Pervasive, tholeiitic long-term refertilization and heterogeneous metasomatism in Northern Victoria Land lithospheric mantle (Antarctica)

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ABSTRACT

A petrological study of mantle, anhydrous spinel-bearing lherzolites and harzburgites from Greene Point (GP) Northern Victoria Land, (NVL), Antarctica, was performed, with the aim of characterising the lithospheric mantle beneath NVL.

Based on mineral major and trace element models, this mantle domain is supposed to represent a residuum after 10 and 20% of partial melting. Moreover, melting models and isotopic results for Sr and Nd systematic, evidence the large contribution of tholeiitic melts percolating through peridotites. The close correlation with trace element contents in cpx phenocrysts from Ferrar and Karoo tholeiites, allows one to ascribe this refertilization event to Jurassic time. This asthenospheric melt was also able to transfer a garnet signature to the NVL mantle segment. The rare presence of glass and secondary phases prove that GP xenoliths were heterogeneously affected by alkaline metasomatism, probably related to the West Antarctic Rift System opening; this is also widely observed in other NVL localities (i.e. Baker Rocks).

At a fixed P of 15 Kbar, T and fO_2 (950°C; $\Delta\log fO_2$ (QFM) -1.70 to -0.38) values, calculated on the basis of Ballhaus et al., (1991) geothermometer, confirm the tendency of the anhydrous GP xenolith population to have higher equilibration T and comparable redox conditions, with respect to the nearby amphibole-bearing Baker Rocks peridotites.

HIGHLIGHTS

Highlights:

Petrological characterisation of Greene Point (Antarctica) mantle xenoliths

Anomalous modal ratios associated with high Al_2O_3 in opx and cpx

Garnet signature inherited from tholeiitic refertilization

KEY WORDS

Mantle xenoliths, tholeiitic refertilization, garnet signature.

1. Introduction

Extensive petrological studies were carried out on mantle xenoliths from Northern Victoria Land (NVL), in order to define the petrological features of this portion of the Antarctic lithospheric mantle domain. Thermobarometric conditions of this area were investigated by Berg et al. (1989) on a suite of granulites entrained in Cenozoic alkaline volcanic rocks from the McMurdo volcanic group and they depicted a geotherm; the data were later confirmed by P-T estimates obtained from mantle xenoliths in Mt. Melbourne lavas (Beccaluva et al.,1991a). Constraints on the nature and evolution of the mantle beneath this region were proposed by Coltorti et al. (2004), who explained the amphibole in mantle xenoliths from Baker Rocks as being a reaction between under-saturated alkaline-silicate metasomatic fluids and pre-existing clinopyroxene and spinel. A suite of anhydrous mantle xenoliths entrained in the Cenozoic volcanic products of the Greene Point (GP) area was investigated by Perinelli et al. (2006). On the basis of clinopyroxene trace element contents, the authors concluded that some portions of the lithospheric mantle originated in the garnet stability field and later equilibrated in the spinel facies. Partial melting event/s were followed by cryptic and modal metasomatism characterised by Fe-Ti addition and variable LREE-enrichments in the clinopyroxene. Isotopic studies on Greene Point and Baker Rocks xenoliths also highlighted an eclogitic component in the mantle source of the magmatism, which is possibly related to the Ross subduction event (Melchiorre et al., 2011). In the above mentioned studies, it is evident that the lithospheric mantle below the West Antarctic Rift System (WARS) is highly chemically and mineralogically heterogeneous, but a complete understanding of its evolution was not achieved. In order to better define the petrological characteristics of the GP (NVL, 73°46,186’S,165°57,003E’) mantle xenolith population, already described by Perinelli et al. (2006; 2011) and Melchiorre et al. (2011), we present a new dataset, which further supports the heterogeneity of the lithosphere beneath this region. The study also proposes a new model which takes into account the evolution of these xenoliths and provides a different explanation for the garnet signature evidenced in some GP clinopyroxene.

2. Geological setting

WARS is one of the largest and least known active rifts in the world. This largely ice-covered area is over 3,000 km long, from Queen Maud Mountains-Northern Victoria Land to Ellsworth-Whitmore-Horlick Mountains, and 750 to 1000 km wide (Le Masurier and Thomson, 1990; Behrendt et al., 1991;1992; Fig. 1). It is geometrically asymmetric: its western flank is placed in Marie Byrd Land, with an average elevation of 3,000 m in the central part and is characterised by a basin and range topography (Le Masurier and Rex, 1989). The opposite flank, in Northern Victoria Land, consists of the Transantarctic Mountains (up to 4,500 m high), which are the uplifted roots of the early Paleozoic Ross Orogen (Stump, 1995 and references therein).

