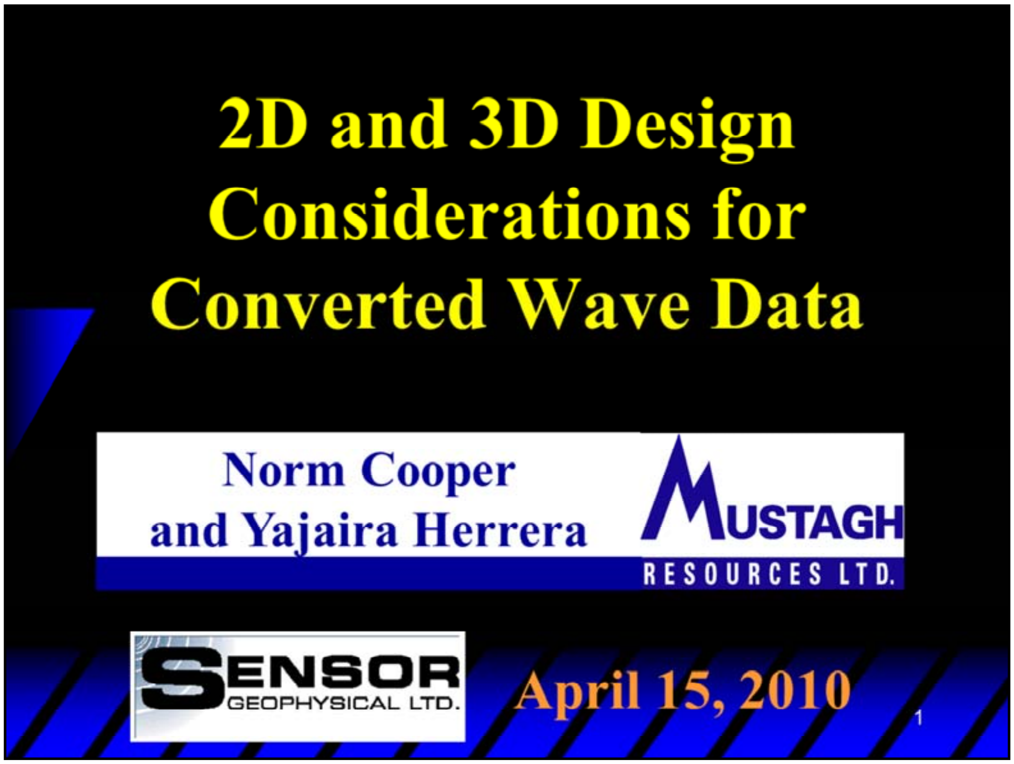
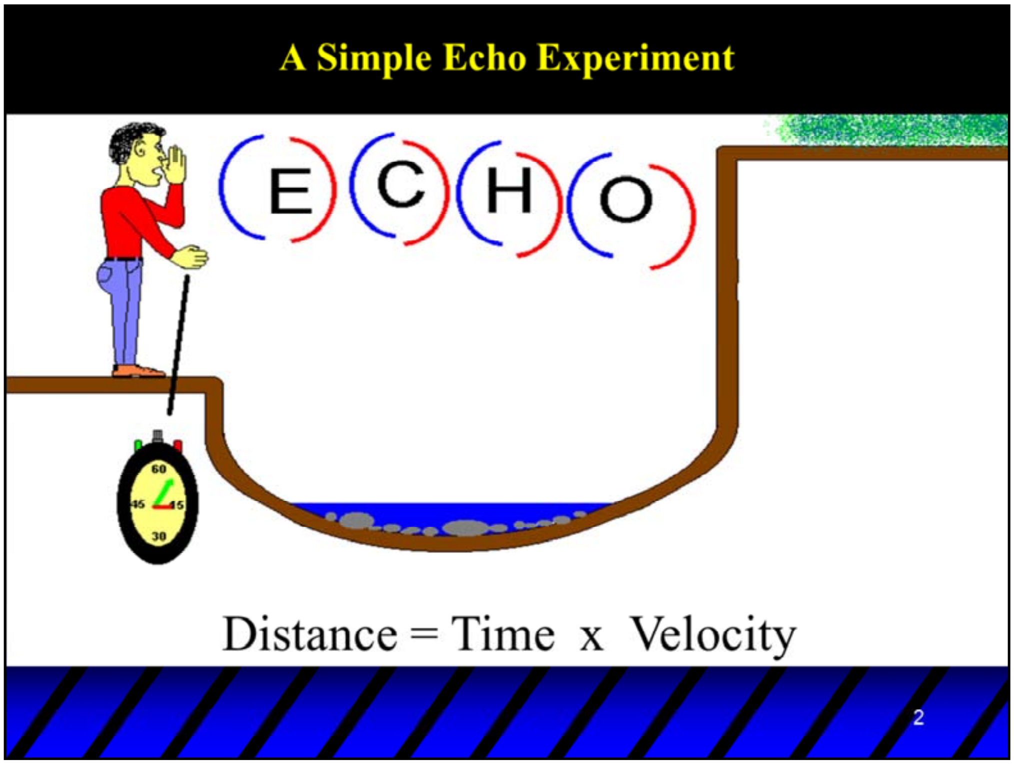


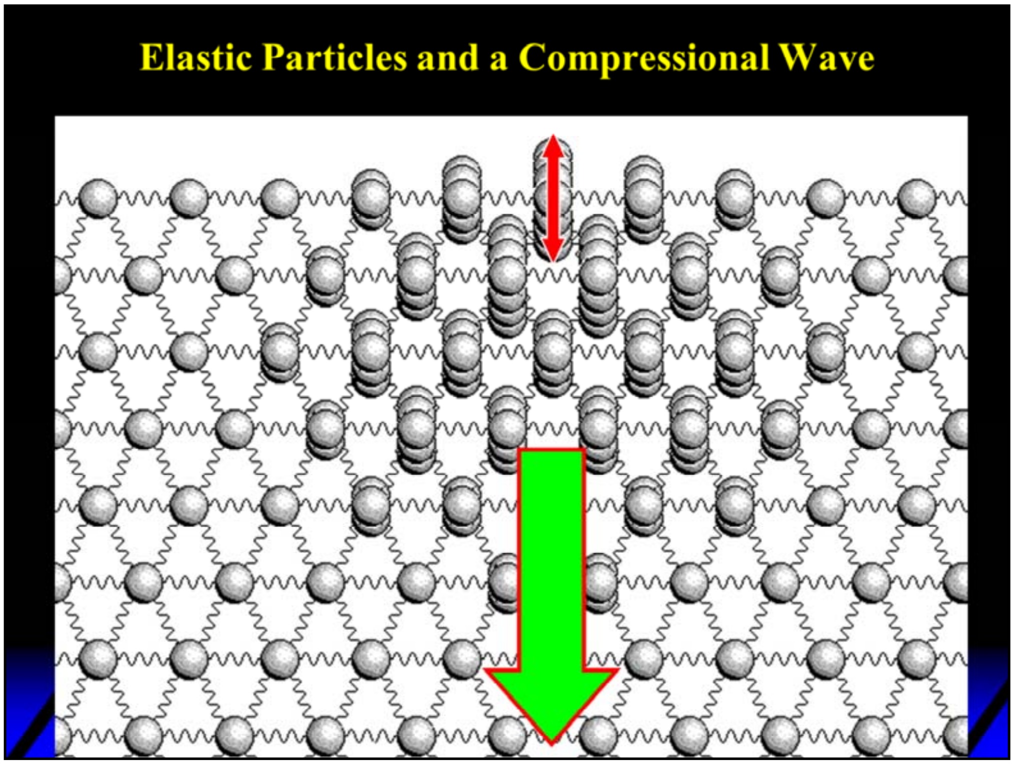
This presentation was prepared as part of Sensor Geophysical Ltd.'s 2010 Technology Forum
presented at the Telus Convention Center on April 15, 2010.



Reflection seismic methods are like a simple echo experiment. We use an energy source to produce sound waves, a receiver to listen to the reflected echoes and a sensitive timing instrument to measure the two-way travel times.

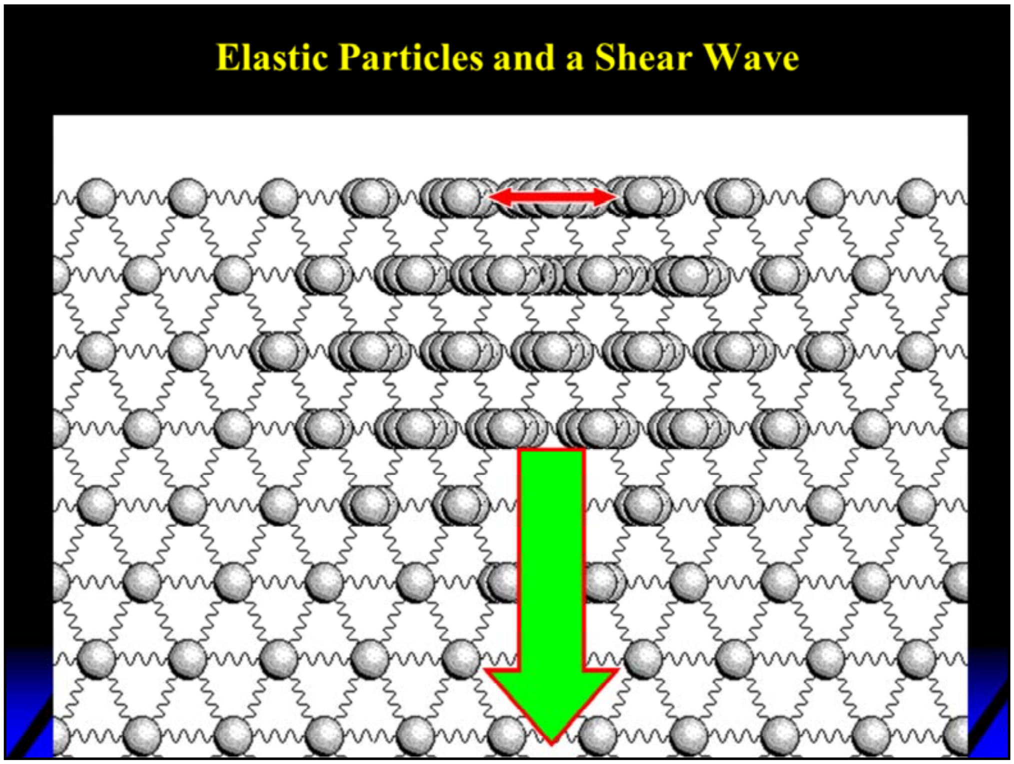
We are usually interested in the distance to our targets, in which case we must have a good knowledge of the velocity at which the sound traveled.

A very basic, but very important equation in seismic is that measurements in distance equal measurements in time multiplied by some velocity.



