Stanford Exploration Project, Report 112, November 11, 2002, pages 97–109

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Multicomponent data regularization

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ABSTRACT

Geometry regularization is a key process for obtaining reliable subsurface images with 3D seismic data. 3D regularization is, so far, a technique mainly used on *PP* land data. Multicomponent ocean bottom cable (OBC) technology simulates 3D land acquisition for multicomponent geophones at the ocean bottom. Reliable subsurface *PS* images, which provide amplitude information, have to go through a regularization process. Converted wave Azimuth Moveout (PSAMO) acts as a regularization operator in the formulation of the geometry regularization process in the least-squares sense.

INTRODUCTION

Multicomponent ocean bottom cable (OBC) technology reestablishes the use and importance of converted wave (*PS*) data, yet opens the door for a series of new and existing problems with *PS* data. Irregular acquisition geometries are a serious impediment for accurate subsurface imaging. Irregularly sampled data affects the image with amplitude artifacts and phase distortions. Irregular geometry problems are more evident in cases in which the amplitude information is one of the main goals of study. For *PS* data, this problem is crucial since most of the *PS* processing focuses on the estimation of rock properties from seismic amplitudes.

The application of inverse theory satisfactorily regularizes acquisition geometries of 3D prestack seismic data (Audebert, 2000; Chemingui, 1999; Duijndam et al., 2000; Rousseau et al., 2000; Albertin et al., 1999; Bloor et al., 1999; Nemeth et al., 1999; Duquet et al., 1998). For *PP* data, there are two distinct approaches to apply: 1) data regularization before migration and 2) irregular geometries correction during migration. Biondi and Vlad (2001) combine the advantages of the previous two approaches. Their methodology regularizes the data geometry before migration, filling in the acquisition gaps with a partial migration operator. The operator exploits the intrinsic correlation between prestack seismic traces. The partial migration operator used is Azimuth Moveout.

The recent development of a converted wave Azimuth Moveout (PSAMO) operator (Rosales and Biondi, 2001) that preserves amplitudes and is fast, enables the extension of Biondi and Vlad's (2001) methodology for converted waves data. Therefore, a complete and accurate

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geometry regularization is now possible for OBC seismic data.

This paper extends already existing methodologies for *PP* regularization in order to handle *PS* data. Due to the asymmetry of ray trajectories in *PS* data, there are more elements to consider in order to solve for irregular geometry problems. Our method for *PS* data regularization uses a *PS* Azimuth Moveout operator (*PS*-AMO) (Rosales, 2002) in order to preserve the resolution of dipping events and correct for the lateral shift of the common conversion point.

Our methodology depends on the ratio between the *P* and the *S* velocities (γ). It also depends on the continuity of the events in the common midpoint gathers. These situations make our regularization an iterative procedure that stops where the difference between the previous and the actual γ sections is relatively small.

We will present a summary of Biondi and Vlad's (2001) methodology for solving the irregular geometry problem using a preconditioned-regularized least-squares scheme. We present and discuss how this method can be extended to handle *PS* data and implement this method on a portion of a real 3D OBC data set.

DATA REGULARIZATION

Regularized least-squares theory is the fundamental basis for solving the geometry regularization problem in this work. To preserve the resolution of dipping events in the final image, the regularization term includes a transformation by Azimuth Moveout (Biondi and Vlad, 2001). Additionally, Biondi and Vlad's method is computationally efficient because they apply the AMO operator in the Fourier domain and precondition the least-squares problem.

For this work, we use an AMO operator designed for converted waves (Rosales and Biondi, 2001). Regularization with this operator intends to: 1) preserve the resolution of the dipping events, 2) correct for the spatial lateral shift of the common conversion point, and 3) handle the amplitudes properly.

We present a general overview of the AMO regularization theory and discuss special considerations for converted waves regularization. We present an iterative methodology to regularize the *PS* data due to the dependency of the PSAMO operator on the ratio between the *P* and the *S* velocities.

AMO regularization overview

Partial stacking the data recorded with irregular geometries within offset and azimuth ranges yields uniformly sampled common offset/azimuth cubes. In order to enhance the signal and reduce the noise, the reflections should be coherent among the traces to be stacked. Normal Moveout (NMO) is a common method to create this coherency among the traces.

