Determination of sonic velocities from KTB borehole acoustic logs.

K. Bram[1] and H. Gatto[2]

Abstract

Sonic logs provide a very detailed information on velocities of seismic waves propagating along the borehole wall. Acoustic measurements were performed in the KTB pilot borehole down to the total depth of 4000 m and in the KTB superdeep borehole so far down to 6000 m. Interval compressional and shear wave velocities in the metabasite units yield average values of 6360 m/s and 3560 m/s. Interval P-wave velocities in the gneiss complexes vary between 5510 m/s and 6150 m/s and the S-wave velocities between 3130 m/s and 3760 m/s. Foliation dipping up to 90° particularly in the gneiss complexes is responsible for seismic anisotropies of 8% and 13% for P- and S-wave velocities, respectively. In consequence, the Vp/Vs - ratio in crystalline rocks appears to be rather a function of structural effects.

Introduction

Sonic measurements in a borehole are a well established link of high resolution information with surface seismics of lower resolution, but much larger lateral extent. In connection with check shot surveys acoustic logging provides a reliable velocity information for correct depth correlation in hydrocarbon exploration.

With regard to the interpretation of the seismic surveys conducted around the KTB drill site (e.g. Schmoll et al., 1989; Dürbaum et al., 1990) where steeply dipping reflector elements prevail, correct depth determination turned out to be a particular difficult problem (e.g. Wiederhold, 1992; Hanitzsch et al., 1992).

In the KTB pilot borehole and in the KTB superdeep borehole, in the following called the "Vorbohrung" and the "Hauptbohrung", respectively, sonic measurements as well as vertical seismic profiles (VSP) were performed. This paper intends to evaluate the time-depth relation of seismic wave

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Authors' address:
1) Nieders. Landesamt für Bodenforschung, Projektgruppe KTB,
P.O.Box 510153, D-30631 Hannover
2) Consultant, KTB Logging Center, P.O.Box 67
D-92667 Windischeschenbach

propagation observed by acoustic logging, which in turn yields a precise velocity-depth function valid at least in the vicinity of the boreholes. If not otherwise stated all depth figures given throughout this paper correspond to logger's depths.

Data acquisition and tools

Acoustic logging:
Conventional sonic logging aims at detecting the arrival of a compressional wave. The inverse of wave velocity, referred to as interval transit time Delta-T (DT) or slowness, is then computed from the difference in transit times for various transmitter-receiver spacings. As a standard four Delta-Ts are recorded analog in real time in a borehole compensated mode which by tradition are spaced: 3'-5' (DT), 5'-7' (DTL), 8'-10' (DTLN) and 10'-12' (DTLF).

To extract more information, the full acoustic sonic waveform is digitized downhole so as to be free of cable induced distortions. The usual recording time is 10 to 20 ms with a sampling rate of 10 μs. The linear array of eight receivers permits the acquisition of more spatial samples of the propagating wavefield than the standard two-receiver tool. This allows to extract more accurately estimates of the slowness for various wave types such as compressional, shear and Stoneley waves by using modern signal processing techniques, like e.g. Slowness Time Coherence (STC) which is based on a digital semblance method (Kimball and Marzetta, 1984). The processing is usually done in receiver and transmitter mode and averaged for borehole compensation.

In this study interval transit times or velocities discussed below have been deduced by the STC method from monopole data for better fitting the prevailing KTB borehole conditions.

Vorbohrung: According to the logging and testing programme for the Vorbohrung, sonic data were obtained during six campaigns covering the depth interval from 27.4 m to 3994 m. The full waveform generated by a monopole source was recorded circumferentially by the Sonic Digital Tool (SDT) with an operating frequency of 18 kHz.

Hauptbohrung: In the Hauptbohrung sonic data are for the time being available from 278 m to 6020 m. The interval from 278 m to 3003 m was logged eccentered with the SDT in combination with the Natural Gamma Spectroscopy Tool to save an extra run. In the following reduced diameter borehole section, the newly developed Dipole Shear Sonic Imager (DSI) acquired the data down to 6020 m. This tool is equipped with one omnidirectional monopole and two unidirectional dipole transducers, as well as 8 receiver stations containing each two in-line mounted hydrophone pairs. The operating frequencies are adjustable between 8 - 30 kHz for monopole and between 80 Hz - 5 kHz for dipole modes.

A more detailed description of both tools can be found in e.g. Serra (1984), Williams et al. (1991) Draxler (1992) or in technical brochures published by the Service Industry.

Vertical Seismic Profiles:
Vertical seismic profiles are commonly used to infer interval and average velocities for surface seismic data interpretation, to elucidate structural information due to their high resolution capacity and to calibrate sonic measurements (check shots). In the Vorbohrung a check shot like survey was conducted down to 478 m, and according to drilling progress was followed by a zero-offset VSP down to a depth of 2200 m (Bram, 1988). Using a dynamite source the level spacing of 25 m turned out to implicate spatial aliasing due to an unexpected high frequency spectrum. Within the ISO 89 experiment a second zero-offset VSP was performed with a level spacing of 12.5 m and the lowermost level at 3622.5 m. In addition to dynamite a vibrator source was used. Shots were recorded with a 5-level three component downhole seismic array (Mylius et al. 1990). For technical details of the surveys and first results refer to Lüschen et al. (1990, 1991). Interpretations of the VSP data are published by Kästner et al. (1989), Hohrath et al. (1992) and Söllner et al. (1992).

As part of the 6000 m logging campaign in the Hauptbohrung a zero-offset VSP was performed in the interval from 6000 m to the casing shoe at 3000 m followed by check-shots every 500 m from the casing shoe up to 500 m depth. The vibrator source was situated 240 m west of the wellhead, and the sweep was set from 8 to 123 Hz. A non-oriented three component digital sonic acquisition tool measured the source signals again every 12.5 m. Technical details and first results are given by e.g. Draxler (1993) and Söllner et al. (1992).

