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IMAGING OF COMPLEX SUBSURFACE STRUCTURES BY VSP MIGRATION

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ABSTRACT

The two-way nonreflecting wave equation can be used to migrate seismic reflection data effectively. In this paper, we apply such a procedure to vertical seismic profiling (VSP) data in order to image various complex structures and to help tackle problems in reservoir development by defining the extent of the porous reservoir rock. Applications show that this migration method correctly images the complicated subsurface layers of the earth and solves lithological problems and structural problems with high signal-to-noise ratios. Various data examples from Chinese oil fields show that the VSP migration was able to image complex geological targets around the borehole which were not clearly revealed by VSPCDP stacked sections and surface seismic sections.

INTRODUCTION

In China, geophysicists started systematic studies of VSPs in the early 1980s, and in 1985 China National Petroleum Corporation listed VSP (vertical seismic profiling) as one of its major Science and Technology Projects during the nation's seventh five-year period. From then on, many VSP data sets were acquired in various areas of China. In these areas there exist several difficult technological problems in the acquisition and processing of VSP data as described by Hardage (1983). Here we will present several examples showing how we tackle reservoir characterization problems by imaging complex structures using a VSP migration algorithm (Zhu et al., 1989).

Reverse-time migration is a general method which has been studied for years following the research of McMechan (1983) and Whitmore (1983). It is based on the symmetry of the full-wave equation in time, which makes it possible to extrapolate the recorded wave fields backwards in time by using essentially the same finite difference code as applied in the forward modelling of the wave field. It is known from Claerbout's imaging principle that the extrapolated wave fields of stacked data at time zero are just the migrated image. However, for vertical seismic profiling (VSP) data, we must extrapolate source and recorded wave fields separately in order to do migration. As pointed out by Claerbout (1971), a reflector exists where the source and the recorded wave fields are in phase.

In the last decade, much work has been done to image the subsurface by VSP data. Balch and Lee (1984) presented their results using a Kirchhoff-style algorithm. However, the problem with this algorithm was the severe migration smiles which are characteristic of Kirchhoff migrations on limited aperture data. Chang and McMechan (1986) have implemented reverse-time migration by using the excitation-time imaging condition. They used smoothed migration velocity functions to reduce migration artifacts produced by model interface reflections. Chang and McMechan's method applied finite-difference wave equation calculations for receiver wave-field extrapolation and applied inexpensive ray tracing calculations for the source wave-field extrapolation. Our application of reverse-time migration and Claerbout's imaging principle to VSP migration is similar to the method described by Chang and McMechan (1986), since this prestack migration can be used for arbitrary source-receiver geometries.

REVIEW OF THE ALGORITHM

Offset VSP data can be viewed as a shot profile with the source in the surface and receivers along a borehole. Thus, we can follow prestack depth migration procedures used in the shot profile migration, as described by Reshef and Kosloff (1986). These procedures consist of three steps,

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source wave-field extrapolation, recorded wave-field extrapolation and imaging. These are the essential steps in what Chang and McMechan (1986) called "reverse-time migration *using the excitation-time imaging condition*".

Without loss of generality, we describe the algorithm by considering the VSP response to a point diffractor as shown in Figure 1, which is a simplified version of a figure from Chang and McMechan's paper. The recording geometry consists of a surface source *S*, a point diffractor *D*, and a borehole receiver *R*. Due to Huygens' principle, this represents a general model since reflections can be considered as a sum of point diffractions, and complicated subsurface reflectors can be represented by a set of appropriate point diffractors. These diffractors act as secondary sources of seismic energy the strength of which is proportional to the reflectivity at that point. A diffracted arrival *SDR* travels from source *S*, is diffracted at *D* and is recorded at *R*. The total diffraction traveltime is given by $t = t_{SD}+t_{DR}$, where t_{SD} is the source–diffractor traveltime and t_{DR} is the diffractor–receiver traveltime. We can migrate the arrival *SDR* by backpropagating the observed arrival back to time $t = t_{SD}$ and then adding the reflection amplitude to the depth image at point *D*. This requires computation of t_{SD}, the excitation time for point diffractors.

The first step of source wave-field extrapolation involves determining the excitation time for all the secondary sources in the medium. The excitation time calculation is done by solving the eikonal equation:

$$\left(\frac{\partial t}{\partial x}\right)^2 + \left(\frac{\partial t}{\partial z}\right)^2 = \frac{1}{v^2}, \qquad (1)$$

where $v(x, z)$ is velocity which varies both vertically and laterally and t denotes time. This equation is used to compute the imaging time of every point in the image space, and this computation corresponds to the simple extrapolation of the source wave field. Equation (1) can be solved in several ways. Here we adopt Vidale's finite-difference scheme (Vidale, 1988) for computing the traveltimes from the source to secondary sources (image points) in the subsurface.

Having determined the source wave-field extrapolation, the next step involves computation of the receiver wave-field extrapolation. For this we use the two-way nonreflecting wave equation:

$$v\frac{\partial}{\partial x}\left(v\frac{\partial P}{\partial x}\right) + v\frac{\partial}{\partial z}\left(v\frac{\partial P}{\partial z}\right) = \frac{\partial^2 P}{\partial t^2}, \qquad (2)$$

where *P* denotes pressure. Not only is it able to describe upgoing and downgoing wave motions like the full-wave equations, it also has the capability of eliminating or reducing reflections during migration – a property formerly considered to be the characteristic of one-way wave equations. Discretizing equation (2) in (x, z, t)-space by the finite-difference technique, we obtain a recursive formula for extrapolating the recorded VSP data in time-reversed order. That is, the recorded data are propagated backward in time from the receiver to a diffractor point. This reverse-time extrapolation is a finite-difference boundary value problem in which time-reversed samples of the traces recorded at the receivers act as boundary values.

The third step of the migration algorithm is applied at every step of the reverse-time extrapolation of the recorded wave fields. At extrapolation time t_{DR}, the diffraction recorded at *R* has backward-propagated from time $t = t_{SD}+t_{DR}$ to time t_{SD}. By applying Claerbout's imaging principle, the reflection sample is effectively imaged by adding the sample amplitude to the depth image at point *D*. This procedure provides a locus of reflection point scattering images for a given source and receiver pair. If this process is repeated for a number of sources and receivers and the reflection image is continually summed, the images constructively interfere at the true reflection points. A detailed description of the above procedure is given by Chang and McMechan (1996).

