1	Crystallographic preferred orientation, magnetic and seismic anisotropy in rocks
2	from the Finero peridotite, Ivrea-Verbano zone, Northern Italy – interplay of
3	anisotropy contributions from different minerals
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27 Abstract

28 Mineral alignment can provide valuable information on a rock's geological history. Many structural, 29 tectonic, or geodynamic studies rely on determining the preferred orientation of rock-forming minerals, either by direct texture determination or using anisotropy measurements as proxies. 30 31 Robust interpretations of anisotropy require detailed understanding of its relationship with texture. 32 This study investigates the texture, magnetic and seismic anisotropies of ultramafic rocks from the 33 Ivrea-Verbano Zone (IVZ), Northern Italy, with a special focus on the interplay between anisotropy 34 contributions carried by different minerals. Texture was obtained from electron backscatter 35 diffraction, magnetic anisotropy from low- and high-field anisotropy of susceptibility measurements, and seismic anisotropy from P- and S-wave velocities along the three principal directions of the 36 37 macroscopic fabric, using 22 mm diameter cores. Texture-based models of magnetic anisotropy agree well with corresponding measurements. Larger variability is observed for seismic anisotropy. 38 39 Possible explanations are (1) velocities were measured in three directions, insufficient to determine 40 the full elasticity tensor, and (2) seismic anisotropy depends on grain boundaries, pores, and cracks in addition to crystallographic preferred orientation. The contributions to magnetic and seismic 41 42 anisotropy of each constituent mineral can interfere positively, leading to a larger overall anisotropy, 43 or negatively, resulting in a weaker anisotropy. Seismic anisotropy is mostly controlled by olivine, 44 whereas magnetic anisotropy can be dominated by olivine, pyroxene, or hornblende. This study illustrates that, although the relationship between texture and anisotropy can be complex, it is 45 46 possible to quantitatively predict magnetic, and to a lesser degree seismic, anisotropy from texture 47 data. Even though both magnetic and seismic anisotropies are common proxies for texture, they are 48 not coaxial, and no simple relationship between the degree of magnetic and seismic anisotropy was 49 found. These results underline the importance of understanding different minerals' contributions to 50 anisotropy in upper mantle rocks. 51 Keywords: magnetic anisotropy, seismic anisotropy, EBSD, CPO, Ivrea-Verbano Zone, Finero

52 peridotite, olivine, hornblende, phlogopite

53 1. Introduction

- 54 Crystallographic preferred orientation (CPO) of minerals arises during deformation of rocks, and thus
- 55 provides information on geodynamic and tectonic processes. When the intrinsic physical properties
- of a mineral are anisotropic, and it possesses a CPO, it can contribute to anisotropy of bulk rock
- 57 properties. Anisotropy and CPO are directly related for properties that depend on the bulk
- properties of a grain, rather than the grain boundaries (Mainprice et al., 2011; Mainprice and
- 59 Humbert, 1994). Correlations between anisotropy and CPO have been described for example for
- 60 thermal conductivity and diffusivity, magnetic susceptibility or seismic velocities (Gibert and
- 61 Mainprice, 2009; Hess, 1964; Khazanehdari et al., 1998; Owens and Bamford, 1976; Owens and
- 62 Rutter, 1978; Nicolas and Christensen, 1987; Tommasi et al., 2001).
- Because anisotropy is a direct consequence of CPO, it often serves as proxy for rock texture. An 63 64 advantage of anisotropy is that it can be characterized more efficiently than CPO. Additionally, a 65 larger volume of grains can be targeted (Engler and Randle, 2009). For this reason, the anisotropies of magnetic susceptibility (AMS) or remanence (AMR), referred to as magnetic fabrics, are often 66 67 used to determine flow directions or strain patterns (Borradaile and Henry, 1997; Borradaile and 68 Jackson, 2010; Hrouda, 1982; Jackson and Tauxe, 1991; Jackson, 1991). Early magnetic fabric studies 69 relied on qualitative and empirical relationships between magnetic and mineral fabrics, postulating 70 that (1) the maximum susceptibility indicates lineation and minimum susceptibility is normal to 71 foliation, and (2) the degree of anisotropy increases with increasing strain (Balsley and Buddington, 72 1960; Hirt et al., 1993; Kligfield et al., 1981). Later studies found correlations between magnetic 73 fabrics and CPO or shape preferred orientation (SPO) of specific minerals (Chadima et al., 2004; 74 Grégoire et al., 1998; Lüneburg et al., 1999; Siegesmund et al., 1995). After the magnetic properties 75 of single crystals have been systematically characterized (Biedermann, 2018, and references 76 therein), it is now possible to model magnetic anisotropy based on CPO data. These models allow to 77 investigate which mineral dominates the anisotropy, and how the anisotropies of different minerals 78 in a rock interfere with one another (Biedermann et al., 2018; Biedermann et al., 2015b; Kuehn et 79 al., 2019; Schmidt et al., 2009).

80 Another advantage is that anisotropy measurements can be obtained for regions in the Earth where 81 no direct texture measurements are possible. For example, seismic anisotropy in the mantle, as 82 observed by shear wave splitting, provides information on mantle flow patterns (Silver, 1996; Silver and Chan, 1988; Vauchez and Barruol, 1996). The relationship between CPO and elastic properties of 83 84 the upper mantle has been well established over the last 50 years (Babuška, 1972; Babuška and 85 Cara, 1991; Carter et al., 1972; Nicolas and Christensen, 1987). Additionally, the link between 86 seismic anisotropy, CPO, deformation mechanisms and stress fields has been investigated 87 extensively for the lower crystalline continental crust (Burlini and Fountain, 1993; Lloyd et al., 2009; 88 Tatham et al., 2008), and sedimentary rocks (Maddock, 2006; Valcke et al., 2006; Wenk et al., 2008). 89 Nicolas and Christensen (1987) observed that olivine CPO forms through crystal reorientation during

90 dislocation creep-dominated deformation in the upper mantle. Because the deformation regime has

- 91 an effect on the olivine CPO observed in continental deformation zones (Tommasi et al., 1999),
- 92 seismic anisotropy may carry information on the deformation regimes active in the lithospheric
- 93 mantle. Modeling seismic anisotropy is much more common than similar magnetic models (Almqvist
- 94 and Mainprice, 2017, and references therein). Some seismic modeling studies have employed AMS
- 95 data for an initial fabric characterization, to define appropriate measurement directions for seismic
- 96 measurements (Gaudreau et al., 2017; Punturo et al., 2017; Schmitt et al., 2007). However, even
- 97 when CPO data were available for these studies, no attempts had been made to model the magnetic
- 98 anisotropy.
- Both seismic and magnetic anisotropy are related to the preferred alignment of a rock's constituent
 minerals. In addition, factors such as porosity, compositional banding, grain boundaries, microcracks,
 fractures and melt inclusions affect the seismic anisotropy (e.g. Babuška, 1984; Kern and Wenk 1990;
 Nur and Simmons, 1969; Siegesmund et al., 1991; Wendt et al., 2003).
- 103 The exact relationship between mineral alignment and anisotropy may be different for magnetic and 104 seismic properties, because each property is defined by different characteristics of a mineral. On the 105 single crystal scale, elastic anisotropy depends on the atomic distance and stiffness of chemical 106 bonds between atoms in each direction. Conversely, magnetic anisotropy is predominantly 107 controlled by the site occupancy, arrangement, and oxidation state of iron atoms in the crystal. As a 108 consequence of their different origins, it is likely that the magnetic and seismic anisotropies of a rock 109 are controlled by different minerals. For example, relatively small amounts of mafic minerals can 110 completely dominate the magnetic anisotropy (Biedermann et al., 2016), whereas the seismic properties are likely dominated by the most abundant mineral (Almqvist and Mainprice, 2017). 111 Additionally, magnetic properties are described by 2nd order tensors, but elasticity, which defines 112 seismic anisotropy, is a tensor of 4th order. Hence, even though both types of physical anisotropies 113 114 are used to describe texture, they do not necessarily carry the same information. Nevertheless, both 115 types of anisotropy are used to infer texture, and it is interesting to establish correlations between
- 116 their principal directions or degrees of anisotropy.
- 117 One challenge when interpreting anisotropies of multiphase aggregates, including rocks, is that the 118 contributions to anisotropy carried by different mineral phases are not always coaxial. Biedermann 119 et al. (2015b) and Kuehn et al. (2019) have observed both positive and negative interferences 120 between magnetic anisotropy components related to different phases. Hence, the orientations of 121 maximum, intermediate and minimum susceptibilities, respectively, can be sub-parallel for several 122 anisotropy components, so that the overall anisotropy is enhanced. Conversely, the minimum 123 susceptibility of one phase may be sub-parallel to the maximum susceptibility of another phase, so 124 that the two components partially cancel each other, resulting in a weak overall anisotropy. 125 Similarly, Michibayashi et al. (2016) suggested that destructive interferences between the P-wave 126 anisotropies of different minerals may be responsible for the observed weak seismic anisotropy in a
- 127 shear zone in slow-spreading oceanic crust of the Philippine Sea.

