Origin of Reflections from the Altenparkstein Fault Zone (KTB)

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1. Introduction.

Since acquisition of the first crustal-scale seismic reflection sections earth scientists have been excited by the high-resolution images of the Earth's interior. The pattern of crustal reflectivity has evoked many hypotheses of its origin which are still speculative and as diverse as composition, fluid-filled fractures or shear zones. The Continental Deep Drilling Program (KTB) in Germany and especially data from 3D-seismics combined with borehole data give an opportunity to prove different models for the geological nature of seismic reflectors which have meanwhile been penetrated by the drillbit. Several types of seismic reflections can be related to tectonic structures and/or tectonic processes. In the seismogenic rigid upper crust, reflections are observed along shear zones, mainly as thrust zones in compression or normal faults in extension.

In a pioneering work, Christensen (Christensen and Szymanski, 1988; Christensen, 1989) studied the seismic attributes of the Brevard fault zone in the Eastern US. Combining synthetic seismograms with laboratory measurements on cores, which were continuously drilled through the fault zone, the author was able to demonstrate that the reflections seen on a seismic surface profile originated within the fault zone from a complex interaction of compositional variation and seismic anisotropy. The resulting structural layering within the Brevard fault zone produces strong multicyclic reflections. This so-called "quarter-wavelength" effect is well known from sedimentary seismics (Velzeboer, 1981) and in a classical paper by Fuchs (1969), it was also proposed to cause reflections from the deep crystalline crust. Apparent enhancement of acoustic contrasts associated with constructive interference due to layering of the proper thickness can increase the amplitude of a compound reflection so that, even if the individual impedance contrast is small, reflections of appreciable amplitude can be recorded. An analysis of the magnitude of reflections by Hurich and Smithson (1989) showed for a layered crustal section consisting of uniformly thick layers with reflection coefficients oscillating between $\pm$ 0.04 that constructive interference is limited to a relatively narrow range of layer thicknesses between 35 and 80 m for a typical 10 - 40 Hz source wavelet.

2. The Altenparkstein Fault Zone (AFZ).

The German KTB-project offers another opportunity to study the nature of geophysical structures. One of the main scientific objectives of this program is to understand the origin of seismic reflections in crustal profiles. Consequently, extensive seismic experiments have been carried out in and around the KTB-well culminating in a 3D reflection seismic survey in a square area of 19 x 19 km with the KTB at its center (Duerbaum et al, 1992). Several seismic reflectors were met in the drilled section of the KTB Vorbohrung and

