

## **PSEUDO VSP GENERATION FROM SURFACE MEASUREMENTS: A NEW TOOL FOR SEISMIC INTERPRETATION**

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### **ABSTRACT**

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The generation of pseudo VSP data from surface measurements opens a new way of understanding and interpreting seismic events. Many events which cannot be identified on seismic surface shot records are rendered easily identifiable through the transformation of surface data into VSP data by a numerical method. The generated pseudo VSP data contains the same information as the surface data but is presented in a different format. The presentation of the VSP data introduces a new dimension to looking at different events, giving an easier interpretation. This underlines the importance of data-reorganization. The comparison of the pseudo VSPs at different locations with the real VSP data will enable us to extend our geological knowledge in all lateral directions and will improve the interpretation of the subsurface model.

A comparison between forward VSP modeling and pseudo VSP generation is presented. A 3-D data volume representation offers an extra aid in the interpretation of various events in different cross sections (shot record, VSP and snapshots). The pseudo VSP generation algorithm is applied to the Marmousi dataset and the result is compared with the modeled VSP data. Finally the application of the pseudo VSP generation algorithm to field data is presented.

**KEY WORDS:** Pseudo VSP, interpretation, wave field extrapolation.

## INTRODUCTION

The ever-increasing costs of drilling have pushed geophysicists to come up with new techniques to reduce the number of malpositioned boreholes and to improve the field development planning.

Vertical Seismic Profiling (VSP) is one of the relatively new geophysical techniques responding to this demand for more successful planning. VSP adds a depth dimension and allows a more detailed seismic view of the subsurface. This offers the potential for better interpretation of the surface seismic data. Vertical seismic profiling has been accepted as a powerful tool to solve many uncertainties appearing in the surface seismic data around wells. For the last two decades a lot of research has been carried out in the field of real VSP and synthetic VSP modeling and their applications. Several authors (Kennett et al. (1980), Wyatt (1981), Balch et al. (1982), Hardage (1983), Balch and Lee (1984), Dillon and Thompson (1984), Fitch (1984), Cassell (1984), Aminzadeh and Mendel (1985), Oristaglio (1985), Stewart and DiSiena (1989)) showed the various advantages of VSP data over surface seismic measurements, around the borehole.

The major advantages of VSP over surface seismic data may be summarized as follows:

- 1) Identifying different wave types: primaries, multiples and P- and S-wave conversions.
- 2) Recording of both up- and downgoing waves at a sequence of depth levels, enabling us to observe reflected and transmitted wave fields through the geological section.
- 3) Separation of up- and downgoing waves, leading to better multiple recognition.
- 4) Because of the close proximity of the receivers to the target zone, the VSP data are generally characterized by a better S/N ratio and a higher resolution (compared with the equivalent surface seismics), offering a detailed seismic view of the subsurface. This increases the reliability of the geological interpretation.
- 5) Lithology can be correlated with the processed VSP data, permitting the prediction of lithologies ahead of the drill bit and around the borehole.

In short, the application of VSP proves to be a useful tool for better seismic interpretation. Considering the advantages of VSP, we propose a new method of VSP generation from surface data, the result being referred to as

*Pseudo VSP.* This method transforms surface data into pseudo VSP data by a numerical procedure (wave field extrapolation). The pseudo VSP generated with only a macro model (of the subsurface) contains all the details of the initial seismic data, but presented in a different format. Many events which cannot be easily identified on surface seismics can be better identified after this new transformation. When a real VSP is available our proposed method will improve the integration of surface data with real VSP data. The computation of pseudo VSPs at different locations, where well information is not available, will thus enable us to extend our geological knowledge in all lateral directions and will improve the interpretation of the subsurface model.

#### THEORY

In principle, downward extrapolation can be applied towards any subsurface point below the seismic detectors. A VSP dataset can thus be obtained by extrapolating the surface wave field (i.e., the shot record) to a range of detector positions in a potential borehole (see Fig. 1). Note that zero offset as well as non-zero offset VSPs can be obtained in this way. This technique of pseudo VSP generation requires high-quality seismic shot records, a description of the source properties and a macro model of the subsurface.

When the wave field is known at the surface, and the source is known and the wave field extrapolation is carried out correctly (correct macro model), then it is possible to reconstruct the wave field at all depths in the subsurface.

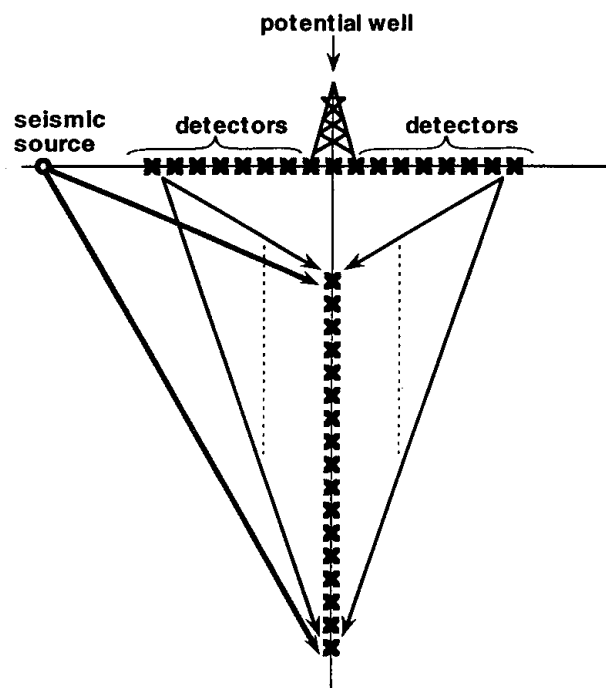


Fig. 1. Transformation of a seismic shot record into a VSP dataset by downward wave field extrapolation.

