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A revised thermal history of the Ronda peridotite, S. Spain: New evidence for excision during exhumation

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ABSTRACT

The Ronda peridotite massif of southern Spain exposes subcontinental lithospheric mantle that records pressure–temperature data and microstructures formed during exhumation beneath the rapidly extending Alboran domain. The peridotite is zoned from garnet- and spinel-bearing mylonites at the structural top, to spinel-bearing tectonites, to melt-percolated spinel-bearing granular peridotites, to plagioclase-bearing tectonites at the structural base. We find microstructural evidence of melt present in the spinel zones prior to the deformation event which exhumed the peridotites, and we therefore reinterpret the spinel tectonites as being a result of deformational overprinting of part of the granular domain. We also reinterpret garnet intergrown with spinel in the mylonite zone as part of the pre-mylonitic porphyroclast assemblage, rather than as a syn-mylonite assemblage. This places mylonite formation within the spinel field, rather than right on the garnet-spinel transition (18 kb). Two-dimensional thermal modeling indicates that these conditions require removal of lithospheric mantle below 100 km followed by exhumation along a low angle shear zone. Excision of material during exhumation is required to explain the steep thermal gradients observed. These results shed light on the mechanisms of back-arc extension, as well as the emplacement of orogenic lherzolites.

1. Introduction

Regions of active continental collision such as the Mediterranean commonly show a wide range of complex behavior at the microplate and sub-plate scales. Cenozoic extension in the Tyrrhenian and Balearic basins, for example, has been attributed to subduction slab roll-back or detachment (i.e. Faccenna et al., 2004; Carminati et al., 1998), but the origin of the Alboran Sea between Spain and Morocco is more controversial (e.g., Gutscher et al., 2002; Platt and Houseman, 2003). The Alboran Sea and the associated Betic-Rif orogenic arc are geometrically and tectonically analogous to the Tyrrhenian Sea and the Calabrian arc, but the lack of clear evidence for subducting oceanic crust beneath the Alboran Sea has led to alternative suggestions for the mechanism triggering extension. These include slab detachment or tearing (Zeck, 1996), delamination of continental lithosphere, possibly including parts of the crust (Calvert et al., 2000; Gao et al., 2004; Song and Helmberger, 2007), or convective removal of the lower part of the mantle lithosphere (i.e. drip-like Rayleigh–Taylor instability) (Platt and Vissers, 1989; Platt et al., 2003a; Molnar and Houseman, 2004).

A key line of analysis to help in differentiating these models is determining the thermal evolution of the mantle during Miocene extension. Exhumed bodies of mantle peridotite like the Ronda and other massifs of southern Spain and northern Morocco provide insight into the thermal evolution of the lithospheric mantle and its relationship to decompression and deformation.

The Alboran domain comprises the Internal Zones of the Betic and Rif Cordilleras, and represents the westernmost extent of Mediterranean arc-related syn-contractional extension associated with the closure of the Tethys ocean (Carminati et al., 1998). This domain formed due to crustal thickening during Early Tertiary convergence between the African plate and the Iberian microplate (Vissers et al., 1995). Through the early Miocene, it underwent rapid extension (Comas et al., 1999; Platt et al., 2003a), accompanied and followed by thrusting of the edges of the domain onto both the Iberian and African margins (Platt et al., 2003b). A later phase of extension (15–8 Ma) was responsible for exhuming the Nevado-Filabride Complex to the east (Behr and Platt, 2012). The Ronda peridotite was exhumed to crustal levels during the early Miocene thinning event and subsequently thrust onto the margin within one of several large nappes that define the present-day

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Betic Cordillera of southern Spain (Tubía, 1994), exposing a ∼6 km slice of sub-continental lithospheric mantle rock that preserves diverse mineral assemblages from almost its entire exhumational path. A similar body is exposed in the Rif mountains of northern Morocco. Heating during exhumation significantly modified the textures and mineral assemblage of the peridotite, and this heat pulse may have been a consequence of the partial removal of some of the underlying lithospheric mantle.

To gain a clearer understanding of the processes that created the Alboran basin and the Betic and Rif Cordilleras, we investigate the history of the lithospheric mantle in this region. The Ronda peridotite massif of the western Betic Cordillera (Spain) exposes fresh lithospheric mantle rocks that preserve assemblages recording almost the entire history of the peridotite body from before extension started until the time they reached the surface. The Ronda peridotite massif displays a distinct mineralogical and textural zonation (Obata, 1980), containing garnet-, spinel-, and plagioclase-bearing assemblages that have been interpreted to represent equilibration at varying pressures within a thermal gradient during exhumation of the body from >20 kbars (∼70 km) to <8 kbars (∼30 km). The upper margin of the massif is mylonitized and juxtaposed against high-grade garnet gneisses of crustal origin that have themselves been exhumed from ∼50 km depth.

