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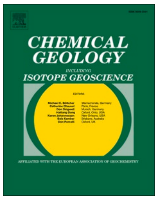

Preserved Nd-Hf-Os isotope variability in replacive channels from the Lanzo ophiolite: Traces of incomplete melt aggregation in the shallow mantle

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ABSTRACT

Long-lived radiogenic isotopes of abyssal peridotites, residues of MORB extraction, show that the asthenosphere is intrinsically heterogeneous, which is inherited from ancient melting events and crustal recycling during Earth's history. Yet, Mid Ocean Ridge Basalts (MORB) have a rather uniform average composition, suggesting that the variability of their mantle source is concealed during their ascent. Here we document that mantle heterogeneity is exceptionally well preserved in high permeability mantle conduits from the Lanzo South mantle massif, Western Italian Alps. Nd-Hf-Os isotopes of decametre-scale replacive bodies provide evidence for the existence of two generations of mantle channels. The first generation consists of dunites concordant to the main foliation of host peridotites. The replacive dunites include clinopyroxene with MORB-like incompatible element signature and initial (160 Ma) εNd and εHf ranging from +4 to +7 and from +10 to +15, respectively. The second generation, made up of pyroxene-poor harzburgites discordant to the main foliation, is geochemically depleted in incompatible elements and its clinopyroxene displays highly radiogenic Hf isotopes (initial εHf up to +202). The mantle channel heterogeneity is confirmed by *Re*—Os isotopes and platinum-groups elements. The MORB-type dunites have high Pt, Pd and, locally, Re, and have ^{187}Os/^{188}Os ratios similar to the host peridotite (0.122–0.128). On the other hand, the depleted bodies have lower Pt, Pd and Re, and ^{187}Os/^{188}Os ratios ranging from those of host peridotites (0.124) to highly unradiogenic values (0.118) in the most refractory sample. The preserved heterogeneity in trace elements, PGE, and Nd-Hf-Os isotopes highlights infiltration of melts from a highly heterogeneous mantle, still partially preserved within these mantle bodies. If applied to present-day Mid Ocean Ridges, our model indicates that the isotopic variability of melts migrating through replacive mantle conduits is by far larger than magmas erupted on the seafloor, which implies that diverse mantle components are mainly delivered and homogenised above the crust-mantle boundary.

1. Introduction

Erupted along the global mid-ocean ridges, MORB (mid-ocean ridge basalts) are the most abundant magmas on Earth, produced by decompression of the asthenosphere in a melting region some hundreds of kilometres wide. To be erupted along the spreading axis, mantle melts must be coalesced from an extremely large area into a narrow zone few kilometres wide. During transport from the source region, MORB can experience magma mixing, crystal fractionation and reaction between migrating magmas and the surrounding mantle, which can influence fundamentally the major, trace elements and isotopic records of the primary mantle melts and thus might conceal the original compositional variabilities in their mantle sources (Grove et al., 1992; Langmuir et al., 1992; Stracke et al., 2003; Wanless and Shaw, 2012; Rudge et al., 2013; Liu and Liang, 2017; Sanfilippo et al., 2021). In addition, retrieving information on the compositional variability of the MORB source is

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further complicated by the heterogeneity of the mantle before entering the melting region. Such a heterogeneity is mainly documented by the extent of radiogenic isotope variability (i.e., Sm—Nd, Lu—Hf and *Re*—Os) of abyssal mantle rocks compared to erupted MORB (Snow et al., 1994; Salters and Dick, 2002; Cipriani et al., 2004; Harvey et al., 2006, 2011; Liu et al., 2008; Liu et al., 2022; Warren et al., 2009; Stracke et al., 2011; Mallick et al., 2014, 2015; Lassiter et al., 2014; Day et al., 2017; Paquet et al., 2022; Sani et al., 2023), which implies the preservation of mantle parcels with different histories of melt depletion and/or chemical enrichments, possibly ranging from highly depleted peridotites to pyroxenite veining or other fertile lithologies. Hence, erupted basalts cannot be used as direct proxies of their source materials, being biased towards the composition of the most fertile (i.e., fusible) components (Stracke and Bourdon, 2009; Salters et al., 2011; Stracke, 2012; Rudge et al., 2013; Sanfilippo et al., 2019, 2021). As our knowledge of the chemical heterogeneity of the mantle increases, the mechanism, style, and depth of melt aggregation are some of the most challenging issues to decipher (Lambart et al., 2019).

Studies of ophiolites provided the evidence that melt transport mainly occurs within high porosity channels, isolated from the host pyroxene-bearing peridotites by pyroxene-poor walls (Aharonov et al., 1995; Kelemen et al., 1995; Spiegelman et al., 2001; Suhr, 1999). These olivine-rich lithologies form as result of disequilibrium between the basaltic melt and the host pyroxene-bearing peridotites and are often referred to as replacive dunites (Quick, 1981). Experimental and theoretical studies confirm that these dunites represent permeability barriers and prevent further interactions between melts and shallow peridotites (Morgan and Liang, 2005; Liang and Parmentier, 2010; Liang et al., 2011). An interconnected network of highly permeable dunite channels may thereby allow basaltic melts to efficiently segregate from their source region (Kelemen et al., 1997; Spiegelman and Kelemen, 2003; Akizawa et al., 2016). However, to what extent a process of reactive melts flow may preserve the chemical variability of the migrating melts is still a matter of debate (see Morishita et al., 2011; Tamura et al., 2016; Sanfilippo et al., 2017; Xiong et al., 2022a; Klaessens et al., 2021).

In this study, we combined the Nd—Hf isotopic compositions of clinopyroxene and whole-rock Os isotopes of several decametre-scale replacive bodies from the Jurassic Lanzo ophiolite (Western Italian Alps) to explore the extent of variability of melts delivered from the mantle towards the lower crust. We revealed the existence of two generations of large-scale replacive bodies, formed by melts having markedly different trace elements and Nd-Hf-Os isotope signatures. We discuss the different behaviour of Os and Nd—Hf isotopes during melt-rock reaction and, on this basis, we inferred that the traces of a heterogeneous mantle are preserved in mantle migration channels. If our idea is correct, it implies that diverse mantle components must be delivered and homogenised within lower crustal reservoirs.

2. The Jurassic Lanzo ophiolite

The Lanzo peridotite massif is in the Western Alps, between the continental units of the Sesia-Lanzo zone and the meta-ophiolites units from the Jurassic Ligurian-Piedmontese basin (Fig. 1). A large proportion of the ultramafic massif is formed by fresh peridotites, consisting of spinel-plagioclase lherzolites/harzburgites, dunites and rare pyroxenites (Boudier, 1978; Bodinier, 1988; Müntener et al., 2005; Piccardo et al., 2007). This mantle sequence is locally intruded by Middle Jurassic MORB-type gabbros (Kaczmarek et al., 2008). Based on the geochemical and geochronological characteristics of these gabbroic and basaltic dykes (Bodinier et al., 1991; Rubatto et al., 1998), and the compositional similarity of the Jurassic sedimentary cover with those of other Jurassic ophiolite sections in the Alps and Apennines (Lagabrielle et al., 1989),

