Factors affecting AVO analysis of prestack migrated gathers

Ye Zheng, Sam Gray, Scott Cheadle and Paul Anderson, Veritas DGC Inc.*

Summary

Prestack migration has become a standard component of seismic data imaging. Recently its application has expanded to include generating migrated gathers for AVO analysis. Prestack imaging relies on the constructive and destructive interference of amplitudes migrated within a suite of restricted offset ranges to reproduce a correctly imaged reflector. However, in cases of typical land 3D surveys, the spatial sampling is often insufficient to perform this procedure with acceptable fidelity for all offsets. As a result, a variety of methods have been developed to account for such inaccuracies in amplitude reconstruction. In this paper, examples of raw migrations are compared to fold compensation and area weighting, for which area weighting provides the best amplitude recovery.

Introduction

AVO analysis is intended to provide an additional interpretive dimension to seismic data beyond structural imaging. AVO relies in part on fitting gradients to amplitude observations over a range of trace offsets. In order that the resulting gradient fits be considered reliable, all steps in the data processing sequence must accurately preserve the natural amplitude variations related to lithology and fluid content. Velocities must be accurate and scaling must maintain relative amplitudes. Interference due to noise and multiples or side effects related to their attenuation must be carefully monitored. Ideally, the imaged data will focus energy at the correct position. Prestack migration is the best available technique for achieving optimal focusing. However, under some conditions, prestack migration may result in spurious amplitude variations unless corrective steps are taken. Wide patch 3D geometries common in land acquisition present some specific challenges that are the focus of this study.

Wide patch acquisition of 3D seismic on land is usually designed to balance the requirements of wavefield sampling and cost, while accounting for culture, topography and other access issues. The result is often characterized by less than ideal sampling. It is spatially irregular on an offset by offset basis and generally so sparse azimuthally that analysis in that domain is often unreliable. To date, only the Kirchhoff algorithm is well suited to the task of prestack time migration (PSTM) of such datasets. Kirchhoff works by migrating input samples to all possible image locations and relies on constructive interference to create the image while destructive interference cancels out the nonviable solutions. The fidelity of this process depends on having a density of sampling that is frequently not present in the recorded data. Additionally, Kirchhoff migration requires that various factors affecting amplitude, including operator anti-aliasing, be taken into account. The migration algorithm and acquisition geometry will be examined in more detail as they pertain to gradient analysis on PSTM gathers.

Kirchhoff migration and amplitudes

In principle, Kirchhoff migration can produce both reflection coefficients and reflection angles at image locations, making it ideal for AVO analysis in areas of moderate structural complexity. Published examples have shown accurate amplitudes after Kirchhoff migration - always, however, on data sets with completely regular acquisition. Figure 1 shows such an example. In this 2.5D example, 3D point-source data have been acquired along a 2D line over a constant-velocity Earth with identical density contrasts along two reflectors, one flat and one with a constant 15-degree dip. These data were acquired along a 2000 m spread with 20 m receiver spacing. They were then migrated two different ways: one using true-amplitude 2.5D migration weights, and the other using standard 2D Kirchhoff migration weights. Figure 1a shows the stack of the true-amplitude migration, with every eighth CDP trace displayed. The stack shows uniform amplitudes along the reflectors. Figure 1b shows a migrated CDP gather from the center of the line obtained using true-amplitude migration, and Figure 1c shows a migrated CDP gather from the same location obtained using standard Kirchhoff migration. Six offsets were summed into each trace in Figure 1b and 1c. The true-amplitude migration has successfully recovered the uniform AVO behavior of both reflectors, and it has also produced nearly identical amplitudes for both reflectors. The standard migration has produced a plausible but incorrect (negative) AVO behavior for both reflectors. In practice, conditions leading to results such as Figure 1b are rare, especially for irregularly sampled 3D land data.

Incorrect choice of migration weights can produce false AVO signatures, as shown in Figure 1c. Surprisingly, anti-aliasing also affects amplitudes since, for given reflector dip, it affects each offset differently. When the data are poorly-sampled, these problems become worse. Even in geologically simple areas, low-fold wide-patch data do not allow enough wavefield cancellation for migration to act properly. Stated differently, at shallow enough depths, the maximum frequency that migration is permitted to use to image a dipping event may well be near the minimum frequency available in the data.

