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The Chicken and Egg Dilemma Linking Dunites and Chromitites in the Mantle–Crust Transition Zone beneath Oceanic Spreading Centres: a Case Study of Chromite-hosted Silicate Inclusions in Dunites Formed at the Top of a Mantle Diapir (Oman Ophiolite)

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The Chicken and Egg Dilemma Linking Dunites and Chromitites in the Mantle-Crust Transition Zone Beneath Oceanic Spreading Centres: A Case Study of Chromite-hosted Silicate Inclusions in Dunites Formed at the Top of a Mantle Diapir (Oman Ophiolite)

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3 **The Chicken and Egg Dilemma Linking Dunites and Chromitites in the**
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6 **Mantle-Crust Transition Zone Beneath Oceanic Spreading Centres: A Case**
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8 **Study of Chromite-hosted Silicate Inclusions in Dunites Formed at the Top**
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10 **of a Mantle Diapir (Oman Ophiolite)**
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ABSTRACT

The mantle-crust boundary beneath oceanic spreading centres is a major chemical and thermal interface on Earth. Observations in ophiolites reveal that it is underlined by a dunitic transition zone (DTZ) that can reach a few hundred meters in thickness and hosting abundant chromitite ore bodies. The dunites have been deciphered as essentially mantle-derived in most ophiolitic massifs, i.e. reactional residues of interactions between peridotite and percolating melt(s). Although both dunite and chromitite in ophiolites have been the focus of many studies, the reasons of their systematic association remain unclear.

In this study we have explored the inclusion content of the chromite grains disseminated in the dunites from the DTZ exposed in the Maqsad area of the Oman ophiolite where a former asthenospheric diapir is exposed. Similarly to chromite in chromitite ore bodies, disseminated chromite grains in dunites contain a great diversity of silicate inclusions. Based on the major and minor element composition of 1794 single silicate inclusions in chromites from 285 samples of dunite and associated rocks in the DTZ, we infer that the disseminated chromites formed by a similar “metallogenic” process to the chromitites, and that, as a whole, dunites from the DTZ actually represent the low grade endmember of a single, giant ore body.

The nature of the silicate inclusions (amphibole and mica among others) enclosed in chromite grains in dunites from the Maqsad DTZ precludes their crystallization from an anhydrous primitive basaltic melt, and rather calls for a crystallization from a melt hybrid between common mafic melts and more exotic Si-, Na- and volatile-rich fluids. The hybrid parent medium of both dunites and chromitites results from the interaction between an asthenospheric diapir (the MORB source), and a colder, altered lithospheric lid and hydrothermal fluids responsible for this alteration. The excess silica in the hybrid melt is provided by the

1
2
3 incongruent dissolution of enstatite from mantle harzburgite and/or from moderate degree of
4 partial melting of the altered gabbroic crust. The chemical composition of the silicate inclusions
5
6 is more variable when enclosed in the disseminated chromites than in the chromitites,
7
8 suggesting a greater variability of melts and/or fluids fractions involved in the genesis of dunites
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10 than of chromite ores. Finally, the DTZ can be viewed as a metamorphic contact aureole
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12 between episodically rising asthenospheric diapirs and formerly accreted axial lithospheric lids.
13
14 Our conclusion about the chicken and egg dilemma linking dunites and chromitites beneath
15
16 oceanic spreading centres (i.e. Do the chromitites form in response to the formation of dunites
17
18 or conversely?) is that the mantle dunitization itself is a potential way for the release of Cr and
19
20 its re-concentration as chromite ores, and that in turn the competition between orthopyroxene
21
22 (+/- plagioclase) and chromite fractionation during this fluid/melt/peridotite reactional process
23
24 is responsible of the great mineralogical and chemical variability of the DTZ dunites.
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35 **Key words:** Oman ophiolite; Maqsad diapir; dunitic mantle-crust transition zone (DTZ);
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37 disseminated chromites; silicate inclusions; melts/fluids hybridization; reactive interfaces
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INTRODUCTION

In the mantle section of ophiolites, chromite ore bodies (chromitites) are, as a rule, surrounded by dunite (e.g. Cassard *et al.*, 1981; González-Jiménez *et al.*, 2014). This observation calls for a genetic link between the two. Dunites and chromitites are particularly abundant along the 'paleo-Moho', where dunites form a dunitic transition zone (DTZ) between the mantle and crustal sections (Moore and Vine, 1971; Greenbaum, 1972; Ceuleneer and Nicolas, 1985; Boudier and Nicolas, 1995; Abily and Ceuleneer, 2013). The development of a DTZ and more generally of dunites within the mantle section, and of the associated chromitites, is not restricted to a specific petrological context. They are present in ophiolites that evolved in tholeiitic (MORB-like) environments where they are associated with troctolites and olivine gabbros, and in depleted andesitic-boninitic environments where the associated lithologies include abundant pyroxenites (e.g. Quick, 1981a, 1981b; Augé, 1987; Ahmed and Arai, 2002; Varfalvy *et al.*, 1996; Rollinson, 2005, 2008; Ceuleneer and le Sueur, 2008; Akizawa and Arai, 2009; Borisova *et al.*, 2012; Abily and Ceuleneer, 2013; Rollinson and Adetunji, 2013). Both dunites and chromitites may result from melt-peridotite reactions in the shallow mantle (e.g. Arai and Yurimoto, 1994; Zhou *et al.*, 1994; Allan and Dick, 1996; Borisova *et al.*, 2012).

Deep-seated dunites associated with mantle harzburgites in ophiolites and in abyssal peridotites are interpreted as products of melt-peridotite reaction by most authors. Dunite formation can be explained by the simple fact that a mantle partial melt produced at depth and migrating to the surface is no longer multiply saturated with the peridotite mineral assemblage at low pressure (e.g. Stolper, 1980). Among other effects, it will induce the dissolution of residual orthopyroxene at shallow depth through the incongruent dissolution reaction leading to olivine precipitation and to the enrichment of the reactant melt in silica and other elements that are minor constituents of orthopyroxene (e.g. Al, Cr, Ca, Na) as well as of clinopyroxene when

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3 present in the former peridotite (e.g. Dick, 1977; Quick, 1981b; Nicolas, 1986; Kelemen, 1990;
4 Kelemen *et al.*, 1992, 1995; Abily and Ceuleneer, 2013). From a historical perspective, this
5 mechanism challenged the classical model of dunite formation by fractional crystallization from
6 a high-Mg melt inspired by the seminal experimental studies of Bowen and widely supported
7 by the study of rhythmic layering in layered intrusions. It is worth noting that Bowen (1927)
8 realized that the fractional crystallization mechanism failed to account for the existence of large
9 volumes of dunites, among other those documented in ophiolites.

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12 In the frame of dunite genesis by melt-peridotite reaction, olivine grains of ‘residual’ origin
13 (mantle-derived) and ‘secondary’ origin (precipitated after orthopyroxene dissolution) are
14 intimately mixed, while their respective proportion may vary spatially at the scale of an outcrop.
15 Other interstitial minerals (mostly chromite, clinopyroxene and plagioclase) in between olivine
16 grains are interpreted as the crystallization products from percolating intergranular melts,
17 consistent with observations at the outcrop and hand specimen scales in ophiolites and abyssal
18 peridotites and with their geochemical signatures (e.g. Benn *et al.*, 1988; Cannat *et al.*, 1990;
19 Ceuleneer, 1991; Girardeau and Francheteau, 1993; Boudier and Nicolas, 1995; Rampone *et*
20 *al.*, 1997; Koga *et al.*, 2001; Kaczmarek and Müntener, 2008; Morgan *et al.*, 2008; Abily and
21 Ceuleneer, 2013; Sanfilippo *et al.*, 2013; Dygert *et al.*, 2016; Basch *et al.*, 2018). In other words,
22 dunites at the mantle-crust transition and more generally peridotites containing melt migration
23 evidence are regarded as products of a multi-stage evolution leading to the intimate association
24 of mineral assemblages issued from different processes: partial melting, reaction melting and
25 crystallization of an interstitial melt (e.g. Rospabé *et al.*, 2018 and references therein). The
26 terms ‘impregnation’ and ‘impregnated peridotite’ have been introduced a long time ago (e.g.
27 Bowen, 1915; Nicolas, 1986) to describe such complex lithologies for which the academic rock
28 names based mostly on thin section scale microscopic observations of monogenic assemblages
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3 are not adapted descriptors. These terms are still of common use (e.g. Benn *et al.*, 1988;
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5 Ceuleneer and Rabinowicz, 1992; Seyler *et al.*, 2001; Dijkstra *et al.*, 2003; Takazawa *et al.*,
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7 2007; Sanfilippo *et al.*, 2013).
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12 Petrologists realized early (e.g. Fisher, 1929) that the formation of large volumes of ore made
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14 almost exclusively of chromite was difficult to reconcile with the classical cumulate theory, i.e.
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16 fractional crystallization followed by crystal/melt segregation. The arguments included mass
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18 balance considerations related among other to the poor solubility of Cr in silicate melts (e.g.
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20 Leblanc and Ceuleneer, 1991), and observation of the frequent association of chromite with
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22 minerals (both interstitial and included within chromite grains) that are not on the predicted
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24 cotectic at any stage of fractional crystallization of common basaltic melts (e.g. Irvine, 1975;
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26 Borisova *et al.*, 2012). The issue concerned both thick layers of huge lateral extent in stratiform
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28 intrusions and pods reaching several hundred meters in size in ophiolites.
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35 Based on the study of chromite ores in ophiolites and in continental layered intrusions, different
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37 mechanisms have been proposed to account for the mobilisation of Cr followed by the massive
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39 crystallization of chromite. They include among others (1) the mixing or ‘hybridization’
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41 between a basalt saturated in Cr and a more silicic melt potentially issued from the country
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43 rocks assimilation or re-melting, (2) an H₂O input, (3) the increase in the total pressure or fO₂
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45 of the parent magma, (4) the saturation in chromite alone in the parent magma following a
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47 decrease in the lithostatic pressure, or a combination of them (e.g. Irvine, 1975, 1977a, 1977b;
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49 Lipin, 1993; Bédard and Hébert, 1998; Matveev and Ballhaus, 2002; Spandler *et al.*, 2005;
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51 Mondal and Mathez, 2006; Naldrett *et al.*, 2012; Latypov *et al.*, 2018). The silicate crystals
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53 included in chromite grains (e.g. amphibole, micas, orthopyroxene) are among the strongest
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55 pieces of evidence supporting the hypothesis of the silica- and/or H₂O-rich character of the
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3 parent melt in both ophiolites and layered intrusions (e.g. Johan *et al.*, 1983, 2017; Talkington
4 *et al.*, 1984; McElduff and Stumpfl, 1991; Spandler *et al.*, 2005; Borisova *et al.*, 2012;
5 *et al.*, 2012; Rollinson *et al.*, 2018; Rospabé *et al.*, 2019b), even if major differences in terms of intensive
6 and extensive parameters of the system (e.g. melt/rock reaction processes vs. pure cumulates),
7 of timing and of boundary conditions make the transposition from one setting to the other risky.
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17 In the Oman ophiolite, the silicate inclusions in mantle and DTZ chromitite ore bodies have
18 been reported in previous studies (Augé, 1987; Lorand and Ceuleneer, 1989; Leblanc and
19 Ceuleneer, 1991; Schiano *et al.*, 1997; Ahmed and Arai, 2002; Borisova *et al.*, 2012; Rollinson
20 *et al.*, 2018; Zagrtidenov *et al.*, 2018; Rospabé *et al.*, 2019b). However, the disseminated
21 chromites from the DTZ and the silicate inclusions they contain (Lorand, 1988; Rospabé *et al.*,
22 2017) have never been studied with such a level of detail, even though they are an optimal
23 target to make the connection between the formation of dunite and the formation of chromitite
24 at mantle-crust transitions in the oceanic lithosphere. In the present study, we report on the
25 nature and the major/minor element composition of silicate inclusions enclosed in chromite
26 grains from 285 samples (dunites and related lithologies) collected along 17 cross-sections
27 covering a large part of the DTZ in the Maqsad area (Sumail massif, Oman ophiolite). This
28 allows us to anchor our discussion of the formation of dunite and chromitite on a robust data
29 set, and to comprehend the spatial variations in the processes leading to their formation in the
30 DTZ. We address the discussion about the question of the prior formation of dunites, without
31 which chromitites cannot subsequently form, or reversely, in the ‘chicken and egg dilemma’
32 spirit to link these two melt/rock (\pm fluids) reaction products.
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56 **GEOLOGICAL BACKGROUND**

57 **Geology of the Oman ophiolite**

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3 The Oman ophiolite is a major geological feature of south-eastern Arabia (Fig. 1a). It accreted
4 along a possibly fast spreading ridge ~ 95-97 million years ago (e.g. Tippit *et al.*, 1981; Rioux
5 *et al.*, 2013) and is the largest oceanic lithosphere fragment (~ 500 x 50 km) preserved from
6 the Tethys. The intra-oceanic thrusting event is close in age with the igneous accretion which
7 indicates that the detachment took place at or near the ridge (e.g. Boudier *et al.*, 1985; Rioux *et*
8 *al.*, 2013, 2016). The final emplacement on the Arabian margin was completed during
9 Maestrichtian times (~ 70 Ma) (Glennie *et al.*, 1973).

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21 The tectonic setting in which the Oman ophiolite formed is still debated. (1) The spatial
22 distribution along the ophiolite of the nature of mafic dikes cutting-across the mantle section,
23 and (2) the geochemical signature of lower crustal cumulates, attest that both MORB and
24 depleted calc-alkaline series coexisted during the igneous evolution of the ophiolite (Benoit *et*
25 *al.*, 1999; Python and Ceuleneer, 2003; Yamasaki *et al.*, 2006; Python *et al.*, 2008; Clénet *et*
26 *al.*, 2010). The MORB kindred of the magmas that formed the crust accreted from the Maqsad
27 diapir, focus of the present study, has been demonstrated by the crystallization sequences and
28 by geochemical arguments (e.g. Benoit *et al.*, 1996; Ceuleneer *et al.*, 1996; Koga *et al.*, 2001;
29 Godard *et al.*, 2003).

40 41 42 43 44 **Geology of the Maqsad Dunitic Transition Zone**

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46 The Sumail massif is located in the southeast part of the Oman ophiolite (Fig. 1a). It exposes,
47 in the Maqsad area, a former axial mantle upwelling evidenced by a characteristic high-
48 temperature plastic deformation pattern recorded by mantle harzburgites (Rabinowicz *et al.*,
49 1987; Ceuleneer *et al.*, 1988; Ceuleneer, 1991; Jousselin *et al.*, 1998). The Maqsad diapir fed a
50 ~80 km-long, N130-oriented paleo-spreading segment with melts of MORB affinity (Python
51 and Ceuleneer, 2003). The dunitic mantle-crust transition zone reaches its maximum thickness
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3 (up to 400 m) above the central part of the Maqsad diapir where it seems to have developed
4 preferentially. At the scale of geological maps (1:100,000), the contact between the mantle
5 harzburgites and the dunitic transition zone (DTZ) is quite well defined. At the outcrop scale,
6 harzburgites and the dunitic transition zone (DTZ) is quite well defined. At the outcrop scale,
7 where not faulted, it appears to be progressive on a few tens of meters, dunite bands interlayered
8 with harzburgites becoming increasingly abundant upsection (Boudier and Nicolas, 1995). A
9 thinner DTZ away from the centre of the diapir may be attributed to a less pronounced
10 development of the dunites themselves, to the compaction of the dunitic mush and/or to the off-
11 axis transposition and thinning related to corner flow (Rabinowicz *et al.*, 1987; Ceuleneer,
12 1991; Jousselin *et al.*, 2000).
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26 Similarly to other mantle dunites and mantle-crust transitions in ophiolites or abyssal contexts,
27 dunites from the Maqsad DTZ have been interpreted as replacive at the expense of mantle
28 harzburgites rather than as pure cumulates (e.g. Rabinowicz *et al.*, 1987; Boudier and Nicolas,
29 1995; Godard *et al.*, 2000; Koga *et al.*, 2001; Rospabé *et al.*, 2017, 2018, 2019a). The two
30 origins are, however, not mutually exclusive: it has been shown that in the uppermost 50 meters
31 of the DTZ, minerals have chemical compositions consistent with the one of cumulates that
32 prelude to the crystallization of the overlying layered troctolites and olivine gabbros, while in
33 the main part of the DTZ (lowermost 250 meters), their composition supports a reactional origin
34 (Abily and Ceuleneer, 2013).
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49 The previous studies dedicated to the Maqsad DTZ evidenced an extremely variable modal
50 content in dunites, evolving from 'pure dunites', made exclusively of olivine and of a few
51 percent of interstitial chromite grains as well as very minor (< 0.5 %) clinopyroxene, to dunites
52 containing from few percent to up to 40 % of interstitial minerals between olivine grains
53 forming the matrix (Rabinowicz *et al.*, 1987; Boudier and Nicolas, 1995; Koga *et al.*, 2001;
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3 Abily and Ceuleneer, 2013; Rospabé *et al.*, 2017, 2018, 2019a). The extensive mapping and the
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5 sampling of hundreds samples allowed estimating that about 40 % pure dunites and 60 %
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7 impregnated dunites constitute the DTZ in this area (Rospabé, 2018).
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12 The interstitial minerals are mostly clinopyroxene and plagioclase developing frequently a
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14 poikilitic texture surrounding and isolating olivine grains as well as chromite (Rabinowicz *et*
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16 *al.*, 1997; Boudier and Nicolas, 1995; Koga *et al.*, 2001, Abily and Ceuleneer, 2013; Zagrtdenov
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18 *et al.*, 2018). However, interstitial orthopyroxene and amphibole together with garnet and
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20 diopside, these latter with compositions intermediate between igneous and hydrothermal end-
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22 members, have been recently discovered (Rospabé *et al.*, 2017). Unexpected in the MORB
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24 environment in which the DTZ developed, and more generally the Maqsad-Sumail massif, these
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26 minerals have been shown to be the witnesses of the involvement of a hydrated and silica-rich
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28 melt or fluid in the formation of dunites in this context (Rospabé *et al.*, 2017, 2018, 2019a). It
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30 was proposed, based on the increasing abundance of such peculiar interstitial minerals
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32 upsection within the DTZ, that the parent melt was hybrid between (1) the uprising MORB
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34 produced in depth by decompression melting within the diapir, and (2) a supercritical fluid rich
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36 in silica - hydrothermal in origin -, or potentially a trondhjemitic melt issued from the hydrated,
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38 partial re-melting of the country rocks.
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47 Chromitite ore bodies are abundant in the Maqsad area (Ceuleneer and Nicolas, 1985). These
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49 ore bodies crop out mainly within the DTZ and in the shallowest (< 1 km) horizon of the mantle
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51 section (Fig. 1b), in this latter case always surrounded by a dunitic envelope at the contact with
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53 host mantle harzburgites. Studies that focused on the Maqsad chromitites evidenced the
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55 occurrence of silicate crystals entrapped in chromite grains, including hydrated minerals and
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57 nominally anhydrous minerals derived from a hydrated parent melt. Clinopyroxene (diopside
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3 to augite), orthopyroxene (enstatite), amphibole (pargasite, hornblende) and mica (phlogopite,
4 aspidolite) are among the most common (Leblanc and Ceuleneer, 1991; Schiano *et al.*, 1997;
5 Borisova *et al.*, 2012; Rollinson *et al.*, 2018; Zagrtednov *et al.*, 2018; Rospabé *et al.*, 2019b).
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7 Base-metal sulphides and platinum-group minerals have also been described as inclusions in
8
9 chromites in both dunites and chromitites (Lorand, 1988; Lorand and Ceuleneer, 1989; Leblanc
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11 *et al.*, 1991). The silicate inclusions are similar to the ones observed in chromitites from other
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13 massifs in Oman (Augé, 1987; Ahmed and Arai, 2002), in other ophiolites (e.g. Johan *et al.*,
14
15 1983, 2017; Talkington *et al.*, 1984; Maibam *et al.*, 2017; Wojtulek *et al.*, 2019), in present-
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17 day ocean floor spinels in peridotites and chromitites (Arai and matsukage, 1998; Matsukage
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19 and Arai, 1998; Tamura *et al.*, 2014, 2016), but also in chromite-rich layers in continental
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21 layered intrusions (e.g. McDonald, 1965; Ballhaus and Stumpfl, 1986; Li *et al.*, 2005; Spandler
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23 *et al.*, 2005; Friedrich *et al.*, 2019).

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33 In the Maqсад area, the similarity between (1) silicate inclusions in disseminated chromites,
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35 widespread in the DTZ, and (2) the interstitial phases in dunites on one hand, supports the
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37 involvement of the hydrated, hybrid melt as early as the upper oceanic mantle dunitization
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39 itself, and (3) with the silicate inclusions in larger chromitite podiforms on the other hand,
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41 supports the strong connection between the dunitization and the dissolution, transport and
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43 precipitation of Cr below oceanic ridges (Borisova *et al.*, 2012; Rospabé *et al.*, 2017, 2018,
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45 2019a, 2020). However, the detailed relationships between the three components, interstitial
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47 minerals in dunites and inclusions in both disseminated chromites and more concentrated
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49 chromitites, remain poorly constrained in the context of ophiolitic dunites produced by
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51 fluid/melt/peridotite reactions, that contrasts for many aspects with dunite/chromitite cumulates
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56 observed in layered intrusions.
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METHODS

Sampling strategy

The regional dip of the Sumail massif is less than 10° to the SE (i.e. the current lithologies stratigraphy closely matches to the original one). The cross-section sampling from deep to shallower levels with an interval of 10 to 20 m vertically has been shown to be an optimal scale to catch the petrological and geochemical trends across the DTZ (Abily and Ceuleneer, 2013; Rospabé *et al.*, 2018, 2019a). The major element composition of silicate inclusions and of their host chromites was acquired for 285 samples collected along 17 cross-sections. Only the core of chromite was analysed, and we avoided the rims frequently altered into ferritchromite or magnetite. We observed that neither olivine nor chromite show significant zoning while interstitial phases like clinopyroxene can be zoned in major and minor elements (Rospabé *et al.*, 2018).

