Laboratory approach to the study of rock dynamic and static elastic anisotropy under high hydrostatic pressure

T. Lokajíček, T. Svitek, M. Petružálek

Institute of Geology, Academy of Sciences of the Czech Republic, v.v.i., Prague, Czech Republic

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Avignon, France, 8-11 September, 2014

ABSTRACT

Knowledge of elastic properties of rocks and their anisotropy is very important parameter for many engineering applications. In our contribution there is presented experimental setup enabling laboratory measurement of dynamic, as well as static elastic anisotropy of rocks and its changes under high hydrostatic pressure. All measurements are carried out on spherical rock samples diameter of which is 50 mm ± 0.01mm. Measuring setup enables spatial distribution of individual elastic parameters to be measured and visualized. Dynamic elastic properties of rock samples can be determined based on simultaneous ultrasonic sounding by P and two perpendicularly polarized S waves. Measurements are carried out in 132 independent directions. In the same measuring net spherical sample strain anisotropy can be determined. All measurements can be carried out under high hydrostatic pressure up to 100 MPa. A feature of new measuring system is demonstrated by experimental data carried out on crystalline rocks. The results show that there can be measured combination of static, as well as dynamic parameters of rocks and to study their 3D anisotropy and its changes under acting hydrostatic pressure. New measuring set up and enhanced data processing will contribute for delineation of basic parameters that control rock mechanical properties and pore space distribution and its changes with hydrostatic stress.

INTRODUCTION

Seismic anisotropy is one of the most important parameters studied by means of laboratory and field prospecting methods. In the Earth's crust, anisotropy may be caused by rock texture, preferentially aligned joints or micro-cracks, by layered bedding in sedimentary formations, or by highly foliated metamorphic rocks. [1, 2, 3, 4, 5]. Seismic anisotropy is particularly important for seismic modeling and prospecting, the exploration of hydrocarbon and mineral deposits, geological processes, etc. More complete information is given by the study of the velocity anisotropy of longitudinal waves Vp for samples in the form of a globe/sphere, which makes it possible to measure the velocities in any direction both under atmospheric and high hydrostatic pressures [6, 7, 8, 9]. Elastic velocities for many crustal rocks have been determined by ultrasonic experiments using high-pressure apparatus e.g. [10]. These experimental studies provided compressional and shear wave velocity data to assess petrological characteristics of lower parts of continental crust. The aim of this contribution is to describe laboratory research of elastic anisotropy by means of ultrasonic methods and to introduce a new high-pressure system for the laboratory study of rocks by P and S-wave ultrasonic sounding on spherical samples. Experimental setup enabling laboratory measurement of dynamic, as well as static elastic anisotropy of rocks and its changes under high hydrostatic pressure is presented.

CONCLUSION

The high-pressure system used to measure P-wave elastic anisotropy in spherical samples under hydrostatic pressure from 0.1 MPa up to 400 MPa is described in [8]. The system enables measurement of P-wave velocities in 132 independent directions under hydrostatic stress up to 400 MPa by means of the pulse transmission method. Such data can be used to calculate the elastic tensor by assuming the ratio between V_P/V_S, what is for isotropic Poisson media equal to 1.7. However, calculations based on the Christoffel equation can give incorrect results, due to missing knowledge of individual shear wave velocity components in significant directions. This contribution deals with the design of a new high-pressure measuring head, which enables the ultrasonic investigation of spherical samples not only by means of P-waves, but also by two couples of perpendicularly oriented shear wave transducers [11]. The HOS approach [12] was used to calculate P-wave arrival time. Measurements can be made in 150 directions (132 of which are independent with a measuring step of 15°), under any hydrostatic pressure up to 100 MPa. The mechanical design of the measuring system enables movement of the spherical sample and the transducers by two step motors. A schematic drawing of the new transducer measuring arrangement is shown in Fig. 1. There are three pairs of transducers (T_P, R_P - P-waves; T_V, R_V – vertically polarized shear waves; T_H, R_H – horizontally polarized shear waves). Shear waves are polarized according to the sphere rotation axis. Fast (S1) and slow (S2) arrival times for SV and SH waveforms were determined manually. In order to calculate the 3D velocity distribution from measured P- and S-wave velocities measured on the sample sphere, we determined the stiffness coefficients by means of the Christoffel equation [13]. The calculation is based on an iterative computation process [14] of the density-normalized elastic tensor parameters. Its eigenvalues represent velocities of longitudinal (P), fast (S1) and slow (S2) shear waves along with the direction of polarization of each wave [15]. For the determination of the complete elastic tensor (21 elastic parameters) it is necessary to know at least 15 P–wave velocities and 6 S–waves velocities in different directions with exact precision. The calculation of the elastic tensor parameters represents a non-linear problem that is linearized by an iterative process. From measured velocities of P-, S1- and S2-waves, differences of individual parameters were calculated and, subsequently, the complete tensor of stiffness components, i.e. 21 elastic parameters are obtained through generalized inversion. We assume that phase velocities are measured. The root-mean-square (RMS) values of the S1- and S2-wave velocities were used as an evaluation criterion of fitting procedure. The RMS values are calculated as follows:

