Pseudo VSP's : A 3-D case study

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Summary

In this paper, the generation of 3-D pseudo VSP data is discussed and illustrated on a dataset. We start with a 3-D shot record *(x,y,z_0,t)*. This shot record has been transformed to a pseudo VSP dataset *(x_0,y_0,z,t)*. The result is compared with a modeled VSP and integrated in combination with the slices from the 3-O migrated volume *(x,y,z)* of data. In combination, the integration of different datasets yields a better insight and understanding of the wave propagation and the various events originating from the complex subsurface model. Some 3-D snapshots are shown to improve the data interpretation, further showing the wave propagation at different times.

Introduction

The method of 3-O pseudo VSP generation from surface data (Ala'i et al., 1995), as shown in this paper is based on the recursive acoustic one-way wave field extrapolation schemes that are aimed at removing propagation effects and thus improving the interpretability of seismic data. In other words, the method that has been used in this paper, results in seismic data as if they were measured in the subsurface instead of measurements recorded at the earth's surface. The total wave field at the surface (3-O shot record *(x,y,z_0,t)*) is decomposed into down- and upgoing wave fields. These wave fields are extrapolated separately and at each depth level, the wave field is extracted for a predefined borehole/detector configuration *(x_0,y_0,z)*, where x_0 and y_0 may be functions of z in case of deviated boreholes. The 3-O wave field extrapolation operators can be formulated in terms of forward extrapolation of the downgoing (source) wave field and inverse extrapolation of the upgoing *(rejected)* wave field. In the wavenumber frequency domain, the monochromatic wave field extrapolation from depth level z_{m-1} to z_m is given by the following expression :

$$\begin{pmatrix}\tilde{P}^+\\ \tilde{P}^-\end{pmatrix}_{z_m} = \begin{pmatrix}\tilde{W}(z_m,z_{m-1}) & 0\\ 0 & [\tilde{W}(z_m,z_{m-1})]^*\end{pmatrix}\begin{pmatrix}\tilde{P}^+\\ \tilde{P}^-\end{pmatrix}_{z_{m-1}}$$

where the asterisk * denotes the complex conjugate. $\tilde{W}$ is called the forward wave field extrapolation operator :

$$\tilde{W}(k_x,k_y,\omega,\Delta z) = exp\left(-j\sqrt{\frac{\omega^2}{c^2}-\left(k_x^2+k_y^2\right)}\,\Delta z\right)$$

with $\Delta z = z_m - z_{m-1}$ .These operators have been transformed to space-frequency domain in an optimized way (Thorbecke and Berkhout, 1994) such that spatial 2-O convolutions can be performed along the x- and y-coordinate, which can be easily generalized to accommodate lateral velocity variations. At each depth level the downgoing and upgoing wave fields are selected at x_0,y_0, thus building up the pseudo VSP step by step.

Numerical Results

In this paper the pseudo VSP method is illustrated by applying it to a 3-O dataset generated using a 3-O visco-elastic finite-difference algorithm (Robertsson et al., 1994).

The model contains three layers where the uppermost layer is a water layer on top of an irregular layer and a dipping plane. Absorbing boundaries have been applied around the entire model. In Fig. 1 the volume of the 3-D model is depicted (3 axes x.y.z are indicated). The dimensions of the model are x_{max}=1000m, y_{max} =500m and z_{max} 800m including a 50m = wide absorbing frame around the cube (see fig. 2a; note that the absorbing frame around the model is not shown). The distance between the gridpoints is 5m in all directions. Notice that the model as depicted in Fig. 1 and 2 is displayed with a coarser grid than 5m. Fig. 2b shows the model with the uppermost water layer removed.

