Prestack imaging with 3-D common-offset-vector gathers

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ABSTRACT

The natural extension of a common-offset gather (or section) from 2-D to 3-D is a common-offset-vector (COV) gather (or volume). A COV gather is a selection of traces with common inline-offset and common cross-line offset. It is similar, but not identical, to a common-offset-and-azimuth gather. For regular, wide-azimuth 3-D acquisition geometries, the prestack data can be subdivided naturally into N 1-fold COV gathers, where N is the nominal fold of the data. The resolution, as well as the data and operator aliasing issues, for a 3-D COV gather (or volume) can be analysed in the inline or crossline direction just like a 2-D common-offset gather (or section).

INTRODUCTION

Getting a reliable image from the prestack migration of 3-D land seismic surveys is difficult because of poor sampling of the prestack data (Canning and Gardner, 1998; Sun et al., 1997). 3-D Kirchhoff prestack migration involves the evaluation of a 5-dimensional integral of a highly oscillatory, irregularly sampled function that is usually aliased in at least 2 out of 4 spatial dimensions. It is difficult to accurately evaluate this integral with discrete summations.

Kirchhoff algorithms are typically used in this situation because they can treat each trace separately, and thereby adapt the migration operator to the variable source-to-receiver azimuths and offsets of the data. However, the accuracy of the result is poorly controlled because the Kirchhoff integrals are essentially being estimated in a crude Monte Carlo fashion: each trace is migrated separately and added into the output volume. Coming out at the end is an image that we hope is reliable, but we have little real assurance that it is. Cary (1999) shows that the outcome is in some ways better, and in some ways worse, than doing migration after stack. In order to get a more uniformly accurate image, the true spatial distribution of traces has to be taken into account. A least-squares approach to migration (Nemeth et al., 1999) can, with the aid of proper model constraints, overcome these problems. However, this is a very expensive solution to the problem. Regularizing individual subsets of the data is a less expensive alternative (Chemengui and Biondi, 1999).

With real 3-D data there is not only the issue of irregular acquisition geometry to contend with (crooked, missing and irregularly spaced receiver lines; missing, repeated or skidded shots), but even with perfectly regular sampling, it is not clear how to treat the data and operator aliasing issues with a typical land geometry of orthogonal shot and receiver lines.

Vermeer and Grimbergen (1998) approached this problem by separately migrating all the cross-spreads in a 3-D prestack dataset, and “tiling” together the separate images, much like the cross-spread approach to 3-D DMO (Padhi and Holley, 1997). However, migrating cross-spreads in 3-D is much the same as migrating shot gathers in 2-D: the migrated image is dominated by edge effects (wavefronting). Obtaining the full, correct image requires the summation of migrations from a regular, fine spacing of shots in 2-D or cross-spreads in 3-D. A completely artifact-free image could be obtained only with extremely expensive acquisition parameters.

The accuracy of 2-D prestack migrations can be controlled with the use of common-offset gathers and sections since in principle each migrated common-offset section can stand alone as a complete image of the subsurface. Creating common-offset sections by binning and stacking together several true constant-offset gathers is a simple, approximate method of regularizing and dealiasing the input (and/or output) data for each common-offset migration. The advantages and disadvantages of migrating this approximate form of minimal dataset are examined elsewhere in this volume (Cary, 1999).

Being able to separately migrate subsets of the full 3-D prestack volume in the same way that common-offset gathers are separately migrated for 2-D data would be extremely useful. Not only would it possibly allow each subset of data to be migrated with a non-Kirchhoff algorithm (e.g. F-K), but it would provide an ideal geometry to strive for during survey design or data regularization, at least as far as sampling signal is concerned. The requirements for sampling noise in order to minimize its effect on the final image is an important issue that is not examined here.

WHAT IS A COMMON-OFFSET-VECTOR GATHER?

So what is the subset of 3-D prestack data that is ideal for prestack imaging purposes? That is, what is the 3-D analog of 2-D common-offset gathers?

The first, and simplest, guess at an answer to that question is a 3-D common-offset gather, where offset is understood to be the absolute value of the distance from the source to the receiver. 3-D common-offset gathers or stacks are commonly used in the processing of 3-D data because they can provide N volumes that cover the entire 3-D survey area, where N is the nominal fold of the data.

However, in order for 3-D prestack migration or DMO to work properly, traces within the gather must have common azimuths as well as common offsets. This is because the migration operator varies with both offset and azimuth. Within a 3-D common-offset gather, traces in neighboring bins can have completely different azimuths, so migration will map the dipping reflections on those traces to separate places in the image space, so the migration wavefronts will not interfere correctly. We need a dataset that can be mapped from a continuous part of data space to a continuous part of image space.

The usual second guess at an answer to the question is a common-offset-and-azimuth gather, since this would seem to overcome the shortcomings of common-offset gathers. In fact, common-offset-and-azimuth gathers would be an ideal type of gather for our needs, so attempts to use this type of gather have been made. For example, Chemingui and Biondi (1999) approach the problem of regularizing 3-D datasets that are acquired with irregular geometries with a method which they call ICO (inversion to common offset), which consists of regularizing the data into a number of common-offset-and-azimuth gathers with azimuth moveout.