Let's define a simple linear model that links the recorded traces (at arbitrary midpoint locations) to the stacked volume (defined on a regular grid). Each data trace is the result of interpolating the stacked traces and equal to the weighted sum of the neighboring stacked traces. In matrix notation, this transforms to:

$$\mathbf{d} = \mathbf{A}\mathbf{m}, \tag{1}$$

where $\mathbf{d}$ is the data space, $\mathbf{m}$ is the model space, and $\mathbf{A}$ is the linear interpolation operator. Stacking can be represented as the application of the adjoint operator $\mathbf{A}'$ to the data traces,

$$\mathbf{m} = \mathbf{A}'\mathbf{d}. \tag{2}$$

This simple operation does not yield satisfactory results for an uneven fold distribution. To compensate for this uneveness, it is common practice to normalize the stacked traces by the inverse of the fold ($\mathbf{W}_m$), thus:

$$\mathbf{m} = \mathbf{W}_m\mathbf{A}'\mathbf{d}. \tag{3}$$

Alternatively, it is possible to apply the general theory of inverse least-squares to the stacking normalization problem. The formal solution of the inverse least-squares problem takes the form:

$$\mathbf{m} = \left(\mathbf{A}'\mathbf{A}\right)^{-1}\mathbf{A}'\mathbf{d}. \tag{4}$$

Biondi and Vlad (2001) show that the fold normalization ($\mathbf{W}_m$) can be approximated as the inverse of $\mathbf{A}'\mathbf{A}$.

With the knowledge of model regularization in the least-squares inversion theory, it is possible to introduce smoothing along offset/azimuth in the model space. The simple least-squares problem becomes:

$$\begin{aligned} 0 &\approx \mathbf{d} - \mathbf{A}\mathbf{m} \\ 0 &\approx \epsilon_D \mathbf{D}'\mathbf{D_h}\mathbf{m}, \end{aligned} \tag{5}$$

where the roughener operator $\mathbf{D}_h$ can be a leaky integration operator. However, the use of a leaky integration operator may yield the loss of resolution when geological dips are present. The substitution of the identity matrix in the lower diagonal of $\mathbf{D}_h$ with the AMO operator correctly transforms a common offset-azimuth cube into an equivalent cube with a different offset and azimuth. This transformation also preserves the geological dip.

The fold, which normalizes the data based on the traces distribution, is introduced by a diagonal scaling factor. The weights, for the regularized and preconditioned problem, are thus computed as:

$$\mathbf{W}_I{}^{-1} = \frac{\mathbf{diag}\left\{\left[\left(\mathbf{D_h}\mathbf{D_h'}\right)^{-1}\mathbf{A}'\mathbf{A}\left(\mathbf{D_h'}\mathbf{D_h}\right)^{-1} + \epsilon_D\mathbf{I}\right]\mathbf{p_{ref}}\right\}}{\mathbf{diag}(\mathbf{p_{ref}})}, \tag{6}$$

where $\mathbf{p_{ref}} = \mathbf{D_h'}\mathbf{D_h}\mathbf{m}$. This fold calculation can be simplified more as:

$$\mathbf{W_I}{}^{-1} = \frac{\mathbf{diag}\left\{\left[\left(\mathbf{D_h}\mathbf{D_h'}\right)^{-1}\mathbf{A}'\mathbf{A}\left(\mathbf{D_h'}\mathbf{D_h}\right)^{-1} + \epsilon_D\mathbf{I}\right]\mathbf{1}\right\}}{\mathbf{diag}(\mathbf{1})}. \tag{7}$$

PS regularization

We previously discussed that by formulating the irregular geometries problem in the least-squares sense it is possible to solve for gaps in the data using a regularization operator. The significant element of the previous section is the use of the AMO operator as the regularization term in the solution of the least-squares problem.

Recently, Rosales and Biondi (2001) developed and implemented an AMO operator for converted waves (PSAMO). This operator acts in the Fourier domain and also handles the amplitudes properly. Due to this new PSAMO operator, it is now possible to solve for the irregular geometries problem on converted wave data by following the same procedure as in the previous section.

Partial stacking requires the data to be coherent among the traces. NMO obtains this coherency well for *PP* data. However, for converted waves we know that the moveout is not a perfect hyperbola, even in constant velocity media.

On conventional *PP* processing, the AMO operator is velocity independent. However, for converted waves the PSAMO operator depends on the ratio between the *P* and the *S* velocities (γ). Therefore, we need *a priori* velocity estimation. This fact suggests that for different γ values we will have different regularization results.

Traditional *PS* processing intends to first sort the data in the common conversion point (CCP) domain. This process has always been dependent on the γ value; therefore, the *PS* processing community performs iterative processing (CCP binning, velocity analysis) until obtaining a satisfactory result.