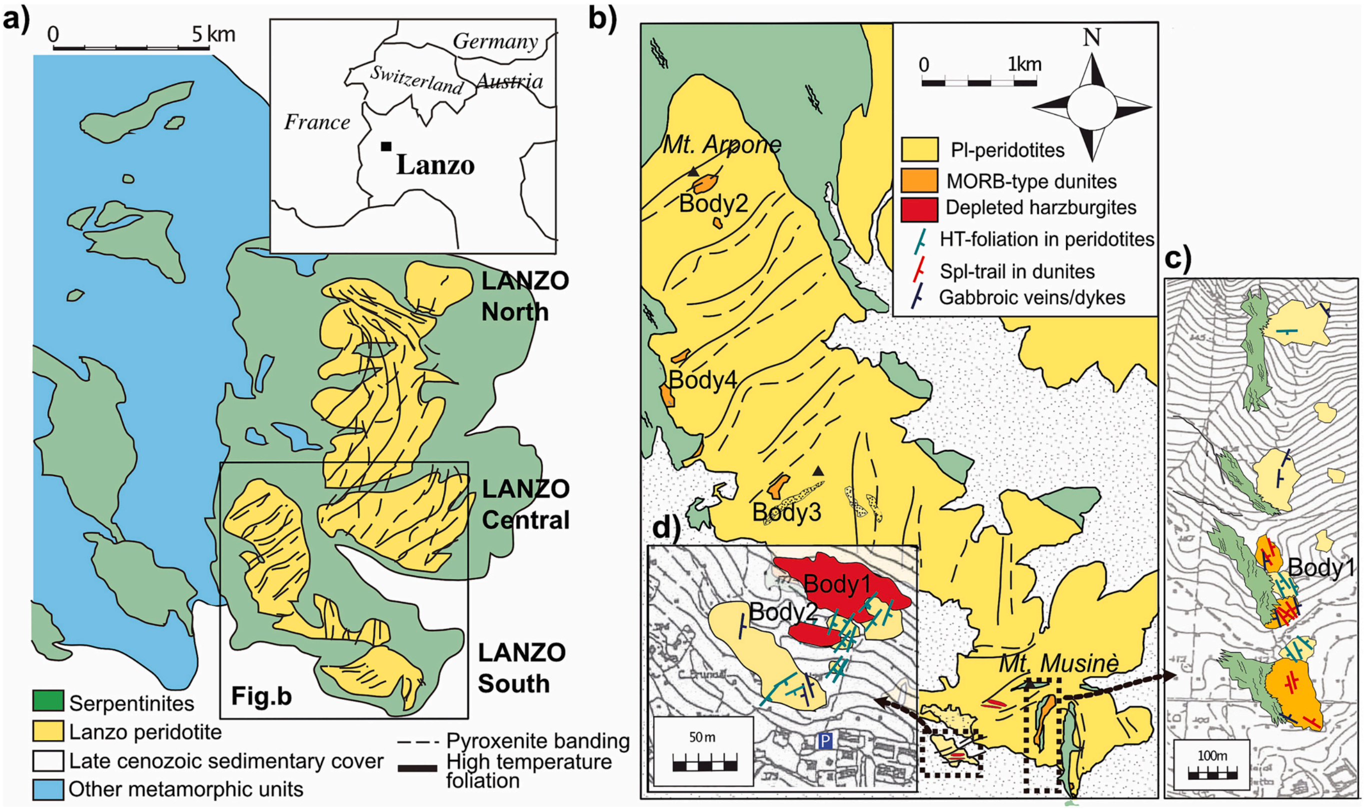

Fig. 1. a) Simplified geological sketch map of the Lanzo ophiolite in the western Italian Alps after Boudier and Nicolas (1977) and location of the studied area (modified from Sanfilippo et al., 2017). b) Location of the studied bodies in the Lanzo South Massif. c) and d) portray the close-up of two Mt. Musinè outcrops where the field relationships of these bodies can be clearly observed. The high-temperature foliation in the host Pl-peridotite, the orientation of the spinel trails in the MORB-dunites, and the orientation of gabbroic veins/dykes are reported.

there is a general consensus that the Lanzo Massif represents an ophiolitic mantle section exposed at the seafloor in the Jurassic (e.g., Müntener et al., 2005; Piccardo et al., 2007; Kaczmarek and Müntener, 2010; Sanfilippo et al., 2014, 2017; McCarthy and Müntener, 2019).

Major, trace elements and isotopic compositions of the peridotites allow the Lanzo ultramafic massif to be subdivided three domains, namely South, Central and North. These domains are physically separated by pre-Alpine mylonitic shear zones, and display distinct geochemical characteristics (Boudier and Nicolas, 1977) (Fig. 1a). The peridotites from the Northern and the Central bodies have fertile chemical compositions and highly depleted Nd isotopic ratios, whereas the peridotites from the Southern body are more refractory and display a Nd isotopic signature similar to MORB (Bodinier et al., 1991). Based on these data, Bodinier et al. (1991) interpreted the Northern and Central portion of the massif as fragments of the sub-continental lithosphere, and the Lanzo South domain as an asthenospheric diapir emplaced during the opening of the Ligurian-Piemontese basin.

These ideas have been reviewed by new concepts developed to explain the similarity of most ophiolitic sections exposed in the Alps and Apennine with the lithosphere formed in hyper-extended magma-poor rifted margins (Müntener and Manatschal, 2006). In particular, the Lanzo South peridotites were proposed to have been formed by a complex history of interaction between a depleted spinel-facies mantle protolith possibly located in the subcontinental mantle and migrating MORB-type melts produced by asthenospheric upwelling in conjunction with the opening of the Jurassic basin (Müntener et al., 2005; Piccardo et al., 2007). These peridotites typically show crystallization of magmatic plagioclase (Pl) and/or pyroxene within the pre-existing peridotite minerals. These minerals were interpreted to have formed by a melt-peridotite reaction that led to a chemical refertilization of the peridotite, thereby erasing the original geochemical signature of the spinel-facies mantle protolith (see also Müntener et al., 2010). For instance, the spinel in the Pl-peridotites has high Cr#, TiO_2 and MgO, resulting from melt-peridotite reaction (Dick and Bullen, 1984). The incompatible trace element compositions of clinopyroxene (Piccardo et al., 2007) and olivine (Sanfilippo et al., 2014) in the Pl-peridotites indicate that the interacting melts had a MORB-like geochemical signature (see also Sanfilippo et al., 2014). The melt-peridotite reaction event forming the Pl-peridotites was followed by the formation of replacive mantle dunites and, afterwards, by the intrusion of MORB-like gabbro dykelets and dykes showing diffuse to sharp contacts with respect to the host rocks. U—Pb ages of zircons in oxide-gabbros yield 158 to 163 Ma, constraining the age of the migration event (Kaczmarek et al., 2008). Hence, it is now thought that the Lanzo South sequence represents a fertilised subcontinental lithospheric domain, intruded and modified by interactions with MORB-like melts during opening of an embryonic oceanic basin akin to the Atlantic or Indian oceans (see Picazo et al., 2016 for a review).

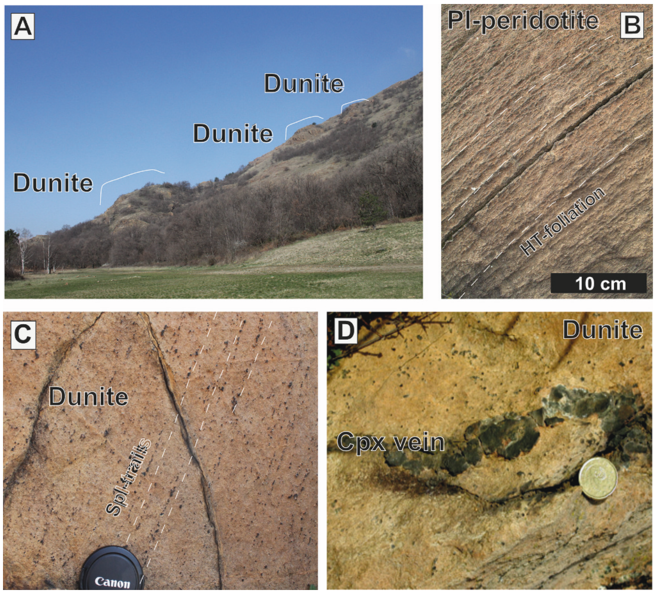

Fig. 2. Field and textural characteristics of the MORB-type dunites. A) Outcrop view of three MORB-type dunite bodies at the Monte Musinè outcrop. B) High temperature foliation in the host Pl-peridotites. C) Detail of a MORB-type dunite showing elongated spinel-trails. E) Irregular clinopyroxene vein intruding a MORB-type dunite.

3. Compositional heterogeneity of the Lanzo South replacive bodies

Large replacive bodies are characteristic of the Southern portion of the massif, where they occur in channel-like bodies up to tens of meter in width (Fig. 1b, c, d). Replacive rocks range in composition from pyroxene-free dunites (Fig. 2) to pyroxene-poor harzburgites (Fig. 3), which are concordant and discordant to the main foliation, respectively (Piccardo et al., 2007). The concordant replacive dunite bodies are widespread in the entire mantle section, whereas the two discordant replacive harzburgites were only found in the southernmost area of Lanzo South (Mt. Musinè; Fig. 1c, d). No direct crosscutting relationships can be observed between the dunite and the harzburgite replacive bodies. However, the fact that the dunite bodies are deformed concordantly with the host Pl-peridotites (see also Boudier and Nicolas, 1977; Boudier, 1978; Piccardo et al., 2007; Sanfilippo et al., 2014), whereas the replacive harzburgites are texturally undeformed (Fig. 3) (see also Sanfilippo et al., 2019), indicates that the latter formed after the main deformative event.

The two generations of replacive bodies have distinct geochemical compositions, which were related to the migration with melts with different geochemical affinities (see Fig. 4) (Sanfilippo et al., 2014, 2017, 2019). The concordant dunites have high Fo olivine (89–90) characterized by minor and trace element compositions similar to MORB phenocrysts. Despite this, olivine (Ol) in some of the selected dunites bodies have anomalously high H contents (15–30 ppm), and high Ti/Li and Ti/Sc ratios, likely related to high contributions of magmas with geochemical compositions acquired by melting of garnet-bearing, enriched lithologies (Fig. 4b). This agrees with the transitional MORB-like incompatible trace elements of the clinopyroxene (Cpx) locally found as interstitial grain or veinlets within the dunite matrix, which is locally enriched in LILE and LREE compared to N-MORB (also see Müntener et al., 2005; Piccardo et al., 2007) (Fig. 4c).

