Transformation of Surface Data into VSP Data

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Summary

A new method is introduced for the transformation of surface data into pseudo Vertical Seismic Profiles (VSP) by a numerical procedure. The pseudo VSP generated with only a macro model contains all the details of the initial seismic surface data. This is in contrast with VSP forward modeling which needs all the details of the subsurface model as input. A comparison between forward VSP modeling and pseudo VSP generation is presented. The used algorithm is sensitive to errors in the macro subsurface model. This sensitivity can be used as a new criterion to verify the correctness of the macro subsurface model. A 3D data volume representation is an extra aid in rhe interpretation of various events in different cross sections (shot record, VSP and snapshot).

Introduction

VSP acquisition has some major advantages because the seismic reflections can be registered in the direct vicinity of a (potential) hydrocarbon reservoir. Obviously. VSP acquisition is only possible after a well has been drilled. For an extensive overview of the basic principles on VSP the readers are referred to Balch and Lee (1984), Cassel (1984) and Hardage (1983). In this paper we present a new seismic processing technique by which seismic shot records are transformed (numerically) into VSPs. The advantages are threefold:

- It enables generating pseudo-VSP data prior to drilling.
- It improves the integration of surface data with real VSP data after drilling.
- It facilitates applying VSP inversion technology to seismic surface data as par, of the prestack seismic migration process.

The proposed method is based on downward extrapolation of the elastic wave field from the surface into the earth. In this way pseudo VSP data can be obtained in an accurate and relatively cheap way. prior to drilling.

The use of surface data is essential in our method. A macro model of the earth is required to transform the wave fields at the surface to the potential borehole. The extrapolations can be performed either in the space-frequency domain (handling also structurally complex geologies) or in the wavenumber-frequency domain. In this paper. only the two-way wave field extrapolation operators are used for the pseudo VSP generation scheme; they are derived in the wavenumber-frequency domain. These operation enable a correct, handling of multiples and wave conversions.

Methodology

In principle, downward extrapolation can be applied towards any subsurface point in an area below the seismic detectors. Hence, by extrapolating the wave field (i.e., the shot record) to a range of detector positions in a potential borehole a VSP data set is obtained (see Figure 1).
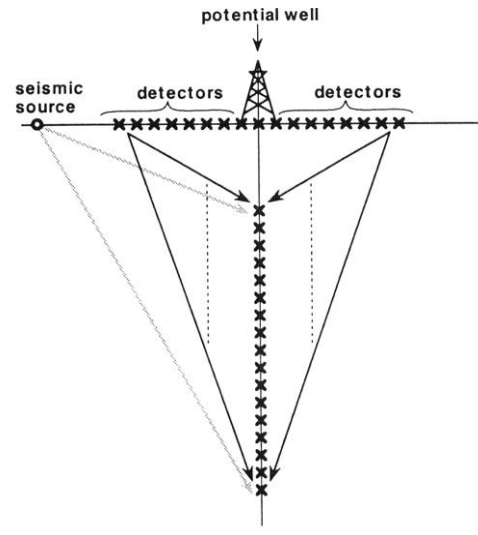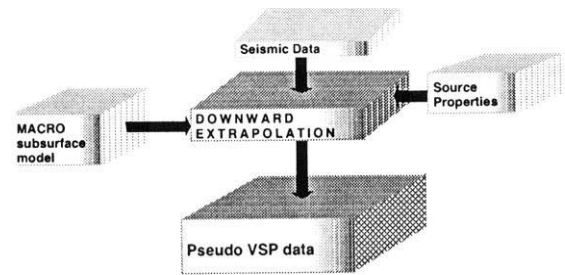

Fig. 1 *Transformation of a seismic shot record into a VSP data set by downward wave field extrapolation.*

The proposed technique requires:

- High quality seismic shot records
- Description of the source properties
- Macro model of the subsurface.

Figure 2 illustrates the method for the generation of the pseudo VSP data from surface seismic data.

