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# Handling irregular geometry in wide-azimuth surveys

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## ABSTRACT

The processing of seismic data for amplitude inversion often neglects an important issue which could be detrimental to amplitude preservation: the effect of sparse and irregular geometry. The problem is severe in wide-azimuth 3-D surveys acquired with the aim of studying the azimuthal variations in the AVO gradient. We present a new technique for processing wide-azimuth surveys that accurately images 3-D seismic data while preserving relative amplitudes describing the offset and azimuth-dependent reflectivity function. The method focuses on both algorithm accuracy and proper handling of irregular geometry and therefore allows for reliable AVO analysis on migrated data. The technique is based on organization of the data into common-azimuth (CA) and common-offset (CO) cubes and allows interpolation into a regular grid before imaging. The regular CA/CO cubes are then migrated using an efficient true-amplitude migration algorithm. We apply this technique in order to invert for a synthetic reflectivity model simulating a real 3-D wide-azimuth land survey over a fractured reservoir. Results show that, as expected, Kirchhoff migration is very sensitive to uneven sampling, which creates strong amplitude distortions. The azimuth moveout (AMO) transformation succeeded in organizing the data as regular gridded cubes while preserving its amplitude information for imaging. We conclude that interpolating seismic data prior to migration is effective in preserving amplitude information and that AMO can effectively correct for the irregular sampling in wide-azimuth surveys.


## INTRODUCTION

Acquiring, processing and interpreting seismic data for true amplitude is a very complex and cumbersome process. The difficulties arise mainly from what could be defined as true amplitude, which is very sensitive to acquisition geometry, processing techniques and algorithms, and interpretation goals. "True-amplitude" processing

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emerged as a new field of research and a re-evaluation of our conventional processing techniques. Therefore, most amplitude studies have focused on the development of amplitude-preserving imaging operators such as DMO and migration (i.e, Beasley and Mobley (1988); Black et al. (1993); Bleistein (1987); Sullivan and Cohen (1987); Schleicher et al. (1993); Ronen et al. (1995)).

Beasley (1994) pointed to the fact that focusing solely on algorithmic accuracy ignores an issue often even more detrimental to amplitude preservation: the effect of sparse and irregular geometry. Gardner and canning (1994) demonstrated some effects of irregular sampling on 3-D prestack migration through synthetic examples using true 3-D land aquisition geometry. Given this effect, the design of any processing sequence has to address both issues of irregular sampling and algorithmic accuracy.

Amplitude-preserved processing aims at providing reliable amplitudes for AVO studies. In 3-D, AVO analysis is routinely performed on partial stacks or angle stacks on which amplitudes are smeared over a range of offsets (or angles). Unfortunately, during this process azimuthal information is completely destroyed by the addition of traces from different source receiver orientation. The stacked trace, therefore, loses some information present in the prestack domain that may be related to lithology, fluid saturation, fracture density and orientation, and anisotropy. Some of the recent work at SEP has focused on the use of azimuth— a parameter inherently recorded in seismic data— in the processing of 3-D surveys. Biondi and Palacharla (**?**) developed an economical and efficient algorithm for 3-D prestack depth migration of common-azimuth data. In the context of 3-D velocity estimation, Clapp and Biondi (1995) showed that inverting for interval velocity is better constrained when data collected along multiple offset-azimuth are jointly inverted. Biondi and Chemingui (**?**) introduced a new partial prestack migration operator named AMO that has a wide variety of applications, such as regularization of data geometry for uneven and sparse coverage, reduction of the size of 3-D surveys by coherent partial stacking (Biondi et al., 1996) and synthesis of common offset and common azimuth data sets. In subsequent SEP reports, Fomel and Biondi (**?**) developed a practical and accurate implementation for the time and space formulation of AMO which properly handles the limited aperture of the operator and avoids aliasing of the operator along its steep traveltime slopes. In order that amplitude variations as function of offset and azimuth are not distorted by the AMO transformation, Chemingui and Biondi (1995) developed an amplitude-preserving function for an accurate AMO algorithm that adapts to our needs for true amplitude processing.

Recently, the issue of whether azimuthal anisotropy, and, more precisely, fracture-induced anisotropy is detectable and measurable on 3-D P-wave data has been posed for research and investigation, i.e, (Lefeuvre, 1994; Lynn et al., 1995a,b). It is evident that this effect can be observed only on data with wide azimuth coverage, a type of surveying that is often considered problematic. The challenge is not the wide azimuth range itself, but the way in which wide azimuth surveys are acquired, where, most often, each azimuth is not sufficiently sampled in midpoints and offsets (Canning and Gardner, 1995). These sampling irregularities may introduce noise, cause amplitude distortions, and even structural distortions, when 3-D prestack migration is applied to the data (Gardner and Canning, 1994; Canning and Gardner, 1995). All these issues related to irregular geometry, undersampling along azimuths, and the need for accurate algorithms, have led some exploration geophysicists to favor narrow azimuth surveys on wide azimuth acquisitions.

