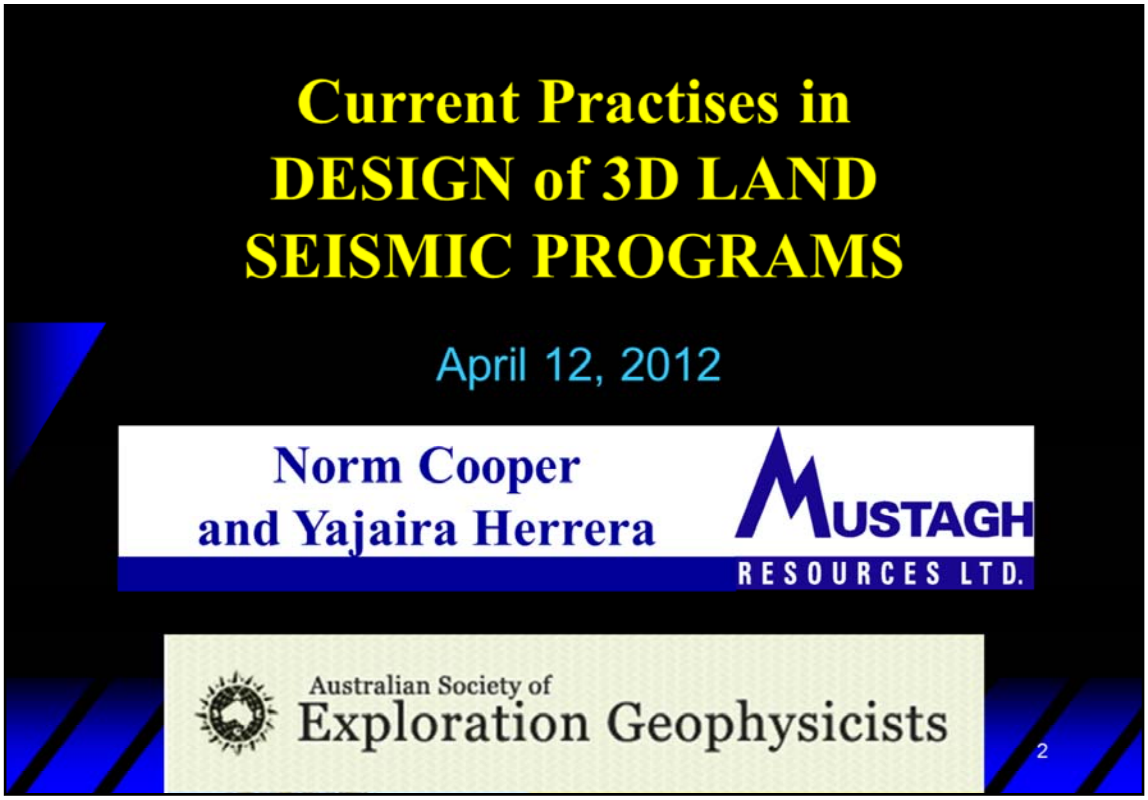
Norm Cooper of Mustagh Resources Ltd. first presented this talk at the December 7, 2012 luncheon meeting of the Pacific Coast Section of the SEG in Bakersfield, California.

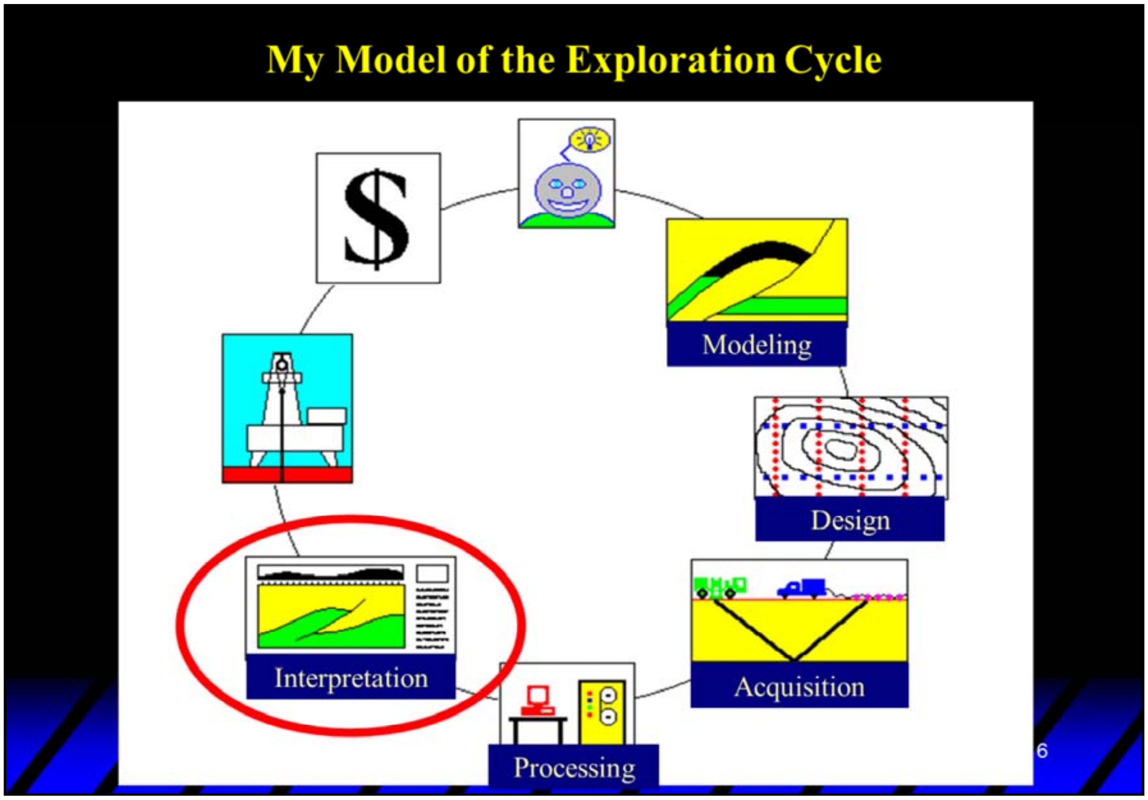


He subsequently presented this talk at the April 12, 2012 evening meeting of the Brisbane Section of the ASEG in Brisbane, QLD.

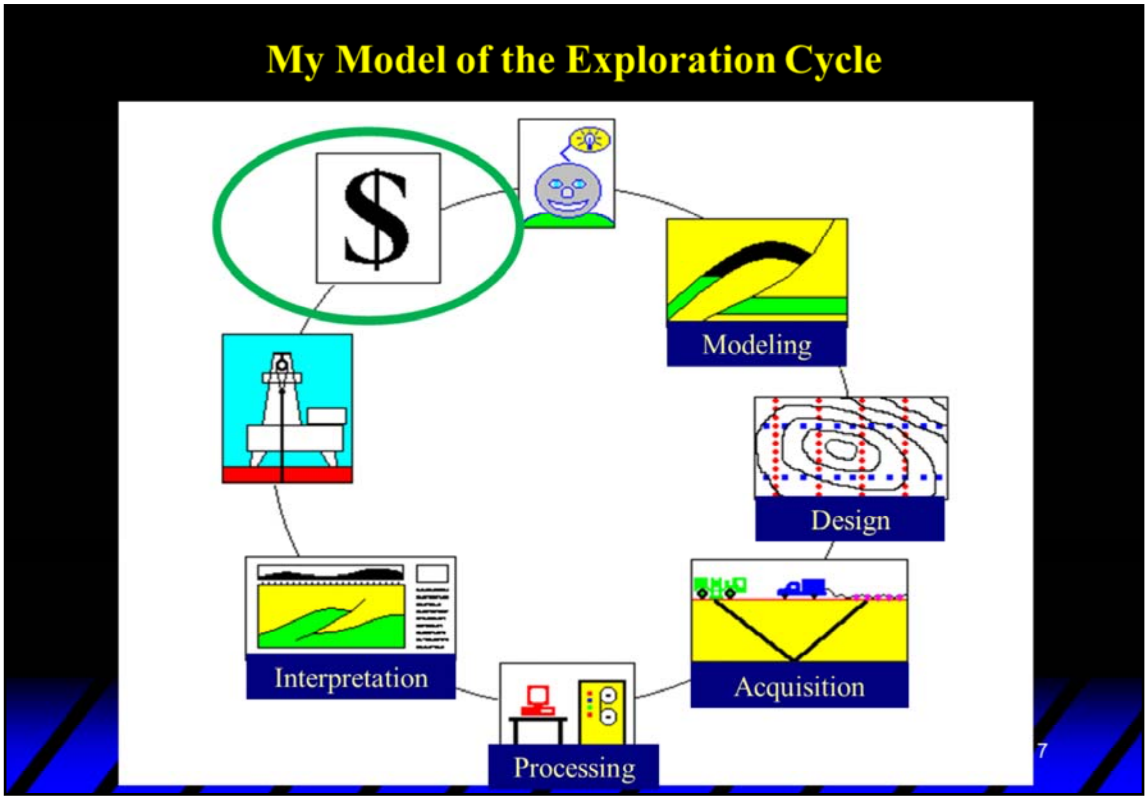
Mustagh Resources Ltd. is named after the Mustagh Tower, a mountain in the Karakoram Himalaya of Northeast Pakistan

Norm was inspired to name his company based on a 1909 Vitorio Sella photograph taken from near Camp Concordia (near K2). The photo in the top right is a reproduction of that famous photo.

Mustagh Resources Ltd. has assisted in the design of more than 3000 projects and has conducted start-up testing on more than 300 seismic crews spanning 50 countries and six continents.

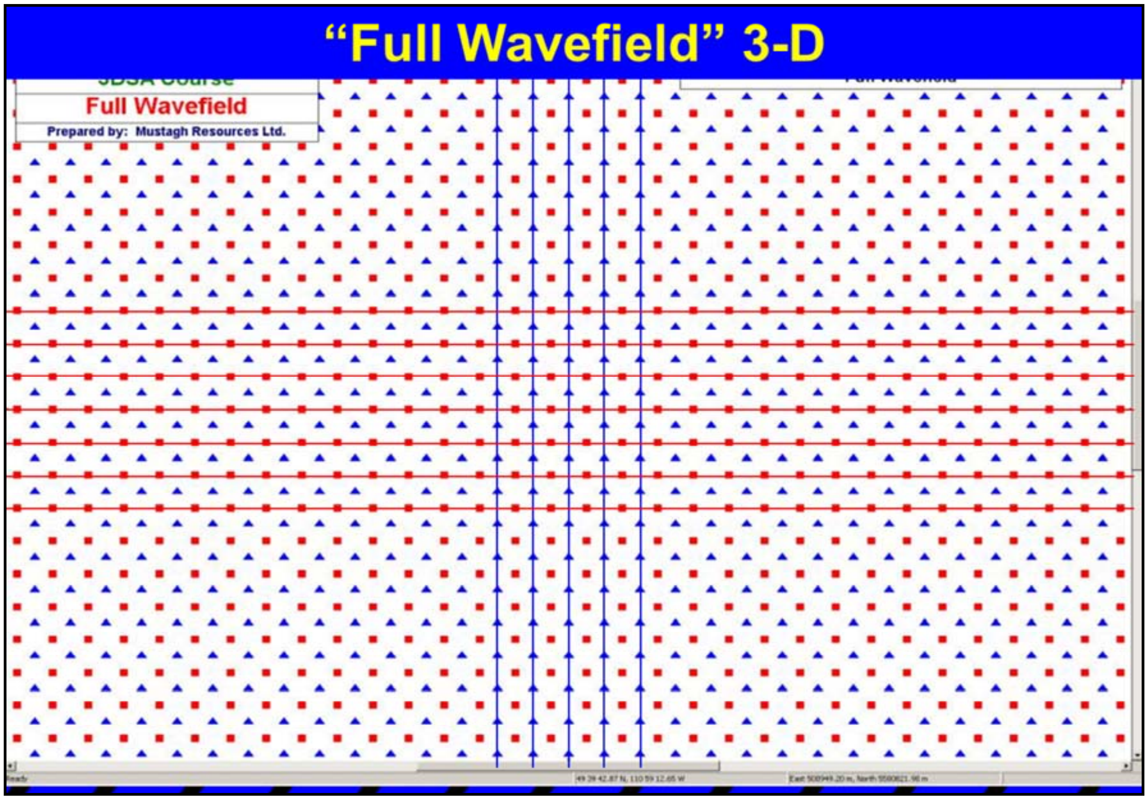


Various elements of reflection seismic contribute to the exploration and development of resources. From a purely scientific perspective, our objective is to produce clear and accurate images of sub-surface geologic features.



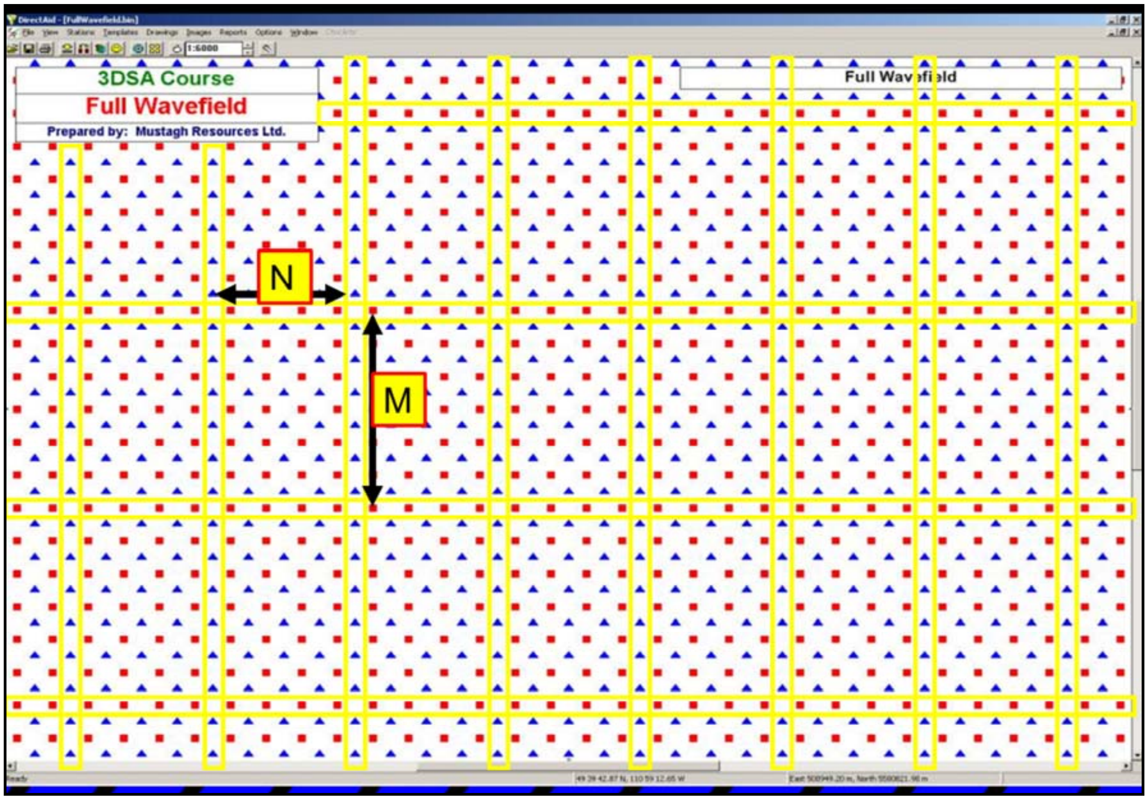
… however, our business objective is to enhance the profitability of our employers and clients. We hope to do this by producing clear and accurate images that help to enhance drilling success and reduce the number of dry holes.

But these images must be obtained at a reasonable economic cost, with acceptable impact to the environment. We must operate safely and be able to effectively use the equipment available to us.

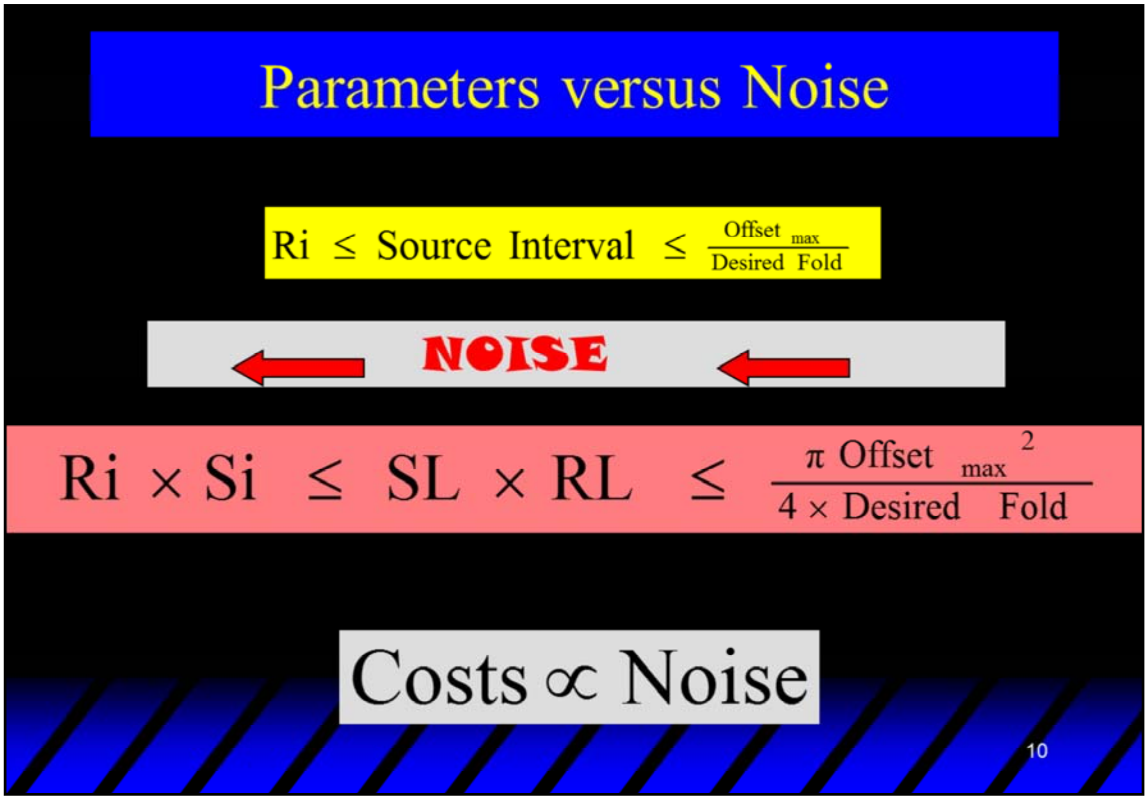


If image quality was our only objective, then design of 3D programs would be quite easy. Simply layout a grid such as above with closely spaced receivers distributed along north-south lines. The line spacing should be similar to the station spacing along the lines. The east-west source grid should have similar spacings to the receiver grid and should be offset from the receiver grid.

We call this a "Full-Wavefield" sampled 3D. Although we know of five such surveys recorded in the world, such a design is generally too expensive and impractical for most exploration and development purposes.

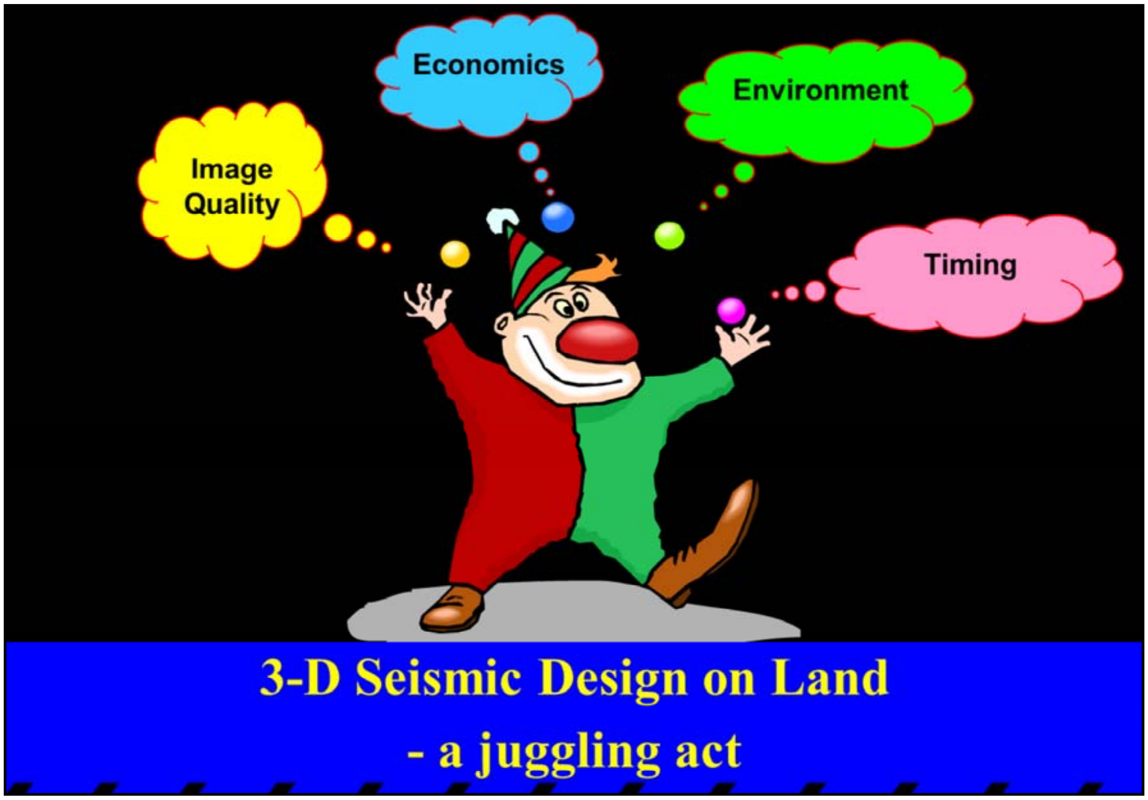


Therefore, one objective of design is to determine how sparsely we can sample the ideal model and still achieve the geophysical imaging objectives. A common practise (but not a necessary one) is to choose a receiver line spacing (RL) that is an integer multiple of the source interval (N x Si) and a source line spacing (SL) that is an integer multiple of the receiver interval (M x Ri).



In 2D designs, we choose a source interval that is less than a factor determined by useable offset (directly related to target depth) divided by the fold desired for the particular geophysical objective. However, if we expect a large contribution of offset-dependent noise, we will choose a smaller source interval. In the limit, we may choose a source interval that is equal to our selected receiver interval.

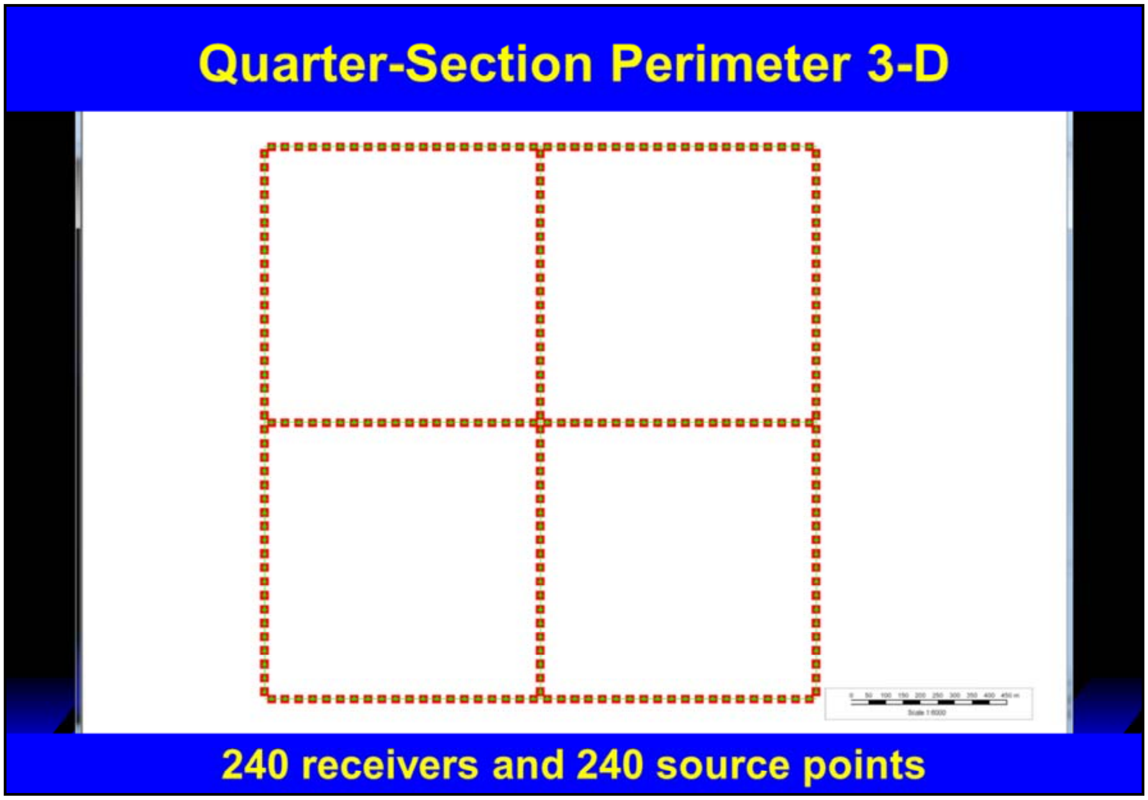
Similarly in 3D design, we choose a box area (SL x RL) determined by offset squared divided by desired fold. However, due to noise considerations, we may reduce this towards a limit of full wavefield sampling.



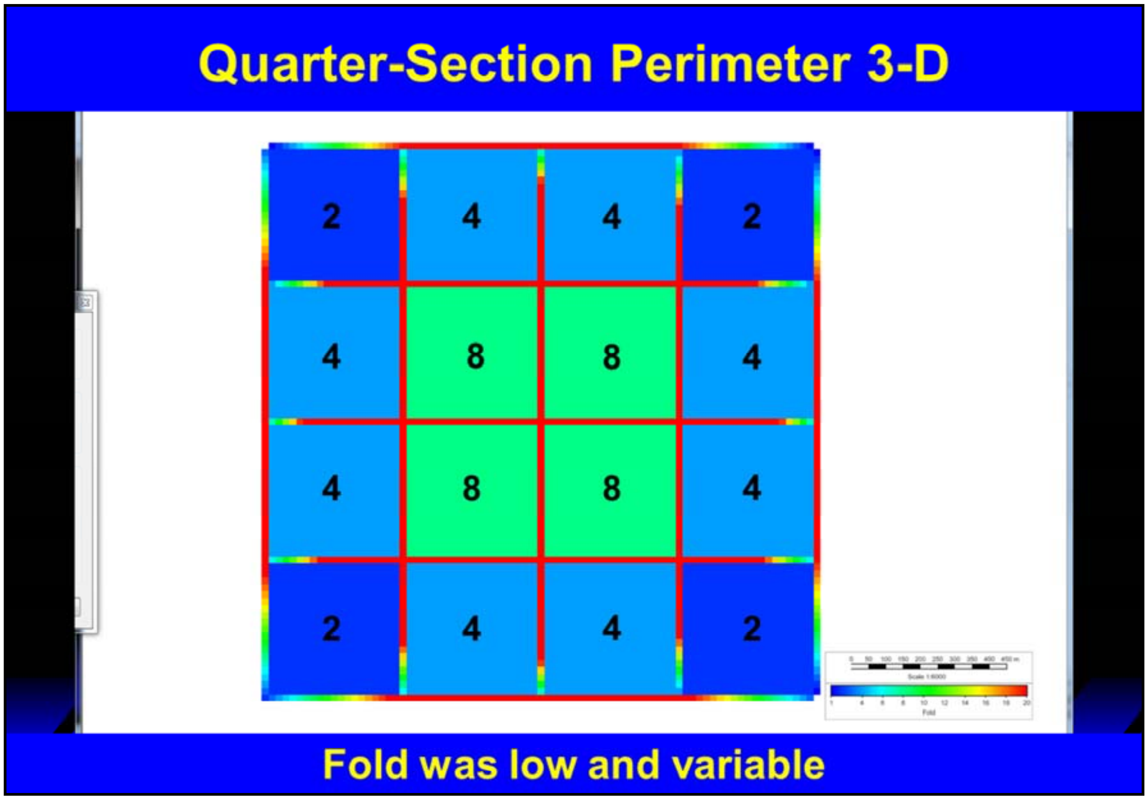
3D design requires a compromise of imaging capabilities against budgetary limits, environmental impact, realistic use of available equipment and timing restrictions.

Effective design requires not only knowledge of geologic objectives, but must also include an understanding of various types of noise, regulatory restrictions, equipment useage and field operations.

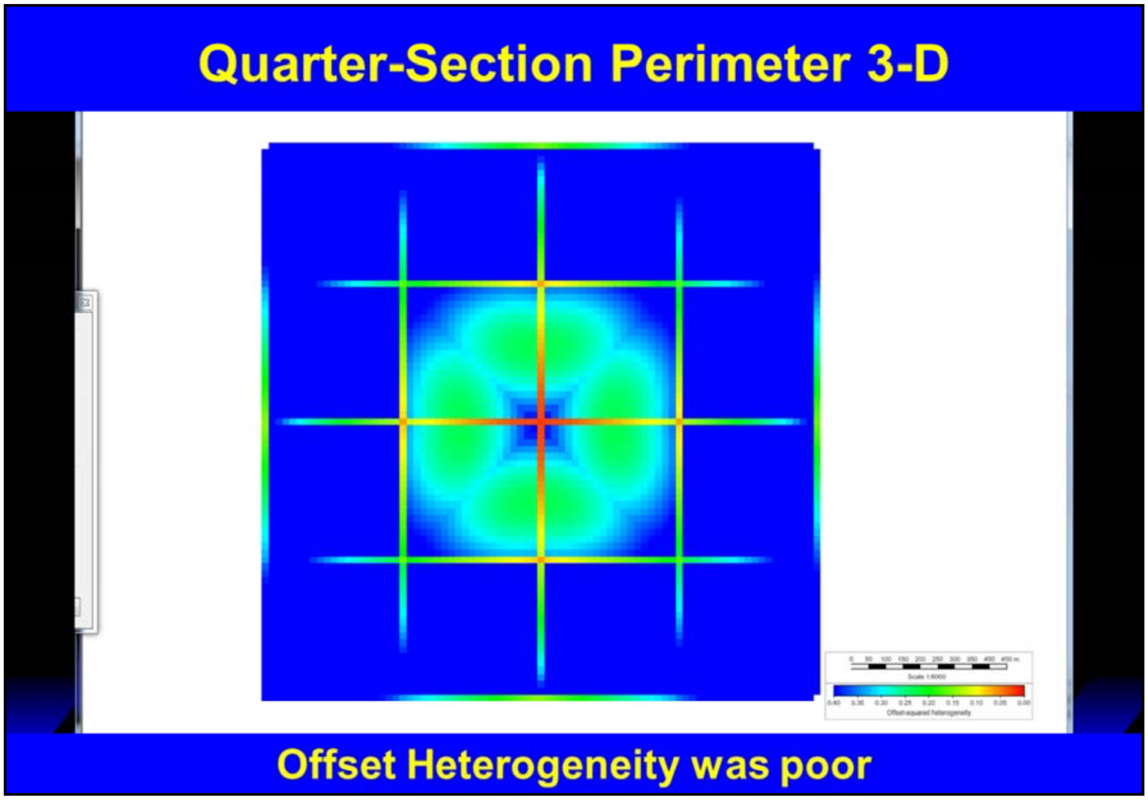
Let's examine a brief history of 3D design. We will begin about 1980 with a pseudo-3D method that was called "Quarter Section Shooting"



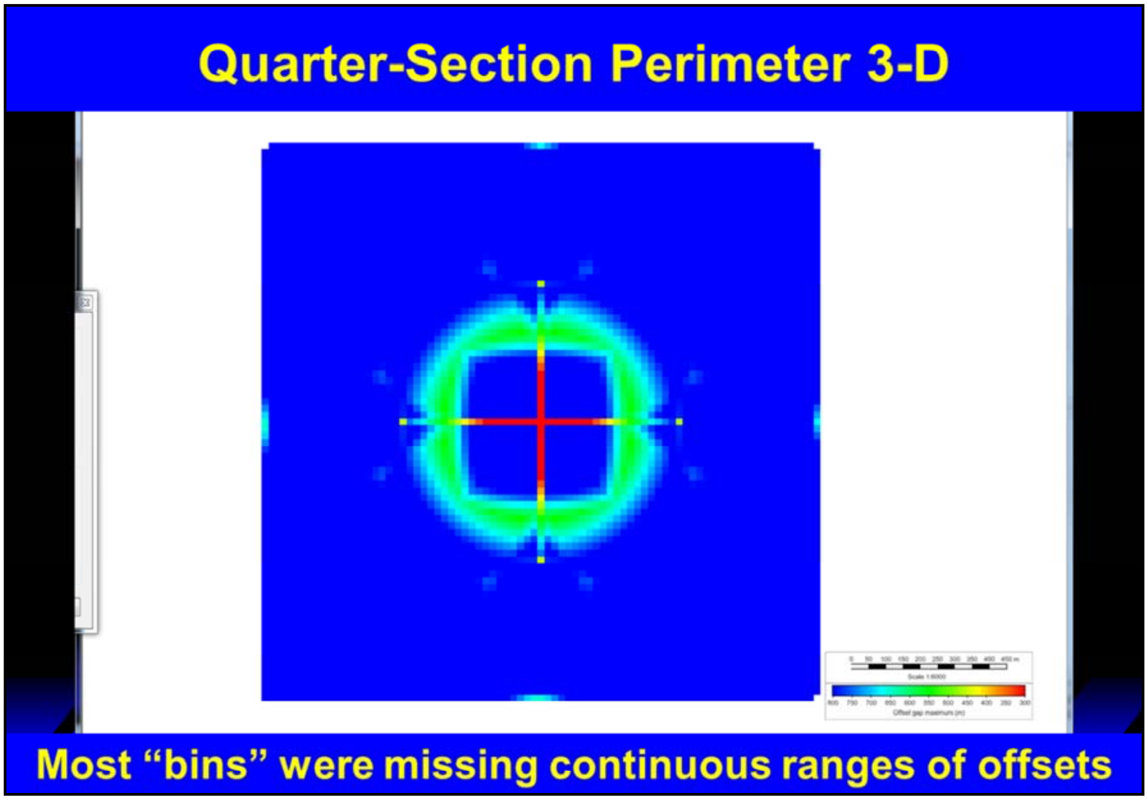
240 receivers were distributed around four adjacent quarter section boundaries (covering one square mile in total). Station spacing was 40 meters and data was often recorded with a master-slave 120-channel recording system. These 240 channels would be recorded as a fixed spread while 240 source points were recorded from similar locations.



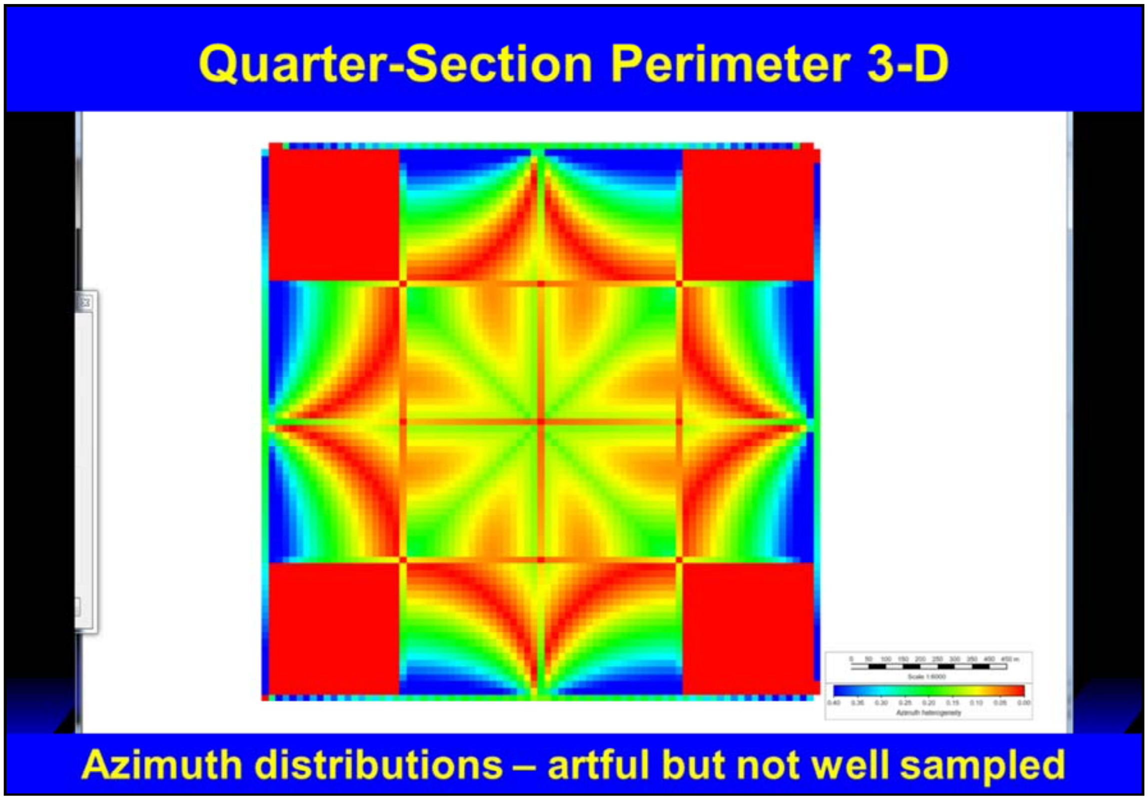
This is a “Fold” plot showing the subsurface coverage obtained in “natural” subsurface bins of 20 x 20 meters. The coverage was not very good, other than in orthogonal stripes every 400 meters, where it reaches 20 fold. One quarter of the subsurface area is 8 fold, one half is only 4 fold and the corner octants form one quarter of the area at only 2 fold.



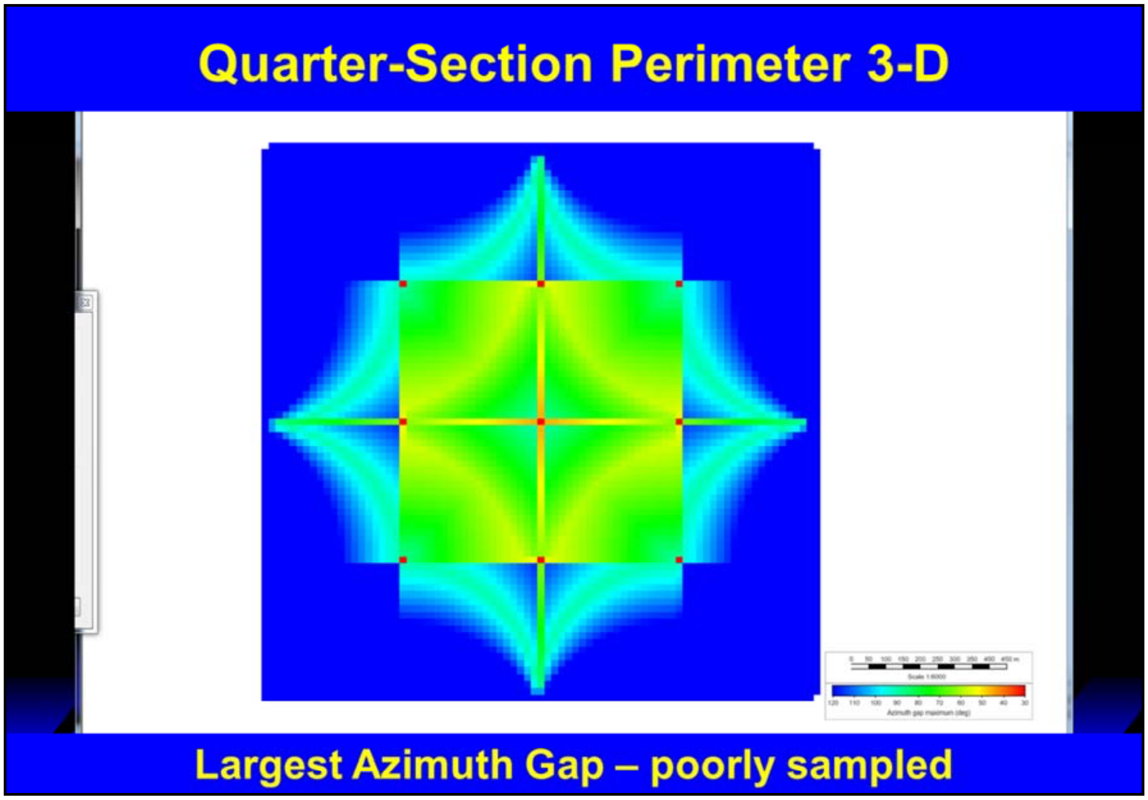
But “Fold” plots are not a good representation of survey quality. The plot above assigns a color to each subsurface bin depending on the uniformity of offset distribution compared to an ideal 3D world. Red is good and blue is bad. Notice that only the central portion of the survey attains moderately acceptable distributions.



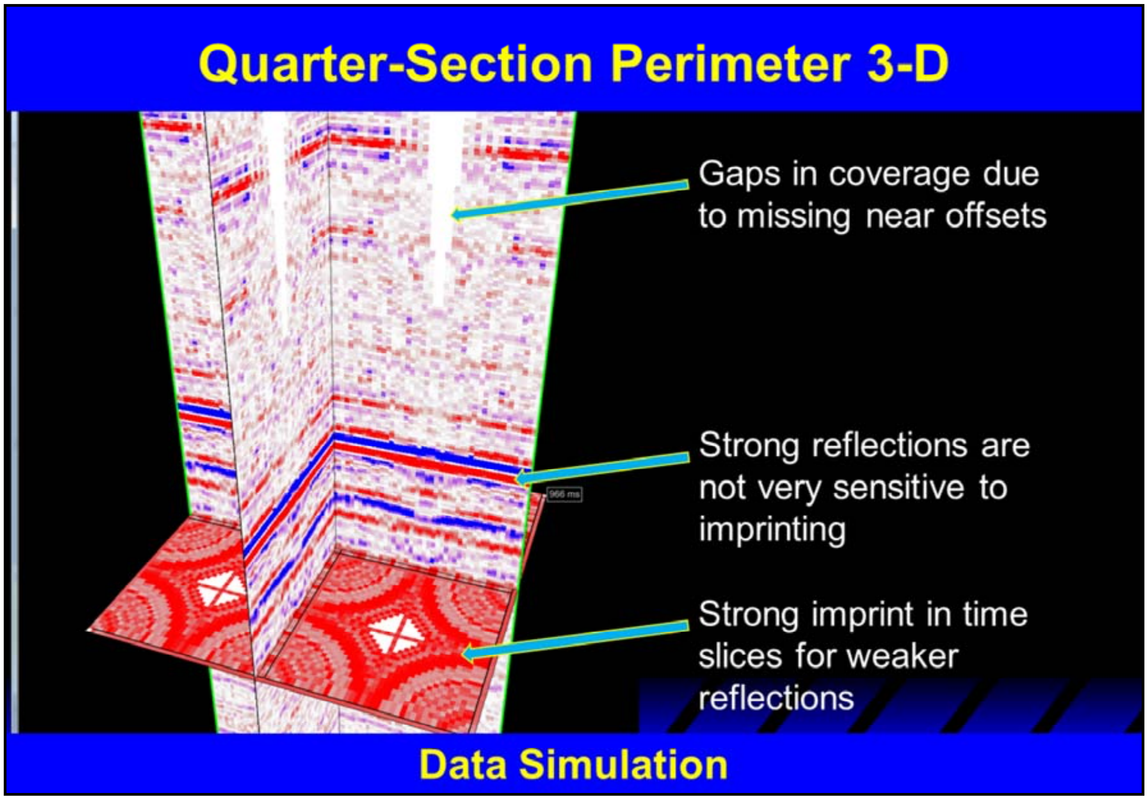
The “Largest Offset Gap” plot reveals that most bins contain large ranges of continuous un-sampled offsets. This is a bad condition for velocity analysis, multiple suppression and migration integrity.