Fig. 2 *Proposed method for the generation of Pseudo VSPs.*

The information on the macro model of the subsurface is present in a seismic shot record in the arrival times of the reflections. 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 which is not possible in the "surface format". An erroneous model as input for a two-way wave field extrapoation algorithm would introduce non-causal solutions, because the arrival, times are not properly handled. So after transformation, the generaled VSP dataset should be inspected on the occurrence of non-causal effects (for instance, reflections that arrive before the direct source wave). If these non-causal effects occur indeed. then the initial macro mode, should be updated iteratively until a physically acceptable VSP dataset is obtained. This facilitates a new and accurate way of macro model estimation.

The theoretical principle behind our method is that if 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), it is then possible to reconstruct the wave field at all depths in the subsurface. For a detailed description of wave field extrapolation and its applications (migration) we refer to Berkhout (1982) and to Wapenaar and Berkhout (1989).

Figure 3 shows the functional diagram of the proposed method for pseudo VSP generation
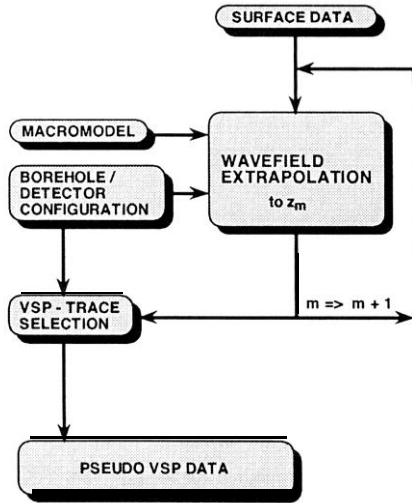
Fig. 3   *Functional diagram for the generation of pseudo VSP data.*

A description of the borehole/detector configuration is necessary to make the correct depth step from one defector level to another.

In this paper we will restrict ourselves 10 the horizontally layered medium. The two-way elastic downward wave field extrapolation can be described (in the wavenumber-frequency domain) as:

$$\overset{\approx}{\overrightarrow{Q}}(z_m) = \overset{\approx}{W}(z_m, z_{m-1}) \overset{\approx}{\overrightarrow{Q}}(z_{m-1}) \tag{1}$$

where the tilde -above a variable refers Lo a spatial Fourier transform from x to k_x

The wave vector $\overset{\approx}{\overrightarrow{Q}}$, which contains the discretized two-way wave fields, is defined as:

$$\overset{\approx}{\overrightarrow{Q}} = \begin{bmatrix} \tilde{V}_z \\ \tilde{\tau}_{xz} \\ \tilde{\tau}_{zz} \\ \tilde{V}_x \end{bmatrix} \tag{2}$$

Finally. the extrapolation operator $\overset{\approx}{W}(z_m, z_{m-1})$ can be defined as:

$$\overset{\approx}{W}(z_m, z_{m-1}) = \begin{bmatrix} \tilde{W}_{11} & \tilde{W}_{12} & \tilde{W}_{13} & \tilde{W}_{14} \\ \tilde{W}_{21} & \tilde{W}_{22} & \tilde{W}_{23} & \tilde{W}_{24} \\ \tilde{W}_{31} & \tilde{W}_{32} & \tilde{W}_{33} & \tilde{W}_{34} \\ \tilde{W}_{41} & \tilde{W}_{42} & \tilde{W}_{43} & \tilde{W}_{44} \end{bmatrix}, \tag{3}$$

where $\tilde{W}_{jk} = \tilde{W}_{jk}(z_m, z_{m-1})$ are scalar operators. For a full treatment of the two-way extrapolation method we refer to Wapenaar et al. (1987).

Applications

Pre-drilling. Well locations are chosen on the basis of a geological interpretation of the seismic image. To make a higher 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 multi-component 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 took
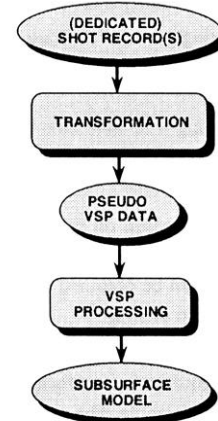
Fig. 4   *VSP inversion technology is indirectly applied to shot record data.*

Based on the result a belter decision can be made whether or not the well should be drilled. The extra costs of the dedicated multi-component acquisition should be seen in comparison with the costs of drilling.

