Moving Source Profiling
A Link between KTB-Borehole Data and Seismic Surface Measurements

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Abstract.

The moving source profiling (MSP) measurements are done by moving seismic sources along a surface line crossing the well site while a chain of geophones, placed within the well bore at a certain depth, records the seismic response. A multifold coverage of the subsurface can be obtained by repeating the source profile for a number of different geophone depths.

This idea of altering the conventional vertical seismic profiling (VSP) geometry to allow illumination of subsurface structure away from the well is an attractive idea because it is designed to better locate horizons below the drill bit. If these target horizons can be correlated with reflectors in usual seismic profiles, recorded on the surface, the latter can be calibrated by the MSP results.

Two MSP experiments were realized in the KTB pilot borehole. The first (MSP 1) included two N-S and E-W orientated source profiles of 10 km length and a single three-component geophone at 3585 m depth. Later a full MSP experiment (MSP 2) was run for one NE-SW orientated source profile and 20 different geophone depths. The source line was extended 7 km to the Northeast and 3 km to the Southwest of the well. A vibrator source produced seismic signals every 50 m. These shots were recorded by three-component geophones at depths from 3210 m to 3685 m with 25 m intervals resulting in a 20-fold coverage of the illuminated subsurface.

Due to the difficulties encountered in crystalline environments, different processing techniques were combined for interpretation of the MSP data set. Aside from comparing measured first-break times with theoretical ones to determine seismic velocities of the overburden an MSP-CDP transformation for migration were applied.

The steeply dipping boundary of the Falkenberg granitic intrusion was mapped as a distinct velocity contrast east of the KTB well. On the other hand, some remarkable seismic reflectors at depths between 4000 m and 10000 m are predicted to be hit by the future KTB main borehole.

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1. Introduction.

In the past decade, sophisticated seismic data acquisition techniques have been developed which include the placing of geophones in downhole arrays. The importance of this method lies in its potential for detecting subsurface detail which is difficult to be obtained from conventional surface seismic data. The Vertical Seismic Profile (VSP) technique is normally executed with a single source position near the well head. Zero-offset VSP's provide subsurface information only within the Fresnel zone surrounding the well. In contrast, the Moving Source Profiling (MSP) data acquisition scheme (Brauner, et al. (1988)) where seismic signals are generated on a profile crossing the well site, allows the illumination of subsurface structure away from the well.

In an integrated seismic survey, like the ISO-89 experiment, the MSP-data might serve to calibrate reflections, recorded on surface profiles, to lithological information from borehole data.

As one can see from the schematic diagram of the MSP-experiment (figure 1), two different kinds of seismic waves travel to the downhole receivers : direct waves (dashed lines) from which the seismic velocity of the overburden can be deduced and reflected waves which will be used to accurately locate target horizons in the neighborhood of the borehole.

In view of the ultradeep KTB-borehole, the most challenging part of the MSP-experiment will be a prediction of discontinuities that should be hit when the drilling operation reaches depths below the pilot hole in which the geophones were placed during the MSP-survey.

Before we can start an interpretation of the experiment, the MSP-reflection response is to be reconstructed into the familiar co-ordinate system of surface seismic sections. As this experiment was - to our knowledge - the first test of the MSP-technique in crystalline environment, it is by no means evident that procedures developed for sedimentary structures are useful or to which extent the established processing steps have to be modified. Additionally, the data acquisition in itself in crystalline environment is a new frontier because the reflecting elements - as seen in pre-site surface seismic surveys - are very short and no specific target horizon was detected which could have been used for planning the MSP-layout.

2. MSP-Experiments.

A first MSP-experiment (MSP 1) was conducted in December 1988 to gain experience with the site-specific problems of data acquisition and processing in the KTB-area. It was planned to get a first insight into the geological structure at the location of the pilot hole and its extension to the neighboring site of the main deep drilling project planned at about 200 m distance. Additionally, the depth extension of the Falkenberg granitic intrusion east of the drill site should be explored. Figure 2 shows the two N-S and E-W vibrator lines of 10 km length. The E-W profile represents an asymmetric split-spread configuration which was extended to the east to include the Falkenberg granite. Along the vibrator lines combisweep signals (20 - 80 Hz) of 20 sec duration were produced at 50 m interval. 5 -10 sweeps were stacked and correlated with an effective recording time of 7 seconds at a sampling rate of 4 msec.

A limitation of the first MSP-experiment was given due to the fact that data were recorded with only one three-component geophone at 3585 m depth. Additionally, a 120 trace geophone spread was layed out along both vibrator profiles (figure 2) to assist in tying the MSP-data to the existing surface seismic profiles, and in order to obtain reliable static corrections.

Within the ISO-89 experiment, a third MSP-profile (MSP 2) was recorded (figure 3). This time a receiver chain of 5 three-component geophones was used which were separated by a distance of 25 m. The deepest geophone position was at 3685 m. Then the receiver-chain was lifted 125 m and the vibrator profile was repeated.

Altogether, the vibrator line was run four times resulting in a 20-fold coverage of the cross section illuminated around the well (figure 4).

As one can see from the schematic map of the two MSP-experiments (figure 2 and 3), the orientation of the vibrator line for the multifold MSP-profile was changed to NE-SW direction to fit into the grid of the surface seismic data (3D-coverage) of the ISO-89 experiment.

3. Data.

A typical example of the raw data of MSP 2 is shown in figures 5a and 5b. The vertical and the H1-component is plotted for one depth position (3210 m).

The clearest coherent events can be associated to the direct P-wave and to the direct S-wave. The latter can be recognized by its larger moveout and also by its different spectral content. Obviously there is a long coda of the S-wave masking possible later reflection events. Without further processing it is very difficult to detect reflections even in the interval between the direct P- and S-wave arrival. The short-period multiples following both phases seem to originate from the weathering layer which is very pronounced at the surface of the Variscan crystalline outcrop forming the geology in the KTB-area. The varying thickness of the weathering zone together with the rough topography is also the reason for the incomplete static corrections.

Later phases can easier be detected in a "brute stack" of 20 depth positions which is shown for the vertical component in figure 6. Especially between the two direct waves some events emerge which could be interpreted as reflections from interfaces below the geophone positions.

Before we start to process these events further, the clear direct P-arrivals will be used to evaluate the velocity distribution of the overburden.

4. Lateral variation of overburden velocities.

From the split-spread E-W profile of the first MSP-experiment, arrival times of the direct P-wave were picked and compared to theoretical travel times, computed by ray-tracing method assuming a simplified geological model. A homogeneous half-space was compared to a model of two adjacent half-spaces, the latter one describing the intrusion of the Falkenberg granite (figure 7). Static corrections for topography and weathering layer were derived from a shallow refraction survey. In an iterative process, theoretical and measured travel times were adjusted by variation of velocities.

Figure 8 shows a comparison between measured first arrival times and the calculated ones for both models. Additionally the differential travel times are plotted at the bottom of fig. 8. The best fit is obtained for an average velocity of 5950 m/s in the western part of the profile approaching the well, whereas a lower velocity of 5580 m/s was found at the eastern end of the profile. This velocity decrease corresponds well with the granitic intrusion, on the other side, an average velocity of 5900 m/s was derived from the conventional VSP - measurements in the KTB pilot hole.

Some extrema in the differential travel times plotted in figure 8 occur independently from the model at offsets of 1.8 km, 2.5 km and 4 km. They reach the same magnitude as the model differences and have to be explained in terms of residual statics. Denser refraction lines are necessary to confirm this conclusion.

Despite these difficulties, it has been demonstrated that a tomographic evaluation of the MSP-data allows to verify lateral velocity changes in the overburden which is especially useful to locate steeply dipping interfaces like the gneiss/granite contact plane east of the KTB borehole.

5. Predicting reflections ahead of the drill bit.

Many uncertainties in surface seismic measurements are a result of having the source and the receiver on the surface, far removed from the target zone. In MSP's, however, since the receivers are located down the borehole, they are closer to the reflecting interfaces so the accuracy relative to surface measurements should be improved.

