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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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The present contribution synthesizes the main petrographic, mineralogical and chemical features of mantle xenoliths uplifted by Phanerozoic lavas. The collections of mantle xenoliths consist predominantly of peridotites but minor pyroxenites are commonly associated. Two main petrogenetic processes are responsible for the features of mantle xenoliths: partial melting and circulation of melts/fluids 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 AUZ (asthenospheric upwelling zones) metasomatism is essentially related to the migration of more or less CO_2-rich alkaline silicate melts and associated fluids while the MWZ (mantle wedge zones) metasomatism is associated with the activity of hydrated liquids (fluids) commonly SiO_2-rich.

1. Introduction

Earth's mantle rock samples come almost exclusively from a depth of <200–250 km with the exception of very rare inclusions in diamonds indicating the occurrence of majorite, calcium- and magnesium-perovskite, ringwoodite and ferropericlase (all from depths of >400 km; *e.g.* Harte and Harris, 1994; Collerson *et al.*, 2000; Pearson *et al.*, 2014; Seitz *et al.*, 2018). Therefore, mantle rock samples do not allow us 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

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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 is complementary to those of geophysics (experimental and modelling). There are four typical occurrences for mantle rock samples: mantle sections of ophiolites, peridotite orogenic massifs, abyssal mantle domains and pyroxenite and peridotite mantle xenoliths in basic lavas. Mantle rocks provide insights into the origin and evolution of the lithospheric mantle and, in particular, to 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 (Fig. 1). Similar studies of the other types of occurrences including xenoliths uplifted by kimberlites and related rocks are crucial for our understanding of the upper mantle composition and evolution. The present study aims to synthesize 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 melt/fluid circulation and associated metasomatic and magmatic processes. Also summarized briefly here is the state of knowledge on the nature and origin of mantle pyroxenites which are, although minor in terms of abundance, very important in our understanding of the history of the Earth's mantle.

2. Mantle processes recorded in peridotite xenoliths

2.1. Partial melting

Mantle peridotites defined as lherzolites, harzburgites and dunites form by far the largest volume of the lithosphere, while wehrlites are rarer. They mostly consist of three main mineral phases; olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx) associated with a minor Al-rich phase being plagioclase (Pl), spinel (Spl) or garnet (Gt) depending on equilibration depth (*e.g.* Wyllie, 1981; Gasparik, 1984; Klemme, 2004). Because

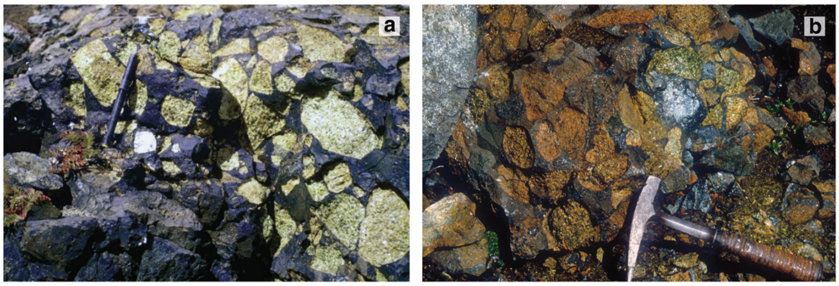

Fig. 1. Mantle xenoliths in two basanitic dykes (emplaced a few million years ago) from Kerguelen Archipelago. The scale is given by the pencil (***a***) and the hammer (***b***).

olivine and the two pyroxenes are the most abundant minerals, the classification of peridotites is based on the modal abundances of them (Streckeisen, 1976).

Under normal geothermal conditions, the upper mantle does not undergo partial melting. However, there are a number of geodynamic cases where anomalous thermal regimes exceed the solidus of peridotite, leading to local or regional partial melting of the upper mantle. Such abnormal thermal regimes are, for instance, encountered in mantle plume settings where the temperature of the plume material is hotter than the surrounding asthenosphere (Farnetani, 2024, this volume). At mid-oceanic ridge settings, this situation occurs in response to the adiabatic decompression of the asthenosphere and in subduction settings the abnormal thermal regime is due to the influx of fluids/melts which percolate into the mantle wedge above.

