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Localized slip controlled by dehydration embrittlement of partly serpentinized dunites, Leka Ophiolite Complex, Norway

Kristina G. Dunkel[a,*], Håkon Austrheim[a], François Renard[a,b], Benoit Cordonnier[a], Bjørn Jamtveit[a]

[a] *Physics of Geological Processes (PGP), Department of Geosciences, University of Oslo, P.O. Box 1048, Blindern, 0136 Oslo, Norway*
[b] *Univ. Grenoble Alpes, ISTerre, F-38000, Grenoble, France*

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ABSTRACT

Dehydration of partly or completely serpentinized ultramafic rocks can increase the pore fluid pressure and induce brittle failure, a process referred to as dehydration embrittlement. However the extents of strain localization and unstable frictional sliding during deserpentinization are still under debate. In the layered ultramafic sections of the Leka Ophiolite Complex in the Central Norwegian Caledonides, prograde metamorphism of serpentinite veins led to local fluid production and to the growth of Mg-rich and coarse-grained olivine with abundant magnetite inclusions and δ^{18}O values 1.0–1.5‰ below the host rock. Embrittlement associated with the dehydration caused faulting along highly localized ($<$10 μm-wide) slip planes near the centers of the original serpentinite veins and pulverization of wall rock olivine. These features along with an earthquake-like size distribution of fault offsets suggest unstable frictional sliding rather than slower creep. Structural heterogeneities in the form of serpentinite veins clearly have first-order controls on strain localization and frictional sliding during dehydration. As most of the oceanic lithosphere is incompletely serpentinized, heterogeneities represented by a non-uniform distribution of serpentinite are common and may increase the likelihood that dehydration embrittlement triggers earthquakes.

1. Introduction

Dehydration of serpentine in partly or completely serpentinized ultramafic rocks increases the pore fluid pressure, lowers the effective confining pressure and potentially contributes to brittle failure by dehydration embrittlement and frictional sliding (e.g., Miller et al., 2003; Raleigh and Paterson, 1965). This process can operate at confining pressures where the total volume change during deserpentinization is positive (Dobson et al., 2002), but possibly also at higher pressures (Jung et al., 2004). The breakdown of serpentine has thus been suggested as one possible mechanism for intermediate-depth earthquakes (50–300 km) in subduction zones (e.g., Hacker et al., 2003; Peacock, 2001). However, experimental studies of deserpentinization have produced ambiguous results regarding strain localization and sliding mode. There is evidence for both unstable (Dobson et al., 2002; Jung et al., 2009) and stable sliding (Chernak and Hirth, 2011; Gasc et al., 2011). Unstable sliding involves an acceleration of the slip towards a dynamic velocity, leading to earthquake nucleation and seismic slip. Due to the discrepancies in the experimental results, the role of deserpentinization in triggering seismogenic failure is still under discussion (Proctor and Hirth, 2015, and references therein).

A relevant issue in this discussion is the role of pre-existing heterogeneities (i.e., fractures, veins, remnant clasts of ultramafic rocks) in the lithologies undergoing slip. Most experiments are carried out in almost pure serpentinite with limited heterogeneities beyond the grain scales. In natural systems however, ultramafic rocks are frequently only partly serpentinized and serpentinization is often focused along fractures or other well-defined zones where fluids gained access to the olivine-rich rocks. These features represent heterogeneities on much larger scales than the grain size. Here we describe an example of partly serpentinized dunites from the Leka Ophiolite Complex (Norway), where dehydration of the serpentinized volumes led to brittle failure and possibly frictional sliding along pre-existing heterogeneities.

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* Corresponding author.
E-mail address: kristina.dunkel@geo.uio.no (K.G. Dunkel).

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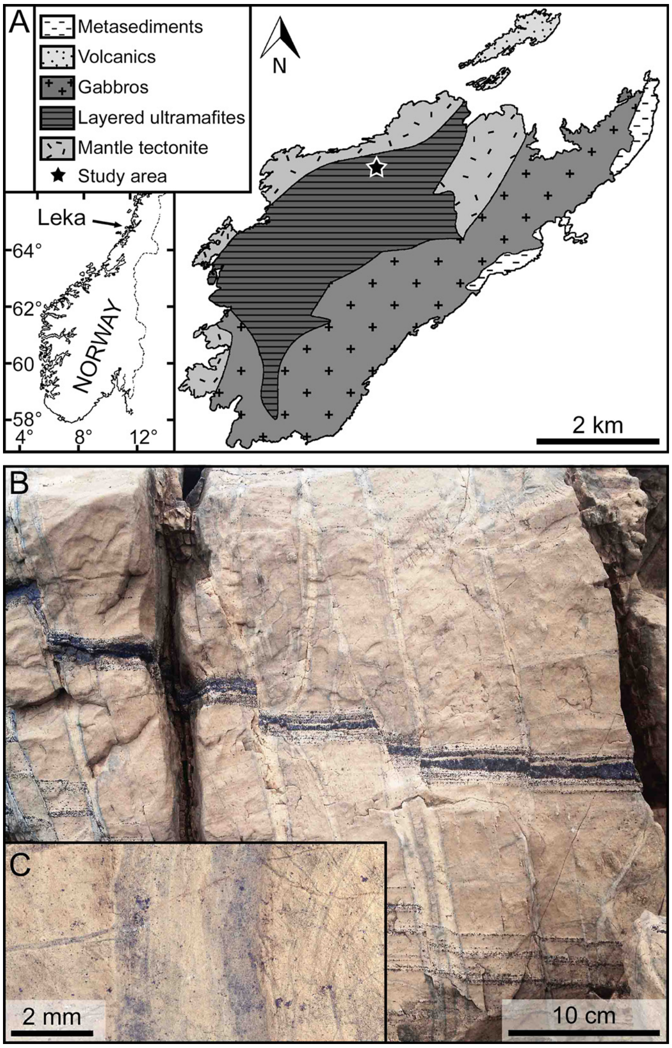

Fig. 1. A. Geological map of the Leka Ophiolite Complex (after Pedersen et al., 1993), showing the study area (WGS84 65.10530, 11.63318) in the layered ultramafites. B. Field image of a dunite in which chromite layers (horizontal) record a sharp offset along the centers of olivine veins (vertical). C. Detailed view of one vein, comparable to the area shown in Fig. 3. The dark edges of the veins are caused by a high density of magnetite inclusions in olivine.