Mitigating acquisition artifacts in PSTM

Due to the general sparsity of azimuth sampling, the following discussion will focus primarily on the offset domain. The issue of fold within individual offset bins is not limited to an individual CDP with a missing offset. Gaps will affect all image locations within the migration aperture, which can extend several kilometers depending on velocity and structural dip. This means that localized geometry artifacts can extend throughout a dataset. Even regular acquisition layouts can result in startling variations in fold patterns from offset to offset, as shown in Figure 2. While the final stacked image of all offsets may appear unaffected, the concern is whether the geometry effects can be mitigated, allowing interference to reproduce the relative amplitude at each offset required by AVO.

Compensating for inadequate sampling may be approached from several directions. One method is to regularize the sampling by interpolating to fill gaps in the recorded wavefield. This requires modeling a trace based on nearby offsets and azimuths. If a reasonable number of such traces are available, the interpolated trace then is assigned a particular offset and azimuth to anneal the offending holes. Interpolation is effective only over relatively short distances of a few bin increments, and reliable interpolators for irregular spatial sampling in 3D are difficult to implement.

Various normalization schemes have been tested in the context of PSTM. The simplest normalizes each trace in an input CDP gather by the gather fold before migration, similar in effect to a stack. Alternatively, traces within a specified offset range can be normalized by the fold within that range. This has the effect of balancing the energy summed within each output offset range, important for AVO. Normalization can also be applied after migration by what is known as the hit count method. Each input sample going into the migration sum is weighted according to various factors related to its position relative to the image point. The number of such weighted samples depends on the spatial sampling. Within each output offset volume, the number of summed samples, i.e. the hit count and their respective weights, is spatially variable. This will contribute to variable amplitudes unrelated to lithology. The input sample weights can be summed in a separate common output offset volume and then used to normalize the summed amplitudes.

Canning and Gardner (1998) described the concept of area weighting, specifically for the case of common offset and common azimuth subsets of the data volume. Ignoring azimuth for the moment, ideally each bin within a common offset range would be occupied, so each trace is responsible for contributing illumination proportional to the area of one bin. If there are unoccupied bins, then surrounding traces must contribute to illuminating those empty areas. By creating a polygonal tiling based on connecting the midpoints between a trace and nearby traces, each trace can then be weighted by the ratio of the tile area to bin area. This in effect scales up each trace according to the extra area it is required to illuminate. Here area weighting will be applied to common offset wide azimuth data, although this is hardly ideal.

Gradient analysis on synthetic models

To test the different normalization methods and area weighting, we performed Kirchhoff PSTM on a 3D synthetic dataset. The model data has a number of flat layers with linearly increasing amplitude with offset. The synthetic was based on an actual orthogonal shooting pattern with modest deviations of line orientations and spacing, with a large obstacle to shooting in one area of the survey. Migrated gathers are output at three CDP locations for each method tested. The CDP on the left side of each panel is close to the shooting obstacle. The actual amplitudes are shown as the continuous heavy line in the graph above the gathers. The model amplitude is shown as the lighter line. Because of the non-uniform offset distribution, the model amplitude is not a straight line.

The result from gather fold normalization before migration is poor (Figure 3a). The amplitude on the output gathers varies significantly with offset, and there is more residual noise than the other methods. The migration with hit count normalization after migration (Figure 3b) has improved the result at the rightmost CDP, but worsened at the leftmost CDP from Figure 3a. The amplitude of the migrated data is closer to the model amplitude for the CDP at the right side, but went to the opposite direction for the leftmost gather in the vicinity of the obstacle. When the input gathers are normalized by the fold within each offset bin (Figure 3c), the migration result is reasonable. Area weighted input gathers, however, gave the best result (Figure 3d). The amplitude of the migrated gathers is close to the model amplitude for all CDPs, except for the near and far offsets, typically the most sparsely sampled range in a 3D. With a robust fitting method, an amplitude gradient close to the true gradient can be found from the migrated gather with area weighting.

