
30 928
31 929
32 930
33 931
34 932
35 933
36 934
37 935
38 936
39 937
40 938
41 939
42 940
43 941
44 942
45 943
46 944
47 945
48 946
49 947
50 948
51 949
52 950
53 951
54 952
55 953
56 954
57 955
58 956
59 957
60 958

31 927 Boudier, F. & Nicolas, A. (1995). Nature of the Transition Zone in the Oman Ophiolite.
32 928 *Journal of Petrology*, **36**, 777-796, doi: 10.1093/petrology/36.3.777.
33
34 929
35 930
36 931
37 932
38 933
39 934
40 935
41 936
42 937
43 938
44 939
45 940
46 941
47 942
48 943
49 944
50 945
51 946
52 947
53 948
54 949
55 950
56 951
57 952
58 953
59 954
60 955

36 930 Bunge, H. J. (1982) Texture analysis in material sciences. *Butterworths, London*
37
38 931
39 932
40 933
41 934
42 935
43 936
44 937
45 938
46 939
47 940
48 941
49 942
50 943
51 944
52 945
53 946
54 947
55 948
56 949
57 950
58 951
59 952
60 953

39 932 Capponi, G., Crispini, L., Silvestri, R. & Vigo, E. (1999). The role of Early Miocene thrust
40 933 tectonics in the structural arrangement of the Voltri Group (Ligurian Alps, Italy): evidence of
41 934 Bandita area. *Ophioliti*, **24**, 13-19.
42
43 935
44 936
45 937
46 938
47 939
48 940
49 941
50 942
51 943
52 944
53 945
54 946
55 947
56 948
57 949
58 950
59 951
60 952

46 936 Ceuleneer, G. & Rabinowicz, M. (1992). Mantle flow and melt migration beneath oceanic
47 937 ridges: Models derived from observation in ophiolites, in mantle flow and melt generation at mid-
48 938 ocean ridges, *Geophysical Monograph Series*, **71**, edited by J. P. Morgan, D.B. Blackman, and J.M.
49 939 Sinton: 123-154, AGU, Washington, D. C.
50
51 940
52 941
53 942
54 943
55 944
56 945
57 946
58 947
59 948
60 949

55 941 Collier, M. L. & Kelemen, P. B. (2010). The Case for Reactive Crystallization at Mid-Ocean
56 942 Ridges, *Journal of Petrology*, **51**, 1913-1940, doi: 10.1093/petrology/egq043.
57
58 943
59 944
60 945

- 1
2
3 944 Chiesa, S., Cortesogno, L., Forcella, F., Galli, M., Messiga, B., Pasquarè, G., Pedemonte, G.
4
5 945 M., Piccardo, G. B. & Rossi, P. M. (1975). Assetto strutturale ed interpretazione geodinamica del
6
7 946 Gruppo di Voltri. *Bulletino della Società Geologica Italiana*, **94**, 555-581.
8 947
9
10 948 Coumans, J. P., Stix, J., Clague, D. A., Minarik, W. G. & Layne G. D. (2016). Melt-rock
11 interaction near the Moho: Evidence from crystal cargo in lavas from near-ridge seamounts.
12 949
13 950 *Geochimica et Cosmochimica Acta*, **191**, 139-164, doi: 10.1016/j.gca.2016.07.017.
14
15 951 De Paolo (1981). Trace element and isotopic effects of combined wallrock assimilation and
16 fractional crystallization. *Earth and Planetary Science Letters*, **53**, 189-202, doi: 10.1016/0012-
17 952 821X(81)90153-9.
18
19 953
20 954
21
22 955 Dick, H. J. B. & Natland, J. H. (1996). Late stage melt evolution and transport in the
23 shallow mantle beneath the East Pacific Rise. In: Gillis, K., Mével, C. and Allan, J. (eds.)
24 956 *Proceedings of the Ocean Drilling Program, Scientific Results*, **147**, 103-134, Ocean Drilling
25 957 Program, College Station, TX.
26
27 958
28
29 959
30
31 960 Dick, H. J. B., Ozawa, K., Meyer, P. S., Niu, Y., Robinson, P. T., Constantin, M., Hebert,
32 961 R., Maeda, J., Natland, J. H., Hirth, J. G. & Mackie, S. M. (2002). Primary silicate mineral
33 962 chemistry of a 1.5-km section of very slow spreading lower ocean crust: ODP Hole 735B,
34 963 Southwest Indian Ridge. In: Natland JH, Dick HJB, Miller DJ, Von Herzen RP (eds) Proc. ODP,
35 964 Sci. Results, vol 176, chap 10. Ocean Drilling Program, College Station, Texas, pp 1-61, doi:
36 965 10.2973/odp.proc.sr.176.001.2002.
37
38 966
39 967
40
41 968 Dick, H. J. B., Tivey, M. A. & Tucholke, B. E. (2008). Plutonic foundation of a slow-
42 spreading ridge segment: Oceanic core complex at Kane Megamullion, 23°30'N, 45°20'W.
43 969 *Geochemistry, Geophysics, Geosystems*, **9**, Q05014, doi: 10.1029/2007GC001645.
44
45
46 970
47
48 971 Dick, H. J. B., Lissenberg, C. J. & Warren, J. M. (2010). Mantle melting, melt transport, and
49 delivery beneath a Slow-Spreading Ridge: The Paleo-MAR from 23°15'N to 23°45'N. *Journal of*
50 972 *Petrology*, **51**, 425-467, doi: 10.1093/petrology/egp088.
51
52
53 973
54
55 974
56
57 975 Dijkstra, A. H., Drury, M. R. & Frijhoff, R. M. (2002). Microstructures and lattice fabrics in
58 976 the Hilti mantle section (Oman Ophiolite): Evidence for shear localization and melt weakening in
59
60

- 1
2
3 977 the crust–mantle transition zone? *Journal of Geophysical Research*, **107**, 2270, doi:
4
5 978 10.1029/2001JB000458.
6
7 979
8 980 Dijkstra, A. H., Barth, M. G., Drury, M. R., Mason, P. R. D. & Vissers, R. L. M. (2003).
9
10 981 Diffuse porous melt flow and melt–rock reaction in the mantle lithosphere at a slow-spreading ridge:
11
12 982 A structural petrology and LA-ICP-MS study of the Othris Peridotite Massif (Greece).
13 983 *Geochemistry, Geophysics, Geosystems*, **4**, 8613, doi: 10.1029/2001GC000278.
14
15 984
16
17 985 Dohmen, R. & Chakraborty, S. (2007). Fe-Mg diffusion in oivine II: point defect chemistry,
18
19 986 change of diffusion mechanisms and a model for calculation of diffusion coefficients in natural
20
21 987 olivine. *Physics and Chemistry of Minerals*, **34**, 409-430, doi: 10.1007/s00269-007-0158-6.
22 988
23
24 989 Donaldson, C. H. (1974). Olivine crystal types in harrisitic rocks of the Rhum pluton and in
25
26 990 Archean spinifex rocks. *Geological Society of American Bulletin*, **85**, 1721-1726, doi:
27 991 10.1130/0016-7606(1974)85<1721:OCTIHR>2.0.CO;2.
28
29 992
30
31 993 Donaldson, C. H. (1976). An experimental investigation of olivine morphology.
32 994 *Contributions to Mineralogy and Petrology*, **57**, 187-213, doi: 10.1007/BF00405225.
33
34 995
35
36 996 Donaldson, C. H. (1977). Laboratory duplication of comb layering in the Rhum pluton.
37
38 997 *Mineralogical Magazine*, **41**, 323-336, doi: 10.1180/minmag.1977.041.319.03.
39 998
40
41 999 Donaldson, C. H. (1982). Origin of some of the Rhum harrisite by segregation of
42
43 1000 intercumulus liquid. *Mineralogical Magazine*, **45**, 201-209, doi: 10.1180/minmag.1982.045.337.23.
44
45 1001
46 1002 Donaldson, C. H., Williams, R.J. & Lofgren, G.E. (1975). A sample holding technique for
47
48 1003 study of crystal growth in silicate melts. *American Mineralogist*, **60**, 324-326.
49
50 1004
51
52 1005 Drouin, M., Godard, M., Ildefonse, B., Bruguier, O. & Garrido, C. (2009). Geochemical and
53
54 1006 petrographic evidence for magmatic impregnation in the oceanic lithosphere at Atlantis Massif,
55
56 1007 Mid-Atlantic Ridge (IODP Hole U1309D, 30°N). *Chemical Geology*, doi:
57 1008 10.1016/j.chemgeo.2009.02.013.
58
59 1009
60

- 1
2
3 1010 Drouin, M., Ildefonse, B. & Godard, M. (2010). A microstructural imprint of melt
4 impregnation in slow spreading lithosphere: olivine-rich troctolites from the Atlantis Massif, Mid-
5 Atlantic Ridge, 30°N, IODP Hole U1309D. *Geochemistry, Geophysics, Geosystems*, **11**, Q06003,
6
7 1012 doi: 10.1029/2009GC002995.
8 1013
9
10 1014
11
12 1015 Dygert, N., Liang, Y. & Kelemen, P. B. (2016). Formation of Plagioclase Lherzolite and
13 associated Dunite-Harzburgite-Lherzolite Sequences by multiple episodes of melt percolation and
14 melt rock reaction: an example from the Trinity ophiolite, California, USA. *Journal of Petrology*,
15 1017
16 57, 815-838, doi: 10.1093/petrology/egw018.
17 1018
18
19 1019
20 2020 Elthon, D. (1987). Mineral chemistry of gabbroic rocks from the Mid-Cayman Rise
21 spreading center, *Journal of Geophysical Research*, **92**, 658-682, doi: 10.1029/JB092iB01p00658.
22
23
24 1022
25
26 1023 Ernst, W. G. & Piccardo, G. B. (1979). Petrogenesis of some Ligurian peridotites: I. Mineral
27 1024 and bulk rock chemistry. *Geochimica Cosmochimica Acta*, **43**, 219–237, doi: 10.1016/0016-
28
29 1025 7037(79)90241-2.
30
31 1026
32
33 1027 Faure, F., Trolliard, G., Nicollet, C. & Montel, J. M. (2003). A developmental model of
34 1028 olivine morphology as a function of the cooling rate and the degree of undercooling. *Contributions
35
36 1029 to Mineralogy and Petrology*, **145**, 251-263, doi: 10.1007/s00410-003-0449-y.
37
38 1030
39
40 1031 Faure, F., Schiano, P., Trolliard, G., Nicollet, C & Soulestin, B. (2007). Textural evolution
41 1032 of polyhedral olivine experiencing rapid cooling rates. *Contributions to Mineralogy and Petrology*,
42
43 1033 **153**, 405-416, doi: 10.1007/s00410-006-0154-8.
44
45 1034
46
47 1035 Ferrando, C., Godard, M., Ildefonse, B. & Rampone, E. (2018). Melt transport and mantle
48 1036 assimilation at Atlantis Massif (IODP Site U1309): Constraints from geochemical modelling.
49
50 1037 *Lithos*, doi: 10.1016/j.lithos.2018.01.012.
51
52 1038
53
54 1039 Francomme, J. E. (2018) Melt-rock interaction at the mantle-crust transition zone in the
55 1040 oceanic spreading lithosphere: an experimental study. *PhD thesis, IRIS (Institutional Research
56
57 1041 Information System)*.
58
59 1042
60

- 1
2
3 1043 Garrido, C. J. & Bodinier, J-L. (1999). Diversity of mafic rocks in the Ronda peridotite:
4
5 1044 Evidence for pervasive melt-rock reaction during heating of subcontinental lithosphere by
6
7 1045 upwelling asthenosphere. *Journal of Petrology*, **40**, 729-754, doi: 10.1093/petroj/40.5.729.
8 1046
9
10 1047 Ghiorso, M. S., Hirschmann, M., Reiners, P. W. & Kress, V. C. I. (2002). The pMELTS: A
11 revision of MELTS aimed at improving calculation of phase relations and major element
12 1048 partitioning involved in partial melting of the mantle at pressures up to 3GPa. *Geochemistry,*
13 1049
14 1050 *Geophysics, Geosystems*, **3**, doi: 10.1029/2001GC000217.
15
16
17 1051
18
19 1052 Gillis, K. et al. (2014). Primitive layered gabbros from fast-spreading lower oceanic crust.
20 1053 *Nature*, **505**, 204-207, doi: 10.1038/nature12778.
21
22 1054
23
24 1055 Godard, M., Bodinier, J-L. & Vasseur, G. (1995). Effects of mineralogical reactions on trace
25 element redistributions in mantle rocks during percolation processes: A chromatographic approach.
26 1056
27 1057 *Earth and Planetary Science Letters*, **133**, 449-461, doi: 10.1016/0012-821X(95)00104-K.
28
29 1058
30
31 1059 Harigane, Y., Michibayashi, K. & Ohara Y. (2011). Deformation and hydrothermal
32 metamorphism of gabbroic rocks within the Godzilla Megamullion, Parece Vela Basinm Philippine
33 1060 Sea. *Lithos*, **124**, 185-199, doi: 10.1016/j.lithos.2011.02.001.
34 1061
35
36 1062
37
38 1063 Hébert, R., Serri, G. & Hekinian, R. (1989). Mineral chemistry of ultramafic tectonites and
39 1064 ultramafic to gabbroic cumulates from the major oceanic basins and Northern Apennines ophiolites
40
41 1065 (Italy) – a comparison. *Chemical Geology*, **77**, 183-207, doi: 10.1016/0009-2541(89)90074-0.
42
43 1066
44
45 1067 Higbie, K. & Tommasi, A. (2012). Feedbacks between deformation and melt distribution in
46 1068 the crust-mantle transition zone of the Oman ophiolite. *Earth and Planetary Science Letters*, **359-**
47
48 1069 **360**, 61-72, doi: 10.1016/j.epsl.2012.10.003.
49
50 1070
51
52 1071 Higbie, K. & Tommasi, A. (2014). Deformation in a partially molten mantle: Constraints
53 1072 from plagioclase lherzolites from Lanzo, western Alps. *Tectonophysics*, **615-616**, 167-181, doi:
54
55 1073 10.1016/j.tecto.2014.01.007.
56
57 1074
58
59 1075 Hoogerduijn-Strating, E. H., Piccardo, G. B., Rampone, E., Scambelluri, M. & Vissers, R.
60 1076 L. (1990). The structure and petrology of the Erro-Tobbio peridotite, Voltri massif, Ligurian Alps:

- 1
2
3 1077 Guidebook for a two-day-excursion with emphasis on processes in the upper mantle. *Ophioliti*, **15**,
4
5 1078 119–184.
6
7 1079
8 1080 Hoogerduijn Strating, E. H., Rampone, E., Piccardo, G. B., Drury, M. R. & Vissers, R. L.
9
10 1081 M. (1993). Subsolidus emplacement of mantle peridotites during incipient oceanic rifting and
11 opening of the Mesozoic Tethys (Voltri Massif, NW Italy). *Journal of Petrology*, **34**, 901-927, doi:
12 1082
13 1083 10.1093/petrology/34.5.901.
14
15 1084
16
17 1085 Husen, A., Renat, R. A. & Holtz, F. (2016). The effect of H₂O and Pressure on Multiple
18 Saturation and Liquid Lines of Descent in Basalt from the Shatsky Rise. *Journal of Petrology*, **57**,
19 1086 309-344, doi: 10.1093/petrology/egw008.
20
21 1087
22 1088
23
24 1089 Jousselin, D., Nicolas, A. & Boudier, F. (1998). Detailed mapping of a mantle diapir below
25
26 1090 a paleo-spreading center in the Oman ophiolite. *Journal of Geophysical Research*, **103**, 18153-
27 1091 18170, doi:10.1029/98JB01493.
28
29 1092
30
31 1093 Jousselin, D., Morales, L. F. G., Nicolle, M. & Stephan, A. (2012). Gabbro layering
32
33 1094 induced by simple shear in the Oman ophiolite Moho Transition Zone. *Earth and Planetary Science
34 1095 Letters*, **331-332**, 55-66, doi: 10.1016/j.epsl.2012.02.022.
35
36 1096
37
38 1097 Karato, S. I., Jung, H., Katamaya, I. & Skemer, P. (2008). Geodynamic significance of
39 1098 seismic anisotropy of the upper mantle: New insights from laboratory studies. *Annual Review of
40 1099 Earth and Planetary Sciences*, **36**, 59-93, doi: 10.1146/annurev.earth.36.031207.124120.
41
42
43 1100
44
45 1101 Kelemen, P. B., Hitehead, J. A., Aharonov, E. & Jordahl, K. A. (1995a). Experiments on
46 1102 flow focussing in soluble porous media, with applications to melt extraction from the mantle.
47
48 1103 *Journal of Geophysical Research*, **100**, 475-496, doi: 10.1029/94JB02544.
49
50 1104
51
52 1105 Kelemen, P. B., Shimizu, N. & Salters, V. J. M. (1995b). Extraction of mid-ocean-ridge
53 1106 basalt from the upwelling mantle by focused flow of melt in dunite channels. *Nature*, **375**, 747–753,
54
55 1107 doi: 10.1038/375747a0.
56
57 1108
58
59
60

