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Enriched mantle source for the Central Atlantic magmatic province: New supporting evidence from southwestern Europe

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A B S T R A C T

Remnants of the Central Atlantic magmatic province (CAMP), emplaced ca. 201 Ma during the rifting phases leading to Pangaea breakup, are still preserved in southwestern Europe (SWE) in the form of sills, dykes and lava flows. Low–Ti (TiO_2 0.48–1.46 wt.%) tholeiitic basalts and basaltic andesites crop out as sills only in the Pyrenean area, as dykes (especially the Messejana–Plasencia dyke) from central Spain to the Atlantic coast, and as lava flows within sedimentary basins in Southern Portugal. Here we present new geochemical data (major and trace elements, mineral chemistry and combined Sr–Nd–Pb–Os analyses) on 132 samples, aiming to investigate the mantle source of these rocks and correlate them with magmatism from other areas of the CAMP. Crustal-like signatures in incompatible element patterns (Nb–Ta troughs, Pb peaks, generally shared by most CAMP rocks) and the enriched Sr–Nd–Pb isotopic characters ($^{87}Sr/^{86}Sr_{200\ Ma}$ 0.70529–0.70657; $^{143}Nd/^{144}Nd_{200\ Ma}$ 0.51238–0.51225; $^{206}Pb/^{204}Pb_{200\ Ma}$ 18.15–18.48; $^{207}Pb/^{204}Pb_{200\ Ma}$ 15.57–15.68; $^{208}Pb/^{204}Pb_{200\ Ma}$ 37.99–38.52) apparently argue in favor of crustal assimilation playing an important role in the evolution of these magmas. However, the low initial $^{187}Os/^{188}Os$ values (0.1298 ± 0.0056) as well as the restricted geochemical variations shown by SWE-CAMP rocks over such a large area limit the crustal assimilation of various Iberian lithologies to small amounts. We thus locate this enrichment in the mantle source, in the form of upper and lower crustal material recycled during earlier subduction-related events. This process, while imparting crustal signatures to incompatible elements and Sr–Nd–Pb isotopes, would not alter the Os isotopic signature, dominated by the peridotite. The mixed contribution of 3–7% of local upper (pelitic) and lower (felsic granulitic) crust is sufficient to enrich a depleted mantle source, which can be either the sub-SWE lithosphere or the upper depleted asthenosphere. Similar processes of crustal recycling within the upper mantle have been recognized to be responsible for the mantle source enrichment in other areas of the CAMP (Eastern North America). Geochemical correlations of the here studied tholeiites with CAMP rocks from other areas inscribe European basalts within the main pulse of CAMP magmatism.

A subset of samples from Southern Portugal (here defined high-Sr dykes) shows different major and trace element geochemistry (e.g. Sr and CaO enrichment, SiO_2 depletion) as well as more radiogenic $^{87}Sr/^{86}Sr_{200\ Ma}$ (0.70669–0.70749) and Pb isotopic ratios (e.g., $^{206}Pb/^{204}Pb_{200\ Ma}$ 18.55) at similar $^{143}Nd/^{144}Nd_{200\ Ma}$ (0.51232–0.51224). This reflects a different magmatic evolution for these rocks, dominated by the late-stage assimilation of 10–20% local carbonates.

1. Introduction

Crustal recycling processes (Chauvel et al., 2009) in the lower (Willbold and Stracke, 2006) or upper (Prelević et al., 2013) mantle have recently drawn growing attention both in the perspective of

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investigating global geodynamics and of unraveling the mantle source of Large Igneous Provinces (LIPs; Melluso et al., 2006; Sobolev et al., 2011). In this study we investigate the ca. 200 Ma basaltic rocks from south-western Europe (France, Spain, Portugal) which are part of the Central Atlantic magmatic province (CAMP; Marzoli et al., 1999) and propose that they originated from a mantle source enriched by recycled crustal rocks during previous subduction processes rather than from a plume-related source (e.g. McHone, 2000; Puffer, 2001).

Following approximately 25 Ma of rifting (Schlische et al., 2003), the breakup of supercontinent Pangaea was heralded by a widespread tholeiitic magmatic event which occurred at the Triassic–Jurassic boundary, centered on the Central Atlantic rifting zone. Today scattered in four continents, the tholeiites initially covered about 11×10^6 km^2 (McHone, 2000), making the CAMP the largest known basaltic LIP on Earth.

Here we investigate the geochemistry of the European offshoot of the CAMP, cropping out along the Iberian Peninsula and southern France (southwestern Europe, SWE) as dykes, sills, lava flows and pyroclastic deposits. We present the first Os isotopic data and new Sr–Nd–Pb isotopic determinations for the SWE-CAMP. These data, along with complementary elemental and mineral chemistry, are here used to define the mantle source of these tholeiites and to compare and correlate them with other studied areas of the CAMP, in the aim of contributing to a better understanding of the genesis of this LIP.

