Tectonophysics 615–616 (2014) 167–181

Contents lists available at ScienceDirect

Tectonophysics

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

Deformation in a partially molten mantle: Constraints from plagioclase lherzolites from Lanzo, western Alps

Katherine Higgie, Andréa Tommasi *

Geosciences Montpellier, CNRS & Université de Montpellier 2, F-34095 Montpellier cedex 5, France

ARTICLE INFO

Article history:
Received 21 August 2013
Received in revised form 2 January 2014
Accepted 5 January 2014
Available online 16 January 2014

Keywords:
Lithosphere–asthenosphere boundary
Deformation
Oriented melt lenses
Melt segregation
Refertilisation
Crystal preferred orientations
Anisotropy

ABSTRACT

We studied the deformation in a partially molten mantle through detailed petrostructural analysis of plagioclase lherzolites from the northwestern part of the central Lanzo massif. These peridotites display a pervasive anastomosed network of millimetre to centimetre-scale plagioclase-rich bands, which grades locally into a planar layering marked by an intercalation of plagioclase-rich and olivine-rich layers up to tens of centimetres wide. Both the anastomosed and the planar layering are subparallel to the deformation fabric, characterized by a foliation defined by the shape-preferred orientation of olivine and by crystal preferred orientation (CPO) of olivine, orthopyroxene, and clinopyroxene. This parallelism, the coexistence of microstructural evidence for melt–rock reactions and for deformation by dislocation creep, and the predominance of axial-[010] olivine CPO patterns, characterized by [010] axes clustered normal to the layering, indicate that deformation and the reactive melt percolation that formed the layering were coeval. Strong heterogeneity in mineral composition in the planar layering domains, with Fe-enrichment in olivine and spinel and highly variable Ti content in spinel in cm-scale plagioclase-rich bands, implies that the latter interacted with higher melt volumes. High Ti contents in pyroxenes and spinel in the anastomosed layering domains point to changes in melt composition, hinting to less effective melt transport. We propose therefore that the planar layering records melt segregation in layers parallel to the shear plane, whereas the anastomosed layering results from melt alignment along grain boundaries subparallel to the shear plane, without segregation. Finite strain in the different layers cannot be quantified, but comparison of the present observations with data from experiments and from other mantle outcrops displaying shear-controlled melt organization suggests that the transition from the anastomosed to the planar layering might record an increase in finite strain, that is, strain localization associated with variations in the instantaneous melt fraction.

1. Introduction

The mechanical behaviour of partially molten regions in the shallow upper mantle and the processes governing melt transport and distribution in these domains are important, yet largely unresolved questions in geodynamics. Very low melt fractions ($\leq$1%) may reduce the rocks' viscosity by more than one order of magnitude (Rosenberg and Handy, 2000; Takei, 2005). On the other hand, deformation may enhance permeability and lead to melt focussing into layers or channels (Holtzman et al., 2003a,b; Katz et al., 2006). These interactions between melt distribution and deformation play an essential role in localizing strain, as documented in shear zones formed at the lithosphere–asthenosphere boundary (Dijkstra et al., 2002; Kaczmarek and Tommasi, 2011; Kelemen and Dick, 1995; Le Roux et al., 2008) and in the middle and lower crusts (e.g., Brown and Solar, 1998; Hollister and Crawford, 1986; Tommasi et al., 1994).

Experiments showed that deformation of partially molten aggregates in shearing leads to melt segregation into bands oriented at $\leq$20° to the shear plane (Holtzman et al., 2003a, 2005; King et al., 2010; Zimmerman et al., 1999). This melt segregation results in further weakening of the melt–rock aggregates (Holtzman et al., 2012). Melt segregation in layers may also produce anisotropy in viscosity (Holtzman et al., 2012), electrical conductivity (Caricchi et al., 2011), and seismic wave propagation and attenuation in the upper mantle (Holtzman and Kendall, 2010; Vauchez et al., 2000). Shear-induced melt organization has been proposed to strongly contribute to seismic anisotropy in rift zones and, more generally, in the lithosphere–asthenosphere boundary (Holtzman and Kendall, 2010).

