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Bulk rock elastic moduli at high pressures, derived from the mineral textures and from extrapolated laboratory data

K Ullemeyer¹, T Lokajčiček², R Keppler¹, R N Vasin³ and J H Behrmann⁴

¹ Institute of Geosciences, University of Kiel, Kiel, Germany

² Institute of Geology AS CR, Prague, Czech Republic

³ Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, Dubna, Russia

⁴ GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

E-mail: kullemeier@geomar.de

Abstract. The elastic anisotropy of bulk rock depends on the mineral textures, the crack fabric and external parameters like, e.g., confining pressure. The texture-related contribution to elastic anisotropy can be predicted from the mineral textures, the largely sample-dependent contribution of the other parameters must be determined experimentally. Laboratory measurements of the elastic wave velocities are mostly limited to pressures of the intermediate crust. We describe a method, how the elastic wave velocity trends and, by this means, the elastic constants can be extrapolated to the pressure conditions of the lower crust. The extrapolated elastic constants are compared to the texture-derived ones. Pronounced elastic anisotropy is evident for phyllosilicate minerals, hence, the approach is demonstrated for two phyllosilicate-rich gneisses with approximately identical volume fractions of the phyllosilicates but different texture types.

1. Introduction

Many studies have shown that the 'extrinsic' crack effects on bulk rock elastic anisotropy are largely sample-dependent and must be determined experimentally, whereas the texture-related 'intrinsic' contribution to bulk rock elastic anisotropy can be predicted from the mineral textures [1]. Existing equipment for the measurement of elastic wave velocity trends as a function of confining pressure P_c is often limited to pressures of the intermediate crust (400 – 600 MPa) [1, 2]. In order to get information on the elastic behavior of rocks in the lower crust, extrapolation of the elastic wave velocities obtained at intermediate pressures to pressures of the lower crust (≈ 1000 MPa) is desirable.

Several model functions were proposed to describe velocity – pressure trends in rocks, for an overview refer to [3]. The relation recommended in [2] appears to be most suitable for the purpose of extrapolation, because it provides the 'intrinsic' velocity trend, which, at high pressures, is assumed to describe the overall velocity trend sufficiently well. It has been shown that the 'intrinsic' velocity trend still can be refined [3], leading to a better estimate of the extrapolated velocities. We used the relations suggested in [2] and [3] to evaluate refined 'intrinsic' velocity trends from cube sample measurements performed at Institute of Geosciences (Kiel) [1]. Complete P - wave velocity distributions were determined on spherical samples at Geological Institute AS CR (Prague) [2] and extrapolated using the concept described below. From combined cube and spherical sample data the elastic constants were calculated for pressures $P_c = 200$ MPa (based on experimental data) and 1000 MPa (based on extrapolated data) [4, 5]. The latter were compared to the texture-derived elastic constants.

Two gneisses (G1 and G2 in the following) bearing approx. 30% phyllosilicates were selected for demonstration of the approach. The main difference between the samples is the texture type of the phyllosilicates, this offers good opportunity to quantify the influence of texture variation of the highly anisotropic phyllosilicates [6, 7] on bulk rock elastic behavior.



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2. Experimental details and data evaluation procedures

Initially, complete (132 sample directions) V_P distributions at $P_c = 200$ MPa were measured on spherical sample. From the velocity distributions the best fit orthogonal coordinate system (X, Y, Z) for cube sample preparation was determined by means of eigenvalue analyses. The cube sample data set comprises V_P , V_{S_1} and V_{S_2} measurements at 16 pressure stages (12 – 600 MPa) for these sample directions. For the common pressure of $P_c = 200$ MPa, the elastic constants were calculated from the V_P distributions and the six cube sample shear wave velocities [4]. The cube sample 'intrinsic' velocity trends were estimated using the relation described in [2] and refined according to the procedure explained in [3]. For extrapolation of the V_P distributions to the desired pressure of $P_c = 1000$ MPa we assumed that the 'intrinsic' pressure gradients derived for the cube sample apply to the spherical sample as well. By this means, the V_P distributions as a whole can be extrapolated, provided that the outlines of the V_P patterns and orientations of the principal directions X, Y and Z do not change significantly. At least, the elastic constants for $P_c = 1000$ MPa were calculated from the extrapolated data sets.

