Flow of Canary mantle plume material through a subcontinental lithospheric corridor beneath Africa to the Mediterranean

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ABSTRACT

We present geochemical data of lavas from northwest Africa, allowing us for the first time to carry out large-scale "mapping" of sublithospheric mantle flow beneath the northwest African plate. Our study indicates that Canary mantle plume material traveled laterally along a subcontinental lithospheric corridor (i.e., at depths that are usually occupied by continental lithospheric mantle) more than 1500 km to the western Mediterranean, marking its route over the last 15 m.y. through a trail of intraplate volcanism. A three-dimensional geodynamic reconstruction, integrating results from geophysical studies, illustrates that long-distance lateral flow of mantle material into and through a subcontinental lithospheric corridor can be caused by a combination of (1) deflection of upwelling plume material along the base of the lithosphere, (2) delamination of subcontinental mantle lithosphere beneath northwest Africa, and (3) subduction suction related to the rollback of the subducting oceanic plate in the western Mediterranean. Although the flow of plume material beneath oceanic lithosphere to mid-ocean ridges or along the base of continental rifts has been previously shown, this study demonstrates that plume material can also flow large lateral distances through subcontinental corridors from suboceanic to nonrifting subcontinental settings, generating continental intraplate volcanism without the need for a plume to be located directly beneath the continent.

INTRODUCTION

The oceanic and continental parts of the northwest African plate host areas with Neogene igneous activity (Lustrino and Wilson, 2007), linked to different geodynamic processes. In the eastern Atlantic Ocean, Canary Islands volcanism is associated with well-resolved low P- and S-wave seismic tomographic velocity anomalies, extending to the core-mantle boundary (see Montelli et al., 2006, including their summary of other seismic tomographic models). The Canary Islands and seamounts to the northeast have intraplate geochemical compositions and form a volcanic chain with a northeast to southwest age progression over the last 70 m.y. (Fig. 1A) (Geldmacher et al., 2005; Hoernle and Schmincke, 1993; Hoernle et al., 1991; Lundstrom et al., 2003). The age progression can be explained by movement of the lithosphere above a deeper upwelling using the same Euler pole and angular plate velocity as other volcanic chains in the Atlantic Ocean. Although other models have been proposed to explain the Canary Islands volcanism (e.g., see summaries in Anguita and Hernan, 2000, and Lustrino and Wilson, 2007), the plume hypothesis can best explain the geophysical, geochemical, and geological constraints (Geldmacher et al., 2005; Hoernle and Schmincke, 1993; Hoernle et al., 1991; Lundstrom et al., 2003).

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In northwest Africa, mafic Neogene intraplate volcanism is found in the Atlas system and along the Mediterranean coast (volcanic fields Siroua, Saghro, Middle Atlas, Guilliz, Gourougou, and Oujda-Oranie; Fig. 1A) (Lustrino and Wilson, 2007). The Atlas Mountains extend from the passive Atlantic-African continental margin adjacent to the Canary Islands to the Mediterranean coast and represent an inverted, failed rift system, formed during the opening of the central Atlantic in the early Mesozoic. Over the past 45 m.y., the former rift was deformed due to compression during the collision of the African and European plates (Gomez et al., 2000). Removal (delamination) of subcontinental mantle lithosphere is proposed to result from the collision of these major plates and to be responsible for intermediate-depth earthquakes and volcanism in the Atlas system (Ramdani, 1998).

Elevated topography, high heat flow, and gravity and geoid anomalies point to the existence of an abnormally shallow lithosphere-asthenosphere boundary beneath the western part of the Atlas system (60–80 km, compared to 130–160 km for normal northwest African lithospheric thickness), as illustrated on six lithospheric profiles across northwest Africa (Urchulutegui et al., 2006; Missenard et al., 2006; Teixell et al., 2005) (Fig. 1). The region of abnormally thin lithosphere forms a northeast-striking subcontinental lithospheric corridor beneath northwest Africa that is ~80–120 km high and ~200–300 km wide and extends from the passive continental margin near the Canary Islands to at least the Middle Atlas (Fig. 1).

The geodynamic evolution of the westernmost Mediterranean is complex, but Miocene subduction rollback of old Tethys oceanic lithosphere, causing progressive delamination (peeling off) of subcontinental lithospheric mantle ca. 8–10 Ma (continental-edge delamination), affected both the lithospheric thickness and mantle flow beneath northern Morocco (Duggen et al., 2003, 2005; Gutscher et al., 2002).