A KTB presite survey (Schmoll et al. (1989)) including two reflection seismic profiles exposed a series of reflections in the uppermost crust which were interpreted as indicating a nappe (ZEV = Zone of Erbendorf-Vohenstrauss). The depth of this old thrust fault was estimated between 4000 m and 5000 m. Since the geophone positions of the MSP-experiment covered a depth range from 3210 m to 3685 m, the base of the ZEV nappe should be imaged in the MSP-data in the time interval between 0.6 s and 1.2 s roughly corresponding to a depth range from 3.6 km to 5.4 km.

Before we can start to correlate coherent energy in the MSP-profile with reflections from surface seismic cross sections, the MSP-data have to be transformed into the familiar coordinate system of a surface seismic section. This migration-like mapping is especially important because the reflecting elements only show short lateral extension which is characteristic for the seismic response of crystalline crust.

Figure 9 outlines the principle of the mapping technique for a constant velocity situation (Dillon and Thomson, 1984). The formulae simply transform a time on a trace to the x-z co-ordinates of a point in the subsurface. For a more complex velocity profile, ray-tracing techniques must be used. This mapping procedure is also known as "MSP-CDP - transformation" because it images the MSP-data into the CDP-domain, equivalent to a CDP-stacked section. To produce traces of constant CDP-increments, the MSP-data are mapped into a series of vertical strips which are refered to as bins, and then a trace is created for each bin by stacking the data that are mapped into that bin. The bin width must be chosen with care so as to achieve good signal quality without degrading resolution. Figures 10 and 11 show the result of the MSP-CDP- transformation for the vertical and horizontal component (H1) of the second MSP-experiment, respectively. Data from 10 depth positions are stacked. Using an average velocity of 5900 m/s derived from VSP-data, one can transform the one-way travel time into depth as marked on the right panel of both figures. A series of reflectors dipping to the east now clearly emerge in the depth section between 3500 m and 5000 m which seem to be terminated by steeply dipping faults. This hypothetical interpretation has to be taken with caution because the mapping procedure is only secure for horizontal events but it introduces errors for dipping reflectors.

To get an impression of the imaging of reflectors into MSP-data, a forward-modeling method was applied. Using a ray-tracing algorithm a reflector with an eastward dip of 10 degrees was modeled into a travel time curve as seen in a MSP-profile (figure 12). For the set-up of the MSP2-experiment (figure 3) we get an MSP-image as plotted in the lower half of figure 12. From this one can conclude that a coherent reflector of 1 km to 2 km lateral extension results from a discontinuity with a width of only 100 m. To obtain the true position of the target horizon, an iterative wavefront modeling should be performed until the resulting depth correlates with the corresponding MSP-depth conversion.

6. *Future work.*

At this stage, only preliminary results of the MSP-processing are available. The MSP-CDP transformation will be refined and true migration procedures will be applied to finally splice together the seismic surface profiles and the MSP-data. Two-dimensional filtering should help to separate the reflected wavefield from downgoing multiples. Last but not least, we want to make use of the information contained in the three-component recordings to identify wave-type and its bearing by polarization techniques.

7. *References*

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Dillon,P.B. and Thomson,R.C.: Offset Source VSP Surveys and their Image Reconstruction. Geophys.Prosp. 32, 5, 790-811, 1984.

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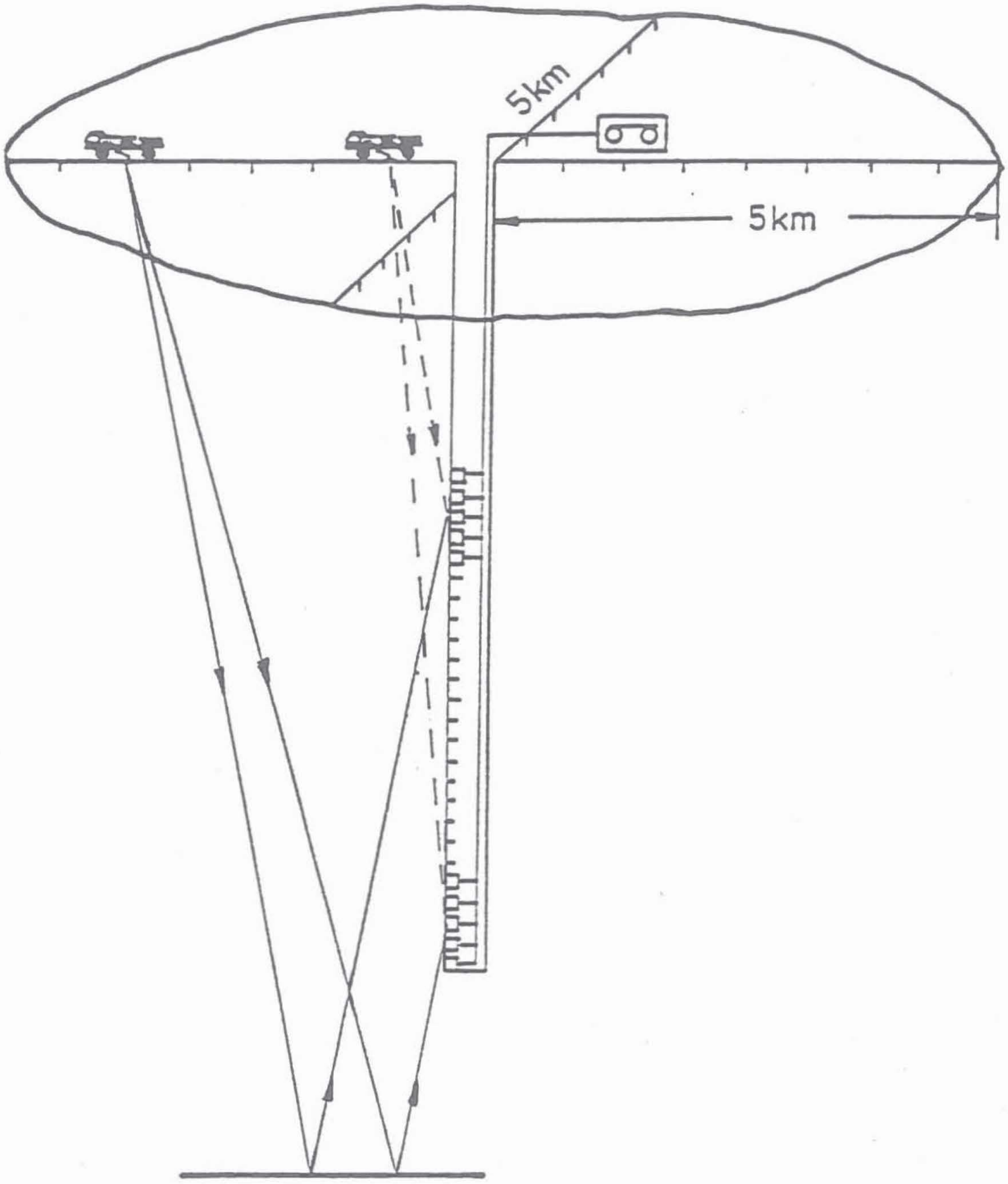


Fig. 1 Schematic diagram of the MSP-experiment.

