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# Nature and origin of heterogeneities in the lithospheric mantle in the context of asthenospheric upwelling and mantle wedge zones: What do mantle xenoliths tell us?

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## Abstract

The present contribution synthetizes the main petrographic, mineralogical and chemical features of mantle xenoliths uplifted by Phanerozoic lavas. The collections of mantle xenoliths predominantly consist of peridotites but minor pyroxenites are commonly associated. Two main petrogenetic processes are responsible for the features of mantle xenoliths: partial melting and melts/fluids circulation and associated metasomatic and magmatic processes. Partial melting processes lead to the formation of residual pieces of upper mantle while two main types of mantle metasomatism could be recognized such as LILE enrichment, the first referring to Asthenosphere Upwelling Settings (essentially mantle plumes, rifting zones and asthenosphere window zones) and the second to Mantle Wedge Settings. The AUS metasomatism is essentially related to the migration of more or less CO<sub>2</sub>-rich alkaline silicate melts and associated fluids while the MWZ metasomatism is associated with the activity of hydrated liquids (fluids) commonly SiO<sub>2</sub>-rich.

## 1- Introduction

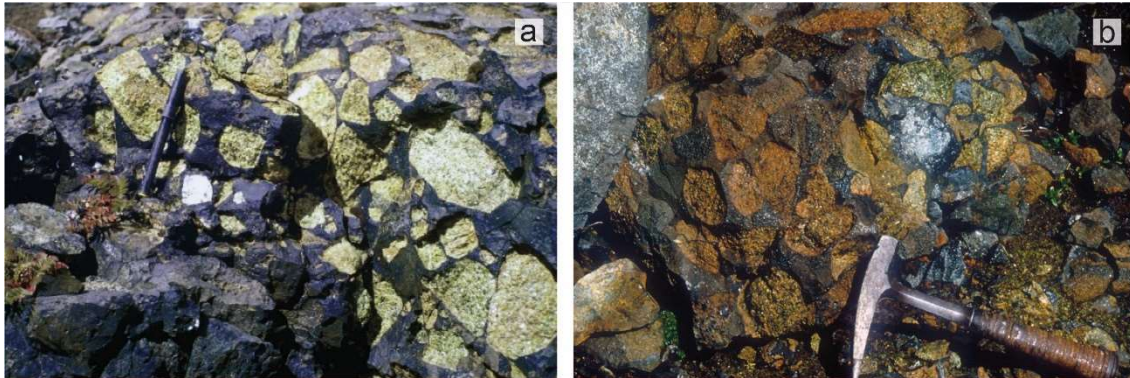
Earth's mantle rock samples almost exclusively come from a depth of less than 200-250 km with the exception of very rare inclusions in diamonds indicating the occurrence of majorite, calcium- and magnesium-perovskite, ringwoodite and ferropericlaes (all coming from more than 400 km depth; e.g. Harte and Harris, 1994; Collerson et al., 2000; Pearson et al., 2014; Seitz et al., 2018). Therefore, mantle rock samples does not allow to assess the nature and evolution of the Earth's mantle heterogeneities at a global scale. However, they provide very important constraints on mantle heterogeneities at the lithospheric scale, particularly in settings such as mid-oceanic ridges, intraplate rifting zones, supra-subduction zones, passive continental margins and cratonic roots (e.g. McInnes et al., 2001; Grégoire et al., 2003; Python and Ceuleneer, 2003; Grégoire et al., 2009; O'Reilly and Griffin, 2013; Tilhac et al., 2017).

The study of the lithospheric upper mantle based on petrological, geochemical and/or petrophysical studies of mantle rocks constitute a complementary approach to those of the geophysics, experiments and modelling. There are four types of occurrences where mantle rock samples could be found: mantle sections of ophiolites, peridotite orogenic massifs, abyssal mantle domains and pyroxenite and peridotite mantle xenoliths in basic lavas. Mantle rocks provide strong insights on the origin and evolution of the lithospheric mantle and in particular on the petrogenetic processes that have affected the upper mantle through geological time in various geodynamic settings.

The present contribution focuses only on mantle xenoliths uplifted by Phanerozoic lavas (Figure1). Similar studies on the other types of occurrences including xenoliths uplifted by kimberlites and related rocks are also crucial for our understanding of the upper mantle composition and evolution. The present study aims at synthesizing the main petrographic, mineralogical and chemical features of the phanerozoic lithospheric mantle-derived peridotite xenoliths. Two main petrogenetic processes are responsible for those features: partial melting and melts/fluids circulation and associated metasomatic and magmatic processes. We also briefly summarize the knowledge on the nature and origin of mantle pyroxenites which are,

1 although minor in terms of abundance, very important for understanding the history of  
2 the Earth's mantle.

3



4

5 Figure 1: Mantle xenoliths in two basanitic dykes (emplaced a few million years ago) from Kerguelen  
6 Archipelago. The scale is given by the pencil (a) and the hammer (b).

## 7 **2- Mantle processes recorded in peridotite xenoliths**

### 8 **2.1- Partial melting**

9

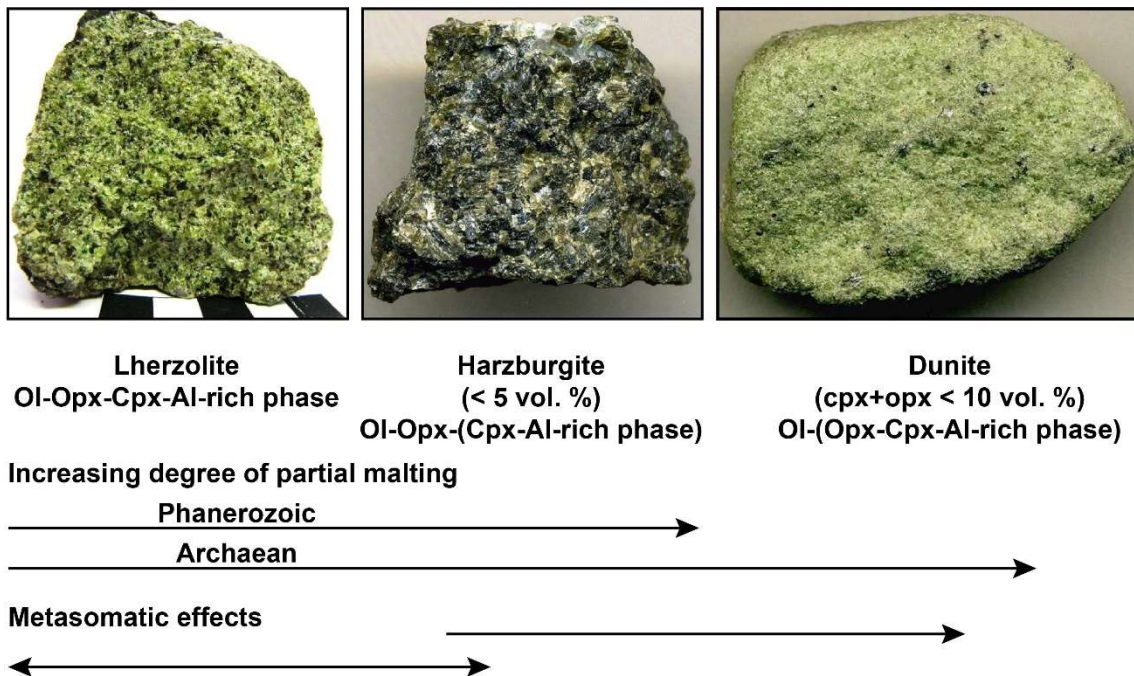
10 Mantle peridotites defined as lherzolites, harzburgites, and dunites form by far the  
11 largest volume of the lithosphere, while wehrlites are rarer. They mostly consist of three  
12 main mineral phases; olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx)  
13 associated to a minor Al-rich phase being plagioclase (Pl), spinel (Spl) or garnet (Gt)  
14 depending on equilibration depth (e.g. Wyllie, 1981; Gasparik, 1984; Klemme, 2004).  
15 Olivine and the two pyroxenes being the most abundant minerals, the classification of  
16 peridotites is based on their modal abundance (Streckeisen, 1976).