Correct analysis of amplitude information requires prestack migration to determine the location and extent of AVO anomalies. The migration algorithm should be derived so that amplitude variations as a function of offset are not distorted by the procedure. In the SEP80 report, Francois Audebert and the migration group at SEP presented an extensive comparative summary about why one should use Kirchhoff migration for 3-D prestack imaging. The group based their conclusions on the capacity for data manipulation and cost comparison of Kirchhoff migration to other competitive algorithms, namely, poststack finite difference, phase shift, and SG migration. They concluded that a simple kinematic Kirchhoff migration is unbeatable in manipulating input data and is cheaper than other methods. Kirchhoff methods evade the question of total cost by being target oriented and are the foremost and nearly the only choice. The analysis did not intend to compare the efficiency of the algorithms and their ability to preserve amplitudes. In regard to the effects of irregular geometry, the group's perception was that Kirchhoff migration does not care if the data is regular or not. They concluded that Kirchhoff methods are the solution to adapting the operator to fit the data and process it in its real time-space coordinates.

In this work, we explore the issue of true amplitude processing in constant offset migration and we argue that Kirchhoff methods are not quite the solution for handling the irregular geometry. We present a method that synthesizes wide 3-D surveys as a collection of lower fold single-azimuth surveys. Therefore, when discrete azimuths are processed independently, each azimuth simulates a marine 3-D survey. After AMO transformation, each common azimuth subset is regularly sampled in midpoint-offsets. Common-azimuth common-offset cubes are then migrated using an amplitude-preserving Kirchhoff migration algorithm. We apply this true amplitude sequence to a synthetic model that simulates a real 3-D survey over a fractured reservoir in the Powder River Basin in Wyoming. The survey was designed in a Button-Patch geometry that aims at providing a wide range of azimuthal coverage that would allow study of the azimuthal variations in the AVO gradient. With the limitation of weak anisotropy, the azimuthal difference in AVO gradient is closely related to crack density, a very important parameter in tight-reservoir characterization.

## TRUE AMPLITUDE SEQUENCE

The processing sequence we propose features mainly data collected on land. AVO analysis on land surveys was always considered problematic because of irregular coverage and missing offsets. However, after organization of land data as common azimuths, land and marine processing should have much in common and the processes we will describe are applicable in either environment.

The basic processing flow in Figure 1 outlines the major steps for amplitude preserving-processing. It includes the important elements for AVO analysis, that is, restoration of relative amplitudes, preservation of amplitudes during data reorganization and regularization, signal-to-noise enhancement by coherent partial stacking, and correct positioning of reflectors. The latter three aspects will be discussed in this paper; a good deal of care is required in the preprocessing stage to restore amplitudes and to suppress the noise.

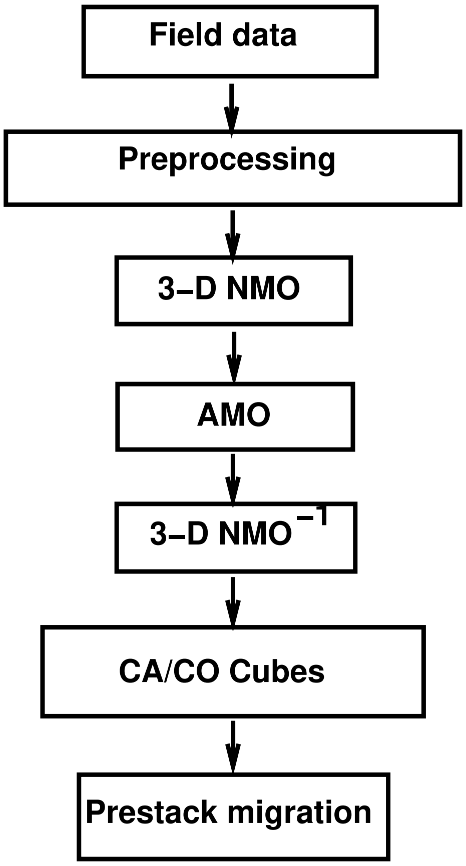


Figure 1: Processing flow chart proposed for amplitude-preserving processing of wide-azimuth surveys. nizar1-flow-usethis [NR]

**Algorithmic accuracy of imaging operators**

True-amplitude imaging aims at producing an angle dependent reflectivity function. This definition is simple enough to allow the operators in our proposed sequence to be considered as "true-amplitude".

We apply the AMO operator (Biondi and Chemingui, 1994) to organize wide azimuth 3-D surveys as common-azimuth common offset cubes. This transformation preserves the amplitude information (Chemingui and Biondi, 1995) as well as structural dip by coherent partial stacking (Biondi et al., 1996). We derived the amplitude-preserving function for the AMO operator based on the FK definition of DMO cascaded with its true asymptotic inverse.

