Journal of Structural Geology 39 (2012) 138–157

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Deformation processes and rheology of pyroxenites under lithospheric mantle conditions

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ARTICLE INFO

Article history:
Received 17 November 2011
Received in revised form
27 February 2012
Accepted 29 February 2012
Available online 15 March 2012

Keywords:
Mantle
Pyroxenite
Plastic deformation
Rheology
Microstructure
Crystal preferred orientations
Garnet
Clinopyroxene
Orthopyroxene
Beni Bousera

ABSTRACT

We combined microstructural observations and high-resolution crystallographic preferred orientation (CPO) mapping to unravel the active deformation mechanisms in garnet clinopyroxenites, garnet–spinel websterites, and spinel websterites from the Beni Bousera peridotite massif. All pyroxenites display microstructures recording plastic deformation by dislocation creep. Pyroxene CPOs are consistent with dominant slip on [001]{110} in clinopyroxene and on [001](100) or [001](010) in orthopyroxene. Garnet clinopyroxenites have however high recrystallized fractions and finer grain sizes than spinel websterites. Recrystallization mechanisms also differ: subgrain rotation dominates in garnet clinopyroxenites, whereas in spinel websterites nucleation and growth also contribute. Elongated shapes and strong intracrystalline misorientations suggest plastic deformation of garnet, but CPOs are weak. Clinopyroxene porphyroclasts in spinel websterites show deformation twins underlined by orthopyroxene exsolutions. Thermodynamic calculations indicate that garnet clinopyroxenites deformed at 2.0 GPa and 950–1000 °C and spinel pyroxenites at 1.8 GPa and 1100–1150 °C. The lower temperatures may explain the faster work rates implied by the finer grained microstructures in garnet clinopyroxenites. Greater stresses may have also reduced the competence contrast between garnet and pyroxene in the garnet pyroxenites and, at the outcrop scale, lowered the competence contrast between pyroxenites and peridotites, favoring mechanical dispersion of pyroxenites in the cooler lithospheric mantle.

1. Introduction

Pyroxenite is an important constituent of the upper mantle. Lithological mapping in continental peridotite massifs, like Lherz in the Pyrenees, Lanzo in the Alps, Beni Bousera and Ronda in the Betic-Rif belt, shows that pyroxenite layers are ubiquitous in these massifs (Kornprobst, 1969, 1970; Dickey, 1970; Garrido and Bodinier, 1999; Bodinier et al., 2008; Gysi et al., 2011). Mantle pyroxenites have been inferred as source material of ocean island basalts in Hawaii (Sobolev et al., 2005) and, to a lesser extent, of mid-ocean ridge basalts (Hirschmann and Stolper, 1996).

Three origins are classically proposed for mantle pyroxenites: recycling of oceanic crust into the convective mantle due to subduction (Polvé and Allègre, 1980; Allègre and Turcotte, 1986), partial crystallization of basaltic melts at depth, or melting and melt-rock reaction products (Loubet and Allègre, 1982; Bodinier et al., 1987, 2008; Suen and Frey, 1987; Pearson et al., 1993; Garrido and Bodinier, 1999). Regardless of their origin, pyroxenites usually occur as layers parallel to the peridotite foliation, suggesting that deformation during mantle flow probably controls their distribution and, hence, the scale of expression of compositional heterogeneity in the upper mantle. However, data on pyroxene deformation mechanisms and rheology are still limited.

Deformation experiments and TEM observations on diopside (Avé Lallemant, 1978; Kollé and Blacic, 1982, 1983; Raterron and Jaoul, 1991; Ingrin et al., 1992; Jaoul and Raterron, 1994; Zhang et al., 2006; Amiguet et al., 2009), orthopyroxene (Turner et al.,

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0191-8141/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2012.02.019

1960; Raleigh, 1965; Green and Radcliffe, 1972; Lally et al., 1972; Kohlstedt and Vandersande, 1973; Ross and Nielsen, 1978; Skrotzki, 1994), and garnet (Ando et al., 1993; Doukhan et al., 1994; Voegelé, 1998; Voegelé et al., 1998a,b; Ji et al., 2003) showed that these minerals may deform by crystal-plastic processes and allowed identifying the active slip systems. For diopside, these studies also determined the pressure and temperature dependence of the critical resolved shear stresses of the various slip and twinning systems. In addition, flow laws were determined for diopside polycrystals under dry (Bystricky and Mackwell, 2001) and hydrous conditions (Chen et al., 2006). Yet, the extrapolation of these results to natural conditions remains difficult. Most studies on natural garnet-bearing pyroxene-rich lithologies focused on eclogites from subduction-related metamorphic terranes deformed under high to ultra-high pressure and low temperature conditions or high-pressure granulitic conditions (e.g., Buatier et al., 1991; Abalos, 1997; Bascou et al., 2001, 2002; Mainprice et al., 2004; Padrón-Navarta et al., 2008). Fewer data exist for mantle pyroxenites deformed under lithospheric or asthenospheric mantle conditions (e.g., Muramoto et al., 2011).

The Beni Bousera peridotite massif encompasses a large variety of mantle pyroxenites deformed under a variety of pressure and temperature conditions (Kornprobst, 1969, 1970; Pearson et al., 1989, 1991, 1992; Targuisti, 1994). Here we present detailed analyses of outcrop-scale structures, microstructures, and crystallographic preferred orientation (CPO) of garnet pyroxenites, garnet–spinel websterites, and spinel websterites from this massif. We combine these microstructural data with petrological modeling to constrain the deformation mechanisms and rheological behavior of pyroxenite in the subcontinental lithospheric mantle for a range of pressure and temperature conditions.

