Modelling of density and elastic wave velocities in the KTB pilot borehole

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The nature of seismic velocities as well as nature of seismic reflectors in the upper continental crust are among the major goals of the KTB project. In-situ seismic velocities are controlled by several factors, i.e. rock composition, metamorphic grade, fabric, pores/cracks and properties of pore fluid. Amount and quality of the borehole observations at the KTB pilot hole make it possible to separate effects of the different factors. The most efficient tool for that is combination of laboratory measurements with petrophysical modelling. The aim of this study is to combine petrological and petrophysical borehole observations, laboratory measurements, and technique of petrophysical modelling (Sobolev and Babeyko, 1994) to understand the nature of seismic velocities in the KTB pilot borehole. We study a depth segment of 1800-3550m, consisting mainly of monotonous (garnet)-(Al_2SiO_5)-muscovite-biotite gneisses with a layer (2470-2690m) of biotite-hornblende gneisses and amphibolites.

We start with calculation of mineralogical compositions along the borehole from bulk chemical compositions which are available each 2m (XRF-analyses of rock flour from drilling mud, KTB-Feldlabor). For that we use (a) technique of the Gibbs free energy minimisation (Sobolev and Babeyko, 1994), (b) internally-consistent database of thermodynamic properties of minerals by Holland and Powell (1990), and (c) PT-path suggested by Reinhardt (1990). Calculated modes (in wt%) of main minerals equilibrated at 500 °C and 400 MPa are presented in Fig. 1.

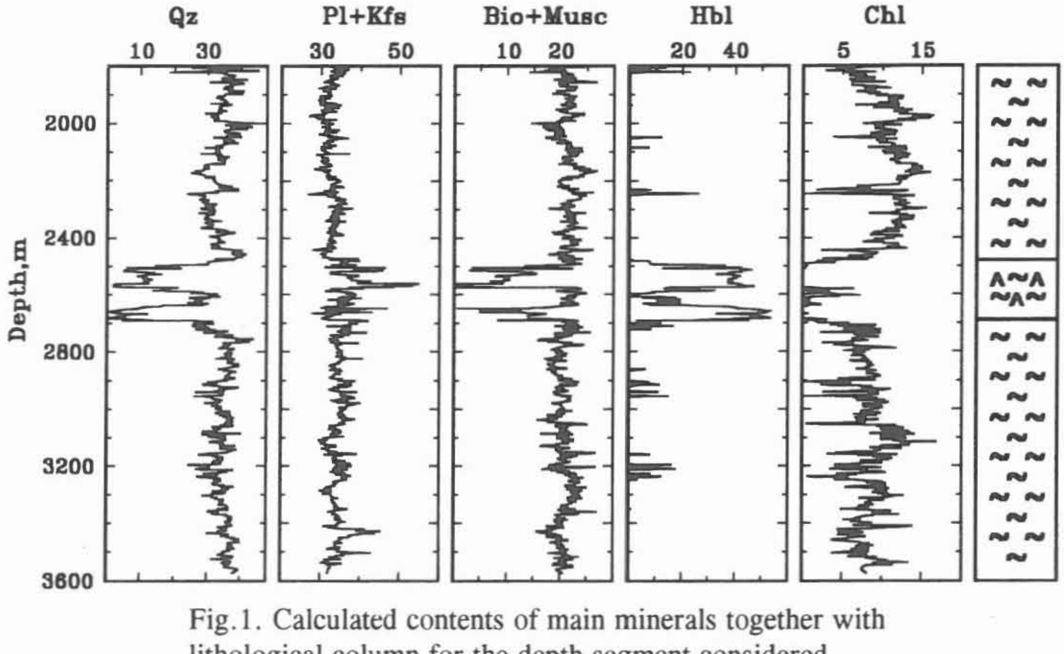

Fig.1. Calculated contents of main minerals together with lithological column for the depth segment considered.

The next step is calculation of density and isotropic elastic properties from thus obtained mineralogical compositions. For that we use experimental measurements of single crystals elastic properties and Hashin-Shtrikman averaging method for composites. Log data were pre-processed with median filter with 5-m window in order to remove outliers, and then smoothed with 30-m gaussian window. The same smoothing was applied to calculated properties. Calculated density fit well log data and measurements on cores (Fig. 2a) being slightly higher (less than 1.5%) reflecting, likely, the effect of porosity. At the same time, calculated velocities differ markedly from sonic data (Fig. 2b,c). While 'composition-controlled' synthetic velocities are nearly uniform in biotite-muscovite gneisses, sonic velocities vary significantly with depth; their variations correlate very well with dip of the foliation plane in the borehole (Fig 2d), demonstrating clear anisotropic behaviour. Experimental measurements

