

Paper 9:

Seismic anisotropy of the crystalline crust: what does it tell us?

WOLFGANG RABEL^{1*} and WALTER D> MOONEY²

¹Institute of Geophysics, University of Kiel, Olshausenstr.40-60, D-24098 Kiel, Germany;

²United States Geological Survey, 345 Middlefield Rd., MS 977, Menlo Park, CA 94025, USA

*Correspondence--tel: +49/431-880-3916; fax: +49/431-880-4432; e-mail: tis01@geophysik.uni-kiel.d400.de

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ABSTRACT

The study of the directional dependence of seismic velocities (seismic anisotropy) promises more refined insight into mineral composition and physical properties of the crystalline crust than conventional deep seismic refraction or reflection profiles providing average values of P- and S-wave velocities. The alignment of specific minerals by ductile rock deformation, for instance, causes specific types of seismic anisotropy which can be identified by appropriate field measurements. *Vice versa*, the determination of anisotropy can help to discriminate between different rock candidates in the deep crust. Seismic field measurements at the Continental Deep Drilling Site (KTB, S Germany) are shown as an example that anisotropy has to be considered in crustal studies. At the KTB, the dependence of seismic velocity on the direction of wave propagation *in situ* was found to be compatible with the texture, composition and fracture density of drilled crustal rocks.

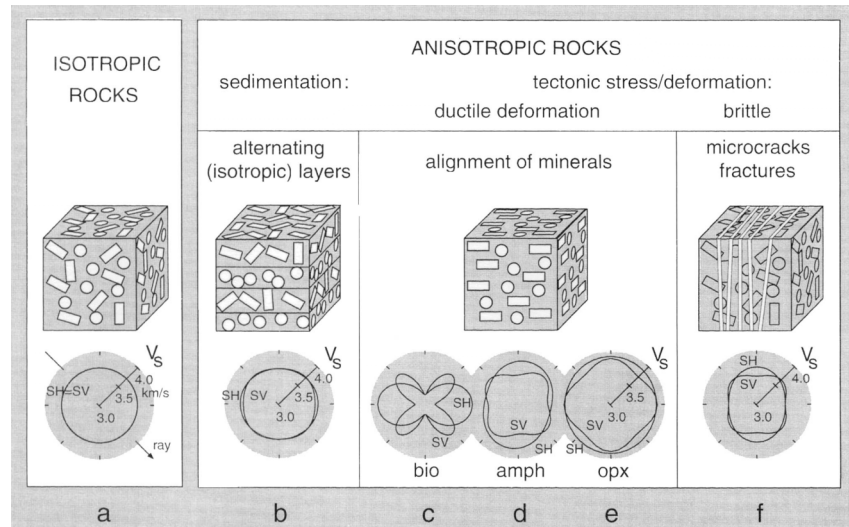
MOTIVATIONS TO STUDY SEISMIC ANISOTROPY *IN SITU*

Rock texture, expressed as the spatial arrangement of minerals, as well as the shape and orientation of pores and fractures, reflects the working of a variety of geological processes, such as tectonic stress and crustal dilatancy. One important consequence of rock texture is that it causes seismic velocities to vary with the direction of wave propagation (seismic anisotropy). Under appropriate field conditions, seismic measurements can serve to recognize and to quantify this anisotropy, which can be valuable in the determination of both rock composition *in situ* and the geological processes that cause it.

Elastically anisotropic media are trirefringent, with three types of body waves - one compressional and two shear waves whose polarization and velocities depend on the direction of propagation. The measurement of these quantities requires non-standard

seismic field configurations (i.e. 2D recording arrays with three-component sensors, and polarized seismic sources). There are basically three geological situations that give rise to seismic anisotropy and that justify special efforts to measure this anisotropy (Fig. 1):

Fig. 1. The primary causes of seismic anisotropy and schematic polar plots of corresponding shear wave velocities (S-wave splitting). (a) Isotropic rocks without ordering of minerals and fabric. (b) Alternating thin isotropic layers. Horizontally aligned mafic minerals: (c)



(d) amphibolite (25 Vol. %) (e) orthopyroxene (25 Vol. %). (f) Vertical fractures. Velocities plotted for the (100)/(001) plane of symmetry for S-waves polarized in the horizontal (SH) and vertical plane (SV), respectively.