The PSAMO operator that we use has the advantage of not demanding the data in the CCP domain. This operator is a cascade operation of converted wave dip moveout (Rosales et al., 2001) (PSDMO) and inverse PSDMO. The input for the PSDMO operator is in the CMP domain after NMO, since this operator performs the lateral shift correction.

After performing NMO on the *PS* data and the *PP* data, the γ value is (Huub Den Rooijen, 1991):

$$\gamma = \frac{v_p^2}{v_{eff}^2}, \tag{8}$$

where v_{eff} is the NMO velocity of the *PS* section.

In order to proceed with the *PS* data regularization, a process that depends on the γ value, we need to have the *PP* section regularized as well as the RMS velocity model. We proceed with the following algorithm:

1. Sort the data in the CMP domain.

2. Estimate velocity model on the *PS* section.

3. Estimate the γ section with equation (8).

4. If it is not the first iteration, compare the previous and the actual γ sections and:
   (a) if they are the same, finish the process.
   (b) if they are not, continue.
5. Apply NMO on the *PS* section.
6. Apply PSAMO regularization.
7. Apply inverse NMO.
8. Go back to step 2.

This is our main methodology to correctly regularize *PS* data.

RESULTS

We apply AMO regularization to a portion of a real OBC data set, the Alba field. The Alba oil field is located in the UK North Sea and elongates along a NW-SE axis. The oil reservoir is 9km long, 1.5km wide, and up to 90m thick at a depth of $1,900$m subsea (Newton and Flanagan, 1993).

Figure 1 illustrates the main problem. Observe the gaps in both the *PP*-CMP and the *PS*-CMP gathers. Our goal is to fill these gaps with energy from the surrounding traces and to preserve the physics of wave propagation.

A multicomponent OBC data set consists of both a *PP* and a *PS* section. Since the literature already presents extended work on *PP* regularization, we will present compact but complete regularization results for the *PP* portion. However, we will present more results and extended analysis for the *PS* section.

We use a portion of the entire 3D cube. This subsection consists of 17 crosslines with 719 cmps each. The *PP* section uses only the absolute value of the offset, for a total of 121 offsets. The *PS* section uses the full offset, however the maximum offset extension is reduced from 8000m. to 4000m. since the contribution of this far offset to this portion of the data is practically null.

PP regularization

Figure 2 presents the *PP* data for one crossline of the data set in study. Observe the holes in the data due to irregularities in the geometry acquisition.

Biondi and Vlad (2001) examined the differences among regularizing the data with normalization, regularization with the leaky integration operator and regularization with the AMO

