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Title: Evidence of subduction-related components in sapphirine-bearing gabbroic dykes (Finero Phlogopite Peridotite): Insights into the mantle sources of the Triassic-Jurassic magmatism at the Europe-Africa-boundary

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Major and trace elements of minerals and bulk rock, as well as the isotope O, Sr and Nd composition of minerals, have been investigated for dykes and host peridotite of two different FPP areas.
The melt migration early developed by porous-flow within cm-thick channels, being characterised orthopyroxene-dissolution. With the progression of percolation and reaction, the melt became silica-saturated and an orthopyroxenite layer was segregated in the centre of the channels. Three different evolution stages, involving opening and enlargement of the conduits, determined the layered internal structure of the dykes. The sapphirine and green spinel segregation took place at T> 1000°C in presence of a melt with transient composition, which interstitially migrated and reacted with the cumulus minerals forming the hornblendite layers. Composition of newly-formed amphiboles indicates that the sapphirine parent melt was Al-rich, depleted to strongly depleted in Hf, Zr, Nb, Ta, Ti, Sc, V, MREE and HREE, and characterised by positive Eu anomaly and (Zr/Hf)N <1. These observations suggest the presence in the transient melt of significant amounts of plagioclase component. Plagioclase assimilation was not observed in the studied veins: it is thus argued that the addition of plagioclase component occurred in hidden magmatic bodies or in the melt source.
The δ18O of vein amphiboles and plagioclase varies from 6.9 to 8.6‰ SMOW, being well above the mantle range, also taking into account fractionation

upon cooling. The additional observation that the orthopyroxene from the wall, reactive orthopyroxenites has "normal "mantle δ18O values (5.8‰) brings us to conclude that reaction with the host, metasomatised peridotite was not apparently responsible for the heavy isotope O composition argued for parent melt of the dyke minerals: the latter must have been imparted by crustal components sitting at deeper mantle depths. This finding evidences as the Northern IVZ records an extremely prolonged release (lasted from the Variscan orogenic cycle to the Mesozoic exhumation of lithospheric mantle at shallower levels) of K-H2O-rich mantle-derived melts polluted by subduction-related components, placing valuable insight into the comprehension of the Triassic-Jurassic magmatism and the geodynamic environment at the Europe-Africa boundary.

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***Highlights (for review)**

Mesozoic Spr-bearing gabbroic dykes with continental crustal components

Reaction between dyke melts and the metasomatised host enhanced the crustal signature

The large Al content of the parent melt caused the segregation of magmatic sapphirine

Dykes record Triassic K-rich Calk-Alkaline to Shosonitic magmatism in Southern Alps

Evidence of subduction-related components in sapphirine-bearing gabbroic dykes (Finero Phlogopite Peridotite): Insights into the mantle sources of the Triassic-Jurassic magmatism at the Europe-Africa-boundary

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Abstract

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Introduction

It is well-known that subcontinental lithospheric mantle (SCLM) may record significant heterogeneities in terms of both lithologies and geochemical composition as a result of the development of different tectono-magmatic events over a large time span (Mukasa and Shervais, 1999; Rivalenti et al., 2007a,b; Mazzucchelli et al., 2009; 2010; 2016; Borghini et al. 2017; Princivalle et al., 2014; Ponce et al. 2015; Rocco et al., 2017). On the other hand, the petrochemical record on both lithospheric mantle and uprising melts can be very different owing to the geochemical affinity of the melt, the composition of the peridotite mantle column, the modalities of melt migration and the P, T, fO2 and fH2 conditions of the system. A unique study case in which to characterize peculiar modifications affecting uprising mantle melts is the Phlogopite Peridotite mantle unit of Finero (Cawthorn, 1975; Siena & Coltorti, 1989). The Finero Phlogopite-Peridotite (FPP hereafter) is one of the most studied mantle massifs on the Earth. It crops out in the northernmost part of the Ivrea-Verbano Zone (IVZ, western Alps, Italy; Fig. 1) and mainly consists of an association formed by Phlogopite-bearing Amphibole harzburgites and dunites, both locally associated to Phlogopite-bearing Amphibole pyroxenites. Such a lithologic association is apparently the result of a main episode of pervasive to channelled porous flow migration of melts containing large volume of crustal components, which induced a virtually complete metasomatic recrystallization (Cawthorn, 1975; Siena & Coltorti, 1989 Hartmann & Wedepohl, 1993; Zanetti et al., 1999, 2016; Grieco et al., 2001, 2004; Morishita et al., 2003, 2008; Raffone et al., 2006; Selverstone & Sharp, 2011; Mazzucchelli et al., 2014; Tommasi et al., 2017).

The available geochronological data indicate that main events of melt migration took place in Paleozoic times (Zanetti et al., 2016; Malitch et al., 2017), but many field, petrochemical and geochronological data points to the development of tectono-magmatic events in Mesozoic times (Stähle et al., 1990, 2001; Grieco et al., 2001; Matsumoto et al., 2005; Morishita et al., 2003, 2008; Zanetti et al., 1999; 2016; Malitch et al., 2017).

Giovanardi et al. (2013) studied the occurrence of late Sapphirine-bearing (Spr) gabbroic dykelet swarm previously reported in literature by Siena & Coltorti (1989) and discovered by M. Mazzucchelli. On the basis of a detailed survey of petrography and the major element mineral compositions, they furnish evidence for a multi-stage dyke formation, which involved fractional crystallization associated to different patterns of melt-rocks interactions.

With the aim of better constraining the nature of the primitive melt and the petrological processes inducing the segregation of Spr in the dykes, new, detailed petrochemical data are here reported for dykes and host peridotites close to the area studied by Giovanardi et al. (2013) and a second one placed in an adjacent area. Particular care has been dedicated to the characterise changes in major and trace element mineral chemistry, as well as in its isotope O, Nd and Sr composition, to document the geochemical fractionation eventually experienced by the flowing melt as a result of the reaction with host peridotite and early cumulates. The genetic and temporal relationships between the dyke emplacement and other events of melt migration recorded by the FPP unit, as well as the related geodynamic scenarios, are also addressed.

Geological setting

In the Finero area (Fig. 1), the IVZ crops out in a pseudo-antiform structure showing the FPP mantle unit at the core, which is flanked by the so-called Finero Mafic Complex (Cawthorn, 1975; Siena & Coltorti, 1989; Lu et al., 1997a, b; Zanetti et al., 2013, 2014; Giovanardi et al., 2014; Mazzucchelli et al., 2014; Langone et al., 2017). The Mafic Complex is divided in three different units: i) the stratigraphically lower Layered Intenal Zone unit (LIZ), in contact with the FPP; ii) the Amphibole-Peridotite (Amph-Pd); and iii) the External Gabbro (EG). The EG is placed in tectonic contact with the Amphibole Peridotite by a Mesozoic high-T shear-zone (Langone et al., 2018). A tectonic contact also characterises the transition towards the amphibolites-facies metasediments and metabasites of the Kinzigite Formation (KF), which represent the metamorphic basement of the Adria plate. Septa of KF rocks are embedded in the EG.

The Finero mafic-ultramafic sequence presents several differences with respect to the southern and central sectors of the IVZ (i.e. the Baldissero and Balmuccia peridotite and the Val Sesia Complex; Quick et at., 1995; Correia et al., 2012; Mazzucchelli et al., 2014 and references therein) providing evidences of a different geological evolution (Zanetti et al., 2013, 2014, 2016; Langone et al., 2017, 2018). In particular, the FPP results completely recrystallized by several events of melt migrations bringing crustal components (Zanetti et al., 1999; 2016; Mazzucchelli et al., 2014 and references therein) and the relationships with the parent melts of the surrounding Mafic Complex are far to be proved (Giovanardi et al., 2014). On the contrary, the peridotites cropping out in the central and southern part of IVZ do not suffered a similar melt-induced recrystallization and were emplaced in the Kinzigite Formation as tectonic slivers before the intrusion of the central and southern Mafic Complex (Quick et at., 1995; Mazzucchelli et al., 2014 and references therein).

The FPP is mainly represented by Phl-bearing Amphibole harzurgites and associated Phl-bearing pyroxenites (Cawthorn, 1975; Siena & Coltorti, 1989; Hartmann & Wedephol, 1993; Zanetti et al., 1999; Raffone et al., 2006; Selverstone & Sharp, 2011; Mazzucchelli et al., 2014; Giovanardi et al., 2018). These lithologies resulted from pervasive metasomatism in a depleted peridotite, which formed secondary Opx, Amph and Phl (Zanetti et al., 1999, Tommasi et al., 2017). Channeled migration events formed dunite bodies containing stratiform to podiform chromitites and, rarely, pyroxenite and hornblendite layers (Grieco et al., 2001, 2004; Zanetti et al., 2016).

Late stages of porous-flow melt migrations crystallized Apatite-Dolomite-bearing wehrlites and Apatite-rich orthopyroxene-bearing peridotites, which sometimes contain carbonate-bearing domains showing marked modal and geochemical gradients with the host rocks (Zanetti et al., 1999; Morishita et al., 2003, 2008; Matsumoto et al., 2005; Raffone et al., 2006). U-Pb analyses on Ap and isotopic Noble Gases data provide Triassic ages (Morishita et al., 2008).

Apatite and Calcite also occur in dykes of Nepheline-bearing syenites, associated to hornblendites, of Triassic age (Stähle et al, 1990, 2001). Lower Jurassic U-Pb zicon age was determined for an alkali pegmatite (Grieco et al., 2001)

The rocks of the FPP related to the main event and the dunite bodies show similar geochemical features and absence of geochemical gradients. The harzburgite-pyroxenite association and the chromitites and pyroxenite layers in dunite bodies are depleted in Nb and HSFE and significantly enriched in K, Rb, Ba, Sr, LREE (Hartmann & Wedephol, 1993; Zanetti et al., 1999, 2016; Mazzucchelli et al., 2014). The mineralogical and compositional features have been considered by several Authors as the evidence of the role of slab-derived crustal component in the percolating melts (Hartmann & Wedephol, 1993; Mazzucchelli et al., 1995; 2016; Rivalenti et al., 1995; 2007a; Zanetti et al., 1999, 2016; Grieco et al., 2001, 2004; Morishita et al., 2003, 2008; Ponce et al., 2015; and others). So far, a variety of different geochemical components has been identified according to the isotopic data. In particular, isotopic Hf (in zircon) and O (in zircon and pyroxenes) composition of chromite minerals points to the presence in the migrating melts of large volumes of continental crust (Zanetti et al., 2016; Malitch et al., 2017), whereas, hydrogen, oxygen and chlorine isotope compositions of Amph and Phl from the harzburgite-pyroxenite association show a variation range (δD from -29 to –86‰, δ^{18}O from 4.9 to 6.1‰ and δ^{37}Cl from -2.0 to +2.1‰) consistent with mixtures of magmatic fluids with sea-water (Hartmann & Wedepohl, 1993; Selverstone & Sharp, 2011).

Giovanardi et al. (2013) reported the occurrence in the FPP of late Spr-bearing gabbroic dykes. These dykes crosscut at high angle the pervasive mantle foliation and the other lithologies, showing different mineralogical and major element mineral chemistry features with respect to other FPP rocks.

Samples and petrography

Two different dykes and their host peridotites from the FPP unit were investigated. The first dike (sample FI09C06, Fig. 2) was collected along the road that connects the National Road 631 to a peridotite quarry located on the right flank of the Rio Creves valley (less than 100 m far from the outcrops studied by Zanetti et al. 1999), while the second one (FI9664 sample) is from a boulder along the Rio Creves, about 30 m upstream of its intersection with the Rio Cannobino. The host peridotite has been collected 8 cm far from the FI09C06 dyke, and close to the contact with the dyke documented by FI9664 sample.

Gabbroic dykes are centimetric in thickness (mostly 2-5 cm; Fig. 2). They show variable strike, usually crosscutting at high angle the harzburgite-pyroxenite association (Fig. 2).

A Mesozoic age for these Spr-bearing dykes is constrained by the observation they also crosscut the foliation of protomylonites in the external domains of Mesozoic shear zones (Matysiak & Trepmann, 2015 and references therein), but are themselves deformed in a few cm-wide mylonitic to ultramylonitic band parallel to the protomylonites foliation (Tommasi et al., 2017). Such a shear zones were active at different crustal levels over a very long, Triassic-Jurassic time interval (235-180 Ma; Langone et al., 2018 and references therein). This is also consistent with the observation the all the late intrusive bodies discordantly intruding the pervasive mantle foliation by hydraulic fracturing do not show ages older than Triassic (Stähle et al., 1990, 2001; Grieco et al., 2001; Matsumoto et al, 2005).

