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Cross Dip Moveout Correction of Crooked 2D Seismic Surveys along Curved Processing Lines

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Summary

We propose a new Cross Dip Moveout (CDMO) correction for crooked-line binned reflection seismic data. First, an optimal slalom/curved processing line that best fits the Common Midpoint (CMP) positions is picked. Next, to address the directional variations along the curved line, the dip parameters are re-envisioned in two ways: First, they are selected regarding the general trend of the acquisition line, and second, they are referenced to a Cartesian, rather than an Inline/Crossline, system. While curved crooked-line binning increases the order of parameters involved for CDMO, it prevents reflection duplication. The proposed methodology was tested on synthetic data as well as field data collected as part of the Metal Earth (ME) project in Larder Lake Ontario, Canada. The results demonstrate improved reflection focusing, as well as the removal of dip-dependant velocities. Finally, the structural information gained from performing CDMO constrained the true orientation of a high impedance reflection.

Introduction

Crustal scaled seismic surveys are often collected along crooked acquisition lines due to their remote locations and logistical/economic restrictions. The line bends cause scattering of the Common Mid-Point (CMP) locations leading to a *swath* 3D dataset. The common way to process crooked-line seismic surveys is to project the CMPs onto a slalom line by employing a crooked-line binning approach (Rodriguez-Tablante et al., 2007). This approach attempts to collapse the 3D data onto a 2D line (Juhlin and Lund, 2011), or lines (Schmelzbach et al., 2007), which are best fitted to the CMP dataspace. Generally speaking, this utilizes long, prism-like bins, which collect CMPs that are sometimes dispersed over several kilometers around the processing line (Van der Velden, 2007). The slalom line can be straight, segmented, or, in this research, a low-order polynomial approximation of the acquisition line. An optimal processing line geometry was chosen in a way to preserve CMP-to-CMP bin fold regularity, as well as to address downstream steps in the data processing workflow such as migration. Notably, the position of the processing line has ramifications for the CDMO correction.

CDMO is an additional step in the prestack data processing sequence that corrects for the smearing of crossline dipping reflectors (Nedimovic and West, 2003). Additionally, CDMO removes anomalous dip-dependant moveout velocities, which can improve migration velocity models (Urosevic and Juhlin, 2007). Finally, the true 3D geometry of reflectors is gleaned by applying CDMO (Beckel and Juhlin, 2019). Therefore, CDMO has proven to be a useful step in the hard rock seismic processing workflow.

In this article, the effectiveness of CDMO is explored as part of pre-stack data processing steps, particularly for the case of using a curved processing line. On one hand, applying a curved processing line optimally regularizes the trace fold amongst CMP bins (Du Bois et al., 1990). However, the slalom line could lead to a variable crossline vector, the direction tangent to the slalom line, for every CMP location. Previous researchers (Nedimovic and West, 2003; Juhlin and Lund, 2011; Schmelzbach et al., 2007; Beckel and Juhlin, 2019; Urosevic and Juhlin, 2007) have considered such a variable crossline vector as a deterrent to utilizing curved slalom lines to perform CDMO. Nonetheless, in this paper, we show that by providing a one-dimensional approximation of the crossline vector for a given slalom line, the CDMO operator can function effectively. Furthermore, it was observed that a curved processing line suppresses artifacts of CDMO, particularly reflection duplication.

Background

CDMO is a necessary processing step for crooked-line binning to mitigate the artifacts caused by dipping reflectors in the crossline direction. If there is a cross-line dip, following stacking, those reflections will smear, as there is a residual common-depth-point time lag, even after Normal and Dip Moveout corrections (NMO and DMO, respectively). The time lag t_{cross} of the zero offset ray paths is dependant on the cross-line distance and the magnitude of dip. It is expressed as

$$\Delta t_{cross} = \frac{\sin\vartheta}{V_{rms}} y, \tag{1}$$

where ϑ is equal to the amount of the dip component in the cross-line direction, V_{rms} is the root mean squared velocity and y is the crossline distance (Larner et al., 1979). This can be expressed as a cross-slowness parameter

$$p_y = \frac{\sin\vartheta}{V_{rms}}, \tag{2}$$

which can then be expressed as a Linear Moveout (LMO) formulation in the τ-p_y domain (restricted to the crossline component of the ray paths)

$$\tau = t - p_y, \tag{3}$$

where τ is the intercept for traveltime t for $p_y = 0$ realized at the position of the CMP bin center. This function models plane waves reflected from a tilted interface over a halfspace in an isotropic media. Analogous to NMO, the cross-slowness field can be applied as a slant stack operation in the CMP domain.

