7^{th} International Conference & Exposition
on Petroleum Geophysics

"HYDERABAD 2008"

P - 609

Vector Kirchhoff Migration of First Order Downgoing Multiples from VSP Data

Min Lou*, Xiaomin Zhao, Fran Doherty, and James Jackson ,
VSFusion – A BakerHughes-CGGVeritas Company

Summary

Migrating Vertical Seismic Profile (VSP) downgoing multiple arrivals can provide a much wider image zone than does the conventional migration of primary reflections. Many methods have been developed to migrate the downgoing multiples. Although most VSP data is recorded using three component downhole receivers, most all of the developed methods migrate only a single scalar component of the multiples. We present a new methodology to perform three-component (3C) vector migration for the 1^{st} order free-surface related multiples which are usually the dominant wavemode in VSP data. We first vertically up-extend the velocity model above, and symmetric about, the free surface. The borehole receivers are then projected to their virtual positions above the free surface. We can therefore treat the 1^{st} order free-surface related multiples as primary reflections recorded by the virtual receivers. This concept is usually referred to as the free-surface mirror symmetry principle. Then, using the up- extended velocity model and the virtual receiver positions, we perform a vector summation of the Kirchhoff pre-stack depth migration for all three downhole receiver components (x, y, z) for the 1^{st} order free-surface related multiples. Test results for both synthetic modeling and field data suggest that our method can accurately produce a much wider seismic image zone than conventional VSP migration which uses only primary upcoming reflections. The image quality is also enhanced by the migration of all three vector components instead of a single scalar component as is done by conventional VSP migration methods.

Introduction

It has been recognized that migrating downgoing multiples can provide a much wider image zone than does migrating only the conventional primary reflections in VSP data. Many methods have been developed to migrate the downgoing multiples. Examples include Yu and Schuster (2004), Jiang et. al. (2005), Fei et. al. (2006), and Jiang et. al. (2007).

The downgoing multiples recorded by three-component borehole receivers have the same 3C vector characteristics as the reflected data. However, almost all the migration methods so far developed migrate only a single scalar receiver component. As it is a difficult to impossible task to rotate the amplitude/energy of the multiple arrivals distributed on the three components onto a single scalar component due to their complex ray paths, the migration of the data recorded on all three components simultaneously instead of one scalar component can theoretically improve the image quality of the multiple reflections. The migration of all three components of the multiple data can also help to reduce image ambiguity and the migration artifacts inherent to any single scalar component migration algorithm.

In this paper we present an alternative methodology to perform 3C 3D vector migration for the 1^{st} order free-surface generated downgoing multiples which usually dominate the VSP wavefield. Using synthetic modeling and field data examples, we demonstrate that the developed methodology is able to produce an accurate and also significantly wider image zone using the 1^{st} order free-surface related multiples than can be acquired using only the conventional upcoming primary reflections.

Methodology

The 1st order free-surface related multiple arrivals are actually upgoing primary reflections that have been reflected back from the free surface, and then propagate down to the borehole receivers. Figure 1 illustrates the ray paths of the 1st order free-surface related multiple from interface $\mathbf{R_2}$ in a 2D geological model. The primary reflections recorded by the borehole geophones provide only a narrow cone of illumination, with the tip of the cone being centered at the shallowest receiver in the borehole. Most primary reflections however, will continue to propagate past the receiver, back to the free surface. The free surface acts as an almost perfect seismic reflector and the primary reflection from the free surface will be strongly reflected back down to the borehole receivers $\mathbf{G_1}$ to $\mathbf{G_n}$. The 1st order multiples will usually be the dominant wave mode in the VSP wavefield as the higher order multiples will attenuate quickly due to their much longer travel distances relative to the 1st order multiples. A comparison of the illumination zone generated by the upcoming primary reflections and the illumination zone generated by the 1st order free-surface related multiples show that the multiples will image a significantly wider geologic area.

The following major steps are used to perform 3C vector migration using the 1st order free-surface related multiples:

(1) Build a mirror velocity model symmetric about the free surface. We vertically up-extend a velocity model beyond the free surface to a distance equal to the deepest receiver depth in the VSP survey, so that the extended velocity model is symmetric about the free surface as shown in Figure 1.