- 1
2
3 1109 Kelemen, P. B., Braun, M. & Hirth, G. (2000). Spatial distribution of melt conduits in the
4 mantle beneath oceanic spreading ridges: Observations from the Ingalls and Oman ophiolites.
5 1110
6 1111 *Geochemistry, Geophysics, Geosystems*, **1**, 1999GC000012.
7
8 1112
9
10 1113 Kelemen, P. B., Kikawa, E., Miller, D. J. and Shipboard Scientific Party (2007). Leg 209
11 summary: processes in a 20-km thick conductive boundary layer beneath the Mid-Atlantic Ridge,
12 1114 14°–16°N. In Kelemen, P.B., Kikawa, E., and Miller, D.J. (Eds.), *Proceedings of the Ocean*
13 1115 *Drilling Project, Scientific Results*, **209**, 1–33, College Station, TX (Ocean Drilling Program), doi:
14 1116
15 1117 10.2973/odp.proc.sr.209.001.2007.
16
17 1118
18
19 1119 Kinzler, R. J. & Grove, T. L. (1993). Corrections and further discussion of the primary
20 1120 magmas of mid-ocean ridge basalts, 1 and 2. *Journal of Geophysical Research*, **98**, 22339-22347,
21 1121 doi: 10.1029/93JB02164.
22
23 1122 Klein, E. M. & Langmuir, C. H. (1987). Global correlations of ocean ridge basalt chemistry
24 1123 with axial depth and crustal thickness. *Journal of Geophysical Research*, **92**, 8089-8115, doi:
25 1124
26 1125 10.1029/JB092iB08p08089.
27
28 1126 Lambart, S., Laporte, D. & Schiano, P. (2009). An experimental study of focused magma
29 1127 transport and basalt-peridotite interactions beneath mid-ocean ridges: implications for the
30 1128 generation of primitive MORB compositions. *Contributions to Mineralogy and Petrology*, **157**,
31 1129 429-451, doi: 10.1007/s00410-008-0344-7.
32
33 1130
34 1131 Laubier, M., Grove, T. L. & Langmuir, C. H. (2014). Trace element mineral/melt
35 1132 partitioning for basaltic and basaltic andesitic melts: An experimental and laser ICP-MS study with
36 1133 application to the oxidation state of mantle source regions. *Earth and Planetary Science Letters*,
37 1134 392, 265-278, doi: 10.1016/j.epsl.2014.01.053.
38
39 1135
40 1136 Le Roux, V., Tommasi, A. & Vauchez, A. (2008). Feedback between melt percolation and
41 1137 deformation in an exhumed lithosphere-asthenosphere boundary. *Earth and Planetary Science*
42 1138 *Letters*, **274**, 401-413, doi: 10.1016/j.epsl.2008.07.053.
43
44 1139
45 1140 Liang, Y. (2003). Kinetics of crystal-melt reaction in partially molten silicates: 1. Grain
46 1141 scale processes. *Geochemistry, Geophysics, Geosystems*, **4**, doi: 10.1029/2002GC000375.
47
48 1142

- 1
2
3 1143
4
5 1144 Liang, Y., Schiemenz, A., Hesse, M. A. & Parmentier, E. M. (2011). Waves, channels, and
6 the preservation of chemical heterogeneities during melt migration in the mantle. *Geophysical*
7 1145 *Research Letters*, **38**, L20308, doi: 10.1029/2011GL049034.
8 1146
9
10 1147
11
12 1148 Lissenberg, C. J. & Dick, H. J. B. (2008). Melt-rock reaction in the lower oceanic crust and
13 its implications for the genesis of mid-ocean ridge basalt. *Earth and Planetary Science Letters*, **271**,
14 1149
15 1150 311-325, doi: 10.1016/j.epsl.2008.04.023.
16
17 1151
18
19 1152 Lissenberg, C. J., MacLeod, C. J., Howard, K. A. & Godard, M. (2013). Pervasive reactive
20 1153 melt migration through fast-spreading lower oceanic crust (Hess Deep, equatorial Pacific Ocean).
21
22 1154 *Earth and Planetary Science Letters*, **361**, 436-447, doi: 10.1016/j.epsl.2012.11.012.
23
24 1155
25
26 1156 Lissenberg, C. J. & MacLeod, C. J. (2016). A reactive porous flow control on Mid-Ocean
27 1157 Ridge magmatic evolution. *Journal of Petrology*, **57**, 2195-2220, doi: 10.1093/petrology/egw074.
28
29 1158
30
31 1159 Manatschal, G. & Müntener, O. (2009). A type sequence across an ancient magma-poor
32 1160 ocean-continent transition: the example of the western Alpine Tethys ophiolites. *Tectonophysics*,
33 1161
34 1162 73, 4-19, doi: 10.1016/j.tecto.2008.07.021.
35
36 1163
37
38 1164 Marroni, M., Molli, G., Montanini, A. & Tribuzio, R. (1998). The association of continental
39 1165 crust rocks with ophiolites in the Northern Apennines (Italy): implications for the continent-ocean
40 1166 transition in the Western Tethys. *Tectonophysics*, **292**, 43-66, doi: 10.1016/S0040-1951(98)00060-
41 1167 2.
42
43 1168
44
45 1169 Miller, D. J., Abratis, M., Christie, D., Drouin, M., Godard, M., Ildefonse, B., Maeda, J.,
46 1170 Weinsteiger, A., Yamasaki, T., Suzuki, Y., Niino, A., Sato, Y. & Takeda, F. (2009). Data report:
47
48 1171 microprobe analyses of primary mineral phases from Site U1309, Atlantis Massif, IODP Expedition
49 1172 304/305. In: Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and
50 1173 the Expedition 304/305 Scientists, *Proceedings of the IODP*, **304/305**, College Station, TX
51 1174 (Integrated Ocean Drilling Program Management International Inc.), doi:
52 1175 10.2204/iodp.proc.304305.202.2009.
53
54
55 1176
56
57 1177
58
59
60

- 1
2
3 1176 Montanini, A., Tribuzio, R. & Vernia, L. (2008). Petrogenesis of basalts and gabbros from
4 an ancient continent-ocean transition (External Ligurides ophiolites, Northern Italy). *Lithos*, **101**,
5 1177 453-479, doi: 10.1016/j.lithos.2007.09.007.
6
7 1178
8 1179
9
10 1180 Morgan, Z. & Liang, Y. (2005). An experimental study of the kinetics of lherzolite reactive
11 dissolution with applications to melt channel formation. *Contributions to Mineralogy and*
12 1181 *Petrology*, **150**, 369-385, doi: 10.1007/s00410-005-0033-8.
13
14 1182
15 1183
16
17 1184 Müntener, O. & Piccardo, G. B. (2003). Melt migration in ophiolitic peridotites: The
18 message from Alpine-Apennine peridotites and implications for embryonic ocean basins.
19 1185 *Geological Society Special Publications*, **218**, 69–89, doi: 10.1144/GSL.SP.2003.218.01.05.
20
21 1186
22 1187
23
24 1188 O'Driscoll, B., Donaldson, C. H., Troll, V. R., Jerram, D. A. & Emeleus, C. H. (2007). An
25 origin for harrisitic and granular olivine in the Rum layered suite, NW Scotland: a crystal size
26 1189 distribution study. *Journal of Petrology*, **48**, 253-270, doi: 10.1093/petrology/eg1059.
27
28 1190
29 1191
30
31 1192 Ottonello, G., Piccardo, G. B. & Ernst, W. G. (1979). Petrogenesis of some Ligurian
32 peridotites – II rare earth element chemistry. *Geochimica et Cosmochimica Acta*, **43**, 1273-1284,
33 1193 doi: 10.1016/0016-7037(79)90118-2.
34
35 1194
36 1195
37
38 1196 Paquet, M., Cannat, M., Brunelli, D., Hamelin, C. & Humler, E. (2016). Effect of
39 1197 melt/mantle interactions on MORB chemistry at the easternmost Southwest Indian Ridge (61°-
40
41 1198 67°E). *Geochemistry, Geophysics, Geosystems*, **17**, 4605-4640, doi: 10.1002/2016GC006385.
42
43 1199
44
45 1200 Piccardo, G. B., Rampone, E. & Vannucci, R. (1990). Upper mantle evolution during
46 1201 continental rifting and ocean formation: evidence from peridotites bodies of the Western Alpine-
47
48 1202 Northern Apennine system. *Membr. Soc. Geol. Fr.*, **156**, 323-333.
49
50 1203
51
52 1204 Piccardo, G. B., Rampone, E. & Vannucci, R. (1992). Ligurian peridotites and ophiolites:
53 1205 from rift to ocean formation in the Jurassic Ligure-Piemontese basin. *Acta Vulcanologica*, **2**, 313-
54
55 1206 325.
56
57 1207
58
59
60

- 1
2
3 1208 Piccardo, G. B., Müntener, O., Zanetti, A. & Pettke, T. (2004). Ophiolite peridotites of the
4 Alpine-Apennine system: mantle processes and geodynamic relevance. *International Geological
5 Review*, **40**, 1119-1159, doi: 10.2747/0020-6814.46.12.1119.
6
7 1210
8 1211
9
10 1212 Piccardo G. B. & Vissers R. L. M. (2007). The pre-oceanic evolution of the Erro-Tobbio
11 peridotite (Voltri Massif, Ligurian Alps, Italy). *Journal of Geodynamics*, **43**, 417–449, doi:
12 1213
13 1214 10.1016/j.jog.2006.11.001.
14
15 1215
16
17 1216 Piccardo, G. B., Zanetti, A. & Müntener, O. (2007). Melt/peridotite interaction in the
18 Southern Lanzo peridotite: Field, textural and geochemical evidence. *Lithos*, **94**, 181-209, doi:
19 1217
20 1218 10.1016/j.lithos.2006.07.002.
21
22 1219
23
24 1220 Piccardo, G. B. & Guarnieri, L. (2010). Alpine peridotites from the Ligurian Tethys: an
25 updated critical review. *International Geological Review*, **52**, 1138–1159, doi:
26 1221
27 1222 10.1080/00206810903557829.
28
29 1223
30
31 1224 Pirard, C., Hermann, J. & O'Neill, H. St. C. (2013). Petrology and geochemistry of the
32 1225 Crust-Mantle boundary in a nascent arc, Massif du Sud ophiolite, New Caledonia, SW Pacific.
33
34 1226 *Journal of Petrology*, **54**, 1759-1792, doi: 10.1093/petrology/egt030.
35
36 1227
37
38 1228 Presnall, D. C. & Hoover, J. D. (1987). High pressure phase equilibrium constraints on the
39 1229 origin of mid-ocean ridge basalts, in: Mysen, B. O. (Ed.), Magmatic processes: Physicochemical
40 1230 principles, *Special publications - Geochemical Society*, **1**, 75-89.
41
42
43 1231
44
45 1232 Quick, J. E. (1981) Petrology and petrogenesis of the Trinity peridotite, an upper mantle
46 1233 diapir in the eastern Klamath mountains, northern California. *Journal of Geophysical Research*, **86**,
47
48 1234 11837-11863, doi: 10.1029/JB086iB12p11837.
49
50 1235
51
52 1236 Quick, J. E. (1982) The origin and significance of large, tabular dunite bodies in the Trinity
53 1237 peridotite, Northern California. *Contributions to Mineralogy and Petrology*, **78**, 413-422, doi:
54
55 1238 10.1007/BF00375203.
56
57 1239
58
59 1240 Rampone, E., Piccardo, G. B., Vannucci, R., Bottazzi P. & Ottolini, L. (1993). Subsolidus
60 1241 reactions monitored by trace element partitioning: the spinel- to plagioclase-facies transition in

- 1
2
3 1242 mantle peridotites. *Contributions to Mineralogy and Petrology*, **115**, 1–17, doi:
4
5 1243 10.1007/BF00712974.
6
7 1244
8 1245 Rampone, E., Piccardo, G. B., Vannucci, R. & Bottazzi, P. (1997). Chemistry and origin of
9 trapped melts in ophiolitic peridotites. *Geochimica et Cosmochimica Acta*, **61**, 4557–4569, doi:
10 1246 10.1016/S0016-7037(97)00260-3.
11
12 1247
13
14 1248
15 1249 Rampone, E., Hofmann, A. W. & Raczek, I. (1998). Isotopic contrasts within the Internal
16 Liguride ophiolite (N-Italy): the lack of genetic mantle-crust link. *Earth and Planetary Science
17 Letters*, **163**, 175–189, doi: 10.1016/S0012-821X(98)00185-X.
18
19 1250
20 1251
21 1252
22 1253 Rampone, E. & Piccardo, G. B. (2000). The ophiolite-oceanic lithosphere analogue: new
23 insights from the Northern Apennine (Italy). *in* “Ophiolites and oceanic crust: new insights from
24 field studies and Ocean Drilling Program”, Dilek, J., Moores, E., Elthon, D. & Nicolas, A. eds.,
25 1255
26 1256 *Geological Society of America, Special Paper*, **349**, 21–34, doi: 10.1130/0-8137-2349-3.21.
27
28
29 1257
30
31 1258 Rampone, E., Romairone, A. & Hofmann, A. W. (2004). Contrasting bulk and mineral
32 chemistry in depleted peridotites: evidence for reactive porous flow. *Earth and Planetary Science
33 Letters*, **218**, 491–506, doi: 10.1016/S0012-821X(03)00679-4.
34
35
36 1261
37
38 1262 Rampone, E., Romairone, A., Abouchami, W., Piccardo, G. B. & Hofmann, A. W. (2005).
39 1263 Chronology, petrology and isotope geochemistry of the Erro-Tobbio peridotites (Ligurian Alps,
40 Italy): records of late Paleozoic lithospheric extension. *Journal of Petrology*. **46**, 799–827, doi:
41 1264 10.1093/petrology/egi001.
42
43 1265
44
45 1266
46 1267 Rampone, E. & Borghini, G. (2008). Melt migration and intrusion in the Erro-Tobbio
47 peridotites (Ligurian Alps, Italy): Insights on magmatic processes in extending lithospheric mantle.
48 1268
49 1269 *European Journal of Mineralogy*, **20**, 573–585, doi: 10.1127/0935-1221/2008/0020-1807.
50
51 1270
52
53 1271 Rampone, E., Piccardo, G. B. & Hofmann, A. W. (2008). Multi-stage melt-rock interaction
54 in the Mt. Maggiore (Corsica, France) ophiolitic peridotites: microstructural and geochemical
55 1272 evidence. *Contributions to Mineralogy and Petrology*, doi: 10.1007/s00410-008-0296-y.
56
57 1273
58 1274
59
60

- 1
2
3 1275 Rampone E., Borghini G., Romairone A., Abouchami W., Class C. & Goldstein S. L.
4
5 1276 (2014). Sm–Nd geochronology of the Erro-Tobbio gabbros (Ligurian Alps, Italy): Insights into the
6 evolution of the Alpine Tethys. *Lithos*, **205**, 236-246, doi: 10.1016/j.lithos.2014.07.012.
7 1277
8 1278
9
10 1279 Rampone, E., Borghini, G., Godard, M., Ildefonse, B., Crispini, L. & Fumagalli, P. (2016).
11
12 1280 Melt/rock reaction at oceanic peridotite/gabbro transition as revealed by trace element chemistry of
13 olivine. *Geochimica et Cosmochimica Acta*, **190**, 309-331, doi: 10.1016/j.gca.2016.06.029.
14
15 1282
16
17 1283 Rampone, E., Borghini, G. & Basch, V. (2018). Melt migration and melt-rock reaction in
18 the Alpine-Apennine peridotites: insights on mantle dynamics in extending lithosphere. *Geoscience
Frontiers*, doi: .
19
20 1285
21
22 1286
23
24 1287 Renna, M. R. & Tribuzio, R. (2011). Olivine-rich Troctolites from Ligurian Ophiolites
25 (Italy): Evidence for Impregnation of Replacive Mantle Conduits by MORB-type Melts. *Journal of
26 Petrology*, **52**, 1763-1790, doi: 10.1093/petrology/egr029.
27
28
29 1290
30
31 1291 Renna, M. R., Tribuzio, R. & Ottolini, L. (2016). New perspectives on the origin of olivine-
32 rich troctolites and associated harrisites from the Ligurian ophiolites (Italy), *Journal of the
33 Geological Society*, doi: 10.1144/jgs2015-135.
34
35
36 1294
37
38 1295 Rosenberg, C. L. & Handy, M. R. (2005). Experimental deformation of partially melted
39 1296 granite revisited: implications for the continental crust. *Journal of Metamorphic Geology*, **23**, 19-
40
41 1297 28, doi: 10.1111/j.1525-1314.2005.00555.x.
42
43 1298
44
45 1299 Ross, K. & Elthon, D. (1997). Cumulus and Postcumulus crystallization in the oceanic crust:
46 1300 major and trace elements geochemistry of Leg 153 gabbroic rocks. In: Karson, J.A., Cannat, M. and
47
48 1301 Miller, D.J. (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results*, **143**, 333-350,
49
50 1302 College Station, TX, doi: 10.2973/odp.proc.sr.153.023.1997.
51
52 1303
53 1304 Saccani, E., Principi, G., Garfagnoli, F. & Menna, F. (2008) Corsica ophiolites:
54
55 1305 geochemistry and petrogenesis of basaltic and metabasaltic rocks. *Ophioliti*, **33**, 187-202.
56
57 1306
58
59
60