The geochemical composition of lavas from the northwest African plate can provide important information about their sources and processes in the upper mantle. We present new major and trace element and Sr-Nd-Pb-isotopic data from mafic Middle Atlas lavas (Tables DR1 and DR2 and details about analytical methods are found in the GSA Data Repository[1]) and integrate these with published geochemical and geophysical results from other (volcanic) areas on the northwest African plate. This study allows the northwest African upper mantle composition to be mapped for the first time and provides new constraints for mantle flow and the origin of continental intraplate volcanism.

RESULTS AND DISCUSSION

Composition of the Upper Mantle Beneath the Northwest African Plate

Mafic lavas with intraplate geochemical signatures on the northwest African plate are interpreted to be derived from sublithospheric mantle sources by low-degree partial melting (Duggen et al., 2005; El Azzouzi et al., 1999; Geldmacher et al., 2005; Hoernle and Schmincke, 1993; Hoernle et al., 1991, 1995; Lundstrom et al., 2003; Lustrino and Wilson, 2007). Mafic igneous rocks from the Middle Atlas have trace element patterns similar to those from the Canary Islands (Fig. 2) and show a similar range of elevated Dy/Yb and Zr/Hf ratios and high FeO but relatively low SiO_2. For the Middle Atlas and the Canary Islands, respectively, Dy/Yb = 2.8–3.4

[1]GSA Data Repository item 2009071, Tables DR1 (major and trace element data) and DR2 (Sr-Nd-Pb-isotope data), and details about analytical methods, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

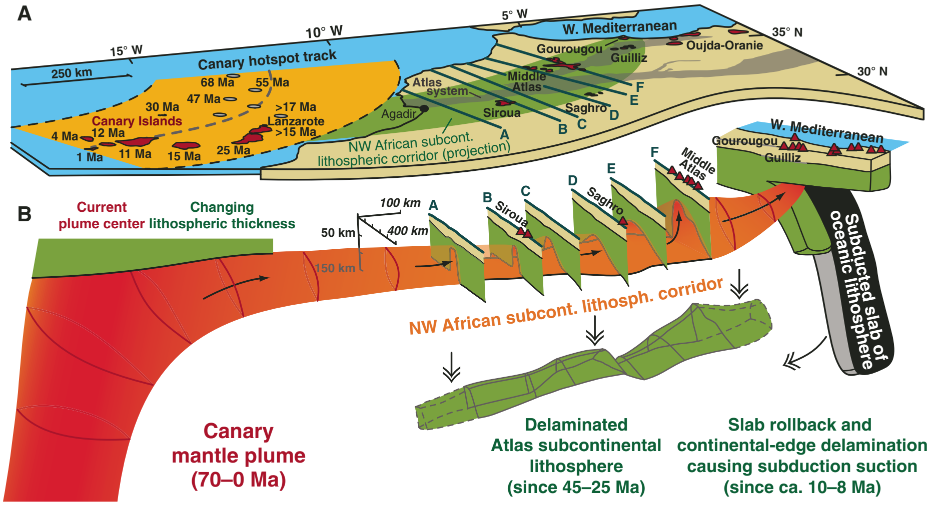

Figure 1. Map of the northwest African plate (A) and flow of Canary mantle plume material under northwest Africa through a subcontinental lithospheric corridor in a three-dimensional model (B). A: The orange area displays the Canary hotspot track on the oceanic side of the northwest African plate with ages of the oldest lavas from each island (red areas) or seamount (gray circles), indicating a southwest-directed age progression and the location of the current plume center beneath the western Canary Islands (Geldmacher et al., 2005). Also shown are the Atlas Mountains (gray field), location of the northwest African subcontinental lithospheric corridor in green, inferred from profiles (A–F) based on geophysical data (Urchulutegui et al., 2006; Missenard et al., 2006; Teixell et al., 2005), and northwest African Neogene continental intraplate volcanic fields. B: The three-dimensional model illustrates how Canary mantle plume material flows along the base of the oceanic lithosphere that thins to the east (Neumann et al., 1995) and into the subcontinental lithospheric corridor beneath the Atlas system, reaching the western Mediterranean. Plume push, eastward-thinning lithosphere, delamination of northwest African subcontinental lithosphere, and subduction suction related to rollback of the subducting slab in the Mediterranean are proposed to be the main mechanisms for causing Canary plume material to flow ≥1500 km to the northeast.