Analytical note

The major and minor element contents of silicate inclusions and of their host chromite was measured *in situ* by electron microprobe, using a Cameca SXFive, a Cameca SXFiveFE (both at Centre de MicroCaractérisation Raimond Castaing, Toulouse, France) and a Cameca SX 100 (Microsonde Ouest, Brest, France). The data sets obtained using the different instruments were compared to make sure that there was no shift between the different instruments. Operating conditions for all analyses were: accelerating voltage: 20 kV; beam current: 20 nA; electron beam diameter: 1 µm; analysis counting time: 10 s on peak for each element, 5 s on backgrounds on both sides of the peak for each type of minerals. The following synthetic and natural minerals standards were used: albite (Na), periclase (Mg), corundum (Al), sanidine (K), wollastonite (Si, Ca), pyrophanite (Mn, Ti), hematite (Fe), chromium oxide (Cr), pure nickel (Ni), sphalerite (Zn), pure vanadium (V), graffonite (P), tugtupite (Cl) and topaz (F). The detection limits are

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3 0.02 wt% for Cl, 0.03 wt% for TiO₂, Al₂O₃, Cr₂O₃, MgO and P₂O₅, 0.04 wt% for SiO₂ and
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5 Na₂O, 0.05 wt% for CaO and K₂O, 0.06 wt% for V₂O₃ and NiO, 0.07% for FeO, MnO, ZnO
6
7 and F, for all mineral phases analysed. The internal precision (%RSD) is better than 2% for
8
9 major elements (e.g. Cr₂O₃ in chromite, MgO in olivine/orthopyroxene, Al₂O₃ in mica,
10
11 amphibole), better than 6% for TiO₂ (e.g. chromite, amphibole) and better than 25% for minor
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13 elements (e.g. Na₂O in clinopyroxene, NiO in olivine).
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19 The analytical strategy was to perform a systematic analysis of individual silicates present as
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21 inclusions in disseminated chromites all along the Maqsad DTZ, with the aim to get (1) a
22
23 general, statistically significant overview of their nature, distribution and chemical variability
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25 at the scale of the DTZ, and (2) their relation with the variability of the composition of their
26
27 host dunitic rocks. This led to the characterization of 1794 individual mineral phases (excluding
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29 alteration rims) present in a total of 1672 inclusions (1582 of them were monomineralic in the
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31 thin section plane) in 822 chromite grains from the 285 samples. We did not determine
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33 compositions of the bulk inclusions. All analyses are provided in Electronic
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35 Appendix 1.
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42 **PETROGRAPHY AND DISTRIBUTION OF SILICATE INCLUSIONS HOSTED BY** 43 44 **DISSEMINATED CHROMITES IN THE MAQSAD DTZ**

45 **Samples description**

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48 We provide major element composition of silicate inclusions and of their host chromite in 9
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50 mantle harzburgites ($n_{\text{analyses}} = 18$), 1 DTZ chromitite ($n_{\text{analyses}} = 15$) and 275 dunites ($n_{\text{analyses}} =$
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52 1761). The dunites include 38.9 % of pure dunites ($n = 107$; olivine, chromite, very minor
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54 clinopyroxene) and 61.1 % ($n = 168$) of dunites containing various interstitial silicates in
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56 variable amounts (clinopyroxene, plagioclase, orthopyroxene and amphibole mainly). This
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3 fairly respects the pure/impregnated dunites proportion previously identified forming the
4 Maqsad DTZ (about 40 vs. 60 %; Rospabé, 2018). The facies are similar to the ones described
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6 by previous studies and the present study includes some samples whose matrix minerals and
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8 whole rock compositions were published in our previous papers (Rospabé *et al.*, 2017; 2018;
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10 2019a; 2020). The impregnated dunites have been grouped in several rock types according to
11
12 their interstitial mineralogy: cpx-bearing-, pl-bearing-, cpx/pl-bearing-, opx/pl/cpx-bearing-
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14 and amph-bearing (\pm opx/pl/cpx) dunites (Rospabé *et al.*, 2018). Dunites were mostly collected
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16 in the DTZ but some samples come from small (a few hectometres) dunitic bodies included in
17
18 the harzburgites from the shallow mantle section (Fig. 1b). The sampling covers the DTZ both
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20 near the centre of the Maqsad diapir and at its periphery to the southwest (Fig. 1b) and sampling
21
22 sites spread vertically in between 567 and 1214 m in altitude. The 9 mantle harzburgites were
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24 collected near the very base of the DTZ or within the dunites/harzburgites alternations (i.e.
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26 transition from the mantle section to the DTZ).
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35 **Chromite texture in DTZ dunites**

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37 Chromite grains are present in all dunites, with no exception and independently from the
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39 occurrence of other interstitial minerals. They occur in variable proportions from a few
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41 disseminated grains with a typical modal content such as 1 or 2 % to more concentrated levels
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43 and schlieren (Figs. 2 and 3). Grain size is generally close to 0.1-0.5 mm but can reach 2 mm
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45 in some samples and their shape is almost systemically rounded (Figs. 2a, b and 3); both size
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47 and distribution are heterogeneous at fine scale. Chromite is interstitial between olivine grains,
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49 and is more rarely enclosed in clinopyroxene oikocryst; chromite is never enclosed in olivine
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51 grains. Schlieren-type textures, or seams, are regularly observed along the DTZ (Figs. 1b, 2c,
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53 d and 3c, d). Samples that contain a particularly high amount of chromite regularly show an
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55 antinodular texture (Figs. 2e-g). Occasionally, chromitite dikelets cut across the DTZ,
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3 sometimes containing dunitic xenoliths (Fig. 2h), and in some places plurimetric massive
4 chromitites form economic ore bodies (Fig. 1b). On a few outcrops chromitites are cross-cut by
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6 N130-oriented gabbro dikes (Fig. 2i, j), i.e. parallel to the strike of the paleo-ridge fed by the
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8 Maqsad diapir (Ceuleneer *et al.*, 1996; Python and Ceuleneer, 2003).
9

14 **Diversity of silicate inclusions in DTZ chromites**

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17 The nature and chemical composition of the silicate inclusions in disseminated chromite grains
18 reveal the ubiquitous presence of clinopyroxene, olivine, amphibole, orthopyroxene, mica, and
19
20 of minor other minerals as detailed below. The most common case is one or two inclusions by
21
22 chromite grain, not present in all grains, which is possibly a bias related to the two-dimensional
23
24 nature of thin section observations; in a given sample we never observed two populations of
25
26 chromite, one devoid of inclusions, the other one containing numerous inclusions. Furthermore,
27
28 peculiar distribution within a chromite grain, such as coronas of inclusions, a common feature
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30 in chromitite from this area (Zagrtdenov *et al.*, 2018; Rospabé *et al.*, 2019b), is rarely observed
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32 in the disseminated chromites in dunites. Silicate inclusions are generally round-shaped or
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34 euhedral equant square-shaped (so called ‘negative crystals’) (Fig. 4a-b), including only one
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36 phase (monomineralic inclusions) or several adjacent, imbricated crystals with clear contacts
37
38 (polymineralic inclusions). The largest inclusions may be irregular in shape. Their diameter
39
40 ranges from a few microns (in 2-D sections) to a maximum of about 100 μm , with a more
41
42 frequent diameter of 40-50 μm . The contact between the included silicates and their host
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44 chromite is in many cases, but not systematically, underlined by a thin alteration rim at the
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46 contact with the host chromite. Alteration rims are generally present when the chromite is
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48 affected by small cracks (Fig. 4) but not only, being sometimes also associated with inclusions
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50 apparently unaffected by such cracks (Fig. 4a-b, f-h). In a few cases, a sulphide phase may be
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52 associated with silicates in a polymineralic inclusion, but both sulphides as well as platinum
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3 group minerals (already reported in association with silicate inclusions in Oman chromitites;
4 e.g. Augé, 1986) are not investigated here. A secondary Cr-oxide corona surrounding a part of
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6 polymineralic inclusions was sometimes observed but is less common than in chromitites
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10 (Borisova *et al.*, 2012; Yao *et al.*, 2020).

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14 Figure 5a shows the relative frequency of occurrence as inclusion of each phase in all dunite
15 samples. This frequency has been calculated on the basis of the presence (1) or absence (0) of
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17 each phase in each sample (total of 534 occurrences), reported in a percentage form (see Figure
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19 5 caption). We observe by decreasing frequency of occurrence: pargasite and hornblende
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21 amphibole (amph), clinopyroxene of various compositions (cpx more abundant than diop, see
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23 just below), orthopyroxene (opx), olivine (ol), plagioclase (pl), garnet (gt), nepheline (ne),
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25 jadeite (jd), pectolite (pct), Na-rich near-albitic feldspar (alb), chlorapatite (Cl-ap). Concerning
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27 clinopyroxene, following Rospabé *et al.* (2017), the distinction is made between the diopside
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29 to augite having clearly an 'igneous' composition (i.e. consistent with a crystallization product
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31 of a basaltic melt), referred to as clinopyroxene or cpx, and the 'hybrid' diopside with
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33 composition intermediate between igneous cpx and gem diopside documented in hydrothermal
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35 systems and that do not plot along igneous fractional crystallization trends (called diopside or
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37 diop).

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46 Amphibole (35.3 %) and clinopyroxene (28.1 %) are by far the two most widespread minerals
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48 in inclusion in disseminated chromite in the Maqsad DTZ, representing together nearly the two
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50 thirds of all the occurrences (63.4 %). The relative frequency of occurrence of other main phases
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52 (diopside, mica, olivine, orthopyroxene) is of 30.9 % all together, ranging individually from 9.2
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54 % (diopside) to 6.3 % (orthopyroxene). Plagioclase and garnet represent together 3.8 % of the
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56 occurrences. Nepheline and jadeite (0.8 and 0.6 % respectively), reported for the first time in
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3 the Oman ophiolite with the exception of a stratiform chromitite cropping out at the base of the
4 DTZ (Fig. 1b) (Rospabé *et al.*, 2019b), and pectolite, albitic feldspar and apatite (0.2 % each)
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6 are very minor mineral phases in inclusions.
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12 Figure 5b represents the detailed relative frequency of occurrence as inclusions of the main
13 phases in each type of dunite. Among the significant observations, we note that:
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17 • Silicate inclusions in pure dunites are characterized by high relative frequencies of occurrence
18 of both amphibole (39.2 %) and clinopyroxene (33.3 %), and less frequent occurrences of
19 diopside (11.3 %), olivine (6.5 %), mica (5.4 %) and garnet (1.1 %) among others.
20
21 Orthopyroxene and plagioclase have never been observed as inclusion in chromite in pure
22 dunites. On the contrary, nepheline and jadeite were observed only in pure dunites with the
23 exception of jadeite also identified in only one cpx-bearing dunite.
24
25 • From cpx- to pl/cpx- to amph-bearing (\pm opx/pl/cpx) dunites, we observe an increase in the
26 relative frequency of occurrence of mica (from 6.3 to 14.4 %) and orthopyroxene (from 4.7 to
27 8.1 %), associated to the decreasing relative frequency of clinopyroxene (from 32.8 to 25.2 %)
28 and diopside (from 17.2 to 6.8 %); the relative frequency of occurrence of diopside inclusions
29 is particularly high in cpx-bearing dunites. Amphibole and olivine do not display a clear
30 evolution of their relative frequency of occurrence from a dunite type to another. Feldspar
31 plagioclase and garnet are minor occurrences in pl/cpx-bearing dunites and amph-bearing
32 dunites. The only one pectolite has been identified in an amph/pl/cpx-bearing dunite.
33
34 • From other impregnated dunites to opx/pl/cpx-bearing dunites are observed much frequent
35 relative occurrences of orthopyroxene (20.3 %), plagioclase (6.8 %) and garnet (5.4 %), and
36 less frequent occurrences of clinopyroxene (14.9 %) and diopside (2.7). The rare occurrences
37 of 1 albitic feldspar and of 1 Cl-apatite in inclusion have been previously reported concerning
38 opx/pl/cpx-bearing dunites (Rospabé *et al.*, 2020).
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Figures 5c and 5d summarize the evolution of the nature of the silicate inclusions in chromite from a dunite type to another. From pure dunites to cpx- and pl/cpx-bearing, and especially to amph-bearing and opx/pl/cpx-bearing dunites, we observe the decrease of the sum of individual occurrences of olivine, clinopyroxene and plagioclase in inclusion on one hand (i.e. the anhydrous mineral assemblage expected from crystallization of an olivine tholeiite at low pressure, consistent with the MORB igneous environment of the Maqsad area), and the increase of the sum of individual occurrences of the more ‘exotic’ (i.e. witnesses of a more siliceous and hydrated parent melt) amphibole, mica and orthopyroxene in inclusion on the other hand. (Fig. 5c). This evolution is still observed when diopside and garnet are taken into account together in addition with the amph-opx-mica association (Fig. 5d). This demonstrates the existence of a strong relationship between the nature of silicate inclusions in disseminated chromites within the DTZ and the nature of interstitial minerals in their host dunites (Borisova *et al.*, 2012; Rospabé *et al.*, 2017, 2020). This evolution in the inclusions content from a host rock type to another is interestingly not related to the modal abundance of the interstitial minerals in the host dunites but only to their occurrence, even where present in minor amounts.

Distribution of silicate inclusions across the DTZ

Inclusions in disseminated chromites in dunites are observed all across the Maqsad DTZ (Fig. 6). Taken individually, whatever they form monomineralic inclusions or are associated in polymineralic inclusions, amphibole and clinopyroxene occur from the base to the top of the DTZ. Diopside, mica, and olivine inclusions are observed mainly within the altitude interval ~ 700 m to 1100-1150 m. Orthopyroxene inclusions occur only above 850 m (i.e. about 200-250 above the base of the DTZ), as does interstitial orthopyroxene in the surrounding matrix. In detail, orthopyroxene inclusions are observed exactly at the two same altitude intervals where

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3 interstitial orthopyroxene occurs (as well as along a third shallower and thinner level for only
4 three occurrences) (Fig. 6). It is interesting to note that the chromitite ore bodies and chromitite-
5 rich intervals in the Maqsad DTZ occur at the same altitude as the three opx inclusions-bearing
6 levels. Both garnet and plagioclase inclusions are mostly restricted to the lower opx-rich level
7 (interstitial garnet and plagioclase in the matrix are widespread at a much larger scale along the
8 DTZ). By the same way, the rare nepheline, jadeite, pectolite, Cl-apatite and near-albitic
9 feldspar inclusions are only observed above the altitude of 850 m.
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21 MAJOR ELEMENT MINERAL COMPOSITIONS

22 Here below are briefly described the most significant chemical features of chromite and of the
23 main mineral phases they contain in inclusion (amph, cpx and diop, mica, ol, opx, gt, pl). A
24 more detailed description of the chemical major element composition of all types of silicate
25 inclusions together with extended diagrams are provided in Electronic Appendix 2.
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35 Chromite

36 Disseminated chromites in dunites from the Maqsad DTZ show broad compositional ranges.
37 They are characterized by X_{Cr} ($100 \times \text{molar Cr}/(\text{Cr} + \text{Al})$) = 38.8-69.6 mol %, X_{Mg} ($100 \times$
38 $\text{molar Mg}/(\text{Mg} + \text{Fe}^{2+})$) = 32.7-68.1 mol %, $Y_{Fe^{3+}}$ ($100 \times \text{molar Fe}^{3+}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$) = 1.23-
39 18.3 mol % and $\text{TiO}_2 = 0.11$ -1.25 wt % (Fig. 7a, b).
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49 Among the most significant contrasts between the different dunite groups, amph-bearing and
50 especially opx/pl/cpx-bearing dunites generally display higher X_{Cr} values, mainly higher than
51 55 in spite of an overlapping at lower values, and TiO_2 content, higher than 0.5 wt %, than in
52 other dunites. Accordingly, two trends can be defined in diagrams showing the evolution of the
53 TiO_2 content as a function of X_{Cr} (Fig. 7b): it increases much faster at a given X_{Cr} in amph-
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3 and especially opx/pl/cpx-bearing dunites than in pure and cpx-bearing dunites; chromite in
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5 pl/cpx-bearing dunites shows intermediate composition.
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10 **Silicate inclusions**

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12 The chemical composition of the main silicate inclusions is described following their
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14 decreasing frequency of occurrence as presented in Figure 5a.
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19 *Amphibole*

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21 Amphibole inclusions are mainly Cr-, Ti-, Na- rich pargasites/pargasitic hornblendes (~ 60 %),
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23 magnesio-hastingsites/magnesio-hastingsitic hornblendes (~ 30 %), and more rarely edenitic
24
25 hornblendes, kaersutites or tschermakitic hornblendes (~ 10 %). They display extensive
26
27 chemical variations in XMg, from 83.8 to 95.0 mol %, and in Al₂O₃ (7.74-15.7 wt %), Cr₂O₃
28
29 (0.04-5.95 wt %) and TiO₂ (0.10-4.95 wt %) contents. The variations in Na₂O (1.36-5.27 wt %)
30
31 and K₂O (near detection limits to 1.42 wt %) contents allow defining a XNa (100 × molar
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33 Na/(Na + K)) evolving from 70.3 to 100.0 mol %. The amphibole inclusions for which P₂O₅,
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35 Cl and F contents were determined show variations from detection limits to 0.30 wt % (mean
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37 0.05 wt %), 0.24 wt % (mean 0.03 wt %), and 0.48 wt % (mean 0.12 wt %) respectively.
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45 The composition of amphibole included in chromite is related to the nature of the host rock,
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47 especially the Al₂O₃ and TiO₂ contents. The Al₂O₃ content in pure and cpx-bearing dunites
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49 spans the entire variation range, with a clear increase with the decrease of XMg (Fig. 8a). On
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51 the contrary, the Al₂O₃ content in opx/pl/cpx-bearing dunites is lower than 12.1 wt % and shows
52
53 a gentle decrease with XMg (plx/cpx- and amph-bearing dunites have an intermediate
54
55 composition). The concentration in TiO₂ in amphibole inclusions increases from pure dunites
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57 (0.29-3.51 wt %) to cpx-, pl/cpx-, amph-, then opx/pl/cpx-bearing dunites (1.67-4.95 wt %).
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3 The TiO₂ content likewise displays a dichotomous chemical distribution (Fig. 8b): it decreases
4 together with XMg in pure dunites and partly in cpx-bearing dunites, increases with the
5 decreasing XMg in amph- and opx/pl/cpx-bearing dunites, and shows a behaviour intermediate
6 between the two trends in part of cpx- and in all pl/cpx-bearing dunites. Variations in both the
7 Na₂O and Cr₂O₃ contents look more scattered when all data are plotted together, but in details
8 as shown in Electronic Appendix 2, they appear to distribute among two distinct trends
9 according to the lithology of the host rock.
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21 *Clinopyroxene*

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23 Clinopyroxenes in inclusion in chromites display XMg = 85.1-96.3 mol %, Al₂O₃ = 0.60-5.65
24 wt %, Cr₂O₃ = 0.18-5.00 wt %, Na₂O = 0.04-1.98 wt % and TiO₂ = 0.05-1.96 wt %. The Al₂O₃
25 content globally increases with the decrease of the XMg (Fig. 9a). The TiO₂ and Na₂O basically
26 increases and decreases respectively from pure dunites (averaged TiO₂ = 0.29 wt % and Na₂O
27 = 0.66 wt %) to opx/pl/cpx-bearing dunites (averaged TiO₂ = 0.53 wt % and Na₂O = 0.40 wt
28 %); compositions are intermediate in inclusions in other dunites (Fig. 9b). The distribution of
29 the variations in Cr₂O₃ as a whole seems random with no particular evolution, similarly to what
30 is observed in the amphibole composition. In detail, this only concerns clinopyroxene in pure
31 dunites while the global random distribution results from the overprint of two reverse trends,
32 with on one hand the common decrease of Cr₂O₃ and XMg in inclusions in cpx- and pl/cpx-
33 bearing dunites, and on the other hand the increase of the Cr₂O₃ content when XMg decreases
34 in amph- and opx/pl/cpx-bearing dunites (Electronic supplement 2).
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52 *Diopside*

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54 As explained here above, inclusions in chromite characterized as ‘diopsides’ display
55 compositions intermediate between ‘igneous’ clinopyroxene and pure hydrothermal diopsides
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3 (Fig. 10) (a distinction introduced in Rospabé *et al.*, 2017). Their XMg (90.7-97.7 mol %) is
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5 higher than in the clinopyroxene inclusions described above. On the contrary, their Al₂O₃ (0.01-
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7 2.46 wt %), Cr₂O₃ (0.08-1.85 wt %), TiO₂ (0.01-0.57 wt %) and Na₂O (0.02-0.94 wt %)
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9 contents, which all decrease with the increasing of XMg (Fig. 10), are lower, especially in the
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11 opx/pl/cpx-bearing dunites.
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16 17 *Mica*

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19 Mica in inclusion shows a composition evolving from phlogopite to aspidolite (Na-phlogopite).
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21 The Na₂O and K₂O contents range from 0.12 to 8.10 wt % and from 0.06 to 9.24 wt %
22
23 respectively (Fig. 11a). It defines a continuous XNa varying from 2.00 to 98.9 mol % with a
24
25 higher frequency of high XNa inclusions (63.1 mol % in average). Contrasted contents in alkalis
26
27 can be observed in different mica inclusions from a single sample, within the same chromite
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29 grain, and even within the same polymineralic inclusion (e.g. 16OM27: two contrasted mica,
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31 associated to an amphibole, with XNa = 7.4 and 67.8 respectively). The continuous evolution
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33 from Na- to K-rich mica is observed in inclusions from all rock types except in pure dunites in
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35 which a gap is observed between aspidolite (XNa = 83.6-98.3 mol) and phlogopite (XNa =
36
37 15.6-37.8 mol %) (Fig. 11a). The XMg is mainly 87.8-96.8 mol % (excepting 83.9 mol % for
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39 one analysis). The TiO₂ ranges from 0.73 to 6.64 wt %. It is more variable and higher in amph-
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41 and opx/pl/cpx-bearing dunites than in other dunite types (Fig. 11b). The mica inclusions for
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43 which Cl and F contents were determined show variations from detection limits to 0.10 wt %
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45 (mean 0.03 wt %) and 0.36 wt % (mean 0.13 wt %) respectively.
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52 53 *Olivine*

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55 Olivine inclusions in chromites are forsterite characterized by Fo ($100 \times \text{molar Mg}/(\text{Mg} +$
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57 $\text{Fe}_{\text{total}})) = 88.6-94.8 \text{ mol } \%$, NiO = 0.19-0.50 wt % and CaO = 0.01-0.27 wt %. Olivine
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3 inclusions generally overlap with the olivine matrix in terms of Fo and NiO, with a higher
4 frequency of high values (Fig. 12a). The CaO content in inclusions is however clearly within
5 the low values variation range displayed by the olivine matrix, except for inclusions in pure
6 dunites that show slightly higher values than dunites containing other interstitial minerals
7 (Electronic supplement 2).
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14 15 16 17 *Orthopyroxene*

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19 Orthopyroxene inclusions in chromites are enstatite with XMg = 87.1-93.5 mol % (apart from
20 1 inclusion with XMg = 82.1 mol %), Al₂O₃ = 0.33-4.31 wt %, Cr₂O₃ = 0.47-1.57 wt % and
21 TiO₂ = 0.02-0.75 wt % (Fig. 12b). The variation in XMg is more variable in amph- and
22 opx/pl/cpx-bearing dunites than in other dunite types; another already evoked feature is that
23 orthopyroxene in inclusion was never observed in pure dunites.
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32 33 *Garnet*

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35 Two types of garnet were analysed: grossular and hydrogrossular according to the calculation
36 of molar proportions (Locock, 2008). The SiO₂ content varies between 34.6 and 39.0 wt % in
37 grossular and between 21.9 to 31.3 wt % in hydrogrossular. It progressively decreases from
38 grossular to hydrogrossular, with the increasing hydrated character (SiO₂ vs. sum of oxides, R²
39 = 0.9452; Electronic supplement 2). The TiO₂ content displays a wide variation range and
40 reaches high values in about the half of the dataset (low-Ti group: TiO₂ = 0.01-0.28 wt % (n =
41 16); high-Ti group: TiO₂ = 0.84-5.42 wt % (n = 11); Fig. 12c). When the TiO₂ content is high,
42 it concerns all garnet inclusions in a given samples.
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54 55 56 *Plagioclase*

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58 Most of the analysed plagioclase inclusions, identified in 8 samples, are anorthitic. The An
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3 content ($100 \times \text{molar Ca}/(\text{Ca} + \text{Na} + \text{K})) = 86.2\text{-}92.0$ mol %, excepting one analysis at 77.0 mol
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content ($100 \times \text{molar Ca}/(\text{Ca} + \text{Na} + \text{K})) = 86.2\text{-}92.0$ mol %, excepting one analysis at 77.0 mol
%. The An content is lower in inclusions in pl/cpx-bearing dunites, varying from 77.0 to 88.6
mol % and reaching 85.5 mol % in average (86.2-88.6 mol % without the singular 77.0 mol %
analysis), than in amph- (89.9-90.6 mol %) and opx/pl/cpx-bearing dunites (86.7-92.0 mol %).