This imaging method is very similar to the procedures used on VSP by Whitmore and Lines (1986), except that Whitmore and Lines compute source wave fields by use of finite-difference wave-field computations rather than using the faster eikonal equation solver.

Applications in Reservoir Development

Hongjinzi Oilfield is one of the major oil producing areas in the Changqing Oilfield. Much seismic work has been done

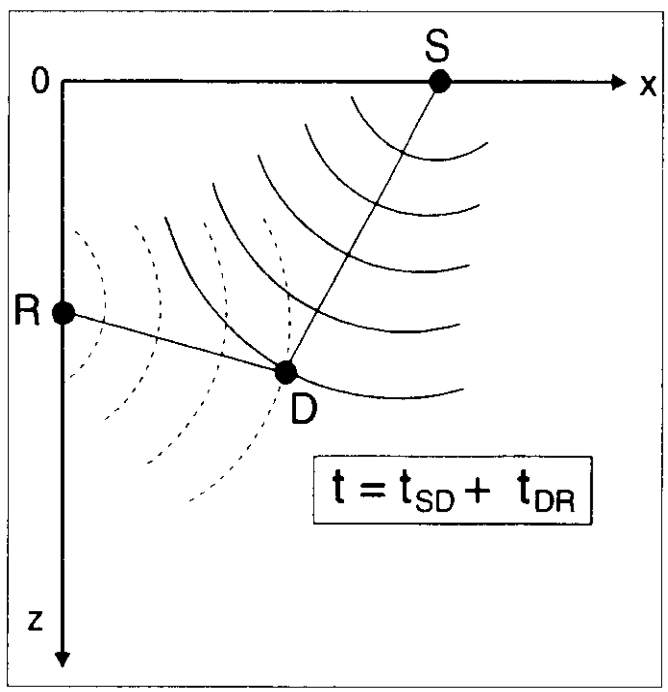

Fig. 1. VSP imaging of a point diffractor *D*. The diffraction along path *SDR* is recorded at receiver *R* at time $t = t_{SD}+t_{DR}$. The excitation time for the diffractor *D* is the direct traveltime t_{SD} from the source *S* to the diffractor *D*. Migration consists of backward propagating the recorded wave field for a time interval t_{RD} and applying Claerbout's imaging principle. The diffraction sample at time $t = t_{SD}+t_{DR}$ is effectively imaged at the diffractor *D* (after Chang and McMechan, 1986).

in this area before, and the very first three-component VSPs in China were acquired there. In the mid-1980s, VSPs were designed and measured in five wells in the oil field by geophysicists from Companie Generale de Geophysique (CGG) and processed by Geophysical Research Institute (GRI) in Zhuozhou, China. The major objectives were to obtain high-resolution reflections, to determine geological horizons and, finally, to determine the detailed geological variations of horizons and lithologies between the wells.

The VSP data set presented here is from well Hong 13-4 in which one zero-offset VSP and three offset VSPs were acquired. Figure 2a shows the position of well Hong 13-4 (a producing well) relative to well Hong 13-5 (a dry hole) and the shotpoint for the offset VSP presented here which is 1000 m from well Hong 13-4. All acquired data were three-component VSPs. We migrated the VSP data set with 1000 m offset. The recordings were taken from depth 2190 m up to 1660 m with a 10-m receiver interval. So a total of 54 traces were uniformly recorded. Following Whitmore and Lines (1986), we preprocessed the three-component VSP data to get a data set suitable for VSP reverse-time migration. The main preprocessing includes vector decomposition, filtering, deconvolution and wave-field separation. The purpose of vector decomposition is to form a component trace in which only the compressional waves are described. Wave-field separation is performed by *f-k* filtering by just selecting the spectrum component corresponding to the upgoing wave

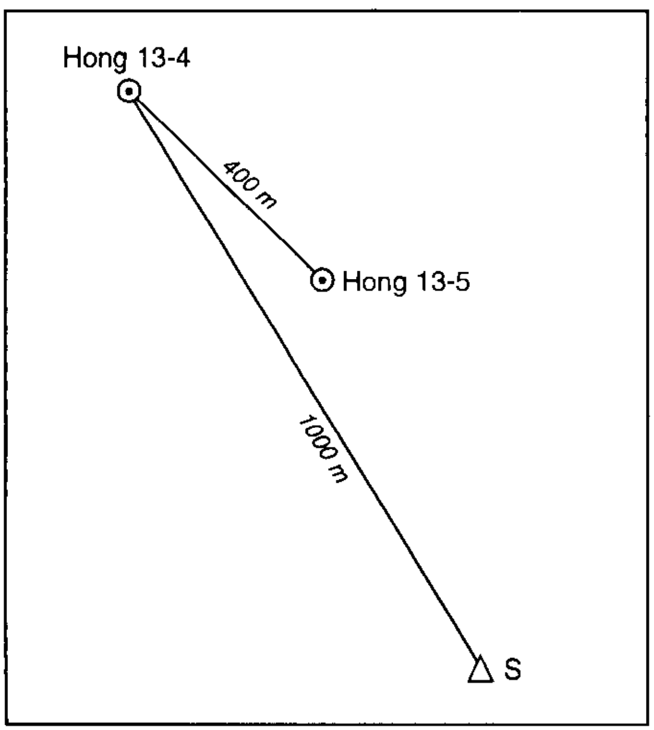

Fig. 2. (a) Relative location map around the Hongjinzi Oilfield. The distance between wells Hong 13-4 and Hong 13-5 is 400 m. *S* represents the shot position corresponding to the VSP data set migrated in this paper. The shot *S* is 1000 m away from Hong 13-4 and it is on the side of Hong 13-5 with respect to well Hong 13-4. The shotpoint *S* is a little bit deviated from the line connecting the two wells.