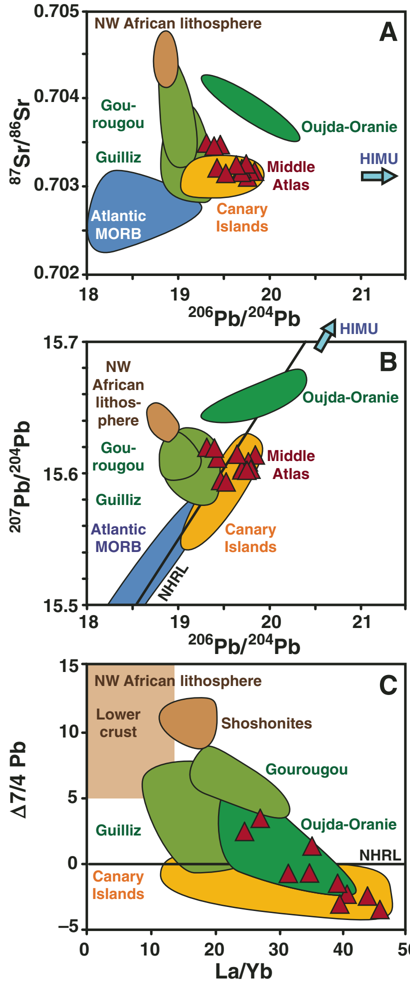

Figure 3. Geochemical diagrams with radiogenic isotope and trace element ratios, illustrating variable mixing between sublithospheric melts with northwest African continental lithospheric material. Mafic intraplate lavas from the Middle Atlas volcanic field (this study) and from the Guilliz and Gourougou volcanic fields (Duggen et al., 2005) point to a sublithospheric mantle source similar to that of the Canary Islands volcanism (Canary mantle plume material). Oujda-Oranie intraplate lavas indicate a similar African lithospheric contaminant but were derived from a different sublithospheric mantle source and don't appear to involve Canary plume material. The isotopic composition of the mafic lavas are age-corrected values (e.g., 12 Ma for three lavas from the southwestern Middle Atlas volcanic field and 1 Ma for lavas for the remainder according to Harmand and Cantagrel, 1984, otherwise as found in the cited literature). Other data sources are intraplate mafic lavas from the Canary Islands (Lundstrom et al., 2003; Widom et al., 1999) and the continental volcanic fields Gourougou, Guilliz, and Oujda-Oranie (Duggen et al., 2005); Moroccan (Gourougou) shoshonites (Duggen et al., 2005); Middle Atlas lower crustal granulites (La/Yb from Moukadiri and Pin, 1998, Δ7/4Pb estimated); Δ7/4 is the vertical deviation from the Northern Hemisphere Reference Line (NHRL) (Hart, 1984); high time-integrated $^{238}U/^{204}Pb$ (HIMU) (Zindler and Hart, 1986).

and 2.8–3.6, Zr/Hf = 37–56 and 34–49, FeO = 11.1%–12.1% and 10.9%–14.2%, and SiO_2 = 38.4%–45.5% and 36.9%–49.8% (Hoernle and Schmincke, 1993; Lundstrom et al., 2003) (Table DR1). Combined with petrological melting experiments, these data argue for the presence of garnet-peridotite and/or -pyroxenite in their mantle source(s) and melting depths on the order of 60–120 km (Hirschmann and Stolper, 1996; Kogiso et al., 1998; Lundstrom et al., 2003), i.e., at depths that are normally occupied by subcontinental lithosphere.

Some northwest African sublithospheric melts have interacted with the overlying lithosphere (Duggen et al., 2005; El Azzouzi et al., 1999; Lundstrom et al., 2003). Isotope (Sr-Nd-Pb) and trace element ratios (e.g., La/Yb and K/La) of the northwest African intraplate lavas form correlations converging at elevated $^{87}Sr/^{86}Sr$, Δ7/4Pb, $^{208}Pb/^{204}Pb$, and La/Yb ratios (e.g., Figs. 3A–3C). These systematics can be explained by interaction of sublithospheric melts, characterized by relatively high $^{206}Pb/^{204}Pb$ but low $^{87}Sr/^{86}Sr$, Δ7/4Pb and La/Yb ratios, with northwest African lithosphere, including metasomatized lithospheric mantle or melts therefrom (e.g., shoshonitic components) and the lower crust (e.g., Atlas lower crustal granulites) (Fig. 3).