A recent study of the shallowmost mantle section (Moho Transition Zone, MTZ) of the Oman ophiolite provided evidence that deformation-controlled melt segregation also occurs in nature and that melt–rock reactions during this process produce compositionally layered peridotites (Higgie and Tommasi, 2012). This study also highlighted a change in olivine crystal preferred orientation from axial-[100] to axial-[010], where the [100] axis becomes distributed in the plane of foliation and [010] concentrated normal to it, in the melt-rich bands. This change

* Corresponding author. Tel.: +33 467144912.
E-mail address: andrea.tommasi@gm.univ-montp2.fr (A. Tommasi).

0040-1951/$ – see front matter
http://dx.doi.org/10.1016/j.tecto.2014.01.007

has been interpreted as due to a combination of melt-assisted glide on preferentially wetted (010) boundaries, local transpressive deformation, and limited activation of the (010)[001] system in olivine (Higgie and Tommasi, 2012). However, these observations come from an end-member situation (active ridge setting, in the vicinity of a mantle diapir), where strong shear deformation affected peridotites containing melt fractions that probably largely exceeded, at least locally, the 1–2% values generally accepted for the upper mantle. One may question if they can be extrapolated to the 'normal' mantle. Here we present a detailed petro-structural study of a section of plagioclase-rich lherzolites from the central domain of the Lanzo peridotite massif in southern Alps, which records interactions with melts at shallow depths in the mantle (<40 km depth; Bodinier et al., 1991).

2. Geological background and study site

The Lanzo massif is a >150 km^2 peridotite body located in the western Alps (Boudier, 1978). It is traditionally interpreted as a part of the mantle section of the Piemont–Ligurian oceanic plate (Lagabrielle et al., 1989), which has been subducted to eclogite facies before fast exhumation during the Alpine orogenesis (Compagnoni and Sandrone, 1979; Kienast and Pognante, 1988). Pervasive eclogitic metamorphic equilibration is however restricted to the borders of the massif (Kienast and Pognante, 1988; Pelletier and Müntener, 2006); most of the massif records a tectono-metamorphic evolution under high-temperature, low pressure conditions interpreted as associated to the extension that formed the Piemont–Ligurian ocean (Bodinier, 1988; Bodinier et al., 1991; Boudier, 1978; Kaczmarek and Muntener, 2008; Lagabrielle et al., 1989).

The massif is split into three bodies: the southern, central and northern bodies (Fig. 1), which are separated by retrogressive shear zones (Boudier, 1978; Kaczmarek and Muntener, 2008; Kaczmarek and Tommasi, 2011). The three bodies have contrasted compositions, which record different evolutions. The northern body is traditionally interpreted as a fragment of subcontinental lithospheric mantle separated from the convective mantle >400 Ma years ago (Bodinier et al., 1991). The southern body was proposed to represent asthenospheric mantle, which rose from the garnet stability field to shallow depths, being submitted to partial melting and melt extraction (6–12%, locally up to 20%) during the formation of the Piemont–Ligurian ocean (Bodinier et al., 1991). The central body, in which the present study area is located, displays transitional geochemical features. It is composed dominantly by plagioclase lherzolites (Boudier, 1978) and was interpreted as a subcontinental mantle lithosphere fragment modified by reactive percolation of low fractions of melts of asthenospheric origin (Bodinier et al., 1991). Reactive transport of MORB-type melts in Central and South Lanzo is recorded in the field by the formation of plagioclase-rich lenses aligned in the foliation or at a low angle to it in the lherzolites, by the development of reactive spinel harzburgite–dunite channels, and by MORB-type gabbro dykes which intrude all lithologies (Bodinier et al., 1991; Boudier, 1978). Reactive melt percolation in Central and South Lanzo is also evidenced by microstructures recording replacement of olivine by orthopyroxene and of clinopyroxene by intergrowths of orthopyroxene and plagioclase (Kaczmarek and Muntener, 2008; Muntener and Piccardo, 2003). Zircon ages in the gabbro dikes date this event at ca. 161–163 Ma (Kaczmarek et al., 2008), whereas the high pressure metamorphism was dated at 45–55 Ma (Rubatto et al., 2008).