The gabbroic dykes contain Spr (Giovanardi et al., 2013) and show a layered symmetric structure consisting of melanocratic zones at peridotite contacts and a leucocratic zone representing the dyke core (Fig. 2). The melanocratic zones, in turn, can be divided in three different bands.

Moving from the host peridotite to the dyke core, the following layers can be recognized:

1) an orthopyroxenite zone (hereafter Opx Zone), established within the ambient peridotite. Opx locally shows recrystallized rims with growth of fine neoblasts of Opx and rarely Ol. Opx presents sometimes exsolution lamellae. Locally, black Sp and Phl occur as accessory phase. Phl is concentrated in interstitial position, but rarely, fills fractures within Opx crystals (Fig. 2). Giovanardi et al. (2013) reported the occurrence of Spr-Amph-bearing recrystallisation front also in the Opx Zone.

2) a first melanocratic zone (hereafter Early Amph Zone) inside the vein formed by dark-brown Amph (up to 1 cm long, named 'Early Amph') and associated small Plg grains, Sp, Phl and Ap; in these zones the magmatic texture is preserved as evidenced by Amph twinning. Ap and Sp mainly occur as rounded inclusions in Amph, whereas Phl is in interstitial position.

3) a second melanocratic zone (hereafter Late Amph Zone), consisting of light-brown to green Amph (named 'Late Amph'), green Sp, Spr and Phl. Spr occurs in three textural positions, namely as: i) inclusions within Late Amph, ii) coronas rimming Sp, and iii) isolated/aggregate crystals in interstitial positions (Fig. 2). Phl is an accessory phase in interstitial positions. Late Amph is smaller than Early Amph, euhedral to anhedral in shape. Intermediate green-brown Amph, often associated with Sp and Spr, is recognized near and through the Early Amph Zone - Late Amph Zone contact. Recrystallization zones with fine-grained texture occur. The Late Amph Zone is not continuous through the dykes. It forms patches, which can occur also only on one side of the leucocratic core of the dyke, or that can extend up to the Opx Zone. The Late Amph Zone is more developed in sample FI9664 (up to about 1.5 cm in thickness) with respect to sample FI09C06 (up to 1 cm in thickness). Besides, Spr crystals in sample FI9664 can reach up to 1.5 mm in size, while in sample FI09C06 they are commonly < 0.2 mm.

4) a leucocratic zone (Leucocratic Zone, hereafter) formed by Plg and subordinate Amph (both magmatic and relict from melanocratic zones). Ap occurs as accessory phase, sometimes included in Plg or in relict of brown Early Amph. Rarely Ap contains calcite inclusions. Plg show twinning (mainly Pericline and subordinately crossed Albite-Pericline), which is often partially or totally erased by recrystallisation induced by late deformation. Magmatic Amph has greenish pleochroism whereas relict Amph, ripped from the melanocratic zones, is brown. Amph often forms single-crystal alignments parallel to the dyke strike, like in a flow-texture. Phl is rare and is associated to Amph. Recrystallization zones show fine-grained equigranular texture. Rarely Fe-oxides, Fe-Ni sulphides and pyrite occur.

The host peridotite away from the contact is a hornblende-harzburgite (according to Giovanardi et al., 2018) in modal composition with porphyroclastic texture. It is characterised by the presence of olivine (Ol) and orthopyroxene (Opx) porphyroclasts, with a secondary, undeformed mineral assemblage dominated by amphibole (15% by Vol.), in association with orthopyroxene, spinel, phlogopite and clinopyroxene, strictly similar to the dominant peridotite-type described by Zanetti et al. (1999) and Tommasi et al. (2017). A detailed petrographic inspection highlight the occurrence of a reacted peridotite zone approaching the Opx Zone. It is characterised by the presence of a secondary mineral assemblage, modally dominated by long (up to 5 mm) phlogopite lamellae, to which are associated subordinate amount of undeformed orthopyroxene, spinel, amphibole and clinopyroxene. In the reacted zone, olivine was stable: conversely, the modal orthopyroxene content is slightly lower than in the peridotite far from the vein. Primary (e.g. Olivine) and secondary minerals into the reacted zones display elongation sub-parallel to the present-day vein strike.

Analytical methods

Sample FI9664, representing the gabbroic dyke and the contact host harzburgite, was analyzed for whole rock major and trace elements. Whole rock major elements and Sc, V, Cr, Co, Ni, Cu, Zn were analysed by X-Ray Fluorescence Spectrometry (XRF), while Li, Rb, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta and Pb were analysed by Inductively Coupled Plasma - Mass Spectrometry (ICP-MS). Analyses were performed following methods described by Mazzucchelli et al. (2010) (data reported in Supplementary material A).

FI9664 and FI09C06 samples were analysed for mineral major element with the electron microprobe JEOL 8200 Super Probe housed at the University of Milano. Analyses were performed following methods described by Ponce et al. (2015). Data are reported in Supplementary Material X.

Mineral trace elements have been determined (as in Rivalenti et al., 2007b) with a LA-ICP-MS housed at I.G.G.-C.N.R., U.O.S of Pavia (data are reported in Supplementary Material Y) using a Perkin Elmer SCIEX DCR-e coupled with a solid-state laser source (Q-switched Nd:YAG, Quantel Brilliant). Data reduction was performed using the GLITTER software. NIST SRM 610 was used as external standard. Ca was used as internal standard for Cpx, Amph and Plg, Si for Ol, Opx and Phl, and Mg for Sp. Precision and accuracy were assessed by repeated analysis of BCR-2g standard, resulting better than 10% relative at ppm concentration level. Further information is reported by Giovanardi et al. (2017).

The sample FI09C06 was selected for determination of O, Nd and Sr isotopic composition in mineral separates, after that the combination of preliminary EMPA and LA-ICP-MS analyses had suggested a more primitive nature for its parent melt.

O isotopes on pure mineral separates from FI09C06 sample were analysed at the I.G.G.-C.N.R., Pisa by conventional laser fluorination with a Finnigan Delta Plus mass spectrometer. 1-1.5 mg aliquots of each phase were necessary to measure the oxygen isotope composition. Analyses were performed following methods described by Perinelli et al. (2011). Data reported in Table 1.

Sr and Nd isotopic ratios on Amph and Plg separates from sample FI09C06 and the host harzburgite were analysed at the laboratories of the Marine Environmental Sciences Laboratory (LEMAR: UBO - CNRS - IRD - Ifremer) of the Institut Universitaire Européen De La Mer (Iuem), Université De

Bretagne Occidentale. Analyses were carried out after dissolution and chromatographic separations using a TRITON Thermo-Ionization Mass Spectrometer (TIMS) following the procedure described in Janin et al. (2012). Analyses were corrected for NBS987 reference material ($^{87}Sr/^{86}Sr$ = 0.710241 ± 0.000019, n = 6) for Sr and La Jolla standard ($^{143}Nd/^{144}Nd$ = 0.511847± 0.000009, n = 3) for Nd. Data reported in Table 2.

Bulk rock chemistry

Gabbroic dyke FI9664 presents higher TiO_2, Al_2O_3, CaO, Na_2O, K_2O, and lower FeO and MgO than the host harzburgite collected at the contact.

The gabbroic dyke has trace element abundances higher than one magnitude order with respect to host harzburgite: only Rb and Li content is similar in both rocks (Fig. 3). The two rock types show some similarities in element fractionation, namely, i) marked enrichments in LREE with respect to M-HREE [$(La/Yb)_N$ is 5.5 and 16-30 for dyke and host harzburgite, respectively; Primitive Mantle data from McDonough and Sun, 1995], ii) $(Th/U)_N$ and $(Zr/Hf)_N$ always <1 and iii) positive Ba and Pb anomaly. Conversely, the $(Nb/Ta)_N$ is 1.6 for the gabbroic dyke and 0.7 for the host harzburgite. gabbroic dyke FI9664.

Linearly-fractionated LREE-enriched patterns are also shown by the nepheline-bearing alkaline dykes described by Stähle et al. (2001). However, these latter possess, in turn, trace element contents significantly higher than that of the gabbroic dyke FI9664. Stahle's dykes also display significant peculiarities in terms of fractionation of highly incompatible trace elements, such as U, Th, Nb, Ta, Ba and Pb, with respect to REE.

The spiderdiagram of the peridotite close to the contact dike FI9664 shows some relevant differences with respect to those reported by Hartmann & Wedephol (1993); i.e. large positive Pb and Hf anomalies, larger Rb, U, Ba, Ta, Nb content, slightly lower LREE content (Fig. 3).

Major element mineral chemistry

Host harzburgites

Mineral composition of the host harzburgite far from the veins is similar to that of the harzburgite-pyroxenite association reported by Zanetti et al. (1999). Amphibole is pargasite in composition, with only one analysis giving Mg-hornblende composition, mica is phlogopite and clinopyroxene is diopside.

Minor differences consist in slightly Fe-richer composition shown by Ol [Fo = 100 x Mg / (Mg + Fe^{2+}_{tot}) molar ratio is 90.4-91.1], Opx, Spinel and Amph. Opx and spinel (Hercynite to Spinel in composition) are also richer in Al. Due to their low Cr#, the FI09C06 oxides straddle the Hercynite – Spinel boundary, while oxide in the FPP is Chromite. Lower Cr content is shown by Amph, which is also characterised by lower Na and larger K.

At the contact with the vein, the Mg# does not change significantly in the minerals. Aluminium decreases in Opx, Sp, Amph and Phl, while Ti is larger in both Amph and Phl. In Amph, Na decreases, being balanced by larger K. Conversely, the Na/K ratio is very variable in Phl.

Opx from the Opx Zone has lower Mg# and CaO and higher Al_2O_3 (Fig. 4). Similarly, its composition is different from the Opx from a Spr-bearing rock found in the LIZ northern unit of the Finero Mafic Complex (Sills et al., 1983): the latter has lower Mg# and higher Al_2O_3 (Fig. 4).

Gabbroic dykes

Notwithstanding the similar internal banding, the two studied dykes show marked differences in terms of major element mineral chemistry. Significant compositional changes are also shown for the different types of Amph (i.e. Early, Late and Leuco; Fig. 6). The unique feature of the amphibole major element chemistry common to both gabbroic dykes is the larger Al content exhibited by the Late Amph: this feature was already highlighted by Giovanardi et al. (2013). Amph from gabbroic dykes is mostly Pargasite in compositions (unit formula calculated according to Ridolfi et al., 2018), but sometimes the Al substitution for Si in Late Amph is higher than 2 a.p.f.u., entering in the Sadaganaite compositional field.

In particular, Amph from sample FI09C06 has distinctly lower Mg# (0.73-0.82) than in sample FI9664 (0.85-0.87). In sample FI09C06, Mg# is lower in Early Amph than in Late and Leuco Amph, while it is exactly the reverse in sample FI9664 (Fig. 6).

FI09C06 Amph also displays the lowest CaO and Na_2O and the highest TiO_2 and K_2O (TiO_2 0.27-2.19 wt.% and 0.31-1.28 wt.% respectively) (Fig. 6).

In sample FI09C06, TiO_2 linearly increases with the decrease of Mg#. TiO_2 is instead higher in the FI9664 Early Amph than in the Leuco Amph, but distinctly higher TiO_2 contents are shown by Late Amph. Again in FI9664 Early Amph the increase of Mg# is associated to increasing Cr and Ca, and to decrease of Na and Al.

As a whole Amph from gabbroic dykes has higher Al_2O_3 and lower Mg# and Cr_2O_3 with respect to others FPP lithologies, resulting similar to the Amph from the Spr-bearing rock in the LIZ (Sills et al., 1983) (Fig. 6). Amph from the two gabbroic-dykes samples shows lower CaO and K_2O than the respective host Amph and higher Na_2O (Fig. 6).

Phl from sample FI9664 presents narrow range of major element contents with respect to sample FI09C06. In sample FI9664, Phl has higher Mg# values with respect to crystals from sample FI09C06 (0.92-0.94 and 0.70-0.90 respectively) and commonly lower TiO_2 (Fig. 5). Phl from the gabbroic dykes shows higher Al_2O_3 and lower Mg# with respect to the Phl from the host peridotite and the harzburgite-pyroxenite association (Fig. 5).

Sp is mainly found in the Late Amph Zone. Unlike the Sp from the host harzburgite, the harburgite-pyroxenite association from Zanetti et al. (1999) and the chromitite layers in dunite bodies (Grieco et al., 2001; 2004; Zanetti et al., 2016), the Sp from the gabbroic dykes does not contain Cr_2O_3 and can be classified as Spinel (Mg# 0.46-0.75).