An important wave-field extrapolation method in seismic processing is the one-way method, where the wave field is decomposed into upgoing and downgoing wave fields. These wave fields are extrapolated separately. The two-way approach is another description for wave-field extrapolation. In the formulation of the two-way extrapolation operators, the upward traveling and downward traveling P and S wave fields are handled simultaneously, which makes the two-way schemes very sensitive to different parameters of the macro subsurface model. The one-way schemes, on the other hand, are robust with respect to errors in the macro subsurface model, but ignore mode conversions (from P to S and vice versa) and internal multiples reflections.

Fig. 2 shows the functional diagram of the proposed method for pseudo VSP generation. The nucleus of the procedure is downward extrapolation of a wave field (acoustic or elastic) from the surface into the subsurface. The macro model, which defines the propagation properties of the earth, is used to calculate the extrapolation operator. With this operator it is possible to extrapolate the total wave field from one depth level to another. A description of the potential borehole/detector configuration is necessary to make the correct depth step from one detector level to another. The wave-field extrapolation is repeated recursively for all depths where detectors are chosen in the potential borehole (see Fig. 3). The result is that we obtain a complete pseudo VSP dataset after all depth steps for the predefined source-receiver VSP survey. Note that with this current scheme it is possible to handle all kind of borehole/detector configurations.

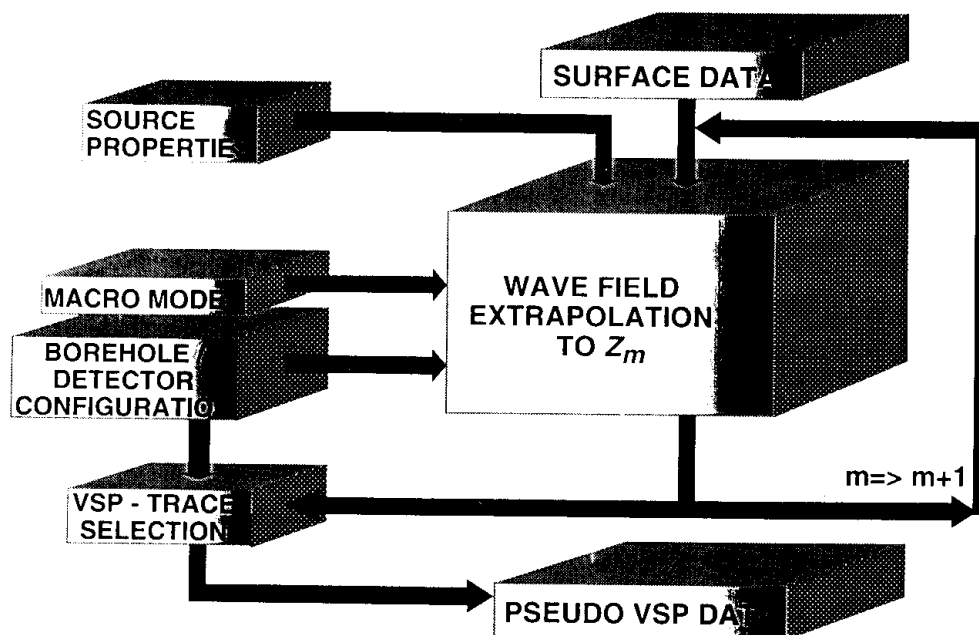


Fig. 2. Functional diagram of the proposed method for generation of pseudo VSP data.