Discussion of acoustic parameters

Fig. 1 shows a comparison of STC processed and analog computed compressional data of the depth interval from 2000 m to 2200 m of the Hauptbohrung. The differences between the various Delta-Ts, either digital or analog are usually very small, except in large breakouts. STC determined slowness values (DTCO), are the lowest throughout this section, hence represent the highest velocity. They are on the average 4μs/m lower than the ones computed analog, whereas DT and DTL are quasi identical with only 1μs/m offset on average. Improved data of DTCO have been obtained in the breakout section around 2100 m where an enlargement can be observed on both calipers.

In the entire Vorbohrung and Hauptbohrung shear waves were excited through a monopole source. In the deeper part of the Hauptbohrung starting at 3000 m, additional shear waves were made available through the excitation of two dipole sources phased 90°. The resulting slownesses are displayed in Fig. 2. As can be seen, only the values from the lower dipole match the ones from the monopole, whereas those from the upper dipole are constantly lower. Anisotropy is not likely the case, for the tool rotated through 360° and the borehole is almost circular. The histograms in Fig. 3a and Fig. 3b highlight these differences. Over the interval, the respective slowness is on average 293 µs/m for the monopole, 290 µs/m for the lower dipole and 276 µs/m for the upper dipole. The reason for these discrepancies is being investigated.

Results and discussion

The composite log in the annex (Plots #2a and #2b) shows the two wells side by side in an identical arrangement, with the Vorbohrung being on the left. The first column contains the maximum caliper, bit size and gamma ray. Compressional and shear wave velocities as well as pips for integrated compressional transit times corresponding to 10 ms are displayed in column 2. For the topmost depth intervals not accessible to logging, constant values of 5700 m/s for Vp and 3000 m/s for Vs have been assumed in order to make the necessary computations from the surface. Both values are average velocities deduced from the upper alternating sequence. Continuous integrated compressional and shear wave transit times as well as the rock density is depicted in column 3. Column 4 represents the simplified lithological profiles of the boreholes.

Influence of well conditions:

Among the various processing modes, data from the borehole compensated mode was chosen and no other borehole corrections applied. When interpreting sonic data care has to be taken to account for large borehole breakouts (Fig. 1). In this interval from 2090 m to 2120 m of the Hauptbohrung breakouts reach almost twice the amount of the borehole diameter. This is immediately reflected by an increase of the DT and the DTL slownesses whereas STC slowness (DTCO) is less affected.
In the Vorbohrung the sonic interval transit times, and hence the velocities, are only occasionally influenced by breakouts. This holds in particular for the upper 600 m. Breakouts, alteration and high fracture density (Röhr et al., 1989), indicated also by a drop of the log derived formation density, account for abnormal velocity decreases e.g. at the depth of about 1630 m and 2160 m to 2180 m. The velocity and

density decrease at 3202 m correlates with a drilling break and a core loss (Müller et al., 1989). Results of an injection test (Jobmann, 1990) do show the existence of a permeable, less dense fracture zone at that depth.

The Hauptbohrung has a much larger borehole diameter and the breakout situation is quite similar but much more enhanced. Beyond the total depths of the Vorbohrung, larger breakouts indicated by the caliper in the Hauptbohrung occur from about 5100 m down to 6000 m (Plot #2b). The minimum caliper, not displayed in this plot, rarely exceeds 30 mm above nominal bit size. The frequently observed abnormally low density values are easily explained by a tool rotation back into the long caliper axis despite the application of a short axis logging technique. This long axis corresponds with the direction of the minimum horizontal stress field (e.g. Brudy et al. 1993, this report). Due to the large borehole diameter of 17 1/2" no density log was run down to 3000 m.

Due to the more spatial sampling of the wavefield, waves travelling in general along the minimum caliper ray path are first recorded. Taking the fastest wave, STC derived velocities are considered to actually reflect formation velocities even in borehole sections with rather strong ellipticity.

<u>Lithological and structural control</u>:
The lithological profiles consist of a sequence of paragneisses and metabasites with intercalated alternating units. These units again are composed of different gneiss varieties and metabasites of variable thicknesses. Below about 3500 m metabasites prevail.

Sonic velocities clearly reflect the lithological changes. As expected, velocities in metabasites are generally higher than in paragneisses. This is well demonstrated e.g. for the metabasite complexes intersected in the Vorbohrung from 1160 m to 1610 m and from 3580 m on. Alternating units show up by a sonic log with strong velocity variations (Plot #2a). The average and interval velocity-depth relations of the compressional and shear waves are shown in Fig. 4 (VB) and Fig. 5 (HB). Interval P-wave velocities, averaged over 50 m in the metabasite complexes, increase sharply to values above 6000 m/s with peak values up to 6600 m/s. The increase of the S-wave interval velocities with maximum values of 3730 m/s is less pronounced. Taking a gross mean the metabasite complex below 3500 m can be characterized by compressional and shear velocities of 6420 m/s and 3560 m/s, respectively. Comparable mean axial P-wave velocities measured on cores (Rauen et al., 1990; Pribnow et al., 1992) are lower. Reasons may be changes in structural features like frequency, distribution and incident angle of fractures and microcracks (influence of pressure-temperature relaxation) or simply fabric loosening while coring with roller cone bits.