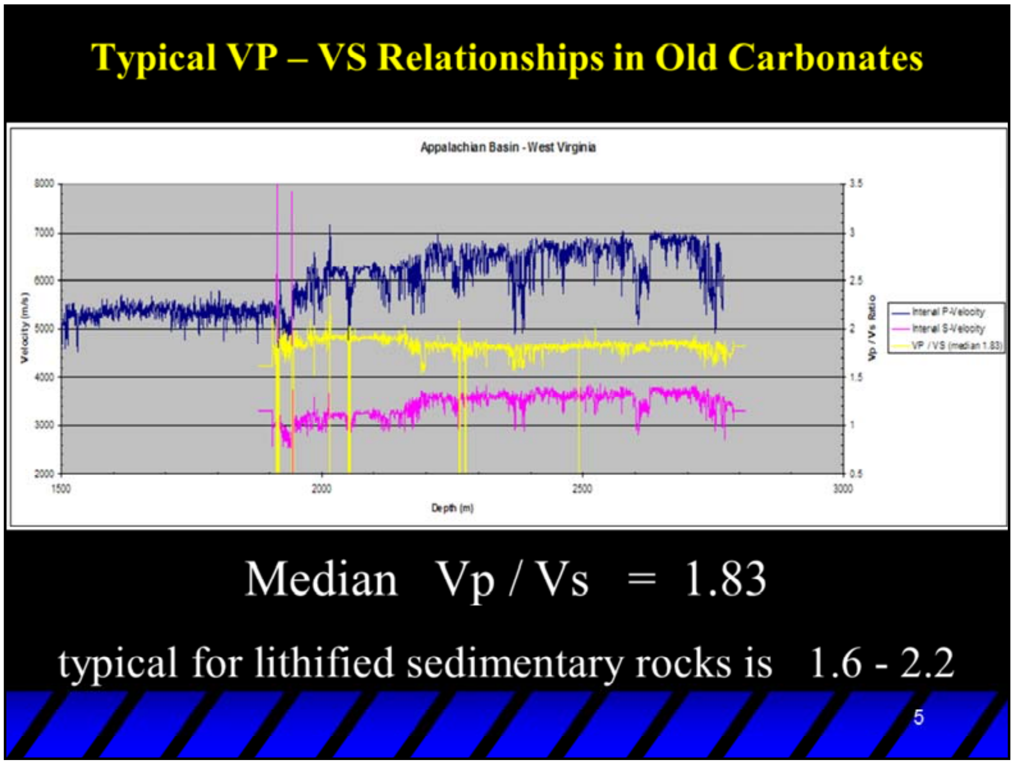
When we speak about the velocity of a rock, we mean how quickly does an elastic wave propagate through the rock.
Hear we show the elastic behavior of a “Compressional” Wave (also known as a “Primary” wave or “P-wave”).

Particle motion is in the same direction as propagation of the elastic wave.



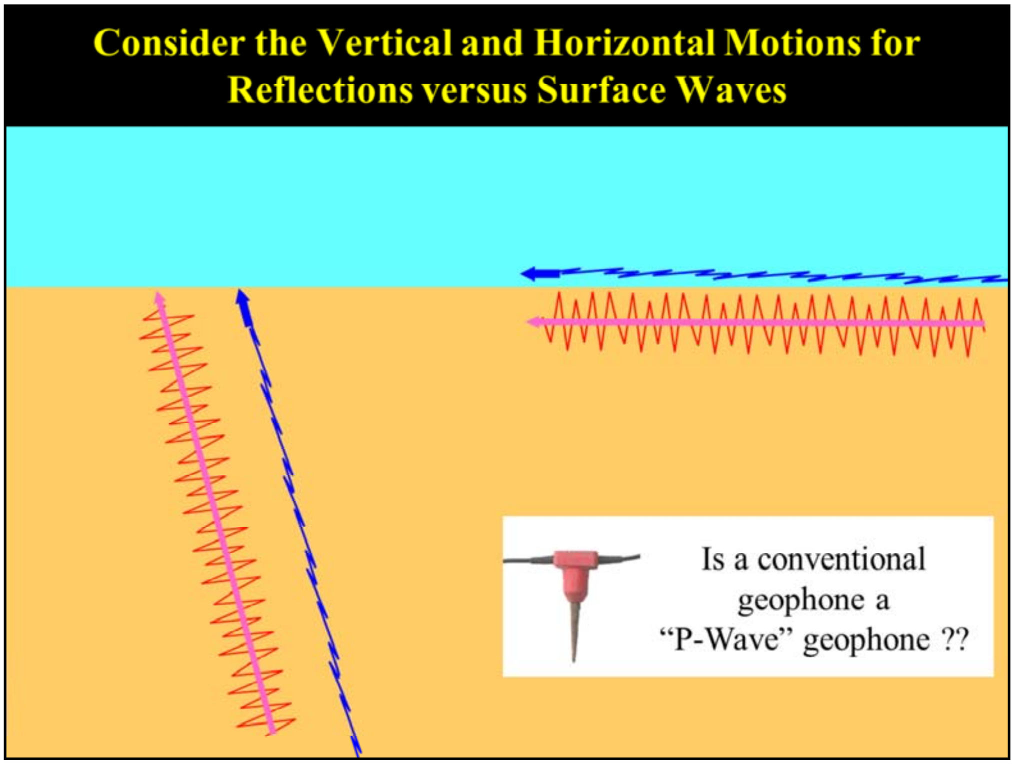
Here we show the behaviour of a “Transverse” wave (or “Shear” wave, or “S-wave”).

Notice that the particle motion is perpendicular to the direction of propagation. Due to the in-direct coupling of the shear wave, it will propagate more slowly than a P-wave.

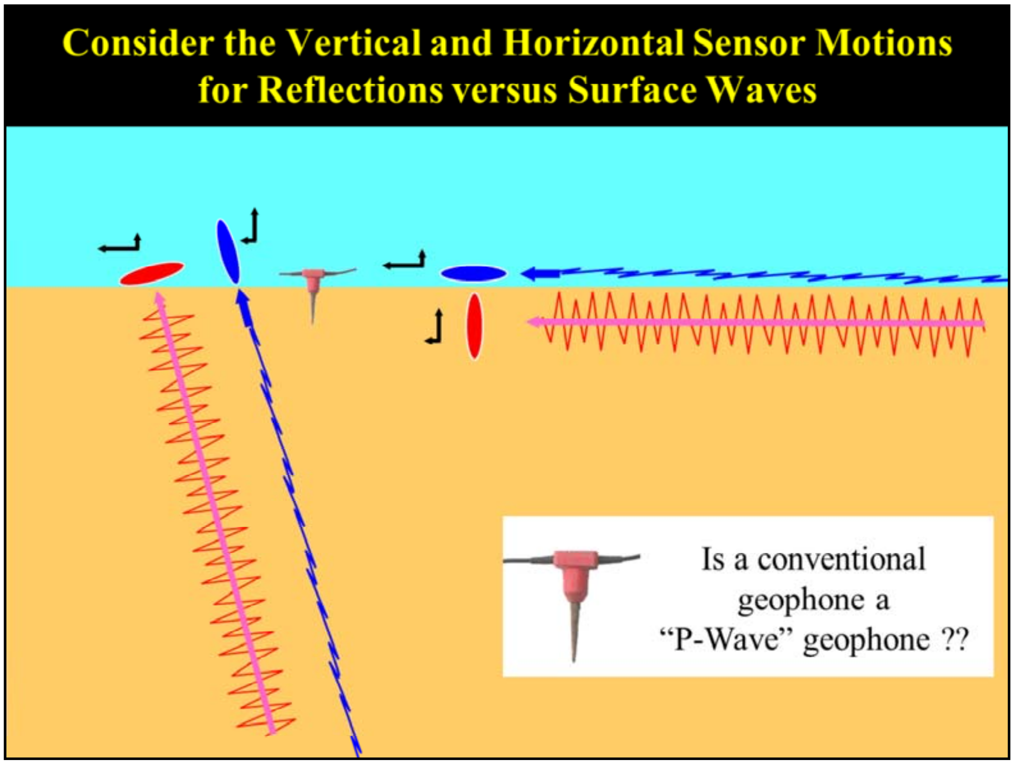


In lithified sedimentary rocks, the S-wave travels at about ½ the speed of a P-wave. The ratio Vp / Vs depends on the rock type and the fluid fill within the rock porosity.

However, for most sedimentary rocks, we expect 2.2 < Vp / Vs < 1.6

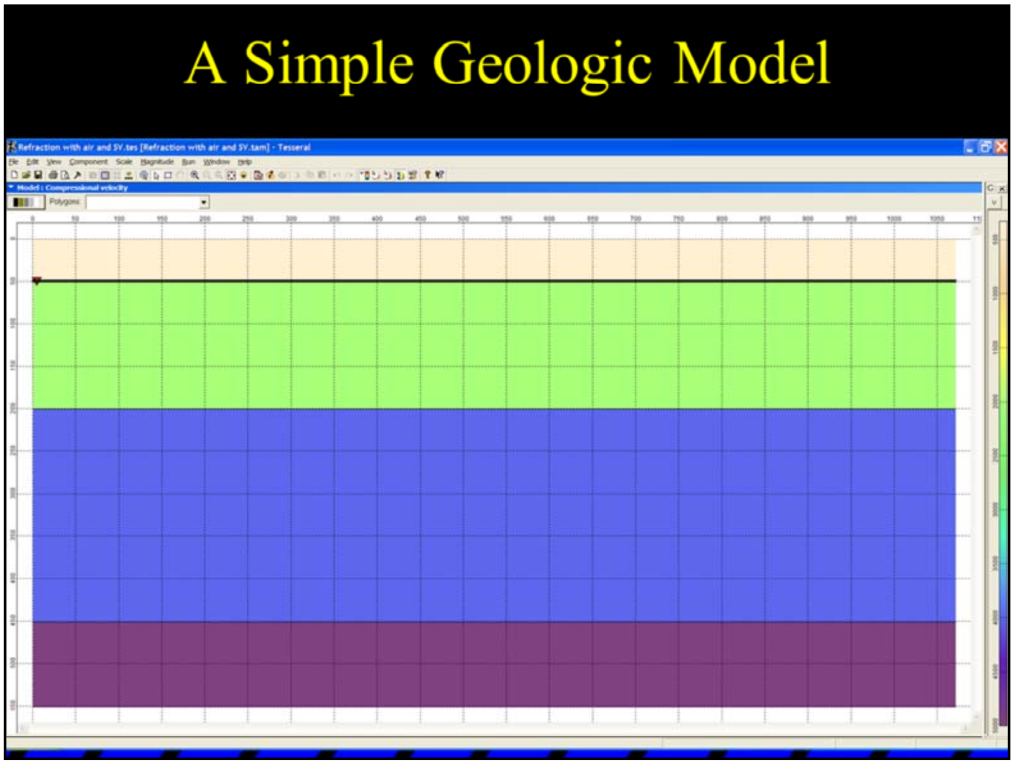


Consider the surface of the earth (boundary between the blue layer and the orange layer above). We will consider shear waves (in red) and P-waves (in blue). We will consider reflections from deep in the earth on the left side of this image and horizontally propagating surface waves on the right side. Many geophysicists think that a single element geophone planted vertically in the surface is a "P-wave" sensor. Is this accurate?