In all the geodynamic settings described above, peridotites undergo partial melting. All the different constituent mineral phases taken alone have different melting temperatures, the lowest being for the Al-rich mineral phases (Pl, Spl, Gt) and then the clinopyroxene, the orthopyroxene and finally the olivine. The petrological experiments conducted to reproduce peridotite partial melting (*cf.* Hirschmann *et al.*, 1998; Bernstein *et al.*, 2007) indicate that melting reactions involve an assemblage of dominant clinopyroxene, Al-rich mineral phase and orthopyroxene or olivine depending on pressure. At low and medium pressure in the spinel stability field (from ~1 to 1.7–2 GPa), olivine crystallizes as a product of the melting reaction [Opx+Cpx+Spl → Ol+Melt; Niu, 1997]; hence the olivine modal content of the peridotite residue increases. At higher pressures in the garnet stability field (>1.7–2 GPa), orthopyroxene crystallizes in the residue of melting [Ol+Cpx+Gt → Opx+Melt; Walter, 1998]; hence the orthopyroxene content increases. Such studies also demonstrate that the eutectic composition of a melt formed by partial melting of peridotite depends on the composition of the latter before melting, on pressure, on temperature, on fluid contents (H_2O, CO_2) and on degree of melting. Therefore, an extreme diversity of melt compositions can be generated from peridotite melting. For example, the partial melting of a mantle lherzolite will first lead to the exhaustion of the Al-rich phase depending on pressure (plagioclase, spinel or garnet) and then of the clinopyroxenes and if the degree of melting is high enough, a harzburgite will form if the cpx content drops to <5% and finally a dunite will form if the sum of opx+cpx is <10% (Fig. 2). For clinopyroxene to disappear from the melting peridotite, the degree of melting needs to be >~20%, (*e.g.* Baker and Stolper, 1994; Hirschmann *et al.*, 1998). On the other hand, to form a dunite by partial melting of a lherzolite, the degree of melting has to reach as much as 40–50% (Bernstein *et al.*, 2007) and therefore this situation is probably limited to Archaean mantle melting processes only (Bernstein *et al.*, 2007).

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

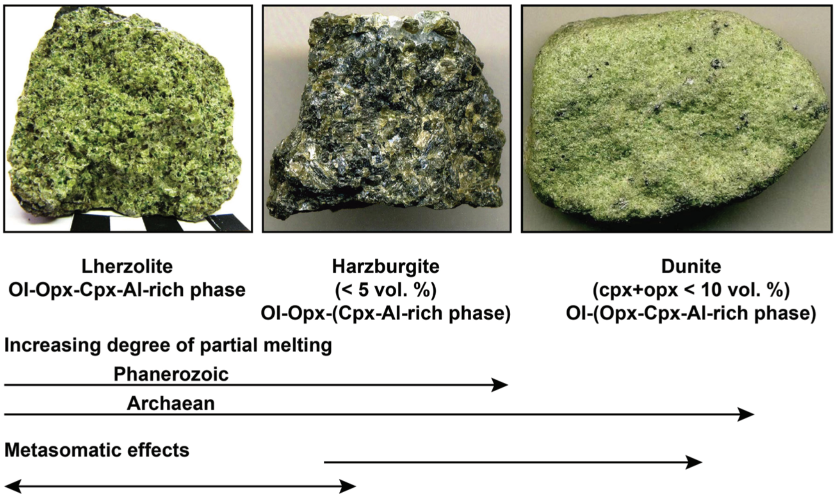

Fig. 2. Types of mantle peridotite (lherzolite, harzburgite, dunite) and their relationships with partial melting and mantle metasomatism. Hand specimens.

transition group especially Ni, Co and Cr behave as compatible trace elements and tend to concentrate in the residue of melting (*e.g.* Norman, 1998, Simon *et al.*, 2008).

2.2. Percolation of melts/fluids in the lithosphere and associated metasomatism

It is (very) rare to find mantle peridotite xenoliths that have been affected only by partial melting processes; the majority have been affected by two main processes – an early partial melting and subsequent metasomatic processes. Each of those processes may affect the rock multiple times. The commonly used definition of mantle metasomatism defines as physical and chemical processes that are implemented during the flow (both pervasive at grain boundaries and focused in dykes or veins) of magma and/or fluids within the upper mantle. The main changes that affect the mantle wall rocks (peridotites) are in microstructure, recrystallization, the possible formation of new minerals (and the disappearance of pristine ones) and the chemical exchanges leading to the enrichment in incompatible trace elements of the mantle peridotites. In some cases, metasomatism at large melt/rock ratio can induce the formation of a new rock such as, for example, the transformation of harzburgite into dunite (*e.g.* Kelemen, 1990; Grégoire *et al.*, 2000a) or also the formation of pyroxenites from peridotites (*e.g.* Liu *et al.*, 2020).

Depending on the geochemical and mineralogical changes they cause, three main types of metasomatism have been distinguished over the years: (1) cryptic metasomatism; (2) modal metasomatism; and (3) stealth metasomatism.

Cryptic metasomatism (Dawson, 1984) triggers only chemical modification of the mantle peridotite and of its constituent minerals without crystallization of new mineral phases. The main geochemical modifications concern the abundance of trace elements which are often associated with a decrease (or increase) in the Mg# and an increase in other basaltic components (*e.g.* Na_2O, Al_2O_3, TiO_2) of the whole rock and minerals (*e.g.* Xu *et al.*, 2000).

Modal metasomatism (Harte, 1983) describes the formation of new mineral phases which are different from the original four phases constituting a mantle peridotite, *i.e.* olivine, orthopyroxene, clinopyroxene and an Al-rich phase (spinel or garnet or plagioclase) associated with geochemical modifications such as described for cryptic metasomatism. As for cryptic metasomatism, the Mg# and other basaltic components (*e.g.* Na_2O, TiO_2) of the whole rock and mineral will also vary, possibly in greater ways than for cryptic metasomatism. The classical metasomatic phases are amphibole and phlogopite. Detailed information is given in Table 1.

