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Duplex Wave Migration and Interferometry for Imaging Onshore Data without Angle Limitations

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SUMMARY

Two migration procedures are described which allow a wide range of steep-dip seismic boundaries to be imaged. The first procedure is based on using duplex waves that suffer mode conversion when passing through seismic heterogeneities. Thus, these are transmitted converted waves, which are still not involved in surface seismic exploration. The second procedure is based on interferometric migration both compressional and converted wave fields, continued downward to the points of mode conversion. For imaging, this procedure uses primary reflected compressional and converted waves, as well as duplex reflected and transmitted compressional and converted waves. This assembly of waves allows us to obtain a migration procedure with, practically, no limitations on the angle of inclination of the seismic boundaries. Examples showing both migrations on synthetic data are provided.

Introduction

Surface seismic exploration uses reflected and refracted waves for imaging purposes. In this case, special conditions are required to create an image without limitations on the angle of inclination of the seismic boundaries, for example, the strong vertical velocity heterogeneity (VVH) to form turning waves as described by Hail et al. (1992). Under these conditions the refracted waves will return to the surface, however the required size of recording aperture is large and for accurate lateral positioning a very accurate depth model over a very wide area is a must.

However, if we use duplex waves (DW) to image a vertical boundary, no VVH need to be present and the recording aperture can be quite small. The DW is produced when a primary event that has been reflected from a deeper event reflects again off from the vertical boundary and then returns to the surface. The path of the DW may also be reversed – first bouncing off the vertical boundary and then the deeper base boundary.

The first paper that described the use of DW to image vertical boundaries on synthetic data was by McMechan (1983). Reverse time migration (RTM) was used in this case, however the inability of RTM to attenuate the primary energy was problematic because its strength was so much greater than that of the DW energy that it masked the image of the vertical boundary. McMechan got around this problem by attenuating the primary energy on the shot gathers before the application of RTM.

Farmez et al. (2006) presented the results of RTM applied to a 3D data set to produce the vertical boundary images from a salt dome. In this case the problem of the hindrance waves was solved by using a reference velocity for the salt that was considerably different from the velocity in the area of the salt dome. This limits the applicability of duplex wave migration (DWM). The essential characteristic that is necessary for this method to work is the significant difference in travel time inside the salt versus its travel time in the sediments surrounding the salt. Faults and fracture zones in reservoir country rock usually have thickness in the order of one seismic wavelength. Defining a substantially different velocity to this narrow interval around the fault will not produce a significantly different travel time for the purpose of attenuating the hindrance wave energy.

Marmalyevskyy et al. (2006) have developed a Kirchhoff method for DWM that is based on the Green's function using the kinematics of DW. The DWM algorithm is designed to image the DW energy that will arrive at a time greater than that of the primary reflections from a base boundary that is one of the sub-horizontal boundaries. This approach requires the base boundary to be specified. A beam tube construction eliminates the migration noise that would result from including the base boundary primary reflections in the migration summation. With this approach both, salt dome's walls (Marmalyevskyy et al., 2005) and sub-vertical tectonic faults (Marmalevskyi et al., 2007) can be imaged. But based on this migration, only sub-vertical boundaries are imaged.

In vertical seismic profiling (VSP), transmitted converted waves are used for imaging without limiting the angle of inclination of the seismic boundaries. Xiao et al. (2007) demonstrated the possibility to obtain interferometric images of transmitted waves for delineating the flanks of salt domes. They used stationary-phase migration (Schuster, 2001) with crosscorelation between the PS and PP transmitted arrivals before phase shift.

Niheil et al. (2000) used the interferometric principle to form seismic images in a wide range of boundary dips. They used RTM of VSP data to produce images of both vertical fractures and horizontal boundaries. They modified the RTM algorithm in such a way that instead of forward continuation of a compressional wave-field from a source, they used the backward continuation of down going compressional wave registered at VSP receivers.

The interferometric principle of VSP-data migration has allowed to create migration procedure less sensitive to velocity heterogeneities in the area between the source and the target object.