field. Band-pass filtering and deconvolution are applied for the same reasons just as they are used in surface seismic data. The preprocessed VSP upgoing wave field is shown in Figure 2b. As is shown in Figure 2b, the separated upgoing VSP data are mainly composed of compressional reflected waves with few converted waves. This makes our migration algorithm easy and suitable to apply with a compressional-wave velocity model only. The velocity model consisted of a stack of horizontal layers with velocity function determined from well logging and VSP first arrivals. The migrated image obtained using our algorithm is given in Figure 2c, where the VSPCDP stacked section and the migrated surface seismic section passing through the wellbore and the shotpoint are also shown. The VSP migrated section matches the surface seismic section reasonably well. What needs to be pointed out is that the formation corresponding to the event at 1305 ms of about 30-m thickness in the migrated section is the reflection from the top of Yanan #5 oil layer which is the major oil producing formation in the oil field. In well Hong 13-4 much oil was found in the formation, but in well Hong 13-5, which is only 400 metres away from Hong 13-4, no oil was found in this formation. The geologists of the oil field had been trying to understand this phenomenon but they could not find a reason either from the surface seismic section or from the VSPCDP section. This problem puzzled the geologists until the VSP migration result was obtained in 1990. Our interpretation of the VSP migrated section indicates that the sandstone of Yanan #5 oil layer pinches out at about 150 metres away from well Hong 13-4. Therefore, the factor causing the difference of oiliness of the formation in the two wells is lithological pinch-out. This pinch-out was apparent on the VSP migration but not clearly shown on the VSPCDP stack or the migrated surface seismic data.

Applications in Imaging Complex Structures

In the Sichuan area, seismic data processing has met with many difficulties in imaging the subsurface because of the complex structures. Carbonate structures exist extensively there. The VSPs performed in the area were expected to help identify horizons and image complex structures more precisely. Here we will present two such examples showing how our migration algorithm helps realize the objectives.

The VSP data were from well Qili #1, a preprospecting well in the eastern Sichuan area, where the structures are very complicated. The dips are different from formation to formation. The borehole goes in a complex trajectory, almost rotationally in the subsurface. The maximum deviation of the wellbore from the well position at the surface is nearly 200 metres. There were six VSP data sets acquired in this well. We used the VSP data corresponding to a shotpoint with 618 m offset. In this offset VSP data set, the seismometer depth ranges from 1000 m to 4160 m with a 20-m depth interval; so, a total of 159 traces were sampled in the well. The preprocessed VSP upgoing wave field is shown in Figure 3. As in the first example, vector decomposition is applied to the

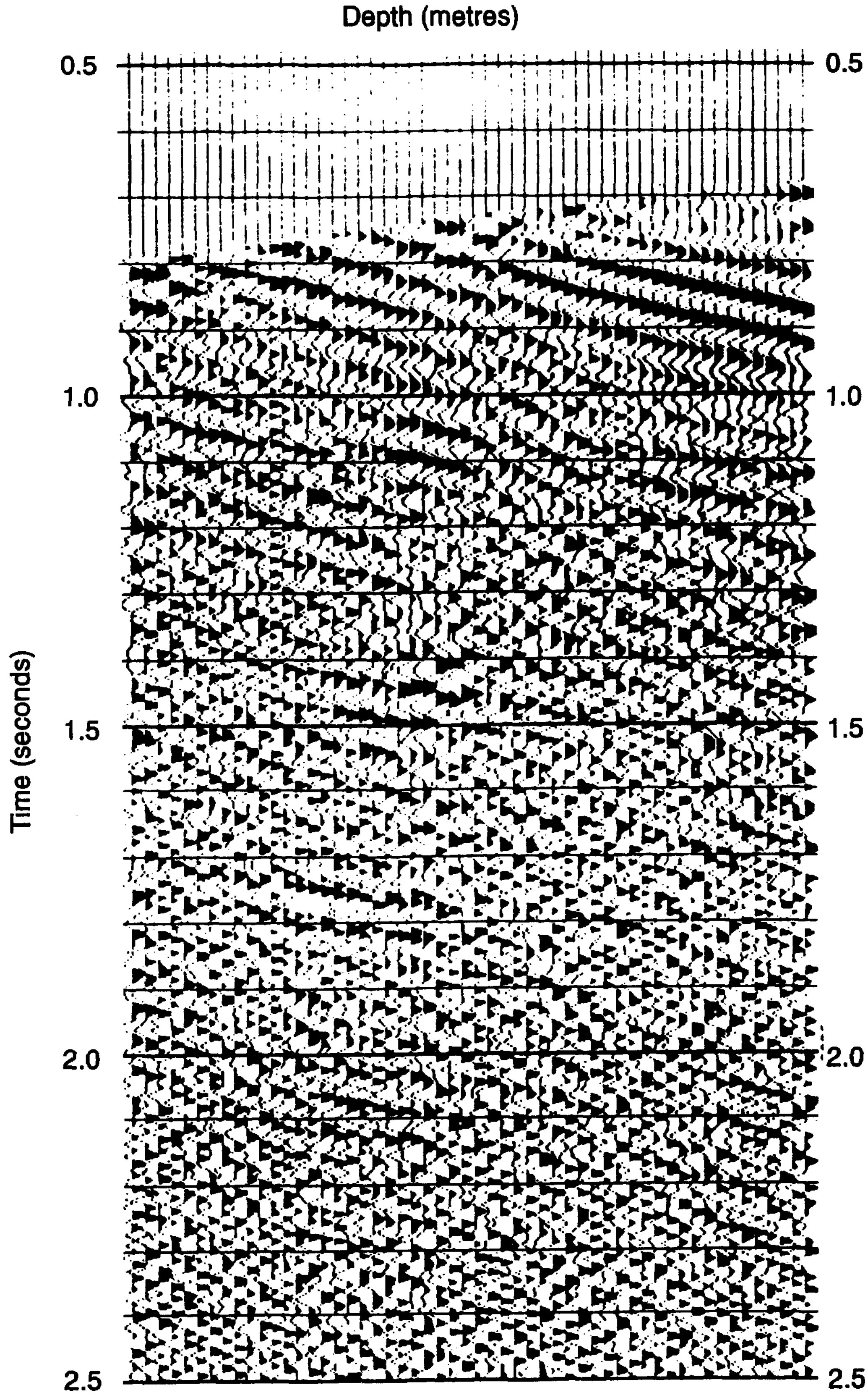

Fig. 2. Cont'd. **(b)** Preprocessed VSP upgoing wave fields of well Hong 13-4. The recordings were taken from depth 2190 m up to 1660 m with a 10-m receiver interval. So a total of 54 traces were uniformly recorded. The 3-component VSP data were preprocessed to get a data set suitable for VSP reverse-time migration. The main preprocessing includes vector decomposition, filtering, deconvolution and wave-field separation. Vector decomposition is used to form a component trace in which only the compressional waves are described. Wave-field separation is performed by *f-k* filtering by just selecting the spectrum component corresponding to the upgoing wave field. Band-pass filtering and deconvolution are applied for the same reasons just as they are used in surface seismic data.