Conversely, decameter-scale discordant replacive bodies are constituted by chemically depleted, orthopyroxene (Opx)-poor harzburgites including rare dunite pods (Fig. 3). Micro-textures indicate a process partial dissolution of deformed Opx and crystallization of unstrained Ol and Cpx. Importantly, Cpx occurs as small grains interstitial to Ol and is often associated to Spl, or as megacrysts organized in cm-scale veinlets (Fig. 3c). These textures show that Cpx crystallized during the last phases of the interaction process, in association with intergranular Spl having lower Cr# compared to the host peridotites (Fig. 4a) (see also Piccardo et al., 2007). Despite the local crystallization of Cpx, the gradual dissolution of Pl and addition of Ol led to a general decrease in bulk-rock Al_2O_3 (Fig. 4d), CaO and incompatible elements (i.e., TiO_2, Na_2O and K_2O, not shown) at increasing MgO. The replacive harzburgites and the rare associated dunites are distinct from the concordant MORB-dunites in olivine and clinopyroxene having depleted incompatible trace element compositions, as portrayed in Fig. 4b and c. Importantly, the clinopyroxene and olivine from these replacive bodies are geochemically more depleted than those in the host Pl-peridotites.

4. Sample selection and analytical methods

We selected three plagioclase(Pl)-peridotites, seven MORB-type

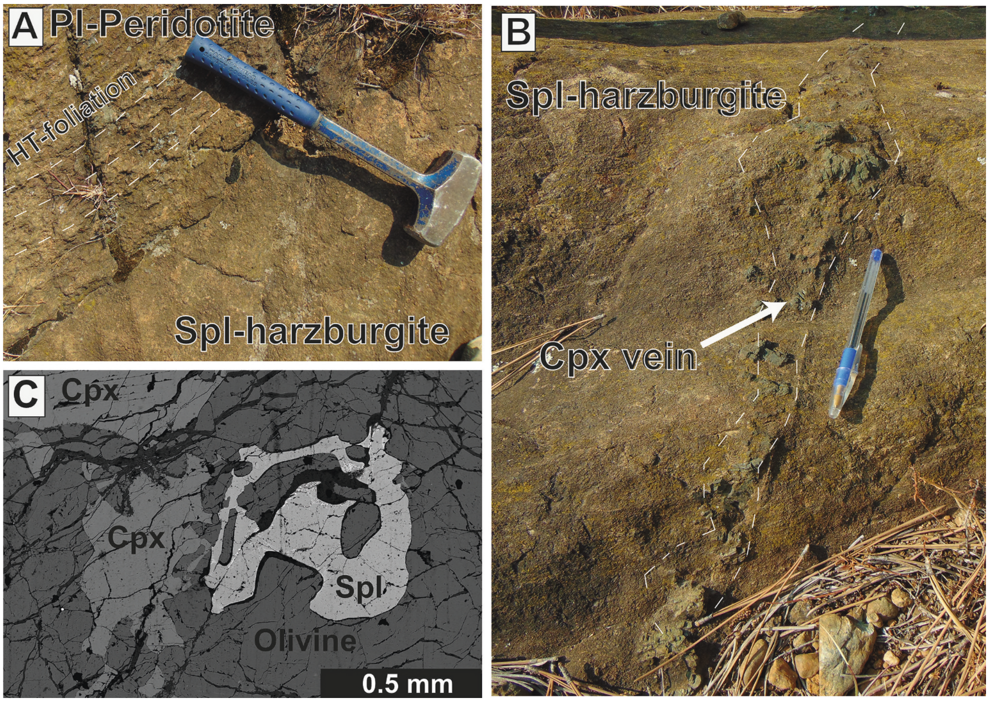

Fig. 3. Field and textural features of the depleted replacive harzburgites. A) Contact zone between depleted replacive harzburgites and deformed Pl-peridotites. Relicts of the high temperature foliation are still visible. B) Irregular clinopyroxene-rich vein crosscutting a depleted replacive harzburgite. C) Interstitial clinopyroxene (Cpx) and Cr-spinel (Spl) in backscattered image.

dunites from four different bodies and eight depleted harzburgites from two different bodies (see Fig. 1b, c, d). All these samples were selected for the whole-rock PGE and *Re*—Os isotopic determinations in the present study. Major and trace and Nd—Hf isotopic compositions of clinopyroxene from the eight depleted harzburgites and two host Pl-peridotites are from Sanfilippo et al. (2019). Major and trace and Nd—Hf isotopic compositions of clinopyroxene from one Pl-peridotite and two Cpx-rich segregation from two MORB-type dunite bodies were also analysed for this study. The major element compositions of mineral phases (Table S1), the trace elements and isotopic compositions of the clinopyroxene (Tables S2 and S3), and the whole rock major, PGE and Re—Os isotope compositions (Tables S4 and S5) are included as supplementary files. Major element compositions of minerals were obtained using a JEOL JXA-8200 electron microprobe located at Dipartimento di Scienze della Terra, Università degli Studi di Milano (Italy) and reported in Table S1. Conditions of analyses were 15 kV accelerating voltage and 15 nA beam current. Counting time was 30 s on the peak and 10 s on the backgrounds. Natural minerals were used as standards and data reduction was carried out using the CITZAF package.

Trace element compositions of clinopyroxene were obtained using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) at C.N.R., Istituto di Geoscienze e Georisorse (Unità di Pavia). We selected an average of 10 cpx grains for each mineral separate, one spot for each grain. Analyses were performed using a PerkinElmerSCIEX ELAN DRC-e quadrupole mass spectrometer coupled with an UP213 deep-UV YAG Laser Ablation System (New Wave Research, Inc.). The laser was operated at a repetition rate of 10 Hz, with 213 nm wavelength and a fluence of ~9.5 J/cm^2. Spot diameter was 100 μm. NIST SRM 610 synthetic glass standard was used as an external standard, and CaO was used as an internal standard. Precision and accuracy of the REE concentration values were assessed through repeated analysis of the BCR2-g standard to be better than ±7% and ± 10%, respectively, at the ppm concentration level. Concentrations and detection limits are reported in Table S2.

Isotopic composition of Nd and Hf of clinopyroxene, dissolution and column chemistry were done at the National High Magnetic Field Laboratory, Florida State University, using the same methodology reported in Sanfilippo et al. (2019). The clinopyroxene separates (~200 mg, hand-picked under binocular microscope) were leached in ~5 ml 2.5 N HCl and ~500 μl <30% H_2O_2 for 20–30 min at room temperature to remove any alteration products. The leached separates were rinsed several times with quartz sub-boiling distilled water. Subsequent dissolution and column chemistry was performed after procedures described in Stracke et al. (2011). Nd and Hf isotopes were measured using the Thermofisher NEPTUNE MultiCollector Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS). The $^{143}Nd/^{144}Nd$ ratios are corrected for mass bias using $^{146}Nd/^{144}Nd$ ratio of 0.7219 and reported relative to La Jolla standard of 0.511850 (see Table S3). Blanks for Nd were ~10 pg. The $^{176}Hf/^{177}Hf$ ratios are corrected for mass bias using $^{179}Hf/^{177}Hf$ ratio of 0.7325 and reported relative to JMC-475 value of $^{176}Hf/^{177}Hf = 0.282150$. Blanks for Hf were < 40 pg. Reproducibility of the LaJolla and JMC475 standards (see Table S3) is similar to their in-run precision.

Whole-rock major element analyses were carried out by inductively coupled plasma atomic emission spectroscopy at the National High Magnetic Field Laboratory, Florida State University. Three blanks and five controls (three before sample group and two after) were analysed per group of samples. Values for standard material and detection limits during the analyses are reported in Table S4. Precision and accuracy are estimated to be better than 2%.