Velocities in the paragneisses are particularly influenced by the amount of dip of the foliation (Figs. 4 and 5). Interval P-wave velocities vary between 5510 m/s and 6150 m/s and S-wave velocities between 3130 m/s and 3760 m/s. Not surprising, the highest velocities can be observed in the section with the steepest dip and the lowest in zones of low dip. Based on the data of the Vorbohrung slowness versus foliation dip has been analysed for the three main paragneiss sections (Figs. 6a-c). The points are grouped in six frequency classes with their respective amounts in brackets. For each interval an ellipse with its origin in the center of gravity is positioned in such a way that it encompasses the majority of the points. Also shown is the regression line and the histogram of each variable. This helps in better locating the different sections in the composite plot in Fig. 6d. Velocities are more affected by dip than by overburden pressure - the lowest velocities occurring in the deepest interval (Fig. 6c). The composite plot in Fig. 6d indicates a hardly noticeable difference between the top and bottom interval whereas the middle section can be clearly distinguished.

Bremer (1993) showed that as a first approach slowness linearly depends on the cosine of the foliation dip. Correcting the above mentioned velocities (values taken at dips of about 20° and 80°) paragneisses reveal a P-wave anisotropy (A = (Vmax - Vmin)/Vmean) of about 8% and an S-wave anisotropy of about 13%. This is in good agreement with anisotropy values reported and discussed e.g. by Lippmann et al. (1989), Kern et al. (1991), Bopp (1992) and Rabbel (1992). The inclination of the Vorbohrung which exceeds only in few and relatively short depth intervals five degrees has been neglected for foliation dip correction, and hence, for anisotropy determination.

A low velocity zone indicated both by sonic and VSP (Söllner et al., 1992) average velocities in the depth range 2800 m to 3600 m is indeed an effect of anisotropy due to a net change of foliation dip from about 50 to less than 20 degrees.

The metabasites are generally more massive and only occasionally well foliated (Lich et al., 1992). Therefore, sonic velocities scatter less, and no anisotropy values have been deduced using the sonic log data. From core analysis a much lower anisotropy has been reported (Rauen et al., 1990).

Lippmann et al. (1989) and Wiederhold (1992) discussed in detail seismic velocities obtained from KTB core measurements and sonic logs. Velocity differences between VSP and sonic measurements in the KTB Vorbohrung are discussed by Hohrath et al. (1992) and Rühl and Hanitzsch (1992). Attention is drawn by these authors that sonic velocities are generally lower than velocities measured on cores or from VSP. On a first glance P-wave sonic velocities appear indeed to be lower in certain depth intervals than the velocities measured on cores or from the VSP surveys. Wiederhold explains these apparent discrepancies by the effects of anisotropy and dispersion stressing the different geometry of the velocity measurements and their different frequency ranges: core measurements are performed in the MHz-range, sonic measurements in the kHz-range and VSP surveys in the order of 100 Hz or less. Rühl and Hanitzsch suggest geometric ray path effects, and thus possible wrong traveltime corrections. Interpreting the VSP run from 6000 m to 3000 m (16" casing shoe) in the Hauptbohrung, Söllner et al. (1992) reports a mean interval velocity of 6490 m/s for the more massive metabasites in the depth range 3625 m to 5325 m. This is in good agreement with the corresponding sonic velocity. Nevertheless, even in these metabasites anisotropy cannot be excluded too, taking into account the observed structural dips of about 55° on average. With this in mind, the reported negative drift between sonic and VSP velocities turns out to be an apparent one.

Sonic velocity cross-multiplied with the density is normally used to produce an acoustic impedance log. The inferred synthetic seismogramme is an important step for tying a borehole in a seismic cross section. Despite the many seismic reflectors observed in the surface reflection data mentioned above, no attempt has been made here to calculate an acoustic impedance log, and hence a synthetic seismogramme. Reasons are simply the strong anisotropic behaviour of the wave propagation and in the majority steeply dipping foliation and structures such as fractures and lithological changes, not accounted for in the routinely used formula.

The Vp/Vs-ratio, easily calculated from sonic log data, is in general a key figure for determining elastic characteristics of rocks allowing for statements on lithology and facies changes as well as for indications of pore filling and porosity variations. In crystalline rocks the ratio appears to be rather a function of structural effects like e.g. foliation dip. This is particularly well demonstrated in Fig. 4: in the paragneiss sections with a foliation dipping more than about 50° the Vp/Vs-ratio, calculated from the sonic interval velocities, drops below 1.7. With decreasing dip, for example in the depth interval from 2700 m to 3600 m, the Vp/Vs-ratio is 1.71 in average. Otherwise stated, the ratio reflects the velocity anisotropy. Care has to be taken, however, when interpreting abnormal high values such as observed e.g. at a depth of 1900 m with relatively good caliper conditions in the Hauptbohrung (Fig. 5). In this case the S-wave velocity obviously decreases much stronger than the P-wave velocity due to a severely altered garnet-sillimanit-biotite gneiss of high fracture density.

In the metabasites the Vp/Vs-ratio lies above 1.75 with an average value of about 1.8. As mentioned above, metabasites may show also structural features like foliation. An increase in the S-wave velocity in the depth interval 3800 m to 3950 m correlates with an increase of the foliation dip whereas the P-wave remains less affected thus reducing considerably the Vp/Vs-ratio.

The Vp/Vs-ratios in the topmost alternating sequence are essentially characterized by borehole breakouts and velocity variations due to surface effects.

Conclusions

In order to assess correctly the information contained in the sonic log data hitherto obtained in the KTB boreholes, the used logging tools are briefly described and the measured acoustic parameters are discussed. STC derived slowness values are considered to actually reflect formation velocities despite severe elliptical breakouts observed particularly in the Hauptbohrung over large depth intervals. Sonic velocities clearly reflect the drilled lithological units: metabasites having generally higher velocities than the paragneisses. The velocities in the paragneisses do show a strong anisotropic behaviour as a result of the foliation dip. Anisotropy amounts up to 8% and 13% for P- and S-wave velocities, respectively.