17 Under normal geothermal conditions, the upper mantle does not undergo partial  
18 melting. However, there are a number of geodynamic cases where anomalous thermal  
19 regimes exceed the solidus of peridotite, leading to local or regional partial melting of  
20 the upper mantle. Such abnormal thermal regimes are, for instance, encountered in  
21 mantle plume settings where the temperature of the plume material is hotter than the  
22 surrounding asthenosphere (Farnetani, this volume). At mid oceanic ridge settings this  
23 situation occurs in response to the adiabatic decompression of the asthenosphere and  
24 in subduction settings the abnormal thermal regime is due to the influx of fluids/melts  
25 which percolate into the mantle wedge above.

1 In all the geodynamic settings described above, peridotites undergo partial melting. All  
2 the different constituent mineral phases taken alone have different melting  
3 temperatures, the lowest being for the Al-rich mineral phases (Pl, Spl, Gt) and then the  
4 clinopyroxene, the orthopyroxene and finally the olivine. The petrological experiments  
5 conducted to reproduce peridotite partial melting (cf Hirschmann et al., 1998; Bernstein  
6 et al., 2007) indicate that melting reactions involve an assemblage of dominant  
7 clinopyroxene, Al-rich mineral phase and orthopyroxene or olivine depending on  
8 pressure. At low and medium pressure in the spinel stability field (from  $\approx 1$  to 1.7-2  
9 GPa), olivine crystallizes as a product of the melting reaction  $[Opx+Cpx+Spl \rightarrow$   
10  $Ol+Melt$ ; Niu, 1997] hence the olivine modal content of the peridotite residue increases.  
11 At higher pressures in the garnet stability field ( $> 1.7-2$  GPa), orthopyroxene  
12 crystallizes in the residue of melting  $[Ol+Cpx+Gt \rightarrow Opx+Melt$ ; Walter, 1998] hence the  
13 orthopyroxene content increases. Such studies also demonstrate that the eutectic  
14 composition of a melt formed by partial melting of peridotite depends on the  
15 composition of the latter before melting, on pressure, on temperature, on fluid contents  
16 ( $H_2O$ ,  $CO_2$ ) and on degree of melting. Therefore, an extreme diversity of melt  
17 compositions can be generated from mantle peridotite melting. For example, the partial  
18 melting of a mantle lherzolite will first lead to the exhaustion of the Al-rich phase  
19 depending on pressure (plagioclase, spinel or garnet) and then of the clinopyroxenes  
20 and if the degree of melting is high enough, a harzburgite will form if the cpx content  
21 drops to less than 5% and finally a dunite will form if the sum  $opx+cpx$  is less than 10%  
22 (Figure 2). To have the clinopyroxene disappeared from the melting peridotite, the  
23 degree of melting needs to be above around 20 %, (e.g. Baker and Stolper, 1994;  
24 Hirschmann et al., 1998). On the other hand, to form a dunite by partial melting of a  
25 lherzolite, the degree of melting has to reach a very high degree such as 40-50%  
26 melting (Bernstein et al., 2007) and therefore this situation is probably limited only to  
27 Archean mantle melting processes only (Bernstein et al., 2007).

28 As the mineralogy changes during increasing partial melting, the geochemical  
29 compositions of peridotites (major, minor and trace elements) also vary. While the  
30 residue becomes more and more magnesian leading to high Mg#, its  $CaO$ ,  $Al_2O_3$ ,  
31  $FeO_t$ ,  $TiO_2$ ,  $Na_2O$  and  $K_2O$  contents strongly decrease in the whole peridotite and  
32 constituent mineral phases. Minor and trace elements are also strongly affected by  
33 melting processes. Incompatible trace elements such as LILE, REE and HFSE tend to

1 concentrate in the newly formed melt during peridotite melting while minor and trace  
 2 elements of the transition group especially Ni, Co and Cr behave as compatible trace  
 3 elements and tend to concentrate in the residue of melting (e.g. Norman, 1998, Simon  
 4 et al., 2008).



6 Figure 2: Types of mantle peridotite (lherzolite, harzburgite, dunite) and their  
 7 relationship with partial melting and mantle metasomatism.

8  
 9 **2.2 - Percolation of melts/fluids in the lithosphere associated metasomatism**

10 It is (very) rare to find mantle peridotite xenoliths that have been affected only  
 11 by partial melting processes and the majority of them have been affected by two main  
 12 processes: an early partial melting and subsequent metasomatic processes. Each of  
 13 those processes may affect the rock multiple times. The commonly used definition of  
 14 mantle metasomatism point it as physical and chemical processes that are  
 15 implemented during the flow (both pervasive at grain boundaries and focused in dykes  
 16 or veins) of magma and/or fluids within the upper mantle. The main changes that affect  
 17 the mantle wall rocks (peridotites) are in microstructure, recrystallization, the possible  
 18 formation of new minerals (and disappearance of pristine ones) and the chemical  
 19 exchanges leading to the enrichment in incompatible trace elements of the mantle  
 20 peridotites. In some cases, metasomatism at large melt/rock ratio can induce the

1 formation of a new rock such as for example the transformation of harzburgite into  
2 dunite (e.g. Kelemen, 1990; Grégoire et al., 2000a) or also the formation of pyroxenites  
3 from peridotites (e.g. Liu et al., 2020).

4 Depending on the geochemical and mineralogical changes they cause, three main  
5 types of metasomatism have been distinguished over the years:

6 1- Cryptic metasomatism

7 2- Modal metasomatism

8 3- Stealth metasomatism

9 Cryptic metasomatism (Dawson, 1984) triggers only chemical modification of the  
10 mantle peridotite and of its constituent minerals without crystallization of new mineral  
11 phases. The main geochemical modifications concern the abundance of trace  
12 elements which are often associated with a decrease (or increase) of the Mg# and an  
13 increase in other basaltic components (e.g. Na<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>) of the whole rock and  
14 minerals (e.g. Xu et al., 2000).

15 Modal metasomatism (Harte, 1983) describes the formation of new mineral phases  
16 different from the original four phases constituting a mantle peridotite, i.e. olivine,  
17 orthopyroxene, clinopyroxene and an Al-rich phase (spinel or garnet or plagioclase)  
18 associated with geochemical modifications such as described for cryptic  
19 metasomatism. As for cryptic metasomatism, the Mg# and other basaltic components  
20 (e.g. Na<sub>2</sub>O, TiO<sub>2</sub>) of the whole rock and mineral will also vary, possibly in greater ways  
21 than for cryptic metasomatism. The most classical metasomatic phases are amphibole  
22 and phlogopite. Detailed information is given further (see table 1).

23 A third type of metasomatism was introduced more recently by O'Reilly and Griffin  
24 (2013) as the stealth metasomatism. It involves the addition of new mineral phases  
25 (e.g. garnet and/or clinopyroxene) to the mantle rock, but might be a "misleading"  
26 metasomatic process since it adds similar mineral phases to those forming the original  
27 mantle peridotite mineral association.

