The architecture of the European-Mediterranean lithosphere: A synthesis of the Re-Os evidence

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ABSTRACT

Rhenium-depletion model ages (T_{RD}) of sulfides in peridotite xenoliths from the subcontinental mantle beneath central Spain (the Calatrava volcanic field) reveal that episodes of mantle magmatism and/or metasomatism in the Iberia microplate were linked to crustal growth events, mainly during supercontinent assembly and/or breakup at ca. 1.8, 1.1, 0.9, 0.6, and 0.3 Ga. A synthesis of available in situ and whole-rock Os-isotope data on mantle-derived peridotites shows that this type of mantle (maximum T_{RD} of ca. 1.8 Ga) is widespread in the subcontinental mantle of Europe and Africa outboard from the Betics-Maghrebides-Appenines front. In contrast, the mantle enclosed within the Alpine domain records T_{RD} as old as 2.6 Ga, revealing a previously unrecognized Archean domain or domains in the central and western Mediterranean. Our observations indicate that ancient fragments of subcontinental lithospheric mantle have played an important role in the development of the present architecture of the Mediterranean lithosphere.

INTRODUCTION

Until now, the timing of formation and the evolution of the Iberian microplate has been constrained mainly from U-Pb ages of magmatic zircons, Hf model ages of inherited zircons, and whole-rock Nd model ages of crustal igneous and metamorphic rocks. However, there has been little robust information on the age of the lithospheric mantle beneath this continental crust; it is the missing key for a full understanding of the geological framework of the Iberian microplate. This gap has now been filled by determining the Re-Os systematics of sulfides in peridotite xenoliths that represent samples of this mantle. Because Re and Os preferentially concentrate in mantle sulfides, unlike those lithophile elements commonly used in other isotopic systems in the earth sciences, their isotopes are uniquely useful in tracking events of mantle melt depletion and refertilization.

In this work we use in situ laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICPMS) to study the Re-Os isotopic composition of sulfides in xenoliths from the Calatrava volcanic field in central Spain. The Calatrava volcanic field contains a suite of peridotite xenoliths from the lithospheric mantle underlying the crust of the Iberian microplate. Our results suggest that the mantle and crust constituting the Iberian microplate have coexisted since at least Paleozoic–Proterozoic time. The comparison of our data with Os-isotopic data from mantle-derived materials from other localities in central and western Europe and Africa allows us to examine the evolution and architecture of the European-Mediterranean mantle, revealing a heterogeneous mantle structure across the region and indicating the presence of a previously unrecognized Archean domain.

GEOLOGICAL SETTING AND SAMPLE BACKGROUND

The Calatrava volcanic field is an intracontinental zone within the Central Iberian Zone of central Spain, where upper crust only from Neoproterozoic time has been preserved. The volcanic field comprises ~200 small monogenetic volcanic centers. An initial minor ultrapotassic event at ca. 8.7–6.4 Ma was followed by the eruption of alkali basalts, basanites, and olivine nephelinites and melilitites from 3.7 to ca. 0.7 Ma that entrained abundant deep-seated xenoliths, dominantly spinel lherzolites of the Cr-diopside suite (after Wilshire and Shervais, 1975), and wehrlites and pblogopite-rich clinopyroxenites of the Al-augite series (Ancochea, 2004). These xenoliths record different types of metasomatism including carbonatitic, silica-undersaturated alkaline, and subduction-related styles (Villaseca et al., 2010; Bianchini et al., 2010; O'Reilly and Griffin, 2012).

The xenoliths studied here come from the El Aprisco (38°50′05″N, 3°50′00″W) olivine melilite maar (Villaseca et al., 2010). They are nine coarse-grained lherzolites and two wehrlites that equilibrated in the spinel facies (1.5–0.7 GPa) at temperatures of 1120–940 °C and contain accessory metasomatic minerals (amphibole, apatite, calcite). Interstitial glass commonly surrounds these metasomatic minerals and contains relics of them as well as incompletely reacted primary silicates and newly formed clinopyroxene, olivine, and spinel (Villaseca et al., 2010).