1 A sequence of finely layered rocks of different stiffnesses is effectively anisotropic at long wavelength even if the matrices of individual layers are isotropic, a phenomenon which has been studied for sedimentary sequences since the early 1950s (Postma, 1955; Krey and Helbig, 1956; Backus, 1962). Recently, the rule of thumb, that effective anisotropy occurs if the wavelength exceeds 10 times the individual layer thickness, was critically examined by Hake (1993) who found a more precise criterion based on the reflectivity of thin layer packets. In finely layered sedimentary environments, accurate depth mapping of geological structures requires a precise knowledge of seismic velocities and, consequently, of their directional dependence.

2 The spatial arrangement of elastically weak zones (inclusions) will also cause anisotropy. An important example is the case of fractures within an initially isotropic rock unit, as may result in a brittle stress regime. This anisotropy, also called 'extensive dilatancy anisotropy' (EDA; Crampin, 1989), will occur when fractures open in the direction of the smallest principal stress component. Estimates of the orientation, density and shape of pores and fractures provide important information to answer questions of hydrological fluid transport or to classify hydrocarbon reservoirs. For example, Clief et al. (1991) reported on correlations between seismic anisotropy and the productivity of hydrocarbon reservoirs in the former USSR. Temporal variations of porosity (such as changes in shape, number, and fluid saturation of pores) can be correlated with variations of tectonic stress. It has been postulated for many years that these processes should cause variations in seismic anisotropy as well (Crampin, 1987). The significance of field measurements verifying temporal variations of shear wave splitting as an earthquake

precursor is, however, still debated (Crampin *et al.*, 1990; Aster *et al.*, 1990; Wyss, 1991).

3 Nearly all rock-forming minerals are anisotropic (Babuska, 1981; Gebrande, 1982). Consequently, all rocks exhibiting a certain degree of textural ordering can be expected to be anisotropic. In particular, this has been proved in laboratory investigations of metamorphic rocks such as schists, gneisses, and mylonites where mineral ordering often is caused by shear deformation in a ductile regime (Kern and Wenk, 1990; Ji and Salisbury, 1993). Thus, as a mirror of texture, seismic anisotropy contains information on the structure and composition of rocks on a scale much less than a wavelength. This information can be used to infer the stress and transport conditions which gave rise to the textural ordering. Chastel *et al.* (1993) showed that pure shear and simple shear regimes are expected to cause different patterns of mineral alignment of ultramafic rocks. For example, the anisotropy of the Earth's upper mantle, known since the 1960s, can be attributed to the orientation of olivine and orthopyroxene crystals and is regarded as direct evidence of convective movement in the mantle (Hess, 1964; Raitt *et al.*, 1969; Ando *et al.*, 1983).

STUDYING CRUSTAL SEISMIC ANISOTROPY *IN SITU*

During the past decades, the most convincing investigations of seismic anisotropy have focused on the Earth's mantle and on sedimentary areas of the crust, the first target being motivated by plate tectonic considerations, the latter one by hydrocarbon exploration. In contrast, the anisotropy of the crystalline part of the crust has only rarely been studied *in situ*, although laboratory results for metamorphic rocks have shown evidence for anisotropy at least since the early 1960s (Christensen, 1965, 1966; Gebrande, 1982). There are several reasons why the anisotropy of the crystalline crust has not traditionally been investigated.

