Metasedimentary and igneous xenoliths from Tallante (Betic Cordillera, Spain): inferences on crust-mantle interactions and clues for post-collisional volcanism magma sources

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4 Figures.

2 Supplementary sections including 1) analytical details and 2) bulk rock data.

ABSTRACT

The deep seated xenolith association exhumed in the Pliocenic volcano of Tallante (Betic Cordillera, Spain) includes protogranular mantle peridotites, felsic (metasedimentary) crustal rocks, as well as cumulus igneous rocks such as norites and amphibole (±phlogopite)-clinopyroxenites. The whole xenolith suite equilibrated at the same pressure (0.7-0.9 GPa) representing the local crust mantle boundary (MOHO) characterized by extreme lithological heterogeneity. This heterogeneity resulted from orogenic processes that induced the juxtaposition of crustal rocks (variably depleted in fusible components) within mantle domains including metasomes, as it is commonly observed in orogenic mantle massifs of the Mediterranean area. In this contribution, we report new mineral compositions of igneous parageneses recorded in these xenoliths, and we present Sr-Nd isotope data on both igneous and metasedimentary xenoliths that integrate those from the literature. Sr-Nd isotopes coherently indicate a restitic character of the metasedimentary xenoliths, which according to model ages were affected by partial melting in Paleozoic times. Sr-Nd isotopic errorchrons on the igneous xenoliths, on the other hand, qualitatively indicate Tertiary ages, which are corroborated by U-Pb zircon datings of one norite xenolith and two composite xenoliths having zircon-bearing norite veinlets. The new data are discussed proposing that MOHO lithologies of Tallante could provide significant source compositions for the genesis of the

Neogene volcanics of the Betic area, which included calcalkaline lavas as well as more potassic products such as lamproites.

Key words: metasedimentary and igneous xenoliths; Sr-Nd isotopic analyses; U-Pb zircon dating; crust-mantle interactions; magma sources.

1. Introduction

The boundary between crust and upper mantle (MOHO) is a first-order lithological and geophysical discontinuity within the lithosphere. It was originally thought as a sharp limit where lithological and geophysical proprieties abruptly change, but more recently there is an increasing consensus, based on high-resolution seismology and petrology of deep-seated xenoliths, that this boundary is transitional (O'Reilly and Griffin, 2013). Its direct access is possible by studying exhumed sections of the lower crust/uppermost mantle or xenoliths sampled by alkali-basalts and kimberlites.

In this view, the Pliocenic volcano of Tallante in the Betic Cordillera (Spain) is noteworthy because Na-dominated alkaline rocks (following subduction-related volcanic episodes) entrained a heterogeneous xenolith association including ultramafic mantle rocks (peridotites), metasedimentary crustal rocks, as well as a wide range of cumulus igneous rocks such as norites and amphibole (± phlogopite)-clinopyroxenites (Rampone et al. 2010; Bianchini et al., 2011).

The diverse xenoliths invariably display notable size (up to 20 cm) and freshness thus attracting an intense petrological interest reflected in a large number of studies mainly focused on the peridotite rocks (Dupuy et al., 1986; Capedri et al., 1986; Arai et al., 2003; Shimizu et al., 2004; 2008; Beccaluva et al., 2004; Rampone et al., 2010; Martelli et al., 2011; Bianchini et al., 2011 and references therein), whereas the crustal lithologies were considered only by Vielzeuf (1983). Recently, Bianchini et al. (2013) discussed the meaning of the whole xenolith suite, emphasizing that metasedimentary lithologies equilibrated at 0.7 ± 0.1 GPa and 1050 ± 100 °C, i.e. at *P-T* conditions overlapping those calculated from pyroxenite and peridotite parageneses (Rampone et al., 2010; Bianchini et al., 2011). Geobarometry therefore suggests the presence of a transitional MOHO that according to seismic evidence is currently estimated at the depth of ~22-23 km (De Larouzière et al., 1988).

