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A numerical and experimental investigation on seismic anisotropy of Finero peridotite, Ivrea-Verbano Zone, Northern Italy

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Abstract. The Ivrea-Verbano Zone offers a unique opportunity to study lower crust/upper mantle rocks unaffected by serpentinization. Peridotites from Finero (North-East Ivrea-Verbano Zone) have been collected to investigate the influence of individual mineral phases on seismic anisotropy. The methods involve experimental ultrasonic P-wave velocity measurements using a hydrostatic pressure vessel, and electron backscatter diffraction (EBSD) analysis to investigate the crystallographic preferred orientation (CPO). CPO was analyzed by large area EBSD scans for major minerals including olivine, orthopyroxene, but also for metasomatic hornblende. The CPO of olivine is confirmed to be the major source of detected seismic anisotropy. Minor influence can arise from hornblende if it is sufficiently abundant.

1. Introduction

One of the causes of seismic anisotropy in the lower continental crust and in the upper mantle is the crystallographic preferred orientation (CPO) of volumetrically dominant rock forming minerals [1] or of textured minerals that are volumetrically less abundant, but with strong single crystal anisotropy [2]. Several velocity measurements have been made for the most representative lithologies of the crust and upper mantle [3–4], and compared to the results of numerical models of rock seismic properties. A common method for calculating the seismic bulk properties of a rock is based on measurements of CPO of the constituent minerals, obtained by electron backscatter diffraction (EBSD) techniques [5]. The Voigt-Reuss-Hill (VRH) estimates [6] are then used to calculate the bulk elastic tensor and various averages are applied to the elastic stiffness tensor. In this study, we accomplished EBSD measurements on two Finero peridotites and microtextural calculations based on these EBSD measurements. Meanwhile, laboratory measurements using a hydrostatic pressure vessel were performed for comparison with the calculated seismic velocity. A novel numerical method, which incorporates EBSD-data into a finite-element (FE) model [7, 8] to simulate elastic waves propagating through an anisotropic and heterogeneous rock model, is presented and discussed.

2. Material and methods

2.1. Sample description

We selected sample ZAP202 and ZAP207, representative of an upper mantle with crustal metasomatic alterations, which were drilled in the Finero ultramafic complex (Ivrea Zone, Northern Italy). The two samples are harzburgites (olivine and orthopyroxene) and contain phlogopite and hornblende in different modal proportions. Clinopyroxene (Cr-diopside) is in low modal proportion and spinel represents less than 1% of the whole rock. Secondary minerals such as oxides and serpentine occur only in negligible quantities. The samples are coarse grained (up to 3 mm diameter). The lineation and foliation were determined on hand specimen and in thin section; the foliation is defined by the planar disposition of phlogopite, and a lineation is defined by the elongation of olivine and/or amphibole.

2.2 Seismic velocity measurements in laboratory
Cores of 26 mm diameter and ca. 30–50 mm length were drilled along three mutually perpendicular directions aligned with lineation and foliation. A hydrostatic pressure vessel is utilized to measure the travel time of compressional waves through the sample up to 200 MPa. Due to the closure of microfractures, the seismic velocity measured during pressurization is lower than depressurization. We report the velocity measured during depressurization as it is reproducible. After systematic calibration, seismic velocities are calculated and extrapolated to 0 MPa from above 100 MPa downwards to reflect the intrinsic mechanical properties.