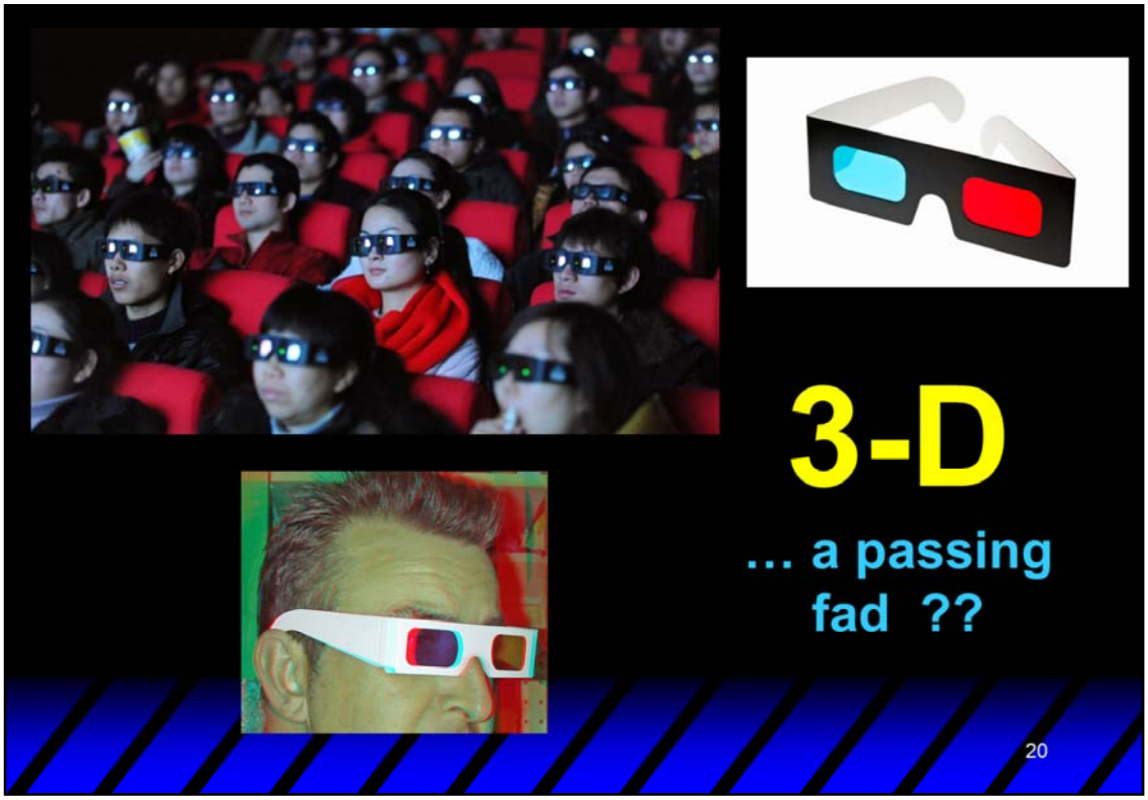
A plot of azimuth homogeneity makes an attractive wall hanging. But it reveals that azimuth sampling is very erratic across the survey.



Similarly, this plot shows that most bins are missing large ranges of azimuths.



Perhaps the best expression of just how poor these "Quarter Section" 3Ds could be is the above display through a cube covering one square mile. This cube was simulated in such a way that no geologic changes occur from trace to trace. The variations are due entirely to bin-to-bin variations in offset distributions. Note the incomplete coverage of shallow events and the very strong geometric imprinting on deeper time slices.

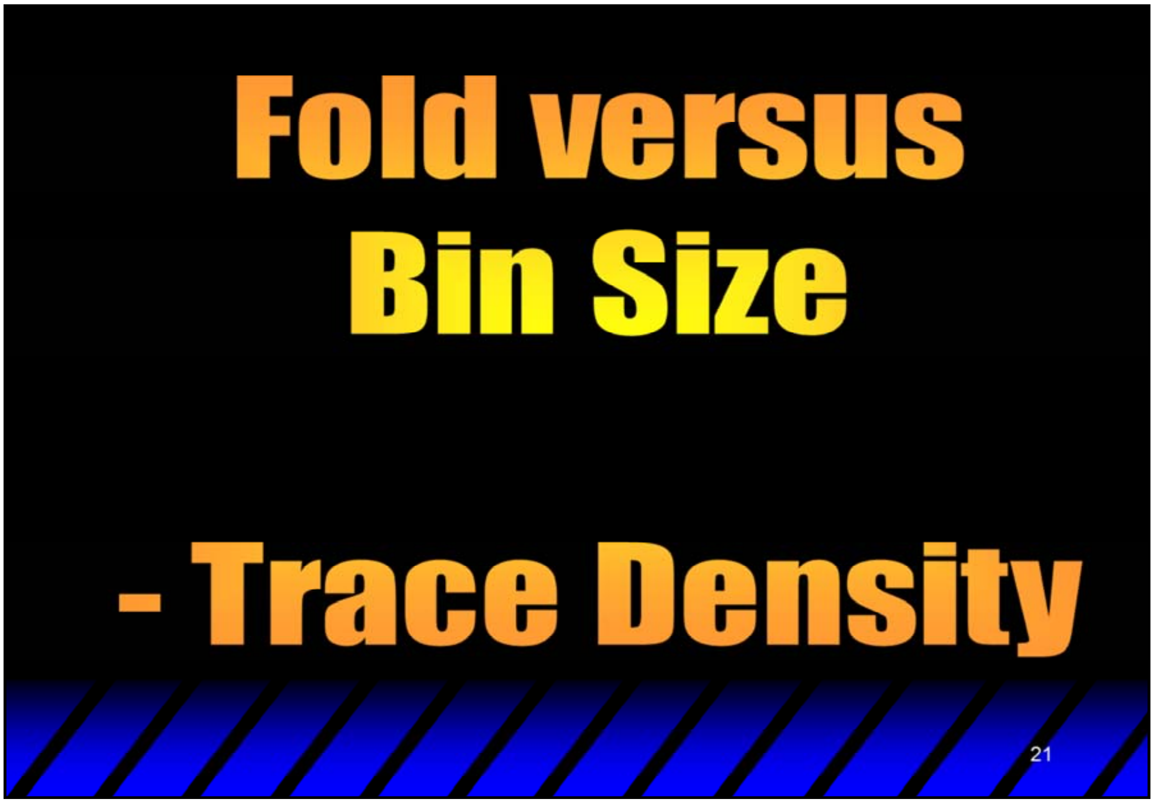


In 1982, I recall telling a class that 3D Land seismic was just a passing fad and would never amount to a very useful exploration tool.

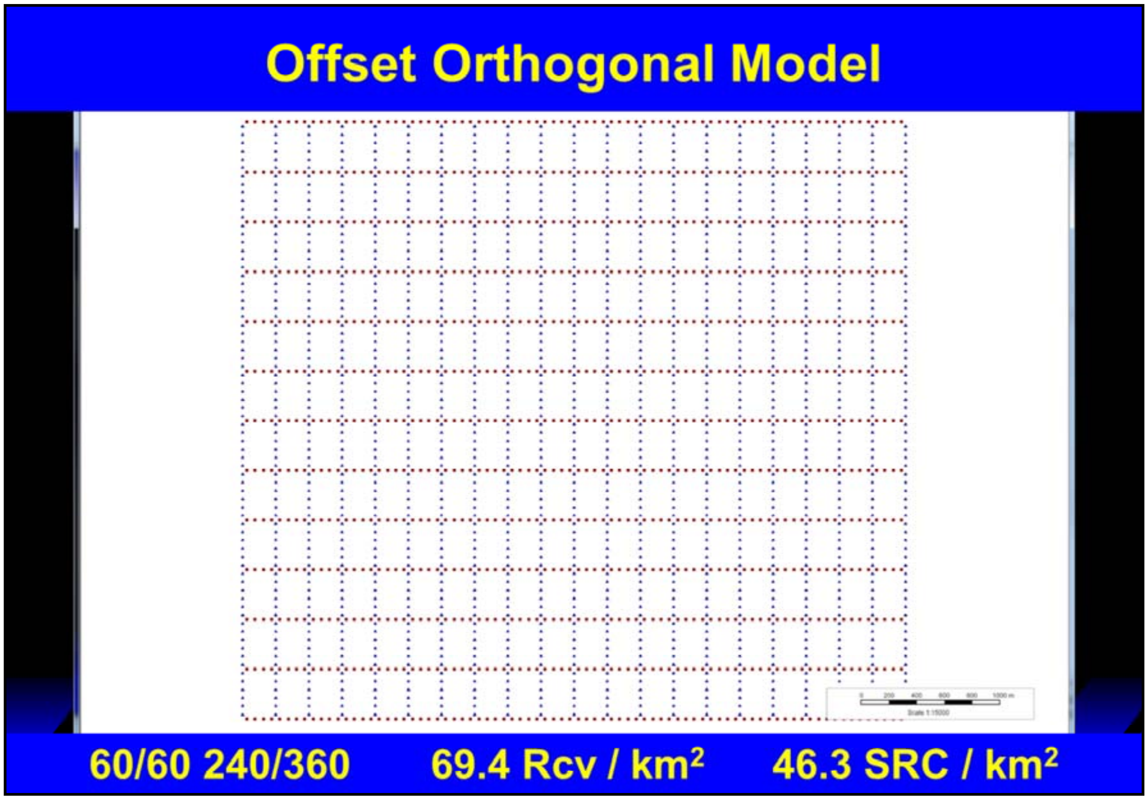
I had a similar opinion of most 3D movies that were enjoying popularity at that time.

It seems I was wrong about the 3D movies with Titanic 3D and Avatar 3D selling out audiences around the world.

I was VERY wrong about the application of 3D in seismic exploration and production.

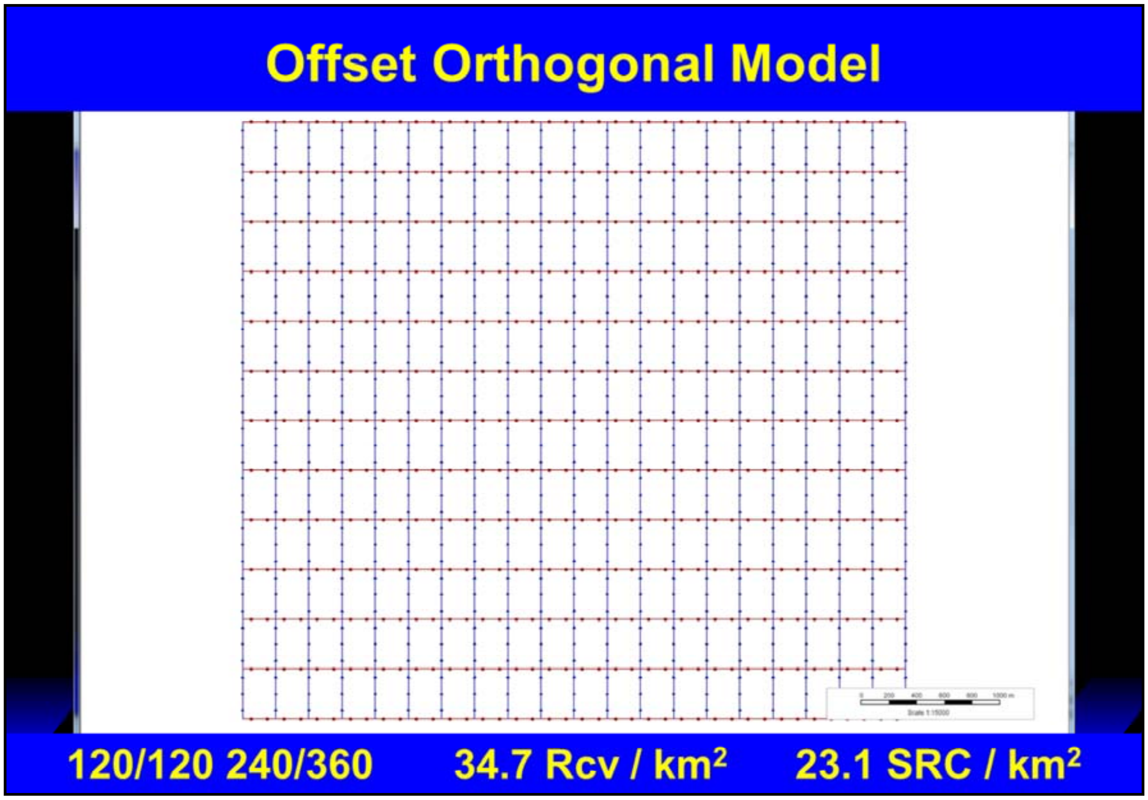


In the early days of 3D design, most designers and users focused on the concepts of fold as collected in natural subsurface bins. The next six slides illustrate one of the problems with these measurements.



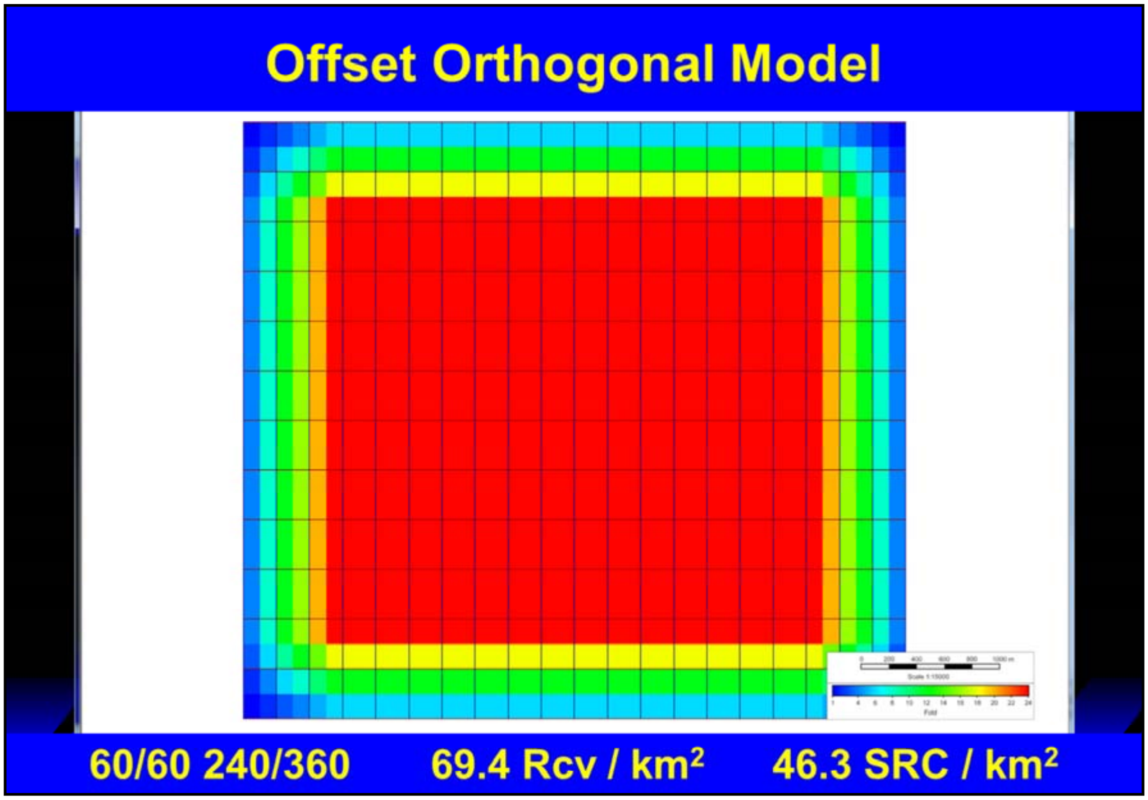
We will compare two models, one of which is this model using an orthogonal geometry with Ri=Si=60 m and RL=240 m, SL = 360 m. The patch used in this survey is a rolling patch of 12 lines and 48 receiver stations per line (effective size of 2880 m x 2880 m). The patch was intended to record almost all traces available within 1500 meter offsets.

The natural bin size will be 30 x 30 meters.

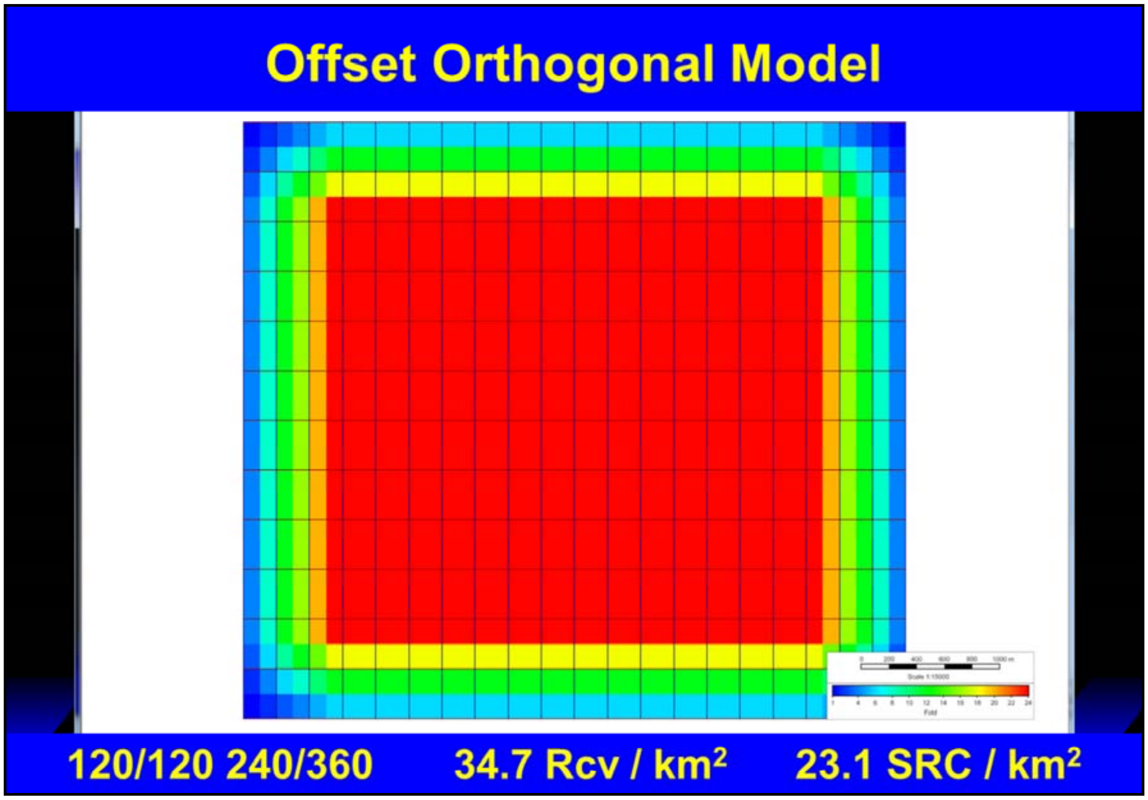


The other model is an orthogonal 3D with Ri=Si=120 m and RL=240 m, SL = 360 m. The patch used in this survey is a rolling patch of 12 lines and 24 receiver stations per line (effective size of 2880 m x 2880 m).

The natural bin size will be 60 x 60 meters.

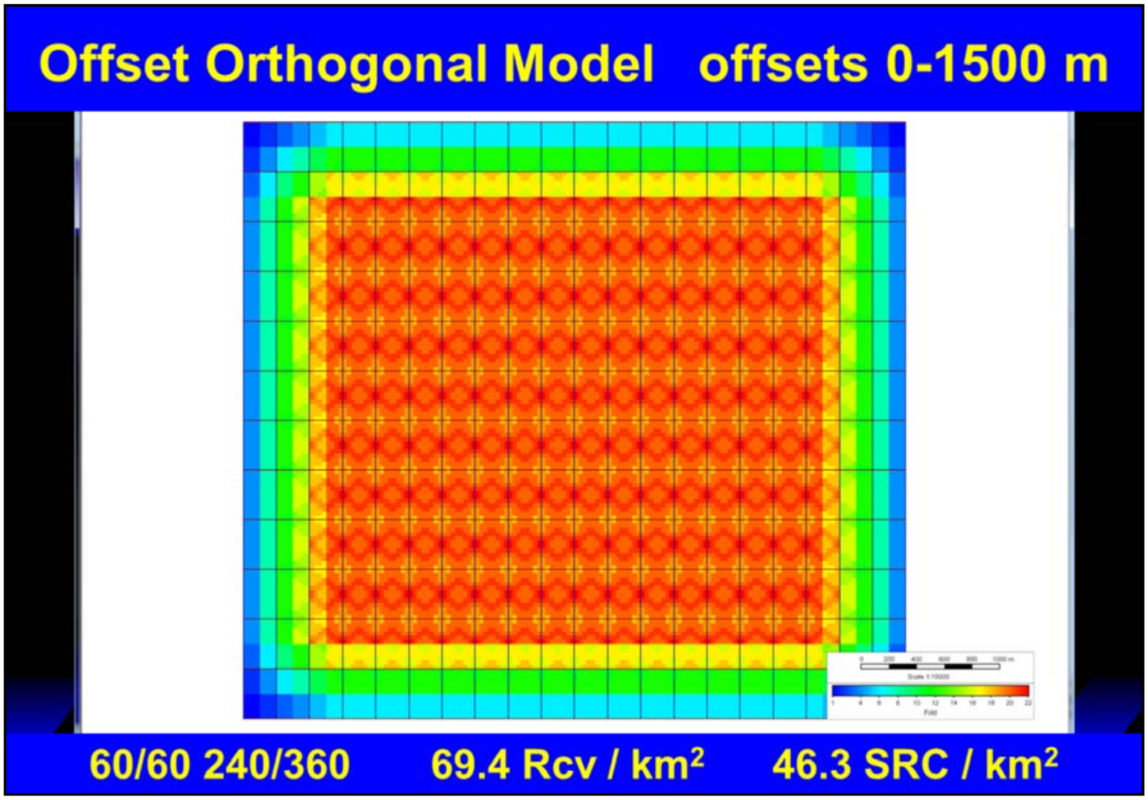


The nominal fold of the survey with 60 meter source and receiver intervals will be 24 in natural bins of 30 x 30 meters.

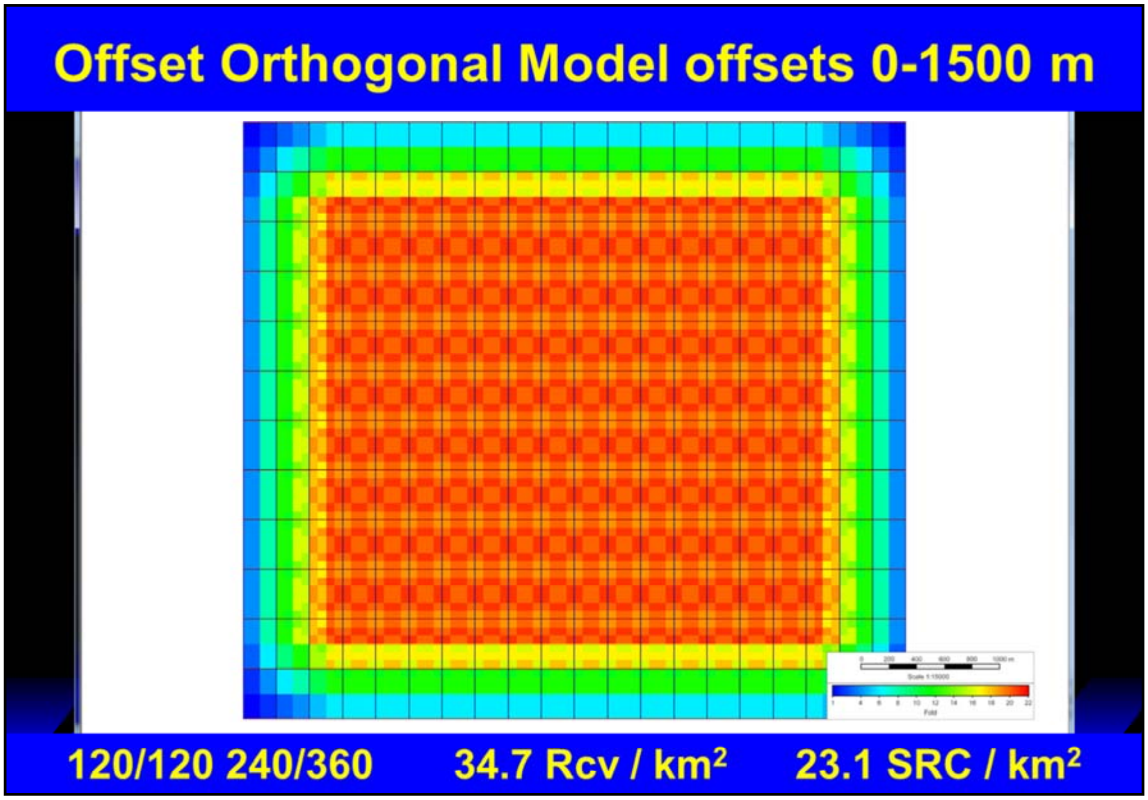


The nominal fold of the survey with 120 meter source and receiver intervals will be 24 in natural bins of 60 x 60 meters.

From the standpoint of nominal fold in natural bins, the two surveys appear equal.

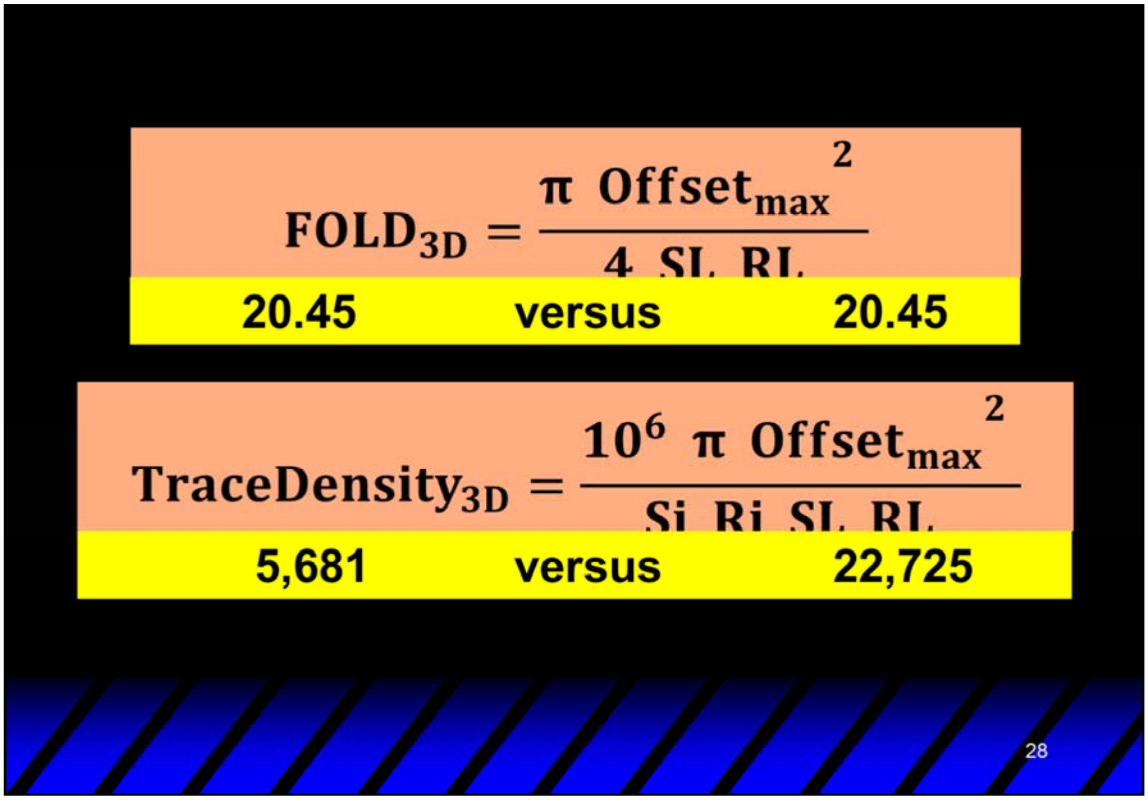


When offset limited to the objective offsets of 0-1500 meters, the fold averages 20.45 and appears mildly patterned. It is always important to consider fold and other statistics using only the traces within probable useable offsets.



The survey with 60 x 60 meter natural bins also has a pattern of fold that averages 20.45

However the pattern is in larger bins and therefore is a bit more pronounced.

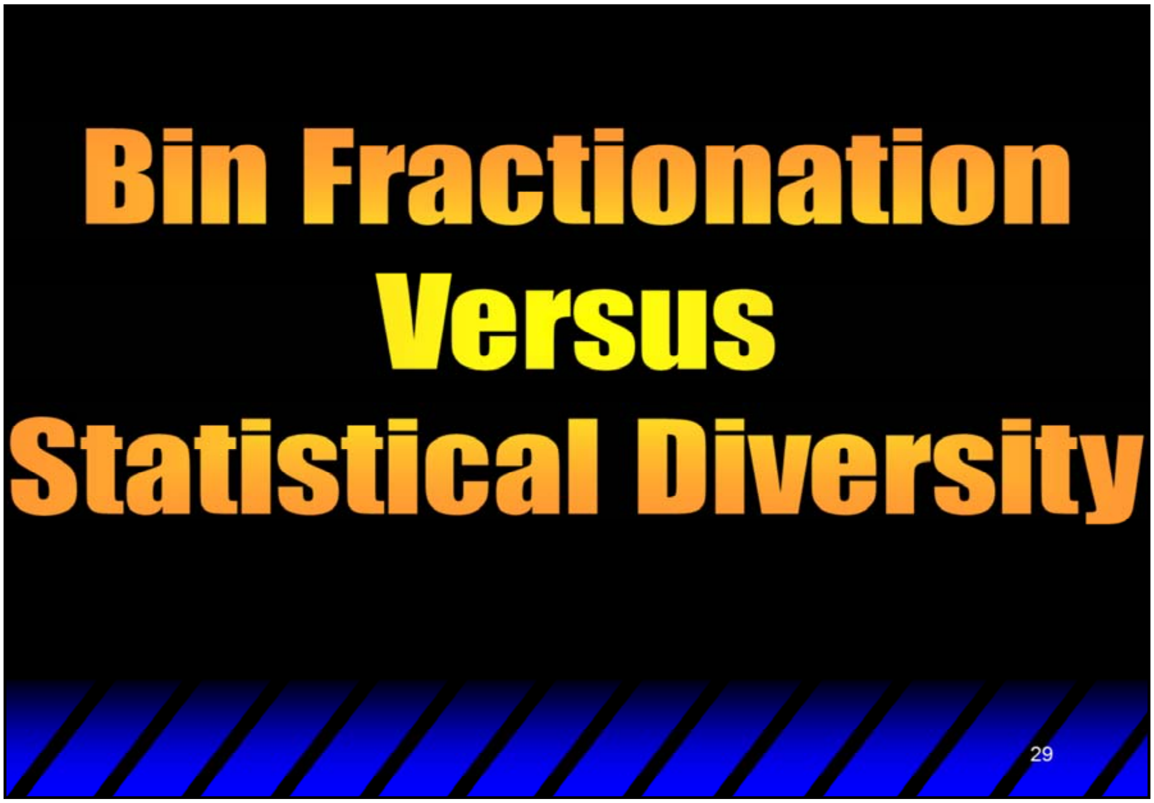


Certainly, 20 fold in 30 x 30 meter bins should NOT be considered equal to 20 fold in bins of 60 x 60 meters !! Fold plots are not a good tool for comparing the difference between surveys that do not share equal bin sizes.

We advocate normalizing the fold by dividing fold by the bin area (expressed in square kilometers). Bin area is Ri/2 x Si/2 with Ri and Si expressed in meters or Ri/2000 x Si/2000 in kilometers. Therefore, normalizing is accomplished by multiplying offset limited fold by 4,000,000 / (Ri x Si)

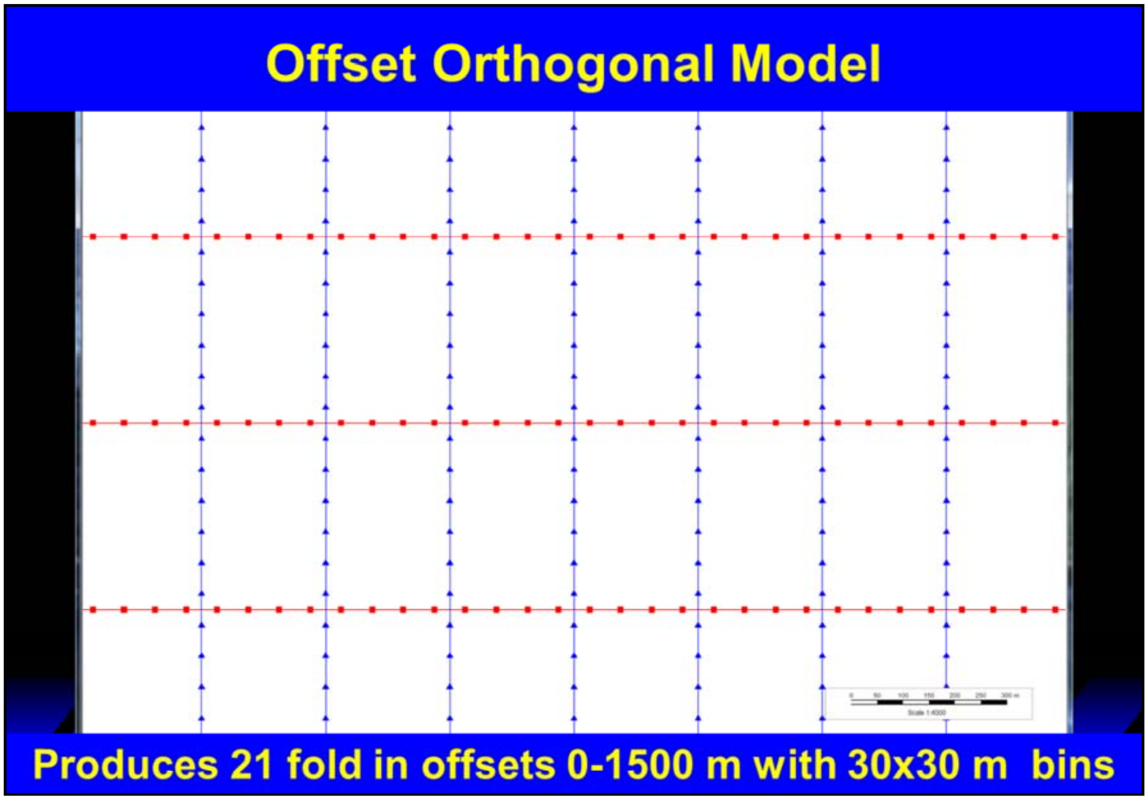
This yields a number we call Trace Density.

Another option is to normalize by the number of natural bins within the expected migration operator.



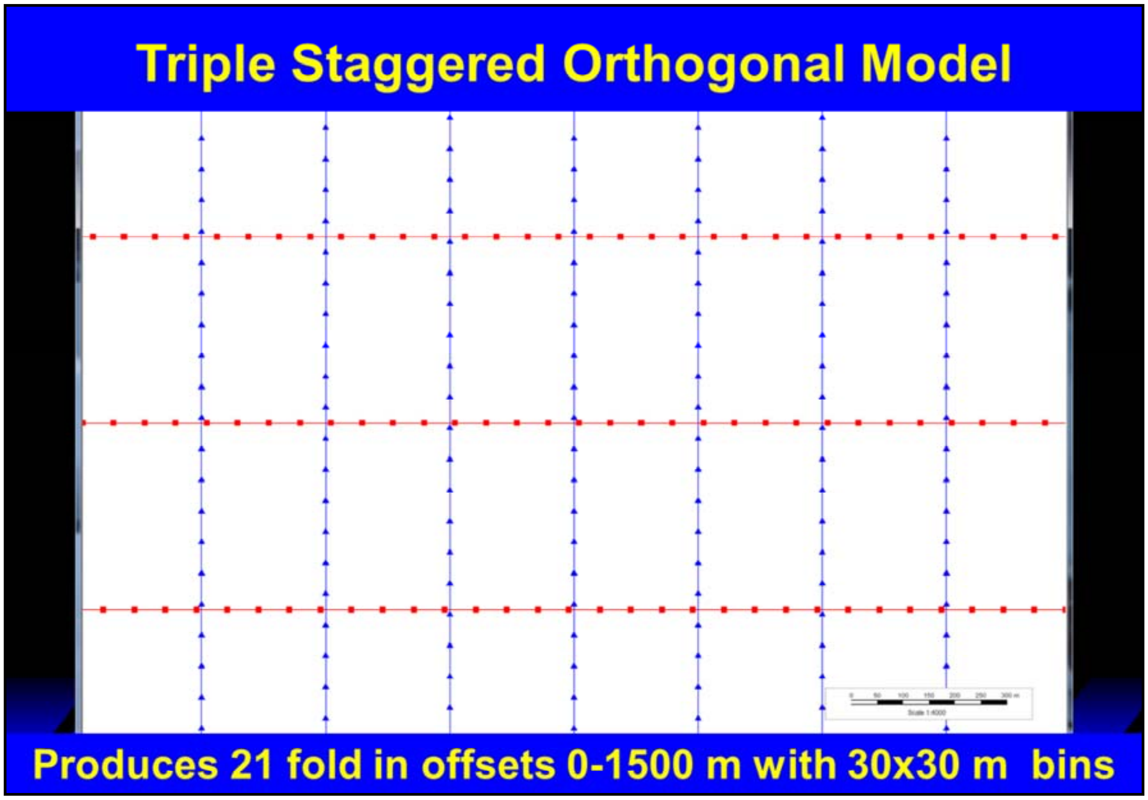
Since the mid-80’s Mustagh has promoted mid-point scattering to enhance statistical diversity. At that time, we also promoted possible benefits of re-binning data in other than natural bins for stacking and post-stack migration (at that time pre-stack migration was not available for Land 3D volumes). Others also experimented with bin fractionation and re-binning and it became a well published process.

However, stacking and post-stack migration are now outdated and we find ourselves in the position of having to demonstrate the fallacies of stacking data in non-natural bins.

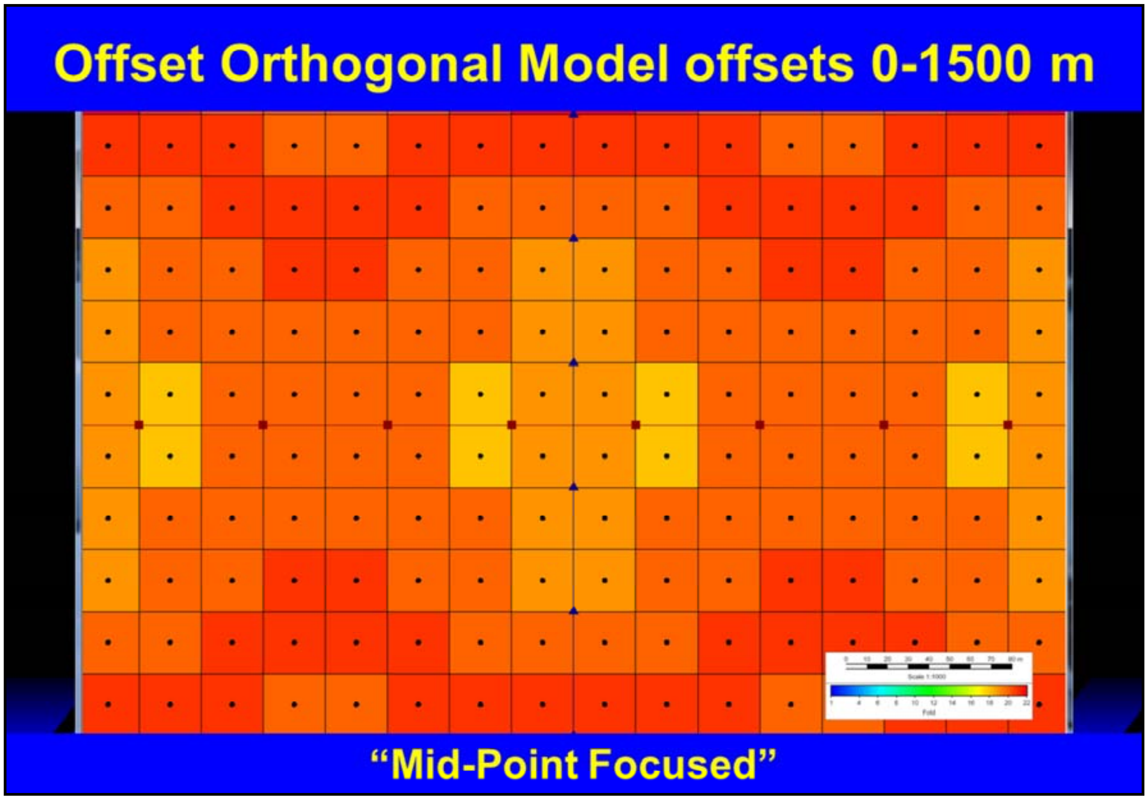


We will compare two models, one of which is this model using an orthogonal geometry with Ri=Si=60 m and RL=240 m, SL = 360 m. The patch used in this survey is a rolling patch of 12 lines and 48 receiver stations per line (effective size of 2880 m x 2880 m). The patch was intended to record almost all traces available within 1500 meter offsets. The lines are arranged so that no source or receiver fall coincident with line intersections.

The natural bin size will be 30 x 30 meters and the offset limited fold in natural bins will be 20.45



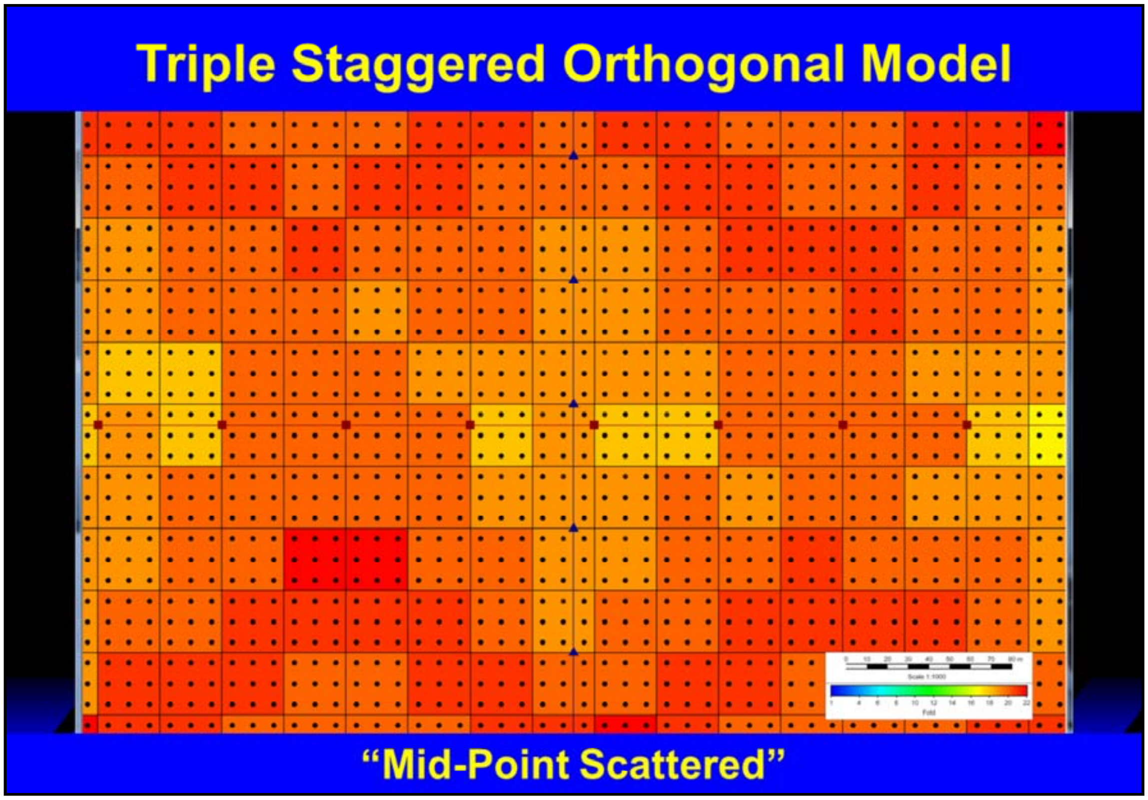
This model uses the same basic parameters. However, the lines are staggered in sets of three. The stagger of points relative to an intersection rotates through a sequence of 1/6, 3/6 and 5/6 of an interval in both the source and receiver lines. We call this a “Triple-Staggered” model.



