From seismic surface measurements to pseudo VSP data : a new tool in 3-D seismic interpretation

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Summary

The method of pseudo VSP generation is a method for transforming the seismic surface data into Vertical Seismic Profiles (VSP) in a numerical way. The main objective of this paper is to present some examples of the pseudo VSP method and its value in interpretation aspects on *3-D* seismic data using *3-D* wave field extrapolation operators. It is shown that the pseudo VSP allows insight and recognition of waves propagating through a 3-D subsurface.

Introduction

VSP has been generally accepted as an important tool for the calibration of seismic surface data processing and for the improvement of geological interpretation in the direct vicinity of the borehole. The technique of pseudo VSP generation transforms surface data into pseudo VSP data (Alá'i and Wapenaar, 1994a). This technique requires the source properties, high quality shot records and a macro description of the subsurface. The pseudo VSP generation method has proven to be an additional tool to improve the interpretation of seismic data by adding a depth dimension to it (Alá'i and Wapenaar, 1994b). The technique is based on downward wave field extrapolation from the surface into the subsurface. An advantage of this method is that the generation of pseudo VSP data before drilling may initiate entirely new processing techniques (indirect application of VSP inversion technology on surface data prior to migration, like identification, separation of up- and downgoing *P*- and *S*-waves, interpolation etc. by means of multidimensional wave field transformations combined with k-ω, p-ω and p-τ filtering). For wave field transformations of vertical seismic profiles we refer to Hu and McMechan (1987). A more practical aspect of our method is that pseudo VSP data can be obtained without *tube noise*, which is probably the strongest coherent noise generally contaminating real VSP data. The operators used in wave field extrapolation are based on the one-way and two-way wave equations. In the one-way methods the total wave field is decomposed into up- and downward traveling wave fields which are handled separately. Furthermore they ignore mode conversions and internal multiple reflections. However, in the use of two-way operators the upgoing and downgoing wave modes are extrapolated simultaneously and the boundary conditions are automatically fulfilled at interfaces. Details on the different operators can be found in Berkhout (1985) and Wapenaar and Berkhout (1989). One of the aims is to generate pseudo VSP data for deviated and horizontal well configurations and laterally positioned where well information is not available.

For the quality of the generated pseudo VSP data it is essential to have a description of the propagation properties of the subsurface. Berkhout and Rietveld (1994) illustrated a method for macro model estimation based on controlled illumination. They show how different illuminating wave fields can encounter different errors in the macro model. The macro model estimation and verification is based on the generation of Common Focus Point (CFP) gathers from the prestack shot records using synthesis operators for focus point illumination. An initial synthesis operator is necessary to construct a CFP gather from all available shot records. The synthesis operator is chosen in order to position a focus point somewhere in depth. The focus point can then be seen as a secondary source. For an extensive discussion regarding the construction of CFP gathers and macro model estimation and verification see Berkhout and Rietveld (1994). The generation of a CFP gather for focus points in a potential well, is equal to a variant of the VSP, called Reverse Vertical Seismic Profile (RVSP). For a RVSP experiment the source is located in the borehole and the geophones are located on the surface. The application of the CFP gathers in relation with the pseudo VSP generation with wave field extrapolation operators is summarized in Table 1.

***Table 1:** The use of different methods in the generation of pseudo VSP data.*

Method	Configuration
Pseudo VSP data generation from a common shot gather	*Wave field extrapolation operator* used to extrapolate detectors at the surface to detectors in depth
Pseudo RVSP data generation from a common receiver gather	*Synthesis operator* used for common focus point illumination : CFP gather (secondary source)

In this paper some examples will be presented on the pseudo VSP generation from a 3-D marine dataset measured through physical modeling in our watertank measurement facility. 3-D wave field extrapolation operators are used in these examples which are based on the one-way wave equation (see Figure 1). The 3-D wave field extrapolation is done by a recursive x,y,ω extrapolation algorithm.

