A Late Oligocene Suprasubduction Setting in the Westernmost Mediterranean Revealed by Intrusive Pyroxenite Dikes in the Ronda Peridotite (Southern Spain)

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ABSTRACT

Contrasting tectonic reconstructions of the westernmost Mediterranean have been proposed to explain the origin of the Alboran marine basin contemporaneously with Cenozoic convergence between the African and European plates. Cr-rich pyroxenites in the Ronda massif record the geochemical processes occurring in the subcontinental mantle of the Alboran domain in the Late Oligocene, thus constraining the geodynamic scenario of Cenozoic extension in the western Mediterranean lithosphere. Clinopyroxene in intrusive Cr-rich websterite dikes crosscutting the Ronda peridotite is strongly depleted in Nb-Ta and enriched in light rare earth elements, as typically observed in arc magmas, and is in trace element equilibrium with Neogene subduction-related lavas from the western and central Mediterranean. Sr-Nd-Pb radiogenic isotopes indicate that the mantle source of the Ronda pyroxenite dikes was contaminated by a subduction component released by detrital sediments likely deposited in passive continental margins. Rather than convective removal or delamination of the lithospheric root, our data strongly support Alboran geodynamic models that envisage slab rollback as the tectonic mechanism responsible for the Miocene lithospheric thinning. The Ronda Cr-rich pyroxenite dikes represent the earliest unambiguous manifestation of subduction-related magmatism in the western Mediterranean and testify to the involvement of terrigenous sediments in the primitive stages of subduction.

Online enhancements: appendix tables.

Introduction

The Betic-Rif orogenic belt in the westernmost Mediterranean region was assembled since the Late Cretaceous to Tertiary during convergence between Iberia and Africa and collision of the Alboran domain with the south Iberian and Maghrebian passive margins. Extension since the Oligocene resulted in the formation of the Alboran marine basin, the exhumation of large bodies of subcontinental lithospheric mantle (the Ronda and Beni Bousera peridotite massifs), and the extrusion of Neogene-Quaternary volcanic rocks (e.g., Lonergan and White 1997; Platt et al. 2003, 2006; Duggen et al. 2004; Faccenna et al. 2004; Booth-Rea et al. 2007). Slab rollback, slab detachment, mantle lithosphere delamination, and convective thinning of the thickened lithospheric root are some of the diverse geodynamic scenarios proposed for the extension of the Betic-Rif orogen and the associated
postorogenic volcanism (e.g., Platt and Vissers 1989; Zeck 1996; Turner et al. 1999; Gutscher et al. 2002; Spakman and Wortel 2004; Duggen et al. 2005; Rampone et al. 2010). Geochemistry of magmatic rocks generated in the mantle may constrain the tectonic configuration during their petrogenesis, but crustal contamination likely masks the original geochemical signature of extruded lavas (Turner et al. 1999; Duggen et al. 2008). On the other hand, assimilation of the continental crust can be excluded for plutonic rocks intruded in the subcontinental lithospheric mantle. Here we present new trace element and Sr-Nd-Pb isotopic data of Late Oligocene–Early Miocene intrusive mantle pyroxenites in the Ronda peridotite massif (southern Spain), evidencing the involvement of a sedimentary component in their source. Our data require a suprasubduction setting for the Ronda peridotite at ~25 Ma, constituting conclusive evidence for Alboran geodynamic models invoking the occurrence of subduction rather than convective removal or delamination of the lithospheric root, as the tectonic scenario of Miocene extension in the westernmost Mediterranean.