During the Ross Orogeny, NW-SE to NNW-SSE striking tectonic discontinuities were generated within the Transantarctic Mountains (Gibson and Wright, 1985; Rocchi et al., 1998; Finn et al., 1999); one of these was the Tinker Campbell Discontinuity that now separates the area of Baker Rocks from that of Greene Point. In 100 million years (from Devonian to Triassic) this orogen became the Kukri Peneplain, successively affected by the Jurassic magmatism of the Ferrar Dolerites, a large igneous province emplaced along the backbone of the Ross Orogen (Schmidt and Rowley, 1986; Storey and Alabaster, 1991; Elliot, 1999). The Cretaceous was characterised by a phase of amagmatic rifting with the formation of four N-S oriented basins in the Ross Sea and a widespread denudation of the Transantarctic Mountains (Stump and Fitzgerald, 1992; Balestrieri et al., 1994; Fitzgerald, 1994; Fitzgerald and Stump, 1997). Since the Eocene, a diffuse igneous activity characterised the WARS (Fig. 1). In NVL, plutons and dike swarms were emplaced into an area of about 400x80 km, known as the Meander Intrusive Group (Müller et al., 1991; Tonarini et al., 1997), while the volcanic products formed the McMurdo Volcanic Group (Kyle, 1990). In this volcanic group, basic lavas carry abundant ultramafic xenoliths, providing a useful source of information on the nature of the lithospheric mantle beneath the rift.

Nodules from GP were found in the talus deposit of several lava flows and the sampling was carried out during the XX Italian Expedition organised by PNRA (Programma Nazionale Ricerche in Antartide) during the 2004/05 Austral summer.

3. Methods

Major element compositions of minerals and glass were determined by combined microscopic and back-scattered electron (BSE) imagining, followed by analysis using a CAMECA SX100 electron microprobe equipped with four WD and one ED spectrometers at the Department of Lithospheric Research, University of Wien (Austria). The operating conditions were as follows: 15 kV accelerating voltage, 20 nA beam current, 20 s counting time on peak position. In order to minimise the loss of Na and K, a 5µm defocused beam and 10 s counting time on peak position were applied for glass analyses. Natural and synthetic standards were used for calibration and PAP corrections were applied to the intensity data (Pouchou and Pichoir, 1991). The concentration of trace elements in pyroxenes and glass was obtained by laser ablation microprobe-inductively coupled plasma mass spectrometry (LAM-ICP-MS) at the C.N.R. Istituto di Georisorse, Pavia (Italy). The basic set and protocol were described by Tiepolo et al. (2003). NIST 610 and NIST 612 standard glasses were used to calibrate the relative element sensitivity. The precision and accuracy of trace element analyses were assessed by the standard sample BCR-2 (reference values from USGS Geochemical Reference Materials Database). Each analysis was corrected with internal standards using CaO for cpx and glass, and SiO_2 for opx. The detection limit is a function of the ablation volume and counting time, and is therefore calculated for each analysis; the ablation volume, in fact, greatly depends on the instrument configuration. As a consequence, the detection limit reduces if spot size, beam power and cell gas flow are decreased. Since analyses for clinopyroxene were performed using a smaller spot size and lower beam power, the detection limit for some elements was up to two times less than that of standard analyses. A beam diameter of 40-100 µm and a scanning rate of 20 µm s^1 were used. The theoretical limit of detection ranges between 10 and 20 ppb for REE, Ba, Th, U, and Zr and 2 ppm for Ti.

4. Petrography

GP mantle xenoliths are anhydrous lherzolites (Lh) and harzburgites (Hz) and are almost equally represented. Because of their relatively small size, the whole-rock analysis was not performed; the modal proportion was estimated by point counting and averaging two runs with more than 2,000 points for each thin section (Table 1). The lherzolites contain olivine (ol, 60-76 vol%), orthopyroxene (opx, 15-27 vol%), clinopyroxene (cpx, 7-13 vol%) and spinel (sp, 1-3 vol%), while the harzburgites contain ol (62-84 vol%), opx (15-35 vol%), cpx (2-5 vol%), and sp (< 1 vol%).

Even considering the modal estimating error as well as the limited representativeness of the lithotypes, two out of three samples (GP78, GP23) were classified as harzburgites because of the anomalously high ol/opx ratio (Table 1) with respect to the common residual peridotite modal proportion (Niu, 2004).