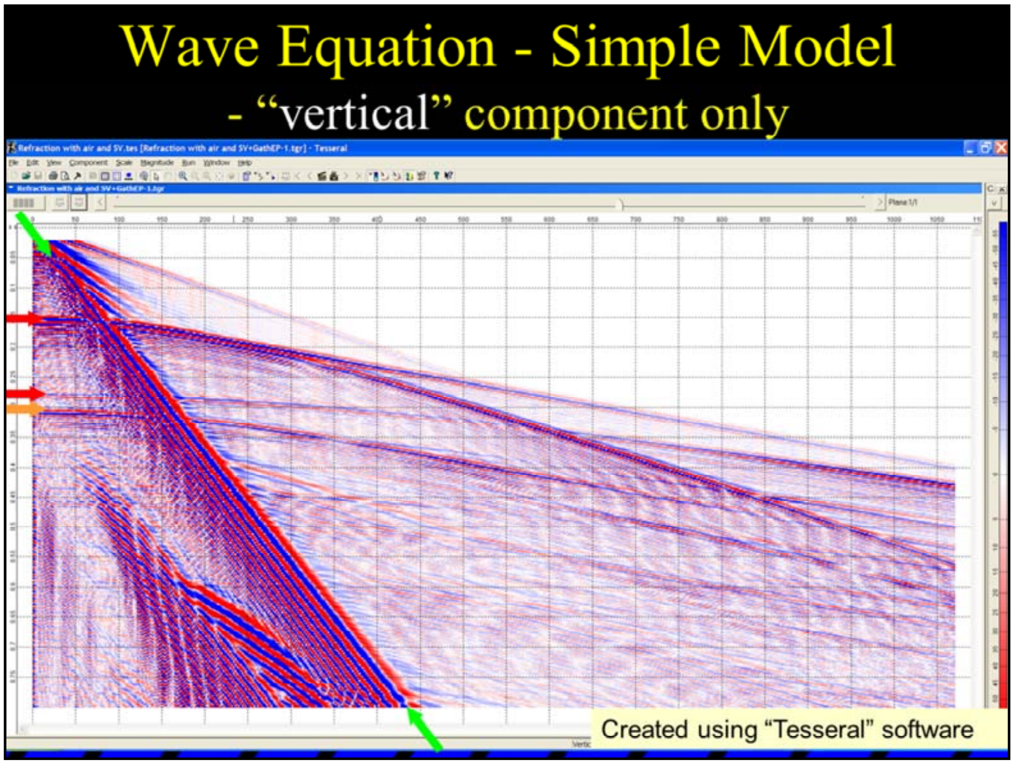


A vertical-element sensor is most sensitive to reflected P-waves and is not very sensitive to reflected or converted shear waves. We usually use AVO methods to "infer" the shear properties of reflections using just vertical element geophones. Using 3-component sensors, we can record stronger components of reflected or converted shear waves directly.

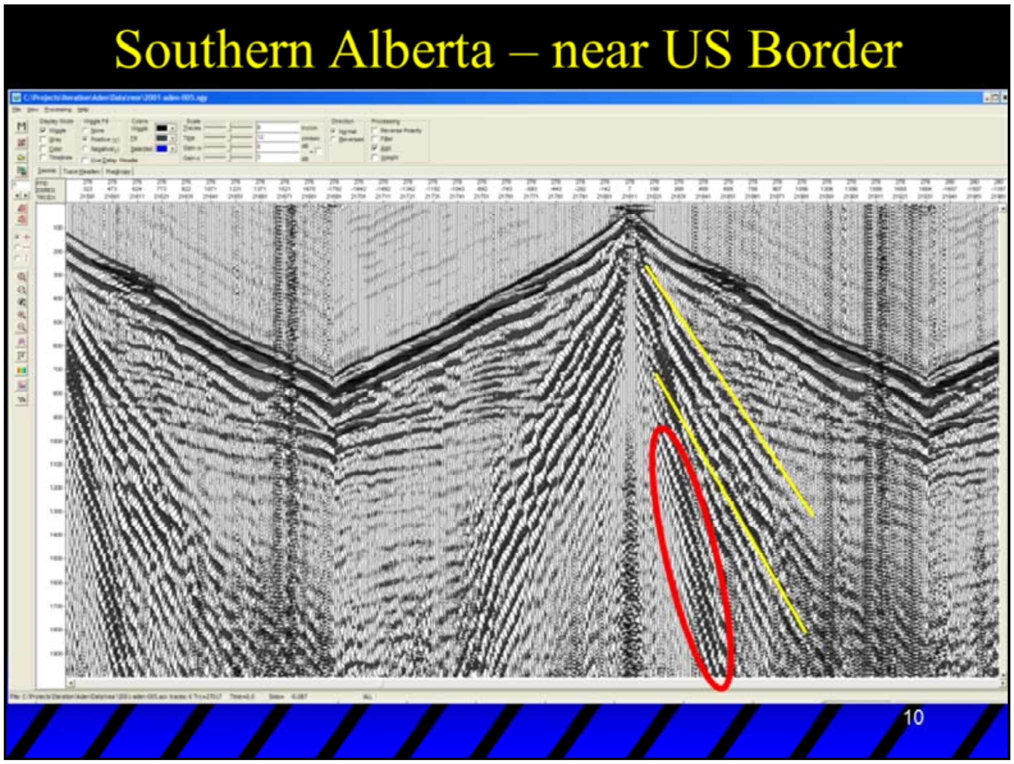
Notice that the vertical element receiver is more sensitive to shear-converted surface waves than it is to surface P-waves. The common use of arrays helps to suppress some of the shorter-wavelength shear components of surface waves.



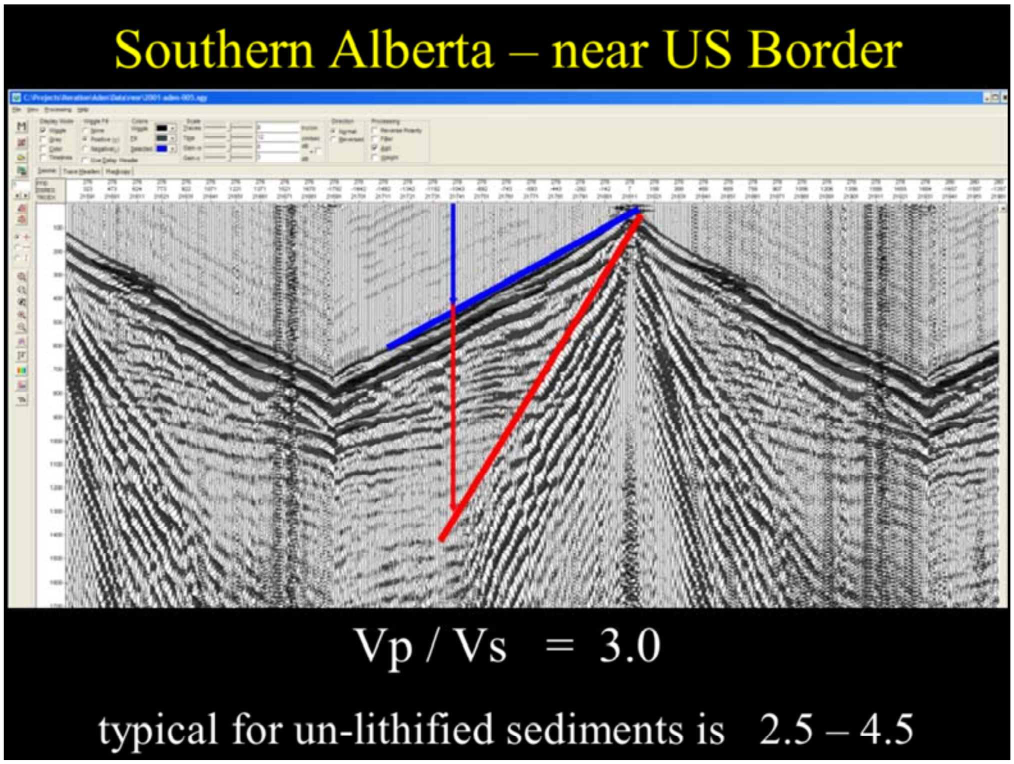
This simple model has a free-air boundary (earth surface) underlain by a homogeneous layer 150 m thick with a P-wave velocity of 2000 m/s, then another layer 250 m thick with a P-wave velocity of about 4000 m/s, and finally a deep, thick layer with a P-wave velocity of 5000 m/s. Each layer is homogeneous and isotropic and boundaries are flat.



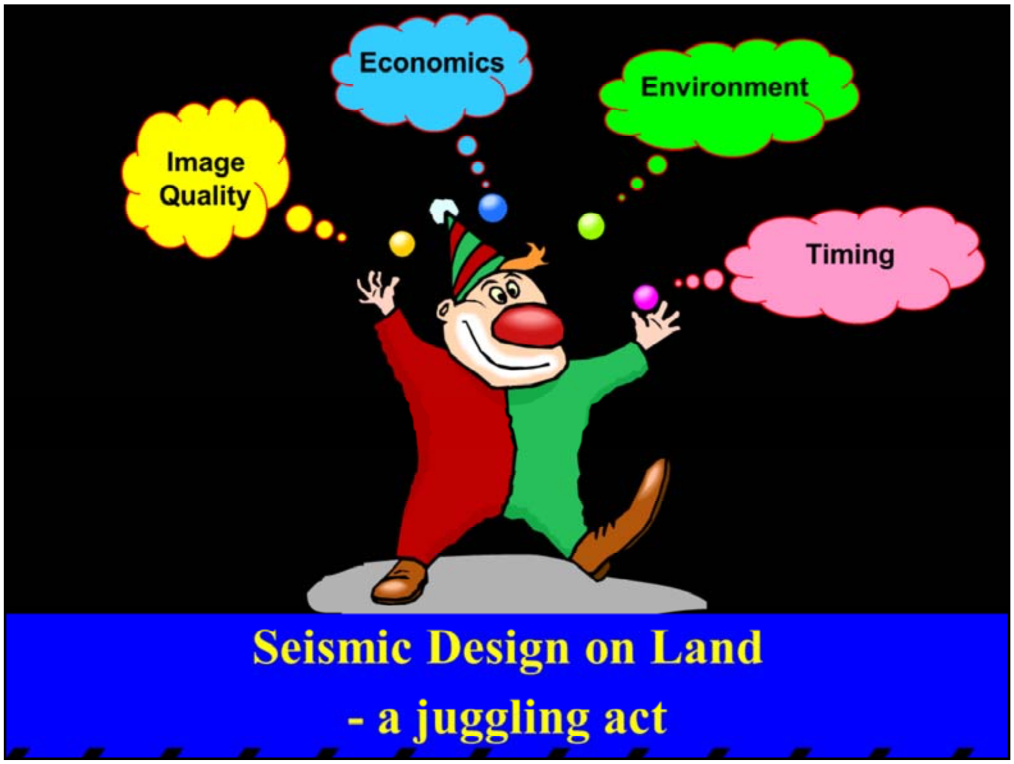
This is the X-T record (seismic shot record) predicted for vertical sensors on the surface using full acoustic modeling in "Tesseral". We see the expected direct wave and refraction as first breaks, but notice that they are fairly weak in amplitude and have fairly short dominant periods (high dominant frequencies). We can see a couple of P-wave reflections with To of 0.150 and 0.275 seconds as we would expect (red arrows). We also see a shallow, first-order multiple reflection with a To of 0.300 seconds (orange arrow). However, the strongest event is a shear-direct wave indicated by the bright green arrows. This is a horizontally-propagating shear wave and has a very strong influence on vertical sensors. Below that and to nearer offsets, we see the "shingle" effect of ground roll as it changes mode from shear to compressional and back to shear.