The trouble with common-offset-and-azimuth gathers is obvious to anyone who has tried to form them from normal 3-D land data (or marine OBC data) that is acquired with orthogonal shot and receiver lines. Even when this type of acquisition geometry is perfectly regular, there is no way to choose the offsets and azimuths in a way that yields a trace at each CMP location. If the pie slices that define the shot-to-receiver azimuths are made too narrow, then there are a lot of empty CMP bins. If they are made wider, then the fold is very irregular from bin to bin. The width of the offset bins can be selected to try to overcome some of these difficulties, but there is no obvious way to do this.

The problems with common-offset-and-azimuth gathers stem from the fact that polar coordinates are being used to gather the data, but Cartesian coordinates are used to acquire the data. The simple solution to the problem is to match the gathering geometry to the acquisition geometry. This naturally leads us to common-offset-vector gathers, which are simply the Cartesian coordinate version of common-offset-and-azimuth gathers.

Instead of thinking of the source-to-receiver vector in terms of offset and azimuth (polar coordinates), it is fruitful to think in terms of inline-offset and crossline-offset (Cartesian coordinates), as illustrated in Figure 1. A common-offset-vector (COV) gather is simply a collection of traces that share the same inline-offset and the same crossline-offset. The inline-offset does not have to equal the crossline offset, but the inline-offsets of all traces must be the same and the crossline-offset of all traces must be the same. It turns out that COV gathers can be constructed and analysed in very much the same way as 2-D common-offset gathers.

True COV gathers are normally sparsely sampled in the CMP domain, just like true common-offset gathers are sparsely sampled for a lot of land 2-D geometries. For 2-D data, the spacing between traces in true common-offset gathers is equal to the source interval, which is often several times larger than the receiver interval. For 3-D geometries the inline direction is normally along the receiver lines, and the crossline direction is normally along the source lines. This implies that the spacing between traces in true COV gathers is equal to the source-line spacing in the inline direction and the receiver-line spacing in the crossline direction. In order to obtain a 1-fold volume of traces that fills in every CMP location with similar values of inline-offset and crossline-offset, the inline-offsets and crossline-offsets need to be binned. It is easiest to use a real 3-D geometry to illustrate these points.

HOW TO MAKE A COMMON-OFFSET-VECTOR GATHER

In order to understand how COV gathers are constructed, an example that uses a real 3-D geometry can be used. The field layout of shots and receivers from this 3-D survey are shown in Figure 2. As with most land 3-D surveys, the shot and receiver lines are orthogonal to each other. The acquisition geometry is approximately regular, although irregularities, as always, do exist. The rules for making COV gathers, which are based on the assumption of regular geometry, will work well where the geometry is regular, and will start to break down where the geometry is irregular. In other words, the guidelines for creating 3-D COV gathers will be as useful as the guidelines

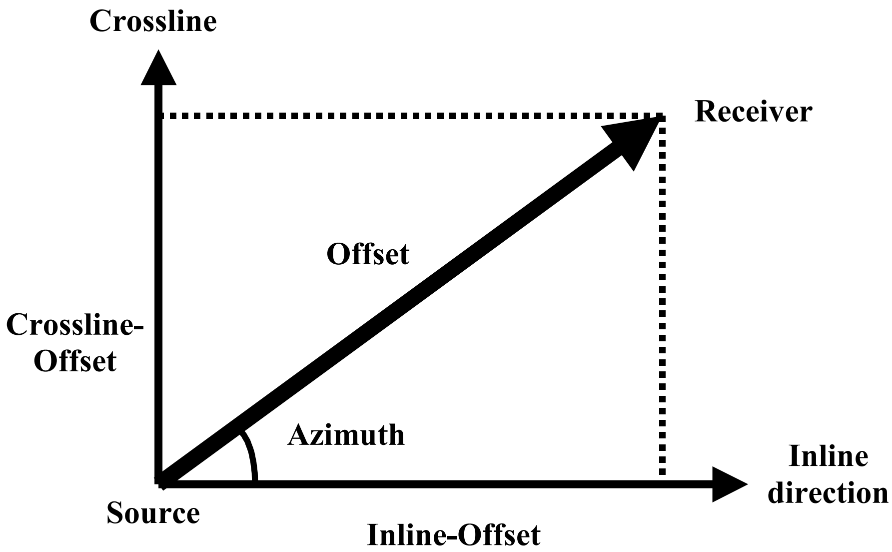


Fig. 1. A common-offset-vector gather is a selection of traces with common inline-offset and common crossline-offset (Cartesian coordinates), instead of common offset and azimuth (polar coordinates).