Sulfides (1–500 μm) were identified in polished thin sections; they are enclosed in olivine and pyroxenes, rarely at the triple junctions between the main silicates, and more commonly in the interstitial glass. Major-element analysis by electron microprobe shows that all the sulfides are Fe-rich monosulfide solid solution, with Fe >38.9 wt% and Ni contents >9.93 wt%. There is no difference in composition between included and interstitial sulfides.

RESULTS AND INTERPRETATION

In Situ Re-Os Model Ages on Mantle Sulfides

The Os-isotope compositions of over 800 individual sulfides ≥50 μm were measured in situ using LA-MC-ICPMS at the ARC Centre of Excellence for Core to Crust Fluid Systems/GEMOC (Macquarie University, Australia) following the procedures described by Pearson et al. (2002). In our data set, only grains with $^{187}Re/^{188}Os < 1.2$ were selected, thus ensuring an accurate correction of the isobaric overlap of ^{187}Re on ^{188}Os. In our analysis we disregarded grains with superchondritic $^{187}Os/^{188}Os$ (>0.1281; Walker et al., 2002) unsupported by their low Re/Os, which yielded geologically unreasonable future Re-Os model ages. Additionally, to ensure high-precision model-age constraints, we used grains only with propagated 2 S.E. analytical uncertainties on $^{187}Os/^{188}Os$ of <0.2 Ga (Table DR1 in the GSA Data Repository[1]).

The 68 sulfides from El Aprisco that meet these criteria have subchondritic $^{187}Os/^{188}Os$ (0.1147–0.1265) with $^{187}Re/^{188}Os$ varying from subchondritic (<0.358) to suprachondritic (0.432–0.572) (Fig. DR1 in the Data Repository; Table DR1). Only those sulfides with $^{187}Re/^{188}Os$ < 0.07–0.08 may preserve undisturbed isotopic signatures representative of mantle melting and/or refertilization events (Griffin et al., 2004). Only 12 of our sulfides display $^{187}Re/^{188}Os$ < 0.08 (italic font in Table DR1). A screening of the other 56 sulfides with $^{187}Re/^{188}Os$ > 0.08 in Re-Os isotope plots reveals that many of the sulfide grains show the effects of recent Re addition, probably associated with the magmatic activity that brought the xenoliths to the surface at ca. 2 Ma. As little or no ^{187}Os ingrowth has occurred since this recent Re enrichment, the T_{RD} of these sulfides (calculated assuming Re = 0 ppm) still provides useful minimum estimates of the timing of mantle events. For grains with $^{187}Re/^{188}Os$ > 0.08 but uncorrelated Re-Os, we have constructed two cumulative plots of Re-depletion model ages: one uses T_{RD} ages of sulfides with "undisturbed" $^{187}Os/^{188}Os$ (grains with $^{187}Re/^{188}Os$ < 0.08 as well as with $^{187}Re/^{188}Os$ > 0.08 lying on horizontal trends in Re-Os plots); the other uses only those grains with $^{187}Re/^{188}Os$ > 0.08 and uncorrelated Re-Os (Table DR1). The two plots produce identical distributions of age peaks. Therefore the T_{RD} obtained from all the 68 sulfide grains selected here can be used to unravel the evolution of the lithospheric mantle beneath Iberia.