(2) Project the borehole receivers to their virtual positions on the mirror velocity model. The true positions of the borehole receivers ($\mathbf{G_1}$ to $\mathbf{G_n}$) are projected to their virtual positions ($\mathbf{G_1'}$ to $\mathbf{G_n'}$) in the mirror velocity model; the true receiver positions and their virtual receiver positions will be symmetric about the free surface (Figure 1). The combination of Steps 1 and 2 is referred to as the mirror symmetric principle for the 1st order free-surface related multiples. Based on this mirror image principle, we can treat all 1st order free-surface multiples recorded by borehole receivers $\mathbf{G_1}$ to $\mathbf{G_n}$ as if they were primary reflections recorded by virtual borehole receivers $\mathbf{G_1'}$ to $\mathbf{G_n'}$. A major advantage in treating the 1st order multiples as primary reflections is that we can make use of almost all existing migration algorithms developed for primary reflections to migrate the 1st order multiples.

(3) Calculate and build travel time tables from every source/virtual receiver position to each image point in the velocity model. There are a number of techniques/methods available to calculate source/receiver to image point travel times. We utilize a fast marching method developed for 3D TTI media (Lou, 2006) to calculate the travel times accurately and efficiently.

(4) Perform three-component (x, y, z) vector summation of the 3D Kirchhoff prestack depth migration for the 1st order free-surface related multiples. Using the travel time tables generated in step 3, we can write the three- component vector summation of the 3D Kirchhoff pre- stack depth migration for the 1st order multiples as:

$$M(i,j,k) = \sum_{s}\sum_{g'} W(i,j,k,s,g')\ [r_x(i,j,k,g')\,A_x(t_s(i,j,k) + t_{g'}(i,j,k)) + r_y(i,j,k,g')\,A_y(t_s(i,j,k)+t_{g'}(i,j,k)) + r_z(i,j,k,g')\,A_z(t_s(i,j,k)+t_{g'}(i,j,k))] \quad (1)$$

where $M(i, j, k)$ is the migration result for each image grid (i, j, k), $W(i, j, k, s, g')$ is a weighting factor which varies with the position of the image point, s is the source and g' is the virtual receiver, $[r_x(i, j, k, g'), r_y(i, j, k, g'), r_z(i, j, k, g')]$ are the x, y, and z receiver components of a unit ray vector of the multiples from the image point (i, j, k) to the virtual receiver g', $t_s(i, j, k)$ is the travel time from the source s to the image point (i, j, k), $t_{g'}(i, j, k)$ is the travel time from the image point (i, j, k) to the virtual receiver g', and $[A_x(t_s(i, j, k) + t_{g'}(i, j, k)), A_y(t_s(i, j, k) + t_{g'}(i, j, k)), A_z(t_s(i, j, k) + t_{g'}(i, j, k))]$ are the three vector component (x, y, z) amplitudes of the receiver g' at travel time $t_s(i, j, k) + t_{g'}(i, j, k)$.

Examples

The methodology was first tested using a dataset generated by ray-tracing modeling a 2D layered model using walkaway VSP survey geometry (WVSP). The model is shown as Figure 2. The model has seven layer interfaces with contrasting P-wave velocities. There are a total of 61 source positions ranging between the X coordinate locations of 2000 and 8000 ft, with a 100 ft interval between source positions. A total of 30 three-component borehole receivers were modeled between the vertical depths of 5000 and 6450 ft spaced at 50 ft intervals. The wellhead position was at an X coordinate of 5000 ft. Two, 2-component (X and Z) common shot gathers are displayed; Figure 3a shows the upgoing (primary reflected) wavefield, and Figure 3b shows the 1st order free-surface related downgoing multiples. The vector migration results for the upgoing primary reflections and the multiples are shown in Figure 4. Although small sections of the three layer interfaces below the borehole receivers have been accurately imaged, the imaged zone is limited to a narrow cone around the borehole with its tip at the shallowest borehole receiver (Figure 5a). The imaged zone of the downgoing multiples however (Figure 4b), shows that the multiple migration image zone has been widely extended laterally above and below the borehole receivers without any significant migration artifacts.

We have also successfully applied the methodology to field VSP data. Figure 5 displays several selected shot gathers from a WVSP data set acquired in the North Sea.