Chemical variability in chromite and silicate inclusions across the DTZ

The Figure 13 shows an overview (i.e. all the cross-sections merged in a single one) of the
major element variations for the chromite and their amphibole inclusions across the whole
Maqsad DTZ. The vertical variations in the composition of other silicate inclusions are
described in details, and for each type of dunite, in Electronic Appendix 2.

As a whole, we observe a higher variability of the chemical compositions of both chromite and
its hosted inclusions above the altitude of 850 m (i.e. about 200-250 above the base of the DTZ).
It corresponds to the appearance of interstitial orthopyroxene and more generally to a higher
amount of interstitial minerals in the higher levels of the Maqsad DTZ (Fig. 6). The main
characteristics that may be highlighted along this upper section are the different trends
depending on the nature of the host rock, with negatively correlated trends in the composition
of inclusions between pure, cpx- and pl/cpx-bearing dunites on one hand, and amph- (\pm
opx/pl/cpx) and opx/pl/cpx-bearing dunites on the other hand (Fig. 13). Accordingly, it appears
that chromite and amphibole (and other silicates) inclusions have compositions specific to the
opx/pl/cpx-bearing dunites lithological type, more and more contrasting with other types of
dunites in the higher levels of the DTZ (e.g. buffered XCr values in between 55 and 60 in
chromite, decreasing XMg and increasing TiO₂ in both chromite and amphibole, increasing
Na₂O in amphibole, upsection).

DISCUSSION

Relationships between the formation of dunite and the formation of chromitite at the crust-mantle transition

Dunites and chromitites in ophiolites as fluid fluid-melt-rock reaction companion products

In ophiolites and present-day oceans, dunites in the mantle section and from the mantle-crust transition zone are mostly interpreted as reactional in origin, replacive after the mantle harzburgites' orthopyroxene dissolution by reacting with interstitial melt (e.g. Dick, 1977; Quick, 1981a, 1981b; Kelemen, 1990; Kelemen et al., 1992, 1995). In the case of the Oman ophiolite and more specifically the Maqsad area, the reactional origin of the DTZ has been strongly evidenced through years, based on field and structural observations (e.g. Ceuleneer and Nicolas, 1985; Rabinowicz *et al.*, 1987; Ceuleneer *et al.*, 1988; Nicolas *et al.*, 1988; Boudier and Nicolas, 1995) and petrology and geochemical signatures (e.g. Godard *et al.*, 2000; Koga *et al.*, 2001; Abily and Ceuleneer, 2013; Rospabé *et al.*, 2017, 2018, 2019a). Among important observations are the alternating mantle harzburgites and dunites at the base of the DTZ showing gradational contacts with the host harzburgite related to the resorption of orthopyroxene along the margins of former melt porous flow channels (Ceuleneer *et al.*, 1996), the systematic presence of a reactional dunitic aureole surrounding chromitites hosted by mantle harzburgites (e.g. Peters & Kramers, 1974; Augé, 1987; both references concerning massifs in the North of Oman), or the minor and trace element contents in olivine and dunite whole rocks that are much closer from mantle olivine and harzburgites than from cumulates (e.g. Kelemen *et al.*, 1995; Godard *et al.*, 2000; Rospabé *et al.*, 2018). Similarly, ol-rich rocks at the mantle-crust transition in other ophiolites and present-day oceans are regularly classified as 'hybrid' with an olivine matrix mostly mantle-derived and other interstitial minerals (e.g. clinopyroxene, plagioclase) that crystallized from migrating melts (e.g. Takazawa *et al.*, 2007; Drouin *et al.*, 2009; Sanfilippo *et al.*, 2015; Basch *et al.*, 2018; see also Bowen (1915) that

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3 introduced early the term ‘hybrid’ to characterize peridotites injected by melts). These are the
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5 ‘impregnated dunites’ which share a common origin with the ‘pure dunites’, the major
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7 difference being the incomplete extraction of interstitial melt before crystallization in response
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9 to cooling (Rospabé *et al.*, 2018).
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14 Most minerals in inclusion in the disseminated chromite grains in the DTZ dunites (pargasitic
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16 amphibole, clinopyroxene, orthopyroxene, K- and Na-mica, olivine, ‘hybrid’ diopside for the
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18 most abundant; Fig. 5), were previously documented in chromitites from the Maqsad area
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20 (Lorand and Ceuleneer, 1989; Leblanc and Ceuleneer, 1991; Schiano *et al.*, 1997; Borisova *et*
21
22 *al.*, 2012; Rollinson *et al.*, 2018; Zagrtednov *et al.*, 2018; Rospabé *et al.*, 2019b). This implies
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24 the existence of common petrogenetic processes at the origin of both dunites and chromitites at
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26 the mantle-crust transition (Rospabé *et al.*, 2017, 2020). This strong correlation is confirmed
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28 on robust statistical grounds in the present work (Figs. 5 and 6).
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35 The same minerals are present in inclusions in chromitites from other contexts: in the massifs
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37 from the north-western part of the Oman ophiolite that evolved in a calc-alkaline environment
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39 (Augé, 1987; Ahmed and Arai, 2002), in other ophiolites worldwide (e.g. Talkington *et al.*,
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41 1984; Robinson *et al.*, 2015; Johan *et al.*, 2017), as well as in chromitites from continental
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43 layered intrusions (e.g. Li *et al.*, 2005; Spandler *et al.*, 2005). However, in spite ophiolitic
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45 chromitites/disseminated chromites and chromitites in layered intrusions share some
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47 similarities, their very contrasting origins must be kept in mind to avoid shortcuts in transposing
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49 processes from a magmatic environment to another. The major difference is that the
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51 surrounding dunite is mostly interpreted as a result of melt-peridotite reaction in ophiolites,
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53 while it is purely cumulative in layered intrusions (even if chromitites are cumulates in both
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55 cases).
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5 Although the mafic dikes that intruded the mantle section of the Maqsad diapir crystallized
6 from a water-poor MORB (Benoit *et al.*, 1996; Ceuleneer *et al.*, 1996; Python and Ceuleneer,
7 2003), the widespread occurrence, in the DTZ, of high-Mg orthopyroxene and amphibole both
8 as interstitial phases in dunites or in inclusions in chromite calls for the local presence, at the
9 top of the diapir, of a Si- and volatile-richer melt than MORB. These orthopyroxenes also
10 contrast with the ones from gabbronorites from the calc-alkaline series ultra-depleted in HFSE
11 (e.g. Ti) observed at the border of the Maqsad diapiric structure: the parent melt of these
12 gabbronorites is attributed to the hydrated re-melting of the formerly frozen, hydrothermalized
13 lithospheric mantle with no initial contribution of MORB, mixing with MORB taking place
14 later during the rise of the diapir and formation of the DTZ (Benoit *et al.*, 1999; Clénet *et al.*,
15 2010). Accordingly, the melt or fluid at the origin of the interstitial mineralogy in DTZ dunites,
16 looking exotic in a MORB context, was not produced by the decompression melting of an
17 asthenospheric diapir and was called 'lithospheric' (Rospabé *et al.*, 2017). It was obviously
18 involved in the formation of the DTZ: hybridized with MORB, it was either the cause or a by-
19 product of the crystallization of chromite and of the formation of associated dunites.
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42 At first glance, the general overview of the relative frequency of occurrence of each silicate
43 phase in inclusion (Fig. 5c-d), from pure dunites to cpx-bearing, pl/cpx-bearing and amph-
44 bearing (\pm opx/pl/cpx), then opx/pl/cpx-bearing dunites, highlights (1) the decreasing
45 abundance of mineral phases that can be regarded as belonging to the MORB kindred (ol, pl,
46 cpx), associated to (2) the increasing abundance of the mineral phases (orthopyroxene,
47 amphibole, mica, garnet, diopside) witnessing the Si-, Na- and volatile-richer component that
48 hybridized with the MORB and triggered the formation of dunites and related lithologies in the
49 DTZ, including chromitites (e.g. Johan *et al.*, 1983; Talkington *et al.*, 1984; Spandler *et al.*,
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3 2005; Borisova *et al.*, 2012; Rospabé *et al.*, 2017). The vertical distribution of the nature of
4 both the interstitial minerals and of the inclusions (Fig. 6) shows that the lithospheric
5 melt/MORB ratio increases upsection. The involvement of such a hybrid melt is consistent with
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10 the conclusions of two previous models proposed for the formation of massive chromitites: (1)
11 the hybridization between a primitive basaltic melt and a silica-rich component on one hand
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13 (e.g. Irvine *et al.*, 1975, 1977a), and (2) the strong role of water (Matveev and Ballhaus, 2002;
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17 Mathez and Kinzler, 2017).

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21 Our data confirm that both silica-rich melt (i.e. Si-richer than MORB) and water are
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23 fundamental parts of the story (i.e. not mutually exclusive), and reveal the role of alkalis
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25 evidenced by the presence of phlogopite and aspidolite inclusions. On the other hand, whole
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27 rock dunite trace element compositions (e.g. REE) have highlighted the importance of fluid-
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29 melt-rock interactions in addition to simpler processes of fractional crystallization and/or
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31 incongruent dissolution of orthopyroxene in dry conditions (Rospabé *et al.*, 2018). The strong
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33 correlation between the bottom to top chemical evolution patterns across the Maqсад DTZ (both
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35 in dunites and chromitites) and the location of syn-accretion normal faults (Rospabé *et al.*,
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37 2019a, 2019b, 2020) supports a hydrothermal origin for the hydrated component, fault planes
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39 being avenues for fluids input at different stages of the Oman ophiolite thermal evolution (e.g.
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41 Abily *et al.*, 2011; Zihlmann *et al.*, 2018). Thermometric studies have likewise supported the
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43 delivery of hydrothermal fluids to the lower oceanic crust and the transition zone beneath
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45 oceanic ridges (e.g. VanTongeren 2008; Dygert *et al.*, 2017; Sun and Lissenberg, 2018, EPSL,
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47 Canil *et al.*, 2019, *Lithos*), also supported by petrological and geochemical studies (e.g. Benoit
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initiated or enhanced the mantle harzburgite dunitization - and thus the release of Si (and, in

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3 lesser extent, Cr, Al, Ti, Na; e.g. Quick, 1981b) following orthopyroxene dissolution - though
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5 fluid-melt-peridotite reactions (Rospabé et al., 2017).
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10 *Mantle harzburgite dunitization as a potential source of Cr*

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12 The concept of dunitization was introduced to describe the transformation of mantle
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14 harzburgites into dunites through the incongruent dissolution of orthopyroxene in reaction to
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16 the percolation of a melt that was saturated in opx when it formed at depth in the mantle and
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18 became undersaturated in this mineral at lower pressure (e.g. Dick, 1977; Quick, 1981a, 1981b;
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20 Kelemen, 1990; Kelemen *et al.*, 1992, 1995). Orthopyroxene contains Cr as minor content
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22 (about 0.5 to 1 wt % in Oman, e.g. Monnier et al., 2006; $^{opx/liq}D_{Cr} = 1.9$, Bédard *et al.*, 1994)
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24 and its dissolution will contribute to feed newly formed chromite grains, as the solubility of Cr
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26 in silicate melts is quite low and the amount of Cr that can be accommodated in newly formed
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28 olivine is moderate (Abily and Ceuleneer, 2013) ($^{ol/liq}D_{Cr} = 0.6$, Bédard *et al.*, 1994). A similar
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30 process, while in a different environment, has been proposed with the assimilation of peridotites
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32 and incongruent dissolution of their pyroxenes to form high XCr chromitites at the contact with
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34 surrounding mafic rocks in the Bay of Islands ophiolite (Bédard and Hébert, 1998). Even if the
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36 volume of chromite (in both ore bodies and scattered in the dunite) is more important in the
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38 DTZ than elsewhere, it represents globally a very weak percentage of the DTZ itself. On the
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40 other hand, the volume of mantle harzburgite available for the reaction is virtually infinite.
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42 Although to quantify this would be hazardous, it is possible that the amount of chromium
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44 liberated by the dissolution of pyroxene highly contribute to the formation ore bodies and
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46 scattered chromites.
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56 On the other hand, it was suggested that dunite channels cropping out in the Oman ophiolite
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58 mantle section contain chromites with a very contrasting composition (e.g. significantly higher
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3 TiO₂ content), in addition to a different texture, than the Cr-spinels in nearby surrounding
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5 mantle harzburgites, which is an argument for the role of dunite channels in the extraction of
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7 MORB from the upper mantle to the crust (Kelemen *et al.*, 1995). The same contrast has been
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9 observed for the Maqsad DTZ dunites (Koga *et al.*, 2001; Abily and Ceuleneer, 2013). A
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11 reasonable hypothesis is that the mantle harzburgite dunitization is, in addition to
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13 orthopyroxene dissolution, also accompanied by the dissolution/reprecipitation of the residual
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15 Cr-spinel (i.e. residual Cr-spinel dissolution, ‘magmatic’ chromite re-precipitation). This is
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17 consistent with the presence, although much less frequent than in the disseminated chromites,
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19 of a few amphibole and mica in inclusion in Cr-spinels in the harzburgites alternating with
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21 dunites at the base of the DTZ. They can represent the incipient stage of the dunitization
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23 process, frozen at the time the igneous activity of the Maqsad diapir stopped, while the much
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25 higher inclusions content in chromites in the DTZ dunites supports their re-precipitation. The
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27 lower TiO₂ content of the inclusions in Cr-spinels in harzburgites than in chromites in dunites
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29 (Figs. 8, 9, 11, 12b; e.g. up to 5 wt % in amphibole) attests on the other hand of the less evolved
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31 character of the hybrid melt that triggered or enhanced the dunitization during this incipient
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33 stage of transformation of harzburgite into dunite recorded at this depth. (Rospabé *et al.*, 2017,
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35 2018). In this frame, an ‘infinite’ source of Cr for the formation of chromitite ore bodies,
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37 especially within the DTZ and within the uppermost mantle beneath oceanic spreading centres,
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39 may be provided by the dunitization itself with the dissolution of both residual Cr-spinel and
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41 pyroxenes and crystallization of a new generation of chromite grains entrapping minerals issued
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43 from the reactant hybrid melt.
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54 **Chromite-hosted silicate inclusions record from high temperature, magmatic events to**
55 **metamorphic to low temperature, alteration processes**
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58 The high diversity in the silicate inclusions content in the Maqsad DTZ disseminated chromites
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3 partly reflects the very large temperature range in which they formed, from magmatic
4 crystallization products to later metamorphism and lower temperature alteration. Olivine,
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6 olivine, orthopyroxene, clinopyroxene, amphibole, mica and plagioclase have compositions consistent
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8 with an igneous origin. About 40 % of the studied samples are pure dunites, i.e. devoid of any
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10 interstitial minerals between olivine grains excepting chromite. These pure dunites, similar to
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12 impregnated dunites, also contain a large cargo of inclusions (mostly amphibole and
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14 clinopyroxene; Fig. 5b) in their scattered chromite grains. Consequently, inclusions cannot have
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16 formed after the formation of chromite by sintering and entrapment of surrounding minerals, or
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18 by the migration of melt that would have been trapped in already formed chromite but not in
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20 the matrix (Rospabé et al., 2020). It is thus likely that the inclusions-forming minerals nucleated
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22 just before the host chromites (e.g. microcrystals in the parent melt) or co-precipitated together
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24 with the chromites from the same parent melt.
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33 The crystallization temperatures can be roughly estimated, although a more precise
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35 determination would require experimental data in chemical systems under (possibly out of
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37 equilibrium) conditions that remain poorly or not explored up to now. At first glance, it could
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39 be supposed that orthopyroxene, pargasite and phlogopite-aspidolite micas crystallized or
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41 precipitated from a melt or fluid at temperature ranging from 1050°C down to 600°C as stressed
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43 by Borisova *et al.* (2012) in the Maqsad DTZ chromitites case (i.e. 600-950°C for mica, 600-
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45 1050°C for enstatite and pargasite, 950-1050°C for host chromite). This is the temperature
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47 stability range for pargasitic amphibole in the presence of H₂O (e.g. Boyd, 1959; Feig *et al.*,
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49 2006; Presnall, 2013). Phlogopite is not stable at temperatures higher than 1000°C while a
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51 miscibility gap exists in the phlogopite-aspidolite solid solution at 2 kbar and 700°C (Costa *et*
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53 *al.*, 2001). The existence of a compositional gap observed in mica inclusions in the Maqsad
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55 chromitites (Borisova *et al.*, 2012), with the clear dichotomy between the phlogopite and
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3 aspidolite end-members, is not observed in the case of the disseminated chromites (Fig. 11).
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5 This might be an artefact related to the lower amount of samples analysed before our survey or,
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7 if real, could reflect a higher equilibration temperature for the mica inclusions in the
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9 disseminated chromites than in the chromitites (Borisova *et al.*, 2012; Arai and Miura, 2016;
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11 see also Costa *et al.*, 2001). Furthermore, the high TiO₂ content in amphibole, mica and in a
12
13 lesser extent orthopyroxene (Figs. 8, 11 and 12) may have increase their thermal stability field
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15 (Augé, 1987 and references therein) to temperatures similar to the ones at which their host
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17 chromite and possibly other clinopyroxene and very scarce plagioclase inclusions crystallized.
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19 The effect of subsolidus re-equilibration between the inclusions, host chromites and
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21 surrounding minerals of the dunites is not investigated here. However, chemical major element
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23 profiles have been performed in samples from a neighbouring stratiform chromitite showing a
24
25 wide range of chromite modal content (Rospabé *et al.*, 2019b). At the thin section scale, we
26
27 have shown that Mg, Fe, Cr and Al vary according to the chromite/olivine ratio but that TiO₂
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29 variations in chromite are totally independent from the modal composition. We thus conclude
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31 that the higher TiO₂ content common to all minerals independently from their habitus in amph-
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33 bearing and opx/pl/cpx-bearing dunites better supports a more evolved parent melt for all the
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35 inclusions, chromites and interstitial minerals in these samples.
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45 One possible explanation would be that the parent melts of interstitial clinopyroxene and
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47 plagioclase are primitive MORB issued from the partial melting of the Maqsad diapir, not or
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49 poorly contaminated by the hydrous, lithospheric component. On the other hand, orthopyroxene
50
51 and amphibole crystallized from a more evolved, Si- and water-rich melt or fluid.
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53 Orthopyroxene and amphibole have likewise been reported (1) along ol, pl and cpx grain
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55 boundaries in gabbros from the lower oceanic crust (Koepke *et al.*, 2005, 2014), and (2) as
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57 globular inclusions, in association with phlogopite and aspidolite, in olivine and plagioclase in
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3 the Murotomisaki Gabbroic Intrusion (MGI, Japan) - chromite also occurs as inclusion in ol
4 and pl in these rocks (Hoshide and Obata, 2009, 2012). It has been proposed that the infiltration
5 of a fluid fraction along grain boundaries in mafic rocks may trigger the hydrated partial melting
6 of the primary minerals, with the concomitant crystallization of both amphibole and
7 orthopyroxene (e.g. Koepke *et al.*, 2005). Experiments have shown that the hydrated partial
8 melting of mafic rocks produces a trondhjemitic melt (Berndt *et al.*, 2005; Wolff *et al.*, 2013).
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10 In this frame, the Si- and water-rich melt or fluid fraction involved in the formation of the exotic
11 silicate inclusions in chromite in the studied DTZ dunites may derive from the hydrated partial
12 melting of mafic lithologies at the base of the crust and/or from the mantle harzburgite
13 orthopyroxene dissolution itself (Rospabé *et al.*, 2017), the hydrated component being issued
14 from the deep introduction of hydrothermal fluids accounted for by the early development of
15 synmagmatic faults (Abily *et al.*, 2011; Rospabé *et al.*, 2019a, 2019b, 2020).
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33 The presence of nepheline, similar to that enclosed in the DTZ disseminated chromites, together
34 with jadeite and albitic feldspar was reported in other ophiolites (e.g. Johan and Le Bel, 1978;
35 Legendre, 1982; Johan *et al.*, 1983, 2017; Talkington *et al.*, 1984; Plissart *et al.*, 2017) as well
36 as in a chromitite associated to abyssal peridotites as reported by Matsukage and Arai (1998).
37 These latter have interpreted nepheline and albite as two associated magmatic products, albite
38 precipitating first followed by the eutectic crystallization of both phases (1100-1200 °C), and
39 finally jadeite as the subsolidus reaction of albite and nepheline at low temperatures (250-300
40 °C) at slightly less than 3 kbar. In the present study, nepheline and jadeite occur as
41 monomineralic inclusions or in polymineralic inclusions in association with amphibole (Fig.
42 4e-f), clinopyroxene or mica. They can be reasonably interpreted as crystallization products
43 from similar melts. In this frame, jadeite might result from the destabilization of nepheline
44 during cooling. Alternatively, nepheline could result from the destabilization of pargasite into
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3 the assemblage diopside + forsterite + nepheline + spinel + anorthite + vapor, at temperature
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5 higher than 1050 °C (Boyd, 1959; see also Holloway, 1973 and Augé, 1987).
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10 The origin of the diopside, grossular garnet and pectolite inclusions is typically controversial
11 as they are classically interpreted as low temperature alteration products in abyssal and
12 ophiolitic materials: this assemblage chiefly replaces the primary minerals during the
13 rodingitization (Ca enrichment, Si loss) of mafic or leucocratic rocks, related to the
14 serpentinization of the surrounding ultramafic rocks or more generally to hydrothermal
15 circulations in temperature conditions of about 300-350 °C (e.g. Schandl *et al.*, 1989; Esteban
16 *et al.*, 2003; Austrheim and Prestvik, 2008; Frost *et al.*, 2008; Bach and Klein, 2009; Ghosh
17 and Morishita, 2011; Akizawa *et al.*, 2016). Following this hypothesis of a secondary origin,
18 diopside and grossular should represent alteration products after clinopyroxene and plagioclase
19 respectively in the studied samples. However, this is unlikely in the case of the Maqsad
20 disseminated chromites: the two relative frequency histograms in Figure 5c-d show that the
21 increasing amount of ‘exotic’ phases (amph, mica, opx + diopside and garnet inclusions) is
22 associated to the decrease in the occurrence of the assemblage ol-cpx-pl in inclusion from pure
23 dunite to impregnated dunitites containing more and more interstitial minerals witnessing a
24 hydrous parent melt. This is observed even when diopside and garnet are taken into account
25 (Fig. 5d), while this correlation should not exist if these two minerals were essentially of
26 secondary origin. This is especially true regarding diopside: it constitutes the third most
27 frequent silicate in inclusion (Fig. 5a), and its frequency of occurrence is not related to the one
28 of the igneous clinopyroxene (Fig. 5b). In addition, diopside in inclusions have compositions
29 spanning between the ‘magmatic’ compositions of clinopyroxene impregnations and the
30 ‘hydrothermal’ compositions of diopside from diopsidites that formed at 600-800 °C following
31 high temperature hydrothermal events (see Python *et al.*, 2007, 2011 for more details). On the
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3 other hand, the high TiO₂ content in some grossular (up to 5 wt %) cannot result from the
4 alteration of plagioclase ± chromite, and the existence of a Ti-rich alteration fluid is unlikely.
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6 Consequently, we suggest that both diopside and grossular garnet formed at lower temperature
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8 than the cpx-opx-mica-amph assemblages, and/or witness the greater proportion of the hydrated
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10 component (relative to MORB) in the hybrid melt involved in the DTZ genesis (Rospabé *et al.*,
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12 2017).
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19 Apatite is a more unusual phase among the inclusions in the Oman ophiolite chromites
20 (Rollinson *et al.*, 2018). Experimental works have shown that apatite appears in crystallization
21 sequences from late-stage, highly evolved MORB (Koepke *et al.*, 2018). Cl-rich apatite (up to
22 3.06 wt % Cl) described in cumulates from present-day oceanic crust has been interpreted as
23 the product of degassing during fractional crystallization, or by the assimilation of a seawater-
24 derived component by the crystallizing mush (Meurer and Natland, 2001). The single
25 chlorapatite observed in inclusion may reasonably represent an additional primary witness of
26 the hybrid Si- and H₂O-rich melt or fluid (e.g. Morishita *et al.*, 2003) involved in the formation
27 of both dunite and chromitite (Rospabé *et al.*, 2017). It could result from a magmatic to
28 metamorphic process involving a high temperature seawater-derived hydrothermal fluid (high
29 Cl content) in a cooling context leading to the cessation of the magmatic activity (Rospabé *et*
30 *al.*, 2020). Although the Cl and F contents in amphibole and mica inclusions studied here are
31 lower than in other examples of layered intrusions (e.g. Boudreau *et al.*, 1986; Mathez and
32 Webster, 2005), the highest values are observed in amphibole approaching the synmagmatic
33 faults (Rospabé *et al.* 2020), and in mica exactly at the elevation where chlorapatite occurs
34 (Electronic Appendix 2 and Fig. 6). Accordingly, this suggests that Cl-rich fluids, potentially
35 seawater-derived, are involved from early stage, at magmatic temperatures, to lower
36 temperatures (see also Arai *et al.*, 2020). In this frame, the consumption of OH relative to Cl
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3 by the crystallization of phlogopite and/or the percolation of chromatographically exotic
4 fluid/melt through the freezing dunitic mush may also have originate the appearance of apatite
5 here, mineralogically similar to what was described in layered intrusions (Mathez and Webster,
6 2005).
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14 The origin of pectolite in inclusion in the disseminated chromites (sample 15OM110B) is more
15 puzzling. It is usually seen as a replacement mineral or as a phase filling the porosity in
16 rodingitized rocks. Its association with amphibole and its very low MgO content cannot be
17 accounted easily for by the replacement of one of the other silicates identified as inclusion,
18 except plagioclase (not observed in this sample) or more probably grossular. The solely report
19 of pectolite in Oman is in a rodingite (fully altered plagiogranites or diopsidite) from the
20 periphery of the Maqsad area, where it fills veins and mineral rims (Momburu, 2015).
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33 As the result of the progressive cooling of the Maqsad DTZ following the cessation of the
34 magmatic activity, the (undoubtedly) low temperature alteration event (i.e. serpentinization)
35 affected both the dunitic matrix and the silicate inclusions in the disseminated chromites. In
36 those, low temperature process is evidenced by the alteration rims at the contact between the
37 inclusions and their host chromite (mostly serpentine, chlorite and tremolite, more rarely
38 carbonates, magnetite and sulphides). Consequently, the chromite-hosted silicate inclusions
39 from the DTZ recorded processes that occurred on a wide range of temperatures, from high
40 temperature, magmatism to metamorphism toward lower temperature alteration conditions.
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53 **The chicken and egg dilemma linking dunites and chromitites**