A narrow-time CDMO operator may not distinguish nearby seismic reflections. Unlike NMO, which is a function of a continuous parameter (V_{rms}) amongst each value of t_0, cross-slowness parameters are often discontinuous. These sharp contrasts are problematic for swath-3D data because of the irregular distribution of fold (Nedimovic and West, 2003). Figure 1 illustrates this issue as applying CDMO on a synthetic gather (Figure 1a) at the wrong τ (Figure 1b) could lead to the repetition of the reflections in the stack (Figure 1c).

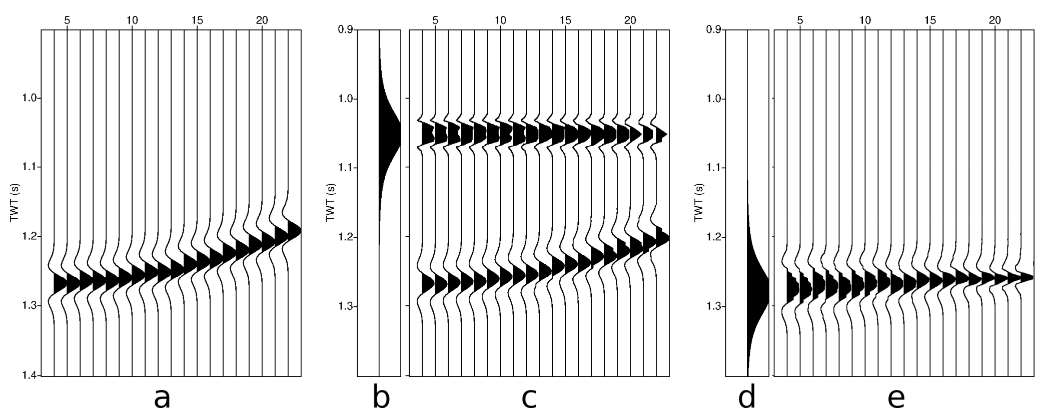

Figure 1 *Principles of CDMO illustrated on a synthetic CMP gather (a) applied at too early of a τ value (b) resulting in (c) and at a correct τ value (d) resulting in (e).*

A remedy for this problem is illustrated in Figure 1d, where the stacking CMP is kept close to the main distribution of arrival times in the gather. Positioning each CMP bin center on the processing line at or near spatial regions of highest fold in a polygonal chain will suppress reflection duplication as shown in Figure 1e. However, this inevitably curves the slalom line, which has to be addressed and corrected since the planar 3D orientation relative to each bin will not be constant. We resolve this issue by considering the 3D traveltime equation for an arbitrary CMP point in Cartesian space given by Levin (1971)

$$t^2 = \left(\frac{2D}{V}\right)^2 + \frac{x^2\left(1 - \sin^2\varphi\cos^2\vartheta\right)}{V^2}, \tag{4}$$

where D is the perpendicular distance between the interface and the dipping plane, φ is the true dip, ϑ is the dipline azimuth and x is the source-receiver offset.

Methods

The Larder Lake transect of the ME Project was chosen to test the proposed CDMO correction. It is located in the Abitibi greenstone belt, Ontario, Canada (Figure 2). The data was acquired using vibroseis as a seismic source on a series of connected logging roads and highways with an approximate north-south direction. A total of 844 shots were collected with a maximum of 2433 channels. The maximum width of the CMP swath, in 10 km offset-windowed data, was approximately 3.0 kilometers.

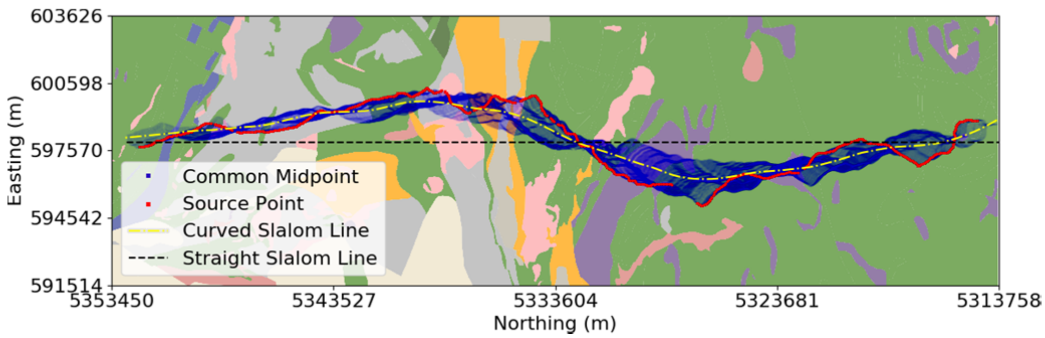

Figure 2 *Larder Lake acquisition line, trace fold and processing geometries used in this study.*