For AVO analysis to be well defined, prestack migration is required to determine the location and extent of AVO anomalies. Migration aims at imaging the reflectivity function based on a one-way representation of seismic data. In this frame, migration can be formulated as an inversion problem (i.e, Sullivan and Cohen (1987);Bleistein (1987);Schleicher et al. (1993); ...). The derivation of the forward-modeling operator provides insight into the form of the inversion operator. In generating the seismic model, each trace is modeled as a weighted sum of image sources on a reflector. Therefore, the Kirchhoff migration of the seismic data involves a weighted sum of filtered surface-recorded traces where the weights are deduced from the inversion theory. In our implementation of the Kirchhoff prestack depth migration, the model is raytraced to evaluate the Green's function traveltimes associated with the source and receiver terms and to compute their corresponding WKBJ amplitudes (Lumley, 1989). Given the scope of this work, we only used a depth-dependent modeling/migration algorithms which will be easily generalized to the full 3-D case, pending the development of a robust 3-D raytracer.

Since both AMO and the migration algorithms were developed for a Kirchhoff style implementation, a great deal of care was taken to avoid the aliasing of the operators. A band-pass time filter, whose maximum frequency is determined by the local slope of the operator, was applied to avoid the aliasing of the operator along its steep traveltime slopes.

### Handling the irregular geometry

The organization of 3-D multifold data on a regular grid is commonly performed by binning the data prior to stacking. This binning technique is an extension of the 2-D CMP sort method to 3-D and is suited for poststack migration and structural interpretation. In the presence of high noise levels and in areas of the survey with limited fold coverage or many missing traces, flexbinning can be applied to increase the fold. However, as noted earlier, these binning and interpolation techniques tend to ignore completely the issue of source receiver orientation and have the detrimental effect of averaging amplitudes over given areas.

We propose applying the AMO operator (Biondi and Chemingui, 1994; Fomel and Biondi, 1995a) to project irregular 3-D surveys with wide azimuthal coverage onto a regular midpoint-offset subsets with a common source-receiver azimuth. The resulting regular geometry lends itself handily to other processing algorithms that require regular grids. An example of an irregularly sampled subset of a 3-D wide-azimuth data is shown in Figure 2. Traces whose source-receiver offset is between 7000 and 9000 ft and azimuth between $-30^o$ and $30^o$ were extracted from a true 3-D land survey and we plotted the surface locations of their common mid-points.

In the next section, we discuss the 3-D land data and its acquisition geometry. We show how we can use the real data example to generate numerical simulations and apply our technique to process a synthetic reflectivity model.

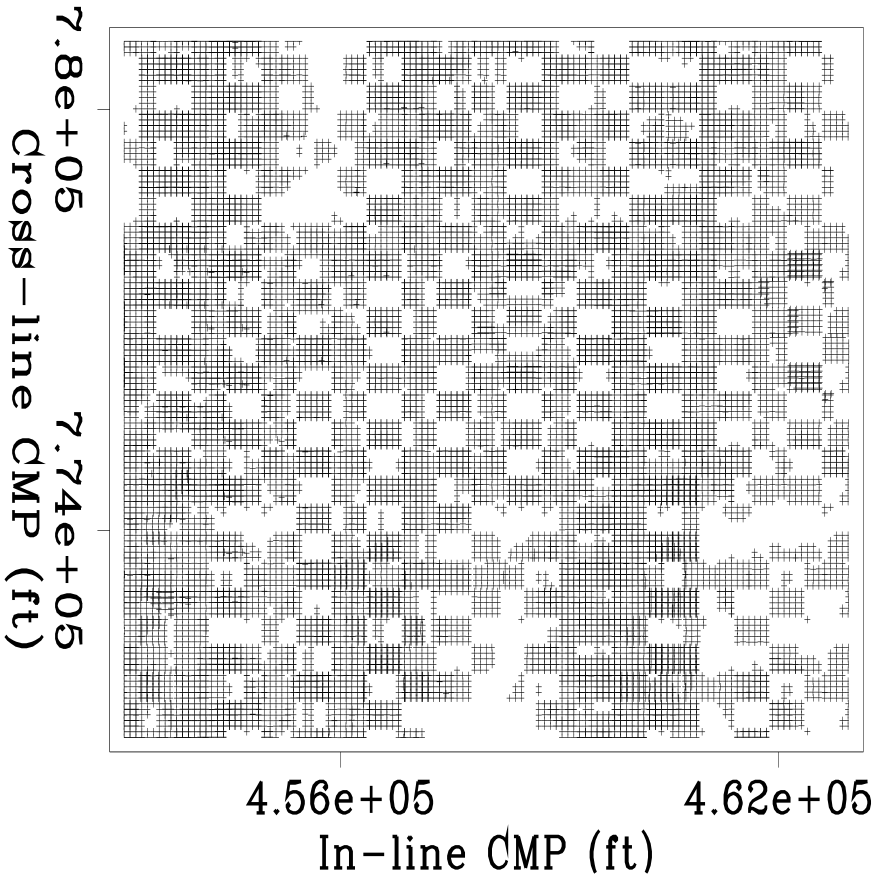


Figure 2: CMP geometry of a subset from a wide azimuth 3-D land survey. nizar1-irregular [ER]