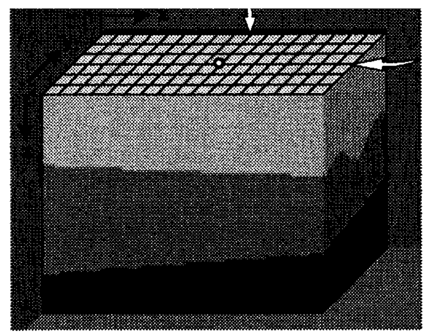


***Fig. 1** Geometry of 3-D model.*

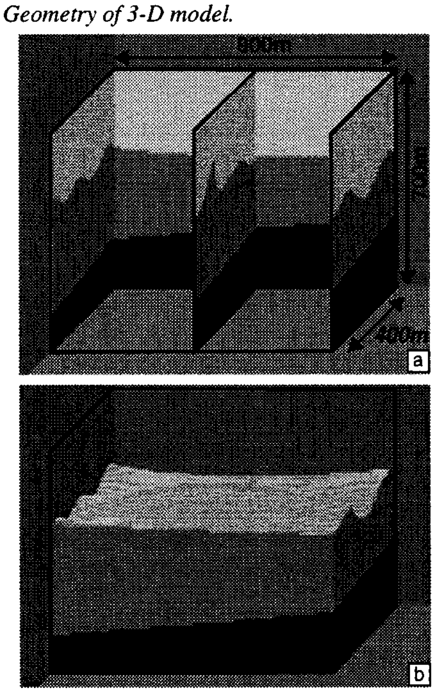


Fig. 2 a)Some slices through model (and dimensions) and b)model after removal of the uppermost water layer:

From this figure the irregular structure of the water bottom can be seen.
A 3-D shot record was modeled using a 3-D finite difference algorithm (Robertsson et al., 1994) with a monopole source located just below the center of the surface : $x=500m, y=250m$ and z=55m (a Ricker wavelet with a central frequency of 25Hz was used). The receivers of the 3-D shot record were placed over the entire (x,y) plane at depth level z=55m (see Fig. 1 for the geometry of the receivers and the source location). The sampling rate in the data is 2.5ms. The elastic material properties of the model are given in Table 1.

Table 1: Material properties of the model.

layer	c_p [m/s]	c_s [m/s]	ρ [kg/m^3]
1	1500	0	1000
2	2000	0	1300
3	3000	1200	1500

The third layer of the model contains a compressional and a shear wave velocity whereas the layers above are acoustic. Q values of 10,000 for both P- and S-waves were used in the viscoelastic finite-difference simulations to obtain a perfectly acoustic/elastic response.

Fig. 3 gives a 3-D view of the interfaces of the model. The black line represents the well location.
Fig. 4a illustrates two vertical sections (x- and y-direction) through the model at the well location. From the slice along the y-axis it can be easily seen that some energy will be diffracted due to the structure. At the well location the 2 slices along respectively the x-coordinate and the y-coordinate are shown in Fig. 5a and b. The corresponding 2-D slices from the 3-D shot record are illustrated in Fig. 5c and d. The black line in the figures represents the well location.

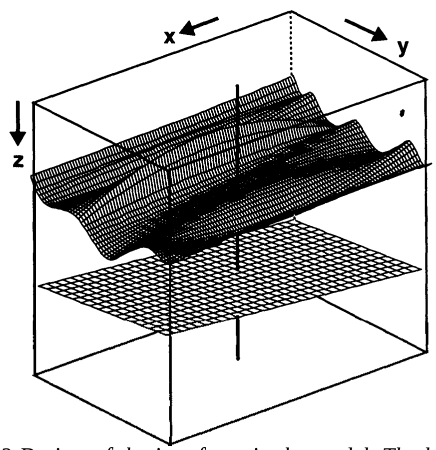


Fig. 3 3-D view of the interfaces in the model. The black line represents the well location.

The numbers 1 and 2 refer respectively to layer boundaries 1 and 2. The events corresponding to these layers have been labeled in the shot record. As can be noticed in Fig. 5b, the structure indicated with number 3 acts as a diffraction point and its corresponding event is indicated with number 3 in the shot record along the x and y-coordinate (Fig. 5c and d).

Event 3 arrives earlier at the surface than the reflections from layer boundary 1. The energy emitted by the diffraction point (along the y-coordinate) is also visible in the shot record (along x; *3-D* out of plane effect). At first glance, it is not obvious to identify the origins of the events indicated with A and B in Fig. 5c. However, a more careful study of the shot record in Fig. 5d shows that both these events are responses from other diffractions which occur in the model. The diffraction points are located one at the left and the other at the right of the model (along the y-coordinate).

The objective of this example was to generate a *3-D* pseudo VSP dataset from the *3-D* shot record and making comparisons with a modeled VSP.
To get a better understanding of the events visible in the shot record, a *3-D* VSP has been modeled in the *3-D* model with the source location chosen to be the same as that for the *3-D* shot record. The *3-D* VSP data is a zero-offset VSP (source at wellhead). The well is vertical and is located at the center of the model (location $x=5OOm$, $y=25Om$, $z=55m$ to z=750m, see also Fig. 3).