The Ronda Peridotite Massif

Extensive studies in the western Ronda peridotite massif (Van der Wal and Bodinier 1996; Van der Wal and Vissers 1996; Lenoir et al. 2001; Soustelle et al. 2009; Garrido et al. 2011) have documented the existence of three petrological, structural, and geochemical domains from N-NW to S-SE (fig. 1A): [1] a garnet-spinel (Grt-Sp) mylonite and foliated spinel tectonite domain representing ancient subcontinental lithospheric mantle (Reisberg and Lorand
Cr2O3 (0.881–0.911) in the spinel peridotite domain, separated from the spinel Eocene–Early Oligocene (Van der Wal and Vissers and strongly thinned in the Jurassic and/or Late in the diamond-stability field (Davies et al. 1993)

Garrido and Bodinier (1999) demonstrated that the structure, petrology, and geochemistry of the Ronda pyroxenites are correlated with the zoning of the massif and identified four pyroxenite groups: [1] garnet pyroxenite, occurring in the spinel tectonite domain and representing the high-pressure vestiges of an old veined subcontinental lithosphere; [2] spinel websterite, occurring along the recrystallization front, formed by partial melting and melt-rock reaction of former garnet pyroxenite; [3] Ti-rich spinel websterite found mainly in plagioclase tectonite and formed by melt-rock reaction and replacement of peridotite (Bodinier et al. 2008); and [4] Cr-rich websterite and orthopyroxenite overprinting the other pyroxenite groups and generated in the waning magmatic stages before the emplacement of the Ronda peridotite into the crust.

Cr-Rich Pyroxenite in the Ronda Peridotite

This article focuses on Cr-rich pyroxenite occurring in Ronda as intrusive websterite dikes cross-cutting spinel tectonite and Grt-Sp mylonite [samples RC75 and RC120; fig. 1A] or as websterite to orthopyroxenite layers concordant with the foliation of spinel tectonite and cropping out near the recrystallization front, in the coarse-granular and plagioclase tectonite domains [samples RC66, RC68, RC70/2, RC71C, RC153–7/2, RC150A, and RC170B; fig. 1A]. Samples have cumulate-like magmatic texture and are principally constituted by variably sized (0.5–3.5 mm) subhedral clinopyroxene [Mg# = Mg/(Mg + Fe2+)] = 0.901–0.953; Cr2O3 = 0.21–1.93 wt% and orthopyroxene [Mg# = 0.881–0.911; Cr2O3 = 0.13–0.96 wt%] and traces of interstitial olivine. Minerals in crosscutting dikes have smaller grain size than in concordant layers. Exsolution lamellae of counterpart pyroxene are common in both clinopyroxene and orthopyroxene. On the basis of textural observations, clinopyroxene generally began to crystallize prior to orthopyroxene and later olivine. Subhedral coarse-grained (1.5–3 mm) spinel [Cr# = Cr/(Cr + Al) = 0.19–0.22; Mg# = 0.757–0.781] has been observed in two samples as embayed grains occasionally with plagioclase coronas and associated with clusters of anhedral clinopyroxene and orthopyroxene. Deformation is absent or moderate and mainly testified by undulose extinction and kink banding of large pyroxene grains in concordant layers. The main petrographic features of the studied samples are summarized in table A1, available in the online edition or from the Journal of Geology office.

The absolute timing of formation of Cr-rich pyroxenite is constrained by intrusive dikes in the Grt-Sp mylonite. Lu-Hf isotopic analyses of Cpx-Grt pairs in garnet pyroxenite in the alike Beni Bousera Grt-Sp mylonite domain yield radiometric ages of 25 ± 1 Ma (Blichert-Toft et al. 1999; Pearson and Nowell 2004), implying that Grt-Sp mylonites formed in the Late Oligocene by decompression and cooling (Platt et al. 2003) below the closure temperature of the Lu-Hf system (ca. 800°C; Pearson and Nowell 2004). The intrusive dike RC120 is nearly vertical (fig. 1B), and although it cuts the Grt-Sp mylonite foliation, it shows gentle folds with axial planes parallel to the foliation (fig. 1B, 1C), indicating intrusion in the waning stages of ductile deformation (ca. 800°C) in the mantle Grt-Sp mylonite. Similar structural relationships have been reported for late crosscutting dikes in the Lanzo orogenic massif (Boudier 1978). These observations constrain the formation of Cr-rich pyroxenite during thinning and exhumation of the Ronda subcontinental lithospheric mantle section around 25 Ma, before its final crustal emplacement in the early Miocene (ca. 21 Ma; Priem et al. 1979).