In the crystalline rocks investigated here, the Vp/Vs-ratio is strongly dominated by structural effects like dipping foliation. This holds especially in the gneiss sections and to a limited extent in some metabasic units. The more massive metabasites have a ratio of about 1.8 and higher, gneisses have ratios less than 1.7 on average depending on the degree of foliation dip.

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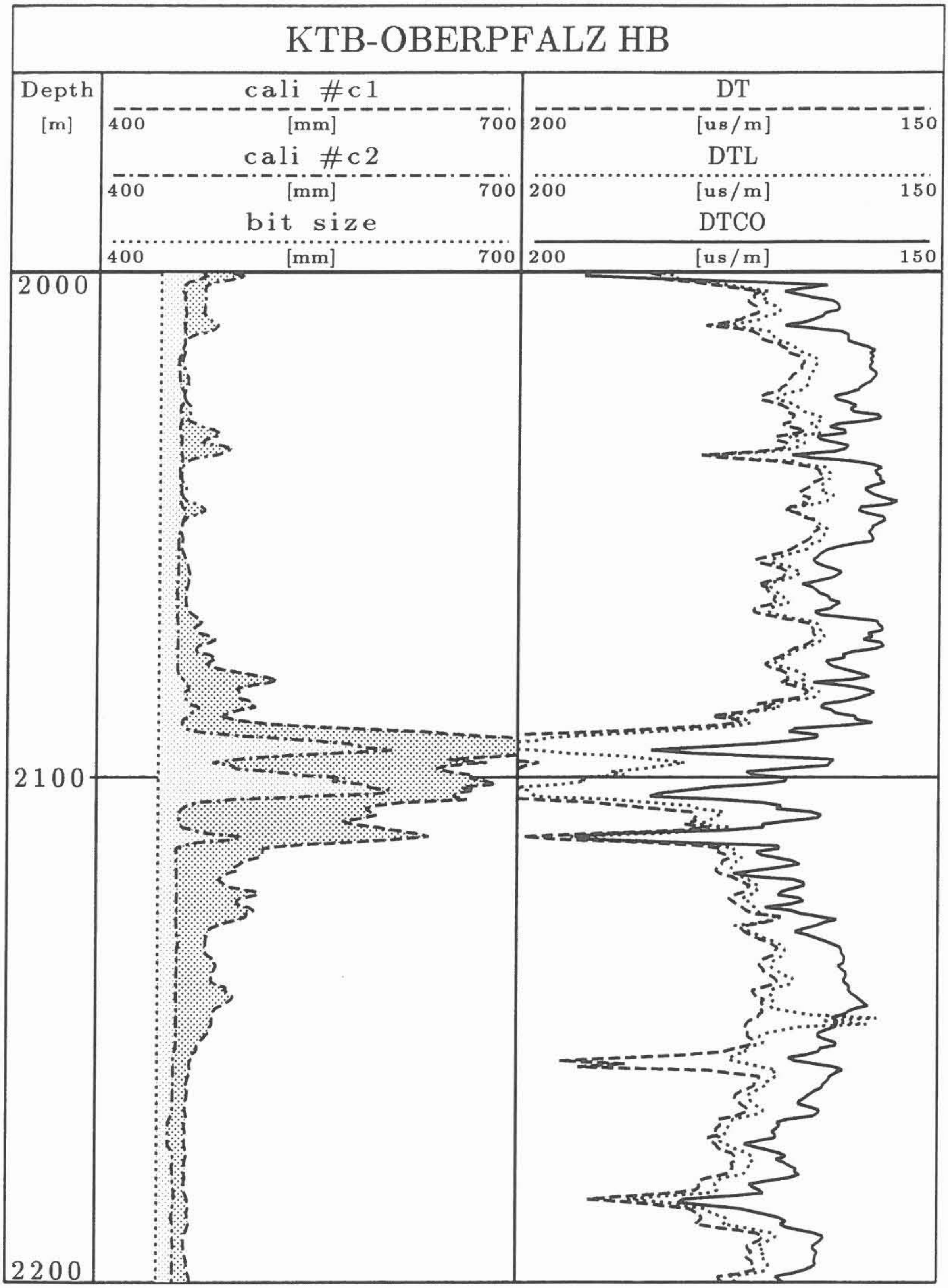

Fig. 1: Comparison of different slowness computations
dt,dtl ... analog first motion detection
dtco ... slowness time coherence

