Seismic Anisotropy: Comparison of Lab-, Logging, and VSP-Data

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Introduction

The continental deep drilling project of the Federal Republik of Germany (KTB) offers a unique opportunity for the direct comparison of geophysical parameters investigated at different scales: **lab, logging** and **VSP**. From selected well cores we have determined the transit times of compressional waves in 132 directions on spherical samples, as well as the transit times of shear waves on cylindrical samples in three directions, both under varying confining pressures of up to 400 MPa. Since we have a rather complete V_P-pattern and six shear wave velocities, the real elastic properties can be evaluated without any assumption of a rock symmetry using an iterative procedure.

In addition, we measured the anisotropy of the magnetic susceptibility (AMS) on samples of the homogeneous paragneiss sequence from the depth interval of 2000-3200 m, to acquire the geographical orientation of the fabric elements (foliation and lineation). From earlier observations it is well known that the directional dependence of the elastic and the magnetic (paramagnetic) properties are particularly controlled by the rock fabric. Since the determination of the foliation and lineation is macroscopically often impossible, their orientation can be obtained via the AMS. This rather complete data set enabled us to investigate the following topics:

1) Comparison of V_P- and V_S- velocities in direction of the borehole with the corresponding in situ logging data.
2) Computation of the elastic constants of the homogeneous paragneiss segment from the depth interval 2000-3200 m from **(i)** lab obtained data, **(ii)** sonic log data and **(iii)** VSP-data.
3) Quantification of a seismic anisotropy model for this paragneiss segment.

Quantified seismic anisotropy

i) VSP vs lab

Quantified seismic borehole experiments (VSP and MASE) were performed at the KTB-location with a special emphasis on shear-wave observations. The determination of the seismic anisotropy is most suitable via shear-wave splitting as a direct indicator. Systematic analysis of the polarization of the split shear waves from the KTB-pilot hole show that the faster S-wave is polarized towards the SE. Rabbel (1992) picked the direct P- and both split S-waves from the depth interval of 2000 and 3000 m (see Fig. 1A). The homogeneous paragneiss sequence within the depth range of 2000-3200 m consists of kyanite- and/or sillimanite-bearing garnet-biotite gneisses with an intercalation of hornblende-gneisses and amphibolites, biotite gneisses and Ca-silicates between 2470 and 2590 m. A conspicuous change in the dip of the foliation from steeply inclined to subhorizontal can be observed at this segment. Fig.1A shows the VSP-velocities versus the varying dip of the foliation. This facilitates a computation of the elastic constants assuming a hexagonal type of symmetry, although only one direction of wave propagation is present (Table 1A). For a direct comparison between the elastic constants of lab-derived and VSP-data we calculated the elastic constants of a paragneiss from depth 3145 m. Fig. 1B shows the qP- and qS-wave velocities, recalculated via the elastic constants. Comparing the results obtained by the VSP and from lab measurements, it follows that qP and the velocity of the faster shear wave (qS1) is well correlated with the dip of the rock foliation. The slower S-wave (qS2) increases up to a dip angle of around 50°, while with the higher dip angles qS2 decreases. The results given in Fig. 1 are in a good agreement with the exception of the qP-velocities.

ii) Sonic vs lab

As in the previous situation, we calculated the elastic constants from sonic-log velocities assuming a hexagonal type of symmetry (Table 1B). Here the faster compressional wave velocities (c_{11} and c_{22} in our reference system) are in good agreement with the corresponding VSP-constants, whereas the c_{33} constant (means normal to the foliation) agrees with the lab-constants.

The seismic model

All paragneiss well cores were geographically reoriented as a routine after drilling. In the upper part the dip of the foliation is steeply inclined (≈ 80°), while at the bottom it changes dramatically to subhorizontal (Fig. 2). To quantify the elastic properties of the paragneiss segment between 2000 and 3200 m, this segment was subdivided into 7 layers by means of the foliation dip. AMS-measurements were carried out in samples from each of these layers .The magnetic lineation and foliation is oriented parallel to the rock lineation and foliation (see DE WALL 1992). Based on this observation, the elastic constants of each layer were geographically reoriented as well. Consequently, we got the corresponding fourth rank tensor for each depth interval. To estimate the average elastic properties, we calculated the Voigt-average considering the orientation of each layer and its corresponding interval length. We can now present the 21 elastic constants of a crustal segment obtained by experimental data (Table 1D).