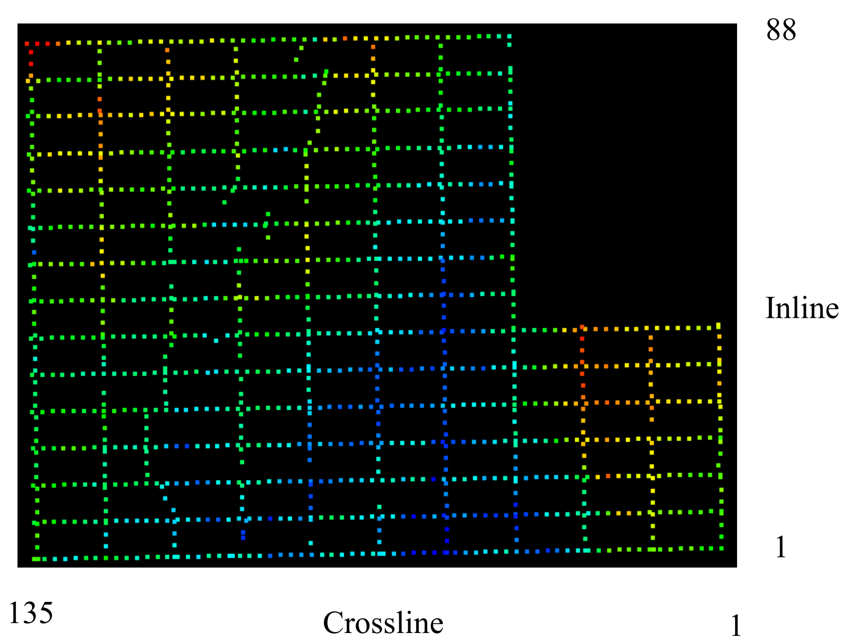


Fig. 2. The field layout for a real 3-D survey with shot-lines (vertical) spaced 400m apart and receiver-lines (horizontal) spaced 200m apart. Like most 3-D surveys, the geometry is mostly regular, but with some irregularities, so the rules for gathering COV traces are suitable over most of the survey.

for creating 2-D common-offset gathers, and the standard tricks for filling in gaps in the coverage (e.g. increasing the offset bin width) can be used in 3-D, just as in 2-D.

The nominal acquisition geometry for the 3-D survey is as follows: the source-line interval is 400m, the receiver-line interval is 200m, the source interval is 64m, and the receiver interval is 30m. The first step in constructing a COV gather is to compute the inline-offset and the crossline-offset for every trace in the dataset. We can now consider the 3-D prestack spatial sampling function as a function of the inline-offset, crossline-offset, inline CMP number and crossline CMP number (Hampson, 1997).

Figures 3 and 4 show two different 2-D projections of the true 4-D sampling function of the present dataset. These two projections illustrate the periodic nature of the inline-offsets and crossline-offsets in the prestack data. Figure 3 is the 2-D projection, or "stacking chart", for traces selected only from inline 44, which runs through the middle of the 3-D. This plot of the wavefield sampling as a function of crossline-offset and crossline CMP number shows that the same crossline-offset is sampled by traces that are separated by the shot-line spacing, 400m. Notice that this is exactly the way that offsets repeat on stacking charts for 2-D data. Figure 4 is the "stacking chart" for crossline 67, which runs through the middle of the dataset in the orthogonal direction. This plot of the wavefield sampling as a function of the inline-offset and inline CMP number shows that the same inline-offset is sampled by traces that are separated by the receiver-line spacing, 200m. Notice that this is exactly the way that offsets would repeat on stacking charts for 2-D data if all receivers became shots and all shots became receivers.

I have used the term "stacking chart" to describe Figures 3 and 4 because they both have the appearance of ordinary stacking charts that we are familiar with from 2-D data. These type of plots could be generated for every inline and crossline in the 3-D dataset. The four prestack coordinates for 3-D seismic data are orthogonal to each other, of course, so the stacking charts in the crossline direction (e.g. Fig. 3) are "decoupled" from the stacking charts in the inline direction (e.g. Fig. 4). This means that inline-offsets and crossline-offsets can be treated independently in the COV gathering process.

We now see that a true COV gather should nominally have traces that are separated by the shot-line spacing along inlines and by the receiver-line spacing along crosslines. Offset bin widths will need to be defined for a "true" COV gather just as for 2-D common-offset gather in order to accommodate irregularities in the acquisition geometry and to accommodate a shot interval that is not an integer multiple of the receiver interval. The inline-offset and crossline-offset bin widths are given by the ratio of the shot-line spacing to the receiver interval (400/30) and the ratio of the receiver-line spacing to the shot interval (200/64), respectively.

A true COV gather is not very useful because the sparse sampling will cause severe data aliased for most geometries. However, an approximate COV gather that has a trace at every CMP location can be formed by increasing the offset bin widths. These approximate COV gathers are extremely useful, for all the same reasons that approximate common-offset gathers are useful for 2-D data.