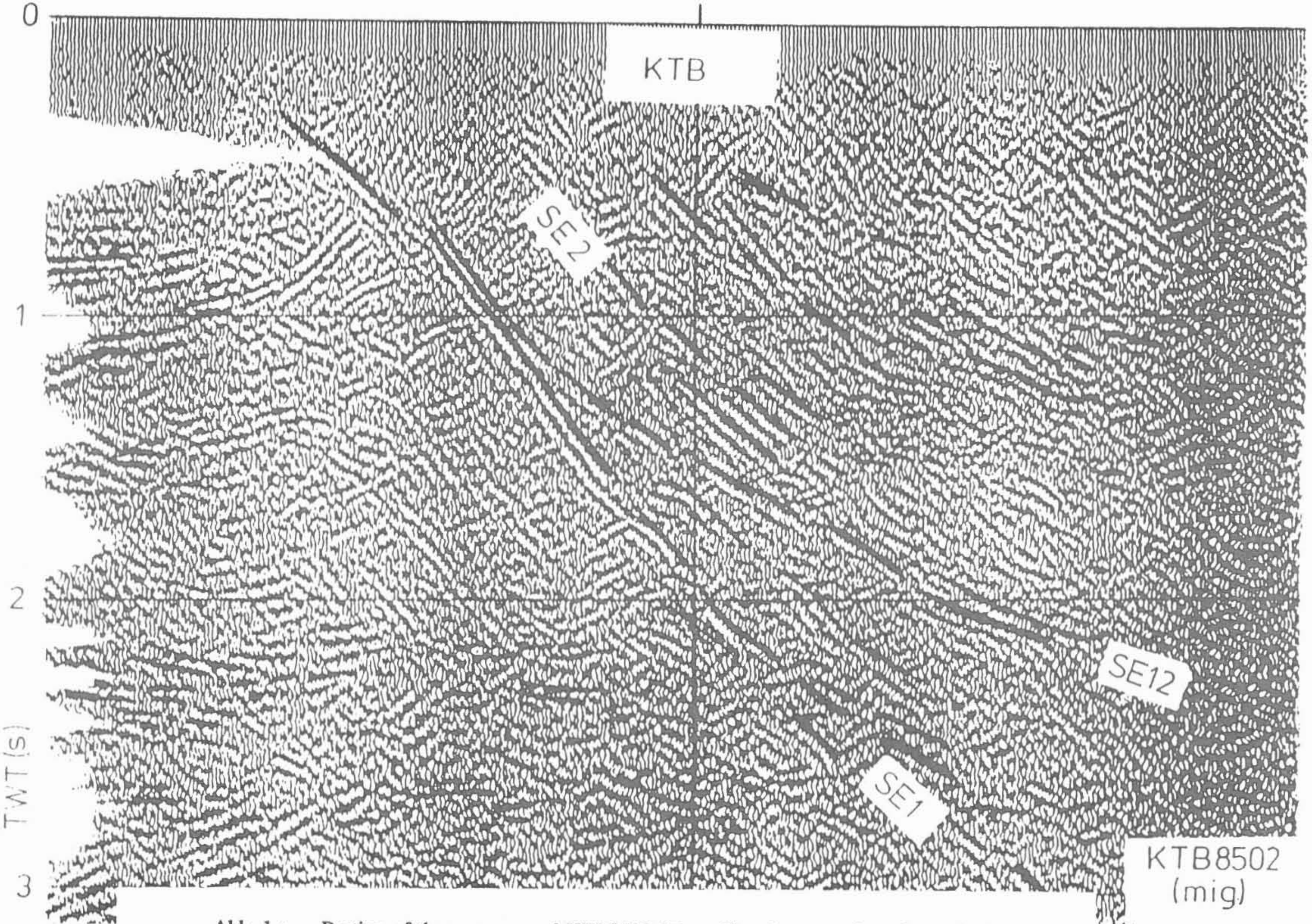


Abb. 1 : Portion of the re-processed KTB8502 2D-profile, phase consistently stacked, migrated and coherency filtered. From DPC, Clausthal.

Hauptbohrung. Comparison between drilling results and seismic reflection observations gives evidence that fault zones are responsible for the reflections in nearly most cases (Figure 1 from DEKORP Research Group, 1992). Especially, the identification of the prominent SE1-reflector as a broad bundle of faults and cataclastic zones from 6700 m to more than 7200 m is in excellent agreement with the depth range predicted from seismic surface measurements and may be taken as a remarkable success for the seismic pre-site survey. At the surface, this 55 degree NE dipping reflector is connected with the Altenparkstein Fault Zone which represents the most important fault zone of the Franconian Lineament (FL). It separates the Oberpfalz crystalline complex in the NE from Permocarboniferous, Triassic and younger sediments in the SW. According to Hirschmann (1993) the FL-zone represents a reverse fault system with total vertical displacement in the order of 2-3 km.

Considering a 55 degree dip of the FL-fault, the vertical length of approximately 500 m along the drilling path yields an extent of about 400 m in normal direction to the fault plane. This estimate matches well to the geological findings at the surface where the FL-fault shows a width of 200 to 400 m. In detail, the fault consists of a sequence of cataclastic zones in paragneiss-amphibolite alterations (20 - 100 m thickness) interlayered by zones of relatively undisturbed rocks.

3. Modeling the AFZ Reflectivity.

The SE-1 reflector (fig. 1) cannot only qualitatively be interpreted in relation to the geological profile in the borehole and in connection with surface exposure, but also quantitatively by using the information from borehole logging. In this respect, KTB offers a rare opportunity to calibrate a prominent crustal reflector in detail.

P-wave velocities and densities, determined from standard borehole measurements (i.e. sonic log and gamma log, respectively) provide the basic data to calculate a seismic impedance log for the AFZ depth range. Due to breakouts, the sonic log data and especially the density data are disturbed and show a large scatter. An extensive editing and smoothing procedure had to be applied. This log processing includes a median filter for despiking and smoothing and a resampling from 12.5 cm intervals to 2 m intervals. As a result, figure 2a and 2b show continuous curves underlayed by a shaded area for the velocity and density profile whereas the dots represent the original measurements.