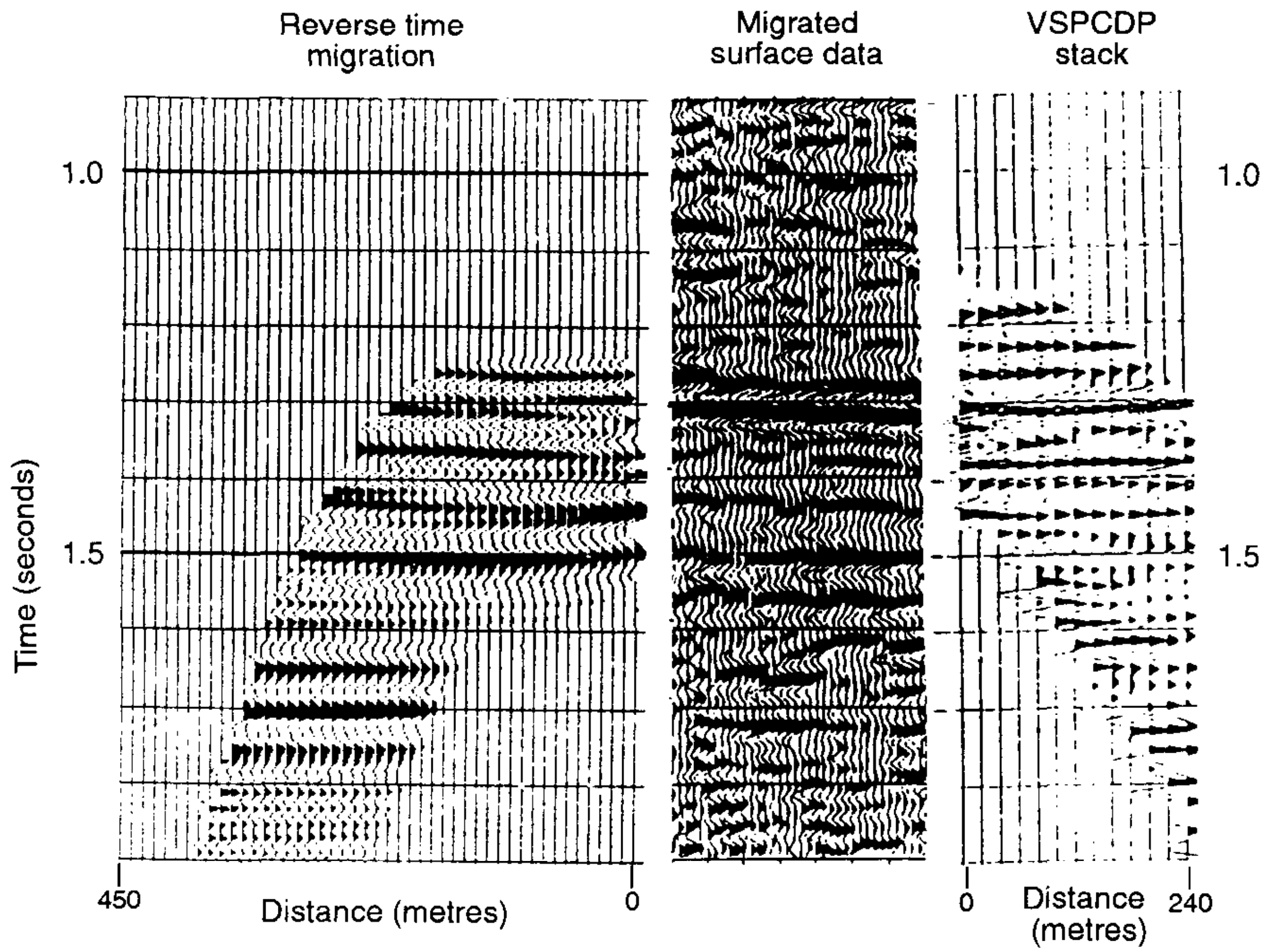

Fig. 2. Cont'd. **(c)** Comparison of images. On the right is the VSPCDP stacked section. The reverse-time migrated image using data shown in Figure 2b lies on the left. A part of the migrated surface seismic section is inserted between them. Well information confirmed that the event in 1305 ms pinches out at about 150 m away from the wellbore. This event is evident on the VSP migration but is not obvious on the migrated surface data or the VSPCDP stack.

three-component VSP data to produce the compressional wave traces. *F-k* filtering is applied to the above composed compressional wave data to produce the upgoing wave field. Deconvolution and band-pass filtering are used as usual. Based on the regional geological information, and the well logging information, a rough structural subsurface model was provided to us by the oil field geoscientists. Combining the information extracted from VSP first breaks, the velocity model was refined. After migrating the data using such a model, we obtained the migrated image in Figure 4, where the VSPCDP stacked section is also shown. The VSPCDP stack did not image the structure well. Though there were no available surface seismic data crossing the VSP section to directly compare with the VSP migrated result, the VSP migrated image was considered to be consistent with well logging in horizons and dips in the region. The geologists of the oil field thought the image in the vicinity of the borehole was especially convincing.