<b>ASTHENOSPHERIC UPWELLING ZONES (AUZ)</b>	<b>MANTLE WEDGE ZONES (MWZ)</b>
<b>Secondary Mineralogy</b> Cpx-Phl-Amp-Fsp-Pl-Ol-Spl-Rt-Ap-Ilm-Arm-Cb-Gl-Su	<b>Secondary Mineralogy</b> Opx-Amp-Cpx-Ol-Phl-Spl-Su-Mag
<b>Geochemistry</b> Major elements - Cpx: Common enrichment in Cr-Na, sometimes only Na or Na- Ti - Amphibole mostly more sodic, lower in Si for a given mg# than those from MWZ metasomatism	<b>Geochemistry</b> Major elements - Opx2 and cpx2 poorer in Al than cpx1 et opx1 - Phlogopite low in Ti - Amphibole mostly less sodic but richer in Si for a given mg# than those from AUZ metasomatism
<b>Trace elements</b> U/ThWallRock variable (commonly U/Th<1) Amphibole and phlogopite are Nb- and Ta-rich	<b>Trace elements</b> U/ThWR high >>1 Amphibole and phlogopite are Nb- and Ta-poor

1

2 Table 1 : Main differences between the two types of mantle metasomatism presented in this study  
3 (mineral abbreviations after Whitney and Evans, 2010 and Gl for glass and Su for sulfide). Cpx:  
4 Clinopyroxene; Opx: Orthopyroxene; Ol: Olivine; Pl: Plagioclase; Spl: Spinel; Phl: Phlogopite; Fsp:  
5 Feldspar; Rt: Rutile; Ap: Apatite; Ilm: Ilmenite; Arm: Armalcolite; Cb: Carbonate; Gl: Glass; Su: Sulfide;  
6 Mag: Magnetite. Cpx1 and 2 and Opx1 and 2 refer to primary Cpx and Opx (1) and metasomatic Cpx  
7 and Opx (2), respectively.

8

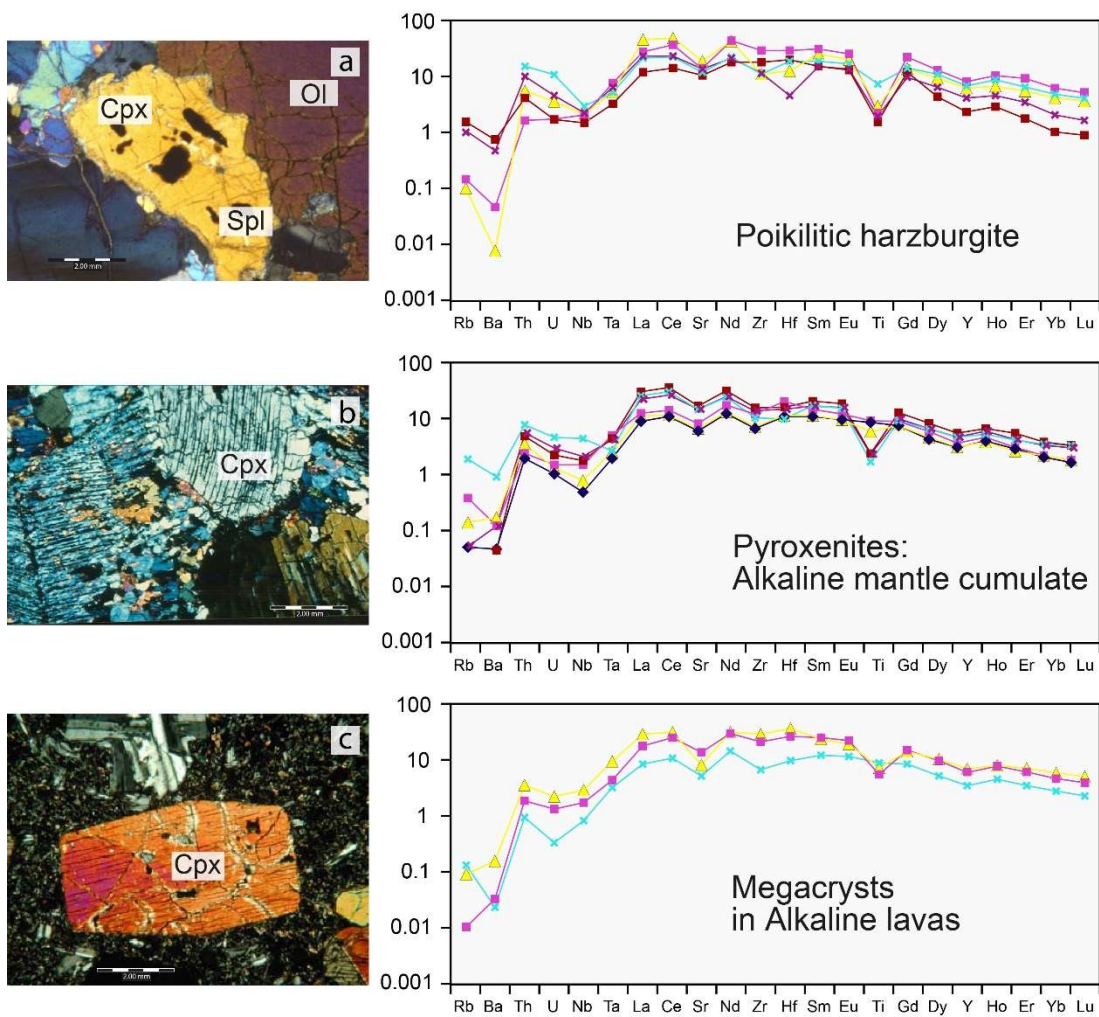
### 9 **3 - Main metasomatic imprints within the phanerozoic upper mantle:**

10 Mantle metasomatism, depending on the original melt/fluid composition and volume as  
11 well as on the duration of the metasomatic event, will result in an increase/decrease in  
12 major and trace elements of the whole-rock and minerals. The nature of metasomatic  
13 mantle melts/fluids may be determined from the changes in the geochemical  
14 compositions of mantle minerals but also from the composition of fluid inclusions in  
15 minerals. The study of fluid inclusions in mantle peridotites (e.g. Schiano et al., 1994;  
16 Hildas et al., 2010; Créon et al., 2017) helps constraining the composition of the fluid  
17 phase associated with metasomatism (H<sub>2</sub>O, CO<sub>2</sub>, ...) and can also provide  
18 temperature constraints at which the fluid inclusions were trapped. A traditional way  
19 for estimating a theoretical composition of the metasomatic agent is to use the trace  
20 element compositions of mineral phases (commonly cpx) and a set of appropriate  
21 partition coefficients between melt or fluid and mineral to calculate a theoretical  
22 composition of the metasomatic agent (e.g. Grégoire et al., 2000a). In some cases,  
23 such as mantle xenoliths from the Kerguelen Islands, it is possible to compare the  
24 composition of the metasomatic clinopyroxenes with those of clinopyroxenes occurring  
25 in deep-seated alkaline pyroxenite segregates and clinopyroxene megacrysts



1 occurring in young alkaline lavas (Figure 3). Metasomatic melts(fluids) in off-craton  
 2 (mostly phanerozoic) regions cover a vast spectrum from silicate to carbonate magmas  
 3 containing variable types and abundances of dissolved fluids and solutes including  
 4 brines, C-O-H species and sulfur-bearing components (O'Reilly and Griffin, 2013). It is  
 5 nevertheless possible to discriminate between two main types of metasomatic agents,  
 6 the first referring to asthenospheric upwelling settings (essentially mantle plumes,  
 7 rifting zones and asthenospheric window zones) and the second to mantle wedge  
 8 settings.