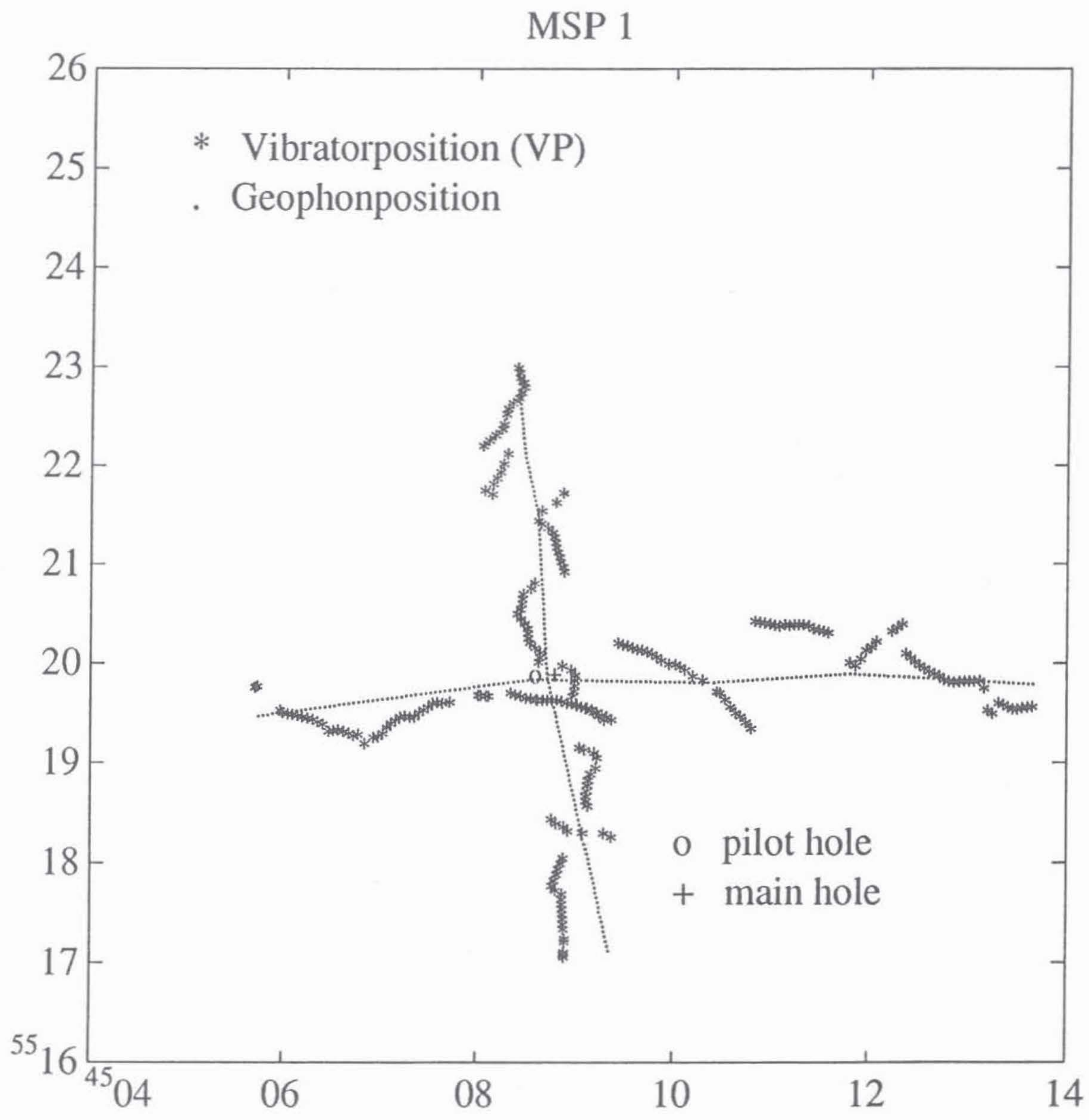


Fig. 2 Vibrator - and geophon profiles of the first MSP-experiment (MSP 1).

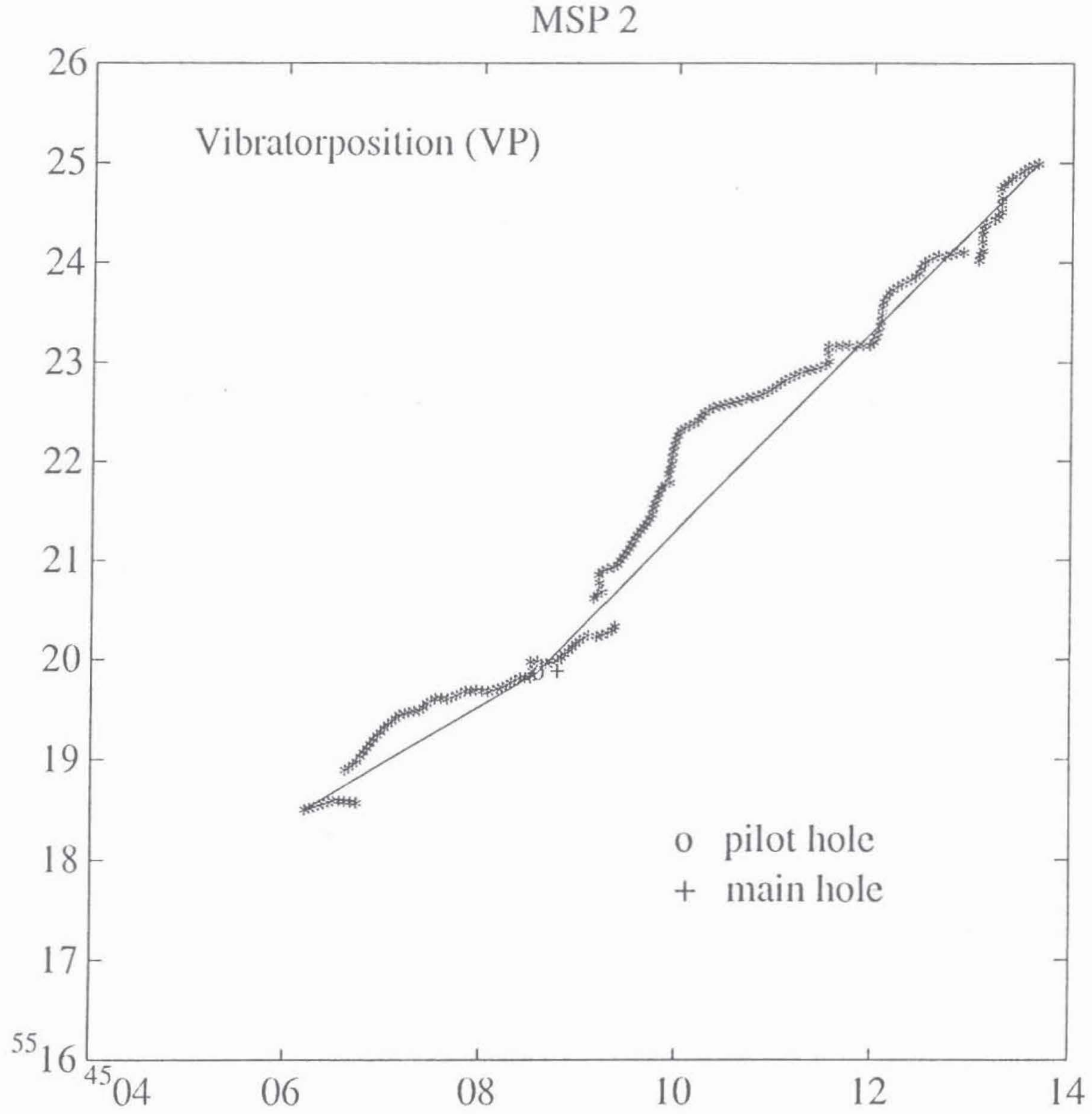


Fig. 3 Vibrator profile of the second MSP-experiment (MSP 2).

