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Ultrasonic velocity drops and anisotropy reduction in mica-schist analogues due to melting with implications for seismic imaging of continental crust

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ABSTRACT

Melt generation in the continental crust is thought to significantly influence seismic bulk velocities and anisotropy, although existing laboratory data provide limited constraints on such seismic attributes. In this study we measured ultrasonic compressional wave speeds (Vp) and anisotropy during sample compaction, mica-breakdown and melt-generation in synthetic, foliated quartz–muscovite aggregates. Measurements were performed at peak conditions of 300 MPa hydrostatic confining pressure and 750 °C, over a six hour time period, for three separate samples where wave propagation directions were aligned at 0°, 45° and 90° with respect to the foliation plane. The experiments are initially marked by sample compaction and rapid reduction in porosity (from 25% to <2 vol%), with a corresponding increase in Vp. During initial stages of the experiment Vp ranges from 4.65 to 5.45 km/s, depending on the direction of the P wave propagation, resulting in up to $\sim$16% anisotropy, which originates mainly from the preferred orientation of muscovite and possible incipient melt lenses oriented parallel to foliation. As the experiment progresses the bulk Vp decreases gradually and Vp anisotropy drops from $\sim$16% to $\sim$2% after five hours into the experiment. The drop in anisotropy is caused by muscovite-breakdown and increasing amount of partial melting of the aggregate. The bulk velocities are considerably lower than predicted for a mixture of muscovite and β-quartz (stable at 300 MPa and 750 °C). Thermodynamic modeling indicates that mica breakdown and production of melt with $\sim$2 wt% dissolved water in the aggregate can explain the low Vp, even though β-quartz is stable; the modeled Vp is $\sim$4.75 km/s at 300 MPa and 750 °C. These ultrasonic attributes signify movement of the melt to fill vacant pores and coating grain boundaries, effectively connecting melt films and reducing seismic anisotropy. The results may apply to regions where crustal melting is on-going, in particular regions of elevated temperature that are only weakly deforming, with coupled anomalously low bulk velocities and seismic anisotropy.

1. Introduction

Field studies, experimental rock deformation and numerical modeling demonstrate that the presence of melt greatly influences the rheology and hence the geodynamics of partially molten regions of the crust and mantle (*e.g.*, McKenzie, 1985; Rutter and Neumann, 1995; Brown, 2007; Kohlstedt and Holtzman, 2009; Misra et al., 2011, 2014). At mid and lower levels in the continental crust and in orogenic settings the seismic method is used extensively to characterize and distinguish regions of crustal anisotropy, presence of fluids and partial melting (*e.g.*, Nelson et al., 1996; Schulte-Pelkum et al., 2005; Nábělek et al., 2009; Guo et al., 2012). It is further understood that the presence of a melt reduces seismic bulk velocity compared to a fully solid medium, but its effect on seismic anisotropy is still unclear (Xie et al., 2013). The geometrical distribution of melt is considered to be of particular importance as indicated when modeling seismic anisotropy, but

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also in general terms of the variation in the bulk seismic velocity (*e.g.*, Schmeling, 1985; Mainprice, 1997). Most past experimental studies of the seismic properties of partially molten aggregates have focused on the bulk elastic-wave response (Takei, 2000; Mueller and Massonne, 2001; Aizawa et al., 2002). These experiments show that the partial melting profoundly changes elastic wave propagation. Mueller et al. (2010) illustrates a succession of stages in which the generation of melt influences the elastic waves. One of their results showed that P waves were evidently more influenced than S waves by the presence of small amounts of melt. This result is however contradicted in part by the results of Takei (2000), who showed that the S wave was more greatly affected than the P wave at melt amounts up to a volume fraction of 0.1. In contrast to the studies mentioned above, with the exception of Ferri et al. (2007), there are no experimental constraints on the impact of melting on seismic anisotropy. Ferri et al. (2007) studied metapelitic crustal xenoliths (garnet–biotite–sillimanite) from El Hoyazo in SE Spain. During partial melting, which was achieved at laboratory conditions peaking at 500 MPa hydrostatic confining pressure and 950 °C, they noted that bulk Vp decreased once the sample was heated above solidus conditions; Vp decreased from 5.69 km/s at 650 °C to 4.90 km/s at 950 °C. In addition the P wave anisotropy increased to 35%, at 950 °C. The high observed anisotropy was ascribed to production of small melt amounts, whose distribution is fabric-controlled, adding to the initial crystallographic anisotropy produced by preferentially oriented biotite.

Despite challenges to extrapolate results from laboratory experiments to nature, they provide insight into the effect of partial melting on rheological and geophysical properties (*e.g.*, van der Molen and Paterson, 1979; Rutter and Neumann, 1995). In the context of laboratory experiments, synthetic aggregates of quartz–muscovite mixtures have helped to understand deformation processes during partial melt generation, as analogues to micaceous quartzite or mica-schist rock (Misra et al., 2009, 2011, 2014; Tumarkina et al., 2011). In this study we use a synthetic aggregate of mixed quartz and muscovite to investigate *in situ* compaction and melt generation in rocks using ultrasonic velocity measurements in the laboratory. Particular attention is given to changes in the elastic wave velocity anisotropy. The experiments were compared to Vp predicted from thermodynamic modeling. Anisotropic mica-rich rocks that undergo partial melting and recrystallization may generate specific seismic signatures due to the combined reduction in elastic wave velocities and in particular a drastic reduction in elastic wave anisotropy.