The last example also comes from a well (Linbei #6) in the eastern Sichuan area. The geological model in Figure 5 shows a well drilled in a structure which is as structurally complicated as the former example. This velocity-depth model was created as follows. As in the second example, the oil field geoscientists provided us with a rough structural model which is based on regional geological information and well-logging data. Secondly, the velocity-depth model was revised by modelling the traveltimes of the first breaks of the VSP data. Thirdly, this model was used to migrate the VSP data. Then, based on the migrated result, the velocity-depth model was finely adjusted. After iteratively updating the model and migration, the final velocity model is obtained, as shown in Figure 5. This modelling procedure is very similar to that described by Whitmore and Lines (1986). In this well, four VSPs were acquired with the objective of determining steep structures near the borehole. There were problems in imaging the steep structures with the design of the two large offset VSPs, so these two VSPs were almost discarded in processing. We essentially used the VSPs for shotpoints V1 and V2 as shown in Figure 5. For the shotpoint V1 with offset 215 m, 151 traces were uniformly recorded from depth 3180 m up to 180 m with a 2-ms sampling rate. The two horizontal components of this data set are of poor quality, and

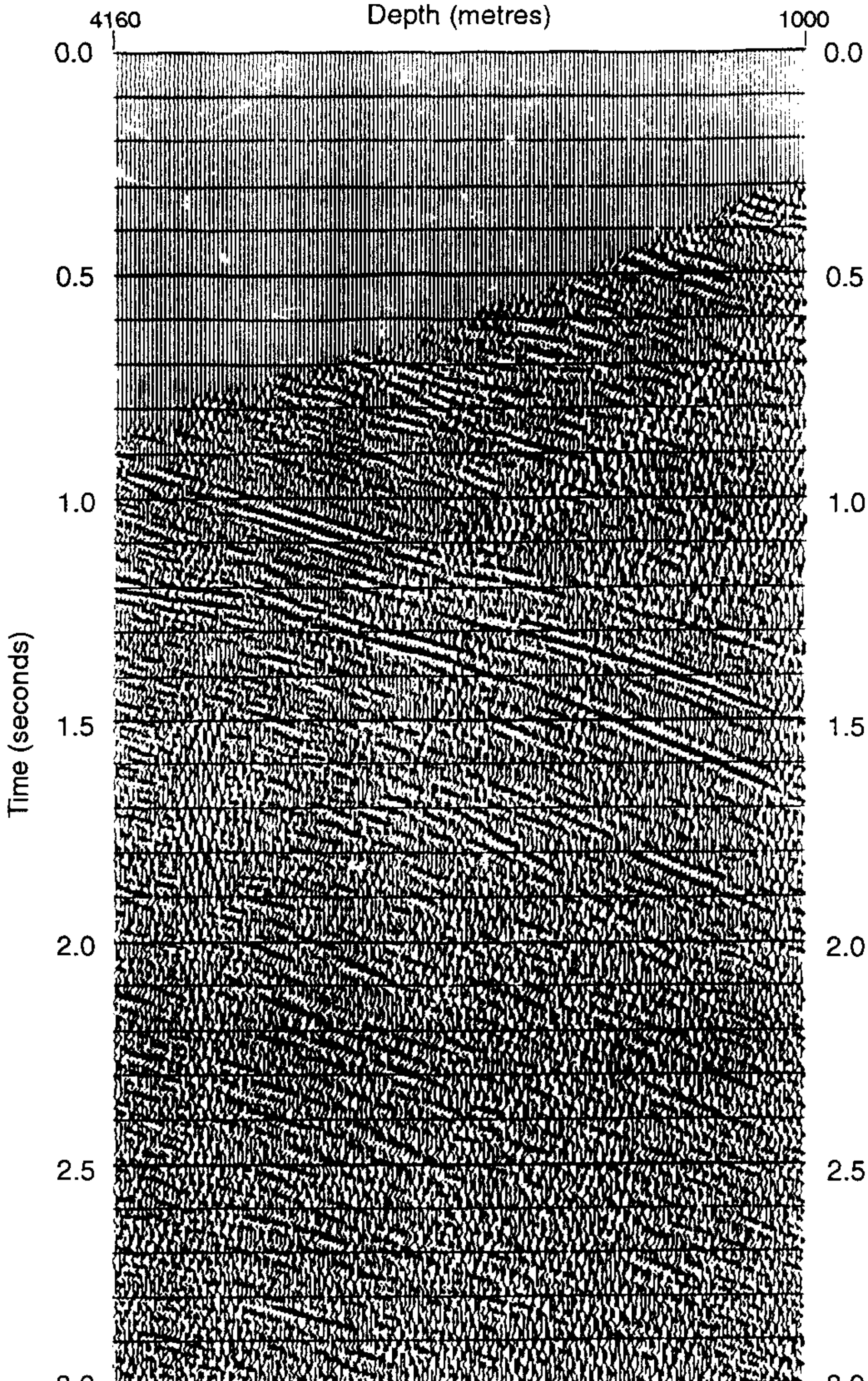

Fig. 3. Preprocessed VSP upgoing wave field of well Qili #1. The offset of this VSP data set is 618 m. Seismometer depth covers range from 1000 m to 4160 m with a 10-m interval. Vector decomposition is applied to the 3-component VSP data to produce the compressional wave traces. *F-k* filtering is applied to the above composed compressional wave data to produce the upgoing wave field. Deconvolution and band-pass filtering are used as usual.