128 This study investigates the CPO, magnetic and seismic anisotropy of samples from the Finero 129 peridotite (Ivrea-Verbano Zone, Northern Italy). The study particularly focuses on (1) how different minerals and their CPOs interact to define the overall anisotropy of the rock, (2) the influence that 130 131 hydrous minerals such as phlogopite or hornblende may have on the bulk rock anisotropy, and (3) if 132 there is any quantitative correlation between magnetic and seismic anisotropy, either in terms of principal directions or anisotropy degree. Correlations between CPO and magnetic/seismic 133 134 anisotropies will be investigated based on measurements and models. The latter makes it possible to 135 disentangle the contributions of individual minerals to the bulk rock anisotropy. The results 136 presented here will help to better understand how anisotropy is related to CPO, and thus lead to 137 more robust interpretations for tectonic and geodynamic studies employing anisotropy as a proxy

138 for texture.

139 **2. Geological setting**

140 The samples characterized in this study are peridotites from the Finero Ultramafic Complex, located 141 within the Ivrea-Verbano Zone (IVZ) in the Western Italian Alps. Because of its easy accessibility, 142 excellent exposure, and the absence of pervasive retrograde metamorphism, the IVZ is one of the 143 most studied lower-crustal transects worldwide. Even though the interpretation of the IVZ and 144 adjacent Serie dei Laghi as a middle- to lower-continental crust have been recently criticized (Boriani 145 et al., 2016 and references therein), it is commonly used as a model to help interpret features of deep 146 crustal seismic profiles (Fountain, 1976; Holliger et al., 1994; Holliger et al., 1993; Khazanehdari et al., 147 2000; Rudnick and Fountain, 1995; Rutter et al., 1999; Tommasi et al., 2017). Only a few main aspects 148 of the IVZ that are relevant to our study will be mentioned here, well aware that the papers we 149 mention represent just a fraction of the significant existing literature.

150 The IVZ mainly consists of a metamorphosed volcano-sedimentary sequence, referred to as the 151 Kinzigite Formation, and gabbroic to dioritic intrusive rocks, referred to as the Mafic Complex (Figure 152 1). The metamorphic grade in the IVZ increases towards the northwest, from upper amphibolite facies 153 adjacent to the Serie dei Laghi, to granulite facies near the northwestern boundary of the IVZ at the 154 Canavese Line tectonic lineament, which separates the IVZ from the Alpine terranes, here represented by the Sesia Zone (Peyronel Pagliani and Boriani, 1967; Schmid, 1967; Zingg, 1983). Metamorphosed 155 156 shales and greywacke (the so-called kinzigites and stronalites), with minor quartzites and meta-157 carbonates, are interlayered with diorites, norites, and metabasites whose abundances gradually 158 change from the southern part (metabasite predominant) to the northermost part (meta-sediments 159 predominant). Mantle peridotite lenses, tectonically interfingered with the metasedimentary rocks 160 (Quick et al., 1995), occur in the northern and western part of the IVZ, near the Canavese Line. The 161 largest of these ultramafic lenses is the Finero peridotite, also called Finero Ultramafic Complex; it lies 162 at the northern tip of the IVZ and consists of a peridotitic slice, enveloped into an intrusive magmatic 163 sequence of mafic and ultramafic rocks. The main peridotite body is harzburgite, locally grading into 164 dunite with layers of chromitite; thin dykes of pyroxenite (websterite) sharply cut the peridotite. The

Finero peridotite is characterized by the presence of hydrated minerals (pargasitic to edenitic 165 166 amphibole and phlogopite) and it is anomalously enriched in minor and trace incompatible elements. These features have been interpreted as a testimony of a later re-fertilization of a primary restitic 167 168 mantle (e.g. Coltorti and Siena, 1994; Lensch, 1968; Rutter et al., 2007). According to Zanetti et al. 169 (1999) the metasomatic harzburgite contains up to 5 % and 25% of phlogopite and amphibole, respectively. Phlogopite and amphibole are also found in the pyroxenitic dykes. Early calculations 170 171 based on sapphirine bearing layers between amphibole-lherzolite and garnetiferous metagabbro 172 suggest conditions of crystallization of 900°C-950°C and 9±1 kbar (0.9±0.1 GPa) (Sills et al., 1983). The 173 Finero peridotite therefore provides a unique opportunity to study seismic and magnetic anisotropy 174 of metasomatic mantle and obtain information on the seismic and magnetic signature of hydrous 175 phases in lower crustal conditions.

176 **3.** Sample description and methods

177 3.1 Sample petrography and microstructures

The Finero peridotite was chosen for this study for two reasons: (1) Its low degree of 178 179 serpentinization makes it possible to study the relationships between texture and anisotropy of 180 physical properties in fresh samples, without the need to account for alteration and secondary 181 minerals. (2) Its reported variability in modal composition, especially with respect to hydrous minerals, allows to study the interplay of anisotropy contributions carried by different minerals. 182 183 Seven peridotite block samples from the Finero Ultramafic Complex with different modal compositions were selected for this study (Figure 1). Optical microscopy observations on thin 184 sections (30µm in thickness) ensured that the abundance of secondary minerals (serpentine in 185 particular) was small, and that the samples were representative of the hydrous mineral content 186 within the Finero peridotite. Samples ZAP201, ZAP202, ZAP204, and ZAP207 are spinel bearing 187 188 harzburgites, and ZAP205 a spinel lherzolite, with phlogopite modal content, as determined from 189 optical microscopy, from 0 to 8 %. Sample ZAP208 tends towards a more dunitic composition. 190 Sample ZAP214 is a harzburgite, but differs from the other harzburgites by its high amphibole 191 content (20%, determined by optical microscopy).

Optical microscopy analyses of thin sections show that the spinel-bearing harzburgites and the lherzolite are characterized by large olivine crystals, with average grain sizes of 1.5 mm (ZAP207) to 2.5 mm (ZAP202). The dunite sample ZAP208 is coarser and displays 3.5 mm average grain size. The amphibole-rich harzburgite ZAP214 possesses the smallest olivine grains (< 1.5 mm on average). In the harzburgites, the olivine grains generally display a shape preferred orientation, which helps define the pervasive foliation of the rocks. In the dunite, olivine displays more polygonal, equiaxial shapes. In all samples, olivine possesses intra-granular deformation features such as undulose

- extinction and subgrain boundaries. Those are especially prominent in ZAP202 and ZAP205 (Figure200 2).
- 201 Orthopyroxene (enstatite) occurs in the harzburgites as dispersed interstitial grains with irregular
- shape and pinnacle terminations at the boundary with olivine (cf the enstatite grains in samples
- 203 ZAP202 and ZAP205 shown in Figure 2). Grain size varies from a few microns, e.g. in the bands
- around coarse olivine grains of sample ZAP204, to a few millimeters, e.g. in ZAP201.
- 205 Clinopyroxenes (diopside) are minor constituents of harzburgites. Clinopyroxene crystals are
- dispersed, with irregular interstitial shapes and variable grain sizes. They are in general smaller than
- 207 olivine and orthopyroxene.
- 208 Amphibole is dispersed through the harzburgite, but may concentrate locally in elongated lenses or
- 209 layers. The crystals tend to be flattened in the foliation plane and slightly elongated parallel to the
- 210 lineation. Their longest axis is up to 2mm long.
- 211 Phlogopite occurs as flakes with grain sizes up to 4-5 mm, and flattened in the foliation plane. The
- 212 phlogopite crystals often display kinks (cf ZAP207 in Figure 2). Pinning of olivine grain boundaries at
- the contact with phlogopite crystals is observed in all samples.
- 214 The microstructure of ZAP214 corresponds to the protomylonites described in Tommasi et al.
- 215 (2017). Large elongated olivine crystals are surrounded by a fine-grained matrix in a core and mantle
- 216 structure (cf ZAP214 a and b in Figure 2). The olivine crystals show subgrain boundaries at high
- angles to their elongation (Figure 2, ZAP214b) The fine-grained matrix around the large crystals has
- been interpreted as the results of a dynamic recrystallization of olivine through bulging and subgrain
- rotation (Tommasi et al., 2017). The area fraction of recrystallized grains in ZAP214 amounts up to
- 220 15%. The fine-grained matrix is locally also composed of small interstitial crystals of clino- and
- orthopyroxene. Pyroxene porphyroclasts have irregular shapes and highly indented grain
- boundaries. Hornblende is particularly abundant in ZAP214, and shows undulose extinction but no
- 223 recrystallization (Figure 2, ZAP214a).
- Table 1 summarizes the modal compositions obtained from optical microscopy and scanning
- electron microscopy (SEM) data (electron backscatter diffraction, EBSD, and energy-dispersive X-ray
- spectroscopy, EDS). Note that ZAP208 was too coarse-grained to provide statistically significant
- 227 results from SEM analysis. For all other samples, both methods result in similar estimates of olivine
- 228 content. However, the concentrations of other minerals can vary. In particular, phlogopite content
- determined from the SEM (EDS and EBSD) data is significantly lower than estimated from optical
- 230 microscopy. This discrepancy may be explained by any of the following: (1) Due to its platy habit and
- 231 dark color, phlogopite's concentration may be overestimated in optical microscopy when it is
- oriented at a small angle to the plane of the section, whereas the SEM only sees the intersection of
- phlogopite and sample surface; (2) not all grains could be indexed, and because micas do not polish
- well, phlogopite may contribute disproportionally to the non-indexed portion of EBSD data; and (3)

different sub-specimens were used for thin sections and EBSD scans, and the phlogopite distributionin the rock may be inhomogenous.