- 1
2
3 1307 Sanfilippo, A. & Tribuzio, R. (2012). Building of the deepest crust at a fossil slow-spreading
4 centre (Pineto gabbroic sequence, Alpine Jurassic ophiolites). *Contributions to Mineralogy and*
5 1308 *Petrology*, **165**, 705-721, doi: 10.1007/s00410-012-0831-8.
6
7 1309
8 1310
9
10 1311 Sanfilippo, A., Dick, H. J. B. & Ohara, Y. (2013). Melt-Rock reaction in the Mantle: Mantle
11 troctolites from the Parece Vela Ancient Back-Arc Spreading Centre. *Journal of Petrology*, **54**, 61-
12
13 1313 885, doi: 10.1093/petrology/egs089.
14
15 1314
16
17 1315 Sanfilippo, A., Tribuzio, R. & Tiepolo, M. (2014). Mantle-crust interactions in the oceanic
18 lithosphere: Constraints from minor and trace elements in olivine. *Geochimica et Cosmochimica
19 Acta*, **141**, 423-439, doi: 10.1016/j.gca.2014.06.012.
20
21
22 1318
23
24 1319 Sanfilippo, A., Tribuzio, R., Tiepolo, M. & Berno, D. (2015a). Reactive flow as dominant
25 evolution process in the lowermost oceanic crust: evidence from olivine of the Pineto ophiolite
26 (Corsica). *Contributions to Mineralogy and Petrology*, **170**, 38, doi: 10.1007/s00410-015-1194-8.
27
28
29 1322
30
31 1323 Sanfilippo, A., Morishita, T., Kumagai, H., Nakamura, K., Okino, K., Hara, K., Tamura, A.
32
33 1324 & Arai, S. (2015b). Hybrid troctolites from mid-ocean ridges: inherited mantle in the lower crust.
34 1325 *Lithos*, **232**, 124-130, doi: 10.1016/j.lithos.2015.06.025.
35
36 1326
37
38 1327 Sanfilippo, A., Morishita, T. & Senda, R. (2016a). Rhenium-osmium isotope fractionation at
39 1328 the oceanic crust-mantle boundary. *Geology*, **44**, 167-170, doi: 10.1130/G37428.1.
40
41 1329
42
43 1330 Sanfilippo, A., Dick, H. J. B., Ohara, Y. & Tiepolo, M. (2016b). New insights on the origin
44
45 1331 of troctolites from the breakaway area of the Godzilla Megamullion (Parece Vela back-arc basin):
46 1332 The role of melt-mantle interaction on the composition of the lower crust. *Island arc*, **25**, 220-234,
47
48 1333 doi: 10.1111/iar.12137.
49
50 1334
51
52 1335 Sanfilippo, A., Tribuzio, R., Ottolini, L. & Hamada, M. (2017). Water, lithium and trace
53 1336 element compositions of olivine from Lanzo South replacive mantle dunites (Western Alps): New
54
55 1337 constraints into melt migration processes at cold thermal regimes. *Geochimica et Cosmochimica
56 Acta*, **214**, 51-72, doi: 10.1016/j.gca.2017.07.034.
57 1338
58
59 1339
60

- 1
2
3 1340 Saper, L. & Liang, Y. (2014). Formation of plagioclase-bearing peridotite and plagioclase-
4 bearing wehrlite and gabbro suite through reactive crystallization: an experimental study.
5 1341
6 1342 *Contributions to Mineralogy and Petrology*, **167**, 985, doi: 10.1007/s00410-014-0985-7.
7
8 1343
9
10 1344 Scambelluri, M., Hoogerduijn Strating, E. H., Piccardo, G. B., Vissers, R. L. M. &
11
12 1345 Rampone, E. (1991). Alpine olivine and titanian clinohumite bearing assemblages in the Erro-
13
14 1346 Tobbio peridotites. *Journal of Metamorphic Geology*, **9**, 79–91, doi: 10.1111/j.1525-
15 1347 1314.1991.tb00505.x.
16
17 1348
18
19 1349 Seyler, M., Cannat, M. & Mével, C. (2003). Evidence for major element heterogeneity in the
20
21 1350 mantle source of abyssal peridotites from the Southwest Indian Ridge (52° to 68°E). *Geochemistry,*
22 1351 *Geophysics, Geosystems*, doi: 10.1029/2002GC000305
23
24 1352
25
26 1353 Soustelle, V., Tommasi, A., Bodinier, J. L., Garrido, C. J. & Vauchez, A. (2009).
27 1354 Deformation and Reactive Melt Transport in the Mantle Lithosphere above a Large-scale Partial
28
29 1355 Melting Domain: The Ronda Peridotite Massif, Southern Spain. *Journal of Petrology*, **50**, 1235-
30
31 1356 1266, doi: 10.1093/petrology/egp032.
32
33 1357
34 1358 Soustelle, V., Tommasi, A., Demouchy, S. & Ionov, D. A. (2010). Deformation and fluid-
35
36 1359 rock interaction in the supra-subduction mantle: Microstructures and water contents in peridotite
37
38 1360 xenoliths from the Avacha Volcano, Kamchatka. *Journal of Petrology*, **51**, 363-394, doi:
39 1361 10.1093/petrology/egp085.
40
41 1362
42
43 1363 Soustelle, V., Walte, N. P., Geeth, M. A., Manthilake, M. & Frost, D. J. (2014). Melt
44
45 1364 migration and melt-rock reactions in the deforming Earth's upper mantle: Experiments at high
46 1365 pressure and temperature. *Geology*, **42**, 83-86, doi: 10.1130/G34889.1.
47
48 1366
49
50 1367 Suhr, G., Hellebrand, E., Johnson, K. & Brunelli, D. (2008). Stacked gabbro units and
51 1368 intervening mantle: A detailed look at a section of IODP Leg 305, Hole U1309D. *Geochemistry,*
52
53 1369 *Geophysics, Geosystems*, **9**, Q10007, doi: 10.1029/2008GC002012.
54
55 1370
56
57 1371 Takazawa, E., Frey, F. A., Shimizu, N., Obata, M. & Bodinier, J-L. (1992) Geochemical
58
59 1372 evidence for melt migration and reaction in the upper mantle. *Nature*, **359**, 55-58, doi:
60 1373 10.1038/359055a0.

- 1
2
3 1374
4
5 1375 Tommasi, A., Mainprice, D., Canova, G. & Chastel, Y. (2000). Viscoplastic self-consistent
6 and equilibrium-based modeling of olivine lattice preferred orientations: Implications for the upper
7 mantle seismic anisotropy. *Journal of Geophysical Research*, **105**, 7893-7908, doi:
8 1377 10.1029/1999JB900411.
9
10 1378
11
12 1379
13 1380 Tribuzio, R., Tiepolo, M., Vannucci, R. & Bottazzi, P. (1999). Trace element distribution
14 1381 within olivine-bearing gabbros from the Northern Apennine ophiolites (Italy): Evidence for post-
15 1382 cumulus crystallization in MOR-type gabbroic rocks. *Contributions to Mineralogy and Petrology*,
16 1383 **134**, 123-133, doi: 10.1007/s004100050473.
17
18 1384
19 1385 Tribuzio, R., Tiepolo, M. & Vannucci, R. (2000). Evolution of gabbroic rocks of the
20 1386 Northern Apennine ophiolites (Italy): Comparison with the lower oceanic crust from modern slow-
21 1387 spreading ridges, *in* Dilek, Y., Moores, E.M., Elthon, D., and Nicolas, A., eds., Ophiolites and
22 1388 Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program: Boulder,
23 1389 Colorado, *Geological Society of America*, **349**, 129–138, doi: 10.1130/0-8137-2349-3.129..
24
25 1390
26 1391 Tribuzio, R., Thirlwall, M. F. & Vanucci, R. (2004). Origin of the Gabbro-Peridotite
27 1392 association from the Northern Apennine Ophiolites (Italy). *Journal of Petrology*, **45**, 1109-1124,
28 1393 doi: 10.1093/petrology/egh006.
29
30 1394
31 1395 Tursack, E. & Liang, Y. (2012). A comparative study of melt-rock reactions in the mantle:
32 1396 laboratory dissolution experiments and geological field observations. *Contributions to Mineralogy
33 1397 and Petrology*, **163**, 861-876, doi: 10.1007/s00410-011-0703-7.
34
35 1398
36 1399 Van den Bleeken, G., Müntener, O. & Ulmer, P. (2011). Melt variability in percolated
37 1400 peridotite: an experimental study applied to reactive migration of tholeiitic basalt in the upper
38 1401 mantle. *Contribution to Mineralogy and Petrology*, **161**, 921-945, doi: 10.1007/s00410-010-0572-5.
39
40 1402
41 1403 Van der Wal, D. & Bodinier, J-L. (1996). Origin of the recrystallization front in the Ronda
42 1404 peridotite by km-scale pervasive porous melt flow. *Contributions to Mineralogy and Petrology*,
43 1405 **122**, 387-405, doi: 10.1007/s004100050.
44
45
46 1406
47 1407
48 1408
49 1409
50 1410
51 1411
52 1412
53 1413
54 1414
55 1415
56 1416
57 1417
58 1418
59 1419
60

1
2
3 1407 Vissers R. L. M., Drury M. R., Hoogerduijn Strating E. H. & Van der Wal D. (1991). Shear
4 zones in the upper mantle: a case study in an Alpine lherzolite massif. *Geology*, **19**, 990-993, doi:
5 1408 10.1130/0091-7613(1991)019<0990:SZITUM>2.3.CO;2.
6 1409
7 1410
8 1411
9 1412
10 1413
11 1414
12 1415
13 1416
14 1417
15 1418
16 1419
17 1420
18 1421
19 1422
20 1423
21 1424
22 1425
23 1426
24 1427
25 1428
26 1429
27 1430
28 1431
29 1432
30 1433
31 1434
32 1435
33 1436
34 1437
35 1438
36 1439
37 1440

Figure captions:

Figure 1: A: Sketch map of the Northern Apennines and Western Alps (redrawn after Piccardo & Vissers, 2007). The red square indicates the location of the Voltri Massif, in the Ligurian Alps; B: Map of the Voltri Massif and location of the studied area within the Erro Tobbio peridotites (redrawn after Piccardo & Vissers, 2007); C: Geological map of the Mt.Foscallo area, in the Erro-Tobbio peridotites. This structural map merges new data measured on the field with previously published data from Borghini *et al.*, 2007 and Borghini & Rampone, 2007.

Figure 2: Troctolite A field structures. A: Troctolite apophysis within the mantle peridotites at the contact between the troctolitic body and the peridotites (“transition zone”), and gabbroic dike crosscutting the association between peridotites and troctolites. B: Plagioclase-rich layering within the host Troctolite A; C: Crosscutting relationship between Troctolite A and Troctolite B; D: Dunitic pod included within the Troctolite A.

Figure 3: Troctolite B field structures. A: Troctolite B crosscutting the layering of plagioclase enrichment in Troctolite A (red dashed lines); B: Irregular contact between Troctolite A and crosscutting Troctolite B; C: Textural complexity within the Troctolite B; The white square indicates the location of (d); D: Dendritic “fishbone” olivine crystal; E: Textural variability of olivine crystals at centimetre-scale within the Troctolite B; The dashed red line separates granular olivine domains from hopper and dendritic olivine domains.

Figure 4: Representative sketch of the crosscutting relationships observed in the field among the impregnated peridotites, the composite troctolitic body, and the gabbroic intrusions.

Figure 5: Textural variability in the Troctolite A. A: Granular olivine matrix embedded in undeformed poikilitic plagioclase; B: Granular olivine matrix embedded in poikilitic clinopyroxene. The largest olivine crystal shows the occurrence of kink bands, highlighted by the red dashed lines. Interstitial plagioclase has been replaced by low-grade alteration phases; C: Corroded olivine grain prior to disruption into several smaller crystals. Interstitial plagioclase has been replaced by low-

1
2
3 1441 grade alteration phases; D: Highly corroded centimetre-size olivine, embedded in poikilitic
4
5 1442 plagioclase.
6
7 1443

8 1444 **Figure 6:** EBSD phase (left column) and olivine misorientation (right column) maps showing the
9
10 1445 textural variability of the olivine matrix within the troctolitic body. A: Troctolite A with dunitic
11
12 1446 aggregates MF96B; B: Troctolite Apophysis MF51A1; C: Troctolite A with dunitic aggregates
13
14 1447 MF7A1; D: Troctolite A without dunitic aggregates MF102B1; E: Troctolite B MF101A. White
15
16 1448 areas in the phase maps are non-indexed pixels, mostly corresponding to altered plagioclase.
17
18 1449

19 1450 **Figure 7:** Textural variability observed into the Troctolite B pseudo-tabular bodies. Plagioclase is
20
21 1451 partly to completely replaced by low-grade alteration phases. A: Fine-grained granular undeformed
22
23 1452 olivines surrounded by a rim of chlorite; B: Partially corroded coarse hopper crystal of olivine,
24
25 1453 associated to poikilitic plagioclase and interstitial clinopyroxene; C: Coarse skeletal olivine
26
27 1454 showing the inner “branches” of olivine, associated to interstitial plagioclase and clinopyroxene; D:
28
29 1455 Single coarsened skeletal olivine associated to interstitial plagioclase.
30
31 1456

32
33 1458 **Figure 8:** Modal compositions and olivine Crystallographic Preferred Orientation of Spinel
34
35 1459 lherzolite, Plagioclase lherzolite, Troctolite apophysis, Troctolite A with and without olivine
36
37 1460 aggregates. One-point-per-grain equal-area, lower hemisphere stereographic projections. The colour
38
39 1461 bar is scaled to the maximum concentration of the three crystallographic axes. The foliation is
40
41 1462 indicated by the red line in oriented samples. J-index refers to the fabric strength.
42
43 1463

44
45 1464 **Figure 9:** Modal composition, olivine and plagioclase Crystallographic Preferred Orientation of
46
47 1465 Gabbroic intrusion and Troctolite B samples. One-point-per-grain equal-area, lower hemisphere
48
49 1466 stereographic projections. The colour bar is scaled to the maximum concentration of the three
50
51 1467 crystallographic axes. The foliation is indicated by the red line in oriented samples. J-index refers to
52
53 1468 the fabric strength.
54
55 1469

56
57 1470 **Figure 10:** A: Range of Forsterite content in olivines in Spinel Lherzolites, Plagioclase Lherzolite,
58
59 1471 Dunite, Troctolites A and Troctolites B; and B: Gabbroic intrusions. Olivine morphology is divided
60
61 1472 into Granular undeformed and Corroded deformed within the Troctolite A, and Granular
62
63 1473 undeformed and Hopper-Dendritic within the Troctolites B.

1
2
3 1474 **Figure 11:** Major elements compositions of clinopyroxene cores (A-B) in all studied samples,
4 plotted against the Mg-number = Mg/(Mg+Fe), and compositional variability with microstructural
5 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
6 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
7 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
8 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
9 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
10 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
11 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
12 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
13 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
14 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
15 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
16 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
17 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
18 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
19 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
20 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
21 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
22 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
23 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
24 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
25 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
26 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
27 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
28 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
29 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
30 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
31 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
32 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
33 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
34 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
35 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
36 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
37 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
38 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
39 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
40 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
41 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
42 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
43 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
44 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
45 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
46 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
47 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
48 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
49 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
50 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
51 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
52 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
53 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
54 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
55 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
56 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
57 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
58 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
59 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent
60 site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent

Figure 12: A-D: Reflected light photomicrographs and corresponding Clinopyroxene major element profile in Troctolite A. Step size is 19µm. B: Cr₂O₃ (wt%); C: TiO₂ (wt%); D: Al₂O₃ (wt%). Total length of the profile is 456µm. E-H: Reflected light photomicrographs and corresponding Plagioclase major element profile in Troctolite A. Step size is 54µm. F: Anorthite content (mol%); G: CaO (wt%); H: Al₂O₃ (wt%). Total length of the profile is 864µm. I-L: Reflected light photomicrographs and corresponding Olivine major element profile in Troctolite A. Step size is 10µm. J: Forsterite content (mol%); K: MgO (wt%); L: FeO (wt%). Total length of the profile is 600µm.

Figure 13: Range of Anorthite content in plagioclase in Troctolites A, Troctolites B and Gabbroic intrusions. Distinction has been made between cores (coloured symbols) and rims (white symbols) of coarse poikilitic plagioclase crystals.