The mixing trends also provide important constraints on the composition of the sublithospheric

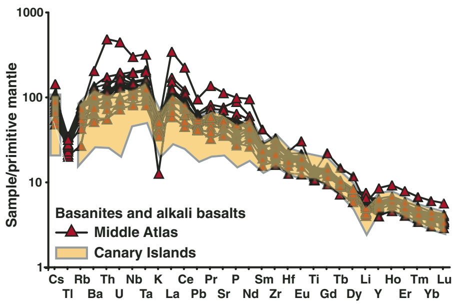

Figure 2. Incompatible trace element diagram showing the similarities in incompatible trace element concentrations of mafic lavas from the Middle Atlas (this study) and the Canary Islands (field defined by n = 36 basanites to alkali basalts with MgO > 8 wt% [Lundstrom et al., 2003] normalized to primitive mantle composition [Sun and McDonough, 1989]).

mantle source from each volcanic area on the northwest African plate. The least-contaminated lavas (low $^{87}Sr/^{86}Sr$, low Δ7/4Pb) of the Middle Atlas, Guilliz, and Gourougou volcanic fields overlap with the field of Canary Islands lavas. The similarity in trace element and radiogenic isotopic composition of the least-contaminated lavas from the northwest African continent (Figs. 2 and 3) suggests that these lavas share a common sublithospheric mantle source with lavas from the oceanic Canary Islands. Mafic lavas from the Oujda-Oranie volcanic field due east of Guilliz and Gourougou, however, define an independent mixing trend. The mixing trend indicates that the lithospheric contaminant is the same but that a different sublithospheric mantle source with a more radiogenic Pb-isotopic composition (Fig. 3) underlies Oujda-Oranie, constraining the eastern boundary of the Canary-type mantle.

Evidence for Flow of Canary Mantle Plume Material Through a Subcontinental Lithospheric Corridor Beneath Northwest Africa

Although the geochemical data indicate a common sublithospheric mantle source for the Neogene lavas from the Canary Islands, Middle Atlas, Guilliz, and Gourougou areas, the continental northwest African volcanic fields are not part of the Canary hotspot track. The age-progressive hotspot track is restricted to the oceanic part of the northwest African plate and is associated with a major mantle upwelling, currently located beneath the western Canary Islands at the southwestern end of the age-progressive hotspot track (Fig. 1). Although older seismic tomographic studies suggested that mantle upwelling beneath the easternmost central Atlantic may also extend beneath the western Mediterranean and Europe (Hoernle et al., 1995), newer studies show that well-resolved positive P- and S-wave seismic anomalies beneath the Canary Islands (≤400 km in diameter) do not extend beneath northwest Africa at depths of 300 and 600 km, ruling out an exceptionally wide Canary plume and suggesting that there is not deep upwelling directly beneath northwest Africa (Montelli et al., 2006). Volcanic rocks with Canary Islands–type geochemical compositions are furthermore restricted to areas above the lithospheric channel in Morocco (Middle Atlas, Guilliz, and Gourougou), whereas those not above the sublithospheric channel (e.g., Oujda-Oranie) have distinct isotopic compositions, indicating a relationship between Canary-like geochemistry and the subcontinental lithospheric corridor (Fig. 3). The geochemical and geophysical constraints now available suggest that Canary mantle plume material only flowed laterally beneath northwest Africa through a lithospheric corridor, causing continental intraplate volcanism above it.

An interplay of several mechanisms may be responsible for the >1500 km lateral flow of plume material from the Canary hotspot to the Mediterranean. First, active mantle upwelling can cause plume material to spread out laterally along the base of the lithosphere through plume push. Thinning of the lithosphere will further enhance the flow of plume material along its base to areas of thinner lithosphere (Sleep, 2008). It has been proposed that the lithosphere beneath the easternmost Canary island (Lanzarote) is thinner than beneath the more western islands based on petrological data from mantle xenoliths (Neumann et al., 1995). It has also been proposed that Canary plume material flows toward the northwest African continental margin along the base of the lithosphere following the hotspot track, possibly within a corridor formed by thermal erosion of the base of the oceanic lithosphere as it moved over the plume (Geldmacher et al., 2005; Hoernle and Schmincke, 1993; Hoernle et al., 1991; Lundstrom et al., 2003). Plume push in combination with eastward thinning of the oceanic lithosphere can explain the flow of mantle material from the plume center, located under the western Canary Islands, to beneath the eastern Canary Islands and into the southwestern end of the subcontinental lithospheric corridor (Fig. 1).