237 3.2 Sample preparation

238 Three mutually perpendicular cores of 22 mm diameter and 30 – 50 mm length were drilled from each peridotite block. The macroscopic foliation and lineation were used as reference frame; 239 240 however, the macroscopic fabric of these massive peridotites is poorly defined. Foliation and 241 lineation, respectively, are defined by the planar distribution of phlogopite and the elongation 242 direction of hornblende and pyroxene, as well as the shape preferred orientation of olivine. The 243 three cores were labeled x, y and z, based on the drilling direction; x indicates core axis parallel to 244 lineation, z core axis normal to foliation, and y refers to core axis within the foliation plane and 245 perpendicular to lineation. Seismic velocity, magnetic susceptibility and CPO were measured on the 246 same cores. Because seismic velocity measurements require longer cores (3 to 4 cm) than AMS 247 measurements (length/diameter ratio of 0.92), the seismic cores were subsampled prior to magnetic experiments. EBSD scans were performed on one core of every site. The ends cut from the cores 248 249 were used to obtain thin sections for petrographic description.

250 **3.3 Crystallographic preferred orientation**

251 After the anisotropy measurements were completed, the surface of one core from each site was 252 polished and lapped with silica gel for EBSD measurements. These were performed on a an 253 EOscanTescan Vega-3 scanning electron microscope (SEM) (Tescan, Brno CZ), at the Scientific Center 254 for Optical and Electron Microscopy (ScopeM) at ETH Zurich. The microscope is equipped with a 255 Pegasus EBSD and EDS system (OIM, Orientation Imaging Microscopy, version 6.2) by Ametek-Edax (Mahway, NJ, USA), and was operated at a beam current of 3-5 nA and 20 kV acceleration voltage. 256 257 The EBSD band positions and the EDS counts were simultaneously recorded during the acquisition scans. Only one phase was indexed during data acquisition, and all relevant mineral phases were 258 259 indexed during post-processing. For this the OIM ChiScan routine was used in combination with 260 user-defined windows defining the possible minerals from the EDS counts. The maps covered an 261 area as large as possible on the 22 mm diameter cores, i.e. about 300 mm², with a step size of 20 262 μm, and were collected by comboscans using beam scanning and field-wide stage motion.

263 Crystallographic preferred orientation was computed from all indexed points on the regularly spaced

264 grid. This allows to weight the individual mineral and orientation distribution by area, and is

265 therefore better suited to calculate physical properties and their anisotropy than CPOs calculated

based on one point per grain. The latter would overestimate the contribution of small grains, and

267 underestimate the contribution of large grains. To be consistent, all CPOs shown in this manuscript

and supplementary files are based on an equally spaced grid.

269 **3.4 Magnetic measurements**

- 270 Magnetic measurements included acquisition of isothermal remanent magnetization (IRM), to
- 271 characterize the ferromagnetic minerals, and determination of AMS in low and high fields. High field
- 272 AMS measurements have the advantage that the sub-fabric carried by paramagnetic minerals (i.e.,
- 273 olivine, phlogopite, pyroxene, amphibole) can be isolated from that of the ferromagnetic grains (e.g.
- 274 magnetite). This is important because magnetite may dominate the susceptibility, but is largely
- 275 irrelevant for describing the alignment of the rock-forming minerals. All magnetic experiments were
- 276 performed at the Laboratory of Natural Magnetism, ETH Zurich.
- 277 3.4.1 Characterization of ferromagnetic inclusions
- 278 IRM acquisition was measured to characterize ferromagnetic inclusions, and to determine their
- 279 saturation fields (if saturated, ferromagnetic contributions can be removed from high-field AMS
- 280 measurements). Cores were initially magnetized at 2 T along the -Z direction with an ASC Scientific
- pulse magnetizer, followed by remagnetization along +Z in increasing fields between 20 mT and 2 T.
- 282 Magnetization was measured after each step using a 2G 3-axis magnetometer. The remanent
- 283 coercivity and saturation field obtained from these measurements are characteristic for a specific
- 284 mineral and the saturation magnetization indicates mineral type as well as concentration.

285 3.4.2 Magnetic anisotropy

- 286 AMS was measured in low and high magnetic fields. Low-field measurements were conducted on an
- Agico (Brno, Czech Republic) MFK1-FA susceptibility bridge operated at a field of 200 A/m and a
- 288 frequency of 976 Hz. The susceptibility tensor was computed based on 15 directional susceptibility
- 289 measurements (Jelinek, 1977). The eigenvalues of this tensor, $k_1 \ge k_2 \ge k_3$, define the principal
- 290 susceptibilities, and the corresponding eigenvectors are referred to as princicpal susceptibility
- 291 directions. If susceptibility is represented by a magnitude ellipsoid, its shape can be described by
- 292 $U = (2k_2 k_1 k_3)/(k_1 k_3)$. The degree of anisotropy can be described by k' =
- 293 $\sqrt{((k_1 k)^2 + (k_2 k)^2 + (k_3 k)^2)/3}$, or alternatively by $P = k_1/k_3$. The mean susceptibility k294 is defined as $k = (k_1 + k_2 + k_3)/3$ (Jelinek, 1981, 1984). The susceptibility tensor determined with 295 low-field methods is a superposition of the susceptibilities carried by diamagnetic, paramagnetic and 296 ferromagnetic minerals.
- 297 High-field anisotropy was measured in order to separate paramagnetic and ferromagnetic
- 298 components, based on the method described in Martín-Hernández and Hirt (2001). Measurements
- were performed on a torque magnetometer in six fields between 1.0 and 1.5 T, both at room
- 300 temperature and at 77 K to enhance the paramagnetic contribution. Deviatoric susceptibility tensors
- 301 are obtained for each component, and the degree and shape of the susceptibility ellipsoid are
- 302 described by k' and U.

303 3.5 Density and seismic velocity measurements

- Both sides of the cores were polished until parallel within 0.02 mm, and oven dried for at least 24
- hours at 80°C prior to density and seismic measurements. Measurements were carried out at the
 Rock Deformation Laboratory at ETH Zurich.

307 3.5.1 Density measurements

- 308 Bulk density (i.e., the density of the entire rock, including minerals and pores) was calculated by
- 309 weighing the cores after dehydration with a highly precise balance ($\pm 5.0 \times 10^{-7}$ kg tolerance), and
- determining the bulk volume (i.e., the volume of the entire rock, including minerals and pores) of
- each core from measured length and diameter, using a caliper ($\pm 2 \times 10^{-5}$ m accuracy). The grain
- density (i.e., the density of the grain fraction, also known as matrix density) was determined on a gas
- displacement He-pycnometer apparatus (Accupyc II 1340, Micromeritics), measuring the matrix
- volume (i.e. the volume of only the minerals, without the pores) of the cores at room conditions. The
- standard deviation of each measurement was lower than 5%. The effective porosity was then
- 316 calculated as the difference between grain and bulk density.

317 3.5.2 Seismic velocities

- 318 The compressional (Vp) and shear (Vs) elastic wave velocities were measured using the pulse
- transmission technique (Birch, 1960) at room temperature (292-307K), and pressures up to 450 MPa
- 320 using an internally heated gas medium apparatus equipped with a hybrid waveguide and embedded
- 321 piezoelectric elements (PZT) to transmit and receive waveforms through the sample. Details of the
- 322 experimental setup are reported in Tisato and Marelli (2013). The specimen lengths were measured
- before and after each experimental run to minimize errors introduced by changes in sample size. All
- 324 velocity measurements were made at a frequency of 1 MHz, and estimated error limits are ~0.7% for
- 325 Vp, 1.5% for Vs, and 1 K for absolute temperature.
- 326 Velocity vs pressure data were fitted based on the four parameter equation proposed by Wepfer
- 327 and Christensen (1991). Velocities were extrapolated to 0 pressure from the linear part of the
- 328 velocity vs pressure plots (cf e.g. Burlini and Fountain, 1993). These fits for the P- and S-wave
- 329 velocities of the x-, y-, and z-core for each sample were then used to calculate the seismic
- anisotropies, Avp and Avs respectively, defined as $A(\%) = \frac{v_{max} v_{min}}{v_{mean}} * 100$ (Birch, 1960). Mean
- 331 pressure derivatives have been calculated using best-fit solutions from the linear part of the velocity-
- 332 pressure relation (150-450 MPa), and mean velocities at 0 MPa were obtained by extrapolation using
- the pressure derivatives.