Both surveys produce an offset-limited fold of 20.45

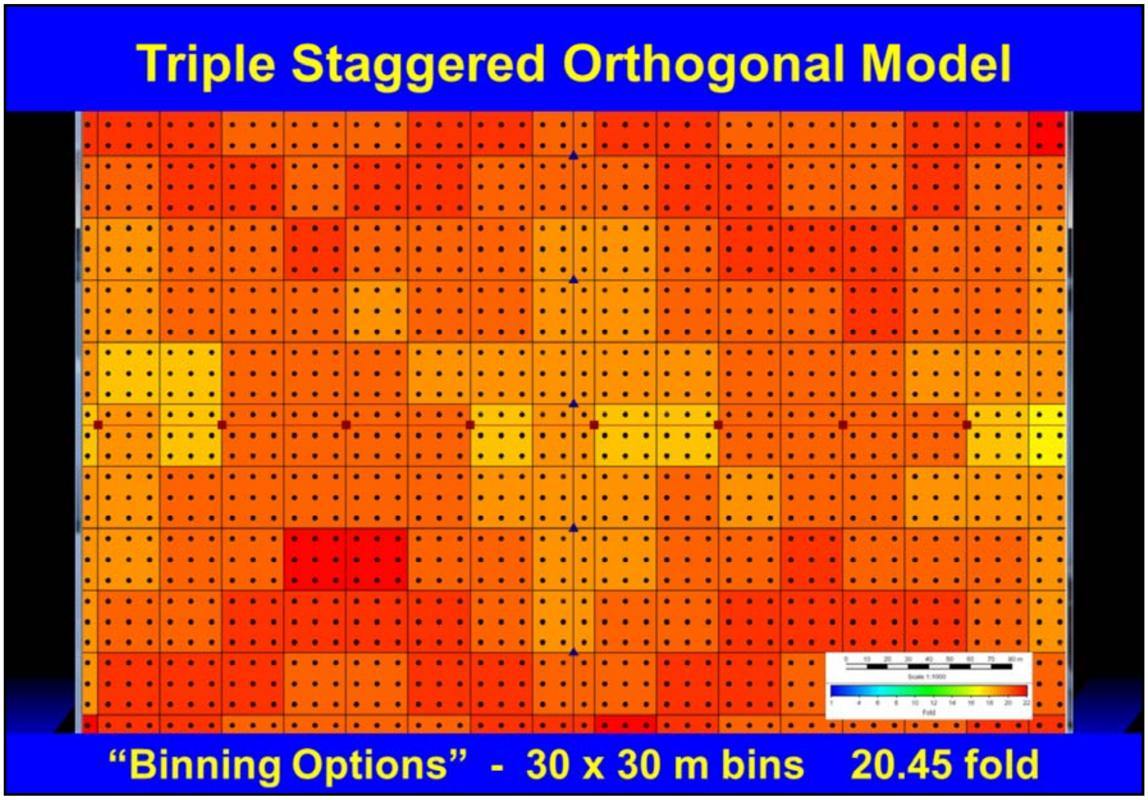
The offset orthogonal design ensures that the geographic mid-point of each source and receiver coincides in the center of each bin (called a "Mid-Point Focussed" design). Therefore, this survey produces clusters of traces with the same mid-point index and the clusters are separated by the natural bin spacing.

In this type of survey, the fold (and other statistical patterns) will repeat every "box". (Note: a "box" is defined as the area bounded by two adjacent source lines and two adjacent receiver lines and the box area is SL x RL)

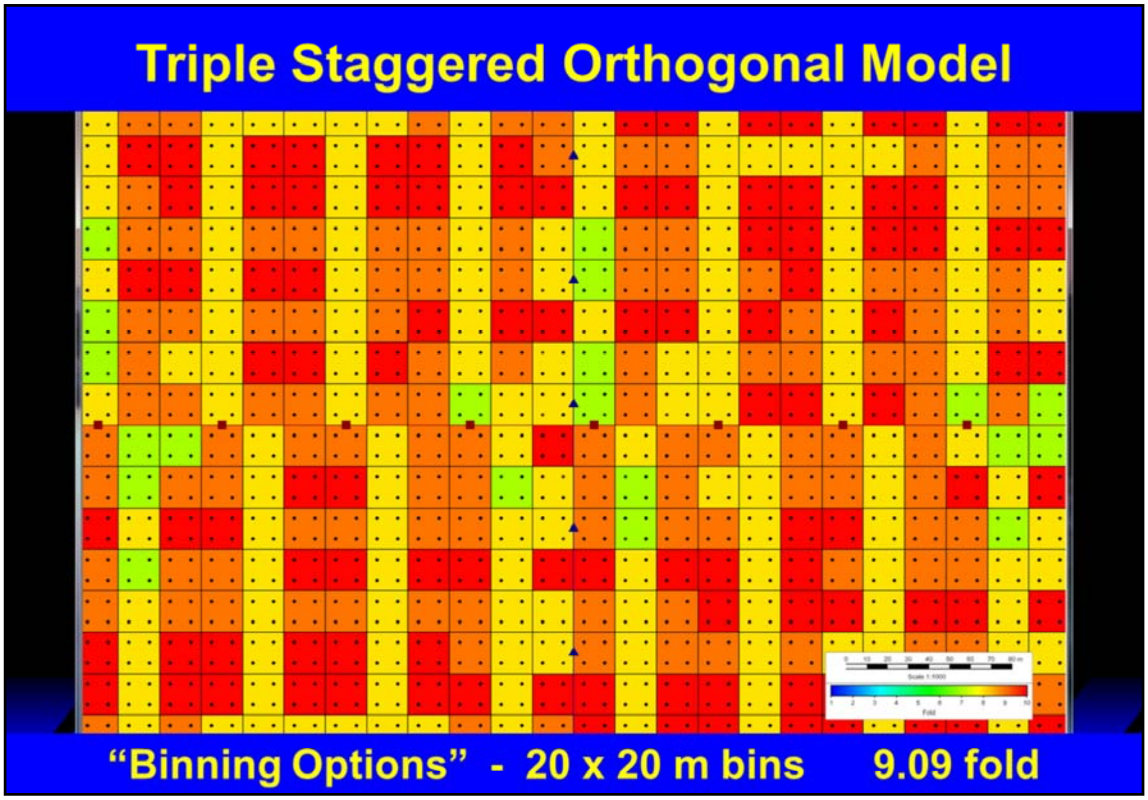


The Triple-Staggered model results in a sub-division of the mid-points within each bin. We obtain nine sets of mid-points separated in each direction by one-third of a natural bin dimension.

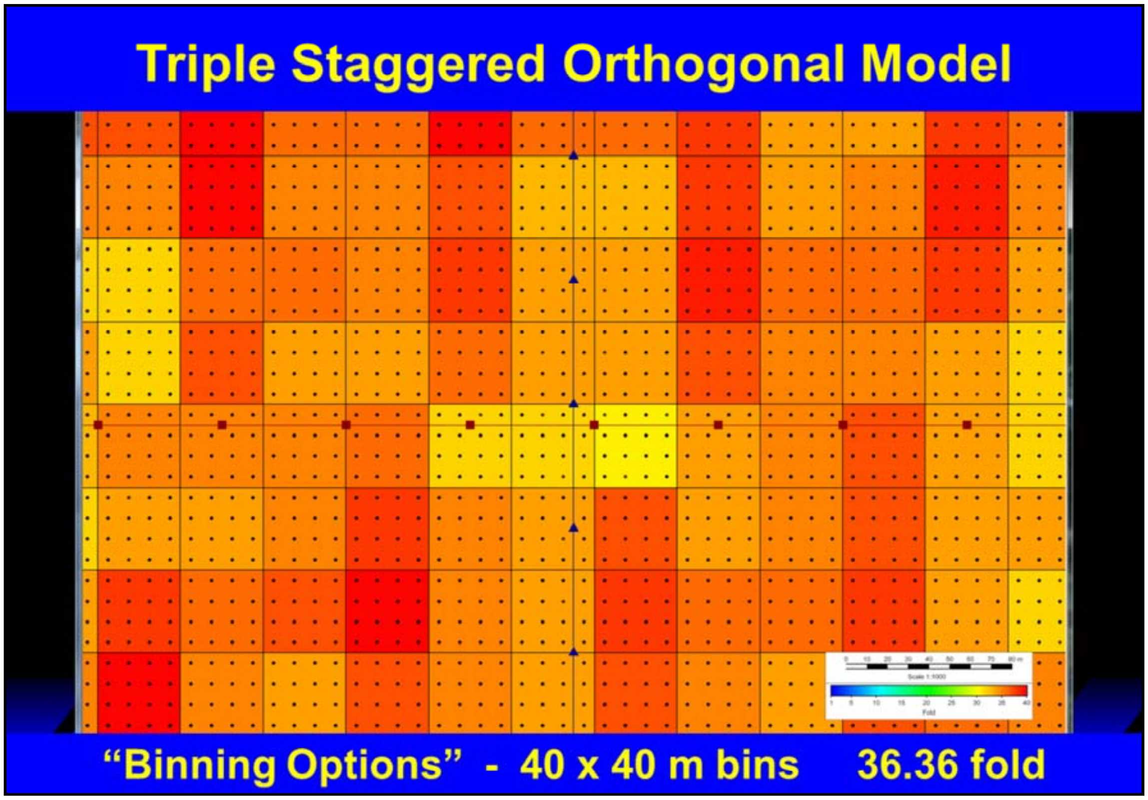
In this type of survey, the statistical patterns do not repeat with every box. The geometric "unit cell" now becomes an area that is 3 boxes by 3 boxes. This suggests we should expect improved statistical diversity.



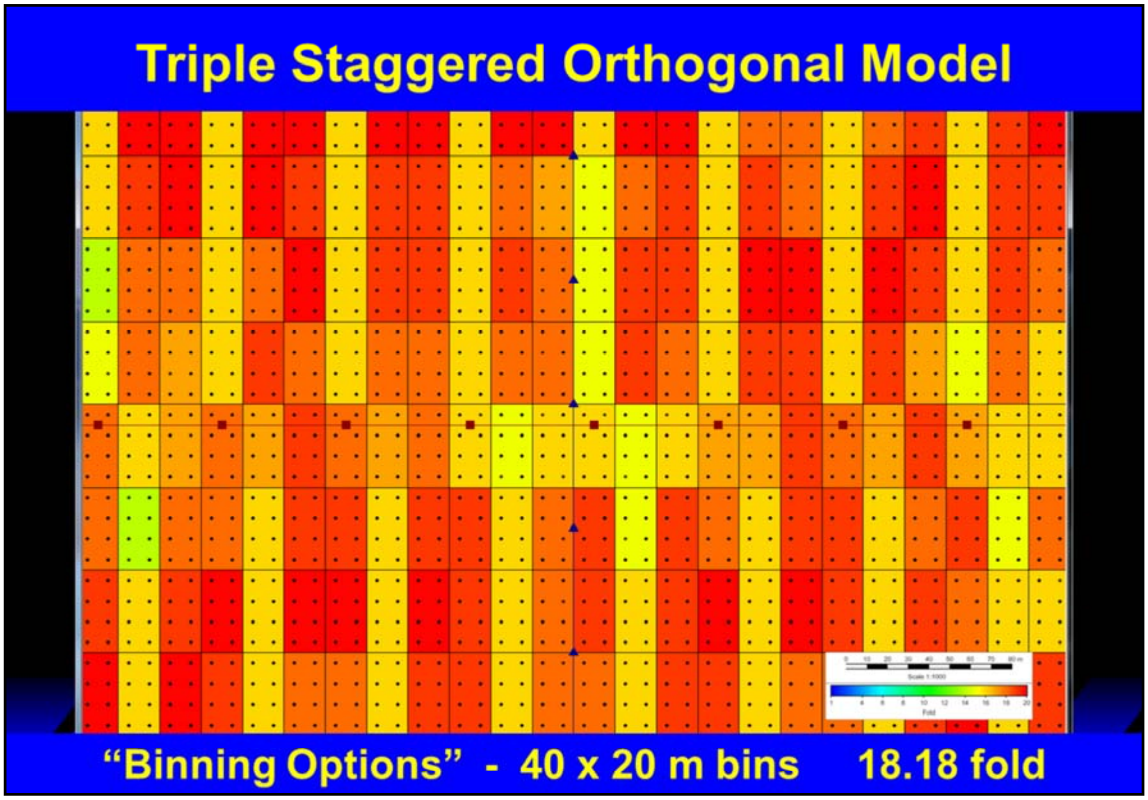
Certainly this survey can be stacked by collecting gathers of traces within natural bins. Such stacked data will have improved statistical distributions compared to the normal offset orthogonal design.



However, if the data quality is good and we desire finer stacked trace spacing (if frequency content justifies improved spatial resolution), then this data could be gathered effectively in 20 x 20 meter bins. The natural fold per bin will be reduced to 4/9 of the original.



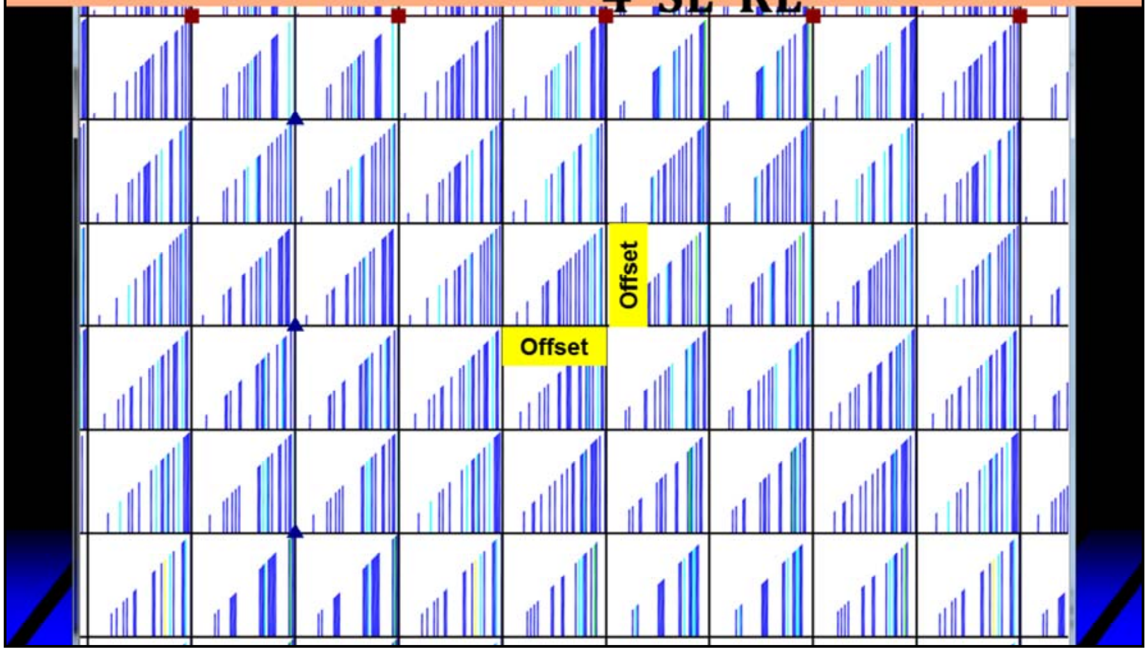
… OR, if the data quality is poor and we desire higher fold per stacked bin, then this data could be gathered effectively in 40 x 40 meter bins. The natural fold per bin will be increased to 16/9 of the original.



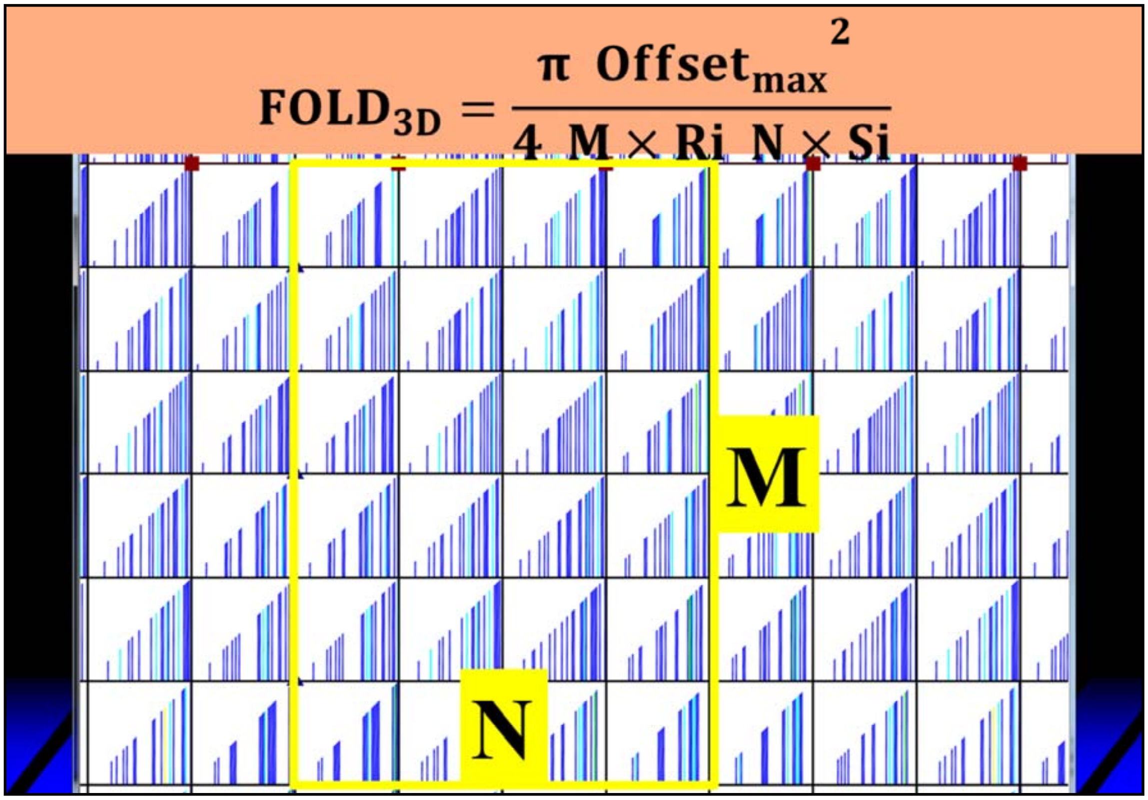
… OR, if the geology proves to be somewhat linear, we could gather in asymmetric bins that are 20 meters in the dip direction and 40 meters in the strike direction. The stacked fold would be 8/9 of the data stacked in natural bins.

These re-binning strategies appear to be a reasonable alternative if we use fold diagrams as our measure of survey quality. However, we have learned that fold diagrams can be very mis-leading in such cases. Therefore we need to examine other statistics.

$$\mathrm{FOLD}_{3D} = \frac{\pi \ \mathrm{Offset}_{max}^{\ 2}}{4 \ \mathrm{SL} \ \mathrm{RL}}$$

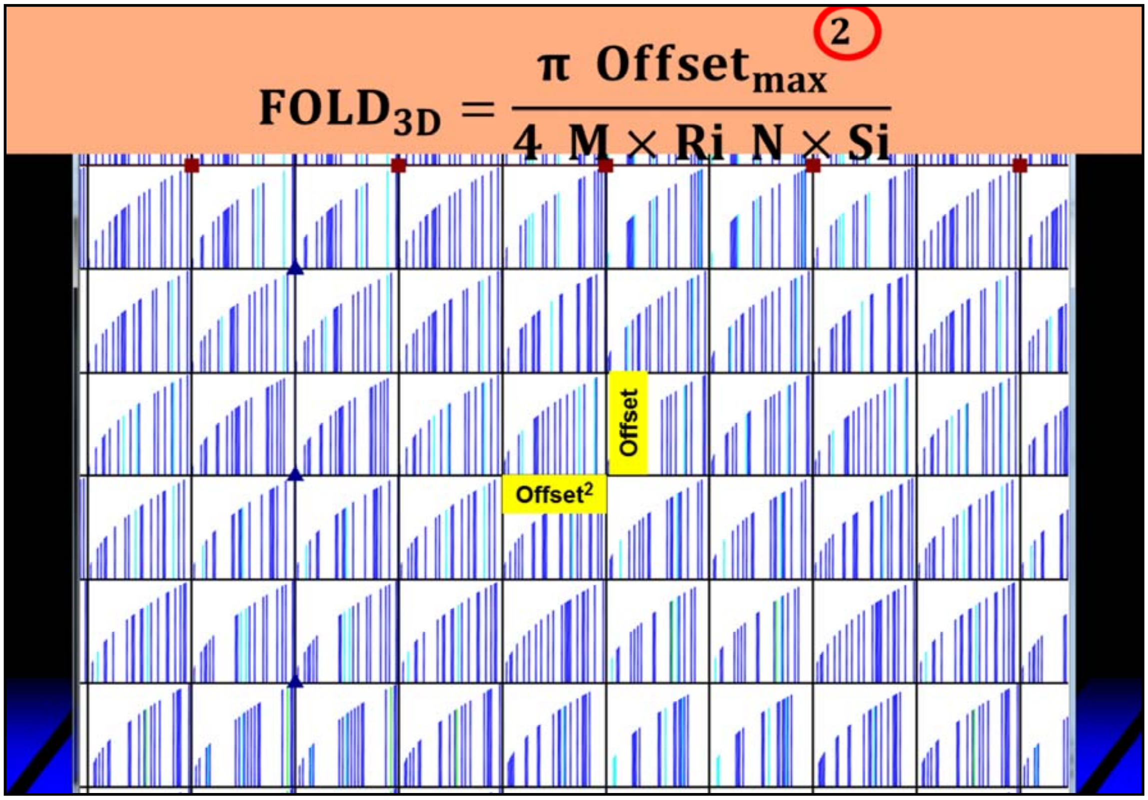


3D designers often use an "Offset Distribution" plot to evaluate the offset sampling of each bin. Each bin contains a line graph. The horizontal distribution of the lines forms bar graphs of equal offset ranges (usually each range is the natural bin size). In this case we represent the offsets in 50 different bars of 30 meter ranges from 0 to 1500 meters. The vertical height of each bar is simply a repetition of the offset statistic, but the color of each bar indicates the number of traces in each range.



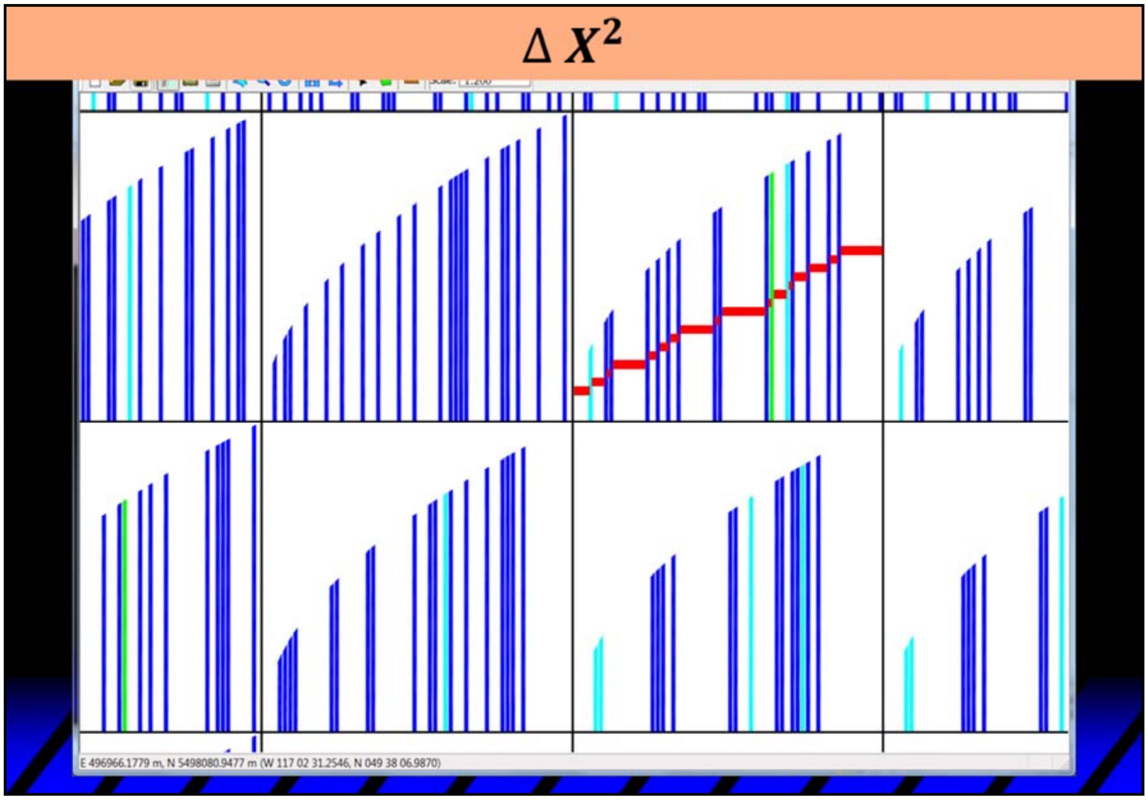
In a full wavefield sampled 3D, the line spacings are equal to the source and receiver intervals. One box contains four bins (one for each quadrant of the box). One advantage of the full wavefield design is that every bin contains all possible offsets and that there is no bin-to-bin variation in offset distribution.

When we select an M x N sparcity, all the possible offsets are re-distributed into the M x N bins in one quadrant of a box. They are not distributed equally by offset. Therefore, we worry about offset distribution and bin-to-bin variation.



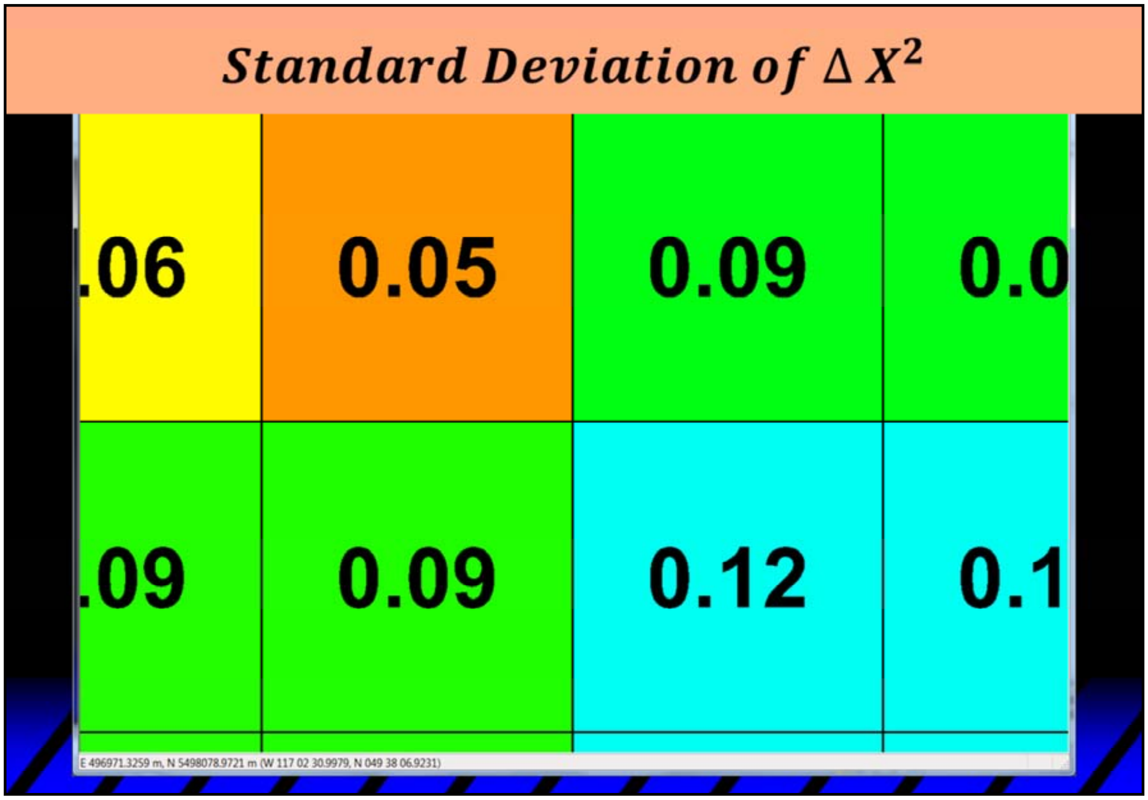
Since fold and other statistics in a 3D are related to offset squared (not just to offset as in 2D programs), then we have found it better to examine distributions of the squares of offsets.

However, these displays are difficult to examine over an entire survey. Therefore, we propose using one number per bin to identify the quality of distribution of offsets in the offset-squared domain.



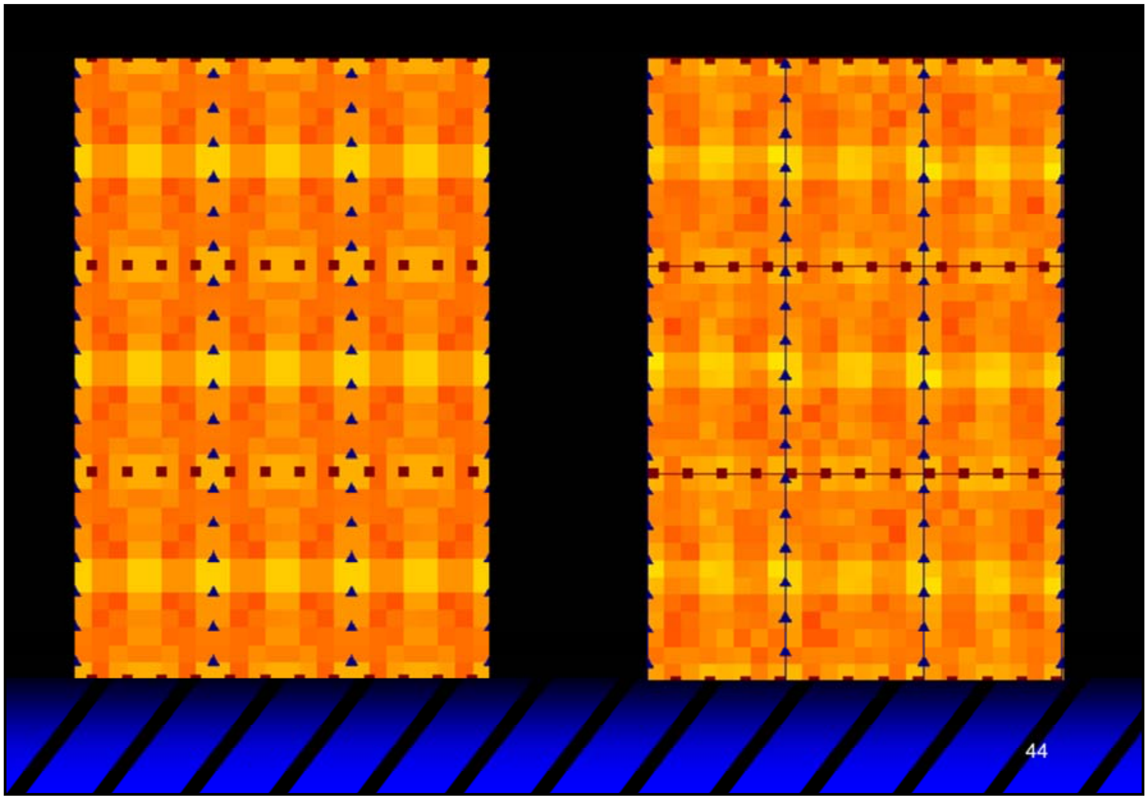
Our first step is to make a list of the differences between successive squared offsets. A histogram of such a list would have a small standard deviation if all delta-X-squared values were about the same. This would represent what we would regard as a well-distributed set of offsets.

If a bin had an irregular (or “clumpy”) distribution of offsets in this domain, then the histogram of delta-X-squared values would tend to be bi-modal and the standard deviation would increase.



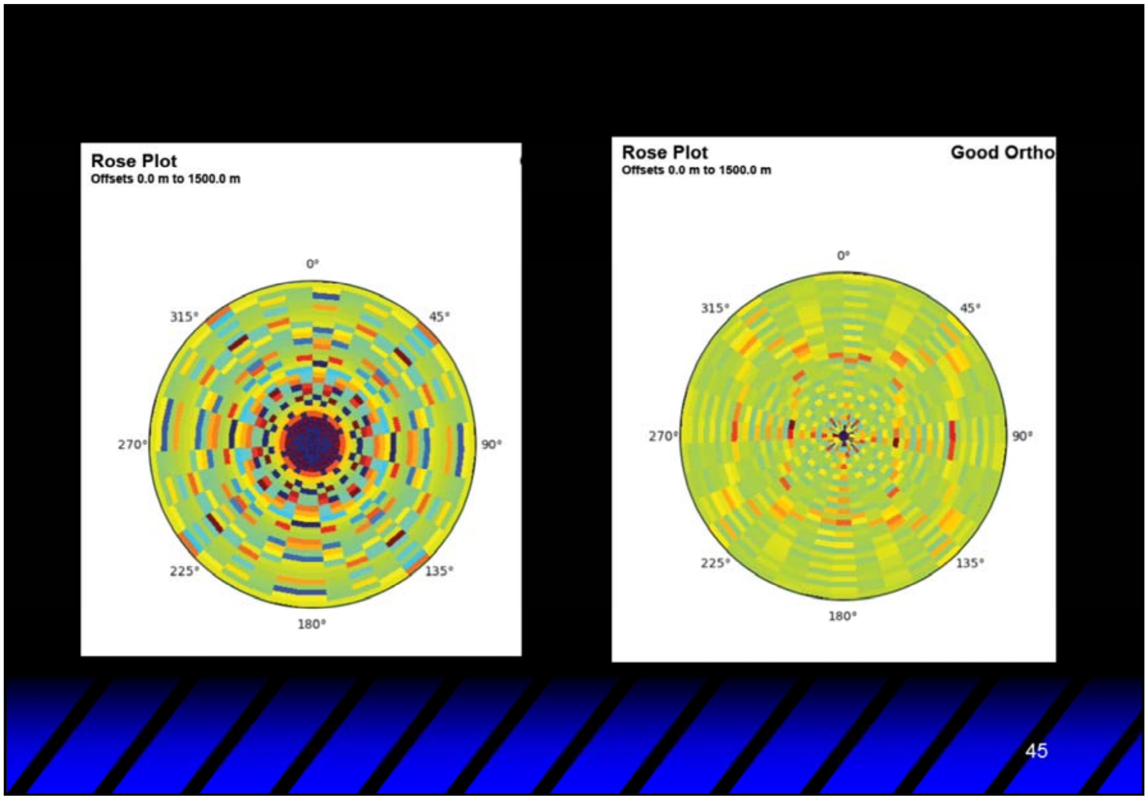
We can replace the offset distribution plot for each bin with a single number (the standard deviation of delta-X-squared values). A low number represents a good distribution and a high number represents a poor distribution. This plot can be viewed at a large scale much like a fold plot.

We call this the offset heterogeneity plot and we have found it to be a more reliable indicator of potential survey quality than a simple fold plot.



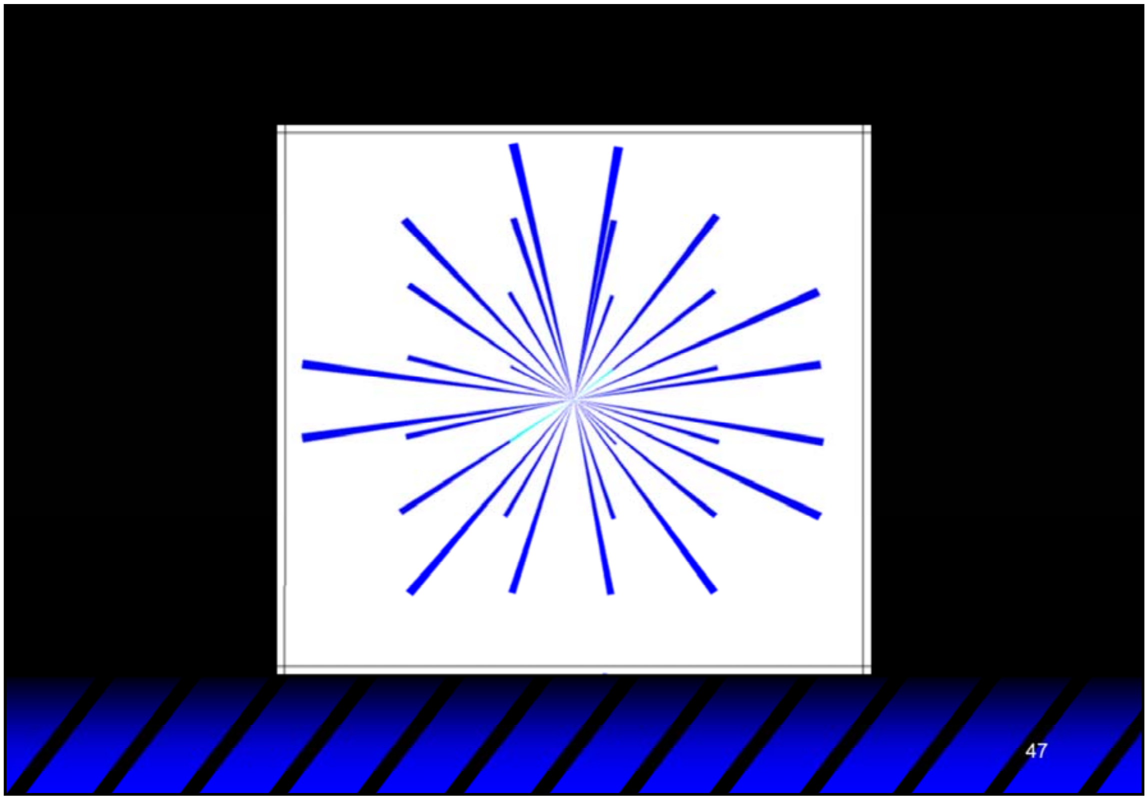
The display on the left is the offset homogeneity plot for the regular offset orthogonal. That on the right is for the triple staggered model. Notice that the statistical patterns on the left are identical for each of the nine boxes displayed while the pattern on the left is unique across the nine boxes.

The color variations on the left are more pronounced that those on the right. The more moderate variation of statistics is one of the advantages of mid-point scatter.



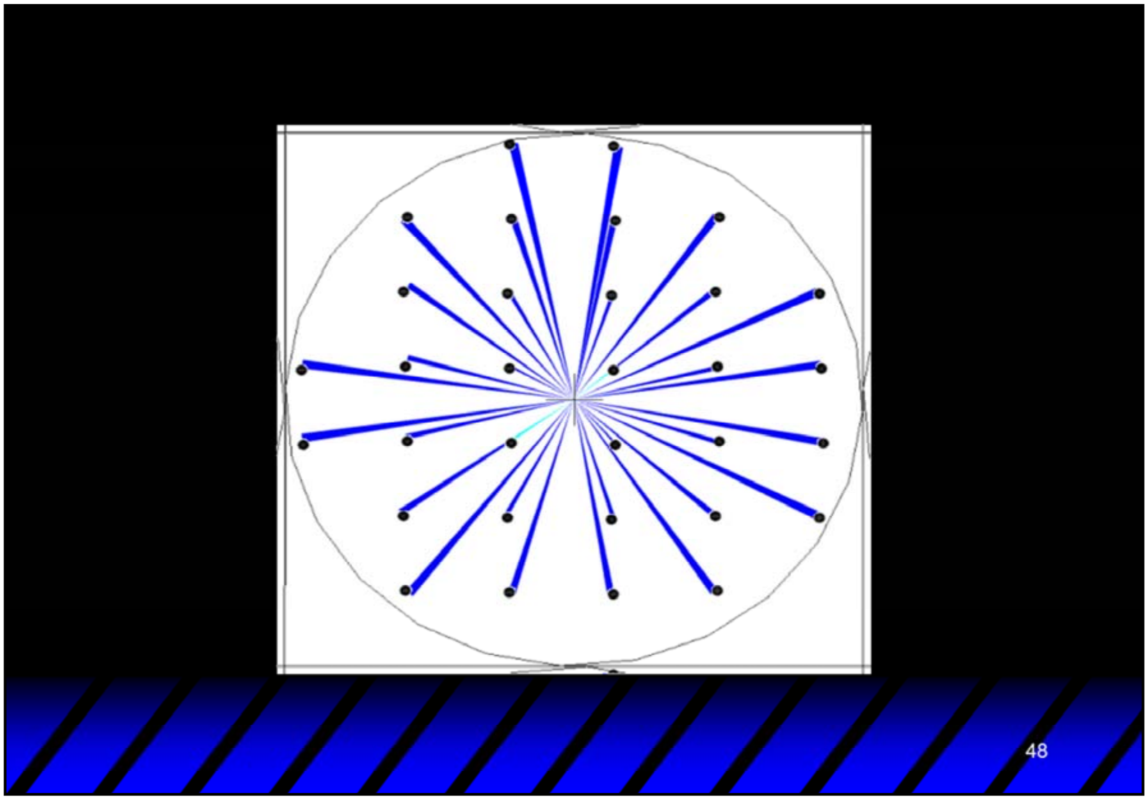
The display on the left is the Rose plot for a 3 x 3 box area of the regular offset orthogonal. That on the right is for the triple staggered model. The Rose plot indicates a surprisingly strong advantage for the triple staggered model.

However, the offset homogeneity plot does not include any analysis of azimuth distributions. The next three slides illustrate the our preferred plot for this statistic.

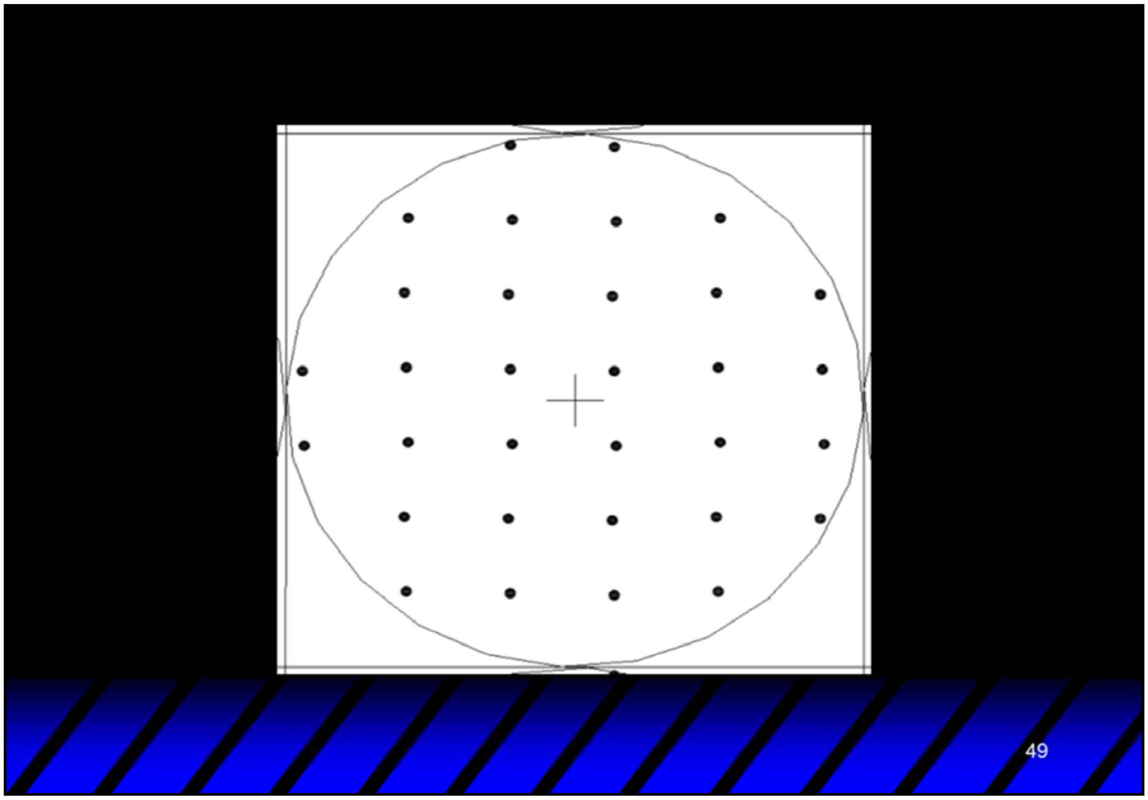


The so called “Spider” plot is a polar plot using vectors to represent the offset (vector length) and azimuth from source to receiver (vector direction from center) for all traces whose mid-points fall within a given bin. It is an attempt to represent the offset-azimuth distribution for each bin. However if two traces share the same azimuth but with different offsets, the longer vector tends to mask the visibility of the shorter vector.

This effect tends to bias perception to the farther offsets and diminish the importance of the nearer offsets.