Using the terminology of Mercier and Nicolas (1975), the GP prevalent textural type is protogranular (Fig. 2), with large (up to 3 mm) grains of opx and ol. Opx occasionally can reach 5 mm in size and is accompanied by strong kink-banded ol (GP23 and CD305; Fig. 2a). Ol is present as large crystals (up to 5 mm in GP23 and CD305). With respect to ol and opx, cpx is smaller (~ 0.5 mm) and often associated with sp, vermicular and lobated in shape (Fig.2 F and G).

In most of the samples, the primary paragenesis does not show evidence of phase destabilisation, although a few xenoliths present some sort of “pyrometamorphic” textures (Coltorti et al.,1999; Beccaluva et al., 2001).These include opx and cpx grains exhibiting partial (spongy rim, Fig. 2E and F) or complete destabilisation, with a progressive replacement by cpx2, and rare glassy patches and veinlets. The latter do not propagate from the host basalt, and do not present textural signs of being linked to basaltic infiltration. The largest cpx grains sometimes show opx exsolution lamellae (i.e. GP 9, Fig. 2H).

5. Mineral chemistry

On the basis of both major and trace element contents of opx and cpx and outlining three distinct compositional fields, three main groups can be identified in GP mantle xenoliths, although some exceptions are also present.

5.1 Lherzolites Group 1 (Lh Group 1)

Lh Group 1 is represented by samples GP 9 and GP 13. Within each sample, opx is homogenous in composition, with an mg# [=Mg/(Mg+Fe)*100 mol] varying between 90.95 and 91.60 and Al_2O_3 contents from 2.60 to 4.28 wt%; GP 9 opx show a tendency towards higher Al_2O_3 values, which however can be attributed to the presence of patent exsolution lamellae (Fig. 3A; Table 2).

Chondrite-normalised trace element patterns of opx are characterised by a systematic depletion of light REE (LREE) with respect to heavy REE (HREE) [$(Ce/Yb)_N$ from 0.020 to 0.027; Fig. 4A; Table 3].

Large unreacted cpx and the core of spongy grains are Cr-rich augites (Morimoto et al., 1988). They present mg# values in the range of 91.55-93.24 and Al_2O_3 contents from 3.55 to 6.02 wt% (Fig. 3B;

Table 4); TiO_2 never exceeds 0.41 wt% and Cr_2O_3 is relatively constant (~ 1.40 wt%). In the chondrite-normalised diagrams, these cpx are depleted in Th, U, Nb, and Ta with respect to LREE (Fig. 5A; Table 5) and show slight Ti, Zr and Hf negative anomalies accompanied by a LREE-enrichment with respect to MREE.

5.2. Lherzolite Group 2 (Lh Group 2)

In terms of major element contents, samples CD305, GP28, GP30, GP25 and GP84 belong to this group; however, GP84 records cpx trace element contents comparable to those of harzburgites (Fig. 5C and 6C), it was therefore removed from the *Lh Group2* and described in the Hz group (*see Hz Group 3*). Three cpx separates (GP73, GP66, GP98) were also analysed. They can be attributed to this group in terms of major and trace elements, although GP73 shows a slight enrichment in LREE with respect to the others.

On the whole, this group shows opx characterised by almost constant mg# values (91.36-92.62) and Al_2O_3 contents ranging from 3.98 to 4.92 wt% (Fig. 3A). At comparable or higher MgO contents (Table 2), opx appear enriched in Al_2O_3. As for *Lh Group 1*, chondrite-normalised trace element patterns are characterised by a systematic depletion of LREE with respect to HREE (Fig4 B; Table 3).

Coherently with opx, cpx major element compositions show Al_2O_3 contents (4.19-6.42 wt%) higher than those of the *Lh Group 1* cpx (Table 4). In chondrite-normalised diagrams, cpx are depleted in Th, U, Nb, and Ta with respect to LREE, and show slight to marked Zr, Hf and Ti negative anomalies (Fig. 5B). The distinct REE profiles are characterised by slightly convex patterns with $(La/Sm)_N$ and $(Dy/Yb)_N$ in the range of 0.15- 0.53 and 1.04 -1.62 respectively (Fig. 6B; Table 5). The GP30 cpx show an unusual (for mantle peridotites) slightly positive Eu anomaly (Eu/Eu*=1.25). *Lh Group 2* cpx HREE profiles suggest a relationship with a co-existing garnet.