- Seismic refraction/wide-angle reflection profiles (DSS), which provide excellent crustal velocity control, are mostly performed along linear profiles making it impossible to detect azimuthal variations of seismic velocities.
- With only a few exceptions, DSS interpretation was based only on P- wave traveltime observations, whereas typical anisotropic variations of P-wave velocity are expected not to exceed a few percentage. However, the crystalline part of the crust appears to be sufficiently heterogeneous to hide possible velocity anisotropy of P-waves in ambiguities of structural resolution. This statement is supported by the 45 year's tradition of nearly contradictionless isotropic interpretation of linear P-wave refraction profiles, while recent investigations showed that the Earth's crust appears to be anisotropic on a broad scale (e.g. Lueschen *et al.*, 1990; Crampin and Lovell, 1991; Mjælde, 1992).
- Near-vertical reflection profiling is limited to a restricted range of wave propagation directions and cannot be used to quantify anisotropic velocity variations.

The key to identifying and quantifying crustal seismic anisotropy is therefore the use of shear waves and the detection of their birefringence ('shear wave splitting').

Figure 1 (b-f) shows some diagrams of shear wave velocity vs. angle of incidence.

It demonstrates that different rock types with aligned minerals may be distinguished by measuring their S- wave birefringence if the anisotropy is caused mainly by the alignment of one component of the mineral assemblage. Figures 1c,d,e correspond to models of metamorphic rocks containing a high amount of horizontally orientated mica, amphibolite, and orthopyroxene, respectively. For comparison, Fig. 1b shows a velocity diagram expected for thin alternating mafic and felsic layers, assumed to be individually isotropic (such type of composition was postulated for laminated lower crust areas, e.g. by Holbrook *et al.*, 1988). The resulting amount of anisotropy for thin layer models (Fig. 1b) is significantly smaller compared to rocks containing ordered mafic minerals (cf. Fig. 1b vs. Fig. 1c, d, e). Moreover, the specific shape of the velocity curves is sensitive to variations of the aligned fraction of the rock forming minerals.

Most rocks are polyphase in composition, so the whole rock anisotropy depends on the average distribution function of mineral content and spatial orientation. In the most general case, a specific type of seismic anisotropy, found *in situ*, is therefore not uniquely related to one specific rock type, but it establishes constraints on the group of probable rock candidates.

The characteristics of the birefringence demonstrated in Fig. 1 provides a useful guide to the design of seismic field surveys intended to quantify seismic anisotropy *in situ*. The experimental layout should consider a number of points as listed below.

1 The basic diagnostic tool is the use of shear waves and the measurement of their polarization in order to detect shear wave splitting. Consequently, receivers have to be three-component geophones. Near-surface rock heterogeneities often add a considerable amount of scatter to polarization records. For the determination of both polarization values and traveltimes, a dense geophone spacing reduces the probability of 'mis-picks' and increases the significance of results. From a theoretical point of view, horizontal and vertical point sources like vibrators are ideal seismic sources for anisotropy investigations since they are able - at least in principle - to generate body waves with specific initial polarization (P, SV, SH type). Single horizontal vibrator sources, however, are not powerful enough to generate high-quality signals penetrating the whole crust. Since arrays of shear wave vibrators might cause serious damage to roadways, explosives are mostly used for deep targets, although they have the disadvantage that the initial source polarization cannot be controlled.

2 Field surveys should account for the 3D character of anisotropy if no interpretation constraints are known a priori. This concept was realized to a high degree in the borehole seismics at the Continental Deep Drilling Site (KTB, Oberpfalz, Germany) which is used as an example in the next section. In particular P-wave refraction surveys along intersecting linear profiles are in most cases not capable of providing convincing information on anisotropy, except when the anisotropy is of azimuthal type.

3 The inversion of traveltimes for seismic anisotropy becomes significantly easier if structural constraints, based on near-vertical reflection profiling, and isotropic reference models of seismic velocity already exist for a target area. Under such preconditions, special features of the subsurface can be 'probed' with reasonable expense and high expectation of success.