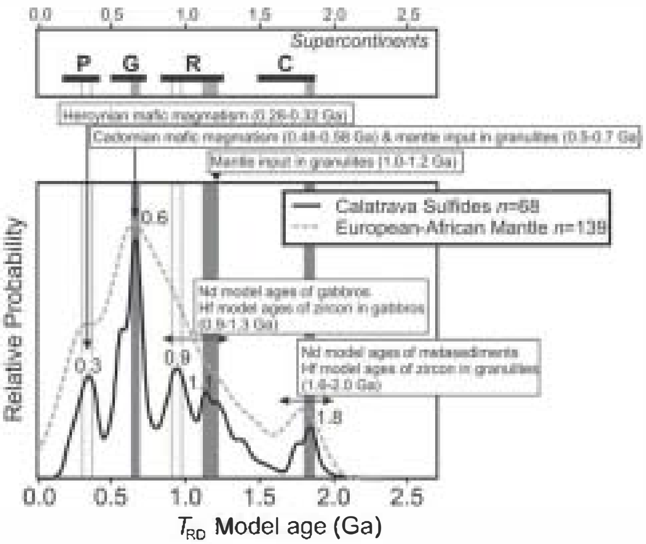

Figure 1. Cumulative-probability plot of Re-depletion model ages (T_{RD}) for El Aprisco (Spain) mantle sulfides of the Calatrava volcanic field (black solid line) compared with age intervals corresponding to events recorded in crust of central Iberia (see references in the text) and major events of supercontinent growth (P—Pangea, G—Gondwana, R—Rodinia, C—Columbia; see references in the Data Repository [see footnote 1]). Events of amalgamation or breakup of supercontinents recorded in the Iberian lithosphere are shown as gray or white dotted columns, respectively. A cumulative-probability curve of T_{RD} model ages for mantle-derived materials from both sides of the Mediterranean realm in central and western Europe and North Africa (gray dashed line) has also been included for comparison (see details in text and in the Data Repository for localities and references). Note that only positive T_{RD} are plotted, and in the case of whole-rock (or mineral-concentrate) results, only data compared against Al_2O_3 or other melt depletion indicators (e.g., Rudnick and Walker, 2009) were considered. To ensure comparison among all localities, T_{RD} were calculated with reference to Enstatite Chondrite Reservoir (Walker et al., 2002) and an uncertainty of 0.1 Ga was assumed for all single data points.

Origin and Evolution of the Iberian Lithosphere: A 1.8 b.y. History of Mantle-Crust Interactions and Supercontinent Assemblies

Figure 1 shows a strong coincidence between the five peaks (at 1.8, 1.1, 0.9, 0.6, and 0.3 Ga) in the distribution of T_{RD} model ages of the El Aprisco sulfides and the timing of well-constrained magmatic events recorded in the overlying crust of Iberia. Most of the ages are older than the exposed crust in the immediate area, implying the possible existence of older crust at depth. Interestingly, the three main peaks in the El Aprisco sulfides at 1.8, 0.6 and 0.3 are consistent with T_{RD} ages obtained for mantle-derived materials of comparable mantle suites on both sides of the Mediterranean realm (central and western Europe and North Africa). The smoother curve for the synthesized European-African mantle data largely reflects the number of intermediate model ages produced by the mixing of sulfide populations in individual whole-rock samples (Fig. 1).

The oldest Paleoproterozoic event (1.8 Ga) seen in the T_{RD} model ages of the El Aprisco sulfides (Fig. 1) correlates with whole-rock Nd model ages (1.7–2.0 Ga) of Neoproterozoic sediments (ca. 560 Ma) of the Central Iberian Zone (Villaseca et al., 1998) and Hf model ages (1.6–1.8 Ga) of inherited zircons from Hercynian granulites (which have lower Paleozoic to Neoproterozoic meta-igneous and metasedimentary protoliths) sampled in migmatite terranes and lower crustal xenoliths from the Central Iberian Zone (Villaseca et al., 2011a). The correspondence of mantle and crustal ages supports the suggestion that primary mantle differentiation and crustal growth in the Iberian lithosphere took place ca. 1.6–2.0 Ga. Reworking of this ancient lithosphere in the Neoproterozoic and Paleozoic may explain the four younger peaks in the sulfide T_{RD} model ages. Thus, the mantle event at ca. 0.6 Ga correlates with the 0.48–0.58 Ga mafic-to-silicic magmatism in the Central Iberian Zone associated with the Cadomian orogeny (Pereira et al., 2010; Bandrés et al., 2004). The involvement of the mantle is evidenced by juvenile Hf isotopic signatures (ε_{Hf} up to +9.7) of inherited zircons (U-Pb age 0.5–0.7 Ga) in the Hercynian granulites. Extensional decompression associated with delamination of lower-crustal rocks may have promoted upwelling and melting of the mantle following the Hercynian collision (Orejana et al., 2009). This would explain the correlation between the magmatic event at 0.3 Ga recorded in mantle sulfides and the silicic and mafic magmatism of both crustal and mantle origin recognized in the Central Iberian Zone at 0.28–0.32 Ga (Fernández-Suárez et al., 2000). Melt production in the mantle beneath Iberia at 0.9–1.3 Ga is reflected in T_{RD} model ages of 0.9–1.1 Ga in mantle sulfides, positive ε_{Hf} signatures (up to +12.8) of 1.0–1.2 Ga inherited zircon in Hercynian granulites (Villaseca et al., 2011a), Hf model ages of 0.9–1.2 Ga in magmatic zircons, and the Nd whole-rock model ages of 1.0–1.3 Ga in the Hercynian gabbros (297–306 Ma) that intruded the Central Iberian Zone (Fig. 1; Orejana et al., 2009; Villaseca et al., 2011b).