The genesis of norite and clinopyroxenite lithologies cannot be simply referred to fractional crystallization and crystal settling in shallow (crustal) magma chambers, as testified by the presence of norite and clinopyroxenite veins cross-cutting peridotite in composite xenoliths (Arai et al., 2003; Shimizu et al., 2004; 2008; Beccaluva et al., 2004; Rampone et al., 2010; Bianchini et al., 2011 and references therein); this indicates that these magmatic rocks represent deep seated cumulates crystallized as millimetric to centimetric dykes in the uppermost lithospheric mantle. In some of these igneous xenoliths some relics (little domains) of an earlier peridotite assemblage are still recognizable.

The possibility that such a transitional MOHO represents a source for orogenic (*s.l.*) magma types (including the Mediterranean lamproites) which pre-dated the Na-dominated alkaline rocks of Tallante in the Betic Cordillera is an intriguing study-case that has not fully understood yet. To address this issue, we integrate the geochemical data set available in the literature reporting new mineral and bulk rock analyses (Tables 1 and 2; Supplementary Table 1) on igneous and composite xenoliths, and present ten new Sr-Nd isotopic analyses carried out on both igneous and metasedimentary xenoliths (Table 3); in-situ LA-ICP-MS U-Pb dating of zircons from a norite xenolith and from two norite veinlets in composite xenoliths are also reported to explore temporal relationships with the possible magma source(s) within the tectono-magmatic framework of the area.

2. Petrography and geochemistry

The metasedimentary xenoliths of Tallante have quartz-rich parageneses containing green spinel ± garnet ± sillimanite ± plagioclase (An_{43-83}) ± alkaline feldspars ($Or_{40}Ab_{60}$). Generally, cordierite occurs between quartz and spinel, suggesting the reaction spinel + quartz = cordierite. Cordierite also forms symplectites with quartz and spinel, a microstructure generally interpreted as a pseudomorph after garnet and/or Al_2SiO_5, which in this case was sillimanite. Accessory phases are rutile, ilmenite and magnetite (Bianchini et al., 2013).

The igneous xenoliths display a cumulus texture, resulting from deep magmatic crystallization processes. They can be subdivided in: a) light coloured norites dominated by plagioclase and orthopyroxene and b) dark coloured amphibole (±phlogopite)-clinopyroxenites containing (in order of abundance) clinopyroxene, amphibole (amph), olivine, phlogopite (ph) and glass (Bianchini et al., 2011; 2013). The two distinct types of igneous lithologies are plausibly related to distinct parental magmas.

The mineral analyses of norite veins and veinlets in composite xenoliths are reported in Table 1. The dominant mineral phases are plagioclase and orthopyroxene; plagioclase varies in composition from oligoclase to labradorite in centimetric veins, whereas it generally shows higher calcium content (labradorite to bytownite) in millimetric veinlets. Orthopyroxene in centimetric veins shows En contents varying between 80 and 84, always lower than that recorded in orthopyroxene of the associated peridotite country rock (En 82-88). In centimetric norite veins the parageneses include sporadic pargasite amphibole, whereas in millimetric norite veinlets a large variety of accessory minerals are recorded; they consist of amphibole, phlogopite, apatite, zircon, rutile and peculiar mineral phases pertaining to the huttonite-monazite series.

The mineral analyses of amphibole (±phlogopite) clinopyroxenites and composite xenoliths characterized by centimetric clinopyroxenite veins crosscutting peridotite matrix are reported in Table 2. Clinopyroxene generally shows an intermediate composition between salite and augite, becoming endiopside in the associated peridotite matrix of composite xenoliths. Amphibole in clinopyroxenites generally displays kaersutite composition rich in potassium and titanium (K_2O up 1.3 wt%; TiO_2 up to 5.8 wt%), whereas it is characterized by less titaniferous pargasite composition in the associated peridotite matrix of composite xenoliths. Olivine in clinopyroxenites varies between Fo 75 and 83, whereas it is characterized by higher Fo content (87-88) in in the associated peridotite matrix of composite xenoliths. Titaniferous phlogopite (TiO_2 up to 3.8 wt%) and silica-undersaturated (TiO_2-rich) glass are also recorded.