Additionally we can compare this result with in situ seismic measurements, for example VSP (JAHNS et al. 1994). Hence, this method might be an important tool for seismic modelling. Fig. 3 shows the recalculated distributions of P- and both S-waves as well as the polarisation directions of the S-waves.

Table 1: Elastic constants derived from A) VSP first breaks, B) sonic data, C) laboratory measurements, and D) Elastic constants of the seismic model (depth range 2000-3200m).

A)	38.44	10.16	14.20	0.00	0.00	0.00
		38.44	14.20	0.00	0.00	0.00
			37.21	0.00	0.00	0.00
				10.89	0.00	0.00
					10.89	0.00
						14.36

B)	38.18	11.40	13.43	0.00	0.00	0.00
		38.18	13.43	0.00	0.00	0.00
			30.25	0.00	0.00	0.00
				9.69	0.00	0.00
					9.69	0.00
						13.39

C)	43.48	11.09	13.20	0.00	-0.10	0.52
		41.27	14.93	0.11	-0.00	0.03
			33.28	0.39	-0.96	0.00
				10.70	0.44	-0.13
					10.42	0.07
						15.65

D)	38.47	14.19	13.09	-0.66	0.73	1.61
		37.56	3.63	0.87	-1.08	2.27
			39.00	0.81	0.77	1.16
				12.72	-1.22	0.69
					12.76	0.54
						12.70

Acknowledgements

We are grateful to the Deutsche Forschungsgemeinschaft (Bonn) for the financial support for the projects We 488/35 and Si 438/2. The sonic log data was provided by the Niedersächsisches Landesamt für Bodenforschung (Hannover).

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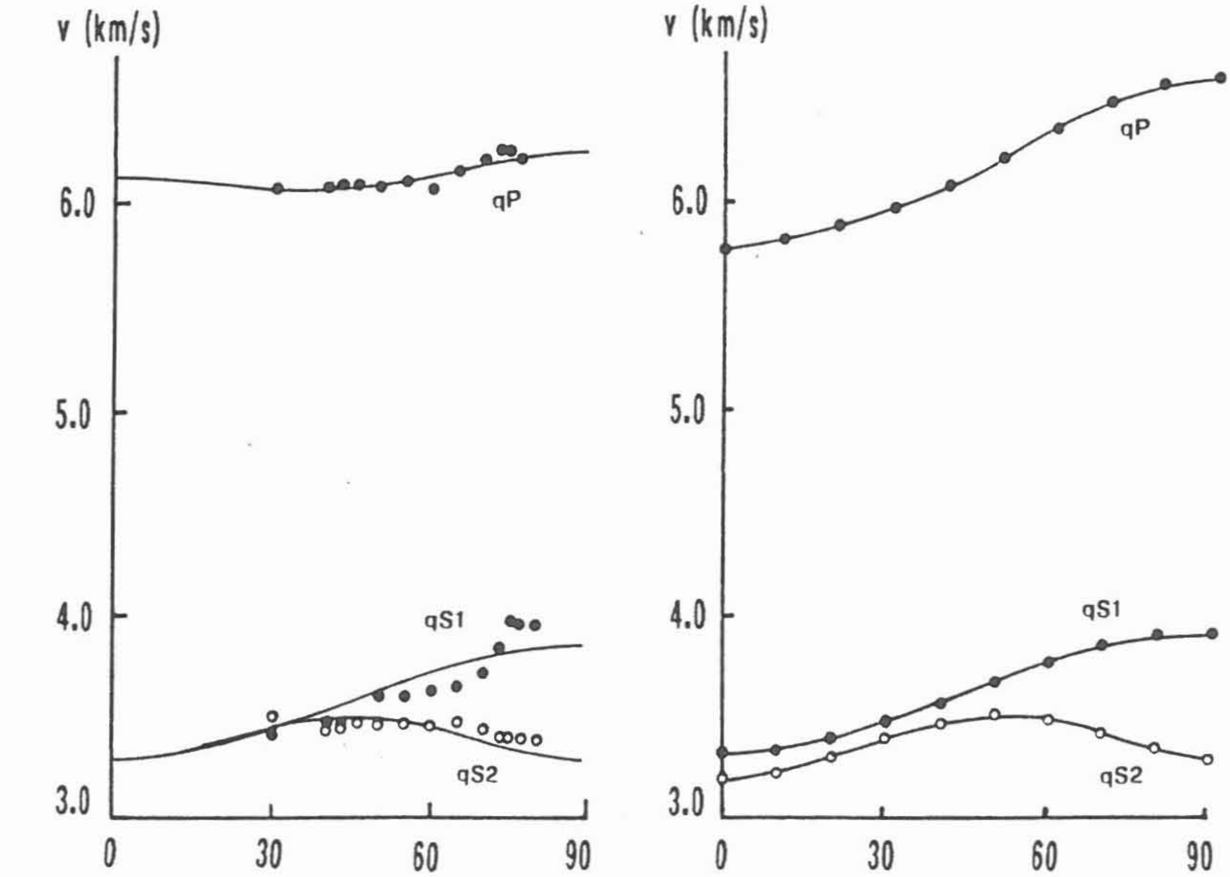