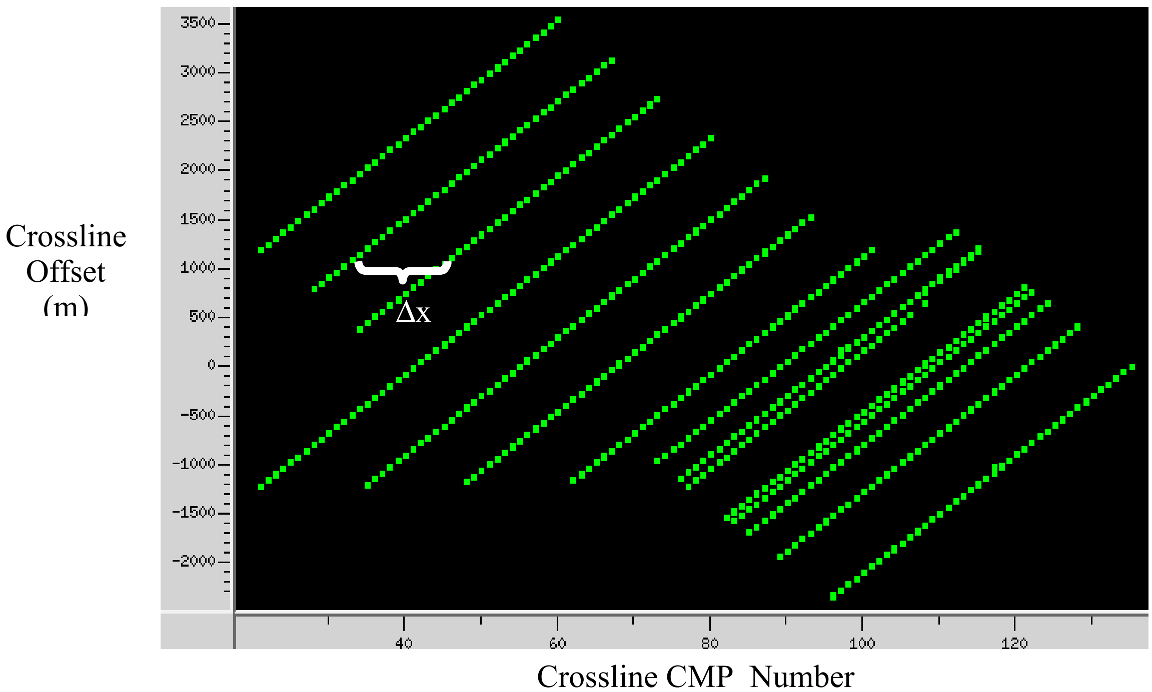


Fig.3. Stacking diagram for inline 44. The interval, Δx, indicates that the periodicity of the crossline-offset is the source-line spacing.

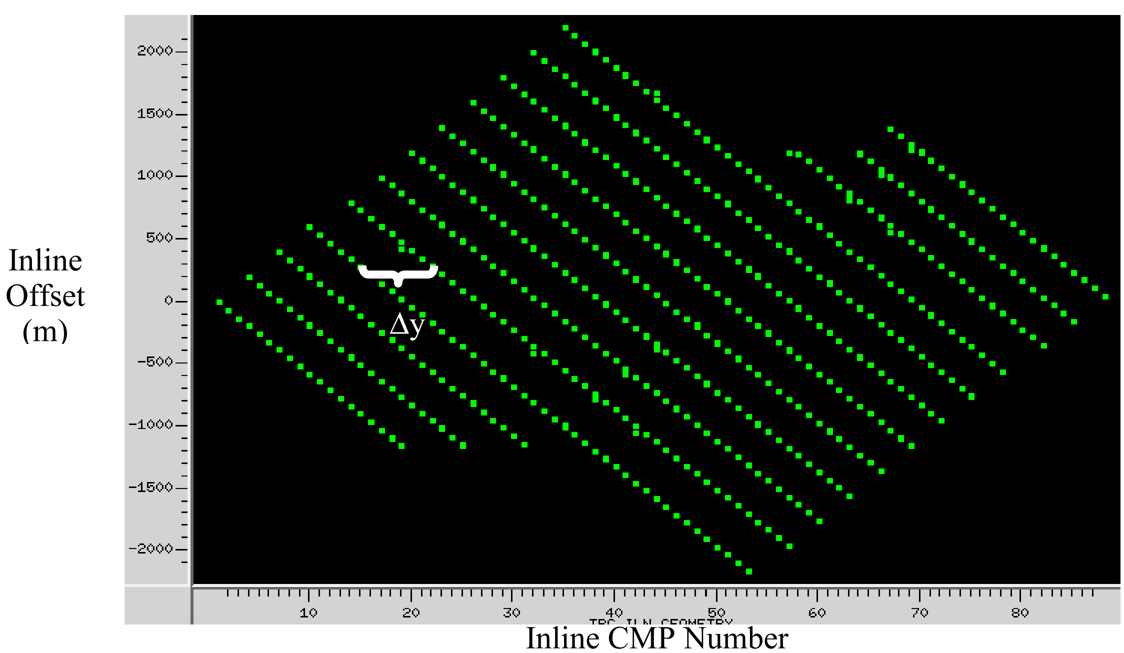


Fig.4. Stacking diagram for crossline 67. The interval, Δy, indicates that the periodicity of the inline-offset is the receiver-line spacing.