The alkaline (silicate to carbonatite) metasomatism observed in some xenoliths of the Calatrava volcanic field in the Tertiary may be responsible for the negative model ages of sulfides with highly radiogenic $^{187}Os/^{188}Os$ unsupported by low Re/Os ratios; these were excluded from this analysis.

Figure 1 shows that the formation of the Iberian lithosphere at ca. 1.6–2.0 Ga coincides with the first-order event of mantle-crust differentiation that occurred during the assembly of the supercontinent Columbia at 1.8–1.5 Ga. The 1.3–0.9 Ga timing of magmatic events recorded for both crustal and mantle materials in Iberia coincide with the amalgamation of Rodinia at ca. 1.25 Ga and its breakup at ca. 0.75 Ga. The peak in T_{RD} at 0.6 Ga correlates with the beginning of continental collisions to form Gondwana (ca. 0.65 Ga), whereas the T_{RD} age peak at 0.3 Ga may be correlated with post-tectonic stages and the initiation of the breakup of Pangea recorded in the Central Iberian Zone at ca. 0.26 Ga (Orejana et al., 2008).

Implications for the Architecture of the European-Mediterranean Lithosphere

Figure 2 shows that mantle-derived rocks on both sides of the Mediterranean realm (central

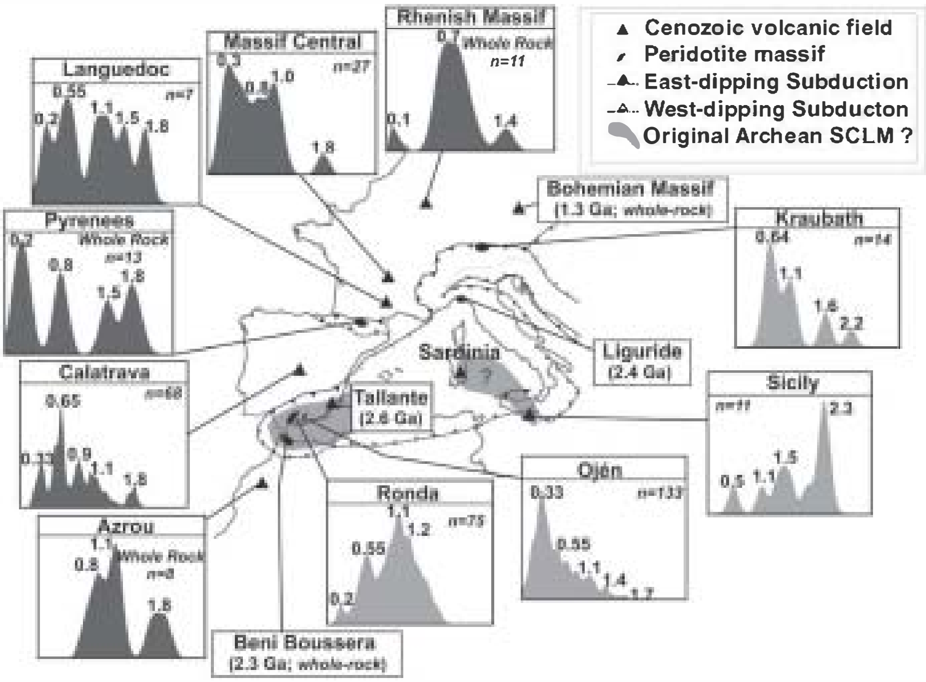

Figure 2. Cumulative-probability plots for Re-Os model ages of sulfides, platinum-group minerals, mineral concentrates, and whole-rock samples of xenoliths from Cenozoic volcanic fields and massifs in the central-western Mediterranean region (age peaks are in Ga; whole-rock ages are minimum ages). Gray fields refer to inferred original Archean subcontinental lithospheric mantle (details in text). SCLM—subcontinental lithospheric mantle. Note that in all cases, only positive Re-depletion model ages (T_{RD}) are shown, except for Beni Boussera (Morocco), for which the Re-Os model age presented is T_{MA}. Whole-rock and mineral-separate Os data were screened following the same criteria as in Figure 1. References for each locality are given in the Data Repository (see footnote 1).

and western Europe and North Africa) yield maximum $T_{RD} \leq 1.8$ Ga, whereas those from the inner Mediterranean region show both younger and older (up to 2.6 Ga) ages. Many sulfides in xenoliths from the mantle beneath western Europe (Calatrava, Languedoc, and Massif Central) show a common oldest peak at 1.8 Ga. This peak is also recognized in whole-rock samples from the Pyrenees (France) and Azrou (North Africa) but is slightly older than the oldest peaks at <1.4–1.3 Ga found in whole-rock samples from central Europe (Bohemian and Rhenish Massifs). Nevertheless, although