The two horizontal components were first rotated to the radial- transverse coordinate system to maximize the horizontal energy in the radial direction. Wavefield separation was done on the vertical and radial components. Figure 5a shows upcoming reflections and Figure 5b shows the downgoing multiples on each component. Figure 6a shows the vector migration results for the upgoing reflections and Figure 6b shows the downgoing multiple migration. The migration of the downgoing multiples produces a high- quality image zone with much wider lateral sub-surface coverage both above and below the borehole receivers than the migration of the upgoing reflections. Figure 7 shows a surface seismic section acquired along the WVSP profile. A comparison of Figure 6b with Figure 7 shows that the dominant reflection events can be closely tied to each other. The image from the VSP downgoing multiples appears to have significantly higher resolution than does the image of the surface seismic data.

Conclusions

The 1st order free-surface related multiples, which usually dominate the downgoing wavefields in VSP data, provide a much wider seismic illumination zone than that seen by conventional primary VSP reflections. We have developed a new methodology to perform three-component vector migration for the 1st order free-surface related multiples. The new method is based on the free-surface mirror image principle and a vector summation algorithm for Kirchhoff pre-stack depth migration. Test results for both synthetic modeling and field VSP data suggest that our method can accurately produce a much wider image zone than conventional VSP migration using primary reflections only. The image quality is also significantly enhanced by the migration of the data recorded on all three vector components instead of one scalar component as is usually done in conventional VSP migration methods.

Acknowledgments

We would like to thank Jorge Lopez of Shell International E&P Inc. and Jitendra Gulati of VSFusion for their constructive suggestions to this work. We also thank Shell for giving permission to publish the field data examples in this paper.

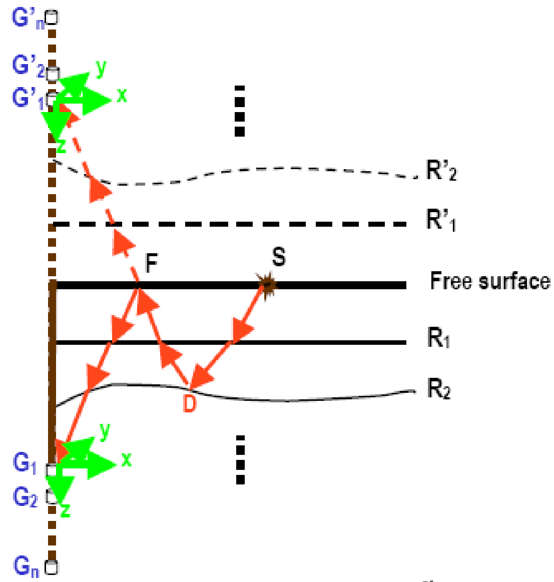

Figure 1. Illustration of principle for 1st order free- surface related downgoing multiple imaging.

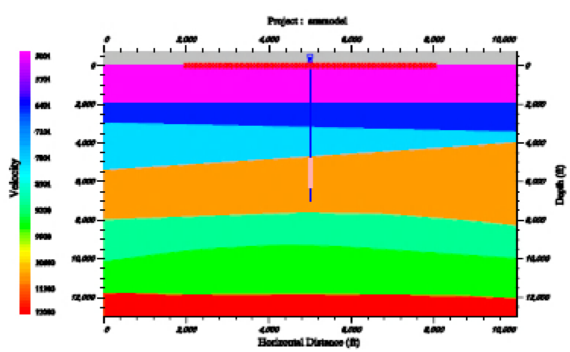

Figure 2. 2D geologic model used for WVSP ray trace modeling.