2.3 Determination of CPO
The core surfaces were ground, polished, and lapped with colloidal silica in order to obtain a smooth surface low in defect content and thus suitable for EBSD measurements. The sides of each core were covered with silver paint to reduce charging problems, but no surface coating was applied. EBSD data were acquired on a scanning electron microscope EOscan (Tescan, Brno CZ), equipped with a Pegasus OIM™ version 6.2 analytical system by Ametek-EDAX (Mahway, NJ, USA). EBSD patterns and energy dispersive X-ray spectroscopy (EDS) counts of specific elements were mapped simultaneously with a beam current of 3–5 nA and 20 kV acceleration voltage. Only one high-symmetry phase was indexed online to increase acquisition speed. The data were later reprocessed using the ChiScan routine of OIM™ Data Collection to re-index all relevant mineral phases filtered by user-defined windows for EDS counts. The MATLAB toolbox MTex [9] is utilized to perform textural analysis, i.e. calculating and plotting the stereograms of CPO and of seismic velocity. Hill averages are presented by averaging the Voigt and Reuss bounds [6]. Thus the effects from CPO are reflected, whereas the grain shape preferred orientations (SPO) are not considered. As the selected samples are massive and lack very strongly developed SPO, such approximation is reasonable. We have also investigated the influence of SPO on seismic anisotropy separately, confirming that assumption [7, 8]

3. Results
The laboratory measured Vp at around 8 km/s are typical for peridotite (Table 1). The seismic anisotropy calculated for room pressure as $(Vp_{max}–Vp_{min})/Vp_{average}$ for sample ZAP202 is significantly lower than for sample ZAP207 (Table 1). The velocities calculated from the EBSD dataset using MTex toolbox [9] are illustrated in Fig. 1. The CPO and seismic velocity stereograms (Hill average) are calculated for the three most important and abundant mineral phases, olivine, enstatite, and hornblende. The results yield that olivine is the most influential mineral phase, which dominates the velocity stereogram. Minor influence can arise from the rest mineral phases as the bulk velocity is generally reduced compared with the olivine velocity stereogram (see colorbars in Fig. 1). Hornblende in ZAP202 yields different maxima velocity direction compared to olivine but is not sufficient to cause a significant change in the bulk velocity distribution. Hornblende abundance (9%) and its sharp CPO are most likely the cause of the higher anisotropy in sample ZAP207.

Table 1 Experimental results on Vp measurements

Sample	Density [g cm^{-3}]	Vp at 0 MPa [km s^{-1}]	Vp at 250 MPa [km s^{-1}]	Vp pressure derivative [10^{-4} km s^{-1} MPa^{-1}]	Anisotropy
ZAP 202 X	3.29	8.318	8.491	6.938	2.4%
ZAP 202 Y	3.29	8.317	9.524	8.249	
ZAP 202 Z	3.29	8.122	8.231	4.343	
ZAP207 X	3.26	8.371	8.523	6.082	7.2%
ZAP 207 Y	3.26	8.084	8.199	4.599	
ZAP 207 Z	3.25	7.762	7.931	6.762	