A third type of metasomatism was introduced more recently by O'Reilly and Griffin (2013) and is referred to as 'stealth metasomatism'. This involves the addition of new mineral phases (*e.g.* garnet and/or clinopyroxene) to the mantle rock; this might be a 'misleading' metasomatic process as it adds similar mineral phases to those forming the original mantle peridotite mineral association.

3. Main metasomatic imprints within the Phanerozoic upper mantle

Mantle metasomatism, depending on the original melt/fluid composition and volume as well as on the duration of the metasomatic event, will result in an increase/decrease in major and trace elements of the whole rock and minerals. The nature of metasomatic mantle melts/fluids may be determined from the changes in the geochemical compositions of mantle minerals but also from the composition of fluid inclusions in minerals. The study of fluid inclusions in mantle peridotites (*e.g.* Schiano *et al.*, 1994; Hidas *et al.*, 2010; Créon *et al.*, 2017) helps to constrain the composition of the fluid phase associated

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

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

with metasomatism (H_2O, CO_2, …) and can also provide temperature constraints at which the fluid inclusions were trapped. A traditional way of estimating a theoretical composition of the metasomatic agent is to use the trace element compositions of mineral phases (commonly cpx) and a set of appropriate partition coefficients between melt or fluid and mineral to calculate a theoretical composition of the metasomatic agent (*e.g.* Grégoire *et al.*, 2000a). In some cases, such as mantle xenoliths from the Kerguelen Islands, it is possible to compare the composition of the metasomatic clinopyroxenes with those of clinopyroxenes occurring in deep-seated alkaline pyroxenite segregates and clinopyroxene megacrysts occurring in young alkaline lavas (Fig. 3). Metasomatic melts (fluids) in off-craton (mostly Phanerozoic) regions cover a vast

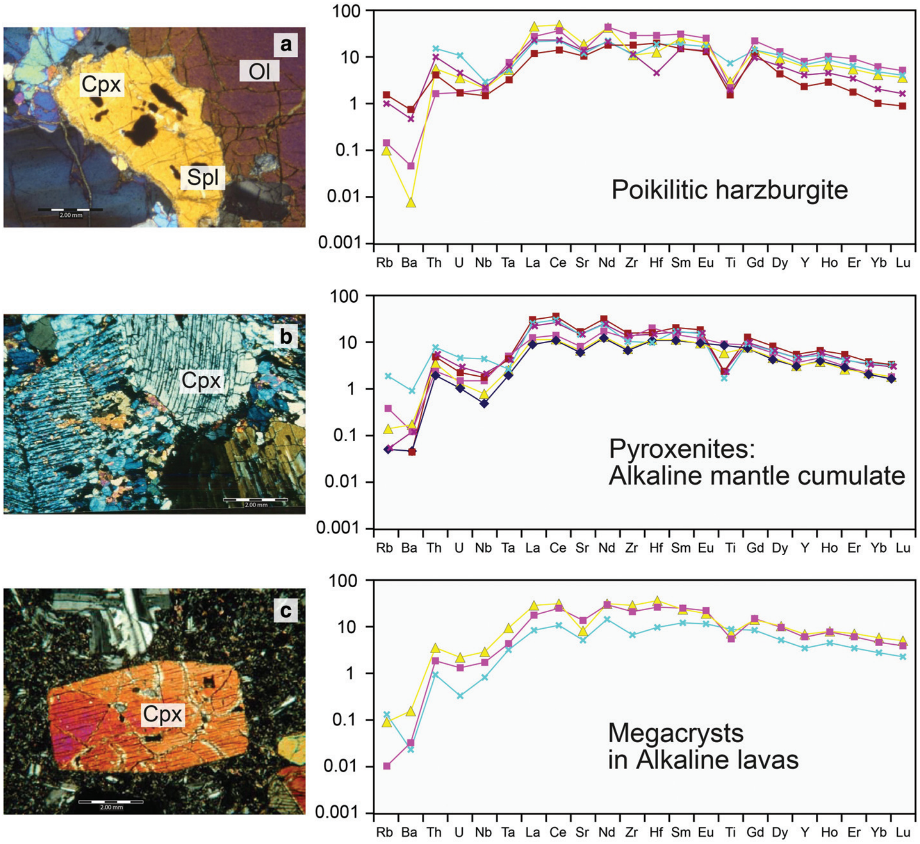

Fig. 3. Comparison between primitive mantle-normalized (McDonough and Sun, 1995) trace element patterns of clinopyroxene from a poikilitic mantle harzburgite (***a***), an alkaline deep pyroxenite cumulate (***b***) and occurring as a megacryst in an alkaline basaltic lava (***c***) from the Kerguelen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

spectrum from silicate to carbonate magmas containing variable types and abundances of dissolved fluids and solutes including brines, C-O-H species and sulfur-bearing components (O'Reilly and Griffin, 2013). It is, nevertheless, possible to discriminate between two main types of metasomatic agents, the first referring to asthenospheric upwelling settings (essentially mantle plumes, rifting zones and asthenospheric window zones) and the second to mantle wedge settings.