Rampone et al. (2010) recognized both types of igneous veinlets within a single composite xenolith, observing that the amphibole-bearing pyroxenite crosscut the norite, thus suggesting that the amphibole-bearing pyroxenite intrusion postdate the norite crystallization; however, in our collection we also observed composite peridotite xenoliths with a norite veinlet intruding a amph-pyroxenite domains. This would indicate that the two magma-types occurred at the same time, forming a network of lithospheric dykes, sometimes showing mutual crosscutting relationships.

A clear influence is propagated from the magmatic veins to the surrounding country rocks, as demonstrated by systematic compositional gradients in modal proportions and mineral compositions of the peridotite paragenesis at increasing distance from the vein contact (Bianchini et al., 2011; Martelli et al., 2011).

Bulk rock analyses of the Tallante metasedimentary xenoliths (Bianchini et al., 2013) show high SiO_2 (up to 75 wt%) and Al_2O_3 (up to 20 wt%) in agreement with their quartz- and Al-silicate-rich modal compositions. The trace element distribution normalized to the Upper Continental Crust (UCC; Fig. 1) reveals a marked depletion of most incompatible elements such as Light Rare Earth Elements (LREE) and Large Ion Lithophile Elements (LILE). Moreover, the comparison between these Tallante xenolith and metasedimentary analogues from Neoproterozoic – Lower Paleozoic Iberian outcrops (Ugidos et al., 2003; Lopez-Guijarro et al., 2008; Pastor-Galán et al., 2013; Villaseca et al., 2014) confirm the extreme low abundance of LILE (e.g. Rb) and LREE (e.g. Nd), thus indicating a restitic character in response to melt extraction during a P-T path that reached suprasolidus conditions.

Norites show relatively high Al_2O_3 (up to 23 wt%) and Na_2O (up to 6 wt%) suggesting accumulation of plagioclase that leads to positive anomalies in Sr and Eu (Bianchini et al., 2013). A general enrichment in the most incompatible trace elements is observed, with REE patterns characterized by enrichment in LREE over HREE (La_N/Yb_N up to 51). Sample TL10 shows a marked positive anomaly in zirconium (610 ppm of Zr) in agreement with the presence of modal zircon (Fig. 2e).

As reported by new bulk rock analyses (Supplementary Table 1), amphibole (phlogopite)-clinopyroxenites display distinct character, including samples that are strictly analogous to the host lava having a trachybasalt composition (SiO_2 ~ 47 wt%, MgO ~ 7 wt%, Na_2O+K_2O=5.6 wt%) and an enrichment in incompatible elements such as LREE (La_N/Yb_N up to 23). Other clinopyroxenites display higher amounts of MgO (up to 20 wt %) and higher content of compatible trace element such as Ni and Co, coupled with lower content of incompatible elements, respect to the host lavas. Therefore, some clinopyroxenites represent orthocumulates from magmas showing remarkable similarity with the host basalt, whereas others represent adcumulates that concentrated mineral phases appeared early in the crystallization sequence losing a significant fraction of fugitive melt.

The intrusion of these dykes in the surrounding peridotite country rocks generated a metasomatic aureole, highlighted by a high incompatible element budget in peridotite portions of composite xenoliths, respect to that recorded in unveined peridotite xenoliths (Fig. 1 e, f). This confirm the result of early investigation of Dupuy et al. (1986) which analyzed distinct peridotite slices of composite xenoliths at increasing distance from the vein contact.