5.3. Harzburgite Group 3 (Hz Group 3)

Harzburgites GP23 and GP78 belong to this group and, on the whole, they follow the same major element residuum trend of *Lh Group 1* (Fig. 3). Referring to its opx composition only, Hz GP81 can be included in the *Hz Group 3*.

Opx present mg# values and Al_2O_3 content between 92.02 and 92.58 and between 2.33 and 3.44 wt% respectively (Table 2). The chondrite-normalised trace elements are also characterised by fractioned REE patterns systematically depleted in LREE. As expected, opx of this group show the most residual character (i.e. Yb_N = 0.44 in Hz GP81; Fig. 4C).

Except for Hz GP81 which shows cpx with Al_2O_3 contents comparable with those of *Lh Group 1*, the rest of the group tends to have cpx with lower Al_2O_3 contents (2.32-3.39 wt%) and higher mg# (93.36-93.92) than both *Lh Groups 1* and *2* (Fig. 3B; Table 4). The trace elements of *Hz Group 3* cpx show the lowest HREE contents (Table 5), with a strong positive fractionated L-MREE and flat HREE [$(Gd/Yb)_N$ = 0.63-3.30; Fig.6c].

Hz GP81 has cpx trace element profiles corresponding to cpx *Lh group 1*; this sample also shows small re-crystalised cpx, that can be texturally ascribed to cpx2 type (Fig. 2); among all groups, they record the highest LREE values [with Yb_N up to 4.14 and $1< (Ce/Yb)_N >4$)] (Fig. 6A).

5.4 Olivine, Spinel and Secondary phases (and glasses)

Although the above described groups can also be distinguished on the basis of ol mg# values (*Lh Group 1*: 90.52-91.31; *Lh Group 2*: 91.24-92.66; *Hz Group 3*: 91.60-92.38; Fig 3C), the three distinct trends are not clearly identifiable. The NiO content is 0.38-0.40 wt%, on average, matching the typical values of mantle olivine and CaO is always close to the detection limit (Table 6).

In the entire xenolith suite, sp follow the expected negative correlation between Cr# [=Cr/(Cr+Al)*100 mol] and mg#, with Cr# ranging from 17.50 to 50.48 and mg# from 67.30 to 82.67, with the harzburgites showing the most restitic composition (Table 7). On the whole, they fit the abyssal peridotite compositional field as defined by Dick and Bullen (1984) (Fig. 3D). Both ol and sp in all lithotypes record an abrupt decrease of mg# accompanied by an increase of TiO_2 contents (sp) approaching the host basalt, as indicated by the displacement towards iron-rich compositions (not included in Fig. 3D) (Bonadiman et al., 2011).

Cpx spongy rims tend to have higher Cr_2O_3 and lower Al_2O_3 contents with respect to the clean portion of the same crystal. Rare glass veins and patches are recognised in all lithotypes. They are silica-rich, rather homogeneous in composition and characterised by high SiO_2 (60.45-67.56 wt%) and alkali contents (K_2O 5.40-6.80 wt%, Na_2O 5.75-8.10 wt%). If we assume the total of the major oxides, which is always close to 100 wt%, as a marker, they contain zero or negligible volatiles contents, (Table 8). In the silica *vs* total alkali diagram (TAS), glasses plot in the Phonolite and Trachyte fields (Fig. 7). Their composition is notably different from that occurring in the amphibole-bearing xenolith suite of the nearby Baker Rocks (BR); it shows remarkable lower TiO_2 and CaO contents (0.38-2.90 wt% and 0.05-0.53 wt%) and relatively higher alkali contents, especially regarding K_2O (Fig. 8; Coltorti et al., 2004; Perinelli et al., 2006). FeO_{tot} and MgO are always below 2.80 and 3.10 wt% respectively (Table 8). Only Al_2O_3 and Na_2O reflect a (negative) correlation with SiO_2, deviating from the BR glasses that show a strong negative correlation of silica with CaO, FeO_{tot} and TiO_2 (Coltorti et al., 2004). It was possible to carry out trace element glass analyses for only two lherzolites of *LhGroup 2*. The glasses record high LILE abundances (Ba up to 288.17 ppm) and are characterised by flat to positive fractioned-REE patterns $(La/Yb)_N$:7.37 - 21.31; Yb_N : 0.98-17.41 (Table 9), with marked Rb and K positive anomalies. With respect to the BR glass population, GP glasses show no evidence of Zr (and Hf) positive anomalies (Fig. 9).