$$RMS^{S1,S2} = \sqrt{\sum \frac{\left(v_{obs}^{S1,S2} - v_{calc}^{S1,S2}\right)^2}{n}}$$

where $v_{obs}^{S1,S2}$ are the observed velocities, $v_{calc}^{S1,S2}$ are the velocities calculated from retrieved elastic tensor and n is the number of directions in which the velocities are measured. The iterative process simultaneously using P-, S1- and S2-wave velocities is very robust and converges very quickly. Figure 2 shows a 3D elastic anisotropy of a quartzite sample using approximated velocities calculated from P-, S1- and S2-wave velocities measured at 60 MPa. Based on known full stiffness tensor, there is shown in Figure 3 - 3D distribution of Young modulus of quartzite sample at 60 MPa. This distribution was calculated by the using of all elastic tensor components according to the formula, $1/E_n=n_in_jS_{ijkl}n_kn_l$, where E_n is Young modulus in the direction n, S_{ijkl} are the components of the elastic compliance tensor [16]. This is an expression valid for linearly

elastic fully anisotropic material. We invented a new mechanism, equipped with high sensitivity resistor that enables measurement of strain anisotropy. Measuring setup shown in Figure 1 does not provide deformation/strain measurement of rock spherical sample with increasing hydrostatic pressure and its anisotropy. Due to this fact, measuring arrangement was modified by using only P-wave sensors T_P and R_P, which are firmly connected with measuring arms – see Fig. 4. Mounted between the tips of the arms was a linear resistor capable of measuring spherical sample diameter changes with a resolution of about 5 μm. The sensor measures spherical sample diameter deviation and it changes with acting hydrostatic pressure. There is also point contact of flat P-wave sensors with the spherical sample surface. This approach can be used to determine not only the bulk modulus of the spherical sample, which describes its volumetric elasticity, but also deviation from uniform deformation due to sample elastic anisotropy. Deformation sensor calibration was carried out by inserting several gauges between sphere and P-wave sensors flat contact plane. Measurement accuracy was proved by means of two homogenous isotropic samples with known elastic parameters. Based on measured strain and acting hydrostatic pressure, there was determined static modulus, which was compared with known one. The new measuring setup was calibrated by using two different isotropic spheres made from materials with known, but different Young moduli. The first was a glass sphere made from high quality sodium potassium glass with an elastic module of E= 50 - 90 GPa, the second was made of Murital C engineering plastic and had a fine crystalline structure and an elastic module of about E= 6 GPa. A migmatite spherical sample was used as real testing material. The migmatite rock-forming minerals were quartz, feldspar, plagioclase, muscovite, biotite and amphibole. The sample exhibited visible foliation and in the foliation plane lineation was observed, caused by the elongation of biotite-amphibole aggregates. Spherical sample was 50 ±0.02 mm in diameter. Figure 5 shows experimental data measured under the arrangement shown in Figure 4. The left column presents the 3D P-wave velocity elastic anisotropy and the right column the strain of a migmatite sample subjected to hydrostatic pressure at 200 and 400 MPa. The P-wave velocity elastic anisotropy shows orthorhombic symmetry with high velocity (red color) in the plane of foliation. Minimum velocity direction, denoted by blue color, is oriented perpendicularly to this plane. Contrary to the P-wave velocity distribution, the strain anisotropy exhibits opposite behavior. The maximum P-wave velocity plane coincides with the minimum strain directions of the migmatite sample and the maximum strain of the migmatite sample coincides with the minimum velocity direction. The new high-pressure head enhanced by two pairs of perpendicularly oriented shear wave transducers is very suitable for investigating the contribution of oriented micro-cracks, lattice (LPO) and shape-preferred orientation (SPO) to the bulk elastic anisotropy of rocks of high anisotropy. All velocity/pressure relations display the well-known initial high-velocity increase with hydrostatic pressure. The non-linear rise is due to the progressive closure of micro-cracks, which indicates the pressure sensitivity of P- and S-waves. Such a study could be carried out with the current system under acting hydrostatic pressures between 0.1 and 100 MPa, since most low-aspect ratio cracks close at the high end of this range. Moreover, a second configuration of the measuring set up with a pair of P-wave sensors equipped with high sensitivity resistor capable to measure deformation of a spherical sample is capable of measuring their static bulk modulus and directional strain anisotropy. Proposed calibration procedures based on isotropic material like glass or engineering plastic proved that the newly constructed measuring head can be used for both dynamic and static bulk anisotropy studies under high hydrostatic pressure. Such a study of static bulk modulus can be carried out under hydrostatic pressures up to 400 MPa, which is the maximum pressure which can be applied in the high-pressure vessel. Unfortunately, it is not possible to measure P and S as well as P with