## FIELD DATA

Arco acquired approximately 4 square miles of 3-D one-component data over a fractured reservoir in the Powder River Basin in Wyoming. The object of the project was to demonstrate that fracture orientation and density can be determined from compressional wave surface seismic surveys in a cost effective manner. The quality of the data is very high, as Figure 3 shows. The cube is a DMO-stack of the 3-D survey, which illustrates the structural image of the data. The dominant geology of the area is flat. The objective target, the Niobrara/Frontier horizon, is about 10,500 ft deep (approximately 2.2 seconds). The top slice of the cube shows the top of the formation of interest. The stacked reflectivity at that depth does not display any major structures.

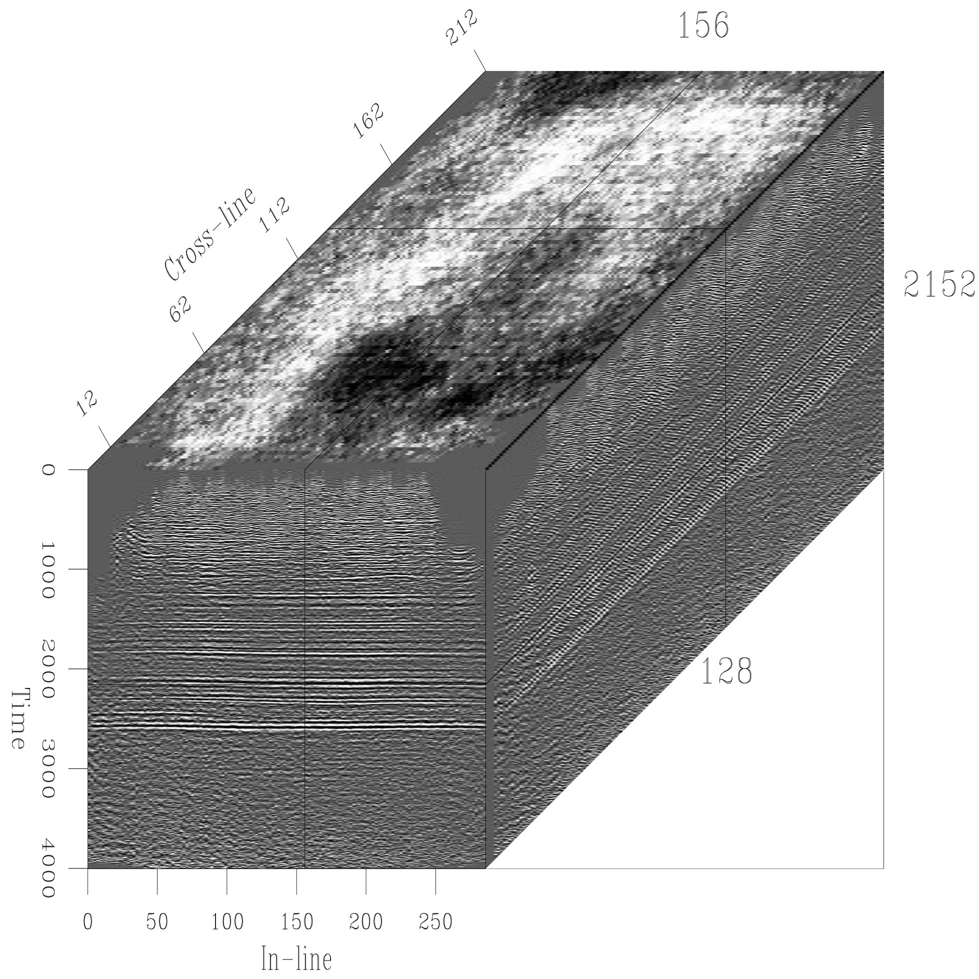


Figure 3: DMO stack of the 3-D survey. nizar1-data-cube [CR]

Previous 2D work in the area showed evidence of anisotropy through shear wave splitting, P-wave velocity analysis, reflectivity studies, and AVO inversion. The data offers itself as a good candidate for testing our techniques for "true-amplitude" processing of wide-azimuth surveys.