Plg from sample FI9664 is commonly more anorthitic with respect to the Plg from sample FI09C06 (An content 82-93 and 36-87, respectively). In both samples, some reversely zoned Plg are recognized.

Spr composition falls near the 7:9:3 composition on the SiO_2-(FeO+MgO)-(Al_2O_3+Cr_2O_3+Fe_2O_3) diagram (Fig. 7). Spr from sample FI9664 is higher in Al_2O_3 with respect to sample FI09C06, while is lower in SiO_2.

SEM investigations at the CIGS laboratories of the Università di Modena e Reggio Emilia performed with an ESEM Quanta-200 (Fei Company-Oxford Instruments) suggest that Ap from different zones of the dykes are Cl-apatites.

Trace elements compositions

Host harzburgite

Amph and Cpx from harzburgite FI09C06 8 cm far from the contact are characterised by LREE-enriched linearly fractionated patterns (Fig.s 8, 9 and 10). Their composition is similar to those of the FPP harzburgite-pyroxenite association (Zanetti et al., 1999). Proceeding towards the contact (i.e. FI9664 sample), Amph and Cpx show upward-convex REE patterns characterised by high variability in absolute content (Fig.s 8, 9 and 10). These patterns are similar to those from Ap-rich domains of Zanetti et al. (1999) (Fig.s 9 and 10).

Gabbroic dykes

The two gabbroic dykes show different trace element compositions. In the FI09C06 sample, Amph from the Early Amph Zone and Leucocratic Zone have L-MREE-enriched upward-convex patterns, similar to those of harzburgite near the contact (Fig. 8). In the Late Amph Zone, some crystals show more fractionated pattern characterized by lower M-HREE and positive Eu anomaly (Fig. 8). These variations are associated to a marked depletion in Ta, Zr, Hf, Y and Sc (and V) (Fig. 10). As a whole, Amph from different zones of FI9664 sample show more fractionated REE patterns characterized by enrichment in LREE and depletion in HREE (Fig. 8) with a nearly flat pattern in the LREE region. Amph from Early Amph Zone of sample FI9664 presents a small Eu positive anomaly ($(Eu/Eu^*)_N$ among 1.04-1.65) which become more evident in the Amph from Late Amph

Zone ($(Eu/Eu^*)_N$ among 1.29-1.62). Amph from FI9664 sample is also enriched in Th, U and Pb (and in Sr to lesser extent) with respect to FI09C06 ones (Fig. 10).

Similarly to Amph, REE patterns of Plg from sample FI9664 are more fractionated than those of Plg from sample FI09C06, (Fig. 8). In both samples, Plg cores are more enriched for absolute element abundances than Plg rims.

Ap displays the typical LREE enrichment and large Th, U and Pb contents (12.31-17.35 ppm, 4.35-5.92 ppm and 2.18-4.19 ppm, respectively). Nb, Ta, Zr, Hf, Ti and Sc form negative anomalies whose values are often below detection limit.

No systematic trace elements variations are found in Phl.

O isotopes

The $\delta^{18}O$ in FI09C06 silicates shows a steady increase from the contact (Opx-zone) to the Leucocratic gabbro in the vein core, through the Early and Late Amph Zones (Fig. 11). In particular, it varies from 5.81‰, std. dev. 0.11, in Opx from Opx Zone, to 6.9‰, std. dev. 0.05, in Amph from the Early and Late Amph Zones, to 8.60‰, std. dev. 0.01, in the Plag of the gabbroic core.

The $\delta^{18}O$ of Opx from Opx Zone lies within the mantle range. They are higher than the $\delta^{18}O$ value reported by Hartmann & Wedephol (1993) for Cpx from the Phl-bearing Amphibole harzburgite (Fig. 11), and for Opx from Ol-chromitites of FPP, but significantly lower than the Opx-from Opx-chromitites (Zanetti et al., 2016).

Vein Amph and Plg have $\delta^{18}O$ values significantly higher than mantle range (Fig. 11). They are close to the highest found in Amph, Phl, Opx, Cpx and Zrc from the Phl-bearing Amphibole harzburgites-pyroxenites (Hartmann & Wedephol, 1993; Selverstone and Sharp, 2011) and chromitite layers of FPP (Zanetti et al., 2016).

The $\delta^{18}O$ obtained for the green spinel associated to sapphirine is markedly lower than those of associated Late Amph ($\delta^{18}O$ = 4.38‰, std. dev. 0.10), as expected due to crystal-chemical constraints (see Bindeman, 2008 and references therein).

Sr and Nd isotopes

The trace element concentrations of the mineral separates of Early and Late Amph matches the differences highlighted by LA-ICP-MS on thin section. The Sr and Nd isotopic compositions of Early Amph and Late Amph from FI09C06 dyke are coincident within the analytical uncertainty (Table 2). Plagioclase from the FI09C06 Leuco Zone shows the same Sr isotopic composition of the amphiboles, and only slightly more radiogenic. Similar Sr isotopic compositions were documented in Amph and Ap from discordant veins from FPP, which are characterised by higher Nd^{143}/Nd^{144} (Morishita et al., 2008). The isotopic composition of dyke minerals is enriched with respect to Depleted Mantle and MORB values, falling in the OIB field (Fig. 12). In particular, they lie between the isotopic compositions of FPP hornblende-syenite dykes (bulk rock from Stähle et al., 1990, 2001) and peridotites (Amph and Cpx from Obermiller, 1994). Amph separated from the host harzburgite (collected far from the contact) show the most enriched radiogenic Sr and unradiogenic Nd values never documented in literature for FPP rocks, considering both peridotites and dykes (Fig. 12).

Discussion

1) Constraints on Melt Percolation through Peridotite

The two veins here studied share exactly the same internal banding of the sample described by Giovanardi et al. (2013). This suggests that all the three veins were part of an interconnected swarm, and this allowed to record the same sequence of petrologic events. According to the process governing the emplacement of other dyke swarms in mantle sectors (e.g. Mazzucchelli et al., 2010 and references therein), it is considered that the melt flowing in the metasomatic haloes and in the conduit was originally similar, suffering severe fractionation due to Assimilation and Fractional Crystallisation. Exceptions will be highlighted and discussed.

The characterisation of the wall peridotite has revealed some peculiarities. It is a common observation that metasomatic haloes of cm-to-m-scale wrapped out late dykes and veins formed by melt segregation at mantle conditions. In most cases, the metasomatic haloes show marked geochemical and mineralogical gradients as a function of the distance from the dike contact (Zanetti et al., 1996; Ionov et al., 2002, Mazzucchelli et al., 2010; Borghini et al., 2016, 2017), which are interpreted as the result of porous flow percolation of melt escaping from the open conduits. Conversely, no progressive mineralogical or compositional variation is documented into the wall peridotite FI9664 at variable distance from the vein (see Supplementary material B). Newly-formed clinopyroxene actually shows trace element heterogeneities, but these are randomly distributed. Conversely, trace element composition of Amph is very homogeneous, indicating a late crystallisation from a unique melt.

The peculiar L/MREE-enriched convex-upward patterns shown by Cpx and Amph from the wall peridotite FI9664 also evidence that their parent melt could not be the same from which crystallised the adjacent Early Amph in dyke FI9664 (which show linearly-fractionated REE patterns). However, according to Amph trace element composition, the melt recorded by the wall peridotite FI9664 had to be quite similar to that producing the Early Amph Zone of dyke FI09C06.

The textural evidence that primary and secondary minerals into the metasomatic haloes display elongation sub-parallel to the present-day vein strike confirms that the development of melt migration channels was associated to some local deformation.

These observations can be reconciled assuming that the metasomatic haloes were not produced by melt escaping normally from the conduit. They were likely established during an early stage of melt migration occurred via focused porous flow along channels developed in correspondence of structural weakness, whose direction was roughly parallel to the strike of the present-day veins.

Detailed petrographic inspection indicates that in the reacted wall peridotite olivine was stable. Conversely, the modal content of orthopyroxene is slightly lower than in the peridotite far from the vein. This evidence brings us to consider that the Opx-saturation of the melts indicated by the segregation of reactive Opx Zone and the presence of few Opx in the veins (Giovanardi et al., 2013) was not a clear, primary characteristic, but possibly a consequence of early stage of reactive melt migration characterised by olivine–precipitation and orthopyroxene dissolution (see Piccardo et al., 2017).

Besides, the mineralogical mismatch between the nearly monomineralic, hydrous-mineral-free Opx Zone and the Early Amph Zone suggests that they were segregated by the melts compositionally different. This hypothesis is confirmed by large differences in terms of isotope O composition recorded by Opx (5.8‰ SMOW) from Opx Zone and the Early Amph Zone (6.9‰ SMOW) within the vein. The lighter isotope O composition of the Opx Zone would support a hybrid composition of its parent melt due to reactive porous flow through the FPP, with buffering of isotope O composition at mantle values.

This conclusion brings us to take into consideration the possibility that Opx-Zone formed before the segregation of the Amph Zones, possibly ad the centre of the migration channels, as observed elsewhere in the FPP. It was successively split in two parts by the opening of the fracture.

2) Melt segregation in the open conduit

Early Amph was segregated when melts started flowing in actually open fractures. It is likely that Amph crystallisation was triggered by the presence of an ultramafic wall, suggesting that Plg was unstable in contact with the orthopyroxenite layers. The development of Amph-rich selvages has been already documented in literature, where hydrous gabbroic rocks come in contact with ultramafic layers (e.g. in the LIZ of Finero Complex, Mazzucchelli et al., 2014). Moreover, it is a common observation that in dykes/veins produced by percolation of late hydrous melts/fluids through oceanic gabbroic rocks, Amph grows in correspondence of wall Cpx, whereas new Plg segregates in textural positions in which the wall mineral is previous Plg (Cortesogno et al., 2004; Tribuzio et al., 2014).

The vein minerals of this study show significant differences in terms of major and trace element mineral compositions. In particular, Amph from FI9664 vein shows a peculiar relative enrichment in highly incompatible trace elements (U, Th, LREE, Na) and compatible elements (Mg, Ca and Cr) with respect to those from FI09C06 vein. Consistently, Phl is Mg-Na-richer and Plg is more anorthitic. Assuming that the dyke swarm was produced by the injection of the unique melt, this relationship cannot be reconciled by a melt evolution only governed by fractional crystallisation. Mazzucchelli et al. (2010) documented the same correlation between compatible and incompatible elements in minerals from cm-thick diorite dykes demonstrating that such geochemical features can be modelled considering an assimilation of host minerals concomitant to fractional crystallisation. Accordingly, we argue that the parent melt of vein minerals FI9664 can be considered more evolved than that of dyke FI09C06 through AFC process. The concomitant enrichment of Na and Ca in the FI9664 vein minerals evidence the role of Amph in the assimilated component. This is also confirmed by the trace element patterns of FI9664 vein amphiboles, in which highly incompatible elements, such as LREE, Th and U, increase, whereas moderately incompatible element such as HREE, Ti and Y decrease, moving towards the fractionation shown by those of host harzburgite away from the contact. The decrease of moderately incompatible elements with the progression of the melt evolution may be indicative of ${}^{Amph/L}D$ higher than 1 (Tiepolo et al., 2007). It is noteworthy that the Al content in FI9664 Early Amph is comparable to slightly lower than in those from FI09C06 vein, suggesting that the assimilation of host minerals was not effective in boosting the Al concentration the evolving melt.

a) Formation of Sapphirine-bearing patches

The petrographic features of the Sapphirine-bearing zones documented on samples are similar to those described by Giovanardi et al. (2013).

The mm-to-cm-thick Sapphirine-bearing patches and stripes are randomly distributed from the internal end of the hornblendite seam to the Opx Zone, even tough are basically concentrated towards the centre of the veins. They are apparently the results of interstitial migration of a melt chemically in disequilibrium with the early cumulus minerals, as testified by actual recrystallization fronts inside large Early Amph. Both interstitial and recrystallized patches show that the injected melt was saturated in Late Amph, Spr and Sp, whereas the saturation in Phl is uncertain, because it occurs only interstitially, and the textural relationships are not unequivocal.