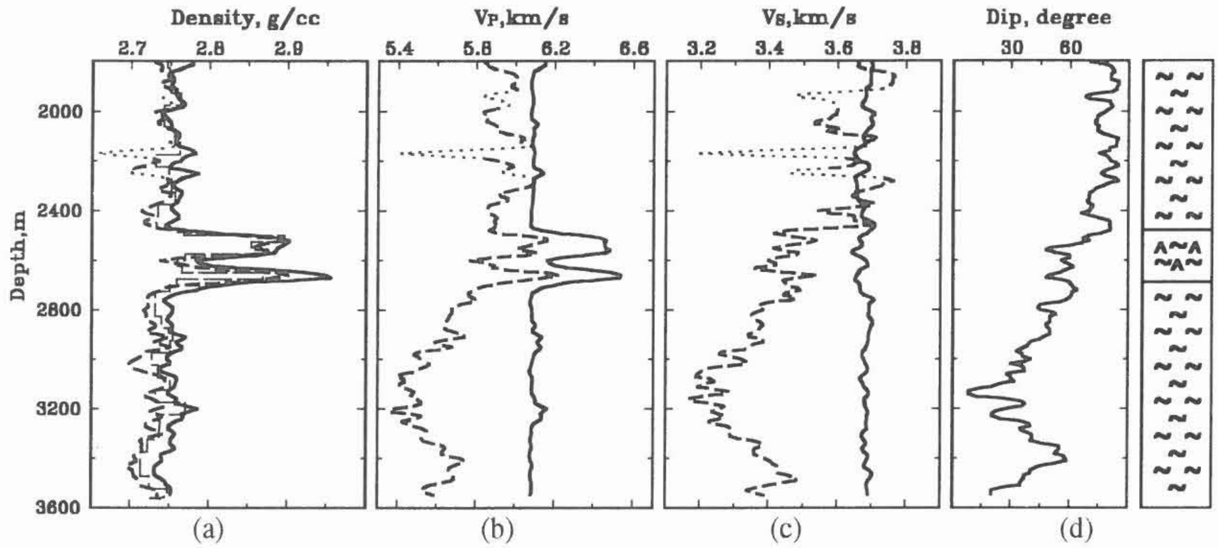

Fig. 2. Comparison of calculated density (a) and isotropic, crack-free velocities (b,c) (solid lines) with log measurements (dashed lines). Also shown is dip of the foliation plane (d). Dotted parts of log curves - intervals with bad borehole calliper. Note strong correlation between sonic velocities and dip of the foliation plane.

of elastic velocities in KTB core samples (Kern et al., 1991; Siegesmund et al., 1993) show that main reason of anisotropy in biotite-muscovite gneisses is preferred orientation of sheet silicates in the foliation plane; anisotropy can also be amplified by cracks parallel to the foliation plane.

Since biotite-muscovite gneisses are very similar in composition (Fig.1, depth segments 1800-2470m and 2690-3550m), they provide excellent opportunity to study effects of anisotropy and cracks on elastic velocities. We restrict our further modelling to these two depth segments.

We calculate effective anisotropic elastic tensor of a rock, C_{ijkl}, assuming that all minerals, except for micas and chlorite, form isotropic rock matrix, while sheet silicates are oriented quazi-parallel to the foliation plane. Experimental measurements of V_P and V_S at 200

MPa in gneisses samples from the two depth segments considered (Kern et al., 1991) were used to model fabric-related anisotropy. To fit average experimental velocities we use average modal compositions in the corresponding depth segments. Optimal fit to velocities measured parallel and perpendicular to the foliation plane was obtained when the orientation of (001)-planes of sheet silicates were assumed to scatter stochastically near the orientation of the foliation plane with the standard deviation ≈ 20° (Fig. 3). Gneisses in the upper part (dotted lines) are more anisotropic than those in the lower part (dot-dashed lines) due to higher content