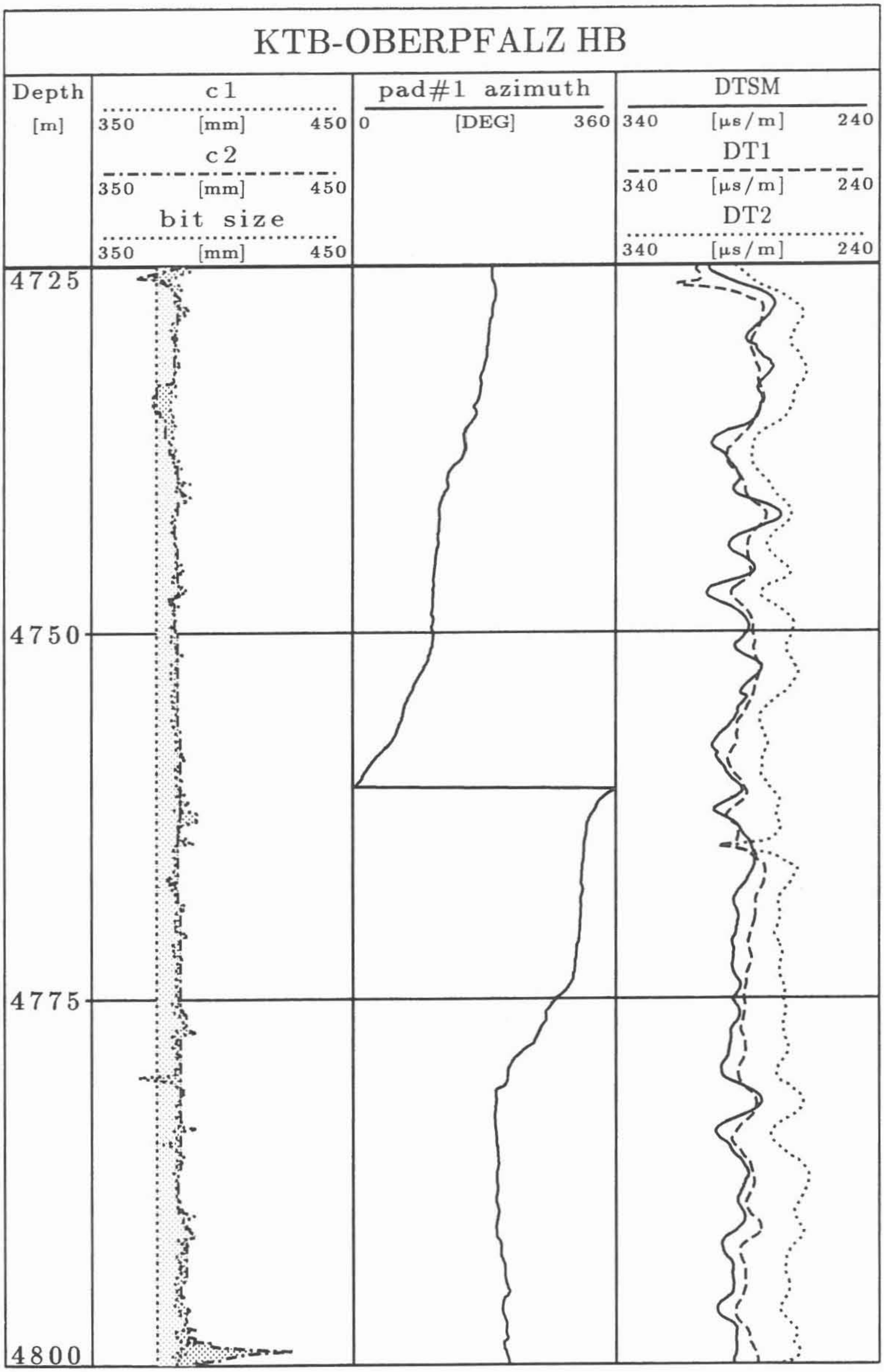

Fig. 2: Comparison of different shear computations
dtsm ... monopole
dt1,dt2 ... lower and upper dipole

