The KTB drilling site: Seismic properties of dry and wet rocks - Experiments and modelling

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Introduction

In this study, we present new laboratory data from combined measurements on the variation of seismic velocities and of crack porosity as a function of pressure on rock samples representing the main lithological rock units (gneisses and metabasites) exposed in the KTB wells. The study focuses largely on the effect that the presence or absence of pore fluids may have on the effect of microfracturing and thus on seismic rock properties. The experiments were performed on unjacketed sample cubes (43mm on edges) in a cubic-anvil apparatus (e.g., Kern, 1982). The pressure dependence of P- and S-wave velocities, velocity anisotropy (A-V_P), shear wave splitting (ΔV_S) and crack-porosity (η) has been investigated for dry and wet (water saturated) conditions.

Experimental results and discussion

At atmospheric pressure, P-wave velocities of the saturated, low-porosity rocks (< 1%) are significantly higher than in dry rocks, whereas the differences for S-wave velocities are less pronounced (Fig. 1). The effect of intercrystalline fluids on seismic properties at increased pressure conditions is particularly reflected by the variation of the Poisson´s ratio because P-wave velocities are more sensitive to fluids than S-wave velocities in the low-porosity rocks (Fig. 2).

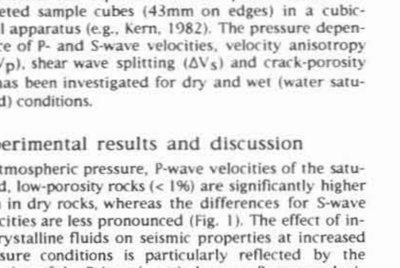

Fig. 1: Effect of pressure on P- and S-wave velocities (a), Vp-anisotropy (b) and shear wave splitting (c) in a garnet-amphibolite (KTB 61C9b) under dry and wet (saturated) conditions.

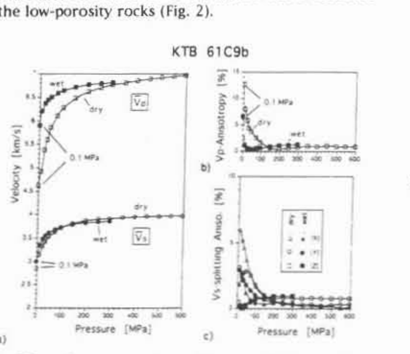

Fig. 2: Effect of pressure on the volumetric strain (a) and the Poisson´s ratio (b) in a garnet-amphibolite (KTB 61C9b) under dry and wet conditions. The insets show the pressure dependence of the experimental determined crack porosity (a), and of the calculated crack density, ε (b).

The experimental data were used to test the validity of the empirical model of O'Connell and Budiansky (1974). This model describes the seismic behaviour of a solid containing a set of randomly distributed, "penny-shaped" flat cracks (described by the crack density parameter, ε) with partial saturation (ξ). The crack density ε is defined as

$\varepsilon = \sum Na^3$, where N is the number of cracks per unit volume and a is the major semiaxis of the flat spherical crack with $a = b >> c$.

O'Connell and Budiansky calculated two different velocity diagrams, considering the effects of fluid saturation and of the aspect ratio of cracks ($\omega = a/c$) separately (Figure 3).

Figure 4a shows that the experimentally derived data fit the model of O'Connell and Budiansky (1974) relatively well for rocks exhibiting Poisson's ratios of about 0.25: *the experimental values for absolutely dry and fully saturated (solid curves) lie close to the limits of the theoretically realized velocity space.*

There is also a correlation between the calculated crack-densities ε (for dry and saturated conditions) and crack-porosities η derived from the experimentally determined volumetric strain curves (Fig. 4b).

From the relation $(c/a) = (\eta/\varepsilon)/(4\pi/3)$ we estimated the aspect-ratio c/a for each data set of η and ε (Fig. 5). In the low pressure range, the aspect-ratios are on the order of 0.001 to 0.01 and remain nearly constant during the initial stage of sample compaction. This indicates a continuos closure of cracks without marked changes of the pore geometry. The final stage of compaction at pressures above 50MPa is associated with a significant change of the aspect ratios.

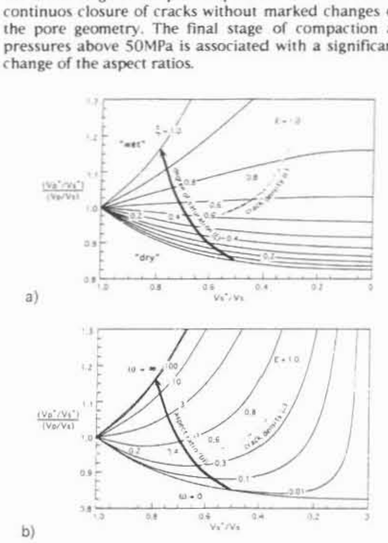

Fig. 3: Modelling of velocity variations in the plot $(V_P^* V_S^*)$ - (V_P/V_S) versus V_S^*/V_S.
(a) for different degrees of saturation, ξ
(b) for fluid-filled cracks exhibiting different aspect ratios c/a (after O´Connell and Budiansky, 1974).
Contours of constant crack density $\varepsilon = N * < a^3 >$ (dashed lines) are indicated in both diagrams.