EXAMPLE: THE CONTINENTAL DEEP DRILLING SITE (KTB, S GERMANY)

After the completion of the KTB pilot drillhole, the German DEKORP group (Deutsches Kontinentales Reflexionsseismisches Programm) performed an extensive seismic survey at the KTB location called Integrated Seismics Oberpfalz 89 (ISO89). In ISO89, 3D near-vertical seismic reflection and wide-angle measurements were complemented by borehole seismic investigations in order to get insight into details of the seismic velocity structure at the KTB site (Duerbaum *et al.*, 1990).

Two types of experiments provided information regarding seismic anisotropy (Fig. 2): Vertical seismic profiling (VSP) and a so-called multiple azimuth shear wave experiment (MASE). For fixed source positions at different offsets and azimuths, VSPs were recorded over the whole depth interval of the borehole. In contrast, borehole geophones were held at a fixed depth in the case of the MASE experiment while horizontal shear wave vibrator sources were moved along two half circles of 4 and 8 km radius being centred at the KTB drillhole.

VSPs with small source offsets served to map detailed velocity depth profiles which could be compared with borehole information concerning the local lithological section, mineral composition of rocks, and fracture density. VSPs with larger source offsets as well as the MASE experiment provided the seismic velocity field on a more regional scale. In the upper 4 km, the KTB borehole mainly penetrates sequences of highly foliated, steeply dipping mica gneiss alternating with amphibolite layers (Roehr *et al.*, 1990). Laboratory measurements of gneiss samples -carried out by the KTB field laboratory during drilling -predicted a considerable amount of seismic anisotropy *in situ* from the beginning of the project (Stroh *et al.*, 1990). This hypothesis could be confirmed at an early stage of VSP data interpretation when shear wave arrivals of orthogonal