6. Geothermobarometric constrains and redox conditions

In order to provide the thermobarometric conditions of this mantle segment, the inter-mineral chemical equilibrium between silicate phases and spinel is evaluated first. The Fe/Mg equilibrium (Kd) among ol, opx and cpx core pairs is calculated using the equations experimentally obtained by Brey and Kôhler (1990) at various temperatures, while the Fe/Mg distribution between opx and sp (core pairs) is estimated following Liermann and Ganguly (2003). In the entire xenolith suite, opx-ol are equilibrated along the two theoretical curves at 900 and 1100 °C (Fig. 10A). Kd $Fe/Mg^{sp/ol}$ *vs* cr# in sp (Liermann and Ganguly, 2003) reveals that sp is also in equilibrium with ol (Fig. 10 B).

Fe/Mg in opx and cpx pairs (not showed) is randomly distributed; this implies that the temperatures estimated by the opx-cpx equilibrium are not reliable. This leads to the selection of the ol-sp thermometer of O'Neill and Wall (1987), modified by Ballhaus et al. (1991), as the trustable geothermometer to evaluate the GP thermal conditions. As no reliable geobarometer exists for spinel-bearing peridotites (Green and Hibberson, 1970; O'Neill, 1981), the pressure can only be constrained by the presence of spinel and for the calculation it is assumed to be 15 Kbar, as for previously studied xenolith suites in the nearby area (Coltorti et al., 2004; Perinelli et al., 2006; Bonadiman et al., 2014)

Irrespective to the lithology, the temperature varies between 888°C and 1073°C with a maximum deviation of ~ 50°C, although for the great majority of the samples it is close to 950°C (Table 1). The intrinsic error of the method is ~30°C (1σ). The highest temperature is observed for the texturally most equilibrated GP13 Lh. By contrast, the lowest temperature is recorded by the GP9 Lh. Considering the large cpx with exsolution lamellae (Fig. 2H), the opx-cpx Brey and Kôhler (1990) geothermometer was only applied to this sample. The estimated temperature of the exsolved crystal is 912°C (σ~ 50 °C), in agreement with the temperatures of the co-existing ol and sp. On the whole, these data confirm the tendency for the anhydrous GP xenolith population to have higher equilibration temperatures with respect to the nearby amphibole-bearing Baker Rocks (BR) peridotites (800-940 °C) (Fig. 11; Coltorti et al., 2004; Perinelli et al., 2012; Bonadiman et al., 2014).

On the basis of the ol-sp temperatures, the redox conditions were estimated using the Ballhaus et al. (1991) oxygeobarometer equation. GP samples yield fO_2 ranging from Δlog (QFM) -1.70 to -0.39, reflecting redox conditions comparable to those of the amphibole-bearing BR xenoliths (Fig. 11). All samples fall into the range of the abyssal peridotites (Δlog fO_2 (QFM) from -2.0 to +1.0), which is close to the mean value of the continental (non cratonic) lithosphere dataset ((Δlog fO_2 = - 0.68 Foley, 2010).

7. Discussion

7. 1 Melting models

In the frame of a hypothetical progressive residual trend, the abundance of the most fusible elements (i.e.: Al, Ti) in the minerals systematically decreases with increasing mg#. The melting degrees (F) are provided by the major element mineral compositions following the method of Upton et al. (2011).

Al is a good parameter, as it is extremely fusible in a basaltic system and it rapidly decreases in opx, cpx and sp with an increase in the degree of partial melting (Ionov and Hofmann, 2007; Faccini et al., 2014). Taking into account the potential Mg/Fe and Al equilibria between opx and sp (Fig 10 A and B), the hypothetical melting curve depicts the Al_2O_3 distribution between the two phases (Fig 12A) and provides reliable results for an estimation of the melting degree. Accordingly, GP opx-sp pairs plot on the theoretical curve and assign to the GP suite a melting degree in the range of 10-17 % (the absence of a primary sp analysis in GP78 prevented the modelling of this sample). In GP9 it is difficult to cluster the melting degree values, as it shows a large span of Al_2O_3 contents, certainly related to the presence of the large exsoluted cpx (Fig 2H), which influences the Al diffusion path.