The following series of petrographic and geochemical features suggest that the sapphirine-bearing mineral assemblages were not simply related to interaction with the parent melt of the Leucocratic Zone, but segregated because of the injection in the dykes swarm of an additional melt component coming from outside of the system:

1) Early Amph at the contact with or embedded by the plagioclase of the Leuco Zone does not show any evidence of comparable reaction;
2) Notwithstanding the significantly different major element composition of Early Amph documented in the two veins of this study, the major element chemistry of Spr-associated Late Amph converge towards specific Al and Mg# values. Phlogopite shows a consistent variation, even though its attribution to Early or Late Amph assemblages is doubtful because of its interstitial position. The data reported by Giovanardi et al. (2013) confirm the trend. This indicates that a unique component with a specific composition was responsible of the Spr segregation in the three sectors of the dyke swarm.
3) Normalised patterns of Late Amph from Spr-bearing areas shows peculiar features, namely stronger LREE/HREE fractionation, depletion in M-HREE, Zr, Hf, Nb, Ta,Ti, Sc and V, and the appearance of positive Eu anomaly. It is also observed the inversion of the $(Zr/Hf)_N$, which is >1 in the Early Amph, but <1 in the Late Amph. The overall fractionation mimics that normally exhibited by Plg.

This evidence, consistently with the apparent increase of the Al content in the system, suggests that the injected melt contained large volumes of Plg component.

Isotopic O, Nd and Sr compositions of Early and Late Amph are very similar, suggesting that the Plg component belonged to the same magmatic cycle producing the dyke swarm.

On the other hand, petrographic survey has never provided evidence of Plg assimilation and/or replacement by Amph or whatever, excluding that the Plg component derived by local assimilation. Thus, it is envisaged that the Plg signature was acquired by the injected melt through: 1) assimilation of cumulus Plg in hidden magmatic bodies; 2) addition in the melt source, where it was likely present has high-P metamorphic equivalent of pristine Plg.

b) The Leucocratic Zone

The petrographic evidence confirms that the formation of the Leucocratic layers was a high energy event, which determined the partial disaggregation of the Early Amph layers, with evident breaking of large Early Amph crystals. It can be locally recognised that two parts of a formerly unique crystal apparently lie on different sides of a vein. Giovanardi et al. (2013) suggested that this stage was accompanied by enlargement of the conduits.

The Nd and Sr isotopic composition of Plg indicates that the parent melt had a cognate origin with those of the hornblendite selvages. This is also confirmed by the trace element composition of the Leucocratic Amph, which is strictly similar to that of the associated Early Amph.

Nevertheless, the observation that the major element chemistry of Leucocratic Amph is intermediate between that of Early and Late Amph, brings has to conclude that the parent melt of the Spr-bearing assemblages could be still present in diluted proportions.

3) Nature of the parent melts

The assessment of the nature of the parent melt of magmatic segregates belonging to narrow, cm-thick veins/dykes intruding mantle peridotites at high-T-P mantle conditions must be done with particular caution, trying firstly to characterize the modifications imparted by fractional crystallization of minerals and the reaction/assimilation with the host rock (e.g. Mazzucchelli et al., 2010 and references therein).

a) Isotope O composition

An important contribution about the definition of the geochemical components in the upcoming melts is provided by the marked zoning in terms of isotopic O composition documented in the sample FI09C06 among i) the Opx Zone, ii) the hornblendite selvage and iii) the Leucocratic Zone.

The $\delta^{18}O$ values of Early and Late Amph (6.9 ‰ SMOW) are well-exceeding the mantle range (Bindeman, 2008; Polat et al., 2018), pointing to large volumes of crustal component in the parent melt of FI09C06 hornblendite. The proportion of crustal component still increases into the leucocratic layer, where a $\delta^{18}O$ value of 7.8 ‰ SMOW can be calculated for the Amph in hypothetical equilibrium with the Plg composition (8.6‰ SMOW), conservatively considering i) a low closure T for FPP of ~850°C (provided by pyroxene-solvus geothermometers), ii) an average value of An70 for plagioclase and iii) the $\delta^{18}O$ mineral fractionation values reported by Bindeman (2008).

Literature data on FFP minerals show a pronounced heterogeneity in merit to the isotopic O composition, with $\delta^{18}O$ values from below to well-above the mantle range (Hartmann and Wedephol, 1993; Selverstone and Sharp, 2011; Zanetti et al., 2016). This is an apparent result of multiple melt-migration events.

Values of $\delta^{18}O$ approaching that Early and Late Amph have been sometimes documented in harzurgites and chromitites (Hartmann & Wedephol, 1993; Zanetti et al., 2016), but the values of the Leucocratic layers are markedly out of range.

Besides, the $\delta^{18}O$ value shown by Opx (5.81 ‰ SMOW) from the Opx Zone provides a very important constraint, indicating as migrating melts, after prolonged interaction with FPP, may have isotopic oxygen composition buffered to the mantle range. The decrease of $\delta^{18}O$ values in the minerals from the hornblendite selvages with respect to those from dyke core, i.e. the Leucocratic Zone, confirms such a buffering effect.

It is concluded that the high $\delta^{18}O$ shown by dyke minerals cannot apparently be the result of interaction between melts and FPP. It was a primary feature of the melts, indicating the occurrence of large amounts of crustal components, which must have been added to the melt in the source regions or, anyway, at deeper mantle depths.

Subduction-related component was identified on the basis of Noble Gases isotopic composition in late, Triassic apatite-rich layers (Matsumoto et al., 2005, Morishita et al., 2003, 2008), overprinting the crustal affinity of the host FPP. Amphiboles from such Ap-layers show the same radiogenic Sr composition of FI09C06 minerals, coupled to slighter more radiogenic Nd composition.

The isotopic composition of Early Amph, Late Amph and Plag from FI09C06 dyke is significantly richer in radiogenic Sr and unradiogenic Nd with respect to those reported by nepheline-bearing Triassic intrusions cutting the FPP (Stähle et al., 1990, 2001), which were interpreted as derived by alkaline melts of OIB-affinity.

The combination of the data of nepheline-bearing alkaline dykes, the Spr-bearing dykes and FFP data define a trend at low radiogenic Nd and large radiogenic Sr, suggesting a mixing between asthenospheric components (OIB, according to Stähle et al., 1990; 2001 and Schaltegger et al., 2015) with components derived from continental crust (see compositional fields in Casetta et al. 2018a). It is apparent that such a trend is approached by the Sr and Nd isotopic composition of Triassic K-rich calc-alkaline to shoshonitic intrusive rocks and lavas of the Eastern Alps (Casetta et al., 2018a; Figure 12).

Speculatively, it can be considered that the crustal components were seated at lithospheric deep levels after the Variscan orogenic cycle (e.g. Bonadiman et al., 1994) and mobilized by asthenospheric magmatism. This scenario is supported by the evidence of continental crustal metasomatism exhibited by mantle bodies involved in the Variscan collisional orogeny, such as

FPP, Ulten (Sapienza et al., 2009) and some of the Bohemian Massif (Becker et al., 1999; Schulmann et al., 2014).

In this frame, it can be noted that the FI09C06 isotopic compositions of Sr and Nd lie on the mixing line between the composition of the Triassic alkaline dykes and the host harzburgite far from the contact. According to AFC simulation, assimilation of significant degrees of the metasomatised peridotite material (15%) into OIB must be taken into account to document the composition of the parent melt of FI09C06 veins.

c) Trace elements

The comparison of the trace element patterns of the Amph from the vein apparently less contaminated by the host peridotite (FI09C06) with those of amphiboles segregated by primary hydrous alkaline basalts (e.g. Demeny et al., 2005) evidences similarity in REE fractionation, but the Early Amph have absolute content nearly one magnitude order higher. Besides, a correlation with primary alkaline mantle melts is not straightforwardly supported by the negative Nb-Ta-Ti anomalies shown by Early Amph.

Equilibrium liquids calculated on the basis the trace element composition of Early Amph from Fi09C06 dyke and amphibole-melt partition coefficients experimentally determined for T of 1015°C in presence of moderately polymerized melts (dataset T2 1015; Tiepolo et al., 2007), match the REE content and fractionation exhibited by Shoshinitic rocks of the Triassic magmatism of the Dolomitic areas (Casetta et al., 2018a; 2018b; see Supplementary material C). The calculated melts also show consistent negative Ti anomalies and $(Nb/La)_N$ close to 1, and slight positive U, Th and Pb anomalies: the latter are more pronounced in the shoshonitic melts. However, a best match in terms of U, Th and Pb concentrations is shown by equilibrium liquids calculated in equilibrium with amphiboles from the 9664 dykes. These observations suggests that the Spr-bearing gabbroic dykes may be the record of the deep mantle input to the Triassic K-rich calc-alkaline to shoshonitic melts erupted into the Eastern Southern Alps, also documenting the fractionation trends responsible for the enrichment in Th, U and Pb.

4 Constraints on the Geodynamic evolution of the Europe-Africa boundary

a) P-T constraints on FPP

Geothermobarometric estimates constrain the intrusion of Spr-bearing dykes at very high-P and T conditions. Ab-initio calculations indicate that primary crystallization field of Spr in the MAS diagram (SiO_2-MgO-Al_2O_3) becomes definitely larger over 1.0 GPa, shrinking at 2.0 GPa (Belmonte et al., 2014). This evidence confirms the experimental results of Liu & Presnall (1990, 2000) and Milholland & Presnall (1998), indicating that magmatic Spr in FPP veins likely crystallised at P ≥ 1 GPa. Equilibrium T estimated with the Spr-Sp Mg-Fe^{2+} exchange thermometer of Sato et al. (2006) and with the Amph-Plg thermometer of Holland & Blundy (1994) are mostly higher than 1000°C (up to 1085°C), confirming the T estimates of Giovanardi et al. (2013). The melt T was thus significantly higher than host harzburgite, which shows solidus T typically corresponding to that of the water-oversaturated peridotite (965°C at P = 1.1 GPa; Giovanardi et al., 2013). The absence of evidence for partial melting in the host FPP confirms that the source of the uprising melts was at greater, mantle depths. The high T, in combination with the large water and volatile contents, may have allowed the melt to migrate via porous-flow along direction of structural weakness (see Tommasi et al., 2017), before the opening of the conduits.

The high-P emplacement conditions are consistent with the scenario for which after Paleozoic metasomatism the FPP remained at greater depths than the large lherzolitic mantle bodies South of the Anzola-Val Grande High-T shear zone (namely, from North to South, Premosello, Balmuccia and Baldissero; Quick et al., 1995), until its exhumation at shallower levels at ~180 Ma (Zanetti et al., 2013, 2016; Langone et al., 2017, 2018; Decarlis et al., 2017, Malitch et al., 2017; Petri et al., 2019).

b) Constraints on the Mesozoic mantle sources at the Africa-Europe Boundary

The outcomes of this study indicate that in Mesozoic times, melts extremely rich in volatiles (H_2O, P, CO_2 and Cl), K, Na and highly-incompatible element rose up from the mantle depths towards the surface. The large amount of the crustal components present in the melts, as testified by the O isotopic composition, bring us to consider that their large Al content, the enrichment in LILE and LREE, and the enriched Nd and Sr isotopic composition consistent were basically a primary feature inherited from the source.

This finding confirms the extreme complexity of the tectono-magmatic scenario recorded by the FPP. In particular, it evidences as the Northern IVZ records an extremely prolonged release (lasted from the Variscan orogenic cycle to the Mesozoic exhumation of lithospheric mantle at shallower levels) of K-H_2O-rich mantle-derived melts polluted by subduction-related components. This explains why FPP records many generations of Phl-bearing mineral assemblages, showing variable filed relationships, geochemical signature and ages (Hartmann & Wedeohol, 1993; Zanetti et al., 1999; 2013; 2016; Stähle et al., 1990; 2001; Greco et al., 2001;2004; Morishita et al., 2003, 2008; Malitch et al., 2017). It also provides a new interpretative frame to previous data indicating the emplacement of melts with subduction-related components in Triassic times (Mastumoto et al., 2005; Morishita et al., 2008, Malitch et al., 2017)

Such a magmatism bearing subduction component appears roughly overlapped to the ascent of silica-undersaturated alkaline melts of OIB-affinity (Stähle et al., 1990, 2001, Schaltegger et al., 2015), which likely have some counterparts also in the Central IVZ (Fiorentini et al., 2018; Galli et al., 2019).

It developed in a concomitant extensional-transtensional tectonic regime, whose origin and geodynamic scenario are still strongly debated (Cassinis et al., 2008; Zanetti et al., 2013; Casetta et al., 2018a,b)

Further investigations are needed to address the issues whether crustal components are remnants of old subduction events (Bonadiman et al., 1994), possibly located at lithospheric levels, reactivated by asthenospheric magmatism with OIB or DM affinity, or whether they were crustal material recycled into asthenospheric mantle sources (Locmelis et al., 2016), or related to the addition of crustal components in relation to some active Mesozoic subduction (Cassini et al., 2008; Schmid et al., 2008; Morishita et al., 2008; Selverstone and Sharp, 2011; Zanetti et al., 2013).