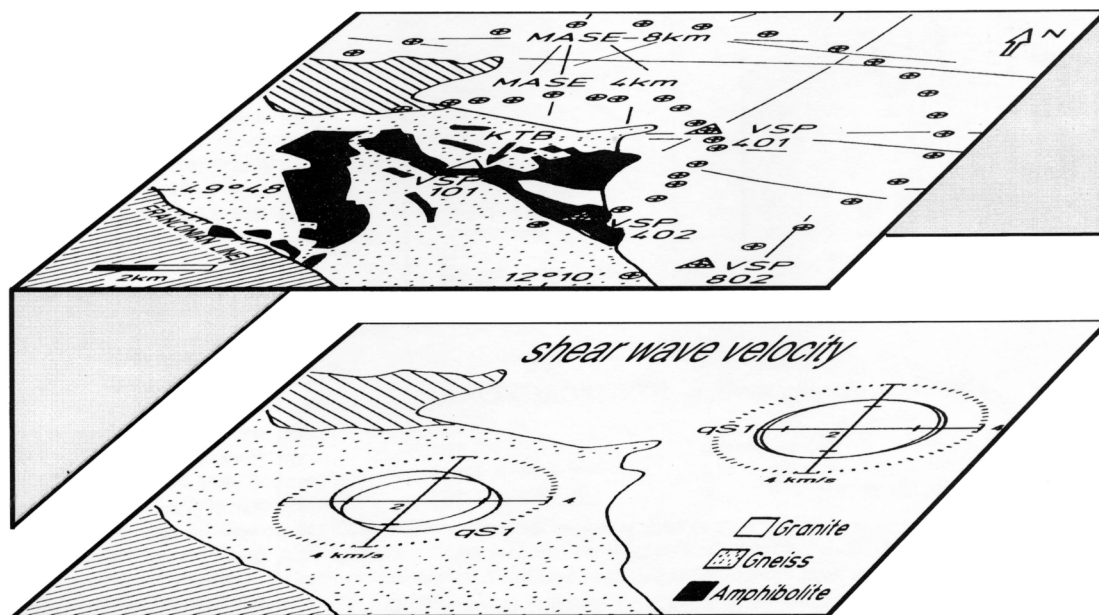
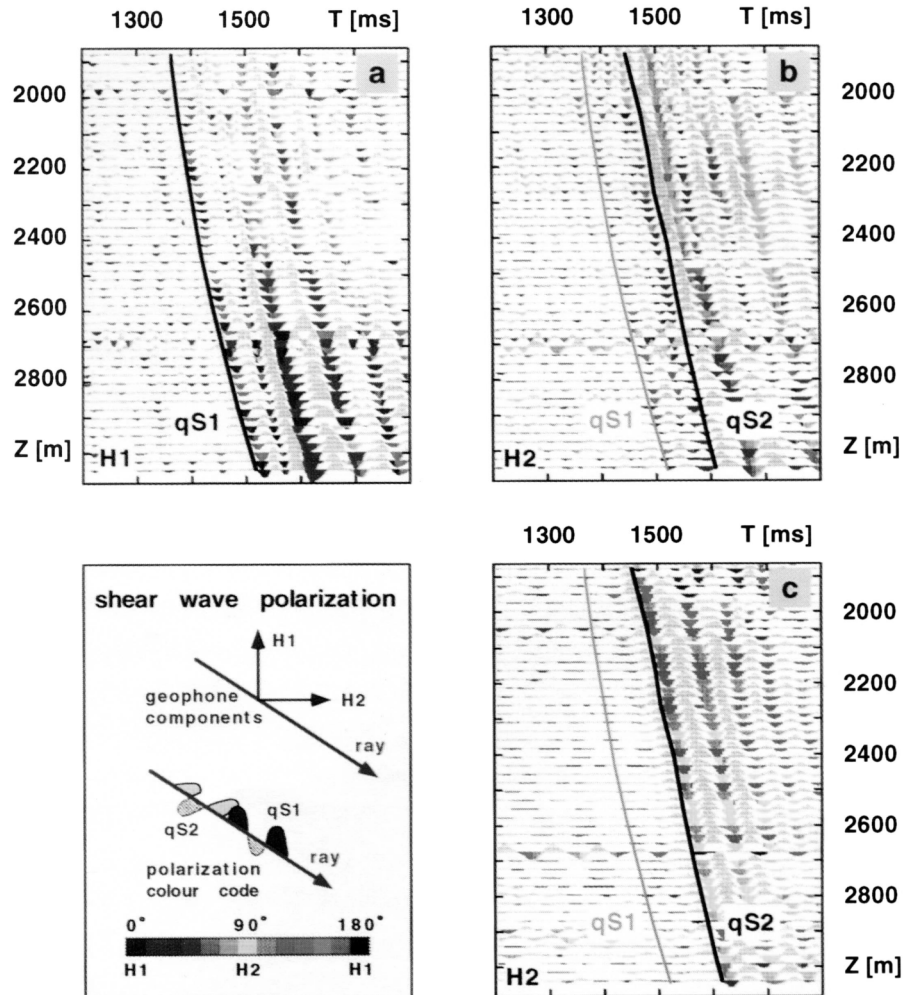


Fig. 2. Top: Simplified geological map of the KTB area (after Roehr *et al.*, 1990) and source positions of DEKORP IS089 borehole seismics (triangles and circles correspond to VSP and multiple azimuth shear wave experiment MASE, respectively). Bottom: Polar plots of s-wave velocities in the horizontal plane derived from offset VSPs and MASE.

polarization and different propagation velocity were observed. By use of different seismic source types (explosives, vertical and horizontal vibrators) it could be proved, moreover, that the polarization of these split S- waves were independent of the initial source polarization and, thus, entirely controlled by rock anisotropy (Fig. 3; cf. Rabbel, 1994). Near-offset VSPs showed that the particle movement of the faster S-wave (qS1-wave)