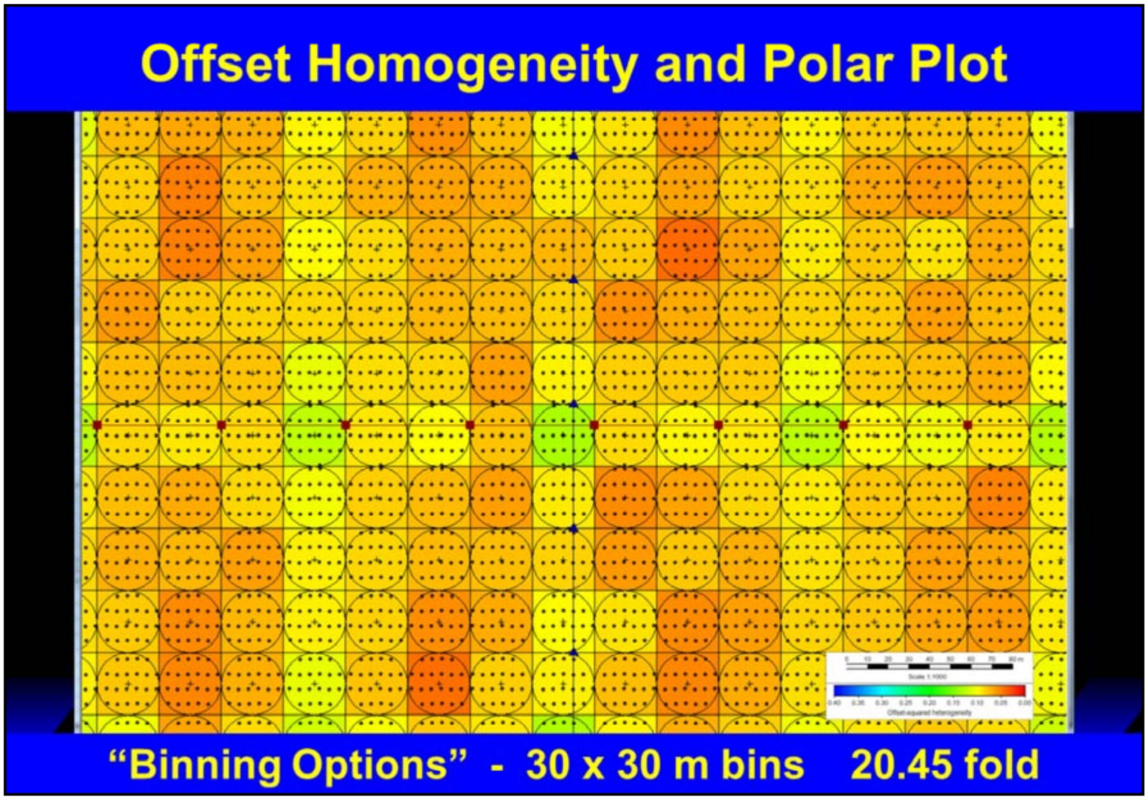


We think that the "feet" of the spider are more important than the legs of the spider!! In other words, a polar plot should be represented by points, not vectors. This is an intermediate plot showing both the vectors and points at the tips of each vector.



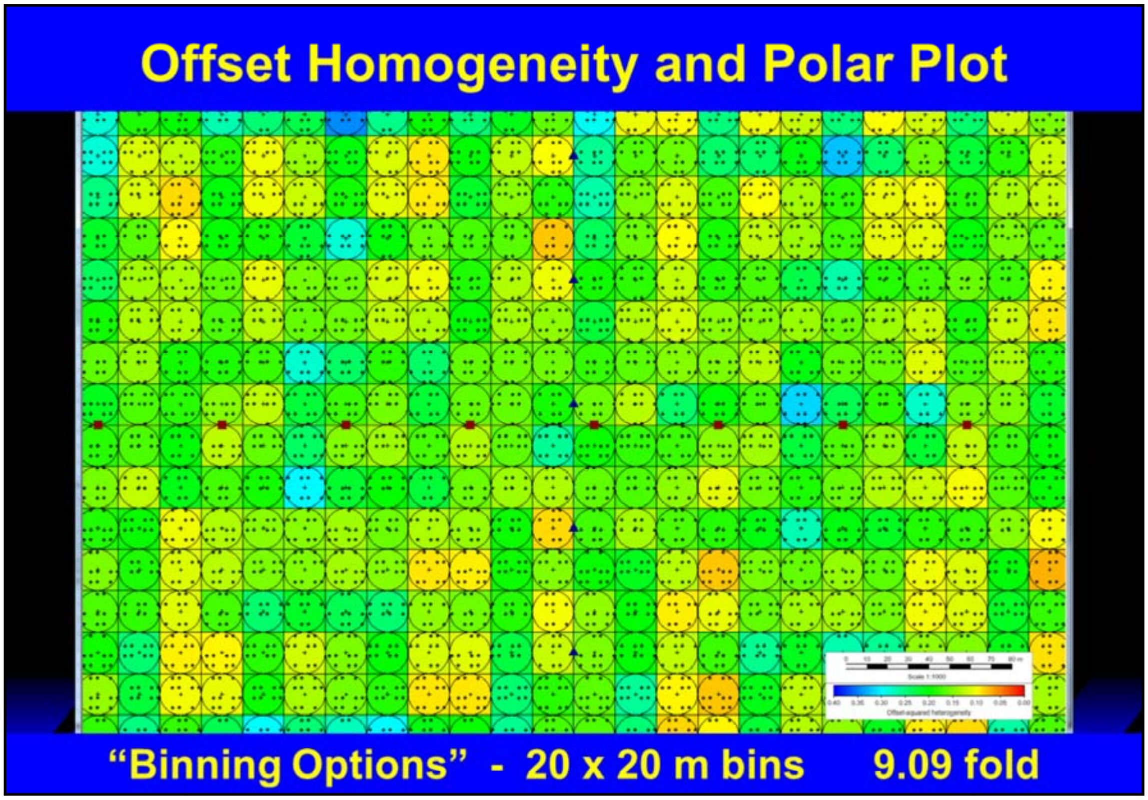
We prefer a simpler plot showing just the polar coordinate points. There is one point for each trace contributing to this bin. Although it is a polar plot, it has an obvious orthogonal arrangement to the coordinates. This comes from the fact that the points were produced from a sparse orthogonal grid on the surface.

The separation of the north-south columns of points is equal to 2 x RL and the separation of the east-west rows of points is equal to 2 x SL.

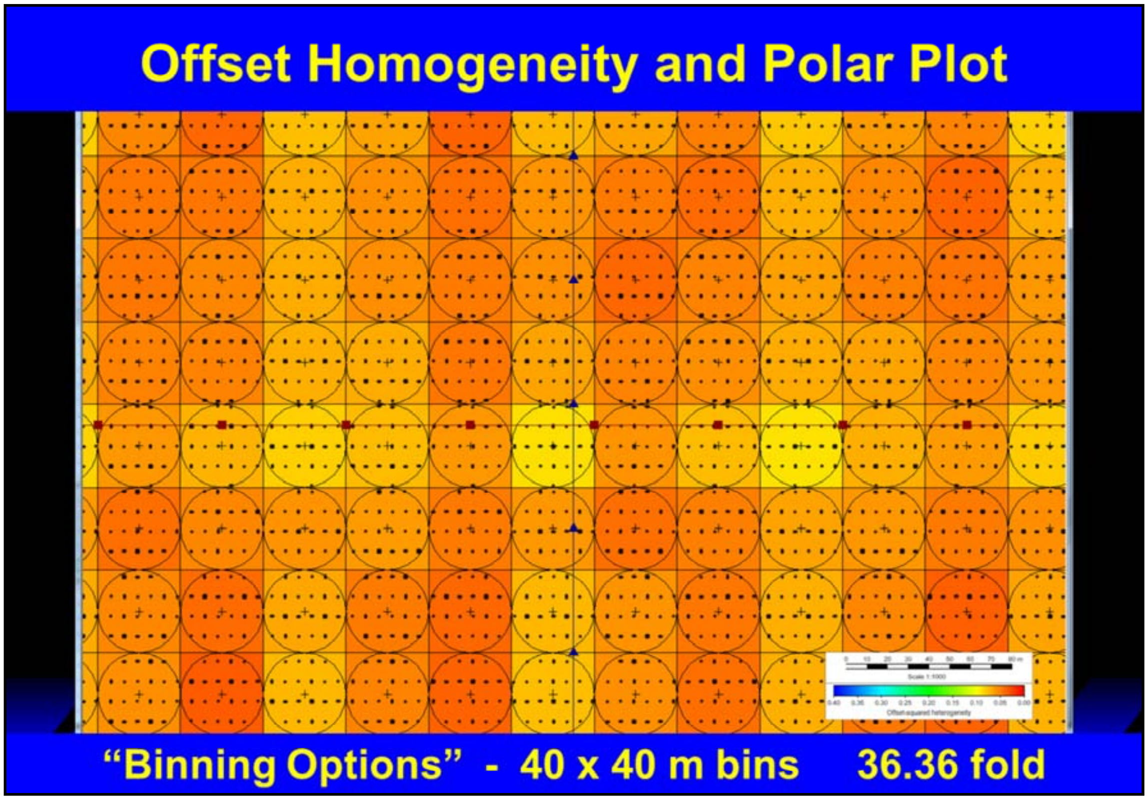


Using the offset heterogeneity statistic for the background color in each bin and the Polar plot of offset and azimuth for the dot pattern in the foreground, let's re-examine the concept of bin fractionation in stacked data.

For the survey collected in natural bins, we see a good quality offset and azimuth distribution in each of the 30 x 30 meter bins.

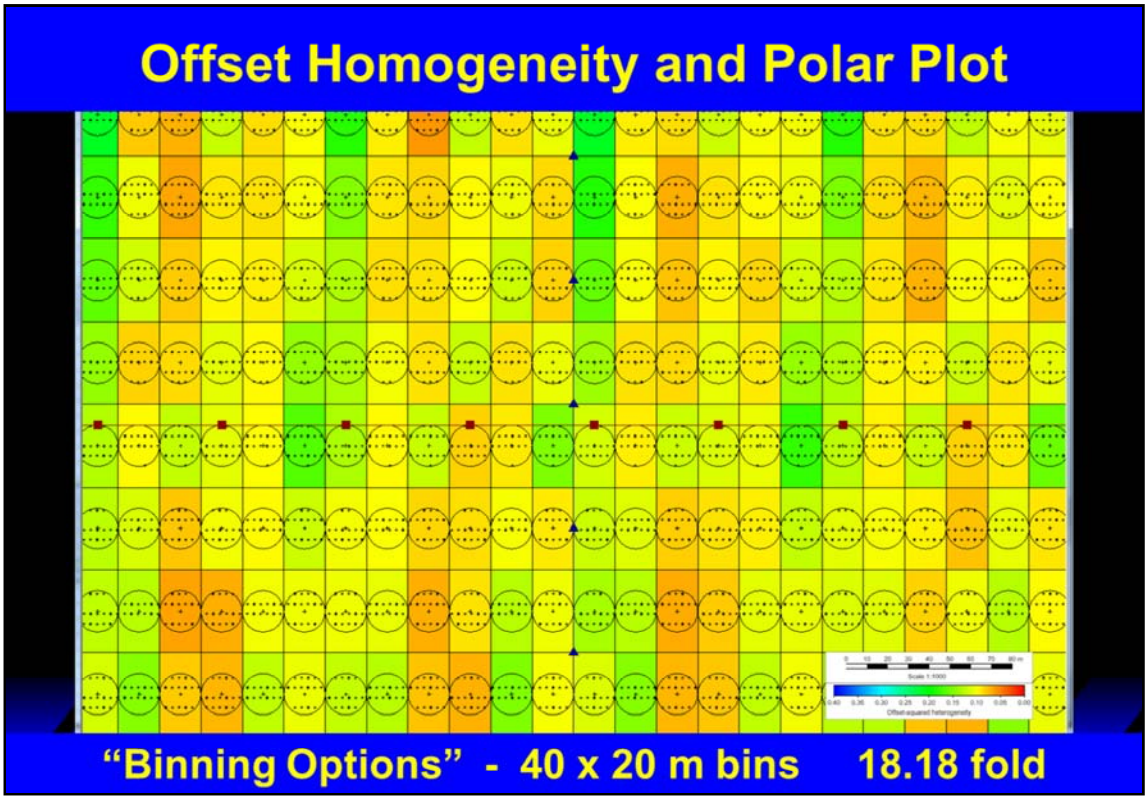


However, when gathered in small bins of 20 x 20 meters, the offset heterogeneity diminishes and we see substantial missing ranges of offset-azimuth statistics in most bins. We also observe a significant bin-to-bin variation in offset-azimuth distributions.



When collected in large 40 x 40 meter bins, we expect fold to increase by a factor of 16/9. However, the offset heterogeneity plot does not show a corresponding improvement. The offset-azimuth distribution in each bin is virtually the same as that in natural bins.

All we have accomplished with the large-bin gathers is to include more traces of offset-azimuth statistics that have already been measured by natural traces. Such duplication of statistics will not provide an increase in stack power for offset or azimuth dependent noise modes such as source generated noise or chaotically scattered noise.

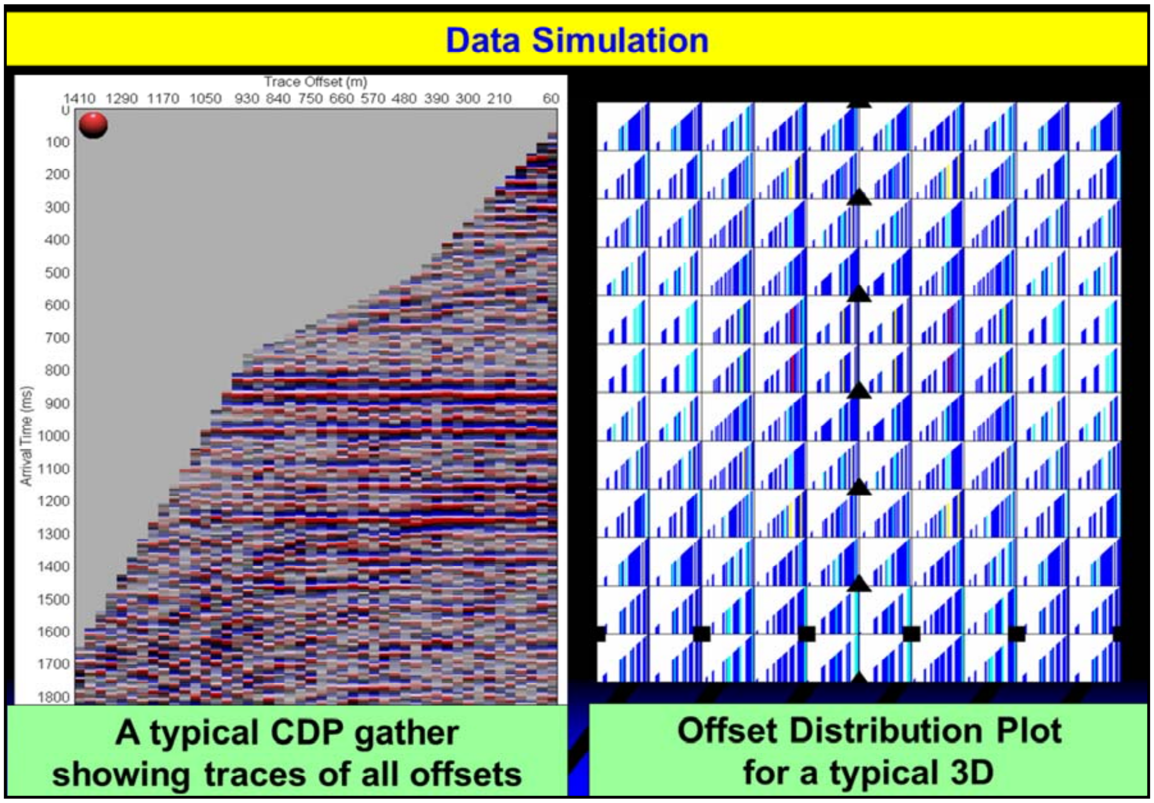


And finally, the asymmetric binning of the original data also produces bin-to-bin irregularities in offset-azimuth distribution.

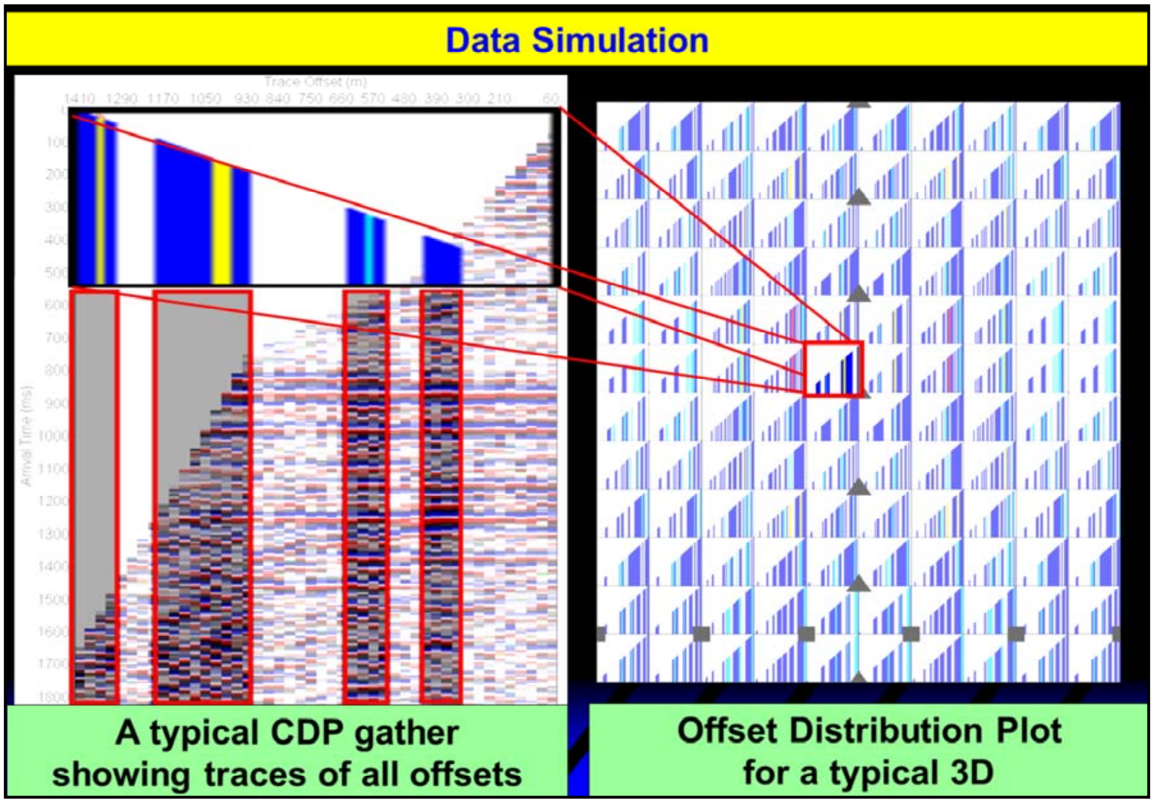
Although fold plots indicate that the re-binning of mid-point scattered data is potentially beneficial, other statistics that investigate offset and azimuth sampling suggest that this practise should be avoided.

However, we want to be clear that it is the re-binning of data for stack and post-stack migration that should be avoided. The mid-point scatter by itself appears to be beneficial to statistical diversity.

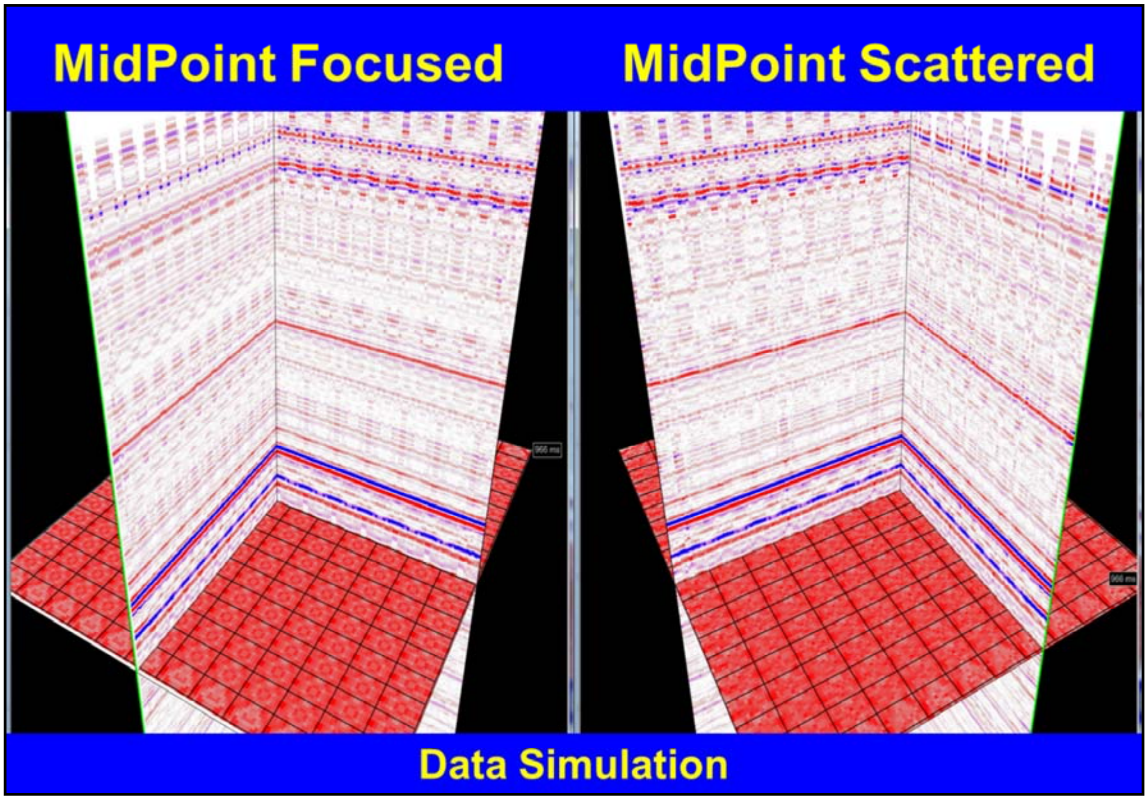
Perhaps the best statistic of all is to see how real data stacks in the presence of offset and azimuth distributions that are less than ideal.



Mustagh has developed a tool called "Data Simulation". The 3-D model predicts the offset distribution of traces in every "bin".
We then select a common offset super-gather (a group of adjacent CDPs sufficient to give one sample of traces at every offset).

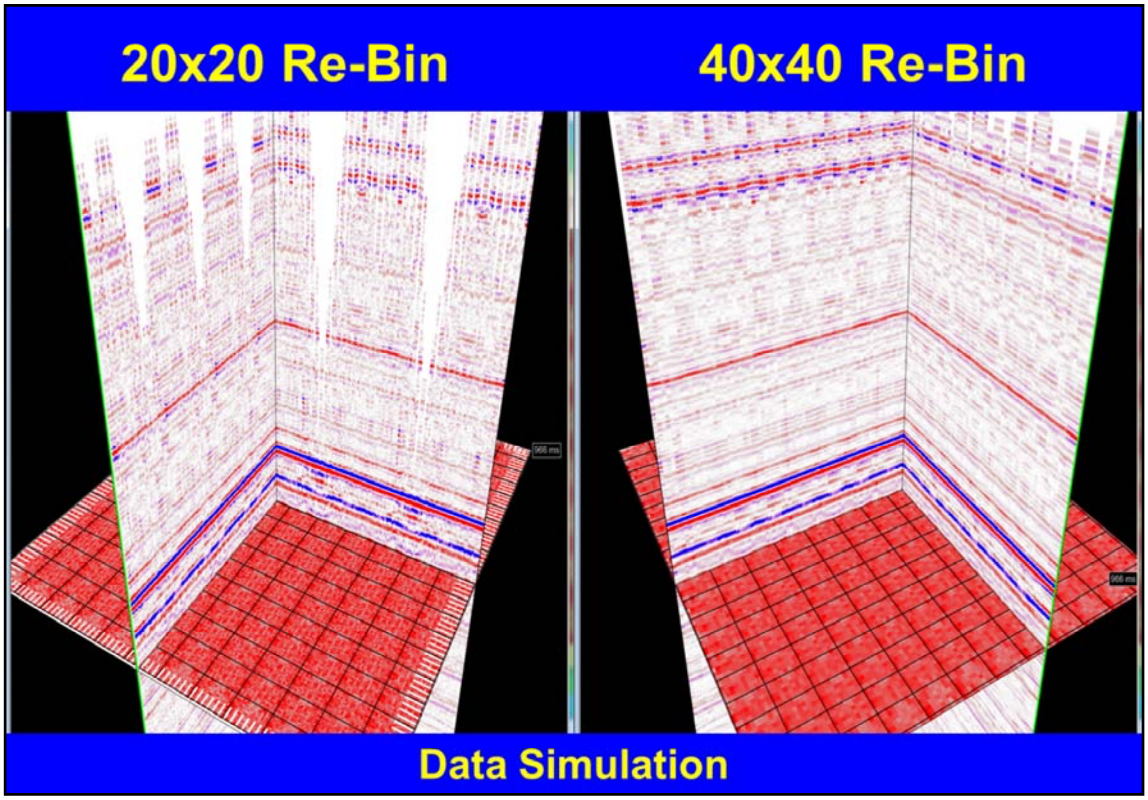


From the model, we determine which offsets belong in a particular bin. We identify traces of these offsets in the reference trace gather. By averaging those only those traces, we produce a simulated stacked trace for that bin. In this manner, we simulate unique stacked traces for each and every bin in the model. Since we use the same reference trace set for all simulations, then the simulated data volume contains no geologic changes. Trace-to-trace differences are entirely due to variations in offset distribution and will reflect the geometric imprint expected from our model.



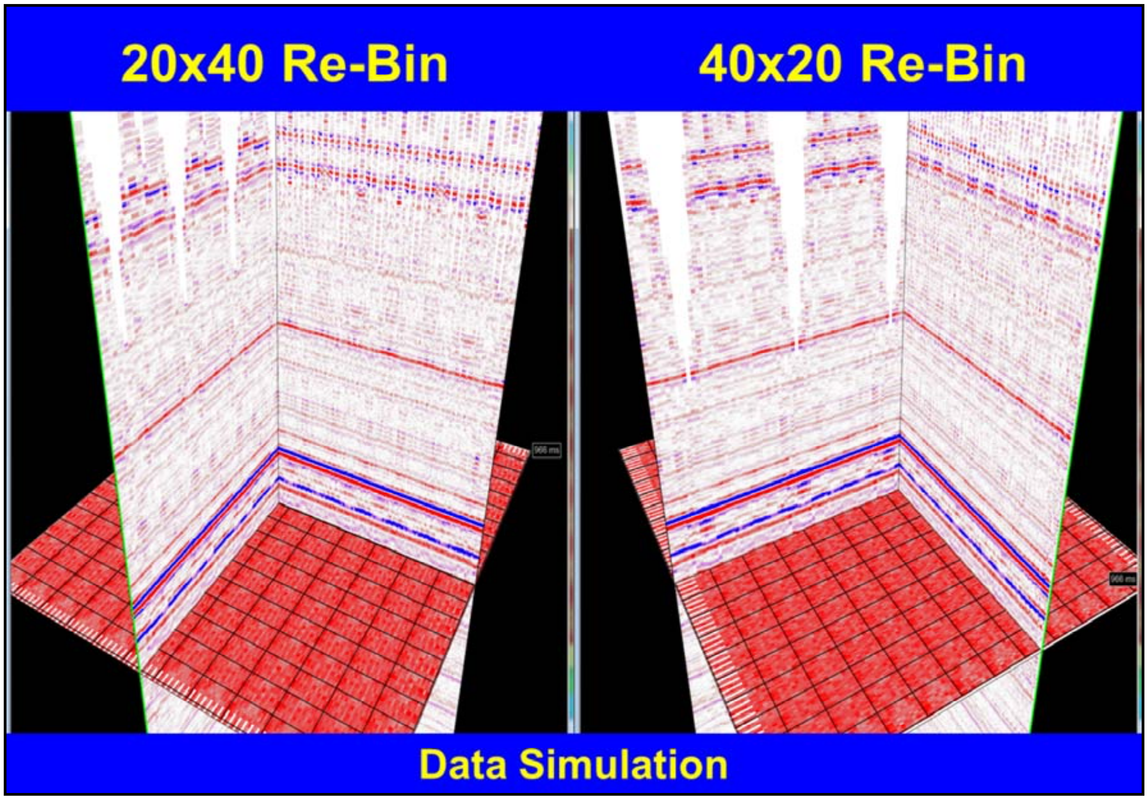
In this simulation we compare the regular offset orthogonal survey on the left with the triple staggered model on the right. Both models are simulated using natural binning to 30 x 30 meter bins.

Notice that the triple staggered design tends to mitigate some of the geometric imprinting observed in the regular offset model (particularly evident in the displayed time slice).

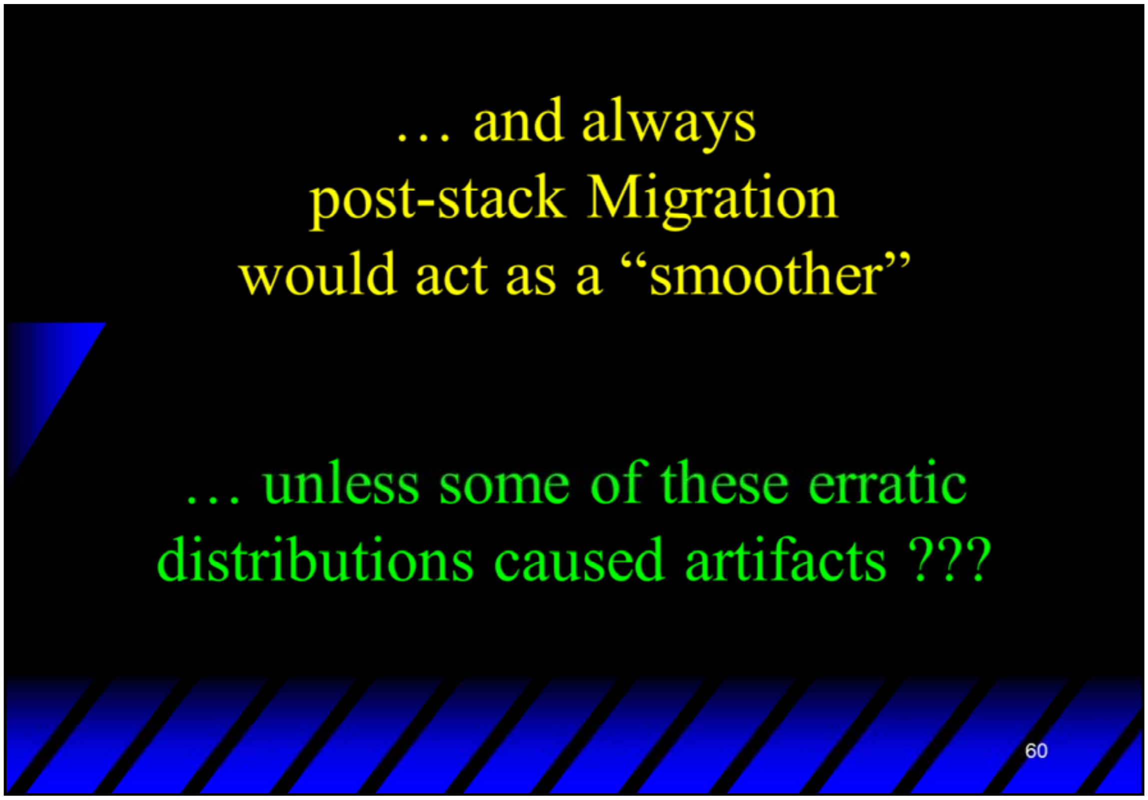


In these displays, we use the triple staggered model to re-bin the data in small bins (20 x 20 meters) on the left or larger bins (40 x 40 meters) on the right. Notice the effect of the irregular sampling on the left. Note the large gaps due to missing near offsets in some of the shallow reflectors.

Now compare the larger bins on the right with the natural bins on the right side of the previous slide. Notice that signal to noise does not appear to be significantly improved. Although the 40 meter bins produce higher fold, the contributing traces are not statistically diverse and the stack power is not noticeably augmented.



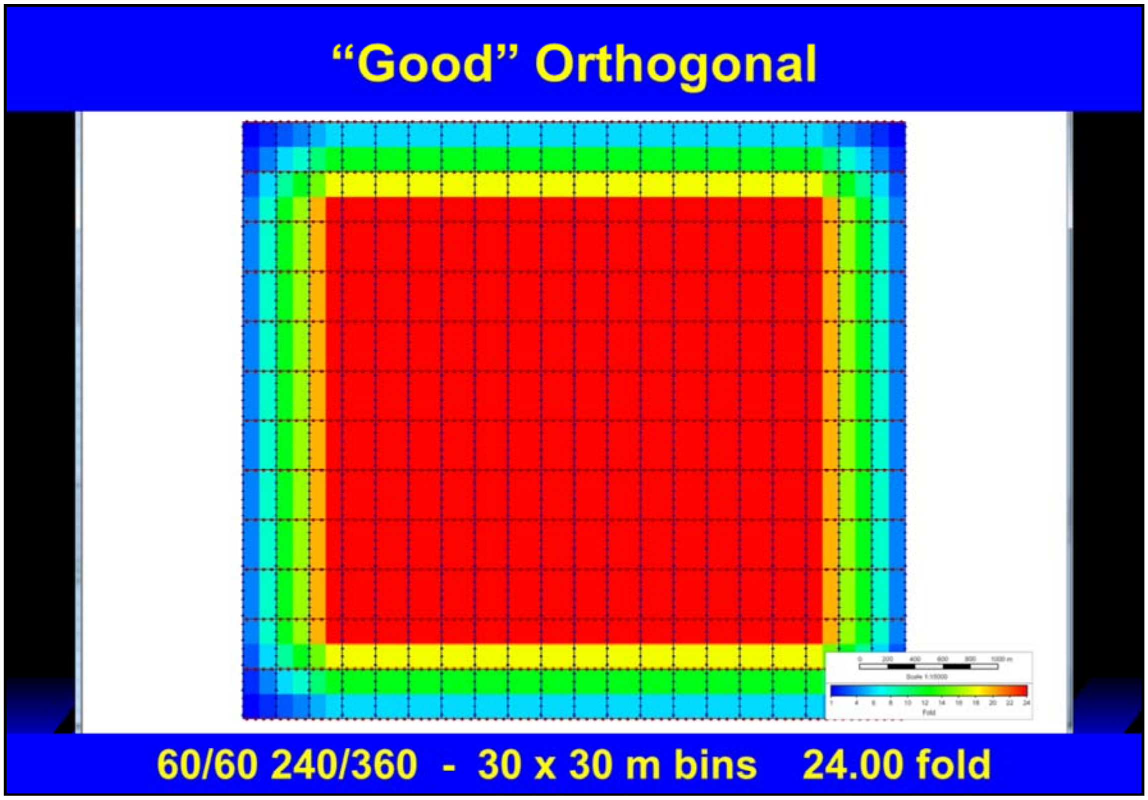
In these two displays, we have used the same data set and re-binned into asymmetric bins. Note that the artifacts have a dramatic negative effect on the shallow data.



Once these deficiencies of re-binning were recognized, we found that many users still tried to apply the technique, using the excuse that the migration process would smooth out bin-to-bin variations. However, our experience has been that the artifacts created by re-binning result in artifacts in the migrated data sets also. We no longer support the re-binning of data in non-natural bins for the purpose of stacking and post-stack migration.

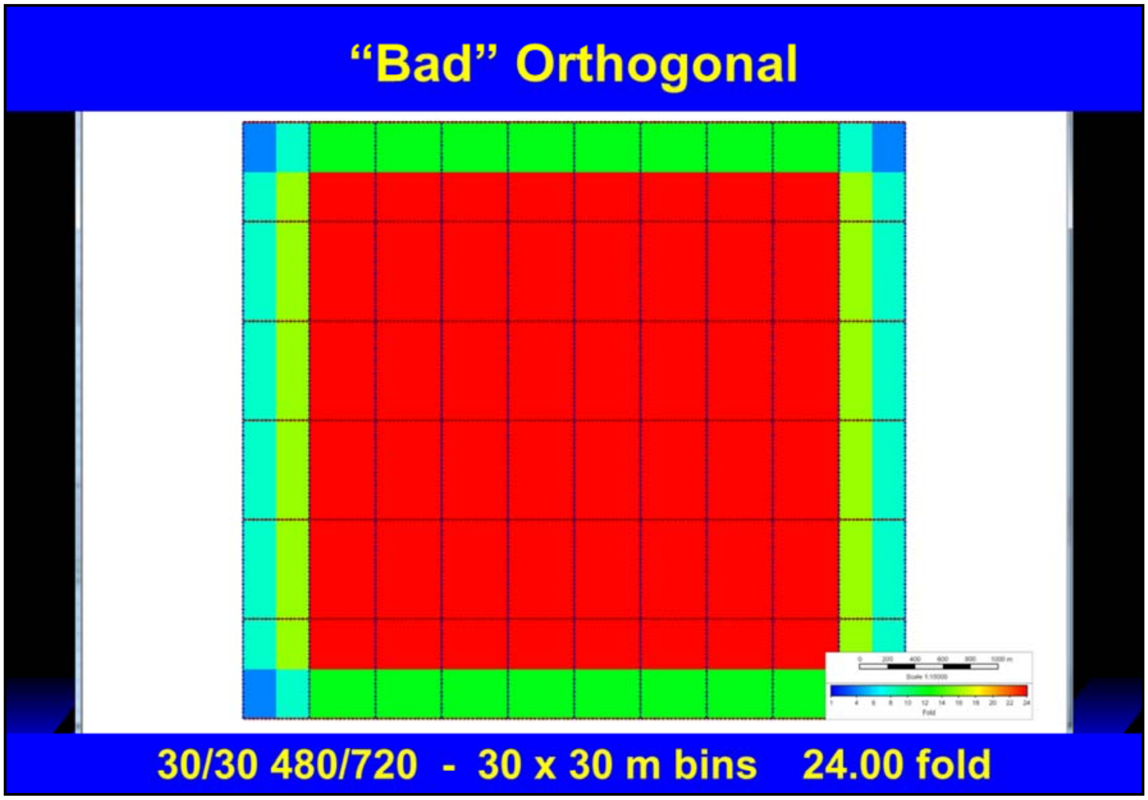
Now that we have emphasized the importance of statistical diversity, let us dispel another practice encouraged by some designers.

Are source and receiver densities the key factors in survey quality? … or do line densities also play an important roll?



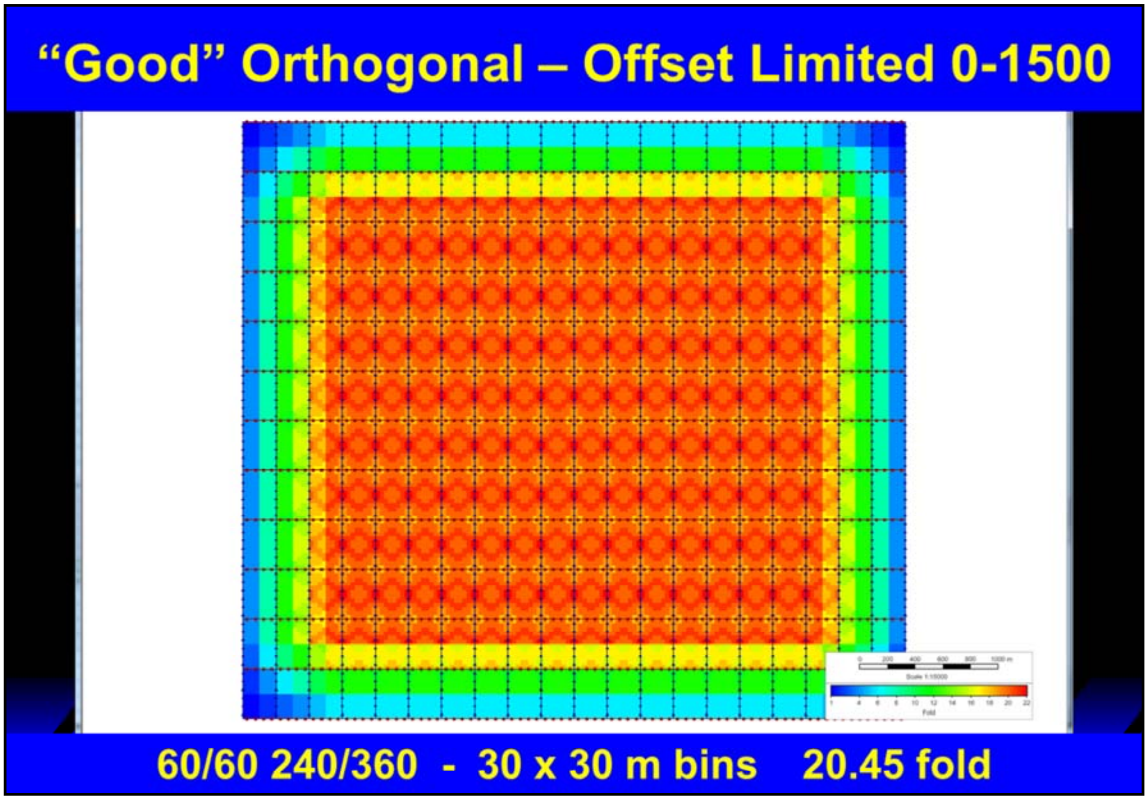
Some proponents claim that line density can be replaced by point density along a sparser set of lines or that source density can be diminished if receiver density is increased in compensation.

We will use the previous model using Ri=Si=60 m, RL = 240 m, SL = 360 m with a rolling patch of 12 x 48. This should yield a fold of 24 in natural bins of 30 x 30 meters.

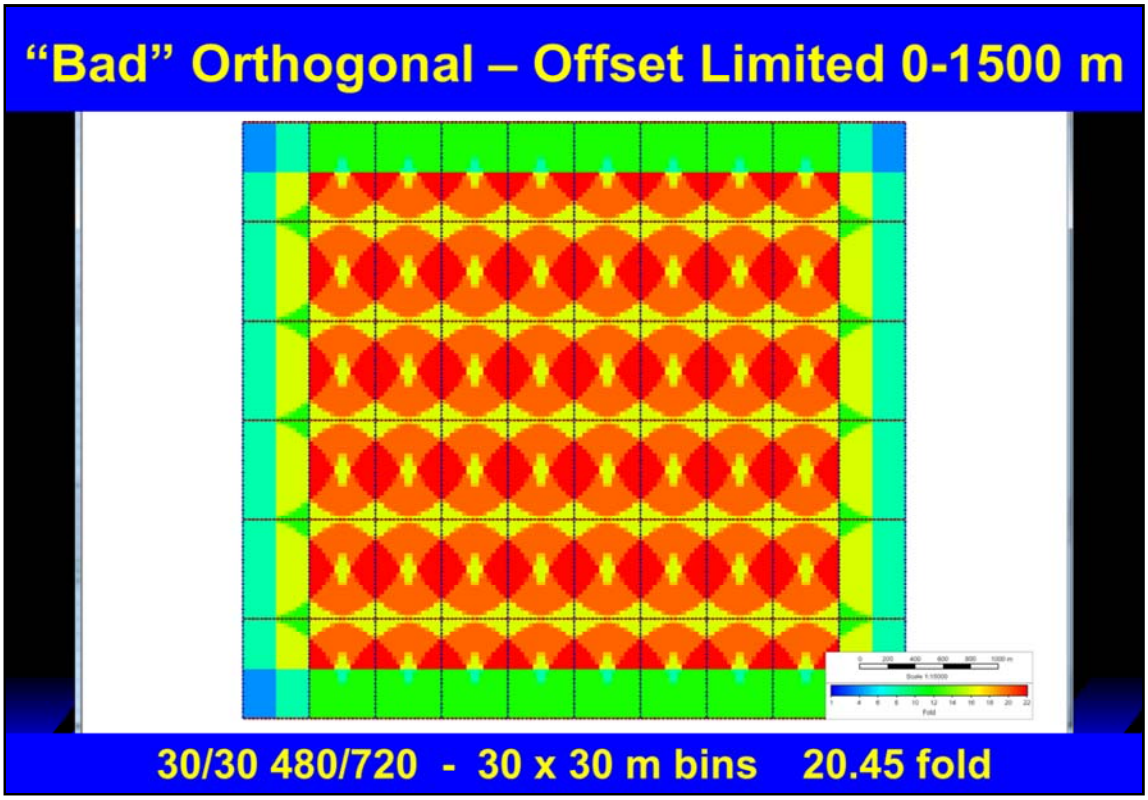


Let’s compare the previous survey to the one in this image. Here we have used Ri=Si=30 m, RL = 480 m, SL = 720 m and the rolling patch is 6 x 96 (still 2880 x 2880 meters). This survey would produce a nominal fold of 6 in natural bins of 15 x 15 meters. However, if collected in the same bins as the previous model, this survey would produce a nominal fold of 24 in 30 x 30 meter bins.