Conclusions and Discussion

Not all prestack migration algorithms are true amplitude, and true amplitude migrations won’t necessarily produce true amplitude gathers for arbitrary acquisition geometries. The uneven distribution of input traces in each offset and azimuth at different locations may cause variations in the amplitude information in the migrated gather. Gather fold normalization before migration does nothing to address common offset or azimuth sampling issues. Hit counting after migration does not work well either, because the damage due to improper operator cancellation has already been done. Offset fold normalization helps considerably, although this does not address variations in the azimuth distribution. Area weighting on input gathers provides an inexpensive method to compensate the irregular contribution of input traces and produces a good migration result for AVO.

Conventional AVO practice has been limited to fitting gradients within CDP gathers, and so methods that address spatial variations of offset distribution alone are applicable. This is at least in part due to the reasonable sampling of offsets that is a feature of most sound land acquisition. However, interest is increasing in looking at the azimuthal variations of amplitude (AVAZ) as well. Conventional acquisition geometries often fail to provide even the sparsest sampling to make azimuthal analysis reliable. Efforts are now being applied to develop 3D prestack interpolation to address both offset and azimuth sampling issues. Whatever progress may be achieved toward that goal, novel acquisition approaches or simply higher surface effort will also be required to take full advantage of the azimuth component for AVO-AVAZ analysis of PSTM gathers.

Reference

Canning, A and Gardner, G.H.F., 1998, Reducing 3-D acquisition footprint for 3-D DMO and 3-D prestack migration: Geophysics, 63, 1177 – 1183.

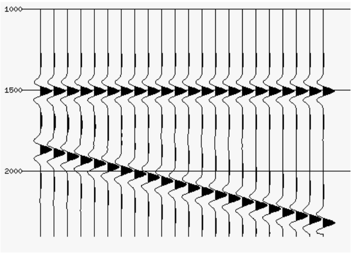

Figure1 (a) True-amplitude 2.5-D migration stack.

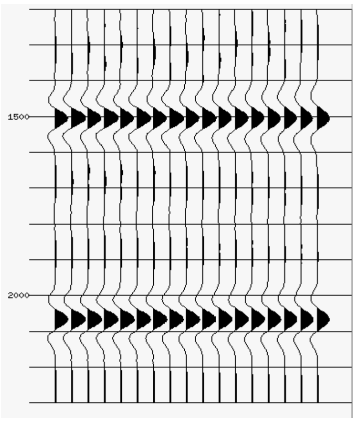

Figure 1 (b) True-amplitude 2.5-D migrated CDP gather with offsets increasing to the right.

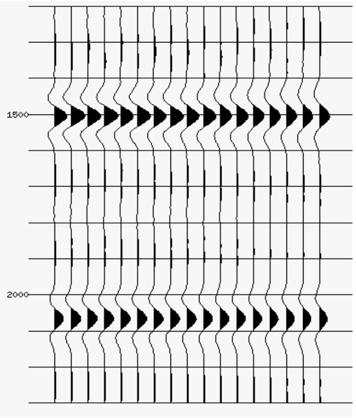

Figure1 (c) 2-D migrated CDP gather with offsets increasing to the right.

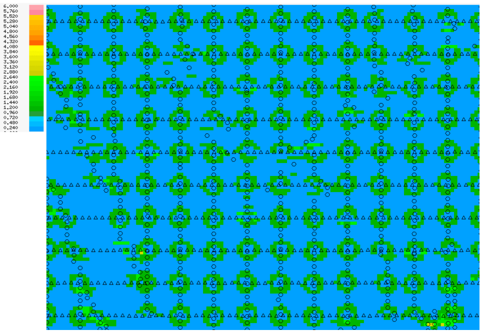

Figure 2 (a) Fold pattern at 150 m offset.

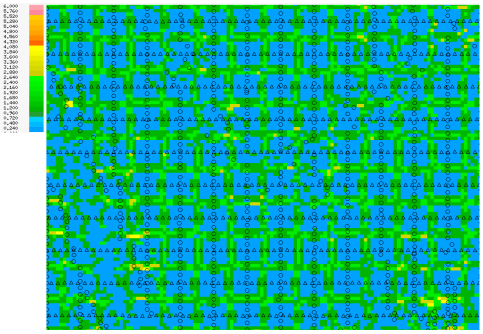

Figure 2 (b) Fold pattern at 350 m offset.