3.1. Metasomatism in asthenospheric upwelling settings

In this type of context, mantle xenoliths uplifted by alkaline lavas mostly prove metasomatism linked to the migration of more or less CO_2-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 (Fig. 4). They could be associated with a great diversity of accessory secondary minerals including

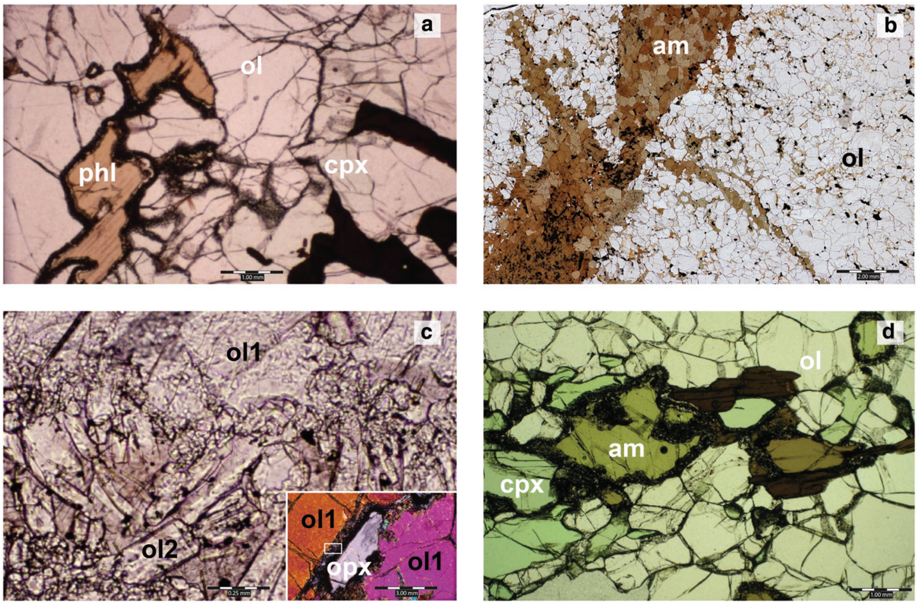

Fig. 4. (***a***) Photomicrograph of a phlogopite-bearing mantle harzburgite from the Kerguelen Archipelago (scale bar: 1mm, from the collection B.N. Moine). (***b***) Photomicrograph of an amphibole-rich dykelet cross-cutting a mantle dunite from the Kerguelen Archipelago (scale bar: 2 mm, modified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

feldspars, olivine, spinel, rutile, apatite, ilmenite, carbonates, sulfides, armalcolite (*e.g.* O'Reilly and Griffin, 1988; Ionov *et al.*, 1999; Grégoire *et al.*, 2000a,b; Moine *et al.*, 2001; Delpech *et al.*, 2004). Associated geochemical modifications mostly comprise a decrease in the MgO/FeO ratio (or Mg#) and an increase in CaO, Al_2O_3, FeO_t, TiO_2, Na_2O and K_2O contents of the metasomatized peridotites. A positive correlation between the Na_2O and the Cr_2O_3 contents of primary clinopyroxenes is also observed frequently, indicating the addition of Cr to the metasomatized peridotites during metasomatism (Fig. 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. Note 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 (Fig. 6). The U/Th ratio is typically <1 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 (*e.g.* 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).

3.2. Metasomatism in mantle wedge settings

Mantle xenolith localities in mantle wedge settings are much less common and, therefore, the diversity of the mineral assemblages described is much less (Grégoire *et al.*, 2001; McInnes *et al.*, 2001; Ishimaru *et al.*, 2007; Grégoire *et al.*, 2008). In this context, some of the uplifted mantle xenoliths contain distinctive vein structures and mineral compositions generated by hydrofracturing and water–rock reaction within the mantle wedge. There is evidence of metasomatic processes associated with the activity of hydrated liquids (fluids) commonly rich in SiO_2 and formed during the dehydration processes

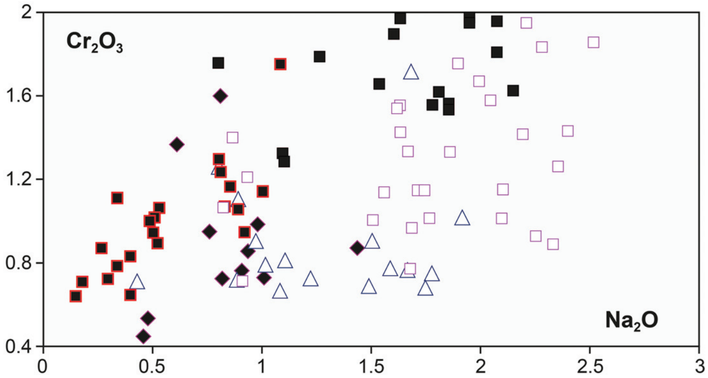

Fig. 5. Cr_2O_3 *vs.* Na_2O for clinopyroxenes from mantle xenoliths from Oman (diamonds), Kerguelen archipelago (black squares; Grégoire, 1994; Grégoire *et al.*, 2001), Cameroon (triangles; Teitchou *et al.*, 2011) and Patagonia (open squares; Dantas, 2007).