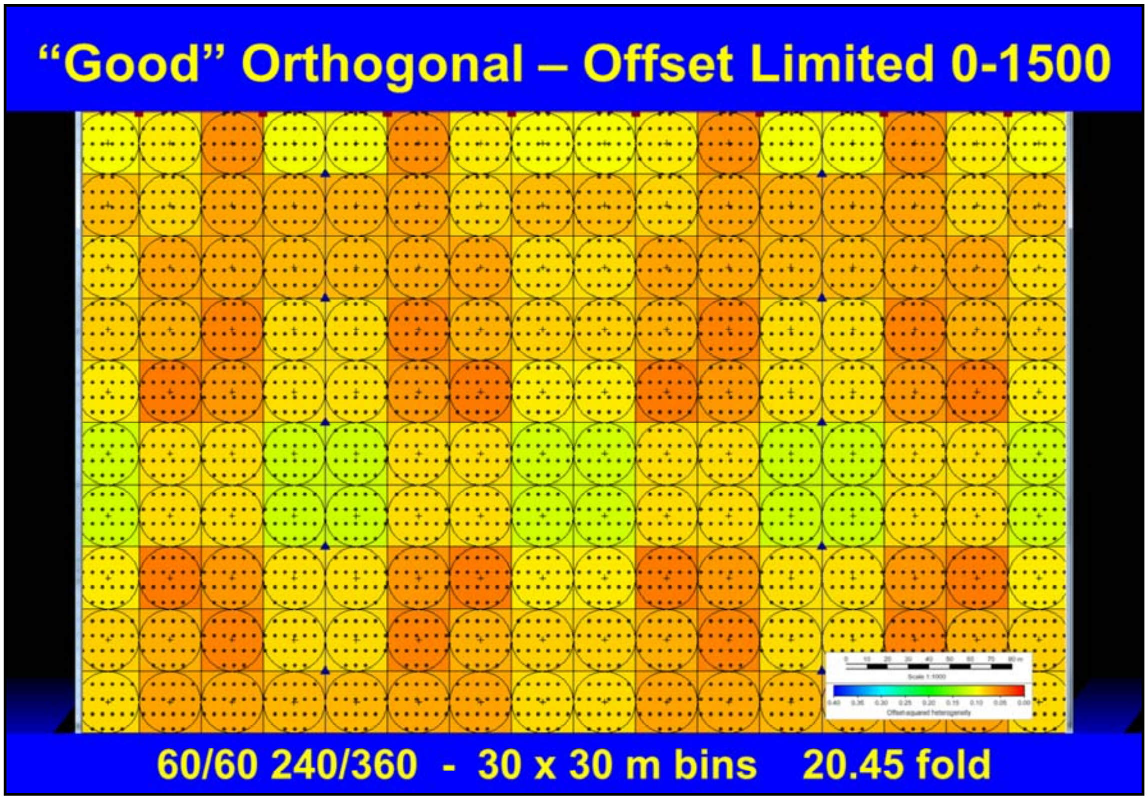
When you flip back and forth between this model and the previous one, it appears we are generating the same fold.



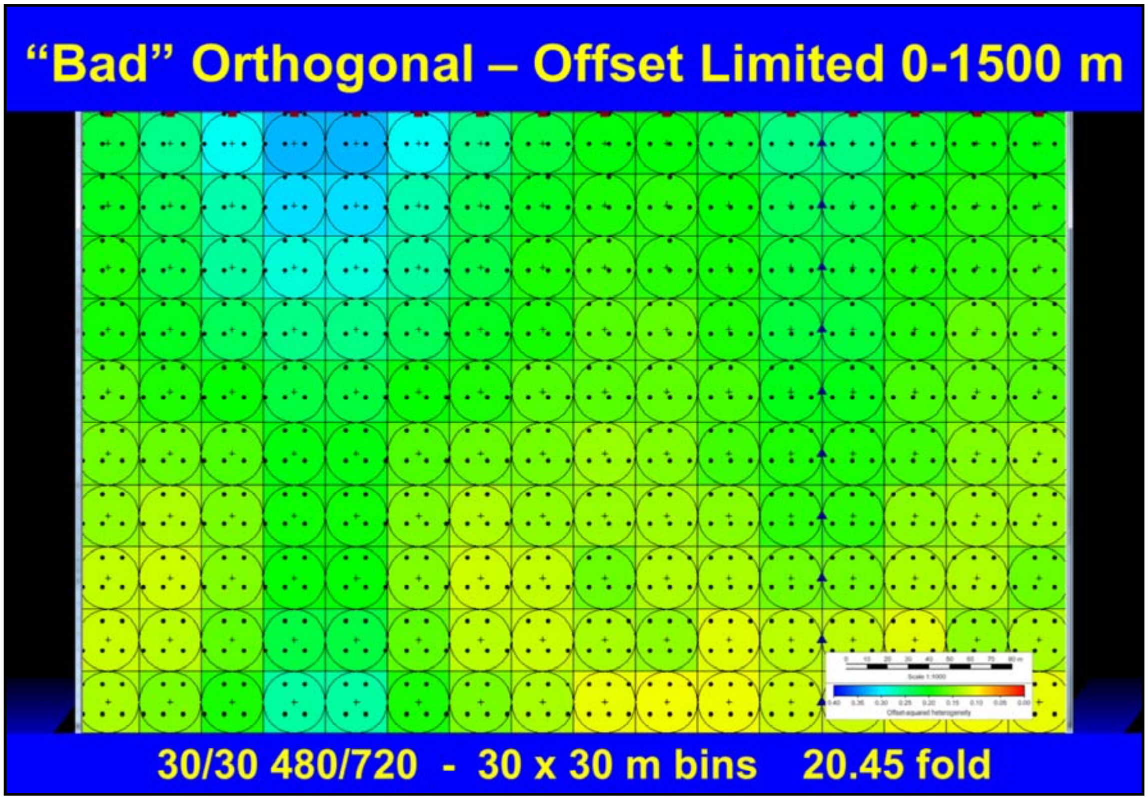
Now let's consider the offset limited fold using only offsets of 0-1500 meters. With the conventional model, we get a mild geometric pattern that is not likely to result in geometric imprinting in real data.



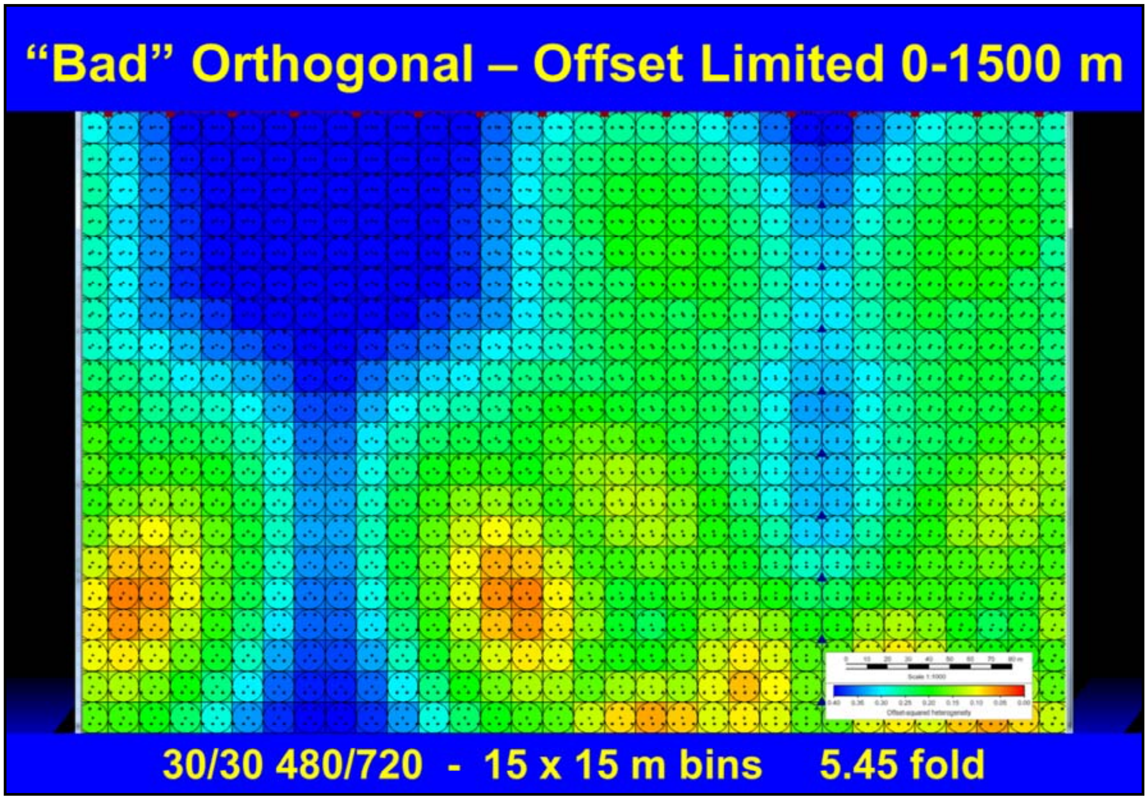
However, the second model produces a similar average fold, but with much more bin-to-bin variation. This strong geometric pattern is far more likely to introduce geometric imprinting in the recorded data.



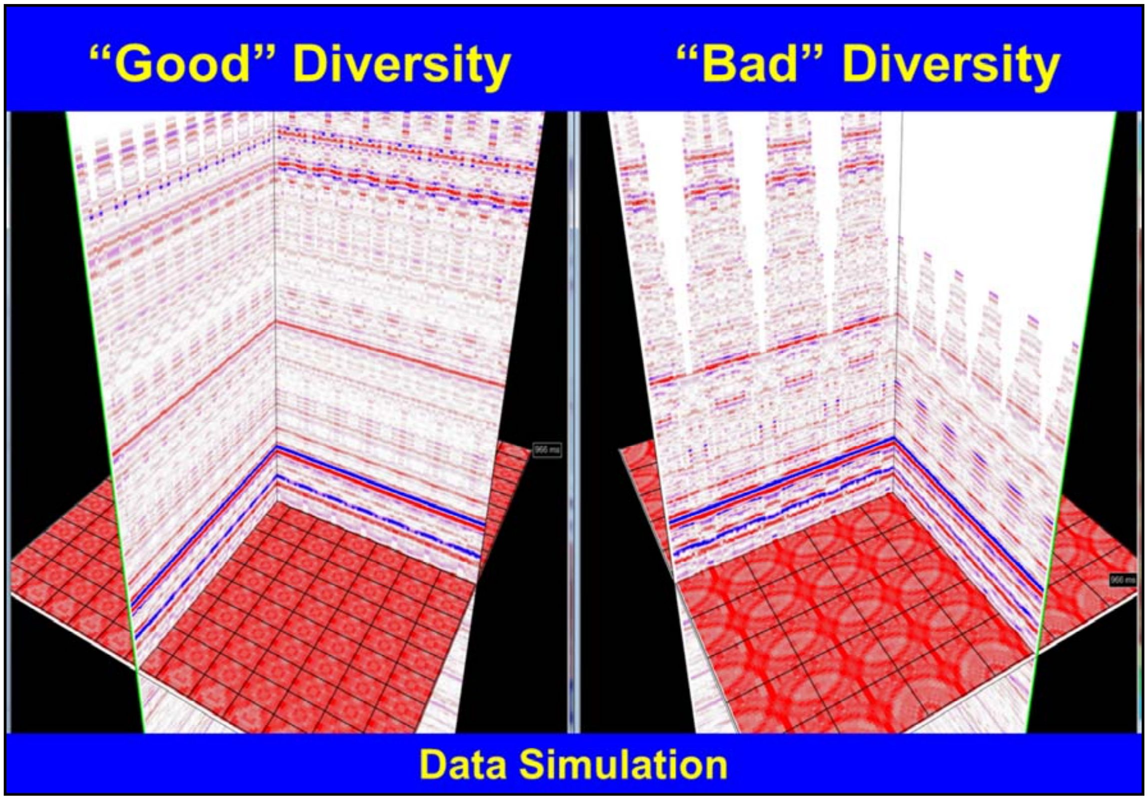
But lets look at the more important statistics of offset heterogeneity (expressed as the background color in each bin) versus the offset-azimuth distribution (expressed as the polar points in the foreground). The normal orthogonal provides the acceptable result that we expect.



However, the model with dense intervals and sparse lines produces a small set of statistics that are repeated four times. These distributions are NOT statistically diverse.

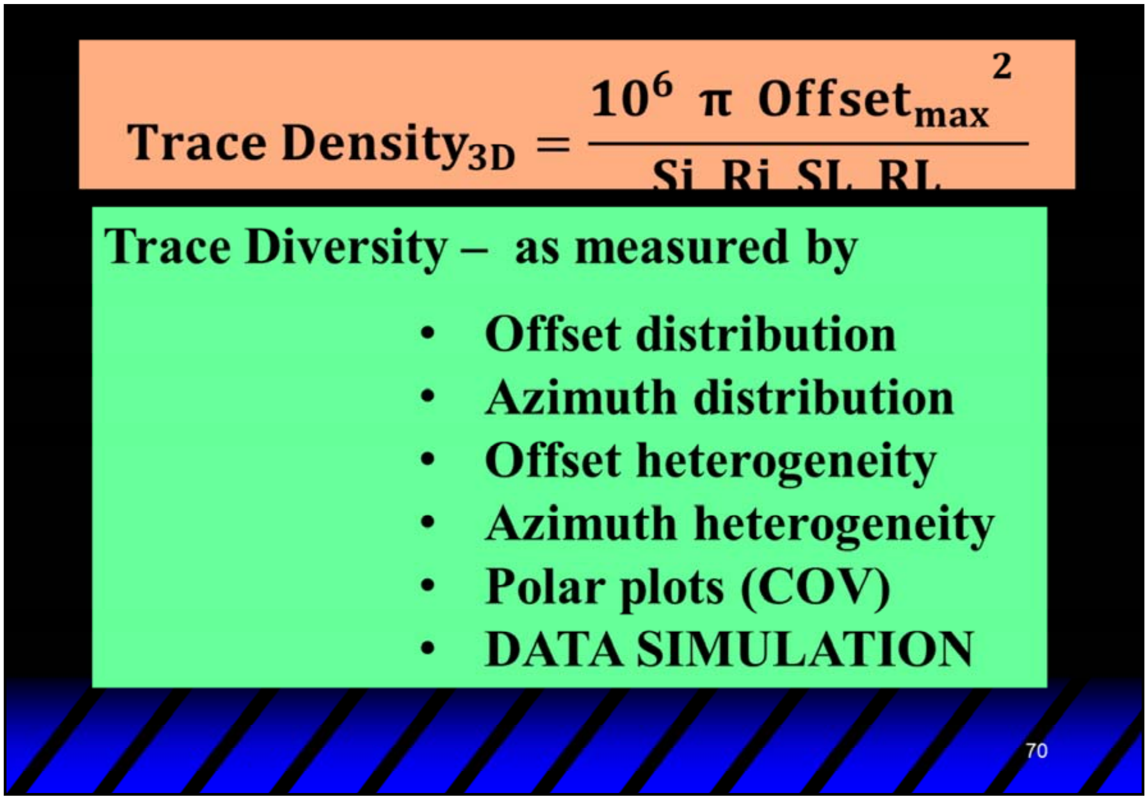


If we collect the alternate design in natural bins of 15 x 15 meters, we see the same poor statistics in each bin. Mixing together four of these bins (as in the previous display) does not significantly improve the statistical diversity.



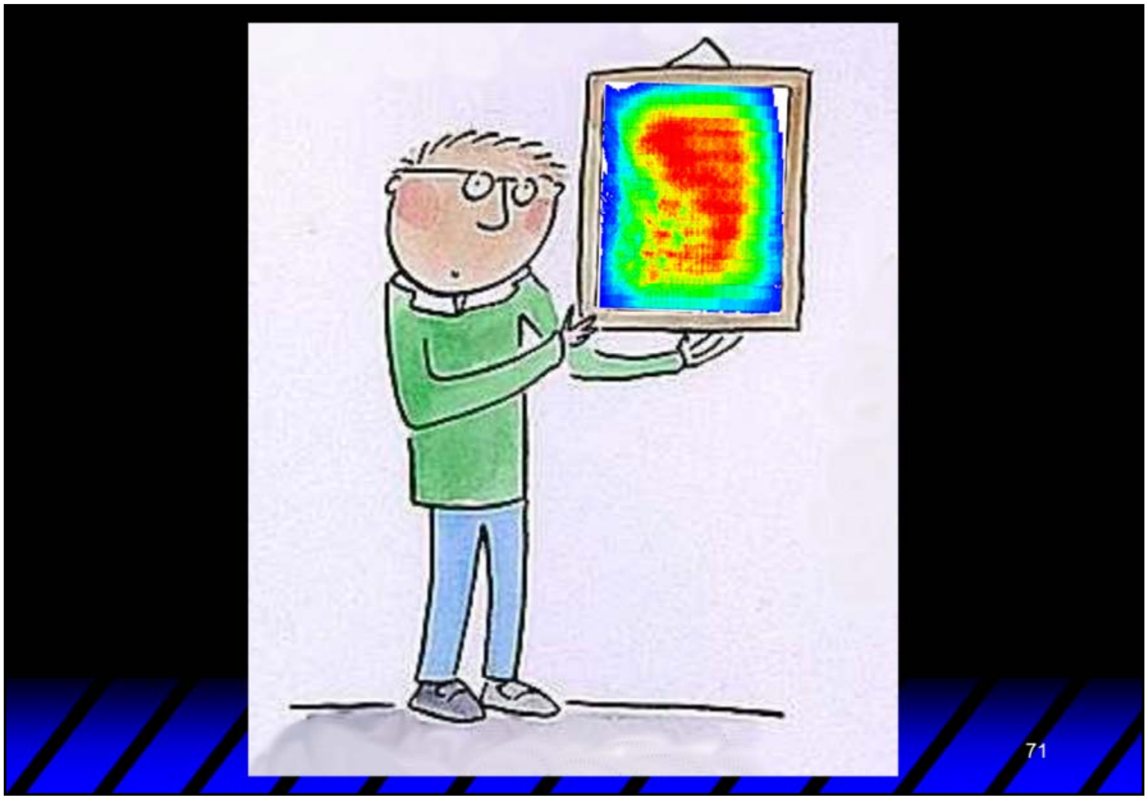
The data simulation for these two models yields a very clear picture of the deficiencies imposed by this type of thinking.

3D designs must use a sufficient density of source and receiver points, but these points should be reasonably well distributed in space. We should NOT embrace models that include high densities of points along sparsely positioned lines.

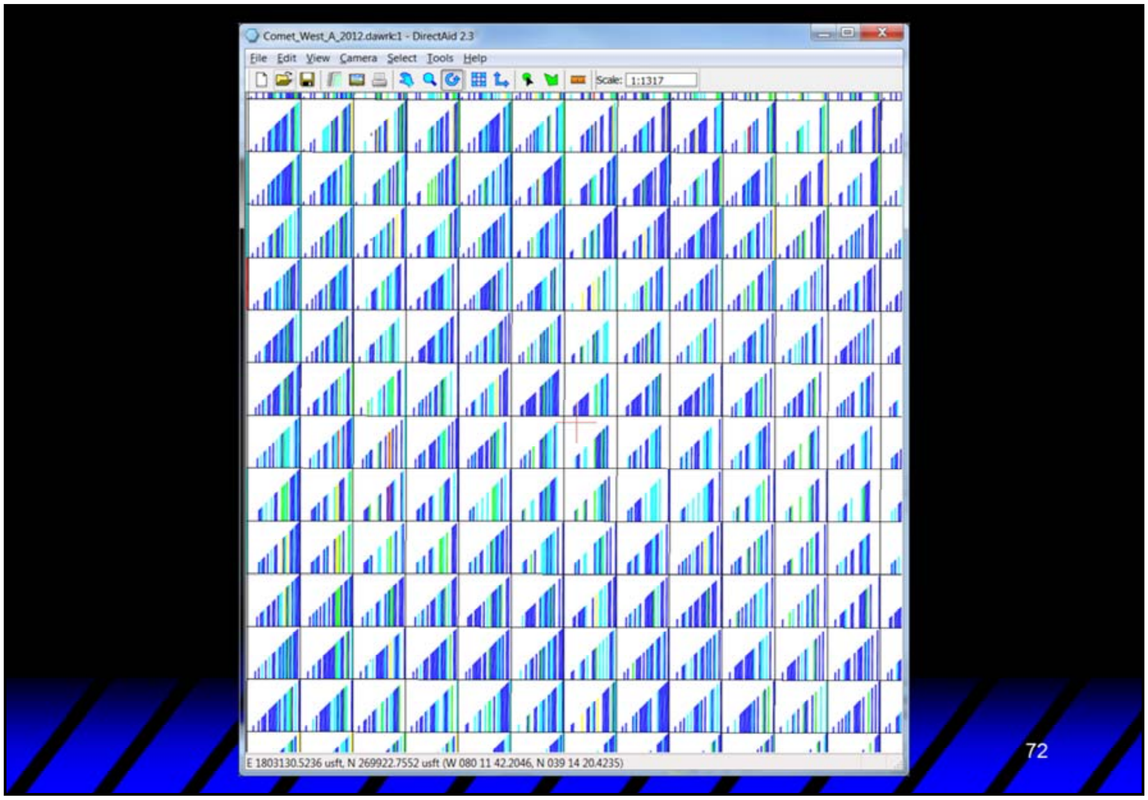


We encourage the use of trace density rather than fold. This is particularly necessary when comparing designs of different natural bin sizes.

We encourage the use of a number of easy to understand displays that reflect diversity of offsets and azimuths. While trace density can be an important aspect of survey quality, it is generally not very effective unless the contributing traces are diverse in the statistics they deliver.



A fold plot, by itself, does not provide very useful information. It can often generate a picture with pretty colors and patterns. … suitable for hanging on the wall as art work, but not very helpful in determining survey quality.

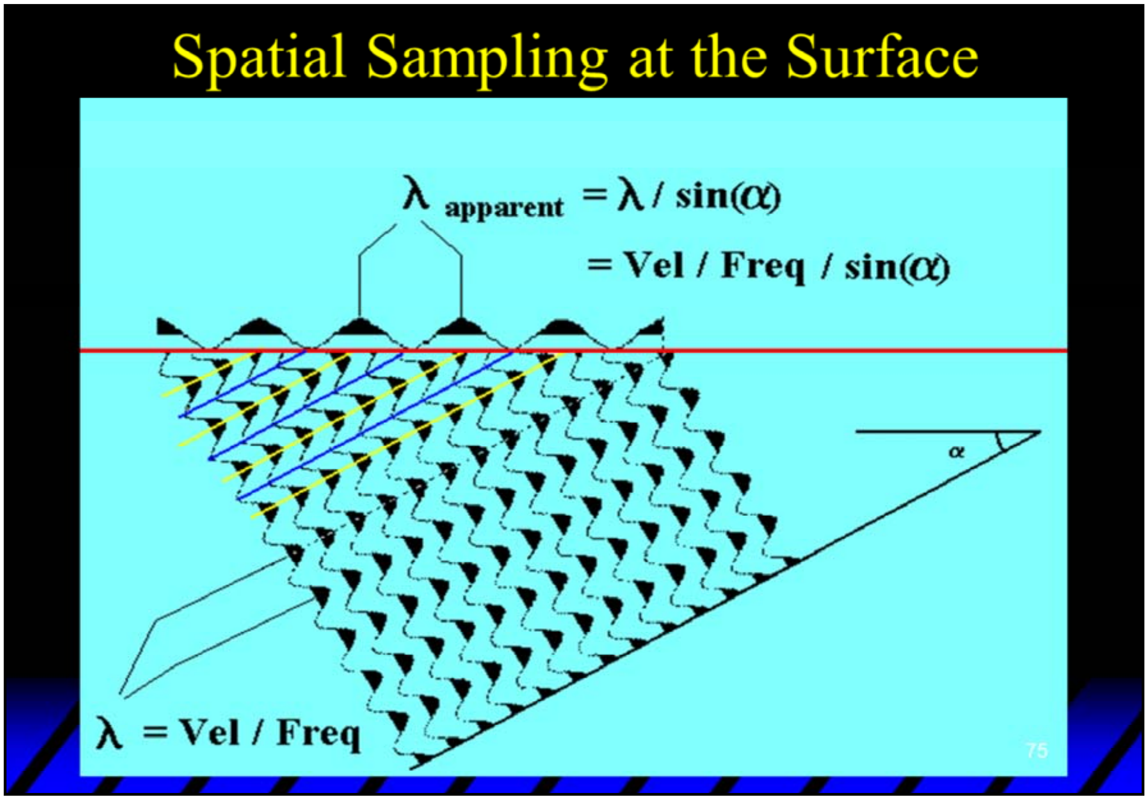


Conventional offset distribution plots and spider plots may contain useful information about statistical diversity …

… but they can be difficult to view and confusing to understand. Therefore, they do not do a good job of conveying the information they contain.

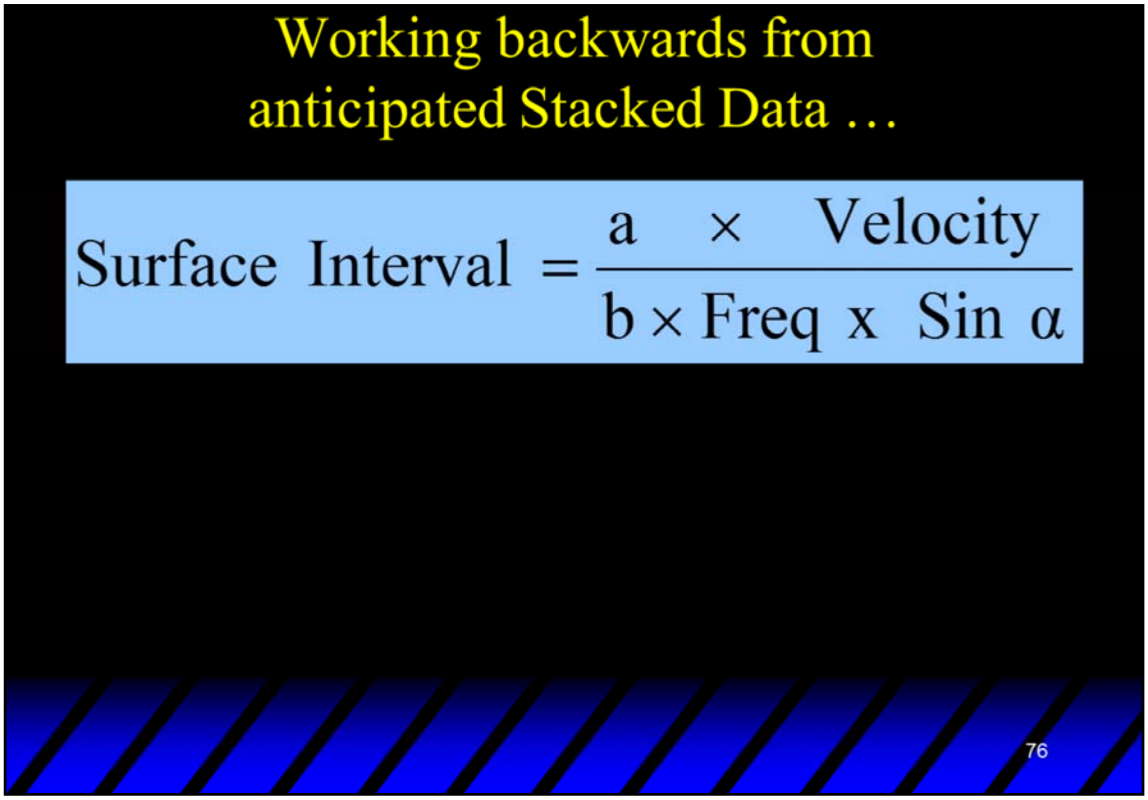
We hope that offset heterogeneity plots, polar plots of offset-azimuth, and data simulation provide more useful tools for survey analysis.

So what about our approach to determining source and receiver intervals? How has that changed since the early days of 3D Design?



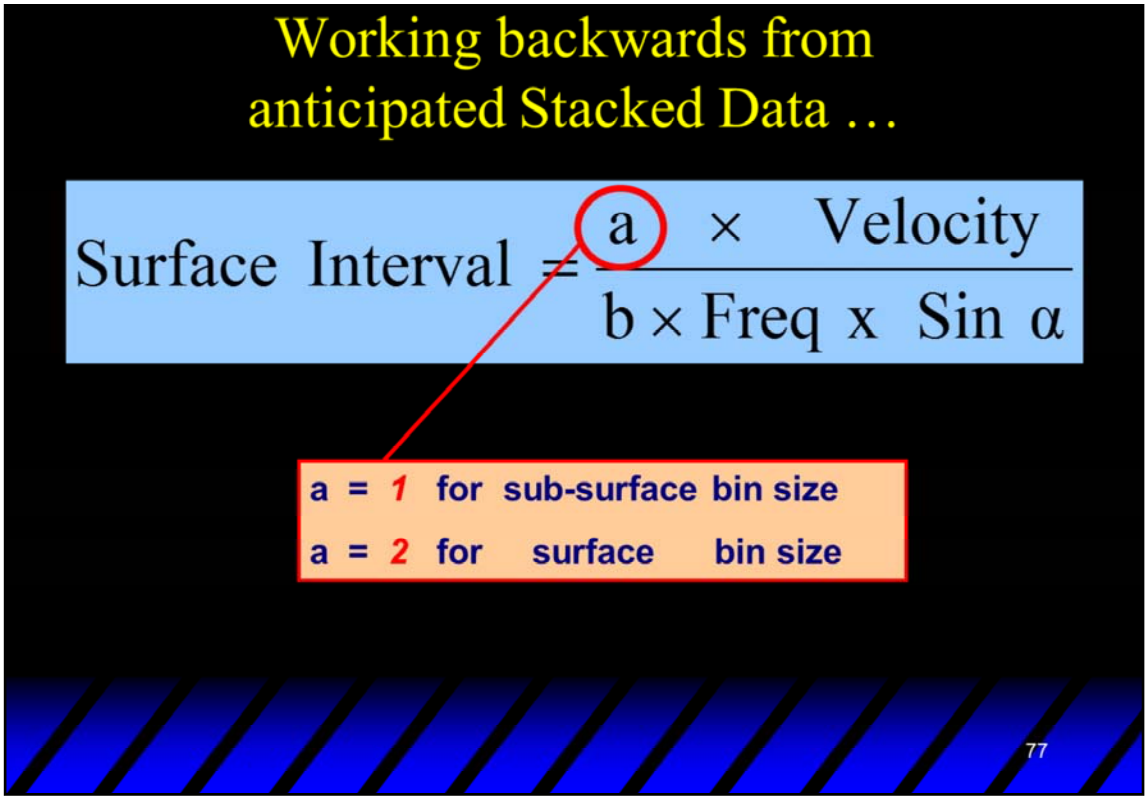
In the early days, we concerned ourselves with the post-stack imaging of geologic reflectors. We tried to ensure that migrated dips would be imaged by traces spaced by a natural bin size small enough that frequencies of interest would not be aliased due to steep dips.

We concerned ourselves with apparent wavelengths of dipping reflectors, slowness as measured in ms of dip per trace and other related measurements.

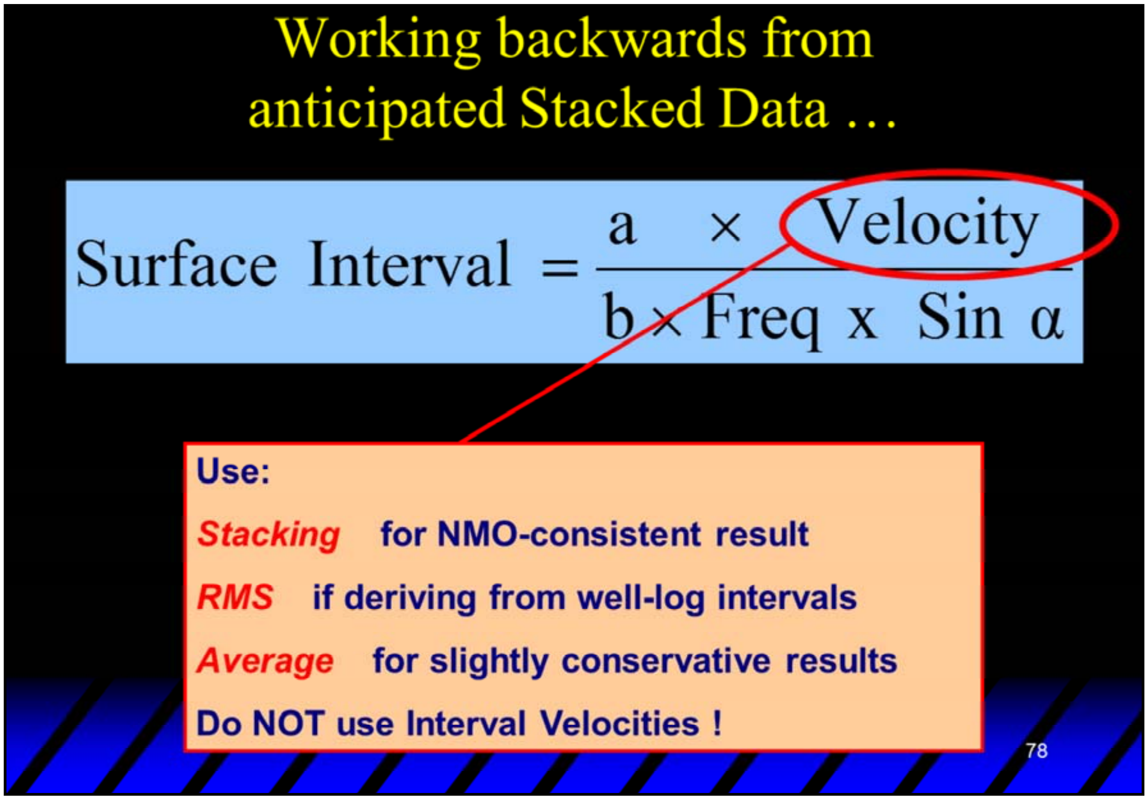


Now we tend to concern ourselves more with proper sampling of emergent wavefields due to single source points.

Whether the former or the latter, our sampling equations tend to have the general form above. Source and receiver intervals tend to be proportional to velocity fields, inversely proportional to recoverable frequency and inversely proportional to geologic complexity.

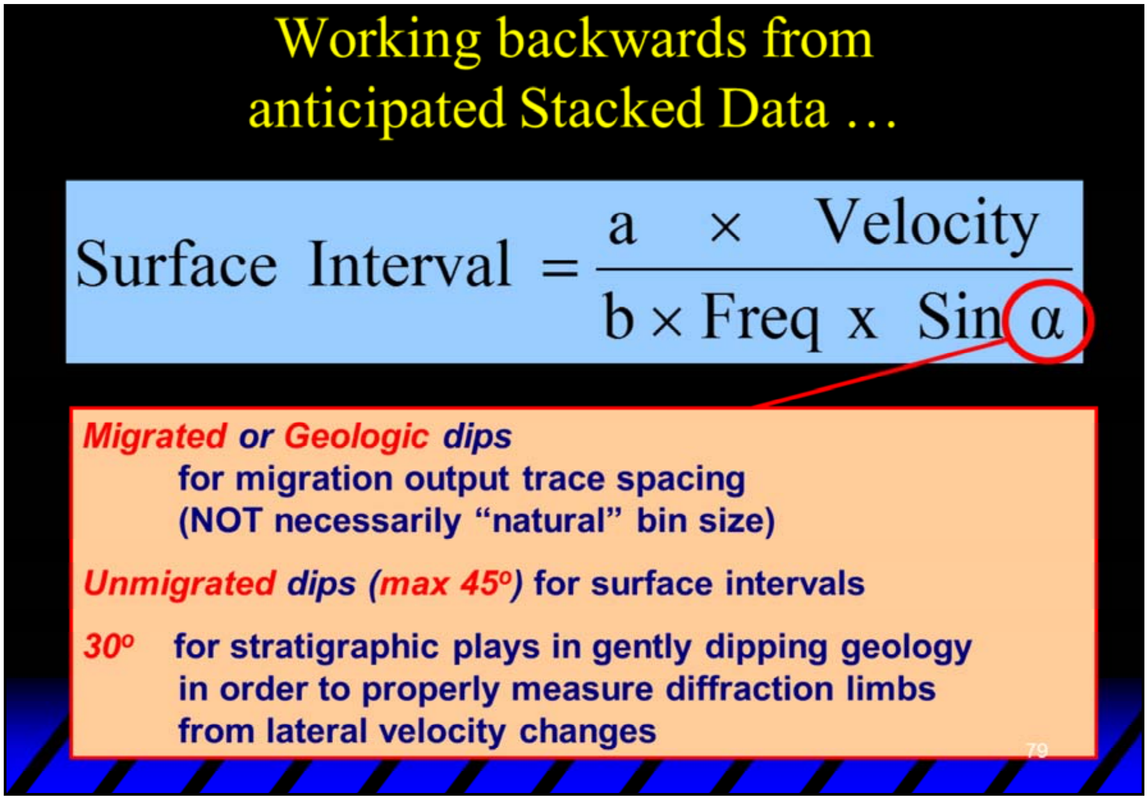


The exact values used in each variation of this equation depend somewhat on the application of the equation. For example, if calculating required subsurface bin size, the interval should be one half of that for surface source or receiver spacing.



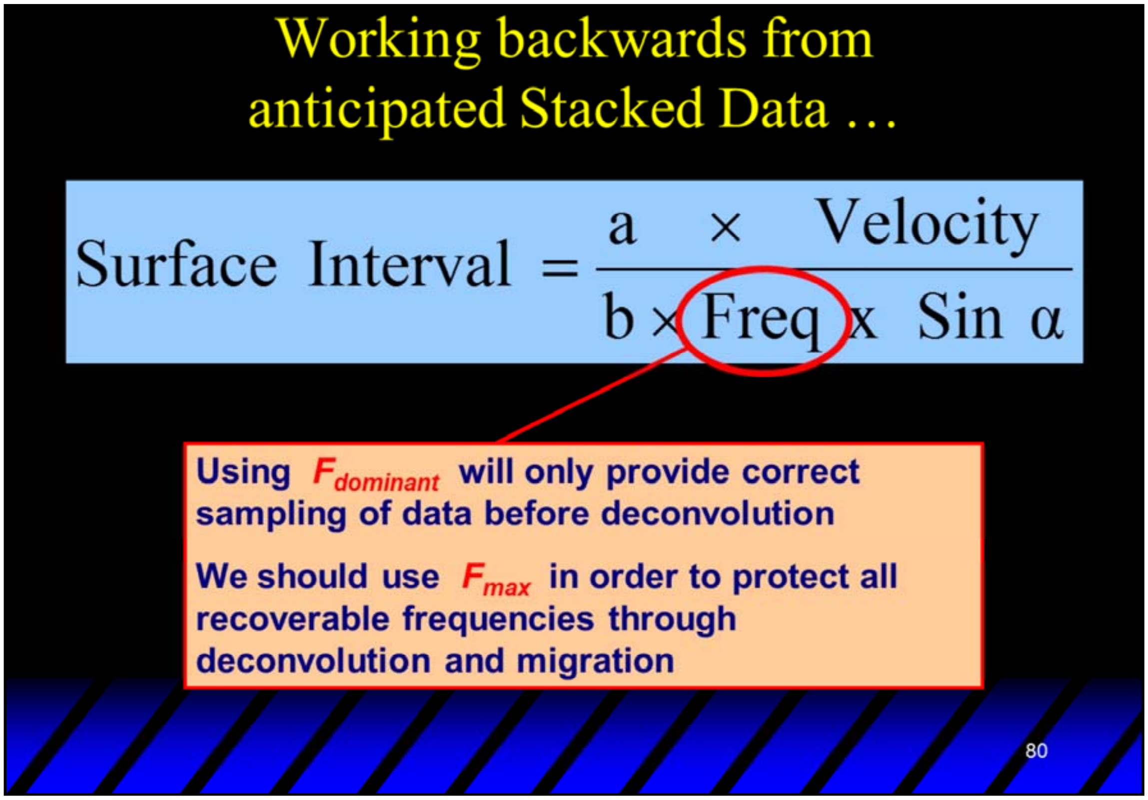
In modern designs, we are mostly concerned with capturing the emerging wavefield. This means that reflections and diffractions will emerge at various angles as a function of offset depending on the velocity field. The main factor that determines the normal move-out of reflections or diffractions is the empirical stacking velocity. Under certain constraints, this can be demonstrated to be the same as the RMS average of interval velocities measured by local well logs. In reality, we can assume that Stacking and RMS velocities are approximately the same. Average velocities (such as used for depth conversions) are known to be smaller than typical stacking or rms velocities by factors ranging from about 85% to 100%

Probably the correct type of velocity to use is Stacking, using rms as an acceptable substitute. Use of average velocities may be acceptable if a "safety factor" of about 90% is desired in the calculated source and receiver intervals.

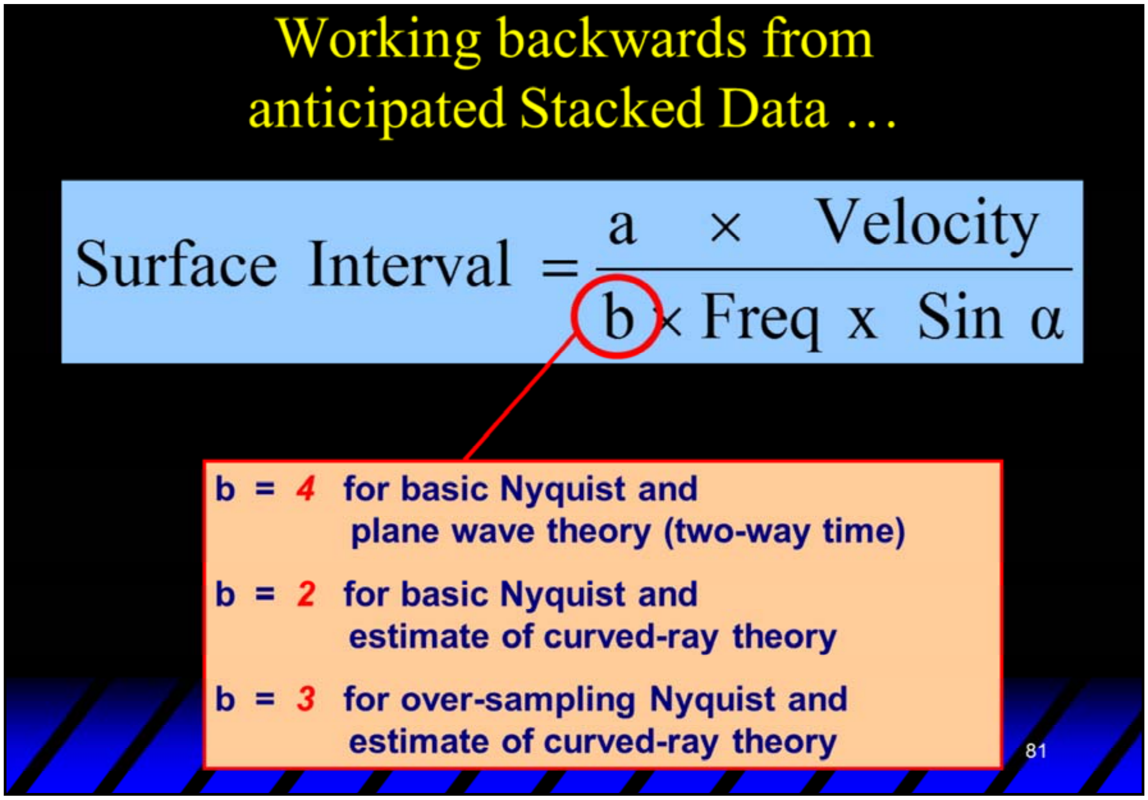


If resorting to the older concept of designing source and receiver intervals to produce the correct trace spacing in natural bins, then the angle in this equation should relate to geologic dips. These would be up to 45 degrees for un-migrated imaging and up to 90 degrees for migrated imaging.