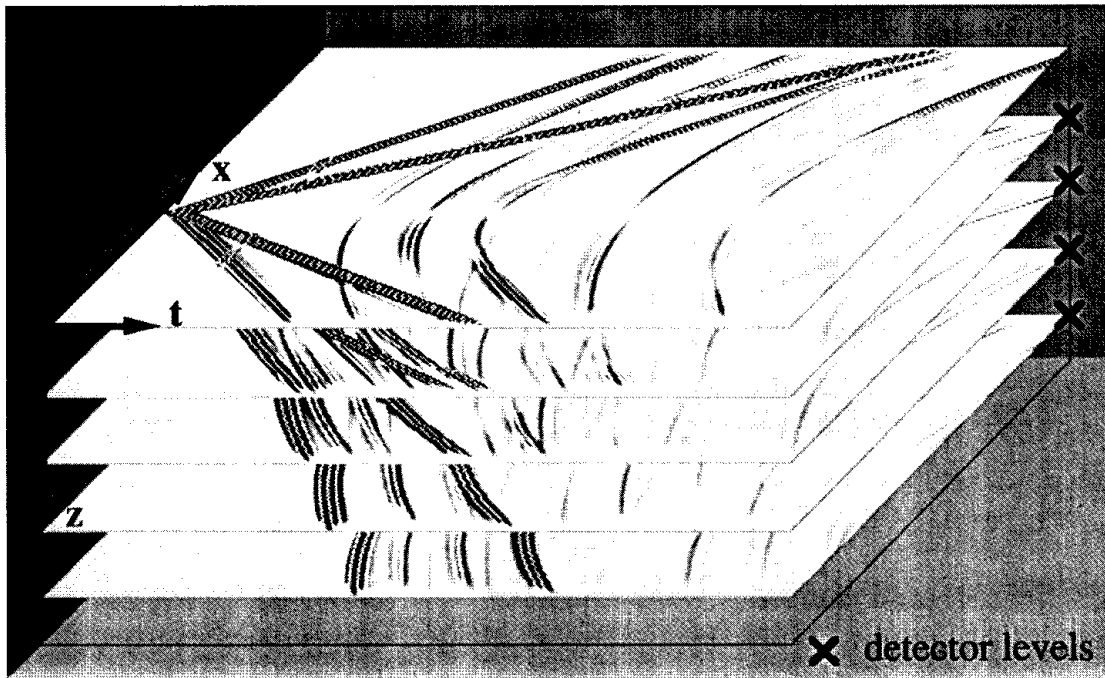


Fig. 3. Downward wave-field extrapolation of a shot record.

The information on the macro model of the subsurface is present in a seismic shot record in the arrival times of the reflections. If an erroneous model is used as input for a two-way wave-field extrapolation algorithm, non-causal solutions are observed, because the arrival times are not properly handled due to a wrongly specified depth or layer velocity. The pseudo VSP generation algorithm is sensitive to errors in the subsurface macro model. This sensitivity can be used in our extrapolation to introduce a *new criterion* for macro model estimation which is not possible in the "surface format". For a detailed description of wave-field extrapolation and its applications (migration) we refer to Berkhout (1982) and to Wapenaar and Berkhout (1989).

## APPLICATIONS

In this section some general applications will be given for the pseudo VSP generation algorithm.

### Pre-drilling

Well locations are generally chosen on the basis of a geological interpretation of the image of the earth's subsurface obtained from seismic surface data. To obtain a better chance of successful drilling, it would be very helpful to predict and evaluate the VSP data that would be measured in the

planned well. With the proposed technique it will indeed be possible to predict these data. For an accurate prediction, however, the seismic data need to be of higher quality than is common in routine seismic acquisition. Therefore, one or more high-quality multicomponent seismic shot records should be acquired at the potential well location. Subsequently, these data are transformed into VSP data and further processed with the existing VSP inversion tools. Fig. 4 illustrates the indirect application of the VSP inversion technology to surface shot record data. Based on the results, a better decision can be made whether or not the well should be drilled. The extra costs of the dedicated multicomponent acquisition should be seen in comparison with the costs of drilling.

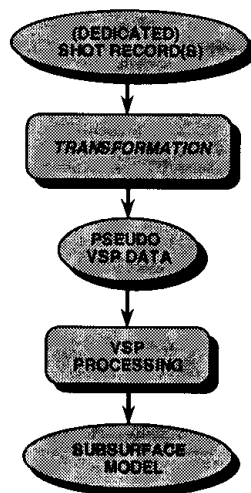


Fig. 4. VSP processing technology is indirectly applied to shot record data.

### Post-drilling

We can also benefit from the pseudo VSP generation method after a well is drilled. An important aid in the interpretation of VSP data is the *comparison* with processed surface data related to the same area. This comparison would benefit from the proposed technique because it transforms the surface data into the *same* "format" as the real VSP data, see Fig. 5. Note that for this comparison purpose it will not be necessary to acquire dedicated multicomponent shot records and standard surface data can be used. Of course, when the interpretation leads to a new potential well location, then we may switch back to the "pre-drilling mode".

So the comparison of the pseudo VSPs at different locations with the real VSP data will enable us to extend our geological knowledge *in all lateral directions* and will *improve* the interpretation of the subsurface.

## Migration

In prestack migration the source wave field and the reflected wave fields are downward extrapolated into the subsurface, followed by applying the imaging principle. The format of the extrapolated wave fields is significantly different from the VSP format. As a result, in the past the techniques in migration and the techniques in VSP processing have been developed separately and have not been integrated. In the DELPHI project we will develop an extension to the prestack migration technology that enables the generation of pseudo VSP data and subsequent application of the existing VSP techniques. It may be expected that the integration of prestack migration and VSP techniques may have important consequences for the way both methods are used in practice.

## EXAMPLES

First, an example will be given of the pseudo VSP generation technique where the extrapolation is performed in the wavenumber frequency domain (only valid for horizontally layered media). This result will be compared with that of VSP modeling. Next, a 3-D volume of data will be shown, illustrating the continuity of the different events in the different planes (shot record, VSP and snapshot). An example for the pseudo VSP generation will be given for a structurally more complex geology, the Marmousi model. The wave-field extrapolation is performed in the space-frequency domain. Finally, the application of the pseudo VSP generation algorithm on field data is presented. In all examples, two-way wave-field extrapolation has been used for the downward wave-field extrapolation of the surface data.