Whole rock *Re*—Os isotopes were analysed at the Institute of Geology and Geophysics, Chinese Academy of Sciences using the isotope dilution method (Chu et al., 2009). The detailed analytical procedure has been described in Liu et al. (2022). About 2 g powders, together with a ^{187}Re—^{190}Os spike and a mixed ^{191}Ir-^{99}Ru-^{194}Pt-^{105}Pd spike, were mixed in Carius tubes, which were digested with reverse aqua regia (i.e., 3 ml 12 N HCl and 6 ml 16 N HNO_3) at 240 °C for ~72 h in an oven. Osmium was extracted from the aqua regia solution by solvent extraction into CCl_4 and further purified by micro-distillation (Birck et al., 1997). Other HSE were firstly separated from the solution into subgroups (Re—Ru, Ir—Pt, and Pd) using a 2 ml anion exchange resin (AG-1 × 8, 100–200 mesh). Subsequently, the Re—Ru was further purified by

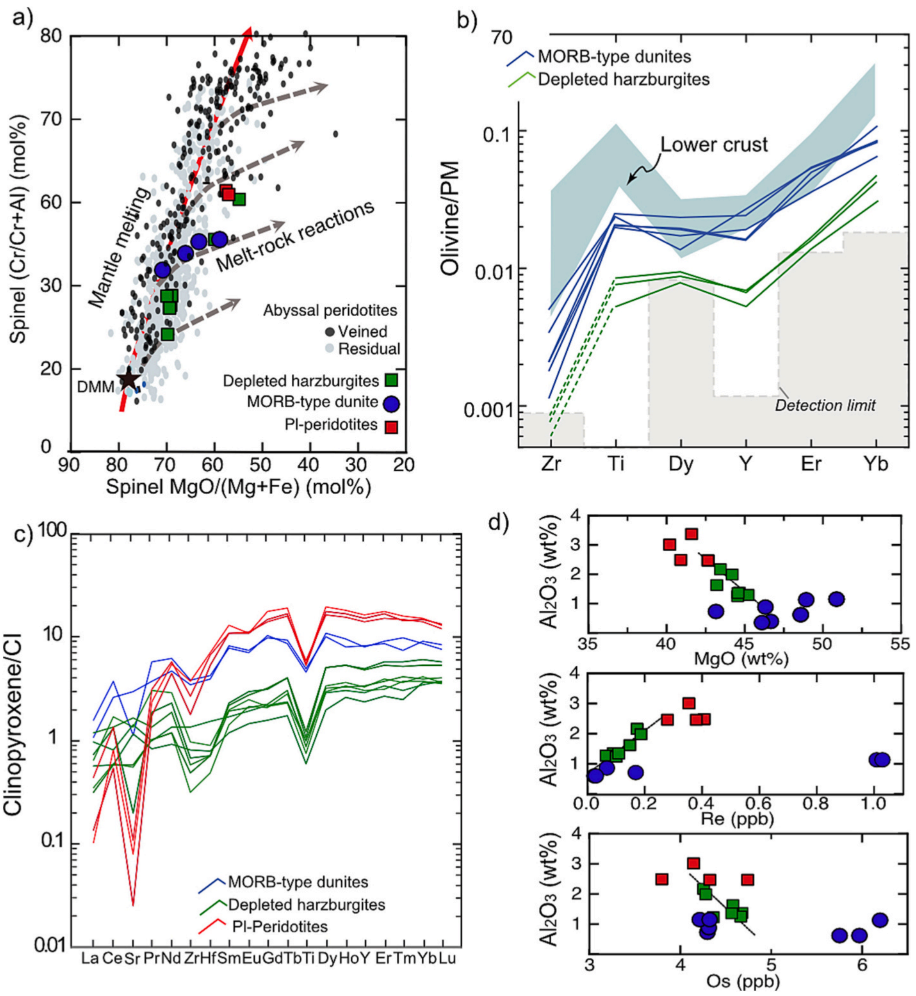

Fig. 4. a) Variability in spinel Mg/(Mg + Fe) (mol%) versus Cr/(Cr + Al) (mol%) of Lanzo South replacive bodies and host peridotites compared to abyssal peridotites (data from Warren, 2016; Sani et al., 2020). Also indicated are melting and melt-rock reaction trends starting from Depleted MORB Mantle (DMM) compositions (see Workman and Hart, 2005). b-c) Chondrite-normalized trace element compositions of olivine and clinopyroxene from the Lanzo South replacive bodies compared to lower crustal gabbros from Alpine-Apennine ophiolites and host harzburgites (data from Sanfilippo et al., 2014). Detection limits of olivine compositions are also indicated with dashed grey line. d) Whole rock covariations between Al_2O_3 (wt%) and MgO (wt%), Os (ppb) and Re (ppb) contents in Lanzo South replacive bodies and host Pl-peridotites. The dashed line indicates correlations for the depleted harzburgites.

a 0.25 ml anion exchange resin; the Pd and Ir—Pt were further purified by an Eichrom LN spec resin to completely remove Zr and Hf.

Osmium concentrations and isotopes were measured by negative thermal ionization mass spectrometry (N-TIMS) on a Neptune Triton in a static mode using Faraday cups. A $Ba(OH)_2$ solution was used as an ion emitter. The measured Os isotopes were corrected for mass fractionation using the $^{192}Os/^{188}Os$ ratio of 3.0827. The Nier oxygen isotope composition ($^{17}O/^{16}O = 0.0003708$ and $^{18}O/^{16}O = 0.002045$) has been used for oxide correction. The in-run precisions for Os isotopic measurements were better than 0.2% (2σ) for all the samples. Johnson-Matthey standard of UMD was used as an external standard, yielding a $^{187}Os/^{188}Os$ ratio of 0.11378 ± 2 (2 s; $n = 5$), which agrees well with the reference $^{187}Os/^{188}Os$ ratio of 0.11381 ± 21 (Brandon et al., 2000). Concentrations of other HSE were measured on a Thermo Fisher Scientific Neptune MC-ICPMS with an electron multiplier in peak-jumping mode or using Faraday cups in static mode, depending on the measured signal intensity. In-run precisions for $^{185}Re/^{187}Re$, $^{191}Ir/^{193}Ir$, $^{99}Ru/^{101}Ru$, $^{194}Pt/^{196}Pt$, and $^{105}Pd/^{106}Pd$ were 0.1–0.3% (2 s). Standards of Re, Ir, Ru, Pt, and Pd were used to correct mass fractionations. The total procedural blanks were 3 ± 1 pg for Os, 5 ± 2 pg for Re, 1 ± 0.5 pg for Ir, 10 ± 4 pg for Ru, 18 ± 9 pg for Pt, and 9 ± 4 pg for Pd ($n = 10$). A $^{187}Os/^{188}Os$ ratio of ~0.15 was obtained for the blank. The standard UB-N was used to monitor the accuracy of the analytical procedure and is reported in Table S5.

5. Results

Major, trace elements and Nd—Hf isotope compositions of Pl-peridotites and replacive harzburgite bodies were discussed by Sanfilippo et al. (2019). The Cpx trace element and Nd—Hf isotope compositions are here briefly summarized along with data from the new MORB-type dunites. The Cpx from the Pl-peridotites have chondrite-normalized REE patterns highly depleted in LREE ($La_N/Sm_N = 0.01–0.04$) and with high M-HREE (15 times CI), and the incompatible element patterns characteristically displaying negative Sr anomaly ($Sr/Sr^*[(Ce_N^*Pr_N)] = 0.03–0.05$) and low Zr_N/Hf_N ratios (0.3–0.4). The interstitial Cpx in the replacive MORB-type dunites are similar to Cpx in equilibrium with MORB, and distinct from those of the host Pl-peridotites in the higher LREE and lower H-MHREE contents. Some of the dunites include Cpx displaying highly variable L/MREE fractionations ($La_N/Sm_N = 0.20–1.13$). In addition, the dunite Cpx does not have Sr negative anomalies ($Sr/Sr^* = 0.9$), in agreement with the lack of Pl, and have chondritic Zr/Hf ratios ($Zr_N/Hf_N = 0.9$). The Cpx in the depleted replacive harzburgites has distinctively depleted REE patterns characterized by low H-MREE contents (3–5 times CI), but typically higher L/MREE ratios ($La_N/Sm_N = 0.14–0.62$). The Cpx in depleted replacive harzburgites lacks significant Sr negative anomaly ($Sr/Sr^* = 0.7–1.6$), similar to the MORB-type dunites, and exhibits a weak fractionation between Zr and Hf ($Zr_N/Hf_N = 0.7–1.1$).