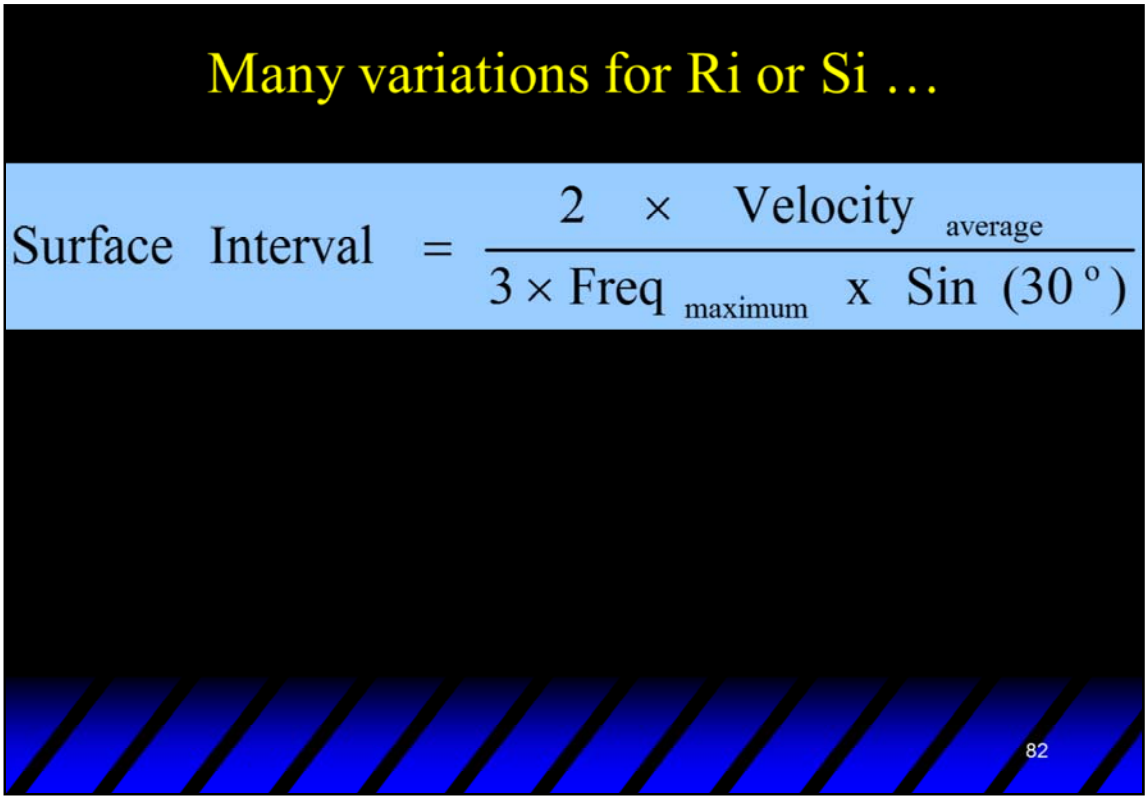
In field data, however, emergent angles for diffractions or reflections seldom exceed 30 to 35 degrees within useful offsets and migration operators. We may increase these angles for surface topography in some rugged situations.



Some designers argue that dominant frequencies determine dominant wavelengths. However, if we want do preserve our full bandwidth through deconvolution, migration and other frequency-domain processes, then it is important to properly measure all frequency components of our emerging signals. Therefore, we recommend using an estimate of the ultimate maximum recoverable frequency.

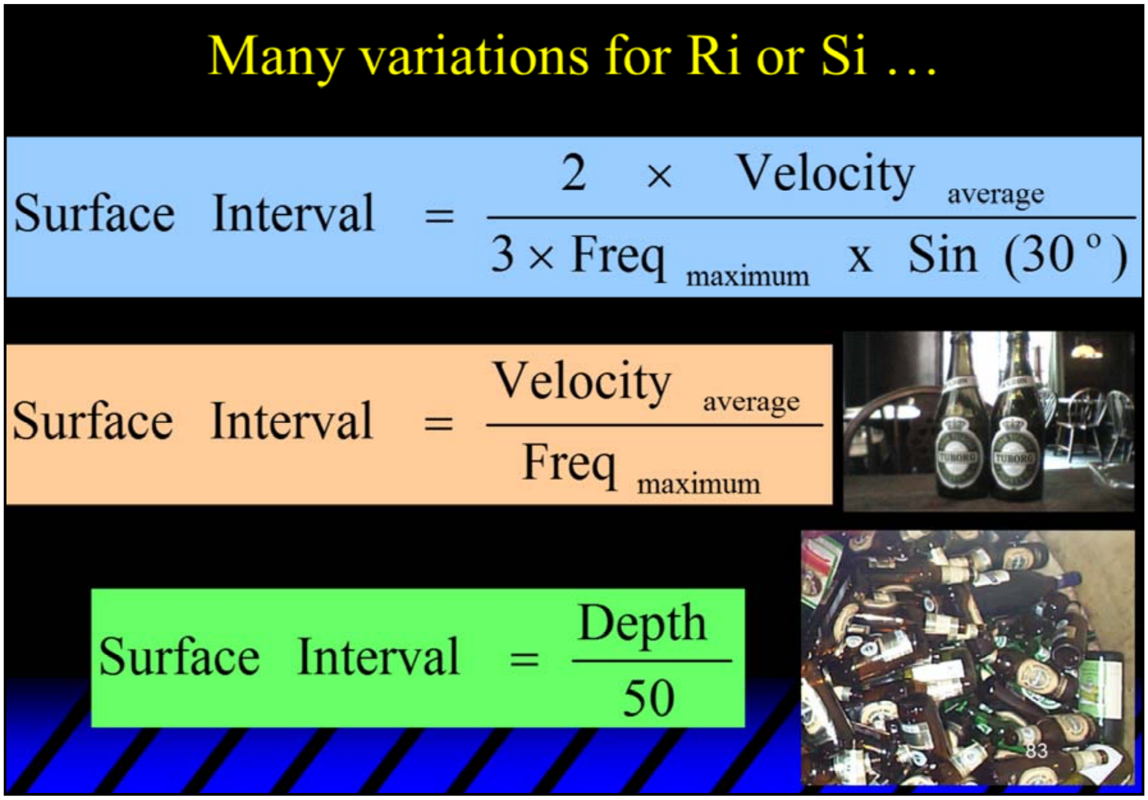


The constant factor in the denominator is basically used to satisfy the implied Nyquist requirement that we measure at least two samples per apparent wavelength. However, for plane wave theory in our basic derivation, we must account for two-way travel time (and this adds another factor of two to this term). More modern theory (that incorporates curved ray theory for materials with vertical anisotropy) acts to offset this consideration. The user should decide whether or not they prefer to oversample (again to maintain a “safety margin”).



The variation in these terms has resulted in many forms of the basic equation over the years. We wish to emphasize that none of these equations provides the "Right" solution. All variations of this equation provide estimates of the required trace spacing depending on a variety of input assumptions and each is only valid over a limited range of circumstances.

Our philosophy has been to select a form of the equation that offers a reasonable margin for error and generally provides a reasonable solution. We also choose design options that allow us to recover from our error if our determination of source and receiver interval results in slightly incorrect sampling. The form of the equation in this slide is the one we generally use in our design spreadsheet.

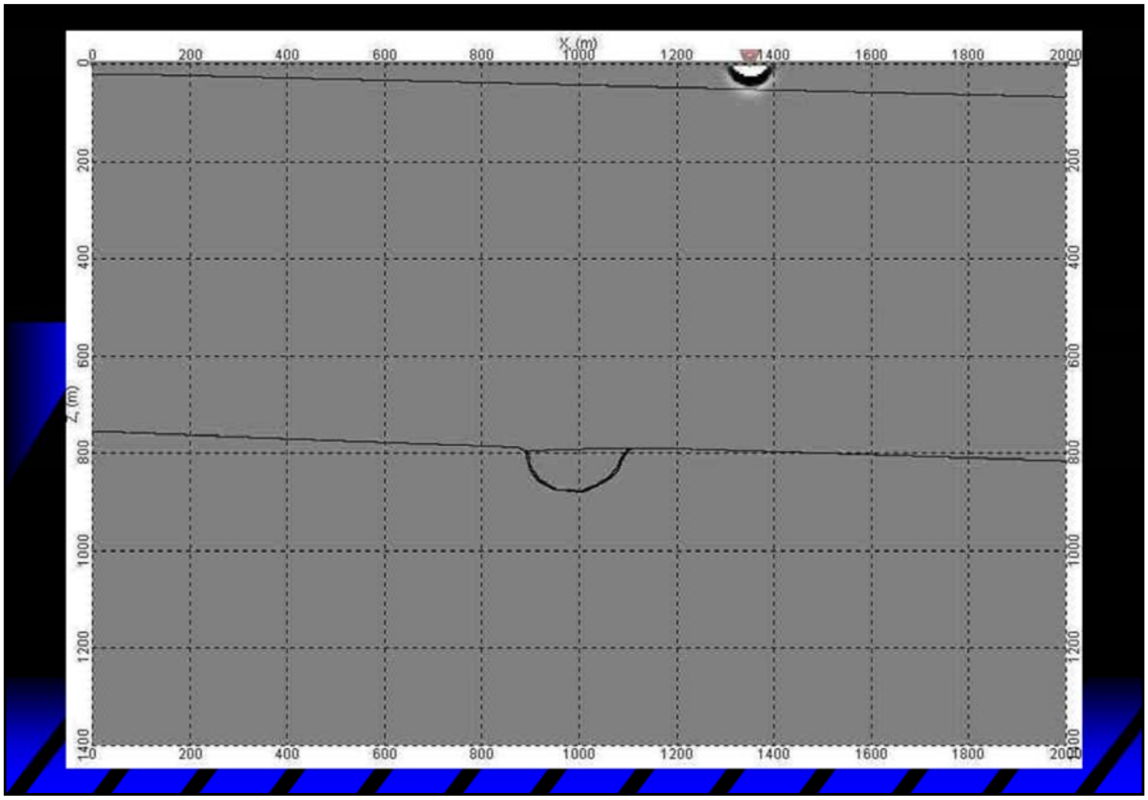


The top equation is useful when programmed into a spreadsheet that accesses the required input variables. However, when we are out for lunch with a client and an estimate of source or receiver intervals is requested, the top equation can be difficult to assess after one or two beers have been consumed. In such cases, we often use a derivative of the basic equation represented by the second equation in this slide.

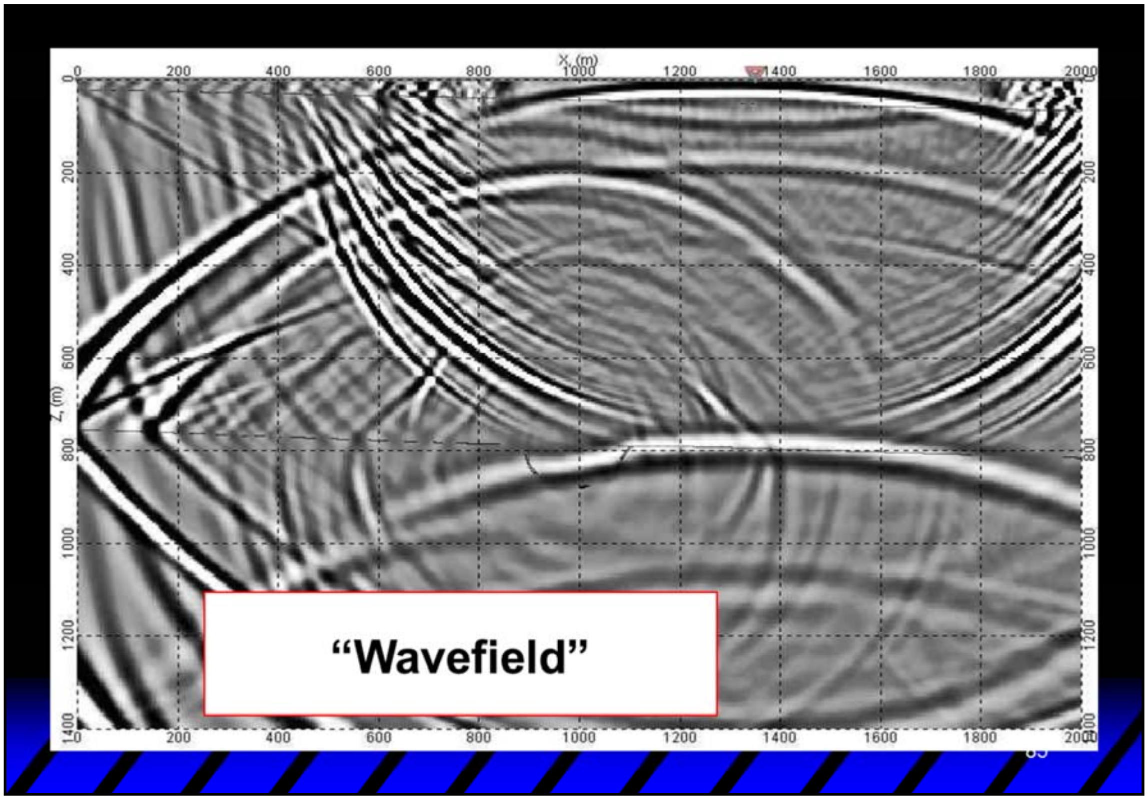
After a longer lunch (and more beers), even the second equation can challenge mental abilities, so we might revert to a moderately defendable derivation represented by the third equation.

The point is that none of these equations are either correct nor incorrect. They are just different variations under different bounding conditions.

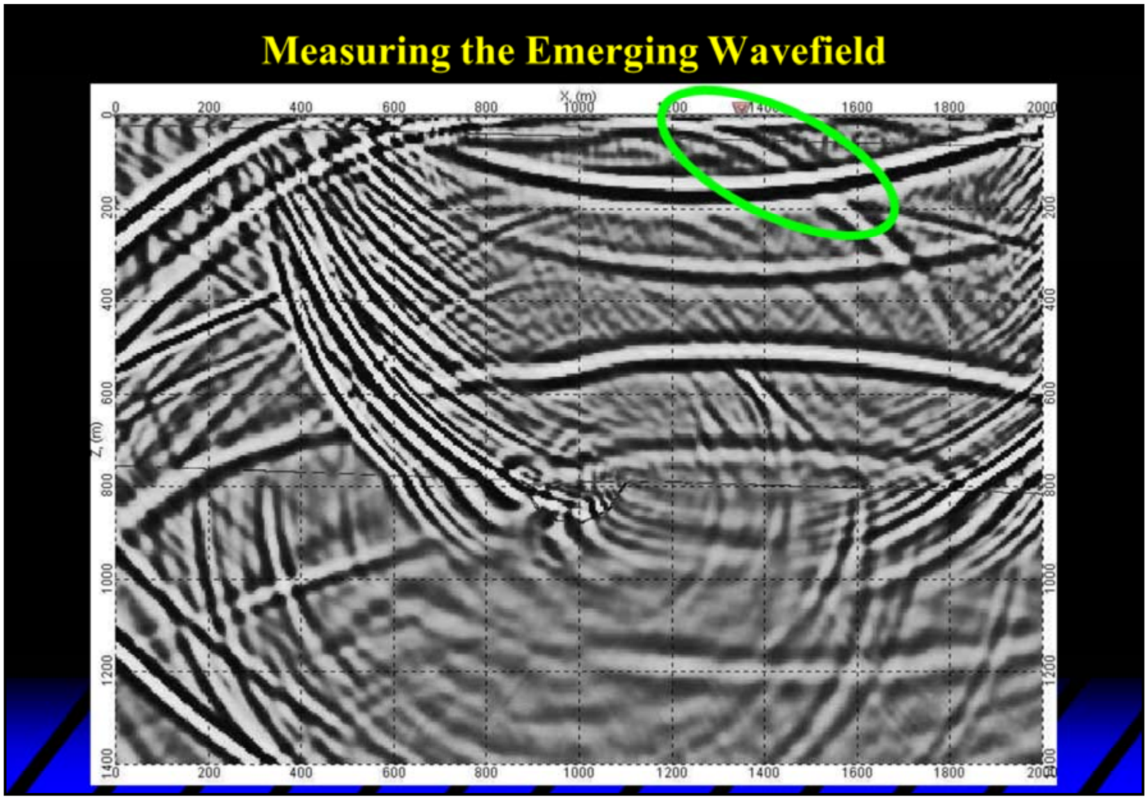
We are not likely to always get a correct sampling by using any one of the variations we have presented. Some method of recovery from any errors must be a key element in 3D design.



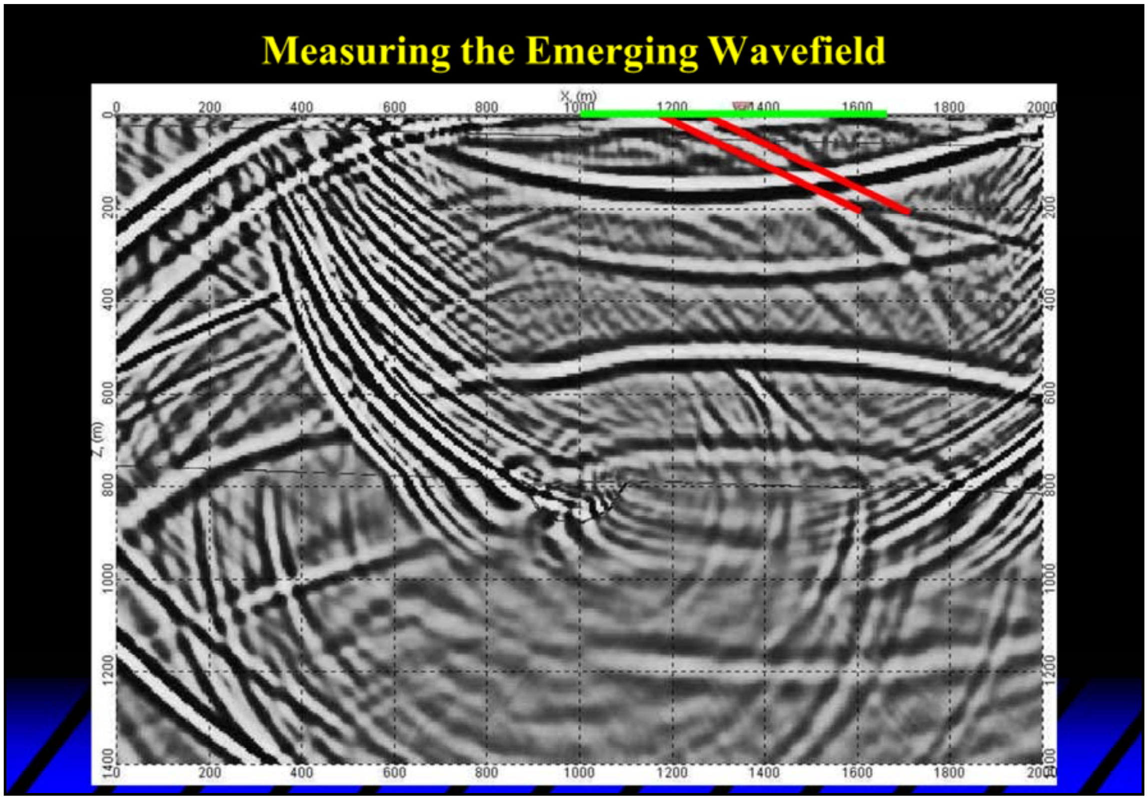
A wave-equation model of a simple geologic target is useful to demonstrate the concept of capturing the wavefield.



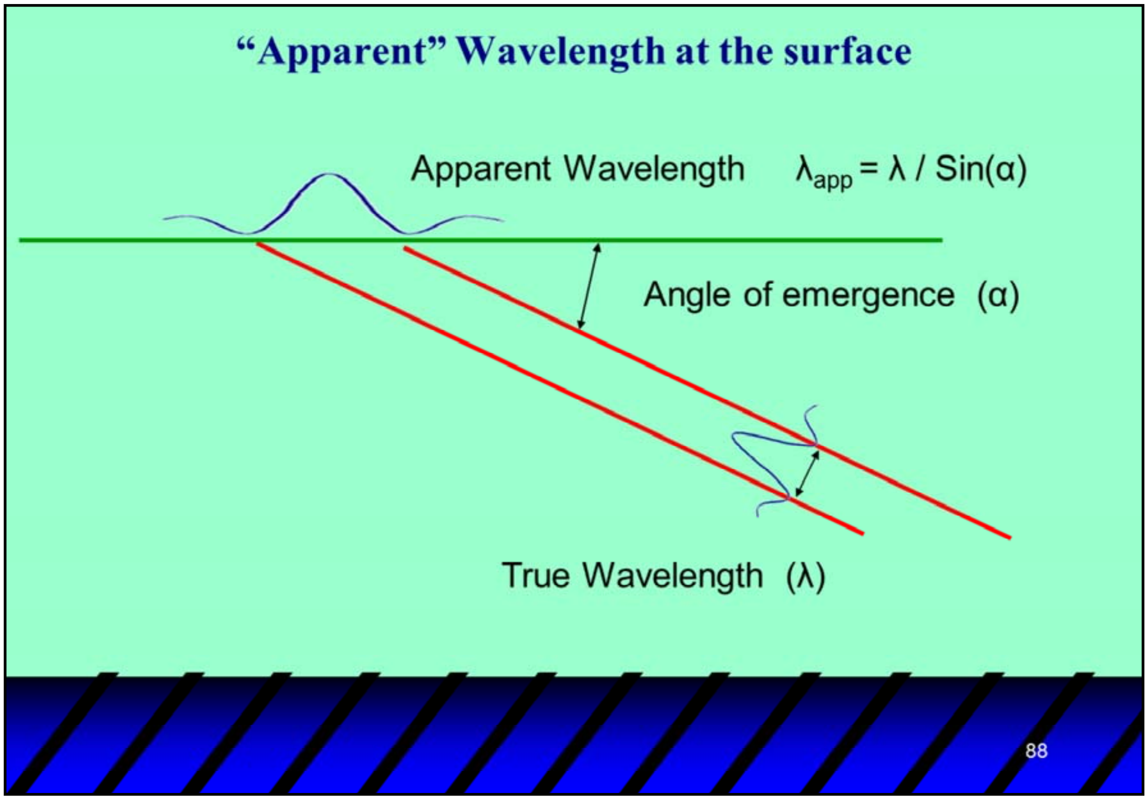
This is a snapshot of the time-variant wavefield of varying pressures that we may generate from a single source point. The wavefield exists at all points in the subsurface, but in normal seismic methods, we only measure a few samples of that wavefield where it emerges to the surface.



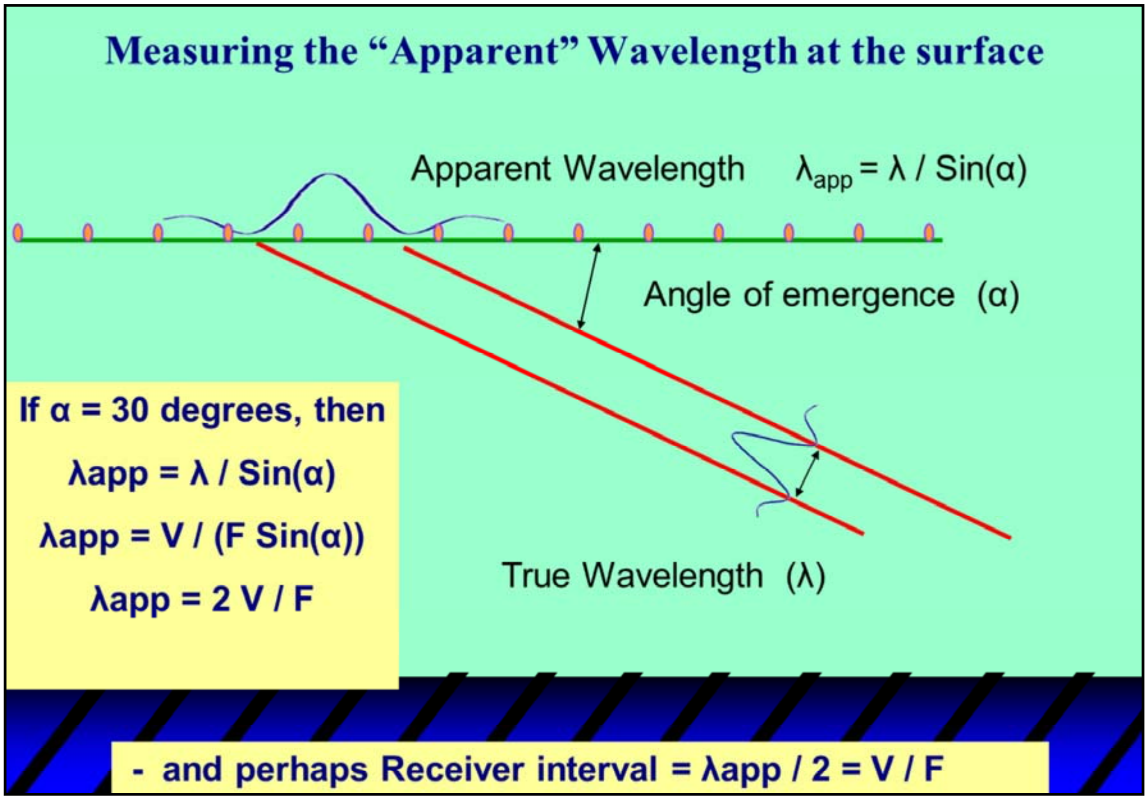
Although much of the wavefield forms curved wave-fronts where they emerge to the surface …



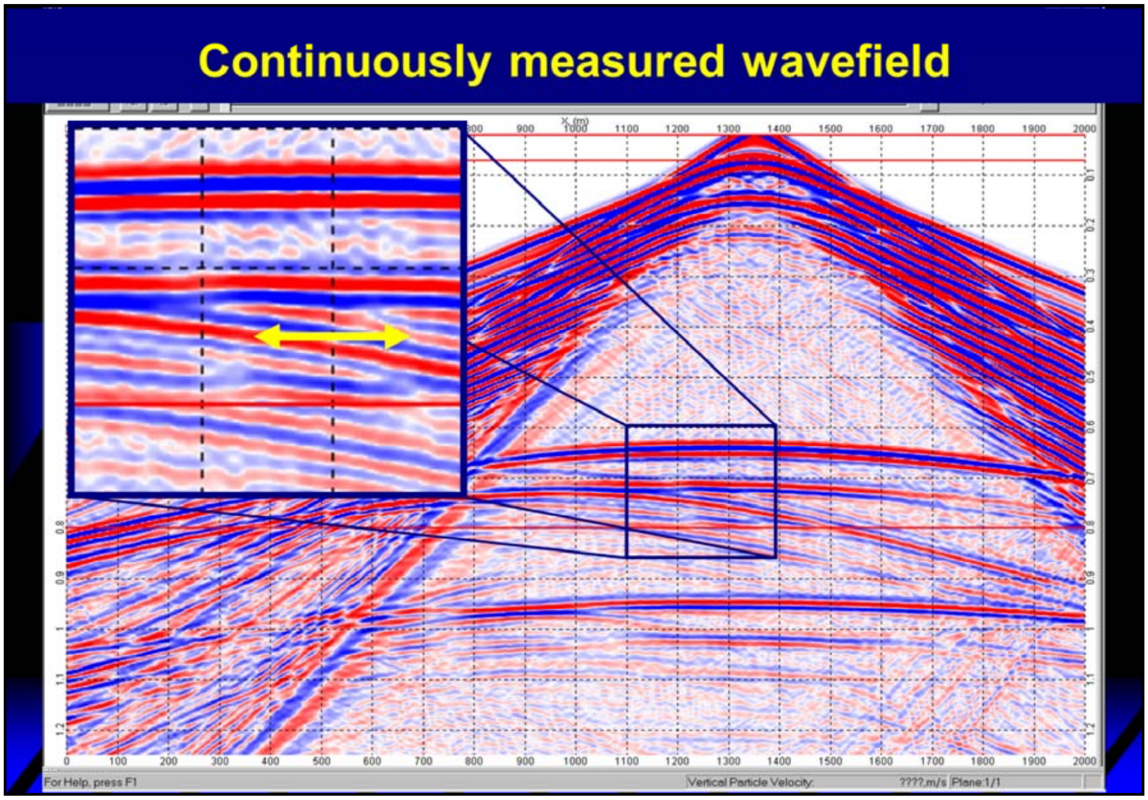
… we can approximate these as local plane-waves emerging against a flat surface.



Locally, we can characterize an emerging reflection or diffraction as a plane wave with a true wavelength = V/F emerging against a flat surface at an angle of emergence of alpha degrees. This will cause the surface of the earth to oscillate as a spatial wave with an apparent wavelength of V / (F sin a)

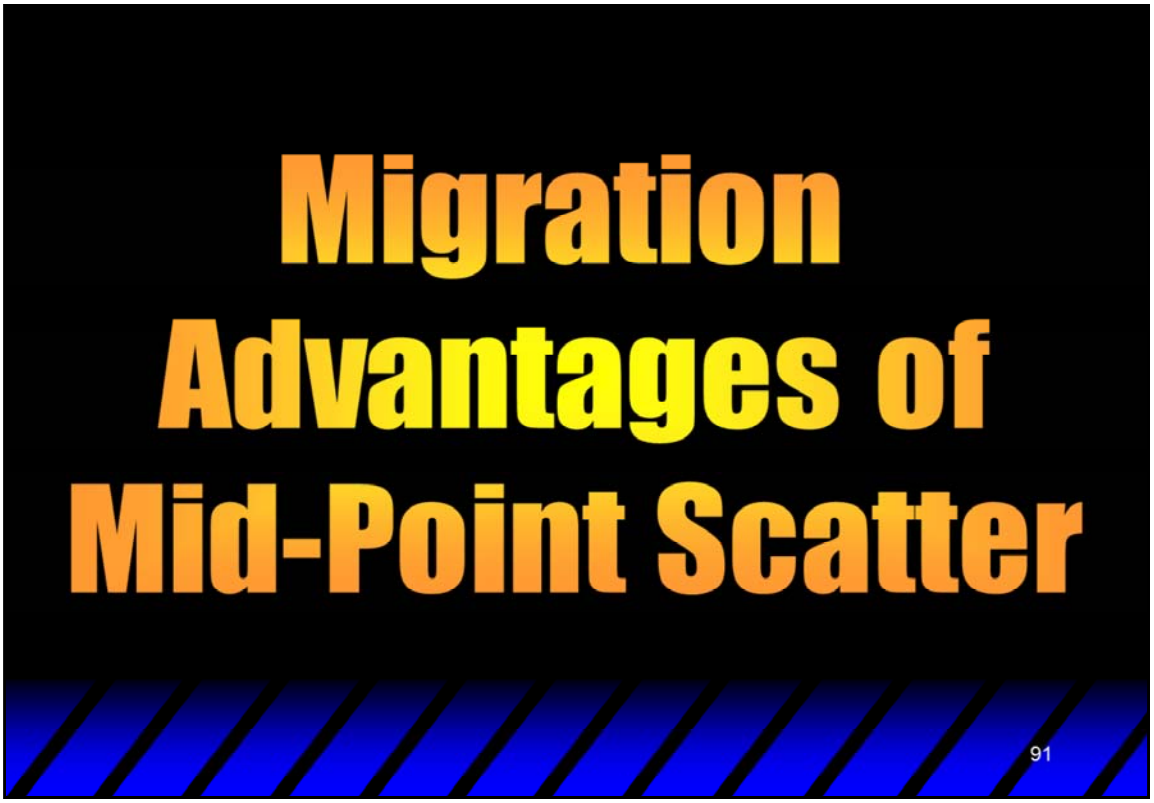


We must sample these emergent wavelengths with recorded traces observed along the surface at a spatial sample interval that is less than a half of the apparent wavelength.

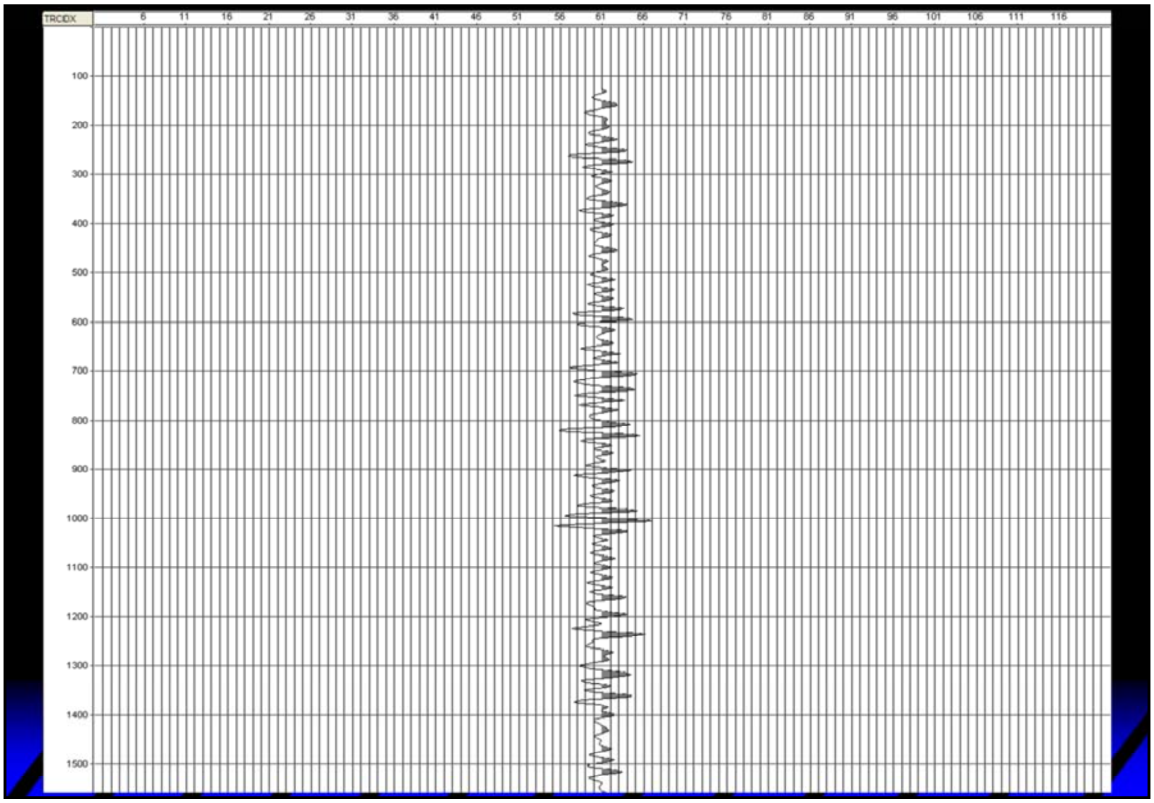


These apparent wavelengths are easily measured on an X-T record as the horizontal separation between any two adjacent peaks (or troughs). We wish to select a surface source or receiver interval sufficiently small to preserve the shortest expected wavelengths of desired signals (reflections and/or diffractions).

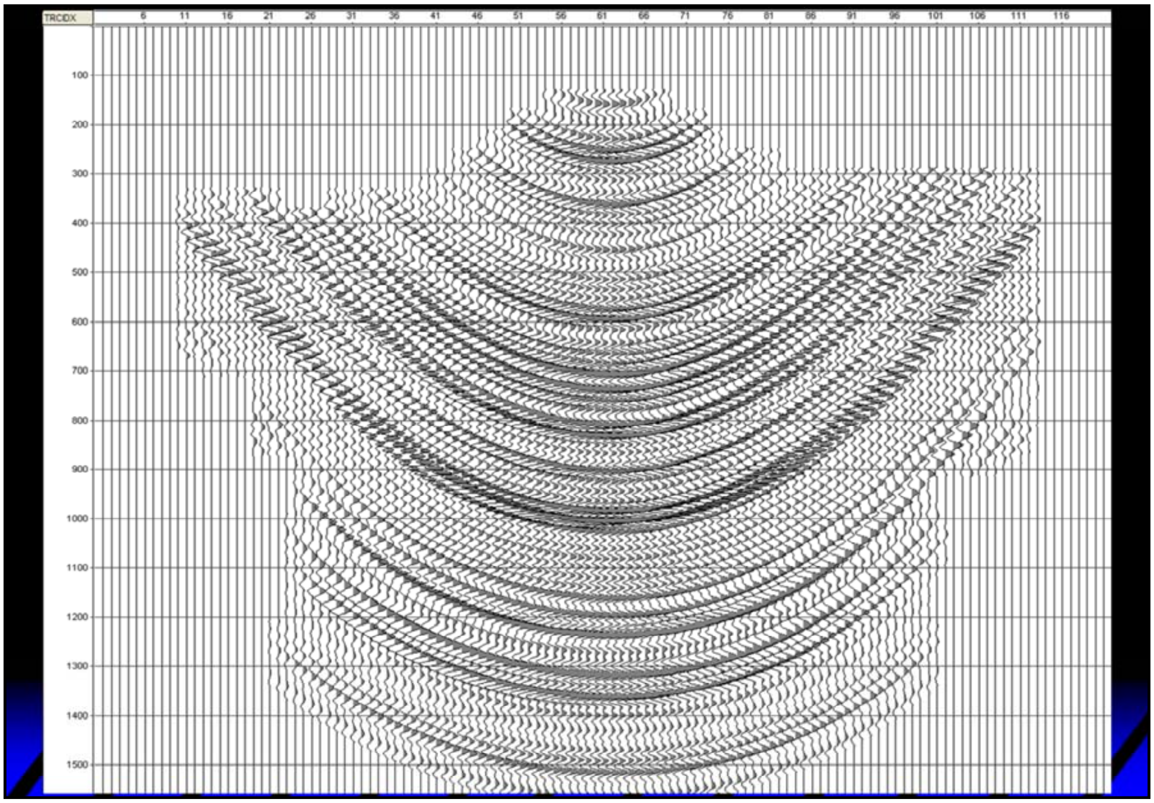
In modern design, we recognize that if we properly sample the emerging wavefield within our useable offsets, than pre-stack migration will be able to convert that image into the necessary detail we require in our final processed data volumes. If we fail to sample the wavefield correctly after each energy point, then we may compromise the pre-stack migration of the data and our results will be less than desired.



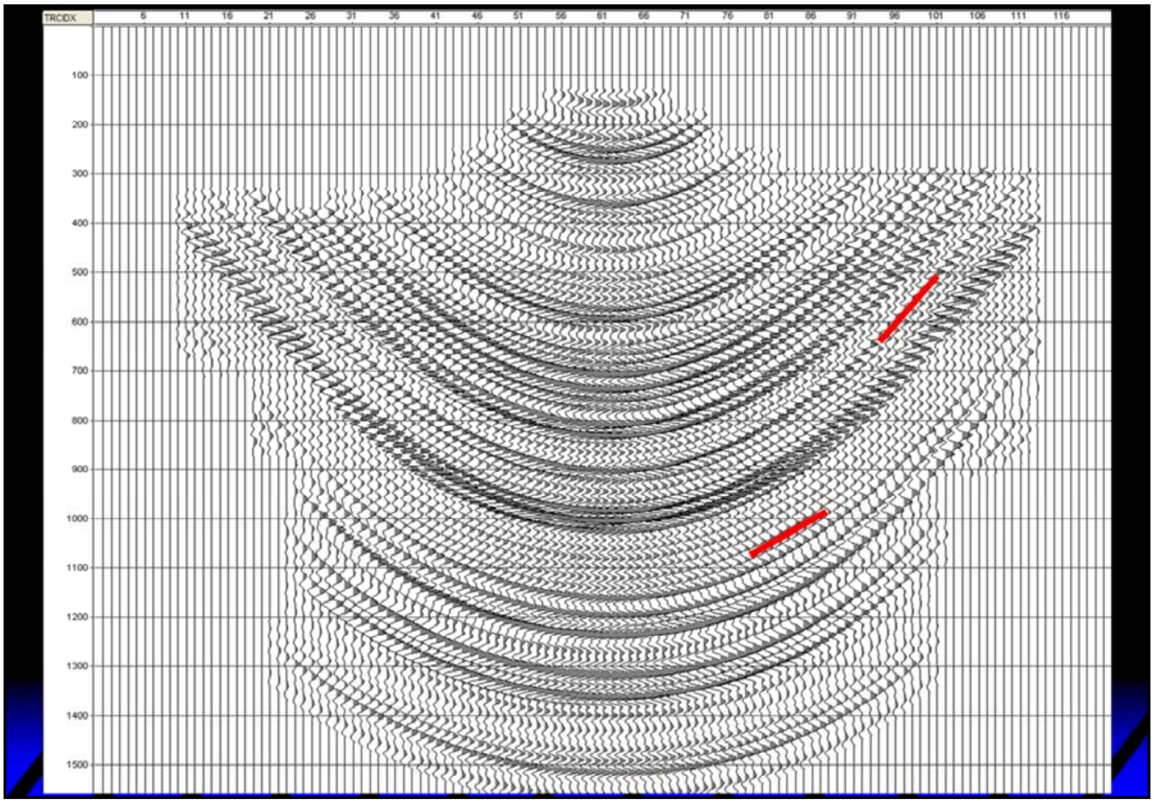
So it is evident that we must understand how migration operates on our recorded data.



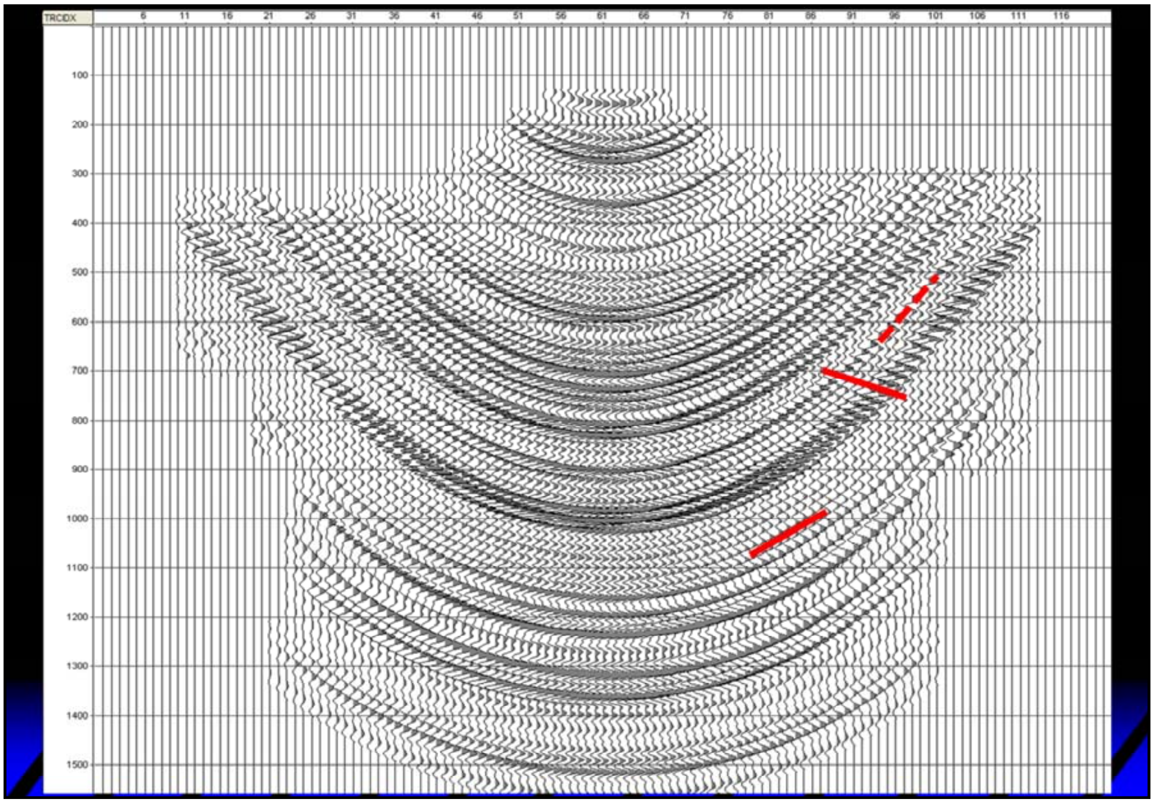
Consider a single trace of a 3-D data volume and all other traces in the volume are dead. If we migrate this volume we will produce a migration "swing operator" or "migration impulse response" for a single trace. This is shown in the next slide.