Fig. 1 A): Seismic velocities derived from VSP versus the dip of foliation of the paragneiss segment from depths 2000 - 3200 m, B): Seismic velocities recalculated via the elastic constants derived from lab measurements.

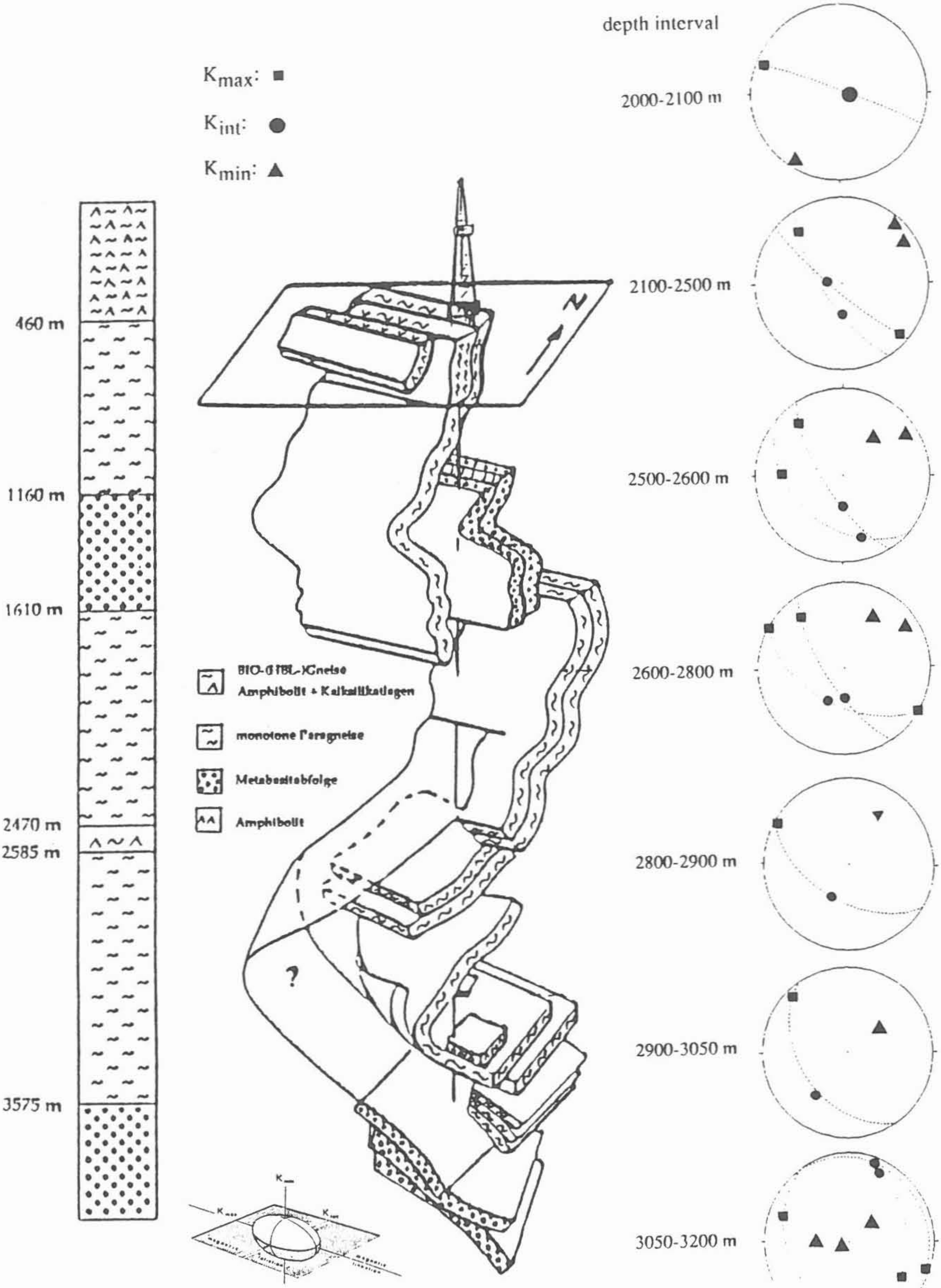

Fig. 2: Lithological profile of the KTB-pilot hole with the varying dipping of the foliation. The stereographic projections display the orientations of the AMS related to the seven model layers.