Partial melting and reactive melt percolation resulted in an important compositional heterogeneity of the massif, which is illustrated by the variation in Al_2O_3 content of the peridotites (Fig. 1). As the aim of the present study was to analyse the relations between melt and deformation, we focused our observations in the northwestern part of the Central Lanzo body, which shows the highest Al_2O_3 contents within the massif, reflecting high plagioclase contents (Bodinier, 1988). Within this domain, the best outcrops, which were selected for the present study, occur in the Rio Ordagna, between N45°15.56, E7°25.665′ and N45°15.511′, E7°25.324′ (Fig. 1). These outcrops are characterized by coarse-grained peridotites with a well-developed layering recorded by variations in the plagioclase content (Fig. 2).

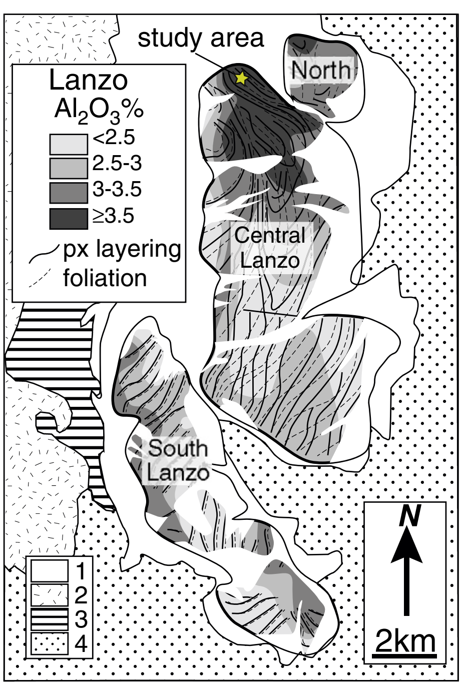

Fig. 1. Simplified map of the Lanzo peridotite displaying the location of the study area in the northwestern part of the Central Lanzo body, which shows the highest Al_2O_3 contents within the massif, reflecting high plagioclase fractions. Al_2O_3 content map and foliation and pyroxenite layering orientations were derived from Bodinier (1988) and Boudier (1978), respectively. (1) Lanzo serpentinite; (2) Piedmontese ophiolitic sequences; (3) Mesozoic metasedimentary rocks; (4) Late cenozoic metasedimentary rocks.

3. Methods

Twenty-one 25 mm-wide geographically oriented cores sampling the different compositional and textural facies observed in a 500 m long almost continuous riverbed outcrop were drilled in three locations separated by ~50 m (Table 1). Due to the necessity to drill on a flat surface, the cores were often drilled oblique to the compositional layering. To sample the textural variability at the cm-scale and to ensure that a representative volume was analysed, for most cores, two polished thin-sections for microstructural analysis and crystal preferred orientation (CPO) measurements were prepared along a vertical plane containing the core axis. Core orientations were used to rotate the crystal preferred orientation data to a geographic reference frame using the Rotctf programme by D. Mainprice (ftp://www.gm.univ-montp2.fr/mainprice//CareWare_Unicef_Programs/). This rotation allowed straightforward comparison between the CPO data from different samples and between the CPO and the orientation of the layering.

CPO of olivine, orthopyroxene, clinopyroxene, and plagioclase were measured by indexation of electron back-scattered diffraction (EBSD) patterns at the Geosciences Montpellier SEM-EBSD facility using a scanning electron microscope JEOL JSM5600 with an acceleration voltage of 17 kV and a working distance of 23 mm. Oxford Instruments Channel+ software was used to process the images and index the minerals with respect to their crystallographic orientation. Orientation maps covering 80–90% of the thin section surface were acquired in automatic acquisition mode. Step sizes between 35 μm and 80 μm were used (at least 1/4 of the smallest grain size) to ensure a correct sampling of the smaller grains. Raw indexation rates ranged from 45% to 80%. Non-indexed areas resulted from polishing defects, alteration, fractures,