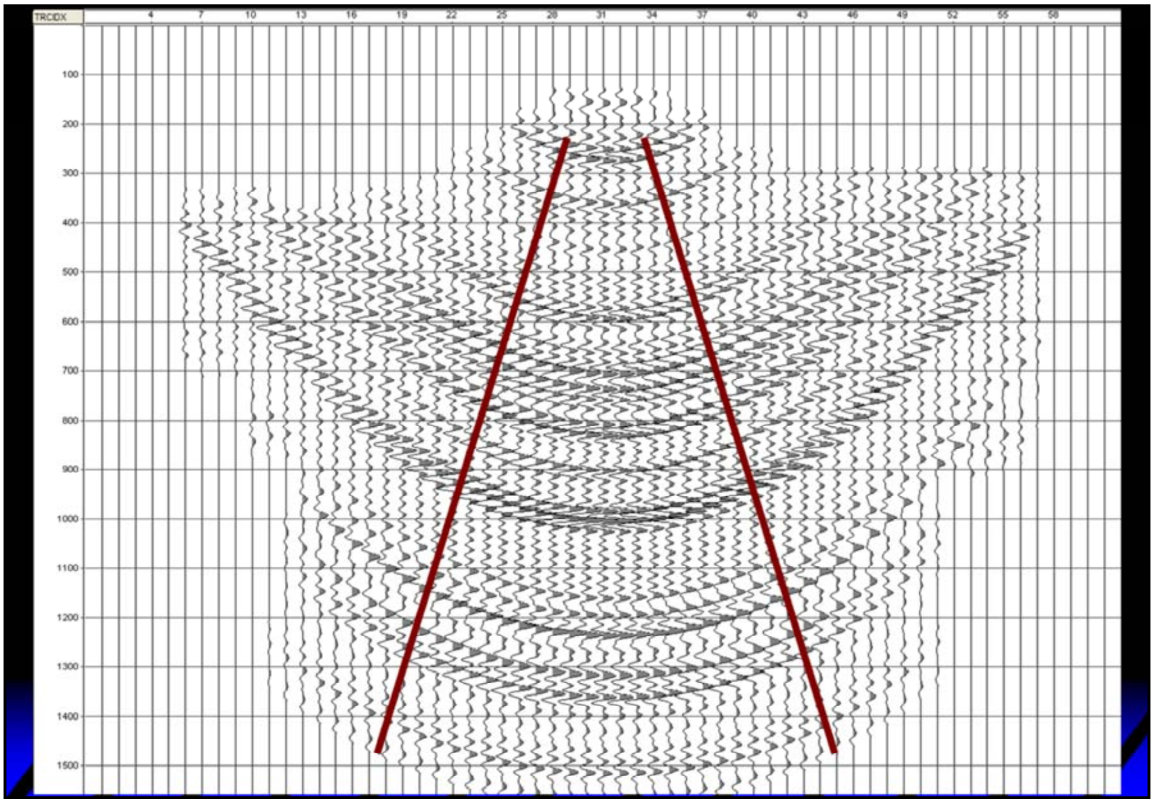
Normally, anti-aliasing of the operator would suppress the far-offset upper limbs (the “arms” of this “paper doll” shape). It is not wise to allow the migration to spatially alias data at slow apparent velocities and high frequencies (ie at apparent wavelengths small compared to the trace sampling). For post-stack migration, the trace spacing is the stacked trace interval (normally the natural bins). This is also true for Pre-Stack migration of data with focused mid-points. However, mid-point scatter via the triple stagger method yields traces with greater diversity of geographic indexes (ie smaller delta-x and delta-y). Therefore, by decreasing delta-x, each migration operator is better sampled in space, and this allows for migration of steeper dips and/or higher frequencies.



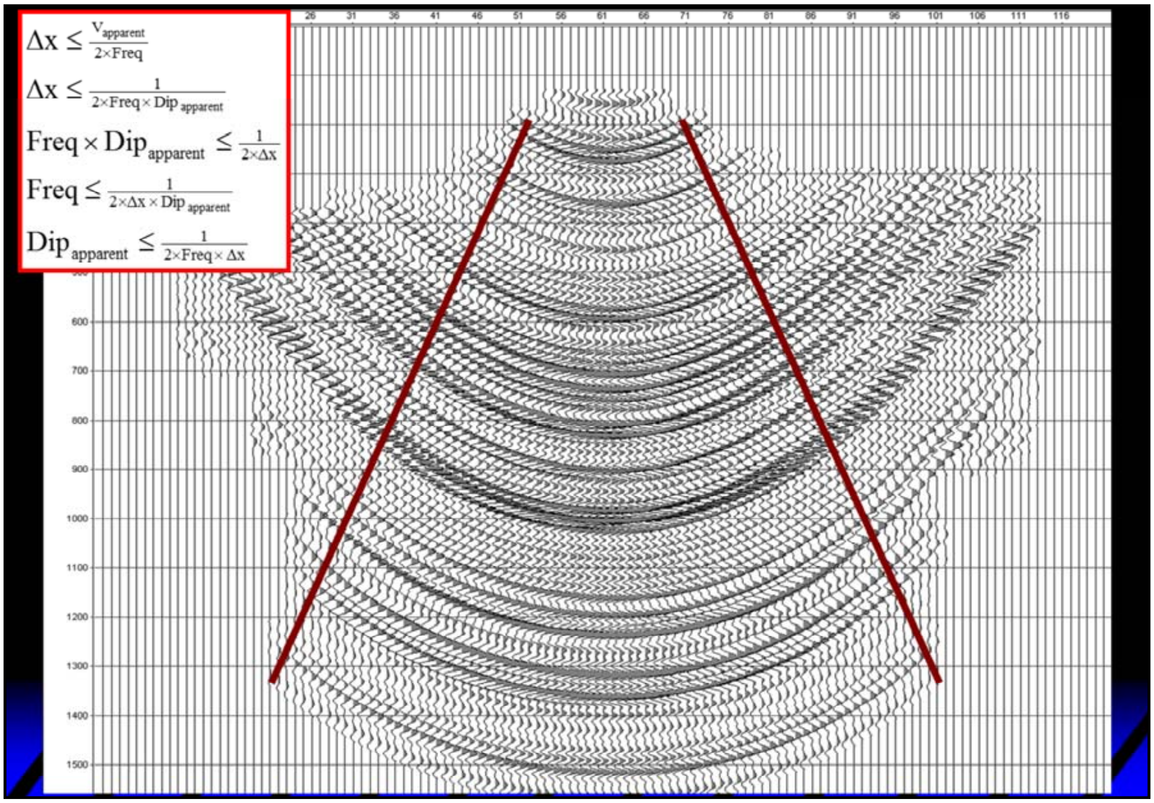
Here we have hi-lited two apparent dips within the operator …



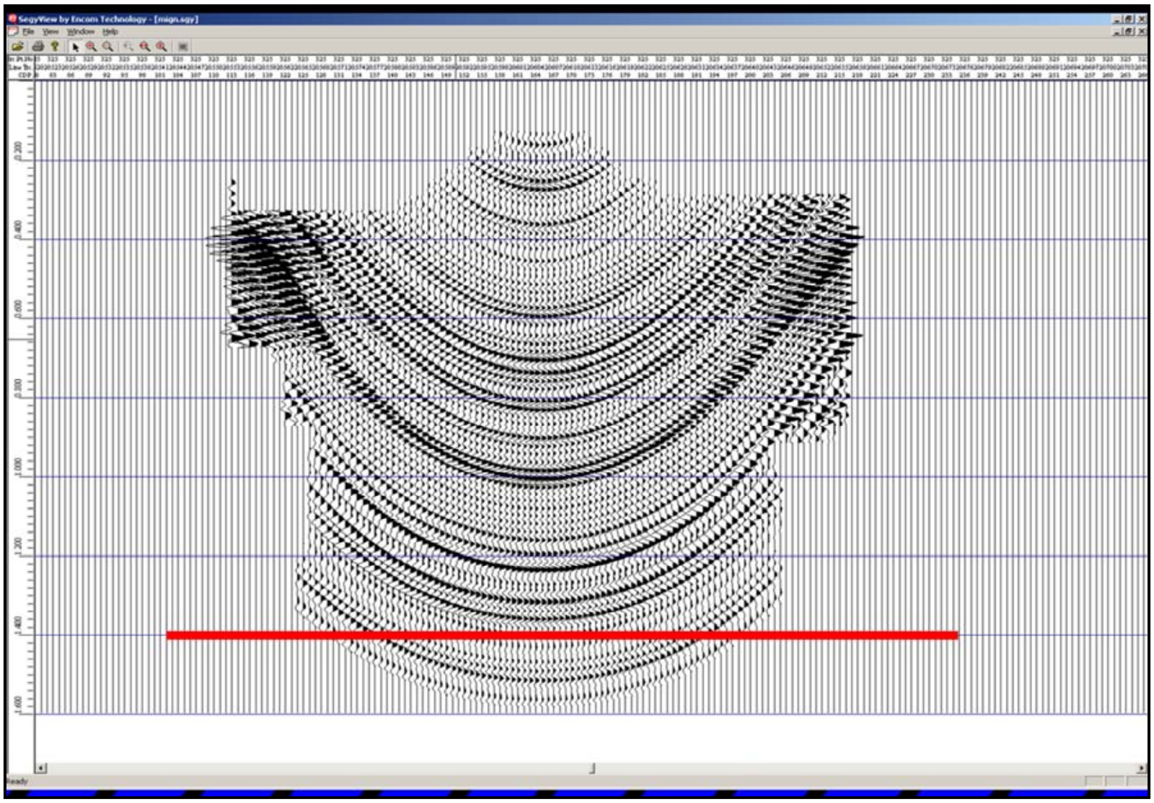
… and here we also show an aliased dip. If the migration operator is allowed to extend into the aliased range with full bandwidth, then we are vulnerable to migration artifacts that sum constructively along the aliased dips. Aliased migration operators have the potential to create artificial reflections.



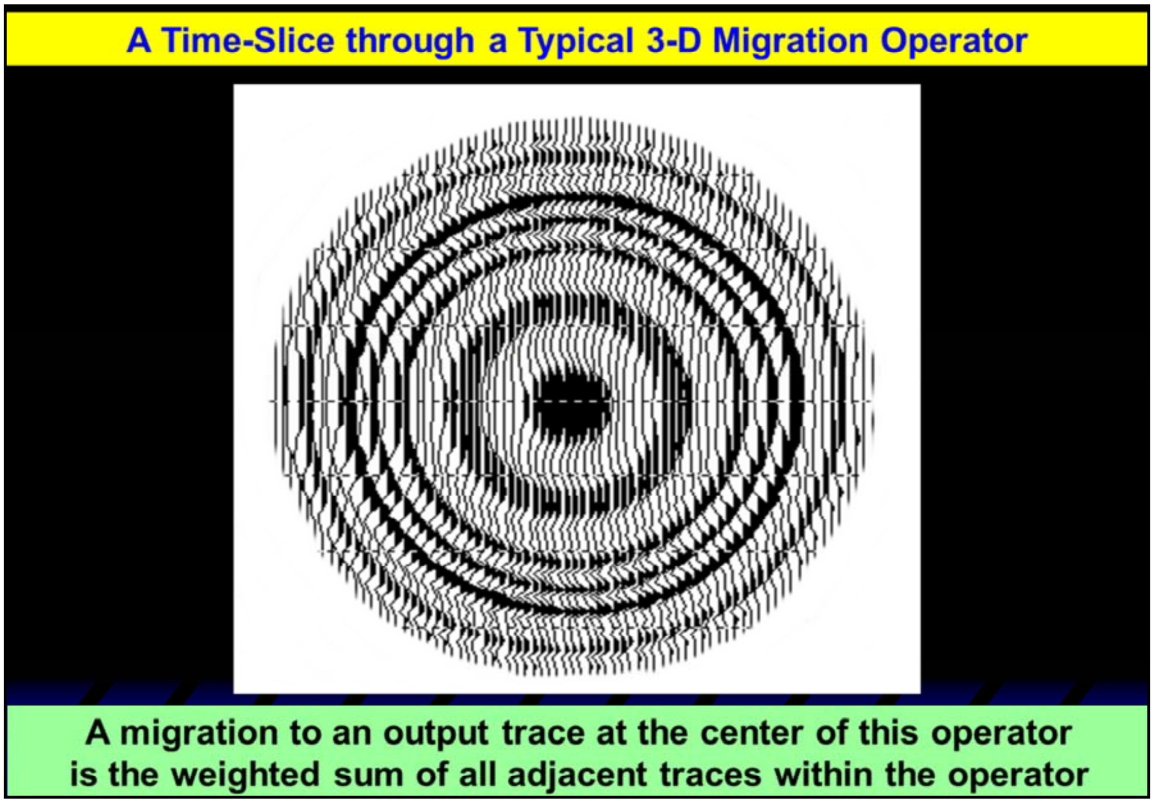
Here is the full operator, sparsely sampled, showing an approximate Anti-Alias limiting function (brown lines).



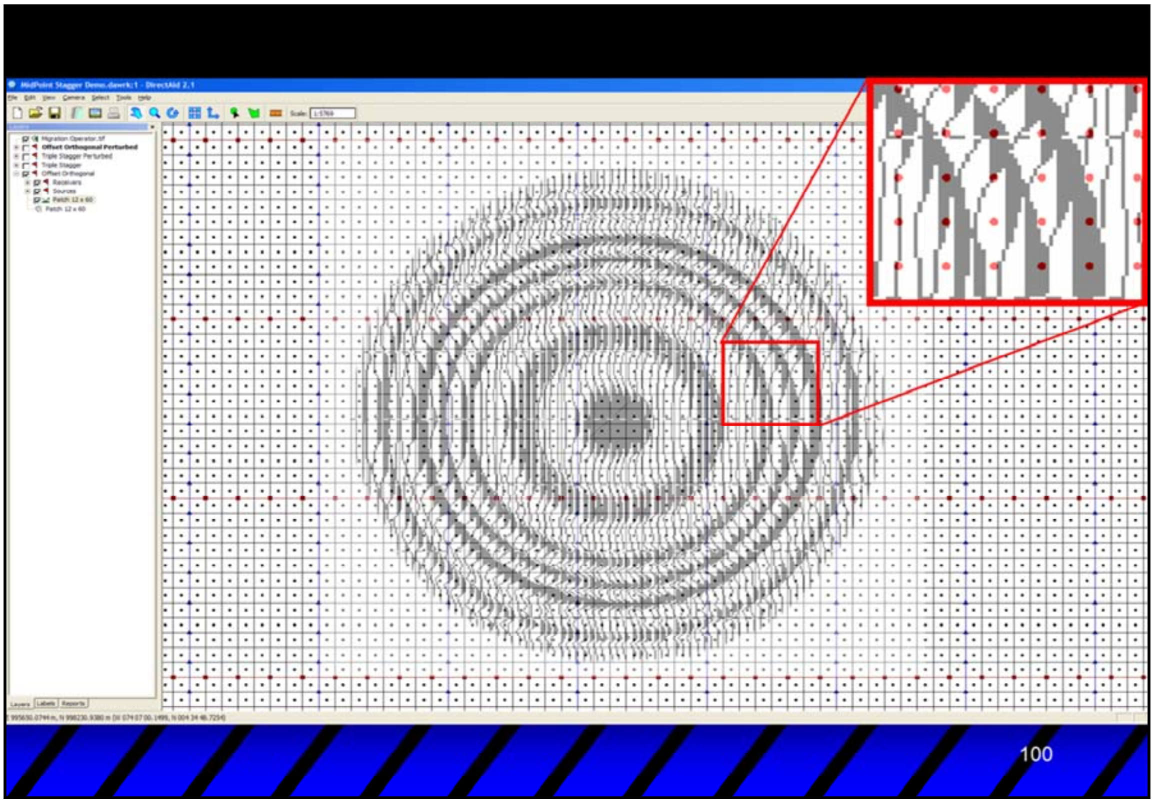
Here is the same operator, but sampled with a smaller trace spacing. Notice how the anti alias limit embraces higher frequencies migrated to stronger dips.
The Nyquist equation for apparent wavelengths demonstrates the same concepts mathematically.



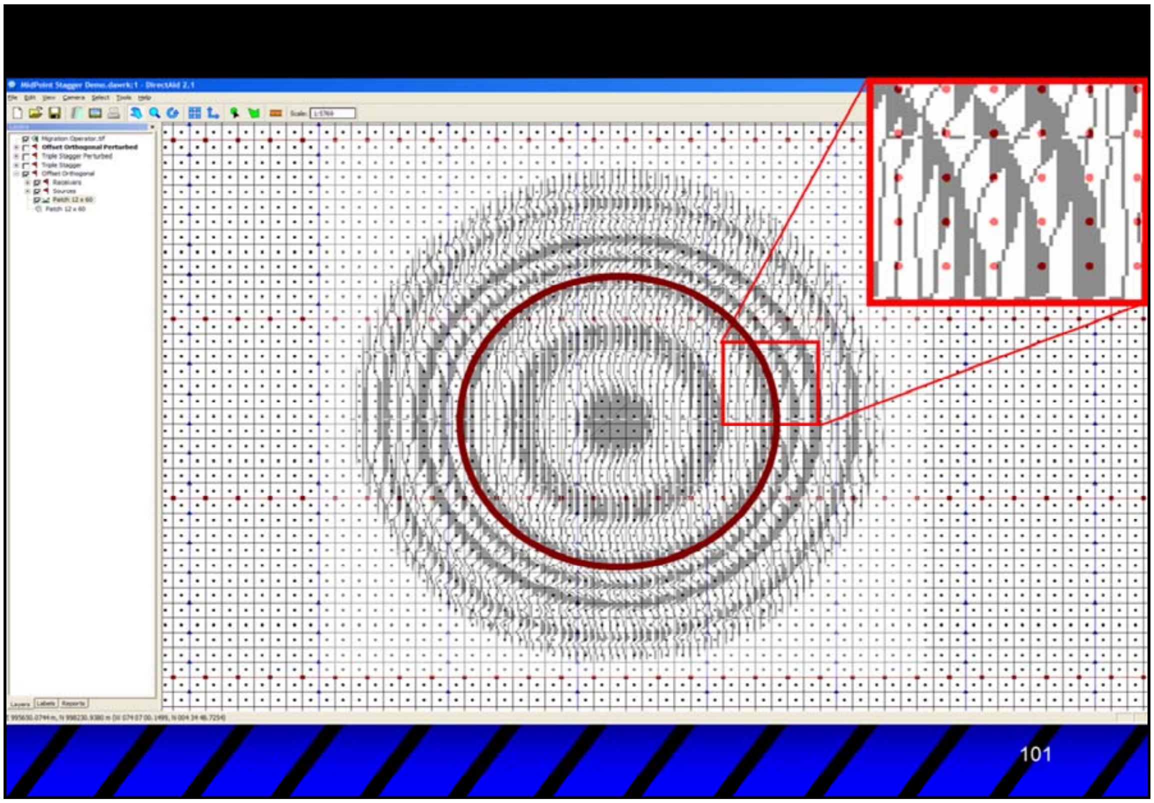
Now imagine a time slice of a full 3D operator. The full time slice might look like the following diagram.



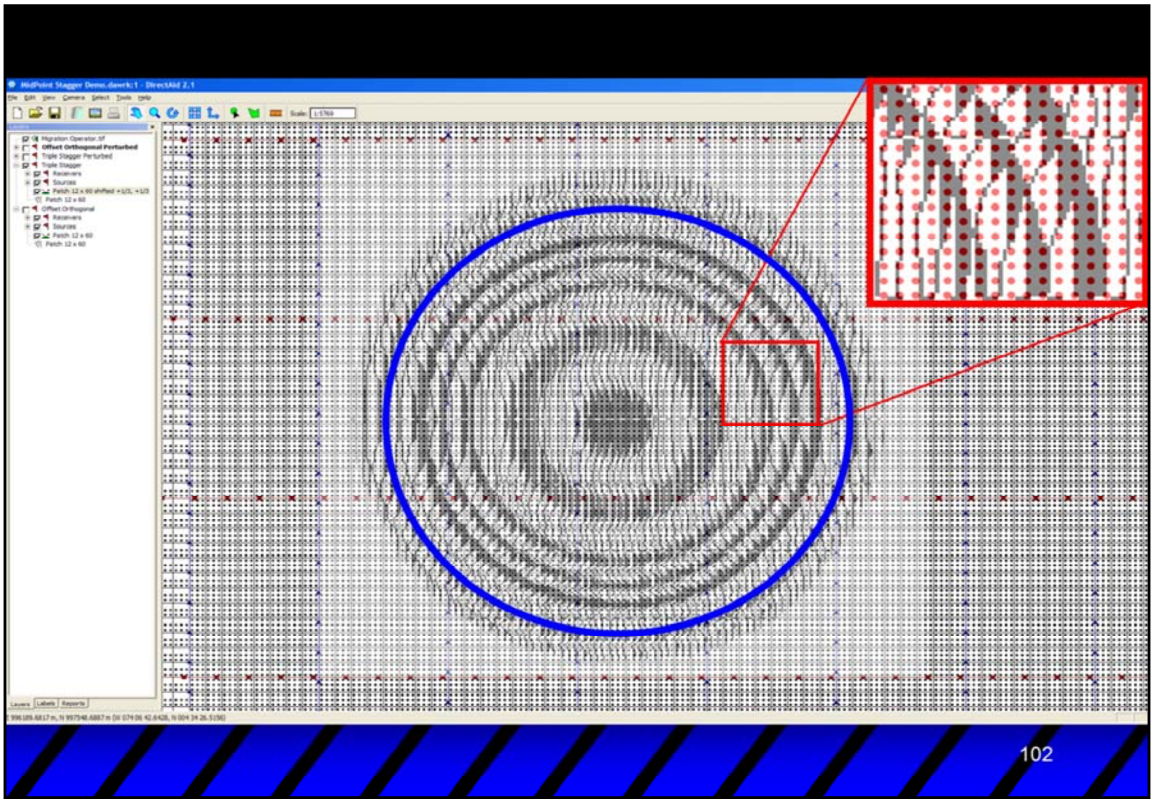
Appreciate that migration can be regarded as the weighted sum of all points within a "Migration Operator" The weighting function has a spatial wavelength related to the bandwidth of the data and the apparent dips.



This migration operator has an aperture (radius) of about 480 meters, corresponding to a very shallow reflector. The model is a normal orthogonal with no forced midpoint scatter. Note that we have traces represented by mid-point indexes separated by the natural bin size. Notice that some of the shorter apparent wavelengths (resulting from migration of higher frequencies) are sampled by less than two traces per wavelength. This represents an aliased part of the operator and its full bandwidth will not be included in the migration.

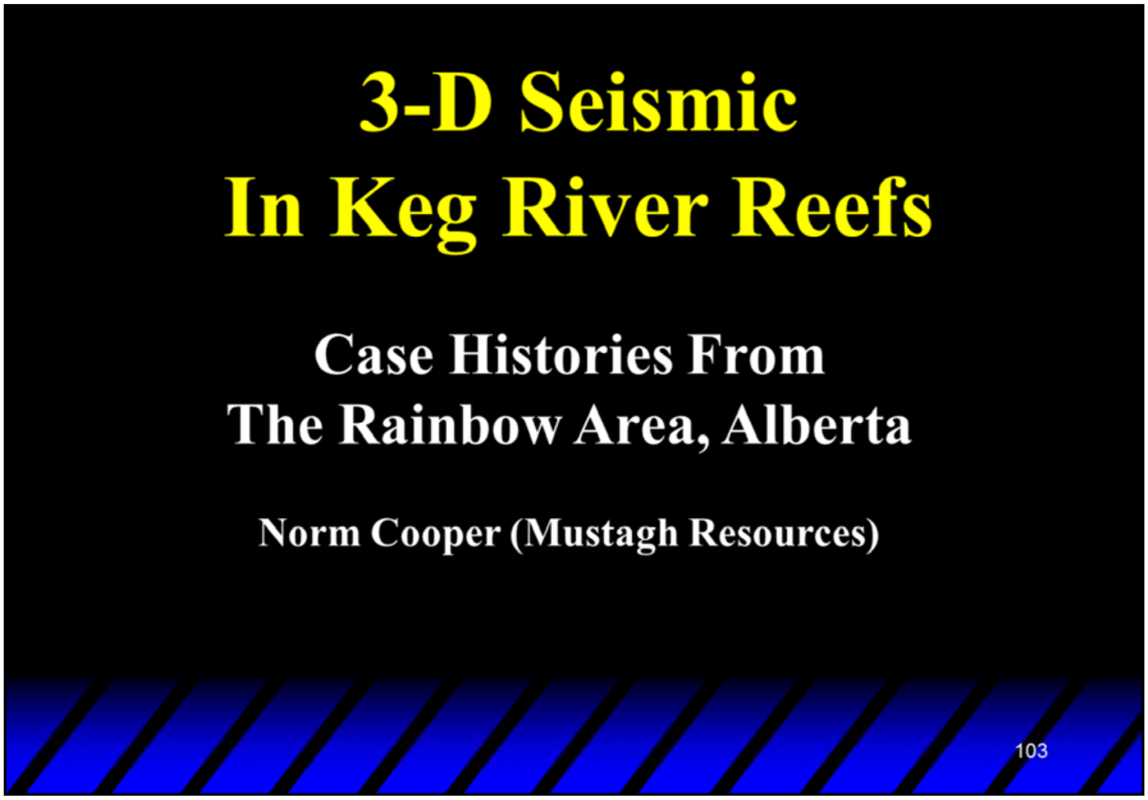


The brown circle indicates the approximate limit of the operator before aliasing occurs. We can, in fact include portions of the operator beyond this limit, but high frequencies must be eliminated to increase spatial wavelengths and eliminate aliasing. The brown circle is the limit for full bandwidth migration.

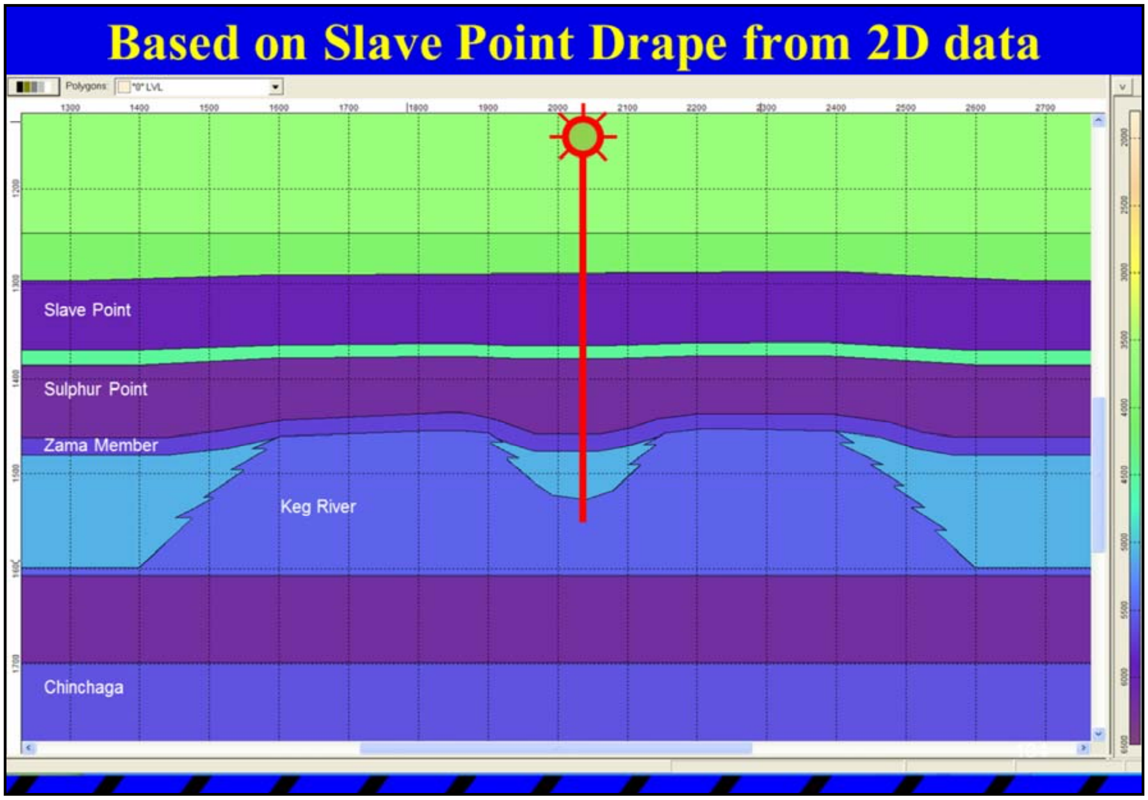


This model is a tiple-staggered orthogonal with a 3x3 forced midpoint scatter. This provides the opportunity for sub-binning at the time of pre-stack migration and therefore better spatial sampling of the migration operator. Notice the improved sampling of peaks and troughs such that there is always more than two samples per wavelength. Higher frequencies and steeper dips will be preserved.

The effective size of the full bandwidth migration operator becomes larger (perhaps the blue circle) and the migration becomes more powerful for focusing signal and attenuating noise.

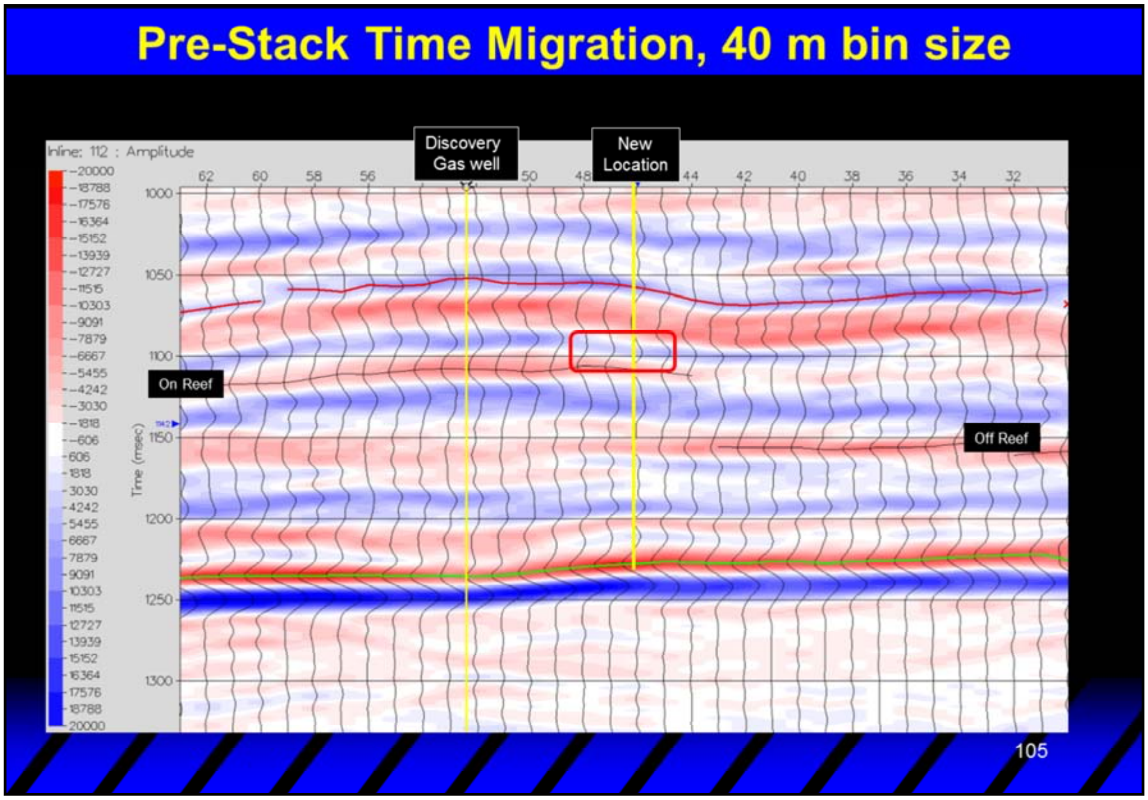


Let's review a case history that demonstrates the advantage of pre-stack migration to smaller than natural bins.

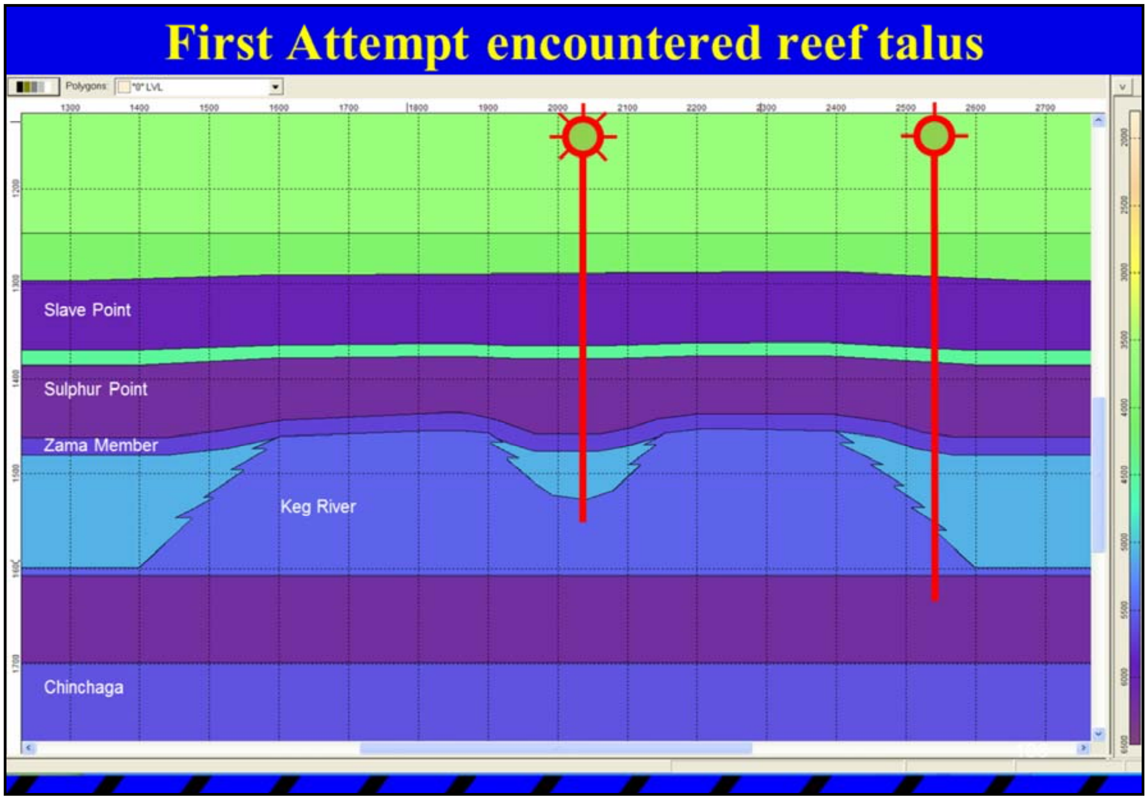


This is a mid-Devonian reef prospect from Northwestern Alberta. The target depth is about 2300 meters. The Slave Point formation is a regional carbonate overlain mostly by Devonian shales. The Keg River interval is known to have pinnacle reefs building on a carbonate platform. These reefs are encased in a limy-shaley off-reef facies. Differential compaction results in Slave Point drape over reef buildups. On older data, the reefs are not directly visible, but reasonable success was obtained by drilling mappable highs on the Slave Point, suggesting drape over an underlying reef. Based on older 2D data, an Calgary-based company drilled a well at the crest of a drape feature and encountered a nearly full build up of Keg River reef. However, it appeared that the well encountered back-reef or lagoonal facies that had acceptable but not outstanding porosity and permeability. It was concluded that over a 20-25 year life, the gas well would produce most of the gas available in the reef.

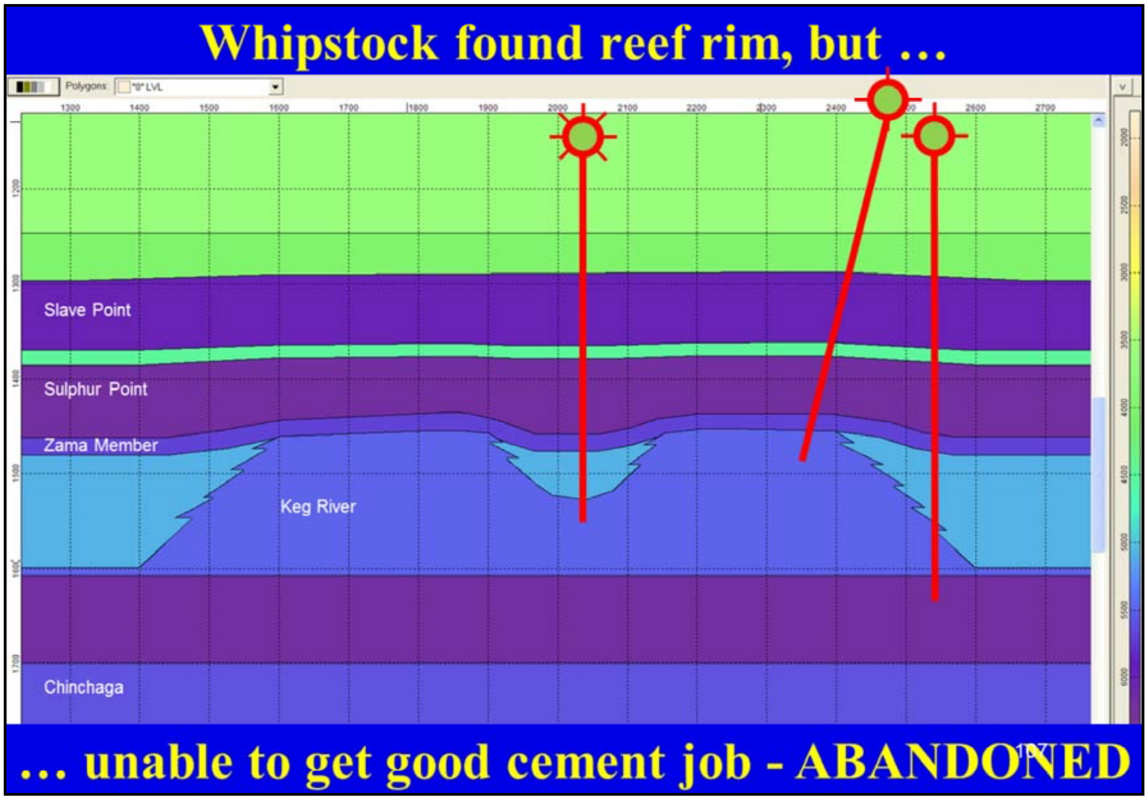
However, the government adopted this area as a new park to protect a unique micro-environment and the oil company was told they would have to vacate their lease within 5 years. The decision was made to seek out the reef rim where a well should encounter enhanced porosity and permeability and where such a well may be able to recover most of the reef's gas reserves in that shortened time frame.



Ian Gordon designed a 3D program to detail the prospect. His design included intentional mid-point scatter. Before completion of the project, he was transferred to a different area of responsibility and another geophysicist took over the completion of processing and interpretation. His interpretation indicated the presence of a possible reef rim as indicated in the red rectangle above and a well location was proposed at the right-most yellow line.

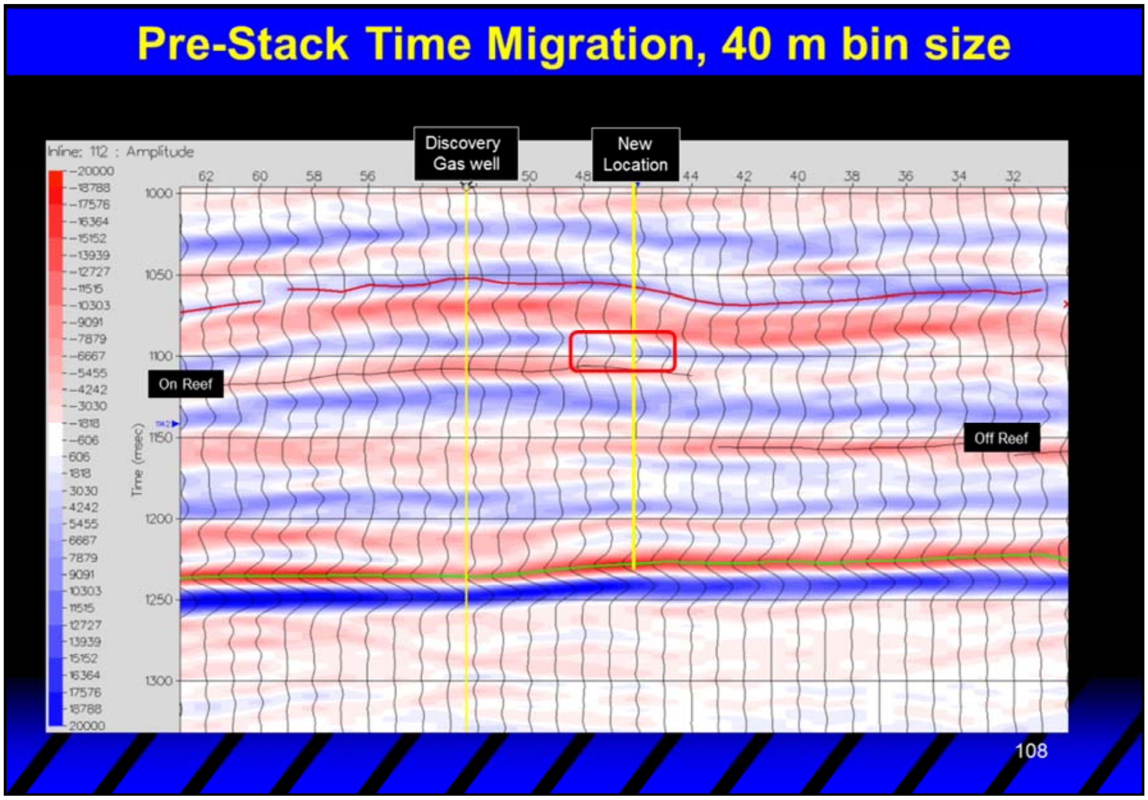


The well found reef talus at a level not far above the reef platform. Geologists concluded that the well just missed the front of the reef and proposed to deviate the well from a point up-hole.

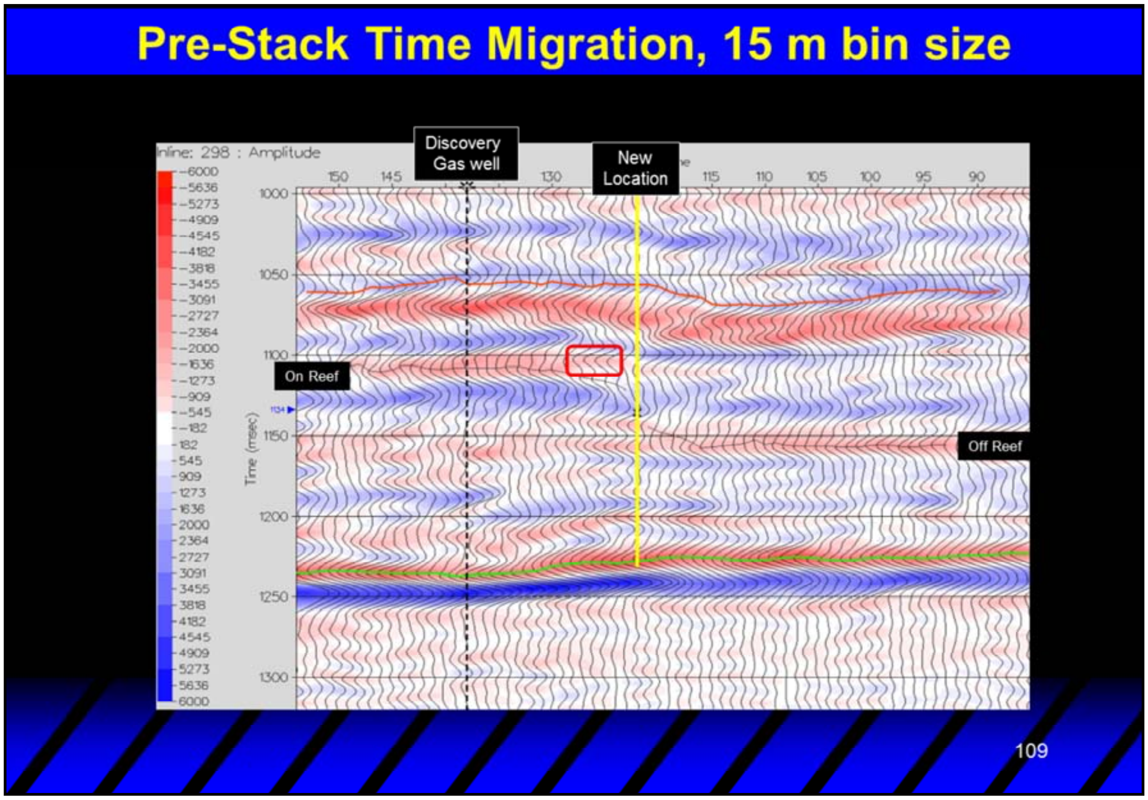


The deviated well segment encountered a full reef rim with excellent reservoir characteristics. However, in order to complete the well, regulations required a good cement job behind casing before the well could be perforated and completed. Unfortunately, due to the reservoir characteristics (and partly due to the attitude of the well bore), a good cement job could not be obtained and the well bore was abandoned.