334 3.5 Modeling of magnetic and seismic anisotropies

- 335 If a physical property of a rock depends on the properties of individual mineral grains rather than
- 336 grain boundaries or fractures, it can be modeled based on a combination of (1) the single crystal
- 337 physical properties of each mineral in the rock, and (2) their abundance and crystallographic
- 338 preferred orientation (Mainprice et al., 2011; Mainprice and Humbert, 1994). The MATLAB toolbox
- 339 MTex (Hielscher and Schaeben, 2008) was used to model both magnetic and seismic properties of
- 340 the cores for which EBSD data was available. Single crystal susceptibility tensors were calculated

341 from data reported by Biedermann et al. (2014b) for olivine, Biedermann et al. (2015c) for enstatite 342 and diopside, Biedermann et al. (2015a) for hornblende, and Biedermann et al. (2014a) for phlogopite. Note that physical properties of crystals need to include all the symmetry elements of 343 344 the crystal itself (Neumann, 1885; Nye, 1957). For monoclinic minerals such as diopside, hornblende, 345 and phlogopite, this symmetry constraint means that one of the principal axes of the susceptibility 346 tensor must be aligned with the 2-fold symmetry axis [010]. No symmetry constraints apply to the 347 position of the other two principal axes with respect to the crystal frame of monoclinic crystals. 348 Incidentally, the other two principal axes for hornblende happen to be parallel to (100) and [001] 349 (Biedermann et al., 2015a), as it would be required by the symmetry of orthorhombic crystals (e.g., 350 olivine and enstatite). For phlogopite, the two larger eigenvalues do not notably differ (Biedermann 351 et al., 2014a), resulting in a tensor with (pseudo-)rotational symmetry in the basal plane (001). 352 Elasticity tensors for calculating compressional and shear wave velocities were obtained from Isaak 353 et al. (1989) for olivine, Chai et al. (1997) for enstatite, Isaak et al. (2005) for diopside, and Brown 354 and Abramson (2016, pargasitic amphibole No. 8) for hornblende. Note that the latter differs from 355 the widely used tensor for amphiboles (Aleksandrov and Ryzhova, 1961), because the initial 356 measurement was likely affected by open cleavage. For phlogopite, the tensor reported by Chheda 357 et al. (2014) was used. The single crystal magnetic and seismic properties are shown in Figure 3. 358 Modal compositions and the CPO of each mineral were derived from EBSD data. Magnetic and

359 seismic tensors were computed for (1) each mineral phase, and (2) the overall anisotropy, defined by 360 a weighted combination of all relevant phases. Average property tensors can be calculated in three 361 ways; Voigt, Reuss and Hill averages, where the latter is the arithmetic mean of the former two (Hill, 362 1952; Reuss, 1929; Voigt, 1887, 1928). For elastic properties, Hill (1952) observed that the Hill 363 average agrees best with measured values. Therefore, Hill averages were used here to compute the 364 averaged seismic tensors. Conversely, because magnetic susceptibility can vary over several orders 365 of magnitude between different minerals, Reuss and Hill averages may result in unrealistic mean 366 susceptibility values. Therefore, Voigt averages were used to compute the total magnetic anisotropy. 367 The contribution of magnetite and other low-abundance phases was not taken into account for the 368 modeling.

369 4. Results

370 4.1 CPO

371 Due to the large grain sizes in comparison to the total EBSD scan area, the significance of the CPO 372 data is limited by counting statistics in the rather small grain populations. Olivine posseses a weak 373 CPO, where the [001] directions are grouped within the foliation plane, and normal to lineation in 374 most samples. The crystallographic [100] directions can be sub-parallel to macroscopic lineation 375 (ZAP204 and ZAP205), normal to foliation (ZAP214), or at an angle to lineation in a plane defined by 376 the lineation and the pole to foliation (ZAP201, ZAP202) (Supplementary Figures A-F). Enstatite 377 shows girdle distributions of [001] in the foliation plane for all samples except ZAP214. The latter 378 displays a maximum of [001] axes normal to the foliation plane, while most samples display a 379 grouping of [100] normal to the foliation plane. The CPO of diopside shows several strong maxima, 380 because only a small number of individual diopside grains have been measured. Therefore, the 381 statistical significance of the diopside CPO is questionable, and will not be discussed further. With 382 the exception of ZAP214, the hornblende (100) poles are aligned with the pole of the foliation plane, 383 and [001] directions form girdle distributions within the foliation plane, sometimes with a sub-384 maximum parallel to lineation. Phlogopite CPOs, similar to those of diopside, are sharp but not 385 statistically relevant. It appears that the macroscopic foliation and lineation of all samples except 386 ZAP214 correlate with the CPO of hornblende, and to a lesser degree enstatite. The hornblende and 387 enstatite CPOs of ZAP214 seem at odds with the macroscopic texture, because their [001] directions 388 are normal to the foliation plane, while hornblende (100) lies in the foliation plane. This means that 389 the foliation and lineation indicated by the hornblende and enstatite CPO are not parallel to the 390 macroscopic features of this sample, i.e. SPO, grain size and compositional banding.

391 4.2 Magnetic anisotropy

- 392 All samples possess significant magnetic anisotropy both in low and high magnetic fields. The 393 principal susceptibility directions are consistent across cores of the same sample and orientation, 394 and the degree and shape of anisotropy are similar for all specimens of the same sample. Low-field 395 AMS results are summarized in Table A, Online Supplementary. Mean susceptibility varies from 396 2*10⁻⁷ m³/kg to 1*10⁻⁵ m³/kg, and is on the order of 10⁻⁷ m³/kg for all samples except ZAP214. Pvalues are highest for samples ZAP207 and ZAP214 where P ~ 1.2, and vary between 1.05 and 1.10 397 398 for samples ZAP201, ZAP202, ZAP204, and ZAP205. Sample ZAP208 shows the largest variation, with 399 *P* ranging from 1.05 to 1.39. The mean deviatoric susceptibility, k', is on the order of 10⁻⁹ m³/kg to 400 10⁻⁸ m³/kg for most samples, again with large variations in ZAP208. ZAP214 has the highest anisotropy degree, with k' around 8×10^{-7} m³/kg. The shape parameter U varies between specimens, 401 402 but is mostly prolate for samples of ZAP201, ZAP202, ZAP207, and ZAP214, and oblate for ZAP204
- 403 and ZAP205. For ZAP208, three specimens have prolate shapes and three have oblate shapes.
- 404 The large variation in mean susceptibilities is likely related to varying contributions of ferromagnetic 405 minerals, which may also affect the low-field AMS. All samples acquire an IRM. The acquisition 406 curves are similar for ZAP201, ZAP202, ZAP204, ZAP205, ZAP207, and ZAP208. Their IRM is saturated 407 in fields of 200 – 300 mT. Sample ZAP214 has even lower coercivity, and saturates well below 100 408 mT (Figure 4a). These low coercivities and saturation fields indicate that the ferromagnetic signal is 409 carried by magnetite, and the magnetite grains are larger in ZAP214 than the other samples. 410 Additionally, the stronger saturation IRM, and higher susceptibility of ZAP214 compared to the other 411 samples indicates a higher concentration of magnetite, which explains its larger mean susceptibility.
- 412 Paramagnetic and ferromagnetic contributions to the high-field AMS at both temperatures are
- 413 summarized in Table B (Online Supplementary). At room temperature, the paramagnetic

- 414 contribution is highest in sample ZAP205, where it contributes 76 % to 82 % of the high-field AMS
- signal. In ZAP201, ZAP202 and ZAP204, the paramagnetic contribution is 55 % 75 %, in ZAP207 it
- 416 varies between 40 % and 60 %, and in specimens from ZAP208 covers the entire range from 41 % to
- 417 86 %. Conversely, the paramagnetic component in ZAP214 is 10% and hence a minor part of the
- 418 high-field AMS. At 77 K, the paramagnetic contribution is enhanced. The orientation of principal
- 419 AMS axes is generally consistent for equally oriented cores and at both temperatures (Figure 4b-h).
- 420 The paramagnetic k' at room temperature varies between $3*10^{-10}$ m³/kg and $1*10^{-9}$ m³/kg, except in
- 421 ZAP214 where it is ca. $2*10^{-9}$ m³/kg.
- 422 Comparing low- and high-field AMS reveals that the low-field principal directions are similar to those
- 423 of the isolated ferromagnetic component at room temperature, suggesting that the low-field AMS is
- 424 strongly dominated by the small fraction of ferromagnetic grains (Figure 4b-h). This highlights that
- 425 only the isolated paramagnetic AMS should be compared to CPO, and that low-field AMS is likely
- 426 inadequate to define the principal fabric directions.

427 4.3 Density and seismic anisotropy

- 428 Measured densities, P- and S-wave velocities are reported in Table 2. Bulk densities vary between
- 429 3.23 and 3.34 g/cm³, and porosity is less than 0.22%. Figure 5 shows the experimental seismic data,
- 430 reported as Vp and Vs versus confining pressure, together with the fitted curves, as well as
- 431 computed anisotropy. The P-wave velocity extrapolated to 0 pressure, Vp0, varies between 7.47
- 432 km/s and 8.49 km/s, with anisotropies ranging from 1.76% to 7.58%. The S-wave velocities (Vs01 and
- 433 Vs02) range from 4.36 km/s to 5.06 km/s.
- 434

435 4.4 Modeled magnetic and seismic anisotropy

- 436 CPO-based models of magnetic and seismic anisotropy indicate that each mineral contributes
- 437 anisotropically to both magnetic and seismic properties of the Finero peridotites. The modelled
- 438 whole-rock minimum susceptibility is normal to the macroscopic foliation in all samples except
- 439 ZAP214, where the CPO and macroscopic features indicate different foliation and lineation
- 440 orientations. The direction of the modelled maximum susceptibility is more variable. The modelled
- 441 maximum and minimum P-wave velocities are sub-parallel to the macroscopic lineation and
- 442 foliation, respectively, in most samples. Exceptions are ZAP201 and ZAP202 which display 45°
- 443 rotations between modelled maximum and minimum velocities and macroscopic features, and
- 444 ZAP214, where the modelled maximum P-wave velocity is normal to foliation, while the minimum
- 445 velocity lies in the foliation plane.
- The models illustrate the whole-rock anisotropies are complex composites of the contributions of
- 447 individual minerals. The maximum and minimum directions of either property can be coaxial for
- 448 several minerals in a sample, but often the directional variability of magnetic and seismic properties
- 449 is distinct for each mineral contribution.