3. Sr-Nd isotope composition

New Sr-Nd isotope analyses are presented in Table 3. The metasedimentary xenoliths (TL29, TL203 and TL380) reveal bulk ^{87}Sr/^{86}Sr ratios between 0.70771 and 0.72604, and ^{143}Nd/^{144}Nd ratios varying between 0.51239 and 0.51259. The ^{87}Sr/^{86}Sr ratios are less radiogenic (and the ^{143}Nd/^{144}Nd ratios are more radiogenic) with respect to the isotope composition of metasedimentary analogues from Neoproterozoic – Lower Paleozoic Iberian outcrops (Ugidos et al., 2003; Lopez-Guijarro et al., 2008; Pastor-Galán et al., 2013; Villaseca et al., 2014). The ^{87}Sr/^{86}Sr ratio is correlated with the parent ^{87}Rb/^{86}Sr ratio, and ^{143}Nd/^{144}Nd ratio is correlated with the parent ^{147}Sm/^{144}Nd ratio (trace element analyses of these rocks are reported by Bianchini et al., 2013). Although the Rb/Sr ratio could be variable in relation to heterogeneous sedimentary protoliths, its positive correlation with SiO_2 suggests the significant influence of partial melting processes in which the most incompatible elements (LILE, such as Rb) were removed in parallel with the most fusible components. Such processes were followed by long-term radiometric ingrowth leading to significant differentiation of the ^{87}Sr/^{86}Sr ratio. Analogously, the distinct Sm/Nd ratios could be established by distinct degree of melting which preferentially extracted Light Rare Earth Elements (LREE) such as Nd respect to heavier REE such as Sm. Note that the higher ^{143}Nd/^{144}Nd value (0.51259) is recorded in sample TL380 which contains garnet, a phase which preserves high Sm/Nd ratio if retained in the residual matrix during melting processes (see the discussion reported by Jung et al., 1998). In any case, qualitative errorchrons suggest that these depletion processes recorded by restitic felsic xenoliths mainly occurred in pre-Tertiary ages. This hypothesis is confirmed by Sm-Nd and Rb-Sr model ages (Fig. 2a, b) calculated relative to the average meta-sedimentary composition of the Iberian basement (Lopez-Guijarro et al., 2008; Villaseca et al., 2014), which suggest that the upper crust beneath Tallante suffered an important melting episode during the Paleozoic, plausibly between 300 and 320 Ma. These ages correspond to Variscan ages obtained on metasedimentary rocks from sections exposed in the neighboring occurrence of Ronda and Beni Bousera (Montel et al., 2000; Ruiz Cruz and Sanz de Galdeano, 2014) and in general conform to ages obtained on high-grade metamorphic rocks and S-type granitoids from various Iberian occurrences (Esteban et al., 2011; Merino Martinez et al., 2014).

Norite xenoliths reveal a heterogeneous Sr-Nd isotope composition including values compatible with a mantle-derived signature for sample TL10 which is characterized by ^{87}Sr/^{86}Sr=0.70497 and ^{143}Nd/^{144}Nd =0.51265, as well as values reflecting a significant involvement of crustal contamination as displayed by sample TL381 which is characterized by ^{87}Sr/^{86}Sr=0.70799 and ^{143}Nd/^{144}Nd=0.51238. It has to be noted that for sample TL10 the bulk rock analyses are integrated with the analyses of its (hand-picked) mineral constituents, i.e. plagioclase (^{87}Sr/^{86}Sr=0.70497) and orthopyroxene (^{87}Sr/^{86}Sr=0.70495, ^{143}Nd/^{144}Nd =0.51267). In this case, the limited isotopic difference between the constituent phases and the bulk rock composition, allows the calculation of errorchrons, which qualitatively indicate Tertiary ages (Fig. 2c, d).

The new Sr-Nd isotope analyses of amphibole (phlogopite)-bearing clinopyroxenites TL17, TL31 and TL42 were carried out on hand-picked amphibole revealing the following compositional range: ^{87}Sr/^{86}Sr=0.70433-0.70547 and ^{143}Nd/^{144}Nd =0.51258-0.51261 approaching the Sr isotopic analyses performed on analogous magmatic xenoliths from Tallante by Capedri et al (1989); in particular, these authors reported the analyses of coexisting amphibole (^{87}Sr/^{86}Sr=0.70469) and apatite (^{87}Sr/^{86}Sr=0.70449) which allows an errorchron calculation qualitatively pointing to Tertiary ages.

The influence of the magmatic injection in the surrounding peridotite country rocks has been evaluated analyzing the isotopic composition of clinopyroxene in the peridotite portion of the composite xenolith TL42, which displays ^{87}Sr/^{86}Sr=0.70408 that although lower than the associated magmatic portion is higher than that generally recorded in unveined peridotite xenoliths (Beccaluva et al., 2004; Luchs, 2012). This comparison indicates that, differently from the minerals included in the veins which plausibly evolved from the same isotopic starting composition, the surrounding mantle is out of equilibrium.