The recipe for making a 2-D common-offset gather with a trace at every CMP is to make the offset bin width equal to twice the shot interval (which follows from the periodicity of offsets in 2-D stacking charts). The periodicities of inline and crossline offsets illustrated in the "stacking charts" in Figures 3 and 4 indicate that the corresponding recipe for making a COV gather with a trace at each CMP location is to make the inline-offset bin width equal to twice the source interval and to make the crossline-offset bin width equal to twice the receiver interval.

There are "positive" and "negative" offset vectors for 3-D data, just like there are positive and negative offsets for 2-D data. If we assume reciprocity of shots and receivers, then "positive" and "negative" offset vectors can be gathered together, since the migration operator for P-P data is insensitive to the exchange of shots and receivers.

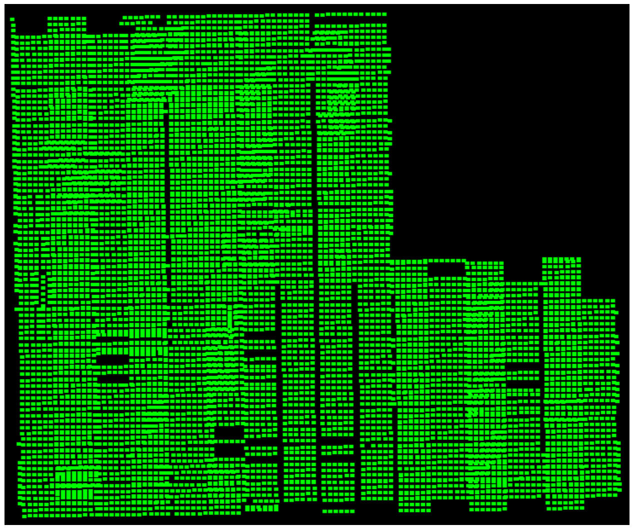
Figure 5 shows the CMP coverage of the "positive" COV gather counterpart (inline offset = 1200 ± 400m; crossline offset = 200 ± 100m) together with its "negative" COV counterpart (inline offset = -1200 ± 400m; crossline offset = -200 ± 100m). Grouping together positive and negative COV gathers can increase the efficiency of the migration algorithm, as well as help to regularize the geometry by filling in gaps in CMP coverage. Fig. 5 shows that the COV gathering recipe works well where the geometry is regular, and starts to break down where the shot lines are irregular.

Several additional characteristics of 2-D common-offset gathers also apply to 3-D COV gathers. For example, the total number of 3-D COV gathers that can be formed with reasonably large coverage of the survey area is equal to the nominal fold of the data, just like 2-D common-offset gathers. Figure 6 shows the selection of COV gathers that are available for the present 3-D survey. The number of offset bins in the inline and crossline directions is given by the rule for calculating the inline fold and the crossline fold (Stone, 1994, p.136), and the total number of bins equals the product of the inline fold and the crossline fold.

Finally, there are parallels between the way that the coverage of 2-D common-offset gathers and 3-D COV gathers vary with offset. As offset increases, the edges of 2-D common-offset gathers, within which live data is recorded, generally move down in time and inward from the survey edges since the mute time increases with offset, and the large offsets are generally not sampled at the ends of the 2-D line. The same kind of thing happens with 3-D COV gathers. Knowledge of how the coverage of COV gathers decreases with inline-offset and crossline-offset is important information for reducing edge effects in applications such as 3-D prestack migration.

A SIMPLE EXAMPLE

Perhaps the simplest process that illustrates how COV gathers can be used for imaging wide-azimuth 3-D surveys is common-conversion-point (CCP) binning of 3-D converted-wave (P-S) data. CCP binning maps P-S data in a depth-variant manner to their true reflection points under the assumption that all reflectors are flat. In most cases, the P-S reflection point is located between the midpoint and the receiver location.



Inline

Crossline

Fig. 5. CMP coverage for positive and negative COV gathers with inline-offset = 1200 ± 200m and crossline-offset = 200 ± 100m. The coverage is uniform except where the source lines are irregularly spaced.