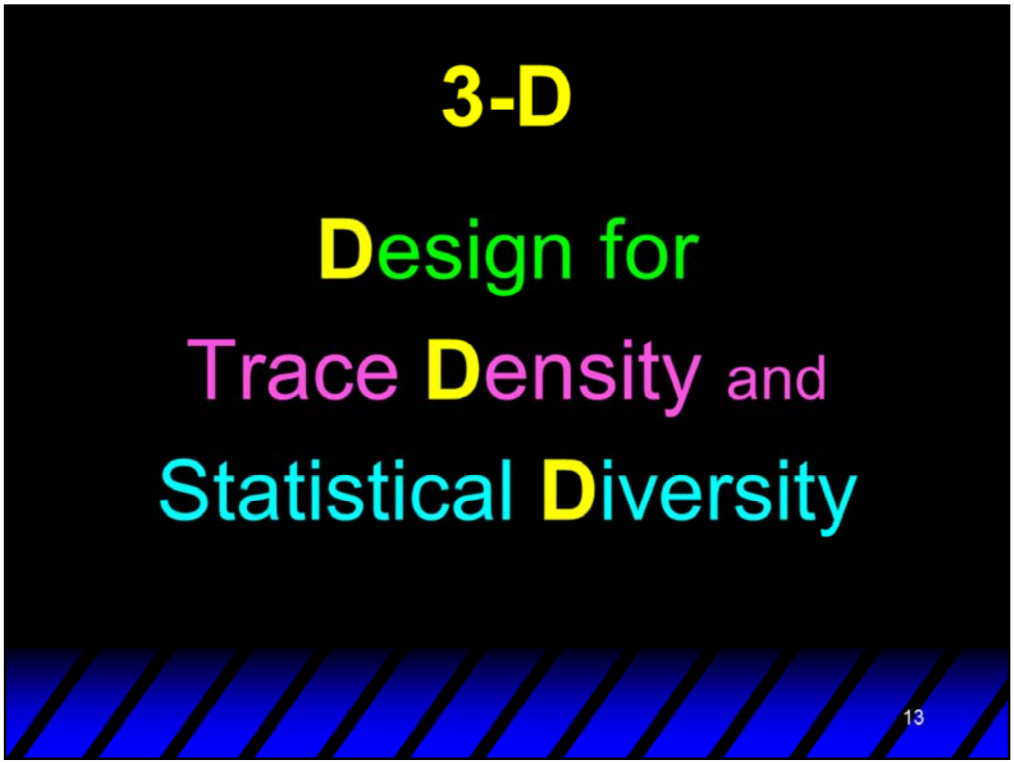
Strong shear-converted surface waves are often seen in real data also. These are indicate in yellow on this image. The "shingled" waves below these (circled in red) are the ground-roll.



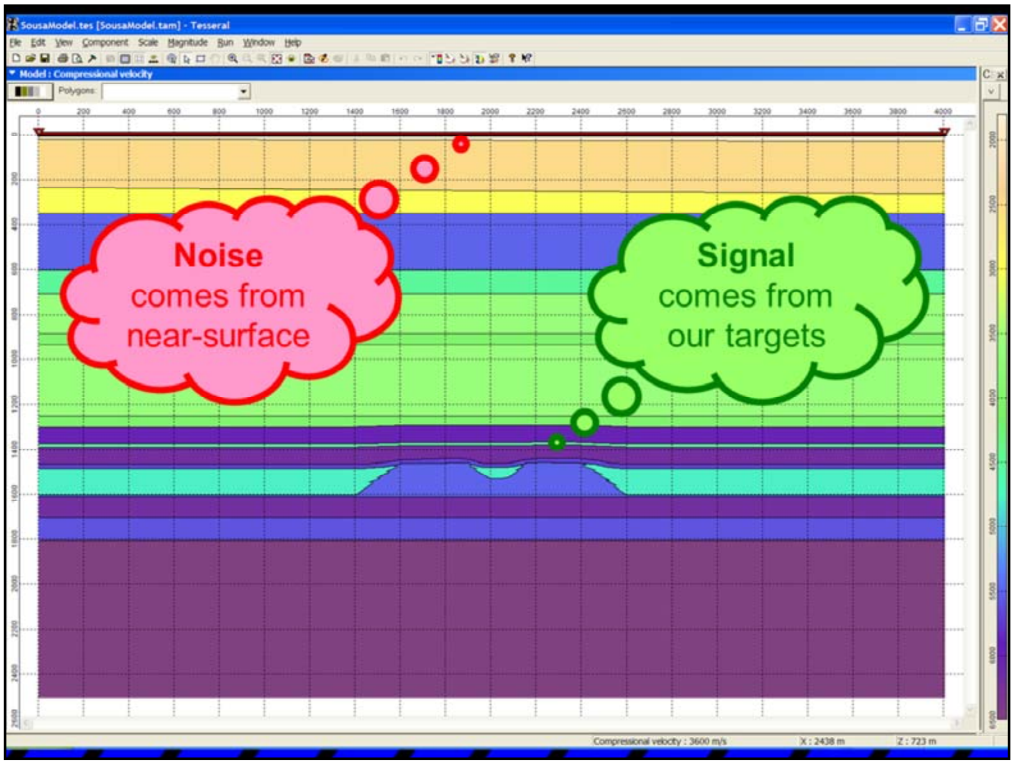
Note that the P-direct wave (blue curve travels from the source to a trace at offset of about 1080 meters in about 450 ms (representing a velocity of about 2400 m/s). The converted shear direct wave follows the same path, but at the velocity of a shear wave. It arrives at the same offset (1080 meters) but requires about 1350 ms to get there. This indicates a Vp / Vs ratio of 3:1 or a shear wave velocity of 800 m/s. It is normal in unconsolidated near-surface sediments that $4.5 < Vp / Vs < 2.5$



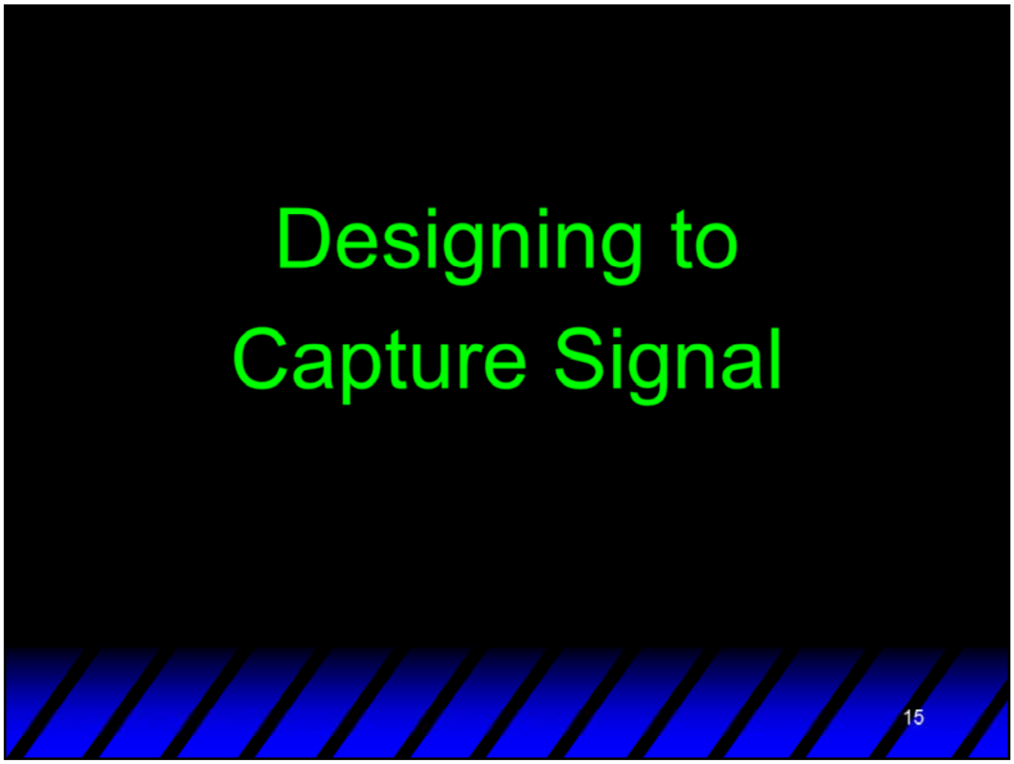
Designing 2D and 3D seismic program parameters can be a bit challenging when all factors are considered. Usually the factors that improve one aspect of our objective will cause a deterioration in some other desirable aspect. Design becomes a bit of a juggling act of compromises.



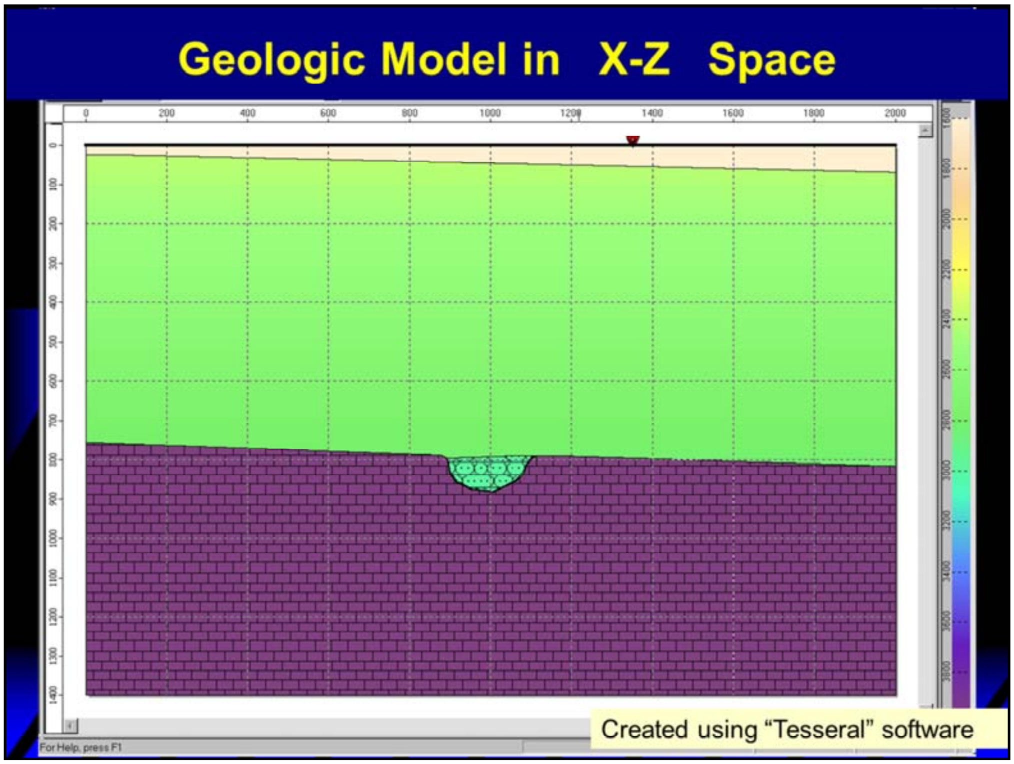
As much as we can, we design 3D surveys to deliver high trace density within our usable offsets (this may be equated to fold normalized by bin size). We also want to ensure we are generating traces of diverse statistical attributes. We do not gain very much if we repeat traces that have identical characteristics in all respects. In statistical diversity, it is important to illuminate our objectives from many different source perspectives and observe the returning wavefield from many different receiver perspectives. This will give us diversity in offset and azimuth distributions.