In onshore exploration, in order to obtain images without any restriction to boundary dips, besides singl-reflected PS and PP waves, DW should be utilized, which convert their mode when reflecting from or transmitting heterogeneities.

In this paper, we consider new methods combining DWM and interferometry for reflected and transmitted PS and PP waves to form images without any restriction to boundary dips in onshore exploration.

Method

Each medium's heterogeneity may be considered a point of wave's mode conversion. In Figure 1, a scheme is shown where a duplex wave is reflected from boundary G and is incident on a vertical boundary (boundary between two media, fracture zone, etc.). At each point of this boundary, four waves will be formed, namely, reflected longitudinal (compressional) P_1P_1, reflected converted P_1S_1, transmitted compressional P_1P_2, and transmitted converted P_1S_2 waves.

By using DWM on these data we can create three images of the sub-vertical boundaries. Two of them will be formed by longitudinal reflected waves (LRW) and converted reflected waves (CRW) by using velocity models for compressional and shear waves. The third image is formed by converted transmitted waves (CTW). In this case, in order to obtain sub-vertical images using Kirchhoff DWM by LRW and CRW, we have to choose the area for imaging located, in general, outside the source-receiver pair. In case of imaging of a sub-vertical boundary by CTW the area for imaging need to be chosen, generally, inside the source-receiver pair. A separate image formation is important from the point of view that the reflection and transmission coefficients for the above specified waves can be of different sign, which will bring to a weakened resultant image.

By using CTW we can image not only sub-vertical boundaries, but also different steep-dip boundaries up to horizontal ones. The only condition to these boundaries is the formation, on them, of converted waves from below incident waves.

A peculiarity of the Kirchhoff DWM is the necessity to provide not only a velocity model for PP- and PS-waves, but also to specify the base sub-horizontal boundary. In many cases this is inconvenient.

When using interferometric migration of PS- and PP-waves for DWM, there no need in specifying the base boundaries. DW from all the sub-horizontal boundaries beneath the target interval are focused. Also, images of boundaries of various dips are formed as a set of points where the wave mode is converted.

Let us consider the possibility of image formation in a wide range of steep-dip boundaries without providing the base sub-horizontal boundary. As above discussed, every point of the sub-vertical boundary through which the duplex wave is transmitted may be considered a point of mode conversion. Assume that the P-waves are recorded on Z-component and while PS-waves on X-component. This is true, particularly, in onshore surveys in the presence of weathering zones, where all waves arrive to the surface almost vertically.

Let us downward continue the wave-field recorded on X-component by using shear wave velocities. By analogy, we can downward continue the wave field recorded on Z-component by using P-wave velocities. A characteristic of these downward continued wave-fields is that on any unknown discontinuity, where mode conversion occurred, the arrival time of the compressional wave will coincide with the arrival time of the converted PS wave. Thus, if we downward continue both the X- and Z-components of a common shot gather and at each level Zi cross-correlate the continued fields according to the equation

$$F(Xi\,,\,Zi)=\sum_{\omega} U_{xi}(Xi\,,\,Zi,\,\omega)\cdot U_{zi}^{*}(Xi\,,\,Zi,\,\omega), \qquad (1)$$

where * means complex conjugation, ω is a frequency, $U_{xi}(Xi\,,\,Zi,\,\omega)$ and $U_{zi}(Xi\,,\,Zi,\,\omega)$ are the spectra of the continued wave-fields at the point (Xi , Zi), then, in conformity with the interferometric principle by Claerbout (1978), a seismic image of the medium F(Xi , Zi) will be formed at the corresponding level.

For interferometric two wave-fields migration (TWFM), we need to know the velocity model above the mode conversion points, but it is not necessary to know the velocity in the part of the section where the first duplex reflection occurred. In the case of primary reflection waves, which allow us to create images of sub-horizontal boundaries, there is not need to know the velocities in the interval from the shot point to the point of the first reflection and even no need to know the shot point location and his static correction.

Thus, requirements to the velocity model and therefore to discontinuities not taken into account decrease significantly. In this image formation, all types of PP- and PS-waves, such as primary reflected, refracted and duplex, will participate. Among the last ones, in a combined approach, we will use reflected and transmitted waves.