Analytical Techniques

Major Elements. Mineral contents of major elements were obtained in ~150-μm-thick sections by electron microprobe using a CAMECA SX 100 instrument at the Service Microsonde Sud-Géosciences Montpellier. Accelerating voltage and beam current were 20 kV and 10 nA, respectively. Counting times were 20–30 s. Average major element compositions of clinopyroxene are displayed in table A2 and of other minerals in table A3, both available in the online edition or from the Journal of Geology office.

Trace Elements in Clinopyroxene. Trace element analyses of clinopyroxene were carried out by laser
ablation inductively coupled mass spectrometry (LA-ICP-MS) at Géosciences Montpellier, using a ThermoFinnigan ELEMENT XR high-resolution ICP-MS, coupled with a Geolas [Microlas] automated platform housing a 193-nm Compex 102 laser from LambdaPhysik. Signals were acquired in time-resolved acquisition, devoting 2 min for the blank and 1 min for measurement of the analytes. The laser was fired employing an energy density of 15 J/cm² at a frequency of 8 Hz and using a spot size of 100–120 μm. Oxide level, measured by the ThO/Th ratio, was below 0.8%. Reference sample BIR-1G was analyzed as unknown during the analytical runs, and its average shows good agreement with working values for this international standard [Gao et al. 2002]. Ca, measured by electron microprobe, was used as internal standard. Analyte concentrations were calibrated against the NIST 612 rhyolitic glass, according to the values of Pearce et al. [1997]. Data were subsequently reduced using GLITTER software [van Achterbergh et al. 2001] by inspecting the time-resolved analysis to check for lack of heterogeneities in the analyzed volume. Ten inspects were performed for each sample. Representative LA-ICP-MS analyses of clinopyroxene samples are shown in Table A4, available in the online edition or from the Journal of Geology office.

**Sr-Nd-Pb Radiogenic Isotopes.** Sr, Nd, and Pb radiogenic isotope ratios were measured in clinopyroxene separates of each sample. Mineral concentrates were obtained by crushing and sieving (100–200-μm mesh), followed by magnetic separation in a Frantz isodynamic device. Highly clean mineral separates were handpicked in alcohol under a binocular microscope and ultrasonically washed several times in acetone and Milli-Q water at 60°C. After powdering, the samples were leached twice for 30 min at 120°C with 2.5 and 6 N HCl, respectively, rinsed several times with ultrapure water between each leaching step, and finally ultrasonicated in 2 N HNO₃ for 15 min.

Digestion and element separation were performed in the Géosciences Montpellier isotopic laboratory following the procedures described in detail by Bosch et al. [2004]. Pb chemical separation was carried out using the AG1X8 anion exchange resin washed in 0.5 N HBr and 6 N HCl. Nd and Sr were separated following an extraction chromatographic method modified from Pin et al. [1994]. Average Nd, Sr, and Pb concentrations in procedural blanks were less than 100, 110, and 90 pg, respectively.

Pb and Nd isotopic ratios were measured by a NuPlasma 500 MC-ICP-MS at the Ecole Normale Supérieure de Lyon. Pb isotope compositions were analyzed using the Tl normalization method described by White et al. [2000]. Each batch of two samples was bracketed by NBS 981 standard splits (average 206Pb/204Pb = 16.9347 ± 30, 207Pb/204Pb = 15.4876 ± 34, 208Pb/204Pb = 36.686 ± 11 [2σ; n = 6]), and an external correction was applied to the samples according to the values reported by Trott et al. [1996]. The Nd isotopic ratios were measured following the method described by Luais et al. [1997], and the average value of the Lyon in-house JMC standard solution [batch 801149A] was 0.512135 ± 18 [2σ; n = 16] for one analytical session. Sr isotopic ratios were measured by a ThermoFinnigan Triton T1 TIMS at the LABOGIS of the Centre Universitaire de Formation et de Recherche de Nîmes. NBS 987 standard was run at the beginning of each analytical session. The average value for NBS 987 was 0.710239 ± 11 [2σ; n = 5]. 87Sr/86Sr ratios were corrected for mass discrimination by normalizing to a 86Sr/88Sr value of 0.1194. Initial isotopic compositions have been calculated at 25 Ma, which is the estimated age of pyroxenite crystallization. However, the generally low Sm/Nd and especially Rb/Sr and U-Th/Pb ratios of clinopyroxene lead the correction for in situ radioactive decay since Late Oligocene to be generally negligible. Sr-Nd-Pb isotopic data are displayed in Table A5, available in the online edition or from the Journal of Geology office.