In figure 3 an impedance log (left panel) is shown which was calculated as the product of velocity and density from figure 2. This impedance log can easily be transformed into a series of reflection coefficients (RC). The result is shown in the second panel on figure 3 and all reflection coefficients are significantly smaller than 0.1. Although the individual reflection coefficients are rather small, the synthetic seismogram (third panel from left in figure 3) exhibits fairly large amplitudes. The synthetic seismogram has been calculated for a simple normal incidence model taking a "kuepper"-signal (Kuepper, 1958) with a main frequency of 20 Hz as a source wavelet. The shape of this source wavelet can be recognized on the rightmost panel in figure 3 where this signal is convolved with two single reflection coefficients with magnitude 0.1 and alternating polarity to provide amplitude comparison.

From the modeling one can conclude that the AFZ reflectivity is enhanced by constructive interference effects due to the internal structure of the fault zone. Certainly the sequence of cataclastic zones in paragneiss-amphibolite alterations play an important role. The high reflectivity of the AFZ cannot be explained by the compositional variation within the fault

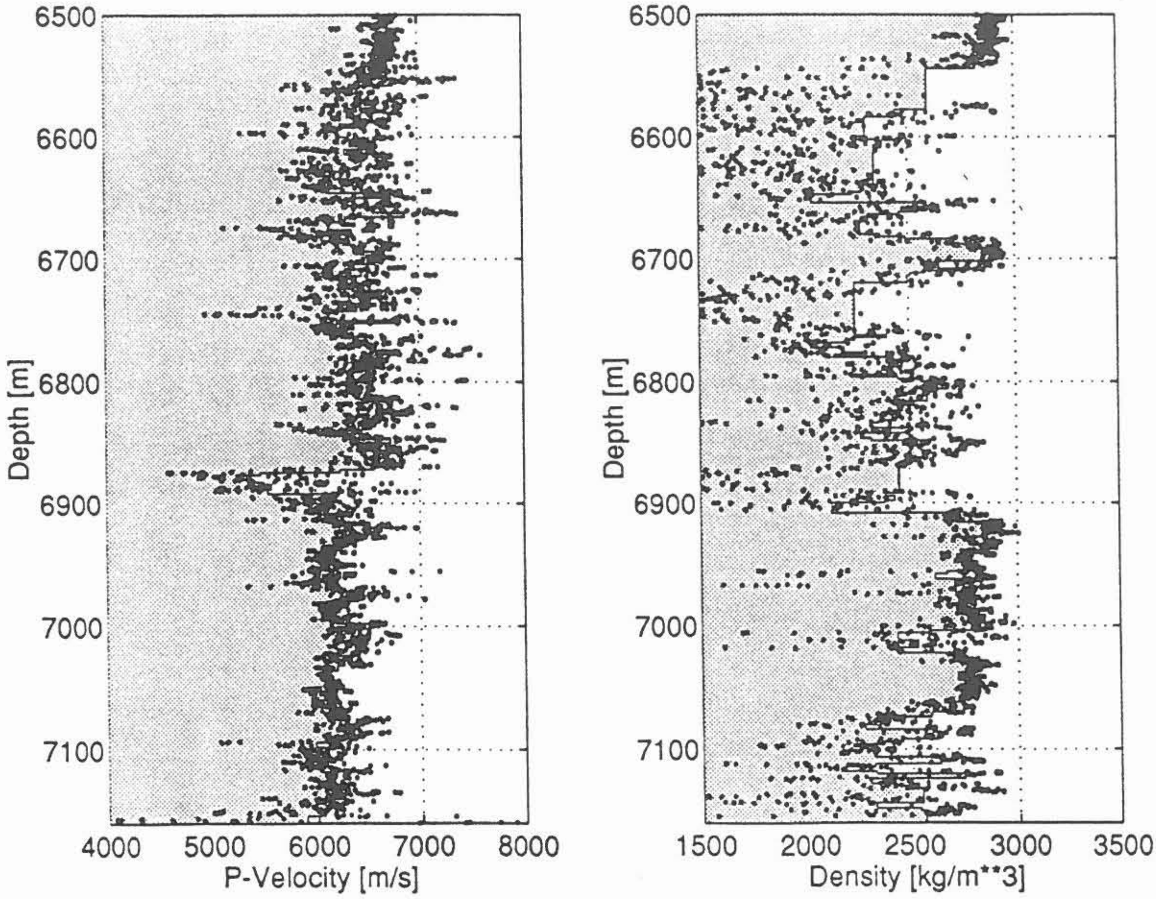


Abb. 2 : Sonic Log and Density Log within Depth-Range of SE-1 Reflector (KTB)