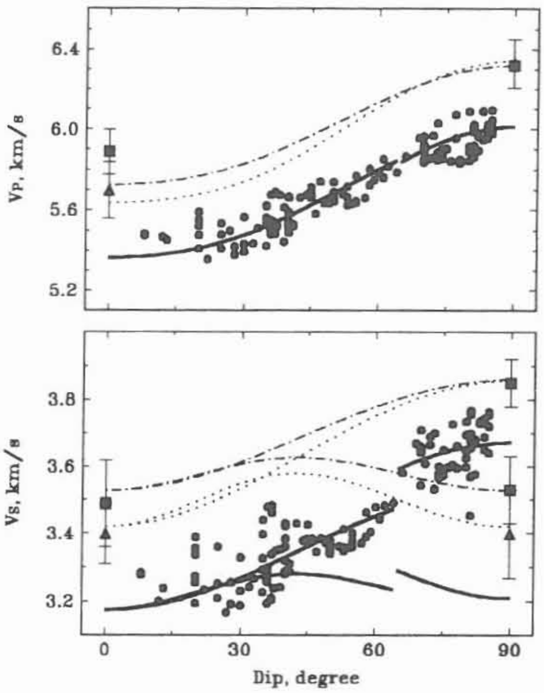

Fig. 3. Observed and modelled velocities vs. dip of the foliation plane. Circles - sonic log data. Triangles - laboratory measurements at 200 MPa for core samples from z<2500m (average and 1σ error-bar for 8 samples) and boxes - for samples from z>2500m (11 samples) (Kern et al., 1991). Broken lines represent models of fabric-related anisotropy (dotted for z<2500m, dot-dashed for z > 2500m) calibrated using measurements by Kern et al. (1991). Solid lines - final models included cracks.

Note: (1) good fit of laboratory measurements at 200 MPa (most cracks are closed) for both P- and S-wave velocities by anisotropic model without cracks, and (2) good fit of sonic log data by anisotropic model with cracks.

of sheet silicates.

However, fabric-related anisotropy alone cannot explain observed log velocities which are significantly lower (Fig. 3, circles, dip>65° corresponds to the upper gneiss segment, dip<65°- to the lower). Adding of cracks to anisotropic rock matrix is necessary. We consider the following types of brine-filled cracks (K_{brine}=2.5 GPa): aligned parallel to the foliation plane, aligned perpendicular to the foliation plane, aligned system of cracks non-correlated with the foliation plane (all- using Hudson's (1980) model), and randomly oriented cracks (Küster and Toksöz, 1974). The best fits for both gneiss intervals was obtained with the cracks non-correlated with the foliation plane: aligned (e.g. horizontal) or randomly oriented (Fig.3, solid lines). For the upper gneiss segment best-fit crack parameters are: horizontal cracks with crack density of 0.06 and aspect ratio of 0.02, or, equally, random cracks with crack density of 0.12 and the same aspect ratio. For the lower gneiss interval these parameters are: 0.08, 0.01 (horizontal cracks) or 0.2, 0.003 (random cracks). Final fit of sonic velocities is shown also in Figure 4 in velocity-depth coordinates. Standard deviation of model calculations from observations is 1% for V_P and 1.5% for V_S.

Higher anisotropy in the upper part produce higher shear wave splitting (about 14%) that is consistent with VSP data of Rabbel (1989).

Conclusions.

The most significant variations of sonic log velocities with depth are not related to rock composition. They correlate very well with variations of dip of foliation plane and reflect rock anisotropy.

Significant fabric-related anisotropy and fluid-filled cracks are required to fit sonic log velocities.

Significant or even dominant are cracks with strike not correlated with the orientation of foliation plane in rocks, which may be related to the drilling or to the in situ stress field.

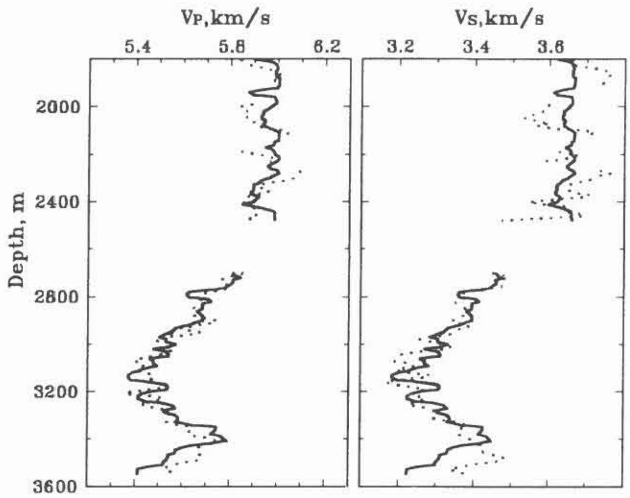

Fig. 4. Final fit of sonic log velocities by two-layered anisotropic model with brine-filled cracks. Dotted lines - sonic log, solid lines - model.

Upper ($z<2470$m) and lower ($z>2690$m) parts of the borehole segment are different in respect to fabric-related anisotropy and aspect ratio of cracks. In the upper part fabric-related anisotropy and cracks aspect ratio are higher.

Our relatively simple, anisotropic model with cracks is consistent with the following borehole observations and laboratory measurements:

- bulk chemical compositions of rock flour from drilling mud;
- metamorphic PT-path for metapelite gneisses;
- laboratory measurements of V_P and V_S on core samples at high confining pressure;
- log density and density measured on cores (average fit 1%);
- P- and S- wave sonic log (average fit is 1% for V_P and 1.5% for V_S;
- shear-wave splitting by VSP.

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