**Geochemistry of Ronda Cr-Rich Pyroxenite.** In terms of trace elements, clinopyroxene in concordant layers is light rare earth element (LREE) depleted [La/Yb]ₙ = 0.1–0.7] and has very variable middle rare earth element/heavy rare earth element ratios [Sm/Yb]ₙ = 0.6–2.2], and its primitive mantle (PM)–normalized patterns generally present negative anomalies in Pb and Ti [fig. 2A]. Cr-rich crosscutting dikes have very different clinopyroxene compositions. They are strongly enriched in LREE [La/Yb]ₙ = 2.8–5.6], and their PM-normalized patterns have negative anomalies of Nb [Nb/Th]ₙ = 0.01–0.11] and Ta [Ta/Th]ₙ = 0.02–0.15]. Fingerprints of subduction-related magmatism, and positive spikes of Pb [fig. 2B]. The patterns of the calculated melts in trace element equilibrium with these compositions strongly coincide with those of the LREE-enriched calcalkaline lavas erupted in the western and central Mediterranean during the Oligocene–Late Miocene and differ from those of other Cenozoic volcanic rocks from the Alboran basin, including the LREE-depleted tholeiitic lavas [fig. 2B].
Figure 2. Representative primitive mantle-normalized trace element patterns of clinopyroxene (Cpx) from Cr-rich concordant layers (A) and crosscutting dikes (B). Symbols as in figure 1. Normalizing values are from Sun and McDonough (1989). In B black lines represent the compositions of melts in equilibrium with clinopyroxene (partition coefficients from Watson et al. 1987; Foley et al. 1996; Ionov et al. 2002 and references therein), the gray field encloses the light rare earth element (LREE)-enriched calcalkaline lavas from the western and central Mediterranean (Duggen et al. 2008 and references therein; Conticelli et al. 2009), and the dashed line encompasses the LREE-depleted tholeiitic lavas from the Alboran basin (Hoernle et al. 1999; Duggen et al. 2004, 2008; Gill et al. 2004).

Age-corrected (25-Ma) ⁸⁷Sr/⁸⁶Sr and ¹⁴⁴Nd/¹⁴⁴Nd of clinopyroxene in concordant layers vary between 0.70238–0.70515 and 0.51245–0.51348, respectively, thus reproducing the variability observed in peridotites and pyroxenites from Ronda and other orogenic massifs and having similar Nd but less radiogenic Sr isotopic ratios than the LREE-depleted tholeiitic lavas from the Alboran basin [Hoernle et al. 1999; Duggen et al. 2004, 2008; Gill et al. 2004].

Discussion

Petrogenesis of Cr-Rich Pyroxenite in the Ronda Massif. The relationship between the outcrop type of Cr-rich pyroxenite (layers concordant with the tectonite foliation vs. crosscutting dikes) and the petrological zoning of peridotite (fig. 1A) indicates a causal link between the genesis of these rocks and the heating event responsible for the formation of the Ronda recrystallization front. Garrido and Bodinier (1999) inferred that Cr-rich pyroxenite crystallized at the waning magmatic stages of this episode from volatile- and silica-rich andesite-like melts. Based on field observations, the clinopyroxene (generally Cr- and Mg-rich) composition [table A2], the plagioclase-free websteritic assemblage [table A1], and the cumulate-like magmatic microstructure [fig. 1D], these authors interpreted dikes as primitive melt intrusions in the relatively cold lithospheric mantle and concordant layers as replacement products of older pyroxenite after permissive percolation and peridotite-melt reaction in the reheated lithosphere.