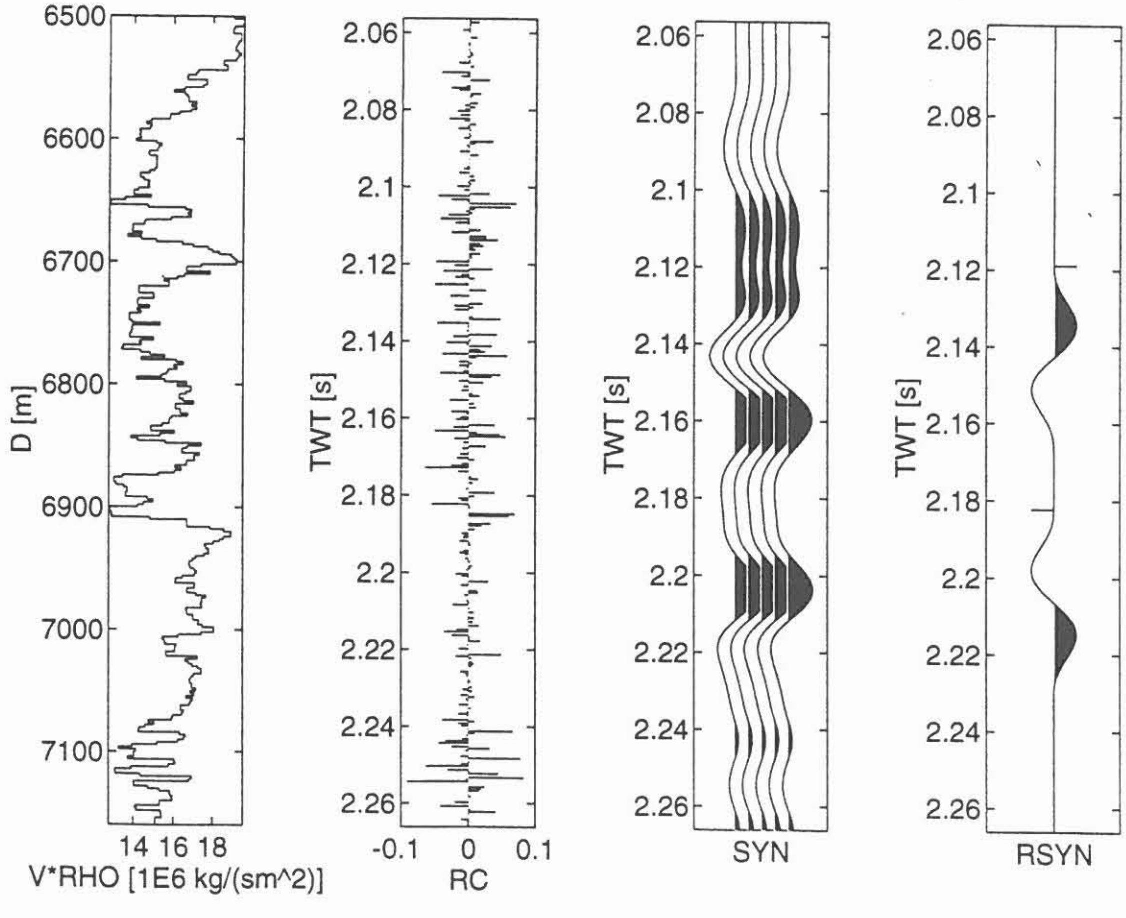


Abb. 3 : Impedance, Reflectivity and Synthetic Seismogram for SE-1 Reflector (KTB) zone. When seismic impedance is derived from lithology by converting mineralogical composition of cuttings into elastic properties (Spangenberg and Umsonst, 1993), the resulting "chemical" impedance log yields very small seismic amplitudes (figure 4). On the other hand, the simple concept of a cataclastic deformation, leading to a reduction of compressional velocity and consequently to a negative reflection coefficient, is not confirmed by the modeling. Instead, the internal structure of the AFZ seems to determine its seismic signature.