2. Geological setting

The Leka Ophiolite Complex crops out on the island of Leka in Nord-Trøndelag, Norway (Fig. 1A), and represents part of the Upper or Uppermost Allochthon of the Norwegian tectonostratigraphy. The ophiolite, whose mafic and ultramafic components crystallized at 497 ± 2 Ma (U/Pb zircon age, Dunning and Pedersen, 1988), formed in a supra-subduction zone setting of the North Iapetus ocean (Furnes et al., 1988). It was obducted during the Caledonian orogeny in Ordovician to early Silurian times (Dunning and Pedersen, 1988) and now occurs in a pull-apart structure resulting from post-orogenic extension (Titus et al., 2002). A dehydration event was proposed for the Leka Ophiolite Complex based on olivine pseudomorphs after serpentinized orthopyroxene in the mantle tectonites (Plümper et al., 2012). Correspondingly, radiogenic and stable isotope compositions of talc-carbonate alteration products in the ultramafic cumulates suggest introduction of fluids derived from deserpentinization of underlying units (Bjerga et al., 2015).

The exact timing and cause of the dehydration event is uncertain, but cross-cutting relationships show that it preceded late lizardite- and antigorite-serpentinization. Plümper et al. (2012) proposed that dehydration may have occurred transiently within the oceanic lithosphere before the obduction of the ophiolite. They excluded contact metamorphism, subduction, and Barrovian-type metamorphism during orogeny as causes for deserpentinization based on the absence of magmatic intrusions, the lack of blueschist- and/or eclogite-facies associations, and the transient nature of the dehydration, respectively, and gave several alternatives to explain the temperature increase required for deserpentinization: Faults may have juxtaposed serpentinized mantle against the hotter end of an adjacent ridge segment. The feedback between mantle hydration and hydrothermal convection at oceanic spreading centers could have led to transient dehydration. Subduction of an active spreading center may have caused the influx of hot asthenosphere through a “slab window” (Shervais, 2001). Here, we present evidence for deserpentinization and associated faulting from a stratigraphically lower part of the ultramafic cumulates than has been investigated by Bjerga et al. (2015) and show that dehydration embrittlement has led to localized slips with earthquake-like properties.

3. Methods

In the field (WGS84 65.10530, 11.63318; Fig. 1A), fault offsets were measured and hand samples and minicores were taken, from which thin sections were made. From selected samples, major element compositions were measured by wavelength-dispersive spectrometry (WDS) with a Cameca SX 100 electron microprobe (Department of Geosciences, University of Oslo), using an acceleration voltage of 15 kV and beam currents between 10 and 20 nA. Iron distribution maps were acquired using WDS on the Cameca SX 100 electron microprobe and using energy-dispersive spectrometry (EDS) on a Hitachi SU5000 FE-SEM (Department of Geosciences, University of Oslo).

Crystallographic orientation data was obtained from electron backscatter diffraction (EBSD) measurements with the CamScan X500FE Crystal Probe at Géosciences Montpellier (CNRS-Université de Montpellier, France), equipped with an Oxford/Nordlys EBSD detector. The Crystal Probe was operated at an accelerating voltage of 20 kV and a working distance of 25 mm. EBSD patterns were indexed automatically using the AZtec software from Oxford Instruments. Crystallographic preferred orientations (CPOs) and grain boundaries were computed using the Matlab toolbox MTEX (version 4.0.11; http://mtex-toolbox.github.io; Bachmann et al., 2010, 2011). Grains were modeled with a misorientation threshold of 10°; grains smaller than 10 pixels were excluded. Non-indexed pixels have been included in the grains to reconstruct the grain distribution before the fragmentation of olivine grains by late serpentine.

For detailed imaging of a fault zone, one three-dimensional micro-computed X-ray tomographic volume of a $4.0 \times 0.9 \times 0.7\ \text{cm}^3$ sample was acquired at the beamline ID19 of the European Synchrotron Radiation Facility in Grenoble, with a spatial resolution equal to the voxel size of 4.66 μm. Tomographic acquisition was performed under continuous rotation of the sample with camera synchronization based on the angular encoder signal of the rotation stage. The exposure time was 0.05 s, the beam energy was 68 keV, and 6000 projections were taken over 360°, resulting in a total scan time of about 6 min. Tomographic reconstruction was performed using the program PyHST2 (Mirone et al., 2014).

Oxygen isotope analyses were conducted to elucidate the conditions of vein formation. The preparation and analysis of two samples were performed in the NordSIM ion microprobe laboratory at the Swedish Natural History Museum, Stockholm. The samples and standards (San Carlos olivine with $\delta^{18}O = 5.30‰$) were embedded into epoxy resin, polished, and gold-coated. $^{18}O/^{16}O$ isotope ratios were determined *in situ* using secondary ionization mass spectrometry (SIMS) on a CAMECA IMS 1280 ion microprobe, operating