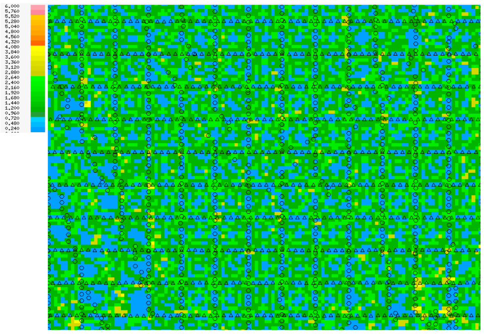

Figure 2 (c) Fold pattern at 550 m offset.

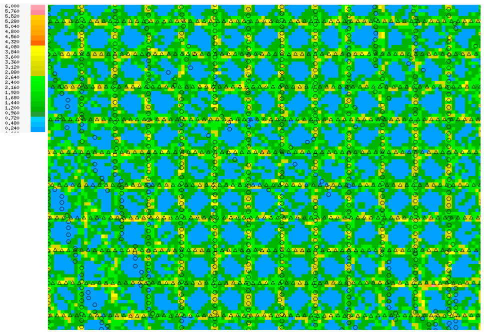

Figure 2 (d) Fold pattern at 650 m offset

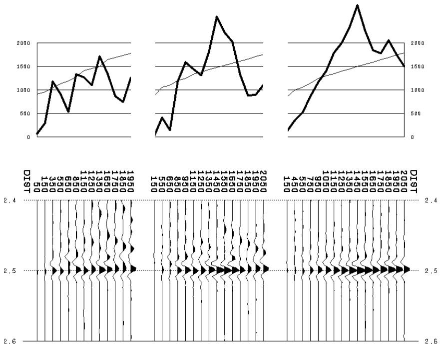

Figure 3 (a) Input gather normalized by the number of traces at each CDP.

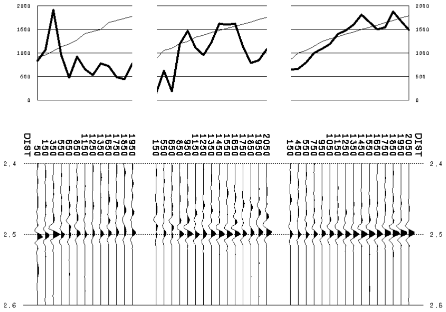

Figure 3 (b) No Scaling on the input gather, hit counting is done during migration and total weight is removed after migration.

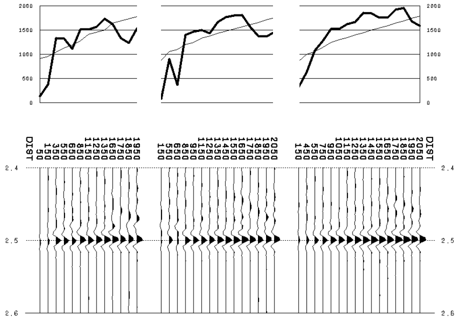

Figure 3 (c) Input gather normalized by the number of traces on event offset bin at each CDP.

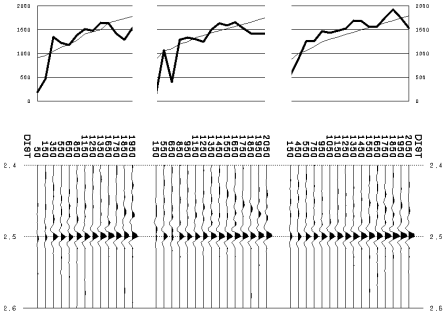

Figure 3 (d) Area weighting is applied to the input gather (radius = 120 m).

Figure 3: Comparison of migrated gathers using different normalization. The leftmost CDP is close to a shooting obstacle. The thick lines on the top of seismic traces represent the amplitude at 2500 Ms. The thin lines are the amplitude of input model. They are not straight because of the non-uniform offset increment.