9



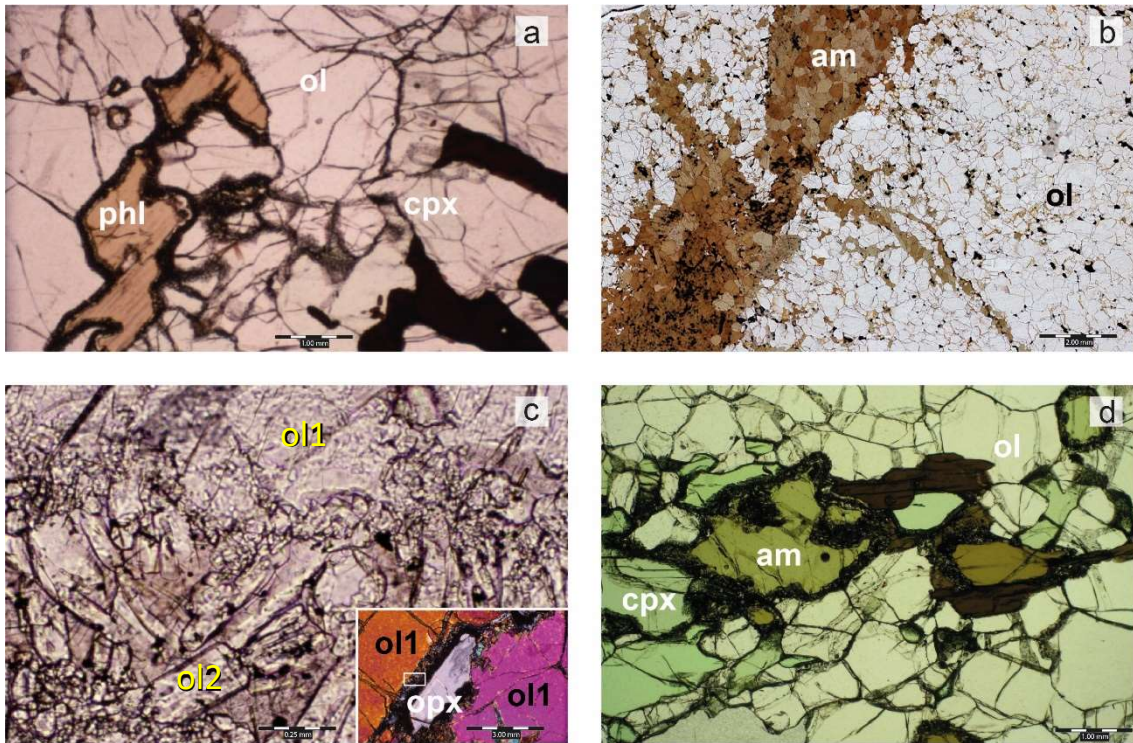
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11 Figure 3: Comparison between primitive mantle-normalised (McDonough and Sun, 1995) trace element  
 12 patterns of clinopyroxene from a poikilitic mantle harzburgite (a), an alkaline deep pyroxenite cumulate  
 13 (b) and occurring as megacryst in an alkaline basaltic lava (c) from the Kerguelen Islands. The three  
 14 types of patterns are similar, indicating that the metasomatic agent affecting the poikilitic harzburgite  
 15 was likely an alkaline mafic silicate melt (Grégoire et al., 2000a and unpublished data). All three photos  
 16 (scale bar: 2 mm) were taken using an optical microscope under crossed polars.

17

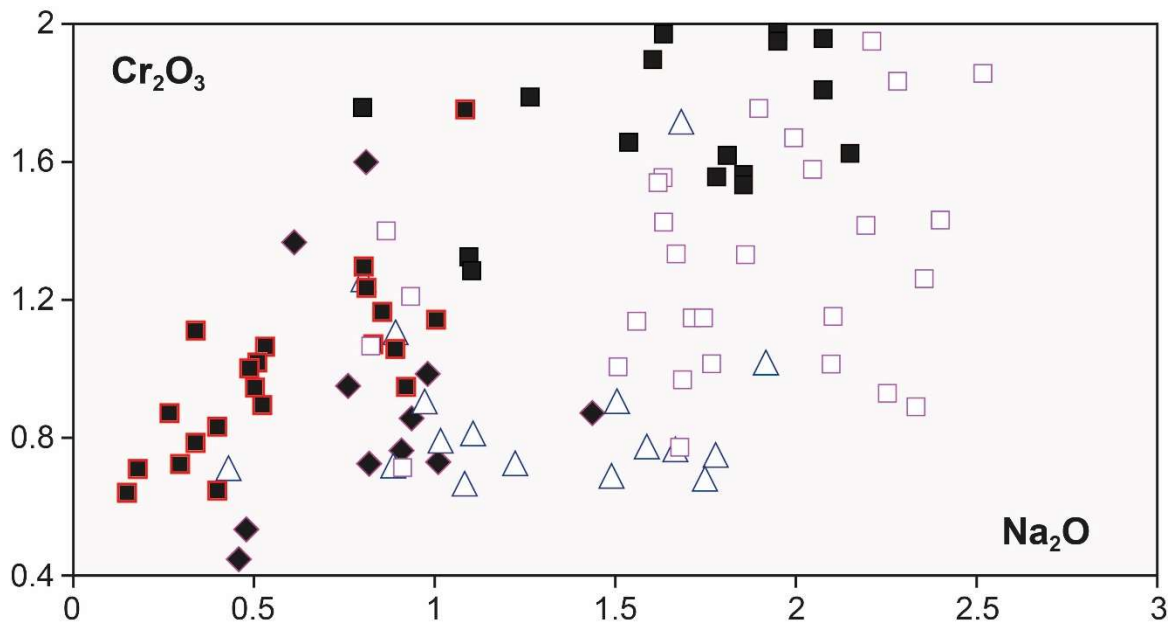
## Metasomatism in asthenospheric upwelling settings

In this type of context, mantle xenoliths uplifted by alkaline lavas mostly evidence metasomatism linked to the migration of more or less CO<sub>2</sub>-rich alkaline silicate melts and associated fluids related to the magmatic activity in the upwelling zone. The most common metasomatic minerals associated with this type of metasomatism are clinopyroxene and interstitial hydrous minerals such as amphibole and/or phlogopite (Figure 4). They could be associated to a great diversity of accessory secondary minerals including feldspars, olivine, spinel, rutile, apatite, ilmenite, carbonates, sulfides, armalcolite (e.g. O'Reilly and Griffin, 1988; Ionov et al., 1999; Grégoire et al., 2000a and b; Moine et al., 2001; Delpech et al., 2004). Associated geochemical modifications mostly comprise a decrease of the MgO/FeO ratio (or Mg#) and an increase in CaO, Al<sub>2</sub>O<sub>3</sub>, FeO<sub>t</sub>, TiO<sub>2</sub>, Na<sub>2</sub>O and K<sub>2</sub>O contents of the metasomatized peridotites. A positive correlation between the Na<sub>2</sub>O and the Cr<sub>2</sub>O<sub>3</sub> contents of primary clinopyroxenes is also frequently observed indicating the addition of Cr to the metasomatized peridotites during metasomatism (Figure 5). The abundance of incompatible elements, such as LILE, REE and HFSE commonly increases in metasomatized peridotites, and the more incompatible the element is the greater the enrichment will be. It should be noted that the same types of trace element patterns of clinopyroxenes can be observed in many localities around the world, simply indicating that the metasomatic agents were very similar (Figure 6). The U/Th ratio is typically below one in such metasomatized peridotites and amphibole and phlogopite, when they occur, are Nb- and Ta-rich (see figure 2 of Coltorti et al., 2007). Much more rarely the metasomatic agents in asthenospheric upwelling zones are pure carbonatite melts, Fe-Ti basaltic melts and tholeiitic melts (eg Hervig et al., 1986; Drury and van Roermund, 1988; Green and Wallace, 1988; Delpech et al., 2004; Moine et al., 2004; Dantas et al., 2009; Grégoire et al., 2010).