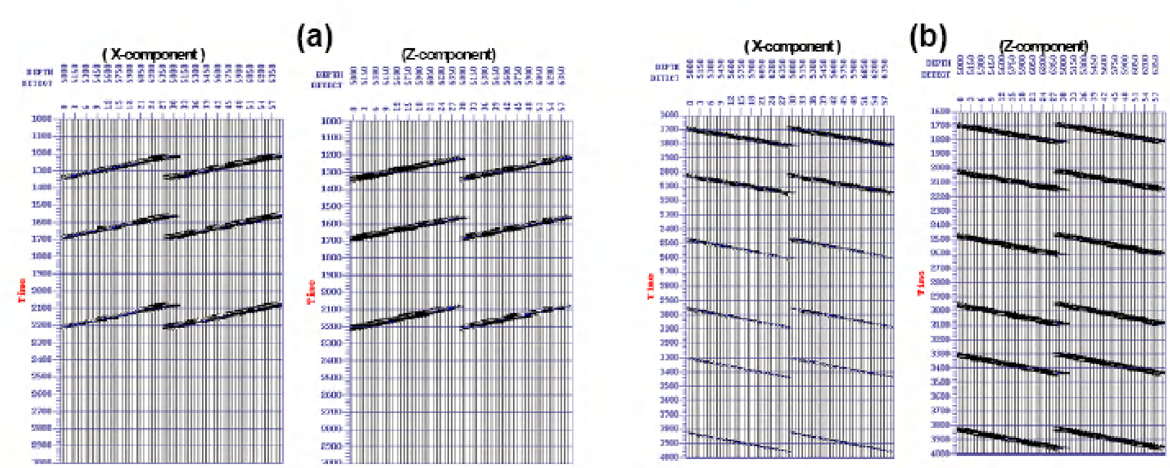

Figure 3. Two selected shot gathers after ray-trace modeling for the model in Figure 2: (a) two-component (X and Z) upgoing primary reflections, and (b) two-component (X and Z) wavefields of 1st order free surface related multiples.

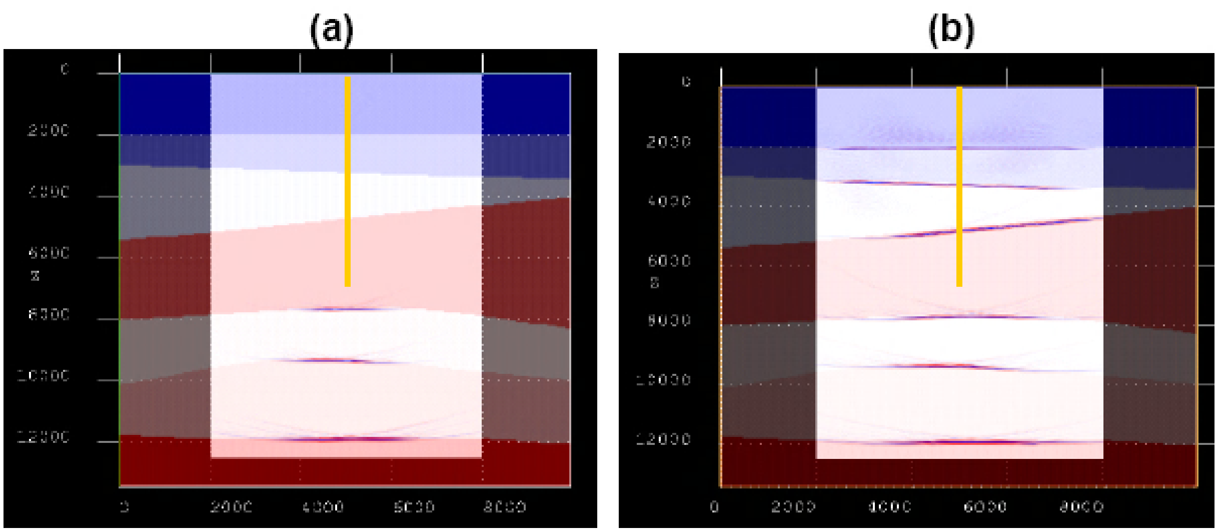

Figure 4. Vector migration results: (a) for the upgoing primary reflections, and (b) for the 1st order free-surface related downgoing multiples. The imaged zone of the multiples has been widely extended above and beyond the borehole receivers.