The initial Nd—Hf isotopic compositions of Cpx are calculated at 160 Ma, following the age of the MORB-type magmatism in Lanzo, as evidenced by i) zircon U—Pb ages of the gabbros crosscutting the Lanzo South peridotites (Kaczmarek et al., 2008) and ii) Pl-Cpx-WR internal isochrons defined by two pyroxenites from Lanzo North (Sanfilippo et al., 2022). Notably, Sanfilippo et al. (2019) showed that early Jurassic ages (160 Ma) are also retrieved from two errorchrons provided by the Cpx in the replacive harzburgites, which document that the isotopic resetting of the Sm—Nd system occurred in the Jurassic (160 Ma), and place fundamental constraints to the age of the melt-rock reaction process The initial Nd and Hf isotopes of the Cpx in the host Pl-peridotites plot in the MORB field (Fig. 5). This agrees with the idea that these rocks experienced a nearly complete equilibration with MORB-like melts during the impregnation event (see Bodinier et al., 1991; Piccardo et al., 2007). The Cpx-rich segregations within the two MORB dunite also plot in the Nd—Hf isotopic field of present-day MORB, although their variability exceed that of basalts from the Alpine-Apennine ophiolites, which have a restricted Nd—Hf isotopic range (see Rampone and Sanfilippo, 2021 for a review). Sample LZ66 Cpx has less radiogenic Nd and Hf isotope compositions ($\varepsilon_{Nd} = +4.2$; $\varepsilon_{Hf} = +8.0$) compared to the host Pl-peridotites, whereas sample LZ31 Cpx has ε_{Nd} and ε_{Hf} similar to those of the host rocks (+7.8 and + 11.8, respectively). On the other hand, Cpx in the depleted replacive harzburgites does not plot in the Nd—Hf isotope MORB field, having Hf isotopes extending by far any melts ever erupted at present-day Mid Ocean Ridges. These Cpx have highly radiogenic, yet variable Hf isotope compositions ($\varepsilon Hf = 40–220$), coupled with MORB-like Nd isotopes. Similar isotopic compositions characterize other melt-reacted harzburgites from the northern sector of the Lanzo massif (Guarnieri et al., 2012) and were documented in abyssal peridotites from the Gakkel (Stracke et al., 2011) and the Mid Atlantic Ridge (Sani et al., 2023). In addition, highly radiogenic Hf isotopes have been documented in plume-related peridotites such as the Salt Lake Crater xenoliths from Hawaii (Bizimis et al., 2003; Salters and Zindler, 1995).

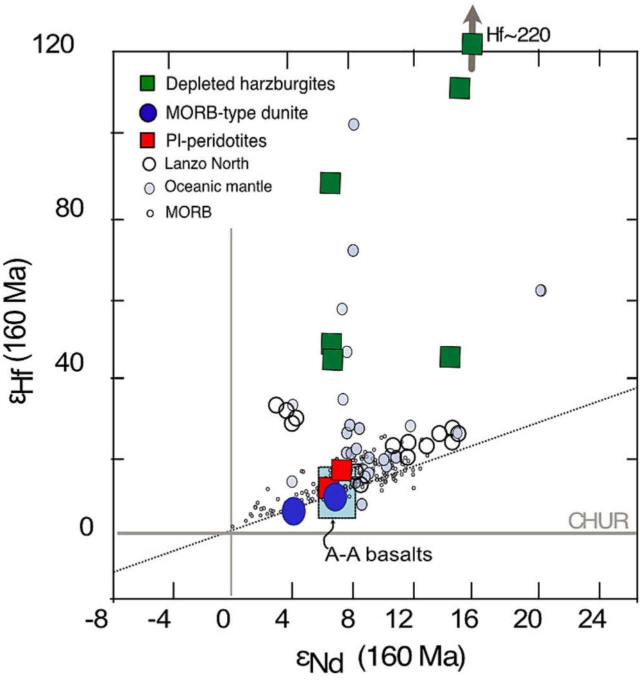

Fig. 5. Initial (at 160 Ma) Nd—Hf isotope compositions of clinopyroxene separates from the replacive bodies of Lanzo South and host Pl-peridotites compared to whole rock compositions of Lanzo North peridotites (Guarnieri et al., 2012) and Alpine-Apennine ophiolite MORB (compiled from Rampone and Sanfilippo, 2021). Also shown are the clinopyroxene Nd—Hf isotope compositions of present-day oceanic mantle peridotites (Stracke et al., 2011; Sani et al., 2023) and Atlantic MORB glasses.

The three rock-types are also characterized by distinct whole-rock PG*E*-normalized patterns. The Pl-peridotites have nearly flat patterns approaching those of the PM, and thereby plotting in the fertile-end of the field of abyssal peridotites. Notably, they have higher Pd and Re compared to the subcontinental peridotites from Lanzo North (Becker et al., 2006) (Fig. 6a), in agreement with their 're-enriched' geochemical nature. The MORB-type dunites are characterized by selective enrichments in Pd and, in some samples, Re relative to the host rocks, whereas the Ir and Pt are only slightly enriched compared to the Pl-peridotites (Fig. 6c). Similar to Re, some samples also have Os higher than the host rocks (Fig. 4d). Taken as a whole, the PGE patterns in the MORB-type dunites stand in the enriched field of the melt-infiltrated (i.e., S-enriched; Luguet et al., 2003) replacive rocks from present-day MOR. Unlike the replacive dunites, the depleted replacive harzburgites are distinct from the host Pl-peridotite in having lower Pd and Re, whereas Os-Ir-Ru and Pt are nearly indistinguishable (Fig. 6b). One sample was selected along the contact between the Pl-peridotites and the depleted harzburgites, and reveals PGE patterns undistinguishable from those of the Pl-peridotite (LZ205, Fig. 6b). Notably, Os, Re (Fig. 4d) and Re/Os ratios (Fig. 7b) in the depleted harzburgites and Pl-peridotites correlate with the whole-rock Al_2O_3 contents, whereas the MORB-type dunites display extremely variable Os, Re and Re/Os ratios, ranging from higher to lower values compared to the host Pl-peridotites (Figs. 4c, 7b). Initial $^{187}Os/^{188}Os$ isotopes (calculated at 165 Ma) can also distinguish the two generations of replacive bodies. MORB-type dunites have initial $^{187}Os/^{188}Os$ ranging from 0.1221 to 0.1277 (Fig. 7a), in the same range as the host Pl-peridotites (from 0.1221 to 0.126). The replacive harzburgites have highly variable initial $^{187}Os/^{188}Os$ (0.1178–0.1238), which decreases with decreasing Re/Os ratio, Al_2O_3 (Fig. 7a, b), CaO and incompatible element contents (not shown). The highest $^{187}Os/^{188}Os$ values of the replacive harzburgites are like those of the Pl-harzburgites. The Pl-peridotites and the depleted harzburgites have similar Pd/Ir ratios, invariably lower than PM, whereas the MORB-type dunites are distinct in Pd/Ir ratios, locally higher than PM (Fig. 7c).

6. Discussion

6.1. *Melt-peridotite reactions and preserved isotopic variability in MORB-type dunites*

Our new Cpx trace elements and Nd—Hf compositions of the concordant dunites bodies coherently indicate migration of mantle melts with an N- to E-MORB geochemical affinity. In detail, Cpx in these rocks are selectively enriched in LREE compared to Cpx from the host Pl-peridotites (Fig. 4), and those in coeval lower crustal sections of the Alpine ophiolites (see also Piccardo et al., 2007). Likewise, the geochemical variability in Ol geochemistry in some of the MORB-type dunites points to a mildly enriched signature of the melts transported in these migration channels (Sanfilippo et al., 2014, 2017). Whole-rock PGE compositions of samples from all 4 dunite bodies selected in this study show high PGE contents, having Pt and Pd contents higher than the host Pl-peridotites, but variable Os and Re contents (Fig. 6c). In particular, all the MORB-dunites are characterized by high Pd/Ir ratios (Fig. 7c), a geochemical signature interpreted to be derived by melt-mantle interaction (e.g., Becker et al., 2006; Marchesi et al., 2013). High Pd/Ir ratios, for instance, characterize the plagioclase-rich dunites and Ol-rich troctolites from Central Indian Ridge (Sanfilippo et al., 2016), considered hybrid crustal lithologies formed at the expenses of former mantle peridotite intruded by migrating MORB melts (see also Tamura et al., 2016), and harzburgites from the mid-Atlantic Ridge modified by S-rich melts (Luguet et al., 2003).