Figure 14: A: Olivine – Clinopyroxene cores Mg# = Mg/(Mg+Fe) (mol%) correlation in the studied samples, compared to theoretical Fe-Mg equilibrium between olivine and clinopyroxenes, after Lissenberg & Dick (2008). The dashed lines represent the calculated olivine-clinopyroxene equilibrium line assuming an uncertainty of ±0.02 on the mineral-melt partition coefficients. B: Anorthite content (mol%) in plagioclase cores versus Forsterite content (mol%) in olivine cores in olivine-plagioclase couples from the studied Troctolites A, Troctolites B and Gabbroic intrusions. C: Anorthite content (mol%) in plagioclase cores versus Mg-number (mol%) in clinopyroxene cores in plagioclase-clinopyroxene couples from the studied Troctolites A, Troctolites B and Gabbroic intrusions. Compositional trends and fields represent olivine-plagioclase and olivine-clinopyroxene couples in olivine gabbros and troctolites from the South-West Indian Ridge (Hole735B: Dick *et al.*, 2002; 61-67°: Paquet *et al.*, 2016), the Mid-Atlantic Ridge Hole U1309D (Ross & Elthon, 1997; Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2009; Miller *et al.*, 2009), the Pineto

1
2
3 1507 gabbroic crust (Sanfilippo & Tribuzio, 2012), and the Alpine-Apennine ophiolites (Hebert *et al.*,
4
5 1508 1989; Tribuzio *et al.*, 1999; Montanini *et al.*, 2008; Sanfilippo & Tribuzio, 2012).
6
7 1509

8 1510 **Figure 15:** Interpretative sketch of the evolution of the olivine textures and associated CPOs during
9
10 1511 progressive olivine-dissolving, plagioclase-crystallizing melt-rock interaction and replacive
11 formation of the Troctolite A. A: Coarse-grained dunite protolith showing an axial-[100] olivine
12 1512 CPO; B: Troctolite A impregnated at low melt-rock ratios, and thus preserving dunitic aggregates
13 1513 and axial-[100] olivine CPO; C: Disaggregated troctolite A, impregnated at high instantaneous
14 1514 melt-rock ratios. The arrows within small olivine grains represent the loss of cohesion of the solid
15 1515 matrix leading to the free rotation of the grains and randoming of the olivine CPO. CPO represented
16 as one-point-per-grain equal-area, lower hemisphere stereographic projections. The colour bar is
17 1516 scaled to the maximum concentration of the three crystallographic axes. J-index refers to the fabric
18 1517 strength.
19 1518
20 1519
21 1520
22 1518
23 1519
24 1519
25 1520
26 1520

27 1521 **Figure 16:** *pMELTs* numerical simulations (Ghiorso *et al.*, 2002) of the major element
28 1522 compositions of plagioclase (Anorthite content) vs A: olivine (Forsterite content), and B:
30 1523 clinopyroxene (Mg-value) during fractional crystallization and reactive crystallization of a sodic
31 1523 primitive MORB, after Saccani *et al.* (2008) (see text for detail). Varying assimilation rates of a
32 1524 dunite (100% olivine) from 1g/°C to 3g/°C of cooling are modelled, and compared to the core
33 1524 compositions of olivine-plagioclase, and clinopyroxene-plagioclase couples analyzed in the
34 1525 Troctolite A and Troctolite B. The green star represents the mineral compositions in equilibrium
35 1526 with the starting melt, and each dot along the crystal line of descent corresponds to a 5°C cooling
36 1526 step. The numbers along the fractional crystallization trend represent the remaining melt fraction at
37 1527 the saturation of plagioclase and clinopyroxene. Compositional fields of oceanic gabbroic suites are
38 1527 plotted as comparison for the South-West Indian Ridge (SWIR Hole 735B: Dick *et al.*, 2002; SWIR
39 1528 61-67°E: Paquet *et al.*, 2016), the Mid-Atlantic Ridge (MAR; Ross & Elthon, 1997; Lissenberg &
40 1529 Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2009; Miller *et al.*, 2009) and the Godzilla
41 1530 Megamullion (Godzilla MM; Harigane *et al.*, 2011; Sanfilippo *et al.*, 2013).
42 1530
43 1530
44 1531
45 1531
46 1532
47 1532
48 1533
49 1533
50 1534
51 1535
52 1535

53 1536 **Figure 17:** Representative sketch of the formation of Troctolite B. A: initial state, host Troctolite A
54 1537 crystal mush; B: prior crystallization of dendritic olivine by the undercooled melt; C: equilibrium
55 1537 crystallization of the fine-grained granular olivines.
56 1538
57 1538
58 1539
59 1539

60 1540 **Figure 18:** *pMELTs* numerical modelling (Ghiorso *et al.*, 2002) of the major element compositions
61 1541 of olivine (Forsterite content), plagioclase (Anorthite content) and clinopyroxene (Mg-value) during

1
2
3 1542 fractional crystallization of the melt modified after reactive equilibrium crystallization and
4 formation of the Troctolite A and Troctolite B, compared to the major elements core compositions
5 1543 of olivine-plagioclase and clinopyroxene-plagioclase couples analyzed in the Erro-Tobbio Gabbroic
6 intrusions. The green star represents the mineral compositions in equilibrium with the starting melt,
7 1544 and each dot along the crystal line of descent corresponds to a 5°C cooling step. Compositional
8 1545 fields of oceanic gabbroic suites similar to [Figure 16](#).
9
10 1546
11
12 1547

13 1548
14
15 1549 **Figure 19:** Interpretative sketches of the geological context and evolution of the peridotitic and
16 troctolitic body. A: Geological context of formation of the Erro-Tobbio troctolitic body at 175Ma,
17 1550 during the onset of the Ligurian Tethys basin rifting; B: Representative replacive formation of the
18 1551 Troctolite A from dunitic protolith, intrusion of the Troctolite B during focused melt percolation
19 1552 and intrusion of gabbroic rocks in fractures.
20
21
22 1553
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

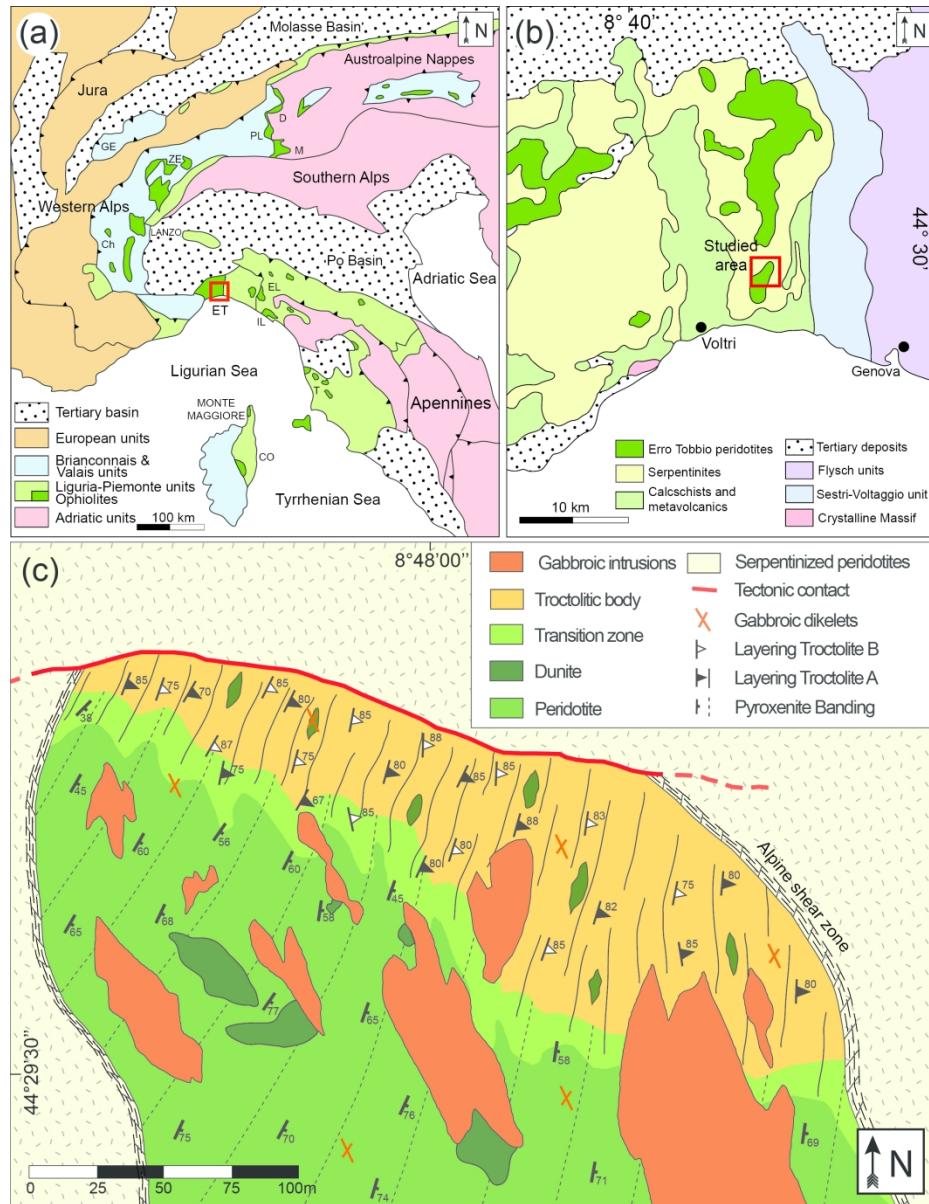


Figure 1: A: Sketch map of the Northern Apennines and Western Alps (redrawn after Piccardo & Vissers, 2007). The red square indicates the location of the Voltri Massif, in the Ligurian Alps; B: Map of the Voltri Massif and location of the studied area within the Erro-Tobbio peridotites (redrawn after Piccardo & Vissers, 2007); C: Geological map of the Mt. Foscallo area, in the Erro-Tobbio peridotites. This structural map merges new data measured on the field with previously published data from Borghini et al., 2007 and Borghini & Rampone, 2007.

209x270mm (300 x 300 DPI)

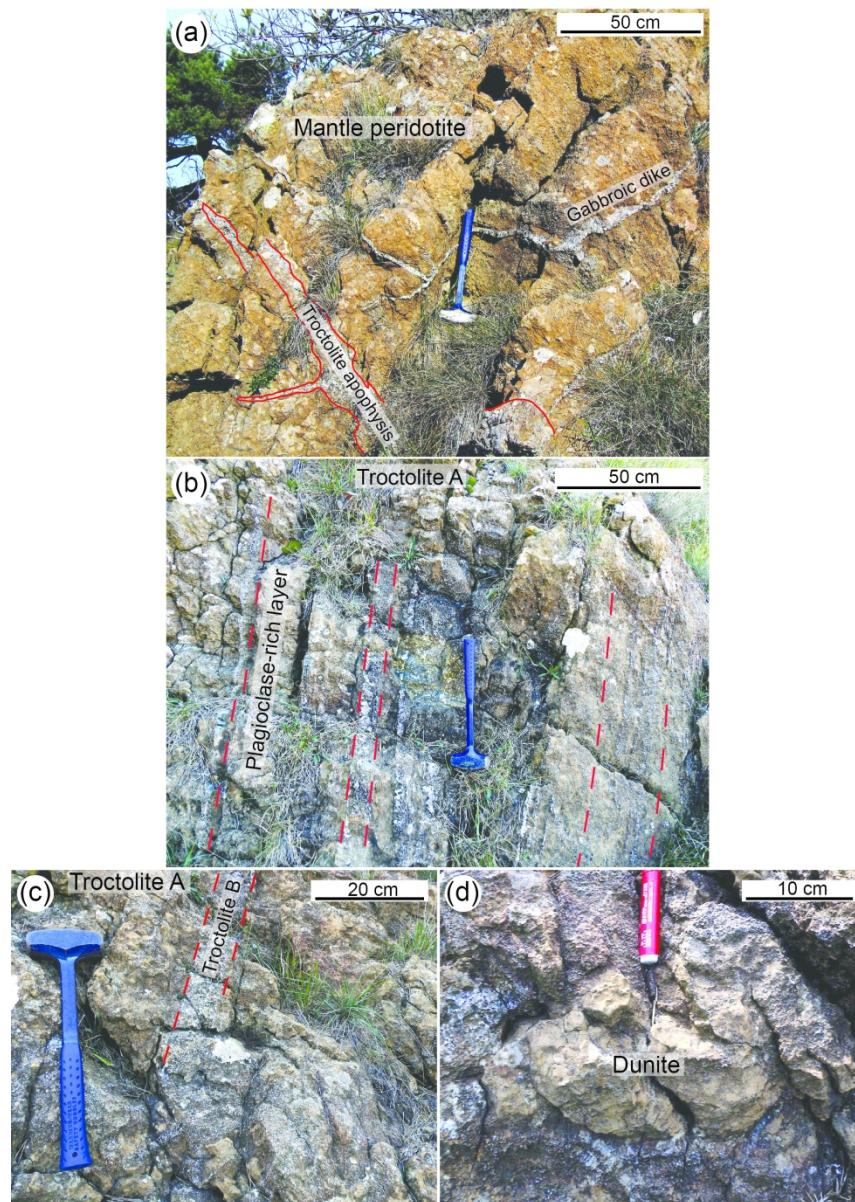


Figure 2: Troctolite A field structures. A: Troctolite apophysis within the mantle peridotites at the contact between the troctolitic body and the peridotites ("transition zone"), and gabbroic dike crosscutting the association between peridotites and troctolites. B: Plagioclase-rich layering within the host Troctolite A; C: Crosscutting relationship between Troctolite A and Troctolite B; D: Dunitic pod included within the Troctolite A.

209x293mm (300 x 300 DPI)

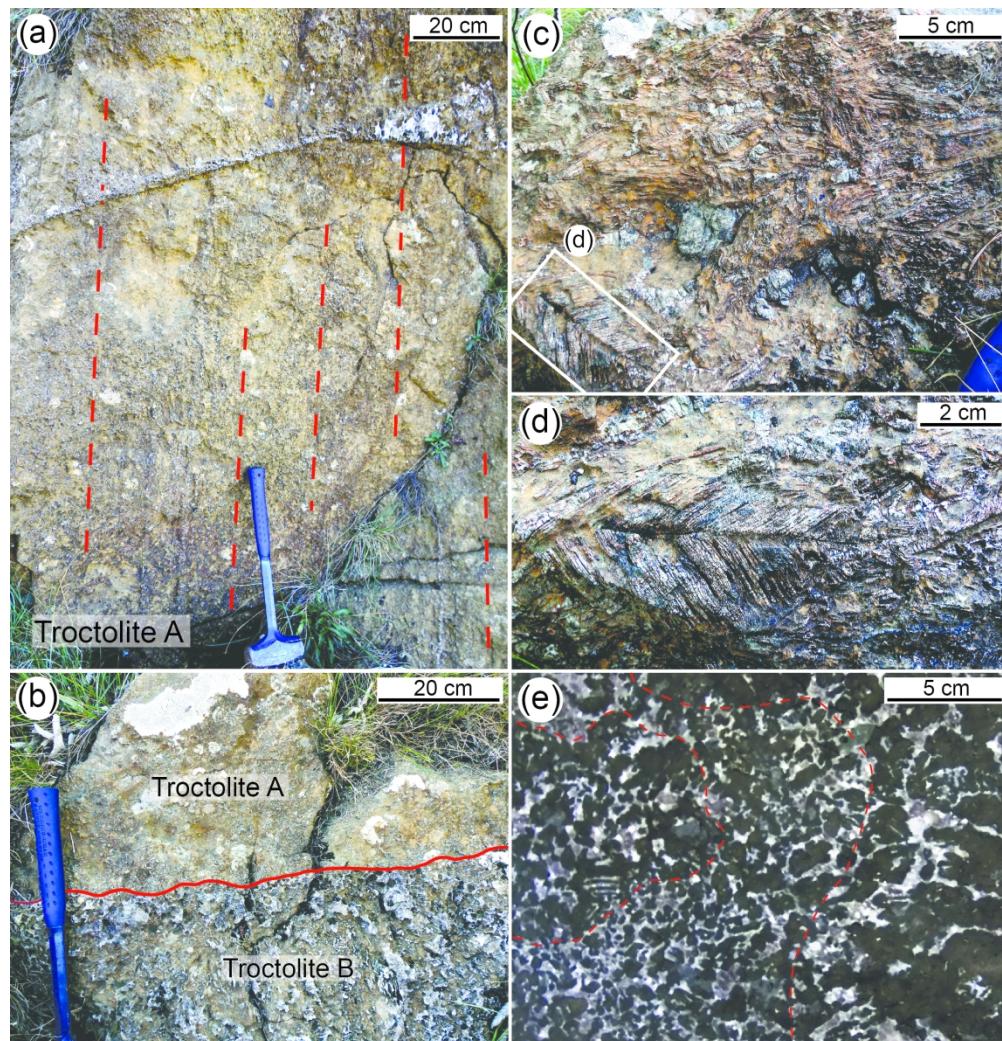


Figure 3: Troctolite B field structures. A: Troctolite B crosscutting the layering of plagioclase enrichment in Troctolite A (red dashed lines); B: Irregular contact between Troctolite A and crosscutting Troctolite B; C: Textural complexity within the Troctolite B; The white square indicates the location of (d); D: Dendritic "fishbone" olivine crystal; E: Textural variability of olivine crystals at centimetre-scale within the Troctolite B; The dashed red line separates granular olivine domains from hopper and dendritic olivine domains.

