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Rheology, microstructure, and fabric in a large scale mantle shear zone, Ronda Peridotite, southern Spain

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A B S T R A C T

The Ronda peridotite massif of southern Spain is a slice of mantle peridotite that records in its mineral assemblages several stages of its thermal and textural evolution during exhumation to crustal levels. The uppermost zone is a garnet- and spinel-bearing mylonite that grades downward into spinel-bearing tectonites. Overall grain-size increases downward, while the proportion of dynamically recrystallized olivine grains decreases downward. Olivine recrystallized grain-size throughout these two upper zones is ~130 μm. Olivine neoblasts are relatively free of substructure and have curved or lobate grain boundaries, suggesting recrystallization by grain boundary migration. Crystallographic orientations of stretched orthopyroxene porphyroclasts indicate a top-SW sense of shear for the marginal mylonites. Crystallographic lattice-preferred orientations (LPO) of olivine grains indicate a dominant slip system of (010)[100]. We propose that these upper two zones of the Ronda peridotite massif represent two stages in the evolution of the shear zone that exhumed the peridotite body through the spinel stability field (~2.0 −1.0 GPa) at a differential stress of ~40 MPa. We estimate a strain rate of ~5×10^{-13} based on the rheology of wet olivine at 1500 MPa and 860 °C. Under these conditions olivine is likely to deform by a grain-size sensitive creep mechanism, which explains the progressive localization of strain into the mylonite zone.

1. Introduction

The nature and width of the downward extension of faults in the upper mantle is highly uncertain (Vauchez et al., 2012). Given the lack of seismicity in the subcontinental mantle, and the experimental evidence for ductility in peridotites deformed at temperatures >700 °C (e.g., Hirth and Kohlstedt, 2003) it is likely that crustal faults pass down into ductile shear zones in the lithospheric mantle. Seismic shear wave splitting data has been interpreted as indicating that mantle shear zones beneath continental transforms such as the San Andreas Fault and the Alpine Fault in New Zealand may broaden out to several tens or even hundreds of km within the lithosphere (e.g., Wittlinger et al., 1998; Herquel et al., 1999; Hartog and Schwartz, 2001; Moore et al., 2002; Rümpker et al., 2003; Baldock and Stern, 2005; Duclos et al., 2005; Becker et al., 2006; Monteiller and Chevrot, 2011), although the precise depth at which the shear zone broadens out is still under discussion (e.g., Karalliyadda and Savage, 2013). Even less is known about the behavior of normal and thrust sense shear zones, which in general are much more difficult to image at depth using geophysical methods. Surface exposures of deformed mantle rocks are therefore of great value in providing information about the deformational behavior of the mantle at depth. We can better understand the variation of behavior with depth by a combination of microstructural and petrological observations of these exposures.

Subcontinental mantle shear zones have been described from several orogenic peridotite massifs, most notably the Voltri and Balmuccia massifs in the Alps (Drury et al., 1989; Ueda et al., 2008) and the Turon de la Técouère massif in the Pyrenees (Vissers et al., 1997). The Ronda massif in southern Spain is the largest exposure of orogenic peridotite, and exposes what is probably the largest and best preserved peridotitic ductile shear zone known. The shear zone has also been interpreted as the margin of a peridotite diapir (Loomis, 1972; Tubia et al., 2004) and as a paleo-subduction zone interface (van der Wal and Vissers, 1993). However, the structural configuration of the upper surface of the massif in contact with

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overlying crustal rocks, and the petrological evidence for decompression before, during, and after deformation, strongly suggests that a lithospheric-scale normal sense shear zone was responsible for exhuming the peridotite to crustal depths (Platt et al., 2003a; Precigout et al., 2007, 2013). In this paper we provide a new data set on the microstructural evolution, stress distribution, and lattice preferred orientation of olivine within the shear zone, and discuss the implications of the data for the tectonic and thermal evolution of the peridotite massif. To address these issues, we investigate the timing and mechanisms of deformation during the formation of the marginal mylonitic shear zone, tectonite zone, and internal shear zones using electron backscatter diffraction (EBSD), grain size analysis, and optical microscopy.

2. Geologic background

2.1. Tectonic setting

The Ronda peridotite massif forms a tectonic slice within the Alpujarride Complex, in the Betic Cordillera of southern Spain. The Alpujarride Complex, together with the related Sebtide Complex in the Rif mountains of northern Morocco, constitutes the major part of an exotic terrane, known as the Alboran Domain, which underlies the Alboran Sea and the internal parts of the Betic-Rif arc. The Alboran Domain formed as a result of tectonic accretion of continental crustal rocks during Early Tertiary subduction within the western Mediterranean (Vissers et al., 1995). It then underwent a phase of rapid extension during the early Miocene (22-18 Ma, Comas et al., 1999; Platt et al., 2003b), accompanied and followed by thrusting of the edges of the domain onto both the Iberian and African margins (Platt et al., 2003c). This second convergent episode was responsible for the subduction and subsequent exhumation of the Nevado-Filabride Complex in the central and eastern Betics in the period 18-8 Ma (Jabaloy et al., 1993; Johnson and Harbury, 1997; Martínez-Martínez et al., 2002; Behr and Platt, 2012; Platt et al., 2005). The Ronda peridotite was exhumed to crustal levels during the early Miocene thinning event and subsequently emplaced onto the Iberian margin as part of the Alpujarride Complex (Tubia, 1994), exposing a ~6 km thick slice of sub-continental lithospheric mantle rock that preserves diverse mineral assemblages from almost its entire exhumational path. A similar body, the Beni Bousera massif, is exposed in the Rif Mountains of northern Morocco (Reuber, 1982; Gysi et al., 2011). The structural history of the Alpujarride Complex has been extensively studied (e.g., Crespo-Blanc et al., 1994; Azañón et al., 1998; Orozco et al., 1998; Platt et al., 2005), but many questions remain regarding how the peridotites were exhumed and emplaced into their present position within it.