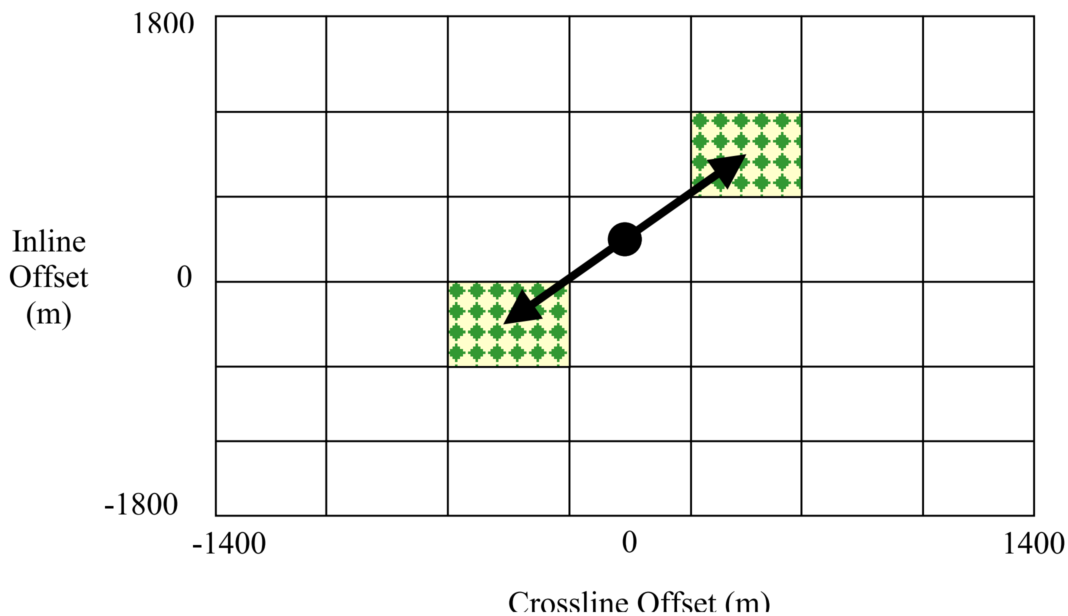


Fig. 6. The distributions of COV gathers for the 3-D survey. The total number of gathers is the nominal fold of the data. The arrows indicate the two "positive" and "negative" COV gathers whose coverage is shown in Fig. 5.

If we look at the region of coverage of a COV volume extracted from a real 3-C, 3-D dataset, which on input is binned according to midpoint, as in Figure 7(a), then CCP binning maps the data at 600ms to a large continuous portion of the total output grid, Figure 7(b), which is what is required of an ideal minimal 3-D dataset. In contrast, a cross-spread that is binned by midpoint, as in Figure 8(a), is mapped to a relatively small continuous portion of the total output grid, Figure 8(b). In both Figures 7(b) and 8(b), gaps appear within the "continuous" portion of each output grid because the binning has been done with nearest neighbor interpolation. If sinc-function interpolation had been used, which takes the bandlimited nature of the wavefield into account, then the empty bins would be filled with data from neighboring bins. An analysis of stacking charts indicates that P-S fold would be more uniform if the data were binned with a "natural" CCP bin size (Eaton and Lawton, 1992) that is larger than the CMP bin size. However, this analysis ignores the bandlimited nature of the data. The average subsurface separation of P-S reflection points for each pseudo-common-offset gather is the CMP interval (Cary, 1999), so the correct bin size for imaging P-S data is still the CMP bin size.

REMARKS AND CONCLUSIONS

A common-offset-vector gather is an ideal subset of a 3-D seismic dataset since it can provide a complete image of most of the output 3-D volume. For regular acquisition geometry, each COV gather can be separately imaged. Ideally, stacking several independently imaged COV volumes should improve the signal-to-noise ratio of the final image, but not its fidelity.

Since true COV gathers are rarely sampled properly, simple guidelines for making COV gathers that will populate all CMP bins, if geometry is regular, have been described that are based on nearest-neighbor interpolation of inline-offsets and crossline-offsets. The interleaved CMP sampling between true 3-D COV gathers leads to approximately dealiased pseudo-COV gathers, with a trace at each CMP location, in the same way that interleaved CMP sampling between true 2-D common-offset gathers leads to approximately dealiased pseudo-common-offset gathers (Cary, 1999). Therefore, COV gathers are the natural choice of geometry to use for 3-D data regularization schemes instead of common-offset-and-azimuth gathers.

Since COV gathers can be analysed independently in the inline and crossline directions, we can take the results from the imaging tests on 2-D common-offset gathers performed by Cary (1999) and apply them directly to 3-D COV gathers. By partial stacking into well-sampled COV gathers before migration, the high frequencies of dipping events in the inline and crossline directions will be smeared in the same way as for 2-D common-offset gathers. However, the events with small dip will be imaged coherently and with reliable waveforms.