54 *The competition between orthopyroxene and chromite crystallization*

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58 Our exhaustive survey allowed us to establish that the distribution of the nature and composition
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3 of the included minerals is not random across the Maqsad DTZ (Figs. 5 and 6). It shows an
4 increasing abundance, upsection, of the silicates witnessing the silica-rich (opx) and hydrated
5 and alkali-rich (amph, mica) nature of their parent melts, inconsistent with crystallization of a
6 common MORB. This evolution mirrors the one of the interstitial silicates in the olivine matrix,
7 particularly marked by the much higher frequency of orthopyroxene above the altitude of 850
8 m (i.e. about 200-250 above the base of the DTZ) together with the higher amount of inclusions
9 of mica (Fig. 6). Interestingly, (1) this correlation holds for the *presence* of each interstitial
10 mineral phase *whatever their apparent modal abundance* in the host dunite, and (2) these levels
11 correspond precisely to the altitude of the main chromitite occurrences in this area.
12 Accordingly, the contrasted assemblages of silicate inclusions depend only on the instantaneous
13 composition of their parent melt (+/- fluid) and less on the variable physical conditions that led
14 to their nucleation and growth.
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33 The dichotomy between the opx/pl/cpx-bearing dunites \pm chromite (including orthopyroxene
34 inclusion) on one hand, and the chromitites \pm minor orthopyroxene (interstitially and in
35 inclusion) on the other hand elegantly illustrates the local competition between the
36 crystallization of orthopyroxene and the concentration of chromite, differently distributed
37 within the same levels. This probably reflects the crossing of the chromite-orthopyroxene
38 cotectic, supporting the preferential fractionation of one of both phases depending on the more
39 or less important contribution of the evolved Si-, Na- and volatile-rich melt fraction relative to
40 the MORB in the hybrid parent melt (e.g. Irvine, 1975, 1977a, 1977b).
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54 Experimental works have shown that an addition of water will shift the phase relations
55 crystallizing from tholeiitic or noritic liquids (e.g. Feig et al., 2010; Mathez and Kinzler, 2017),
56 basically with a shift from the assemblage pl+opx+cpx, to pl+opx, to pl \pm ol, to chromite \pm ol
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3 depending on the water partial pressure (i.e. amount of water in the melt). In the present case,
4 plagioclase is scarce as inclusion, but orthopyroxene in interstitial position is systematically
5 observed with plagioclase and clinopyroxene \pm amphibole and was never observed alone or
6 associated only with clinopyroxene. On the other hand, the crystallization of olivine is not
7 obviously identified in this context, the system being already made of olivine following the
8 dunitization of the mantle harzburgites. Consequently, it can be deduced that a higher
9 contribution of Si-, Na- and volatile-rich fraction relative to the MORB in the hybrid melt - at
10 least for its hydrated character and potentially to its silica-richer character - will allow to the
11 massive fractionation of chromite/chromitite rather than orthopyroxene (+ plagioclase) in some
12 specific levels of the DTZ.
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28 *The cycle of dunites-chromitites formation*

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30 The observations reported above led us to formulate three end-membered working hypotheses
31 for the links between the DTZ dunites and chromitites:
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37 (1) *The prior formation of dunite triggers the subsequent formation of chromitite:*

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39 Chromitites formed following a *widespread process first*. Dunites form at the expense of
40 residual mantle harzburgites following fluid-melt-rock reactions. The dissolution of the residual
41 pyroxenes (mostly orthopyroxene) and Cr-spinel releases a relatively high amount of Cr.
42 Interstitial impregnations in dunites, comprising disseminated chromites, crystallize at different
43 places along the DTZ. The residual melts, saturated in Cr, are extracted and hybridized along
44 fault zones where they will massively crystallize to form chromitite ore bodies (Boudier and
45 Al-Rajhi, 2014; Zagrtdenov *et al.*, 2018). In this scenario the fault zones are also the media for
46 the continuous hydrothermal, seawater-derived fluids (potentially supercritical) introduction
47 down to the DTZ (e.g. higher Cl content in amphibole approaching fault zones; Rospabé *et al.*,
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3 2020). In this hypothesis, the chromitite cannot form without the prior mantle harzburgite
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5 dunitization, making the dunite formation the chicken at the origin of the existence of the
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7 chromitites, the eggs.
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12 The analysis of both the chromite and the enclosed silicate inclusions shows a systematic
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14 decoupling between the compositions in pure and cpx-bearing dunites on one hand, and the
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16 ones in amph- to opx/pl/cpx-bearing dunites (e.g. higher XCr in chromite, higher TiO₂ in
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18 chromite and inclusions) on the other hand. These lithologies represent two end-members in
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20 the chemical variation ranges we observed, likely deriving from the primitive MORB
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22 (clinopyroxene, plagioclase) and from the lithospheric evolved melt (orthopyroxene,
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24 amphibole). With a few exceptions, the composition of chromite and associated silicate
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26 inclusions in the DTZ chromitites are very frequently close to the one in pl/cpx-bearing dunites,
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28 thus intermediate between the two other contrasted main trends (Figs. 7 and 8). This may
29
30 represent the perfect condition to fractionate only chromite from the melt hosting Cr, itself
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32 being a mixture between residual fluid-melt fractions issued from the two end-members, mostly
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34 in the vicinity of syn-magmatic, syn-hydrothermal faults (e.g. Fo and XMg buffered to high
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36 values both in olivine and chromite, potentially related to a higher oxygen fugacity with the
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38 higher amount of water; Feig *et al.*, 2006).
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47 (2) *The prior formation of chromitite triggers the subsequent formation of dunite:*

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49 Chromitites formed in response to a *localized process first*. The hybridization between the
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51 MORB and the evolved Si-, Na- and volatile-rich melt or fluid occurs within or along
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53 discontinuities (e.g. magmatic breccias developed by melt and/or fluid influxes along a fault
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55 zone reaching an unconsolidated mush; Rospabé *et al.*, 2019a, 2019b, 2020). Chromite
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57 massively precipitates within or in the direct vicinity of the hybridization area leading to the
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3 formation of chromitite ore bodies along faults or shear zones. Residual melts invade the
4 surrounding upper mantle and/or DTZ to enhance the dunitization process and crystallize the
5 disseminated chromites interstitially between olivine grains, together with other interstitial
6 minerals such as orthopyroxene (Rospabé *et al.*, 2017). In this scenario, the massive chromitite
7 formation process is the chicken and the dunitites, especially the impregnated dunitites that contain
8 a large diversity of interstitial minerals, are the eggs. Dunitic aureoles surrounding mantle
9 chromitites have in some case been interpreted following such process (e.g. González-Jiménez
10 *et al.*, 2014).

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24 (3) *Both dunite and chromitite form simultaneously:*

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26 An intermediate hypothesis is to consider *contemporaneous widespread and localized*
27 *processes*, assuming that one lithology did not form in response to the formation of the other at
28 the scale of the whole mantle-crust transition zone, but that both dunitites (and their disseminated
29 chromites and other impregnations) and chromitites formed at the same time along the DTZ.
30 This model calls for spatial variations in the involvement and contribution of the MORB and
31 of the hybrid melt (i.e. spatial rather than temporal variations), as well as of the spatial
32 development of the fault zones. In other words, both dunitites and chromitites can each be the
33 chicken/egg of the other, according to the local chemical, physical and thermal conditions at a
34 given place within the DTZ.
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49 To revolve these main hypotheses, the three assumptions are finally right in a way depending
50 on the time and spatial scale at which the processes occur. Chromitites in ophiolites cannot
51 form without the prior mantle harzburgite dunitization (the dissolution of opx and Cr-spinel
52 contributing to the source of Cr in addition to the Cr transported in MORB), but also seem to
53 be deeply linked to the formation of the more exotic amph- and opx/pl/cpx-bearing dunitites.
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3 This defines a cycle which can restart at each step of the mantle dunitization process at the top
4 of the mantle diapir, which also depends on the extent of hybridization between the MORB and
5 the evolved Si-, Na- and volatile-rich lithospheric melts. This is in agreement with the cyclic
6 nature of the melt delivery and of the tectonic-hydrothermal activity beneath oceanic spreading
7 centres.
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17 **CONCLUSION**

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19 The genesis of chromitites, at least in the context of ophiolites, is usually addressed by the study
20 of the most remarkable ore bodies. In the present study, we adopted a different approach by
21 extensively surveying the chromite-hosted silicate inclusions in disseminated chromites in
22 dunites hosting the ore bodies. They are among the products of the fluid-melt-peridotite reaction
23 that led to the development of the dunitic mantle-crust transition zone. Our results suggest that
24 the ore genesis processes involved in the formation of chromitites are not restricted to the ore
25 bodies themselves but operated on the much larger scale, the one of the whole DTZ. It leads to
26 consider the entire DTZ as an ore deposit. In this spirit, the DTZ dunites may be regarded as a
27 low-grade dispersed ore. The hybrid Si-, Na- and volatile-rich fluids or melts involved in the
28 formation of both dunites and chromitites are issued from the interaction between the hot
29 uprising Maqsad diapir (producing MORB more or less continuously), and the colder,
30 hydrothermally altered, previously crystallized, and potentially re-melting lithospheric lid. In
31 this frame, the mixing between the different fluid or melt fractions is clearly related to the
32 synmagmatic tectonic. To conclude, the DTZ can be viewed as a contact metamorphic aureole
33 between asthenospheric diapirs and hydrated lithospheric lids, and its formation beneath
34 oceanic spreading centres has undoubtedly a major impact on the global geochemical cycles.
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28 REFERENCES

- 30 Abily, B. & Ceuleneer, G. (2013). The dunitic mantle-crust transition zone in the Oman
31 ophiolite: Residue of melt-rock interaction, cumulates from high-MgO melts, or both?
32 *Geology* **41**, 67–70.
- 33 Abily, B., Ceuleneer, G. & Launeau, P. (2011). Synmagmatic normal faulting in the lower
34 oceanic crust: Evidence from the Oman ophiolite. *Geology* **39**, 391–394.
- 35 Ahmed, A. & Arai, S. (2002). Unexpectedly high-PGE chromitite from the deeper mantle
36 section of the northern Oman ophiolite and its tectonic implications. *Contributions to*
37 *Mineralogy and Petrology*. Springer-Verlag **143**, 263–278.
- 38 Akizawa, N. & Arai, S. (2009). Petrologic profile of peridotite layers under a possible Moho in
39 the northern Oman ophiolite: An example from Wadi Fizh. *Journal of Mineralogical and*
40 *Petrological Sciences* **104**, 389–394.
- 41 Akizawa, N., Tamura, A., Fukushi, K., Yamamoto, J., Mizukami, T., Python, M. & Arai, S.
42 (2016). High-temperature hydrothermal activities around suboceanic Moho: An example
43
44
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2
3 from diopside and anorthosite in Wadi Fizh, Oman ophiolite. *Lithos* **263**, 66–87.
4
5 Allan, J. & Dick, H. B. (1996). Cr-rich spinel as a tracer for melt migration and melt-wall rock
6 interaction in the mantle: Hess Deep, Leg 147. *Proceedings of the Ocean Drilling*
7 *Program: Scientific Results* **147**, 157–172.
8
9
10
11 Amri, I., Benoit, M. & Ceuleneer, G. (1996). Tectonic setting for the genesis of oceanic
12 plagiogranites: evidence from a paleo-spreading structure in the Oman ophiolite. *Earth*
13 *and Planetary Science Letters* **139**, 177–194.
14
15
16
17
18 Arai, S. & Matsukage, K. (1998). Petrology of a chromitite micropod from Hess Deep,
19 equatorial Pacific: a comparison between abyssal and alpine-type podiform chromitites.
20
21
22
23
24
25
26
27 Arai, S. & Miura, M. (2016). Formation and modification of chromitites in the mantle. *Lithos*
28
29
30
31
32 Arai, S. & Yurimoto, H. (1994). Podiform chromitites of the Tari-Misaka ultramafic complex,
33 southwestern Japan, as mantle-melt interaction products. *Economic Geology* **89**, 1279–
34
35
36
37
38
39
40
41
42
43 Arai, S., Miura, M., Tamura, A., Akizawa, N. & Ishikawa, A. (2020). Hydrothermal
44 Chromitites from the Oman Ophiolite: The Role of Water in Chromitite Genesis. *Minerals*
45
46
47
48
49
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51
52
53
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57 Augé, T. (1986). Platinum-group-mineral inclusions in chromitites from the Oman ophiolite.
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2
3 reaction path modeling. *Lithos* **112**, 103–117.
4

5 Ballhaus, C. G. & Stumpfl, E. F. (1986). Sulfide and platinum mineralization in the Merensky
6 Reef: evidence from hydrous silicates and fluid inclusions. *Contributions to Mineralogy
7 and Petrology* **94**, 193–204.
8
9

10
11
12 Basch, V., Rampone, E., Crispini, L., Ferrando, C., Ildefonse, B. & Godard, M. (2018). From
13 mantle peridotites to hybrid troctolites: Textural and chemical evolution during melt-rock
14 interaction history (Mt. Maggiore, Corsica, France). *Lithos* **323**, 4–23.
15
16

17
18
19 Bédard, J. H. (1994). A procedure for calculating the equilibrium distribution of trace elements
20 among the minerals of cumulate rocks, and the concentration of trace elements in the
21 coexisting liquids. *Chemical Geology* **118**(1-4), 143–153.
22
23

24
25
26 Bédard, J. H. & Hébert, R. (1998). Formation of chromitites by assimilation of crustal
27 pyroxenites and gabbros into peridotitic intrusions: North Arm Mountain massif, Bay of
28 Islands ophiolite, Newfoundland, Canada. *Journal of Geophysical Research: Solid Earth*
29 **103**, 5165–5184.
30
31
32

33
34
35 Benn, K., Nicolas, A. & Reuber, I. (1988). Mantle-crust transition zone and origin of wehrlitic
36 magmas: Evidence from the Oman ophiolite. *Tectonophysics* **151**, 75–85.
37
38

39
40 Benoit, M., Ceuleneer, G. & Polvé, M. (1999). The remelting of hydrothermally altered
41 peridotite at mid-ocean ridges by intruding mantle diapirs. *Nature* **402**, 514–518.
42
43

44
45 Benoit, M., Polvé, M. & Ceuleneer, G. (1996). Trace element and isotopic characterization of
46 mafic cumulates in a fossil mantle diapir (Oman ophiolite). *Chemical Geology* **134**, 199–
47 214.
48
49

