An insight into the first stages of the Ferrar magmatism: ultramafic cumulates from Harrow Peaks, northern Victoria Land, Antarctica.

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Abstract

Ultramafic xenoliths hosted in Cenozoic hypabyssal rocks were collected from Harrow Peaks (northern Victoria Land, Antarctica) and analysed for in situ (major and trace elements) geochemical purpose. Samples are generally small (<10 cm) and consist of spinel bearing lherzolites, harzburgites, composite xenoliths and one orthopyroxenite, the latter is a lithotype rarely observed in mantle xenoliths of this region and elsewhere in Antarctica. Most of these rocks show equigranular texture with the olivine's boundaries often converging at 120° triple points. The composite xenoliths are formed by large clinopyroxene and/or amphibole veins and a dunitic matrix, characterised by olivine with forsterite contents from 87.46 to 90.21.

Both lherzolites and harzburgites have olivine modal contents that relate to spinel (Cr#: 24.79-63.28) and olivine (Fo: 84.24-88.39) compositions, which do not reflect any residual trend due to a melting process. In turn, all the studied Harrow Peaks xenoliths (including the orthopyroxenite) have olivine ascribed to a cumulus phase, and the presence of the orthopyroxenite suggests that the

inferred melt from which they stemmed, was close to silica saturation. In this view, the geochemical characteristics of lherzolites/harzburgite, dunites and orthopyroxenite were modelled as cogenetic products of a crystallising process occurring at the mantle-crust boundary depth.

The initial crystallisation of olivine from a high Mg-primitive melt (Mg# 72-picrites?) is the main forming process of this group of xenoliths, and the potential temperature of crystallisation was estimated at ~1300 °C, based on the olivine/melt equilibrium. Fe/Mg and REE mineral-melt equilibrium models proved that the Harrow Peaks melts could be related to the initial stage of the Jurassic Ferrar magmatism. These cumulitic fragments stationed in the shallow mantle and were subsequently affected by a late stage alkaline metasomatism, sporadically detected in the northern Victoria Land lithosphere. The metasomatic process formed the LREE-enriched alkaline-type amphiboles, with a complete geochemical disequilibrium with the anhydrous (dunite and orthopyroxenite) matrix.

During the Cenozoic, the xenoliths were brought to the surface by alkaline lavas belonging to the McMurdo volcanism, connected to the West Antarctica Rift System opening.

1. Introduction

The West Antarctic Rift system (WARS) is one of the largest continental rift areas in the world and is comparable to the East African Rift in scale (Martin et al., 2015; Le Masurier and Thomson 1990). Since the Cenozoic it was affected by alkaline magmatism represented by the products of the McMurdo volcanic and Meander intrusive groups (Kyle 1980). The most primitive volcanic products from Victoria Land contain mafic and ultramafic xenoliths in a large spectrum of lithologies that testify for a complex mantle/crust evolution of the Subcontinental Lithospheric Mantle (SCLM). Evidence of mantle partial melting and enrichment events (due to both alkaline metasomatism and refertilisation by tholeiitic melts) as well as crystallization of alkaline melts at the Moho depth have been largely documented (Gamble et al., 1988; Beccaluva et al., 1991; Cooper et al., 2007; Martin

et al., 2015; Pelorosso et al., 2016). Geochemical and isotopic data trace back the refertilisation process of SCLM in the northern Victoria Land prior to the Cenozoic (Melchiorre et al., 2011; Pelorosso et al., 2016), suggesting a possible connection with the most important magmatic activity in Antarctica, which occurred before the Cenozoic: the Jurassic magmatism, part of the Karoo-Ferrar Large Igneous Province. The Jurassic magmatism produced outcrops that stretch over 3500 km from the Theron Mountains of Antarctica to southeast Australia (Elliot & Fleming 2004), including several volcanic bodies such as mafic sills, flood basalts (i.e. Kirkpatrick basalt, Vestfjella ferropicrites), phreatomagmatic volcanic rocks, layered mafic intrusions (i.e. Ferrar dolerite sill) and mafic dykes (Kyle et al., 1989; Fleming 1995; Elliot et al., 1999; Storey et al., 2013; Heinonen and Luttinen, 2010; Bedard et al., 2007). In the Harrow Peaks (74.0 2785°S 164.47466°E, [Fig. 1](#)), where the alkaline Cenozoic magmatism is dominant as well as in many other northern Victoria Land magmatic localities, lavas brought to the surface ultramafic xenoliths. The samples available for this study were collected during the XX Italian Expedition organised by PNRA (Programma Nazionale Ricerche in Antartide) in the 2004/05 Austral summer. They are mainly (amphibole bearing) spinel peridotites, but composite xenoliths are also abundant. The Harrow Peaks samples include dunites and one orthopyroxenite, which are rarely observed or absent in the xenolith populations sampled in the region and carried by the same magmatic system.

A few of these xenoliths were studied by Gentili et al. (2005) in order to evaluate the role of amphibole formation in the modification of the original redox condition of this mantle domain. The quoted authors revealed extremely high redox conditions ($\Delta \log \text{QFM } f\text{O}_2 = \sim +5, +7$) for the amphibole formation, in clear disequilibrium with the peridotite matrix.