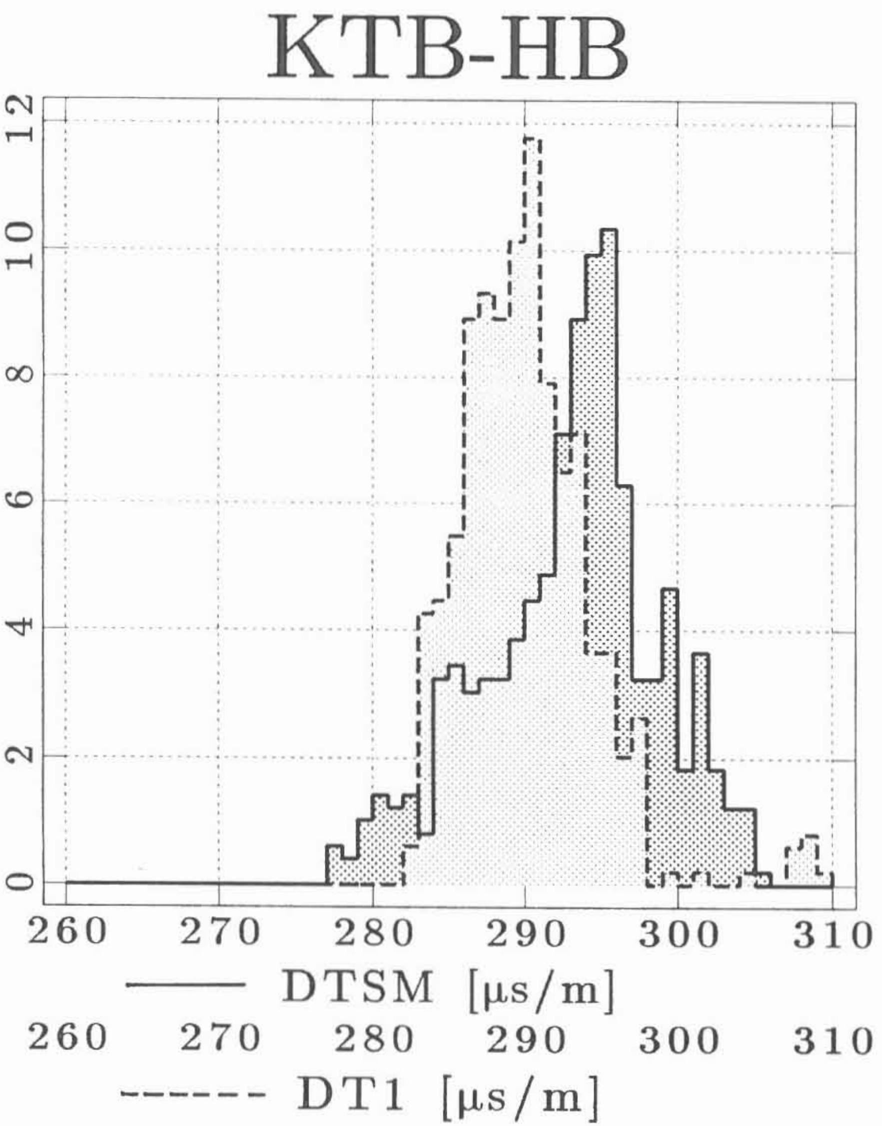

Fig. 3a: Slowness of monopole and lower dipole shear from 4725m to 4800m

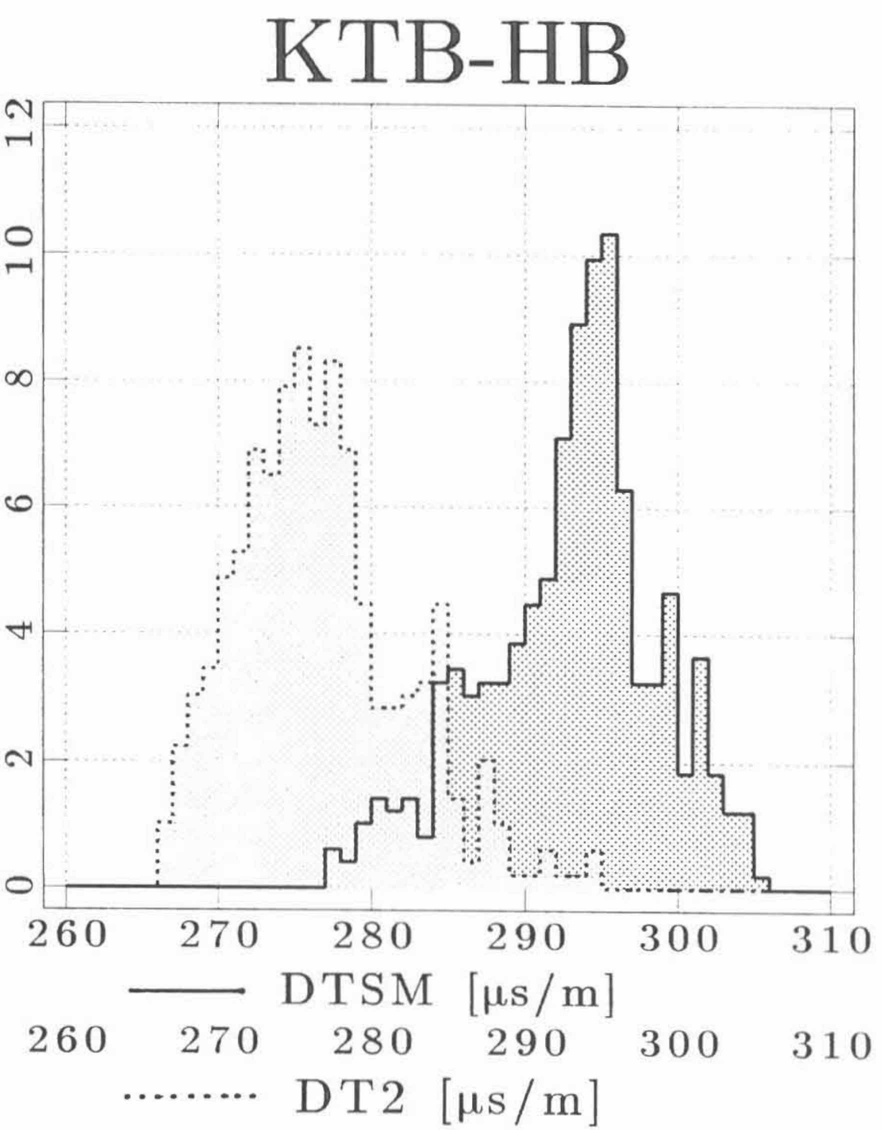

Fig. 3b: Slowness of monopole and upper dipole shear from 4725m to 4800m

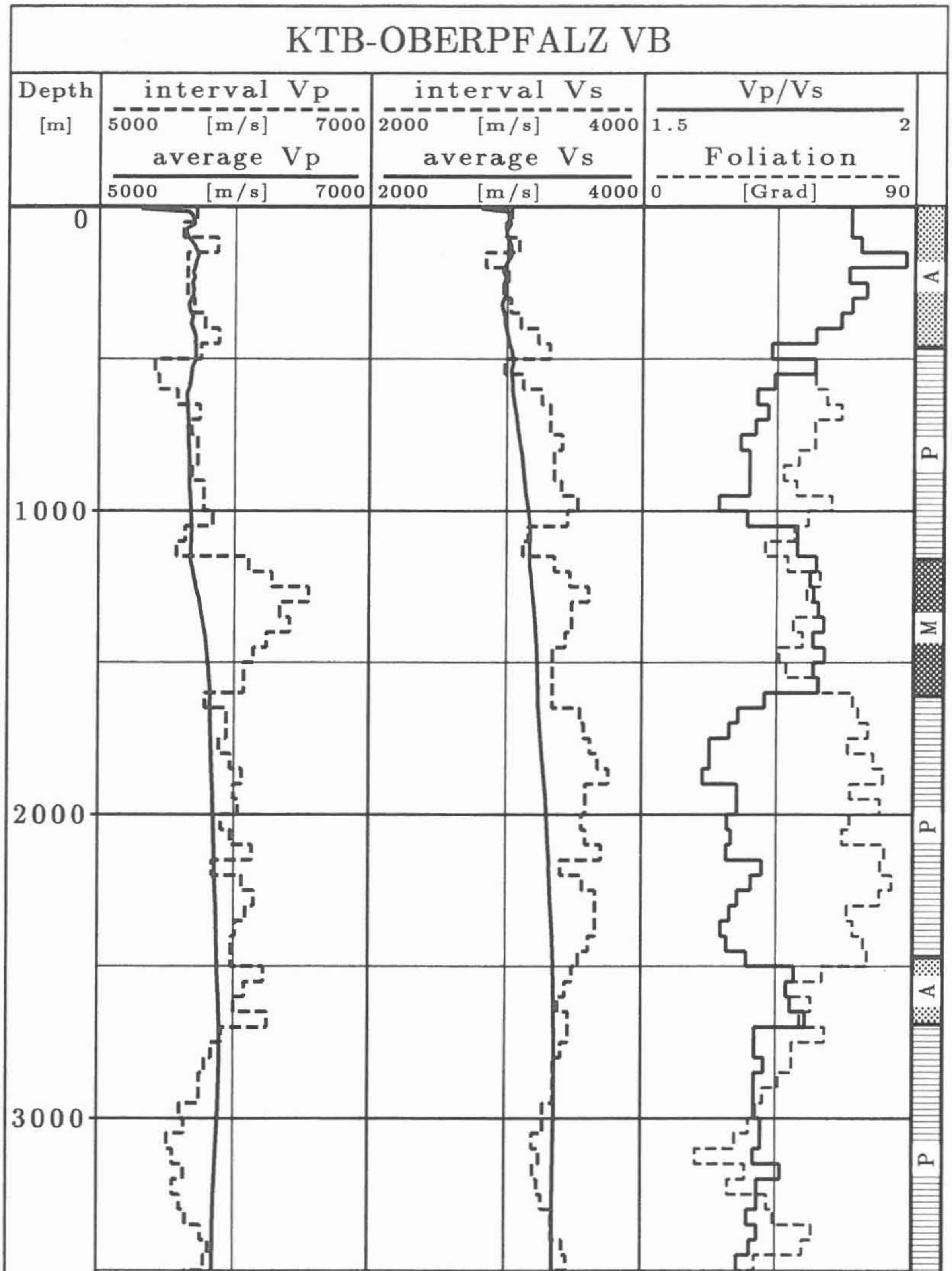