The Sr-Nd isotope values of metasedimentary and igneous xenoliths from Tallante are plotted in the ^{87}Sr/^{86}Sr *vs* ^{143}Nd/^{144}Nd diagram of Fig. 3, together with the composition of mantle xenoliths from the same site (Beccaluva et al., 2004; Luchs, 2012). The analyses of metasedimentary and igneous xenoliths extend the compositional spectrum of the ultramafic xenoliths, and partially overlap the compositional field of the Cenozoic orogenic (*s.l.*) volcanism of the Betic-Alboran realm, which is characterized by calcalkaline, high-potassium calcalkaline and ultrapotassic serial affinities (Duggen et al., 2004; Conticelli et al., 2009). This evidence highlights that the extreme heterogeneous chemical and isotopic characters of the Betic-Alboran volcanic rocks, which include extreme lamproitic compositions, could - at least in part - be related to multiple deep sources and do not necessarily require shallow level contamination processes in superficial magma chambers.

4. U-Pb zircon geochronology

The thin section of the Zr-rich norite sample TL10, a sample previously studied by Bianchini et al (2013), was carefully scanned by Electron Microscope (SEM) to find out the possible presence of zircon (Fig. 3e). The investigation revealed the presence of a zircon crystal having diameter of ~ 70-80 micrometers, which allowed U-Pb geochronological investigation by LA-ICP-MS. Prior to age determination, the zircon grain was investigated at the SEM by acquiring cathodoluminescence (CL) images (see inset in Fig. 3e;). According to the CL image, zircon shows a brighter irregular core surrounded by a nearly homogeneous domain with low CL emission. Four U-Pb analyses were performed on different locations of the zircon grain and only one analysis, from the low CL domain and close to the brighter core, revealed a concordant age of 6.8±2.0 Ma. The interpretation of this single concordant zircon age is not straightforward. It could represent a magmatic age indicating the timing of the zircon crystallization, or it could merely reflect a resetting of the U-Pb system in connection with a Cenozoic magmatic event, as suggested for zircons included in metasedimentary lithologies of the Betic basement by Zeck and Withehouse (2002). The second hypothesis is corroborated by additional datings on zircons (crystal size ~ 20-40 micrometers) recorded in millimetric norite veinlets of samples TL117 and TL347 (Table 1), exhibiting U-Pb ages of 4.4 (±1.0) and 2.2 (± 0.2) Ma, respectively.

On the whole, the data reported in the previous section and these U-Pb zircon ages suggest that important magmatic activity involved the region during the Cenozoic, as also supported by an Ar-Ar age of 10.5±0.6 Ma obtained on a Tallante phlogopite-rich xenolith (Turner et al., 1999). Noteworthy, a magmatic age of 6.8±2.0 Ma would discard the previous hypothesis delineated by Bianchini et al. (2013), who interpreted the norites as coeval with the felsic metapelites, possibly formed in relation to pre-Cenozoic tectono-magmatic cycles, observed in some Iberian occurrences of the Paleozoic basement (Villaseca et al., 2007).

If confirmed, the new age constraints would imply that norite xenoliths are plutonic equivalents of the Tertiary orogenic volcanism which is known in the Betic area. This volcanism was characterized by calcalkaline (*s.l.*) and shoshonite magmas at 13.4–6.8 Ma, followed by ultrapotassic magmas at 8.0-6.4 Ma (Turner et al., 1999, Duggen et al., 2004; 2005).

In any case, the obtained age of 6.8±2.0 approaches the slightly older SHRIMP ages (10.0-8.1 Ma) obtained by other authors (Zeck and Williams, 2002; Cesare et al., 2003; 2009) on zircon and monazite of metasedimentary xenoliths collected in the neighboring volcanic occurrences of El Hoyazo, Mazarron and Mar Menor.