For the texture measurements the neutron diffraction was applied to ensure sufficient grain statistics, because large sample volumes had to be investigated. The measurements were performed at the SKAT texture diffractometer at the pulsed reactor IBR-2M in Dubna, Russia [8]. Recording TOF spectra offered the opportunity to evaluate the textures by means of 'Rietveld Texture Analysis' (RTA) [9, 10], which is the most promising method to extract the mineral textures from diffraction spectra with many peak overlaps. We used the MAUD software for the texture evaluation [11, 12]. Subsequently, the elastic constants of bulk rock were modeled from the textures applying the Voigt averaging scheme.

3. Results and discussion

In addition to the composition of the samples (G1: muscovite–17%, chlorite–13%, quartz–38%, albite–28%, microcline–3%, calcite–1%; G2: muscovite–15%, biotite–14%, chlorite–5%, quartz–47%, albite–19%), RTA revealed girdle-like pole density distributions for the muscovite and chlorite (001) pole figures of sample G1. Due to this characteristic, the texture strength is weak, as indicated by texture indices f_2 of 1.28 and 1.11 and maximum pole densities of 2.01 and 1.36 [m.r.d.], respectively (Fig. 1). In contrast, the (001) pole figures of muscovite, biotite and chlorite of sample G2 display axial symmetric pole density distributions and mostly stronger textures, with texture strengths $f_2 = 4.25/1.40/1.02$ and pole density maxima of 12.4/4.09/1.25 [m.r.d.], respectively (Fig. 1).

The textures of the other rock constituents are not presented, because they are weak or particular volume fractions are minor. Nevertheless, all textures were included in the averaging procedure.

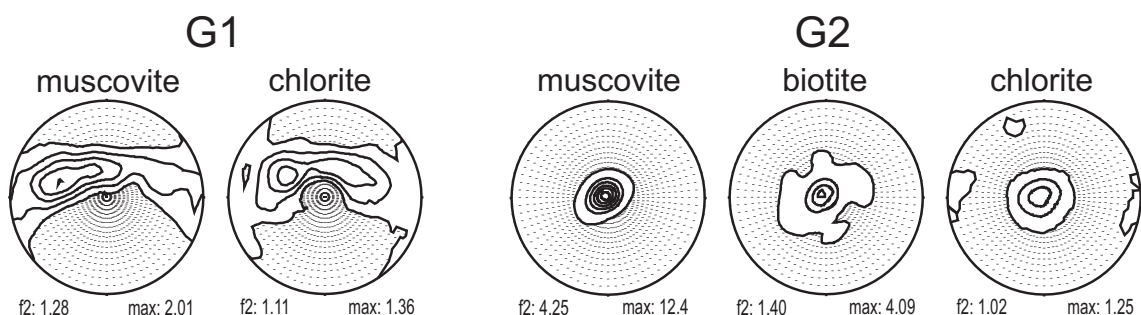


Figure 1. Phyllosilicate basal plane pole figures of samples G1 and G2. f_2 : texture index; max: maximum pole density [m.r.d.]. Dots in the pole figures indicate pole densities < 1.0 [m.r.d.].

The cube sample P -wave velocity trends for sample G1 suggest orthorhombic symmetry of the V_P distribution, this is confirmed by the spherical sample measurements at 200 MPa. The refined 'intrinsic' trends for directions Y and Z converge, leading to an axial symmetric V_P distribution at 1000 MPa. The V_P distributions (200/1000 MPa) of sample G2 are axial symmetric (Fig. 2A). Both samples show shear wave splitting for directions X and Y, which is more pronounced for sample G2 (Fig. 2B).