If we take into account Al_2O_3 *vs* MgO intra-mineral distribution in opx (Fig 12B), it reflects not only a residual character but also a more complex process. In fact, with the exception of opx in GP13 Lh (that coherently reflect the same value of partial melting degree deduced by the opx-sp curve), the entire suite follows a melting trend shifted towards higher MgO contents with respect to the theoretical curve. This effect is also observed in cpx, where the Al_2O_3 *vs* MgO theoretical melting curve (Fig. 12C) is not followed by any sample, with the exception of GP13. In this framework, it is difficult to assign a potential residual melting degree on the basis of only intra-mineral px major element compositions. GP13 Lh is texturally well equilibrated (Fig. 2G) without any modal disproportion among the peridotitic phases (Table 1) and all the melting models applied coherently indicate F around ~10-12% (Table 10)

In the GP xenolith suite, the melting degree estimated by the Al_2O_3 opx-sp distribution is in agreement with that calculated using HREE (Yb) and Y in cpx (F=8-23%; Fig. 12D) (Johnson et al., 1990; Hellebrand et al., 2002; Bonadiman et al., 2005).

It is important to note that, although GP13 Lh represents the most equilibrated GP peridotites, a discrepancy in the F values between major and trace melting models is recorded (Table 10). Taking into account the F results from the two methods and the potential error of these estimates, reliable F values can be attributed by considering the average between the values obtained from opx-sp and HREE methods (averaged F range: 11- 23 %; Table 10)

7.2 Isotopic composition

In fig. 13 GP peridotites depict a trend that moves from DMM towards the EMI enriched composition (Melchiorre et al., 2011). GP 25 is the least radiogenic sample falling close to the DMM field, although it is characterised by a slightly higher $^{87}Sr/^{86}Sr$ isotopic ratio (0.70277) with respect to the depleted reservoir. GP98 and GP73 plot near the HIMU field ($^{87}Sr/^{86}Sr$ 0.70310, 0.70338 and $^{143}Nd/^{144}Nd$ 0.51299, 0.5128 respectively), while GP66 ($^{87}Sr/^{86}Sr$ 0.70434 and $^{143}Nd/^{144}Nd$ 0.51261) has an isotopic composition similar to that of the typical subcontinental lithospheric mantle (SCLM) from Victoria Land (Nardini et al., 2009; Melchiorre et al. 2011; Perinelli et al., 2011).

The progressive radiogenic enrichment trend of the GP mantle xenoliths may be reproduced assuming that an old asthenospheric DMM-like component (Workman and Hart, 2004) represented by GP 25, interacted with a Sr radiogenic reservoir (i.e the EM-like component). This radiogenic end member is identified in the Ferrar dolerites, which represent the Gondwana low-Ti province (Cox et al., 1967; Cox 1988). They are characterised by higher $^{87}Sr/^{86}Sr$ (>0.707) and lower $^{143}Nd/^{144}Nd$ (<0.5124) with respect to worldwide continental flood basalt (CFB) provinces (Demarchi et al., 2001). A simple Sr-Nd linear mixing between the DMM component and the Ferrar dolerites (Elliot et al., 1999) isotopic compositions is able to reproduce the GP isotopic variability, inferring a contribution of ~5-10% of the Ferrar component.

In a larger frame, the isotopic data for the NVL Cenozoic lavas (Nardini et al., 2009) point towards the HIMU-like isotopic component, as most of the BR amphibole-bearing mantle xenoliths, supporting the hypothesis of the intensive interaction of a Baker Rocks mantle fragment with the Cenozoic alkaline melt (Coltorti et al., 2004). This leads to hypothesise that the NVL mantle domain interacted with the Jurassic melt and this was able to move the isotopic composition towards the EM end member. As testified by a few GP and the majority of BR samples, this interaction was subsequently obscured by the isotopic fingerprint of the younger metasomatism related to the Cenozoic magmatism (Fig. 13).

7.3 The role of the Jurassic tholeiitic melt

Using the mineral percentages *vs* the F model traced for abyssal peridotites (Niu, 2004), only GP13 records chemical (and textural) features representing a coherent melting residua (F ~10%; Fig. 14). In all the other samples, whether the cpx modal percentage of lherzolites properly fits the theoretical trend (Fig. 14) or not, opx shows an anomalously high ol/opx ratio.

This disproportion, with respect to the expected modal composition, combined with an apparent textural equilibrium and the absence of different generations of opx (i.e. Patagonia; Melchiorre et al., 2015), suggests that the peridotite matrix suffered a long term interaction with a sub-alkaline (silica-saturated) melt. This melt was able to increase the opx volume and, contemporaneously, its Al_2O_3 content.