Fig. 6a and b illustrate an integrated display of the *2-D* slice from the *3-D* shot record along the y-coordinate and the *3-D* modeled VSP data for a better understanding of the various events.
The origin of event 3 is revealed in the *3-D* modeled VSP data. The diffractor starts emitting energy upward and downward at a depth above the first reflector (see indication in Fig. 6b).
A *3-D* pseudo VSP dataset has been generated from the *3-D* shot record using one-way wave field extrapolation operators. In the use of one-way operators the upgoing and downgoing waves are separately handled and boundary conditions are thus not taken into account at layer boundaries. The generated *3-D* pseudo VSP is displayed in Fig. 6c for making a comparison with the modeled VSP. The events prior to the direct wave have been zeroed. An event that is fully absent in the pseudo VSP is the event that is indicated with number 4. This event is a reflection from the boundary of the model (along the y direction).
Fig. 4b shows the same slices as in Fig. 4a (at the well location) but through the *3-D* migrated volume (1 shot). The *2-D* slices of the *3-D* shot record migration along the x and y-coordinate are also depicted in Fig. 6. (respectively Fig. 6d and e). Notice the integration of the generated *3-D* pseudo VSP data with the *2-D* slices of the *3-D* migrated volume (see black arrows). The *3-D* migration is done by a recursive x,y,ω algorithm (performed in the space frequency domain). The *3-D* wave field extrapolation operators used to extrapolate the wave field from the surface into the subsurface are based on the one-way wave equation.

To get a better understanding of the event numbered 4, some 3-D snapshots have been generated which are depicted in Fig. 7. Fig. 7a, b and c are different views of the snapshot at time $t=300ms$ and Fig. 7d shows the snapshot for time $t=600ms$. The event number 4 has been indicated in the snapshot of Fig. 7a. It is now clear that this originates from the boundary on the side of the model. The boundary reflections (y-direction) could have been made significantly weaker by a better choice of grid parameters in the finite-difference simulation. However, this was not the purpose of this investigation.

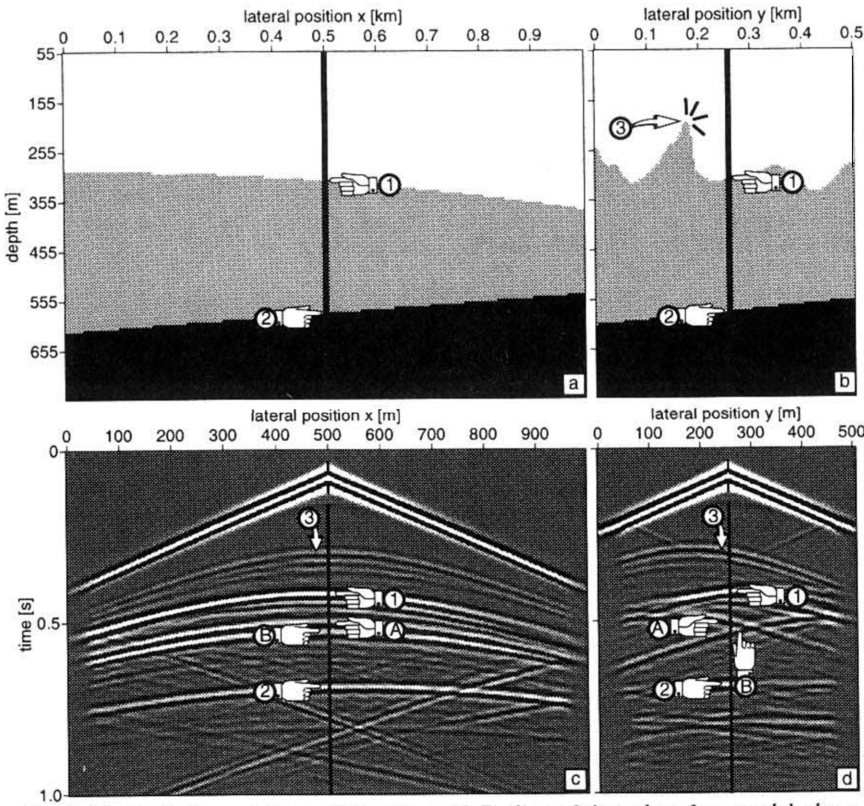


Fig. 5 Vertical slices at the well location a)2-D slice of the subsurface model along the x-coordinate and b)along the y-coordinate. c) 2-D slice from the 3-D shot record at the well, along x and d)2-D slice along y.