Here we present new petrological and geochemical data of this unique group of ultramafic xenoliths, which provide evidence for a magmatic origin and show to what extent these rocks have been affected by metasomatic event(s), and their relationships with Victoria Land SCLM.

2. Sample description and Petrography

The ultramafic xenoliths found in the Harrow Peaks lavas are rather small (2 to 5 cm) and sub-rounded in shape; samples showing textural and geochemical evidence of host-basalt contamination (Bonadiman et al., 2011) were included in the study for a comparative purpose.

Three out of the eight samples selected for this study are composite xenoliths. Hydrous phases (mainly amphibole) occur in all samples, showing significantly different grain size and modal contents from sample to sample.

The mineral modal proportion was determined by point counting, averaging two runs with more than 2,000 points for each thin section (2.5 x 4.0 cm): the results were confirmed by thin section colour code analyses (ImageJ© software) and reported in Table 1. Based on the classification diagram for mafic and ultramafic rocks (Fig. 2; Streickeisen, 1974), the Harrow Peaks xenoliths consist of spinel-bearing lherzolites (HP151, HP164 and HP166), one harzburgite (HP144) and one orthopyroxenite (HP163).

The composite xenoliths combine various lithologies that make difficult to apply the standard nomenclature for ultramafic rocks. HP124 and HP143 are made up of a dunite matrix crossed by clinopyroxene (HP143, Fig. 3a) and clinopyroxene + amphibole + rare phlogopite (HP124, Fig. 3b) veins; HP121 is also composite with a harzburgite matrix (for containing up to 6% and 4% of modal orthopyroxenes and clinopyroxenes, respectively), crosscut by a large amphibole vein (Fig. 3c). The textural similarities and the high olivine modal contents (Fig. 2; Table 1) led us to equate HP121 sample with the rest of the composite dunites.

Regardless of the lithology, most of the samples exhibit tabular to equigranular textural types (Mercier & Nicolas 1975) with equidimensional, polygonal in shape olivines (1 mm) delimited by boundaries often converging at 120° (i.e. Figs. 4a, b). The modal content of the orthopyroxene is higher in lherzolites (18 - 26 volume. %) with respect to the harzburgite (13 vol. %). The clinopyroxene in lherzolites/harzburgite is small and interstitial (Fig. 4e); small irregular spinel is scattered within the olivine grains. Amphibole is present both as disseminated crystals (i.e. HP124;

Fig. 4b) or in veins (i.e. HP121; Fig.4d), and it is associated with rare phlogopite (HP124). The “layered” textural effect evidenced in some samples (i.e. HP143 or HP151; Figs. 3a, e) is marked by a trail of small irregular spinels within the olivine grains, and/or by the amphibole/clinopyroxene veins in clear textural disequilibrium with the dunite matrix (HP121; HP124 and HP143). The predominant equigranular texture exhibited by Harrow Peaks xenoliths is completely absent in most of the xenolith suits from the same volcanic district (i.e. Baker Rocks and Greene Point), where the protogranular texture is commonly observed. In addition, secondary textures (i.e. glassy patches and sieved pyroxenes, spongy rims) are rarer with respect to other Antarctic xenolith occurrences (Coltorti et al., 2004; Pelorosso et al., 2016). They consist of glassy thin menisc between minerals (including disseminated amphiboles) or small pools (<100 microns) containing microlites of olivine, spinel and clinopyroxene (HP124, HP143, HP144, and HP151).

3. Analytical Methods

Bulk major and trace element analyses were precluded due to the small size of the xenoliths. Instead, thin and thick sections were prepared for in situ analytical protocols. Major element compositions of minerals and glass were determined by a CAMECA SX100 electron microprobe equipped with four wavelengths dispersive (WD) and one Energy Dispersive (ED) spectrometer, at the Department of Lithospheric Research, University of Wien (Austria). The operating conditions were 15 kV accelerating voltage, 20 nA beam current and 20 s counting time on peak position. In order to minimise Na and K loss, 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 concentrations of trace elements in pyroxene and glass were obtained by a Laser Ablation Microprobe-Inductively

Coupled Plasma Mass Spectrometry (LAM-ICP-MS) at Geosciences Montpellier Université de Montpellier and at igg CNR, Pavia. Both laboratories applied the same analytical protocol and processing data system.

Each analysis took 120s: 60s background acquisition (gas blank) and 60s acquisition for the sample. The analyses were corrected with internal standards using CaO for clinopyroxene and glass, and SiO₂ for orthopyroxene. 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, consequently, the detection limit decreases if spot size, beam power and cell gas flow are reduced. A beam diameter of 40-100 µm and a scanning rate of 20 µm/s 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.

Data were processed using the Glitter[®] software (van Achterbergh et al., 2001), and element concentrations were calibrated against the NIST612 certified reference material, using the values of Pearce et al. (1997).

4. Mineral chemistry

Major element data collected by electron microprobe and reported as wt % oxides are provided for olivine, orthopyroxene, clinopyroxene and spinel in [Tables S1, S2 and S3](#), as well as for amphibole in [Table S4 of Supplementary Material](#).