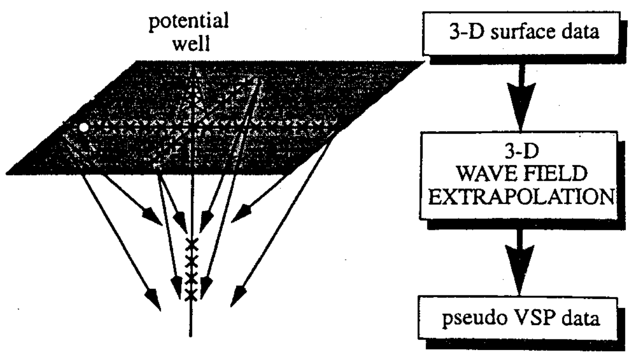

Fig. 1 *Pseudo VSP generation from 3-D surface seismic measurements (3-D wave field extrapolation).*

Example on a 3-D marine watertank dataset

In this section some results will be presented on pseudo VSP data generation using 3-D extrapolation operators applied on a 3-D marine dataset measured in our watertank over a physical scale model. For a description of the watertank facility see Koek et al. (1995).
The shot records are acquired by measuring the different hydrophone stations one by one. The source is repeatable and therefore any acquisition geometry can be obtained in this way. The level of the marine acquisition is *set to* z=0m. Figure 2 shows the physical 3-D model that is used for the 3-D data acquisition. The faults in the structure are crossed under an azimuth angle of 45 degrees. This has been designed to include some 3-D effects. The materials in the scale model are mainly rubber like materials and do not support any shear waves. Their physical properties are listed in Table 2.

Table 2: The materials used in the watertank model.

Layer no.	Material	Velocity [m/s]	Density [kg/m^3]
1	water	1487	1000
2	silgel	1018	959
3	beewax	2190	1035
4	silgel	1018	959
5	devcon	1510	1070

The data was recorded, using parallel shot lines with an in-line sampling (North-South direction) of 20m and a cross-line sampling (East-West direction) of 60m. The positioning will be referenced via their East-West (EW) and North-South (NS) location on the model. The configuration for the data acquisition in the watertank is summarized in Table 3.

Table 3: The shooting geometry of the watertank data.

geometry	7 streamer marine data acquisition
scale	1 : 20000
nearest offset	100 m
far offset	2560 m
number of shots	250
shot spacing	20 m
number of detectors per streamer	120 detectors in-line detector spacing : 20 m cross-line detector spacing : 60 m
registration time	2460 ms
time sampling interval	4 ms
number of time samples	616

Hydrophones were used with 7 parallel streamers (with in-line sampling of 20m and cross-line sampling of 60m), centered behind the source position (see Figure 2a). Figure 2b shows some vertical cross sections, to get a better view on the faults and domes of the 3-D model. We have used one shot record to generate pseudo VSP data, the well being located at the nearest offset of the middle streamer. The well position for the pseudo VSP generation is illustrated in Figure 2 (NS3160, EW3680). Furthermore in Figure 2b two slices are shown to get an idea about the model around the well. Figure 3 (top) shows the 4th streamer registration on line EW3680 of the total shot record measured in the watertank and the pseudo VSP generation from the total 7 streamer shot record (Figure 3, bottom). The seismic data was recorded without surface-related multiples. The data is displayed in this integrated way to have a better interpretation of the data in the different dimensions. Note that the registration time for the data is larger than shown here. The pseudo VSP data has been muted before the direct source wave field. For the generation of the pseudo VSP data, 3-D wave field extrapolation operators have been used which are based on the one-way wave equation. For a discussion on 3-D extrapolation operators and their applications in 3-D migration the reader is referred to Thorbecke and Berkhout (1994).

Note that in this case, all the 2-D cross sections of the 3-D model through the well can be used for the interpretation of the data. Figure 4 illustrates the relation between the 3-D shot record, near offset section, 2-D zero-offset migration and 3-D pseudo VSP generation (Figure 4a, b, c and d resp.). The 100m near-offset section is depicted in Figure 4b (after time-gain filter and NMO). As noticed the pseudo VSP data is not directly integrated to the shot record, but via the near offset section and the zero-offset migration. Following events through these paths gives a clear view on the propagation of the waves through the 3-D watertank model. The intersections are mapped correctly to their reflector depth except 2 events causing an intersection with the downgoing source wave field. The events, indicated by I and II should not intersect the downgoing source wave field, because both events are internal multiples (see raypaths in Figure 4d). Due to high contrast between the adjacent layers, the data contains internal multiples. The primary reflections are numbered in Figure 4c (α to δ). In the one-way wave field extrapolation scheme, the boundary conditions are not fulfilled at the reflector. Therefore these events are extrapolated below the reflecting interface and cause an intersection with the downgoing source wave field. However, in the use of two-way wave field extrapolation operators the internal multiples are handled correctly, because in the two-way schemes the boundary conditions are automatically fulfilled if a correct macro model is used. These internal multiples which are not removed from the data, appear at some depth levels in the migrated section. The 2-D zero-offset migration (Figure 4c) contains some 3-D effects (indicated by the grey arrows; crossing of faults under azimuth angle).