Port-drilling. An important aid in the interpretation of VSP data *is* the comparison with processed surface data related to the same area. This comparison would draw a large benefit from the proposed technique because it enables to transform the surface data info the same "format" as the real VSP data.
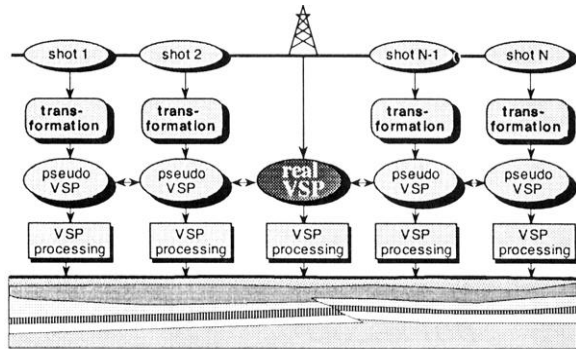

Fig. 5 *Improvement of the integration of surface data with VSP data.*

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 sub-surface model. Note that for this comparison purpose it will not be necessary to acquire dedicated multi-component 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."

Extension of the pre-slack migration techology. In pre-stack 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 are significanlly different from the VSP format. As a result. in the past the techniques in migration and the techniques in VSP have been developed separately and have not been integrated. In this project we will develop an extension to the pre-stack 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 pre-slack migration and VSP techniques may have important consequences for the way both method? are used in practice.

Example

Figure 6a shows the combination of modeled surface and offset VSP data using an elastic finite difference algorithm corresponding to a vertical stress source τ_{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. The comparison of the upper and lower panel shows the time-coincidence of the events. This figure clearly shows the 'simplicity' of VSP data. Both data sets 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. Figure 6b shows the pseudo VSP data.

computed from surface data (modeled in the wavenumber frequency domain). The effects of the f-k filtering applied to the surface data, in order to correctly locate it within the window of the propagating waves, can be seen in this figure. The same macro model is used as for the VSP (modeling. Figure 6c illustrates the Pseudo VSP generated from the surface data in Figure 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.
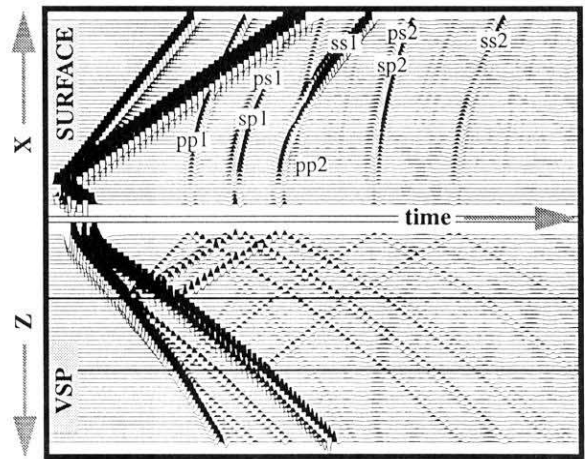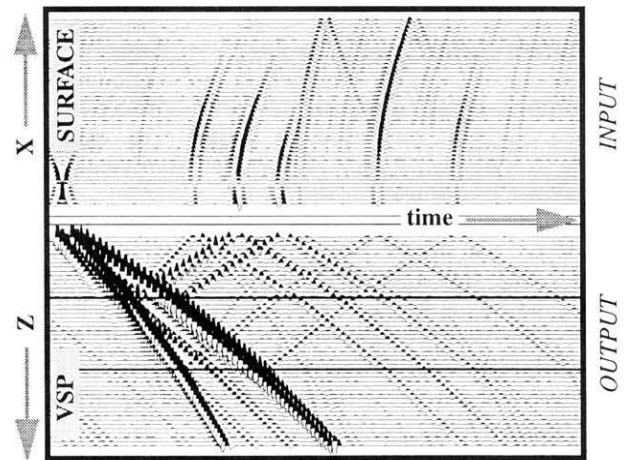