On the other hand, the cpx in a fertile mantle, having a more compatible behaviour for basic melt components, maintains its model percentage, but certainly not its geochemical features (i.e.Al_2O_3, REE). In fact, a strong similarity in REE contents can be observed between the cpx of both *Lh Group 2* and those calculated in equilibrium with the Ferrar Dolerites (Kyle, 1980; Antonini et al., 1999), using the $Kd^{cpx/th}$ from GERM database (Fig. 15).

The magmatic expression of these mantle re-fertilising melts can therefore be identified in the Jurassic tholeiites of the Ferrar Group (ca. 177 Ma) which, together with Paraná (ca. 130 Ma) and Karoo (ca. 180 Ma) represent one of the three major CFB provinces of the southern hemisphere.

In Western Dronning Maud Land (Karoo large igneous province), Riley et al. (2005) report dolerites with geochemical features that reflect a genesis in the presence of garnet in the mantle source. In patchy areas, the NVL mantle segment records a potential garnet signatures as observed in *Lh Group2* samples and documented by Perinelli et al. (2006) and Melchiorre et al. (2011).

The MREE/HREE ratios $(Gd/Yb)_N = 0.98\text{-}1.57$) and a slightly depleted LREE pattern *in Lh Group 2* cpx (Fig. 6B), associated with the high mg# and high Al_2O_3, rule out the likelihood that a melting episode occurred in the garnet-facies and successively re-equilibrated in the spinel stability field (see also Bonadiman et al., 2005; Fig. 16). On the contrary, the garnet signature observed in a few GP lherzolites may reflect the chemistry of the impregnating tholeiitic melts generated from garnet-bearing lherzolites (Riley et al. 2005).

Taking into account that the Ferrar province is generally considered as an extension of the Karoo large igneous province (Harris et al., 1991; Luttinen et al., 1998) and is related to the same event that emplaced the Ferrar dolerites in the NVL region, it is reasonable to think that the asthenospheric (garnet facies) Ferrar tholeiitic magmatism was also responsible for the garnet signature in the refertilised GP mantle domain (mainly *Lh Group 2*).

Finally, the recent metasomatic event (mainly documented in the *Hz Group 3*) is textually supported by spongy rims in large cpx, glassy patches and veinlets and is clearly geochemically expressed by the LREE enriched cpx. These recall those of the nearby BR amphibole-bearing xenolith suite. According to Coltorti et al. (2004) and Perinelli et al. (2006), these features are, in fact, related to the percolation of an alkaline SiO_2-undersaturated melt belonging to the Cenozoic magmatic system of the McMurdo volcanic group.

8. Conclusions

The entire GP mantle xenolith suite reflects a NVL mantle segment equilibrated in a thermal regime of ~950 °C, with redox conditions close to ~ -1.04 log units below QFM. Compared with amphibole-bearing mantle xenoliths from nearby localities, the GP xenolith population presents higher T at comparable oxidised conditions.

Based on major sp-opx major elements, and HREE in cpx, *Lh Group 1* and *Lh Group 2* may represent a residuum after ~10 to 17% of partial melting in the spinel stability field, which was afterward largely modified by the interaction with tholeiitic and, to a lesser extent, alkaline melts, most probably affecting the mantle domain at different times.

The tholeiitic magmatism that preceded the Gondwana break up (Jurassic), was able to reset the peridotitic system, modifying its mineralogical and geochemical features (i.e.: peridotite mineral disproportion and high opx-cpx Al_2O_3 contents; slightly convex to flat REE cpx patterns), and transferring a garnet signature into the NVL mantle region.

During the Cenozoic, the magmatic system related to the WARS opening locally interacted with the previously re-fertilised peridotitic system, almost completely obscuring the previous refertilization event.

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Figure Captions

Fig.1

Map of northern Victoria Land showing the location of Greene Point and Becker Rocks. In Fig. are shown Ferrar and McMurdo Volcanic products respectively. Inset shows the location of Victoria Land.

Fig. 1 Photomicrograph of representative microstructures in the GP xenoliths. A) Protogranular lherzolites (CD305) comprising large opx and ol; B) Harzburgites (GP81) with pervasive presence of opx surrounded ol grains and small grains of cpx; (C) and (D) lherzolite GP30 characterised by large opx and ol grains, and equilibrated cpx grains; (E) and F) Lherzolite GP25 with large opx surrounded by spongy cpx and lobated sp; (G) lherzolite GP13, characterised by the presence of large sp grains surrounding cpx and larger opx and ol grains; (H) lherzolite GP9; in the picture a detail of the large cpx grain characterised by opx exolution lamellae.