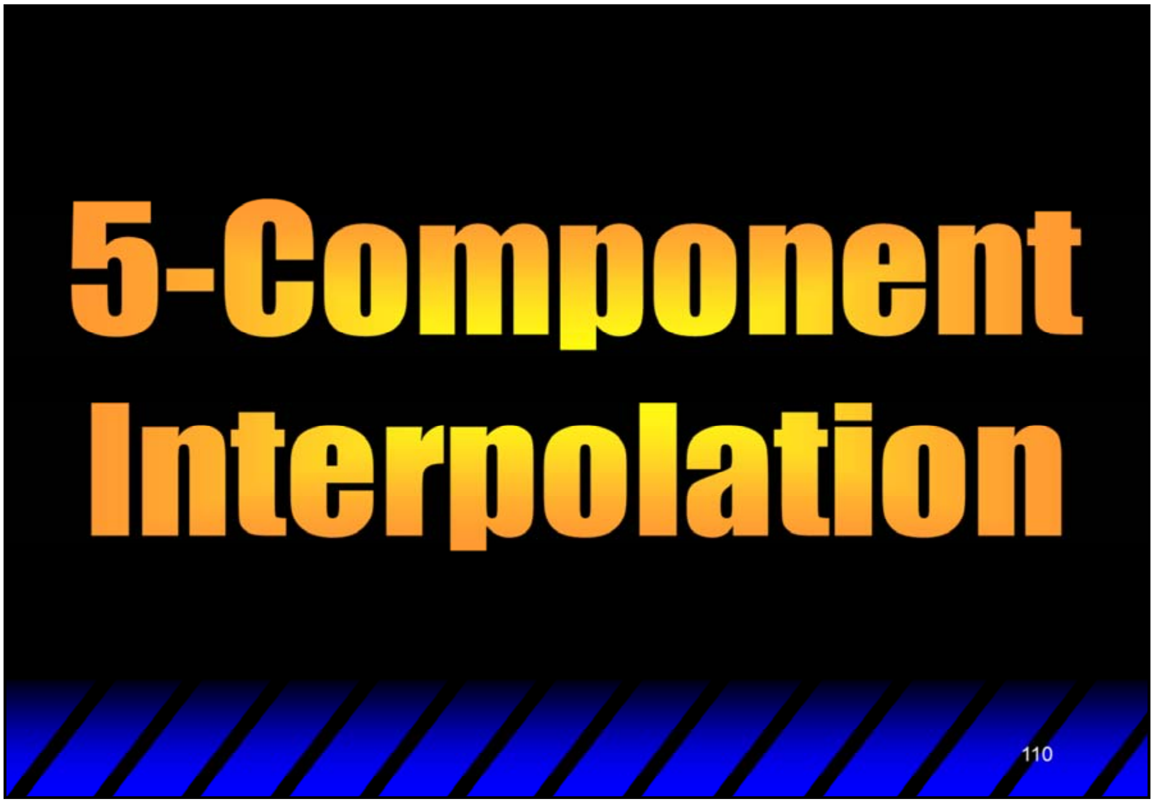
Subsequent economic analysis indicated that a new well into the known reef rim, with the associated completion risk, was not justified given the remaining time allowed to extract reserves. The original well produced a moderate amount of gas for 5 years and then the project had to be abandoned.



The original geophysicist for the project, hearing about the project failure, asked to be involved in the post mortum so he could learn what aspects of the 3D design contributed to the failure. When he first saw the final migrated and interpreted data, he was surprised to learn that the data had been migrated only to natural bin sizes. The second geophysicist on the project was not aware that there were other options. Ian called for more processing tests to see if the data volume would benefit from prestack migration to smaller output bins.

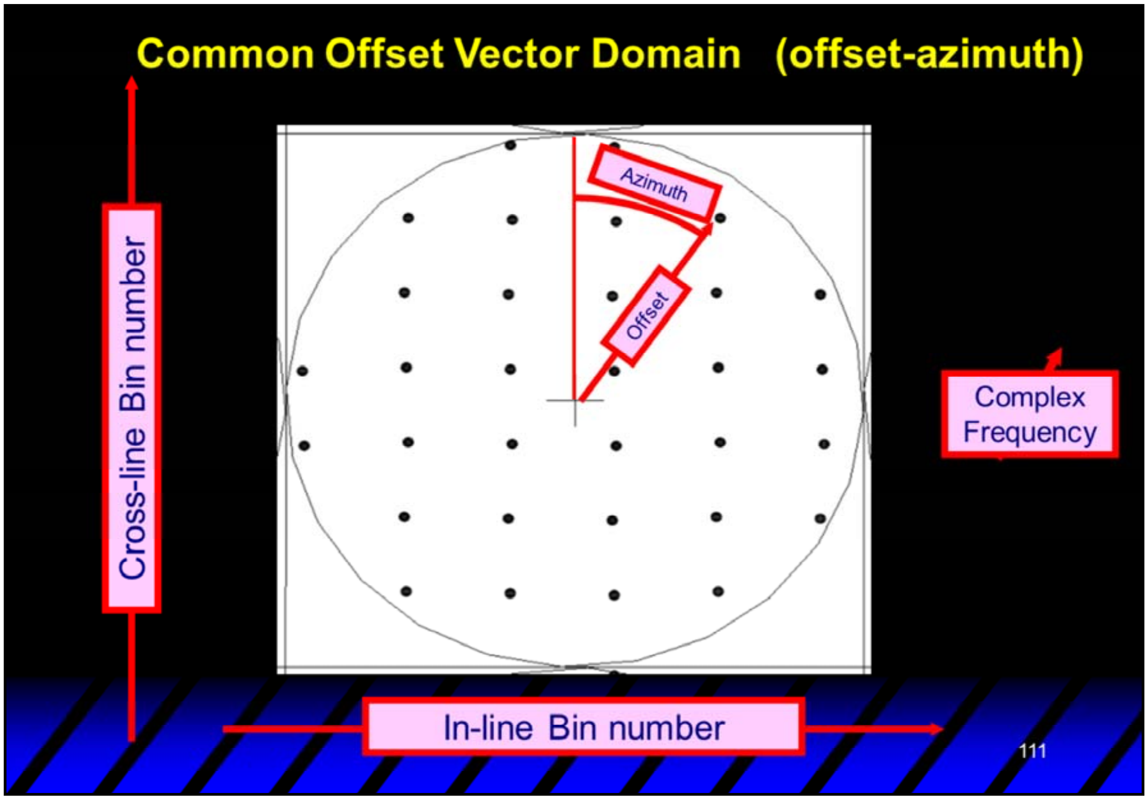


This is the same data except migrated to 15-meter output intervals. Note in increase in migrated frequency content and the improved spatial resolution. The four troughs hi-lited in the red rectangle are a clear indicator of the porous reef rim. If this image had been produced as part of the interpretation, it is most likely that the development well would NOT have been located in front of the reef. The well location would have been selected to coincide with the interpreted reef rim (which we no know to be the true location of the rim). The well would have entered the reservoir vertically and on prognosis. It is very likely that the completion would have been successful and this would have been a much happier story.

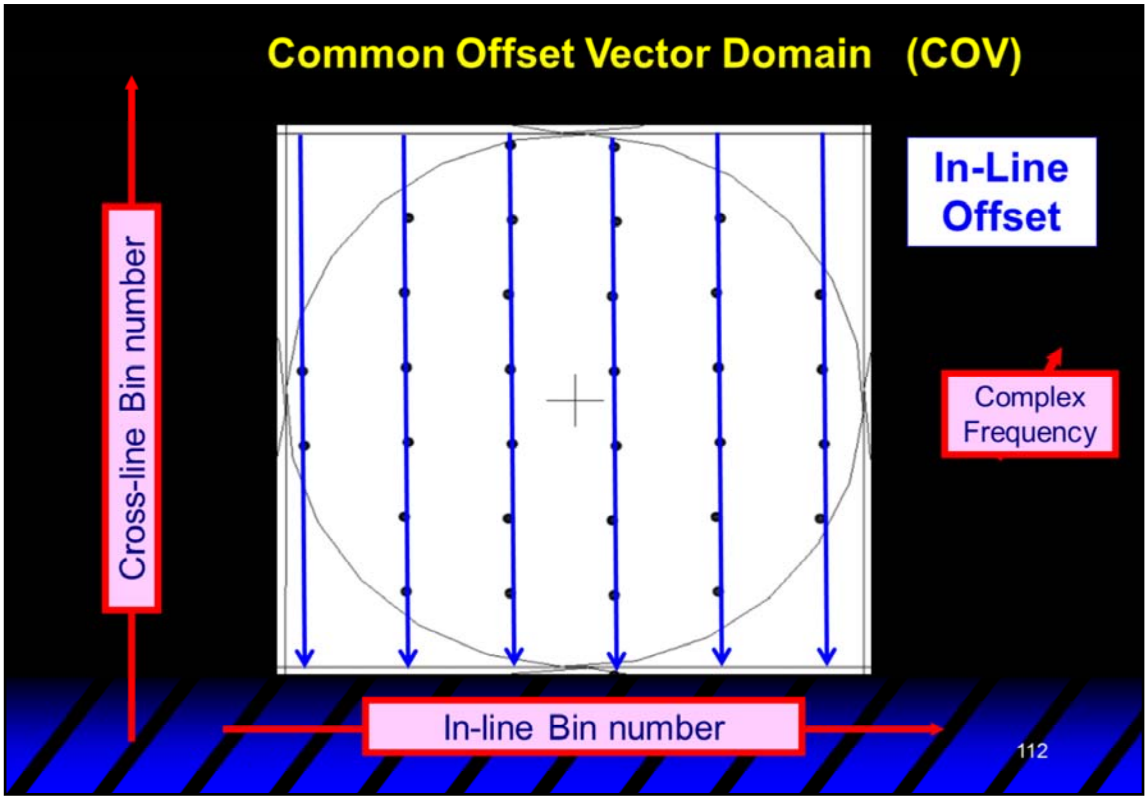


We have progressed from designing survey parameters in order to create a good final stack and post-stack migration. We now focus our design methods on parameters that deliver characteristics most required by a pre-stack migration operator. If we do this, then the migration process can be used to produce a clear and accurate image. This requires design for mid-point scatter as well as proper sampling of the wavefield in the source domain, receiver domain and CDP domain. It requires the recognition and evaluation of type and extent of local noise factors.

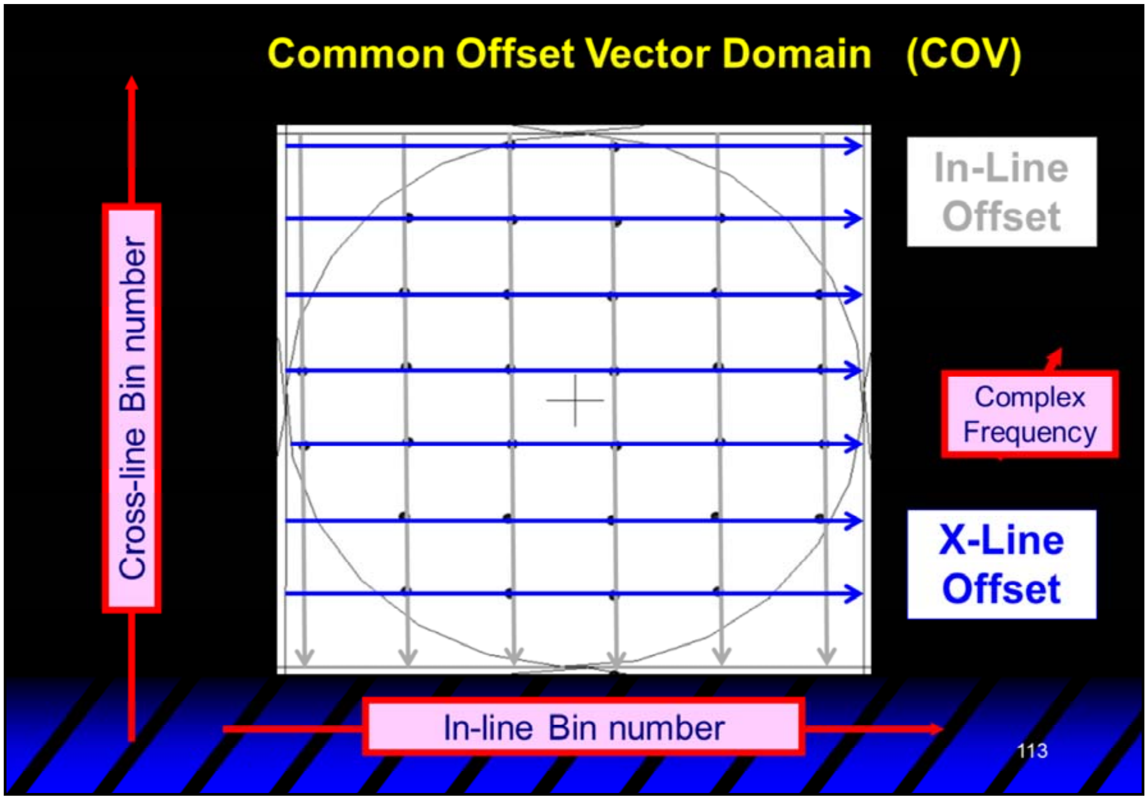
The current evolution of 3D Design lies in data reconstruction techniques that allow "interpolation" of certain statistics that may be missing in conventional data volumes.



The popular phrase today is 5-component interpolation. To understand the 5 components, consider one bin of a 3-D volume with pre-stack traces as per this display. Remember that the plot represents the offset and azimuth of each contributing trace presented in a polar plot. For the popular Cadzow filters, each trace is transformed into the complex frequency domain. Then the data volume can be reconstructed with improved sampling by applying interpolation that considers adjacent traces across the in-line bin direction, the cross-line bin direction, the azimuth domain and the offset domain. The fifth dimension is up and down to adjacent complex frequency values.

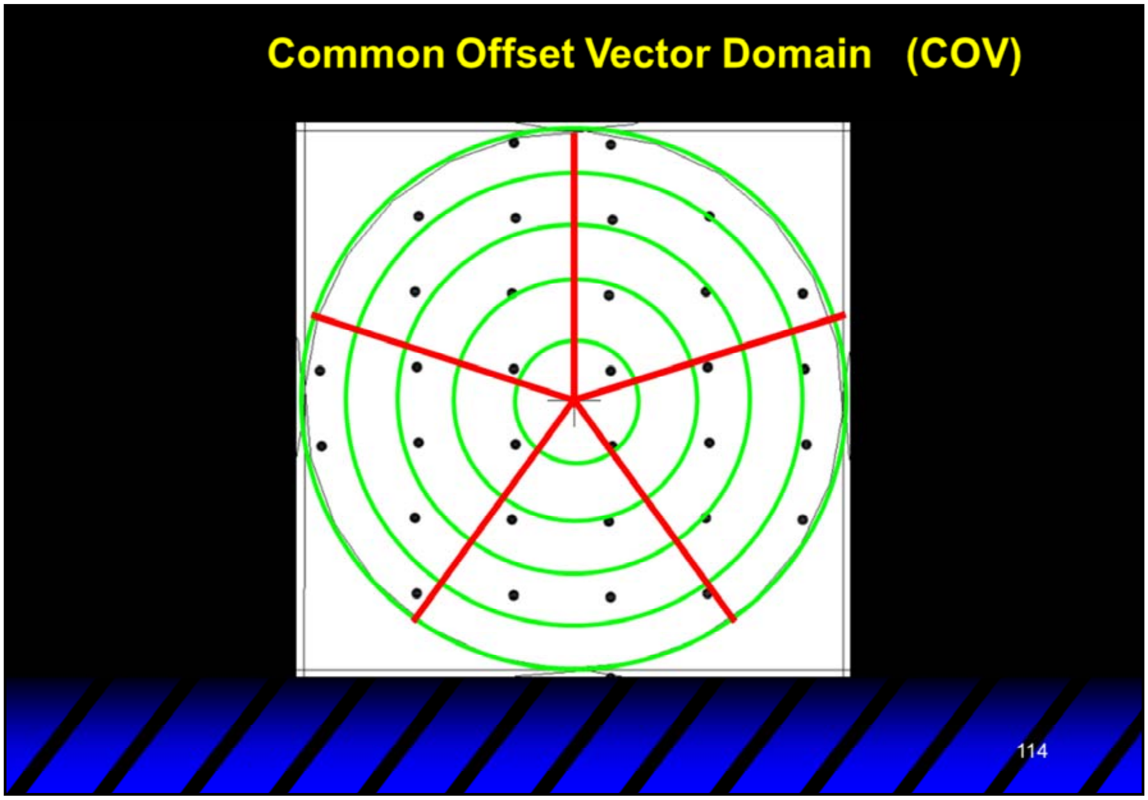


Variations on this method use In-line offset and Cross-line offset in lieu of offset and azimuth for two of the components. This slide demonstrates the concept of the in-line offset function (the weighted sum of polar contributions in this direction) …

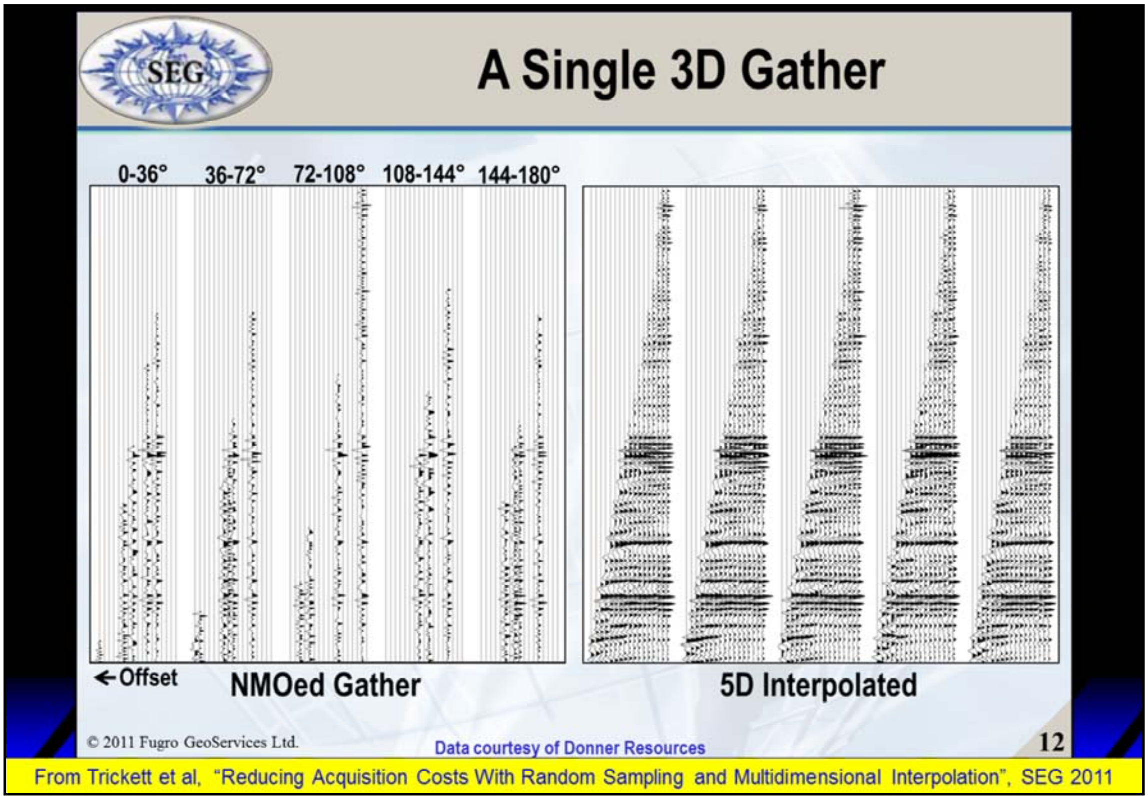


… and this slide demonstrates the cross-line offset function.

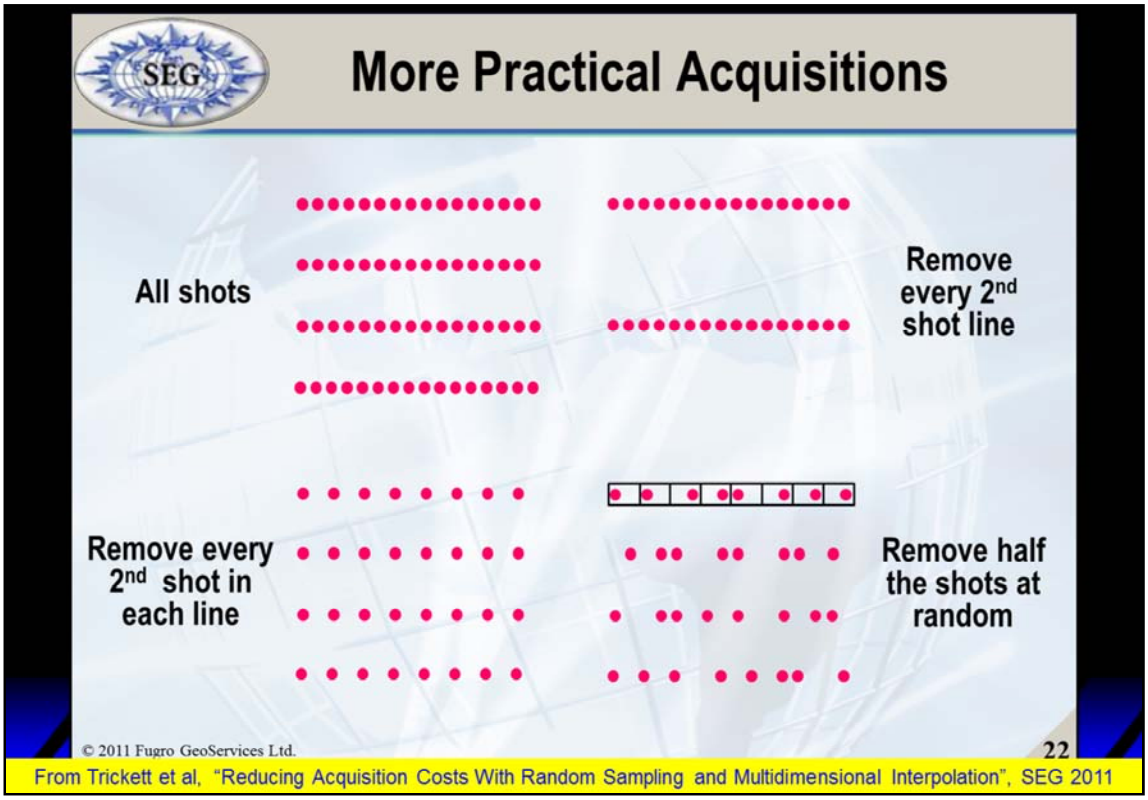
Stewart Trickett and others have demonstrated that an interpolation that includes only one or two domains is weak and unstable. However, the full interpolation using all domains simultaneously provides a very robust data reconstruction.



It is becoming more common to work with pre-stack migrated gathers in both offset and azimuth (AVAZ studies). In such studies, we wish to examine trace attributes in subsets of offset and azimuths. In the above plot, we have divided a 32-fold bin into 5 azimuth ranges and each azimuth range into 5 offset ranges. Some of these cells are populated by up to three traces, but some have no traces. Such poor population of these cells makes analysis of attributes very unstable and very vulnerable to noise. Obviously, we desire much denser acquisition grids, but this would add dramatically to the cost of the surveys. Another option would be to work in "macro-bins" or "super-bins" that average over several adjacent natural bins. But then, of course, we sacrifice spatial resolution.

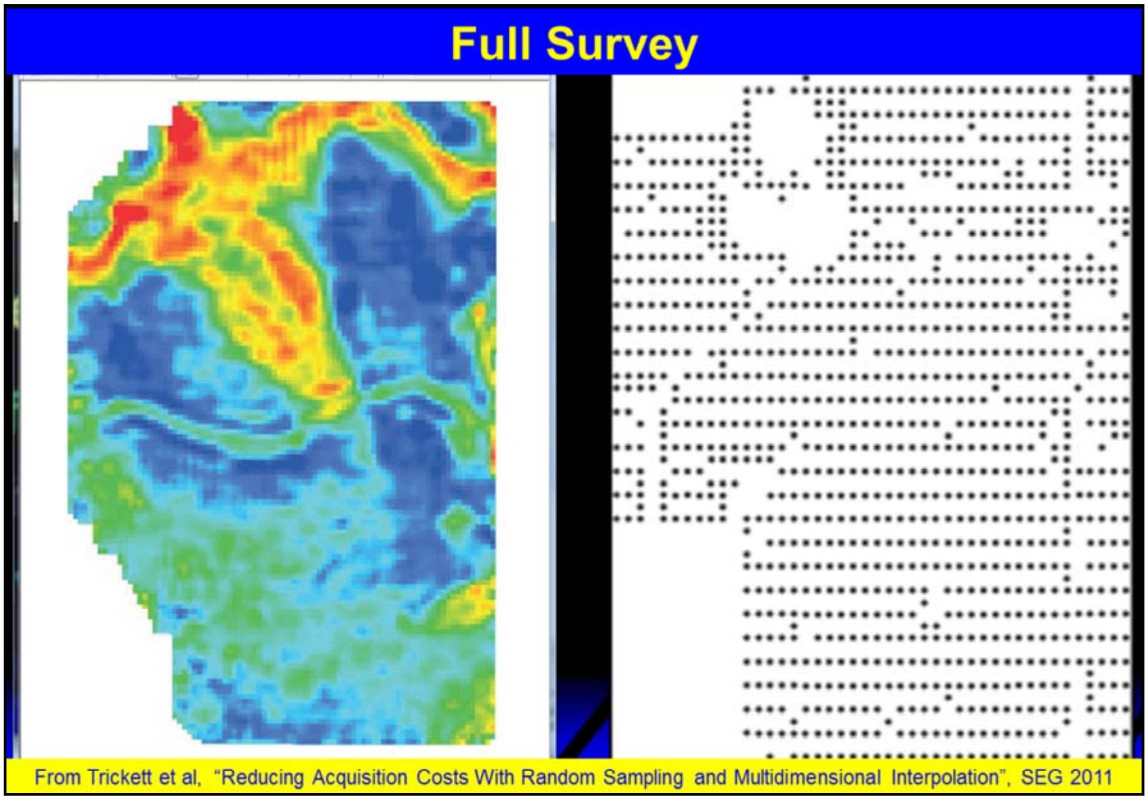


In this image taken from a recent paper by Stewart Trickett, et al, he shows the power of trace interpolation and filtering my matrix completion and rank reduction filtering using 5-component Cadzow methods. On the left are offset-sorted gathers for five azimuth ranges from a typical 3D volume. On the right is a re-constructed data volume that includes much greater population of each azimuth range. The AVO character of reflections and multiples appears to be accurately predicted.

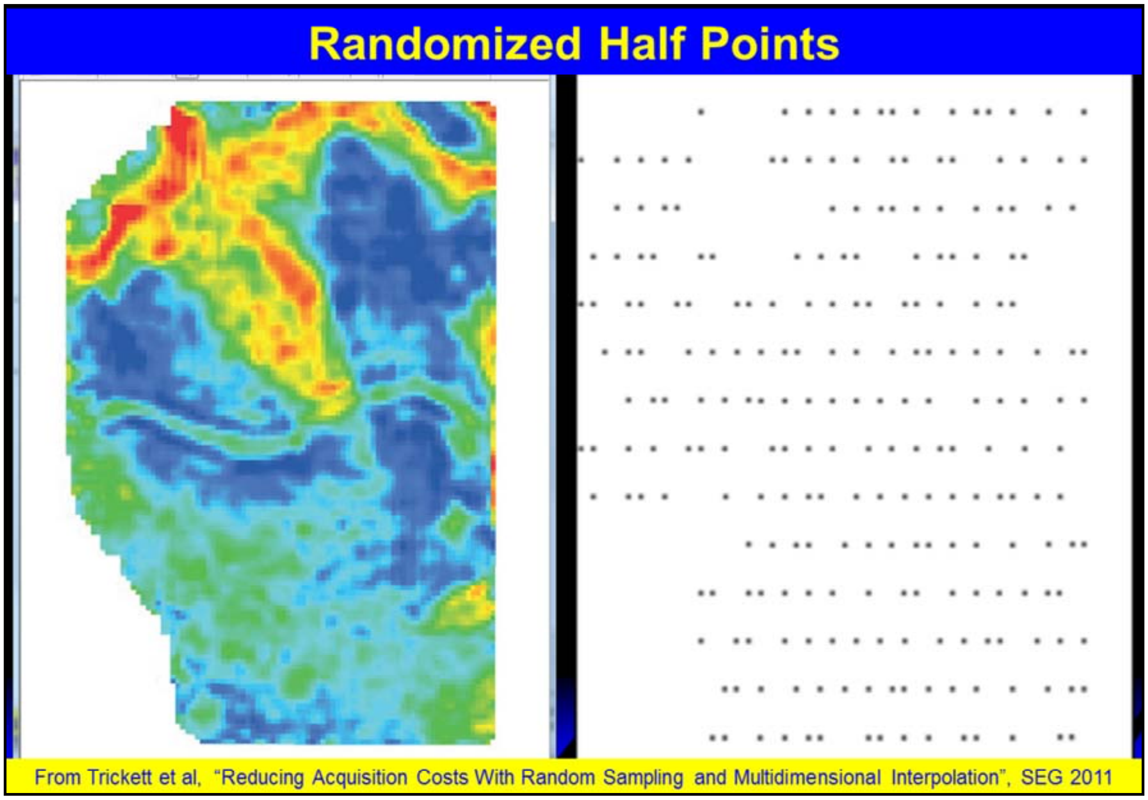


Other work by the same authors has used a densely populated 3D to produce a final data volume. Then the original data set was decimated to half the shot density using three different methods. Each decimation was reconstructed to the original density using modern interpolation methods. The reconstructed data volumes were then compared to the original full data volume.

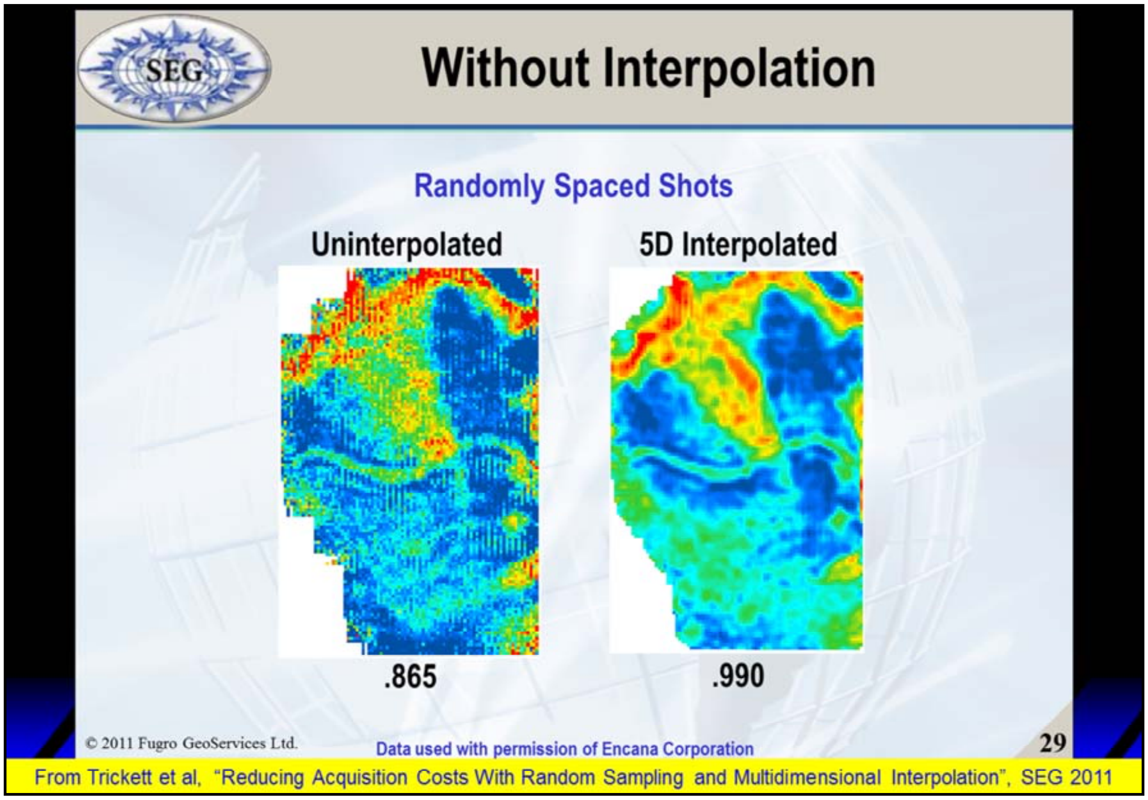
The three decimations included the removal of every second source line, the regular removal of every second source point along each line, and the removal of half the shots on each line using a random selection of either odd or even in each pair of shots.



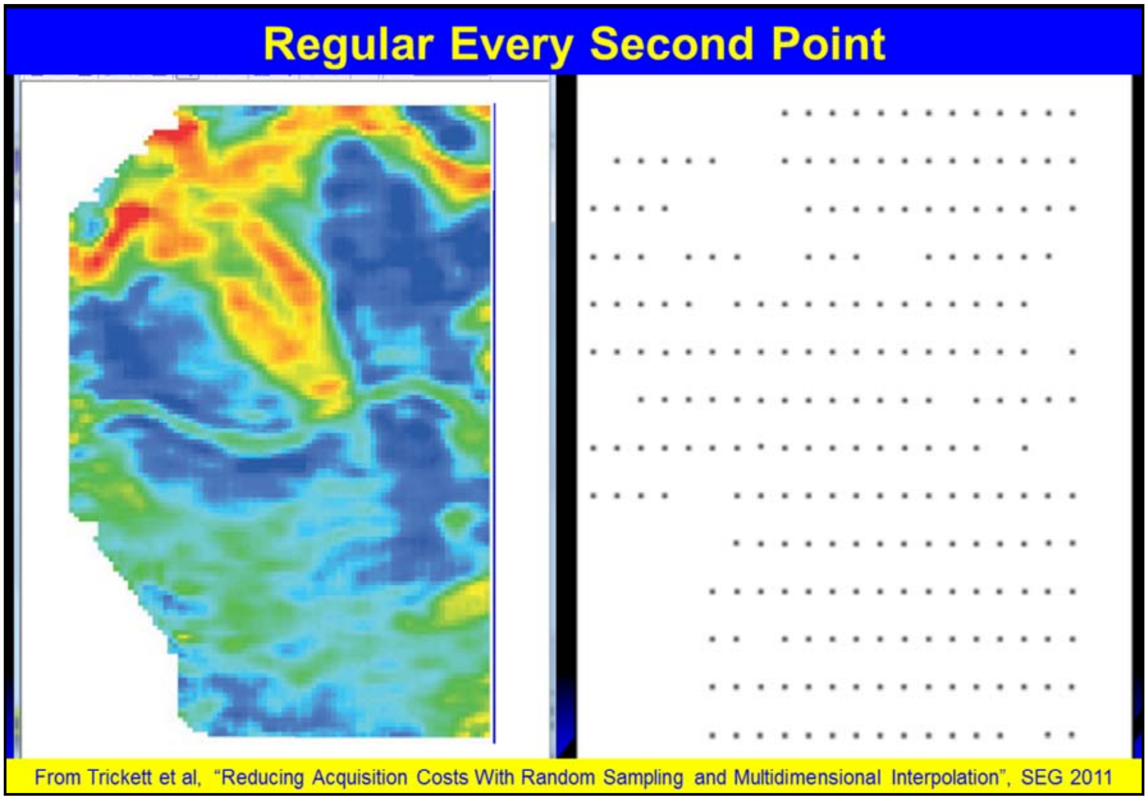
This slide shows the original full data set.



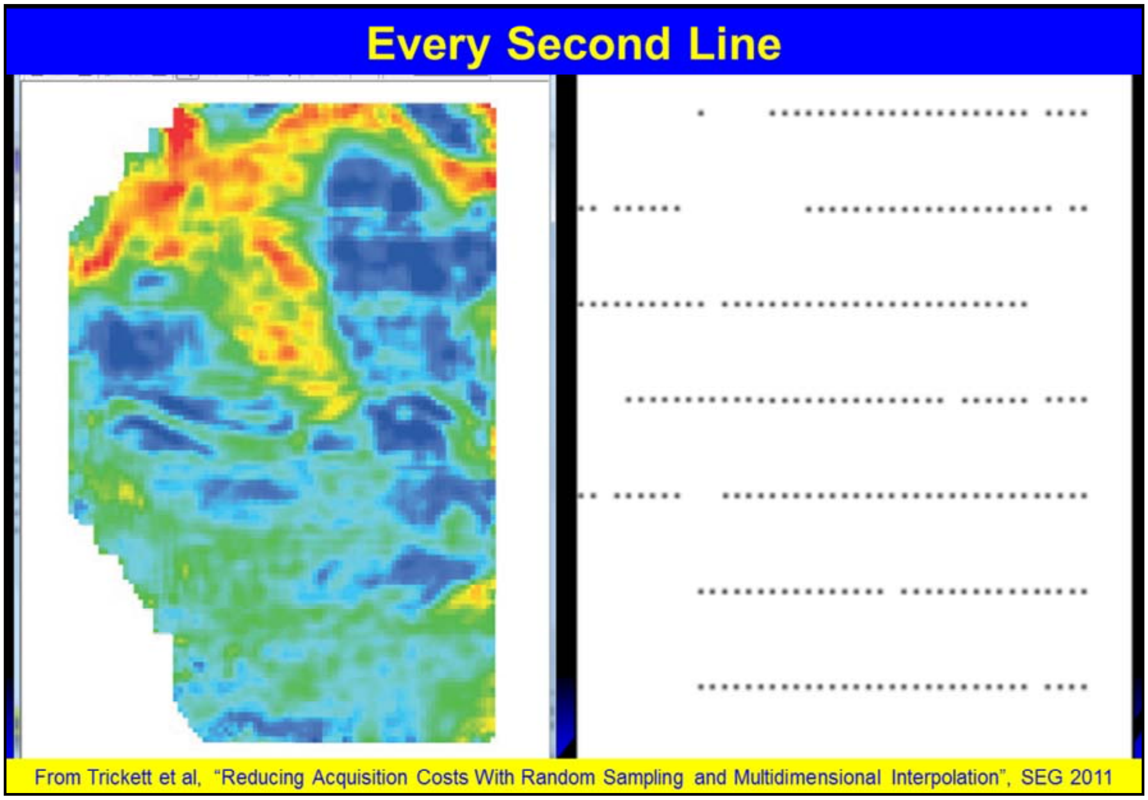
This shows the reconstructed data from a data set with half the shots removed by random selection of odd or even in pairs of shots. This provides an almost identical data set.



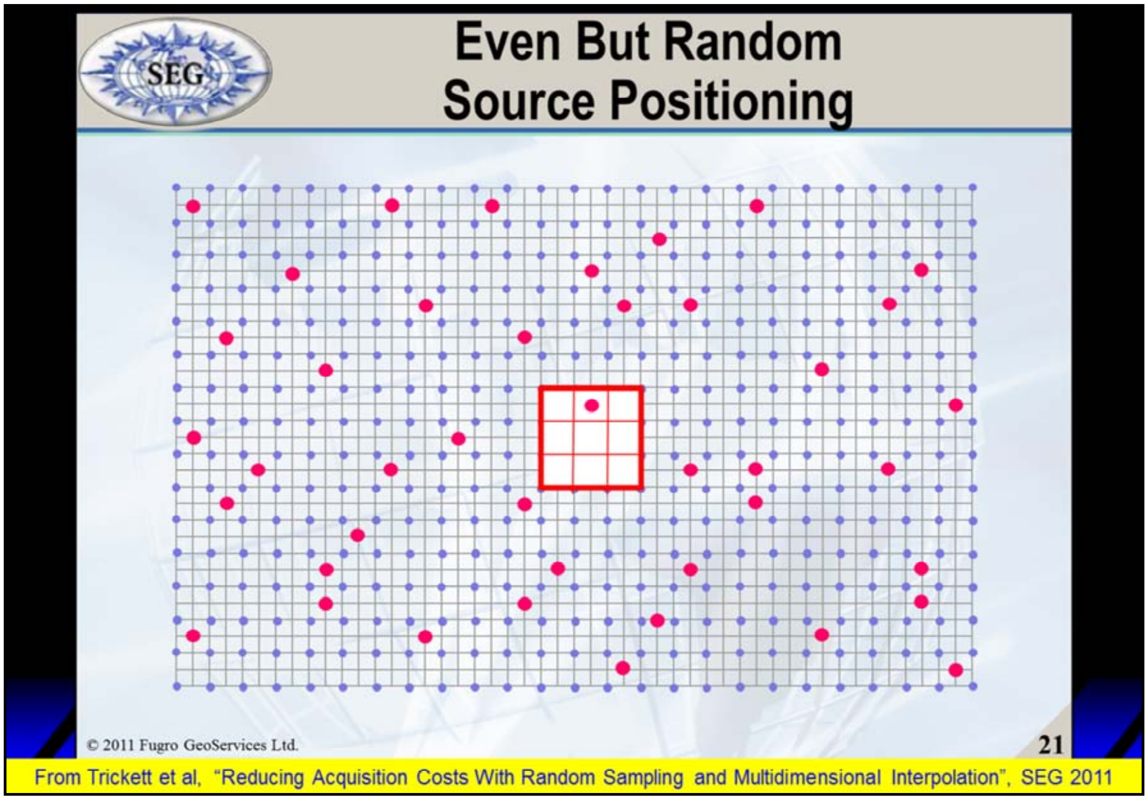
In this image, Trickett shows the un-interpolated data set using random selection of pairs of points on the left and the interpolated version on the right. The numbers below each display are the correlation coefficients of each data volume when compared with the original full data set. The interpolation proves to be 99% reliable.



The reconstructed data volume from a decimation using a regular sampling of every second shot is good but not quite as good as the random removal of every second shot.



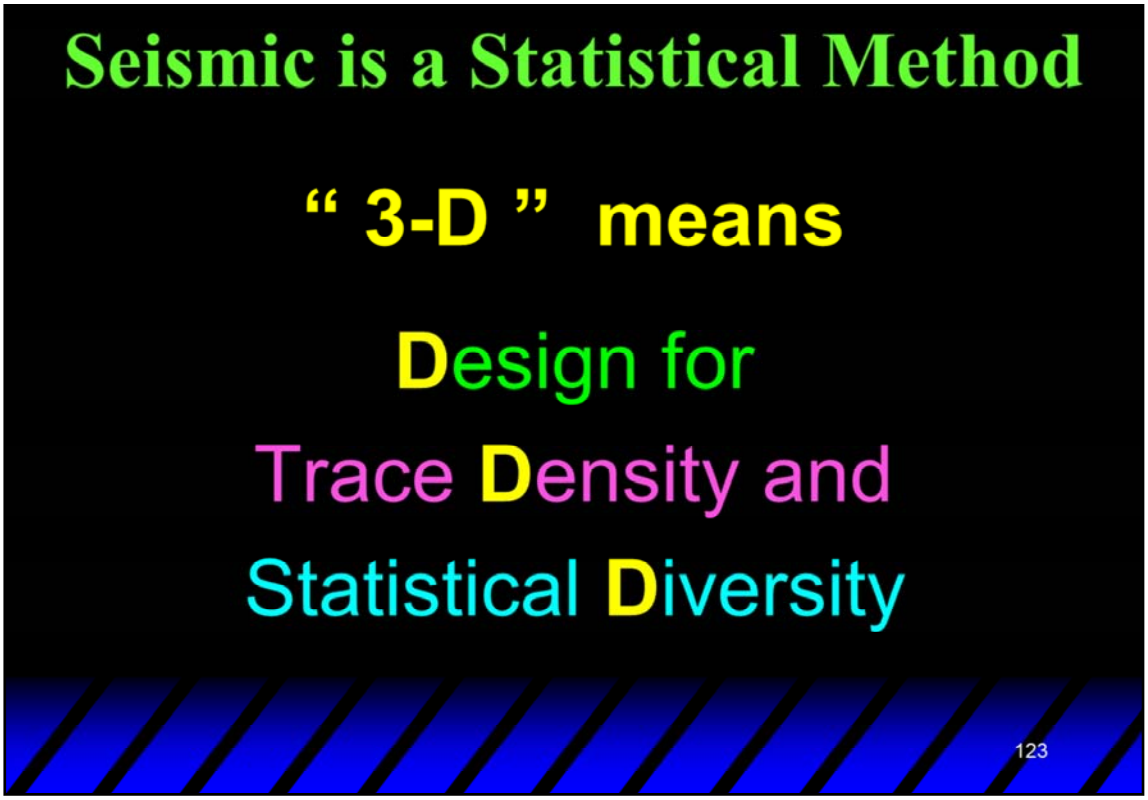
The reconstruction of the data decimated to half the source lines picks up a fairly strong geometric imprint. Trickett concludes that the 5-D Cadzow interpolation works best when data deficiencies are not regularized.



Trickett proposes that a randomization of sparse shots is an effective design that is well suited to data reconstruction.

Perhaps our task over the next few years is to modify our design criteria to produce a data set that is well suited to interpolation. Then the interpolation can produce the data set that is well suited to pre-stack migration. Then the migration can produce a clear and accurate image of the sub-surface geology.

… such is the evolution of the design of 3D programs



A mantra to live by in the field of 3D design is an acronym associated with the term “3D”. Think of “3D” not as three dimensions …

… think “Design for Density and Diversity”

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