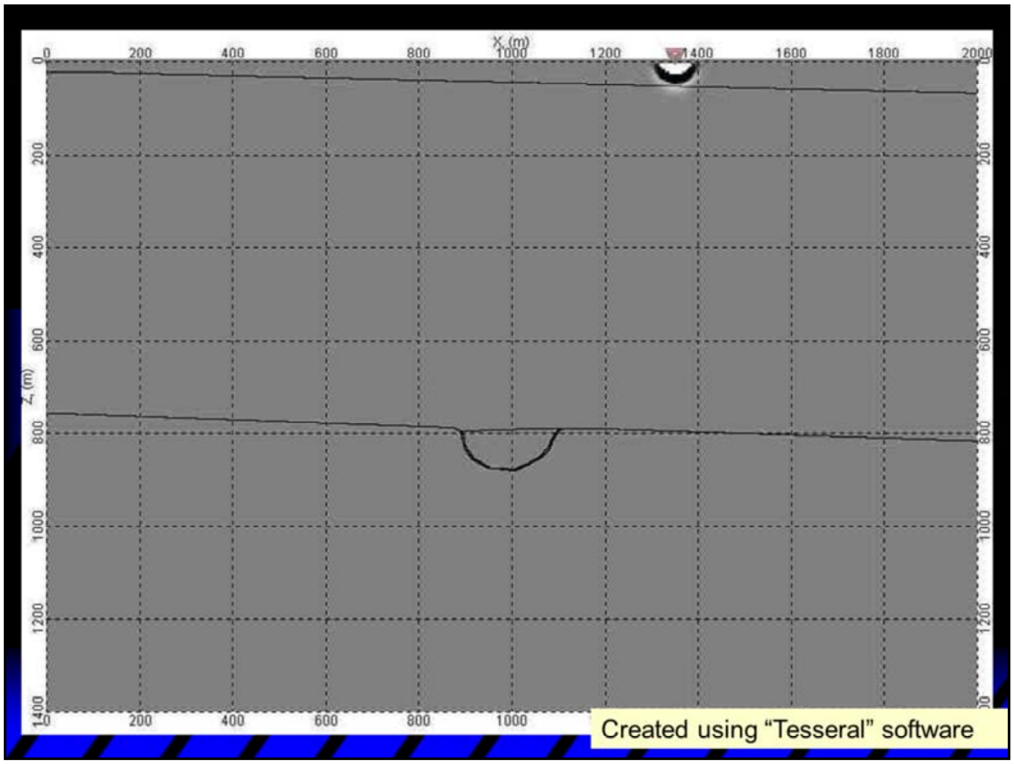
When we design surveys, we must consider the characteristics of the reflected wavefield with respect to the reflections and diffractions that must be properly measured according to Nyquist principles. However, we must also consider the extend and modes of noise in our data. If we have short-wavelength noise modes in our data, that can be more demanding to measure than reflection signals.



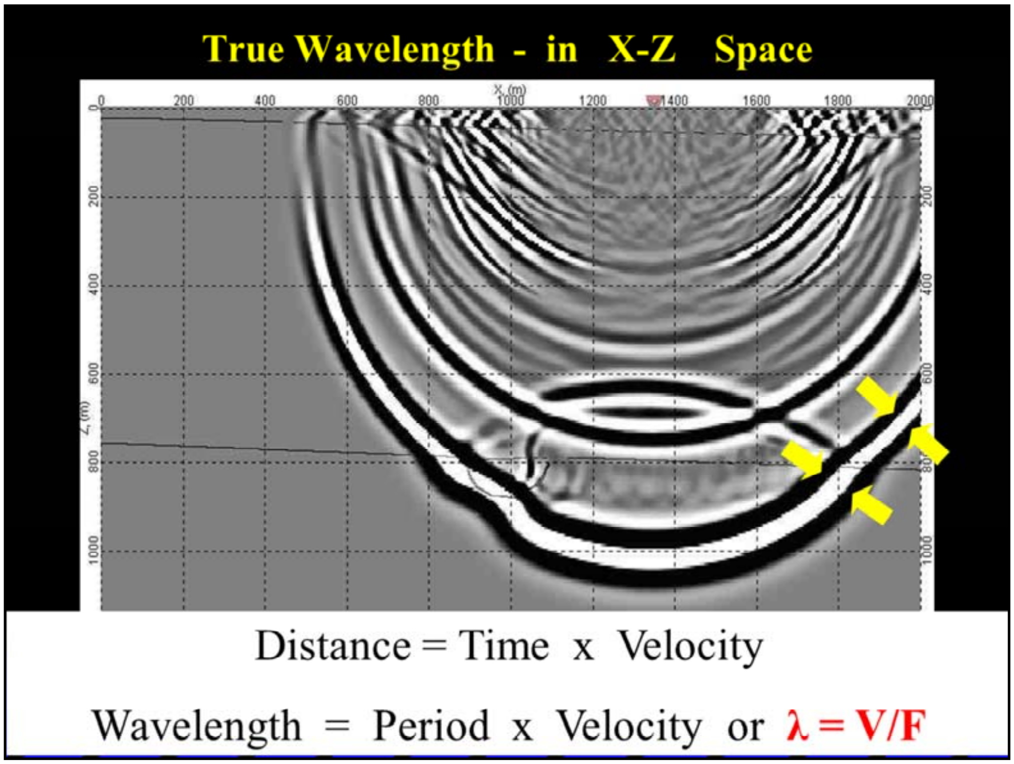
Let’s look at conventional considerations when determining spatial sampling for surface receiver groups.



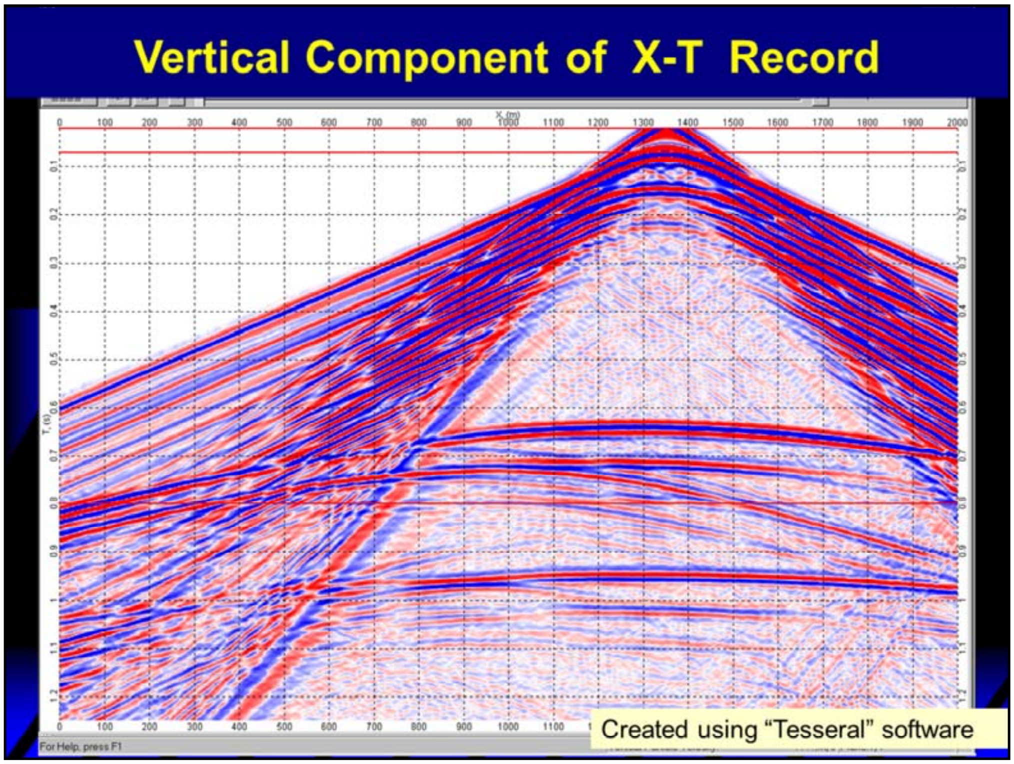
Let's consider a simple geologic model with a low-velocity layer thickening slightly to the right. We have a clastic rock section (about 2800 m/s) overlying carbonates (about 4000 m/s). On this slightly dipping reflecting boundary, we have introduced an incised channel containing some different (slightly faster) clastic materials. What signal events do we expect to generate when a single source point is initiated (at inverted red triangle)?