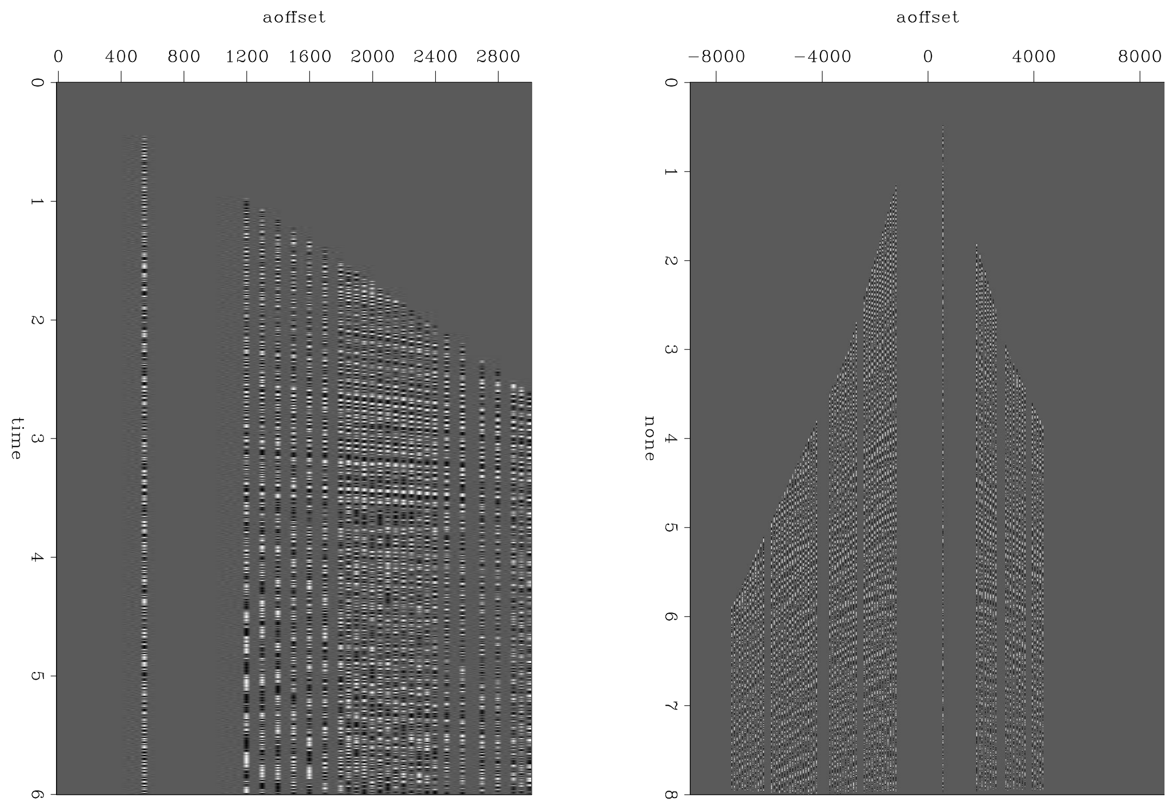

Figure 1: CMP gather for the *PP* (left) and the *PS* (right) components for one crossline of the 3D cube daniel2-cmps [ER]

operator. They conclude that the precondition of the regularized least-squares problem with the AMO operator yields more continuous results.

On this part of the problem, we only present the final interpolation results using normalization and AMO regularization. Figure 3 presents the fold maps calculated using both normalization (top) and AMO regularization (bottom). Note that even though the fold maps are similar, as expected, the fold distribution is smoother using AMO regularization. Also note that with AMO regularization, the fold reduces to the half. This fact affects the final solution of the least-squares problem.

Figure 4 compares the result of geometry regularization using normalization (top) and AMO regularization (bottom). Differences lie in the amplitudes and the borders.

PS regularization

Figure 5 exhibits the *PS* portion of the data set. Again, observe the holes in the data, as well as the presence of more offset.

The data is sorted into CMP gathers. We do not present the data in common conversion point (CCP) gathers because the input of the regularization program performs the binning, and