DEKORP ISO89/KTB vertical seismic profiling

VSP 402
 source offset 4 km
 source azimuth SE

seismic source:
 a,b - dynamite
 c - horizontal vibrator (H2)

Fig. 3. VSP seismogram sections of shear wave arrivals with colour coded-polarization direction. Source position 4 km SE of KTB (VSP 402 in Fig. 1). Orientation of geophone components (H1 and H2 subvertically and NE-SW orientated, respectively) and colour code of polarization shown in the box (bottom left); the particle motion is tangential to the wavefront. (a) and (b): split s-waves generated by dynamite shots (qS1 and qS2, subvertically (H1) and subhorizontally (H2) polarized, respectively). (c) Pure subhorizontally polarized qS2-wave generated by a transversely orientated horizontal vibrator source (cf. Fig. 3b).

was parallel to the strike direction of gneiss foliation which, in addition, coincides with the direction of maximum horizontal tectonic stress (about N150°E) as inferred from various types of borehole stress analysis (Mastin *et al.*, 1990; Zoback *et al.*, 1993). In terms of a hexagonal type of symmetry, a quantitative estimate of gneiss anisotropy *in situ* could be obtained for a gneiss packet at 2.2-3 km depth (Fig. 4). From drillcore analysis it was known that this gneiss layer is of nearly homogeneous mineral composition although the orientation of the foliation changes continuously with depth from near vertical to about 30°. Therefore, the anisotropic velocity variation could be obtained from precise velocity measurements only of vertically propagating waves (Fig. 4a). The corresponding velocity diagram clearly displays the signature of mica-rich rocks previously shown in Fig. 1c. Differences between observed and average velocities (i.e. velocity residuals) could be explained by varying fracture density with depth (Fig. 4b). Fracture density data were provided by the KTB field laboratory-based on the inspection of drillcores.

In the vicinity of the KTB borehole, shear wave polarization studies and travelttime inversions of both offset VSPs and multiple azimuth MASE data have demonstrated local variations of seismic anisotropy (Rabbel, 1994). Whereas the KTB is situated within a metamorphic gneiss-amphibolite sequence, late- and post-Variscan granites are found in adjacent areas (Fig. 2). Within the metamorphic zone the observed