2. The Beni Bousera peridotite

The Beni Bousera peridotite massif crops out in the Rif orogenic belt, which forms the southern limb of the Betic-Rif arcuate Alpine orogen surrounding the Alboran sea in the westernmost Mediterranean (Fig. 1). The Beni Bousera massif is mainly composed of lherzolite with minor harzburgite and dunite (Kornprobst, 1969; Reuber et al., 1982). Three main tectono-metamorphic domains can be distinguished from SW to NE (Fig. 1): (i) mylonitic garnet and spinel mylonites (Kornprobst, 1969; Reuber et al., 1982; Saddiqi et al., 1988; Tabit et al., 1997) that overlie (ii) mylonitic to porphyroclastic peridotites containing garnet pyroxenite layers (Ariègite subfacies; Targuisti, 1994), which in turn overlie (iii) coarse-grained porphyroclastic to granular spinel peridotites with differing amounts of spinel pyroxenite layers (Seiland subfacies; Targuisti, 1994). Garnet- and/or spinel pyroxenite layers are common in the entire massif and may locally comprise up to 50% of an outcrop section (Fig. 2). Available structural data (Reuber et al., 1982), which are confirmed by our ongoing structural mapping of

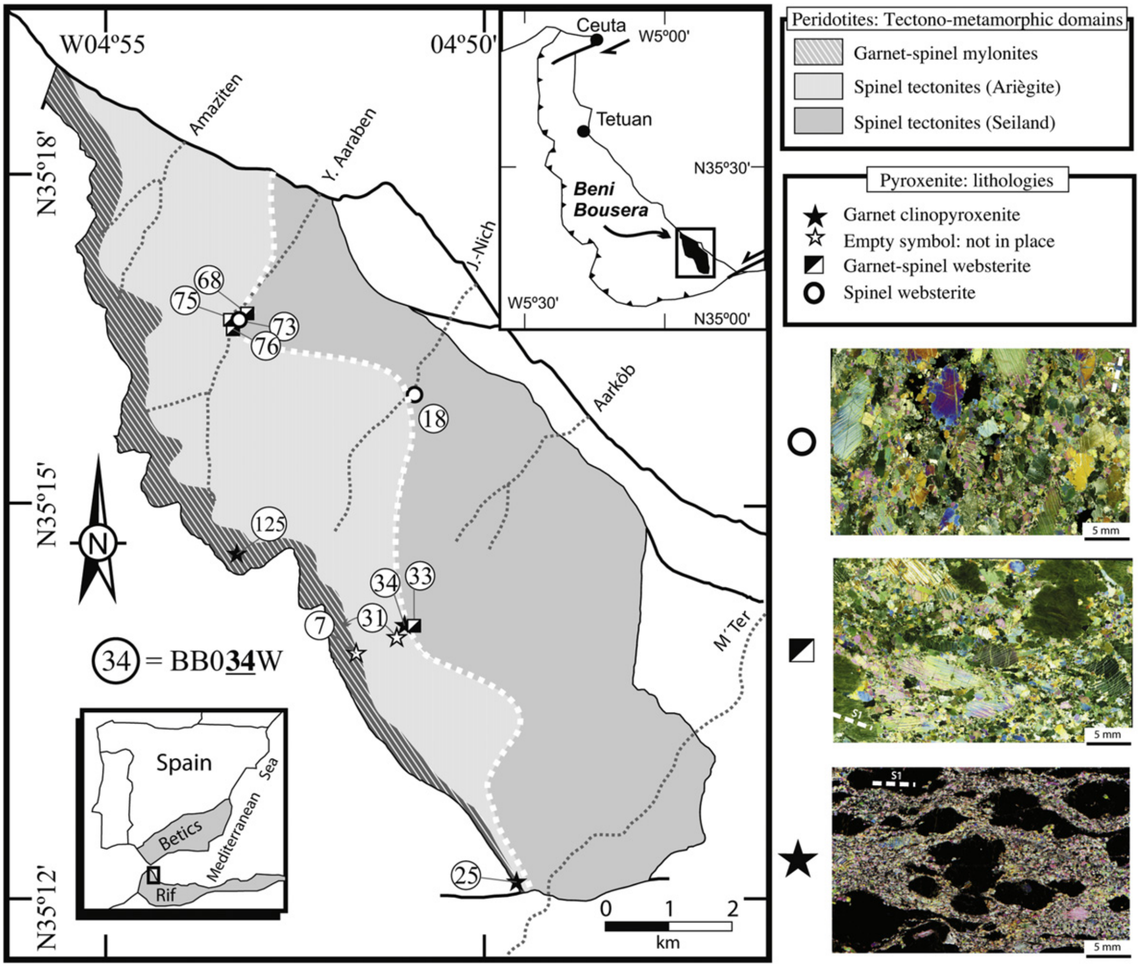

Fig. 1. Geological map of the Beni Bousera peridotite massif showing the distribution of tectono-metamorphic domains and the location of the studied pyroxenite samples. Photomicrographs illustrate the variation of pyroxenites microstructures at the scale of the massif.