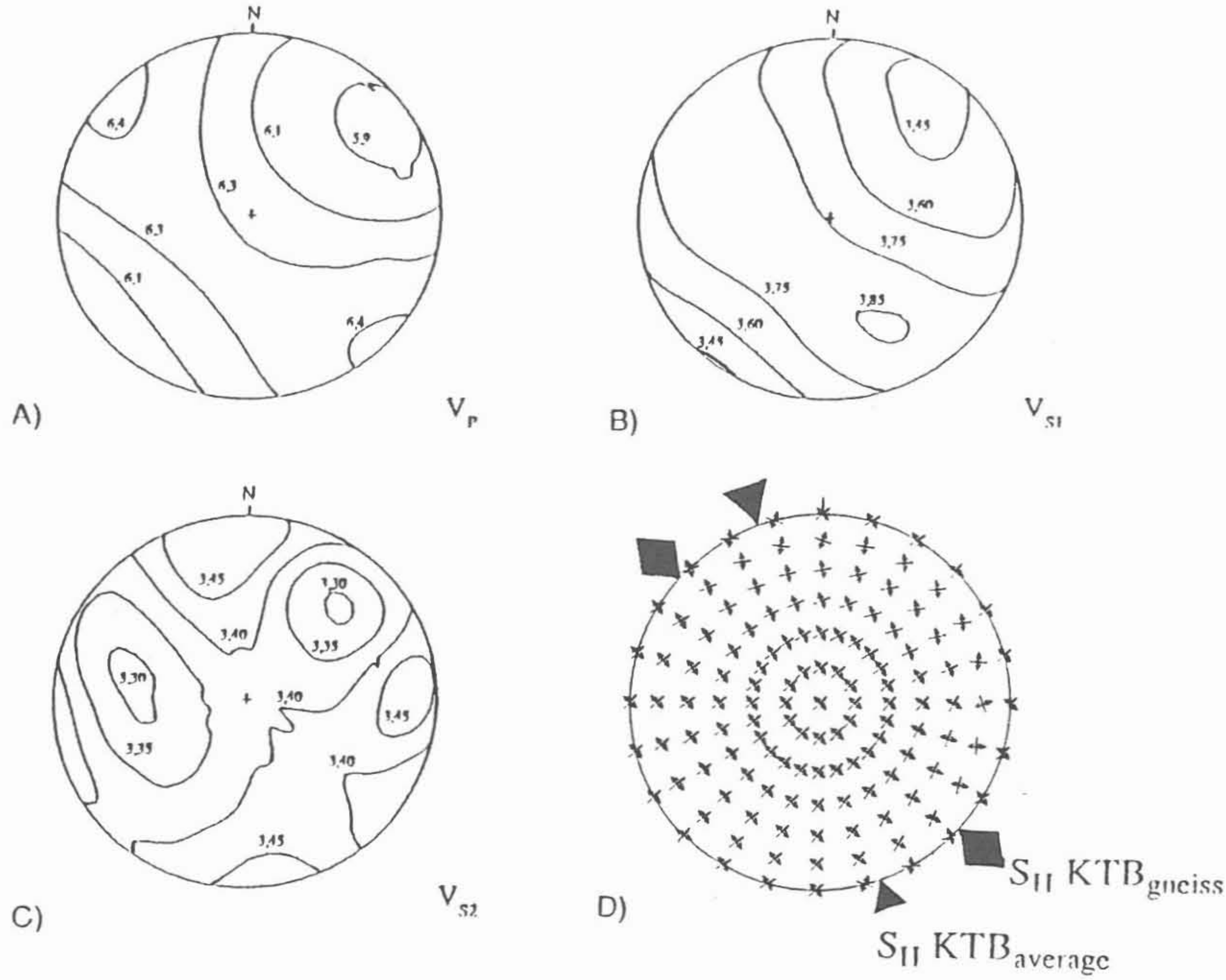

Fig. 3 A), B) and C): Velocity-distributions V_P, V_{S1} and V_{S2} of the paragneiss segment calculated via the Voigt-average, D): Polarisation directions of the faster (S1, marked with arrows) and of the slower (S2, without arrows) shearwave. In direction of the borehole (normal to this paper plane) the polarisation direction of S1 is NW-SE.

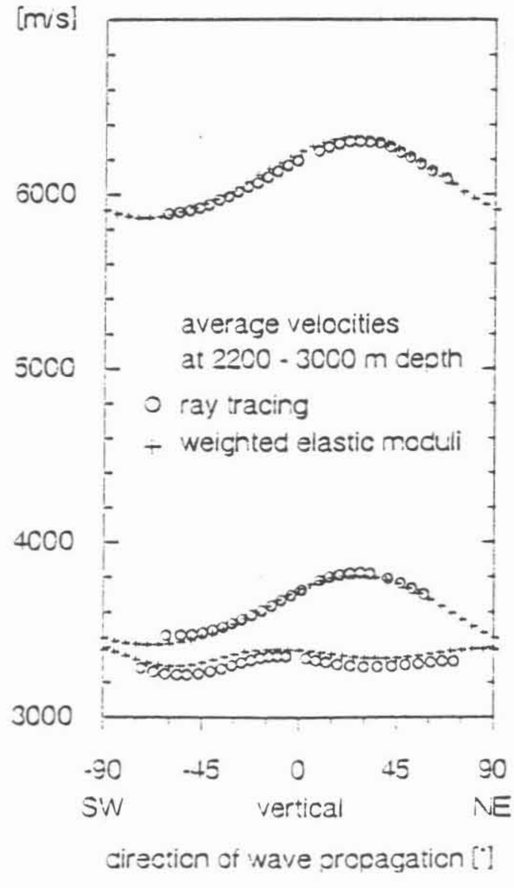

Fig. 4: Computed seismic velocities for the ray propagation normal to the strike of the gneiss foliation i) circles ray tracing velocities computed for the mean transit times for the seven layer model, ii) crosses: velocities computed with the weighted elastic tensor. The slower S-wave velocities of the weighted elastic constants are systematically a little bit higher than the model-velocities, whereas the faster S- and the P-wave velocities are in very good agreement. This shows the validity of our developed model.