### Acquisition Geometry

The survey was designed with the aim of providing a wide range of azimuthal coverage that would allow study of the azimuthal variations in the velocities, the reflectivity maps and the AVO gradient. A Button-Patch geometry was chosen and a total of ten patches were deployed. Figure 4 shows the survey layout and the pattern of the buttons. The survey used a total of 840 shots and 3840 receivers. Each geophone array is composed of 12 geophones over a 30 ft circle. Figure 5 shows the actual receiver's geometry where some geophone groups are missing and some buttons were not covered because of field conditions. A full fold of 20 was achieved across the

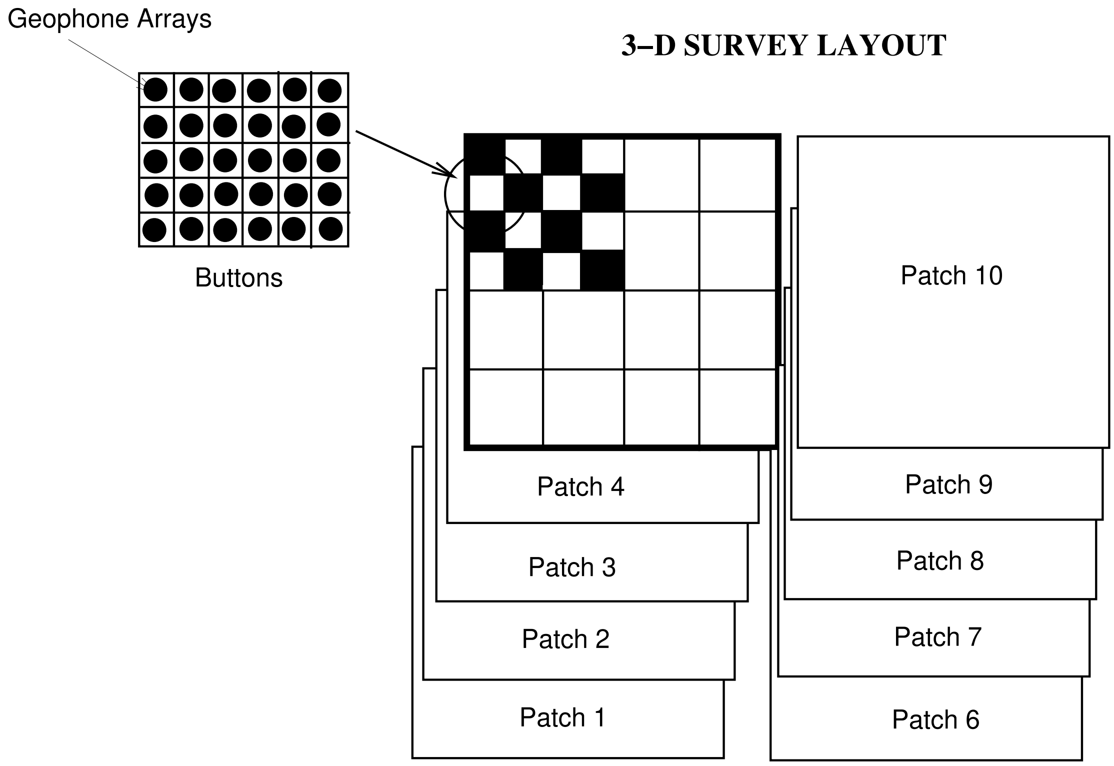


Figure 4: Button-Patch acquisition geometry (provided by Darnal, J. M; Arco Exploration and Production Technology. nizar1-layout [NR]

interest zone of 4.5 miles. The nominal and maximum offsets are 12,000 and 18,000 ft. The maximum reflection angle at the target, as determined from the far absolute offset, is about 60 degrees.

## SYNTHETIC EXPERIMENT

To examine the amplitude behavior of the imaging operators in the sequence, we designed a synthetic reflectivity model which simulates a flat reflector with amplitude anomalies along its surface. The model is 10,000 by 10,000 feet wide, which is about the size of the real survey area. The anomaly zones take the form of circles of high reflectivity. Figure 6 shows a cross section of the synthetic model taken at the top of the flat reflector. The edges of the model are tapered to avoid numerical diffractions from the modeling algorithm. For the sake of simplicity, we consider a medium with a constant velocity of 10,000 ft/sec.

In a first experiment, we modeled the reflector using regular constant offset geometry. The survey simulates a zero-azimuth acquisition, and an offset of 8000 ft with regular mid-point spacing of 62.5 ft. Figure 7 shows the migration of the regular CA/CO cube. As expected, the migration produced a nice image and successfully