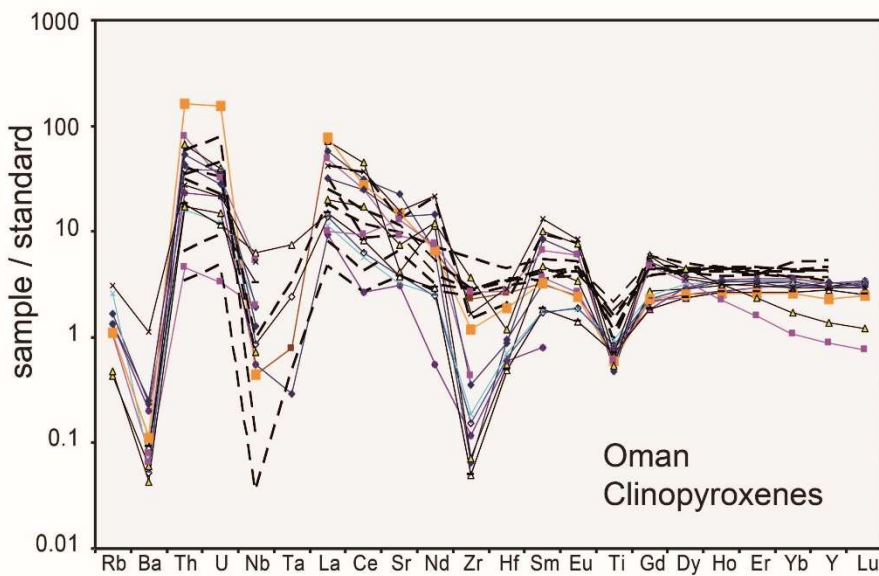
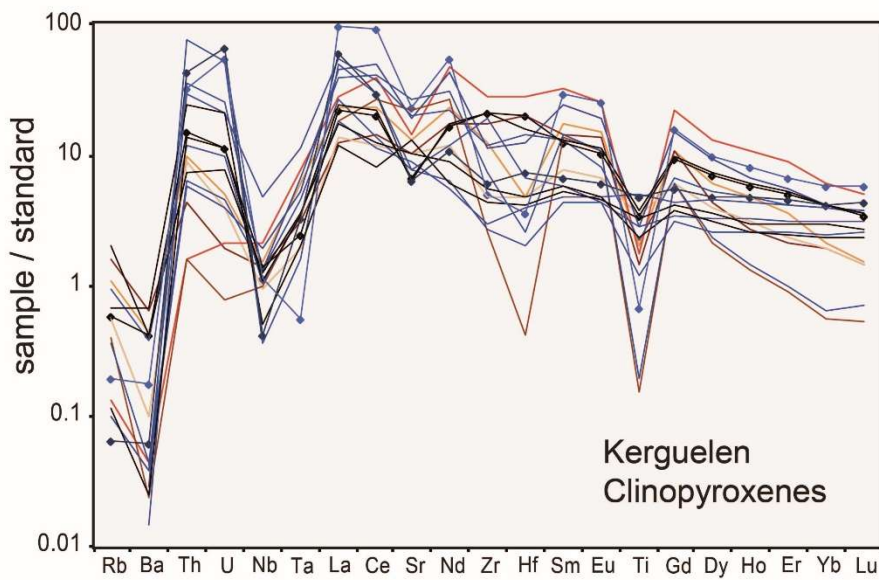
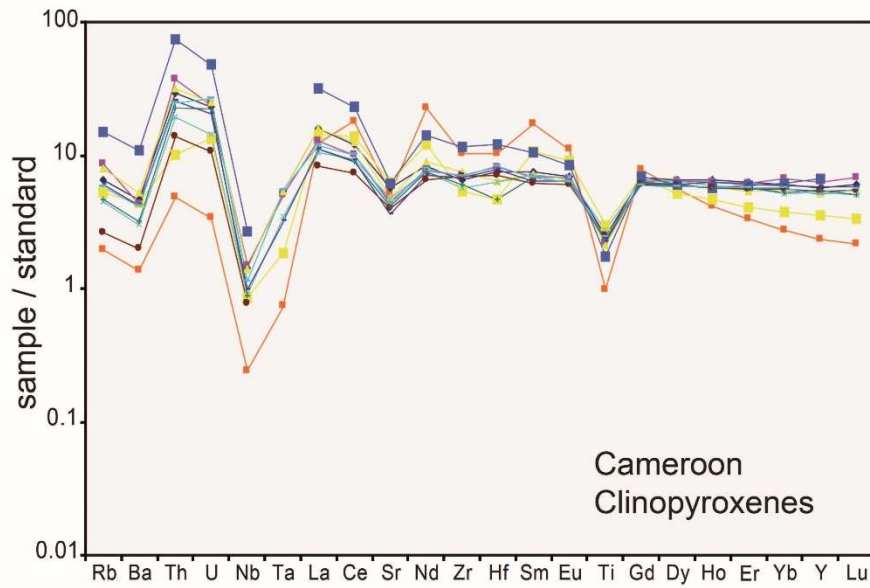


1  
 2 Figure 4. (a) Photomicrograph of a phlogopite-bearing mantle harzburgite from the Kerguelen  
 3 Archipelago (scale bar: 1mm, from the collection B.N. Moine). (b) Photomicrograph of an amphibole-  
 4 rich dykelet cross-cutting a mantle dunite from the Kerguelen Archipelago (scale bar: 2 mm, modified  
 5 after Moine et al., 2001). (c) Photomicrograph of a contact area of a metasomatic vein (bottom) of  
 6 euhedral olivine 2, interstitial feldspar and opaque oxide grains and needles replacing orthopyroxene in  
 7 a mantle harzburgite xenolith from Kerguelen Archipelago (scale bar: 0.25 mm, modified after Ionov et  
 8 al., 1999). The inset image represents a larger view (scale bar: 3 mm) in which the detailed zone is  
 9 indicated by the black rectangle. (d) Photomicrograph of a metasomatic amphibole and clinopyroxene  
 10 mineral assemblage in a mantle peridotite xenolith from central Patagonia (scale bar: 1mm, modified  
 11 after Dantas, 2008). Phl: phlogopite; cpx: clinopyroxene; ol: olivine; am: amphibole

12



1  
 2 Figure 5:  $\text{Cr}_2\text{O}_3$  versus  $\text{Na}_2\text{O}$  for clinopyroxenes from mantle xenoliths from Oman (diamonds),  
 3 Kerguelen archipelago (black squares; Grégoire, 1994; Grégoire et al., 2001), Cameroon (triangles;  
 4 Teitchou et al., 2011) and Patagonia (open squares; Dantas, 2007).



1 Figure 6: Primitive mantle-normalised (McDonough and Sun, 1995) incompatible trace element patterns  
2 for clinopyroxene from mantle xenoliths analyzed by LA-ICP-MS from the Kerguelen Archipelago,  
3 Cameroon and Oman (modified from Grégoire et al., 2000a and 2009; Teitchou et al., 2011,  
4 respectively).