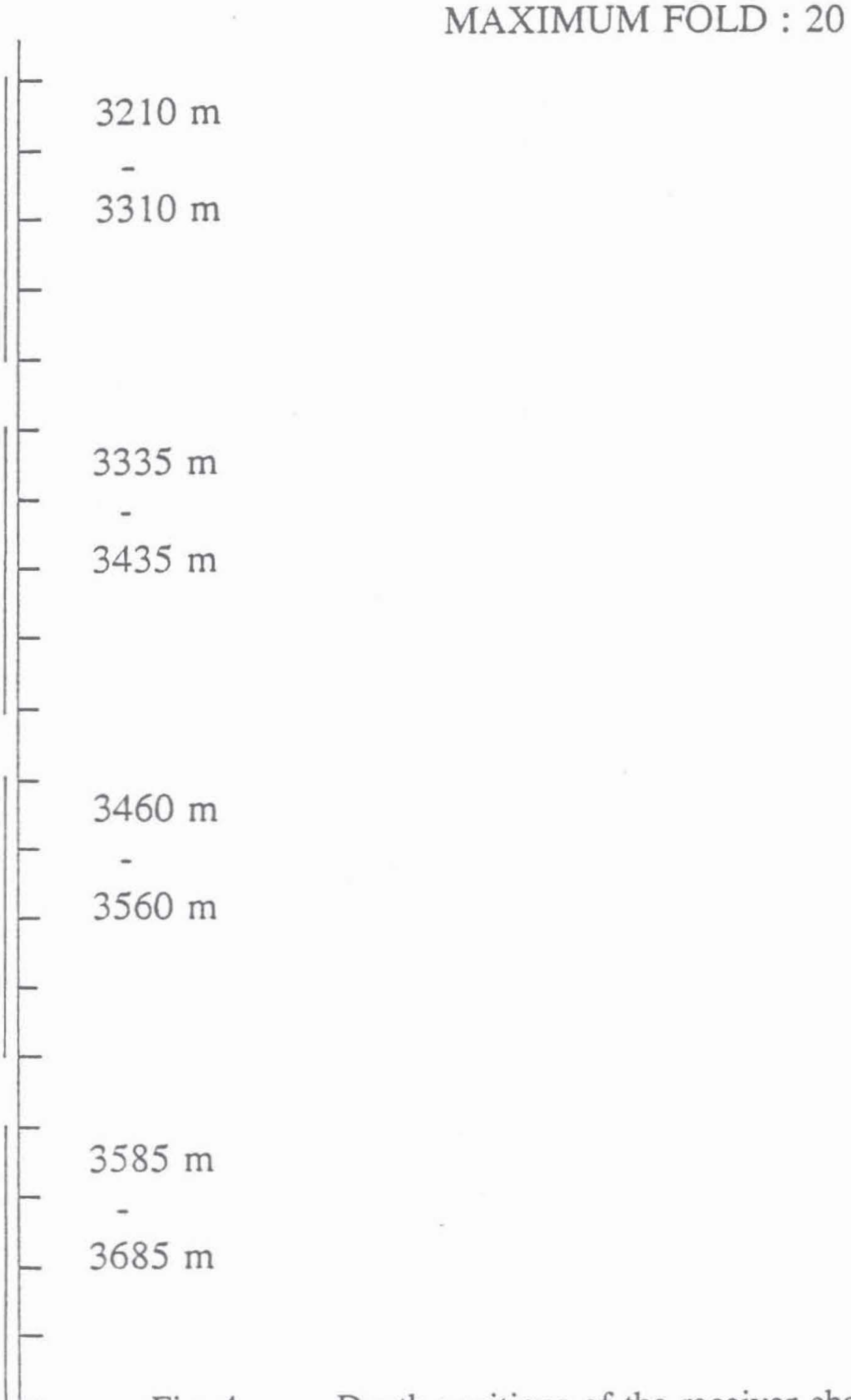


Fig. 4 Depth positions of the receiver chain, leading to a 20-fold coverage.

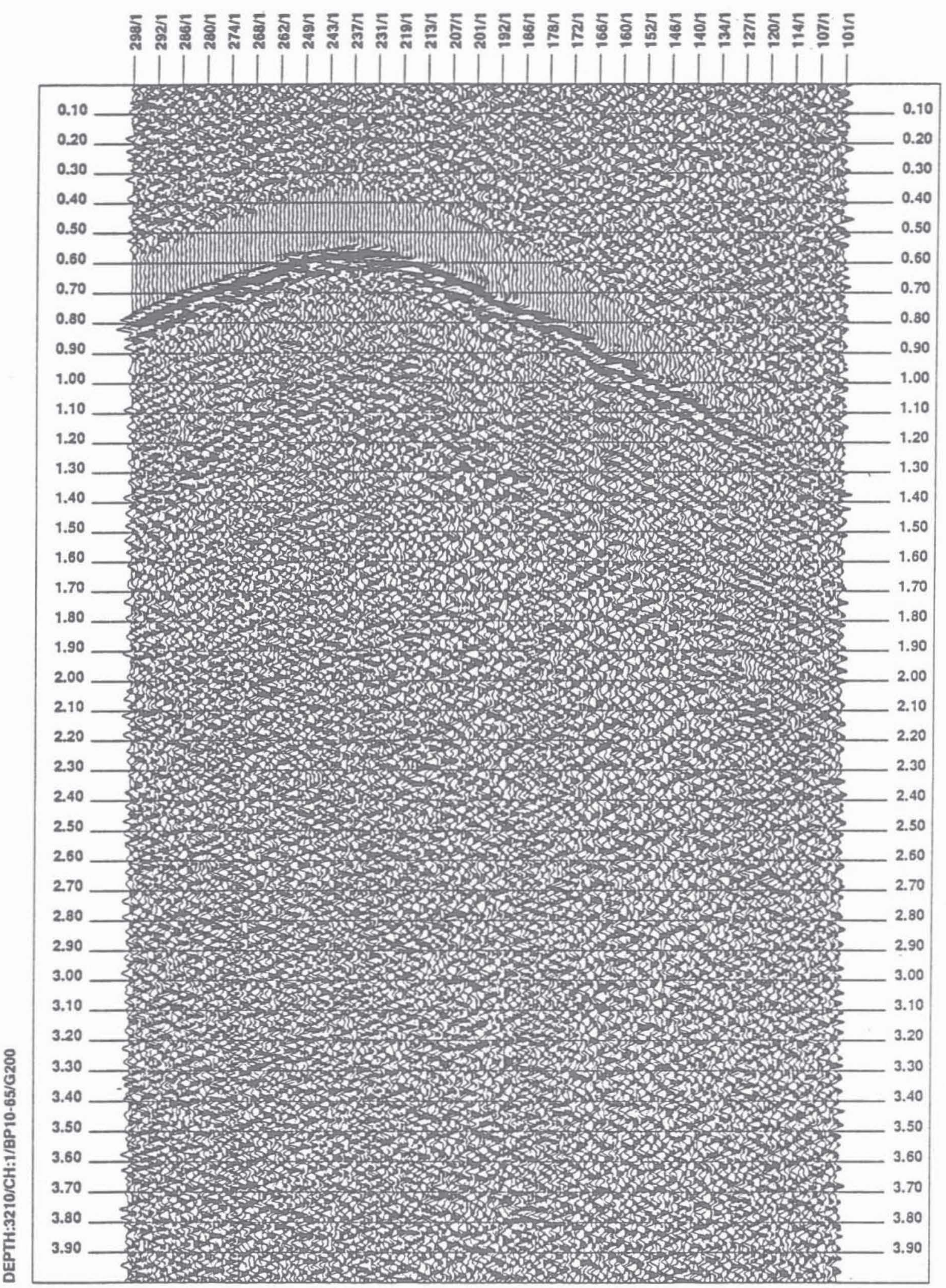


Fig. 5a Raw data from depth position 3210 m.
(Z-Component)