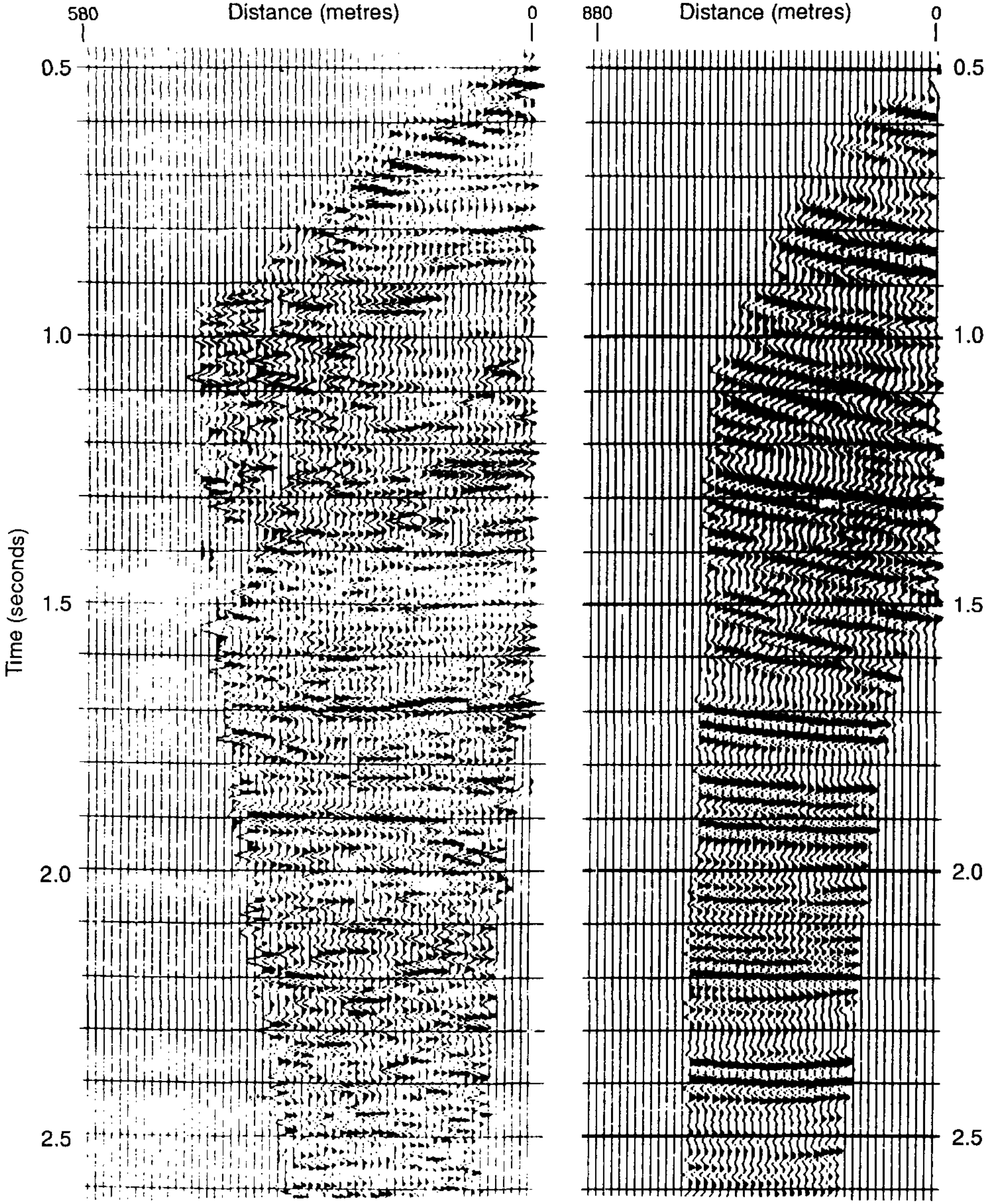

Fig. 4. Comparison of VSP reverse-time migrated image with the VSPCDP stacked section. Note the steep events in the migrated image with respect to those in the VSPCDP section. The dips shown in the migrated image are thought to be convincing.

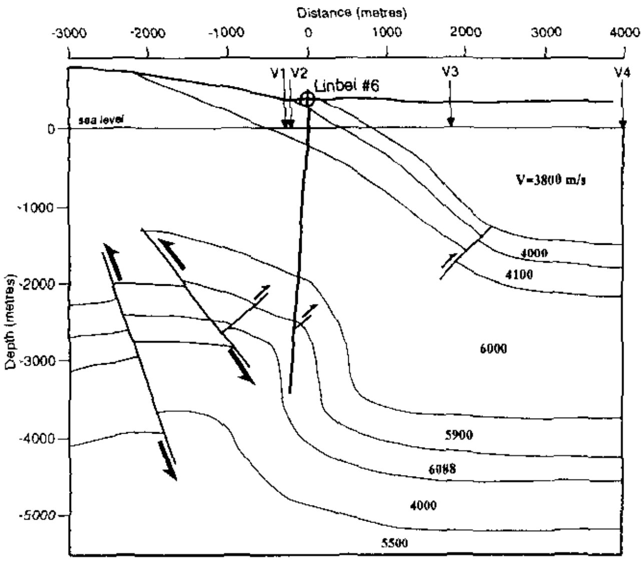

Fig. 5. Geological model in the area of well Linbei #6. The data from shotpoints V3 and V4 are problematic in imaging the steep structures near the wellbore. The shotpoints V1 and V2 are not in the same plane with the wellbore. This model was built up in stages as described in the text.

they contain almost no useful information about the compressional waves. There is no evident improvement in the composed compressional wave component compared to the vertical component traces. So, we used only the z-component traces in migration. After *f-k* filtering, the vertical component of the upgoing wave field is shown in Figure 6. The wave-field separation was not totally successful. As indicated in Figure 6, there still remained periodical downgoing waves (tube waves) which appeared in the depth range 1400 m-920 m with about 350 ms period. These tube waves are mainly caused by bad coupling conditions in the well casing. There also existed strongly dipping events which were considered to come from out of the offset VSP plane (sideswipe). Bad coupling between the geophone and the casing caused records in several segments to contain little information. In addition, the signal-to-noise ratio of the separated upgoing wave fields was somewhat low. The vertical upgoing wave field of V2 is shown in Figure 7, which is on a slightly different line with respect to V1. To this data set, much effort was spent on VSPCDP stacking based on the ray theory, but little gain was obtained. Such limitations of VSPCDP stacking method are outlined by Stewart (1991). Fortunately, our migration algorithm was successfully applied to the data set. The migrated images of the above two VSP data sets are shown in Figure 8. It is seen that the images in the two VSP migrated sections match very well at the borehole tie point. And from well logging and other geological information, it is believed that the dips are correct in the section above 1.3 s. The geologists were satisfied with the migrated images and they used the information in their interpretations. Therefore, the VSP migrations were judged to be successful.

From all the examples which were tested, we can see that all the migrated sections have very good signal-to-noise ratios, which is the benefit of using the two-way nonreflecting wave equation. In general, the VSP migrations showed superior resolution compared to other imaging methods.

Conclusions

The VSP migration using the two-way nonreflecting wave equation can describe wave propagation in all directions and it can also eliminate or reduce unwanted reflections during migration. It is able to accommodate lateral and vertical velocity variations. VSP migration is very successful in applications with imaging complex structures and with reservoir development problems. The final migrated section has a characteristic of high signal-to-noise ratio and is better in resolving thin bed structures near the well than either VSPCDP stacked sections or migrated surface sections.