Second, delamination of subcontinental lithosphere beneath the northwest African Atlas system (Ramdani, 1998) is likely to be responsible for the existence of the subcontinental lithospheric corridor (Fig. 1B). Delamination could have been caused by the inferred shortening of 17%–45% and thickening of a lithospheric root, resulting from the African-European collision (since the early Miocene and most likely since ca. 45 Ma) (Gomez et al., 2000). Since the Atlas Mountains comprise an inverted failed rift system (Gomez et al., 2000), we propose that Mesozoic rifting may have weakened the Atlas mantle lithosphere, making it more susceptible to delamination during the subsequent African-European collision. Removal of subcontinental lithospheric mantle and formation of a lithospheric corridor could have drawn Canary plume material into the lithospheric channel under the Atlas system, eventually widened by thermal erosion related to the flow of Canary mantle through the corridor (Fig. 1B). The process can also explain why sublithospheric melts were generated at 60–120 km melting depths (as inferred above), although normal northwest African lithospheric thickness is on the order of 130–160 km.

Third, it has been proposed that rollback subduction of Tethys oceanic lithosphere beneath the westernmost Mediterranean triggered delamination of subcontinental lithosphere beneath the northern edge of Morocco since 8–10 Ma (Duggen et al., 2005). The inflow of sublithospheric mantle may have generated intraplate volcanism in the Guilliz and Gourougou areas. Recently trench-parallel/arc-parallel mantle flow in the mantle wedge has been demonstrated with both geochemical and geophysical techniques and has been shown to be associated with trench retreat/rollback (and advance), such that the retreating plate causes lateral flow of mantle into the area from which it has retreated (Faccenna et al., 2005; Hoernle et al., 2008; Long and Silver, 2008). Combined slab rollback and continental-edge delamination could therefore have caused suction of material from the Middle Atlas area toward the westernmost Mediterranean (Fig. 1B). Horizontal flow of the Canary plume material beneath northwest Africa is likely to have terminated beneath the Gourougou volcanic field adjacent to the Mediterranean coast, since Miocene volcanism in the westernmost Mediterranean basin has a geochemical signature typical of subduction zone lavas, and intraplate volcanism in this area is absent (Duggen et al., 2008). As noted above, mafic lavas from the nearby Oujda-Oranie volcanic field, which do not lie above the subcontinental lithospheric corridor, do not show a geochemical affinity to the Canary lavas (Fig. 3), indicating that they are not derived from Canary plume material.

It has been shown that flow of mantle plume material can take place beneath oceanic lithosphere to mid-ocean ridges (Schilling, 1973) or along the base of continental rifts (Ebinger and Sleep, 1998). Our study demonstrates that plume material can flow large lateral distances from suboceanic to nonrifting subcontinental settings through subcontinental corridors also, causing continental intraplate volcanism without the need for a plume to be located directly beneath the continent.

Anomalously Voluminous Volcanic Events on the Northwest African Plate and Other Surface Expressions of the Mantle Processes

The Middle Atlas hosts the most voluminous Neogene volcanic field in northwest Africa (Fig. 1A). Based on geophysical data, the subcontinental lithospheric corridor is widest and shallowest under the Middle Atlas region (Fig. 1B, profile F). Inflow of Canary mantle material into the widening and shallowing subcontinental lithospheric corridor can explain why the most voluminous igneous episode of the northwest African continent in the past million years took place in the Middle Atlas: A greater vertical component of flow combined with greater amounts of material at wider and shallower parts of the corridor will result in greater amounts of mantle material undergoing decompression partial melting, producing larger magma volumes.

Geophysical data suggest that ~50% of the present thickening and elevation of the Atlas Mountains results from buoyant sublithospheric material (Teixell et al., 2005), indicating that the inflow of Canary mantle plume material into the lithospheric corridor is an ongoing process and may be directly contributing to the high elevation of the Middle Atlas. The inflow of Canary mantle, causing uplift of the overlying lithosphere, may thus partly be responsible for the devastating 1960 earthquake in Agadir (Fig. 1A) that killed about a third of the city's population and left most of the remainder homeless (Meghraoui et al., 1998). Finally, the mechanism also provides an explanation for the long-standing riddle as to why the secondlargest recorded tholeiitic eruption occurred on one of the oldest Canary islands (A.D. 1730–1736 Lanzarote Timanfaya fissure eruption) (Carracedo et al., 1992). Without flow of Canary mantle plume material into the northwest African subcontinental lithospheric corridor, volcanism on the easternmost Canary Islands is likely to have been extinct long ago or at most to have generated only minor volumes of lava.

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