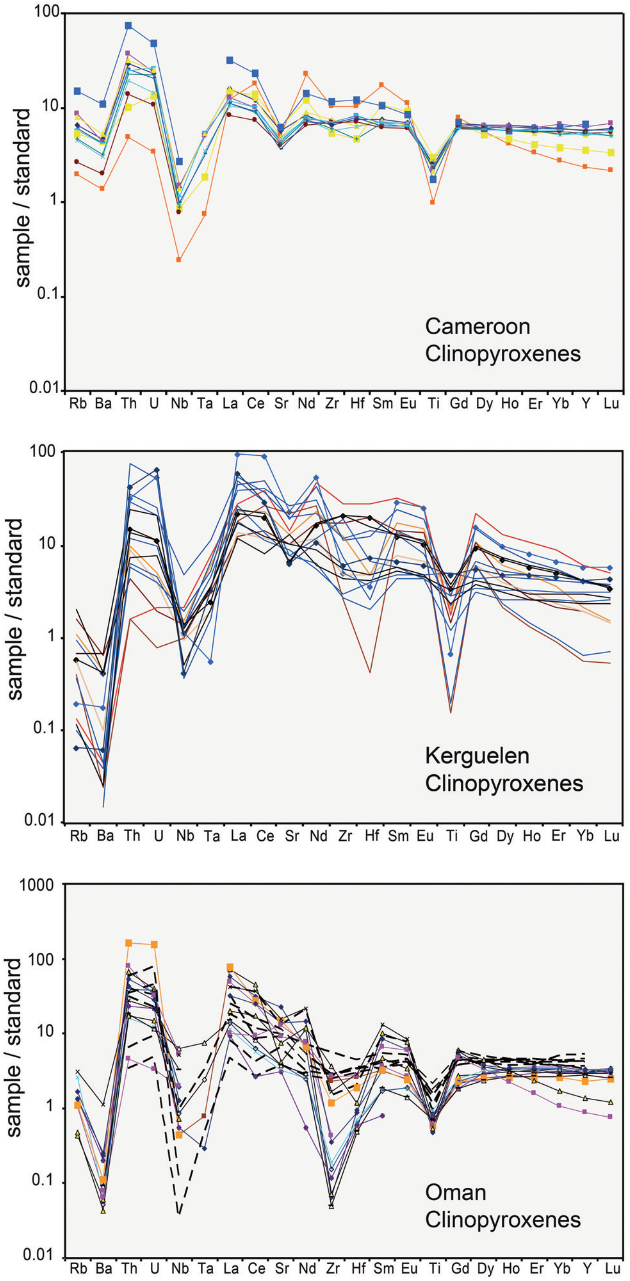

Fig. 6. Primitive mantle-normalized (McDonough and Sun, 1995) incompatible trace element patterns for clinopyroxene from mantle xenoliths analyzed by LA-ICP-MS from the Kerguelen Archipelago, Cameroon and Oman (modified from Grégoire *et al.*, 2000 and 2009 and from Teitchou *et al.*, 2011, respectively).

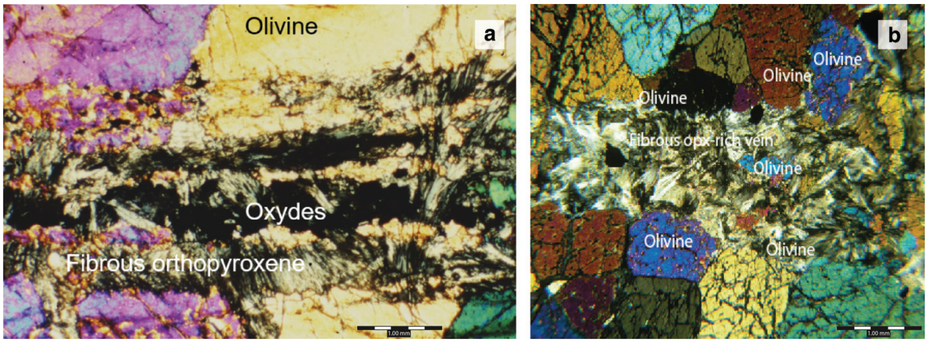

Fig. 7. (***a***) Photomicrograph of a 1 mm wide fibrous orthopyroxene-rich vein from a mantle harzburgite xenolith from Lihir (scale bar: 1mm, modified after McInnes *et al.*, 2001). (***b***) Photomicrographs of a fibrous orthopyroxene-rich vein cross-cutting a spinel dunite xenolith from Monglo (scale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

of subducting slabs. The typical metasomatic minerals in this case are fibrous orthopyroxene and clinopyroxene commonly associated with hydrous minerals such as amphibole and/or phlogopite as well as accessory secondary olivine, spinel, magnetite, ilmenite and sulfides (Fig. 7). The metasomatic pyroxenes (Opx, Cpx) display lower Al and Ca contents compared to their primary counterparts from the host mantle peridotite (Fig. 8). Those metasomatic orthopyroxenes and clinopyroxenes display primitive-