The continuation of the wave-field can be performed by any of the known algorithms: in the spectral domain, finite-difference method based on one-way or two-way wave equations or Kirchhoff method. It should be noted that in this case we do not have the issues that arise with RTM, due to the necessity to provide non-reflective boundaries.

Examples

Figure 2 shows the described above approach to imaging by using different types of duplex waves. This figure illustrates a model of a sub-vertical layer with a thickness of 80 m (in Figure 2a the vertical layer is marked with an arrow) and presents images obtained by using duplex LRW (Figure 2 b), CTW (Figure 2 c) and CRW (Figure 2 d). From this figure one can see that in this case the image with the best quality is obtained by using CTW (Figure 2 c).

CTW are created not only on vertical discontinuities but also on discontinuities with arbitrary angles of inclination. This fact is used in DWM by CTW for seismic imaging without limiting the angle of inclination of the boundaries.

Figure 3 shows a model (Figure 3 a) and its image (Figure 3 b) where horizontal and vertical boundaries are formed simultaneously. Artifacts formed in the junctions of horizontal and vertical layers are related to the presence of duplex LRW and CRW.

Figure 4 demonstrates an example of simultaneous image of vertical and horizontal boundaries obtained by interferometric TWFM. In this case primary and duplex PP and PS reflected waves were used. It is worth mentioning, that a large difference in velocities between P- and S-waves allows high quality images to be obtained, even in the case when PP- and PS-waves are recorded in the same component.

To perform TWFM, it is not imperative to use only the PP- and PS-waves. These could be two different type wave-fields, connected with each other by common reflection or transmission points. The selection of these wave-fields allows migration procedures with new useful properties to be obtained.

For example, let us form two fields. The first one is created by downward continuing a common shot gather field and by using P-wave velocity model. The second one is created by upward continuing the field of the same gather and by using the P- velocity model of the medium that is symmetric (relative to the observation surface) to the real medium.

Then the image of the medium is created by the cross- correlation (see Eq. 1) of the first and second wave fields at the levels Zi^{+} and Zi^{-}, which indicate levels higher and lower to the surface, respectively. Primary waves from all the boundaries in the medium will form an image as a result of their cross-correlation with the surface-related first-order multiples. In the same way, first-order multiples will image all the boundaries by cross-correlation with the second-order multiples and so on. Furthermore, noise related to multiples will not be observed in the image.

Figure 5 depicts an example of seismic imaging by using multiple waves. On the left, it is shown the result obtained with TWFM. On the right, it is shown an image obtained by Kirchhoff migration. In the last case, there are two boundaries. The second boundary is an artifact produced by the first-order multiples.

Conclusions

Two methods were described and examined for imaging a wide range of steep-dip seismic boundaries. The first one is based on using duplex transmitted converted waves, while the second one on two mutually-related reflected and/or transmitted wave-fields. Transmitted converted waves, which are not still widely used nowadays in onshore seismic exploration, play an important role in the imaging of wide range steep-dip boundaries. These waves are caused by various geological discontinuities, with fracture zones among them. These zones attract much attention in oil and gas seismic exploration.

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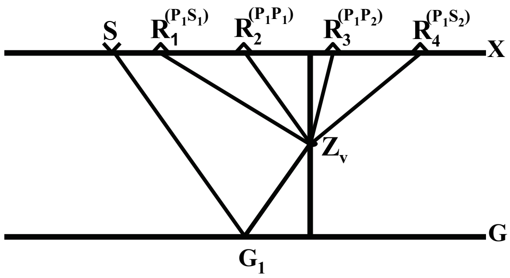

Figure.1 Scheme of the formation of four types of duplex waves at a vertical boundary.