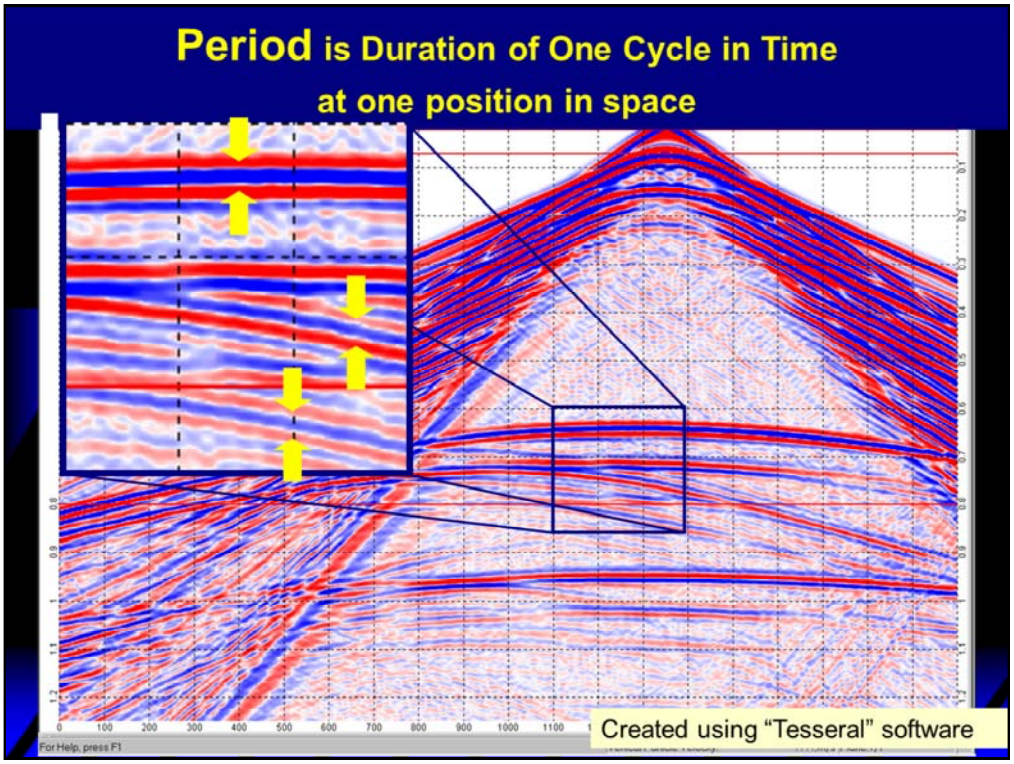
This animation shows the propagation of a pressure wave through the model. (refer to ShotModel.gif). Notice the simple reflection from the flat carbonate surface. Then note the diffraction from the convex left edge of the incised channel. Now note the surface waves propagating horizontally from the source point across the near-surface.



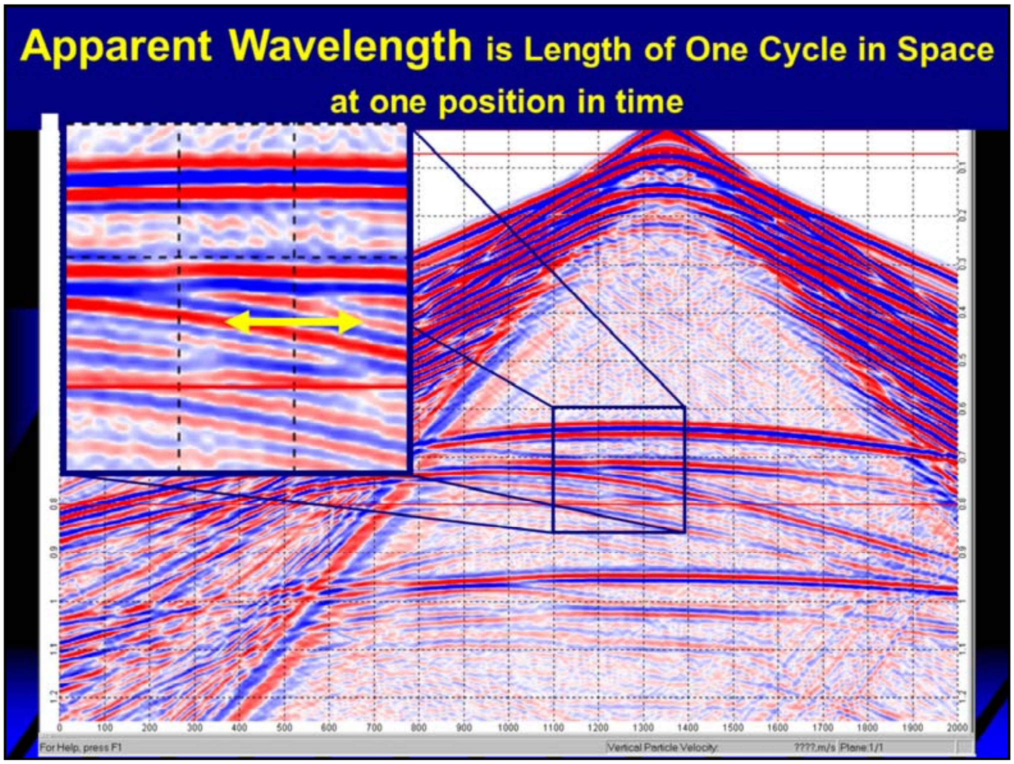
In this spatial model (X-Z domain), note the wavelength of the propagating wavefront in the slow clastics versus the wavelength in the faster carbonates. Obviously, wavelength is directly proportional to velocity. For shear waves, whose velocities are about half that of P-waves, we might expect shorter wavelengths and therefore greater resolution. In reality, this is often offset by the fact that the shear waves tend to be much lower dominant frequencies.



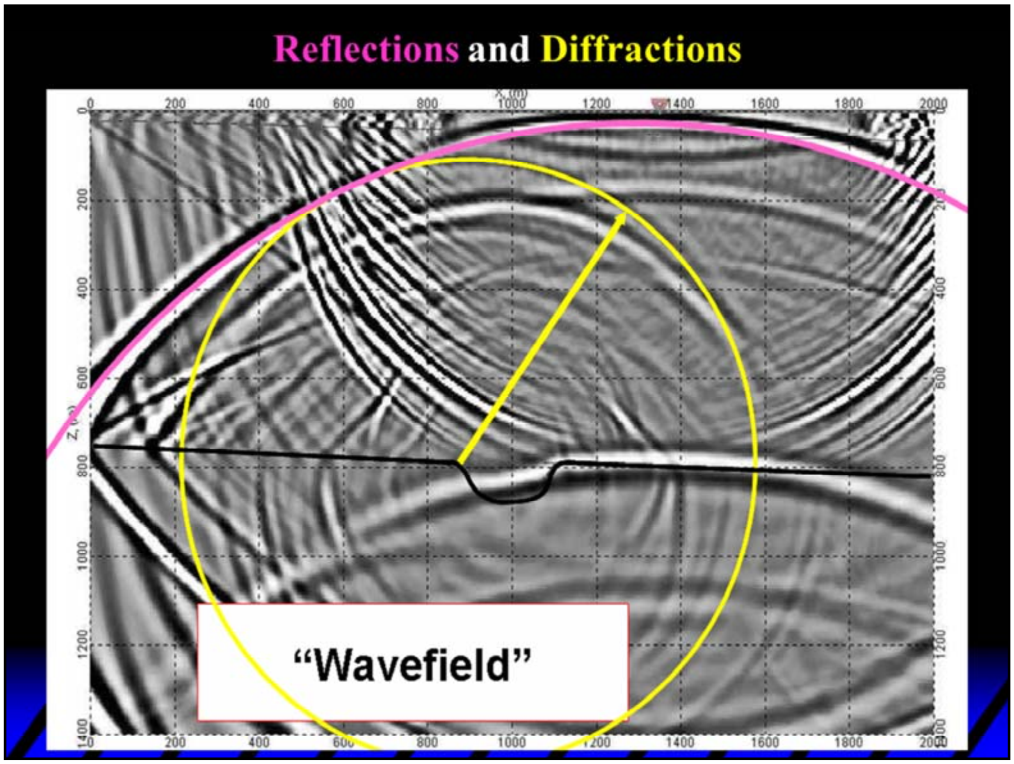
This is the seismic record (X-T domain) that we expect to result from the previous model. This shows the amplitude output for a single-component vertical velocity sensor located every 2 meters across the surface of the model. Can you pick out the simple reflections? How about the diffractions? What about the reverberating surface waves?



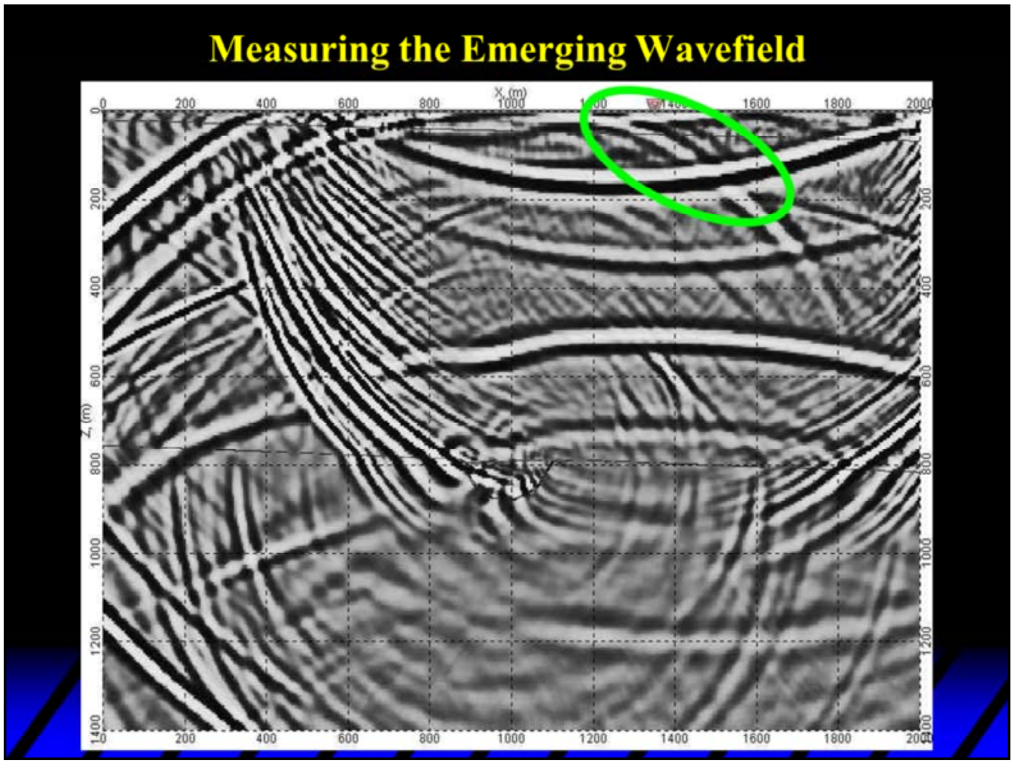
A seismic record is a 3-dimensional plot of amplitude versus time and spatial position across the surface. The vertical time between each peak-trough-peak cycle is the period of the data.