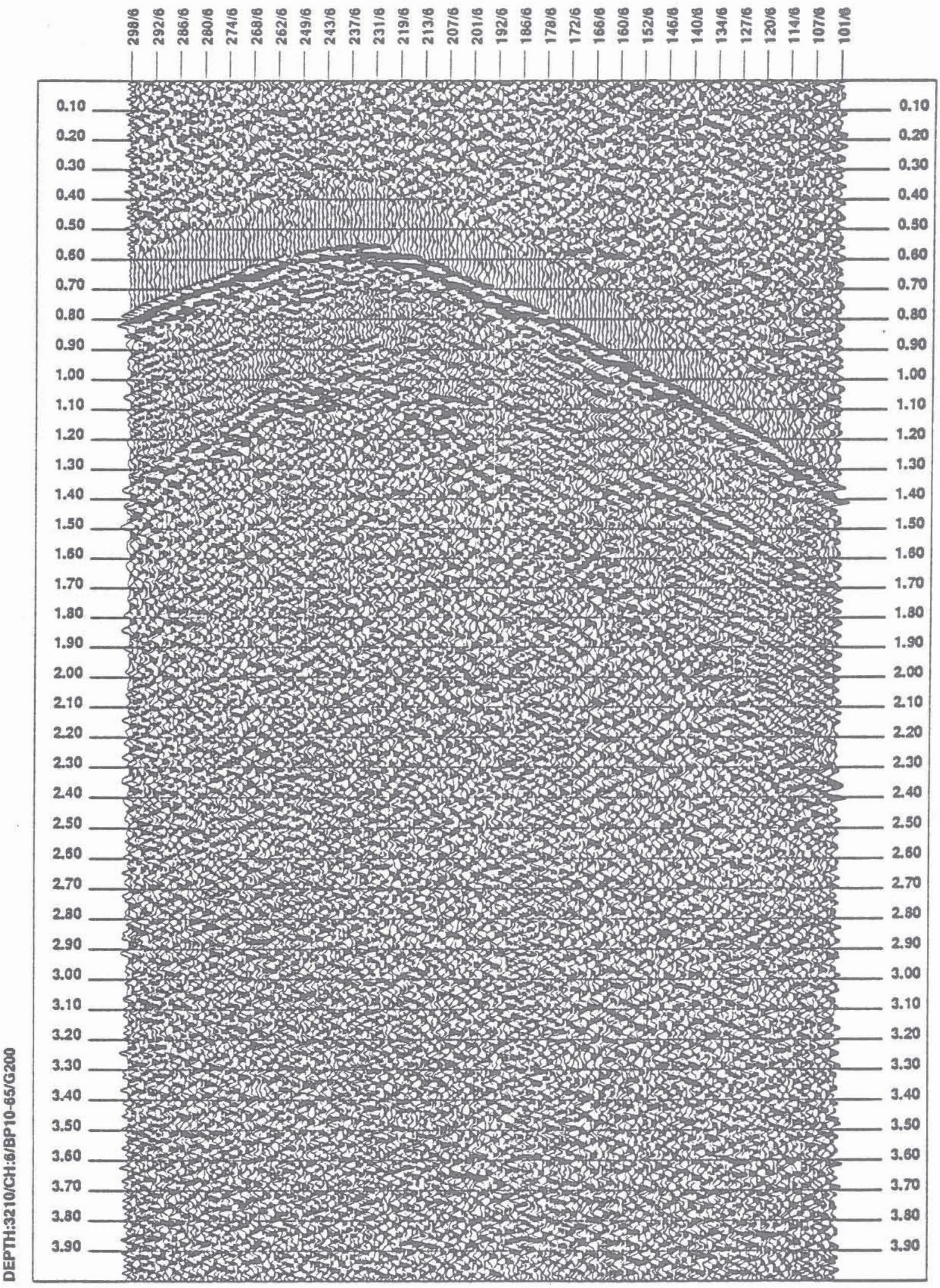


Fig. 5b Raw data from depth position 3210 m.
(H1-Component)

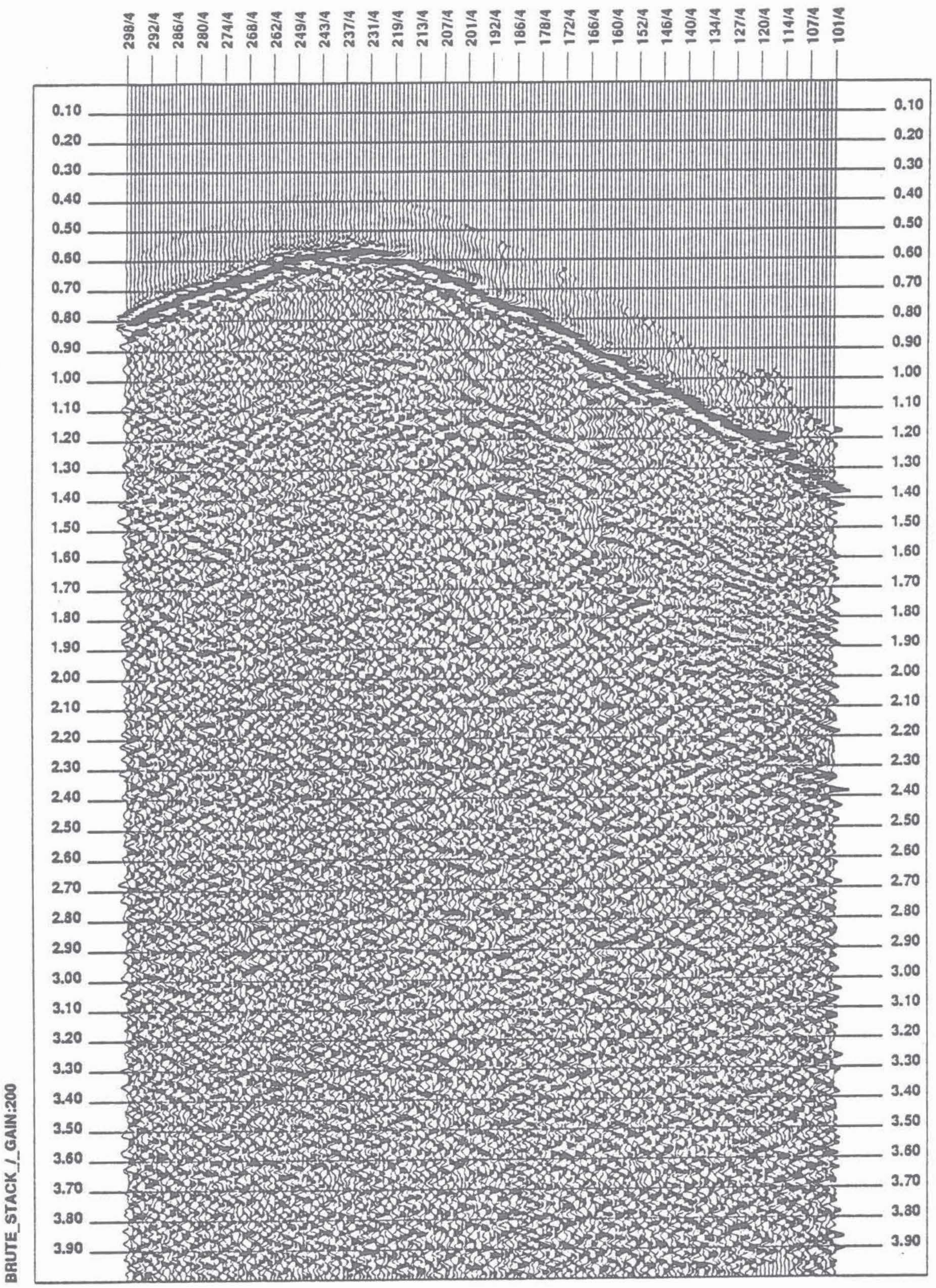
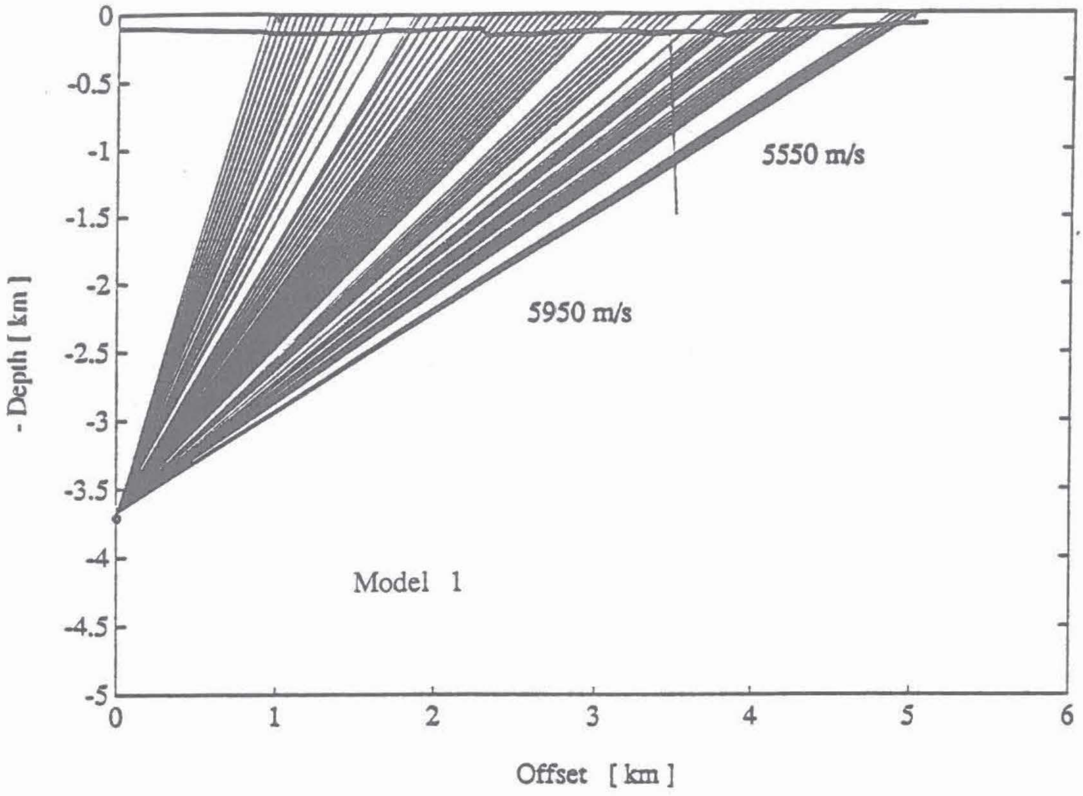