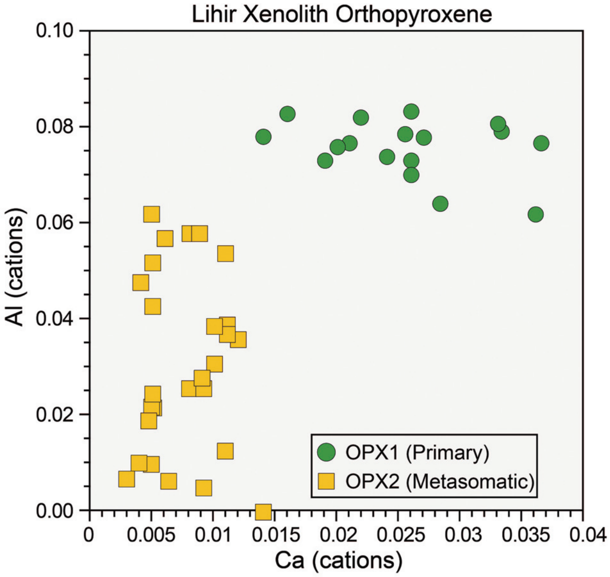

Fig. 8. Al *vs.* Ca (cations) for the two orthopyroxene generations from Lihir mantle xenoliths (Grégoire, pers. comm.). The metasomatic fibrous opx (OPX2) has smaller Al and Ca values than the primary opx (OPX1).

mantle-normalized trace element patterns characterized by strong positive U and strong negative Nb, Ta, Zr, Hf and Ti anomalies, respectively. These patterns are in good agreement with an origin of their metasomatic parental liquid linked to dehydration processes of subducting slab (*e.g.* McInnes *et al.*, 2001; Grégoire *et al.*, 2001; Fig. 9). Hydrous metasomatic minerals such as phlogopite and amphibole will, overall, display low HFSE contents (Ti, Nb and Ta). Moreover, amphibole in mantle wedge settings is less sodic and has larger Mg# values than metasomatic amphiboles from 'asthenospheric upwelling zones' (see Fig. 1 from Coltorti *et al.*, 2007). Finally, the whole-rock U/Th

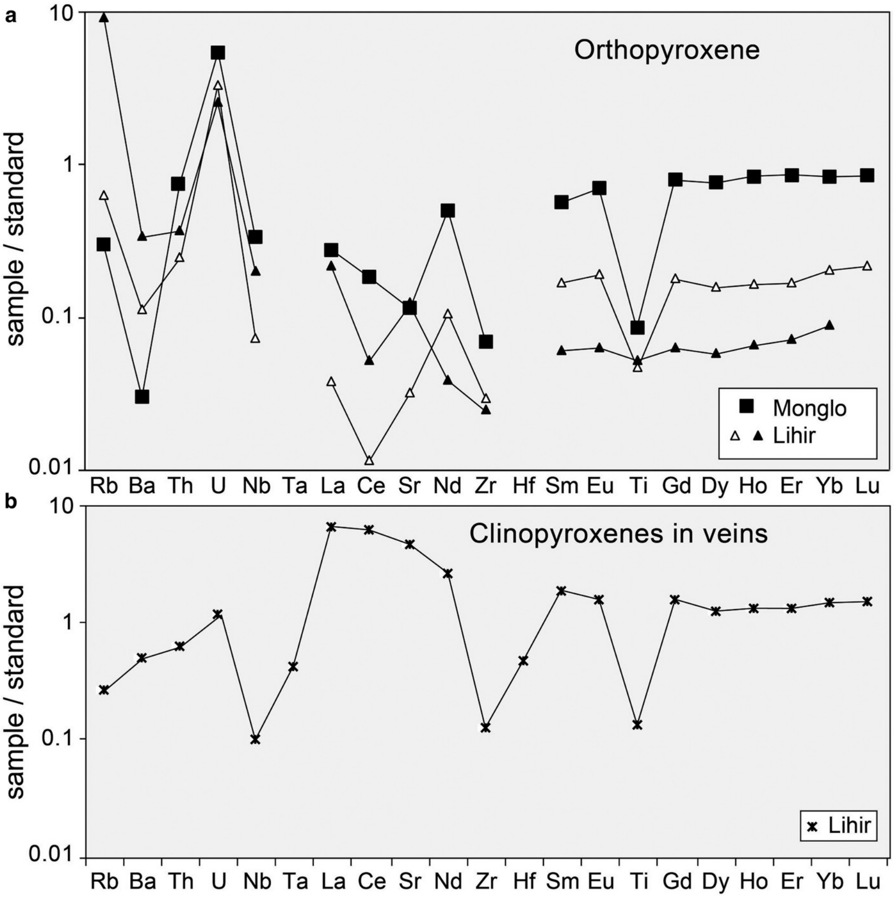

Fig. 9. Primitive mantle-normalized (McDonough and Sun, 1995) incompatible trace element patterns for fibrous metasomatic orthopyroxene (OPX2) occurring in mantle xenoliths from Monglo and Lihir and for secondary clinopyroxene associated with the fibrous orthopyroxene (OPX2) of the Lihir mantle xenoliths analysed by LA-ICP-MS (modified after Grégoire *et al.*, 2001, for Lihir, and after Grégoire *et al.*, 2008, for Monglo).