209x218mm (300 x 300 DPI)

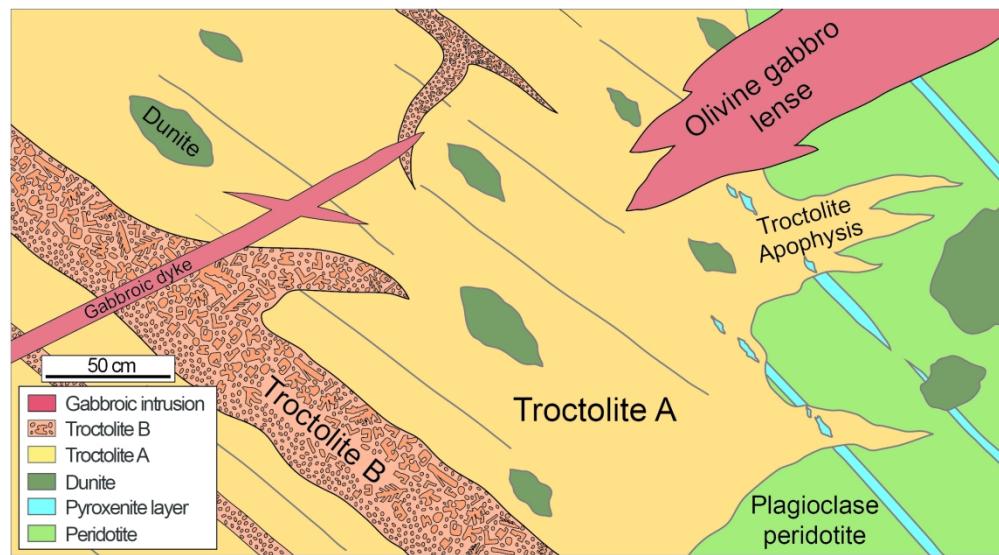


Figure 4: Representative sketch of the crosscutting relationships observed in the field among the impregnated peridotites, the composite troctolitic body, and the gabbroic intrusions.

210x115mm (300 x 300 DPI)

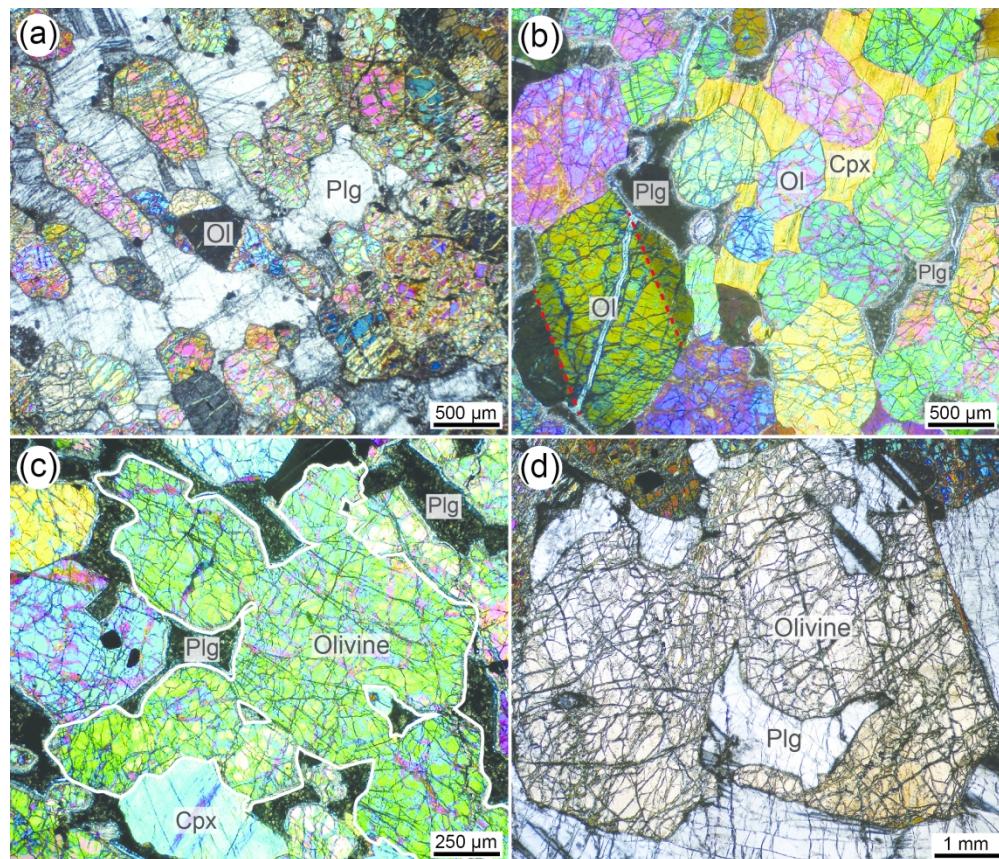


Figure 5: Textural variability in the Troctolite A. A: Granular olivine matrix embedded in undeformed poikilitic plagioclase; B: Granular olivine matrix embedded in poikilitic clinopyroxene. The largest olivine crystal shows the occurrence of kink bands, highlighted by the red dashed lines. Interstitial plagioclase has been replaced by low-grade alteration phases; C: Corroded olivine grain prior to disruption into several smaller crystals. Interstitial plagioclase has been replaced by low-grade alteration phases; D: Highly corroded centimetre-size olivine, embedded in poikilitic plagioclase.

209x179mm (300 x 300 DPI)

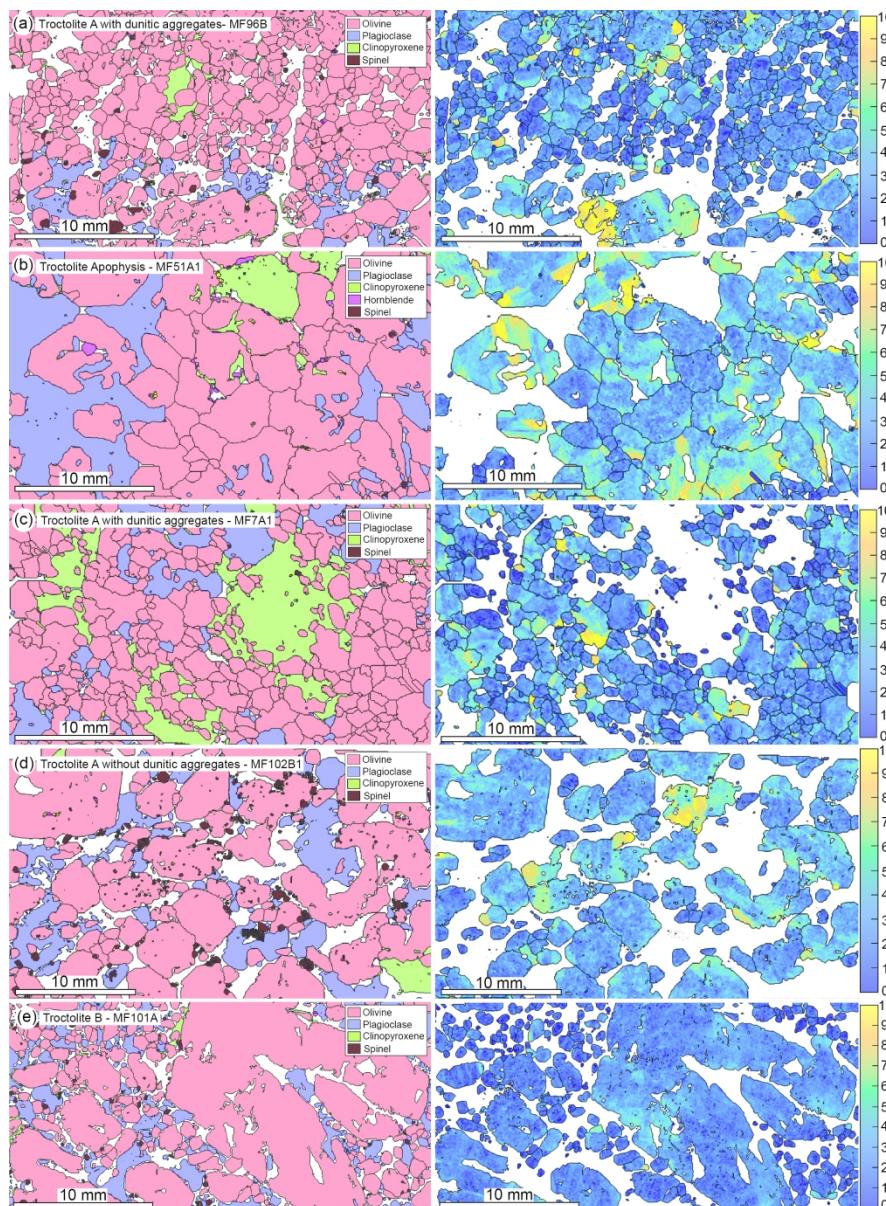


Figure 6: EBSD phase (left column) and olivine misorientation (right column) maps showing the textural variability of the olivine matrix within the troctolitic body. A: Troctolite A with dunitic aggregates MF96B; B: Troctolite Apophysis MF51A1; C: Troctolite A with dunitic aggregates MF7A1; D: Troctolite A without dunitic aggregates MF102B1; E: Troctolite B MF101A. White areas in the phase maps are non-indexed pixels, mostly corresponding to altered plagioclase.

209x284mm (300 x 300 DPI)

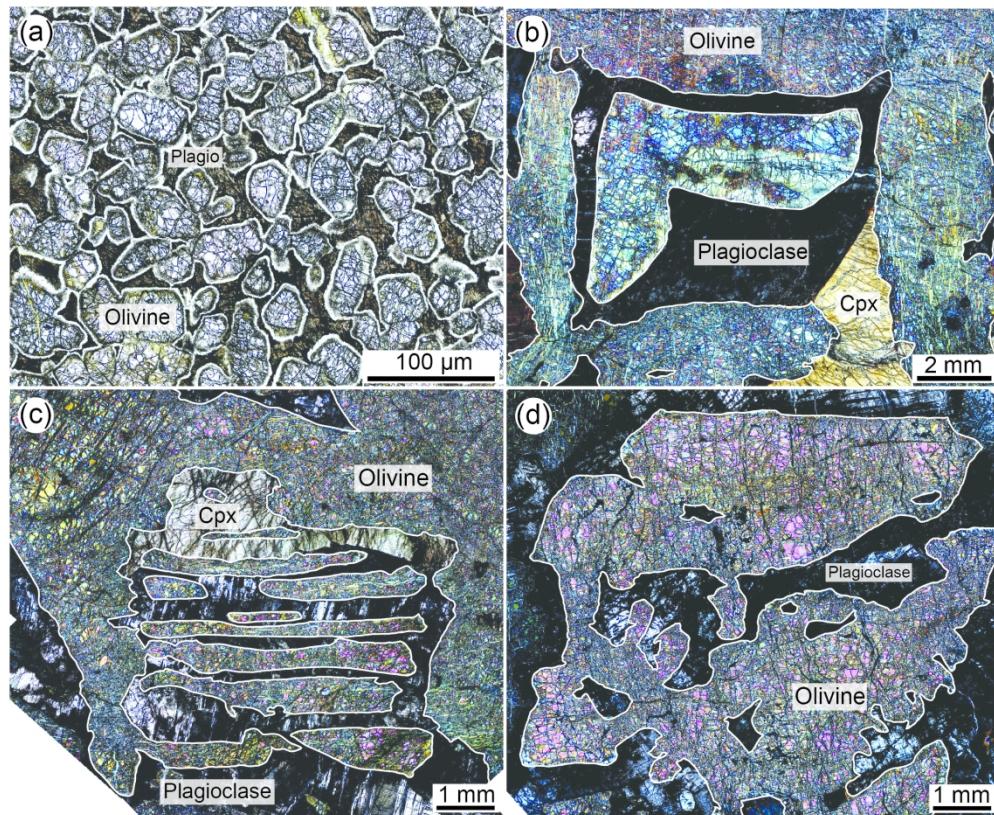


Figure 7: Textural variability observed into the Troctolite B pseudo-tabular bodies. Plagioclase is partly to completely replaced by low-grade alteration phases. A: Fine-grained granular undeformed olivines surrounded by a rim of chlorite; B: Partially corroded coarse hopper crystal of olivine, associated to poikilitic plagioclase and interstitial clinopyroxene; C: Coarse skeletal olivine showing the inner "branches" of olivine, associated to interstitial plagioclase and clinopyroxene; D: Single coarsened skeletal olivine associated to interstitial plagioclase.

212x173mm (300 x 300 DPI)

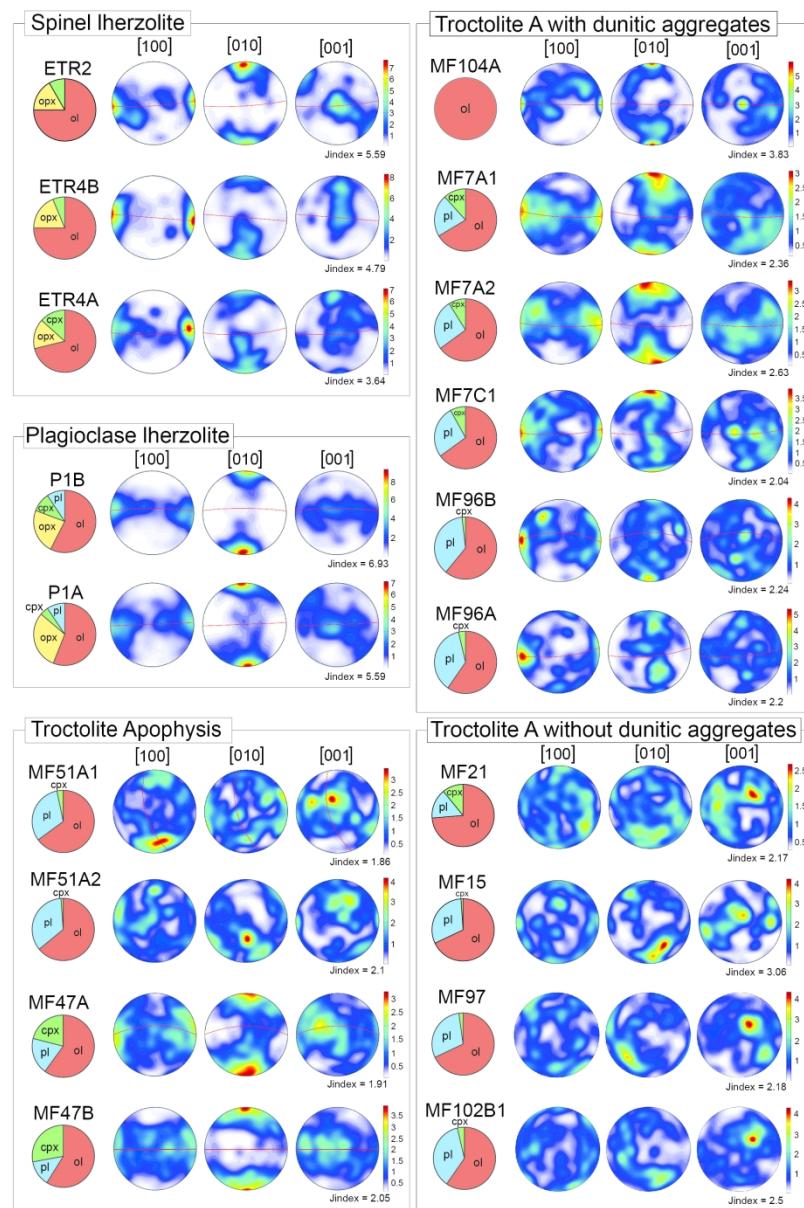


Figure 8: Modal compositions and olivine Crystallographic Preferred Orientation of Spinel Iherzolite, Plagioclase Iherzolite, Troctolite apophysis, Troctolite A with and without olivine aggregates. One-point-per-grain equal-area, lower hemisphere stereographic projections. The colour bar is scaled to the maximum concentration of the three crystallographic axes. The foliation is indicated by the red line in oriented samples. J-index refers to the fabric strength.

194x291mm (300 x 300 DPI)

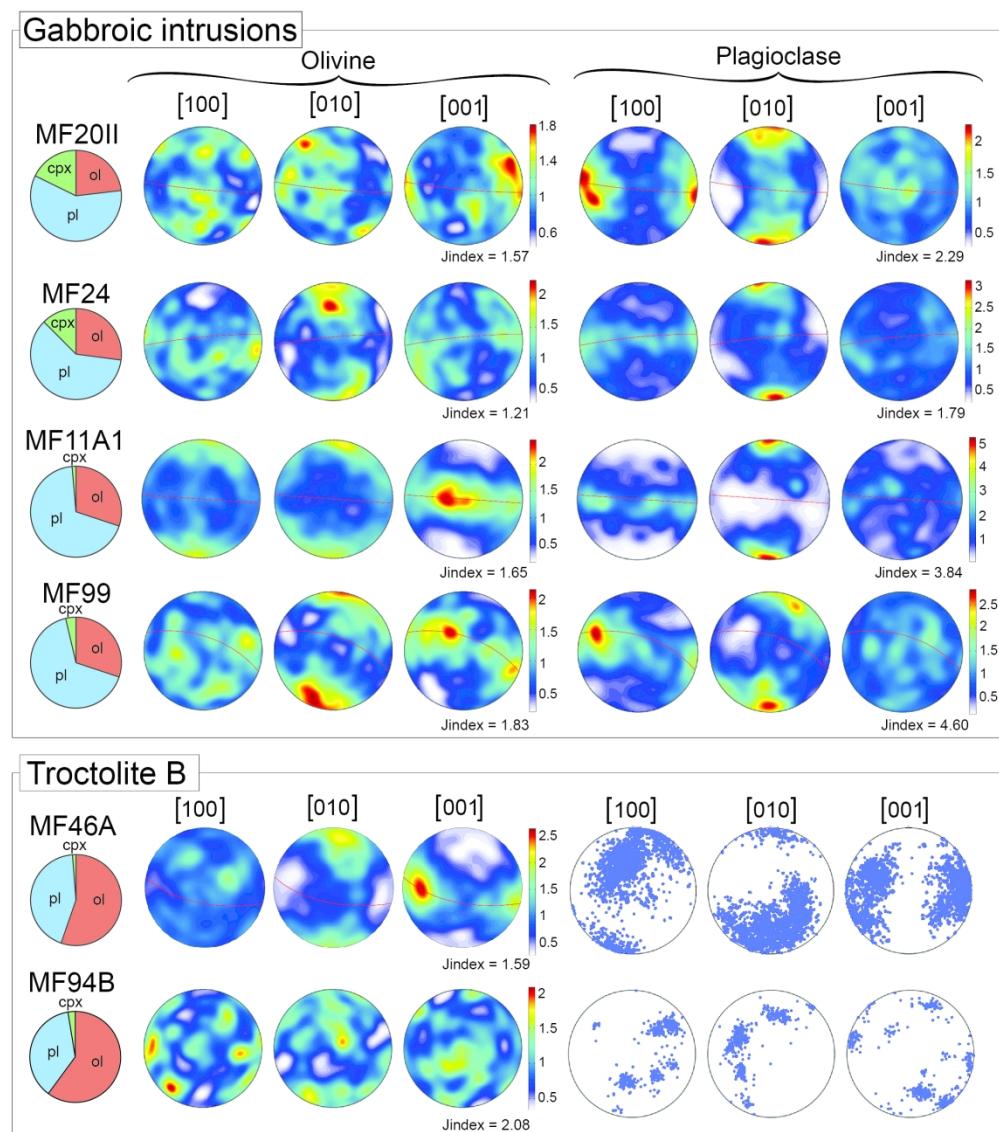


Figure 9: Modal composition, olivine and plagioclase Crystallographic Preferred Orientation of Gabbroic intrusion and Troctolite B samples. One-point-per-grain equal-area, lower hemisphere stereographic projections. The colour bar is scaled to the maximum concentration of the three crystallographic axes. The foliation is indicated by the red line in oriented samples. J-index refers to the fabric strength.