At low pressure conditions, mantle melts are undersaturated in

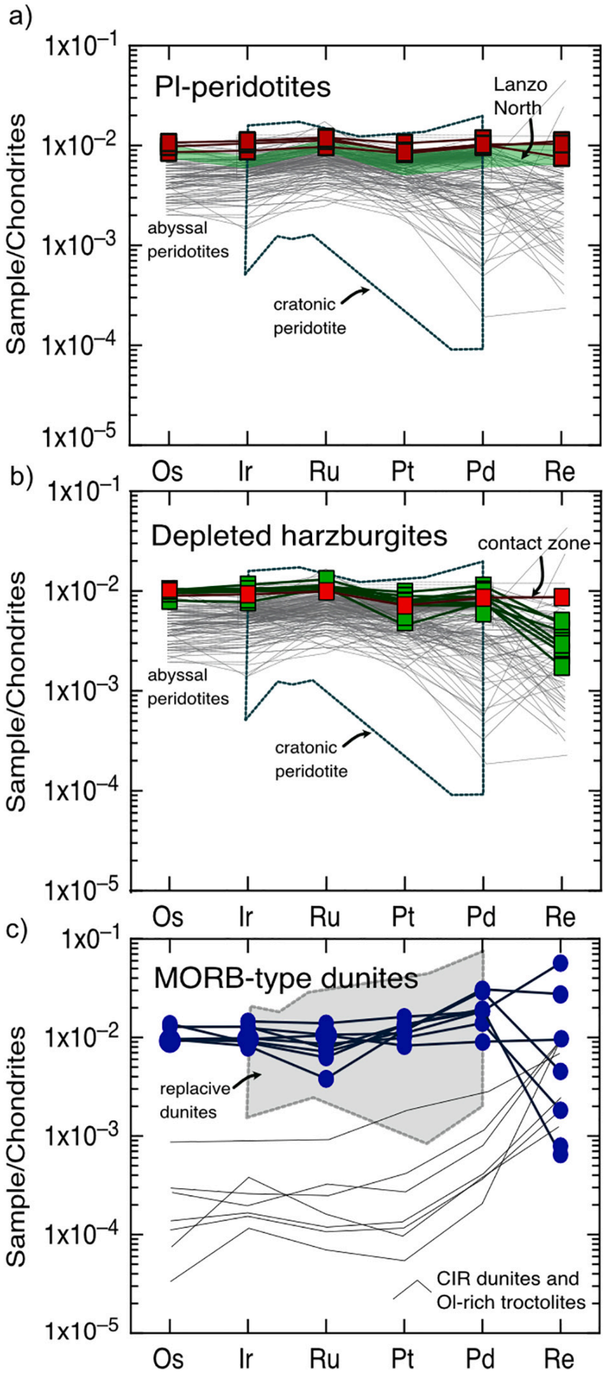

Fig. 6. Chondrite-normalized platinum-group element concentrations for Lanzo South Pl-peridotites (a), depleted harzburgites (b) and MORB-type dunites (c) (CI chondrite values from Horan et al., 2003) compared to the compositions of abyssal peridotites (see Snow and Reisberg, 1995; Luguet et al., 2001, 2003; Harvey et al., 2006, 2011; Marchesi et al., 2014; Lassiter et al., 2014; Day et al., 2017), cratonic peridotites (from Becker et al., 2006) and replacive dunites (Rehkamper et al., 1999; Buchl et al., 2004; Standish et al., 2002; Harvey et al., 2011; Marchesi et al., 2014). Olivine-rich troctolites and dunites from the crust-mantle boundary exposed at the Uraniwa Hills, Central Indian Ridge (Sanfilippo et al., 2016), are also shown.

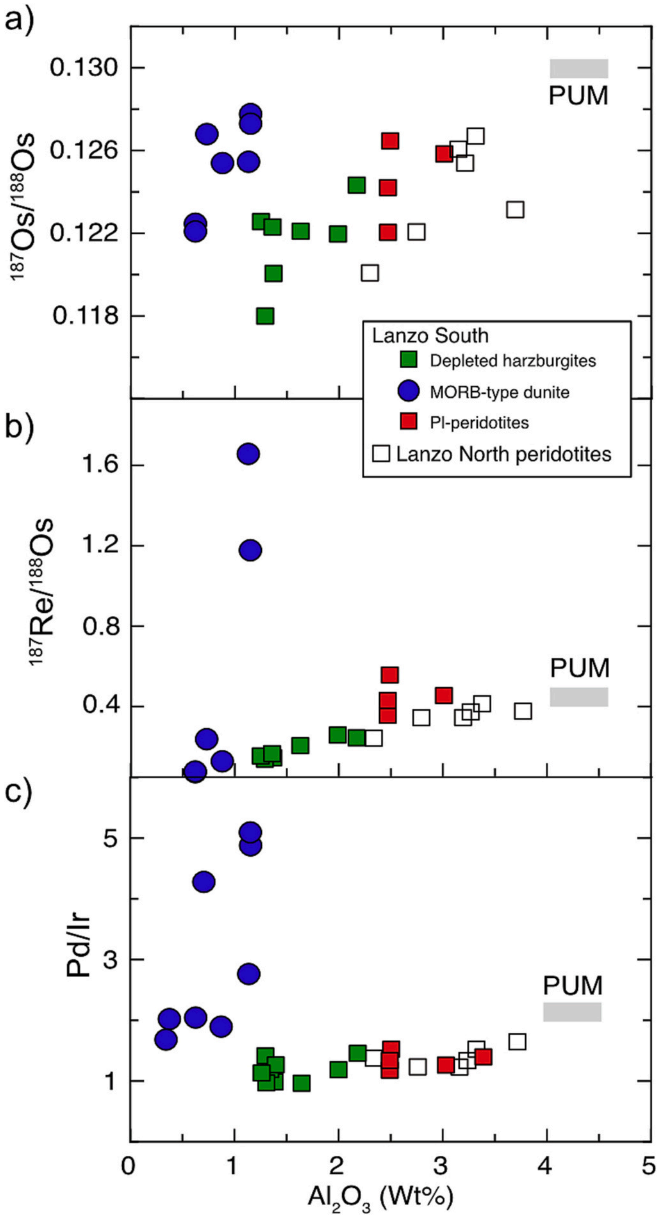

Fig. 7. Bulk rock Al_2O_3 versus (a) $^{187}Os/^{188}Os$, (b) $^{187}Re/^{188}Os$ and (c) Pd/Ir ratios of Lanzo South replacive bodies and host Pl-peridotites. Also shown are peridotites from Lanzo North (Lorand et al., 2000; Becker et al., 2006). Primitive Upper Mantle values from Becker et al. (2006).

sulphides (Mavrogenes and O'Neill, 1999) and may preferentially dissolve interstitial radiogenic sulphides from a peridotite matrix. It has been argued that this process may cause an increase in S and gradually enriches the $^{187}Os/^{188}Os$ ratios of the migrating melt (Sen et al., 2011). The subsequent crystallization of large quantities of olivine and spinel during the interaction process may drive the melt towards S saturation, which leads to the crystallization of magmatic sulphides having the Os isotopic signature of the migrating melt (Bézos et al., 2005; Xiong et al., 2022a, 2022b). However, owing to the low Os content of the interstitial sulfides in peridotites (Alard et al., 2002, 2005), the selective assimilation of these sulfides will hardly modify the overall Os isotopic composition of a melt-reacted peridotite. Rather, the extent to which the melt-reacted peridotite may record the composition of the migrating melt depends on the melt-rock ratios and on the efficiency of the crystallization process, i.e., the mass of sulphides crystallized during the interaction. In particular, we note that the dunites with the lowest whole rock Al_2O_3 contents are depleted in Re relative to both Pt and Pd (Fig. 4d; 6c), which are likely formed by extensive reaction with the migrating melts. Given the very low degrees of serpentinization in these samples (LOI $< 1\%$), the low Re cannot be attributed to secondary Re loss during hydrous alteration (Lorand et al., 2000). More likely, the low

Re contents in these dunites can be due to the fact that Re is less chalcophile than PGE (Brenan, 2008; Mungall and Brenan, 2014), which are accumulated in the rock as soon as the melt becomes sulphide-saturated, whereas some Re is retained in the melt. This agrees with the local occurrence of sulphides grains in association with the spinel trails in the central part of the dunite bodies, and indicates that magmatic sulphides were added at the closure of the porosity, when the migrating melt is likely to have equilibrated extensively with the original mantle matrix (see Reisberg, 2021). On the other hand, the MORB-type dunite samples having high Re and Re/Os ratios also have high Al_2O_3 contents (Fig. 4d; 7b). These samples likely record lower melt-rock ratios and despite the local equilibration with melt increased the overall Re contents, their Os concentrations were still buffered by the former Pl-peridotites, retaining $^{187}Os/^{188}Os$ similar to that of the host rocks. The Os isotope variability of the different samples is thereby dependent on the melt rock ratio and on the original isotopic heterogeneity of the host peridotite (Klaessens et al., 2021).