4.1 Mineral major element compositions

Olivine is the ubiquitous phase of the Harrow Peaks peridotites; however, despite the variety of the lithological types and the presence of composite xenoliths, it has a relatively narrow range of composition. The forsterite (Fo) content, calculated as $[Mg/(Mg+Fe_{tot}) \times 100 \text{ atomic formula units}]$,

varies from 86.60 to 90.45, and the NiO content from 0.26 to 0.47 wt %, reported as sample average (Fig. 5a; Table S1 of Supplementary Material); Fo values of olivine (~3% in volume) in orthopyroxenite HP163 and lherzolite HP164 are not included in this compositional range; they are in the range of 80.45-85.88, reflecting the common chemical zoning of cumulus olivines (Fig. 5a; Table S1 of Supplementary Material).

Orthopyroxene varies in the range of $\text{En}_{66.62-83.89}\text{Fs}_{0.19-0.21}\text{Wo}_{0.038-0.17}$ with Mg# [Mg# = molar $\text{Mg}/(\text{Mg}+\text{Fe}_{\text{tot}}) \times 100$] = 83.27-89.60 showing an apparent equilibrium with the coexisting olivine in all the investigated samples, and remarkable differences from those of the residual peridotites. Orthopyroxene presents Al_2O_3 contents mostly in the range of 1.24 to 3.32 wt %, and Cr_2O_3 and TiO_2 (as sample compositional averages) always <0.50 and <0.20 wt %, respectively (Fig. 5b; Table S2 of Supplementary Material).

Spinel is chemically heterogeneous, varying in composition from sample to sample without any clear relationship with the lithological types. In composite xenoliths HP124 and HP143 it shows high variable Cr# [Cr# = molar $\text{Cr}/(\text{Cr} + \text{Al}) \times 100$] (24.25-61.69) and Mg# (60.81-52.26) values, with TiO_2 (0.5- 1.04 wt%) contents approaching the spinel composition of HP163. HP121 contains relatively low-Ti spinel ($\text{TiO}_2=0.26-0.36$ wt %) with the lowest Fe_2O_3 (0.71 wt % as sample average) recorded by the Harrow Peaks xenolith population (Fig. 5c; Table S3 of Supplementary Material). Spinel from harzburgite HP144 and lherzolite HP151 present the highest and the lowest Cr# values, respectively, at similar low Fe_2O_3 (2.54-3.71 wt%) and (lowest) TiO_2 (<0.22 wt %) (Fig. 5c). The spinel composition in terms of Cr# is also compared to the Fo content in the Arai (1994, Fig. 6) in which Harrow Peaks samples plot outside the mantle array theoretical field.

Clinopyroxene occurs in this group of ultramafic xenoliths in evident textural disequilibrium with the olivine + spinel + (orthopyroxene) assemblage. It is Cr-rich augite following the Morimoto (1989) classification scheme, and heterogeneous in composition from one grain to another. Irrespective of lithology, Mg# values span from 85.63 to 93.89 with $\text{TiO}_2 < 0.55$ wt % and $\text{Al}_2\text{O}_3 < 4.13$ wt % as sample averages (Figs., 7a, b; Table S4 of Supplementary Material). Only a few grains

of clinopyroxene concentrated in veins of both HP124 and HP143 dunites have TiO_2 and Al_2O_3 contents that reflect a host basalt low-pressure perturbation (Figs. 7 a, b). Among the possible exchanging cations in M1 and M2 clinopyroxene sites, the only correlation observed is the progressive Na enrichment at lower Mg#.

Amphibole is texturally related to the clinopyroxene and generally occurs as vein in dunites, while it is small and disseminated in lherzolites and the orthopyroxenite. It is chemically classified as kaersutite (HP121, HP143 and HP163), magnesio-hastingsite (HP124) and ferri-kaersutite (HP164), following the Leake et al. (1997) scheme, with Mg# ranging from 82.86 to 90.39 and TiO_2 and Al_2O_3 contents varying from 1.05 to 4.19 wt% and 11.43 to 14.86 %, respectively (Gentili et al., 2015, Figs. 7c, d; Table S5 of Supplementary Material). The Harrow Peaks amphibole group had already been investigated for a crystallochemical study that led to the discovery of a new amphibole type: the ferri-kaersutite (Gentili et al. 2015). Based on the crystallochemical model of Oberti et al. (2000), Harrow Peaks amphibole have lattice parameters primary ascribable to the magmatic-type (Gentili et al. 2015), whereas amphiboles from the rest of Antarctic xenoliths have chemical and structural characteristics that fall within the “mantle-type” (Oberti et al. 2000; Bonadiman et al., 2014).

Phlogopite grains occurring in HP124 appear chemically zoned (Mg# ~ 91-92), coherent with the observed variability of the other phases forming the vein. They have TiO_2 and Al_2O_3 contents between 1.41-2.19 wt% and 13.88-15.86 wt%, respectively; alkalis are instead constant (Na_2O ~0.60 wt%, K_2O ~ 9.60 wt%, Table S5 of Supplementary Material).

Glass is extremely variable in composition (Table S6 of Supplementary Material) with SiO_2 contents ranging from 56.21 to 68.35 wt %, in relation to the textural position and adjacent mineral type, as well as the xenolith's lithology.

4.2 Pyroxene trace elements

Trace element concentrations of pyroxenes averaged *per* sample are reported in [Table 2](#), whereas all the LA-ICP-MS data are in [Tables S7 –S10 of Supplementary Material](#).