450 5. Discussion

451 **5.1 Measured vs modeled anisotropy**

452 Paramagnetic susceptibility, P- and S-wave velocities as modeled from the CPO data have been
 453 compared to the measurements in terms of principal or minimum and maximum directions, as well

454 as anisotropy degree and shape (Figure 6-7, Table 3, online supplementary figures). Because the

455 models allow separating the contributions of each mineral phase, the dominant carrier minerals for

456 magnetic and seismic anisotropy, respectively, were also determined. Finally, the interplay of

457 anisotropy contributions of different minerals was explored.

458 5.1.1 Agreement between measured and modeled anisotropies

459 Good agreement is observed between measured and modeled principal susceptibility directions, i.e.,

460 differences between model and measurement are generally smaller than the measured inter-

461 specimen variation. The one exception to this general observation is ZAP207, where the k_1 and k_2

- directions deviate about 45° between model and measurement, likely a consequence of the small
- 463 difference between k_1 and k_2 principal susceptibilities.
- Degree and shape of paramagnetic anisotropy agree for most sets of models and measurements, but 464 465 not for all of them (Figure 8). A possible explanation for this is that the anisotropy degree strongly 466 depends on iron content in single crystals, but due to the lack of chemical data, average single 467 crystal tensors were used. Additionally, other minerals, e.g. serpentine, may contribute to the AMS, 468 but were not considered in the models. Note that the CPOs of some minerals were not statistically 469 relevant and may be unrepresentative. Also, sample heterogeneity may result in unrepresentative 470 EBSD data, possibly resulting in discrepancies between models and measurements. Still, the 471 generally good agreement between measured and modeled magnetic anisotropy indicates that the 472 CPOs derived from the EBSD data, despite the statistical limitations described in Section 4.1, are
- 473 sufficiently representative of the samples.

474 Larger variations are observed between measured and modeled maximum and minimum P-wave 475 velocities. Note that the seismic data is not sufficient to calculate the full seismic tensor, and that the 476 modeled maximum and minimum P-wave velocities are generally not parallel to the structural x-, y-477 and z-axes, along which seismic velocities were measured. When the three measurement directions 478 do not include the true minimum and maximum velocities, the minimum measured velocity 479 overestimates the true minimum velocity, and analogously, the maximum measured velocity 480 underestimates the true maximum velocity. In this case, the seismic measurements underestimate 481 the true elastic anisotropy. For this reason, seismic models and measurements cannot be directly 482 compared in terms of principal directions, and the measured anisotropy is a lower threshold 483 constraining the true seismic anisotropy. Instead, the velocities parallel to x, y and z, for which 484 measurements are available, will be compared, and the measured maximum and minimum

- velocities are checked against the more complete velocity distribution provided by the models.
- 486 Modeled and measured minimum P-wave velocities are consistent for samples ZAP205 and ZAP207,

- 487 and the maximum velocities are consistent for ZAP202, ZAP204 and ZAP205. In ZAP201, model and
- 488 measurement are oblique (Figure 7). The minimum measured P-wave velocity of ZAP214 is sub-
- 489 parallel to the maximum modeled P-wave velocity, and vice versa. This apparent discrepancy in
- 490 ZAP214 is likely related to the different orientations of CPO fabric as compared to the fabric of the
- 491 macroscopic fabric features, namely shape preferred orientation and banding. Note that the models
- 492 take into account exclusively CPO, whereas seismic measurements are affected by the
- 493 microstructure in addition to CPO. The modeled velocities are almost always faster than those
- 494 measured, and the modeled degree of anisotropy is generally lower than that measured (Figure 8).
- 495 The latter is unexpected, given that the measurements represent a minimum estimate of seismic
- anisotropy. This indicates that factors other than CPO have a major influence on the seismic
- 497 measurements, in that they reduce velocities and increase anisotropy. These may include
- 498 microcracks and pores, grain boundaries, and additional minerals, such as serpentine.
- 499 5.1.2 Carrier minerals for magnetic and seismic anisotropies
- 500 Olivine is the main constituent of all samples, and largely controls their seismic anisotropy. The
- 501 contributions of other minerals to seismic anisotropy are minor. Even for samples ZAP207 and
- 502 ZAP214 that contain a relatively high percentage of hornblende, it appears that the orientation of
- 503 minimum and maximum velocity is dominated by olivine. Particularly in ZAP214, the olivine and
- 504 hornblende CPOs are such that the fast P-wave velocity in olivine [100] is sub-parallel to the fast axis
- 505 of hornblende [001], so that their contributions interfere positively, leading to an overall stronger
- 506 anisotropy.
- 507 The magnetic anisotropy is more complex, and can be dominated by olivine, pyroxene or
- 508 hornblende, or a combination of all minerals. The magnetic tensor of ZAP204 is strongly influenced
- 509 by enstatite and hornblende, and the minimum susceptibility of ZAP214 is controlled by hornblende.
- 510 In most other samples, olivine has the strongest influence on the rock magnetic anisotropy. The
- 511 magnetic tensors of olivine, hornblende and enstatite can either be in constructive (ZAP205,
- 512 ZAP207) or destructive (ZAP202, ZAP204) interference.
- 513 Seismic and magnetic anisotropies reflect the CPOs of different minerals, and may be dominated by
- 514 different details of the orientation distribution of a given mineral. While seismic anisotropy is
- 515 dominated by olivine, the most abundant mineral, magnetic anisotropy can be controlled by
- 516 minerals that are less abundant. Single crystal seismic properties (e.g., mean velocity) are rather
- 517 uniform for the different minerals composing these rocks, whereas magnetic susceptibility and its
- 518 anisotropy can vary largely from one mineral to another. Enstatite and hornblende generally have a
- 519 higher k' than olivine, and therefore contribute over-proportionally to the overall susceptibility
- 520 anisotropy. Olivine's contribution to anisotropy is predominantly controlled by the grouping of [001]
- 521 in the case of magnetic anisotropy, but by the orientation distribution of [100] for seismic
- 522 properties. The fact that different crystallographic directions control magnetic and seismic
- 523 anisotropy is related to the difference in single crystal properties: single crystal magnetic
- 524 susceptibility in olivine is prolate, with the maximum susceptibility being parallel to [001], whereas
- 525 the maximum P-wave velocity is parallel to [100]. This may be exploited to investigate the details of
- 526 olivine orientation distributions in future studies.
- 527 5.2 Correlations between rock texture, magnetic and seismic anisotropy

- 528 Both modelled and measured minimum susceptibilities are normal to the macroscopic foliation
- 529 plane in all samples except ZAP214, where the minimum susceptibility lies in the foliation plane and
- 530 perpendicular to lineation. A large scatter in minimum directions is observed in ZAP204. The
- 531 maximum susceptibility is always at an angle to macroscopic lineation, and often nearly
- 532 perpendicular to lineation in the foliation plane.

533 The measured seismic P-wave velocity is smallest normal to foliation except in sample ZAP204 where 534 the two velocities measured normal to lineation are very similar. The fastest P-wave velocity is observed parallel to lineation in all samples except ZAP207 and ZAP214 where it is observed in the 535 536 foliation plane, but normal to lineation. Larger directional variability is observed in the models. Note 537 that these peridotites are massive rocks, with poorly defined macroscopic foliation and lineation. 538 Furthermore, lineation is defined by hornblende and pyroxenes, whereas the seismic P-wave 539 anisotropy appears to be dominated by olivine. Nevertheless, the disagreement between the seismic 540 models and measurements illustrates that CPO is not the only factor defining seismic anisotropy.

541 No straightforward relationship exists between the orientations of mineral fabric, magnetic and 542 seismic anisotropies in these complex rocks, containing several constituent minerals contributing to 543 their physical properties. Neither the principal susceptibility nor the minimum and maximum 544 velocity directions necessarily coincide with the macroscopic foliation and lineation. This is observed 545 both for magnetic anisotropy, which can be reliably modeled based on CPO, and for seismic 546 anisotropy, where larger discrepancies are observed between model and measurement. The reason 547 for this is that the macroscopic foliation and lineation are defined mainly by hornblende and mica (as 548 well as serpentinization and grain size banding in ZAP214), whereas the seismic anisotropy is 549 controlled by olivine, and the magnetic anisotropy is a complex fabric consisting of contributions 550 from olivine, pyroxenes and hornblende in various proportions. A particularly important result of this 551 study is that the maximum and minimum velocities and susceptibilities are generally not parallel to 552 each other. This observation would advise against the use of AMS data to define the 3 measurement 553 directions for seismic anisotropy measurements, and suggests that seismic anisotropy was 554 underestimated in previous studies (Gaudreau et al., 2017; Punturo et al., 2017). Further, the results 555 presented here highlight the need for more than 3 independent measurements of the elasticity 556 tensor, e.g. based on the experimental method proposed by Mah and Schmitt (2001, 2003)

- 557 There is no clear correlation between the degree of magnetic and seismic anisotropy, again likely a
- result of the different carrier minerals (Figure 9). This is consistent with results by Schmitt et al.
- 559 (2007) who found a decrease of the seismic anisotropy degree with increasing serpentinization, but
- 560 no systematic correlation with magnetic anisotropy in ophiolite.