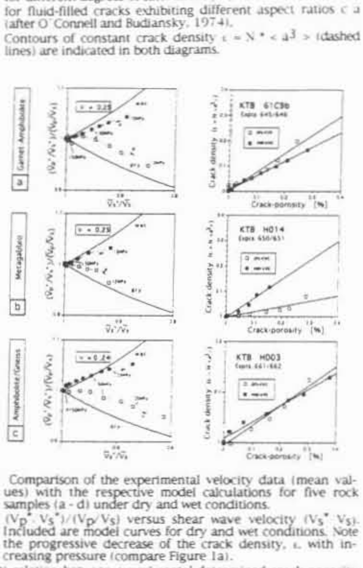

Fig. 4: Comparison of the experimental velocity data (mean values) with the respective model calculations for five rock samples (a - d) under dry and wet conditions.
(left) $(V_P^* V_S^*)/(V_P/V_S)$ versus shear wave velocity (V_S^*/V_S). Included are model curves for dry and wet conditions. Note the progressive decrease of the crack density, ε, with increasing pressure (compare Figure 1a).
(right) relation between experimental determined crack-porosity and calculated crack-density.

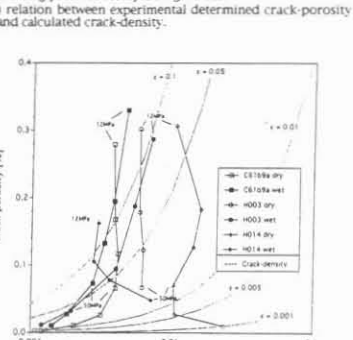

Fig. 5: Variation of the pore geometry of three KTB-samples (dry and wet) during compaction Isolines indicate crack densities.

Comparison with VSP-data

Figure 6 compares the laboratory data (dry samples; 50 MPa and intrinsic) with VSP-measurements representing seismic *in situ*-rock properties from the KTB-pilot hole reported by Rabbel (1992). The rock sequences penetrated by the KTB-pilot hole are dominated by biotite gneisses exhibiting mostly steep but varying dip and strike of foliation. In the depth interval of 2 to 3 km, the dip of rock foliation changes slowly from 80 to 30 deg. Based on the assumption of a quasi-hexagonal aggregate symmetry in the gneisses, we used the experimental data to calculate the variation of P-wave velocities and of shear wave splitting as a function of the dip of the foliation

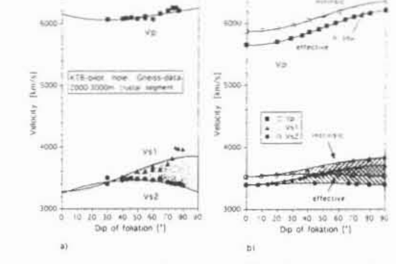

Fig. 6: Variation of P- and S-wave velocities (shear wave splitting) with the dip of the foliation plane for the depth interval of 2-3 km of the KTB pilot hole. The data refer to biotite gneisses exhibiting hexagonal symmetry.
(a) Seismic in-situ velocities as a function of the dip of foliation at the KTB drilling site. The data represent near offset VSPs, together with model curves of least squares fitting (Rabbel, 1992).
(b) Variation of P- and S-wave velocities (shear wave splitting) with the dip of the foliation plane as derived from laboratory measurements (at 50 MPa, effective and crack-free). For comparison, the data of Rabbel (1992) are indicated: stippled line (Vp) and shaded area (Vs)

Comparison with the VSP data reveals that, qualitatively, the experimentally derived variation of shear wave splitting with the dip of foliation compares fairly well with that observed in the seismic experiment. However, shear wave splitting measured in the laboratory is significantly lower than observed in-situ, and, importantly, the variation of the corresponding P-wave velocity (and thus P-wave anisotropy) is markedly higher. The observed discrepancies can, probably, be related to effects of intercrystalline fluids

As shown by Kern et al. (in press), microcracks can be selectively kept open by a deviatoric stress, and thus give rise for an increase of shear wave splitting. Because S-waves are less sensitive to fluids than P-waves at conditions of very low pore-fluid pressure, shear wave splitting remains nearly unaffected by intercrystalline fluids, whereas P-wave velocities are significantly increased by fluids on grain boundaries. Assuming that the seismic in-situ velocities and averaged laboratory data are representative for the same rock unit and taking into account that the laboratory data were obtained from dry samples, our experimental findings may give hints that the relatively high in situ P-wave velocities and low P-wave anisotropy at the KTB location (compared to the velocity data measured on dry rock samples) are caused by fluids on grain boundaries.

Conclusions

The experimental results suggest that combined V_P-V_S-measurements may give evidence for the presence fluids on grain boundaries and, in addition, may provide an estimate of the in-situ crack-densities. The comparison of the laboratory data with VSP-measurements of the KTB-pilot hole suggests that the in-situ seismic properties of the crustal section penetrated by the pilot hole are affected by intercrystalline fluid films.

References

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