In the chondrite-normalised REE+Sr+Zr+Hf+Ti+Y diagram, orthopyroxene displays a H-MREE downward trend, with the slope increasing in the Yb and Lu region and with an ubiquitous positive Ti anomaly ([Fig. 8](#)). HP121 and HP143 are composite xenoliths with orthopyroxene-bearing dunite matrix, but only HP143 contains a few orthopyroxenes large enough for in situ trace element analyses. In detail, the chondrite-normalised trace element distribution of HP143 orthopyroxene mimics that of the HP164 lherzolite (clinopyroxene modal contents ~11 in volume %) and, to a lesser extent, that of the HP151 lherzolite (clinopyroxene ~9 in volume %), with $Yb_N/Gd_N = 4.16$ and remarkable Ti ($Ti/Ti^* = 5.6$) positive and Sr ($Sr/Sr^* = 0.84$) negative anomalies. HP166 lherzolite (clinopyroxene ~7 in volume %) displays orthopyroxene with high Zr, Hf (and Ti) and M-HREE contents, depicting a M-HREE chondrite normalised profile ~7 times higher, but LREE and LILE contents comparable to the orthopyroxene in lherzolites (and dunite). HP166 orthopyroxene shows coupled strong Ti and Zr (Hf) positive anomalies. In turn, orthopyroxene in HP144 harzburgite (clinopyroxene ~3 and orthopyroxene ~13 in volume %) contains the lowest M-HREE (plus Ti), but the highest LREE and LILE concentrations of the entire xenolith population ([Table 2](#)), exhibiting almost flat or slightly L-REE enriched patterns ($Ce_N/Nd_N \sim 2$), ([Fig. 8](#), [Table 2](#)).

Disseminated clinopyroxene is scarce in Harrow Peaks xenoliths. HP164 is the clinopyroxene-richest sample with 11 volume % of modal content ([Table 1](#)). Clinopyroxene is extremely variable in terms of trace element contents and, coherently with major elements behaviour, without any correlation with the “fertile” character of the rock ([Fig. 9a](#); [Table 2](#)). In the chondrite normalised incompatible multi-element variation diagram, it shows negative Sr and Ti anomalies. The large compositional variability is even more evident in chondrite normalised REE diagrams ([Fig. 9b](#)) with overall enriched (La_N 9.02-89.9 and Yb_N 3.30-20.0 times chondrite) patterns, ranging from almost flat / slightly (i.e. HP143 $La_N/Yb_N = 2.36$) to highly (i.e. HP124: $La_N/Sm_N = 6.89$; $La_N/Yb_N = 12.53$) LREE enriched. Strongly MREE enriched upward convex patterns (HP166:

Gd_N/Yb_N=2.36; Gd_N/La_N=2.17) can also be observed. The clinopyroxene of HP151 and HP166 lherzolites displays significant negative Eu anomalies (Fig. 9b).

Clinopyroxene (~7 volume%) in orthopyroxenite HP163 is compositionally variable; most of the grains reproduce the convex upward pattern shown in HP166 lherzolite (at a lower degree of enrichment, Fig. 9b), and a few small crystals evidence a progressive LREE enrichment (La_N = 15.4-179, Fig. 9b).

Clinopyroxene concentrated in veins in composite xenoliths (HP143, HP124) has generally low HREE contents (Yb_N=3.03 for HP143 and 6.85 for HP124), with less pronounced or absent negative Sr and Ti anomalies with respect to the disseminated clinopyroxene of lherzolites and harzburgite. It shares (almost) flat chondrite-normalised REE distribution patterns, but different degrees of LREE enrichments (La_N/Yb_N=2.80-8.65). As observed in lherzolites HP151 and HP166, a Eu anomaly also characterises the small clinopyroxene in the amphibole-bearing vein of HP121 composite xenolith.

4.3 Amphibole trace elements

Amphibole is characterised by incompatible trace element chondrite-normalised patterns of similar shape but at various degrees of trace element enrichment (i.e. Ba_N=13.1-95.6; Nd_N=11.1-46.1, Fig. 11a) and with systematic Nb and Ti positive anomalies (Fig. 10a). The trace element poorest contents are recorded by the rare amphibole in the thick clinopyroxene vein of the HP143 composite xenolith (Figs. 3a, 4c and Fig. 10b). They perfectly mimic the coexisting clinopyroxene REE pattern (Fig. 10b). Conversely, the highest trace element concentrations are measured in veined amphibole in HP121 composite xenolith that reflect a pure alkaline-like REE pattern (i.e. ~ La_N 43.1, Nd_N 46.1, Yb_N 11.3). Veined amphibole in HP124 composite xenolith is also characterised by a gently convex REE pattern (Fig. 10b), but depleted in LREEs with respect to the associated clinopyroxene. In HP164 lherzolite, the disseminated amphibole roughly displays a pattern similar to the coexisting

clinopyroxene (Fig. 9b), but with higher LREE contents (i.e. amphibole: $La_N = 32.2$; clinopyroxene $La_N = 11.0$, Fig. 9b). Overall, the Harrow Peaks amphibole appears more heterogeneous and trace element depleted with respect to that of the nearby Baker Rocks mantle xenolith population (Figs. 10a, b; Coltorti et al., 2004).