561 5.3 Influence of hydrous minerals on physical properties

562 The hydrous minerals, hornblende and phlogopite, influence the magnetic anisotropy of the

- 563 peridotite rocks from the IVZ. Specifically, the principal susceptibility directions of ZAP207 and
- 564 ZAP214 are controlled by hornblende CPO, and have different orientations than the anisotropy
- 565 contribution of either olivine or enstatite. In samples where the anisotropy of hornblende interferes
- 566 positively with that of olivine (ZAP201, ZAP205, ZAP207), the overall anisotropy is increased with
- respect to the olivine contribution alone. In samples ZAP202, ZAP204, and ZAP214, where the
- bornblende and olivine anisotropy interfere destructively, the overall anisotropy is diminished.

- 569 The influence of hydrous minerals on seismic anisotropy is smaller in that the minimum and
- 570 maximum velocity directions are defined by the olivine contribution in all samples. The degree of
- anisotropy, on the other hand, is affected by the presence of hornblende. Similar to the magnetic
- 572 properties, the contributions of olivine and hornblende can lead to a larger or smaller seismic
- anisotropy than the olivine contribution on its own. Positive interferences are observed in ZAP205,
- 574 ZAP207, and partly ZAP214.
- 575 More work on different geological settings with different CPOs will be needed to establish a more
- 576 detailed understanding of the relationship between texture and anisotropy of physical properties in
- 577 general, and specifically the influence of certain mineral phases on these relationships.

578 6. Conclusions

- 579 Mineral texture has been compared to anisotropy of physical properties for a suite of rocks from the 580 Finero peridotite in the IVZ. Whereas the minimum susceptibility of most samples is normal to their
- 581 macroscopic foliation, there is often a large deviation between maximum susceptibility and lineation
- 582 direction. CPO-based models of the magnetic anisotropy shows that (1) the paramagnetic anisotropy
- 583 can be reliably modeled in terms of principal directions, and to a lesser extent in terms of anisotropy
- 584 degree and shape, and (2) the main carrier minerals of the magnetic anisotropy can be olivine,
- 585 pyroxene, or hornblende, or a combination thereof. Note that the contributions of these mineral
- 586 groups can interfere positively or negatively, depending on the sample.
- 587 Seismic velocities measured along three directions often indicate the correct macroscopic lineation 588 and foliation. However, CPO-based models of seismic anisotropy do not generally agree with these 589 measurements. In particular, the modeled maximum and minimum velocity directions are generally 590 measurements of the standard directions.
- not parallel to any of the structural directions. This suggests that more than three measurement
 directions are needed to fully capture the seismic anisotropy. Additionally, the discrepancy between
- 592 measured and modeled seismic anisotropies illustrates that seismic properties are affected by
- 593 factors other than CPO, such as microcracks and fractures, porosity, the number and alignment of
- 594 grain boundaries.
- 595 Anisotropy measurements capture a volume and hence a larger number of grains than EBSD
- 596 measurements obtained on a surface. Therefore, anisotropy measurements may be representative
- of the overall grain alignment in a sample on which direct texture determination is limited by poor
- 598 counting statistics. Whereas our results clearly illustrate that magnetic anisotropy is not reliable at
- 599 predicting the maximum and minimum velocity directions, magnetic anisotropy is a fast and efficient
- 600 statistical tool to determine whether drill cores are representative of a larger sample. The
- agreement between modeled and measured magnetic anisotropy can also be used to support
- statistical relevance of the CPO of the phases dominantly carrying the magnetic anisotropy.
- 603 Because macroscopic fabric, magnetic and seismic anisotropy are predominantly defined by
- 604 different carrier minerals, there is no straightforward relationship between them. The principal axes
- are in general not coaxial, and we did not observe any correlation between the magnetic and seismic
- 606 degrees of anisotropy. Contributions of different minerals can interfere constructively or
- 607 destructively, thus resulting in a larger or smaller overall anisotropy than the anisotropy of the
- dominant mineral alone. The results and models shown here, in particular the interplay between the

- anisotropies of different constituent mineral phases, allows a deeper understanding of physical
- anisotropy in complex, multi-phase aggregates. This detailed and profound understanding will help
- 611 future interpretations of textures, and hence geodynamic processes, based on anisotropy data.

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848 Appendix: Definition of magnetic and seismic tensors

849 Matlab code defining magnetic and seismic single crystal properties is given below:

```
850
             %% definition of coordinate systems for magnetic properties
851
             cs hbl= crystalSymmetry('2/m',[ 9.803 18.046 5.313],[ 90, 105.05, 90
             ]*degree,'x||a*','z||c', 'mineral','hornblende');
852
             cs en = crystalSymmetry('mmm', [ 18.2457 8.7984 5.1959], [ 90.,
853
             90.0,90.]*degree,'x||a','z||c','mineral','enstatite');
854
             cs cpx = crystalSymmetry('2/m', [9.7456, 8.9198, 5.2516], [90.0, 105.86,
855
             90.0]*degree, 'x||a*', 'z||c', 'mineral', 'clinopyroxene');
856
857
             cs ol = crystalSymmetry('mmm', [ 4.8195, 10.4788,
                                                                                                                               6.0873], [ 90.0, 90.0,
             90.0,]*degree,'x||a','z||c','mineral','olivine');
858
859
             cs mica = crystalSymmetry('2/m', [ 5.308 9.190 10.155], [ 90.00, 100.08,
860
             90.00]*degree, 'x||a', 'z||c*', 'mineral', 'phlogopite');
861
862
             %% single crystal magnetic properties
863
             % olivine
             k1_ol = 1.6668e-7;
864
             k2 ol = 1.5794e-7;
865
866
             k3 ol = 1.5566e-7;
867
             susc ol = [k2 ol 0 0; 0 k3 ol 0; 0 0 k1 ol];
868
             C ol = tensor(susc ol, cs ol)
869
870
             % enstatite
871
             k1 en = 1.9393e-7;
872
             k2 en = 1.8078e-7;
873
             k3 en = 1.7526e-7;
874
             susc en = [k2 en 0 0; 0 k3 en 0; 0 0 k1 en];
875
             C en = tensor(susc en, cs en)
876
877
             % hornblende
878
             k1 hbl = 2.0439e-7;
879
             k2 \ hbl = 2.0140e-7;
880
             k3 hbl = 1.7789e-7;
881
             susc hbl = [k3 hbl 0 0; 0 k1 hbl 0; 0 0 k2 hbl];
882
             C hbl = tensor(susc hbl, cs hbl)
883
884
             % diopside
885
             k1 cpx = 3.6816e-8;
886
             k2 cpx = 3.6021e-8;
887
             k3 cpx = 3.2197e-8;
888
             susc cpx = [(k1 cpx+k3 cpx)/2 0 (k1 cpx-k3 cpx)/2; 0 k2 cpx 0; (k1 cpx-k3 cpx)/2; (k1 cpx-k3 cpx)/2;
889
             k3 cpx)/2 0 (k1 cpx+k3 cpx)/2];
890
             C cpx = tensor(susc cpx, cs cpx)
891
892
             % mica
893
             k1 mica = 1.3634E-07;
894
             k3 mica = 1.1390E-07;
895
             susc mica = [k1 mica 0 0; 0 k1 mica 0; 0 0 k3 mica];
896
             C mica = tensor(susc mica, cs mica)
897
```

```
899
     %% single crystal elastic properties
900
     % clinopyroxene
901
     rho cpx= 3.2860;
902
     cs cpx = crystalSymmetry('2/m',[ 9.7456 8.9198 5.2516],...
903
      [ 90.0000 105.8600 90.0000]*degree,'x||a*','z||c',...
904
      'mineral','clinopyroxene');
905
     M cpx =....
906
      [[ 228.10
                   78.80
                           70.20
                                    0.00
                                           7.90
                                                   0.001;...
                                  0.00
907
           78.80 181.10
                          61.10
                                           5.90
                                                   0.00];...
      Γ
908
           70.20
                  61.10 245.40
                                   0.00
                                           39.70
                                                   0.00];...
      Γ
909
            0.00
                    0.00
                           0.00
                                  78.90
                                           0.00
                                                   6.40];...
      Γ
910
            7.90
                    5.90
                          39.70
                                   0.00
                                          68.20
                                                   0.00];...
      ſ
911
           0.00
                    0.00
                           0.00
                                   6.40
                                          0.00
                                                  78.10]];
      [
912
     S cpx = tensor(M cpx, cs cpx);
913
914
     % enstatite
915
     rho en = 3.3060;
916
     cs en = crystalSymmetry('mmm', [ 18.2457 8.7984 5.1959],...
917
     [ 90.0000 90.0000 90.0000]*degree,'x||a','z||c',...
918
      'mineral','enstatite');
919
     M en =....
920
     [[ 236.90
                  79.60
                                   0.00
                                           0.00
                         63.20
                                                   0.001;...
921
           79.60 180.50
                                           0.00
                          56.80
                                  0.00
                                                   0.001;...
      [
922
                 56.80 230.40
           63.20
                                   0.00
                                          0.00
                                                   0.001;...
      [
923
           0.00
                   0.00
                          0.00
                                 84.30
                                           0.00
                                                   0.001;...
      [
924
           0.00
                   0.00
                           0.00
                                  0.00
                                         79.40
                                                   0.001;...
      [
925
           0.00
                   0.00
                            0.00
                                   0.00
                                          0.00
                                                  80.10]];
      [
926
     S en = tensor(M en, cs en);
927
928
     % olivine
929
     rho ol= 3.221;
930
     cs ol = crystalSymmetry('mmm', [ 4.8195 10.4788 6.0873],...
931
     [ 90.0000 90.0000 90.0000]*degree,'x||a','z||c',...
932
      'mineral','olivine');
933
     M ol =....
934
      [[ 328.00
                  69.00
                         69.00
                                   0.00
                                           0.00
                                                   0.00];...
935
           69.00 200.00
                         73.00
                                   0.00
                                           0.00
                                                  0.00];...
      Γ
936
           69.00
                   73.00 235.00
                                   0.00
                                           0.00
                                                  0.00];...
      ſ
937
            0.00
                   0.00
                           0.00
                                 66.70
                                          0.00
                                                   0.00];...
      ſ
938
            0.00
                    0.00
                            0.00
                                   0.00
                                         81.30
                                                  0.001;...
      ſ
939
            0.00
                   0.00
                            0.00
                                   0.00
                                          0.00
                                                  80.9011;
      Γ
940
     S ol = tensor(M ol,cs ol);
941
942
     % hornblende
943
     rho hbl= 3.163;
944
     cs hbl = crystalSymmetry('2/m', [ 9.803 18.046 5.313],...
945
      [ 90, 105.05, 90 ]*degree, 'x||a*', 'z||c',...
946
      'mineral', 'hornblende');
947
      M hbl =....
948
      [[ 141.60
                   57.10
                          49.60
                                   0.00
                                         -0.20
                                                   0.001;...
949
           57.10 197.80
                          60.90
                                   0.00 -10.90
                                                   0.001;...
      [
                                   0.00 -31.40
950
                          225.40
           49.60
                  60.90
                                                   0.001;...
      [
951
           0.00
                                   75.80
                                          0.00
                                                   3.30];...
       [
                  0.00
                          0.00
952
       [
           -0.20
                 -10.90
                          -31.40
                                   0.00
                                           49.90
                                                   0.00];...
953
           0.00
                 0.00
       [
                          0.00
                                    3.30
                                          0.00
                                                   51.7]];
954
     S hbl = tensor(M hbl,cs hbl);
955
956
     % mica
957
     rho mica= 2.872;
958
     cs mica = crystalSymmetry('2/m', [ 5.308 9.190 10.155],...
959
     [ 90.00 100.08 90.00]*degree,'x||a','z||c*',...
```