these whole-rock ages were screened against indices of melt depletion in the rock (e.g., Al_2O_3; Rudnick and Walker, 2009), they must been seen as a guide and can only be regarded as minimum values as they may integrate multiple generations of sulfides (e.g., Alard et al., 2002; Griffin et al., 2004). All these data are consistent with the existence of a common Paleoproterozoic mantle on both sides of the Mediterranean realm, formed ca. 1.8 Ga as recorded in the other parts of the European basement.

In contrast, Os-bearing minerals from xenoliths and peridotite massifs from the inner Mediterranean region (Sicilian Hyblean Plateau, Kraubath ultramafic massif) show a common oldest T_{RD} peak at ca. 2.3 Ga, identical to the oldest whole-rock model age (T_{MA}) of 2.3 Ga obtained by Pearson and Nowell (2004) for pyroxenites of the Beni Boussera Massif in northern Morocco and the 2.4 Ga peak in primary magmatic sulfides from peridotites of the internal Ligurides (Italy) (Alard et al., 2005). A slightly older peak at 2.6 Ga has recently been reported by Konc et al. (2012) in sulfides from mantle xenoliths from the Tallante volcanic field in southern Spain. These ages clearly identify an older lithospheric mantle formed near the Archean-Paleoproterozoic boundary at ca. 2.2–2.6 Ga, sitting within the more recent Betics-Magbrebides-Appenines front (Fig. 2) generated during the Alpine-Betic orogeny.

Seismic, gravity, and heat-flow data suggest that the structure to 70 km beneath the Mediterranean Sea consists of ribbons of continental lithosphere (Valencia through the Balearic promontory, the Sardinia-Corsica block, and the Hyblean Plateau beneath Sicily) separated by areas of thinned subcontinental lithosphere or new oceanic crust (the Alboran, Liguro-Provençal, Vavilov, and Marsili Tyrrenian sea basins) (e.g., Gueguen et al., 1997; Booth-Rea et al., 2007). In the ribbon beneath Sicily, xenolith data suggest that thinned Archean continental crust overlies subcontinental mantle of the same age (Sapienza et al., 2007). Thus all of these continental ribbons and the subcontinental Archean-Paleoproterozoic mantle widespread through the Betics-Magbrebides-Appenines front may be the fragmented remnants of an Archean microcontinent within the inner Mediterranean area. The repetition of model age peaks at ca. 0.9–1.2, ca. 0.4–0.7, and ca. 0.3 Ga in the mantle both within and outside the central-western Mediterranean realm (Fig. 2) suggests that this microplate was strongly modified and fragmented (but survived) during supercontinent assembly-disruption cycles since Paleoproterozoic times.