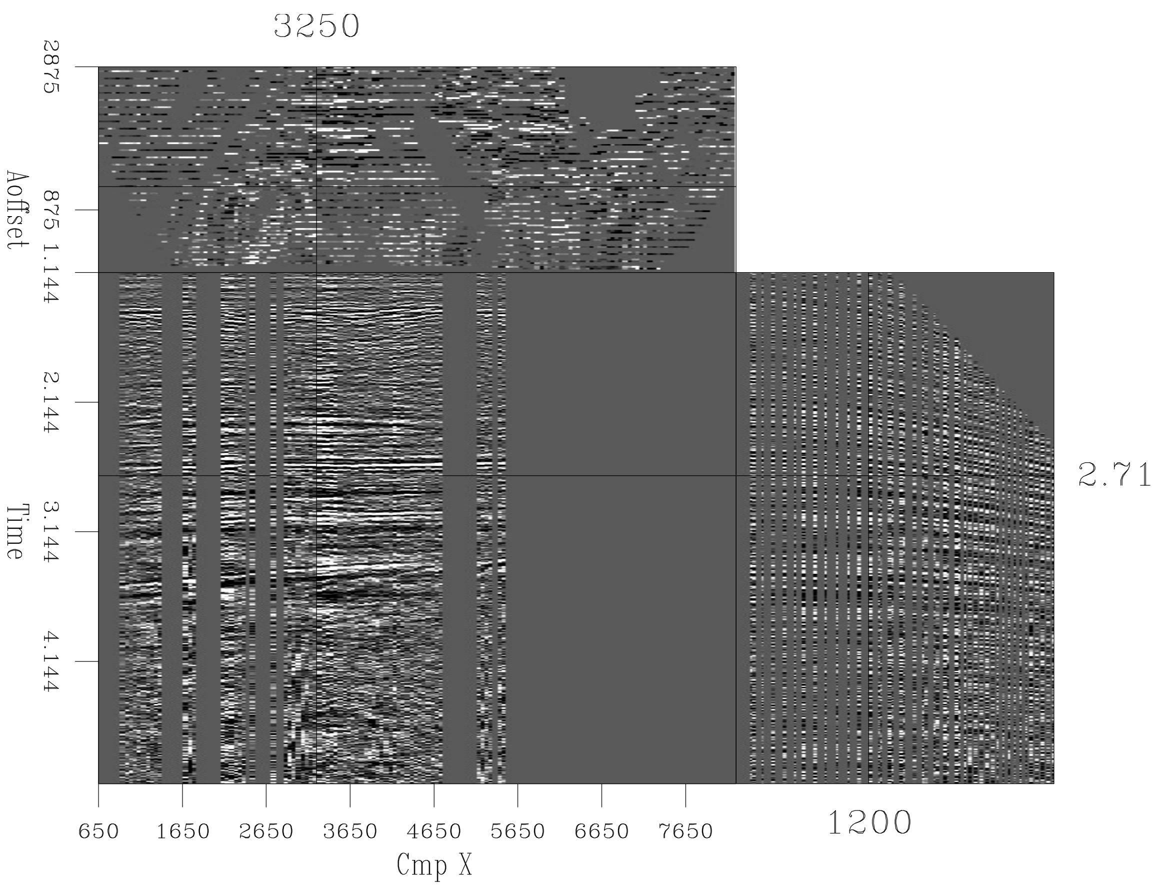

Figure 2: One *PP* crossline section of the data in study daniel2-data [ER]

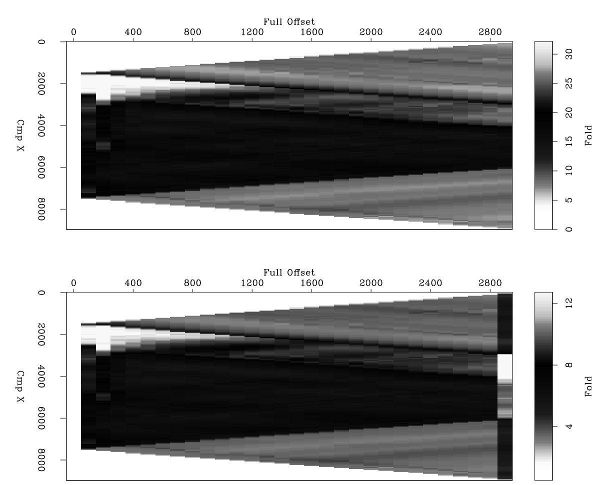

Figure 3: Fold, using normalization (top) and AMO regularization (bottom) daniel2-fold [CR]