5. Discussion

Geochemical and textural features of Harrow Peaks ultramafic xenoliths highlighted remarkable differences between this locality and others in Antarctica. Primarily, their modal compositions do not depict any trend attributable to a common mantle residual path (Fig. 2; Bodinier and Godard, 2003; Workman and Hart, 2005) and secondly, the Fo content of olivine, in relation to the modal content, is difficult to ascribe to i) residual (melting) trend defined by the mantle peridotites from other localities in Antarctica (Fig. 5a), or ii) alkaline cumulate rocks such as those sampled from Mt. Overlord (~ 50 Km from Harrow Peaks, Perinelli et al., 2017) or in tholeiitic magmatic products as those of the Basement Sills (Bedard et al., 2007, Fig. 5a). In addition, there is not an observed correlation between spinel and olivine, as expected in a potential residual trend, with the sole exception of the composite xenolith HP21, where spinel Fo and Cr# values of the dunitic matrix intercept the mantle array curve in a region that reflect a moderate fertile lherzolite (melting degree < 20%), inconsistent with the rock lithotype (Fig. 6).

Moreover, clinopyroxene, which is extremely low in modal content, tends to have Mg# values comparable to those of the clinopyroxene from Antarctica mantle peridotites (Fig. 7a, b), but without any relationship with potential residual (i.e. decreasing of Al_2O_3 with the increasing of Mg#) or metasomatic (i.e. enrichment in TiO_2 or Al_2O_3 at comparable Mg#) trends (Coltorti et al., 2004; Perinelli et al., 2006; 2008; 2011; Armienti and Perinelli 2010; Pelorosso et al., 2016, 2017).

Thus, all the mentioned characteristics suggest that xenoliths from Harrow Peaks do not represent a simple peridotite residuum after melt extraction. Consequently, we discuss the origin of these

xenoliths as potentially representing cumulates that crystallised from various silicate melts migrating through the mantle and separated at mantle-crust boundary P-T conditions.

5.1 *Formation of Harrow Peaks xenoliths*

T-P-fO₂ equilibration conditions of the Harrow Peaks xenolith suite have been previously explored by Gentili et al. (2015), using a crystallochemical approach based on the amphibole dehydrogenation. The study highlighted a strong discrepancy between the redox conditions recorded by the amphibole dehydration equilibrium ($\Delta\text{QFM} = +5 - + 6.8$) and those of the coexisting peridotite mineral assemblage ($\Delta\text{QFM} = - 2.78 - - 0.2$) finally equilibrated at $\sim 854 - 940^\circ\text{C}$ (calculated at $P = 1.5 \text{ GPa}$). Using the same approach, this decoupling was not detected for the amphibole-bearing lherzolites and harzburgites of the nearby area of Baker Rocks where amphiboles and peridotite matrix converge to $f\text{O}_2$ values between QFM and $\Delta\text{QFM} - 1.78$ (Bonadiman et al., 2014).

We re-examined the Harrow Peaks samples in view of the suggested possible magmatic origin and integrated previously determined thermobarometric results with new chemical data and new samples.

Temperature values calculated using the combination of olivine-spinel Fe-Mg exchange thermometers of Wood and Virgo (1989) and Ballhaus et al. (1991) in the lherzolites, harzburgite and dunitic portions of composite xenoliths, suggest that these xenoliths finally equilibrated between 800 (orthopyroxenite HP163) and 1200°C (lherzolite HP151).

Presuming that the initial crystallisation of olivine is the main forming process of this group of xenoliths, the potential temperature of crystallisation was also calculated based on olivine/melt equilibrium, assuming that the Fe/Mg ratio of olivine (on sample average) was still close to the initial crystallization conditions. This is reasonable since they were extracted from the forming melts, and cumulated as monomineralic or bimineralic systems. Experimental determinations of Fe-

321 Mg diffusivity in such a system reveal that for an olivine composition of Fo₈₃₋₉₀ the closure
322 temperature is reached fast, and the estimated length scales for diffusion in a given time strongly
323 decreased (Chakraborty 1997; Costa and Dungan, 2005).

324 The FeO-MgO (and SiO₂) contents of the theoretical melt/s in equilibrium with dunitic portions of
325 composite xenoliths were inferred comparing various ^{Fe/Mg}Kd olivine/melt (Norman et al. 2002;
326 Putirka et al. 2008; Oeser et al. 2015) models. Using the equation [21] of Putirka (2008), and
327 assigning a maximum H₂O content of 1 wt %, the best fit obtained for the high Mg# HP121 is a melt
328 composition having Mg# 71.5. For HP124, HP143, the majority of lherzolites (Mg# 88) and the
329 harzburgite (Mg# 89), the melt in equilibrium (melt 2) is obtained by fractionation of ca. 4 % olivine
330 and 0.8 % of spinel from melt 1 (Tables 3, 4).

331 Furthermore, the olivine in the orthopyroxenite sample (Mg# 80.46) results to be in equilibrium
332 with a slightly evolved melt (melt 3) obtained by additional fractionation of ca. 5% of olivine, 4 %
333 of orthopyroxene, 1 % of clinopyroxene and 0.5 of plagioclase from melt 2 (Table 4).