ratio of such metasomatized peridotites is commonly large ($\gg 1$), as in the metasomatic pyroxenes.

The main petrological differences between the two main types of Phanerozoic mantle metasomatism described above are summarized in Table 1.

4. Mantle pyroxenites: rare, important and diverse

Pyroxenite xenoliths are subordinate to peridotite xenoliths at almost all localities, but they represent a petrologically significant mantle rock type (*e.g.* France *et al.*, 2015). This rock type ranges from orthopyroxenite through websterite to clinopyroxenite, with the common occurrence of olivine, garnet and/or spinel. Numerous processes have been proposed to explain the origin of pyroxenite mantle xenoliths leading to a very active and sometimes controversial discussion between specialists (*e.g.* France *et al.*, 2015). The main origins proposed for such rocks are as follows: (1) they represent crystallization products from mafic silicate melts circulating through the lithospheric mantle (*e.g.* Grégoire *et al.*, 1998; Dantas *et al.*, 2009; Puziewicz *et al.*, 2011); (2) *in situ* melting/dissolution and subsequent crystallization of pyroxenes in pyroxenite layers (*e.g.* Dick and Sinton 1979; Liu *et al.*, 2020); and (3) melt–rock reaction between peridotite and transient melts (*e.g.* Chen *et al.*, 2014; Liu *et al.*, 2020). Whatever process causes pyroxenites, it is obvious that they contribute significantly to the occurrence of petrological heterogeneities within the lithospheric mantle. Moreover, as their geochemical and isotopic compositions are strongly influenced by the process responsible for their formation, these heterogeneities could be highly variable. The heterogeneity of compositions of the clinopyroxene in pyroxenites from various localities and geodynamic contexts is illustrated in Fig. 10 (modified from Dantas, 2007). For example, in the case of the pyroxenite xenoliths from the Kerguelen Islands, they are all considered to be deep segregates from basaltic melts. Two types of pyroxenites (Fig. 11) have been distinguished based on the affinity of basaltic melts; one referring to melts with a tholeiitic-transitional affinity (Type IIa; high Mg# and low TiO_2 content) and one to melts with alkaline affinity (Type IIb; lower Mg# and higher TiO_2 content; Grégoire *et al.*, 1998). Liu *et al.* (2020) distinguished three types of pyroxenite xenoliths from basalts of the Yangyuan craton area (China) based on the compositions of their constituent clinopyroxenes (Fig. 12). Those authors proposed that type I pyroxenites represent a natural example illustrating the metamorphic segregation theory proposed by Dick and Sinton (1979) which explains the heterogeneous lithology of the upper mantle by pyroxene-rich veins formed by the dissolution and precipitation of pyroxene in the host peridotite during plastic flow, including during metasomatism. They therefore represent original peridotites with pyroxene enrichments at the local centimeter scale. They also show that type II pyroxenites formed during reactions between an asthenosphere or juvenile lithospheric mantle-derived melt and the host mantle peridotite. Finally, the type III pyroxenites were suggested to originate from fractional crystallization of various parental magmas (Liu *et al.*, 2020) and therefore would resemble the deep mantle segregates from the Kerguelen Islands (Figure 3b).