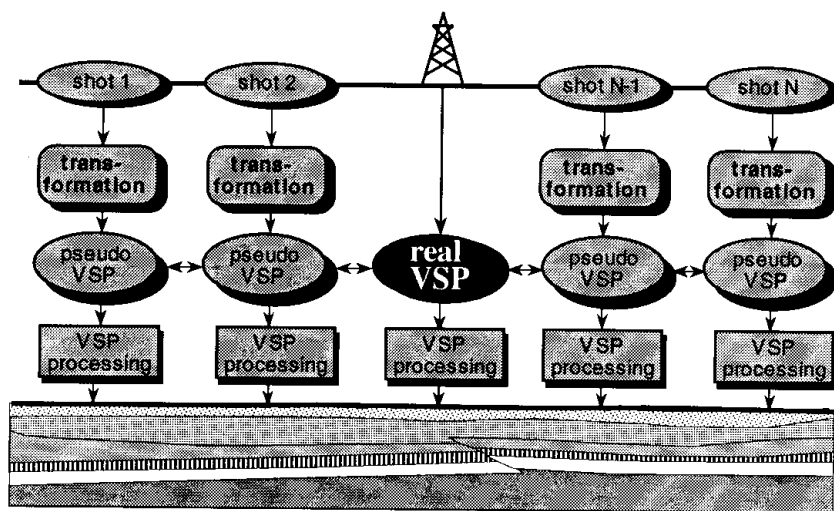


Fig. 5. Improvement of the integration of surface data with VSP data.

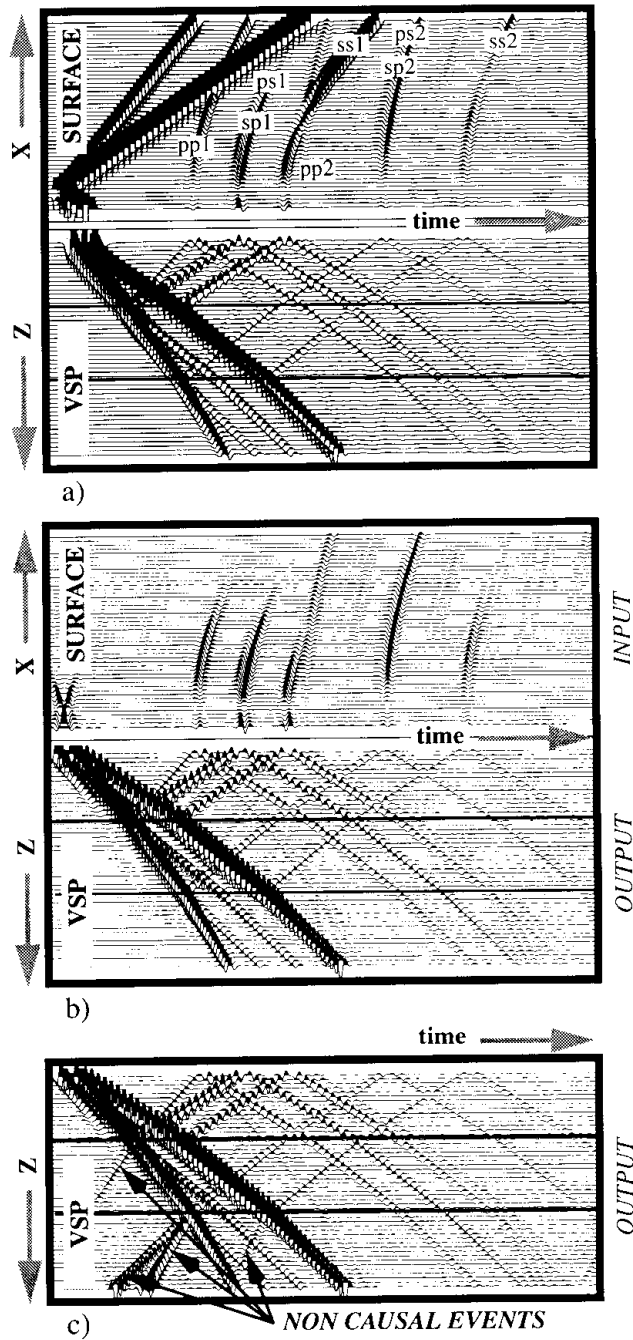


Fig. 6. a) VSP modeling. b) Pseudo VSP generated with correct macro model. c) Pseudo VSP generated with erroneous macro model.

Fig. 6a shows the integration of modeled surface and offset VSP data using an elastic finite-difference algorithm corresponding to a vertical stress source  $\tau_{zz}$  and horizontal  $V_x$  receivers. Various events are indicated in this figure. The principle of this research is to transform shot records into VSPs, thus transforming the upper panel into the lower panel by a numerical method.



This figure clearly shows the 'simplicity' of VSP data. Both datasets contain the *same* information but are represented in different formats for an easier interpretation of the different events. This shows the importance of reorganization of data. Fig. 6b shows the pseudo VSP data, computed from surface data (by downward extrapolation in the wavenumber frequency domain). The f-k filtering effects applied to the surface data, in order to correctly locate it within the window of the propagating waves for any layer, can be seen in this figure. The same macro model is used as for the VSP modeling. Fig. 6c illustrates the pseudo VSP generated from the surface data in Fig. 6b, using an erroneous macro model (5% error in the velocity of the second layer). This gives rise to many non-causal events. Note that these effects accumulate with depth and do not influence the events of the layer above. This illustrates the potential of our method for macro model estimation. This will be further evaluated in the DELPHI project.