A slalom line was carefully fit to CMP locations by repeatedly applying a mean filter to the receiver line until its vertices were all close to the centers of maximum fold (yellow dashed line in Figure 2). The Mid-points were binned every 12.5 meters along this line at a maximum radius of 5.0 km. For comparison, we also used a straight processing line with a north-south orientation (black dashed line in Figure 2). For the straight processing line, we binned CMPs in 12.5 meter intervals and 5.0 km radius. We also simulated a synthetic seismic data set with two dipping reflectors using the same acquisition layout and slalom/straight processing lines (Figure 3). The CDMO was performed on both real and synthetic data set using both slalom and straight processing lines.

To apply CDMO on the field data, the dip magnitudes had to be derived from it. This was done with constant moveout analysis as described by Urosevic and Juhlin (2007). A dip precision of 1.0 degrees was investigated over a range of ±30.0 degrees. With these parameters, N_1 the size of the set of dips along any directional component (inline or crossline), equals 60. Addressing both inline and crossline components, Equation 4, is a function of two dip parameters (ϑ and φ), and therefore, the solution set for it, N_2, for a given range is $\frac{N_1^2}{N_1}$ times greater in size than N_1. With the above precision, N_2 becomes two orders of magnitude larger than N_1. To avoid excessive grid-searching across this large set, a first-order solution akin to Equation 1 was used to keep N 60. This is only valid under the assumption that *the period of a reflection is much greater than the period of the slalom line*. In other words, the geological structures extend much further than the curvatures in the survey, while remaining planar. Essentially, for a single dipping reflector, the CDMO direction cosines applied at one CDP at one end, will be equivalent to a second one applied at the other end (the magnitude may change). Therefore, a uniform ratio of directional components addresses variations in inline-crossline coefficients as a first-order approximation. Finally, it is advantageous to include the function parameters in terms of Cartesian coordinates rather than the Inline-Crossline position to keep singular CMP-to-CMP bin parameters at any given event.

Results

Figures 3a and 3b show the 3D orthographic depiction of CDMO applied to the synthetic data across both the straight and curved slalom lines, respectively. Figures 3c and 3d show the 2D plot of Figures 3a and 3b along the straight and curved slalom lines, respectively. While CDMO on a straight line removes cross-line smearing, moveout stretching and reflection duplication corrupt the image in parts of the seismic section. However, these artifacts are removed when a curved processing line is used.