206x233mm (300 x 300 DPI)

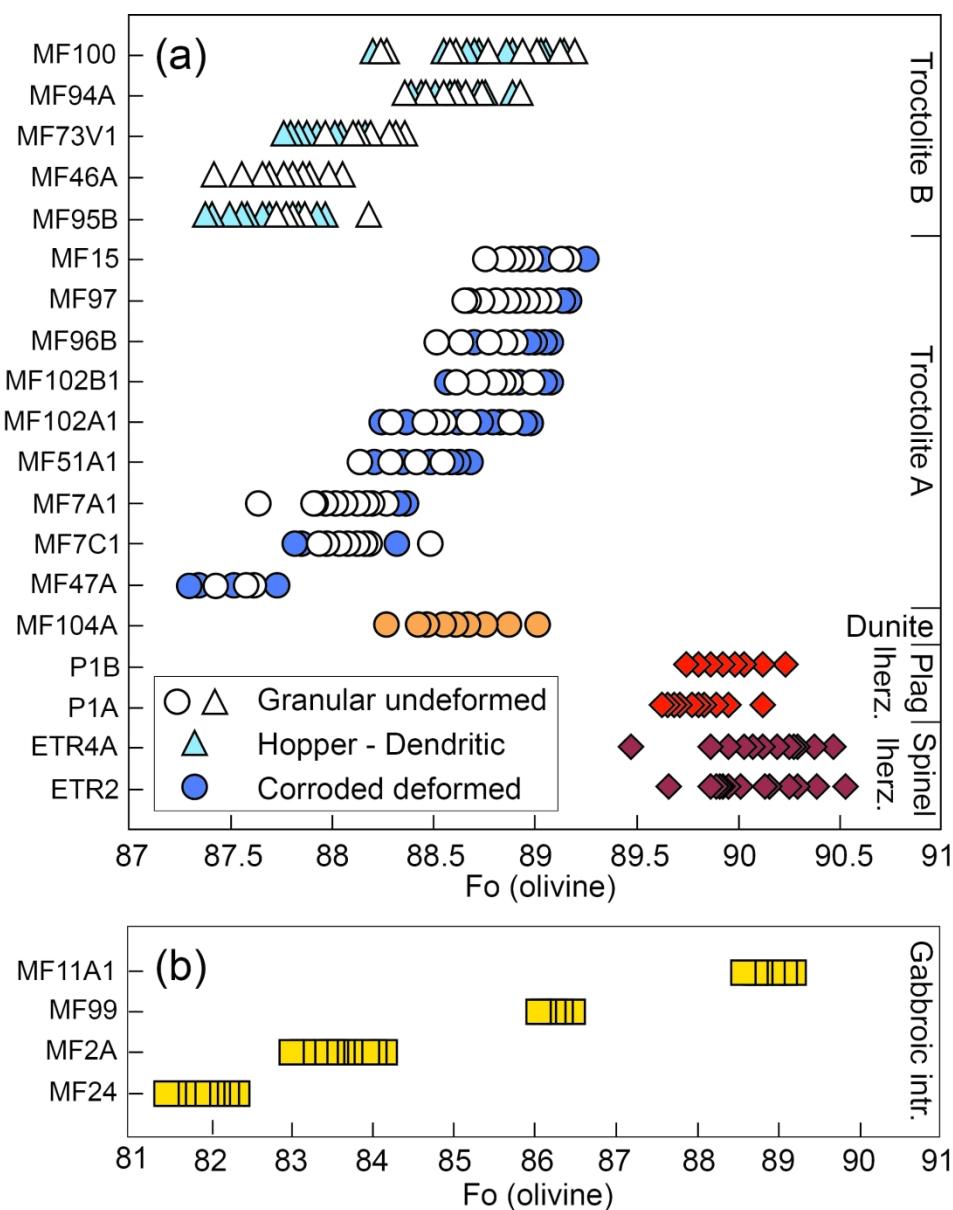


Figure 10: A: Range of Forsterite content in olivines in Spinel Lherzolites, Plagioclase Lherzolite, Dunite, Troctolites A and Troctolites B; and B: Gabbroic intrusions. Olivine morphology is divided into Granular undeformed and Corroded deformed within the Troctolite A, and Granular undeformed and Hopper-Dendritic within the Troctolites B.

186x235mm (300 x 300 DPI)

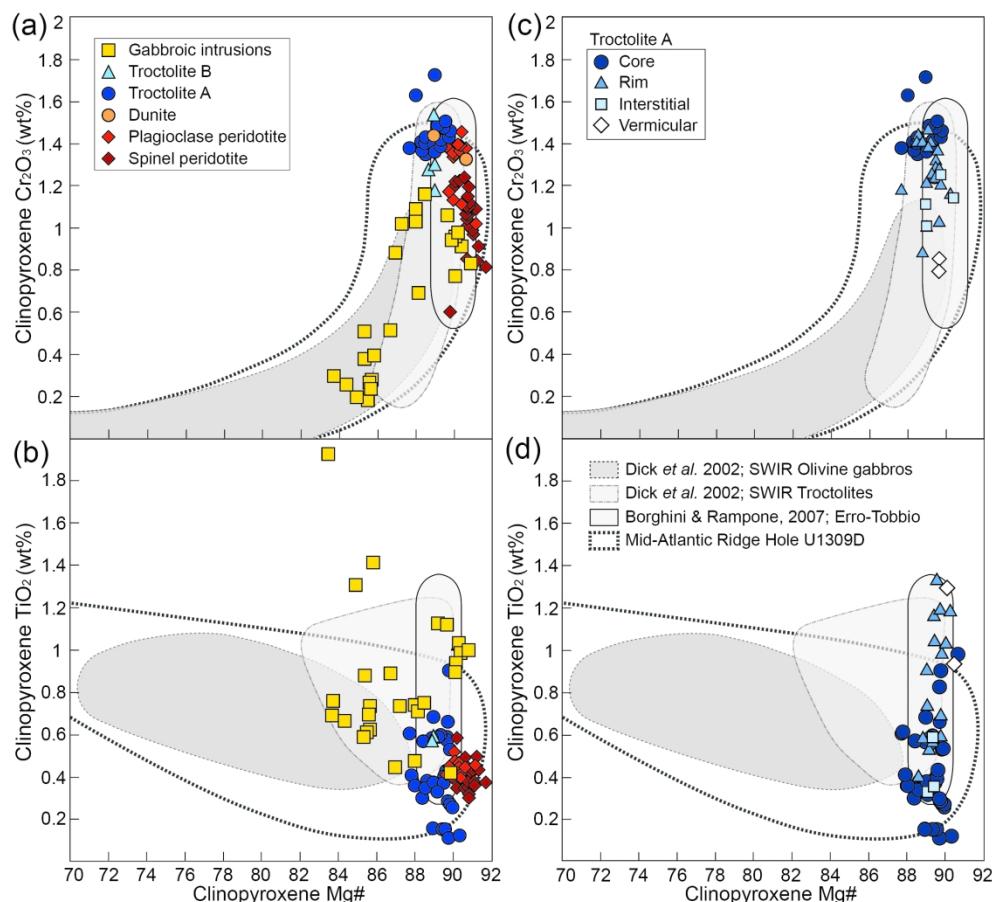


Figure 11: Major elements compositions of clinopyroxene cores (A-B) in all studied samples, plotted against the Mg-number = Mg/(Mg+Fe), and compositional variability with microstructural site (C, D) in Troctolites A. A-C: Cr₂O₃ (wt%); B-D: TiO₂ (wt%). Compositional fields represent compositions of olivine gabbros and troctolites from the South-West Indian Ridge, after Dick et al. (2002), Olivine-rich troctolites from the Erro-Tobbio, after Borghini & Rampone (2007), and Troctolites, olivine gabbros and gabbros from the Mid-Atlantic Ridge Hole U1309D, after Suhr et al. (2008), Drouin et al. (2009); Miller et al. (2009) and Ferrando et al. (2018).

212x193mm (300 x 300 DPI)

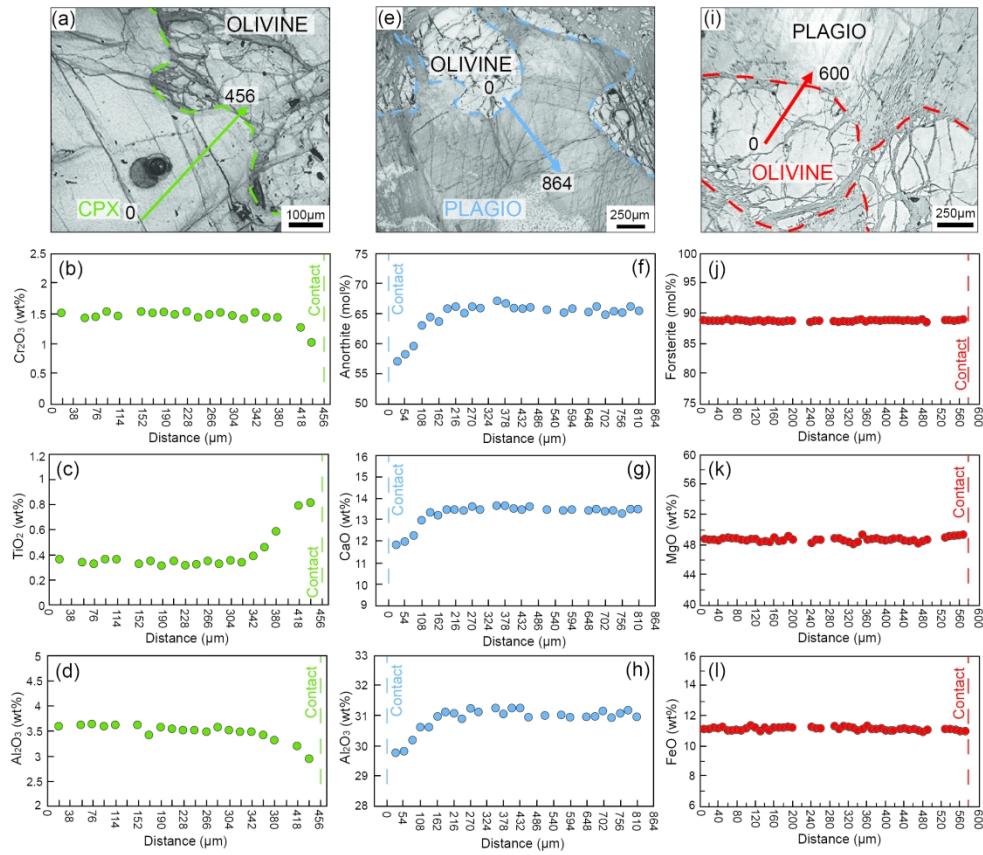


Figure 12: A-D: Reflected light photomicrographs and corresponding Clinopyroxene major element profile in Troctolite A. Step size is 19μm. B: Cr₂O₃ (wt%); C: TiO₂ (wt%); D: Al₂O₃ (wt%). Total length of the profile is 456μm. E-H: Reflected light photomicrographs and corresponding Plagioclase major element profile in Troctolite A. Step size is 54μm. F: Anorthite content (mol%); G: CaO (wt%); H: Al₂O₃ (wt%). Total length of the profile is 864μm. I-L: Reflected light photomicrographs and corresponding Olivine major element profile in Troctolite A. Step size is 10μm. J: Forsterite content (mol%); K: MgO (wt%); L: FeO (wt%). Total length of the profile is 600μm.

210x181mm (300 x 300 DPI)

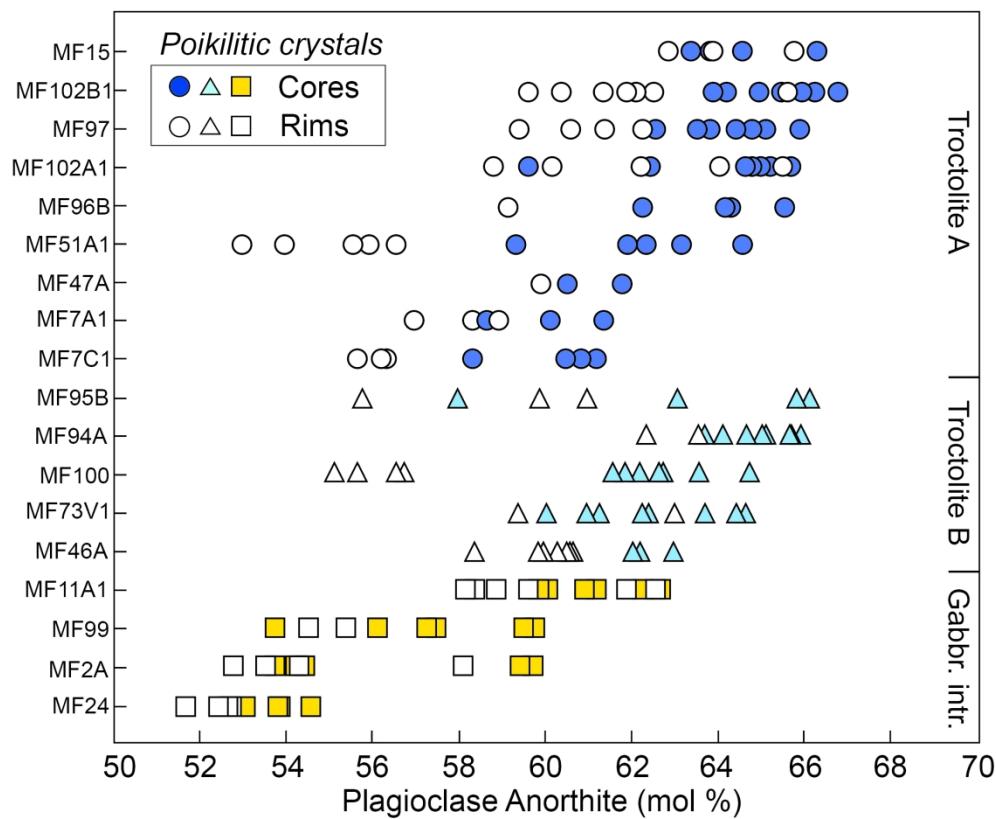


Figure 13: Range of Anorthite content in plagioclase in Troctolites A, Troctolites B and Gabbroic intrusions. Distinction has been made between cores (coloured symbols) and rims (white symbols) of coarse poikilitic plagioclase crystals.