Fig. 6 Brute Stack, obtained by stacking all 20 MSP's after time correction for geophon spacing.



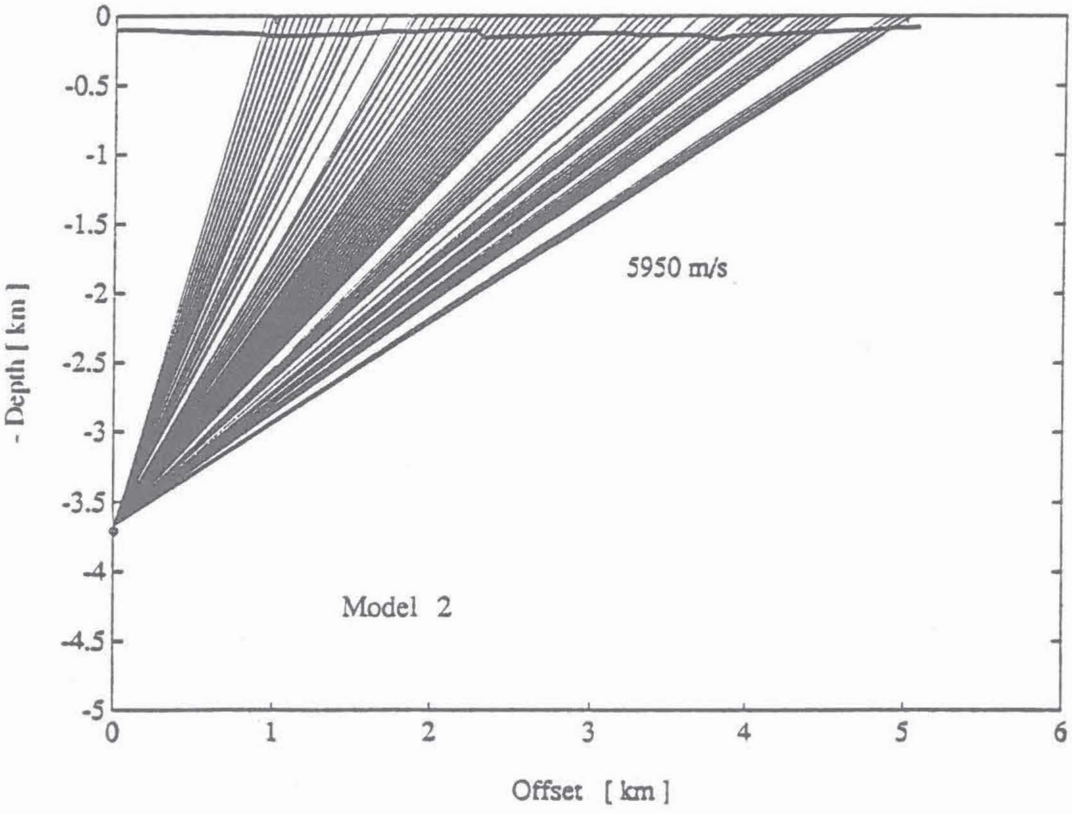


Fig. 7 Models used for first-break analysis. See text for further comments.

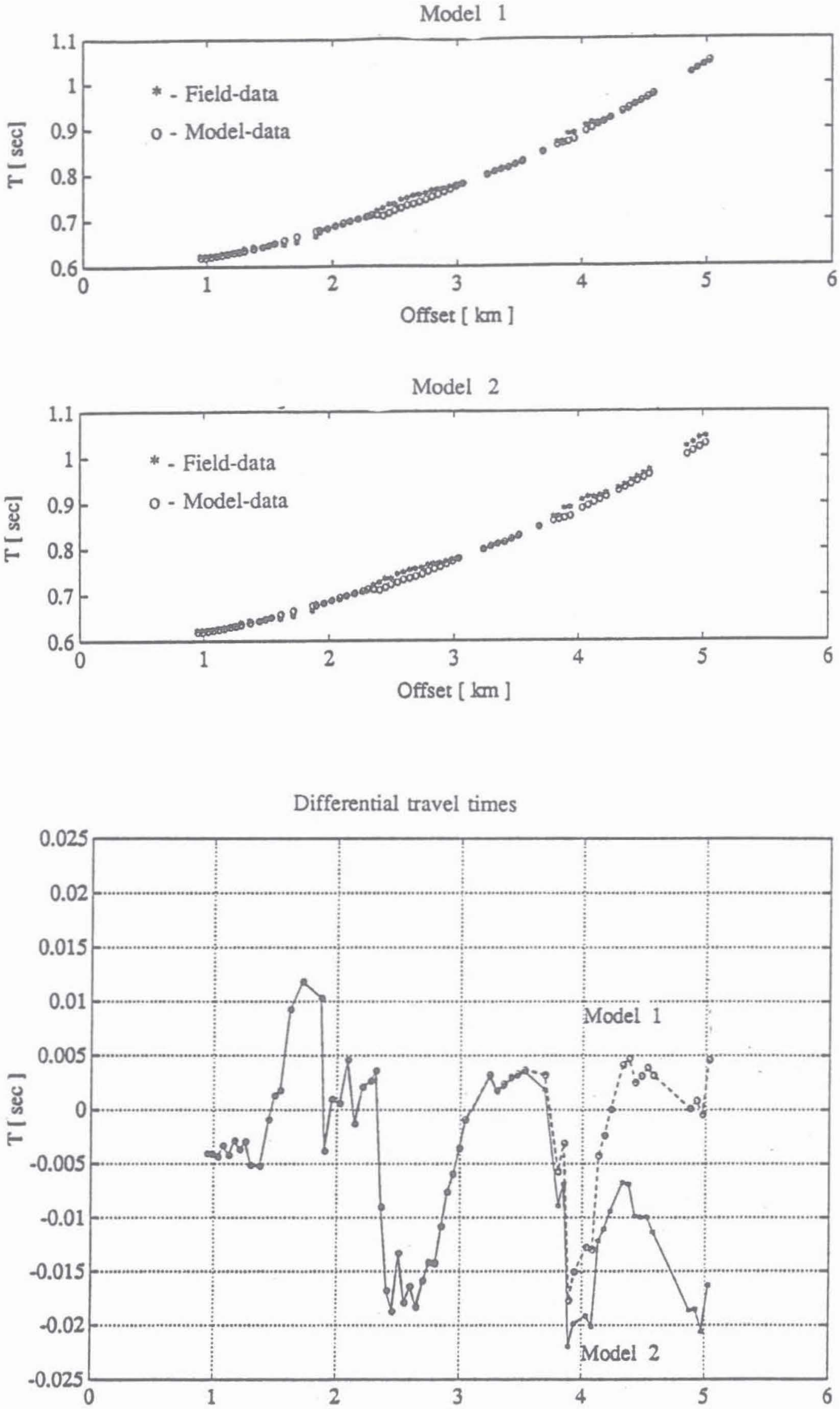


Fig. 8 Results of first-break analysis. See text for further comments.