Fig. 4: Velocity profiles of KTB-VB

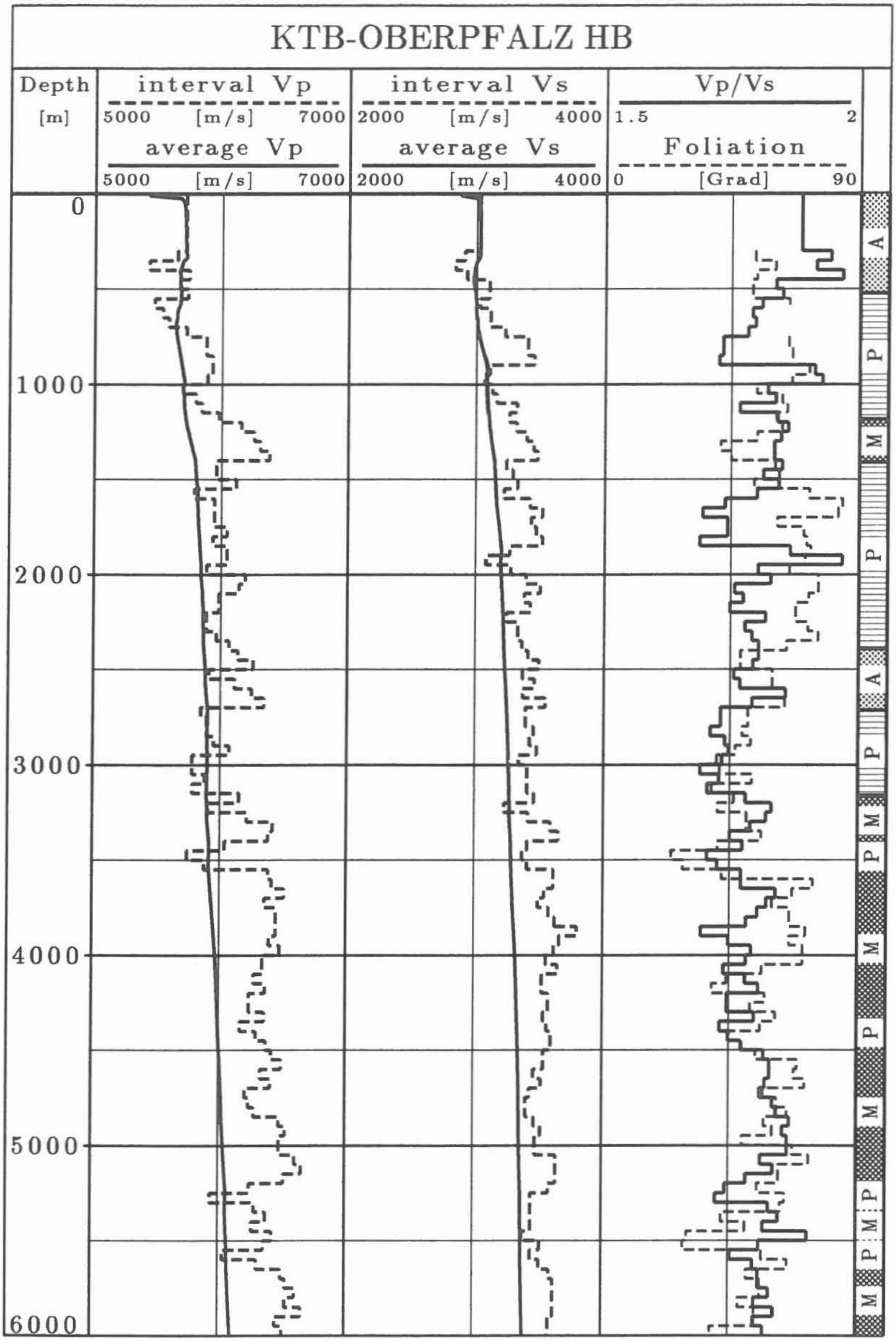

Fig. 5: Velocity profiles of KTB-HB

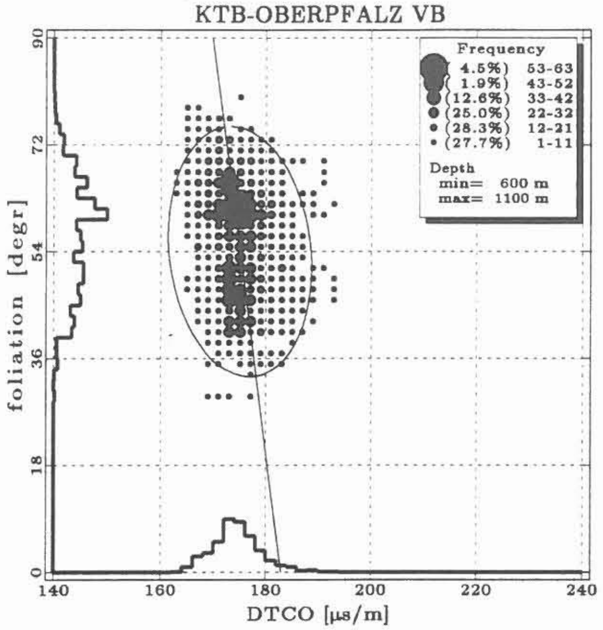

Fig. 6a Slowness versus dip in gneiss (600 - 1100m)

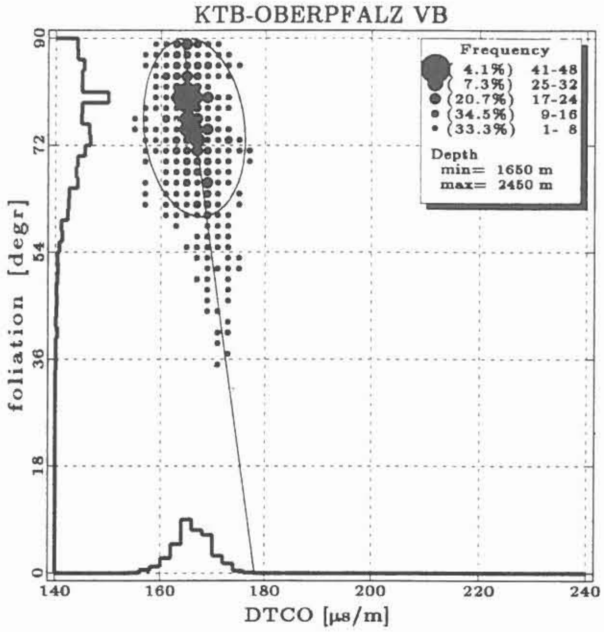