2. Tectonic and lithostratigraphic evolution of southwestern Europe (late Paleozoic to late Triassic)

CAMP remnants in southwestern Europe are preserved within the Armorican and Aquitanian terranes (France) and the Iberia micro-plate (Spain–Portugal), whose tectonostratigraphy results from the overlapping effects of the Cadomian and Variscan orogenies (e.g., Ribeiro et al., 2007 and references therein). The Permian evolution that followed the Variscan amalgamation was strongly constrained by lithospheric weaknesses represented by steeply dipping NNE–SSW and E–W crustal structures (leading to the development of extensional basins) and was marked by the intrusion of abundant S- and I-type granitoids at 300–280 Ma and late stage Upper Permian alkaline basic magmatism (Bea et al., 1999; Villaseca et al., 1998, 2009). The SWE area inherited Hercynian structural patterns with a general E–W trend (e.g., the NW Pyrenean and the Gibraltar fault zones; Manspeizer, 1994) and dextral strike-slip movements, while subsequent Triassic extension produced subsiding basins filled by continental red sandstones and shales of the Silves Formation (Carnian?–Norian) followed by sabkha-type evaporite deposits and terrigenous sediments of the Dagorda Formation (Norian–Hettangian; Azerêdo et al., 2003; Gómez et al., 2007). The volcanic products of the Portuguese CAMP are intercalated within the Dagorda Formation, whereas the wall rocks of the Pyrenean sills are represented by Norian sediments of the Isabena Formation (Arnal et al., 2002) or by Keuper salt diapirs. The Central Atlantic rift developed an asymmetric geometry and during the early Mesozoic continental stretching several distinct basins formed along the present-day West Iberian Margin. Extensional faults related to rifting controlled the geometry and subsidence history of these basins, whose evolution was marked by somewhat distinct tectonostratigraphic histories (e.g., Pereira and Alves, 2011). Most of these basins, currently found either off-shore or on-shore, roughly define a N–S alignment (Alentejo, Lusitanian, Peniche and Galicia). The Algarve basin developed almost perpendicularly as a pull-apart basin related to left-lateral transtensional shear zone separating Iberia from Africa as a consequence of the relative eastward drift of Africa (e.g. Terrinha et al., 2002). In this extensional scenario, ultimately leading to the opening of the Central Atlantic Ocean, such basins suffered several rifting episodes. CAMP magmas were emplaced during the second rifting episode identified by Pereira and Alves (2011) during the transition from continental to marine influenced sedimentation.

3. CAMP in southwestern Europe (SWE-CAMP)

European CAMP crops out in a pattern typical of this magmatic province elsewhere (McHone, 1996), where frequent dyke swarms/groups are accompanied by a few isolated but very large dykes, and minor occurrences of sills and volcanic extrusions (lava flows and pyroclastic deposits), preserved in basinal volcano-sedimentary series. The samples for this study ($n = 132$) were collected in Spain, Portugal and France (sampling sites in Fig. 1; further outcrop description and sampling details are included in the Supplementary material).

CAMP dykes emplaced across the SWE are epitomized by the 530 km long, 5–200 m thick Messejana–Plasencia dyke (Bertrand and Millot, 1987; Cebriá et al., 2003; Sebai et al., 1991), trending NE–SW across the Iberian Peninsula from Central Spain to southwestern Portugal (61 samples; sites 17 to 32) and intruding the local metapelitic and granitic basement. Other smaller dykes, generally referred to as coastal dykes, crop out in Brittany (north-western France; Jourdan et al., 2003; Marzoli et al., 2014; not sampled) and in Southern Portugal where they are either roughly coast-parallel, N–S trending or parallel to the Messejana dyke (3 samples; sites 33 to 35).

Sills and lava flows are instead enclosed within more restricted areas. Numerous sills (27 samples; sampling sites 1–16) occur along most of the Pyrenean chain within the Aquitanian basin (France) and within the Cantabrian range (Spain). The lava flows crop out in volcano-sedimentary sequences (up to 8 flows, total thickness up to 130 m) in the E–W trending Triassic–Jurassic basin of Algarve, Southern Portugal (28 samples; sites 36 to 45), and in a narrow N–S basin of similar age (Santiago do Cacém basin, Alentejo; 2 samples; sites 46 and 47). Strongly altered lava flows were also observed in the southern edge of the Lusitanian Basin (Sesimbra region; not sampled).

Several thin dykelets (<1 m thick; 11 samples; sites 35–47) attributed to a late event crosscut the Portuguese extrusive sequence and were also sampled. They trend E–W to N110E (parallel to the orientation of the basins), though their distinction from the lava flows is often difficult. These dykes, along with 2 lava flows, are grouped together in this work as high-Sr dykes, due to their geochemistry (Sr > 230 ppm; CaO > 12.5 wt.%; see Sections 7.2 and 7.3), as was also previously observed by Martins et al. (2008), who referred these basalts to as high-Ca rocks.

4. Methods

Major and trace element compositions of the SWE-CAMP rocks were analyzed by X-ray fluorescence (XRF) at the Centre d'Analyses Minéralogiques, University of Lausanne (CH; Phillips PW1400; OF, MD and AL samples), at the University of Lyon (FR; Phillips PW1400; P or E samples) or at the University of Padova (IT; Philips PW2400; PIM samples). Trace elements were analyzed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) at the École Normale Supérieure of Lyon (FR) or at the University of Grenoble (FR). Mineral major element compositions were analyzed at Lausanne or at the IGG-CNR Padova (Italy) on a Cameca SX50 electron microprobe.

Sr–Nd–Pb isotopic compositions were determined using a Thermo-Ionization Mass Spectrometer (TIMS; Finnigan MAT262) at the University of Geneva (CH; OF, MD, AL, E and P samples) or at the Laboratory of Isotopic Geology at the Universidade de Aveiro (PT; PIM samples) after leaching and cascade chemical separation from a unique sample aliquot.

Re and Os concentrations (by isotopic dilution) and Os isotopic compositions were analyzed at the CRPG-CNRS of Nancy (France) by negative thermal ionization mass spectrometry (NTIMS; Finnigan MAT262). Re isotopic compositions for isotope dilution calculations were measured by ICPMS (Micromass Isoprobe).

After irradiation in the CLICIT facility of the TRIGA reactor at Oregon State University (U.S.A.), plagioclase separates were analyzed for $^{40}Ar/^{39}Ar$ at the Geoscience Azur laboratory of Nice (FR) by laser step-heating under a Coherent Innova 70-4 continuous argon-ion