In the context of convergence of Africa and Europe during the Tertiary, dismembered blocks of this ancient microplate could have spread, colliding with passive margins (Iberia, Maghrebide, Adria), thus contributing to the development of subduction-related volcanic arcs within the inner Mediterranean (Faccenna et al., 2004; Booth-Rea et al., 2007; Garrido et al., 2011; Carminati et al., 2012). We suggest that these major tectonic events have stripped off most of the old continental crust, leaving behind residues of ancient subcontinental mantle. This mantle, buoyant relative to the asthenosphere, would have continued to ride over the small-scale convective cells detected by seismic tomography at depths >200 km (O'Reilly et al., 2009; Faccenna and Becker, 2010), then become part of the oceanic basin and serve as the basement for the accumulation of oceanic basalts and sediments. An analogous process has been described in detail from the Internal Ligurides, where a typical Mesozoic oceanic volcanic-sedimentary section overlies the Archean mantle peridotites (Rampone et al., 2005). It is important to note that some portions of the Archean subcontinental lithospheric mantle within the inner Mediterranean were refertilized (Mg# = 89–90 of olivine in peridotite) by the passage of subduction-related fluids in the Cenozoic. However, these fluids were not able to erase the old Archean Re-Os signatures preserved in some sulfides (Marchesi et al., 2010).

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REFERENCES CITED

Alard, O., Griffin, W.L., Pearson, N.J., Lorand, J.-P., and O'Reilly, S.Y., 2002, New insights into the Re-Os systematics of sub-continental lithospheric mantle from in situ analysis of sulphides: Earth and Planetary Science Letters, v. 203, p. 651–663, doi:10.1016/S0012-821X(02)00799-9.

Alard, O., Luguet, A., Pearson, N.J., Griffin, W.L., Lorand, J.-P., Gannoun, A., Burton, K.W., and O'Reilly, S.Y., 2005, In situ Os isotopes in abyssal peridotites bridge the isotopic gap between MORBs and their source mantle: Nature, v. 436, p. 1005–1008, doi:10.1038/nature03902.

Ancochea, E., 2004, La región volcánica del Campo de Calatrava, *in* Vera, J.A., ed., Geología de España: Madrid, Geological Survey of Spain (IGME)–Geological Society of Spain (SGE), p. 676-677.

Bandrés, A., Eguíluz, L., Pin, C., Paquette, J.L., Ordóñez, B., Le Fèvre, B., Ortega, L.A., and Gil Ibarguchi, J.I., 2004, The northern Ossa-Morena Cadomian batholith (Iberian Massif): Magmatic arc origin and early evolution: International Journal of Earth Sciences, v. 93, p. 860–885, doi:10.1007/s00531-004-0423-6.

Bianchini, G., Beccaluva, L., Bonadiman, C., Nowell, G.M., Pearson, D.G., Siena, F., and Wilson, M., 2010, Mantle metasomatism by melts of HIMU piclogite components: New insights from Fe-lherzolite xenoliths (Calatrava Volcanic District, central Spain), *in* Coltorti, M., et al., eds., Petrological Evolution of the European Lithospheric Mantle: Geological Society of London Special Publication 337, p. 107–124.

Booth-Rea, G., Ranero, C.R., Martínez-Martínez, J.M., and Grevemeyer, I., 2007, Crustal types and Tertiary tectonic evolution of the Alborán sea, western Mediterranean: Geochemistry Geophysics Geosystems, v. 8, Q10005, doi:10.1029/2007GC001639.

Carminati, E., Lustrino, M., and Dogiloni, C., 2012, Geodynamic evolution of the central and western Mediterranean: Tectonics vs. igneous petrology constraints: Tectonophysics, doi:10.1016/j.tecto.2012.01.026 (in press).

Faccenna, C., and Becker, T.W., 2010, Shaping mobile belts by small-scale convection: Nature, v. 465, p. 602–605, doi:10.1038/nature09064.