50
51 Berndt, J., Koepke, J. & Holtz, F. (2005). An experimental investigation of the influence of
52 water and oxygen fugacity on differentiation of MORB at 200 MPa. *Journal of Petrology*
53 **46**, 135–167.
54
55

56
57
58 Borisova, A. Y., Ceuleneer, G., Kamenetsky, V. S., Arai, S., Bédard, J. H., Abily, B., Bindeman,
59
60

- 1
2
3 I. N., Polvé, M., De Parseval, P., Aigouy, T. & Pokrovski, G. S. (2012). A new view on
4 the petrogenesis of the Oman ophiolite chromitites from microanalyses of chromite-hosted
5 inclusions. *Journal of Petrology* **53**, 2411–2440.
6
7
8
9
10 Bosch, D., Jamais, M., Boudier, F., Nicolas, A., Dautria, J. M. & Agrinier, P. (2004). Deep and
11 high-temperature hydrothermal circulation in the Oman ophiolite–petrological and
12 isotopic evidence. *Journal of Petrology* **45**, 1181–1208.
13
14
15
16
17 Boudier, F. & Al-Rajhi, A. (2014). Structural control on chromitite deposits in ophiolites: the
18 Oman case. *Geological Society, London, Special Publications* **392**, 263–277.
19
20
21 Boudier, F., Bouchez, J. L., Nicolas, A., Cannat, M., Ceuleneer, G., Misseri, M. & Montigny,
22 R. (1985). Kinematics of oceanic thrusting in the Oman ophiolite: model of plate
23 convergence. *Earth and Planetary Science Letters* **75**, 215–222.
24
25
26
27
28 Boudier, F. & Nicolas, A. (1995). Nature of the moho transition zone in the Oman ophiolite.
29 *Journal of Petrology* **36**, 777–796.
30
31
32
33 Boudreau, A. E., Mathez, E. A. & McCallum, I. S. (1986). Halogen geochemistry of the
34 Stillwater and Bushveld Complexes: evidence for transport of the platinum-group
35 elements by Cl-rich fluids. *Journal of Petrology* **27**, 967–986.
36
37
38
39
40 Bowen, N. L. (1915). The later stages of the evolution of the igneous rocks. *The Journal of*
41 *Geology* **23**, 1–91.
42
43
44
45 Bowen, N. L. (1927). The origin of ultrabasic and related rocks. *American Journal of Science*
46 **80**, 89–108.
47
48
49
50
51 Boyd, F. R. (1959). Hydrothermal investigations of amphiboles. *Researches in geochemistry*
52 377–396.
53
54
55
56 Cannat, M., Bideau, D. & Hébert, R. (1990). Plastic deformation and magmatic impregnation
57 in serpentinized ultramafic rocks from the Garrett transform fault (East Pacific Rise).
58 *Earth and Planetary Science Letters* **101**, 216–232.
59
60

- 1
2
3 Cassard, D., Nicolas, A., Rabinowicz, M., Moutte, J., Leblanc, M. & Prinzhofer, A. (1981).
4
5 Structural classification of chromite pods in southern New Caledonia. *Economic Geology*
6
7 **76**, 805–831.
8
9
10 Ceuleneer, G. (1991). Evidence for a Paleo-Spreading Center in the Oman Ophiolite: Mantle
11
12 Structures in the Maqsad Area. Springer Netherlands, 147–173.
13
14 Ceuleneer, G. & Le Sueur, E. (2008). The Trinity ophiolite (California): the strange association
15
16 of fertile mantle peridotite with ultra-depleted crustal cumulates. *Bulletin de la Société*
17
18 *Géologique de France* **179**, 503–518.
19
20
21 Ceuleneer, G., Monnereau, M. & Amri, I. (1996). Thermal structure of a fossil mantle diapir
22
23 inferred from the distribution of mafic cumulates. *Nature* **379**, 149–153.
24
25
26 Ceuleneer, G. & Nicolas, A. (1985). Structures in podiform chromite from the Maqsad district
27
28 (Sumail ophiolite, Oman). *Mineralium Deposita* **20**, 177–184.
29
30
31 Ceuleneer, G., Nicolas, A. & Boudier, F. (1988). Mantle flow pattern at an oceanic spreading
32
33 centre: the Oman peridotite record. *Tectonophysics* **151**, 1–26.
34
35
36 Ceuleneer, G. & Rabinowicz, M. (1992). Mantle flow and melt migration beneath oceanic
37
38 ridges: models derived from observation in ophiolites, in mantle flow and melt generation
39
40 at mid-ocean ridges. In: Morgan, J. P., Blackman, D. B. and Sinton, J. M. (eds) *Mantle*
41
42 *Flow and Melt Generation at Mid-Ocean Ridges*. American Geophysical Union,
43
44 *Geophysical Monograph Series* **71**, 123–154.
45
46
47 Clénet, H., Ceuleneer, G., Pinet, P., Abily, B., Daydou, Y., Harris, E., Amri, I. & Dantas, C.
48
49 (2010). Thick sections of layered ultramafic cumulates in the Oman ophiolite revealed by
50
51 an airborne hyperspectral survey: Petrogenesis and relationship to mantle diapirism. *Lithos*
52
53 **114**, 265–281.
54
55
56 Costa, F., Dungan, M. A. & Singer, B. S. (2001). Magmatic Na-rich phlogopite in a suite of
57
58 gabbroic crustal xenoliths from Volcán San Pedro, Chilean Andes: Evidence for a solvus
59
60

- 1
2
3 relation between phlogopite and aspidolite. *American Mineralogist* **86**, 29–35.
4
5
6 Dick, H. J. B. (1977). Partial Melting in the Josephine Peridotite: I, The Effect on Mineral
7
8 Composition and Its Consequence for Geobarometry and Geothermometry. *American*
9
10 *Journal of Science* **277**, 801–832.
11
12 Dijkstra, A. H., Barth, M. G., Drury, M. R., Mason, P. R., & Vissers, R. L. (2003). Diffuse
13
14 porous melt flow and melt - rock reaction in the mantle lithosphere at a slow - spreading
15
16 ridge: A structural petrology and LA - ICP - MS study of the Othris Peridotite Massif
17
18 (Greece). *Geochemistry, Geophysics, Geosystems* **4**.
19
20
21 Drouin, M., Godard, M., Ildefonse, B., Bruguier, O. & Garrido, C. J. (2009). Geochemical and
22
23 petrographic evidence for magmatic impregnation in the oceanic lithosphere at Atlantis
24
25 Massif, Mid-Atlantic Ridge (IODP Hole U1309D, 30 N). *Chemical Geology* **264**, 71–88.
26
27
28 Dygert, N., Kelemen, P. B. & Liang, Y. (2017). Spatial variations in cooling rate in the mantle
29
30 section of the Samail ophiolite in Oman: Implications for formation of lithosphere at mid-
31
32 ocean ridges. *Earth and Planetary Science Letters* **465**, 134–144.
33
34
35 Dygert, N., Liang, Y. & Kelemen, P. B. (2016). Formation of plagioclase lherzolite and
36
37 associated dunite–harzburgite–lherzolite sequences by multiple episodes of melt
38
39 percolation and melt–rock reaction: an example from the Trinity Ophiolite, California,
40
41 USA. *Journal of Petrology*, **57**, 815–838.
42
43
44 Esteban, J. J., Cuevas, J., Tubía, J. M. & Yusta, I. (2003). Xonotlite in rodingite assemblages
45
46 from the Ronda peridotites, Betic Cordilleras, Southern Spain. *Canadian Mineralogist* **41**,
47
48 161–170.
49
50
51 Feig, S. T., Koepke, J. & Snow, J. E. (2010). Effect of oxygen fugacity and water on phase
52
53 equilibria of a hydrous tholeiitic basalt. *Contributions to Mineralogy and Petrology* **160**,
54
55 551-568.
56
57
58 Feig, S. T., Koepke, J. & Snow, J. E. (2006). Effect of water on tholeiitic basalt phase equilibria:
59
60

1
2
3 An experimental study under oxidizing conditions. *Contributions to Mineralogy and*
4
5 *Petrology* **152**, 611–638.
6

7 Fisher, L. W. (1929). Origin of chromite deposits. *Economic Geology* **24**, 691–721.
8

9
10 Friedrich, B. M., Marques, J. C., Olivo, G. R., Frantz, J. C., Joy, B. & Queiroz, W. J. A. (2019).
11
12 Petrogenesis of the massive chromitite layer from the Jacurici Complex, Brazil: evidence
13
14 from inclusions in chromite. *Mineralium Deposita* **55**, 1105–1026.
15

16
17 Frost, B. R., Beard, J. S., Mccaig, A. & Condliffe, E. (2008). The formation of micro-rodingites
18
19 from IODP hole U1309D: Key to understanding the process of serpentinization. *Journal*
20
21 *of Petrology* **49**, 1579–1588.
22

23
24 Gerbert-Gaillard, L. (2002). Caractérisation Géochimique des Péridotites de l'ophiolite
25
26 d'Oman : Processus Magmatiques aux Limites Lithosphère/Asthénosphère. Université
27
28 Montpellier II.
29

30
31 Ghosh, B. & Morishita, T. (2011). Andradite-uvarovite solid solution from hydrothermally
32
33 altered podiform chromitite, rutland ophiolite, Andaman, India. *Canadian Mineralogist*
34
35 **49**, 573–580.
36

37
38 Girardeau, J. & Francheteau, J. (1993). Plagioclase-wehrlites and peridotites on the East Pacific
39
40 Rise (Hess Deep) and the Mid-Atlantic Ridge (DSDP Site 334): evidence for magma
41
42 percolation in the oceanic upper mantle. *Earth and Planetary Science Letters* **115**, 137–
43
44 149.
45

46
47 Glennie, K. W., Boeuf, M. G. A., Clarke, M. H., Moody-Stuart, M., Pilaar, W. F. H. &
48
49 Reinhardt, B. M. (1973). Late Cretaceous nappes in Oman Mountains and their geologic
50
51 evolution. *AAPG Bulletin* **57**, 5–27.
52

53
54 Godard, M., Dautria, J. M. & Perrin, M. (2003). Geochemical variability of the Oman ophiolite
55
56 lavas: Relationship with spatial distribution and paleomagnetic directions. *Geochemistry,*
57
58 *Geophysics, Geosystems* **4**.
59
60

- 1
2
3 Godard, M., Joussetin, D. & Bodinier, J. L. (2000). Relationships between geochemistry and
4 structure beneath a palaeo-spreading centre: A study of the mantle section in the Oman
5 ophiolite. *Earth and Planetary Science Letters* **180**, 133–148.
6
7
8
9
10 González-Jiménez, J. M., Griffin, W. L., Proenza, J. A., Gervilla, F., O'Reilly, S. Y., Akbulut,
11 M., Pearson, N. J. & Arai, S. (2014). Chromitites in ophiolites: How, where, when, why?
12 Part II. The crystallization of chromitites. *Lithos*, 140–158.
13
14
15
16
17 Greenbaum, D. (1972). Magmatic processes at ocean ridges: evidence from the Troodos massif,
18 Cyprus. *Nature Physical Science* **238**, 18–21.
19
20
21 Holloway, J. R. (1973). The system pargasite-H₂O-CO₂: a model for melting of a hydrous
22 mineral with a mixed-volatile fluid-I. Experimental results to 8 kbar. *Geochimica et*
23 *Cosmochimica Acta* **37**, 651–666.
24
25
26
27
28 Hoshide, T. & Obata, M. (2009). Zoning and resorption of plagioclase in a layered gabbro, as
29 a petrographic indicator of magmatic differentiation. *Earth and Environmental Science*
30 *Transactions of the Royal Society of Edinburgh* **100**, 1–15.
31
32
33
34
35 Hoshide, T. & Obata, M. (2012). Amphibole-bearing multiphase solid inclusions in olivine and
36 plagioclase from a layered gabbro: Origin of the trapped melts. *Journal of Petrology* **53**,
37 419–449.
38
39
40
41
42 Hoshide, T. & Obata, M. (2014). Spinel inclusions in olivine and plagioclase crystals in a
43 layered gabbro: a marker and a tracer for primary phenocrysts in a differentiating magma
44 reservoir. *Contributions to Mineralogy and Petrology* **168**, 1049.
45
46
47
48
49 Irvine, T. N. (1975). Crystallization sequences in the Muskox intrusion and other layered
50 intrusions-II. Origin of chromitite layers and similar deposits of other magmatic ores.
51 *Geochimica et Cosmochimica Acta* **39**.
52
53
54
55
56 Irvine, T. N. (1977a). Origin of chromitite layers in the Muskox intrusion and other stratiform
57 intrusions: A new interpretation. *Geology* **5**, 273–277.
58
59
60

- 1
2
3 Irvine, T.N. (1977b). Chromite crystallization in the join Mg_2SiO_4 - $CaMgSi_2O_6$ - $CaAl_2Si_2O_8$ -
4 $MgCr_2O_4$ - SiO_2 . *Carnegie Institute. Washington Yearbook* **76**, 465–472.
5
6
7
8 Johan, Z., Dunlop, H., Le Bel, L., Robert, J. L. & Volfinger, M. (1983). Origin of chromite
9
10 deposits in ophiolitic complexes: evidence for a volatile- and sodium-rich reducing fluid
11
12 phase. *Fortschritte der Mineralogie* **61**, 105–107.
13
14
15 Johan, Z. & Le Bel, L. (1978). *Sur la genèse des couches et nodules de chromite dans les*
16
17 *complexes ophiolitiques. Rés. Sci. Tech. BRGM.*
18
19
20 Johan, Z., Martin, R. F. & Ettler, V. (2017). Fluids are bound to be involved in the formation
21
22 of ophiolitic chromite deposits. *European Journal of Mineralogy* **29**, 543–555.
23
24
25 Jousselein, D. & Nicolas, A. (2000). The Moho transition zone in the Oman ophiolite-relation
26
27 with wehrlites in the crust and dunites in the mantle. *Marine Geophysical Researches* **21**,
28
29 229–241.
30
31
32 Jousselein, D., Nicolas, A. & Boudier, F. (1998). Detailed mapping of a mantle diapir below a
33
34 paleo-spreading center in the Oman ophiolite. *Journal of Geophysical Research: Solid*
35
36 *Earth* **103**, 18153–18170.
37
38
39 Kaczmarek, M. A. & Müntener, O. (2008). Juxtaposition of melt impregnation and high-
40
41 temperature shear zones in the upper mantle; field and petrological constraints from the
42
43 Lanzo Peridotite (Northern Italy). *Journal of Petrology* **49**, 2187–2220.
44
45
46 Kelemen, P. B. (1990). Reaction between ultramafic rock and fractionating basaltic magma I.
47
48 phase relations, the origin of calc-alkaline magma series, and the formation of discordant
49
50 dunite. *Journal of Petrology* **31**, 51–98.
51
52
53 Kelemen, P. B., Dick, H. J. B. & Quick, J. E. (1992). Formation of harzburgite by pervasive
54
55 melt/rock reaction in the upper mantle. *Nature* **358**, 635–641.
56
57
58 Kelemen, P. B., Shimizu, N. & Salters, V. J. (1995). Extraction of mid-ocean-ridge basalt from
59
60 the upwelling mantle by focused flow of melt in dunite channels. *Nature* **375**, 747–753.

- 1
2
3 Koepke, J., Berndt, J., Horn, I., Fahle, J. & Wolff, P. E. (2014). Partial melting of oceanic
4 gabbro triggered by migrating water-rich fluids: a prime example from the Oman
5 Ophiolite. *Geological Society, London, Special Publications* **392**, 195–212.
6
7
8
9
10 Koepke, J., Botcharnikov, R. E. & Natland, J. H. (2018). Crystallization of late-stage MORB
11 under varying water activities and redox conditions: Implications for the formation of
12 highly evolved lavas and oxide gabbro in the ocean crust. *Lithos* **323**, 58–77.
13
14
15
16
17 Koepke, J., Feig, S. T. & Snow, J. E. (2005). Hydrous partial melting within the lower oceanic
18 crust. *Terra Nova* **17**, 286–291.
19
20
21
22 Koga, K. T., Kelemen, P. B. & Shimizu, N. (2001). Petrogenesis of the crust-mantle transition
23 zone and the origin of lower crustal wehrlite in the Oman ophiolite. *Geochemistry,*
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
- Latypov, R., Costin, G., Chistyakova, S., Hunt, E. J., Mukherjee, R. & Naldrett, T. (2018).
Platinum-bearing chromite layers are caused by pressure reduction during magma ascent.
Nature communications **9**, 1–7.
- Leblanc, M. & Ceuleneer, G. (1991). Chromite crystallization in a multicellular magma flow:
Evidence from a chromitite dike in the Oman ophiolite. *Lithos* **27**, 231–257.
- Leblanc M., Ceuleneer G., Al Azri H. & Jedwab, J. (1991). Concentration hydrothermale de Pd
et de Pt dans les péridotites mantellaires du complexe ophiolitique d'Oman. *Comptes*
Rendus Académie des Sciences **312**, 1007–1012.
- Legendre, O. (1982). Minéralogie et géochimie des platinoïdes dans les chromitites
ophiolitiques. Comparaison avec d'autres types de concentrations en platinoïdes.
Université Pierre et Marie Curie, Paris VI.
- Li, C., Ripley, E. M., Sarkar, A., Shin, D. & Maier, W. D. (2005). Origin of phlogopite-
orthopyroxene inclusions in chromites from the Merensky Reef of the Bushveld Complex,
South Africa. *Contributions to Mineralogy and Petrology* **150**, 119–130.

- 1
2
3 Lipin, B. R. (1993). Pressure increases, the formation of chromite seams, and the development
4 of the ultramafic series in the Stillwater Complex, Montana. *Journal of Petrology* **34**, 955–
5 976.
6
7
8
9
10 Locock, A. J. (2008). An Excel spreadsheet to recast analyses of garnet into end-member
11 components, and a synopsis of the crystal chemistry of natural silicate garnets. *Computers*
12 & *Geosciences* **34**, 1769–1780.
13
14
15
16
17 Lorand J.-P. (1988). Fe-Ni-Cu sulfides in tectonite peridotites from the Maqsad district, Sumail
18 ophiolite, southern Oman: implications for the origin of the sulfide component in the
19 oceanic upper mantle. *Tectonophysics* **151**, 57-73.
20
21
22
23
24 Lorand, J.-P. & Ceuleneer, G. (1989). Silicate and base-metal sulfide inclusions in chromites
25 from the Maqsad area (Oman ophiolite, Gulf of Oman): A model for entrapment. *Lithos*
26 **22**, 173–190.
27
28
29
30
31 Maibam, B., Foley, S., Luguet, A., Jacob, D. E., Singh, T. B., Ray, D., Panda, D. K. & Keppler,
32 R. (2017). Characterisation of chromites, chromite hosted inclusions of silicates and metal
33 alloys in chromitites from the Indo-Myanmar ophiolite belt of Northeastern India. *Ore*
34 *Geology Reviews* **90**, 260–273.
35
36
37
38
39
40 Mathez, E. A. & Kinzler, R. J. (2017). Metasomatic chromitite seams in the Bushveld and Rum
41 layered intrusions. *Elements* **13**, 397–402.
42
43
44
45 Mathez, E. A. & Webster, J. D. (2005). Partitioning behavior of chlorine and fluorine in the
46 system apatite-silicate melt-fluid. *Geochimica et Cosmochimica Acta* **69**, 1275–1286.
47
48
49 Matsukage, K. & Arai, S. (1998). Jadeite, albite and nepheline as inclusions in spinel of
50 chromitite from Hess Deep, equatorial Pacific: Their genesis and implications for
51 serpentinite diapir formation. *Contributions to Mineralogy and Petrology* **131**, 111–122.
52
53
54
55
56 McDonald, J. A. (1965). Liquid immiscibility as a factor in chromite seam formation in the
57 Bushveld igneous complex. *Economic Geology* **60**, 1674–1685.
58
59
60

- 1
2
3 McElduff, B. & Stumpfl, E. F. (1991). The chromite deposits of the Troodos complex, Cyprus-
4
5 evidence for the role of a fluid phase accompanying chromite formation. *Miner.*
6
7 *Mineralium Deposita* **26**, 307–318.
8
9
10 Meurer, W. P. & Natland, J. H. (2001). Apatite compositions from oceanic cumulates with
11
12 implications for the evolution of mid-ocean ridge magmatic systems. *Journal of*
13
14 *Volcanology and Geothermal Research*.
15
16
17 Mombro, M. (2015). Diopsidites, granites et autres lithologies exotiques associées aux grandes
18
19 zones de circulation hydrothermale dans le manteau océanique : Étude géochimique
20
21 (isotopes, traces). Université Toulouse III - Paul Sabatier.
22
23
24 Mondal, S. K. & Mathez, E. A. (2007). Origin of the UG2 chromitite layer, Bushveld Complex.
25
26 *Journal of Petrology* **48**, 495–510.
27
28
29 Monnier, C., Girardeau, J., Le Mée, L. & Polvé, M. (2006). Along-ridge petrological
30
31 segmentation of the mantle in the Oman ophiolite. *Geochemistry, Geophysics, Geosystems*
32
33 **7**.
34
35
36 Moores, E. M., & Vine, F. J. (1971). The Troodos Massif, Cyprus and other ophiolites as
37
38 oceanic crust: evaluation and implications. *Philosophical Transactions of the Royal*
39
40 *Society of London. Series A, Mathematical and Physical Sciences* **268**, 443–467.
41
42
43 Morgan, Z., Liang, Y. & Kelemen, P. (2008). Significance of the concentration gradients
44
45 associated with dunite bodies in the Josephine and Trinity ophiolites. *Geochemistry,*
46
47 *Geophysics, Geosystems*, **9**.
48
49
50 Morishita, T., Arai, S. & Tamura, A. (2003). Petrology of an apatite-rich layer in the Finero
51
52 phlogopite - peridotite, Italian Western Alps; implications for evolution of a
53
54 metasomatising agent. *Lithos* **69**, 37–49.
55
56
57 Naldrett, A. J., Wilson, A., Kinnaird, J., Yudovskaya, M., & Chunnett, G. (2012). The origin
58
59 of chromitites and related PGE mineralization in the Bushveld Complex: new
60

