Crosswell Imaging by 2-D Prestack Wavepath Migration

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ABSTRACT

Prestack wavepath migration (WM) is applied to 2-D synthetic crosswell data, and the migrated images are compared to those from constrained prestack Kirchhoff migration (KM). Preliminary results show that WM can effectively locate the fault boundary, and slightly improve the image resolution compared to the KM method. However, both the KM and WM images are suitable for interpretation. It is shown that the WM images contain fewer migration artifacts, but the signal strength in the WM images is typically weaker than that in the KM images.

INTRODUCTION

Prestack migration of crosswell seismic data has proven to be a useful tool for imaging interwell velocity structure. Once the primary reflections have been effectively extracted from the data, VSP-CDP mapping (Lazaratos et al., 1992) or prestack migration (Qin and Schuster, 1993; Cai and Schuster, 1993) can usually generate satisfactory crosswell images.

Among the migration methods used for crosswell imaging, the Kirchhoff migration is usually used as a standard for comparison with other migration methods. It is well accepted that, for simple interwell geology, prestack KM is suitable for resolving interwell geological structures, as long as some anti-aliasing constraints are added in the migration. However, when the interwell structure becomes more complex, problems may arise with KM. For example, the up-going and down-going waves will be more difficult to separate, and the far-field migration artifacts will be more difficult to suppress.

One possible solution is prestack WM (Sun, 1999, 2000a, 2000b) in which the event energy is migrated to a Fresnel zone that surrounds the specular reflection point. Thus, in principle, WM can give rise to fewer far-field migration artifacts. The restriction on positive incidence angles is equivalent to an up-going and down-going separation filter, which allows WM to automatically separate the wavefield.

In this report, I will apply WM to 2-D synthetic crosswell data, where the associated interwell geology is somewhat complex. The key objectives of this report are to determine whether WM can reduce artifacts and create a crosswell image with acceptable quality. I also will compare the quality of WM images to constrained KM images.

METHODOLOGY

Crosswell Constrained Kirchhoff Migration

The formula I used for constrained KM is:
where $s$ represents the source, $g$ represents the geophone, and $M(r)$ is the image at the point scatterer $r$; $N_s$ is the number of common shot gathers and $N_g$ is the number of geophones for a single shot; $A_{sr}$ and $A_{rg}$ are the geometric spreading factors proportional to the distance between the two points in the subscripts; $\theta$ is the angle between the vertical direction and the ray direction at the receiver position; $\tau_{sr}$ and $\tau_{rg}$ are the traveltimes for energy to propagate between the two points in the subscripts; $z_s$ and $z_g$ are the depths of the source and the geophone, respectively, and $D$ is the observed particle velocity seismogram.

Some preprocessing is performed to extract useful reflections from the data, and some constraints are used in the migration for generating a better image. The key steps in the constrained KM can be summarized as below:

- Direct waves are removed from the data. In the seismic trace, we will retain the events arriving between the direct P-wave and the direct S-wave, and the rest of the trace is muted.
- By applying an F-K filtering, the wavefield is separated as up-going reflections and down-going reflections, and different reflections will be migrated to different portions in the model space.
- A reflector dipping angle constraint is used to decrease the migration smile. For synthetic data, the threshold value of the dipping angle can be chosen according to the known geological information.
- At the reflector, any ray with an incidence angle larger than 60 degrees will be simply eliminated.
- At the geophone location, a weighting coefficient is used to compensate the recording loss.
- The loss due to geometric spreading is compensated in the migration.
- The ray coverage in crosswell geometry is compensated according to the number of rays visiting the same reflector point.

**Crosswell Wavepath Migration**

Unlike KM, which only needs the traveltime for migration, WM requires both traveltime and ray direction information. The formula I used for crosswell WM is:

\[
M(r)\mid_{r \in \text{raypath}} = \sum_{s=1}^{N_s} \sum_{g=1}^{N_g} \cos\theta \frac{1}{A_{sr}A_{rg}} D(z_s, z_g, \tau_{sr} + \tau_{rg}),
\]

where $H(r)$ is a function of the event amplitude and can be defined as:

\[
H(r) = \begin{cases} 
1 & \text{if } D(z_s, z_g, \tau_{sr} + \tau_{rg}) > \text{threshold value}; \\
0 & \text{otherwise.}
\end{cases}
\]

When $H(r)$ is non-zero, the event in the trace is regarded as strong enough and will be picked by the algorithm. An incidence angle associated with this picked event is then computed, and a ray will be traced into the medium. Unlike Equation 1 in which the point scatterer could be anywhere along the corresponding quasi-ellipse in the model space, Equation 2 further requires the point scatterer to be along the computed raypath.
The constraints listed above for KM can still be applied to WM; however, some of them are superfluous. In WM, for example, once the incidence angle is computed from the data, a ray can be shot from the geophone into the medium. If only up-going rays are allowed, then WM automatically separates up-going from down-going energy.

Other constraints, like the reflector dipping angle constraint and the reflector incidence angle constraint are not as useful to WM as they are to KM. Strictly speaking, no additional constraints are necessary for WM in which the event energy can be migrated to the true reflection point.