218x182mm (300 x 300 DPI)

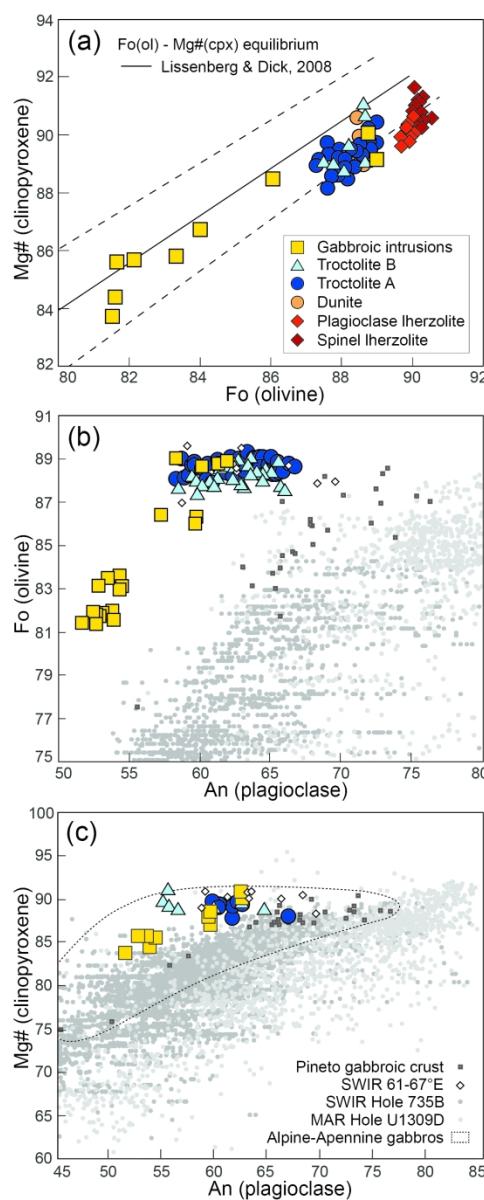


Figure 14: A: Olivine – Clinopyroxene cores $Mg\# = Mg/(Mg+Fe)(mol\%)$ correlation in the studied samples, compared to theoretical Fe-Mg equilibrium between olivine and clinopyroxenes, after Lissenberg & Dick (2008). The dashed lines represent the calculated olivine-clinopyroxene equilibrium line assuming an uncertainty of ± 0.02 on the mineral-melt partition coefficients. B: Anorthite content (mol%) in plagioclase cores versus Forsterite content (mol%) in olivine cores in olivine-plagioclase couples from the studied Troctolites A, Troctolites B and Gabbroic intrusions. C: Anorthite content (mol%) in plagioclase cores versus $Mg\#$ (mol%) in clinopyroxene cores in plagioclase-clinopyroxene couples from the studied Troctolites A, Troctolites B and Gabbroic intrusions. Compositional trends and fields represent olivine-plagioclase and olivine-clinopyroxene couples in olivine gabbros and troctolites from the South-West Indian Ridge (Hole735B: Dick et al., 2002; 61-67°: Paquet et al., 2016), the Mid-Atlantic Ridge Hole U1309D (Ross & Elthon, 1997; Lissenberg & Dick, 2008; Suhr et al., 2008; Drouin et al., 2009; Miller et al., 2009), the Pineto gabbroic crust (Sanfilippo & Tribuzio, 2012), and the Alpine-Apennine ophiolites (Hebert et al., 1989; Tribuzio et al., 1999; Montanini et al., 2008; Sanfilippo & Tribuzio, 2012).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

121x295mm (300 x 300 DPI)

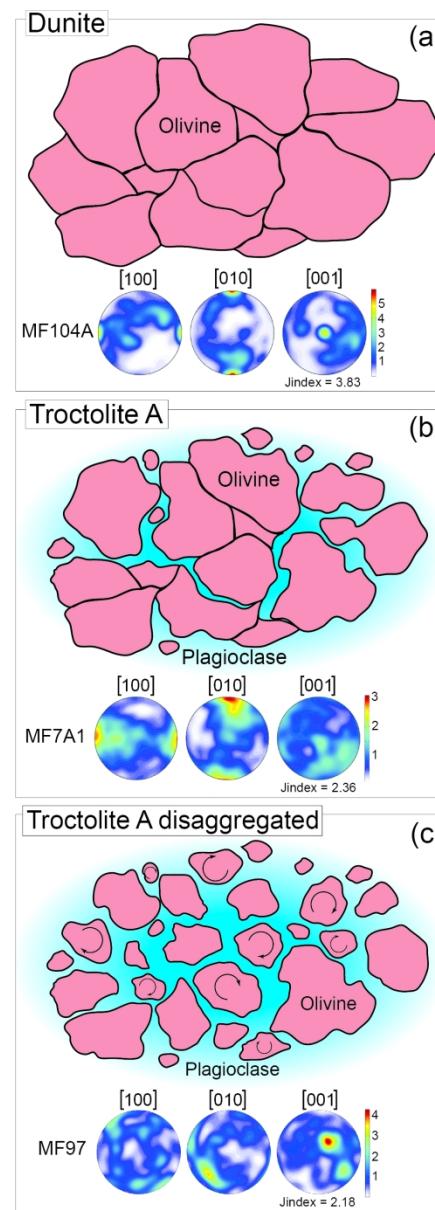


Figure 15: Interpretative sketch of the evolution of the olivine textures and associated CPOs during progressive olivine-dissolving, plagioclase-crystallizing melt-rock interaction and replacive formation of the Troctolite A. A: Coarse-grained dunite protolith showing an axial-[100] olivine CPO; B: Troctolite A impregnated at low melt-rock ratios, and thus preserving dunitic aggregates and axial-[100] olivine CPO; C: Disaggregated troctolite A, impregnated at high instantaneous melt-rock ratios. The arrows within small olivine grains represent the loss of cohesion of the solid matrix leading to the free rotation of the grains and randoming of the olivine CPO. CPO represented as one-point-per-grain equal-area, lower hemisphere stereographic projections. The colour bar is scaled to the maximum concentration of the three crystallographic axes. J-index refers to the fabric strength.

96x265mm (300 x 300 DPI)

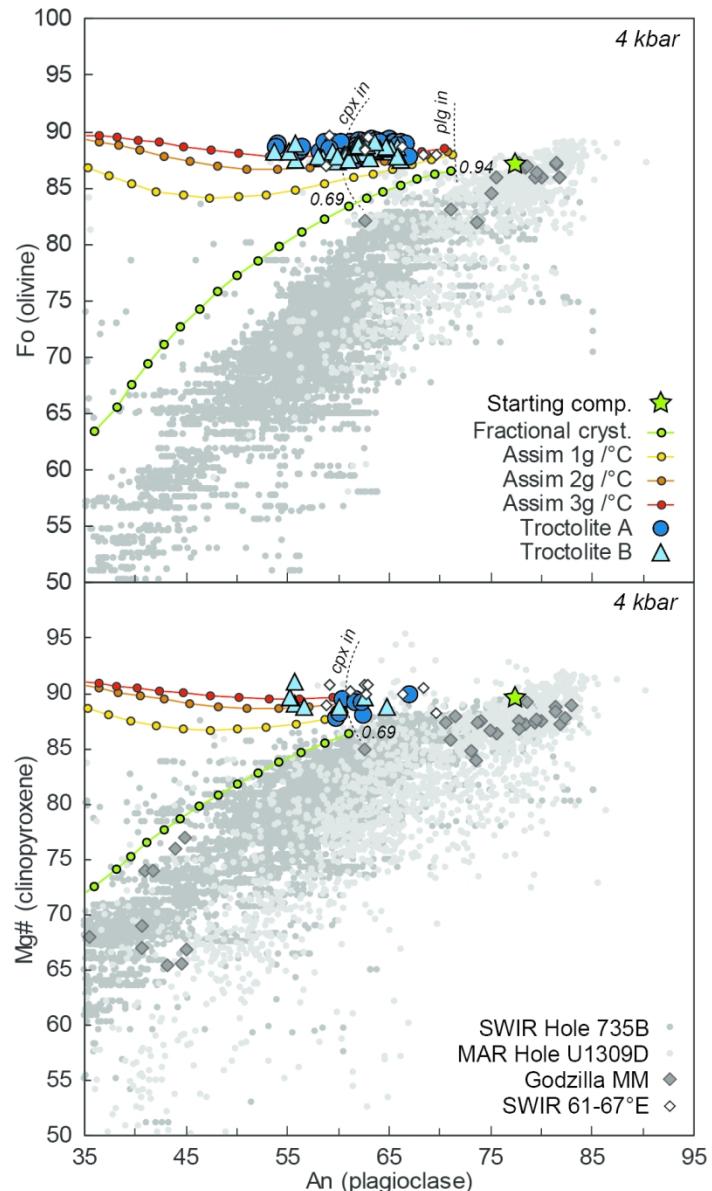


Figure 16: pMELTs numerical simulations (Ghiorso et al., 2002) of the major element compositions of plagioclase (Anorthite content) vs A: olivine (Forsterite content), and B: clinopyroxene (Mg-value) during fractional crystallization and reactive crystallization of a sodic primitive MORB, after Saccani et al. (2008) (see text for detail). Varying assimilation rates of a dunite (100% olivine) from 1g/°C to 3g/°C of cooling are modelled, and compared to the core compositions of olivine-plagioclase, and clinopyroxene-plagioclase couples analyzed in the Troctolite A and Troctolite B. The green star represents the mineral compositions in equilibrium with the starting melt, and each dot along the crystal line of descent corresponds to a 5°C cooling step. The numbers along the fractional crystallization trend represent the remaining melt fraction at the saturation of plagioclase and clinopyroxene. Compositional fields of oceanic gabbroic suites are plotted as comparison for the South-West Indian Ridge (SWIR Hole 735B: Dick et al., 2002; SWIR 61-67°E: Paquet et al., 2016), the Mid-Atlantic Ridge (MAR; Ross & Elthon, 1997; Lissenberg & Dick, 2008; Suhr et al., 2008; Drouin et al., 2009; Miller et al., 2009) and the Godzilla Megamullion (Godzilla MM; Harigane et al., 2011; Sanfilippo et al., 2013).

1
2
3 107x165mm (300 x 300 DPI)
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

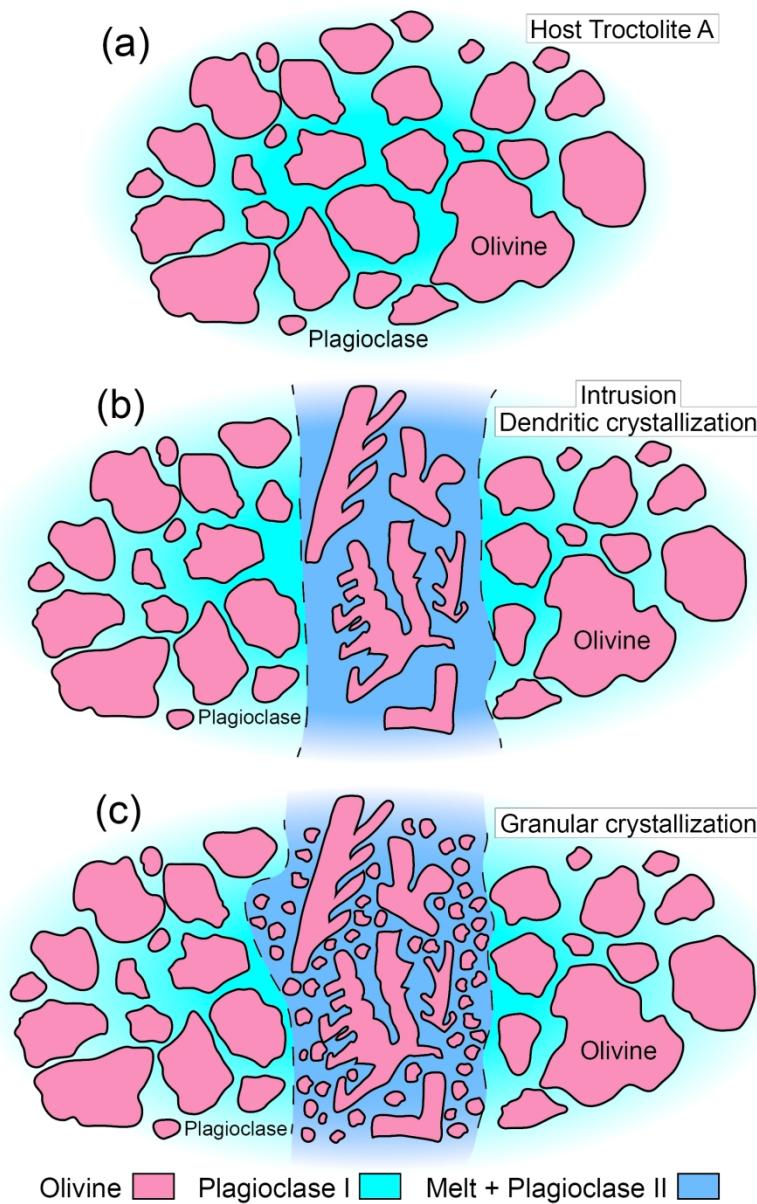


Figure 17: Representative sketch of the formation of Troctolite B. A: initial state, host Troctolite A crystal mush; B: prior crystallization of dendritic olivine by the undercooled melt; C: equilibrium crystallization of the fine-grained granular olivines.

167x250mm (300 x 300 DPI)

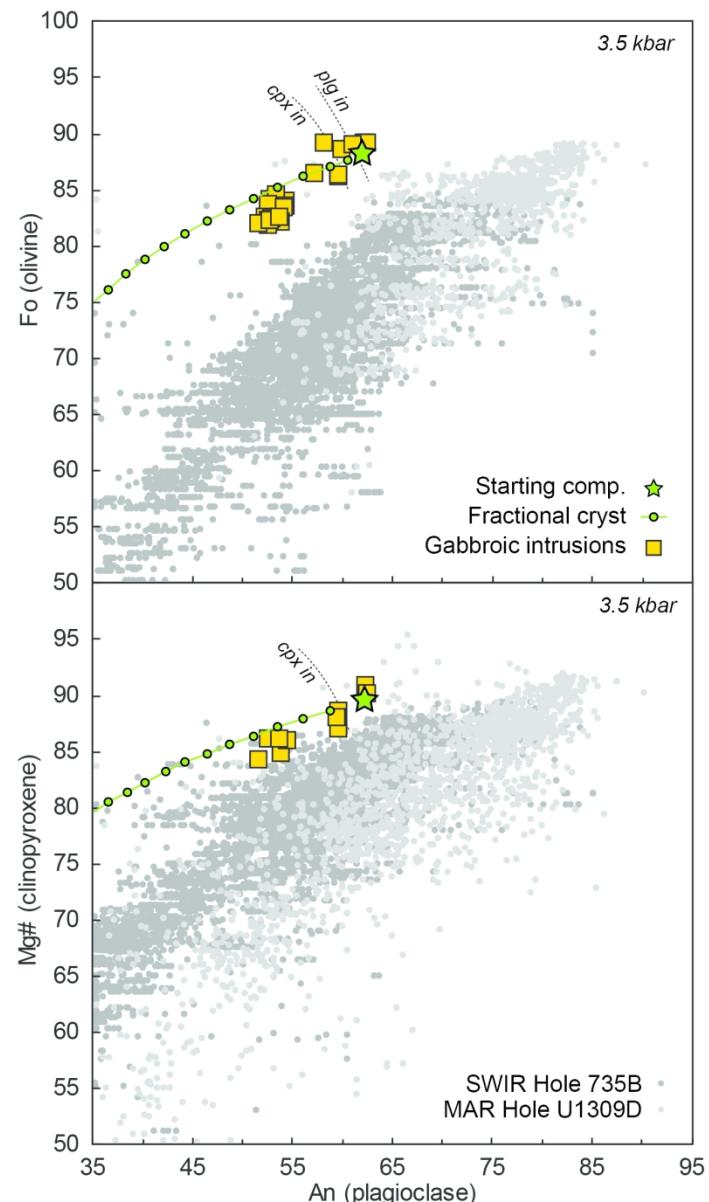


Figure 18: pMELTs numerical modelling (Ghiorso et al., 2002) of the major element compositions of olivine (Forsterite content), plagioclase (Anorthite content) and clinopyroxene (Mg-value) during fractional crystallization of the melt modified after reactive equilibrium crystallization and formation of the Troctolite A and Troctolite B, compared to the major elements core compositions of olivine-plagioclase and clinopyroxene-plagioclase couples analyzed in the Erro-Tobbio Gabbroic intrusions. The green star represents the mineral compositions in equilibrium with the starting melt, and each dot along the crystal line of descent corresponds to a 5°C cooling step. Compositional fields of oceanic gabbroic suites similar to Figure 16.