Figs. 7a and 7b show a 3-D volume of data illustrating the different cross sections (shot record, VSP, snapshot). Having this volume allows us to obtain a pseudo VSP at any lateral position (x-position). It is not of importance *how* this 3-D volume of data has been built (e.g., walkaway VSP, downward extrapolation of surface data (our method) or snapshots (modeled along the time axis)). Once the 3-D volume of data has been built, we can take a slice in any direction in which we wish to identify the different events at a specific plane. Fig. 7a clearly illustrates the different planes x-t, x-z and z-t of this volume, which represent in fact the shot record, the snapshot and the VSP, respectively. The continuity of the events in the different planes adds another *dimension* to the interpretation of the events. A remarkable event in Fig. 7a is the headwave (see arrows in the snapshot and VSP). The VSP adds a new dimension (depth dimension) to the surface seismic data: it establishes a unique link between a geological interface in depth and its time event on a surface seismic section.

Figs. 8a, 8b and 8c show the unfolded 3-D volume of data at three different times  $t_1$ ,  $t_2$  and  $t_3$ . Each figure consists of two parts, a left part and a right part. The left part shows the shot record in combination with the snapshot. The lateral position of the well is displayed in these figures. The right part illustrates the integrated shot record / VSP display at the position of the well. The time axis is common to both the datasets. These figures represent, in fact, three pictures of the wave propagation for increasing time. The intersection of the well with the events in the snapshot are depth coincident with the events in the VSP. It is clear that with the increase of time the events in the snapshot become more difficult to identify, but the events in the generated VSP are still clearly identifiable. The generated VSP gives much more insight into the propagation of the waves and the interpretation of the different events. It is common practice to use the snapshots to understand the complexity of a shot record. The investigation of snapshots gives insight, but to understand what is really going on it is proposed to generate a pseudo VSP. By generating a pseudo

VSP, we will get much more insight into the different events because all the complex events are identifiable. This is a powerful method of studying complex shot records.

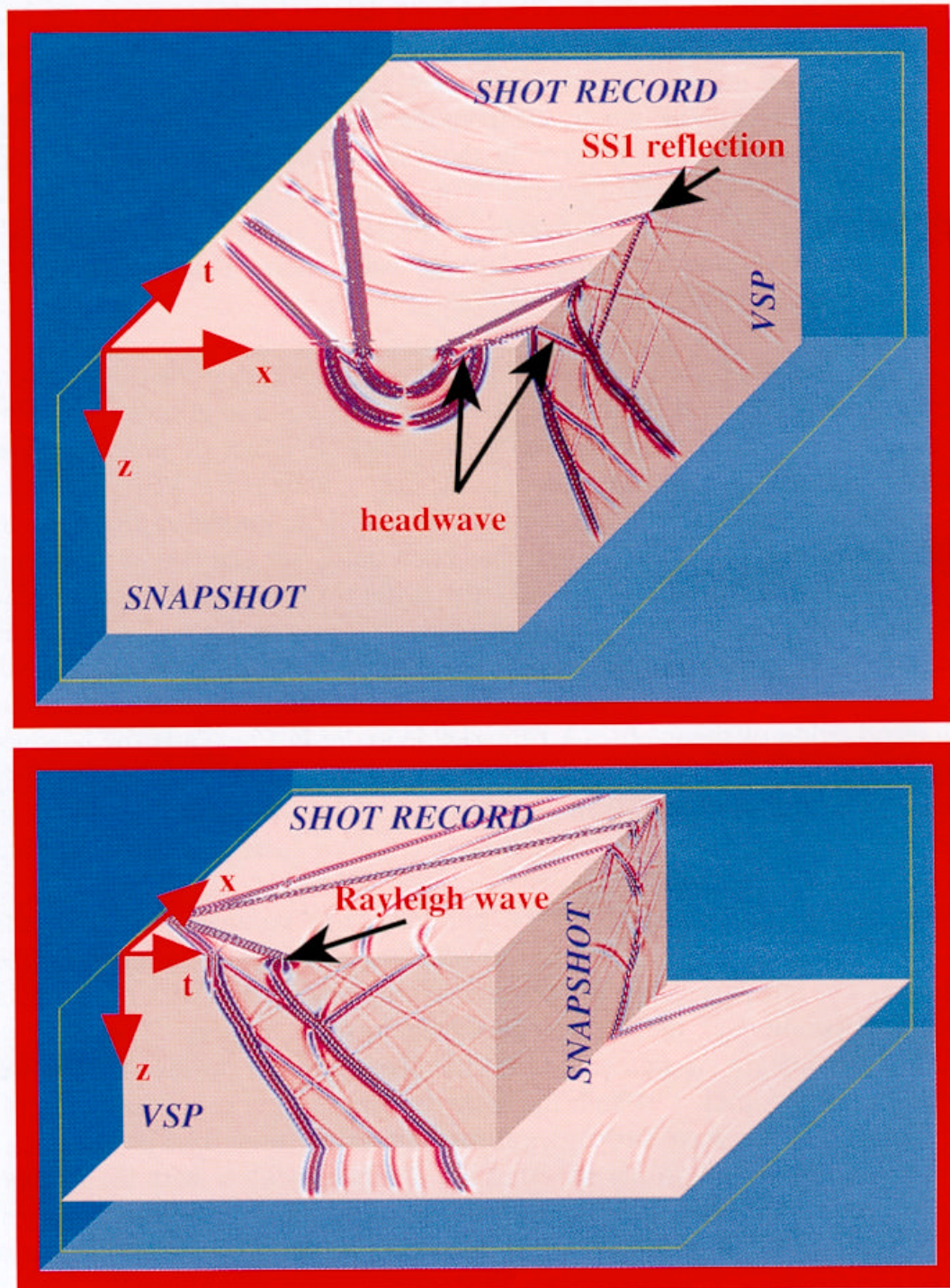


Fig. 7. a) 3-D volume of data illustrating the different cross sections (shot record, VSP, snapshot):  $V_x$  registrations for a  $\tau_{zz}$  source. b) Another view of the same data volume.