Fig. 6a *VSP modeling.*

Fig. 6b *Pseudo VSP generated with correct macro model.*
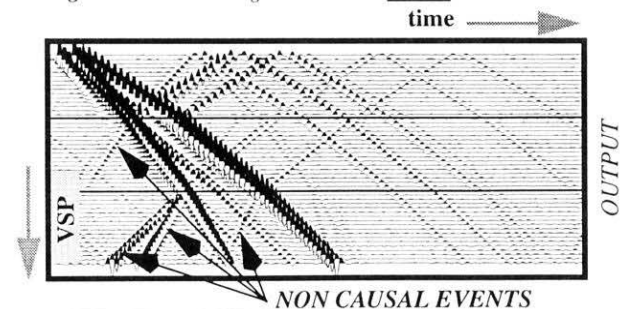

Fig. 6c *Pseudo VSP generated with erroneous macro model.*

Figures 7a and b show a 3D volume of data illustrating the different cross sections (Shot record, VSP, snapshot): V_x registrations for a τ_{zz} source. Having this volume allows us to obtain a pseudo VSP at any lateral x-position. It is not of importance how this 3D volume of data has been built up (e.g. walkway VSP. downward extrapolation of surface data (our method) or snapshots (registered along the time axis)). Once the 3D volume of data has been built up, we can take a slice in any direction in which we wish to identify the different events a, a specific plane. Figure 7a illustrates clearly 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 *dimen*sion to the interpretation of the events. A remarkable even, in Figure 7b is the headwave (see arrows in the snapshot and VSP).
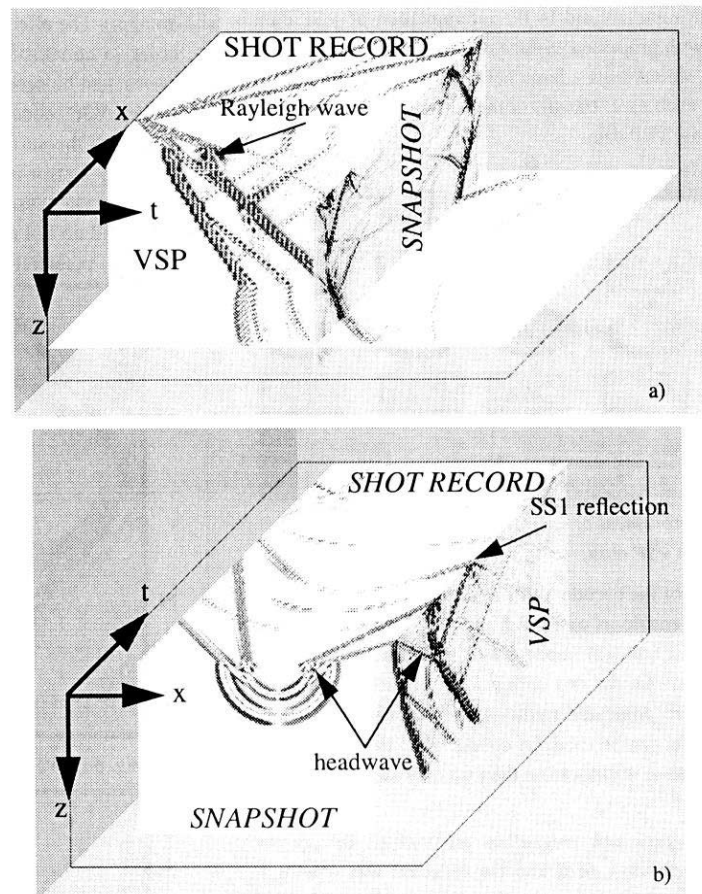

Fig. 7   *3D volume of data illustrating the different cross sections (Shot record, VSP, snapshot) :*
                V_x registrations for a τ_{zz} source.

Conclusions

With the proposed procedure it will be 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 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 pre-stack seismic processing.
- True and pseudo VSP data may allow a new way to apply lateral prediction.
- The pseudo VSP generation algorithm can be used to introduce a new technique of macro model estimation (based on its sensitivity to errors in the macro model).
- 3D volume representation of the data is an extra aid in the interpretation of various events in different cross sections (shot, record, VSP, snapshot).

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