It is a matter the fact that the major (in particular the enriched composition in K and Al), trace and Sr and Nd isotopic composition of the sapphirine-bearing gabbroic rocks approach the geochemical feature shown by Triassic K-rich calc-alkaline to shoshonitic magmatism of the Dolomites area (eastern Alps) (Casetta et al., 2018a,b). Thus, it is confirmed that the study of the magmatic events at the roots of the continental crust of the Adria plate can provide a unique opportunity to constrain the tectono-magmatic evolution of at the Europe-Africa boundary.

Concluding remarks

New, very detailed surveys on Mesozoic Spr-bearing gabbroic dykes within the FPP unit led to describe different stages of melt migration (from porous-flow migration in peridotite channels to flow in open conduits) and constrain the presence in the parent melts of large amounts of continental crustal components that were acquired in the source region or at deeper lithospheric mantle levels.

The reaction between dyke melts and the strongly metasomatised FPP enhanced the crustal signature.

The large Al content of these melts allowed for the segregation of magmatic sapphirine, which is marker of high-P-T conditions of intrusion.

This dyke swarm possibly represents a record of the mantle input to the K-rich calk-alkaline to shosonitic magmatism widespread during Triassic in the Southern Alps area.

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Figure captions

Figure 1: geological map of the Finero area, modified after Mazzucchelli et al. (2014).

Figure 2: A) sample FI09C06 crosscutting the host harzburgite foliation. The centre of the dyke is formed by the Leucocratic Zone, while the melanocratic zones (i.e. Opx Zone, Early Amph Zone and Late Amph Zone) are indistinguishable; B) phlogopite vein cutting the Opx Zone; C-F)

occurrences of sapphirine in sample FI09C06 (C and D) and sample FI9664 (E and F). The figures show the increase of sapphirine size, from µm (C) to millimeter (D and E) up to centimeter (F).

Figure 3: PM primitive mantle-normalized bulk rock trace element patterns of gabbroic dyke and host harzburgite. PM values are from McDonough and Sun (1995). Literature values from the harzburgite-pyroxenite association from (1) Hartmann and Wedephol (1993) and from nepheline-bearing hornblende syenitic dykes from (2) Stähle et al. (2001) are reported for comparison.

Figure 4: Orthopyroxene major element contents from host harzburgites, dykes and literature data. Plotted literature data are: harzburgite-pyroxenite association orthopyroxene from (1) Zanetti et al. (1999) and orthopyroxene from sapphirine-bearing rock from the Mafic Complex from (2) Sills et al. (1983).

Figure 5: Phlogopite major element contents from host harzburgites, dykes and literature data. Plotted literature data are: harzburgite-pyroxenite association phlogopite from (1) Zanetti et al. (1999).

Figure 6: Amphibole major element contents from host harzburgites, dykes and literature data. Plotted literature data are: harzburgite-pyroxenite association amphibole compositions from (1) Zanetti et al. (1999) and (2) Morishita et al. (2008), amphibole from Ap-rich veins from FPP from (1) Zanetti et al. (1999) and (2) Morishita et al. (2008) and amphibole from sapphirine-bearing rock from the Mafic Complex from (3) Sills et al. (1983).

Figure 7: Sapphirine compositions plotted in the (MgO+FeO)-(Cr_2O_3+Fe_2O_3+Al_2O_3)-SiO_2 diagram (mol. %). Literature data are from sapphirine from the Finero Mafic Complex (Sills et al., 1983) and from sapphirine 1 from Higgins et al. (1979).

Figure 8: REE patterns of clinopyroxene and amphibole from the gabbroic dykes and the respectively host rocks divided for samples and position. Values are normalized to Chrondrite-I (CI, values from Lyubetskaya and Korenaga (2007). $\delta^{18}O$ values (normalized to SMOW) from phases of sample FI09C06 are reported near the REE patterns according to their position in the sample.

Figure 9: PM primitive mantle-normalized trace element patterns of clinopyroxene from host harzburgite. PM values are from McDonough and Sun (1995). Plotted literature data are: clinopyroxene and amphibole average compositions from harzburgite-pyroxenite association from (1) Zanetti et al. (1999) and (2) Morishita et al. (2008), clinopyroxene and amphibole average from Ap-rich veins from FPP from (1) Zanetti et al. (1999) and (2) Morishita et al. (2008) reported as Ap-veins.

Figure 10: PM primitive mantle-normalized trace element patterns of amphiboles from gabbroic dyke and host harzburgite. PM values are from McDonough and Sun (1995).

Figure 11: $\delta^{18}O$ normalized to SMOW. From literature are reported the field of mantle and variation of MORB from Rollinson (1993), mantle ultramafics and mantle-derived melts from (*) Bindeman (2008). Finero literature data are reported from harzburgite-pyroxenite association from Hartmann and Wedephol (1993) and Selverstone and Sharp (2011) and from chromitite in dunite bodies from Zanetti et al. (2016).

Figure 12: $^{143}Nd/^{144}Nd$ vs $^{87}Sr/^{86}Sr$ recalculated at 225 Ma of Amph and Plg from the various zone of FI09C06 sample (host and dyke). (1) Amph data of FPP from Obermiller (1994); (2) bulk rock of the Finero Mafic Complex from Lu et al. (1997b); (3) Alkaline dyke in FPP from Stähle et al. (1990); (4) Alkaline dyke in FPP from Stähle et al. (2001); (5) Mesozoic shoshonitic magmatism

(SS: Silica-Saturated; US: Undersaturated-Silica) in the Predazzo area from Casetta et al. (2018); DMM from Workman and Hart (2005). Mixing model was calculated between the two end-members the alkaline dyke S9 of Stähle et al. (1990) and the hosting peridotite FI09C06. Data for the melt in equilibrium with the alkaline dyke S9 are: $^{143}Nd/^{144}Nd$ = 0.512607, $^{87}Sr/^{86}Sr$ = 0.703720 (from Stähle et al., 1990; recalculated at 225Ma), Nd = 8.333 ppm and Sr = 830 ppm (calculated from LA-ICP-MS Plg analysis of albitite dykes similar to the dyke of Stähle et al., 1990, using the K_d of Dohmen and Blundy, 2014; average Nd = 0.25 ppm, Sr = 5810 ppm). Data for the melt in equilibrium with the host FPP peridotite are $^{143}Nd/^{144}Nd$ = 0.512130, $^{87}Sr/^{86}Sr$ = 0.708501 (recalculated at 225Ma), Nd = 67.5 ppm and Sr = 909 ppm (calculated using the K_d of Ionov et al., 2002).

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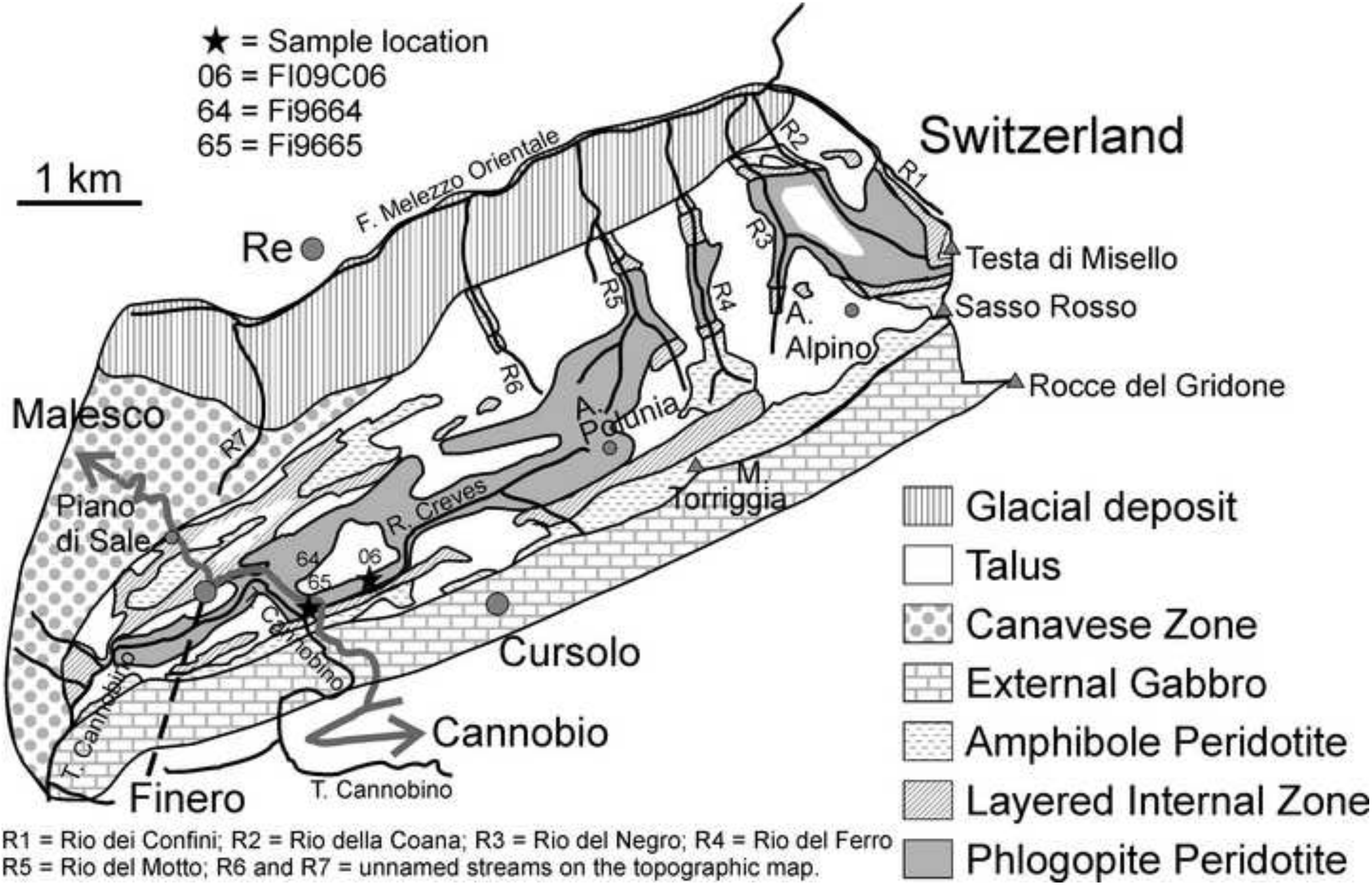

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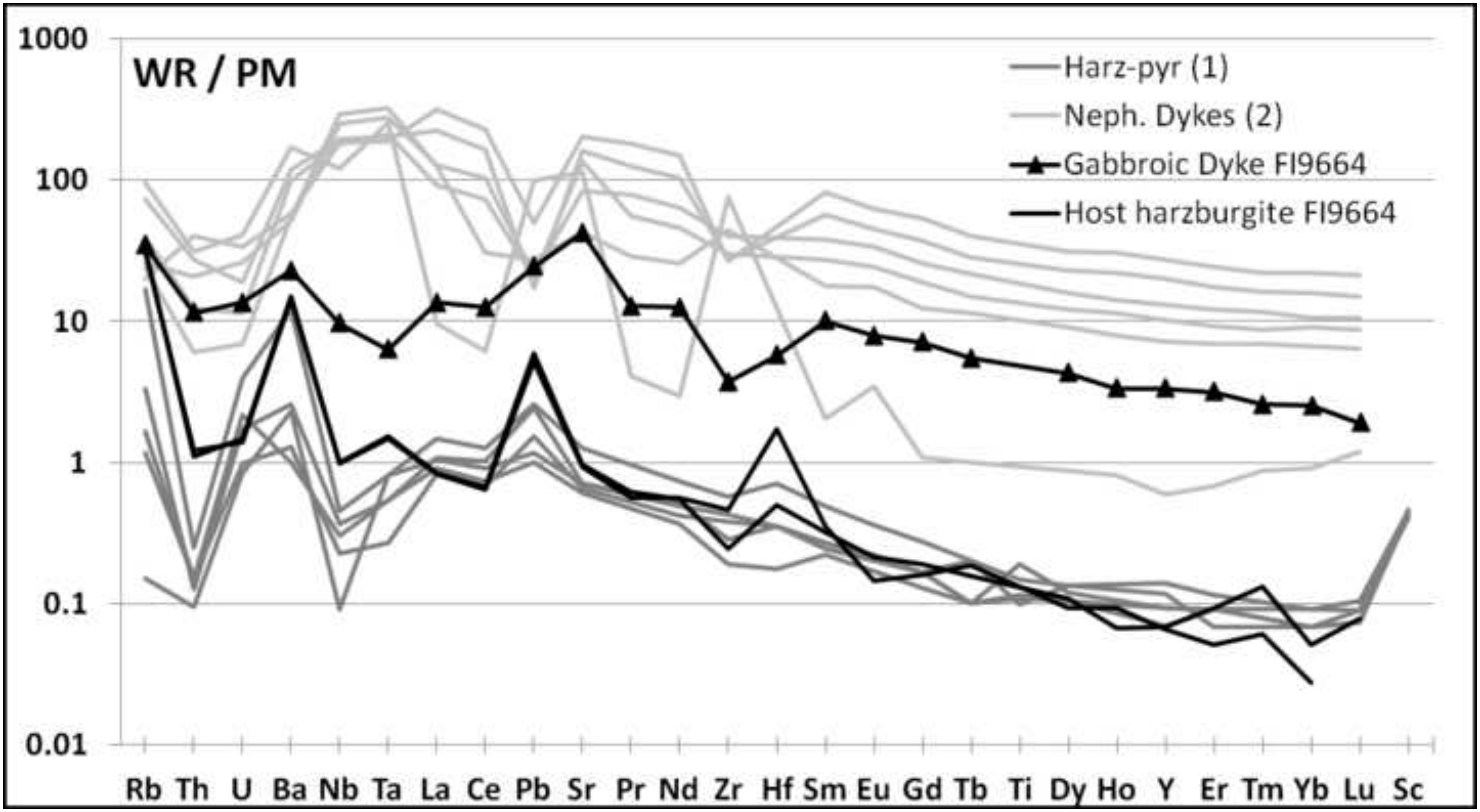