- 1
2
3 mineralogical and petrological constraints. *Mineralium Deposita* **47**, 209–232.
4
5 Nicolas, A. (1986). A melt extraction model based on structural studies in mantle peridotites.
6
7 *Journal of Petrology* **27**, 999–1022.
8
9
10 Nicolle, M., Jousselein, D., Reisberg, L., Bosch, D. & Stephant, A. (2016). Major and trace
11
12 element and Sr and Nd isotopic results from mantle diapirs in the Oman ophiolite:
13
14 Implications for off-axis magmatic processes. *Earth and Planetary Science Letters* **437**,
15
16 138–149.
17
18
19 Nonnotte, P., Ceuleneer, G. & Benoit, M. (2005). Genesis of andesitic–boninitic magmas at
20
21 mid-ocean ridges by melting of hydrated peridotites: geochemical evidence from DSDP
22
23 Site 334 gabbro-norites. *Earth and Planetary Science Letters* **236**, 632–653.
24
25
26 Peters, T. J. & Kramers, J. D. (1974). Chromite deposits in the ophiolite complex of northern
27
28 Oman. *Mineralium Deposita* **9**, 253–259.
29
30
31 Plissart, G., Monnier, C., Diot, H., Mărunțiu, M., Berger, J. & Triantafyllou, A. (2017).
32
33 Petrology, geochemistry and Sm-Nd analyses on the Balkan-Carpathian Ophiolite (BCO
34
35 – Romania, Serbia, Bulgaria): Remnants of a Devonian back-arc basin in the easternmost
36
37 part of the Variscan domain. *Journal of Geodynamics* **105**, 27–50.
38
39
40 Presnall, D. C. (2013). Phase Diagrams of Earth-Forming Minerals. *Mineral physics and*
41
42 *crystallography: A handbook of physical constants* **2**, 248–268.
43
44
45 Python, M. & Ceuleneer, G. (2003). Nature and distribution of dykes and related melt migration
46
47 structures in the mantle section of the Oman ophiolite. *Geochemistry, Geophysics,*
48
49 *Geosystems* **4**.
50
51
52 Python, M., Ceuleneer, G. & Arai, S. (2008). Chromian spinels in mafic-ultramafic mantle
53
54 dykes: Evidence for a two-stage melt production during the evolution of the Oman
55
56 ophiolite. *Lithos* **106**, 137–154.
57
58
59 Python, M., Ceuleneer, G., Ishida, Y., Barrat, J.-A. & Arai, S. (2007). Oman diopsidites: a new
60

- 1
2
3 lithology diagnostic of very high temperature hydrothermal circulation in mantle peridotite
4
5 below oceanic spreading centres. *Earth and Planetary Science Letters* **255**, 289–305.
6
7
8 Python, M., Yoshikawa, M., Shibata, T. & Arai, S. (2011). Diopsidites and Rodingites:
9
10 Serpentinisation and Ca-Metasomatism in the Oman Ophiolite Mantle. *Dyke Swarms:*
11
12 *Keys for Geodynamic Interpretations*. Berlin, Heidelberg: Springer Berlin Heidelberg,
13
14 401–435.
15
16
17 Quatrevaux, F. (1995). Etude pétrologique des péridotites des massifs de Maqсад et Wuqbah,
18
19 ophiolite d'Oman. Université Paris Diderot Paris 7.
20
21
22 Quick, J. E. (1981a). Petrology and petrogenesis of the Trinity Peridotite, an upper mantle diapir
23
24 in the Eastern Klamath Mountains, Northern California. *Journal of Geophysical Research:*
25
26 *Solid Earth* **86**, 11837–11863.
27
28
29 Quick, J. E. (1981b). The origin and significance of large, tabular dunite bodies in the Trinity
30
31 peridotite, northern California. *Contributions to Mineralogy and Petrology* **78**, 413–422.
32
33
34 Rabinowicz, M., Ceuleneer, G. & Nicolas, A. (1987). Melt segregation and flow in mantle
35
36 diapirs below spreading centres: evidence from the Oman ophiolite. *Journal of*
37
38 *Geophysical Research: Solid Earth* **92**, 3475–3486.
39
40
41 Rampone, E., Piccardo, G. B., Vannucci, R. & Bottazzi, P. (1997). Chemistry and origin of
42
43 trapped melts in ophiolitic peridotites. *Geochimica et Cosmochimica Acta* **61**, 4557–4569.
44
45
46 Rioux, M., Bowring, S., Kelemen, P., Gordon, S., Miller, R. & Dudás, F. (2013). Tectonic
47
48 development of the Semail ophiolite: High-precision U-Pb zircon geochronology and Sm-
49
50 Nd isotopic constraints on crustal growth and emplacement. *Journal of Geophysical*
51
52 *Research: Solid Earth* **118**, 2085–2101.
53
54
55 Rioux, M., Garber, J., Bauer, A., Bowring, S., Searle, M., Kelemen, P. & Hacker, B. (2016).
56
57 Synchronous formation of the metamorphic sole and igneous crust of the Semail ophiolite:
58
59 New constraints on the tectonic evolution during ophiolite formation from high-precision
60

- 1
2
3 U-Pb zircon geochronology. *Earth and Planetary Science Letters* **451**, 185–195.
4
5 Robinson, P. T., Trumbull, R. B., Schmitt, A., Yang, J.-S., Li, J.-W., Zhou, M.-F., Erzinger, J.,
6 Dare, S. & Xiong, F. (2015). The origin and significance of crustal minerals in ophiolitic
7 chromitites and peridotites. *Gondwana Research* **27**, 486–506.
8
9 Rollinson, H. (2005). Chromite in the mantle section of the Oman ophiolite: A new genetic
10 model. *Island Arc*, 542–550.
11
12 Rollinson, H. (2008). The geochemistry of mantle chromitites from the northern part of the
13 Oman ophiolite: inferred parental melt compositions. *Contributions to Mineralogy and*
14 *Petrology* **156**, 273–288.
15
16 Rollinson, H. & Adetunji, J. (2013). Mantle podiform chromitites do not form beneath mid-
17 ocean ridges: A case study from the Moho transition zone of the Oman ophiolite. *Lithos*
18 **177**, 314–327.
19
20 Rollinson, H., Mameri, L. & Barry, T. (2018). Polymineralic inclusions in mantle chromitites
21 from the Oman ophiolite indicate a highly magnesian parental melt. *Lithos* **310–311**, 381–
22 391.
23
24 Rospabé, M. (2018). Etude pétrologique, géochimique et structurale de la zone de transition
25 dunitique dans l’ophiolite d’Oman : Identification des processus pétrogénétiques à
26 l’interface manteau/croûte. PhD thesis, Université Paul Sabatier, Toulouse III, 628 pp.
27
28 Rospabé, M., Benoit, M., Ceuleneer, G., Hodel, F. & Kaczmarek, M.-A. (2018). Extreme
29 geochemical variability through the dunitic transition zone of the Oman ophiolite:
30 Implications for melt/fluid-rock reactions at Moho level beneath oceanic spreading
31 centers. *Geochimica et Cosmochimica Acta* **234**, 1–23.
32
33 Rospabé, M., Benoit, M., Ceuleneer, G., Kaczmarek, M.-A. & Hodel, F. (2019a). Melt
34 hybridization and metasomatism triggered by syn-magmatic faults within the Oman
35 ophiolite: A clue to understand the genesis of the dunitic mantle-crust transition zone.
36
37
38
39
40
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43
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49
50
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53
54
55
56
57
58
59
60

1
2
3 *Earth and Planetary Science Letters* **516**, 108–121.

4
5 Rospabé, M., Ceuleneer, G., Benoit, M., Abily, B. & Pinet, P. (2017). Origin of the dunitic
6
7 mantle-crust transition zone in the Oman ophiolite: The interplay between percolating
8
9 magmas and high-temperature hydrous fluids. *Geology* **45**, 471–474.

10
11 Rospabé, M., Ceuleneer, G., Benoit, M. & Kaczmarek, M.-A. (2020). Composition gradients
12
13 in silicate inclusions in chromites from the dunitic mantle-crust transition (Oman
14
15 ophiolite) reveal high temperature fluid-melt-rock interaction controlled by faulting.
16
17 *Ophioliti* **45**, 103–114.

18
19 Rospabé, M., Ceuleneer, G., Granier, N., Arai, S. & Borisova, A. Y. (2019b). Multi-scale
20
21 development of a stratiform chromite ore body at the base of the dunitic mantle-crust
22
23 transition zone (Maqsad diapir, Oman ophiolite): the role of repeated melt and fluid
24
25 influxes. *Lithos* **350**, 105235.

26
27 Sanfilippo, A., Dick, H. J. & Ohara, Y. (2013). Melt–rock reaction in the mantle: mantle
28
29 troctolites from the Parece Vela ancient back-arc spreading center. *Journal of Petrology*
30
31 **54**, 861–885.

32
33 Sanfilippo, A., Morishita, T., Kumagai, H., Nakamura, K., Okino, K., Hara, K., Tamura, A. &
34
35 Arai, S. (2015). Hybrid troctolites from mid-ocean ridges: inherited mantle in the lower
36
37 crust. *Lithos* **232**, 124–130.

38
39 Schandl, E. S., O'Hanley, D. S. & Wicks, F. J. (1989). Rodingites in serpentinized ultramafic
40
41 rocks of the Abitibi greenstone belt, Ontario. *The Canadian Mineralogist* **27**, 579–591.

42
43 Schiano, P., Clocchiatti, R., Lorand, J.-P., Massare, D., Deloule, E. & Chaussidon, M. (1997).
44
45 Primitive basaltic melts included in podiform chromites from the Oman Ophiolite. *Earth*
46
47 *and Planetary Science Letters* **146**, 489–497.

48
49 Seyler, M., Toplis, M. J., Lorand, J. P., Luguet, A. & Cannat, M. (2001). Clinopyroxene
50
51 microtextures reveal incompletely extracted melts in abyssal peridotites. *Geology* **29**, 155–
52
53
54
55
56
57
58
59
60

1
2
3 158.
4

5 Spandler, C., Mavrogenes, J. & Arculus, R. (2005). Origin of chromitites in layered intrusions:
6 Evidence from chromite-hosted melt inclusions from the Stillwater Complex. *Geology* **33**,
7 893–896.
8
9

10
11
12 Stolper, E. (1980). A phase diagram for mid-ocean ridge basalts: preliminary results and
13 implications for petrogenesis. *Contributions to Mineralogy and Petrology* **74**, 13–27.
14

15
16
17 Sun, C. & Lissenberg, C. J. (2018). Formation of fast-spreading lower oceanic crust as revealed
18 by a new Mg–REE coupled geospeedometer. *Earth and Planetary Science Letters* **487**,
19 165–178.
20
21
22

23
24 Takazawa, E., Abe, N., Seyler, M., Meurer, W. P. & Kelemen, P. B. (2007). Hybridization of
25 dunite and gabbroic materials in Hole 1271B from Mid-Atlantic Ridge 15 N: implications
26 for melt flow and reaction in the upper mantle. *Proceedings of the Ocean Drilling*
27 *Program: Scientific Results* **209**, 1–23.
28
29
30
31

32
33 Talkington, R. W., Watkinson, D. H., Whittaker, P. J. & Jones, P. C. (1984). Platinum-group
34 minerals and other solid inclusions in chromite of ophiolitic complexes: Occurrence and
35 petrological significance. *TMPM Tschermaks Mineralogische und Petrographische*
36 *Mitteilungen* **32**, 285–301.
37
38
39
40

41
42 Tamura, A., Morishita, T., Ishimaru, S., Hara, K., Sanfilippo, A., & Arai, S. (2016).
43 Compositional variations in spinel-hosted pargasite inclusions in the olivine-rich rock
44 from the oceanic crust–mantle boundary zone. *Contributions to Mineralogy and Petrology*
45 **171**, 39.
46
47
48
49

50
51 Tamura, A., Morishita, T., Ishimaru, S. & Arai, S. (2014). Geochemistry of spinel-hosted
52 amphibole inclusions in abyssal peridotite: Insight into secondary melt formation in melt-
53 peridotite reaction. *Contributions to Mineralogy and Petrology* **167**, 1–16.
54
55
56
57

58 Tippit, P. R., Pessagno, E. A. & Smewing, J. D. (1981). The Biostratigraphy of Sediments in
59
60

1
2
3 the Volcanic Unit of the Samail Ophiolite. *Journal of Geophysical Research: Solid Earth*
4
5 **86**, 2756–2762.
6

7 VanTongeren, J. A., Kelemen, P. B. & Hanghøj, K. (2008). Cooling rates in the lower crust of
8
9 the Oman ophiolite: Ca in olivine, revisited. *Earth and Planetary Science Letters* **267**, 69–
10
11 82.
12

13
14 Varfalvy, V., Hébert, R. & Bedard, J. H. (1996). Interactions between melt and upper-mantle
15
16 peridotites in the North Arm Mountain massif, Bay of Islands ophiolite, Newfoundland,
17
18 Canada: implications for the genesis of boninitic and related magmas. *Chemical Geology*
19
20 **129**, 71–90.
21
22

23
24 Wojtulek, P. M., Schulz, B., Delura, K. & Dajek, M. (2019). Formation of chromitites and
25
26 ferrogabbros in ultramafic and mafic members of the Variscan Ślęza ophiolite (SW
27
28 Poland). *Ore Geology Reviews* **106**, 97–112.
29

30
31 Yamasaki, T., Maeda, J. & Mizuta, T. (2006). Geochemical evidence in clinopyroxenes from
32
33 gabbroic sequence for two distinct magmatisms in the Oman ophiolite. *Earth and*
34
35 *Planetary Science Letters* **251**, 52–65.
36

37
38 Yao, Y., Takazawa, E., Chatterjee, S., Richard, A., Morlot, C., Créon, L., Al-Busaidi, S. &
39
40 Michibayashi, K. (2020). High resolution X-ray computed tomography and scanning
41
42 electron microscopy studies of multiphase solid inclusions in Oman podiform chromitite:
43
44 implications for post-entrapment modification. *Journal of Mineralogical and Petrological*
45
46 *Sciences* **115**, 247–260.
47

48
49 Wolff, P. E., Koepke, J. & Feig, S. (2013). The reaction mechanism of fluid-induced partial
50
51 melting of gabbro in the oceanic crust. *European Journal of Mineralogy* **25**, 279–298.
52

53
54 Zagrtdenov, N. R., Ceuleneer, G., Rospabé, M., Borisova, A. Y., Toplis, M. J., Benoit, M. &
55
56 Abily, B. (2018). Anatomy of a chromitite dyke in the mantle/crust transition zone of the
57
58 Oman ophiolite. *Lithos* **312**, 343–357.
59
60

1
2
3 Zhou, M. F., Robinson, P. T. & Bai, W. J. (1994). Formation of podiform chromitites by
4
5 melt/rock interaction in the upper mantle. *Mineralium Deposita* **29**, 98–101.

6
7
8 Zihlmann, B., Müller, S., Coggon, R. M., Koepke, J., Garbe-Schönberg, D. & Teagle, D. A.
9
10 (2018). Hydrothermal fault zones in the lower oceanic crust: An example from Wadi
11
12 Gideah, Samail ophiolite, Oman. *Lithos* **323**, 103–124.

13 14 15 16 17 **FIGURE CAPTIONS**

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19 **Figure 1:** (a) Simplified geological map of the Oman ophiolite. (b) Geological map of the
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21 Maqsad area in the Sumail massif, showing the location of the 275 dunite samples (red points)
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23 from the dunitic mantle-crust transition zone (DTZ) and of the chromitite and 9 mantle
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25 harzburgites (orange and white points) studied in this article for their chromite-hosted silicate
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27 inclusions. Are also shown the location of the main mantle and DTZ chromitite ore bodies in
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29 this area (white stars) and of minor mantle chromitites and remarkable chromite concentrations
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31 in the DTZ (e.g. seams (schlieren) and high amount of disseminated chromites in dunite,
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33 chromitite dikes; orange stars).

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40 **Figure 2:** Overview of the texture of chromite in the Maqsad DTZ dunites, from the less (a) to
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42 the more concentrated ore (h). (a, b) Scattered, disseminated chromites in dunite. (c, d)
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44 Chromite seams, or schlieren, in dunites and (e-g) antinodular texture with the chromite
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46 crystallized interstitially between olivine grains. (h) Chromitite dike including dunitic
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48 xenoliths. (i, j) Chromite-rich layers cross-cut by a later N130-oriented olivine-gabbro dike (i)
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50 and cross-cut and resorbed by a gabbroic dike/impregnation (j).