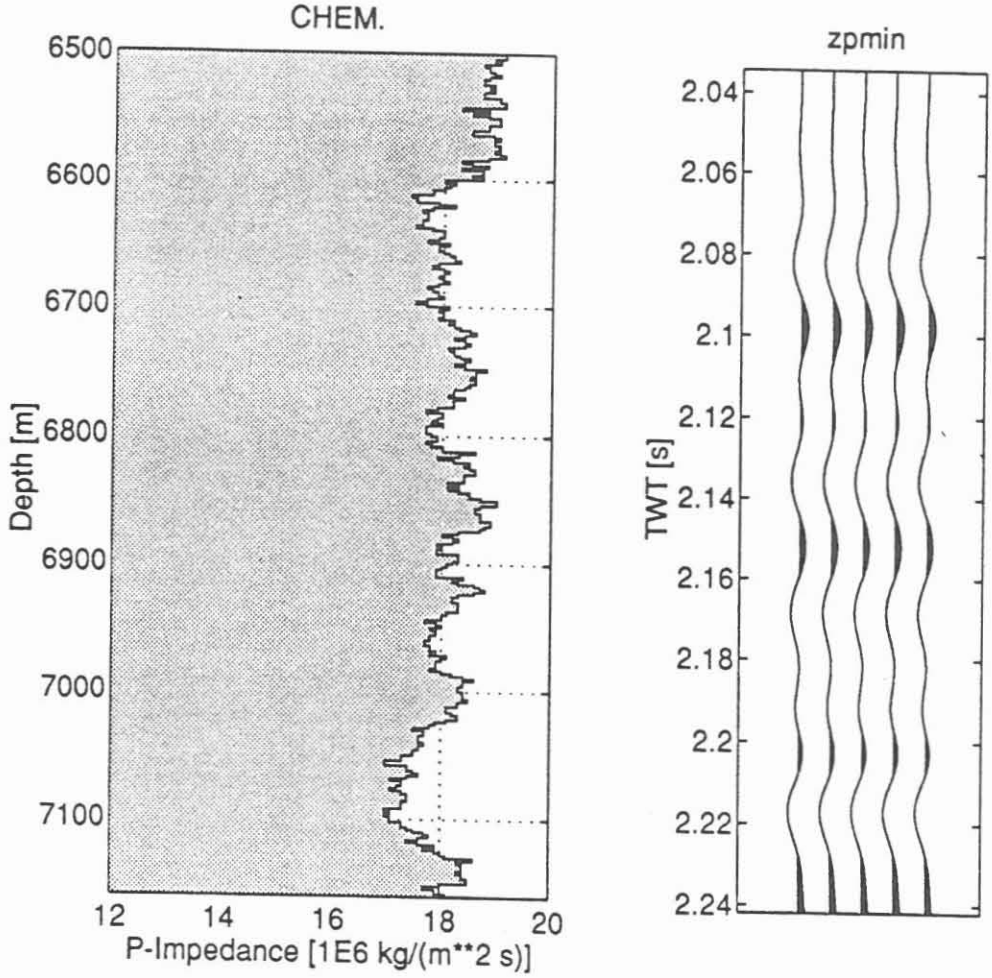


Abb. 4 : Impedance log (left) calculated from Mineral Composition of Cuttings and Corresponding Synthetic Seismogram

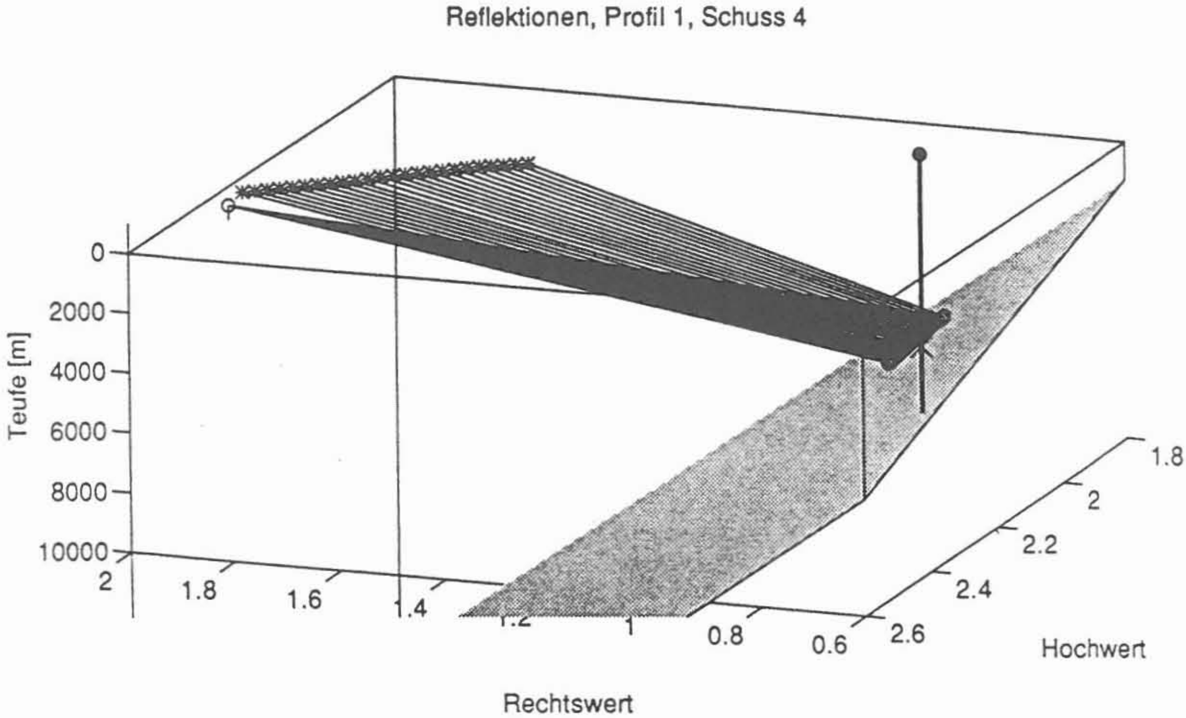
4. Comparison between Modeling and Field Data.