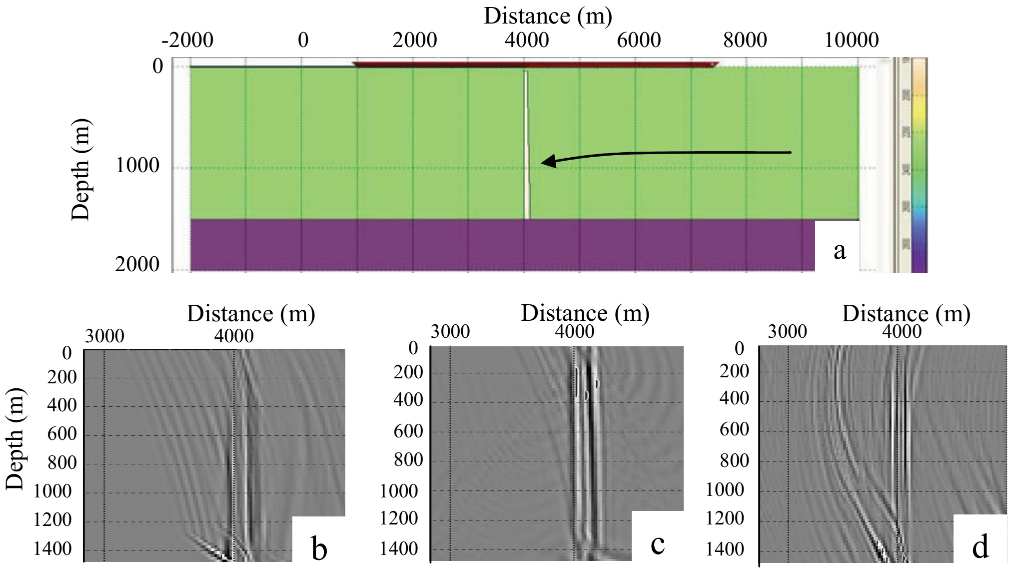

Figure 2. Image of a thin vertical dike obtained with different types of duplex waves.
Model (a); images obtained with: compressional reflected wave (b), transmitted converted wave (c); reflected converted wave (d). The dike of a 80 m thickness is marked with the arrow.

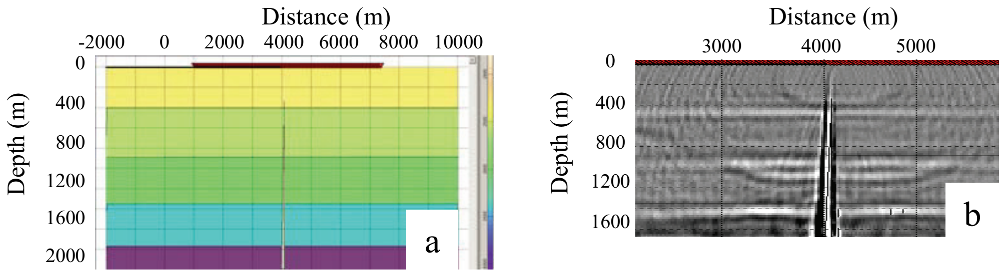

Figure 3. Model of a dike thinning to the top in a horisontally layered medium (a) and image obtained with transmitted converted duplex waves (b). The image contains both horizontal and vertical boundaries.

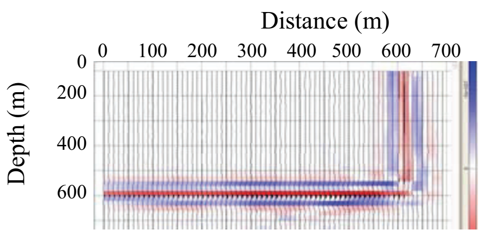

Figure 4. Image obtained with TWFM.
Primary reflections as well as duplex compressional and converted waves were used.

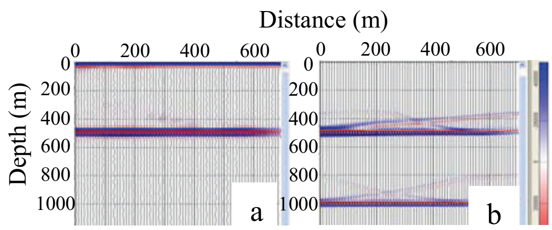

Figure 5. Images obtained with primary and multiple reflections: TWFM (a) and Kirchhoff migration (b).