In this scenario, crosscutting dikes reflect better than concordant layers the primary composition of percolating melts, whereas the parental magmas of the latter intensely interacted with mantle rocks. Trace element [fig. 2B] and Sr-Nd-Pb isotopic [fig. 3] compositions of clinopyroxene in crosscutting dikes show clear subduction-related affinity that is less evident in concordant layers. This observation supports the interpretation that the Cr-rich melts percolating through the Ronda mantle section originally had a subduction signature clearly preserved in dikes but progressively obliterated in concordant layers by melt-rock reaction with enclosing peridotite and pyroxenite. Indeed, melt percolation in
the mantle may generate isotopic variations similar to those observed in Cr-rich pyroxenite from the Ronda massif [Le Roux et al. 2009].

Interestingly, clinopyroxene in concordant layers partly overlaps the composition of Atlantic pelagic sediments and subduction-related Alboran lavas in terms of Pb [fig. 3B, 3C] but not in terms of Sr-Nd isotopes [fig. 3A]. Pb isotopes thus seem to retain better than Sr-Nd the imprint of a subduction-related component in the melt. This may reflect the higher incompatible character of Pb compared to Sr and Nd and its higher abundance in the percolating melt (i.e., the melt in equilibrium with clinopyroxene in crosscutting dikes; fig. 2B), which may hamper the reequilibration of Pb with the peridotite matrix more efficiently than for Sr-Nd [Návov and Stolper 1987]. However, we note that the Pb isotopic compositions of Atlantic sediments and subduction-related lavas from the Alboran basin significantly overlap those of mantle peridotite and pyroxenite [fig. 3B, 3C]. Consequently, Pb isotopes hardly discriminate the contributions of the subduction and mantle components in the melt, and we cannot exclude that Pb in concordant layers significantly reequilibrated with mantle rocks as shown by Sr and Nd [fig. 3A].

**Origin of the Subduction-Related Component.** The refractory composition, the subduction-related trace element affinity [fig. 2B], and the strongly radiogenic 87Sr/86Sr and unradiogenic 143Nd/144Nd isotopic ratios of clinopyroxene [fig. 3A] strongly support that the Cr-rich pyroxenite dikes in the Ronda massif were derived from a depleted mantle source contaminated by crustal components. The crustal imprint may have been imparted either by flux of

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**Figure 3.** Age-corrected (25-Ma) Sr-Nd (A) and Pb (B, C) radiogenic isotope ratios of clinopyroxene from Cr-rich pyroxenites in the Ronda massif [red circles, concordant layers; green squares, crosscutting dikes]. Data of orogenic peridotites [green area], Al-augite [Aug] pyroxenites [pink area], garnet [Grt] pyroxenites [light blue circles], and Cr-diopside pyroxenites [blue squares; inner white dot indicates samples from the Beni Bousera massif] are from Pearson et al. [1993], Becker [1996], Bodinier and Godard [2003] and references therein, and Le Roux et al. [2009]. Data of light rare earth element [LREE]–enriched calcalkaline [yellow area] and LREE-depleted tholeiitic [orange area] lavas from the western and central Mediterranean [corrected to 25 Ma for comparison] are from the same references as in figure 2. Field of Atlantic pelagic and terrigenous sediments [dashed line] are from Ben Othman et al. [1989], Revel et al. [1996], Hoernle [1998], Duggen et al. [2004], and Jolly et al. [2006]. Field of modern deep-sea turbidites in B and C [dotted line] is from Hemming and McLennan [2001]. Solid curve in A models the mixing between a lherzolite from the Ronda massif [Lenoir et al. 2001] assumed to have the isotopic composition of RC150A and a melt derived from Atlantic sediment [orange star, Jolly et al. 2006], partition coefficients are from Johnson and Plank [1999]. Labels indicate the percentages of melt contribution.
exotic fluids/melts from a subducting slab or by in situ melting of old garnet pyroxenite with crustal-related geochemical signature. Garnet pyroxenites, interpreted as ancient (>1 Ga) subducted crust recycled into the mantle, are common components of the Betic-Rif orogenic massifs (Pearson et al. 1993; Garrido and Bodinier 1999; Pearson and Nowell 2004), and melting of these rocks was proposed to explain the subduction-related signature of the LREE-enriched calcalkaline lavas in the western Mediterranean (Hoernle et al. 1999; Turner et al. 1999). However, the Sr-Nd isotopic compositions of common garnet pyroxenite in orogenic peridotite massifs are unsuitable for generating the enriched isotopic signatures of the Ronda Cr-rich websterite dikes (fig. 3A). Instead, these isotopic compositions can be accounted for by melting of a depleted mantle source contaminated by fluids/melts derived from subducted sediments (fig. 3A). In particular, the highly radiogenic Sr and unradiogenic Nd isotopic ratios of these dikes (fig. 3A) combined with relatively high 207Pb/204Pb, 208Pb/204Pb and low 206Pb/204Pb (fig. 3B, 3C) support the interpretation that the sediment component in their mantle source had turbiditic-terrigenous instead of true pelagic affinity, as also inferred for some Cr-rich pyroxenite from the Beni Bousera massif (fig. 3) on the basis of Hf isotopes (Pearson and Nowell 2004).