Fig. 6b Slowness versus dip in gneiss (1650 - 2450m)

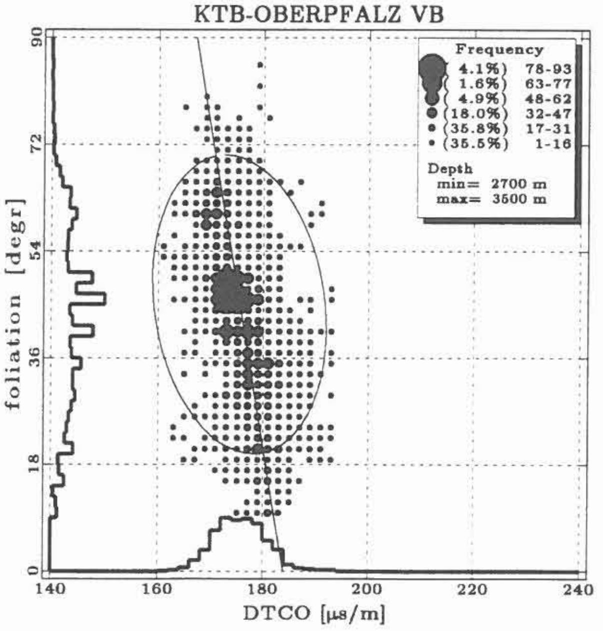

Fig. 6c Slowness versus dip in gneiss (2700 - 3500m)

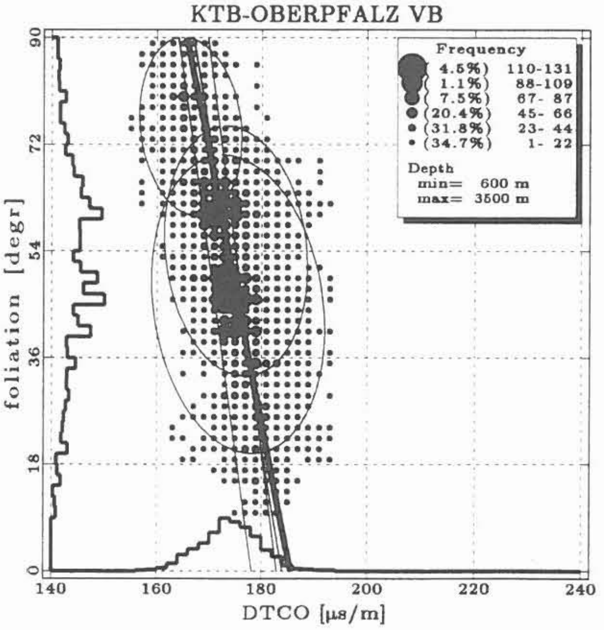

Fig. 6d Slowness versus dip in gneiss (600 - 3500m)