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56 **Figure 3:** Selection of photomicrographs showing an increasing amount of chromite in dunites
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58 from the Maqsad DTZ. Picture (a) illustrates that chromite is systematically located between
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3 olivine grains, frequently at grains triple junctions.
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8 **Figure 4:** Photomicrographs (reflected light) of a few examples of inclusions in disseminated
9 chromites in dunites from the Maqsad DTZ. Pictures are of samples 16OM124 (a), 15OM05
10 (b), 15OM110B (c and d), 15OM71A (e), 15OM90A (f), 16OM138 (g), 16OM124 (h) (b and
11 h modified after Rospabé *et al.*, 2017). Abbreviations are as follows: amph, amphibole; asp,
12 aspidolite; cpx, clinopyroxene; diop, diopside; gt, grossular garnet; ne, nepheline; ol, olivine;
13 opx, orthopyroxene; phl, phlogopite.
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24 **Figure 5:** Relative frequency histograms of the identified silicate minerals in inclusion in
25 disseminated chromites in 275 samples of dunites from the Maqsad DTZ. (a) Relative
26 frequency of occurrence of each mineral phase as silicate inclusions in all samples (n
27 occurrences = 524; n analyses = 1761). The relative frequency of occurrence has been
28 calculated according to the presence (1) (i.e. what we call ‘occurrence’) or absence (0) of each
29 phase in inclusion in each sample in order to determine how frequently a particular
30 mineral is encountered in the total inclusion population. For
31 example, amphibole was analysed 754 times in 185 samples, and diopside 84 times in 48
32 samples. Following this, we considered 185 occurrences of amphibole, 48 occurrences of
33 diopside, and identified in this way a total of 524 occurrences all phases included, making
34 amphibole and diopside representing 35.3 % (185/524) and 9.2 % (48/524) of the total
35 respectively. Mineral phases are ranked in descending order of their relative frequency of
36 occurrence. Abbreviations are as follows: alb, albitic feldspar; amph, amphibole; Cl-ap,
37 chlorapatite; cpx, clinopyroxene; diop, diopside; gt, garnet; jad, jadeite; ne, nepheline; ol,
38 olivine; opx, orthopyroxene; pct, pectolite; pl, plagioclase. (b) Relative frequency of occurrence
39 of the main mineral phases in inclusion in each host dunite type. (c, d) Relative frequency
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3 histograms showing the evolution of the sum of individual occurrences of olivine + plagioclase
4 + clinopyroxene on one hand, and of the sum of individual occurrences of orthopyroxene +
5 amphibole + mica (+ diopside + garnet) on the other hand, according to the host rock type in
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7 which these silicate inclusions have been identified. Note that this evolution is related to the
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12 *nature* of the interstitial minerals in host rocks only, and is entirely independent from the *modal*
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14 *content* of these interstitial minerals (i.e. all samples showing the same mineralogy were
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16 classified in the same dunite type whatever their mode).
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21 **Figure 6:** Vertical distribution of the inclusions in disseminated chromites along the Maqsad
22 DTZ in comparison with the distribution of interstitial minerals in host dunites. Note that the
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24 occurrences of each mineral are plotted vertically as a function of the altitude of sampling for
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26 all 17 cross sections merged (i.e. the massif is tilted by less than 10°). Approximate stratigraphic
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28 depths cannot be calculated as the limits between the harzburgitic mantle section and the base
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30 of the transition zone, and between the top of the transition zone and the base of the lower crust,
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32 cannot be observed or deduced precisely in some cases (e.g. the top of the DTZ
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34 eroded or affected by faults, the base of the DTZ covered by
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36 quaternary sediments). To the left are shown the altitude intervals at which outcrop the
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38 main chromitiferous levels within the DTZ, with from the base to the top the Buri and Al
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40 Juyaynah areas, the stratiform chromitite and the nodular dike (see their location in Figure 1b).
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47 Abbreviations are the same as in Figures 4 and 5.
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51 **Figure 7:** Major and minor element composition of chromites disseminated in the Maqsad DTZ
52 dunites, from one DTZ chromitite sample, and of Cr-spinels in mantle harzburgites. Are
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54 represented (a) the XCr (100 × molar Cr/(Cr + Al)) as a function of the XMg (100 × molar
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56 Mg/(Mg + Fe²⁺)) and (b) the TiO₂ content as a function of the XCr. The colour of the dots
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3 reflects the different types of host dunites depending on the nature of their interstitial minerals
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5 between olivine grains (see the legend below the two plots). Chromite in the chromitite and Cr-
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7 spinels in mantle harzburgites studied here are the big black diamonds and grey squares
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9 respectively. Compositions are compared to data from the literature for DTZ chromitites (small
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11 black diamonds) (Lorand and Ceuleneer, 1989; Leblanc and Ceuleneer, 1991; Borisova *et al.*,
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13 2012; Rollinson and Adetunji, 2013; Zagrtidenov *et al.*, 2018; Rospabé *et al.*, 2019b) and mantle
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15 harzburgites (small grey squares) (Quatrevaux, 1995; Gerbert-Gaillard, 2002; Monnier *et al.*,
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17 2006) from the Maqsad area.
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24 **Figure 8:** Major and minor element composition of amphibole inclusions in disseminated
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26 chromites in the Maqsad DTZ dunites (number of analyses $n = 754$), in one DTZ chromitite
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28 sample ($n = 2$), and in Cr-spinels in mantle harzburgites ($n = 5$). Are represented (a) the Al_2O_3
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30 and (b) TiO_2 contents as a function of the XMg ($100 \times$ molar $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$). Symbols are
31
32 the same as in Figure 7. Compositions are compared to data from the literature for amphibole
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34 inclusions in DTZ chromitites from the Maqsad area (small black diamonds) (Lorand and
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36 Ceuleneer, 1989; Leblanc and Ceuleneer, 1991; Schiano *et al.*, 1997; Borisova *et al.*, 2012;
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38 Zagrtidenov *et al.*, 2018; Rospabé *et al.*, 2019b) and for interstitial amphibole in Maqsad DTZ
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40 dunites (small white dots) (Rospabé *et al.*, 2017, 2018, 2019a).
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48 **Figure 9:** Major and minor element composition of clinopyroxene inclusions in disseminated
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50 chromites in the Maqsad DTZ dunites ($n = 593$), in one DTZ chromitite sample ($n = 1$), and in
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52 Cr-spinel in one mantle harzburgite ($n = 1$). Are represented (a) the Al_2O_3 and (b) TiO_2 contents
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54 as a function of the XMg ($100 \times$ molar $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$). Symbols are the same as in Figure 7.
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56 Compositions are compared to data from the literature for clinopyroxene inclusions in DTZ
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58 chromitites from the Maqsad area (small black diamonds) (Lorand and Ceuleneer, 1989;
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3 Leblanc and Ceuleneer, 1991; Borisova *et al.*, 2012; Rospabé *et al.*, 2019b) and for interstitial
4 clinopyroxene in Maqsad DTZ dunites (small white dots) (Rospabé *et al.*, 2017, 2018, 2019a).
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10 **Figure 10:** Major and minor element composition of diopside inclusions in disseminated
11 chromites in the Maqsad DTZ dunites ($n = 84$). Are represented (a) the Al_2O_3 and (b) TiO_2
12 contents as a function of the XMg ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}^{2+})$). Symbols are the same as in
13 Figure 7. Compositions are compared to data from the literature for interstitial diopside in
14 Maqsad DTZ dunites (small white dots) (Rospabé *et al.*, 2017, 2018, 2019a) and for
15 hydrothermal diopside in diopsidites and rodingites from the Oman ophiolite (black stars)
16 (Python *et al.*, 2007, 2011).
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28 **Figure 11:** Major and minor element composition of mica inclusions in disseminated chromites
29 in the Maqsad DTZ dunites ($n = 119$), in one DTZ chromitite sample ($n = 7$) and in Cr-spinel
30 in one mantle harzburgite ($n = 1$). Are represented (a) the K_2O content as a function of the Na_2O
31 content and (b) the TiO_2 content as a function of the XMg ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}^{2+})$).
32 Symbols are the same as in Figure 7. The black lines in panel (a) represent constant XNa ratio
33 ($100 \times \text{molar Na}/(\text{Na} + \text{K})$) values (in mol %). Compositions are compared to data from the
34 literature for mica inclusions in other DTZ chromitites from the Maqsad area (small black
35 diamonds) (Lorand and Ceuleneer, 1989; Schiano *et al.*, 1997; Borisova *et al.*, 2012; Rospabé
36 *et al.*, 2019b).
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52 **Figure 12:** Major and minor element composition of olivine, orthopyroxene and garnet
53 inclusions in disseminated chromites in the Maqsad DTZ dunites ($n_{\text{ol}} = 50$, $n_{\text{opx}} = 63$, $n_{\text{gt}} = 39$),
54 in one DTZ chromitite sample ($n_{\text{ol}} = 5$), and Cr-spinels in mantle harzburgites ($n_{\text{ol}} = 6$, $n_{\text{opx}} =$
55 5). Are represented (a) the NiO content as a function of Fo ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}_{\text{total}})$) in
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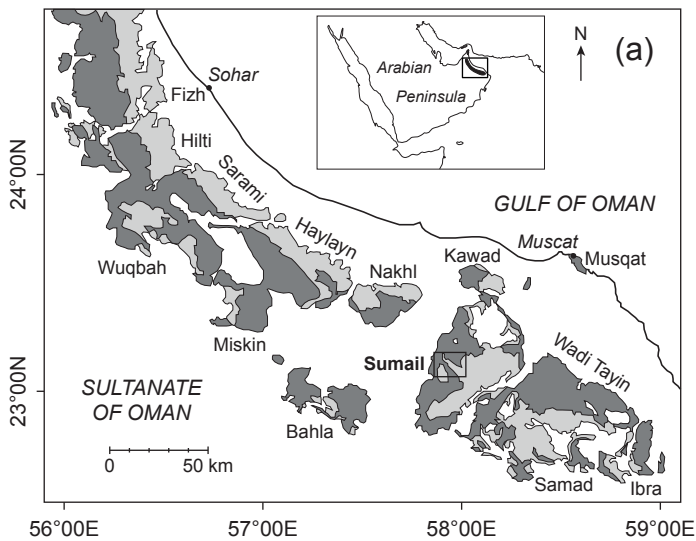
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3 olivine, (b) the TiO_2 content as a function of the XMg ($100 \times$ molar $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$) in
4 orthopyroxene and (c) the TiO_2 content as a function of the SiO_2 content in garnet. Symbols are
5 the same as in Figure 7. In panel (a) the composition of olivine inclusions in disseminated
6 chromites in dunites is compared to the one of olivine from nuclei around which grown the
7 chromite nodules forming the nodular dike (small black diamonds) (Zagrtdenov *et al.*, 2018),
8 and to olivine constituting most of the matrix of host dunites (small white dots) (Rospabé *et al.*,
9 2018, 2019a). In panel (b) the composition of orthopyroxene inclusions in disseminated
10 chromites is compared to data from the literature for DTZ chromitites (small black diamonds)
11 (Lorand and Ceuleneer, 1989; Borisova *et al.*, 2012; Rospabé *et al.*, 2019b), for interstitial
12 orthopyroxene in DTZ dunites (small white dots) (Rospabé *et al.*, 2017, 2018, 2019a), and for
13 residual orthopyroxene in mantle harzburgites (small grey squares) (Quatrevaux, 1995;
14 Gerbert-Gaillard, 2002; Monnier *et al.*, 2006; Nicolle *et al.*, 2016) from the Maqsad area. In
15 panel (c) the composition of garnet inclusions in disseminated chromites is compared to the one
16 of garnet inclusions from the nodular dike (Zagrtdenov *et al.*, 2018) and the stratiform
17 chromitite (Rospabé *et al.*, 2019b) (small black diamonds), and of the one of interstitial garnet
18 in the Maqsad DTZ dunites (small white dots) (Rospabé *et al.*, 2017).

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42 **Figure 13:** Vertical evolution of the composition of disseminated chromites and amphibole
43 inclusions along the Maqsad DTZ, plotted as a function of the altitude of sampling. Data are
44 plotted all together, without distinction between the 17 cross-sections sampled in the frame of
45 this study. Are represented (a) the XMg ($100 \times$ molar $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$), XCr ($100 \times$ molar
46 $\text{Cr}/(\text{Cr} + \text{Al})$) and TiO_2 content in chromite and (b) the XMg ($100 \times$ molar $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$),
47 TiO_2 , Na_2O and F contents in amphibole. Symbols are the same as in Figure 7. The vertical
48 evolution of the composition of other silicates inclusions are provided in Electronic Appendix
49 2, and these variations are also shown separately according to the different types of host dunites.
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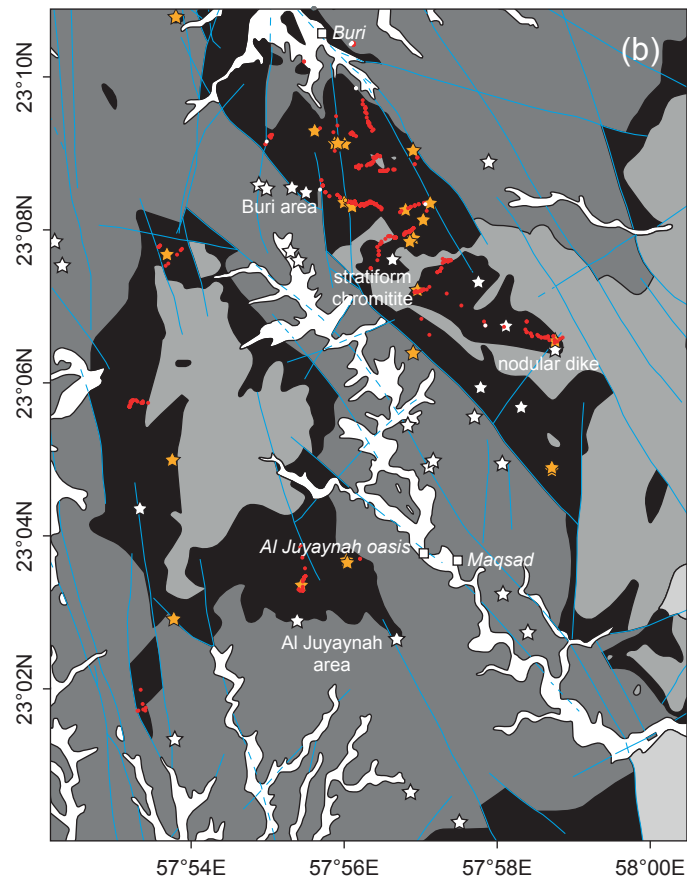
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5 **ELECTRONIC SUPPLEMENTS**
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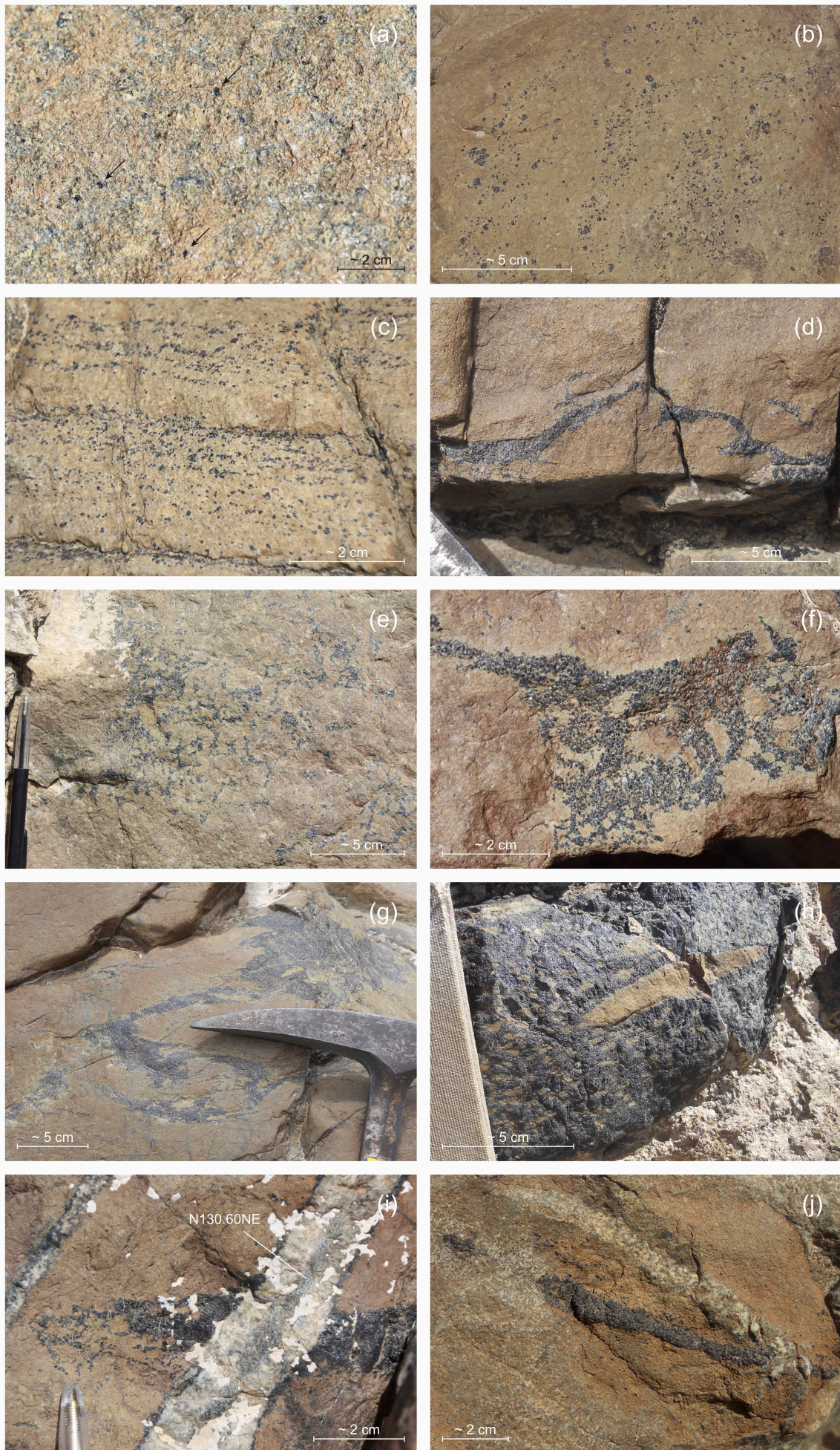
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8 **Electronic supplement 1:** Major element composition of the studied silicate inclusions and of
9
10 their host chromites
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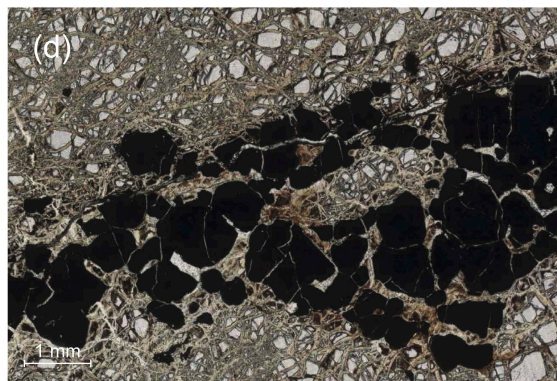
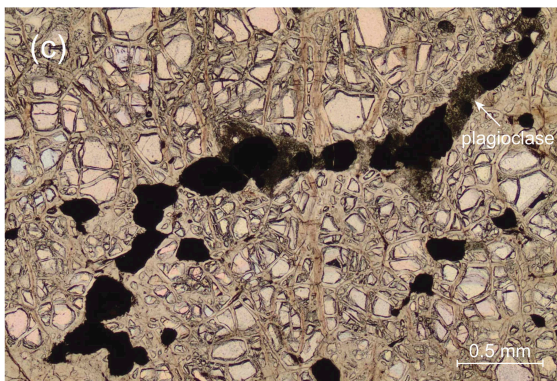
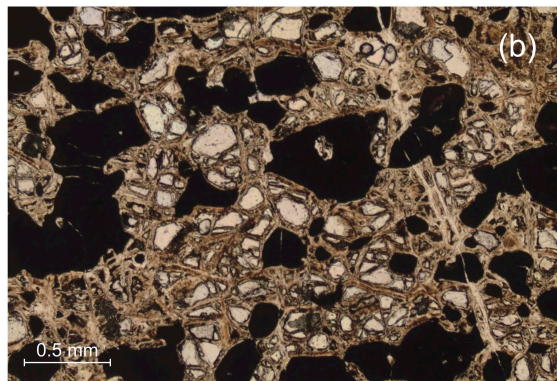
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14 **Electronic supplement 2:** Extended description of the major element mineral compositions
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16 (with extended versions of Figures 7, 8, 9, 10, 11, 12 and 13).
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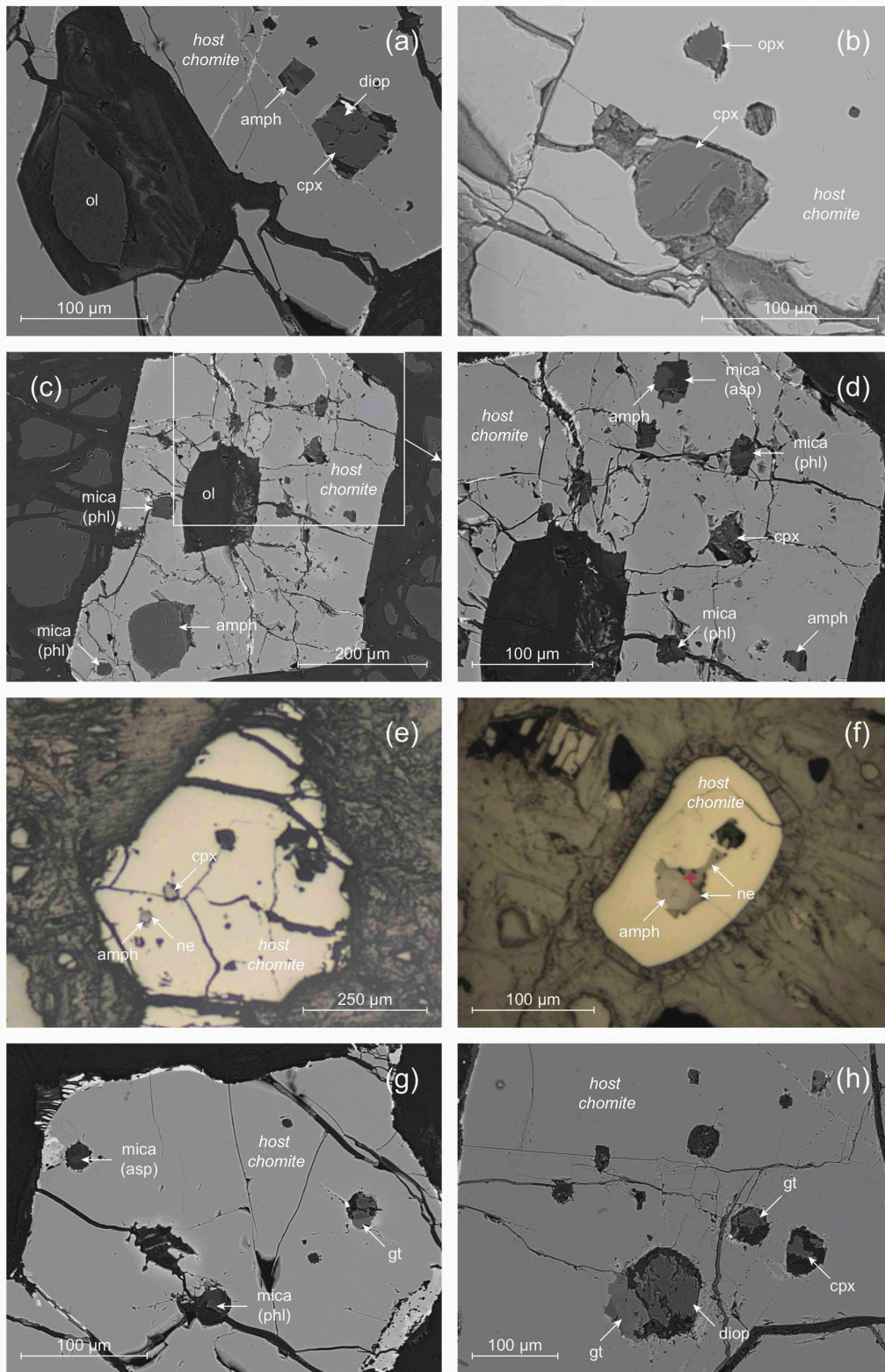
- Crustal units
- Lower crustal layered cumulates
- Dunitic transition zone (DTZ)
- Mantle harzburgites
- ☆ Main chromitite occurrences
- ★ Minor chromitite occurrences (schlieren, dikes)
- DTZ dunites samples
- DTZ chromitite sample
- mantle harzburgites samples
- faults