Duggen et al. (2004, 2008) showed that the LREE-depleted tholeiitic lavas from the central Alboran basin were formed by partial melting of a depleted mid-ocean ridge basalt mantle source contaminated by hydrous fluids from subducted oceanic lithosphere. On the other hand, LREE-enriched calcalkaline lavas erupted in the Betic-Rif orogenic belt and in an arcuate marine region subparallel to it show common imprint of crustal contamination possibly subsequent to the addition of sediment melts to their mantle source. The coincidence between the trace element and Sr-Nd isotopic compositions of LREE-enriched calcalkaline lavas and those of melts in equilibrium with Cr-rich pyroxenite dikes intruded in the Ronda massif (figs. 2B, 3A) suggests that the subduction component in the subcontinental mantle of the Alboran domain was mainly added by a melt derived from subducted sediments instead of fluids; moreover, this strong compositional resemblance corroborates the subduction affinity of the LREE-enriched calcalkaline lavas in the western Mediterranean not being exclusively acquired by crustal assimilation but partly reflects subduction-related processes active in their mantle source (Duggen et al. 2004, 2008).

Tectonic Implications for the Western Mediterranean in Cenozoic Time. Our study shows that andesitic-like melts with a subduction-related component crystallized in Late Oligocene–Early Miocene in the Ronda lithospheric mantle. At this time, the Ronda peridotite constituted the subcontinental lithospheric mantle of the Alboran domain, which was undergoing strong thinning and melting (Le-noir et al. 2001) coevally with Early Miocene extension in the overlying Alpujarride-Malague packing crust (Balanyá et al. 1997; Platt et al. 2003). This extensional setting, jointly with the presence of intrusive Cr-rich pyroxenite dikes with an exotic subduction-related component, strongly indicates a suprasubduction setting for the latest evolutionary stages of the Ronda peridotite.

Multidisciplinary studies have shown that Cenozoic slab rollback played a fundamental role in the geodynamic evolution of the Betic-Rif orogen (e.g., Facenna et al. 2004; Booth-Rea et al. 2007). Slab rollback promoted extension and drifting of the Alboran lithospheric domain from the Valencian margin (Iberia-Eurasian plate) in the Eocene to the south Iberian and the African passive margins in the Miocene (fig. 4). The onset of drifting possibly caused the intrusion of Late Eocene–Early Oligocene tholeiitic to calcalkaline dikes in the internal Betic zone cropping out northeast of Malaga (Duggen et al. 2004). In Late Oligocene–Early Miocene different domains formed in the region between Iberia and Africa, including thinned continental crust and a Flysch trough composed of turbiditic deposits likely floored by oceanic crust (Durand-Delga et al. 2000; fig. 4). Westward migration of the Alboran orogenic wedge in Late Oligocene to Middle Miocene encountered these different domains, producing their collision-subduction and the associated high to intermediate pressure/low temperature metamorphism of the