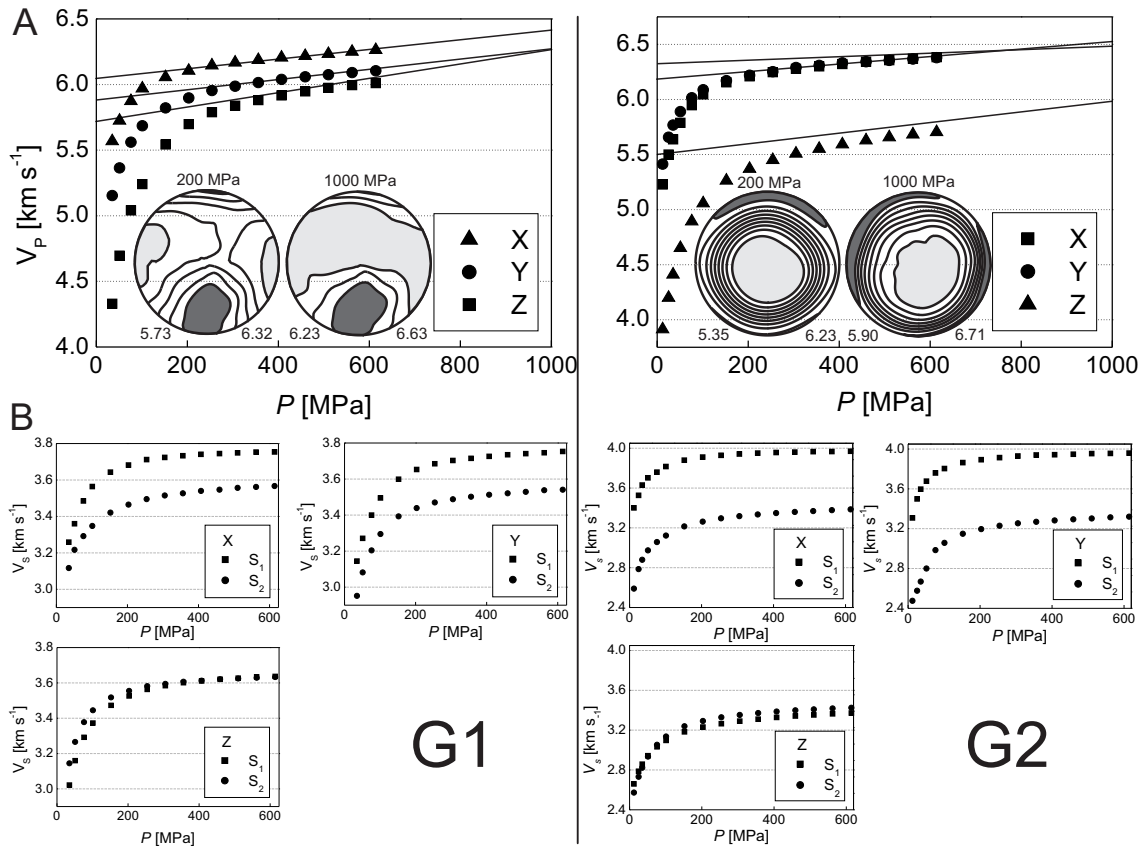


Figure 2. Compilation of velocity measurements. **A:** Cube sample P -wave trends. Straight lines: refined 'intrinsic' velocity trends. Inset diagrams: experimental (200 MPa) and extrapolated (1000 MPa) P -wave velocity distributions [km s⁻¹] from spherical sample measurements. Dark-shaded/light-shaded regions indicate regions of maximum/minimum velocity. **B:** shear wave splitting.

For both samples, recalculated P - and S -wave distributions from particular sets of elastic constants (Fig. 3) demonstrate the diminishing effect of the crack fabric. Anisotropies of the V_P distributions at $P_c = 200/1000$ MPa decrease only slightly with increasing pressure, which can be also inferred from consistent increase of the minimum and maximum velocities. The degree of anisotropy is larger for the well-textured sample G2. In contrast, a large drop of anisotropy is observed for the texture-derived V_P distributions, mainly due to the much larger difference of the minimum velocities. The maximum velocities of the '1000 MPa' and 'texture-derived' V_P distributions are comparable within the expected error ranges, *i.e.*, the crack influence vanishes for sample directions perpendicular to the phyllosilicate basal plane pole density maxima but persists for directions parallel to the maxima. Hence, there is some correlation between the phyllosilicate basal plane pole figures and the crack fabric. Due to these observations, we expect differences of the experimental and texture-derived S -wave distributions as well. The shapes of the 'G1' S -wave patterns differ largely, but the texture-derived velocity variations are in the order of some tenths of meters and, therefore, observed differences may be erroneous and should not be judged. In contrast, the 'G2' S -wave patterns are considered to be more reliable due to larger velocity variation of the texture-derived S -wave distributions. The general layout is axial symmetric, however, the texture-derived S -wave distributions show distinct maxima on the girdle-like velocity distributions. Such differences support the above assumption that some crack influence persists even at confining pressures of 1000 MPa.