deformation during a single loading cycle, as the P and S measurement requires moving the arms to eliminate sensor contact with the sphere, which would result in a significant reduction in the accuracy of the diameter measurement. Use of sliding P-wave sensors in contact with the sphere, this results in accurate measurement of deformation changes. The accuracy of P-wave velocity determined by ultrasonic measurements on spherical samples during high-pressure hydrostatic loading at hydrostatic pressure is 50 m/s. Based on the *RMS* value (fitting evaluation criteria), and comparison of S1- and S2-wave velocities obtained by different computation types, it can be seen that the most reliable velocity approximations are determined from all P-, S1- and S2-wave velocities. In this case, the velocity accuracy was determined to be approximately 50 – 70 m/s and 70 – 90 m/s for the velocity model of S1- and S2-wave velocities, respectively. The velocity model determined from measured P-, S1- and S2-wave velocities can be considered sufficiently reliable. Elastic tensor, from which approximated velocities are calculated, contains 21 independent parameters that completely describe entire properties of the material under the study. The knowledge of elastic parameters can be used for further analysis, as shear wave splitting. It is also possible to compute modulus of elasticity (Young, bulk, Poisson ratio, etc.) and their anisotropy. Ultrasound experiments on spherical samples under hydrostatic pressure can also determine the directional and pressure dependencies of each monitored parameter. The use of data obtained from this kind of experiments lends itself to broad possibilities. Advantage of proposed method is that it does not need any *a priori* assumptions regarding the symmetry class or the orientation of the symmetry axes of rock samples under the study.

ACKNOWLEDGEMENTS

This work was partially supported by the Grant Agency of the Czech Republic, project Nos. P104/12/0915, 13-13967S, MSMT Kontakt II – LH13102 and by the long-time research development support of the Institute of Geology AS CR, v.v.i. - RVO67985831.

REFERENCES

1. Christensen N.I. 1966. Elasticity of ultrabasic rocks. *J. Geophys. Res.* 71: 5921–5931.
2. Babuška V., M. Cara. 1991. *Seismic Anisotropy in the Earth*. Kluwer Academic, Dordrecht.
3. Birch, F. 1961. The Velocity of Compressional Waves in Rocks to 10 kbar. Part 2. *J. Geophys. Res.* 66:
4. Petružálek M., J. Vilhelm, T. Lokajíček and V. Rudajev. 2007. Assesment of P-wave anisotropy by means of velocity ellipsoid. *Acta Geodynamica et Geomaterialia.* 4: 23–31.
5. Petružálek, M., J. Vilhelm, V. Rudajev, T. Lokajíček, and T. Svitek. 2013. Determination of the anisotropy of elastic waves monitored by a sparse sensor network. *International Journal of Rock Mechanics and Mining Sciences, accepted*
6. Pros, Z., and V. Babuška. 1967. A Method for Investigating the Elastic Anisotropy on Spherical Rock Samples. *Zeitschrift fur Geophysik*. 33: 289–291.
7. Pros, Z. and V. Babuška. 1968. An Apparatus for Investigating the Elastic Anisotropy on Spherical Samples. *Studia Geoph. et Geod.* 12: 192–198.
8. Pros, Z., T. Lokajíček and K. Klíma. 1998. Laboratory Approach to the Study of Elastic Anisotropy on Rock Samples. *Pure appl. geophys.* 151: 619–629.
9. Nadri D, Bóna A, Brajanovski M and Lokajíček T 2011 Estimation of stress-dependent anisotropy from P-wave measurements on a spherical sample Geophysics 76