5. Discussion

The deep seated xenoliths exhumed by Pliocene alkaline basalts at Tallante represent samples of the crust mantle boundary, which in the Betic area seems a locus characterized by extreme lithological heterogeneity (Fig. 4). Such heterogeneity plausibly reflects the sequence of subduction(s), continental collision(s) and recent lithospheric thinning which induced tectonic interlayering and juxtaposition of slices of crustal rocks in the mantle (Bianchini et al., 2013).

On the whole, the presented data suggest that the extreme ^{87}Sr/^{86}Sr-^{143}Nd/^{144}Nd heterogeneities of Neogene volcanic products in the Betic area not necessarily require the occurrence of crustal contamination during ponding/fractional crystallization in shallow level magma chambers (i.e. Assimilation-Fractional-Crystallization processes). In our view, the geochemical ingredients necessary to generate these compositions can be attained close to the MOHO, where mantle domains previously enriched by crustal-derived fluids/melts in Late Palaeozoic are still adjacent to crustal lithologies. In this scenario, such an extremely heterogeneous MOHO, preserving memory of multiple metasomatic episodes, could represent a significant source for the genesis of the Neogene volcanics of the Betic area, which include calcalkaline lavas as well as more potassic products such as lamproites.

Magma genesis in orogenic setting is particularly difficult to be decoded and notional petrological models implying mantle-derived basalts coupled with shallow-level AFC processes could represent an over-simplification. In particular, the presented data can be useful for a re-evaluation of earlier petrogenetic models of the Betic volcanism, such as those of Benito et al. (1999), who envisaged the existence of effective shallow level crustal contamination processes to explain the observed trace element and isotopic features of the Betic volcanic rocks.

The Betic volcanism was triggered by adiabatic decompression related to post-collisional extension, also facilitated by mantle dynamics induced by the concomitant subduction (Beccaluva et al., 2011). In this framework, multiple geochemical components were available to produce the various orogenic magmas observed in the area. As concerns the most exotic lavas, i.e. the lamproites, the widespread igneous veining recorded in composite mantle xenoliths from Tallante coupled with very refractory peridotite compositions known from neighboring xenolith occurrences in the Iberian margin (Bianchini et al., 2007) seem to provide reliable source components (Bianchini et al., 2007; Conticelli et al, 2009). In this view, we tested several melting scenarios involving the various lithologies recorded by the Tallante xenoliths (Fig. 4) to evaluate their potential as magma sources for the Betic volcanics, also including lamproite compositions. In particular, modelling was carried out according to least-squares mass balances (Wright and Doherty, 1970), using the composition of mineral phases recorded in the Tallante mantle xenoliths that were properly "mixed" in order to fit the composition of the Betic volcanic rocks. The least-squares regression, proposed for melting modelling by Beccaluva et al. (2007), was obtained on a excel spreadsheet. For example, Betic lamproites have been modelled using the mineral composition of an unveined harzburgite (TL1; Beccaluva et al., 2004) doped with phlogopite, plagioclase and apatite from the reported norite parageneses. The results are reported in Table 4 for distinct lamproite compositions from type localities such as Jumilla, Cancarix and Vera (Turner et al., 1999). Although the inferred melting coefficients vary slightly for distinct lamproite compositions, best solutions of the least-squares regression invariably indicate incongruent melting conditions:

$$\mathrm{Opx + Ph + Cpx + Sp + Pl_A \rightarrow lamproite + Ol + Pl_B}$$

The least-squares regression therefore suggests that the genesis of these magmas require formation of olivine in the residua, together with a plagioclase increase that become significantly more calcic respect to the starting composition.

While the incongruent melting of orthopyroxene (with formation of olivine) is documented for orogenic magma-types such as lamproites ~~(REF)~~, the source presence of plagioclase and its incongruent melting is generally not taken into proper account. The increase of the anorthite component from $\mathrm{Pl_A}$ to $\mathrm{Pl_B}$ is consistent with experimental data on plagioclase evolution during melting of mica- and Pl-bearing systems (Stevens et al., 1997; Patino Douce and Harris, 1998) and has been also observed in restite xenoliths from another Betic volcanic occurrence (Cesare ~~et al.~~, 2000); the incongruent melting of plagioclase, thus provide silica (and potassium) that are key components of lamproite magmas.