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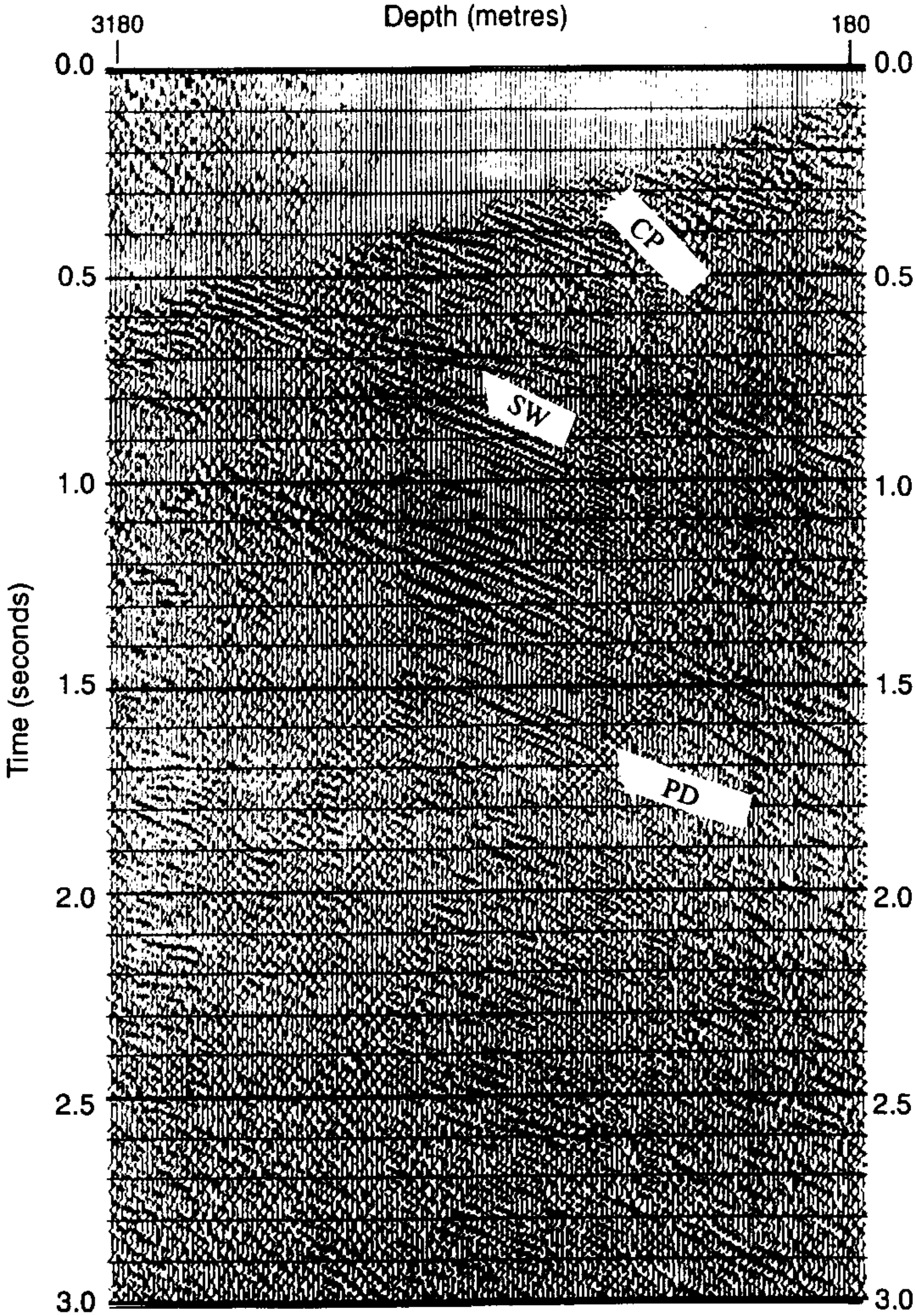

Fig. 6. Upgoing wave fields of the offset VSP with source in V1. The offset is only 215 m to this data set. Receiver depths range from 180 m to 3180 m with a 20-m interval. There are still downgoing waves appearing in the section, and there also exist coupling problems in the depth range from 1400 m to 920 m. The label CP represents coupling problems, SW labels sideswipe and PD represents periodical downgoing waves.