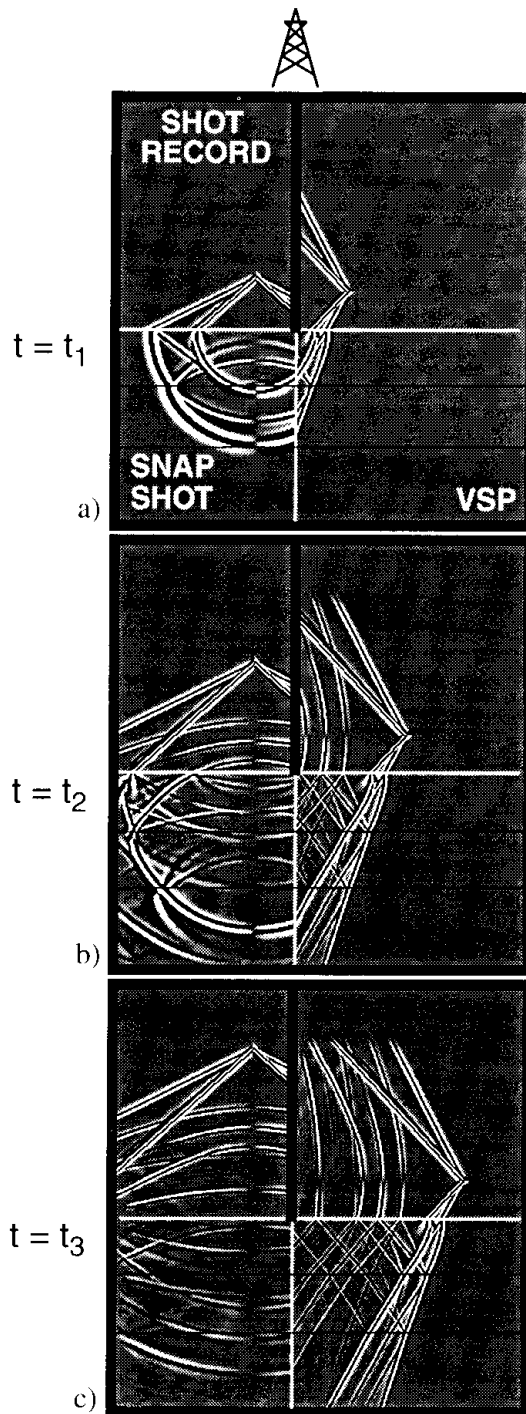


Fig. 8. Snapshots, VSPs and shot records illustrating the wave propagation for increasing time a) at time  $t_1$ , b) time  $t_2$  and c) time  $t_3$ .

In the following example a pseudo VSP will be generated from the well-known Marmousi dataset. The data was modeled with an acoustic, second-order (in space and time) finite-difference scheme. The acquisition geometry is a moving end of spread configuration containing 96 geophone groups, with an

initial offset of 200 m. The number of shots modeled was 240. The source and receiver spacing was 25 m. The data has a length of 4 s with a sampling interval of 4 ms. The first and last shot positions were positioned respectively at 3000 and 8975 meters. For a more detailed description of the model and dataset see Versteeg and Grau (1991). From the first shot gather of the Marmousi dataset we generate the pseudo VSP at a 725 m offset. Fig. 9 shows the Marmousi model, the first shot gather of the Marmousi dataset and the pseudo VSP. The vertical axis of the model has been exaggerated to match it with the VSP data. The thin water-layer reverberations have been removed from the shot gather and the missing near offsets were interpolated using a CMP interpolation technique. The pseudo VSP is generated by downward extrapolation of the wave field in the space frequency domain (lateral variations can be handled properly)