5

### 6 Metasomatism in mantle wedge settings

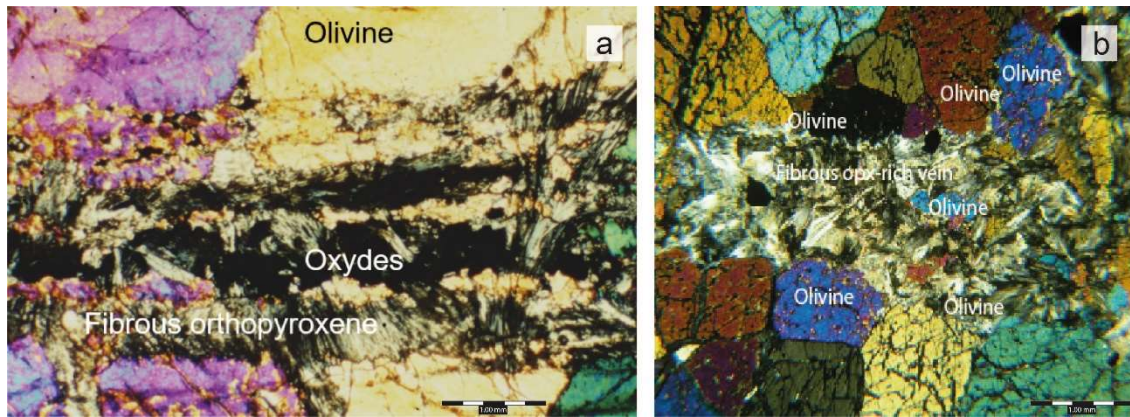
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8 Mantle xenoliths localities in mantle wedge settings are by far less common and  
9 therefore the diversity of described mineral assemblages are much lower (Mc Innes et  
10 al., 2001; Grégoire et al., 2001; Ishimaru et al., 2007; Grégoire et al., 2008). In this  
11 context, some of the uplifted mantle xenoliths contain distinctive vein structures and  
12 mineral compositions generated by hydrofracturing and water-rock reaction within the  
13 mantle wedge. There are evidences of metasomatic processes associated with the  
14 activity of hydrated liquids (fluids) commonly rich in SiO<sub>2</sub> and formed during the  
15 dehydration processes of subducting slabs. The typical metasomatic minerals in this  
16 case are fibrous orthopyroxene and clinopyroxene commonly associated with hydrous  
17 minerals such amphibole and/or phlogopite as well as accessory secondary olivine,  
18 spinel, magnetite, ilmenite and sulfides (Figure 7). The metasomatic pyroxenes (Opx,  
19 Cpx) display lower Al and Ca contents compared to their primary counterparts from the  
20 host mantle peridotite (Figure 8). Those metasomatic orthopyroxenes and  
21 clinopyroxenes display primitive-mantle normalized trace element patterns  
22 respectively characterized by strong positive U and strong negative Nb, Ta, Zr, Hf and  
23 Ti anomalies. These patterns are in good agreement with an origin of their metasomatic  
24 parental liquid linked to dehydration processes of subducting slab (e.g. McInnes et al.,  
25 2001; Grégoire et al., 2001; Figure 9). Hydrous metasomatic minerals such as  
26 phlogopite and amphibole will overall display low HFSE contents (Ti, Nb and Ta).  
27 Moreover, amphibole in mantle wedge settings is less sodic and has higher Mg# than  
28 metasomatic amphiboles from « asthenospheric upwelling zones » (see Figure 1 from  
29 Coltorti et al, 2007). Finally, the whole rock U/Th ratio of such metasomatized  
30 peridotites are commonly high (>>1), as in the metasomatic pyroxenes.

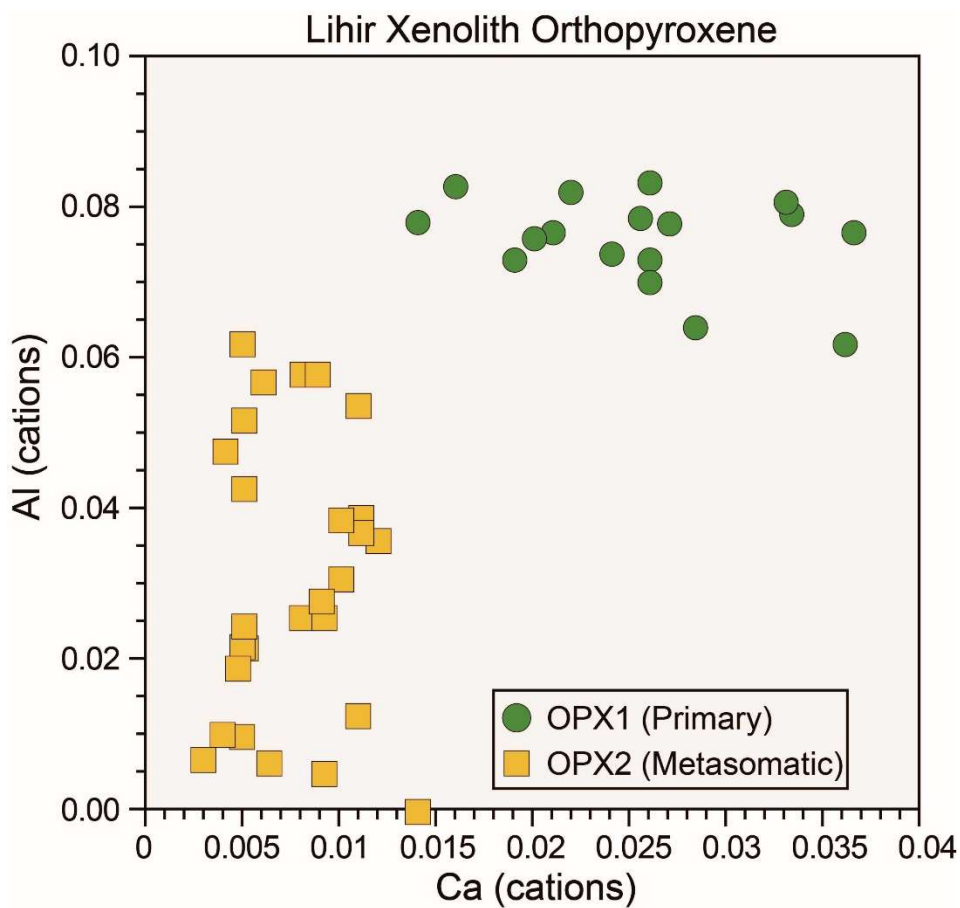
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32 Table 1 summarizes the main petrological differences between the two above  
33 described main types of Phanerozoic mantle metasomatism.

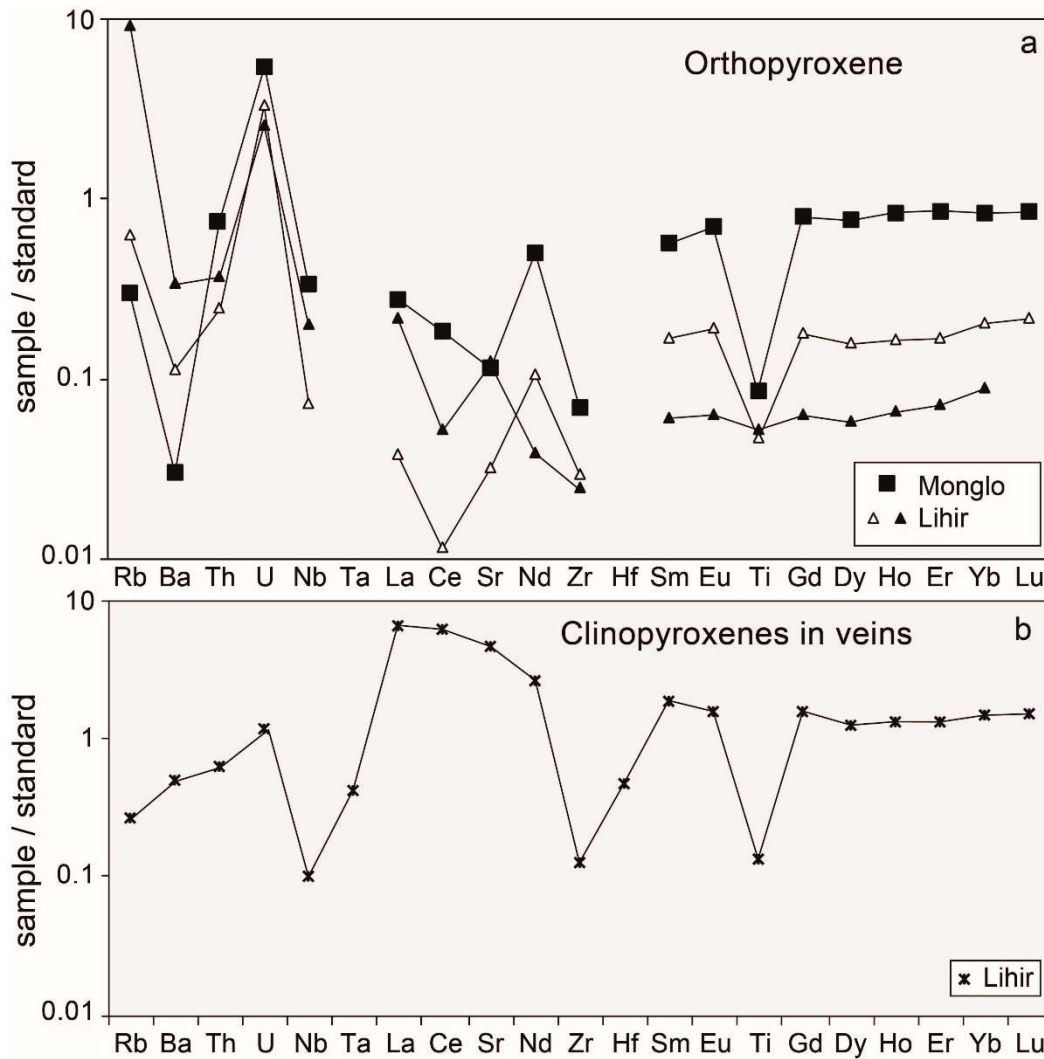
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1  
2 Figure 7. (a) Photomicrograph of a 1 mm wide fibrous orthopyroxene-rich vein from a mantle harzburgite  
3 xenolith from Lihir (scale bar: 1mm, modified after McInnes et al., 2001). (b) Photomicrographs of a  
4 fibrous orthopyroxene-rich vein cross-cutting a spinel dunite xenolith from Monglo (scale bar: 1 mm,  
5 modified after Grégoire et al., 2008).