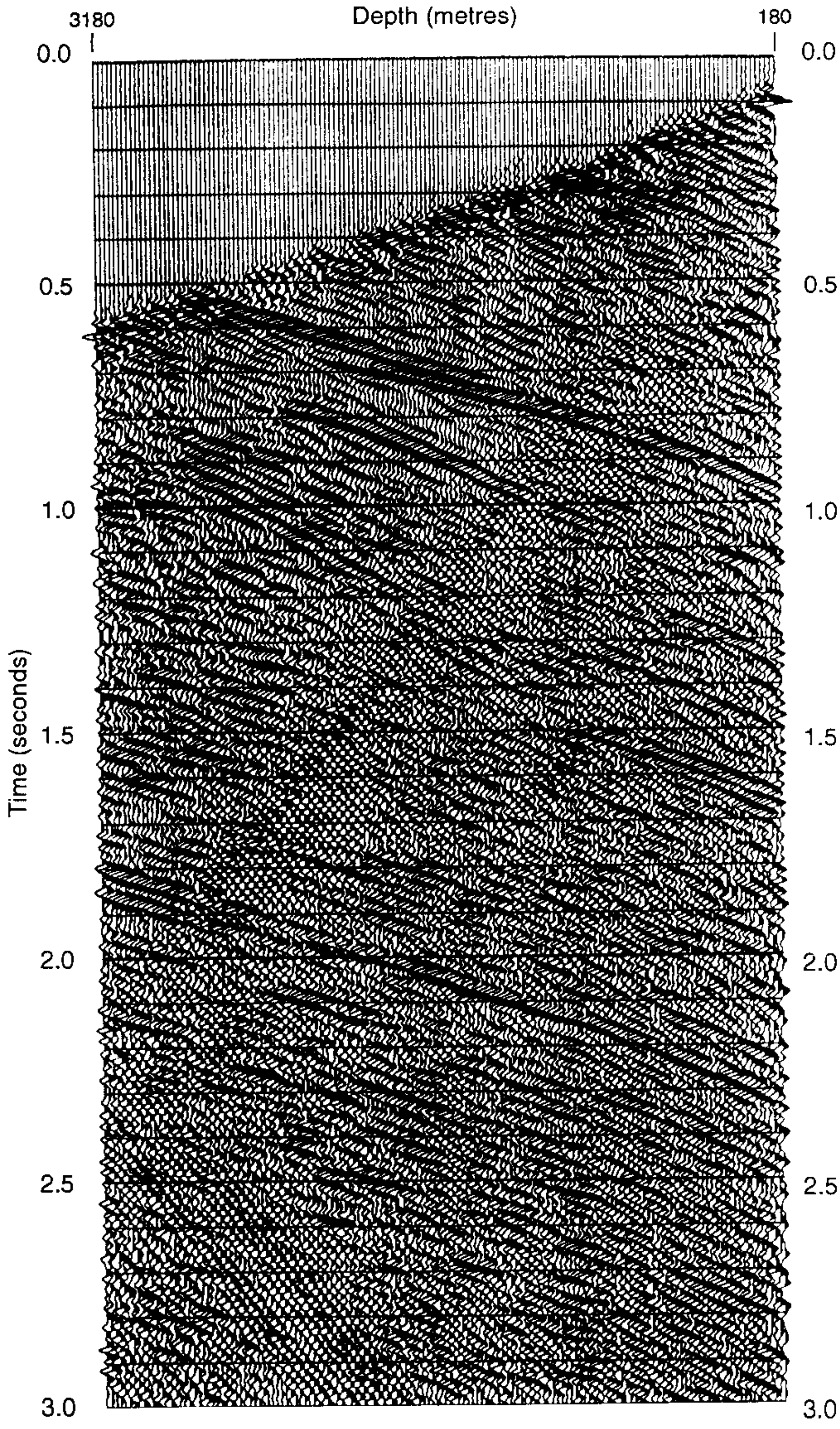

Fig. 7. Upgoing wave fields of the offset VSP with source in V2. There are still tube waves left in the entire section. The recording range is just the same as that in Figure 6.

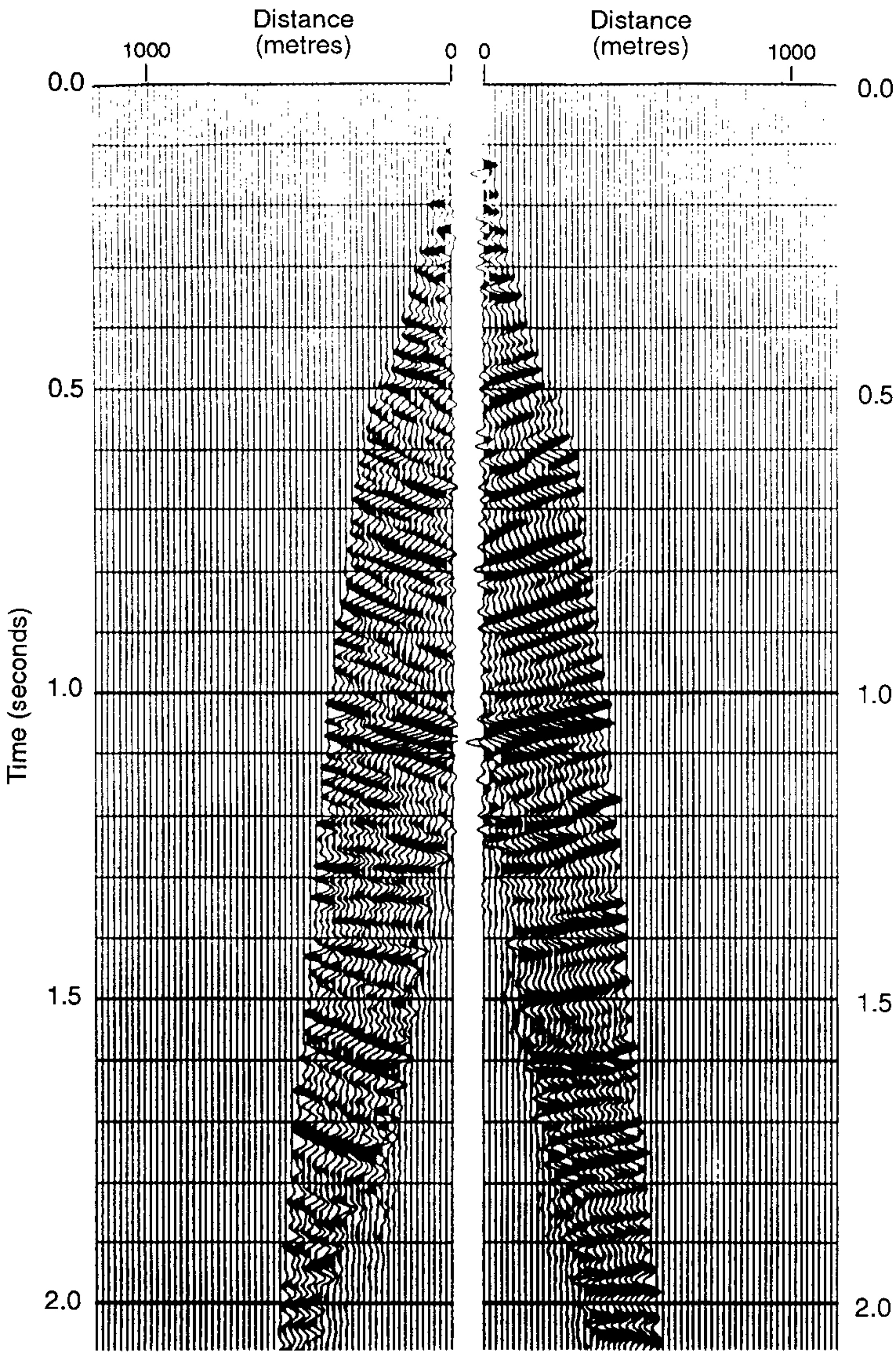

Fig. 8. Migrated images of VSP data. On the left is the migrated image of VSP data corresponding to source point V1, and the image of the data corresponding to source point V2 is shown on the right. The two images agree very well at the borehole tie point.