KTB pilot hole / seismic velocities of gneiss

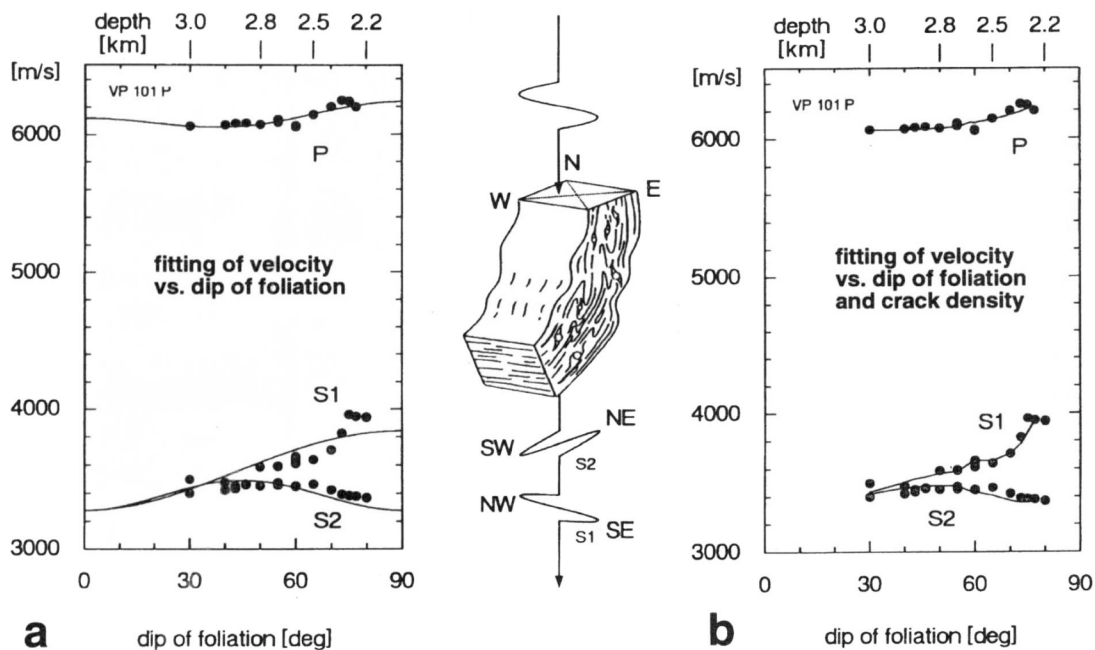


Fig. 4. Velocities of P- and split S-waves (S1 and S2, respectively) for biotite gneiss at 2.2- 3.0 km depth of the KTB pilot hole, derived from near-offset VSP. Least-squares fitting of velocity (a) vs. dip of foliation and (b) vs. dip of foliation and known fracture density in terms of hexagonal symmetry. The change of rock foliation with depth and the polarization of the split S-waves are sketched in the center of the figure.

shear wave anisotropy was found to be high (around 14%) and seems to be primarily controlled by the strike and dip of metamorphic layers, and their texture. In the granite area (Fig. 2) the S-wave anisotropy is low (less than 3%) and differs in orientation significantly from the metamorphic rocks: the axis of high horizontal velocity was found parallel to the strike of fracture zones within the granite (Fig. 2). Local stress measurements from the same granite complex point to a similar direction (Baumgaertner *et al.*, 1987).

Most evident from these observations is a striking correlation between seismic anisotropy and, both macro-scale geological structures and micro-scale mineralogical composition. A uniform regional pattern of anisotropy was not found.

In contrast to the above outlined borehole seismic results, near-vertical shear wave reflections from mid-crustal depths display a 90° reversed polarization pattern (Lueschen, 1994). These reflections stem from the so-called Erbendorf-body, a major structure, that was previously identified in a P-wave reflection survey, its top at about 10 km depth (Simon and Gebrande, 1994). S-wave reflection records from this body show a NE-SW polarization of the fast arrivals, which are followed by delayed ones of orthogonal particle movement. These results indicate that the rock anisotropy changes with depth. Possible explanations for this behaviour include a rotation of the plane of rock foliation or a different mineralogical composition. If a correlation of anisotropy and stress holds, one might also postulate significant changes of the stress regime with depth. These important questions may be answered by additional borehole seismic experiments to be conducted after the KTB is drilled to its final depth.

FINAL REMARKS

The determination of seismic anisotropy offers the possibility to determine both the composition and physical properties of the crust with significantly greater refinement than conventional deep seismic refraction or reflection profiles. Measurements of seismic anisotropy at the KTB have provided reliable information on crustal rocks *in situ*, including mineral composition and texture, fractures, and, the state of stress. Recent laboratory investigations of KTB rock samples, which were performed under simulated *in situ* pressure conditions, confirmed these seismic results (Kern *et al.*, 1991; Popp, 1994; Siegesmund *et al.*, 1993). The agreement of seismic and laboratory data opens an encouraging perspective for studies of deep crustal layers which cannot be accessed by drilling. The relationship between seismic velocities and the composition of lower crust material, for example, is highly ambiguous, even if both average compressional and average shear wave velocities are known (Holbrook *et al.*, 1992). Mineral alignment can be expected in the ductile parts of the crust (as, for instance, in extensional areas), and studies of seismic anisotropy can help to discriminate between different rock candidates. Such investigations would require adequate seismic field measurements, and a large laboratory data base of anisotropic elastic tensors of rocks (e.g. xenoliths). The study of seismic anisotropy in the crystalline crust is a frontier research area that promises new and exciting insights into the composition and physical state of the crust.

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