Figure 4. Reconstruction of the tectonic evolution of the western Mediterranean in the Eocene-Miocene. The westward-migrating Alboran domain and the subducting Flysch trough are marked in dark gray.
basement of the Iberian and the Maghrebian passive margins (Booth-Rea et al. 2007; Negro et al. 2007). Dehydration/melting of Flysch-derived sediment stack coeval with melting of the subcontinental mantle nicely accounts for the timing and geochemical signature of the Ronda Cr-rich pyroxenite dikes.

The first unambiguous evidence of arc-related volcanism in the westernmost Mediterranean occurred at ca. 15–16 Ma in the Algerian margin (Maury et al. 2000) and later migrated westward to the eastern Alboran basin and the Rif in Serravallian-Messinian time (Duggen et al. 2004, 2005). Ronda Cr-rich pyroxenite dikes hence fill the chronological gap between the emplacement of the Malaga dikes (37–30 Ma; Turner et al. 1999; Duggen et al. 2004) and the extensive Miocene volcanism in the Alboran region. Cr-rich pyroxenite dikes in the Ronda massif thus represent the Late Oligocene plutonic product of the subduction-related tectonic processes that caused the migration of the Alboran domain and shaped the western Mediterranean since the Paleogene (fig. 4). The geochemistry of the Miocene Alboran volcanism however reflects the involvement of fluids and melts derived from pelagic sediments of the subducted Tethys oceanic lithosphere (Duggen et al. 2004, 2005; Gill et al. 2004), thus differing from the Ronda Cr-rich pyroxenite dikes that require a higher contribution of terrigenous sediments in their petrogenesis. This temporal source evolution may reflect an increasing transport of oceanic sediments to the westernmost Mediterranean subduction zone in the Middle to Late Miocene. Extensive eruption of volcanic rocks may have been favored by rapid and important lithospheric thinning in the Early Miocene (23–18 Ma; Platt et al. 2003, 2006), whereas the presence of a thick continental lithosphere in the Late Oligocene may have hampered the extrusion of the lavas equivalent to the Cr-rich pyroxenite dikes intruded in the Ronda massif.

**Conclusions**

Cr-rich websterites in the Ronda peridotite massif have different trace element and Sr-Nd-Pb isotopic compositions of clinopyroxene, depending on their structural occurrence in the field. Clinopyroxene in layers parallel to the foliation of spinel tectonite is LREE-depleted and has Sr-Nd-Pb isotopic compositions that overlap those of mantle peridotites and pyroxenites from orogenic massifs. On the other hand, crosscutting dikes in the NW region of Ronda have clinopyroxene that is strongly enriched in LREE and Pb, strongly depleted in Nb-Ta, and in trace element equilibrium with the Oligocene-Miocene calcalkaline lavas erupted in the western and central Mediterranean. Pyroxenite dikes in the Ronda peridotite massif thus differ from mafic dikes in other orogenic massifs from western Europe, which have alkaline (Lherz, France) or mid-ocean ridge basalt (Lanzo, Italy) composition. Sr-Nd-Pb radiogenic isotopic ratios corroborate that the mantle source of the Cr-rich pyroxenite dikes in the Ronda massif was contaminated by a subduction component issued from terrigenous sediments. The subduction-related composition of Cr-rich pyroxenite dikes in Ronda cannot have been induced by crustal contamination but demonstrates that a slab was subducting beneath the subcontinental lithospheric mantle of the Alboran domain in the Late Oligocene. Our data thus strongly support tectonic models that envisage slab rollback as the tectonic mechanism responsible for the Miocene extension in the westernmost Mediterranean instead of delamination or convective removal of the thick lithosphere.

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