2. Sample materials and experimental setup

2.1. Sample manufacture

The experimental material consisted of a mixture of equal volumes quartz and muscovite. Quartz and muscovite powders were obtained from Alberto Luisoni Industrial Minerals and Synthetics (http://www.a-lusioni.ch), where the former consists of high-purity SiO_2, and the latter has an average composition of $(K_{0.9}Na_{0.1})(Al_{1.6}Fe_{0.3}Mg_{0.1})[Si_{3.2}Al_{0.8}O_{10}](OH)_2$. Electron microprobe measurements of the muscovite allowed for detection of minor amounts of other elements. Most notably TiO_2 reached up to ∼0.3 wt% in some measured grains, as well as small amounts (<0.1 wt% but >0.02 wt%) of CaO, BaO, P_2O_5 and Cr_2O_3. Synthetic aggregates were chosen because they allowed control of composition and the preparation of an initial homogeneous layering of the quartz–muscovite starting material. In addition, the two phases have significantly different elastic properties. Muscovite has high elastic anisotropy (Vaughan and Guggenheim, 1986), and tabular, lamella shape. Quartz in contrast has a lower anisotropy, both in terms of shape and elasticity (McSkimin et al., 1965; Ohno et al., 2006; Calderon et al., 2007). Both minerals occur as common components in continental crustal rocks, and the aggregate may be described as a synthetic analogue of a micaceous quartzite or mica-schist. Initial sizes of quartz and mica grains were 6 to 12 µm and 30 to 40 µm, respectively. Single crystal quartz had a density of 2.65 g/cm^3, whereas the muscovite density was 2.82 g/cm^3. The powder mixture was placed in a cylindrical stainless steel canister (5 cm diameter, ∼25 cm length) and uniaxially pressed with a stress of 200 MPa. The canister was then mechanically sealed and welded, and further compacted by hot isostatic pressing (HIP) at 165 MPa pressure and 580 °C for 24 hours, in order to consolidate the powder mixture and produce the synthetic rock-aggregate. The pressure for HIPing was chosen to be near the maximum possible applicable pressure (180 MPa), and the temperature was chosen because it would provide a possibility to solidify the aggregate but not alter the initial composition of the aggregate due to mineral reactions.

Cold-pressing gave rise to a foliation marked by a preferred orientation of muscovite grains with their basal plane orthogonal to the compaction direction. However, the high strain rate used during cold-pressing may effectively not orient the muscovite as well as in the case of natural deformation because of a much lower strain rate and because of pressure–dissolution processes that would more effectively orient the muscovite in a given stress-field. The creation of a synthetic foliation also produces quartz-rich lenticular clusters that are porous. Pore-collapse in these lenses is reduced during cold-pressing because of the rigidity of the quartz grains. In order to investigate the effect of anisotropy, three specimens were drilled from the sample canister: one normal to the foliation (90°), one parallel to the foliation (0°), and one at 45° to the foliation. Specimens of 15 mm diameter and 25 to 30 mm length were cut with a diamond-coated drill bit from the sample material. The specimens had a porosity of ∼25 ± 1%, as determined with a He-pycnometer and volume of the specimens. Further information on manufacturing of synthetic quartz–muscovite aggregates can be found in Misra et al. (2009) and Tumarkina et al. (2011).

2.2. Melting experiment and acoustic measurement setup

The ultrasonic pulse transmission technique was used to measure time of flight of longitudinal compressional elastic waves (P waves; Birch, 1960). Experiments were performed on specimens housed in an internally heated Paterson type gas-medium apparatus modified to measure ultrasonic velocities, at experimental conditions of 750 °C and 300 MPa hydrostatic confining pressure (*e.g.*, Burlini et al., 2005; Ferri et al., 2007; hereafter the pressure conditions referred to in the text refers to hydrostatic confining pressure). This temperature was chosen in order to ensure breakdown of muscovite and partial melting in the sample. A confining pressure of 300 MPa was used in order to provide stable conditions, *i.e.*, an experimental constraint required to avoid leaks of confining pressure for the duration of the experiment, and at the same time provide pressure conditions that approach middle crustal conditions. Although this pressure is lower than expected in the mid-crust (about 400 to 500 MPa at depths between 15 to 20 km, and typical density of 2.75 g/cm^3), it is anticipated that the role of confining pressure is secondary in importance compared to the temperature applied when considering the effect of partial melting. The sample assembly was jacketed with an iron cylinder, which prevented the confining gas-medium from entering the sample. To protect the ultrasonic transducers from high temperature, the sample was placed between buffer rods of alumina and zirconia. Two alumina disks with 3 mm thickness were placed on each side of the sample in order to separate the sample from the buffer rods. Two R-type thermocouples were placed in contact