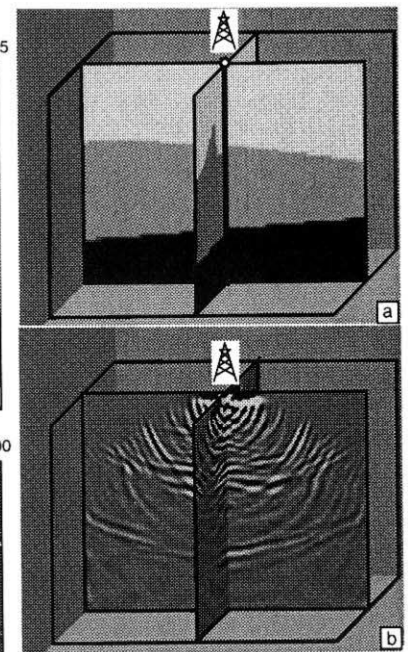
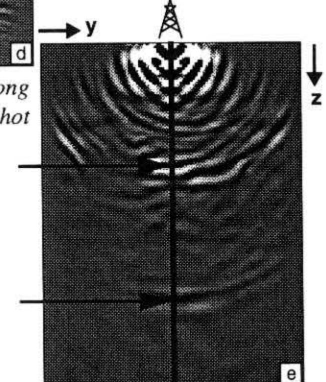


Fig. 4 Slices through model and migrated volume at the well.



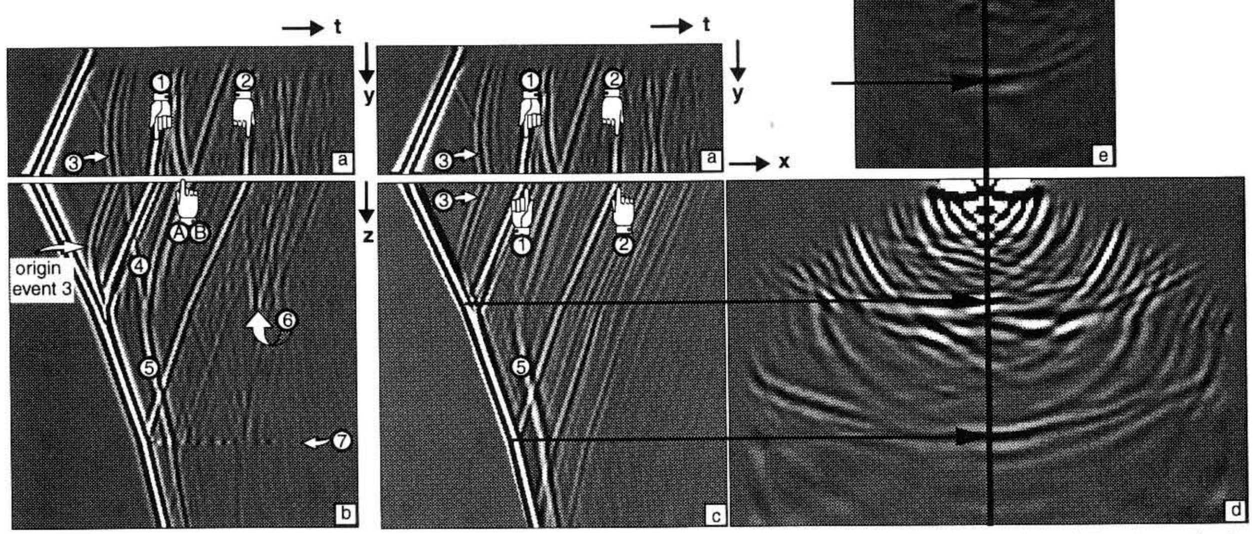


Fig. 6 a)2-D slice from 3-D shot record (along y), b)3-D modeled VSP, c)3-D pseudo VSP, d)2-D slice from 3-D migrated volume at well (along x-coordinate) and e)2-D slice from 3-D migrated volume at well (along y-coordinate); the black line indicates the location of the well.

Furthermore the primary reflection from the diffractor as discussed earlier is indicated in this snapshot with the number 3 (see also its correspondence with the event numbered 3 in Fig. *7c).*
The origin of the events labeled A and B in Fig. 6b, are diffractors starting emitting energy upward and downward. It is very interesting to see its correspondence with the pseudo VSP data in Fig. 6c. The event number 5 represents the downward propagation of the diffraction energy. Comparison of the modeled VSP and the pseudo VSP shows that the internal multiple events indicated in Fig. 6 with number 6 is absent in the pseudo VSP (Fig. 6c). This is because for the generation of the pseudo VSP data, one-way operators have been used which do not take any boundary conditions into account. Finally the event number 7 in the modeled VSP is visible because the 3rd layer contains also some shear energy. The event visible in Fig. 6b is a guided wave between the acoustic layer and the elastic layer (so-called Stoneley waves) generated at the roughness due to the discretization of the "flat" dipping plane (Fig. 3) (Dougherty and Stephen, 1988). This event is absent in the pseudo VSP because only acoustic waves are handled.