Faccenna, C., Piromallo, C., Crespo-Blanc, A., Jolivet, L., and Rossetti, F., 2004, Lateral slab deformation and the origin of the western Mediterranean arcs: Tectonics, v. 23, TC1012, doi:10.1029/2002TC001488.

Fernández-Suárez, J., Dunning, G.R., Jenner, G.A., and Gutiérrez-Alonso, G., 2000, Variscan collisional magmatism and deformation in NW Iberia: Constraints from U-Pb geochronology of granitoids: Journal of the Geological Society, v. 157, p. 565–576, doi:10.1144/jgs.157.3.565.

Garrido, C.J., Gueydan, F., Booth-Rea, G., Precigout, J., Hydas, K., Padrón-Navarta, J.A., and Marchesi, C., 2011, Garnet lherzolite and garnet-spinel mylonite in the Ronda peridotite: Vestiges of Oligocene backarc mantle lithospheric extension in the western Mediterranean: Geology, v. 39, p. 927–930, doi:10.1130/G31760.1.

Griffin, W.L., Graham, S., O'Reilly, S.Y., and Pearson, N.J., 2004, Lithosphere evolution beneath the Kaapvaal Craton: Re-Os systematics of sulfides in mantle-derived peridotites: Chemical Geology, v. 208, p. 89–118, doi:10.1016/j.chemgeo.2004.04.007.

Gueguen, E., Doglioni, C., and Fernández, M., 1997, Lithosphere boudinage in the Western Mediterranean back-arc basin: Terra Nova, v. 9, p. 184–187, doi:10.1046/j.1365-3121.1997.d01-28.x.

Konc, Z., Marchesi, C., Garrido, C.J., González-Jiménez, J.M., Griffin, W.L., Alard, O., Hidas, K., O'Reilly, S.Y., and Pearson, N.J., 2012, Provenance and evolution of the western Mediterrauean lithospheric mantle beneath the eastern Betics (S. Spain): Insights from in-situ analyses of Os isotopes and platinum-group elements in sulphides from the Tallante mantle xenoliths: Geophysical Research Abstracts, v. 15, EGU12929.

Marchesi, C., Griffin, W.L., Garrido, C.J., Bodinier, J-L., O'Reilly, S.Y., and Pearson, N.J., 2010, Persistence of mantle lithospheric Re–Os signature during asthenospherization of the subcontinental lithospheric mantle: Insights from in situ isotopic analysis of sulfides from the Ronda peridotite (Southern Spain): Contributions to Mineralogy and Petrology, v. 159, p. 315–330.

O'Reilly, S.Y., and Griffin, W.L., 2012, Mantle metasomatism, *in* Harlov, D.E., and Austrheim, H., eds., Metasomatism and the Chemical Transformation of Rock: Lecture Notes in Earth System Sciences: Berlin, Springer-Verlag, p. 467–528, doi:10.1007/978-3-642-28394-9_12.

O'Reilly, S.Y., Zhang, M., Griffin, W.L., Begg, G., and Hronsky, J., 2009, Ultradeep continental roots and their oceanic remnants: A solution to the geochemical "mantle reservoir" problem?: Lithos, v. 112, p. 1043–1054, doi:10.1016/j.lithos.2009.04.028.

Orejana, D., Villaseca, C., Billström, K., and Paterson, B.A., 2008, Petrogenesis of Permian alkaline lamprophyres and diabases from the Spanish Central System and their geodynamic context within western Europe: Contributions to Mineralogy and Petrology, v. 156, p. 477–500, doi:10.1007/s00410-008-0297-x.

Orejana, D., Villaseca, C., Pérez-Soba, C., López-García, J.A., and Billström, K., 2009, The Variscan gabbros from the Spanish Central System: A case for crustal recycling in the subcontinental lithospheric mantle?: Lithos, v. 110, p. 262–276, doi:10.1016/j.lithos.2009.01.003.