2.2. The Ronda peridotite

The peridotite massif is zoned texturally and mineralogically (Obata, 1980; van der Wal and Vissers, 1993), containing from top to bottom, garnet- and spinel-bearing lherzolitic mylonites, spinel-bearing tectonites, spinel-bearing granular peridotites, and plagioclase-bearing tectonites (Fig. 1). Peak pressures recorded in these rocks decrease downwards, whereas peak temperatures increase downwards, a distribution that indicates partial re-equilibration of the different zones during exhumation and heating (van der Wal and Vissers, 1993; Lenoir et al., 2001; Johanesen et al., 2014).

The garnet-spinel mylonites form a zone up to 500 m thick along the upper margin of the massif, and are characterized by highly stretched orthopyroxenes up to 3 cm long, and porphyroclasts up to 1 cm across of garnet, lying in a matrix of dynamically recrystallized olivine, pyroxene, and spinel. The garnet is relict from a garnet peridotite assemblage that equilibrated at conditions around 2.4–2.7 GPa and 1020–1100 °C (Garrido et al., 2011). Precigout et al. (2007) use the garnet-bearing assemblage for the conditions of mylonite formation, however Johanesen et al. (2014) argue that the porphyroclastic nature of the garnet-bearing assemblage is not in equilibrium with the fine-grained mylonites, and give conditions of 1.0–1.8 GPa and 800–900 °C (using two-pyroxene geothermometers and the pressure range of the spinel stability field) for the main mylonitic assemblage. The mylonites are juxtaposed against high-grade gneisses of crustal origin that record peak pressures ~1.4 GPa (Argles et al., 1999), which form the lowest part of a highly attenuated sequence of crustal rocks forming a metamorphic envelope to the peridotite (Balanya et al., 1997; Argles et al., 1999). The marginal mylonite zone may represent a ductile fault along which the peridotite massif was exhumed from mantle depths (Precigout et al., 2007, 2013), and then juxtaposed against the overlying crustal rocks (Platt et al., 2003b; Johanesen et al., 2014).

The garnet-spinel mylonites are underlain by a broader zone of coarser-grained spinel-bearing peridotite tectonites, which have a strong shape fabric defined by oriented orthopyroxene and spinel. The main coarse-grained assemblage equilibrated at pressures in the range 1.0–2.1 GPa, and temperatures in the range 1000–1150 °C (Johanesen et al., 2014). Olivine and pyroxene show variable degrees of plastic deformation and dynamic recrystallization (Precigout et al., 2007). The relationship between the tectonites and the mylonites is debated (van der Val and Vissers, 1996; Precigout et al., 2007). Van der Wal and Vissers (1996) describe the transition from the mylonites to the spinel tectonites as relatively sharp with cross-cutting relationships between the two and the foliation in the spinel tectonites warping into and being cut off by the mylonites. Zones of mylonite also occur within the tectonites close to the boundary. Grain-size measurements by Precigout et al. (2007) suggest a gradual increase in overall grain size downward across the tectonite zone, however, and inferred that there is a continuous gradient of strain across the two zones.

The tectonites pass down into granular spinel peridotites, characterized mainly by coarse (2 mm–1 cm) olivine and pyroxenes, usually with no shape fabric, and spinel that locally forms trails indicating an earlier fabric. The coarse grain size has been attributed to annealing recrystallization, and the upper margin of this zone has been referred to as the recrystallization front (van der Wal and Bodinier, 1996; Lenoir et al., 2001). The nature of this boundary is controversial, however (Soustelle et al., 2009; Johanesen et al., 2014). The granular peridotites also contain pods of fine-grained granular material with grain size less than 5 mm (van der Wal and Bodinier, 1996), and alternating bands of dunite and Cr-rich clinopyroxenite, which have been interpreted as channels of melt percolation (Garrido and Bodinier, 1999; Bodinier et al., 2008). These rocks therefore reached solidus temperatures at relatively low pressures (<2.1 GPa) (van der Wal and Bodinier, 1996; Lenoir et al., 2001; Garrido and Bodinier, 1999; Soustelle et al., 2009). This zone also displays textures indicative of interstitial melts, which predate the deformation in the tectonite and mylonite zones (Johanesen et al., 2014).

The structurally lowest and most extensive zone comprises plagioclase-bearing peridotites, which equilibrated at the lowest pressures observed (<0.8–0.9 GPa) (Obata, 1980). This unit has a variably developed but locally well-defined foliation defined by a shape fabric of pyroxenes and dark to nearly opaque spinels, which are rimmed with undeformed plagioclase as an accessory phase. The foliation is associated with folds (van der Wal and Vissers, 1996; Hidas et al., 2013) and locally developed mylonite zones that have been interpreted in terms of top-SW shear (Hidas et al.,