This mylonite could represent the ductile fault along which the peridotite massif was excised and juxtaposed against crustal materials, possibly as the main mechanism of emplacement into the crust. An alternative tectonic scenario for peridotite exhumation cites mantle diapirism as the emplacement mechanism (Loomis, 1972; Tubía et al., 2004). Tubía et al. (2004) argue that a narrow asthenospheric diapir ascended through lithospheric mantle during extension of the Alboran domain, causing peridotite to intrude into the thinning crust. The structure of the peridotite, being asymmetrically zoned, with a marginal mylonite on one side and bounded by different crustal nappes on either side, supports fault-emplacement rather than the diapir model (van der Wal and Vissers, 1993; Precigout et al., 2007). We combine thermobarometry and microstructural evidence with a 2D thermal model to determine the P–T history of the lithospheric mantle during Miocene thinning of the Alboran domain.

The exact mechanism that triggered thinning of the lithosphere, as well as the mechanism of emplacement of the peridotite slices, is still debated. We seek to better constrain the conditions of peridotite emplacement and exhumation recorded by the Ronda peridotite massif, and we present new thermal and microstructural constraints on its uplift.

2. Background

The Ronda peridotite massif comprises four major zones based on mineral assemblage and texture, presented in Fig. 1 (Obata, 1980). The most extensive of these is the plagioclase-bearing peridotite zone, which formed at the shallowest pressures observed (less than 8–9 kbars) (Obata, 1980). This unit has a well-defined foliation, with shape fabric defined by pyroxenes and dark to nearly opaque spinels, which are rimmed with undeformed plagioclase as an accessory phase. This zone is also the most serpentinized. The other three zones crop out only in the western portion of the massif. Structurally overlying the plagioclase zone is the granular spinel peridotite, characterized mainly by coarse (2 mm to 1 cm) olivine and pyroxenes, usually with no shape fabric, and spinel, which locally forms trails indicating an earlier fabric. This zone also contains pods of granular material with grain size less than 5 mm (van der Wal and Bodinier, 1996). Above the granular zone is the spinel peridotite tectonite, which has a strong shape fabric defined by oriented orthopyroxene and spinel. Along the northern margin or structural top of the massif is the garnet- and spinel-bearing mylonite, which contains stretched pyroxene porphyroclasts, as well as relict garnet porphyroclasts surrounded by a mylonitic matrix including fine grained olivine, pyroxene and spinel. Also abundant in all units are pyroxenite and gabbroic layers of variable compositions, described extensively by Garrido and Bodinier (1999). Garnet in both the peridotites and pyroxenites is always rimmed, and sometimes completely replaced, by a fine-grained symplectitic corona, called kelyphite, consisting of spinel, orthopyroxene, olivine, plagioclase, and ilmenite.

Disagreements regarding the history of the Ronda peridotite exist on the following points:

1. The relationship between the mylonites and tectonites. According to van der Wal and Vissers (1993), the mylonites overprint the spinel tectonite, which represents the relict primary mantle fabric. Precigout et al. (2007) interpret the mylonites and tectonites as a continuous kilometer-scale ductile strain gradient in which the tectonite and mylonite development were contemporaneous. The scale of the zone of active deformation has serious implications for the nature of the shear zone(s) that thinned the lithospheric mantle and emplaced the Ronda peridotites at the base of the crust.
2. Interpretation of garnet and garnet-spinel porphyroclasts in the mylonite zone. Instances of garnet growing on or with spinel have complicated attempts to interpret the P–T history of the massif. Van der Wal and Vissers (1993) interpreted kelyphite rims on spinel to indicate the rocks cooled and increased in pressure to grow a second phase of garnet, subsequently replaced by kelyphite. Precigout et al. (2007) explain the presence of the garnet-spinel assemblage as being caused by chemical alteration due to strain-enhanced diffusion around pyroxenite layers. Garrido et al. (2011) cite garnet growing with spinel in the marginal mylonite zone as evidence that the mylonite developed along the garnet-spinel transition. All workers appear to agree that these garnet-spinel assemblages are of a different generation from the large spinel-free garnets in the mylonites. The timing of garnet growth constrains models for exhumation because the upper margin of the peridotite massif must have stayed cool enough to prevent the garnet from reacting away.
3. The relationship between the spinel tectonites and the granular zone. The spinel tectonite grades into granular spinel peridotite across a narrow zone referred to as the recrystallization front or melt percolation front (van der Wal and Bodinier, 1996; Lenoir et al., 2001). The narrow transition zone is characterized by gradual coarsening and a highly variable bulk rock CaO/MgO ratio (Lenoir et al., 2001). Within the coarse granular zone are lenses of fine granular material with a higher clinopyroxene to orthopyroxene ratio, interpreted to result from melt-consuming reactions in the later stages of melt percolation (Lenoir et al., 2001). These geochemical and structural observations indicate that the melt percolation event overprinted and annealed the deformational spinel tectonite fabrics. On the other hand, in the Carratraca massif of the Ronda peridotite ("Car" in Fig. 1C), margin-parallel mylonite and tectonite fabrics overprint the granular domain, now present as 1–2 km long lenses within the tectonites (Tubía et al., 2004). Melt presence within the peridotite reflects a heat pulse to the base of the unit that directly relates to geodynamic models of the Mediterranean Sea region. By better constraining the timing of melt versus exhumation, we can narrow down the possible scenarios that triggered extension.

To reconcile these contrasting lines of evidence, we focus on the timing and pressure–temperature conditions of the deformation event(s) and granular zone formation.