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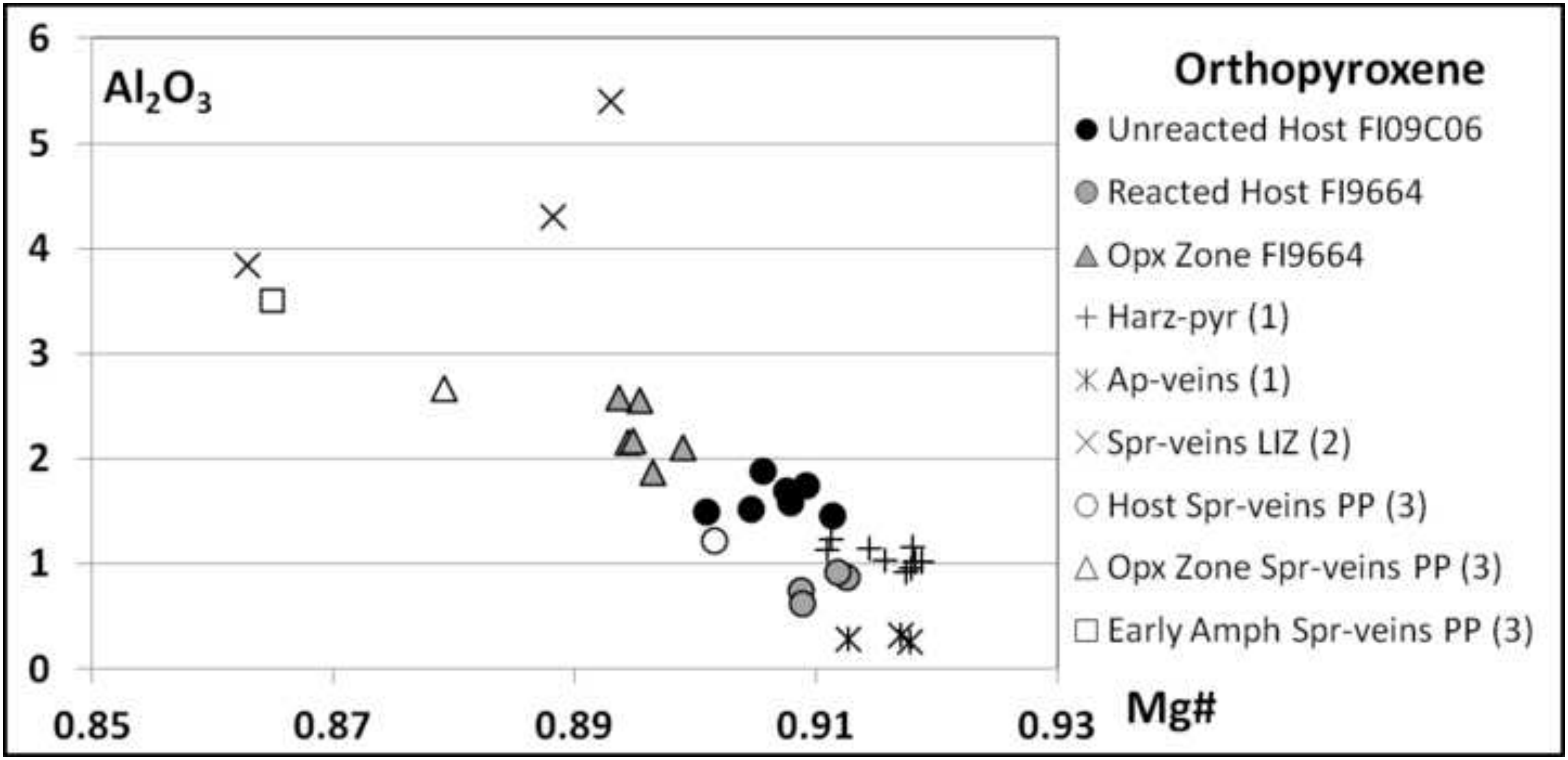

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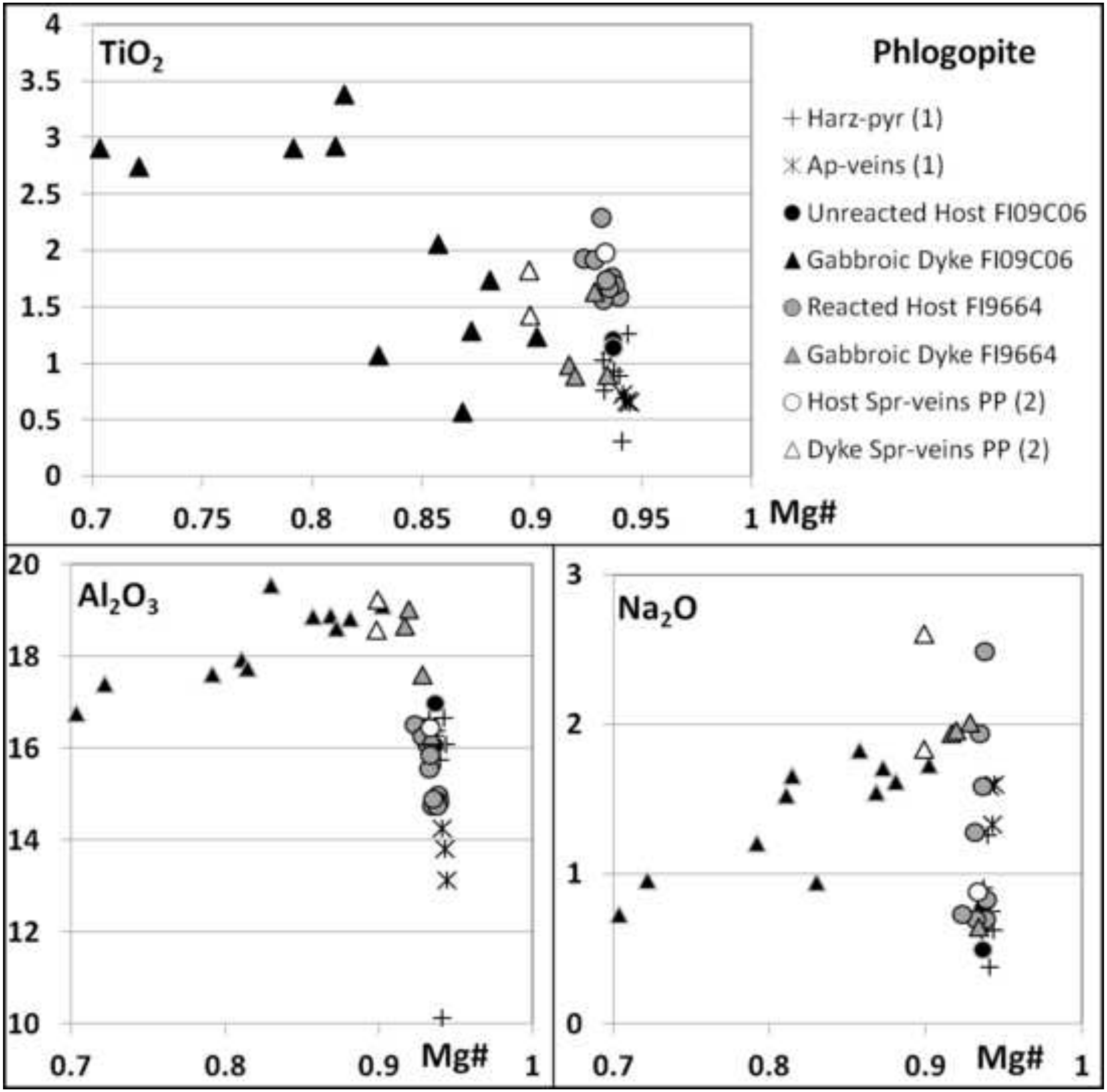

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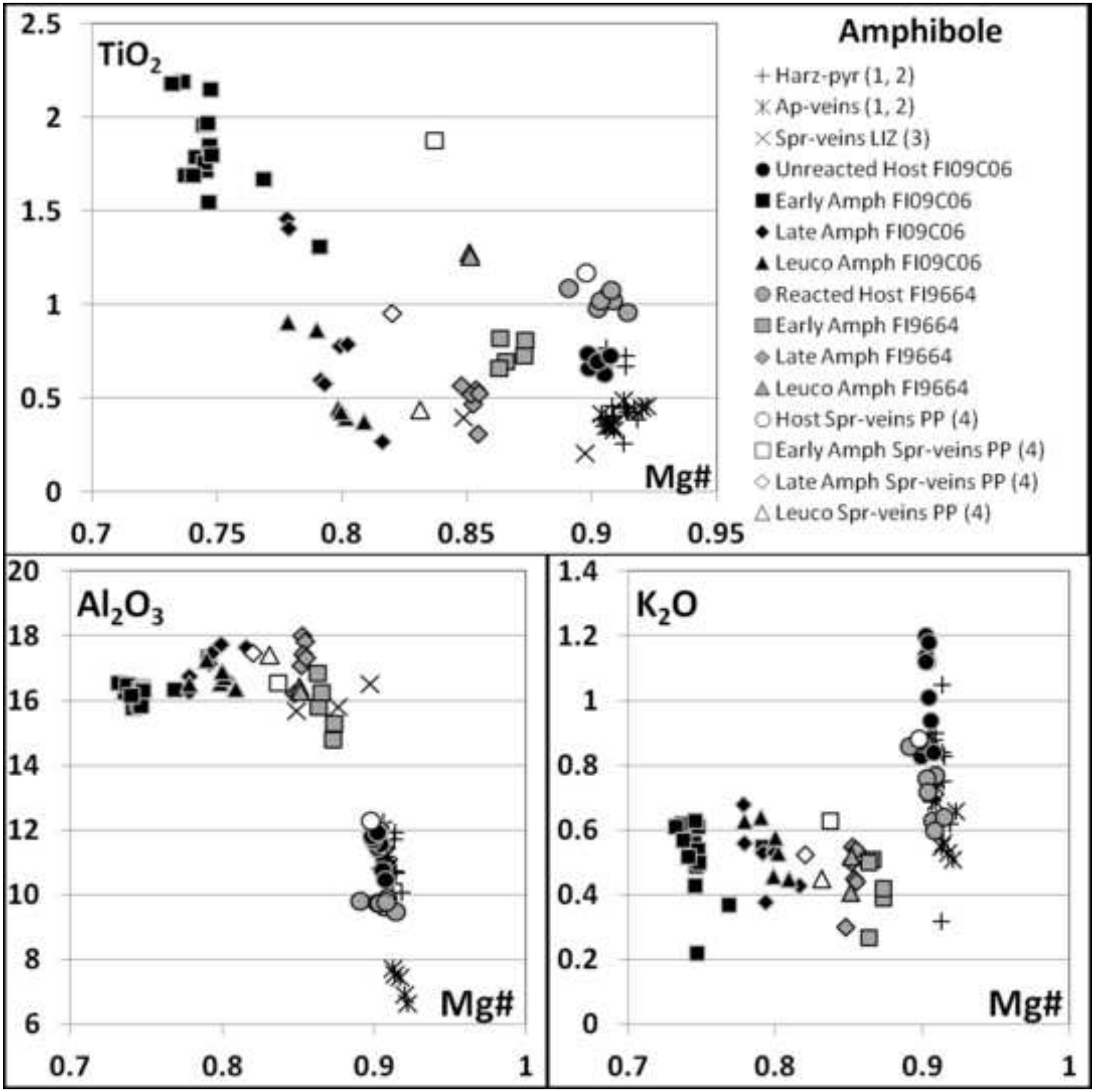