It is worth noting that the compositions of two MORB-type dunites having Cpx-rich segregations (i.e., LZ66 and LZ31) reveal a Nd—Hf isotopic variability that seems to agree with the whole-rock Os isotope compositions. The Cpx in the two samples ranges from isotopic values identical to those of the host Pl-peridotites for sample LZ31 ($\mathcal{E}Nd = 7.8$ and $\mathcal{E}Hf = 11.8$) to less radiogenic than the host rocks for sample LZ66 ($\mathcal{E}_{Nd} = 4.2$ and $\mathcal{E}_{Hf} = 7.5$). Likewise, the Os isotope compositions of the two dunite bodies varies from relatively low ($^{187}Os/^{188}Os = 0.1221$) to relatively high values ($^{187}Os/^{188}Os = 0.1277$) for LZ31 and LZ66, respectively). These values are in the range of the host Pl-peridotites and we cannot exclude that such a variability can be inherited from the host rock. However, the coherence between Nd—Hf and Os isotopes seems to indicate that the different replacive dunite bodies record traces of the Os isotopic compositions of the migrating melts. These rocks may have acted as migration pathways for mafic melts having slightly different isotopic compositions, nevertheless in line with the isotopic range of erupted MORB and of the host peridotites (Fig. 5).

6.2. *Formation of depleted harzburgites as an incomplete melt-rock reaction process*

Melt-peridotite interactions also had a leading effect on the composition of the depleted replacive harzburgites. These rocks have been interpreted as product of interaction between the host Pl-peridotites and a melt with ultra-depleted trace element compositions and highly radiogenic Nd—Hf isotopes (Sanfilippo et al., 2019). In the field, these bodies show gradational contacts with the Pl-peridotites, with evidence that the melt-rock reaction process produced a partial annealing of the tectonite structure of the Pl-peridotites converted into isotropic harzburgites. In addition, the harzburgite shows large, kinked Opx partly adsorbed by cm-sized undeformed olivine, and interstitial Cpx associated with chromite having lower Cr# than those in the host rock (Figs. 3; 4a). The field and textural evidence for a replacive origin are further supported by the chemistry of the clinopyroxene. Compared to the Cpx in host Pl-peridotites, the interstitial Cpx in the harzburgites has markedly lower M-HREE contents but higher and variable LREE, which result in overall flat REE patterns characterized by low LREE/M-HREE fractionations (Fig. 4c). The lower M-HREE contents of the Cpx in the depleted harzburgites compared to those of the host rocks require that the migrating melts had a depleted geochemical signature, whereas the local enrichments in LREE indicate that this mineral crystallized at a reduced porosity (see Piccardo et al., 2007; Sani et al., 2020). Similarly, Cpx in all selected harzburgites retain highly radiogenic Hf isotope signatures, coupled to less radiogenic $^{143}Nd/^{144}Nd$ ratios (Fig. 5). Based on the replacive nature of these rocks, Sanfilippo et al. (2019) proposed that the depleted incompatible trace elements and the Nd—Hf isotopic signature were caused by incomplete interactions between melts having an ultra-depleted affinity and the host Pl-peridotites. The preservation of Sm—Nd Jurassic errorchrons, coexisting with Lu—Hf errorchrons giving an apparent age > 1Ga, indicates that the interaction process occurred in the Jurassic and caused the total reset of the Nd isotopes. The Hf isotopes, on the other hand, were only partially reset during the melt-rock reaction process, and the preserved covariation in $^{176}Lu/^{177}Hf$ versus $^{176}Hf/^{177}Hf$ ratios does not have age significance but represents a mixing line (see also Stracke et al., 2011; Sani et al., 2023). Hence, contrary to what proposed for the ultra-depleted mantle peridotites sampled in oceanic environments (Liu et al., 2008; Bizimis et al., 2003; Stracke et al., 2011; Byerly and Lassiter, 2014; Tilhac et al., 2022; Sani et al., 2023), the ultra-depleted chemical and isotopic signatures of the Cpx in the Lanzo replacive harzburgites might have been caused by interactions with melts generated by ancient, refractory sources (Sanfilippo et al., 2019). To what extent the PGE and $^{188}Os/^{187}Os$ data in this study sustain this idea will be hereafter discussed.

The replacive harzburgites preserve covariation between whole-rock Re, Os, $^{188}Os/^{187}Os$, and lithophile elements (see Fig. 4d; 7; Tables S4 and S5), which can be potentially attributed to a process of ancient mantle melting followed by radiogenic Os ingrowth (Reisberg and Lorand, 1995; Harvey et al., 2006; Liu et al., 2008; Stracke et al., 2011; Luguet and Reisberg, 2016). In this scenario, the PGE contents of the Lanzo Pl-peridotite would represent the starting peridotite, preserving PM-like PGE compositions and gradually shift towards more refractory compositions during old event of melt-extraction (see also Becker et al., 2006). If this was the case, however, the high MgO contents of the replacive harzburgite would indicate a strongly refractory character, well above the sulphide exhaustion point. However, the refractory harzburgites reveal depletions in only in Re, whereas Pd, Pt, Ru and Ir are similar to those of the host Pl-peridotites, much higher than the PGE patterns expected for residues at high melting degrees (see Fig. 6b). Indeed, unlike residues of mantle melting, the fractionation between Ir and Pd (Fig. 7c), or Pt (not shown) is nearly constant in all Lanzo harzburgites, and like those of the host Pl-harzburgites, despite the large variations in Al_2O_3 contents would require large variations in melting degrees. Hence, the high PPGE (Pt and Pd) and low Re of the refractory harzburgites agree with an origin by melt-rock reaction (Reisberg, 2021).

Melt-rock reaction might have caused a modification of the $^{187}Os/^{188}Os$ compared to that of the host Pl-peridotites. One scenario to explain the decrease in Os isotope ratio is that the percolation of a mafic melts along the grain boundaries might have promoted a gradual removal of interstitial sulphides, rich in Re and having high $^{187}Os/^{188}Os$ (Alard et al., 2002; Luguet et al., 2003; Harvey et al., 2006; Marchesi et al., 2014). However, even if unradiogenic Os sulphides are generally found as inclusions within the silicate phases, experimental studies indicate that the grain boundary diffusivity of Os can be several orders of magnitude higher than other lithophile elements (e.g., Hayden and Watson, 2007). Hence, at asthenospheric temperatures and given enough time the original Os isotopic signature can be partly or totally redistributed amongst the different sulfide populations in a sample that suffered old events of melting or melt-rock reaction (Reisberg, 2021). For instance, this is shown by the preservation of low Os, skeletal sulphides with relatively high Re/Os but unradiogenic $^{187}Os/^{188}Os$ in refractory abyssal peridotites (0.117; Harvey et al., 2006). Hence, given that the isotopic differences between intergranular and enclosed sulphides should be minimal at asthenospheric temperatures (see Lassiter, 2018), removal of intergranular sulphides should have a minor effect on the $^{187}Os/^{188}Os$ of the bulk rock.

A plausible scenario is that the decrease in Os isotopic ratio was caused by interaction with the ultra-depleted melt, which inherited low $^{187}Os/^{188}Os$ ratios (e.g., 0.118) from a source having ancient portions of mantle asthenosphere (Byerly and Lassiter, 2014; Stracke et al., 2019; Sani et al., 2023). Following this idea, the general decrease in bulk $^{187}Os/^{188}Os$ ratios was driven by the gradual re-equilibration of the peridotite matrix with the ultra-depleted migrating melt (Day et al., 2017), similar to what is proposed for the lithophile elements and Nd—Hf isotopes (Sanfilippo et al., 2019). A similar scenario also agrees with the relationship between whole rock $^{187}Os/^{188}Os$ and the Cpx ε_{Hf} (Fig. 8), which show that the sample from the depleted replacive harzburgite retaining the lowest $^{187}Os/^{188}Os$, and less depleted whole rock compositions, also has the lowest Cpx ε_{Hf}. On the other hand, those retaining the most depleted compositions in term of whole rock and Cpx ε_{Hf} have $^{188}Os/^{187}Os$ like the host Pl-peridotites. Given the strongly different affinity of Os and Hf for the peridotite and melt phase, respectively, this covariation can be explained by different melt-rock ratios for the different samples. The conversion of Pl-peridotites into refractory harzburgites causes the dissolution of plagioclase and interstitial sulphides into the melt, thus lowering the whole rock in Al, Ca and incompatible elements contents, along with Re. At low melt-rock ratio, the melt-reacted peridotite retains a less refractory whole-rock composition, but the migrating melt preserves its original radiogenic Hf isotopic signature due to limited chemical equilibration with the host rock. The overall Hf budget is strongly controlled by the melt phase, and the crystallizing Cpx would still retain the original melt composition, poor in incompatible elements and having radiogenic Hf isotopes. On the other hand, the whole-rock PGE contents and Os isotope ratios would be still controlled by the host peridotite, thereby preserving high $^{187}Os/^{188}Os$. At high melt flux, the peridotite becomes gradually more refractory (low Al and Ca contents, low Re; see also Reisberg, 2021), but the melt has interacted extensively with the host rock. The highly radiogenic Hf—Nd isotopic compositions of the melt are modified by interaction with the Pl-peridotite and gradually shifted towards less radiogenic values. The bulk $^{187}Os/^{188}Os$ ratios, on the other hand, would be less dependent on those of the pre-existing peridotite, and is shifted towards the migrating melt.