Pearson, D.G., and Nowell, G.M., 2004, Re-Os and Lu-Hf isotope constraints on the origin and age of pyroxenites from the Beni Bousera peridotite massif: Implications for mixed peridotite-pyroxenite mantle sources: Journal of Petrology, v. 45, p. 439-455, doi:10.1093/petrology/egg102.

Pearson, N.J., Alard, O., Griffin, W.L., Jackson, S.E., and O'Reilly, S.Y., 2002, In situ measurement of Re-Os isotopes in mantle sulfides by laser ablation multicollector-indnctively coupled plasma mass spectrometry: Analytical methods and preliminary results: Geochimica et Cosmochimica Acta, v. 66, p. 1037–1050, doi:10.1016/S0016-7037(01)00823-7.

Pereira, M.F., Apraiz, A., Chichorro, M., Silva, J.B., and Armstrong, R.A., 2010, Exhumation of high-pressure rocks in northern Gondwana during the Early Carboniferous (Coimbra-Cordoba shear zone, SW Iberian Massif): Tectonothermal analysis and U-Th-Pb SHRIMP in situ zircon geochronology: Gondwana Research, v. 17, p. 440-460, doi:10.1016/j.gr.2009.10.001.

Rampone, E., Romairone, A., Abouchami, W., Piccardo, G.B., and Hofmann, A.W., 2005, Chronology, petrology and isotope geochemistry of the Erro-Tobbio peridotites (Ligurian Alps, Italy): Record of late Palaeozoic lithospheric extension: Journal of Petrology, v. 46, p. 799–827, doi:10.1093/petrology/egi001.

Rudnick, L.R., and Walker, R.J., 2009, Interpreting ages from Re-Os isotopes in peridotites: Lithos, v. 112, p. 1083–1095, doi:10.1016/j.lithos.2009.04.042.

Sapienza, G.T., Griffin, W.L., O'Reilly, S.Y., and Morten, L., 2007, Crustal zircons and mantle sulfies: Archean to Triassic events in the lithosphere beneath south-eastern Sicily: Lithos, v. 96, p. 503–523, doi:10.1016/j.lithos.2006.11.007.

Villaseca, C., Barbero, L., and Rogers, G., 1998, Crustal origin of Hercynian peraluminous granitic batholiths of central Spain: Petrological, geochemical and isotopic (Sr,Nd) arguments: Lithos, v. 43, p. 55–79, doi:10.1016/S0024-4937(98)00002-4.

Villaseca, C., Ancochea, E., Orejana, D., and Jeffries, T.E., 2010, Composition and evolution of the lithospheric mantle in central Spain: Inferences from peridotite xenoliths from the Cenozoic Calatrava volcanic field, *in* Coltorti, M., et al., eds., Petrological Evolution of the European Lithospheric Mantle: Geological Society of London Special Publication 337, p. 125–151.

Villaseca, C., Belousova, E., Orejana, D., Castiñeiras, P., and Pérez-Soba, C., 2011a, Presence of Palaeoproterozoic and Archean components in the granulite-facies rocks of central Iberia: The Hf isotopic evidence: Precambrian Research, v. 187, p. 143–154, doi:10.1016/j.precamres.2011.03.001.

Villaseca, C., Orejana, D., Belousova, E., Armstrong, R.A., Pérez-Soba, C., and Jeffries, T.E., 2011b, U-Pb isotopic ages and Hf isotope composition of zircons in Variscan gabbros from central Spain: Evidence of variable crustal contamination: Mineralogy and Petrology, v. 101, p. 151–167, doi:10.1007/s00710-010-0142-6.

Walker, R.J., Horan, M.F., Morgan, J.W., Becker, H., Grossman, J.N., and Rubin, A.E., 2002, Comparative ^{187}Re-^{187}Os systematics of chondrites: Implications regarding early solar system processes: Geochimica et Cosmochimica Acta, v. 66, p. 4187-4201, doi:10.1016/S0016-7037(02)01003-7.

Wilshire, H.G., and Shervais, J.W., 1975, Al-augite and Cr-diopside ultramafic xenoliths in basaltic rocks from western United States: Physics and Chemistry of the Earth, v. 9, p. 257–272.