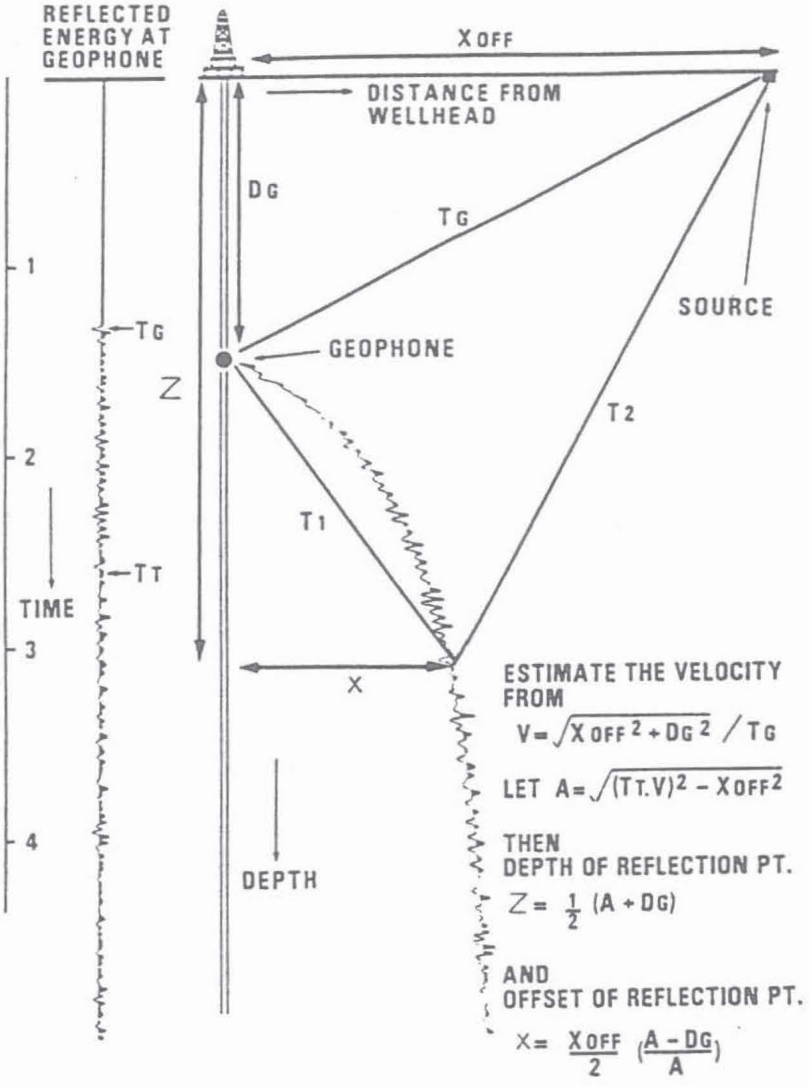


Fig. 9 Principle of MSP-CDP transformation. Every sample is shifted according to the formulas above.

CDP-TRANSFORMATION AND STACK

H1-COMPONENT 3210 M - 3435 M FOLD 10

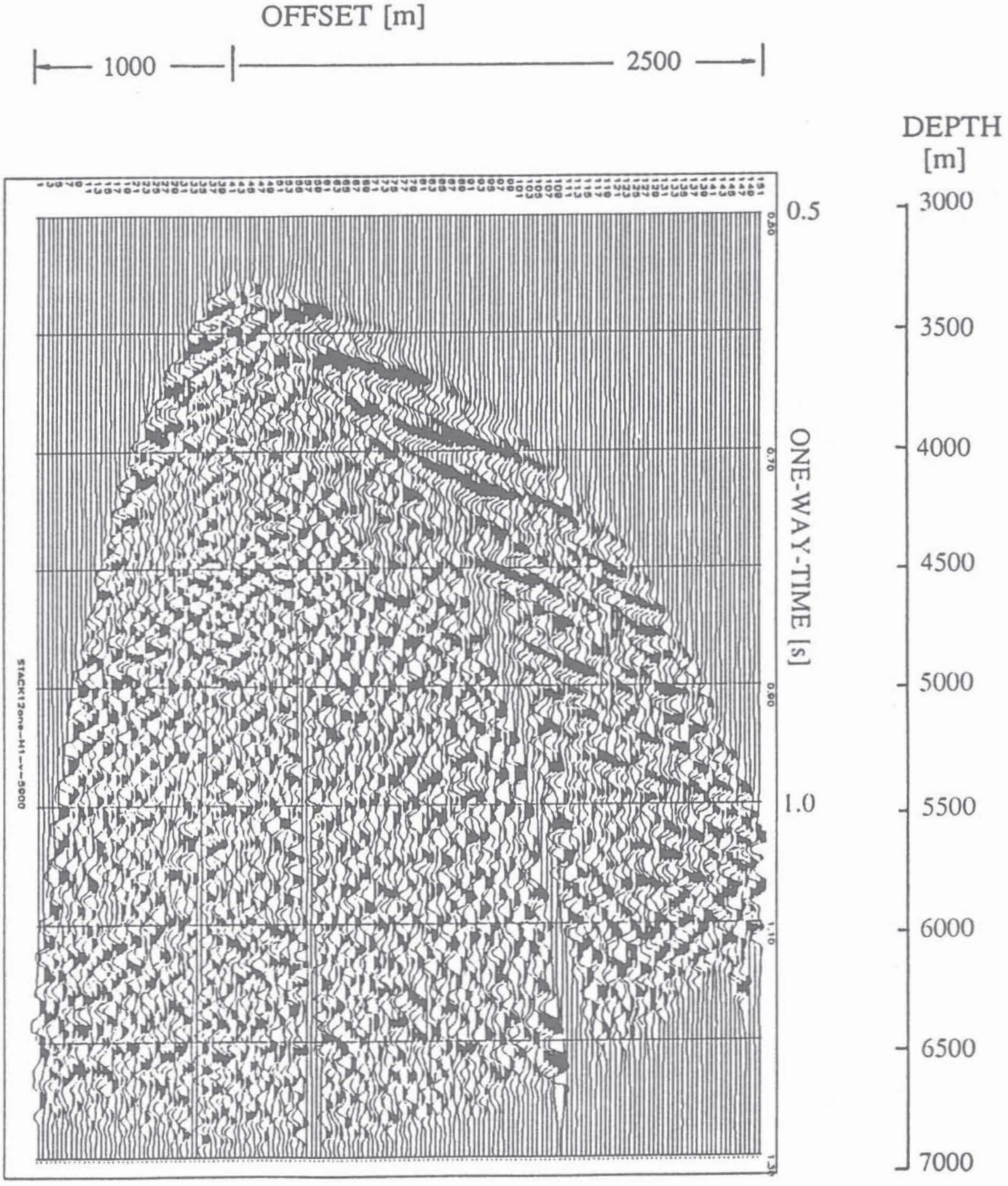


Fig. 11 Result of stacked CDP transformations. (H1-Component).