Basically, the contrasting control of Os vs. Nd—Hf abundances by whole rocks vs. melts causes a contrasting behaviour of the isotope systematics during melt-rock reaction. Different melt-rock ratios, thereby, produce the covariation between Os and Hf isotopes observed for the Lanzo replacive harzburgites. We note that the covariation in Fig. 8 can be preserved only if the reacting melt is geochemically more depleted than the host peridotites, a combination fortuitously preserved in the Jurassic Lanzo ophiolite (see McCarthy and Müntener, 2019; Rampone and Sanfilippo, 2021), but unusual at a mature Mid Ocean Ridge. In contrast, melt extraction from the mantle causes an increase in the Lu/Hf ratio, coupled to synchronous removal of Re, which with time, will develop a highly radiogenic Hf isotopic composition coupled with low $^{187}Os/^{188}Os$. Such a relationship is manifested by the Gakkel Ridge peridotites (Fig. 8), considered ancient residues of partial melting (Liu et al., 2008; Stracke et al., 2011), and not in the Lanzo South harzburgites.

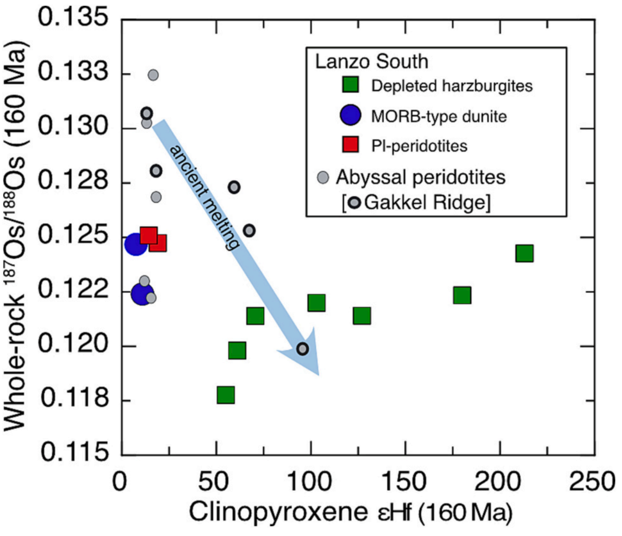

Fig. 8. Bulk rock $^{187}Os/^{188}Os$ versus clinopyroxene εHf (initial values at 160 Ma) of Lanzo South replacive bodies and host Pl-peridotites. Also indicated are abyssal peridotites (data from Liu et al., 2008; Stracke et al., 2011; Day et al., 2017). Note that ancient melting would produce inverse correlations in Os versus Hf isotope ratios as a consequence of radiogenic Os and Hf ingrowth, as displayed by the refractory peridotites from Gakkel Ridge.

6.3. *Melt migration in chemically isolated melt pathways*

Our results suggest that magma mixing inside the replacive dunite channels in Lanzo was limited. Rather than enriched magmas from fertile mantle component, we document that channelized magma transport mainly preserved melts from refractory lithologies, witnesses of ancient melting events. The efficiency of melt mixing is dependent both on the length scale of the heterogeneity and on the velocity of magma transport (Liu and Liang, 2017). If mantle heterogeneities are small, the chemical signature of primary magmas can be easily diluted soon after their creation. On the other hand, heterogeneity can be better preserved if the size of the heterogeneity is large enough to limit efficient mixing during transport. It is therefore likely that these refractory mantle components were large enough to generate their own network of channels to account for preservation of isotopic heterogeneity. On the other hand, our study reveals that primary melts from more fertile lithologies were more efficiently mixed during melt transport (Stracke and Bourdon, 2009), forming a network in the dunite with isotopic and trace element compositions plotting in the field of MORB. This can be related either to the size of these enriched endmember, or to the fact that melts from fertile materials are more prone to melt–rock reactions with the ambient depleted peridotites (Lambart et al., 2009) and their occurrence can easily nucleate channelization (Katz and Weatherley, 2012; Liu and Liang, 2019). In both cases, the MORB-type replacive dunites preferentially transport melts from the most fusible component in the lowermost part of the melting region, efficiently mixed with melts from DM-like lithologies. On the other hand, ultra-depleted melts from ancient mantle were transported in chemically isolated pathways. Despite their refractory character, thermodynamic models showed that depleted mantle peridotites retaining ancient traces of melt depletion can produce substantial amount of melts before exhaustion of Cpx (Byerly and Lassiter, 2014; Sani et al., 2020), in agreement with the local occurrence of ultra-depleted isotopic compositions in olivine melt inclusions form the Azores (Stracke et al., 2019), and with the local occurrence of erupted MORB having anomalously high Hf isotopes (Blichert-Toft et al., 1997; Salters et al., 2011; Sanfilippo et al., 2021). The unradiogenic Os signature of these ancient melting residues can be potentially transferred to their primary melts, along with highly radiogenic Hf and Nd isotope compositions. However, melting of such lithologies requires substantially lower pressures, thereby discouraging mixing between magmas derived from more enriched components and preserving their extreme isotopic compositions. We note that in Lanzo South melts with such an ultra-depleted chemical signature are found in discordant replacive mantle bodies that, unlike the MORB-type dunites, formed after the regional deformative event related to the emplacement of the sequence at shallow conditions. Hence, the ultra-depleted geochemical signature of melts from ancient refractory mantle lithologies has a higher chance to be preserved within shallow migration channels.

Despite magma chambers processes having a critical effect in mixing and averaging the primitive magma compositions, further concurrence with our hypothesis comes from recent investigations on abyssal gabbros. For instance, the widespread occurrence of high anorthite plagioclase in gabbros and in crystal cargoes of MORB indicates that the contribution of ultra-depleted mantle lithologies is by far higher than that revealed by erupted MORB (Neave and Namur, 2022). Furthermore, significant variations in Nd and Sr isotopes are preserved in crystal cores from some primitive gabbros from the Atlantis Massif core complex, at Mid Atlantic Ridge (Lambart et al., 2019). These variations encompass the range of isotopic variability of erupted MORB in the entire MAR and provide evidence that melts from a heterogeneous mantle were delivered to the lower crust before extensive mixing. Although we cannot exclude the PGE (including Os) contents of replacive bodies might be partly inherited from the host peridotites, we here show a case where replacive mantle bodies still preserve traces of a Nd-Hf-Os isotopic variability reflecting heterogeneous melts migrating throughout the abyssal mantle. This implies that the limited isotopic variability recorded by erupted MORB is mainly the consequence of mixing at crustal level (Lambart et al., 2019). Melts from ancient and depleted asthenospheric mantle portions have high chance to be delivered towards the crust-mantle boundary with limited extent of aggregation. It is therefore critical to define the degrees of chemical heterogeneity of lower crustal reservoirs before magma mixing and melt-rock reaction further complicate the transfer of the original mantle heterogeneity to the erupted melts.

7. Concluding remarks

This study documents a complete geochemical characterization of two generations of decametre-scale replacive mantle bodies from the Jurassic Lanzo South ophiolite, Western Italian Alps. We show that these replacive bodies can be considered migration pathways for primitive mantle melts produced during the opening of the Ligurian-Piedmontese basin. The Cpx and Ol in the MORB-dunites point to a mildly enriched signature of the melts transported in these migration channels and is also indicated by the high PPGE contents and $^{187}Os/^{188}Os$ ratios similar to those of the host peridotites (0.122–0.128). The discordant harzburgites, on the other hand, are geochemically depleted, and have Hf isotopes in Cpx extending by far the isotopic variability of erupted MORB. Preserved correlations between PGE, Os isotopes and whole-rock compositions are dependent on melt-rock reaction and indicate that the depleted character was inherited by incomplete interaction with a migrating melt having a highly depleted character. In essence, the MORB-like dunite experienced the migrations of melts having variable contributions from enriched lithologies, already partly mixed with melts from DM-peridotites. The depleted harzburgites, instead, mostly acted as migration pathways for melts sourced by ancient, highly depleted lithologies. Therefore, we postulate that melts from ancient and depleted mantle portions have higher chance to be delivered towards the crust-mantle boundary with limited extent of aggregation. If the traces of preserved Nd-Hf-Os isotopic variability documented in the Lanzo replacive bodies is a common feature in melt migration mantle channels, this implies that magma mixing at deep crustal levels may have a primary, hitherto poorly recognized role in determining the chemical heterogeneity of erupted melts. Hence, the chemical heterogeneity of lower crustal reservoirs needs to be better characterized to understand to what extent the original mantle heterogeneity is transferred to the erupted basalts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available as electronic supplementary material

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemgeo.2023.121779.

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