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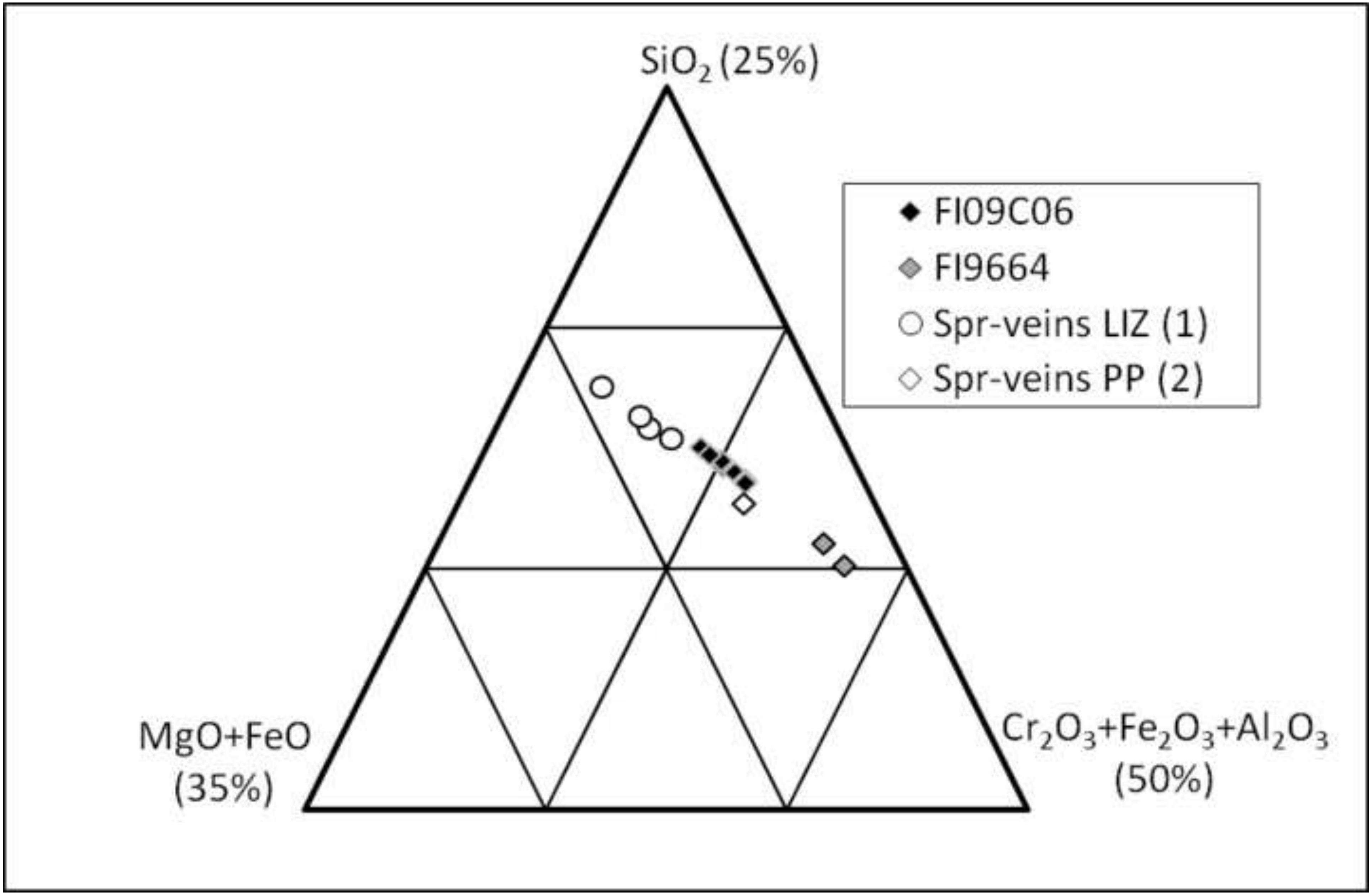

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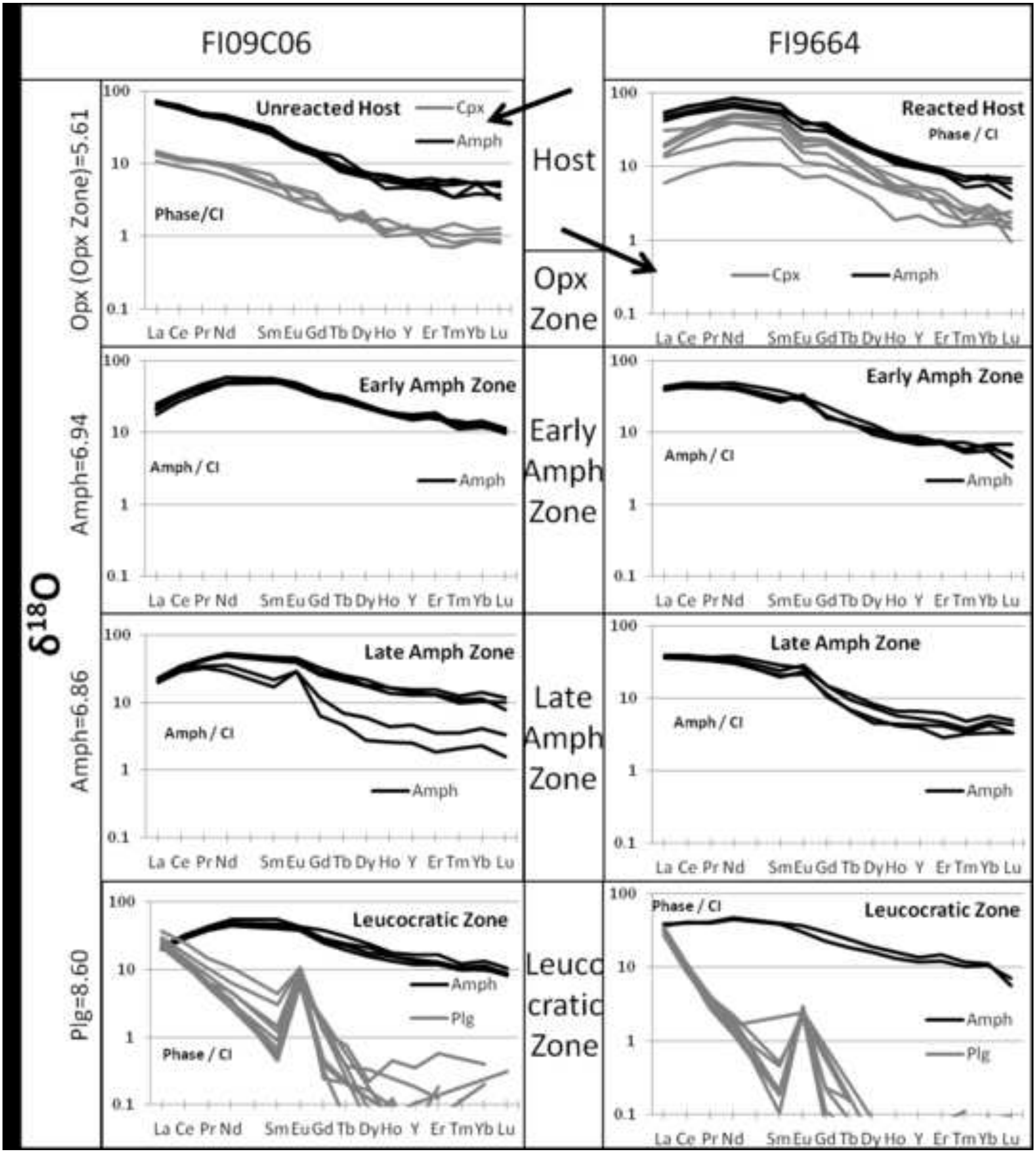

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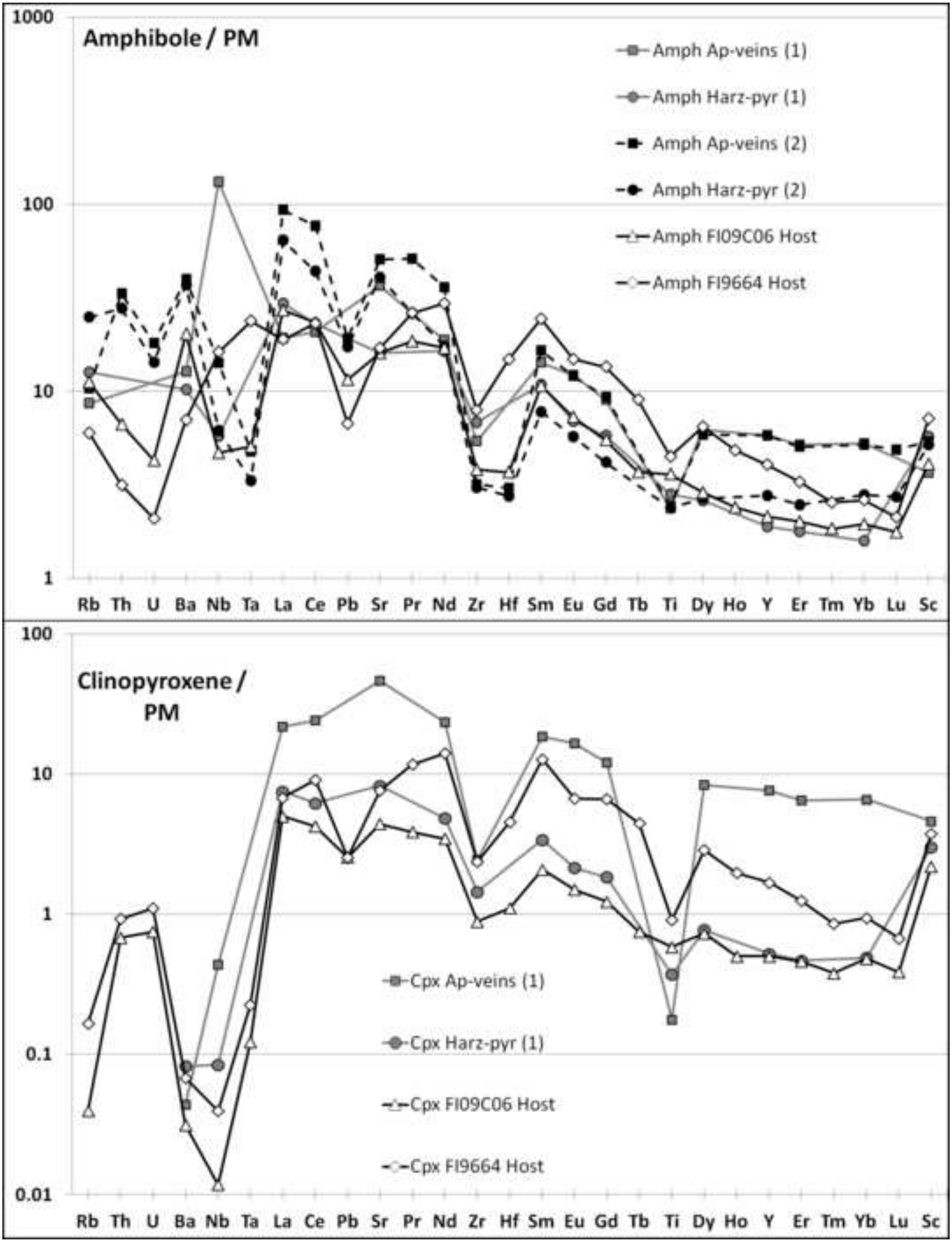