An important thing to note in the pseudo VSP data display is that all event appearing or disappearing at certain depth levels are 3-D effects.

Next some results are presented in which a line source response is constructed from the prestack data (a so-called *areal* shot record) and used as input to the pseudo VSP generation method. The geometry for this experiment is depicted in Figure 5a. Note the position of the pseudo VSP data (on a fault). Due to the 3-D structure of the model it can occur that the major contribution of the reflections are out of plane reflections. In this experiment the pseudo VSP is generated on two different lateral positions to show its value in the interpretation and showing the propagation paths of the waves in time and depth.

Figure 5b shows the registration of the 4th of 7 streamers of the constructed areal shot record, 3-D pseudo VSP, 2-D zero-offset migrated section and the velocity model. It can be clearly seen in the generated pseudo VSP that the amplitude of the first event decreases in arriving at the first reflector depth. This is because the main contribution of this reflection comes from a position away from the well (an out-of-plane reflection; see also Figure 5a). The faults in the structure are crossed under an azimuth angle of 45 degrees.

Secondly the 3-D pseudo VSP is generated on a lateral position crossing the top of the dome. The result is displayed in Figure 5c. Note that in this pseudo VSP the first primary does not show any amplitude decrease because here we do not have the 3-D effects on crossing the dome. The intersections are mapped correctly except for the internal multiples.

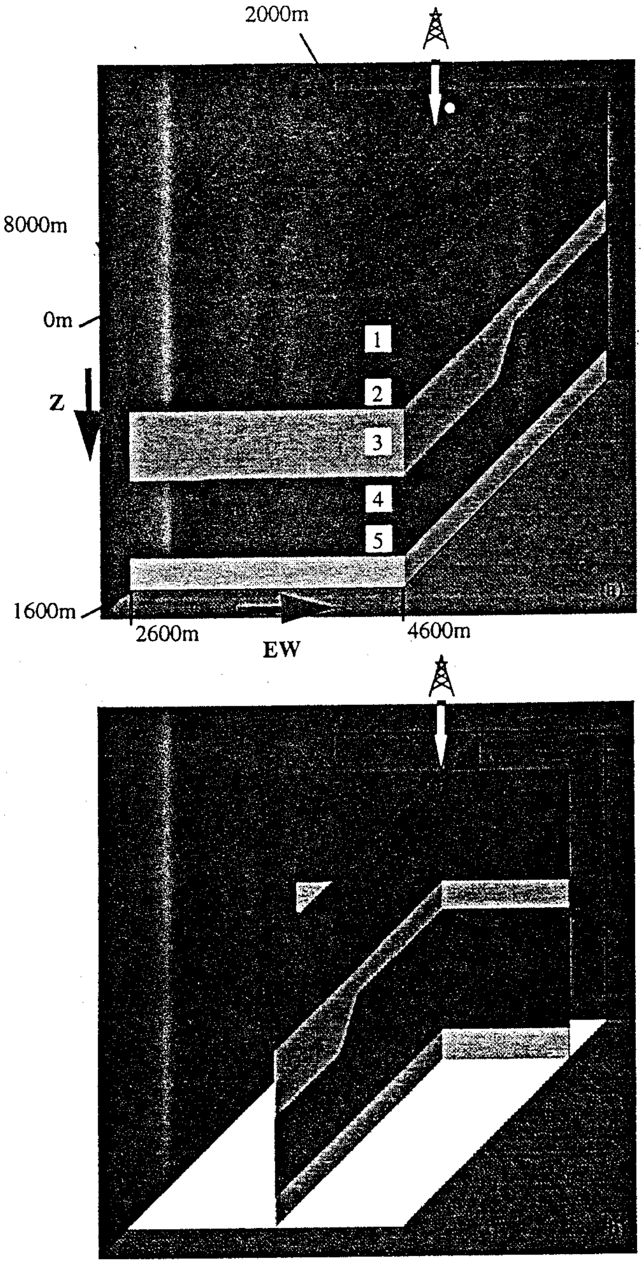

Fig. 2 The watertank 3-D subsurface model.

The propagation path for the waves propagating through the model are displayed in the pseudo VSP (black arrows). The internal multiples are not handled correctly and cause an intersection with the downgoing source wave field. These intersections for the internal multiples appear also in the migrated section (see arrows for 2 particular internal multiple reflections).