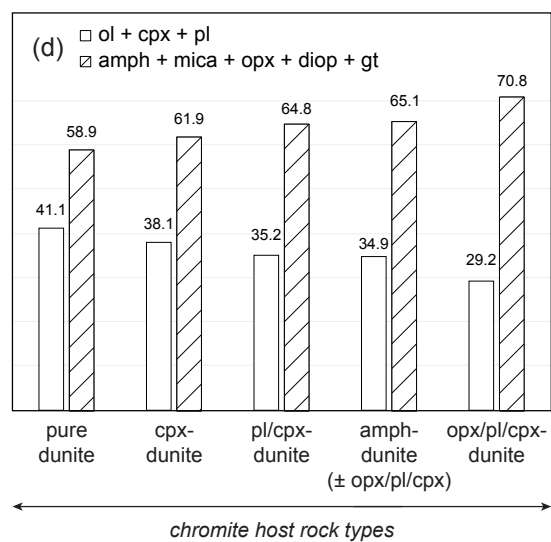
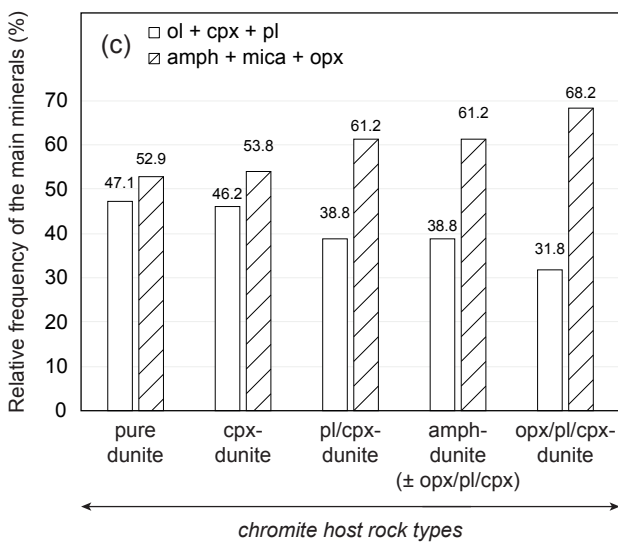
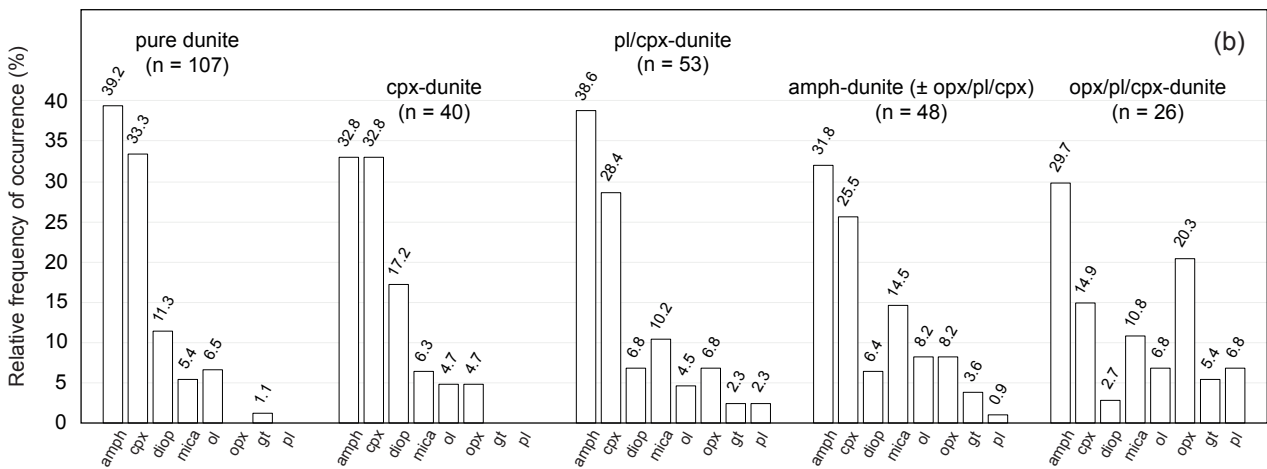
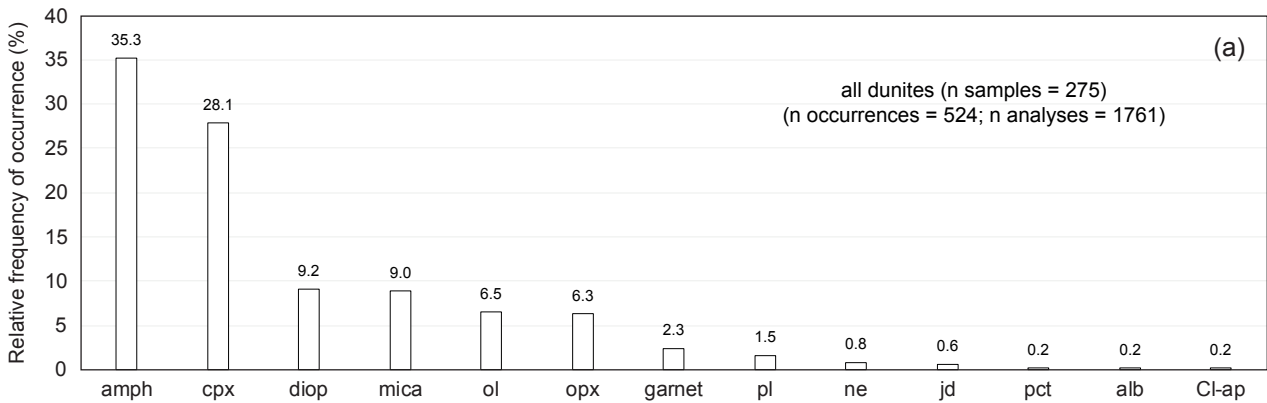




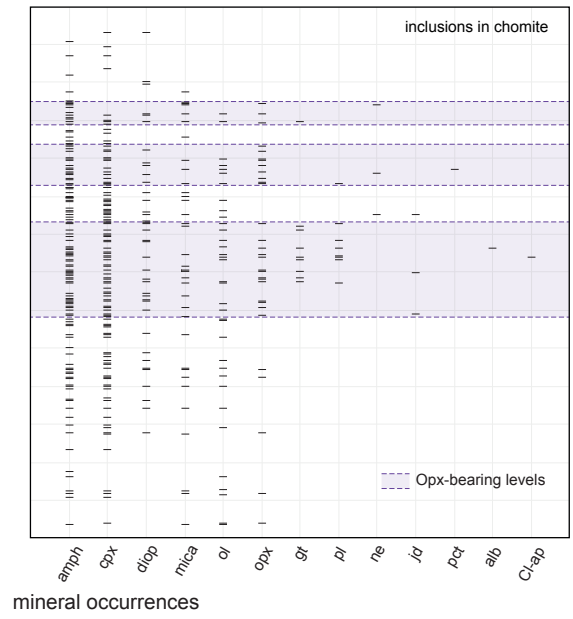
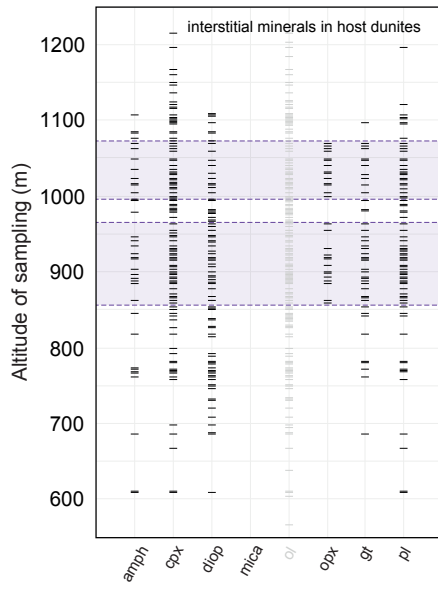
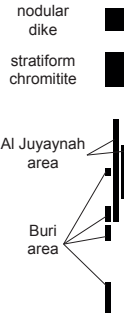


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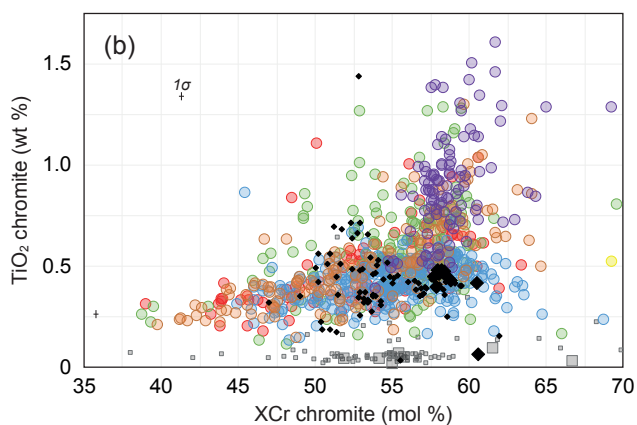
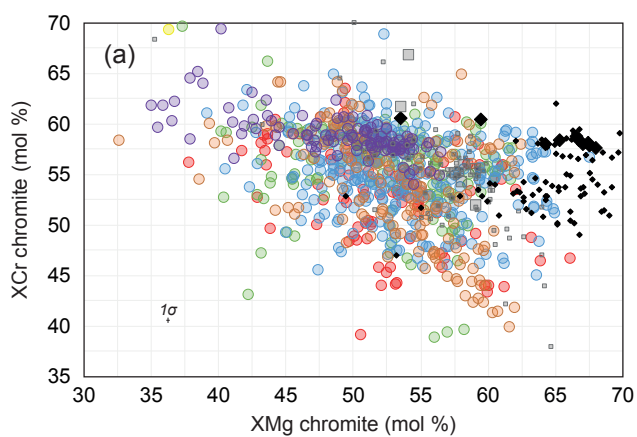




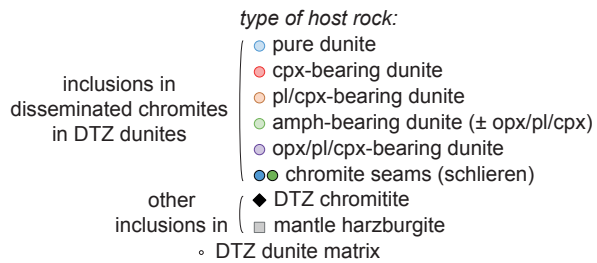
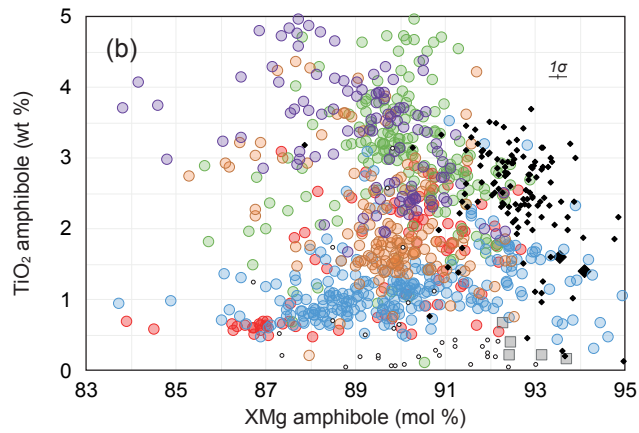
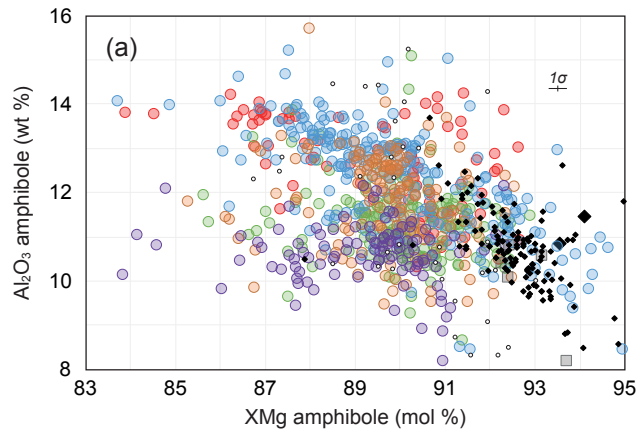
Main chromitite ore bodies in the Maqсад DTZ

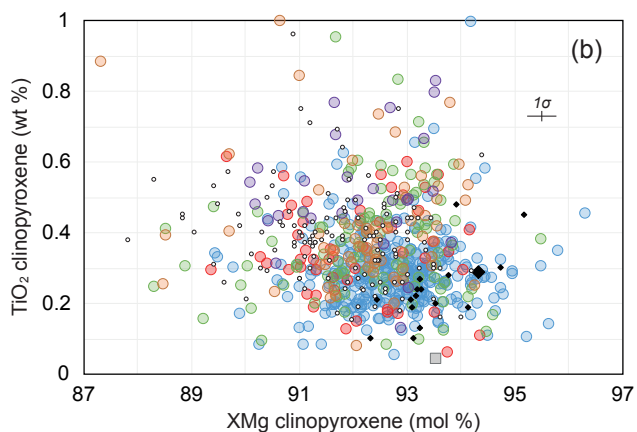
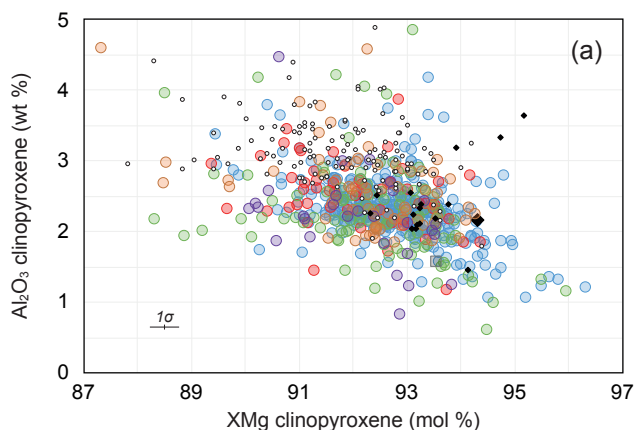


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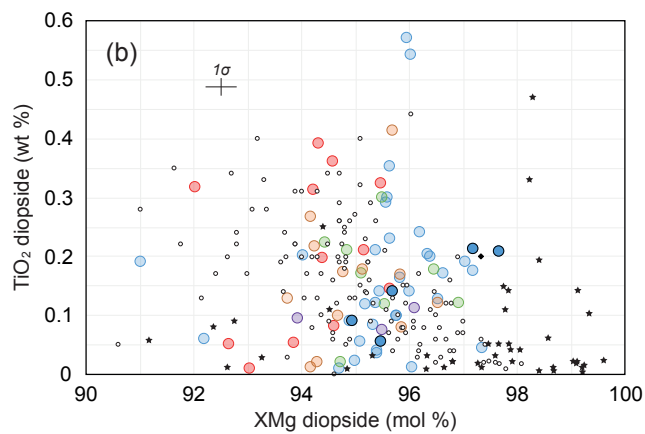
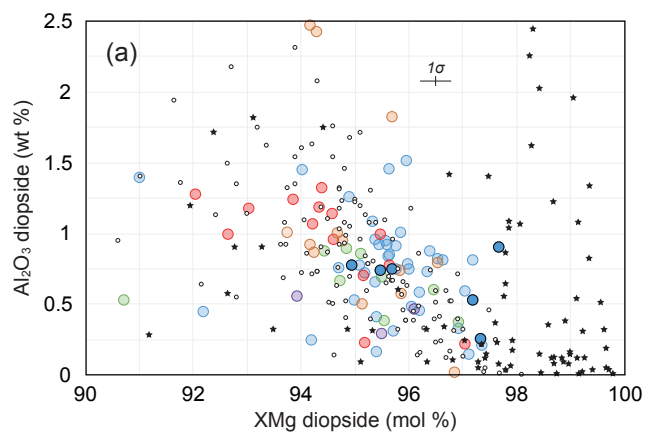


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- type of host rock:
- pure dunite
 - cpx-bearing dunite
 - pl-bearing dunite
 - pl/cpx-bearing dunite
 - amph-bearing dunite (± opx/pl/cpx)
 - opx/pl/cpx-bearing dunite
 - chromite seams (schlieren)
 - ◆ DTZ chromite
 - mantle harzburgite
- disseminated chromites in DTZ dunites





- type of host rock:*
- pure dunite
 - cpx-bearing dunite
 - pl/cpx-bearing dunite
 - amph-bearing dunite (\pm opx/pl/cpx)
 - opx/pl/cpx-bearing dunite
 - chromite seams (schlieren)
- inclusions in disseminated chromites in DTZ dunites
- ◆ DTZ chromitite
 - mantle harzburgite
- other inclusions in DTZ dunite matrix
- DTZ dunite matrix

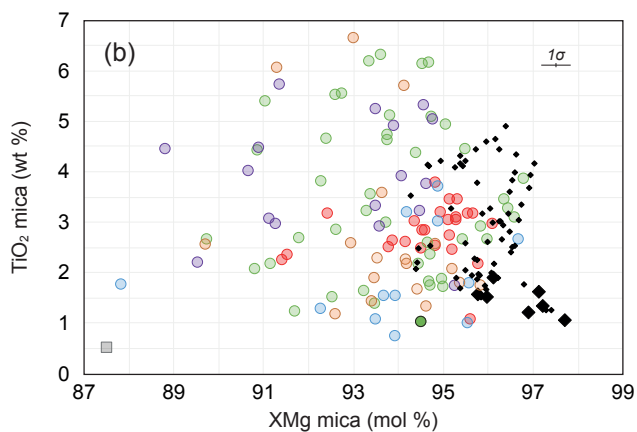
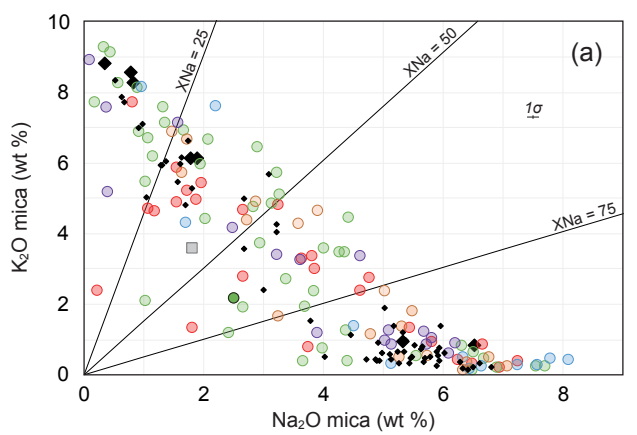


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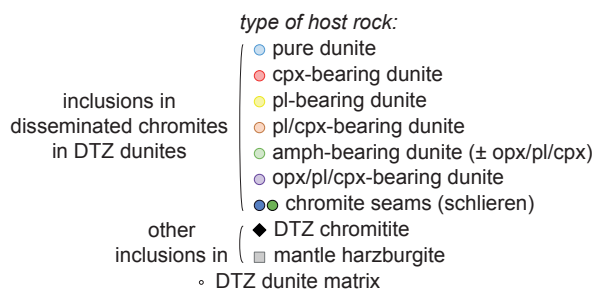
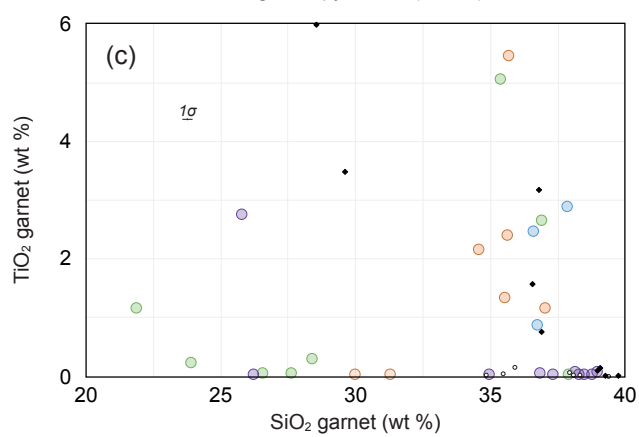
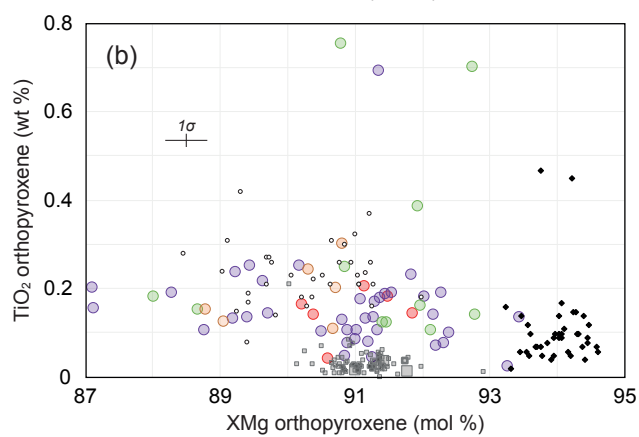
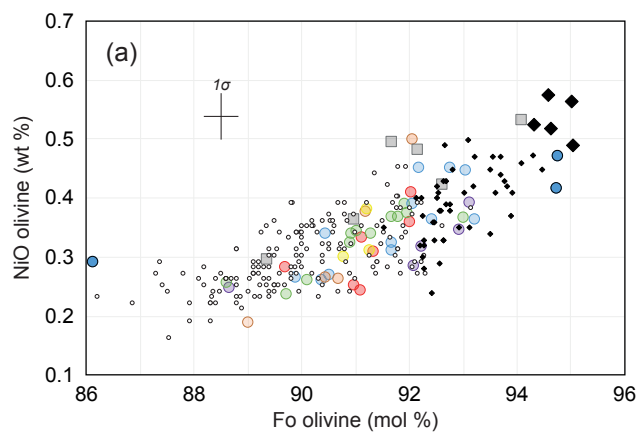
type of host rock:

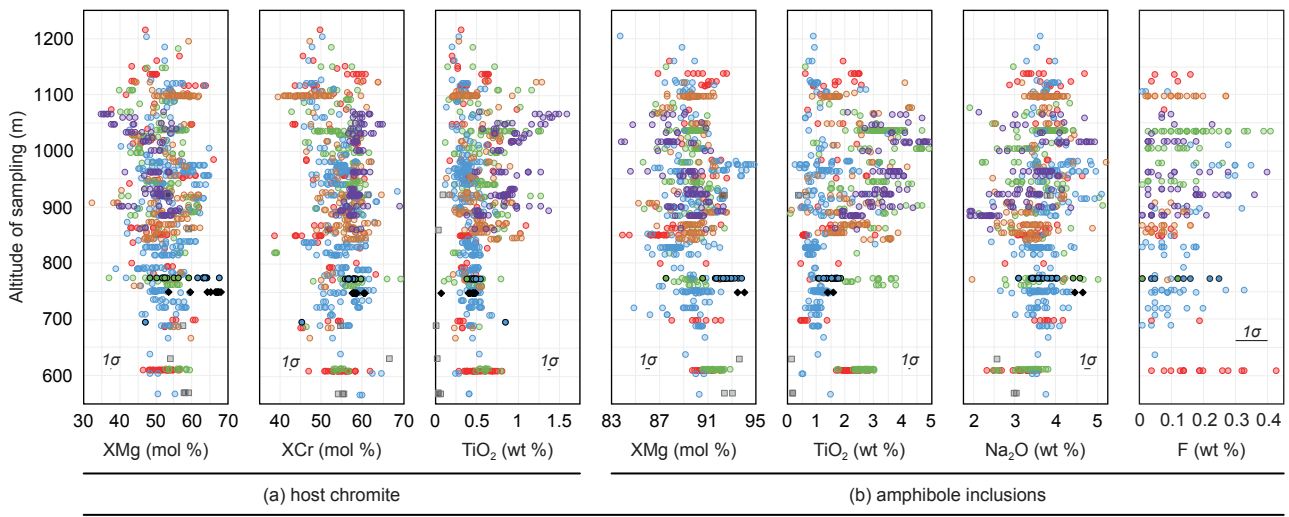
- pure dunite
- cpx-bearing dunite
- pl/cpx-bearing dunite
- amph-bearing dunite (± opx/pl/cpx)
- opx/pl/cpx-bearing dunite
- chromite seams (schlieren)
- DTZ dunite matrix
- * diopside/rodingite diopside

inclusions in disseminated chromites in DTZ dunites



- type of host rock:
- pure dunite
 - cpx-bearing dunite
 - pl/cpx-bearing dunite
 - amph-bearing dunite (± opx/pl/cpx)
 - opx/pl/cpx-bearing dunite
 - chromite seams (schlieren)
 - ◆ DTZ chromitite
 - mantle harzburgite
- inclusions in disseminated chromites in DTZ dunites
- other inclusions in





type of host rock:

● pure dunite	● pl-bearing dunite	● amph-bearing dunite (± opx/pl/cpx)	● chromite seams (schlieren)
● cpx-bearing dunite	● pl/cpx-bearing dunite	● opx/pl/cpx-bearing dunite	◆ DTZ chromitite
			■ mantle harzburgite

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