334 Overall, the calculated melts show compositions that span between high-Mg tholeiites (picrites?)
335 and typical tholeiitic basalts, in a co-genetic evolution of the liquid line of descent. In this respect,
336 the HP121 dunitic portion represents the primitive crystallised product of the Kirkpatrick basalt
337 precursor (Kyle, 1980; Fleming 1995). The olivine potential crystallisation temperature, obtained
338 by iterative calculations using simultaneously melt compositions and Fo-contents (Putirka, 2008),
339 is in the narrow range of 1314-1202± 27 °C, with, coherently, the highest values recorded for the
340 olivine of the HP121.

341 The barometric conditions under which the Harrow Peak xenoliths were finally equilibrated are
342 firstly deduced by the presence of spinel as the sole aluminium phase (0.9 < P < 2.5 GPa, Wood,
343 1974). However, an attempt to evaluate the region where the crystallised phases olivine, olivine+
344 (orthopyroxene) and orthopyroxene + (olivine) separated from the hypothetical (calculated melt/s)
345 was carried out applying the geobarometers of Putirka (2008) and Nimis and Ulmer (1998), based
346 on orthopyroxene/melt and clinopyroxene/melt equilibrium, respectively. The obtained values

(Table 3) limit the stationing of Harrow Peaks cumulates in the P field of 1.3 (HP143) – 0.5 (HP163) GPa. Considering that the estimated error (for the method) is ± 0.2 GPa, the obtained values are coherent with those reported by Perinelli et al. (2011, 2017), which constrain the crust/mantle boundary (Moho).

5.2 Parental Melt modelling

The predominant mineral assemblages (olivine+spinel) of the composite xenoliths, the occurrence of orthopyroxenite and the calculated olivine (and orthopyroxene)/melt equilibrium, reveal that the parental liquid had high MgO contents (Mg# 72) and was close to silica saturation. Such melts are associated with an anomalous high temperature (excess T_{ex}) melting of the Phanerozoic mantle (picrites) or the Archean cratons (komatiites). Picrites or komatiites either present cumulitic olivine or are olivine-saturated even at high pressure, so that they can reach such high MgO and Mg# (Lee et al., 2006; Class, 2008).

All the studied Harrow Peaks xenoliths (including orthopyroxenite HP163), have olivine as cumulus phase, whose composition differs from most of the Antarctic ultramafic olivine cumulates, commonly ascribed to the Cenozoic alkaline magmatism of the West Antarctic Ridge System (Fig.5a; Gamble and Kyle, 1987; Gamble et al., 1988; Perinelli et al., 2017). Harrow Peaks' rocks instead represent products crystallised at mantle depth, close to the Moho discontinuity, from the precursor melt/s of the Ferrar Group tholeiitic magmatism (Kyle 1990, Fleming 1995), or from the high Mg-tholeiites (low Ti –picrites), similar to those of Vestfalja (Heinonen and Luttinen, 2008; 2010).

The calculated primitive melt forming the dunite matrix of HP121 has Mg# (up to 72) higher than any documented melt (Mg# 59-68), directly or indirectly (i.e. mantle metasomatic melt) related to the Cenozoic magmatic system, which is responsible for xenoliths rising to the surface (Coltorti, et. al. 2004; Perinelli et al. 2008; Nardini et al., 2009). In this respect, the HP121 dunite represents

373 the primitive crystallised product of the Kirkpatrick basalt (Ferrar Group) precursor (low Ti
 374 picrites), whereas dunite portions of HP124 and HP143 composite xenoliths and harzburgite
 375 /lherzolite samples are fractionated and accumulated by melt/s close in composition to the exposed
 376 Ferrar tholeiitic magmas (i.e. Kirkpatrick basalt; dolerites; Kyle 1980; Fleming 1995) in a co-
 377 genetic liquid line of descent (Table 4). The scarceness of olivine and the low Mg# of
 378 orthopyroxene in HP163 orthopyroxenite, point towards a cumulate of the same evolved melt
 379 (Table 4).

380 In such a frame, it is not easy to understand the role of clinopyroxene (and amphibole). The few
 381 clinopyroxene grains of HP121 and those concentrated in amphibole-bearing veins in HP124 and
 382 HP143, as well as the clinopyroxene occurring in harzburgite and lherzolites, generally show high
 383 Mg# (90-91) and Fe/Mg clinopyroxene/olivine distribution coefficients ($^{Fe/Mg}Kd$ 0.59-0.97) out of
 384 the range of equilibrium values ($^{Fe/Mg}Kd$ clinopyroxene/olivine = 0.83-0.86, Putirka 2008). Applying
 385 the $^{Fe/Mg}Kd$ clinopyroxene/melt formulation of Putirka et al. (2008) and Mollo et al. (2017) to the
 386 previous calculated Harrow Peaks parental melts, the ideal liquidus clinopyroxene has a $^{Fe/Mg}Kd$
 387 clinopyroxene/melt of 0.24-0.27. The Harrow Peaks clinopyroxene instead, is characterised by
 388 $^{Fe/Mg}Kd$ values (0.18-0.32) that cannot be equilibrated with most of the calculated melts (Table 3).

