Crosswell Imaging by 2-D Prestack Wavepath Migration

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ABSTRACT

Prestack wavepath migration (WM) is applied to 2-D synthetic and field crosswell data, and the migrated images are compared to those from constrained prestack Kirchhoff migration (KM). The results with synthetic data show that WM can effectively locate the fault boundary, and gives good image resolution similar to the KM method. 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. The results with field data show that the WM images look similar to the KM image, all of which roughly correlate with the P-wave sonic logs.

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, 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 to 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 first apply WM to 2-D synthetic crosswell data, where the associated interwell geology is somewhat complex. I will then apply WM to McElroy field data. 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:
\[
M(r) \mid r \in model\ space = \sum_{s=1}^{N_s} \sum_{g=1}^{N_g} \cos \theta \frac{1}{A_{sr}A_{rg}} D(z_s, z_g, \tau_{sr} + \tau_{rg}),
\]

(1)

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 up-going and down-going reflections are separated, 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:

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

(2)

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

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

(3)

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 the 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 $0.5V_p$ (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>
</thead>
<tbody>
<tr>
<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>
</tr>
</tbody>
</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 filtering is 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 constrained 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 dip 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 image can be formed by stacking the migrated energy along the actual reflection points. Even though the interface continuity might be poor, the position of the interface should be well imaged. However, in KM, the shape of the boundary is reconstructed 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 somewhat 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.

2-D FIELD DATA EXAMPLE

The WM algorithm is now tested on a 2-D crosswell data set, the McElroy data. There are 201 shots evenly distributed along the well from depths of 811 m to 963 m, with a source interval of 0.76 m. For each common shot gather, there are 186 hydrophones evenly distributed from depths of 822 m to 963 m, with a trace interval of 0.76 m. The offset between the wells is 56 m, and the velocity model is discretized into a (295,801) grid, with grid point intervals of 0.19 m.

I follow the same processing as used in the wave equation traveltime and waveform inversions (Zhou and Schuster, 1996; Wang, 1998). The data are 200-1400 Hz bandpass filtered, followed by muting everything in the trace except the arrivals between the direct P-wave and the direct S-wave. The tube waves are then suppressed by using a median filter, and the up-going and down-going reflections are separated by applying a F-K velocity filter.

Figure 7 shows a raw common shot gather, where the data are dominated by complex wave modes including direct P and S arrivals, P-P and S-S reflections, P-S transmitted and reflected conversions, and tube waves. Figure 8 shows the same common shot gather as Figure 7 after suppressing the tube waves and eliminating the direct arrivals. Figure 9 shows the extracted up-going P-P reflections, whereas Figure 10 shows the extracted down-going P-P reflections for the same shot. The migration velocity model is shown in Figure 11 which was obtained from ray tracing tomography (Zhou and Schuster, 1996).

Figure 12 shows the constrained KM image, where the P-wave sonic logs and the associated synthetic seismograms are displayed besides the KM image. It can be seen that the KM image roughly correlates with the synthetics, especially for the main structures located at depths of 835 m and 930 m.

Figure 13 shows the obtained WM image. Similar to the KM imaging, the WM algorithm is now applied to data where the up-going and down-going reflections are separated. The WM image looks somewhat similar to the KM image, and roughly correlates with the sonic logs. However, the WM image appears to have artificial structures in the layers. Recall that in the above synthetic example, the main advantage of WM algorithm is its better ability to resolve the dipping fault. For this field data set, the interwell structure is flat, which can possibly explain why WM can not improve the image quality noticeably.

In order to verify that WM has a wavefield-separating feature inherent in the algorithm, the next step is to apply WM directly to data without wavefield separation. Figure 14 shows the obtained WM image, which looks similar to the WM image in Figure 13 and correlates with the sonic logs. The image continuity in Figure 14 is worse, but noticeably, more structural details have been revealed. I believe that in the wavefield separation, F-K dip filtering can sometimes create artificial signals, and smooth some incoherent events into coherent ones. Using incidence angle information, WM can avoid the F-K filtering or other similar filtering steps and migrate the un-separated data. This provides us with another way for crosswell imaging.

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 appears to resolve steeply dipping fault
boundaries slightly better. Image resolution, especially for the dipping layers, is slightly better in
the WM images than in the associated KM images.

Applying 2-D WM to McElroy field data shows that WM can generate an image with similar
quality to the constrained KM, except more artifacts seem to be present in the WM image. Both
the WM and KM images roughly correlate with the P-wave sonic logs.

Unlike KM, which requires the separation of up-going and down-going reflections before mi-
gration, WM can directly migrate data without separating the wavefield. The application of WM
to un-separated data seems to be helpful when the interwell structure is complex, or when the
contaminated data can not be cleaned effectively.

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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.
Figure 7: A raw common shot gather, where the source is located at a depth of 887 m.
Figure 8: The same common shot gather as Figure 7 except after processing. In the processing, the data were 200-1400 Hz bandpass filtered, the tube waves were suppressed, and the direct arrivals were eliminated.
Figure 9: The P-P up-going reflections extracted from the common shot gather shown in Figure 8.
Figure 10: Same as Figure 9 except the P-P down-going reflections.
Figure 11: The migration velocity model obtained from a P-wave traveltime tomography.
Figure 12: Prestack constraint KM image for McElroy field data. Up-going and down-going reflections were separated before migration. Both the source well and the receiver well sonic logs and their associated synthetics are plotted beside the KM image.
Figure 13: Same as Figure 12 except the WM image. Up-going and down-going reflections were separated before migration.
Figure 14: Same WM image as Figure 13 except that the up-going and down-going reflections were not separated before migration.