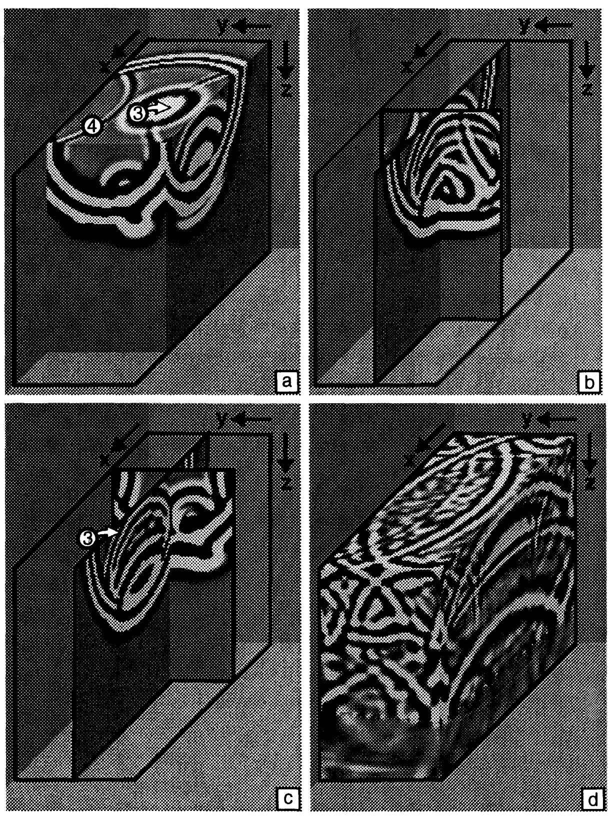


***Fig. 7** Various views and slices of 3-D snapshots: a) to c) snapshots at t=300ms and d)at t=600ms.*

Fig. 8 illustrates some slices of the *3-D* shot record at the same times as displayed for the *3-D* snapshots. The horizontal slices represent the time slices at respectively time *t=300ms* and time *t=600ms.* Note the correspondence with the snapshots at *z=55m* (source depth) of Fig. 7. The vertical slice in Fig. 8a represents the *2-D* slice from the *3-D* shot record along the y-coordinate (same as Fig. 5d).

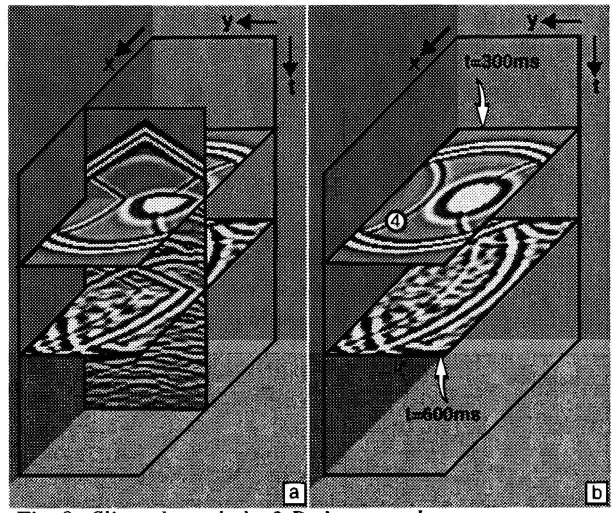


***Fig. 8** Slices through the 3-D shot record.*

Conclusions

In this paper we have demonstrated the generation of *3-D* pseudo VSP data from surface measurements. The data has been generated from a *3-D* shot record that was modeled in a *3-D* subsurface consisting of an irregular interface above a dipping layer. Different datasets have been integrated for a better understanding and interpretability of the seismic data. The pseudo VSP data has been compared with the VSP data that was modeled at zero offset (with respect to the shot location at the surface). The generation of the pseudo VSP showed the clear appearance of diffraction energy which was emitted in the model. The appearance of the diffraction energy was visible in the shot record and the VSP data. Finally, some *3-D* snapshots were shown as well, to illustrate the wave propagation through the model at various increasing times.

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