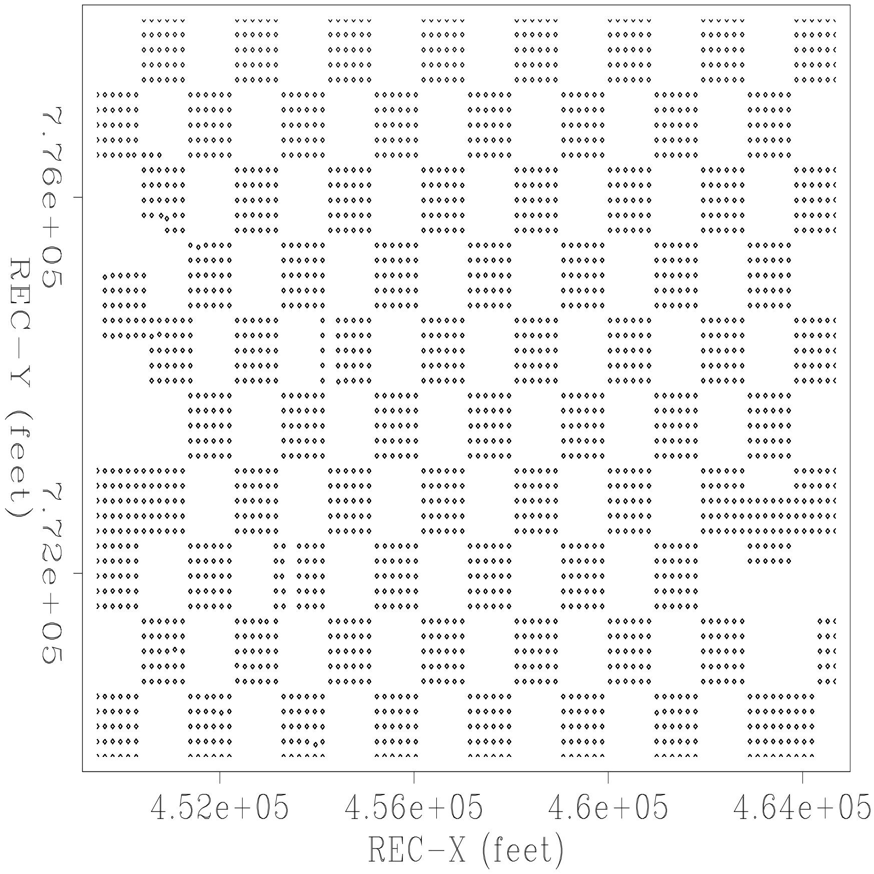


Figure 5: Layout of the receiver groups in the 3-D survey. nizar1-geometry [ER]

inverted for the reflectivity function along the reflector. The edges of the circular anomalies have been slightly smeared along the zero-azimuth acquisition direction (in-line direction).

In a second experiment, we modeled the reflector using the Button-Patch geometry of the real 3-D survey. We extracted a total of 24,000 traces whose source-receiver azimuth is between $-30^o$ and $30^o$ with an absolute offset range from 7000 to 9000 ft. The results of the migrated image are shown in figure 7. The reflectivity map has a very poor resolution and suffers amplitude distortions scattered along all the flat reflector. A direct correlation is noted between the areas of low coverage and the resolution of the reflectivity map. The two anomalies on the left of section suffered the most distortion since many of the missing traces correspond to that side of the map. Figure 9 shows the location of the anomalies overlaying the mid-point geometry of the input traces. The two left anomalies are poorly sampled, much beyond aliasing. We conclude that Kirchhoff migration on its own was unable to preserve the amplitude of the reflector and resolve for the anomalous locations in the presence of very sparse and irregular coverage.

In a final experiment, we applied the AMO transformation to regularize the geometry and reconstruct the data as a zero-azimuth cube with an 8000 ft effective absolute offset and constant mid-point spacing of 62.5 ft. The CA/CO cube is then imaged using the 3-D prestack depth migration algorithm. Figure 10 shows the results of the migration after applying AMO. The migrated image shows better resolution than the previous experiment. The AMO transformation before migration eliminated most of the amplitude distortions along the horizontal reflector and nicely imaged the location of the anomalies. The lower left zone is better defined, whereas the upper left anomaly is still not fully recovered. That anomaly corresponds to an extreme case of poor trace coverage. The AMO operator in its Kirchhoff implementation could not perfectly reconstruct the reflectivity at that location. We conclude that interpolating the data and regularizing its geometry before migration can help a great deal in preserving its amplitude. AMO lends itself as a convenient tool for organizing the data for common-azimuth processing while correcting for its sparse and irregular coverage.