A special seismic field experiment was conducted (Wenzel et al, 1994) to study the INternal STRUCTure (INSTRUCT) of the FL-fault system. The geometry of this experiment was chosen such that the fault zone in the vicinity of the drilled section should be hit by normal rays to obtain a simple seismic image of high resolution. The ray geometry for shotpoint 4 and profile 1 (figure 5, upper part) shows that the Altenparkstein Fault Zone (AFZ) is hit by the INSTRUCT experiment in the vicinity of the borehole. Projecting the reflection points into the fault plane (lower part of figure 5), it can be seen that the intersection with the borehole is not exactly met but that the reflecting points lie somewhat southeast of the borehole. Many assumptions went into these calculations (i.e. no ray refractions, constant dip of the AFZ) which are only approximately fulfilled in the KTB environment. Nevertheless the reflection points seem to be close enough to the borehole to probe the geological section as described in the last paragraph. This is especially true if the extent of the Fresnel zone for these reflections is taken into account.

Figure 6 shows the seismic data from the INSTRUCT profile 1. With 30 kg charges fired in 30 m boreholes, the FL-reflector is clearly visible in these single-coverage seismograms. Due to the large offset of shot and profile from the borehole, the reflection time of the AFZ is about 4 sec TWT. Although there is some variation in the signature and also in the continuity of the reflector, it is mostly a two cycle signal comparable with the characteristics of the synthetic seismogram (figure 4). This comparison is highlighted in figure 7 where five traces from profile 1 are plotted in the right panel which should correspond to the closest reflection points of the AFZ in relation to the KTB borehole. These reflections match the signature of the synthetic seismogram fairly well. Obviously the fit of the data is no proof of the model because the seismic data are band-limited in frequency and the interpretation is principally ambiguous.

5. Conclusions.

In conclusion, the most prominent reflector in the KTB-area, representing the Altenparkstein Fault Zone as part of the Franconian Lineament, seems to be enlarged by constructive interference of reflections which are produced by a number of cataclastic and undisturbed zones interlayered subparallel to the fault zone. This interpretation confirms similar results from the Brevard fault zone (Christensen and Szymanski, 1988). Model studies, discussed in this paper help to place constraints on the possible causes of deep seismic reflections. Critical to this study has been the availability of continuous logging data in the KTB borehole which penetrated the fault zone in a depth of about 7000 m where seismic surface measurements had earlier found a pronounced reflector. The synthetic seismogram, calculated from the impedance log, can explain the signature of the surface profile.



