Earth and Planetary Science Letters 491 (2018) 193–206

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Controls on the rheological properties of peridotite at a palaeosubduction interface: A transect across the base of the Oman–UAE ophiolite

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ARTICLE INFO

Article history:
Received 23 October 2017
Received in revised form 28 February 2018
Accepted 14 March 2018
Available online xxxx
Editor: J. Brodholt

Keywords:
plate boundary
strain localisation
olivine microstructure
Oman–UAE ophiolite
phase mixing
mantle wedge

ABSTRACT

Studies of experimentally deformed rocks and small-scale natural shear zones have demonstrated that volumetrically minor phases can control strain localisation by limiting grain growth and promoting grain-size sensitive deformation mechanisms. These small-scale studies are often used to infer a critical role for minor phases in the development of plate boundaries. However, the role of minor phases in strain localisation at an actual plate boundary remains to be tested by direct observation. In order to test the hypothesis that minor phases control strain localisation at plate boundaries, we conducted microstructural analyses of peridotite samples collected along a ∼1 km transect across the base of the Oman-United Arab Emirates (UAE) ophiolite. The base of the ophiolite is marked by the Semail thrust, which represents the now exhumed contact between subducted oceanic crust and the overlying mantle wedge. As such, the base of the ophiolite provides the opportunity to directly examine a former plate boundary.

Our results demonstrate that the mean olivine grain size is inversely proportional to the abundance of minor phases (primarily orthopyroxene, as well as clinopyroxene, hornblende, and spinel), consistent with suppression of grain growth by grain-boundary pinning. Our results also reveal that mean olivine grain size is proportional to CPO strength (both of which generally decrease towards the metamorphic sole), suggesting that the fraction of strain produced by different deformation mechanisms varied spatially. Experimentally-derived flow laws indicate that under the inferred deformation conditions, the viscosity of olivine was grain-size sensitive. As such, grain size, and thereby the abundance of minor phases, influenced viscosity during subduction-related deformation along the base of the mantle wedge.

We calculate an order of magnitude decrease in the viscosity of olivine towards the base of the ophiolite, which suggests strain was localised near the subduction interface. Our data indicate that this rheological weakening was primarily the result of more abundant minor phases near the base of the ophiolite. Our interpretations are consistent with those of previous studies on experimentally deformed rocks and smaller-scale natural shear zones that indicate minor phases can exert the primary control on strain localisation. However, our study demonstrates for the first time that minor phases can control strain localisation at the scales relevant to a major plate boundary.

1. Introduction

Earth's lithosphere consists of highly viscous tectonic plates with deformation localised within less viscous material at plate boundaries (e.g., Bercovici and Karato, 2003). However, the processes that control the development of *plate boundary-scale* shear zones remain poorly constrained. Generating strain localisation in plate-tectonic models has proven challenging, primarily due to a lack of clarity on the best rheological parameterisation (e.g. Tackley, 2000). An often proposed mechanism for localised weakening is localised grain-size reduction, as exemplified by the occurrence of mylonites in ductile shear zones (e.g., Rutter and Brodie, 1988). Studies of small-scale natural shear zones (Hansen and Warren, 2015; Herwegh et al., 2011; Toy et al., 2010;

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https://doi.org/10.1016/j.epsl.2018.03.027
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Warren and Hirth, 2006) and experimentally deformed rocks (Farla et al., 2013; Hiraga et al., 2010) have demonstrated that volumetrically minor phases in polyphase rocks can control strain localisation by limiting grain-growth, enhancing and maintaining grain-size reduction, and thereby promoting grain-size sensitive creep. Theoretical models of grain-size evolution in polyphase rocks have suggested that, via this positive self-weakening feedback, minor phases play a fundamental role in the development and long-term maintenance of weak plate boundaries (e.g., Bercovici and Skemer, 2017; Mulyukova and Bercovici, 2017).

During shearing, increased intracrystalline strain drives dynamic recrystallisation and grain-size reduction (e.g., Poirier and Guillopé, 1979). Sufficient grain-size reduction can promote grain-size sensitive deformation mechanisms and associated rheological weakening (e.g., Drury, 2005). However, grain-size reduction is opposed by surface energy-driven grain growth, which increases with decreasing grain size (de Bresser et al., 1998, 2001). The steady state grain size depends on the relative contributions of grain-size reduction and grain growth (Austin and Evans, 2009; Derby and Ashby, 1987). In monophase rocks, the resulting equilibrium grain size tends to fall near the transition between the dislocation creep and diffusion creep fields, thus limiting the magnitude of rheological weakening possible through increased activity of grain-size sensitive deformation mechanisms (de Bresser et al., 1998, 2001). In polyphase rocks, however, an even finer grain size can be maintained by a well-mixed (i.e., dispersed) minor phase that pins grain boundaries, limiting grain-boundary migration and grain growth (e.g., Toy et al., 2010; Cross and Skemer, 2017). As such, by promoting and maintaining a finer grain size than would be expected in a monophase rock at a given stress, the presence of minor phases appears critical in promoting grain-size sensitive deformation and thus the dynamic rheological weakening necessary for strain localisation. This concept has been successfully implemented in analyses of plate boundary formation and stability with encouraging results (Bercovici and Ricard, 2012, 2014). However, while observations of the role of minor phases in strain localisation have been made from the thin-section to the outcrop scale, it remains to be tested with direct observation whether this process is applicable to strain localisation at an actual plate boundary.