10. Kern H., B. Liu and T. Popp. 1997. Relationship between anisotropy of P and S wave velocities and anisotropy of attenuation in serpentinite and amphibolite. *Journal of Geophysical Research.* 102: 3051–3065.
11. Lokajíček T, Kern H, Svitek T., Ivankina T.I. 2014: 3D velocity distribution of P- and S-waves in a biotite gneiss, measured in oil as the pressure medium: Comparison with velocity measurements in a multi-anvil pressure apparatus and with texture-based calculated data, PEPI, 231, 1-15,PEPI, DOI:10.1016/j.pepi.2014.04.002.
12. Lokajíček T and Klíma K 2006 A first arrival identification system of acoustic emission (AE) signals by means of a high-order statistics approach. *Meas. Sci. Technol.* 17, 2461-2466
13. Červený, V, 2001. Seismic Ray Theory, Cambridge University Press, New York.
14. Svitek, T. 2012. Determination of elastic anisotropy from P and S waves based on ultrasonic sounding on spherical samples. *33rd ESC 2012 Moscow*, ES2:P086, p. 43.
15. Klíma, K. 1973. The computation of the elastic constants of an anisotropic medium from the velocities of body waves. *Studia geoph. et geod.* 17, 115–122.
16. Asaro, R. J. , Lubarda, V. A. 2006, MECHANICS OF SOLIDS AND MATERIALS, Cambridge University Press

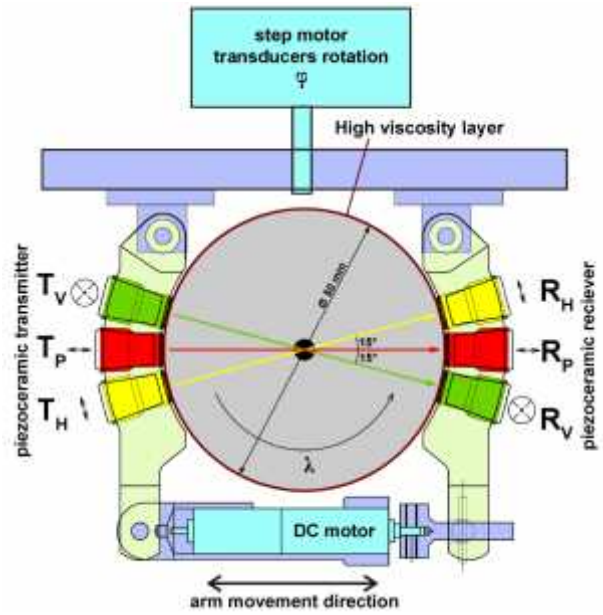

Figure 1.Schematic drawing of the new measuring setup. TP, RP – pair of longitudinal piezoceramic transducers (T-transmitter, R-receiver); TV, RV – pair of shear-wave transducers with vertical polarization; TH, RH – pair of shear-wave transducers with horizontal polarization. λ – direction of sphere rotation, ϕ – direction of arm rotation, step motor to rotate arms with transducers, DC motor – motor to eliminate contact between the sphere and transducers to enable arm movement and position the sphere and transducers.

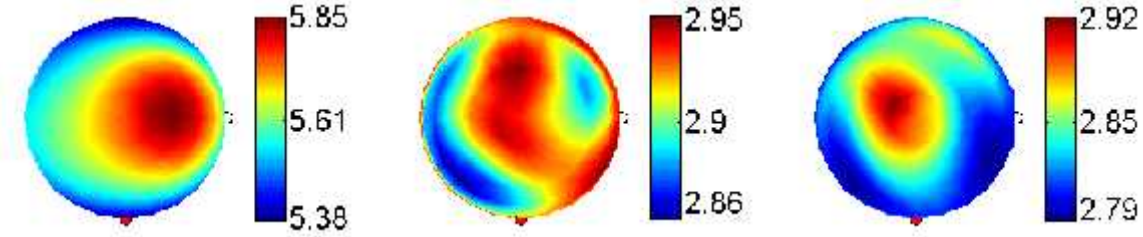

Figure 2: 3D velocity anisotropy of P, S1 and S2 calculated velocities obtained for measured data at 60 MPa.