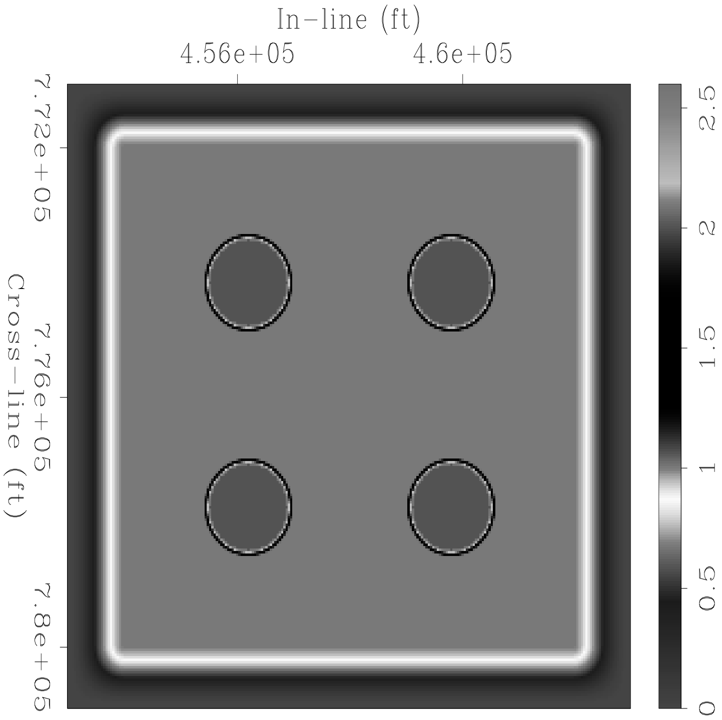


Figure 6: Synthetic reflectivity model of a flat reflector. The white circles are zones of high reflection coefficient of 2.5 in a constant background of unit reflectivity. nizar1-model [ER]

## CONCLUSION

We have presented a new technique for processing wide-azimuth surveys that accurately images 3-D seismic data while preserving relative amplitudes describing the

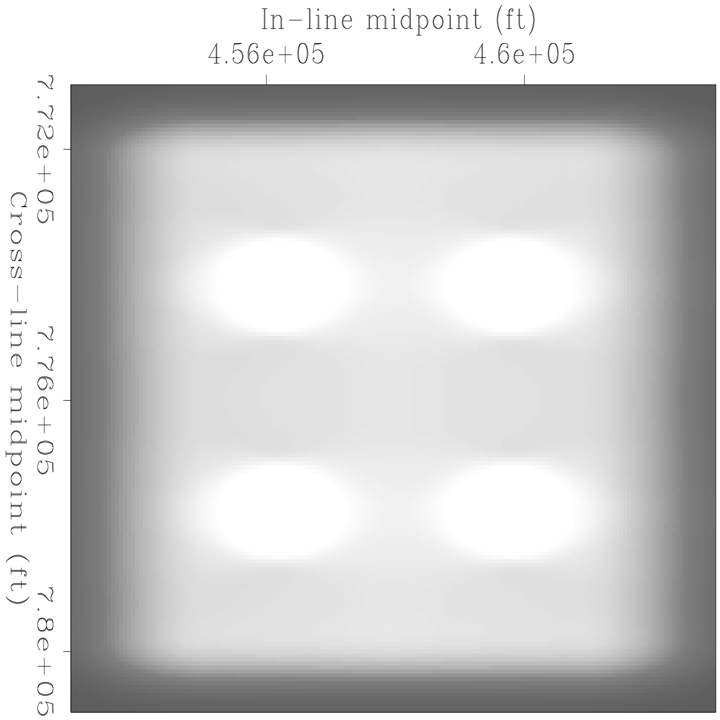


Figure 7: Image of the reflectivity map obtained by migrating a regular cube from a zero-azimuth constant-offset experiment. nizar1-mig-reg [CR]

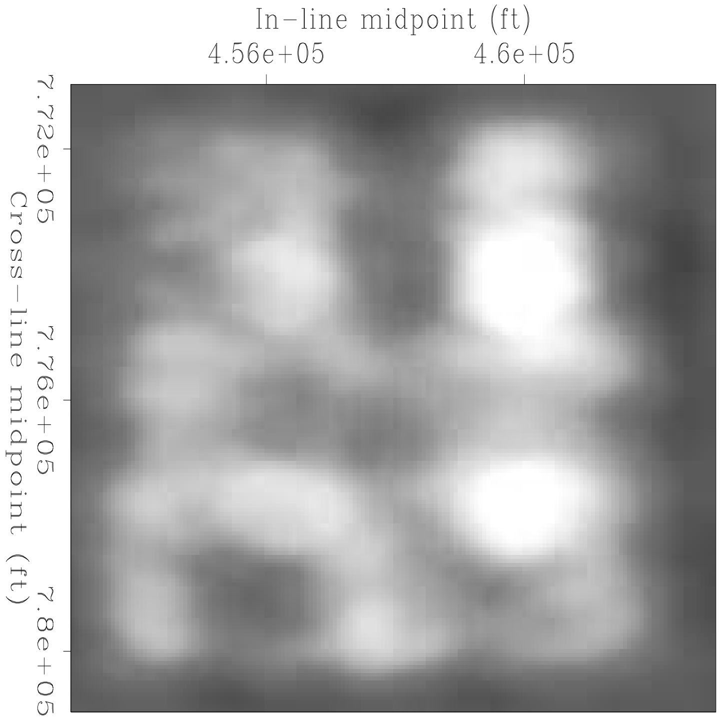


Figure 8: Reflectivity map obtained by direct Kirchhoff migration traces modeled using the real 3-D irregular geometry nizar1-mig-irr [CR]