On the other hand, the 2-D results (which ignore the impact of noise) suggest that 3-D surveys that are acquired with widely-spaced source and receiver lines should be capable of generating coherent images of the signal by stacking into COV gathers after migration, but the waveforms will be unreliable because of imprinting of the acquisition geometry. To obtain coherent images and reliable waveforms in

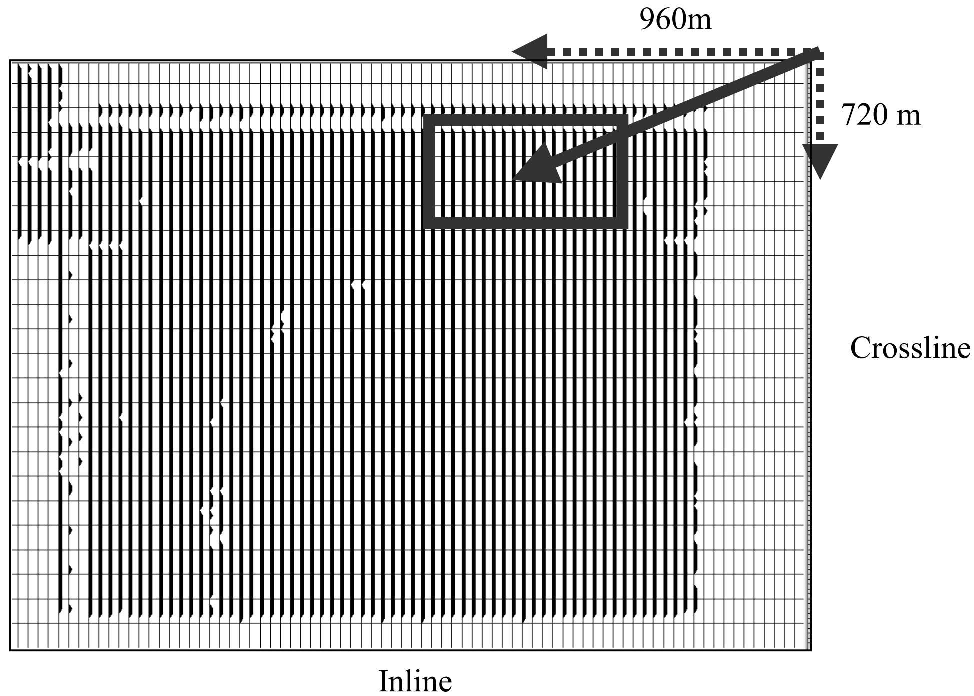


Fig. 7(a). CMP coverage of a common-offset-vector gather before CCP binning. The main arrows indicate the average inline-offset and crossline-offset of traces within the gather, and the box indicates the offset bin widths used to define the gather.

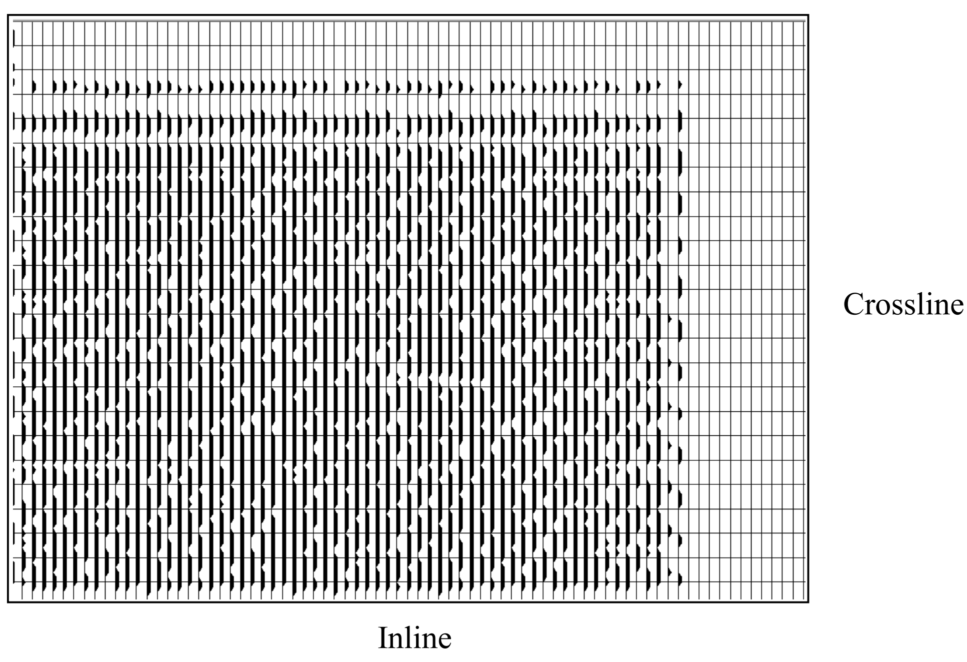


Fig. 7(b). The COV gather after CCP binning with nearest-neighbor interpolation. The traces have been shifted downward and to the left (toward the receiver) by CCP binning.