Here we test the hypothesis that minor phases control strain localisation at plate boundaries by examining mantle rocks at a palaeosubduction interface. We analysed peridotite samples collected across a basal section of the Oman-United Arab Emirates (UAE) ophiolite. The ophiolite formed above a subduction zone during the late Cretaceous (MacLeod et al., 2013; Pearce et al., 1981; Rioux et al., 2016). The base of the ophiolite is bound by the Semail thrust, which represents the fossilised contact between subducted Tethyan crust and overlying mantle wedge (e.g., Searle and Malpas, 1980; Searle and Malpas, 1982; Cowan et al., 2014). Whereas previous studies have had to extrapolate data from experiments or natural shear zones of a small scale and/or uncertain tectonic context, the Semail thrust provides the opportunity to directly examine a former plate boundary. We used electron backscatter diffraction (EBSD) to quantify trends and relationships in grain size, modal mineral abundance, and crystallographic preferred orientation (CPO). Our results support microstructural and rheological models in which minor phases hinder olivine grain growth, which promotes diffusion creep, and thereby strongly influences strain localisation at plate boundaries.

2. Geologic setting

The Oman–UAE ophiolite (Fig. 1) is a thrust-bound slice of oceanic lithosphere formed at *ca*. 96.4–95.5 Ma in the hanging wall of a newly initiated, northeast dipping, intraoceanic subduction zone (Pearce et al., 1981; Rioux et al., 2012, 2013, 2016; Macleod et al., 2013). The ophiolite consists of upper-mantle peridotite overlain by a crustal section of gabbros, sheeted dykes, basaltic flows and pillows, and pelagic sediments (e.g., Glennie et al., 1973). Following subduction initiation, tholeiitic basalts, gabbros, and sediments were subducted beneath the newly forming ophiolite to form the metamorphic sole (Searle and Malpas, 1980, 1982; Gnos, 1998; Cowan et al., 2014). Burial, accretion to the base of the ophiolite, and the onset of exhumation of the sole occurred within about one million years of subduction initiation (Hacker, 1994; Rioux et al., 2016). Following exhumation of the sole, deformation stepped to shallower levels in the foreland as convergence was accommodated by in-sequence stacking of rise, slope, and shelf sedimentary packages (e.g.; Searle, 1988). By *ca*. 79 Ma, the continental margin reached the subduction zone and was subducted to eclogite facies in the southeastern part of the ophiolite in Oman (Warren et al., 2005). The obduction process was complete by ∼70 Ma and is marked by the return of shallow-marine passive margin sedimentation (Glennie et al., 1973).

For the most part, the mantle section of the ophiolite does not exhibit any obvious structure (Fig. 2a). However, the basal few hundred metres of the ophiolite exhibits a mylonitic fabric, with grain size that is smaller and foliation that is more pronounced towards the base of the ophiolite (Figs. 2b–d). The base of the ophiolite is marked by the Semail thrust, which placed the ophiolite over the metamorphic sole, a thrust slice of highly sheared amphibolite, quartz schist, and metachert that was scraped off the downgoing slab and accreted to the base of the mantle wedge (Fig. 1).

Several structural and petrological characteristics suggest that the mylonitic fabric in the peridotites adjacent to the Semail thrust is related to the early high-temperature history of subduction. (1) Deformation was ductile and distributed over hundreds of meters. (2) In addition to olivine and orthopyroxene, the mylonitic peridotites also contain clinopyroxene and hornblende, which have previously been interpreted to be related to fluids released from the downgoing slab (Prigent et al., 2014, 2015). Microstructural evidence (discussed in more detail in Section 4.1) indicates that these phases were present during deformation at temperatures in excess of 650 °C. (3) Although the mineral assemblage of the peridotites is not suitable for thermobarometry, thermobarometric estimates for garnet–clinopyroxene amphibolites from the metamorphic sole immediately beneath the Semail Thrust in Oman provided peak metamorphic conditions of 770–900 °C and 11–13 kb (Cowan et al., 2014). U–Pb zircon ages of *ca*. 96 and 94 Ma (Rioux et al., 2016) that date peak metamorphism of the sole overlap with crystallisation of the crustal section of the ophiolite at *ca*. 96.4–95.5 Ma (Rioux et al., 2013, 2012). Thus, it seems reasonable to assume that peridotites in the adjacent hanging-wall were deformed at similarly high temperatures.

While many studies have investigated the pressure, temperature, and deformation history of the metamorphic sole (e.g., Searle and Malpas, 1980, 1982; Hacker, 1990, 1994; Hacker and Mosenfelder, 1996; Gnos, 1998; Cowan et al., 2014; Rioux et al., 2016) and shear zones within the mantle section (e.g. Dijkstra and Drury, 2002; Michibayashi and Mainprice, 2004; Michibayashi et al., 2006; Linckens et al., 2011), relatively few have focused on the mylonitized peridotites along the base of the ophiolite. In a review of ophiolitic mantle sections, Nicolas et al. (1980) differentiate between an upper section with a coarse-grained porphyroclastic to granular texture, and a lower section with a fine-grained porphyroclastic to mylonitic texture. They interpret the upper peridotites as preserving high-temperature asthenospheric flow beneath an oceanic spreading centre, that is overprinted by the mylonitic and porphyroclastic textures related to lower-temperature thrusting during emplacement of the ophiolite. Boudier and Coleman (1981) conducted a microstructural analysis of peridotites from a