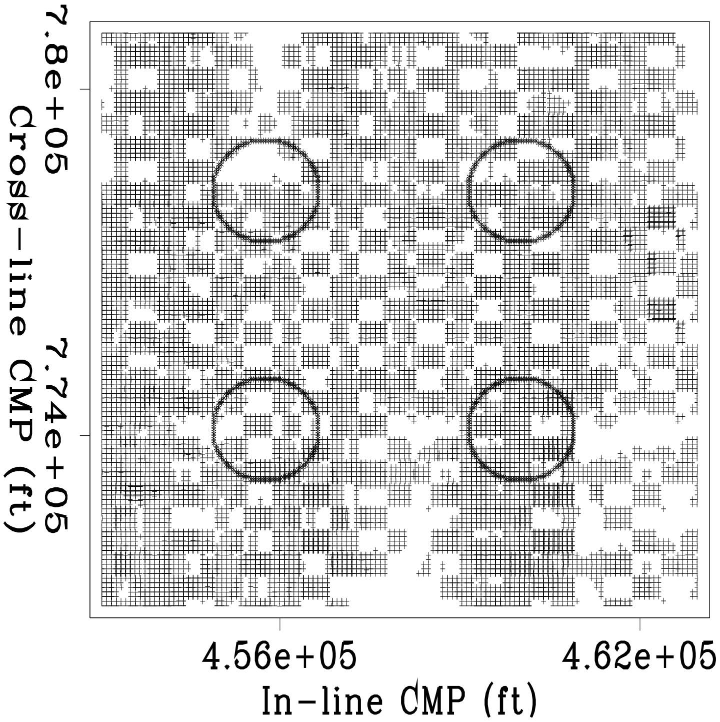


Figure 9: Location of the amplitude anomalies overlaying the mid-point geometry of the recording traces. nizar1-overlay [ER]

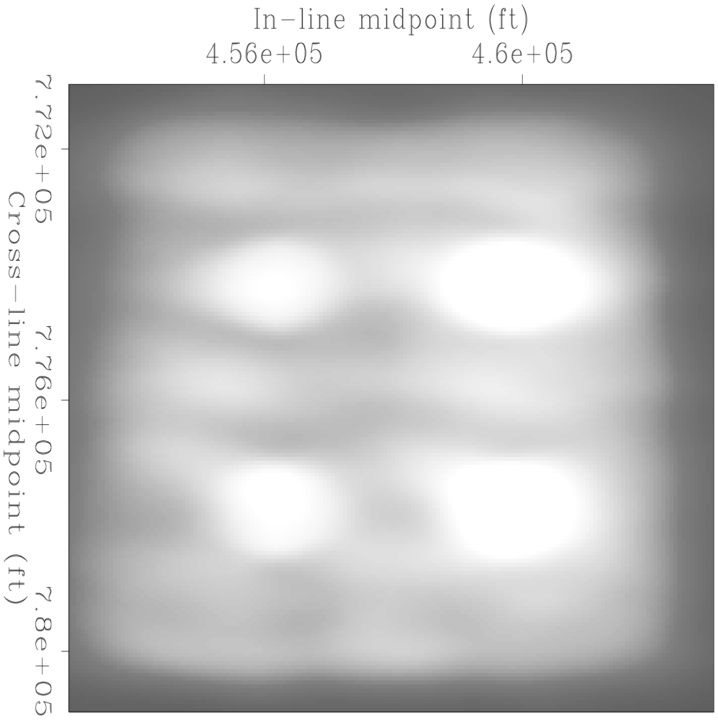


Figure 10: Reflectivity map obtained by migrating the data after applying the AMO transformation to an effective zero-azimuth and a constant offset of 8000 ft. nizar1-amo [CR]

offset and azimuth-dependent reflectivity function. The technique is based on organization of the data into common-azimuth (CA) and common-offset (CO), which allows interpolation to a regular grid before imaging. The method addresses both issues of algorithmic accuracy and proper handling of irregular geometry and therefore allows for reliable AVO analysis on migrated data. We applied this technique to invert for a synthetic reflectivity model which simulates a real 3-D wide-azimuth land survey over a fractured reservoir. Results showed that Kirchoff migration was unable to preserve amplitudes in case of sparse and irregular coverage. The AMO transformation before migration succeeded in reconstructing the data as regular gridded cubes while preserving its amplitude information for imaging. We conclude that (a) interpolating seismic data prior to migration is a promising method for preserving amplitude information; (b) AMO is an effective tool for organizing the data for common-azimuth processing while correcting for the sparse and irregular coverage in wide azimuth 3-D acquisition.

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