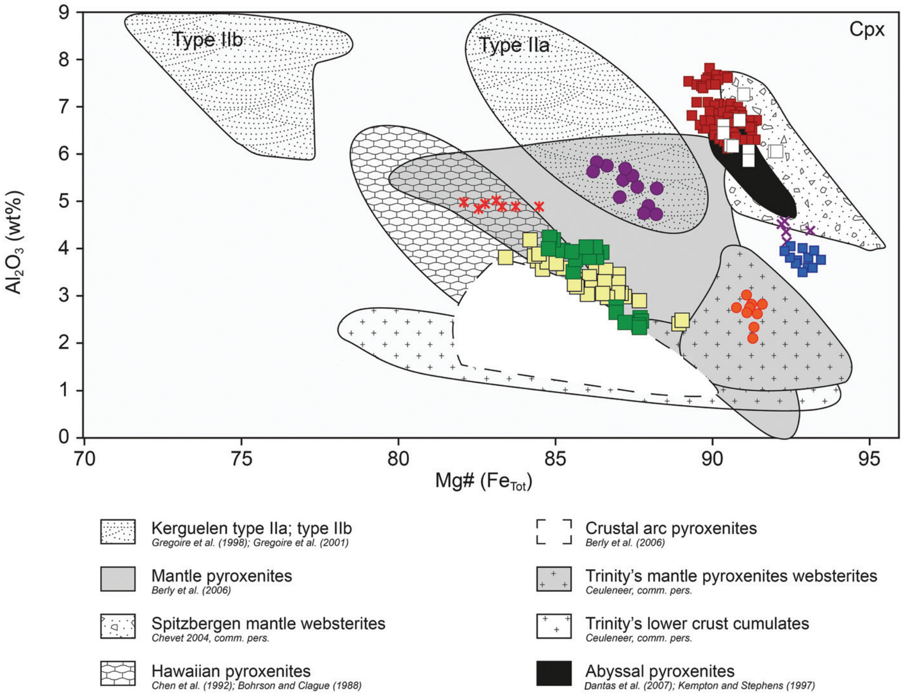

Fig. 10. Al_2O_3 *vs*. Mg# diagram for clinopyroxenes from Patagonian mantle pyroxenite xenoliths, in comparison with pyroxenites from several geodynamic contexts (abyssal, ophiolite, arc and oceanic intraplate) worldwide (modified from Dantas, 2007). The different types of symbol represent the diversity of the pyroxenite xenoliths from Patagonia (see Dantas, 2007 for details).

5. Implications

It is now well recognized that a link does exist between the main petrogenetic processes affecting the mantle peridotites, the formation of mantle pyroxenites and the physical properties of the upper mantle. Indeed, all these processes imply changes in the petrological, mineralogical and chemical characteristics of the upper mantle and therefore changes in its physical properties (density, porosity, seismic properties…). For example, partial melting processes in the mantle decrease its density, increase its seismic velocity and decrease the heat production of the mantle residue generated by extracting heat-producing elements (U, Th, K) and therefore affect the rheology of the residual mantle. Metasomatic processes usually have the opposite effects to those of partial melting. The lithospheric mantle has recorded multiple partial melting, magmatic and metasomatic events since its formation. These events have repeatedly overprinted primary mantle rocks leading to a complex heterogeneous lithospheric mantle. Finally, when pieces of the heterogeneous lithospheric upper mantle are recycled within the convective mantle they will imply changes in the composition of the latter and will participate in its heterogeneity.

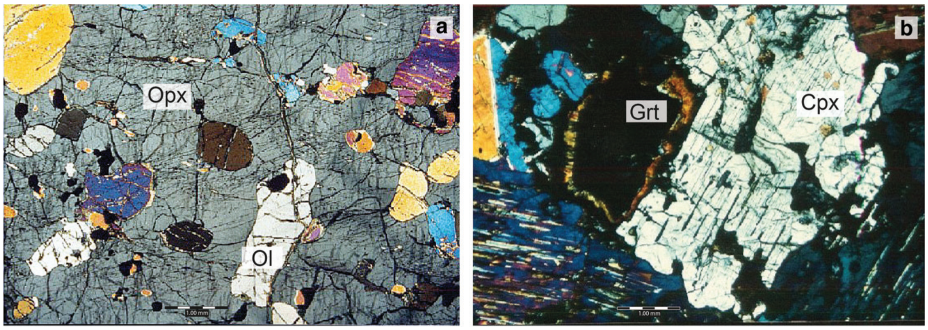

Fig. 11. Photomicrographs of pyroxenite mantle xenoliths from the Kerguelen Archipelago (scale bar: 1 mm, from the collection of M. Grégoire). (***a***) Cumulative olivine-bearing websterite of tholeiitic-transitional affinity; and (***b***) garnet-bearing clinopyroxenite of alkaline affinity. Cpx: clinopyroxene;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

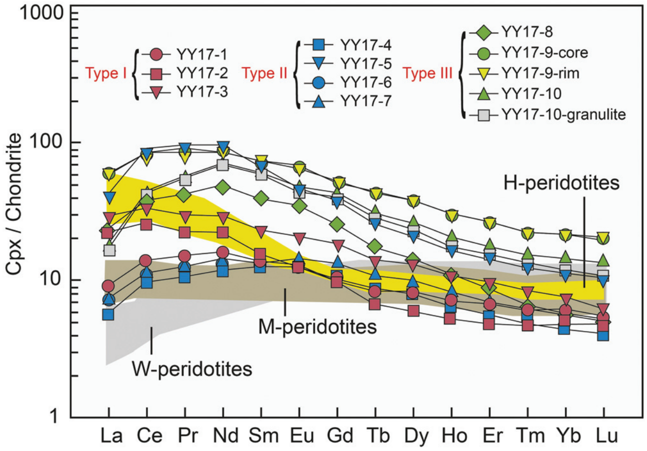

Fig. 12. Chondrite-normalized REE patterns for the clinopyroxene from the Yangyuan pyroxenite xenoliths (modified after Liu *et al*., 2020). Yangyuan peridotites: H-peridotites: highly metasomatized peridotites; M-peridotites: moderately metasomatized peridotites and W-peridotites: weakly metasomatized peridotites.

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