960 'mineral','phlogopite'); 961 M_mica =.... 0.00 -16.00 0.00 -5.00 0.00 -1.00 [[181.00 962 48.00 12.00 0.00];... 48.00 185.00 963 12.00 0.00];... [62.00 -1.00 0.00 12.00 964 12.00 0.00];... [965 [14.00 -6.00];... 0.00 0.00 0.00 $\begin{bmatrix} -16.00 & -5.00 & -1.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & -6.00 \end{bmatrix}$ 966 20.00 0.00];... 967 68.00]]; 0.00 968 S_mica = tensor(M_mica,cs_mica); 969 970 971

973 Figures and Tables



974

975 Figure 1: (a) Geographical location of the studied area; (b) Geological sketch of the Ivrea Verbano

276 Zone in the westernmost Southern Alps and of the tectonic units of the Southern and Western Alps

977 (modified after Brack et al., 2010); (c) Sample locations and simplified geological map of the

978 ultramafic body in the Finero area, and its country rocks in the sampled area. Geographic coordinates

979 in WGS84/UTM zone 32N.



981 Figure 2: Microstructures under optical microscope (cross-polarized light) of each analyzed sample group. Sample names indicated at top left corner. Samples ZAP201, ZAP202, ZAP204, ZAP205 and 982 983 ZAP207 are harzburgites, ZAP208 a dunite, and ZAP214 a harzburgite with protomylonitic texture. 984 Note the following details of the microstructures: for olivine: Shape preferred orientation (ZAP201y to 985 207y), polygonal shape (ZAP208y), core-mantle structure (ZAP214a, b), sub-grain boundaries 986 (ZAP204y, ZAP205y); for enstatite: irregular shape and pinnacle termination (arrows in ZAP201y); for 987 phlogopite: pinning of olivine grain boundaries at the contact with phlogopite. Minerals: OI – olivine, 988 *En – enstatite, Di – diopside, PhI – phlogopite, Am – amphibole, Srp serpentine.*



989

990 Figure 3: Single crystal magnetic and seismic properties in a crystallographic reference frame.

991 Principal directions (black squares, triangles and circles) are indicated for magnetic tensors, and

992 minima and maxima (black circles and squares) for compressional wave velocities.



993

994 Figure 4: Magnetic results. (a) Isothermal remanent magnetization (IRM) acquisition, showing that

995 low-coercivity grains such as magnetite dominate the ferromagnetic grains. (b) Overview of

- 996 anisotropy degree and shape measured in different field and temperature conditions. (c-i)
- 997 Comparison of low-field AMS to the paramagnetic and ferromagnetic components isolated from
- 998 high-field AMS for the y-cores of each site. RT and LT refer to room temperature and 77 K,
- 999 respectively, at which high-field experiments were performed. Repeat measurements of low-field
- 1000 AMS show good reproducibility of directional data.



Figure 5: Effect of pressure at room temperature on P-wave (Vp) and S-wave (Vs) velocities on a 1002 1003 representative Iherzolite sample, ZAP205. Velocities are measured along the three structural 1004 directions: X parallel to lineation, Y normal to lineation and parallel to foliation, and Z normal to 1005 foliation (inset). Six shear-wave velocities were measured, using shear-wave notation similar to 1006 stress-strain notation: the first index indicates the direction of particle motion, and the second 1007 indicates the plane of wave propagation. For each direction, the linear regression of the 1008 velocity/pressure curve above 100 MPa is used to calculate a set of reference values of velocity at 0 1009 pressure; here only the compressional wave along X and the shear wave propagating along X in the 1010 foliation plane (XY) are shown. Elastic wave velocities are fit to the empirical formula proposed by Wepfer and Christensen (1991), relating velocity to confining pressure, and anisotropy for P and S 1011 1012 waves (dashed line, thick and thin respectively) is then calculated from the fitting curves, as 1013 explained in the text.



1015	Figure 6: Orientation density functions and modeled and measured magnetic and seismic
1016	anisotropies for sample ZAP205. Modal composition determined from EBSD data; numbers in
1017	brackets indicate the measurements for each phase. All data shown in a coordinate system defined
1018	by the sample's macroscopic foliation and lineation (indicated in white grey on the thin section
1019	photograph). Scale bar 1 mm. Orientation density functions measured on a regularly spaced grid, and
1020	shown as multiples of uniform distribution (color scale). Modeled physical properties (color scale) and
1021	principal directions for the magnetic tensor (white asterisk) for each phase and the entire rock are
1022	shown in addition to measurements for magnetic and P-wave anisotropy (black symbols, where
1023	square, triangle and circle indicate the maximum, intermediate and minimum principal axes,
1024	respectively) on the rock samples. Cf the online supplementary for similar figures for the other
1025	samples.





Figure 7: Comparison between modeled (color scale) and measured (symbols) principal directions of magnetic and seismic anisotropies. For magnetic properties, squares, triangles and circles define the maximum, intermediate and minimum principal susceptibilities respectively, and white asterisk indicate the principal directions of the modeled tensors. Measured maximum and minimum P-wave velocities are indicated by squares and circles, respectively. Circles on the vs1-vs2 plot indicate the measured differences between vs1 and vs2 using the same color scale as the models.



Figure 8: Comparison of modeled and measured anisotropy parameters for magnetic susceptibility
(a,b), P-waves (c,d) and S-waves (e,f). Dashed lines indicate equal values for measurement and
model.



1038 Figure 9: Relationship between measured magnetic and seismic degree of anisotropy for P-waves (a)

1039 and S-waves (b,c). For the magnetic anisotropy the average of the 2 measured specimens cut from

1040 the longer core for seismic measurements is shown.