Discussions and Conclusions

We presented the successful application of the pseudo VSP generation on 3-D data using 3-D one-way wave field extrapolation operators. It is shown that the generation of pseudo VSP data allows insight in the entire wave propagation problem since it shows the response to the source pulse at any depth point in the subsurface. The advantage of this type of response is that it improves the understanding of the different events in complex shot records by creating a unique relation of these events with the depth dimension. In the future we want to combine the concept of 3-D areal shot record migration (Rietveld, 1995) with the pseudo VSP generation, by generating VSPs at several lateral positions and for different borehole/detector configurations (e.g. deviated or horizontal well types) during the depth migration. In this way we expect to get a significantly better interpretation of the events visible in the areal shot record and their positioning in the 3-D depth image (new interpretation technique). This integration with the migrated section gives insight in the migrated section and shows its value in interpretation. In the 3-D case multiple 2-D migrated sections through the chosen well position can be chosen to show the integration with the 3-D pseudo VSP allowing a better interpretation in 3-D structures of the subsurface. The events in the pseudo VSP can appear or disappear at certain depth levels due to the influence of 3-D structures on wave propagation. We think that the pseudo VSP generation project may open a new way of 3-D data acquisition, data processing, migration and interpretation. It is expected that the inherent *simplicity* of pseudo VSP will allow a more detailed interpretation of lateral variations in the reservoir.

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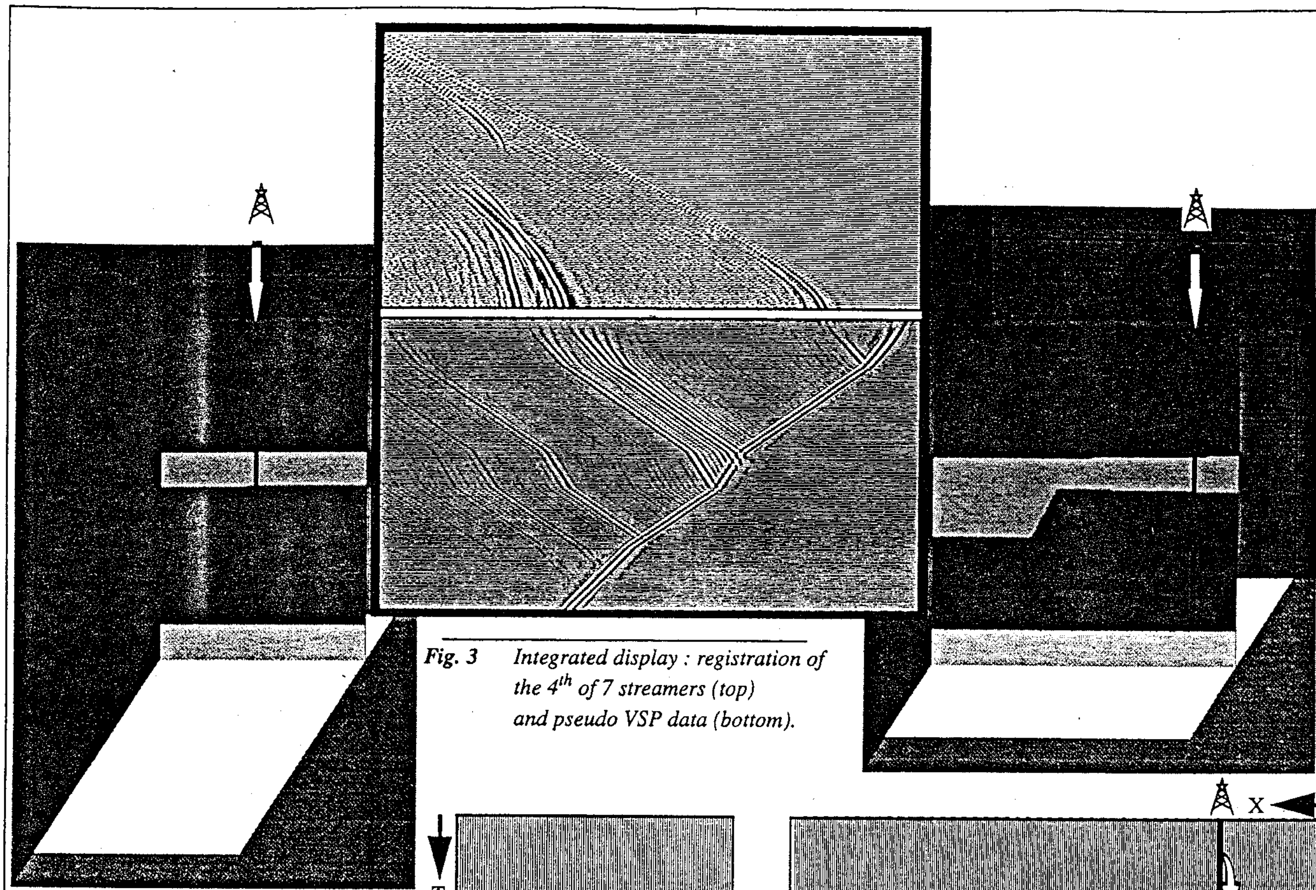