Fig. 3 (A) orthopyroxene compositional variation in terms of Al_2O_3 vs. mg# [(MgO/MgO+FeOtot) molar]; (B) clinopyroxene compositional variation in terms of Al_2O_3 *vs* mg#, in the figures are represented the three different groups (*Lh Group 1*, *Lh Group 2*, *Lh Group 3*) on the basis of ps major element compositions. (C) olivine compositional variation in terms of NiO *vs* mg#, (D) spinel compositional variation in terms of cr# [Cr/(Cr + Al) at.%] vs. mg#. Squares are for lherzolites, circle for harzburgites and triangles for cpx separates.

Fig. 4 Chondrite normalised rare earth element (REE) patterns of orthopyroxenes in the GP xenoliths. (A) *Lh Group 1*, (B) *Lh Group 2*, (3) *Hz Group 3*. Symbols as in Fig. 3.

Fig. 5 Chondrite normalised multi-element diagrams of clinopyroxenes in the GP xenoliths. (A) *Lh Group 1*, (B) *Lh Group 2*, (3) *Hz Group 3*. Symbols as in Fig. 3.

Fig. 6 Chondrite normalised rare earth element (REE) patterns of clinopyroxenes in the GP xenoliths. (A) *Lh Group 1*, (B) *Lh Group 2*, (3) *Hz Group 3*.
The shadow areas represent: *Lh Group 1* dark grey, *Lh Group 2* in light grey, and *Hz Group 3* in grey. Symbols as in Fig. 3.

Fig. 7 Total alkali silica (TAS) (after Le Bas, et al., 1992) of GP and BR glasses. Samples from GP fall on the Phonolite and Trachyte fields, while BR, presenting a higher variability, span from the trachy-basalt to trachy-dacite compositions.

Fig. 8 GP and BR glasses plotted on major element discrimination diagrams (after Coltorti et al., 2000).

Fig.9 Chondrite normalised multi-element diagrams of glass in the GP xenoliths. In comparison are also represented data of BR glass (grey shaded).

Fig. 10 Fe/Mg equilibrium diagrams for ol *vs* opx (A), ol *vs* sp (B). In (A) the equilibrium lines are from Brey & Kôhler (1990) at 800, 900 and 1100 °C. In (B) KdSp-Ol is Fe-Mg partitioning between ol and sp determined on the basis of the Liermann & Ganguly (2003) model. (Fe/Mg) indicates $Fe^{2+/}$Mg, as calculated by stoichiometry for each mineral. Symbols as in Fig. 3.

Fig. 11 Temperature and ($\Delta \log fO_2$) FQM = fO_2 relative to the buffer reaction FMQ calculated with the formula of Ballhaus et al. (1991). T is fixed at 15 Kbar. Grey circles GP, dark squares BR.

Fig. 12 Plot of Al_2O_3 in opx *vs* Al_2O_3 in sp (A), Al_2O_3 *vs* MgO in opx (B) and cpx (C) melting trends (Upton et al., 2011). In (D) melting degrees are estimated on the basis of HREE (Yb) and Y, following the fractional melting model within the spinel stability field based on Zou (1998). In (A) (B) and (C) the Al_2O_3 and MgO contents of PM were calculated on the basis of the McDonough & Sun (1995) mantle model. Model parameters as in Bonadiman *et al*. (2005) and Faccini *et al*. (2013). Thick marks on curves indicate partial melting percentages (F), numbers in brackets are ideal cpx modal contents at F. Symbols as in Fig. 3.

Fig. 13 ^{143}Nd/^{144}Nd *vs* ^{87}Sr/^{86}Sr plot of GP clinopyroxene. Crossed line represents the mixing line between the GP sample and the Ferrar Dolerites (Kyle, 1980). Amphibole bearing BR xenoliths and Cenozoic alkaline lavas also plot into the mixing line.

Fig. 14 Observed modes of olivine, opx and cpx (%) in GP xenoliths *vs* F (extend of melting). PM composition is from Mc Donough and Sun (1995). Symbols as in Fig. 3.

Fig. 15 Comparison between REE patterns of *Lh Group 2* and those calculated in equilibrium with the Ferrar Dolerites (Kyle, 1980), using the $Kd^{cpx/th}$ from GERM database. Symbols as in Fig. 3.

Fig. 16 Comparison between REE patterns of cpx *Lh Group 2* with those of cpx suggesting melt in garnet-facies, successively re-equilibrated in the spinel stability field (Bonadiman et al., 2005).