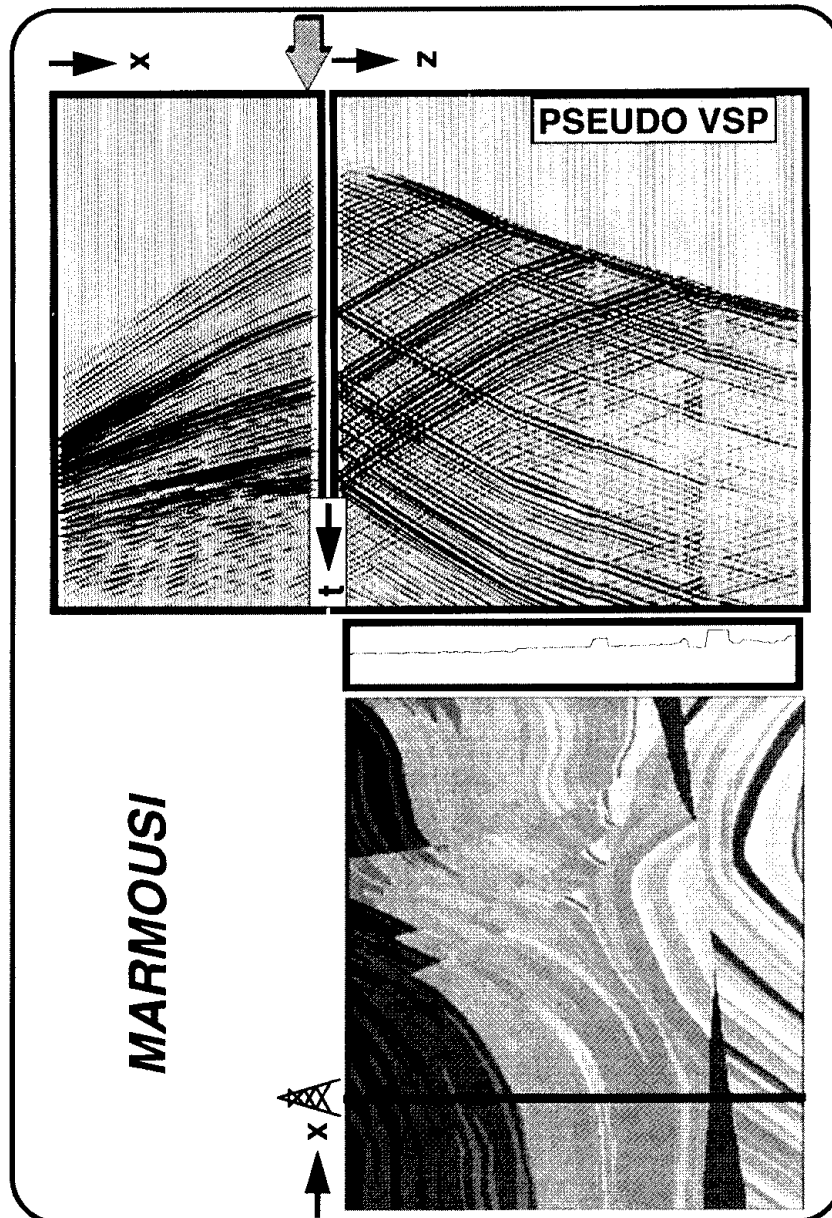


Fig. 9. The Marmousi model, the first shot gather and the generated pseudo VSP.

using acoustic two-way extrapolation operators. In the space-frequency domain the operators are spatial convolutions. The integrated shot record / VSP display allows an easy interpretation of the different events. Following an event in the shot record and the VSP through to the macro subsurface model enables us to have a clear interpretation of the different events. To ascertain the correctness of the generated pseudo VSP, a comparison is necessary with the modeled VSP related to the same area of interest. Fig. 10 shows the pseudo VSP and the VSP modeling result for the same lateral position (of the well). The modeled VSP is computed with an acoustic finite-difference algorithm. Comparing the results of the generated pseudo VSP with that of VSP modeling, we see that the internal multiples up to the first order are handled correctly (see arrow at the right in Fig. 10a). Due to some numerical errors, some non-causalities appear at the layer interfaces. The non-causalities that appeared before the direct wave have been zeroed because they are not correct and meaningless.

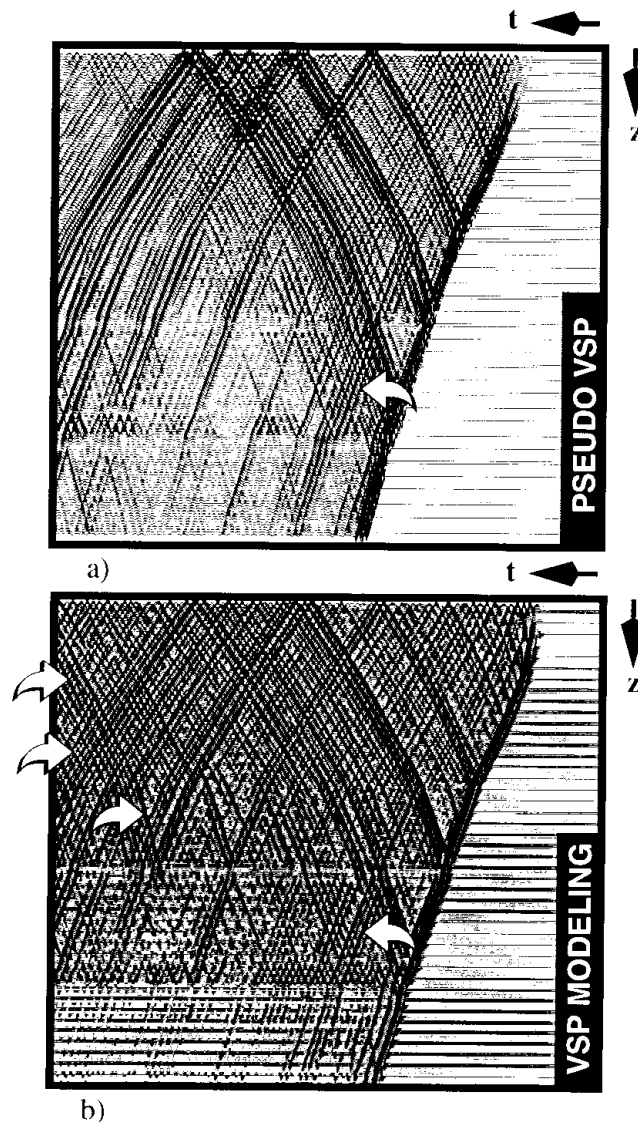


Fig. 10. a) Pseudo VSP generation and b) VSP modeling from the Marmousi dataset.

A remarkable difference between the generated pseudo VSP and the modeled VSP are the multiples at the left (see arrows in Fig. 10b) which are not present in the generated pseudo VSP. The absence of the internal multiples in the pseudo VSP is due to the limited registration time in the surface shot data.