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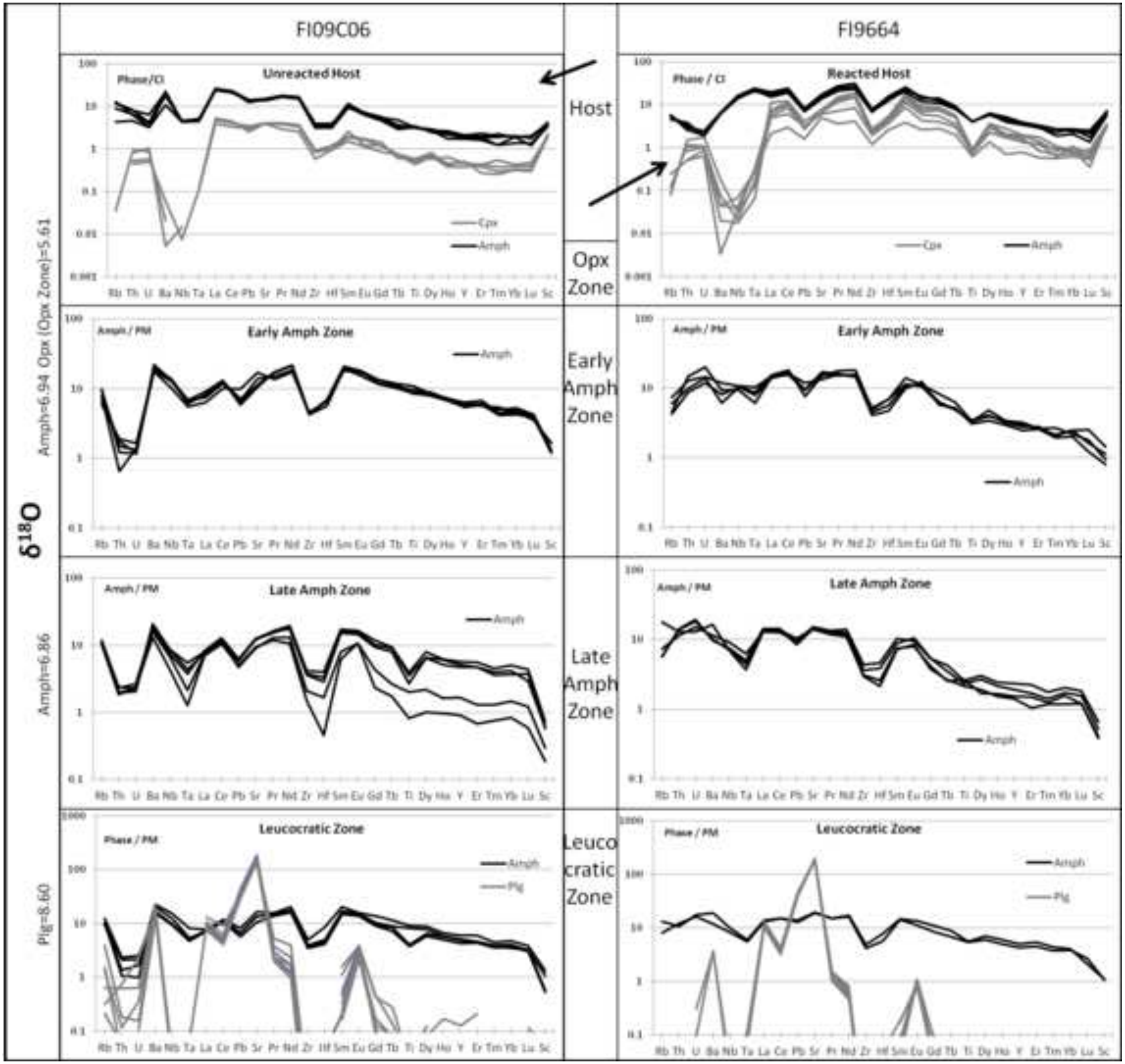

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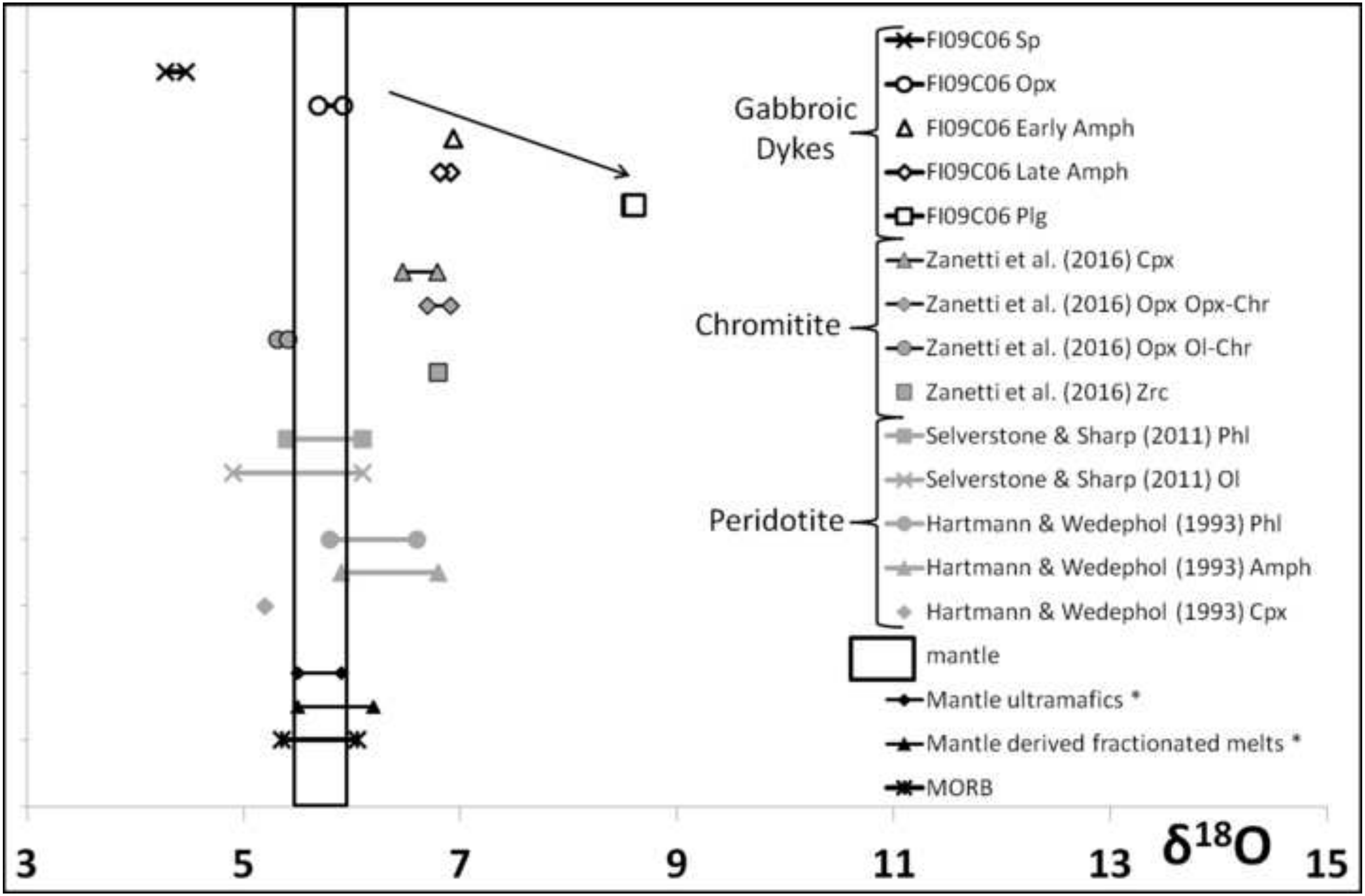

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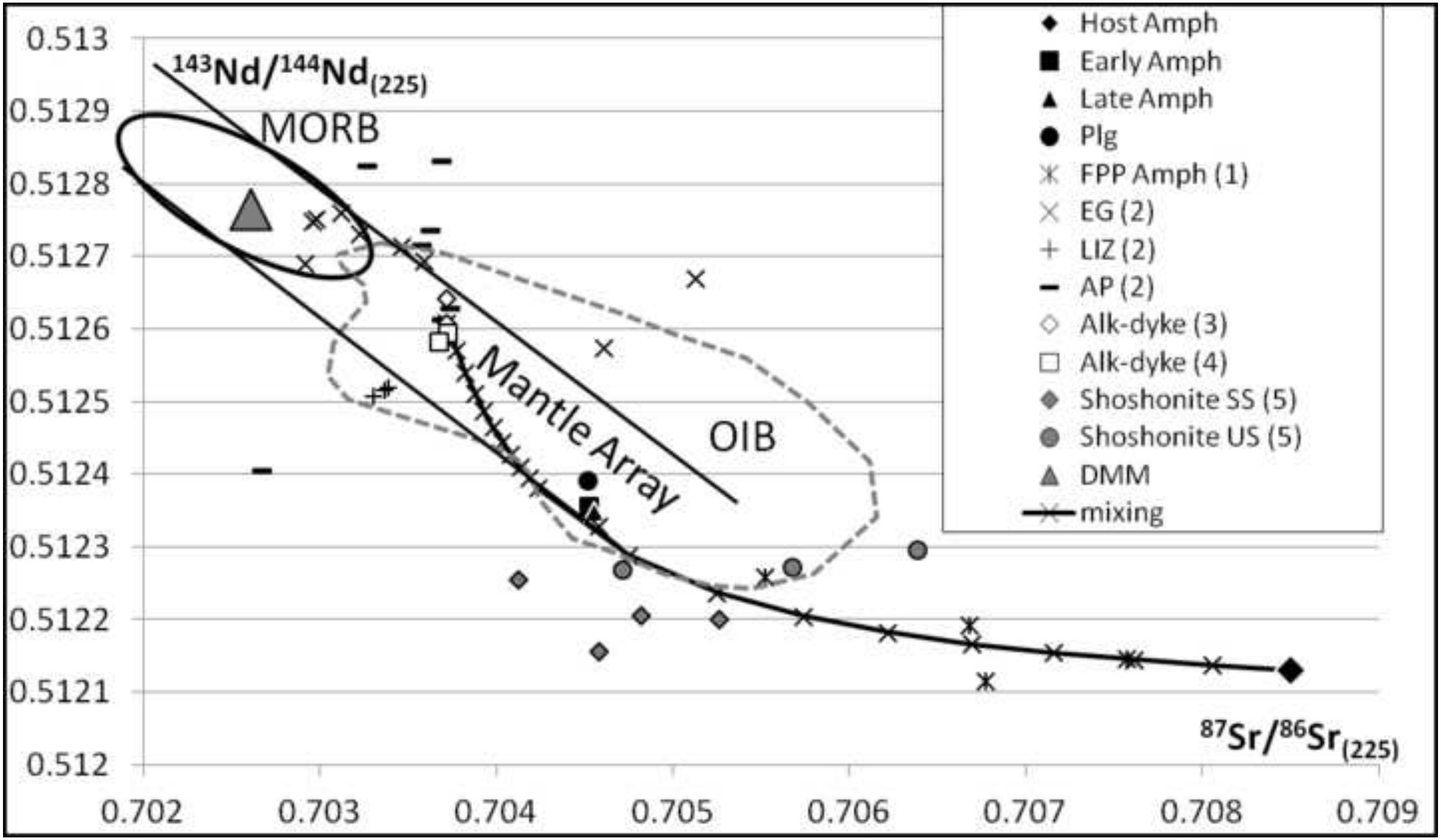

Table 1: O isotopic composition of minerals from the Spr-bearing gabbroic dykes.

Sample	**Phase**	**$\delta^{18}O$**	**std. dev.**
FI09C06	Early Amph	6.94	0.00
FI09C06	Late Amph	6.86	0.05
FI09C06	Plg	8.60	0.01
FI09C06	Opx	5.81	0.11

Table 2

Table 2: Sr and Nd isotopic composition of minerals from sample FI09C06 from the Spr-bearing gabbroic dykes and the host peridotite.

Rock	Phase	Rb	Sr	$^{87}Sr/^{86}Sr$	2SE	$^{87}Rb/^{86}Sr$	Nd	Sm	$^{143}Nd/^{144}Nd$	2SE	$^{147}Sm/^{144}Nd$
Host	Amph	6.5	281.2	0.708713	0.000008	0.066372	19.7	4.2	0.512317	0.000008	0.126796
Dyke	Early Amph	6.8	324.4	0.704722	0.000008	0.060834	24.8	8.1	0.512646	0.000008	0.197559
Dyke	Late Amph	8.6	189.5	0.704971	0.000008	0.131167	16.8	4.0	0.512559	0.000006	0.142593
Dyke	Plg	0.6	3109.7	0.704519	0.000008	0.000568	2.2	0.2	0.512482	0.000006	0.061238

Supplementary material A

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Supplementary material C
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