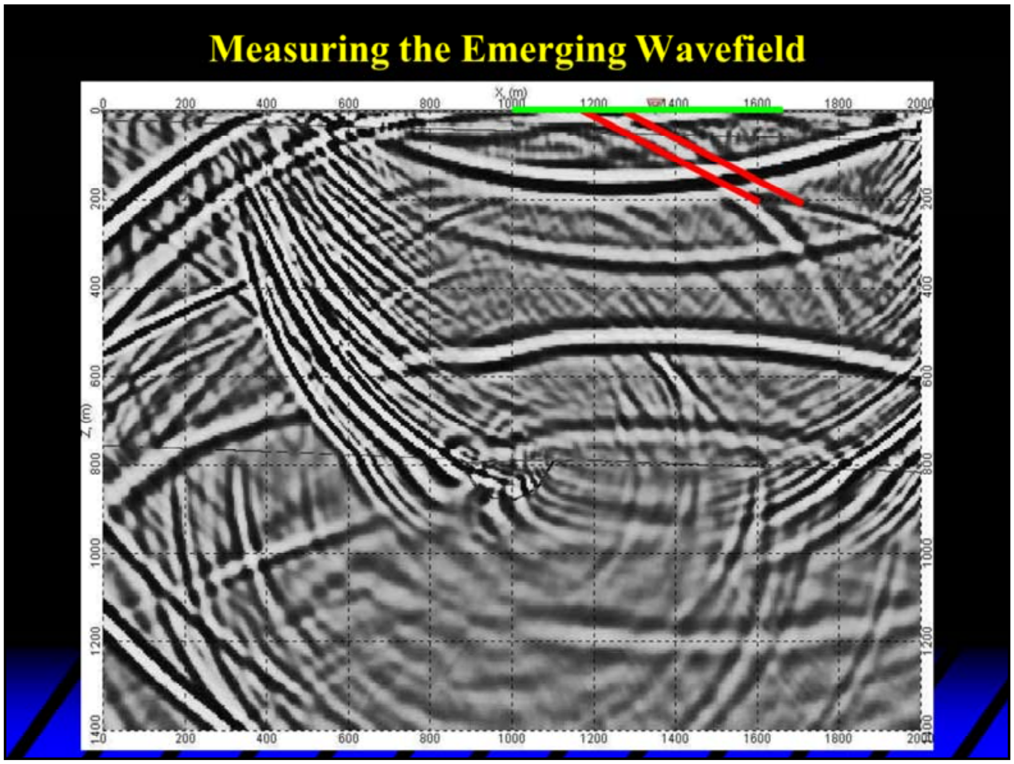
A seismic record is a 3-dimensional plot of amplitude versus time and spatial position across the surface. The horizontal distance between each peak-trough-peak cycle is the apparent wavelength of the data.



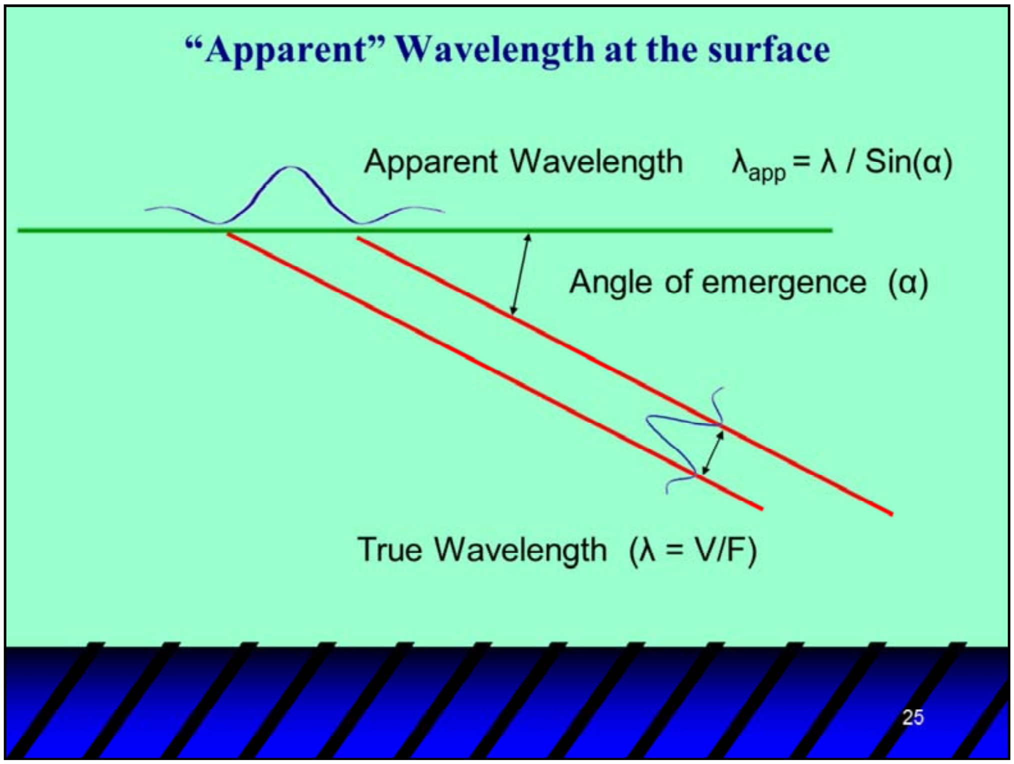
Our reflection signals are part of the wavefield that emerges over time at the surface, where we measure it. Note that in the X-Z domain simple reflections through a homogenous and isotropic medium will form a circle with a focal point that is at the image point of the source reflected orthogonally through the reflector. Diffractions form a circle with a focal point that is at the diffractor. For this reason, diffractions will always be more curved than reflections as they emerge at the surface. This means that their apparent wavelengths will be shorter and diffractions will be the most demanding part of our signals for measurement.



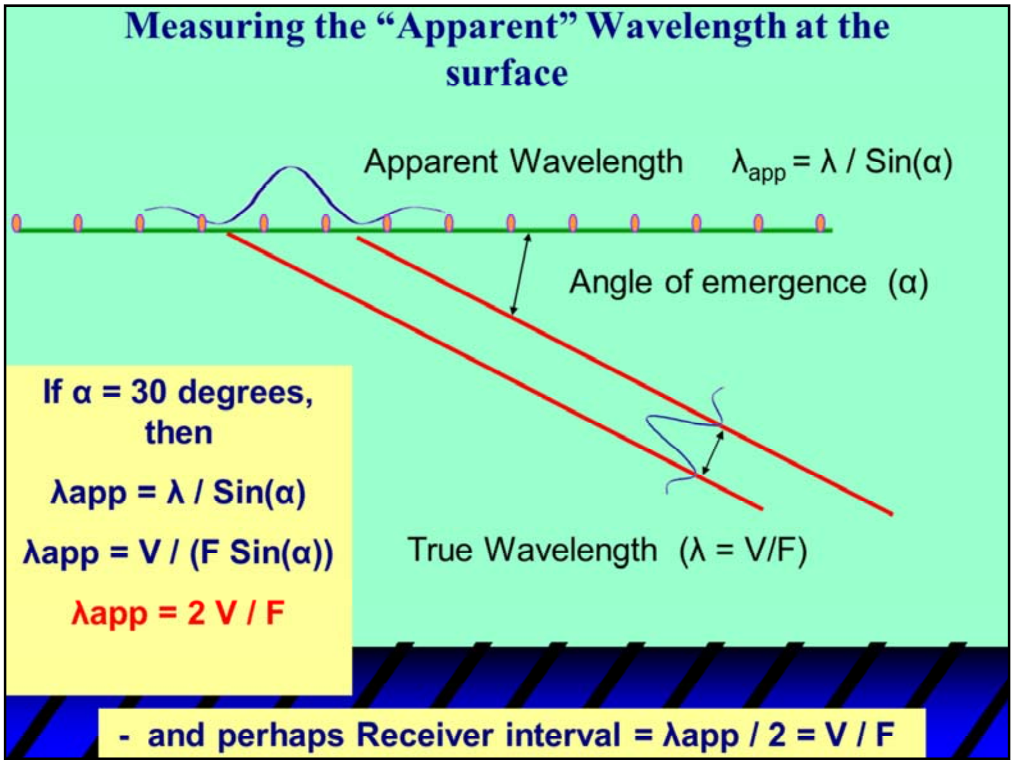
In this image we focus your attention on the emerging diffraction.



Locally, we can treat the emerging diffraction as an emerging plane wave, which leads to the next analyses.

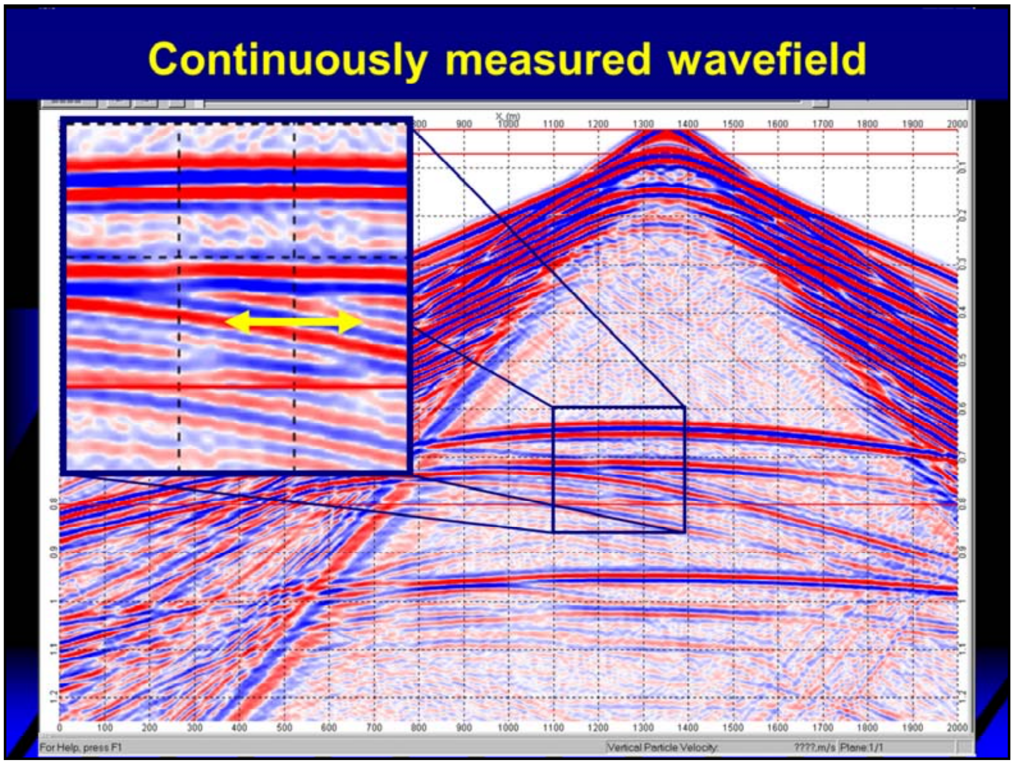


The length of the propagating wave in space is λ, which is V/F. We call this the "True Wavelength"