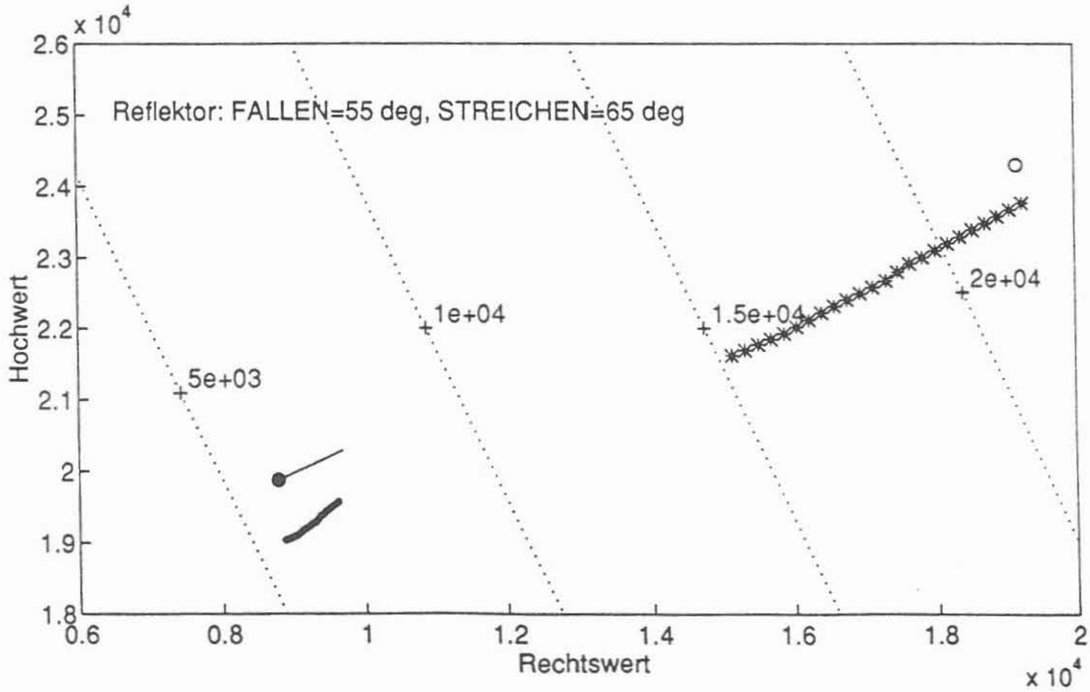


Abb. 5 : Ray Geometry and Reflection Points for INSTRUCT Experiment

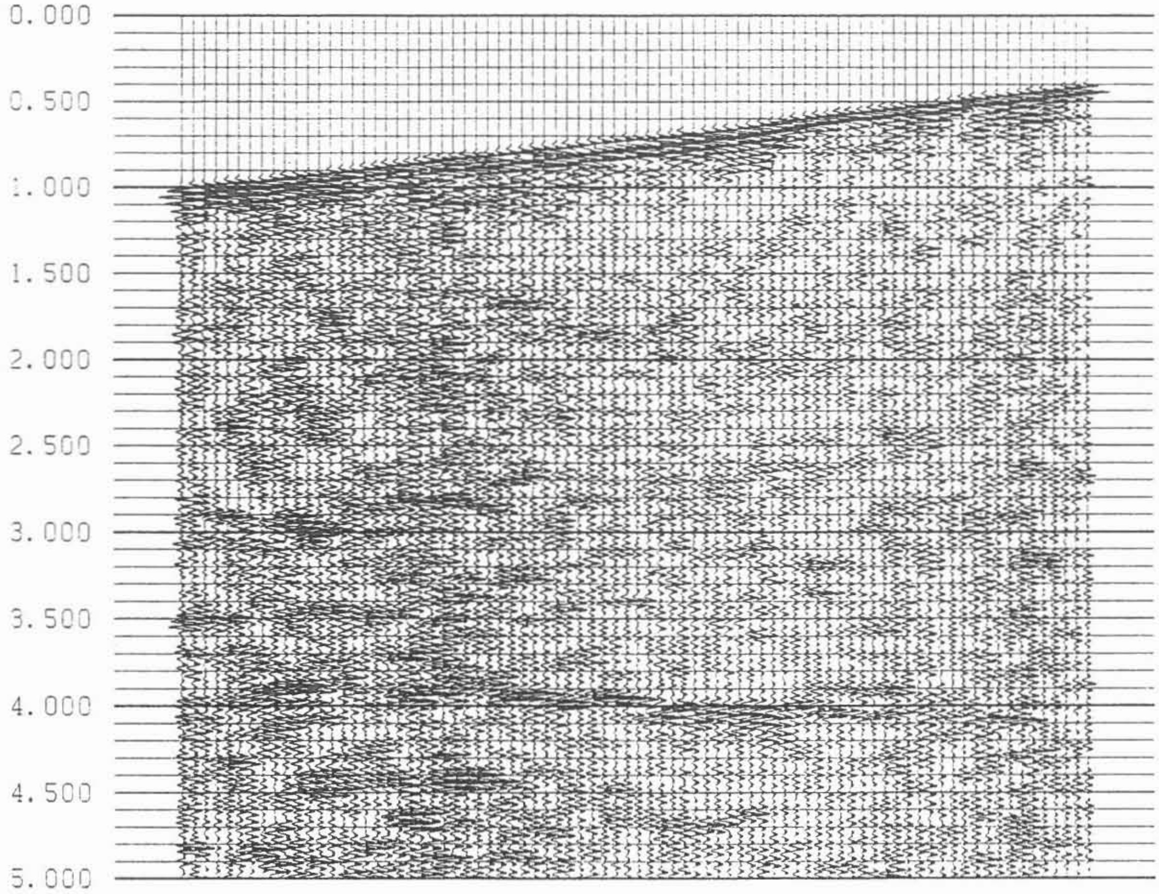


Abb. 6 : INSTRUCT Reflection Profile 1 (Shotpoint 4)