6  
7 Figure 8. Al vs. Ca (cations) for the two orthopyroxene generations from Lihir mantle xenoliths (Grégoire,  
8 pers. comm.). The metasomatic fibrous opx (OPX2) has smaller Al and Ca values than the primary opx  
9 (OPX1).



1  
 2 Figure 9: Primitive mantle-normalised (McDonough and Sun, 1995) incompatible trace element patterns  
 3 for fibrous metasomatic orthopyroxene (OPX2) occurring in mantle xenoliths from Monglo and Lihir and  
 4 for secondary clinopyroxene associated with the fibrous orthopyroxene (OPX2) of the Lihir mantle  
 5 xenoliths analysed by LA-ICP-MS (modified after Grégoire et al, 2001 for Lihir and Grégoire et al., 2008  
 6 for Monglo).

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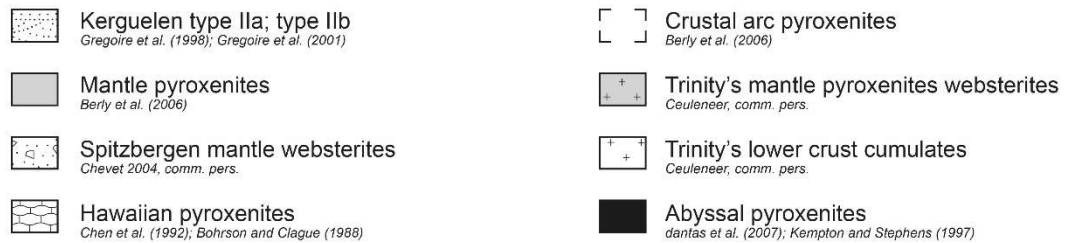
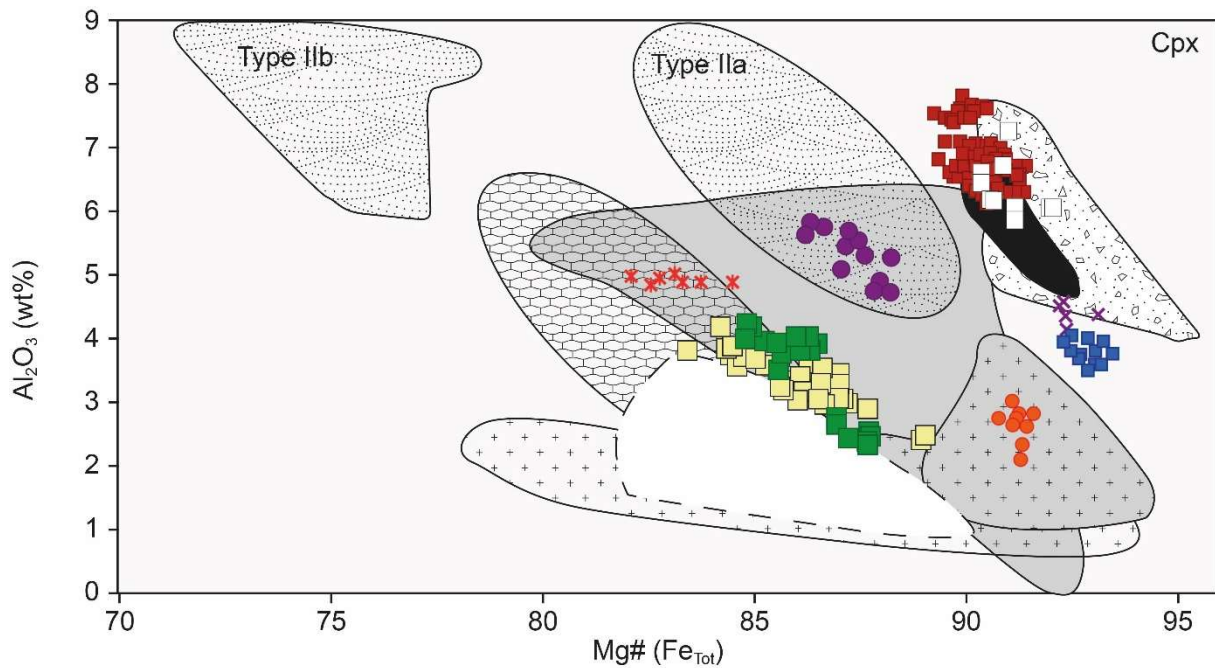
#### 8 **4 - Mantle Pyroxenites: Rare, important and diverse**

9

10 Pyroxenite xenoliths are subordinate to peridotite xenoliths at almost all localities, but  
 11 they represent a petrologically significant mantle rock type (e.g. France et al., 2015).  
 12 Their rock type ranges from orthopyroxenite through websterite to clinopyroxenite, with  
 13 the common occurrence of olivine, garnet and/or spinel. Numerous processes have  
 14 been proposed to explain the origin of pyroxenite mantle xenoliths leading to a still very  
 15 active and sometimes controversial discussion between specialists (e.g. France et al.,  
 16 2015). The main origins proposed for such rocks are the following:

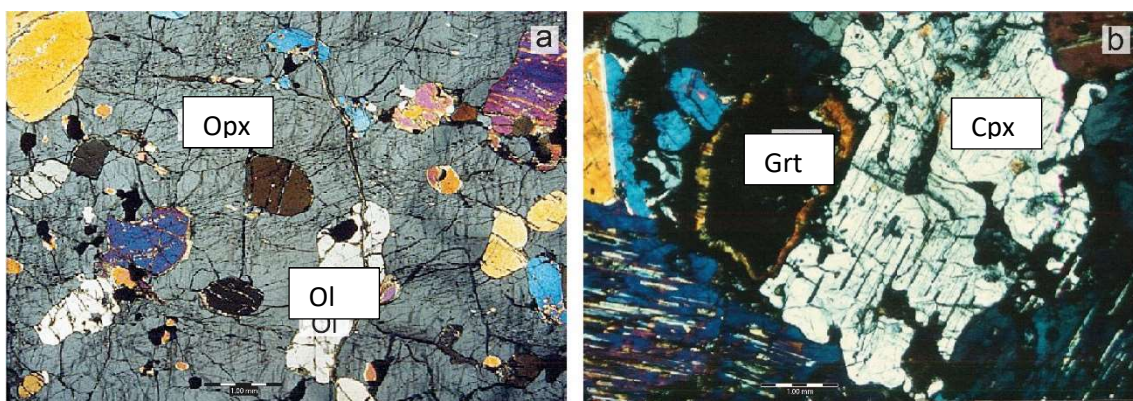


1 (i) they represent crystallization products from mafic silicate melts circulating through  
2 the lithospheric mantle (e.g. Grégoire et al., 1998; Dantas et al., 2009; Puziewicz et al.,  
3 2011), (ii) in situ melting/dissolution and subsequent crystallization of pyroxenes in  
4 pyroxenite layers (e.g. Dick and Sinton 1979; Liu et al., 2020), and (iii) melt–rock  
5 reaction between peridotite and transient melts (e.g. Chen et al., 2014; Liu et al., 2020).  
6 Whatever the process causes pyroxenites, it is obvious that they greatly contribute to  
7 the occurrence of petrological heterogeneities within the lithospheric mantle. Moreover,  
8 as their geochemical and isotopic compositions are strongly influenced by the process  
9 responsible for their formation, these heterogeneities could be highly variable. Figure  
10 10 illustrates the heterogeneity of compositions of the clinopyroxene of pyroxenites  
11 from various localities and geodynamic contexts (modified from Dantas, 2007). For  
12 example, in the case of the pyroxenite xenoliths from the Kerguelen Islands, they are  
13 all considered as deep segregates from basaltic melts. Two types of pyroxenites  
14 (Figure 11) have been distinguished based on the affinity of basaltic melts; one  
15 referring to melts with a tholeiitic-transitional affinity (Type IIa; high Mg# and low TiO<sub>2</sub>  
16 content) and one to melts with alkaline affinity (Type IIb; lower Mg# and higher TiO<sub>2</sub>  
17 content; Grégoire et al., 1998). Liu et al. (2020) distinguished three types of pyroxenite  
18 xenoliths from basalts of Yangyuan craton area (China) based on the compositions of  
19 their constituent clinopyroxenes (Figure 12). They propose that the type I pyroxenites  
20 represent a natural example illustrating the metamorphic segregation theory proposed  
21 by Dick and Sinton (1979) that explains the heterogeneous lithology of the upper  
22 mantle by pyroxene-rich veins formed by the dissolution and precipitation of pyroxene  
23 in the host peridotite during plastic flow, including during metasomatism. They  
24 therefore represent original peridotites with pyroxene enrichments at the local  
25 centimeter scale. They also evidence that Type II pyroxenites formed during reactions  
26 between an asthenosphere or juvenile lithospheric mantle-derived melt and the host  
27 mantle peridotite. Finally, the type III pyroxenites were suggested to originate from  
28 fractional crystallization of various parental magmas (Liu et al., 2020) and therefore  
29 would resemble to the deep mantle segregates from the Kerguelen Islands (Figure 3b).  
30

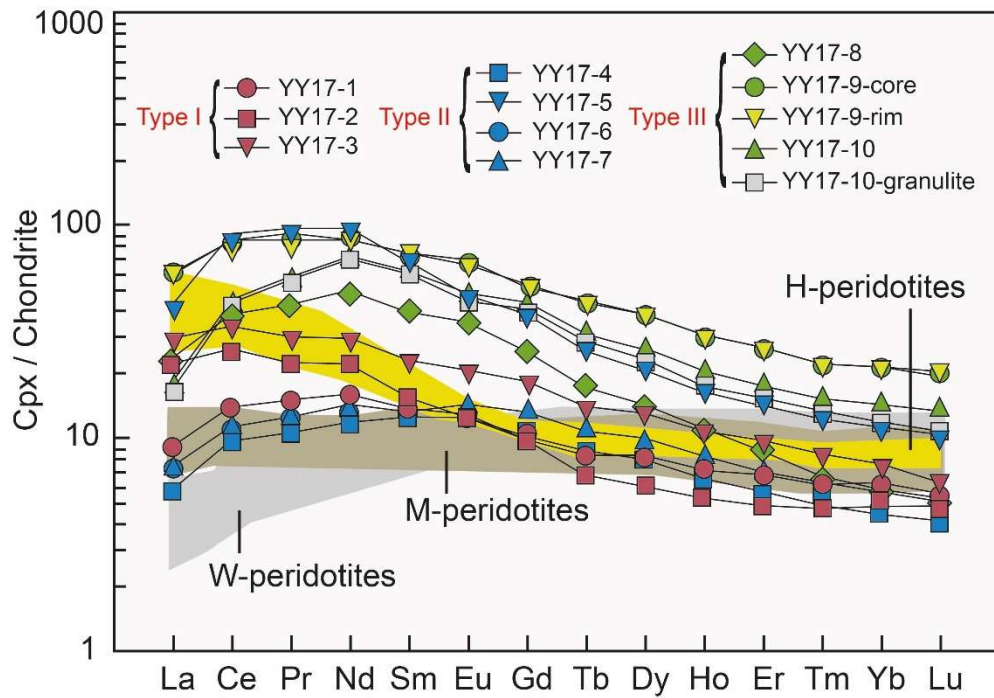


1  
2 Figure 10:  $\text{Al}_2\text{O}_3$  vs  $\text{Mg\#}$  diagram of clinopyroxenes from Patagonian mantle pyroxenite xenoliths, in  
3 comparison with pyroxenites from several geodynamic contexts (abyssal, ophiolite, arc and oceanic  
4 intraplate) worldwide (modified from Dantas, 2007). The different types of symbol represent the diversity  
5 of the pyroxenite xenoliths from Patagonia (see in Dantas, 2007 for details).

6



7  
8 Figure 11: Photomicrographs of pyroxenite mantle xenoliths from the Kerguelen Archipelago (scale bar:  
9 1 mm, from the collection of M. Grégoire). (a) Cumulative olivine-bearing websterite of tholeiitic-  
10 transitional affinity; and (b) garnet-bearing clinopyroxenite of alkaline affinity. Cpx: clinopyroxene; Grt:  
11 garnet; Ol: olivine; Opx: orthopyroxene.



1  
 2 Figure 12: Chondrite-normalized REE patterns for the clinopyroxene from the Yangyuan pyroxenite  
 3 xenoliths (modified after Liu et al., 2020). **Yangyuan peridotites:** H-peridotites: Highly Metasomatized  
 4 Peridotites, M-peridotites: Moderately Metasomatized Peridotites and W-peridotites: Weakly  
 5 Metasomatized Peridotites.

6

## 7 **5 - Implications**

8

9 It is now well recognized that a link does exist between the main petrogenetic  
 10 processes affecting the mantle peridotites, the formation of mantle pyroxenites and the  
 11 physical properties of the upper mantle. Indeed, all these processes imply changes in  
 12 the petrological, mineralogical and chemical characteristics of the upper mantle and  
 13 therefore changes in its physical properties (density, porosity, seismic properties...).

14 For example, mantle partial melting processes decreases its density, increases its  
 15 seismic velocity, decreases the heat production of the generated mantle residue by  
 16 extracting heat-producing elements (U, Th, K) and therefore affects the rheology of  
 17 that residual mantle. Metasomatic processes usually have the opposite effects to  
 18 partial melting. The lithospheric mantle has recorded multiple partial melting, magmatic  
 19 and metasomatic events since its formation. These events have repeatedly overprinted  
 20 primary mantle rocks leading to a complex heterogeneous lithospheric mantle. Finally,  
 21 when pieces of the heterogeneous lithospheric upper mantle are recycled within the

1 convective mantle they will imply changes in the composition of the latter and will  
2 participate to its heterogeneity.

3

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10

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