Finally, some results are shown which are obtained by the application of the pseudo VSP generation algorithm on a field dataset. The example is a land dataset (courtesy of NAM, Assen). The acquisition geometry parameters are as follows: split-spread geometry, number of shots 301, shot spacing 30 m, number of detectors per shot 120, detector spacing 30 m, near- offset 115 m, far-offset 1935 m, registration time 4 s and time sampling interval 4 ms.

The missing near-offsets were interpolated using a CMP interpolation technique. Fig. 11 illustrates the integration of shot # 181 and the generated pseudo VSP and the migrated section. The prestack depth migration was performed using a 2-D shot record, recursive depth migration in the space-frequency domain (Rietveld and Berkhout, 1994). The displayed macro model (at the well location) is used for the pseudo VSP generation and also for the migration. The correspondence of the different events in these figures is remarkable. The reflection shown by the arrow is not represented in the macro model. Still we observe a corresponding event (target reflection, see arrow) in the generated pseudo VSP and in the migrated section.

## CONCLUSIONS

With the proposed procedure it is possible to obtain VSP data in a target area *prior* to drilling. Once a target area is selected, it is very attractive to acquire one high-quality shot record and transform this into a pseudo VSP dataset for a candidate borehole. Summarizing:

- Pseudo VSP data can be generated from seismic *surface* data and a *macro* subsurface model.
- Pseudo VSP data may facilitate an accurate *comparison* between true VSP data and surface data.
- Pseudo VSP data may also facilitate important *extensions* to prestack seismic processing, in particular seismic imaging.
- Integration of true and pseudo VSP data may allow a new way to apply lateral prediction.
- With the two-way extrapolation, internal multiples up to the first order are handled correctly, even when the macro model is not exact.

- The sensitivity of two-way extrapolation for macro-model errors is being used to develop a new technique for macro-model estimation.
- 3-D volume representation of the data is an extra aid in the interpretation of various events in different cross sections (shot record, VSP, snapshot).

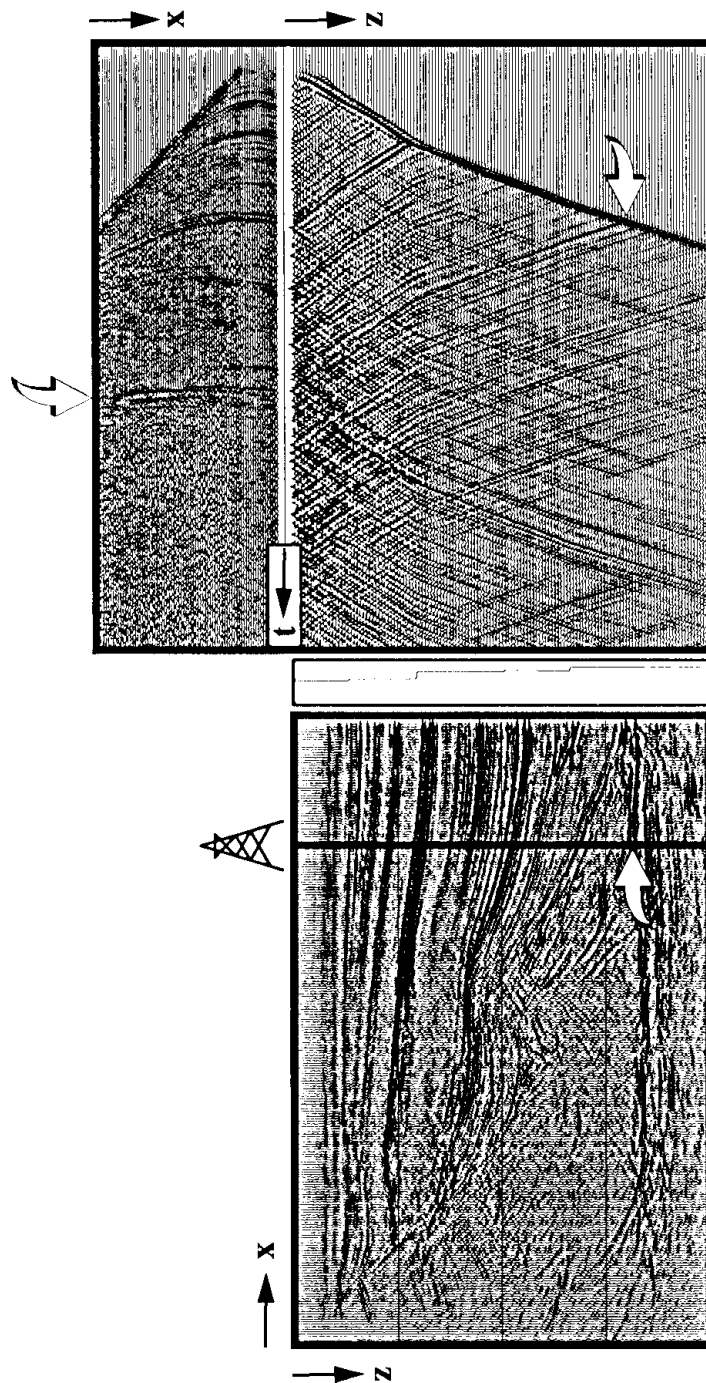


Fig. 11. Pseudo VSP generation from field data (courtesy of NAM, Assen), shot gather and prestack depth-migrated section.

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