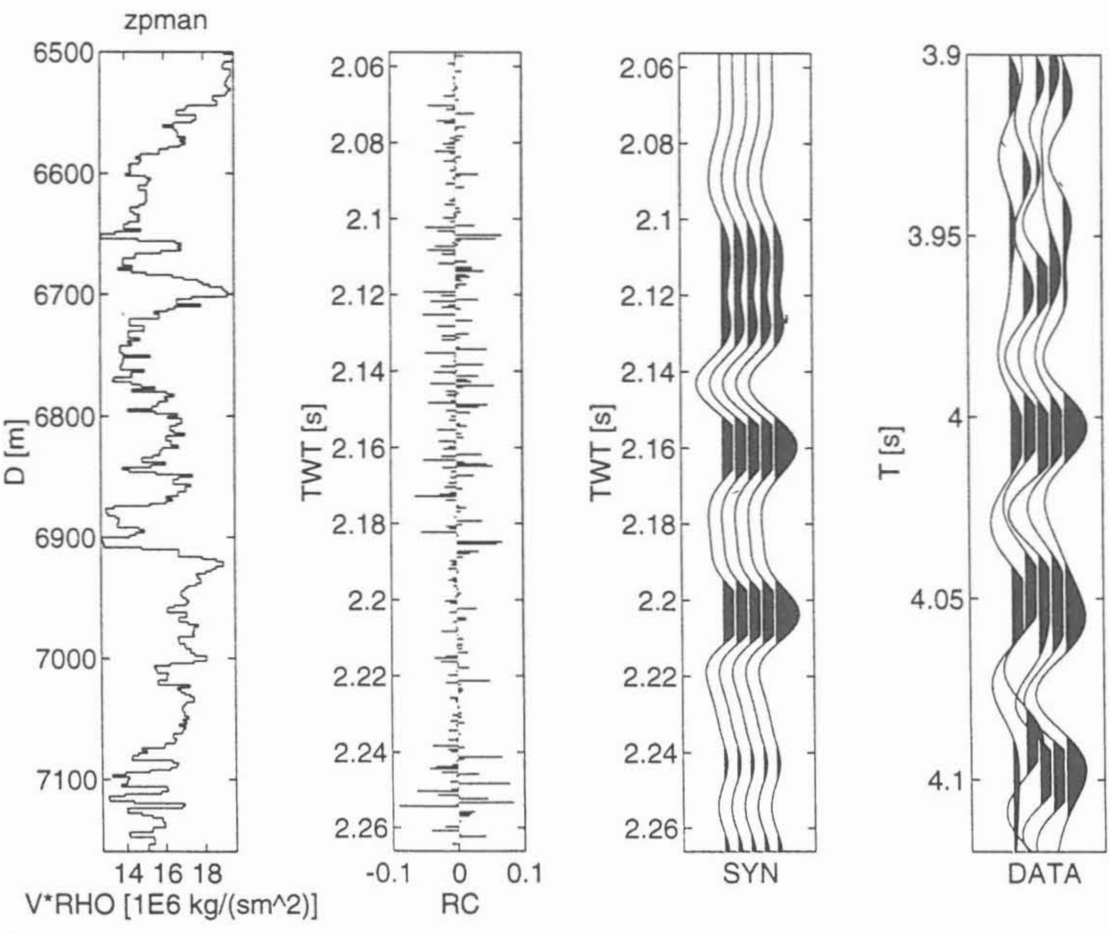


Abb. 7 : Comparison between Synthetic Seismogram and INSTRUCT Reflection Data

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