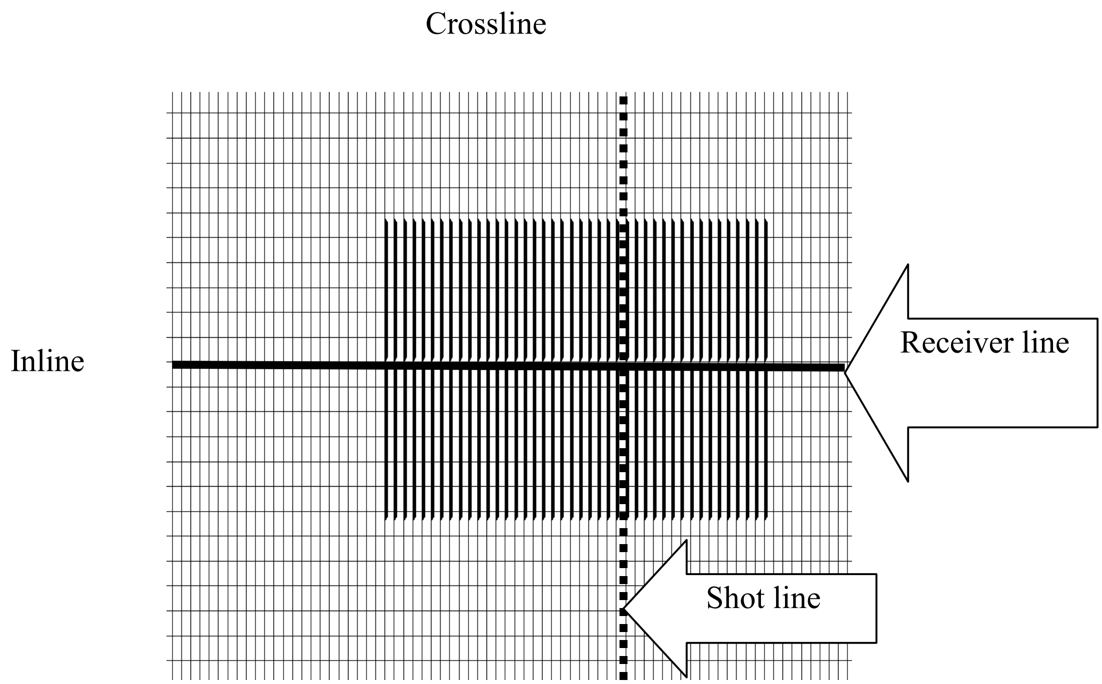


Fig. 8(a). The CMP coverage of a single cross-spread before CCP binning.

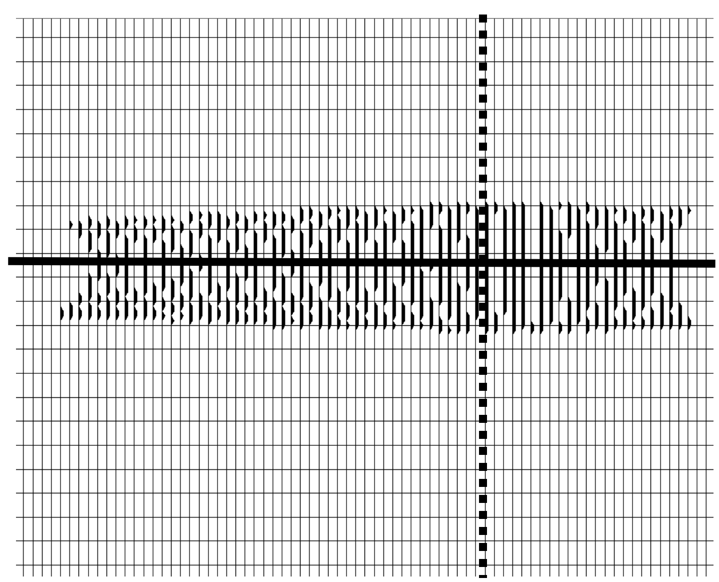


Fig. 8(b). The CCP coverage of the cross-spread in Fig. 8(a). The traces have moved toward the receivers after CCP binning.

structurally complex areas, small shot-line and receiver-line spacings appear to be required, unless some method such as least-squares migration, or least-squares DMO is capable of removing the footprint effect.

It is common to design wide-azimuth 3-D surveys with the aim of making the offset and azimuth distributions uniform within CMP bins. If prestack imaging is going to be performed with COV gathers instead of with common-offset-and-azimuth gathers, a more appropriate design criterion would be to make the inline-offset and crossline-offset distributions uniform within bins. This design criterion would ensure that COV gathers are well-sampled. Since COV gathers emerge naturally from regular orthogonal acquisition geometries, the COV design criteria should be easy to satisfy, as long as the geometry can be kept fairly regular.

As far as amplitude-versus-offset (AVO) and velocity analysis are concerned, imaging with COV gathers would have an impact. If dips are small, then stacking into COV gathers before prestack migration would yield reliable amplitudes for AVO and velocity analysis, but there would be a relatively small number of absolute offsets and azimuths sampled. If dips are large, and shot-line and receiver-line spacings are large, stacking into COV gathers after prestack migration is to be preferred, but it is doubtful that AVO analysis would be reliable because of the acquisition footprint that originates from the prestack migration. If azimuth-dependent velocity analysis before or after migration is required, this would be workable with COV gathers since azimuths are still being sampled in a somewhat regular fashion.

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