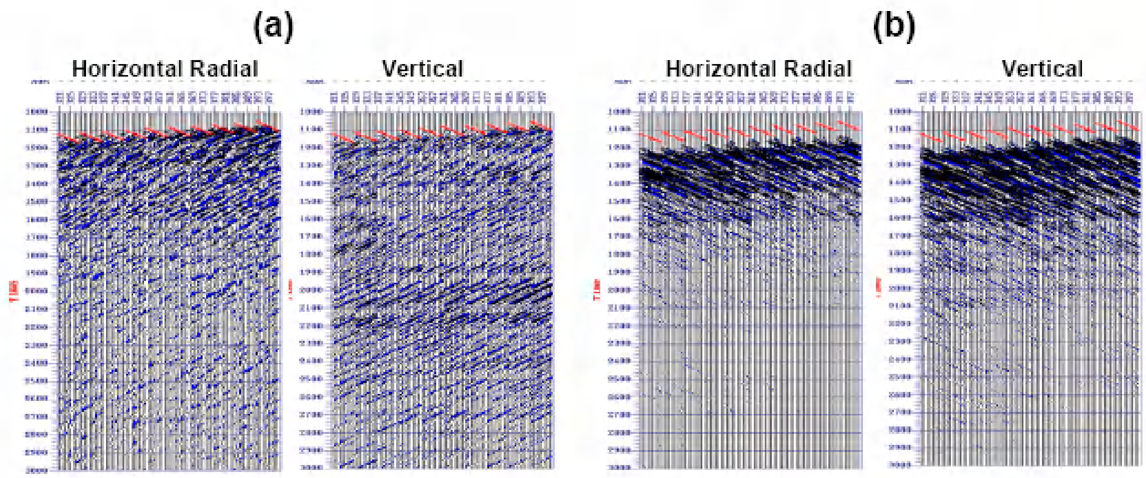

Figure 5. Selected shot gathers from a walkaway VSP data set acquired in the North Sea: (a) two- component (horizontal radial and vertical) upgoing reflections, and (b) two-component (horizontal radial and vertical) downgoing multiples.

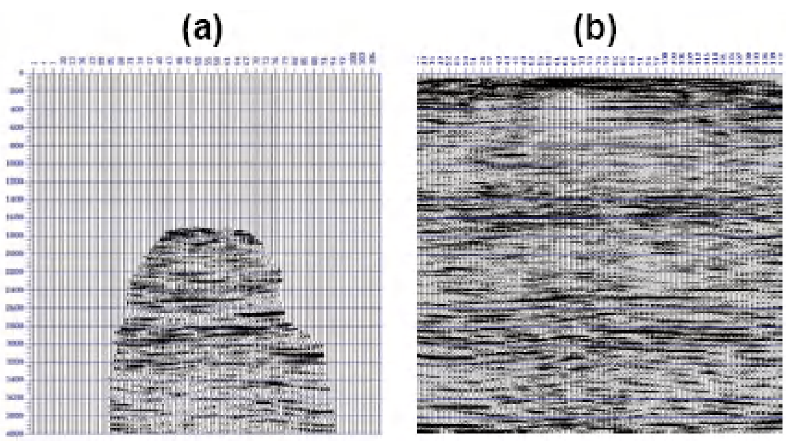

Figure 6. Vector migration results of the walkaway VSP data in Figure 5: (a) for the upgoing reflections, and (b) for the downgoing multiples.

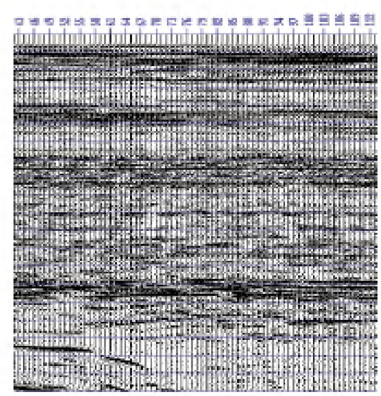

Figure 7. Surface seismic line acquired over the WVSP profile in Figure 6.

Edited References

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2007 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

References

Fei, T., and Q. Liu, 2006, Wave equation migration for 3D VSP using phase-shift plus interpolation: 76th Annual International Meeting, SEG, Expanded Abstarcts, 3457–3461.

Jiang, Z., J. Sheng, J. Yu, G. Schuster, and B. Hornby, 2007, Migration methods for imaging different-order multiples: Geophysical Prespecting, 55, 1–19.

Jiang, Z., J. Yu, G. Schuster, and B. Hornby, 2005, Migration of Multiples: The Leading Edge, 24, 315– 318.

Lou, M., 2006, Efficient and accurate traveltime computation in 3D TTI media by the fast marching method: 76th Annual International Meeting, SEG, Expanded Abstracts, 184– 188.

Yu, J., and G. Schuster, 2004, Enhancing illumination coverage of VSP data by crosscorreelogram migration: 74th Annual International Meeting, SEG, Expanded Abstracts, 2501–2504.