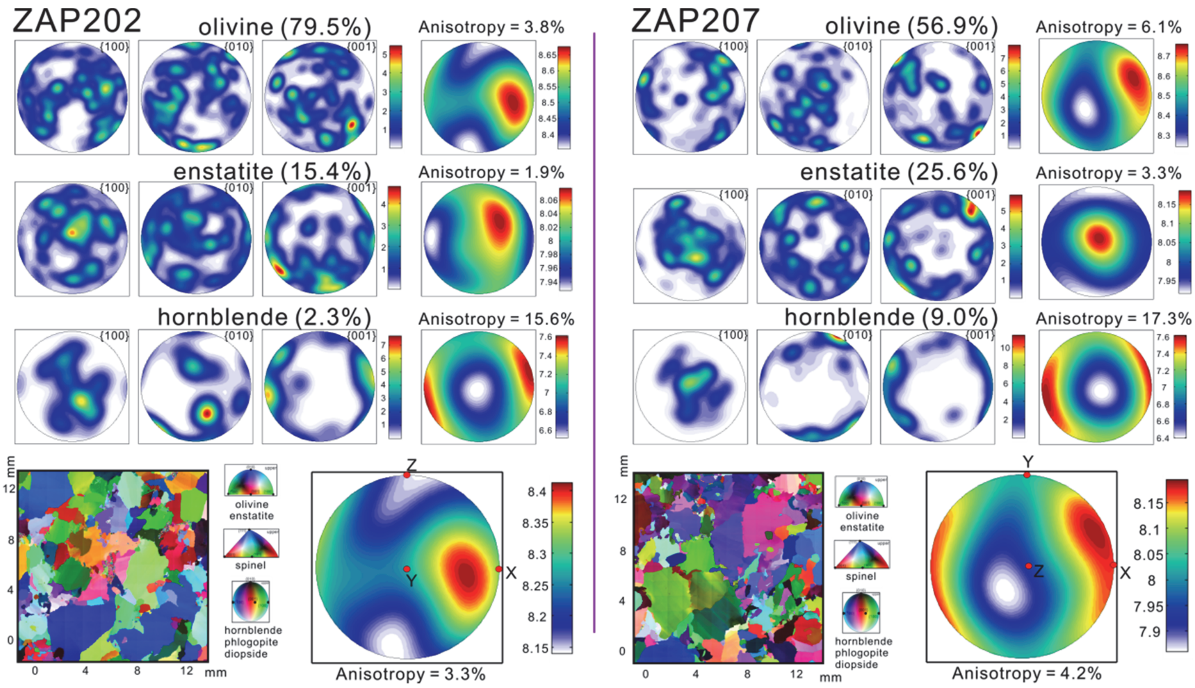

Figure 1 Pole figures (in m.u.d.) and stereograms of calculated Hill Vp velocities (in km/s) of samples ZAP202 and ZAP207. The modal compositions are given after the mineral names (in area %). Calculated anisotropies are given for individual mineral phases and the bulk rock. Hand specimen orientations equal to core directions are indicated on the bulk rock velocity stereograms. EBSD crystallographic orientation maps are provided on the bottom left. Minor amounts of spinel, phlogopite and clinopyroxene are not listed here.

4. Discussion

We performed laboratory measurements using a hydrostatic pressure vessel and classic VRH calculation on Finero peridotite samples. Moderate degree of seismic anisotropy has been observed in the reported peridotite samples ZAP202 and ZAP207. Olivine is confirmed to be the most dominant mineral phase on seismic anisotropy. Enstatite has lower degree of anisotropy in the abundant mineral phases. Although highly anisotropic, phlogopite has very low modal concentration and can be neglected. If its modal percentages would be higher, a significant influence on bulk velocity can be caused by such strongly anisotropic phase. SPO is observed but is not considered based on current calculation. Hornblende has higher modal composition and is sufficient to influence on the overall higher anisotropy of sample ZAP207. There is some extent of discrepancy between the seismic anisotropy of laboratory data and the calculated one, especially for ZAP207; the potential cause may be the presence of preferentially aligned fractures that were not recorded on EBSD data. Therefore, more EBSD sections, or even three-dimensional analysis of larger sample volumes are required to achieve closer correlation between laboratory measurements and numerical calculations.

The advantage of laboratory measurements is that the velocity is directly representative for the full sample core, but the involved experimental effort often hinders researchers from measuring seismic velocity in many directions. In many situations, the directions of maximum and minimum velocity do not coincide with the directions of the selected (typically three perpendicular) cores. The numerical calculation, on the other hand, provides complete information in the form of stereogram but may neglect important features, such as fractures

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and SPO. Therefore, comprehensive investigation is imperatively required to provide thorough understanding on seismic anisotropy. New approaches, such as EBSD-based FE model can provide a promising alternative. The main idea of such FE simulation we have developed is to use the measured CPO on the X-Y grid in the sample surface plane to construct a map of rotated elastic tensors on the same spatial coordinates, which in turn are the mesh to perform FE wave propagation simulations [7, 8].

5. Conclusions

Olivine dominates the seismic anisotropy in these reported Finero peridotite samples. Minor influence can arise from highly anisotropic hydrous mineral phases if they are textured and their modal percentage is high enough. Coherence is found between the laboratory measurements and the calculation but discrepancies still exist possibly due to fractures or SPO.

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