389 This is clear for the HP121 and HP124 composite xenoliths ($^{Fe/Mg}Kd$ clinopyroxene/melt = 0.18-
 390 0.15), whereas the HP143 composite xenolith, where the clinopyroxene almost entirely forms the
 391 monomineralic large vein (Figs. 2, 3), is the only sample that records a potential equilibrium of
 392 clinopyroxene with its matrix olivine, and with a calculated melt ($^{Fe/Mg}Kd$ clinopyroxene/melt =
 393 0.27) having Mg#=68 (Table 3). HP143 clinopyroxene is characterised by notably lower REE
 394 contents with a slight LREE-enrichment and flat M-REE patterns ($La_N/Ce_N=1.25$). Moreover, it does
 395 not present the high Eu negative anomaly, which instead characterises most of the Harrow Peaks
 396 clinopyroxenes. Overall, the HP143 REE profile is coherent with the equilibrium with a tholeiite-
 397 like forming melt and is clearly distinct from the alkaline-type clinopyroxene of HP121 and HP124
 398 dunites (Fig.9b).

Furthermore, we use the REE of the HP143 clinopyroxene to evaluate the HP143 parental melt REE contents. The ^{REE}Kd clinopyroxene/melt dataset used for the calculations is reported in Table S11 of Supplementary Material. The resulting profile mimics those of the Ferrar tholeiites and, coherently with the major element results, it suggests a potential equilibrium between the HP143 clinopyroxene and a parental tholeiitic melt (Fig. 11).

To sum up, HP121 and HP163 are cumulates from hypothetical parental melts that represent two extremes: the most primitive and the most evolved terms of a hypothetical liquid line of descent, respectively, suggesting that the parental melt of the Kirkpatrick basalt was a (low alkaline) picrite, which stationed in the shallow mantle. The melt system, modified in time and space, produced the rest of the Harrow Peaks ultramafic rocks, including the orthopyroxenite, at a shallower level. For all, but HP143, clinopyroxene and amphibole were formed by a different magmatic or metasomatic episode/s associated with more evolved melts that reasonably also crystallised plagioclase; this phase, even if not present in these cumulus fragments, may have imprinted the scattered Eu negative anomaly (Fig.9).

5.3 Geodynamic implications

The study of the Harrow Peaks xenoliths is clearly relevant as they represent the initial stages of the Ferrar magmatism. The importance of the Ferrar magmatism in West Antarctica is widely attested (Kyle 1980; Fleming 1992; Elliot 1999); the large volume of magmas generated by this event permeated part of the lithospheric domains beneath northern Victoria Land, refertilising the residual peridotitic upper mantle (Pelorosso et al., 2016).

The Ferrar large igneous system includes various magmatic bodies; among them, the doleritic Basement Sill from the McMurdo Dry Valleys represents the plumbing system of the Ferrar flood basalt eruptions (Bedard et al., 2007). The rock forming the sill displays a cumulate texture similar to that observed in layered intrusions and is characterised by an “orthopyroxene enriched base”

(Bedard et al., 2007); in that view, the unique investigated orthopyroxenite HP163 could be representative of the same basement.

Orthopyroxenites are quite rare among the Antarctica xenoliths suites. To the best of our knowledge the only other one documented is associated with clinopyroxenites and peridotite xenoliths hosted in basalts of the Mount Morning eruptive centre (Martin et al., 2015).

In northern Victoria Land, orthopyroxenites were also found as part of the layered sequence from Niagara Icefall (northern Victoria Land, Tribuzio et al., 2008); they were interpreted as cumulates of a boninitic melt related to the development of a back arc basin in an active continental margin.

Similarities between the Harrow Peaks ultramafic cumulates and the Niagara Icefall layered rocks include: i) the occurrence of high Mg# dunites (Mg# values = 91-94) coexisting with orthopyroxenites (Mg# values=84-88); ii) the matching of REE abundances and profiles of clinopyroxenes from the Niagara Icefall gabbro with that of the HP143 clinopyroxene (Fig. 11). Therefore, considering the mentioned examples from different geodynamic settings, we cannot exclude *a priori* that the Harrow Peaks cumulates represent fragments of cumulus “layers” crystallised and separated from tholeiitic or boninitic melts. However, Harrow Peaks cumulates are hosted in lavas sampled in the Wilson Terrane, where the Ferrar outcrops are represented by the Ferrar Dolerite Dufek Intrusions and the Kirkpatrick Basalts (Hergt et al., 1989; Fleming et al., 1995; Elliot et al., 1999). Thus the hypothesis that the investigated suite of samples could represent cumulus rocks from the most primitive Ferrar melt seems the most plausible.

Tracing the origin of Harrow Peaks cumulates back to the Jurassic, it is reasonable that they remained located within the shallow lithospheric mantle ($P \sim 1$ GPa) up to the Cenozoic (~ 50 Ma), when the alkaline magmatism associated with the West Antarctic Rift brought them to the surface. The Cenozoic (late stage) alkaline metasomatism pervaded large portions of mantle domains and cumulates suites in Victoria Land (Coltorti et al., 2004; Perinelli et al., 2006, 2008, 2011; Martin et al., 2015; Pelorosso et al., 2016, 2017), and affected the Harrow Peaks lithospheric portion, as

testified by the presence of alkaline-like amphiboles (phlogopite) and the LREE-enrichment in clinopyroxene (HP121 and HP124).