The important role of the norite veins in the magma sources of the Betic volcanics is also corroborated by the presence of peculiar Th-REE rich minerals that can contribute the extreme incompatible element enrichment typical of lamproites.

6. Conclusions

The study of the xenolith association recorded at Tallante suggests petrological models which relate the heterogeneous post-collisional volcanism to the involvement of complex magma sources generated by the polyphase formation of deep *mélanges* of crustal and mantle rocks (Bianchini et al., 2008; Cebriá et al., 2009; Conticelli et al., 2009; Prelevic et al., 2013).

It has to be noted that the complexity of these mantle sources cannot be ascribed to the exclusive effect of the Cenozoic subduction/collision process. As delineated by isotopic constraints provided by Tommasini et al. (2011) and Pe-Piper et al. (2014) as well as by geological and petrological inference specific of the Betic region (Pérez-Valera et al., 2013) the formation of Mediterranean-type lamproites necessarily require mantle metasomes, i.e. metasomatically enriched domains, partially acquired in Paleozoic times. This inference is corroborated by the xenoliths from Tallante that bear compelling evidence of complex multistage tectono-magmatic phases, including Paleozoic (the metasedimentary parageneses) and Tertiary (the igneous parageneses) episodes.

The Tallante xenolith suite can therefore help to understand multi-stages and multi-components crust-mantle interactions also in other circum-Mediterranean collisional settings. Future investigations will be focused on other heterogeneous xenoliths suites sampled close to collisional boundaries such as those of the Veneto Volcanic Province in the Southern Alps to highlight possible analogies and differences at regional scale (Morten, 1979; Gasperini et al. 2006; Beccaluva et al., 2007).

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Captions

Table 1. Analyses of representative mineral phases of norite veins and associated peridotite country rocks.

Table 2. Analyses of representative mineral phases of amphibole (± phlogopite) clinopyroxenite and associated peridotite country rocks.

Table 3. Sr and Nd isotopic analyses of metasedimentary and igneous (norite and clinopyroxenite) xenoliths from Tallante. TL42 is a composite xenolith including an igneous (clinopyroxenite) vein and the surrounding host peridotite.

Table 4. Least-squares mass balance calculations to explain the petrogenesis of orogenic magmas such as the Betic lamproites (Turner et al., 1999). Theoretically, the magma source would be a peridotite (harzburgite TL1; Beccaluva et al., 2004) crosscut by a norite vein. Melt. coeff. represent the proportion in which the composition of source phases contribute to the melt.

Fig. 1. Trace element distribution in metasedimentary (a, b), norite (b, c) and clinopyroxenite (e, f) xenoliths from Tallante. Upper crust normalization values are from Rudnick and Gao (2004); Primordial mantle and chondrite normalization values are from Sun and McDonough (1989).

Fig. 2. Temporal constraints on the genesis of the investigated xenoliths from Tallante; (a) and (b) reports model ages of the metasedimentary xenoliths of Tallante respect to an average composition of the Iberian metamorphic basement calculated from the data provided by Lopez-Guijarro et al. (2008) and Villaseca et al. (2014); (c) and (d) are two point pseudo-isochrons (errorchrons) calculated on the norite xenolith TL10; (e) Back scattered SEM image of norite TL 10, showing the more important mineral constituting the paragenesis, and emphasizing the presence of a zircon crystal which is focused in the inset reported in the right/upper part of the figure. In this inset, we report a CL image of the zircon crystal with the LA-ICP-MS spot locations and the U-Pb concordant age. White and black/white circles indicate locations of the analytical spots providing concordant and discordant U-Pb data, respectively.

Fig. 3. Sr vs Nd isotopic ratios of the studied crustal xenoliths from Tallante, compared with the composition of a) mantle xenoliths from the same site (Beccaluva et al., 2004; Luchs, 2012) and the Cenozoic orogenic (*s.l.*) volcanics from the Betic-Alboran Domain (Duggen et al., 2014; Conticelli et al., 2009).

Fig. 4. Schematic representation of the xenolith types recorded at Tallante, which also summarize the available thermobarometric estimates and Sr-Nd isotopic compositions.