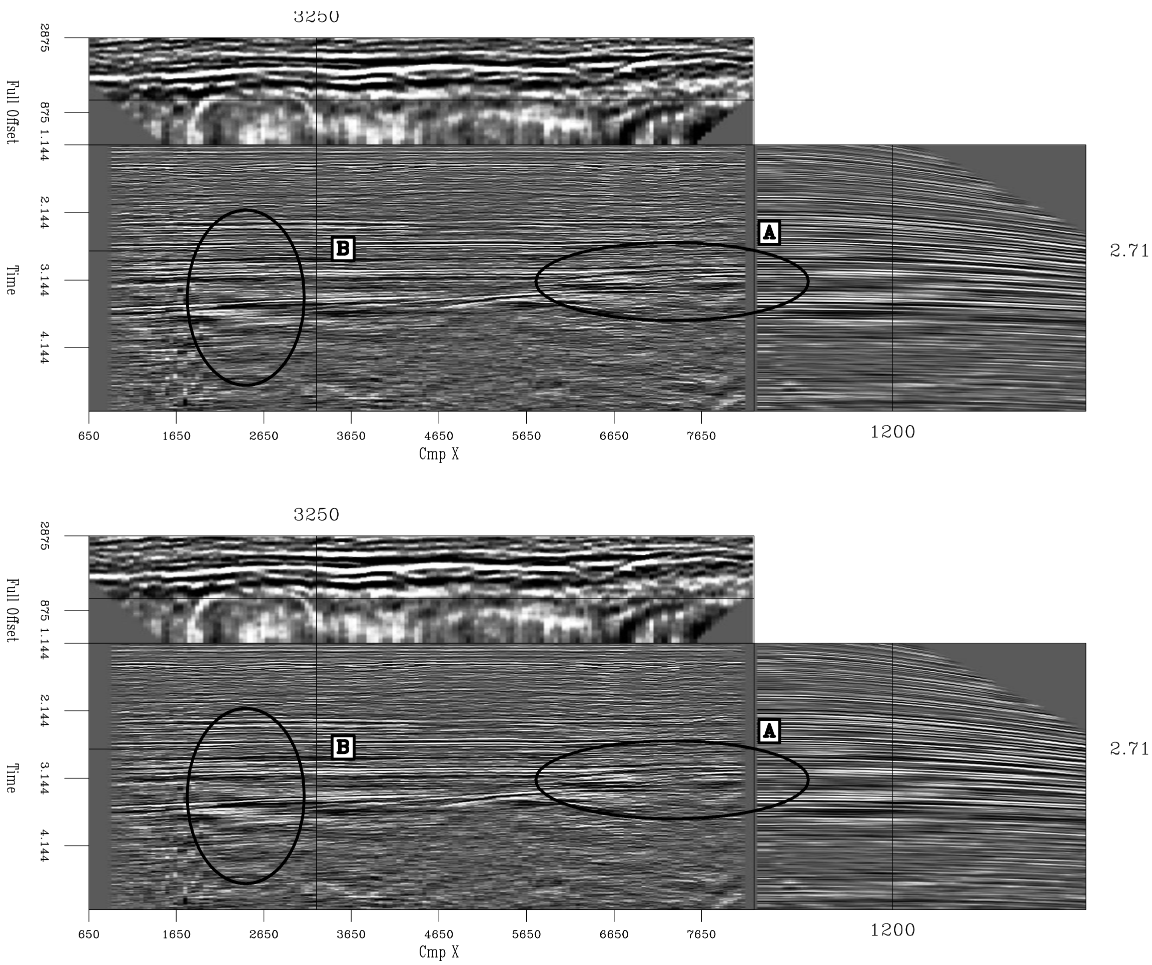

Figure 4: Data regularization results, using normalization (top) and the AMO operator (bottom). Note the main difference in the dipping events in the areas A and B daniel2-comp [CR,M]

the PSAMO operator performs the lateral shift correction from the CMP point to the CCP point based on the γ value.

We proceed with the methodology discussed in the previous section. We perform the PSAMO regularization process because it is the only one that corrects for the lateral shift displacement of the common conversion point. There are only two iterations so far.

Figure 6 presents two PSAMO regularization results for two iterations of our methodology. For each iteration note that the moveout of the events is not a perfect hyperbola. This characteristic corresponds to the nature of propagation of *PS* waves.

Observe the difference in the moveout of the events between the two iterations of our methodology (top and bottom parts of Figure 6). This is due to the different velocities on each iteration. However, both results satisfactorily fit the data.

Figure 7 present a zoom of our results and the original data. It is easier to observe that