114x198mm (300 x 300 DPI)

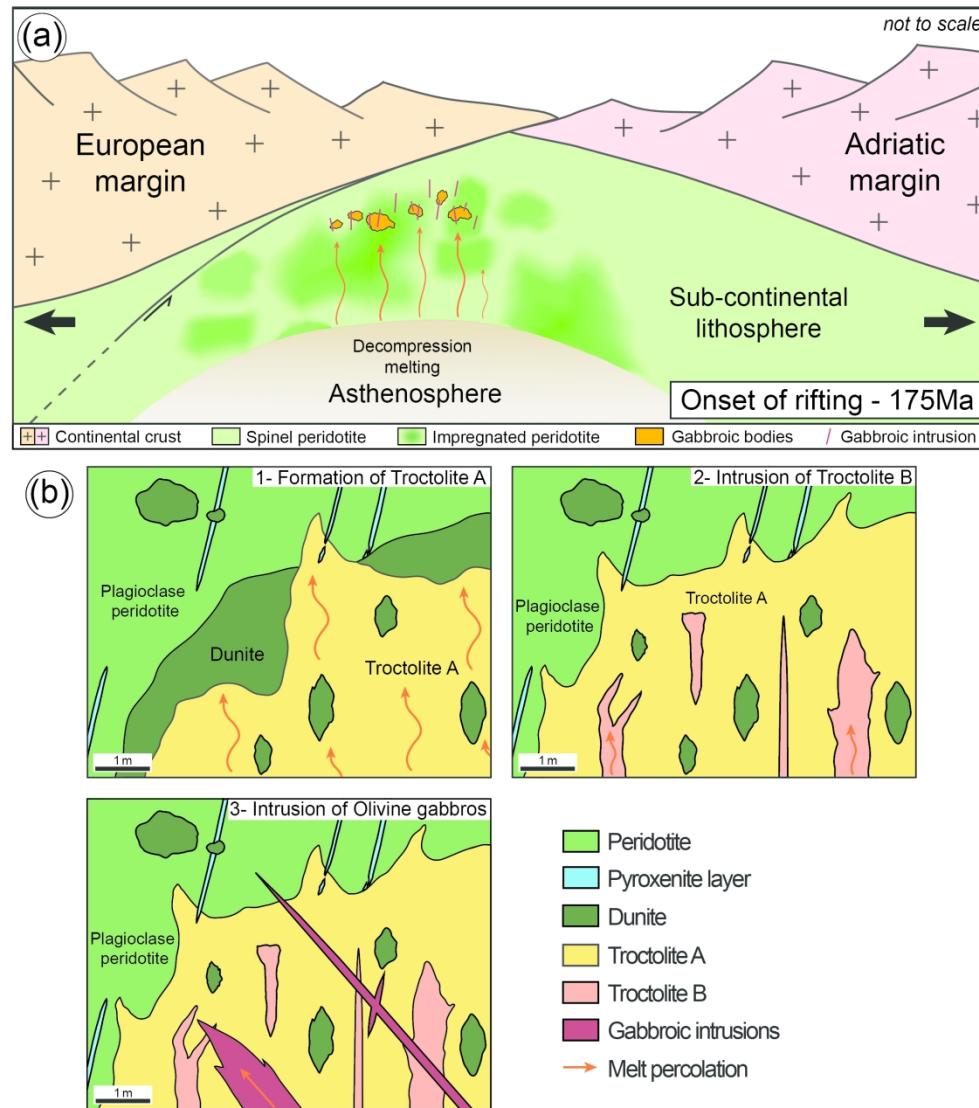


Figure 19: Interpretative sketches of the geological context and evolution of the peridotitic and troctolitic body. A: Geological context of formation of the Erro-Tobbio troctolitic body at 175Ma, during the onset of the Ligurian Tethys basin rifting; B: Representative replacive formation of the Troctolite A from dunitic protolith, intrusion of the Troctolite B during focused melt percolation and intrusion of gabbroic rocks in fractures.

210x237mm (300 x 300 DPI)

Table 1: Studied samples, lithotype, modal composition, and PfJ Olivine

Sample	Lithotype	Modal compositions				PfJ Olivine		
		Olivine	Plagio	Cpx	Opx	[100]	[010]	[001]
ETR2*	Spinel Lherzolite	78	0	7	15	2.33	2.84	2.02
ETR4B*	Spinel Lherzolite	75	0	5	20	2.24	1.64	1.56
ETR4A*	Spinel Lherzolite	71	0	14	15	2.08	1.65	1.32
P1B*	Plagio. Lherzolite	57	10	11	22	2.12	3.61	1.50
P1A*	Plagio. Lherzolite	56	10	4	30	1.90	2.67	1.40
P1*	Plagio. Lherzolite	55	12	11	22	2.53	4.17	2.23
MF40*	Plagio. Lherzolite	53	5	12	30	2.07	3.13	1.63
MF104A	Dunite	97	0	3	0	1.61	1.66	1.44
MF21*	Troctolite A	74	15	11	0	1.08	1.12	1.19
MF15*	Troctolite A	68	31	1	0	1.22	1.50	1.54
MF97	Troctolite A	68	30	2	0	1.19	1.33	1.4
MF51*	Troctolite Apophysis	67	32	1	0	1.77	1.68	1.88
MF7A1*	Troctolite A	66	23	11	0	1.52	1.58	1.23
MF7A2*	Troctolite A	65	26	9	0	1.39	1.77	1.21
MF7C1*	Troctolite A	65	27	8	0	1.24	1.40	1.12
MF51A1*	Troctolite Apophysis	65	32	3	0	1.37	1.24	1.39
MF51A2*	Troctolite Apophysis	64	35	1	0	1.25	1.48	1.41
MF96A	Troctolite A	60	39	1	0	1.14	1.28	1.17
MF96B	Troctolite A	61	37	2	0	1.25	1.18	1.13
MF102A1	Troctolite A	60	36	4	0	1.52	1.42	1.65
MF102B1	Troctolite A	60	36	4	0	1.19	1.34	1.42
MF47A*	Wehrlite Apophysis	60	19	21	0	1.16	1.44	1.17
MF47B*	Wehrlite Apophysis	59	13	28	0	1.22	1.47	1.14
MF102A2	Troctolite A	55	40	5	0	2.58	1.90	2.06
MF94B	Troctolite B	60	38	2	0	1.11	1.09	1.07
MF95A	Troctolite B	60	34	6	0	1.21	1.19	1.23
MF72Ga*	Troctolite B	59	31	10	0	1.41	1.31	1.37
MF95B	Troctolite B	59	36	5	0	1.37	1.28	1.36
MF72I*	Troctolite B	57	41	2	0	1.15	1.12	1.21
MF46A*	Troctolite B	55	44	1	0	1.04	1.23	1.3
MF73V2	Troctolite B	55	39	6	0			
MF94A	Troctolite B	55	42	3	0	2.50	1.85	1.85
MF73V1	Troctolite B	50	48	2	0	1.43	1.40	1.44
MF100	Troctolite B	45	51	4	0	1.64	1.88	1.71
MF11A1*	Troctolitic gabbro	30	69	1	0	1.08	1.10	1.3
MF99	Troctolitic gabbro	30	66	4	0	1.06	1.18	1.17
MF24*	Olivine gabbro	27	59	13	1	1.02	1.13	1.07
MF20*	Olivine gabbro	21	60	18	1	1.02	1.04	1.05
MF2B*	Olivine gabbro	16	63	19	2			
MF2A*	Olivine gabbro	15	68	16	1			

Plagio = Plagioclase; Cpx = Clinopyroxene; Opx = Orthopyroxene.

*samples investigated in previous studies (Rampone *et al.*, 2004, 2014, 2016; Borghini & Rampone, 2007; Borghini *et al.*, 2007; Rampone & Borghini, 2008). See text for further detail.

1
2 **Table 2: Representative major elements olivine composition.**

3 4 wt%	5 Spinel 6 Lherz. 7 Corr.Def	8 Plagio. 9 Lherz. 10 Corr.Def	11 Dunite 12 Corr.Def	13 Troctolite A		14 Troctolite apophysis		15 Wehrlite apophysis		16 Troctolite B		Troct. 17 gabbro 18 Granu.	Troct. 19 gabbro 20 Granu.	Olivine 21 gabbro 22 Granu.	Olivine 23 gabbro 24 Granu.
SiO ₂	41.18	41.10	40.80	40.52	40.42	40.86	40.57	40.89	40.66	40.70	40.49	40.63	40.43	39.74	39.70
TiO ₂	0.04	0.02	0.02	0.03	b.d.l.	b.d.l.	0.03	0.04	0.04	0.02	b.d.l.	0.01	b.d.l.	b.d.l.	0.03
Al ₂ O ₃	0.01	b.d.l.	0.01	b.d.l.	0.02	b.d.l.	0.03	b.d.l.	b.d.l.	b.d.l.	0.04	b.d.l.	0.02	b.d.l.	b.d.l.
Cr ₂ O ₃	b.d.l.	b.d.l.	0.02	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.01	b.d.l.	0.05	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
FeO	9.64	10.05	11.29	11.65	11.75	11.31	11.29	11.81	11.96	11.61	11.52	11.11	13.38	16.11	17.57
MgO	49.47	48.99	47.65	48.05	48.02	48.01	48.21	47.33	47.33	47.90	48.05	48.22	46.49	44.35	43.16
MnO	0.11	0.16	0.21	0.18	0.15	0.23	0.15	0.20	0.22	0.18	0.17	0.17	0.21	0.27	0.33
NiO	0.37	0.43	0.28	0.30	0.28	0.33	0.29	0.27	0.31	0.31	0.32	0.33	0.26	0.21	0.14
CaO	0.03	0.06	0.09	0.06	0.04	0.07	0.05	0.05	0.04	0.08	0.02	0.04	0.01	b.d.l.	0.01
Total	100.85	100.83	100.37	100.81	100.69	100.84	100.63	100.60	100.58	100.86	100.63	100.54	100.80	100.68	100.96
Mg#	90.14	89.68	88.27	88.03	87.93	88.33	88.39	87.72	87.58	88.03	88.14	88.55	86.10	83.07	81.41

21 Mg# = Mg/(Mg+Fe); Spinel Lherz. = Spinel lherzolite; Plagio. Lherz. = Plagioclase lherzolite; Troct. Gabbro = Troctolitic gabbro

Table 3: Representative major elements clinopyroxene composition.

	Spinel Lherz. wt%	Plagio. Lherz.		Dunite	Troctolite A		Troct. apophysis		Wehrlite apophysis Core	Troctolite B		Troct. gabbro Core	Troct. gabbro			Olivine gabbro Core	Olivine gabbro Core
		Core	Rim	Core	Core	Rim	Core	Rim	Core	Core	Rim	Core	Core	Rim	Core	Core	
SiO ₂	51.24	51.70	50.98	52.05	52.31	51.70	52.74	51.05	52.62	51.45	52.14	51.46	51.76	51.72	51.92	52.70	
TiO ₂	0.36	0.40	0.50	0.98	0.40	0.92	0.58	1.00	0.35	0.64	1.02	0.92	0.73	0.75	0.89	0.73	
Al ₂ O ₃	6.59	4.48	4.87	2.96	3.61	3.34	3.05	2.99	3.51	3.62	3.23	3.28	3.35	3.21	2.80	2.51	
Cr ₂ O ₃	1.10	1.46	1.34	1.32	1.43	1.16	1.08	1.00	1.29	1.40	0.91	0.94	1.01	1.15	0.51	0.28	
FeO	2.83	3.01	3.20	3.08	3.45	3.22	3.43	3.37	3.42	3.57	3.17	3.23	4.33	3.76	4.63	5.15	
MgO	15.23	15.81	16.05	16.64	16.51	16.32	16.68	17.61	16.09	15.94	16.32	16.49	16.56	16.21	16.93	17.25	
MnO	0.07	0.02	0.07	0.12	0.07	0.08	0.18	0.07	0.10	0.11	0.09	0.10	0.15	0.17	0.27	0.16	
NiO	0.07	0.06	0.07	0.02	b.d.l.	0.04	0.04	0.06	b.d.l.	0.05	0.04	0.11	0.07	0.06	b.d.l.	0.03	
CaO	22.25	22.86	22.29	21.74	20.90	22.03	21.47	21.26	22.17	21.60	22.49	21.85	20.61	21.61	22.65	20.30	
Na ₂ O	0.71	0.38	0.26	0.65	0.62	0.56	0.05	0.58	0.55	0.64	0.62	0.46	0.46	0.60	0.35	0.45	
Total	100.45	100.20	99.65	99.56	99.29	99.37	99.31	99.00	100.10	99.02	100.03	98.83	99.03	99.23	100.66	99.57	
Mg#	90.56	90.35	89.94	90.59	89.51	90.03	89.66	90.30	89.34	88.84	90.17	90.10	87.21	88.48	86.70	85.65	

Mg# = Mg/(Mg+Fe); Spinel Lherz. = Spinel lherzolite; Plagio. Lherz. = Plagioclase lherzolite; Troct. Apophysis = Troctolite apophysis; Troct. Gabbro = Troctolitic gabbro

Table 4: Representative major elements plagioclase composition

wt%	Troctolite A		Wehrlite apo.		Troctolite apo.		Troctolite B		Troc. gabbro	Troc. gabbro		Olivine gabbro		Olivine gabbro	
	Core	Rim	Core		Core	Rim	Core	Rim	Core	Core	Rim	Core	Rim	Core	Rim
SiO ₂	52.22	54.11	52.74		52.08	54.76	51.21	52.95	52.08	53.41	53.73	53.53	55.03	54.53	54.05
TiO ₂	0.10	0.10	0.02		0.21	0.09	b.d.l.	0.06	0.30	0.10	0.07	b.d.l.	b.d.l.	0.08	0.04
Al ₂ O ₃	30.39	29.14	30.43		30.53	28.54	30.97	29.93	30.51	29.96	29.73	29.36	28.78	29.26	29.02
Cr ₂ O ₃	b.d.l.	b.d.l.	b.d.l.		b.d.l.	b.d.l.	0.02	0.03	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
FeO	0.16	0.15	0.20		0.02	0.02	0.23	0.17	0.30	0.33	0.20	0.35	0.27	0.27	0.30
MgO	0.03	0.01	0.05		0.01	b.d.l.	b.d.l.	0.02	0.05	0.04	0.07	b.d.l.	b.d.l.	0.05	0.02
MnO	0.02	0.03	b.d.l.		0.01	b.d.l.	0.01	b.d.l.	0.02	0.07	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
NiO	0.03	b.d.l.	0.06		b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.02	b.d.l.
CaO	13.35	11.25	12.78		12.79	11.17	13.14	12.15	12.71	11.84	11.39	11.14	10.93	10.90	11.02
Na ₂ O	3.96	5.27	4.38		4.27	5.27	3.99	4.58	4.25	4.87	5.07	5.16	5.39	5.46	5.22
K ₂ O	0.03	0.04	0.04		0.02	0.03	0.02	0.04	0.02	0.02	0.03	b.d.l.	b.d.l.	0.02	0.03
Total	100.28	100.11	100.70		99.93	99.88	99.59	99.93	100.25	100.64	100.29	99.54	100.40	100.59	99.70
An	65.07	54.12	61.72		62.34	53.94	64.54	59.45	62.30	57.33	55.39	54.40	52.84	52.45	53.82

An = Ca/(Ca+Na); Wehrlite apo. = Wehrlite apophysis; Troctolite apo. = Troctolite apophysis; Troct. Gabbro = Troctolitic gabbro

Table 5: Representative major elements orthopyroxene composition

wt%	Spinel Lherz. Core	Plagioclase Lherzolite Core	Olivine Gabbro Core
SiO ₂	55.40	56.18	55.43
TiO ₂	0.10	0.24	0.21
Al ₂ O ₃	4.88	2.39	2.63
Cr ₂ O ₃	0.73	0.65	0.82
FeO	6.26	6.27	5.95
MgO	32.10	32.64	31.69
MnO	0.15	0.08	0.14
NiO	0.08	0.07	0.10
CaO	0.85	1.52	3.22
Na ₂ O	0.03	0.01	0.03
Total	100.57	100.05	100.22
Mg#	90.14	90.27	90.47
			84.53

Mg# = Mg/(Mg+Fe); Spinel Lherz. = Spinel lherzolite;

b.d.l. = below detection limit

Table 6: Representative major elements spinel composition

<i>wt%</i>	Spinel Lherz.	Dunite	Troc. A	Troc. apo.	Troc. B	Troc. Gabbro
SiO ₂	b.d.l.	0.03	0.02	b.d.l.	0.05	b.d.l.
TiO ₂	0.07	2.91	1.66	1.27	2.01	1.39
Al ₂ O ₃	53.68	15.19	17.90	16.33	21.41	12.89
Cr ₂ O ₃	14.82	38.02	35.94	38.79	35.93	42.77
Fe ₂ O ₃	1.03	11.65	b.d.l.	b.d.l.	7.83	b.d.l.
FeO	12.78	23.60	36.35	35.93	23.20	35.89
MnO	b.d.l.	b.d.l.	0.23	0.03	b.d.l.	0.38
NiO	b.d.l.	b.d.l.	0.27	0.02	b.d.l.	0.12
MgO	18.31	8.76	6.82	7.29	8.93	6.79
CaO	b.d.l.	0.01	0.03	b.d.l.	0.01	b.d.l.
Total	100.69	100.17	99.23	99.67	99.41	100.29
Cr#	0.16	0.63	0.57	0.61	0.53	0.69
Mg#	0.70	0.31	0.25	0.27	0.34	0.25

Mg# = Mg/(Fe+Mg); Cr# = Cr/(Cr+Al+Fe³⁺); b.d.l.= below detection limit

Table 7: Input and output melt compositions of pMELTS numerical simulations of reactive and fractional crystallization

wt%	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	Mg#	Ca#	Liquidus	ΔT _{liq}
Ini.Melt ^a	49.93	1.21	16.85	0.87	7.01	0.13	9.5	10.45	3.61	0.03	99.59	70.75	61.54	1261°C	0
5g Assim. ^b	49.5	1.16	16.05	0.85	7.11	0.13	11.4	9.95	3.44	0.03	99.62	74.08	61.51	1297°C	36
10g Assim ^b	49.11	1.1	15.32	0.84	7.21	0.12	13.12	9.50	3.28	0.03	99.63	76.43	61.55	1322°C	61
15g Assim ^b	48.75	1.05	14.65	0.83	7.3	0.12	14.7	9.09	3.14	0.03	99.66	78.21	61.53	1344°C	83
Mod.Melt ^c	52.81	1.94	15.82	0.77	5.50	0.00	8.03	10.68	4.41	0.04	100.0	72.24	57.23	1222°C	-

Mg# = Mg/(Mg+Fe); Ca# = Ca/(Ca+Na); Liquidus = Liquidus temperature; -ΔT_{liq} = T_{liq} (modif) - T_{liq} (initial)

a: Initial primitive melt composition used for fractional and reactive crystallization modeling, after Saccani *et al.* (2008).

b: Melt composition and liquidus temperature after assimilation of 5, 10 and 15 grams of olivine during 5°C cooling.

c: Melt composition modified after reactive crystallization process, used as initial melt for fractional crystallization process of the olivine gabbros.