Fig. 3 *Integrated display : registration of the 4th of 7 streamers (top) and pseudo VSP data (bottom).*

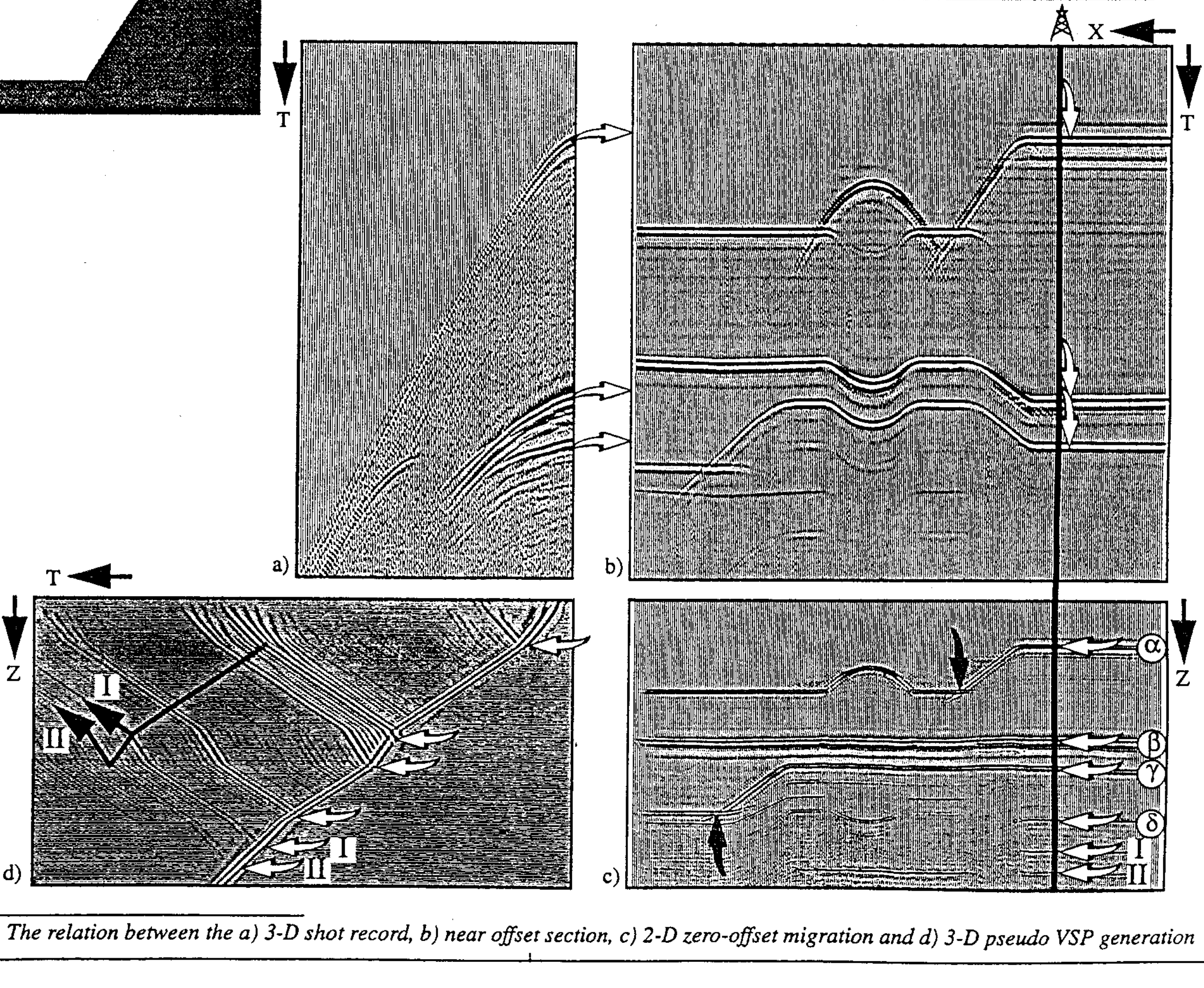
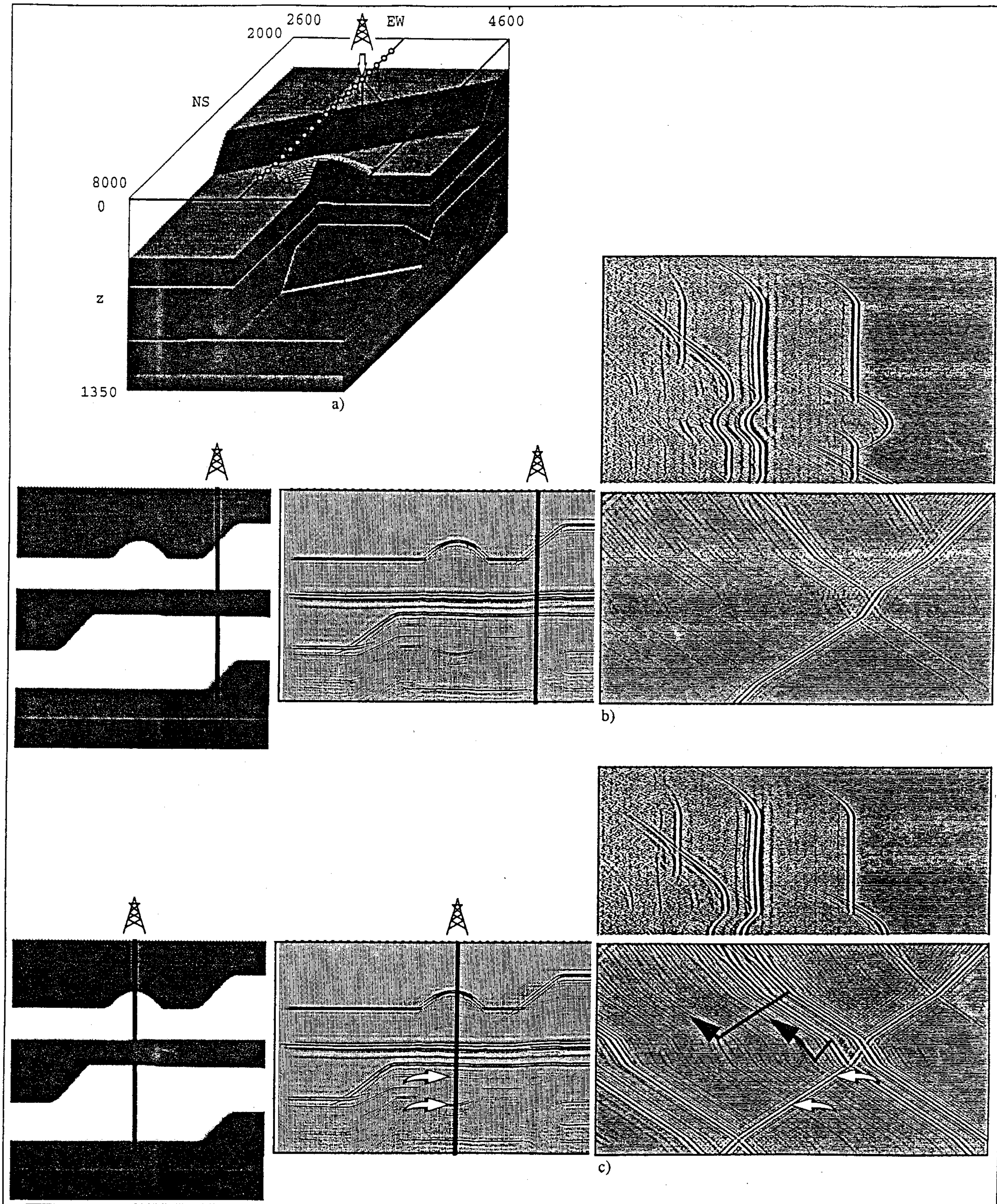


Fig. 4 *The relation between the a) 3-D shot record, b) near offset section, c) 2-D zero-offset migration and d) 3-D pseudo VSP generation*



a)

b)

c)

Fig. 5 *Pseudo VSP generated at 2 different lateral positions from the areal shot records using 3-D wave field extrapolation operators. The areal shot records are displayed only up to the well position.*