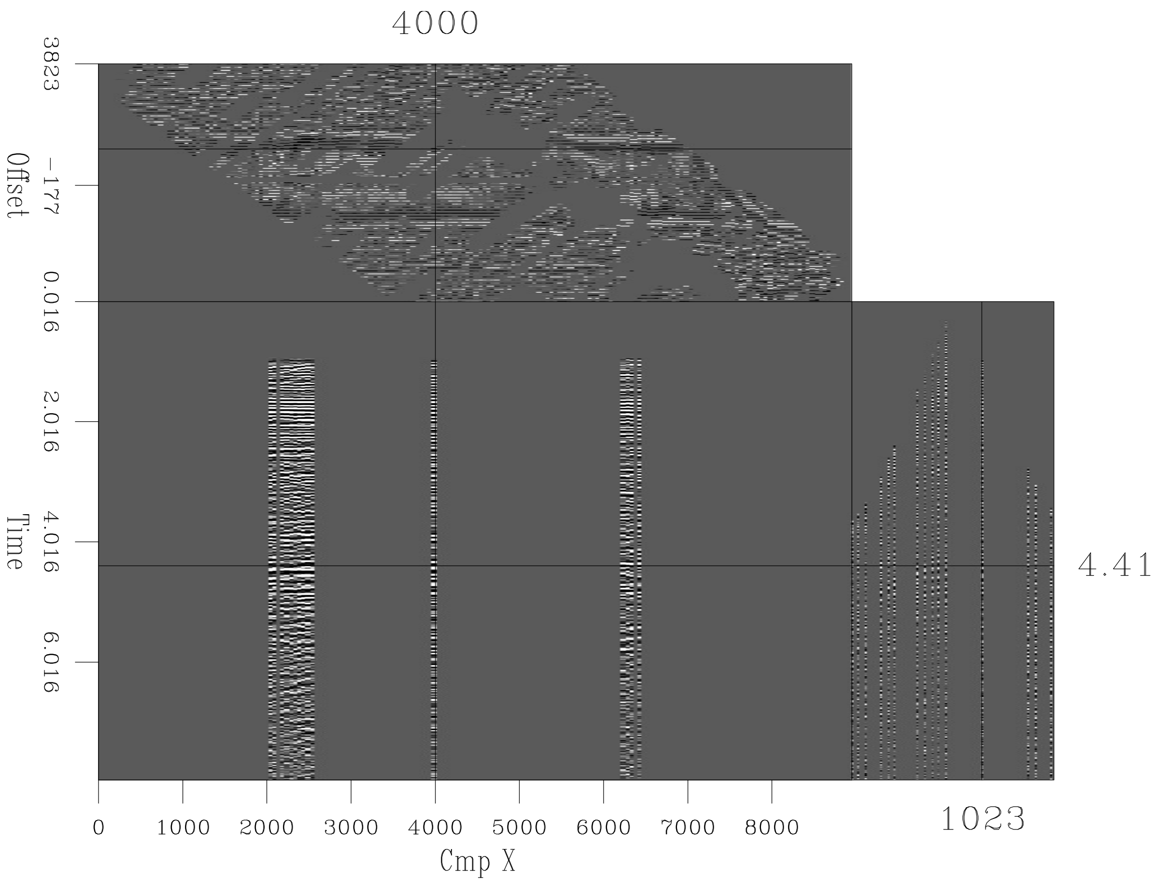

Figure 5: *PS* section for the same crossline on Figure 2 daniel2-data_ps [ER]

both results fit the data. However, the second iteration is more realistic since it better follows the information of the surrounding traces.

SUMMARY AND FUTURE WORK

We used least-squares inverse theory with the AMO operator as the regularization term. This method satisfactorily solved for interpolation of a 3D irregular data set.

We implemented a similar approach for regularizing the *PS* section of the OBC data set. For this problem, an iterative procedure is needed due to the dependence of the AMO operator on the γ value.

In order to obtain better results in the future, we recommend the use of a higher NMO approximation to obtain coherence among the traces to be stacked on the *PS* section. Additionally, formulating the γ estimation problem in a least-squares sense should allow a better constraint for its calculation, creating better *PS* regularized sections. This is an ongoing project.