1041

- 1042 Table 1: Modal compositions (volume %) of the samples determined by (a) point count analysis with
- 1043 petrographic optical microscope (cf. Hefferan and O'Brien, 2010 for a description of the method), and
- 1044 (b) SEM (EDS and EBSD) analyses:

a) Modal compo	sition from	optical mic	roscopy				
	ZAP201	ZAP202	ZAP204	ZAP205	ZAP207	ZAP208	ZAP214
Olivine	70	70	76	70	70	80	65
Enstatite	9	15	13	13	10	9	10
Diopside	15	10	3	8	10	10	0
Hornblende	0	0	6	0	0	0	20
Phlogopite	5	3	1	8	3	0	0
Serpentine	0	0	0	0	1	0	2
Spinel	1	2	1	1	6	1	3
b) Modal compo	sition from	SEM					
	ZAP201x1	ZAP202z2	ZAP204x2	ZAP205y2	ZAP207z1	ZAP208x1	ZAP214x2
Olivine	75	70	76	71	56	*	64
Enstatite	18	11	19	12	25	*	7
Diopside	2	1	0	0	8	*	1
Hornblende	3	2	4	3	9	*	24
Phlogopite	1	0	0	0	0	*	0
Spinel	1	1	1	1	0	*	1
Not indexed	1	15	1	13	2	*	4

1045 * ZAP208x1 is coarse-grained, so that the EBSD data is not statistically representative

- 1046 Table 2: Bulk density, grain density, effective porosity and seismic measurements. Seismic velocities
- 1047 are given as P- and S-wave speeds (Vs01 and Vs02 denoting the two perpendicular particle motions
- 1048 for S-waves) extrapolated to 0 pressure, and their pressure derivatives. For P-waves, the anisotropy
- 1049 *A(%)* was calculated using the average of the three measurements as mean velocity.

Sample	Bulk density (g/cm ³)	core	Grain density (g/cm ³)	Porosity (%)	Vp0 (km/s)	Pressure derivative (m·s ⁻¹ /MPa)	Anisotropy Avp (%)	١	Vs0 ₁ (km/s)	Pressure derivative (m·s ⁻¹ /MPa)	Vs0 ₂ (km/s)	Pressure derivative (m·s ⁻¹ /MPa)	Anisotropy Avs ₁ (%)	Anisotropy Avs ₂ (%)	Vs0 ₁ -Vs0 ₂ (m/s)	Average
ZAP201	3.27		3.28	0.22		1 1 1										
		х			8.28	0.39			4.68	0.28	4.63	0.20			55	i
		у			8.11	0.40			4.72	0.15	4.62	0.20			96	i
		z			8.02	0.44	3.26		4.66	0.19	4.54	0.24	1.19	1.89	120	90
740202	2 20		2 20	0.10												
ZAPZUZ	5.29	~	5.29	0.19	0.22	0.47			4 70	0.20	4 59	0.44			205	
		x v			8.32	0.47			4.75	0.25	4.58	0.44			203	
		y Z			8.02	0.58	3.64		4.70	0.33	4.55	0.35	1.38	1.04	167	198
740204	2.20		2 22	0.12												
ZAP204	3.26	v	3.2/	0.13	8 34	0.30			4.65	0.39	1.64	0.22			17	
		v			8.34	0.30			4.03	0.39	4.04	0.22	-		186	
		7			8.09	0.45	3 31		4.72	0.20	4.34	0.25	4 78	5 52	117	107
		-			0.05	0.15	5.51		4.50	0.50	1.55	0.24	-1.70	5.52		107
ZAP205	3.28		3.28	0.20												
		x			8.40	0.87			4.77	0.26	4.57	0.28			207	
		v			8.32	0.58			4.78	0.30	4.59	0.27			187	
		z			7.78	1.04	7.58		4.63	0.34	4.62	0.31	3.08	1.23	12	135
ZAP207	3.26		3.26	0.09												
		x			7.81	0.44			4.71	0.32	4.53	0.28			173	
		y			8.12	0.40			4.74	0.22	4.48	0.25			257	
		z			7.75	0.52	4.78		5.06	0.33	4.43	0.23	7.30	2.31	630	353
ZAP208	3.23		3.23	0.19												
		x			7.89	0.60										
		v			7.48	0.90			Not measured							
		z			7.47	0.70	5.44									
740214	3 34		3 34	0.03												
201 214	5.54	x	3.34	0.03	7.80	0.02			4.52	0.64	4.36	0.69			160	
		v			7.91	0.28			4.65	0.38	4.59	0.36			60	1
		z			7.55	0.41	4.64		4.54	0.46	4.47	0.76	2.84	5.14	70	97

- 1051 Table 3: Comparison of measured and modeled data for magnetic and seismic properties. Magnetic
- 1052 data is represented as deviatoric principal susceptibilities, the degree (k') and shape (U) of the
- anisotropy, and seismic data is shown as P- and S-wave velocities parallel to the 3 structural
- 1054 *directions, as well as anisotropy degree A(%) for Vp0.*

Magnetic ani	sotropy						
		Mean susceptib	Principal suscep	tibilities		Anisotropy para	meters
Sample		k (m3/kg)	k1-k (m3/kg)	k2-k (m3/kg)	k3-k (m3/kg)	k' (m3/kg)	U
ZAP201x	Model	1.60E-07	1.29E-09	-2.66E-10	-1.03E-09	9.64E-10	-0.34
ZAP201x1	Measurement		1.05E-09	-8.52E-11	-9.67E-10	8.26E-10	-0.13
ZAP201x2	Measurement		1.23E-09	-3.10E-10	-9.18E-10	9.04E-10	-0.43
74P2027	Model	1 63E-07	7 83F-10	-1 76E-10	-6 07E-10	5 81F-10	-0.38
ZAF 2022 7AP20271	Measurement	1.052-07	1 15E-00	-1.70E-10	-0.07E-10	8 39F-10	-0.38
7AP20221	Measurement		8 00F-10	-9.36E-10	-7 90F-10	6 49F-10	-0.48
	Weddurement		0.002 10	5.502 12	7.502 10	0.452 10	0.02
ZAP204x	Model	1.63E-07	4.12E-10	7.88E-12	-4.20E-10	3.40E-10	0.03
ZAP204x1	Measurement		6.74E-10	-1.43E-10	-5.31E-10	5.03E-10	-0.36
ZAP204x2	Measurement		4.57E-10	-1.79E-10	-2.76E-10	3.25E-10	-0.73
7AP205x	Model	1 63F-07	2 22F-09	-3 54F-10	-1 86F-09	1 68F-09	-0.26
74P205x1	Measurement	1.002 07	1 84F-09	-1 69E-10	-1 68E-09	1 44F-09	-0.14
74P205x1	Measurement		1.87E-09	-2 15E-10	-1 60E-09	1.44E 05	-0.19
LAI 205X2	Medsurement		1.022 05	2.152 10	1.002 05	1.402 05	0.15
ZAP207z	Model	1.55E-07	1.22E-09	7.32E-10	-1.95E-09	1.39E-09	0.69
ZAP207z1	Measurement		1.18E-09	-3.34E-10	-8.44E-10	8.58E-10	-0.50
ZAP207z2	Measurement		1.02E-09	-1.84E-11	-9.98E-10	8.22E-10	-0.03
740044		1 645 07	4 225 00	4 005 40	4 045 00	4 225 02	0.47
ZAP214x	Model	1.61E-07	1.33E-09	4.88E-10	-1.81E-09	1.33E-09	0.47
ZAP214x1	Measurement		2.82E-09	-5.19E-10	-2.30E-09	2.12E-09	-0.30
ZAPZ14XZ	Measurement		2.54E-09	-2.47E-10	-2.29E-09	1.985-09	-0.15
Seismic aniso	tropy	Density	P-wave velocitie	S		Anisotropy para	meter
Sample		rho tot (g/cm3)	vpx (km/s)	vpy (km/s)	vpz (km/s)	A vp %	
ZAP201x	Model	3.23	8.49	8.38	8.43	1.29	
ZAP201	Measurement		8.28	8.11	8.02	3.26	
ZAP202z	Model	3.23	8.55	8.37	8.49	2.21	
ZAP202	Measurement		8.32	8.18	8.02	3.64	
ZAP204x	Model	3.21	8.67	8.52	8.32	4.18	
ZAP204	Measurement		8.34	8.07	8.09	3.31	
740205	Madal	2.20	9.65	9.63	9.16	4 5 5	
ZAF203X	Measurement	5.20	8.03	8.02	7.78	4.55	
2AI 203	Weasurement		0.40	0.52	7.78	7.56	
ZAP207z	Model	3.17	8.55	8.39	8.27	3.32	
ZAP207	Measurement	0.17	7.81	8.12	7.75	4.78	
ZAP214x	Model	3.10	8.34	8.26	8.61	4.19	
ZAP214	Measurement		7.80	7.91	7.55	4.64	
		S-wave velocitie	S				
Sample		vs1x (km/s)	vs1y (km/s)	vs1z (km/s)	vs2x (km/s)	vs2y (km/s)	vs2z (km/s)
ZAP201x	Model	5.00	4.96	4.99	4.94	4.89	4.90
ZAP201	Measurement	4.68	4.72	4.66	4.63	4.62	4.54
7402027	Madal	E OE	F 01	E 04	4.00	1 90	4.00
ZAF 2022	Measurement	1 79	1.76	4 72	4.55	4.65	4.50
202	Weasurement	4.75	4.70	4.72	4.50	4.55	4.55
ZAP204x	Model	5.05	5.05	4.98	4.97	4.88	4.87
ZAP204	Measurement	4.65	4.72	4.50	4.64	4.54	4.39
ZAP205x	Model	5.10	5.10	5.00	4.95	4.92	4.87
ZAP205	Measurement	4.77	4.78	4.63	4.57	4.59	4.62
ZAP207z	Model	5.05	5.05	4.91	4.90	4.85	4.85
ZAP207	Measurement	4.71	4.74	5.06	4.53	4.48	4.43
ZAP214x	Model	5.01	4.95	5.00	4.80	4.78	4.92
ZAP214	Measurement	4.52	4.65	4.54	4.36	4.59	4.47