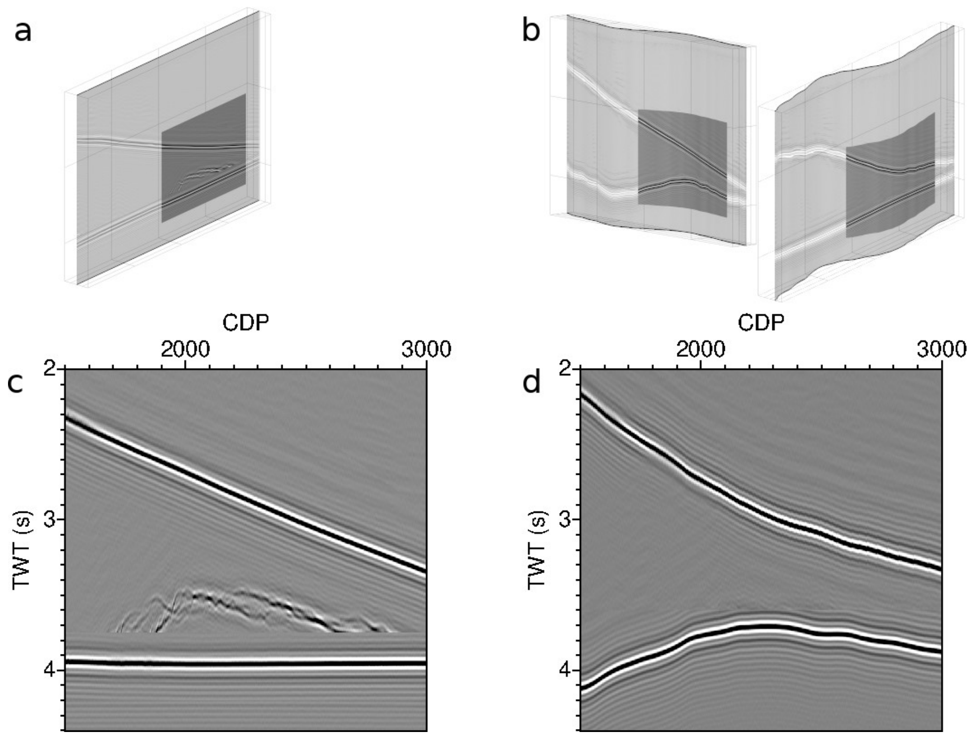

Figure 3 *a) and b) show the 3D orthographic rendering of the results of applying CDMO on synthetic data with two dipping planar events on a straight and curved slalom lines, respectively. c) and d) show the 2D plotting along the slalom lines of a and b, respectively.*

Figure 4a, shows a zoomed patch of the final time-migrated stack from the Larder Lake transect data with cross-dipping group of reflections. Figure 4b shows the same data but with +15 degrees of CDMO applied along the curved processing line. Overall, the amplitude of reflections improved and became more continuous, while a few steeply dipping events that were not imaged before became apparent. With the given orientation of the line, this translates to a cross-dip component of +15E. The inline dip was estimated from the stack to be +26N, and therefore, from the two components, the true strike and dip were calculated to be 030N and 29 degrees, respectively. Finally, after repeating the velocity analysis, the optimal NMO velocity reduced by 400 m/s demonstrating removal of the dip-dependant velocity anomaly.

Discussion and Conclusion

The results of CDMO applied to both synthetic and field data demonstrate the significance of removing cross-dip effects. This not only focuses the reflections but improves the velocity model by removing the dip-dependance of moveout velocities. Furthermore, discovering the optimal CDMO parameter provides structural information that can be plotted and overlaid onto reflections to enhance interpretation.

Applying CDMO on a curved line while still using a first-order approximation was more effective in comparison to the straight-line practice. Reflection duplication was suppressed in the synthetic data using a single parameter along the entire strike of the survey, irrespective of the direction changes in the slalom line. Similarly, in the field data, a reflection package was optimally enhanced with a uniform-parameter CDMO, even though the line bends substantially at that location. Curved line binning provided a longer survey plus gave a 3D aspect to the final stack which helps reveal the complex structural geology. Plotting and integrating geophysical data in 3D is now commonplace in software such as *OpendTect* (dGB Earth Sciences), for example. Considering that, the processor, in choosing a slalom line, has the onus of providing the 3D spatial positioning of the final stacked seismic section. It is ideal from a data integration perspective to keep the section as close as possible

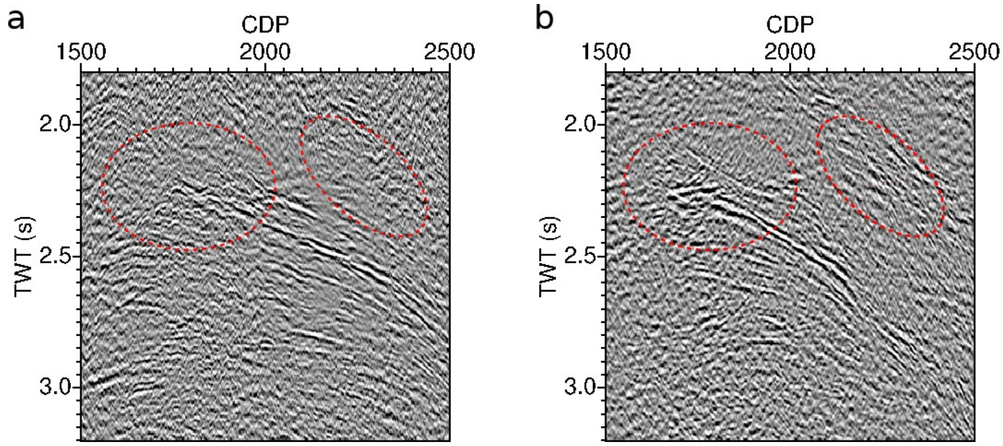

Figure 4 *Final migrated results of the field data without (a) and with (b) CDMO applied. Red dashed circles highlight improvements made to the reflections in the stack.*

to other geophysical and geological models collected under similar land access constraints, and thus curved processing lines are ideal. In conclusion, a CDMO operator that operates on curved lines effectively focuses the image while conforming with the best practices of the hard-rock data processing workflow.

Acknowledgments

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