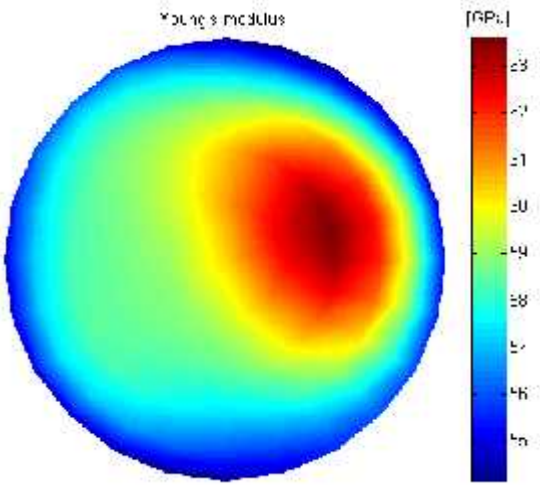

Figure 3: 3D distribution of quartzite Young modulus at 60 MPa.

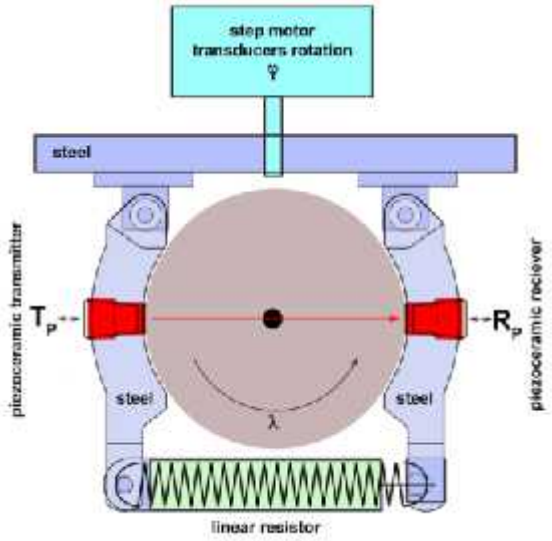

Figure 4: Schematic drawing of the new measuring setup. T_P, R_P – pair of longitudinal piezoceramic transducers (T-transmitter, R-receiver). λ – direction of sphere rotation, linear resistor – measures the diameter changes of the sphere at P-wave sensor contact points.

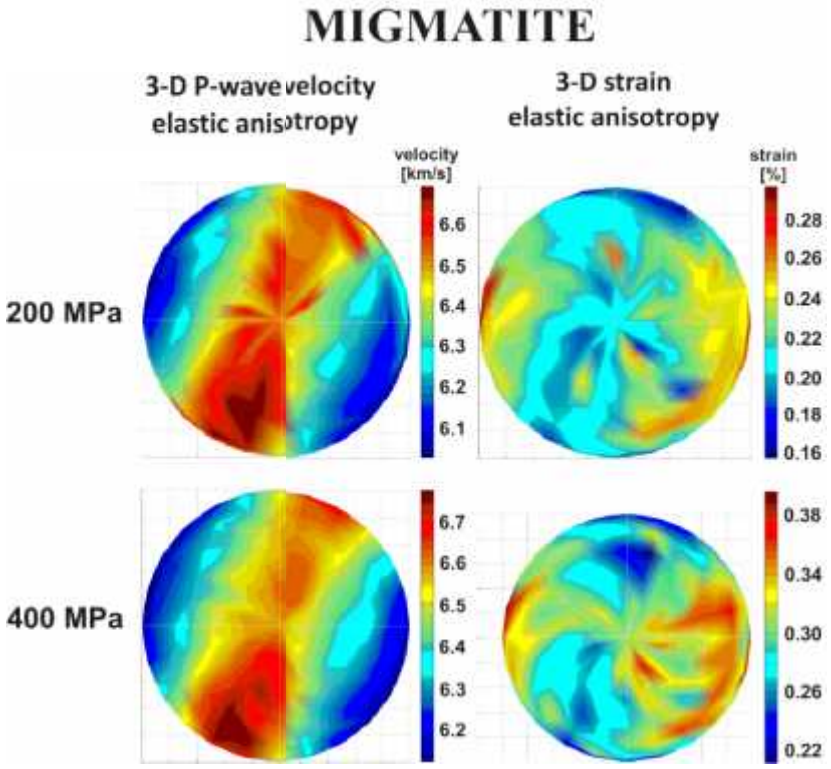

Figure 5: P-wave velocity elastic anisotropy of quartzite sample (left column); strain anisotropy of quartzite sample (right column) measured at 200 and 400 MPa.