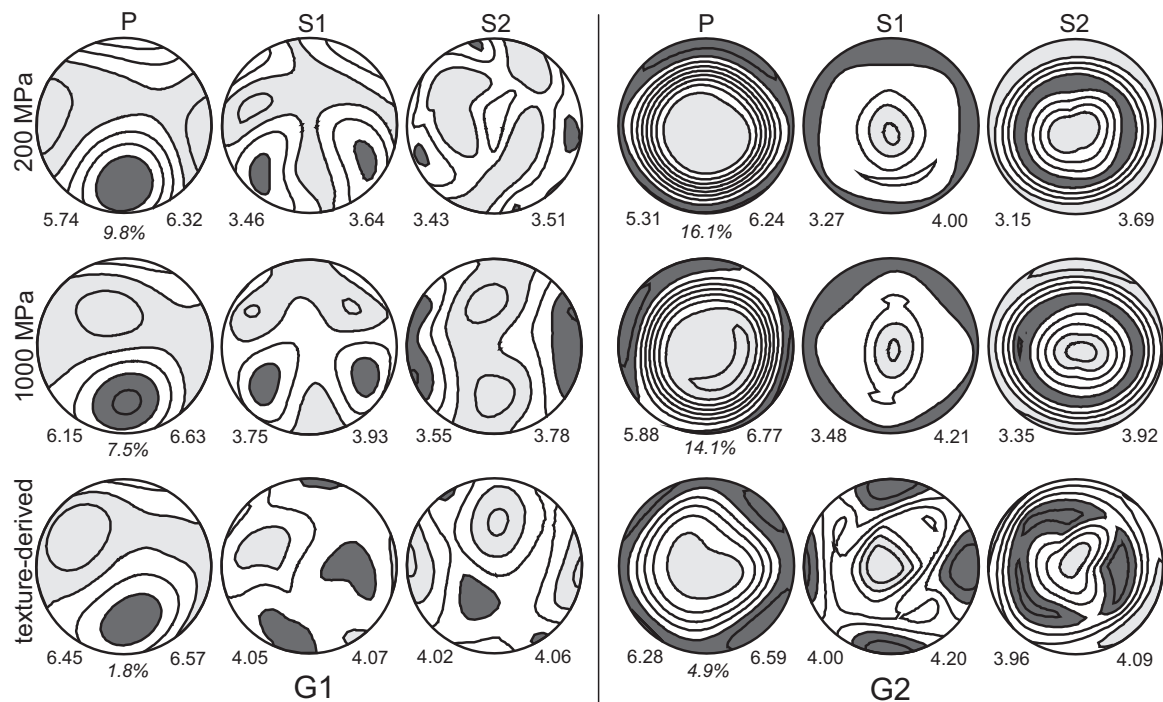


Fig. 3. Recalculated P - and S - wave distributions [km s⁻¹]. The minimum and maximum velocities are indicated, percentages refer to anisotropy $(V_{p_{\max}} - V_{p_{\min}}) / V_{p_{\text{mean}}}$. Dark-shaded/light-shaded regions indicate regions of maximum/minimum velocity.

4. Conclusions

We conclude that elastic anisotropy of rocks containing large volume fractions of phyllosilicates is mainly controlled by the phyllosilicate textures. This holds true for strong axial symmetric textures and for weak girdle-like textures as well. The contribution of the other mineral phases is neglectable due to weak textures and/or small volume fractions. Differences between the recalculated ‘1000 MPa’ and ‘texture-derived’ P - and S - wave distributions indicate persisting crack influence even in the lower crust. The correlation between the phyllosilicate basal plane pole figures and the crack fabric offers the opportunity to model the influence of the crack fabric from particular textures [12].

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