CDP-TRANSFORMATION AND STACK

Z-COMPONENT 3210 M - 3435 M FOLD 10

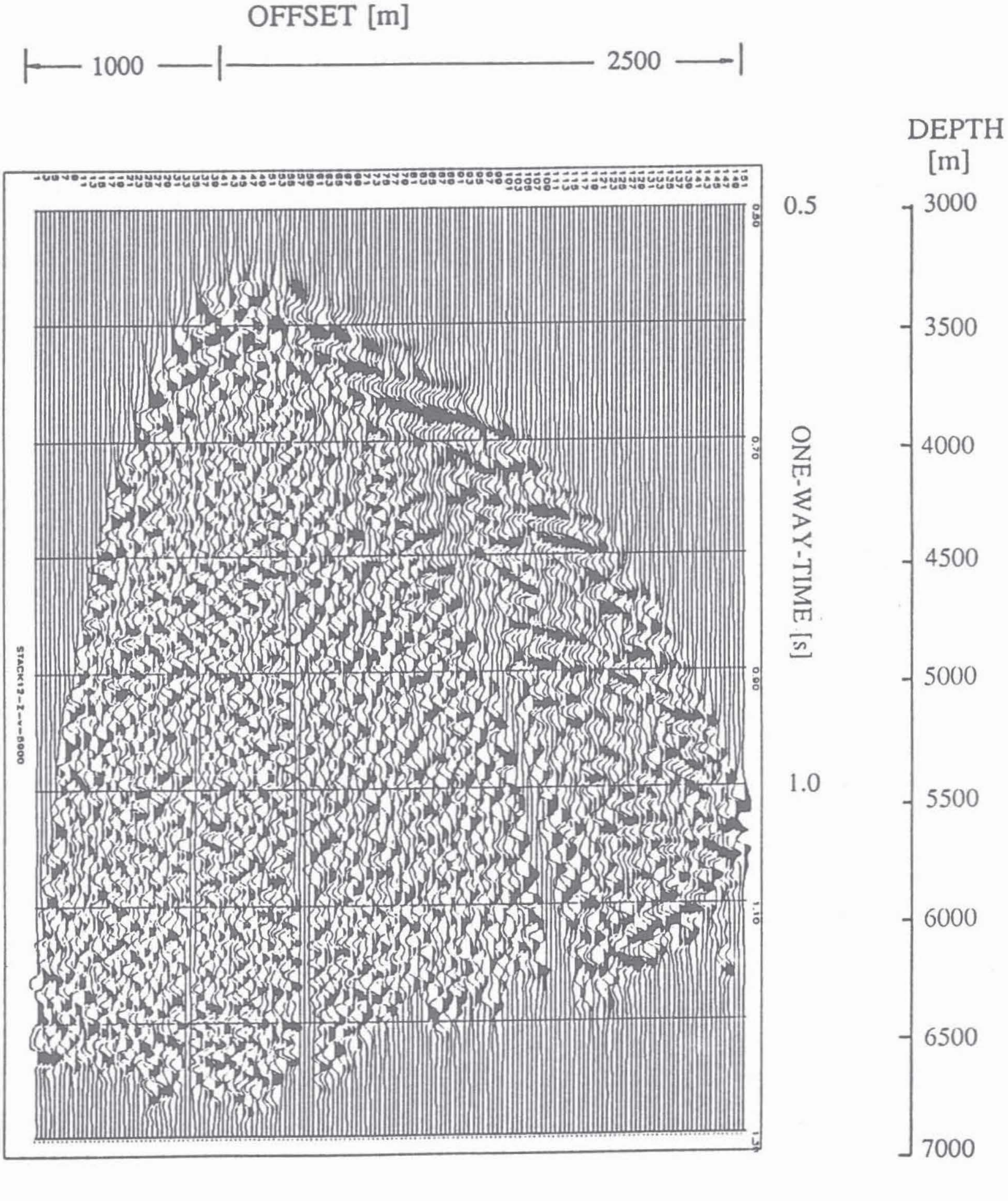


Fig. 10 Result of stacked CDP transformations. (Z-Component).

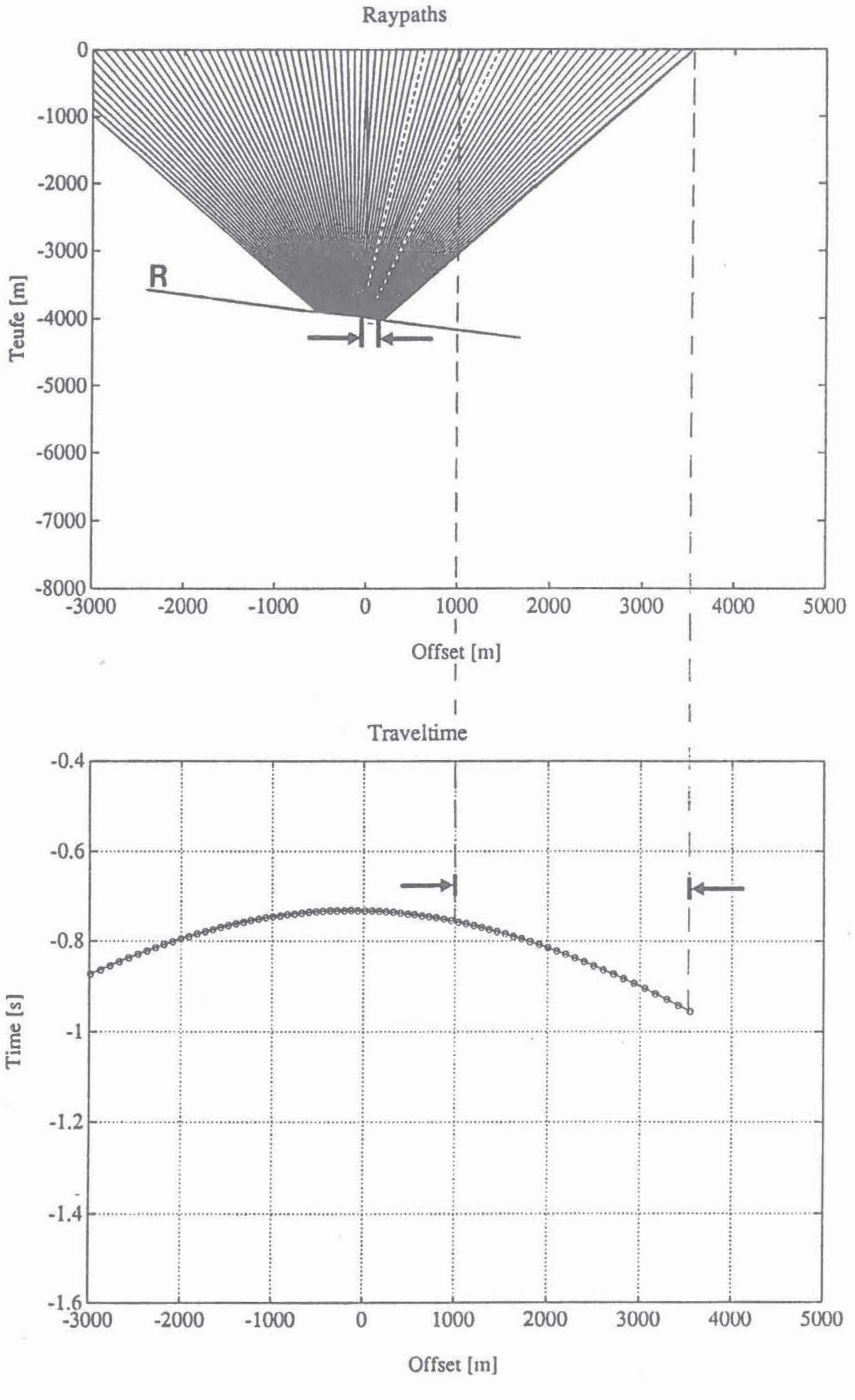


Fig. 12 Illumination of subsurface according to source offset.