Conclusions

1. The textural and geochemical characteristics of Harrow Peaks xenoliths evidence that these ultramafic rocks represent deep crustal/mantle cumulates crystallised from a primitive picritic melt with a potential temperature ~ 1300 °C;
2. The presence of orthopyroxenite in the system demonstrates that the inferred melt was saturated in SiO₂;
3. The mineral/melt equilibrium allowed to identify the parental melt as corresponding to the first stages of the Ferrar magmatism;
4. During Cenozoic, the lithospheric mantle beneath Victoria Land was variably affected by an alkaline metasomatism related to the magmatic system, which was responsible for the xenoliths sampling. This process also affected the Harrow Peaks district as testified by the occurrence of hydrous phases in complete geochemical disequilibrium with the anhydrous cumulus matrix.

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Figure Captions

Figure 1. Sketch map of northern Victoria Land and location of Harrow Peaks outcrop (red star). Greene Point (Melchiorre et al., 2011; Pelorosso et al., 2016), Baker Rocks (Coltorti et al., 2004; Perinelli et al., 2006, 2008) and Handler Ridge (Pelorosso et al., 2017) are also reported (green stars). The map of northern Victoria Land is modified from Estrada et al. (2016), the Antarctica view is from Google Earth.

Figure 2. Harrow Peaks xenoliths in the olivine-orthopyroxene-clinopyroxene IUGS classification diagram. (*) Dunitic matrix of composite xenoliths. The residual path (annotated by melting %)

from PM (Primordial Mantle, McDonough and Sun, 1995) to clinopyroxene consumption is also calculated (dashed line) using theoretical and experimental results of Jensing and Holland (2015) and Herzberg (2004).

Figure 3. Thin sections of Harrow Peaks mantle xenoliths, which are mainly characterised by equigranular textural type. HP143, HP124, HP121 composite xenoliths (a, b, c) consist of large clinopyroxene and amphibole veins cross-cutting a dunitic matrix. a) HP143 with evident spinel trails. Important to note that the real modal content of spinel do not correspond to the black areas as in the thin section. b) HP124 is characterised by dunitic matrix and the thinnest vein containing also phlogopite. c) HP121 with the largest monomineralic vein that has been partly removed for crystallochemical investigations (Gentili et al., 2015). Harzburgite HP144 (d) and high clinopyroxene lherzolite (e). High orthopyroxene lherzolites (f, g) and orthopyroxenite (h).

Figure 4. Photomicrographs of representative microstructures from Harrow Peaks xenoliths. Polygonal large olivine with boundaries-converging at 120° (a, b), detail of the large clinopyroxene vein with embryonic amphibole (c). Tabular olivine zone and amphibole vein in sample HP121 (d). Lherzolite HP166 characterised by equigranular olivine, orthopyroxene and small clinopyroxene (e). Large orthopyroxene in the orthopyroxenite HP163 (f)

Figure 5. Chemical composition of (a) olivine (NiO vs. Fo), (b) orthopyroxene (Al_2O_3 vs. Mg#), (c) spinel (Mg# vs. Cr#); (*) Dunitic matrix of composite xenoliths. Compositional fields defined by Victoria Land peridotites (Coltorti et al., 2004; Martin et al., 2015; Pelorosso et al., 2016, 2017), Mt Overlord cumulates (Perinelli et al., 2017) and Basement sill leucotroctolites (Bedard et al., 2007) are reported for comparison.

734 **Figure 6.** Plot of spinel Cr# vs Fo content of coexisting olivine of Harrow Peaks ultramafic xenoliths.
735 (*) Dunitic matrix of composite xenoliths. The olivine–spinel mantle array is from Arai (1994).
736 Melting trend (annotated by melting %) is from Park et al. (2017); peridotite fields are modified
737 from Park et al. (2017).
738
739 **Figure 7.** Harrow Peaks clinopyroxene (a, b) and amphibole (c, d) compositions in term of Mg# vs.
740 TiO₂ and vs. Al₂O₃. Compositional fields reported for comparison in (a, b) are as in **figure 5**.
741
742 **Figure 8.** Chondrite-normalized trace element (REE+Sr+Zr+Hf+Ti+Y) distribution for Harrow
743 Peaks orthopyroxene (represented as sample average). Chondrite values from McDonough and Sun
744 (2005)
745 **Figure 9.** Chondrite-normalized trace-element patterns a) and Rare Earth Elements (REE) patterns
746 b) for Harrow Peaks clinopyroxene represented ad sample average, except for HP163
747 (orthopyroxenite). Due to the large trace element variability, all the analyses of the few HP163
748 clinopyroxenes are reported. Chondrite values from McDonough and Sun (2005)
749
750 **Figure 10.** Chondrite-normalized trace-element patterns (a) and REE patterns (b) of amphibole. For
751 comparison, the compositional field defined by the amphibole from northern Victoria Land
752 peridotites (Coltorti et al., 2004) is also reported. Chondrite values from McDonough and Sun
753 (2005)
754
755 **Figure 11.** Trace element composition modelling of melt 2, as calculated (major elements) in **Table**
756 **3**. The reconstructed melt 2, assumed in equilibrium with HP143 clinopyroxene, is obtained using
757 REE $K_d^{cpx/melt}$ data from GERM. The resulting profile converges on a tholeiitic melt that resembles
758 the Ferrar basalt (Kyle 1980; Fleming et al., 1995). In turn, HP143 clinopyroxene profile mimics

759 those occurring in the ultramafic sequence (cumulates) from Niagara Ice Falls (Tribuzio et al.,
760 2008). Chondrite-normalized values from McDonough and Sun (2005).