**2-D SYNTHETIC DATA EXAMPLE**

The synthetic data are generated by a 2-D elastic finite-difference modeling program for the fault model shown in Figure 1, where the P-wave velocity $V_p$ (Figure 1a) ranges from 2300 m/s to 3500 m/s. The S-wave velocity is taken to be 0.5$V_p$ (Figure 1b), and the empirical formula $\rho(x) \approx \sqrt{V_p(x)}$ is used to assign the density distribution $\rho(x)$ from the P-wave velocity distribution. Table 1 shows the related modeling parameters.

Table 1. The parameters for 2-D crosswell forward modeling. Here the model is discretized into a $(N_x, N_z)$ grid, with grid intervals of $(dx, dz)$. There are $N_s$ sources and $N_g$ vertical component geophones along the left-side and right-side of the model, respectively. The source function is a Ricker wavelet with a peak frequency of $F_s$, and the time axis is sampled to be $dt$.

<table>
<thead>
<tr>
<th>$N_x$</th>
<th>$N_z$</th>
<th>$dx$</th>
<th>$dz$</th>
<th>$N_s$</th>
<th>$N_g$</th>
<th>$F_s$</th>
<th>$dt$</th>
</tr>
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<td>121</td>
<td>281</td>
<td>0.75m</td>
<td>0.75m</td>
<td>36</td>
<td>71</td>
<td>120Hz</td>
<td>0.1ms</td>
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</table>

Figure 2 shows a synthetic common shot gather, where both the direct P-wave and direct S-wave are very strong and must be removed. In order to separate the up-going P-P reflections and down-going P-P reflections, F-K filterings are applied to the data. Figure 3 shows the extracted up-going P-P reflections, whereas Figure 4 shows the extracted down-going P-P reflections for the same shot.

Figure 5a shows the constraint KM image, and Figure 5c shows the WM image, both of which correlate well with the true model shown in Figure 5b. For the flatter layers in the top left part of the model, the events in the WM image are weaker than and not as continuous as those in the KM image. However, the WM image shows a slightly better delineation of wedges A and B, especially for their dipping boundaries. It is also shown that WM resolves the dipping fault noticeably better than KM. The dipping angle of the fault in this study is about 40 degrees, and I believe that WM can perform even better than KM for steeply dipping faults and for more complex salt boundaries. The reason is that WM migrates the seismic energy from a single event to its actual reflection point. The entire interface can be formed by stacking these actual reflection points. Even though the interface continuity might be poor, the position of the interface should be clear and correct. However, in KM, the shape of the boundary is achieved by stacking and canceling many quasi-ellipses. For a crosswell survey whose source and receiver apertures are limited, the stacking and canceling are usually insufficient for steeply dipping layers. It is difficult to quantify the resolution differences between the KM and the WM images, but it appears that WM slightly improves the image resolution in some places of the image, like layers D and E.

It is well accepted in crosswell research that the separation of up-going and down-going reflections is not a problem. However, as the interwell structure becomes more complicated, or as the source frequency is so high that the data is spatially aliased, the reflection separation might present problems. This worry is unnecessary for WM in which the moveout information has been implicitly included in the incidence angle information. My next step is to test WM on data without up-going and down-going separation.
Figure 6a shows the KM image where the shallow reflectors are blurred. Obviously, this image is much worse than the KM image shown in Figure 5a. In contrast, the WM image in Figure 6c does not show large differences compared to the WM image in Figure 5c, but does suggest the need for separation.

**DISCUSSION**

Applying 2-D WM to synthetic data shows that WM can generate crosswell images with acceptable quality. Compared to 2-D constrained KM, WM resolves steeply dipping fault boundaries noticeably better. Image resolution, especially for the dipping layers, is slightly better in the WM images than in the associated KM images.

Unlike KM, which requires the separation of up-going and down-going reflections before migration, WM can sometimes be applied to data without separating the wavefield. Future work will apply WM to crosswell field data. Any sponsor who can provide us with field data of complex interwell structure will be highly appreciated.

**ACKNOWLEDGEMENTS**

I am grateful for the financial support from the members of the 2000 University of Utah Tomography and Modeling/Migration (UTAM) Consortium.

**REFERENCES**


Sun, H., 2000a, 2-D prestack wavepath migration applied to the Husky data: Utah Tomography and Modeling/Migration Development Project, 1999 Annual Report, 75-84.

Figure 1: The P- and S-wave velocity structure of the fault model.
Figure 2: A synthetic common shot gather generated by a 120 $Hz$ Ricker wavelet source. The source is located at a depth of 84 $m$. 
Figure 3: The P-P up-going reflections extracted from the common shot gather shown in Figure 2.
Figure 4: Same as Figure 3 except the P-P down-going reflections.
Figure 5: (a) Prestack KM image for the synthetic fault data. Up-going and down-going reflections were separated before migration; (b) Associated velocity model; (c) Same as (a) except the WM image, where the steeply dipping fault is resolved noticeably better than (a).
Figure 6: (a) Prestack KM image without up-going and down-going separation; (b) Associated velocity model; (c) Same as (a) except the WM image. Without wavefield separation, KM creates a blurred image, whereas WM gives rise to an image with acceptable quality.