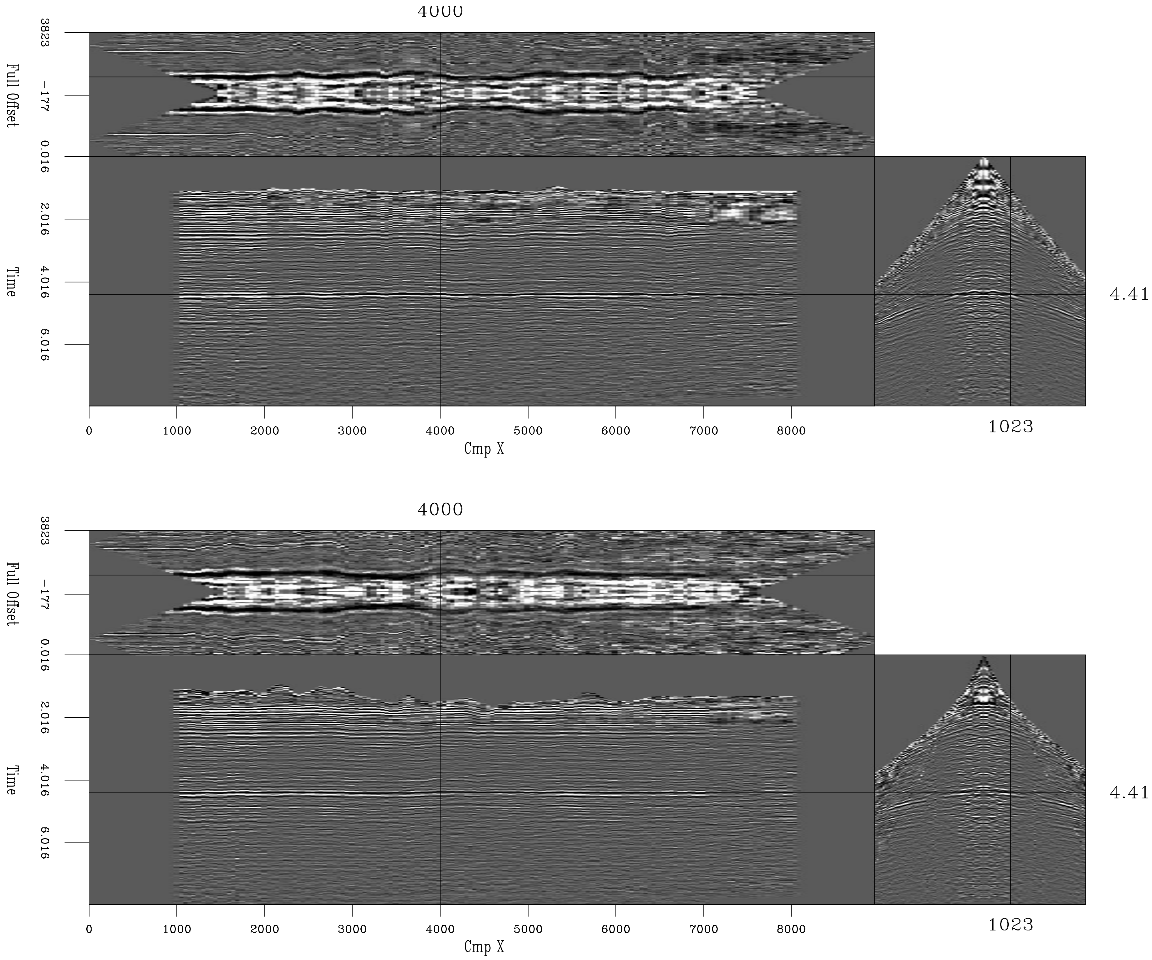

Figure 6: *PS* regularization results. First (top) and second (bottom) iteration of our methodology daniel2-comp_ps [CR,M]

ACKNOWLEDGMENTS

We want to thank ChevronTexaco for providing the data set.

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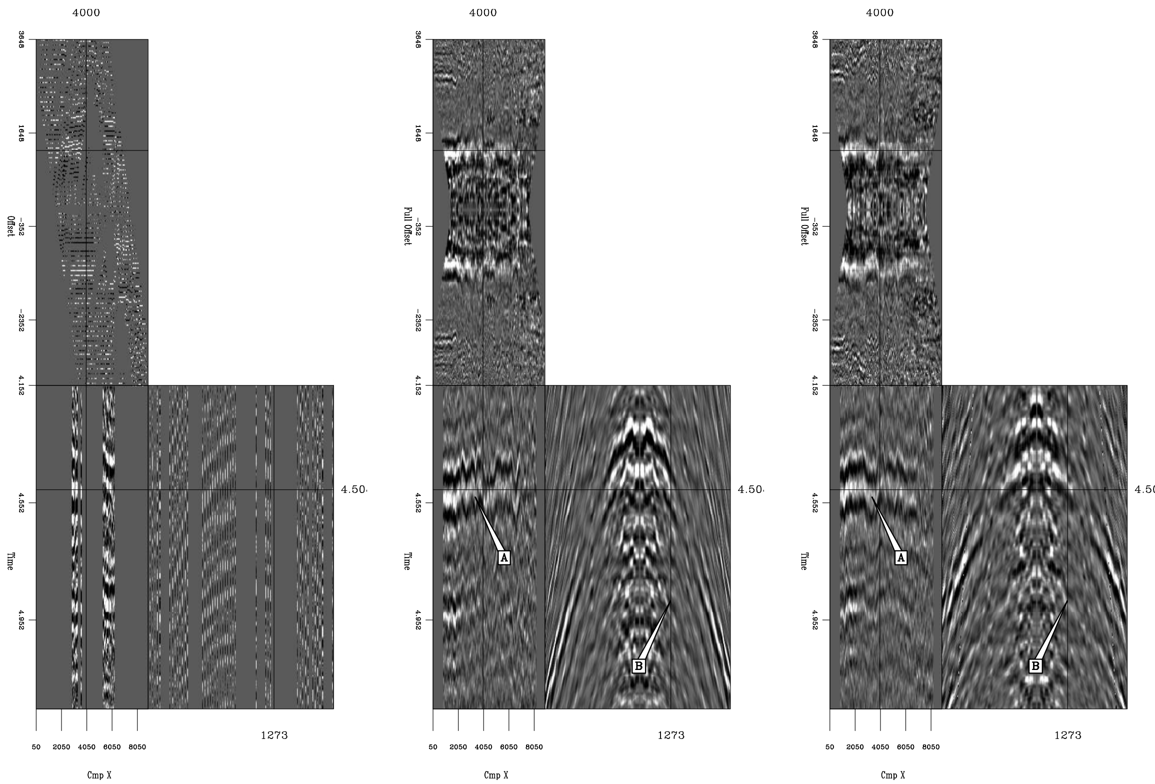

Figure 7: Zoom of Figure 6. From left to right, the original data, the first and the second iterations. Note how event A is more continuous in the second iteration, and event B presents a more realistic *PS* moveout (not a perfect hyperbola daniel2-detail [CR,M]

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