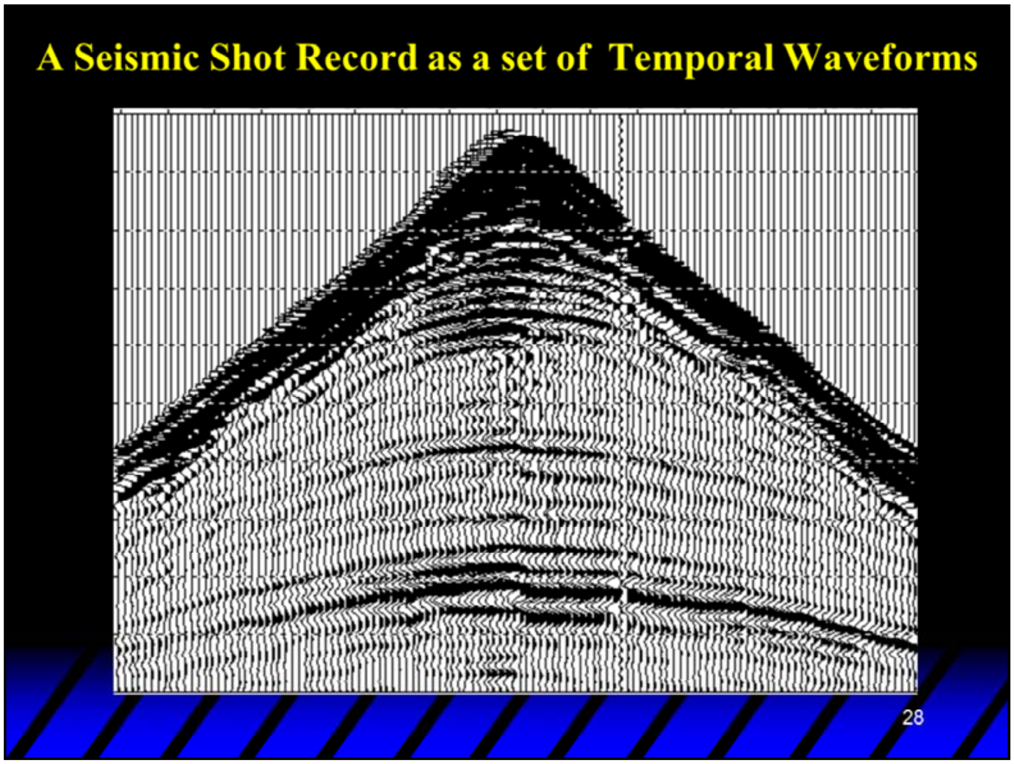


The emerging wavefront intersects the surface at an angle α . The apparent length of the emerging wave along the surface is called the "Apparent Wavelength" and is simply $\lambda / \sin(\alpha)$.

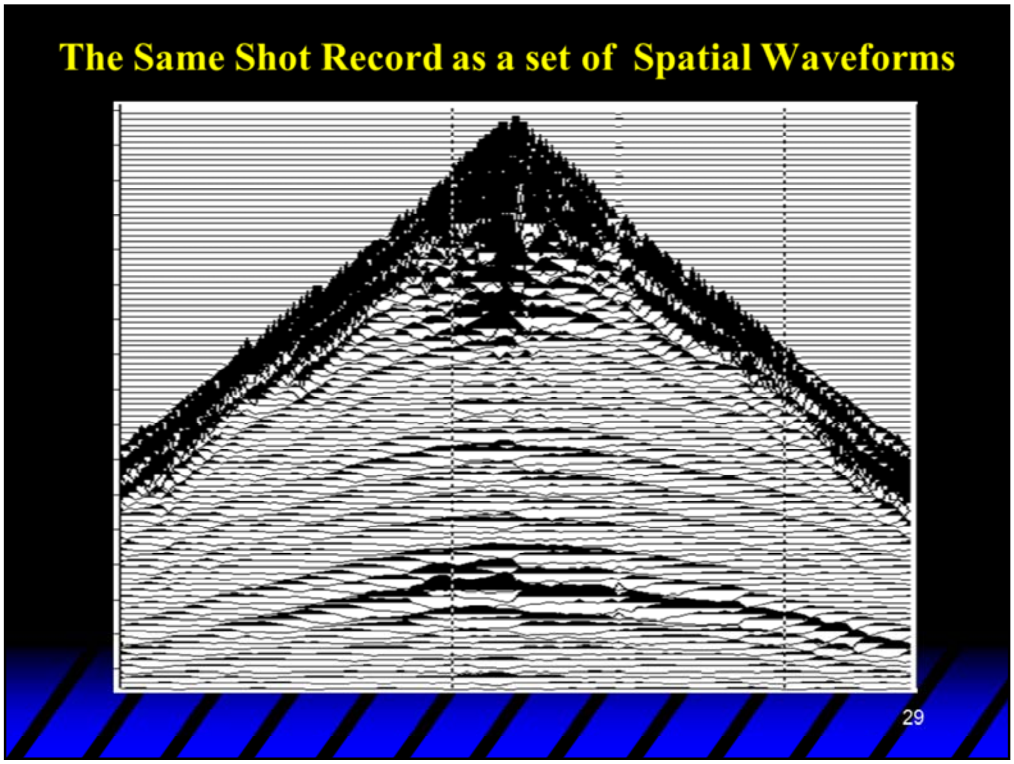
Typically, the greatest angle of emergence of interest to us when migrating a diffraction may be about 30 degrees, so $\sin(\alpha)$ is just 0.5 and $\lambda app = 2 \lambda = 2 V / F$. Nyquist requires that we record at least two measurements per cycle, which means that our receiver interval should be
$Ri \leq V / F$. Note that for shear waves, which have slower velocities, our receiver intervals should be about half of what we would normally use for P-waves (if the frequencies and angles of emergence are consistent).



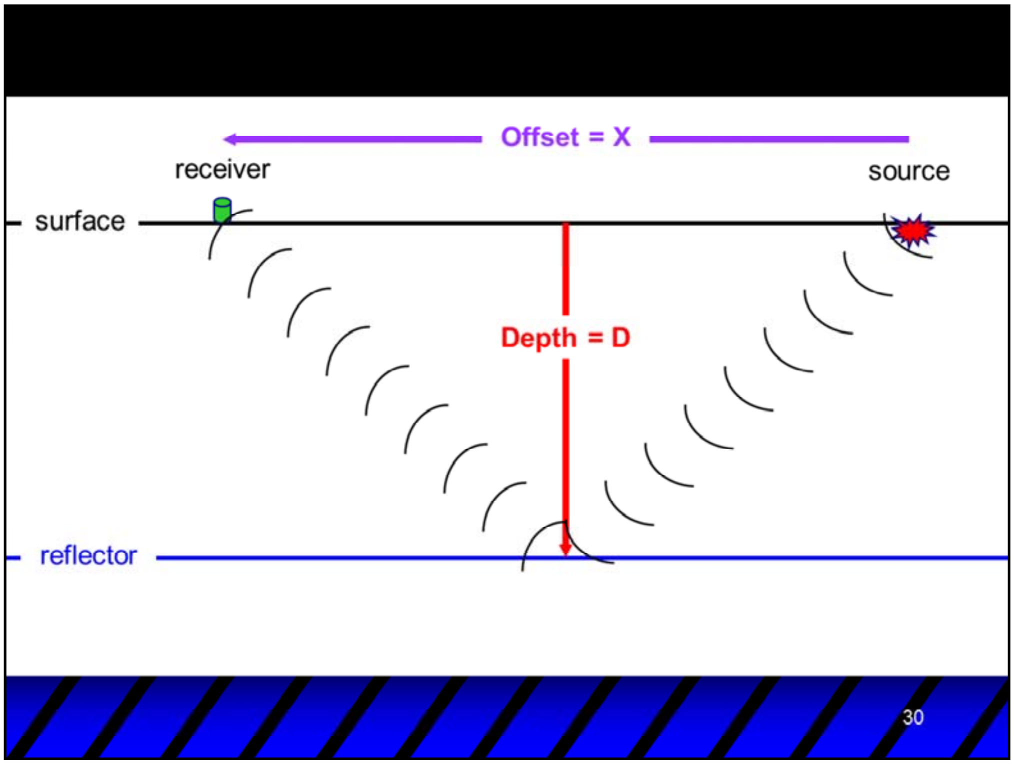
We can try to calculate apparent wavelength using equations such at those in the previous pages. But if we have real X-T data to examine, it may be more valid to measure apparent wavelengths directly from the record. Notice that any horizontal line on an X-T record is a line of constant time. That is a true representation of how the wavefield is emerging at the surface for that length of time after the shot was initiated. Few geophysicist realize that an X-T shot record at all points is an image of what is happening at the surface (as a function of where the surface is relative to the shot and as a function of time after the shot was initiated. When measuring directly from common-source records, we should consider the data after deconvolution (as decon will shorten the wavelengths).



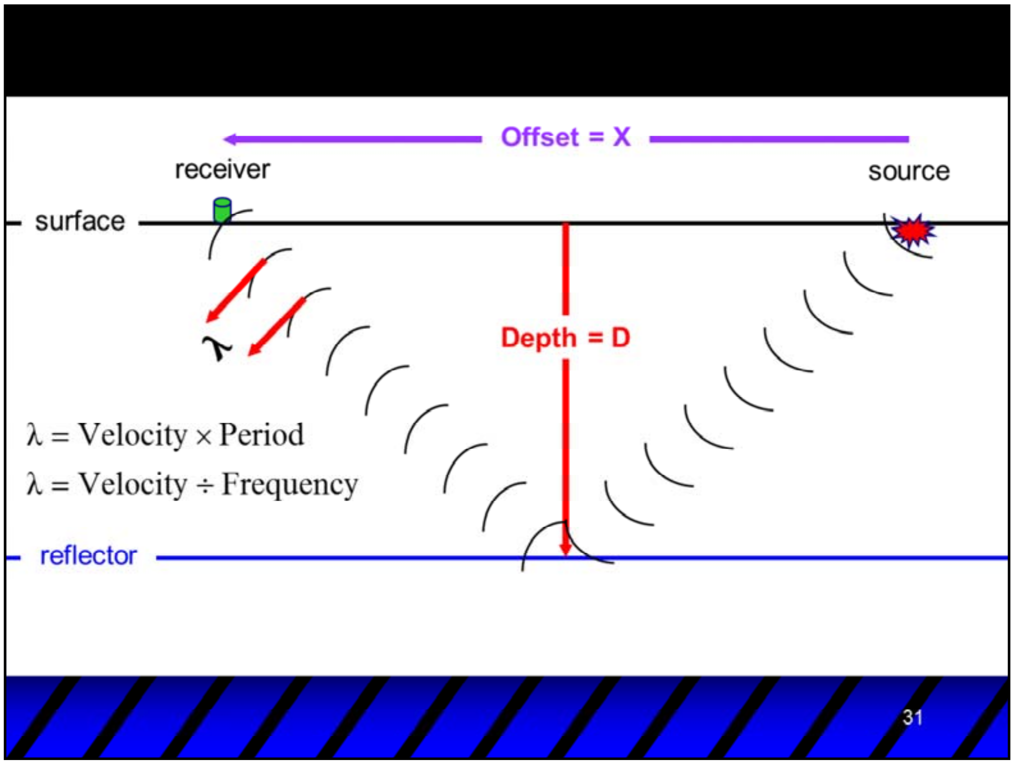
A common-shot record is a series of amplitude values in time and space. If we think of this like a spreadsheet with rows and columns, each with a value, then the value is the amplitude of the sample, the columns are “traces” and the rows are values for different traces at a constant time. The separation between rows is our sample interval and the separation between columns is our trace spacing. Our normal practice is to display this data as a series of graphs connecting the amplitudes down each column. Each column forms a trace for a certain receiver station. From these graphs we can measure dominant period and dominant frequency (1 / P).



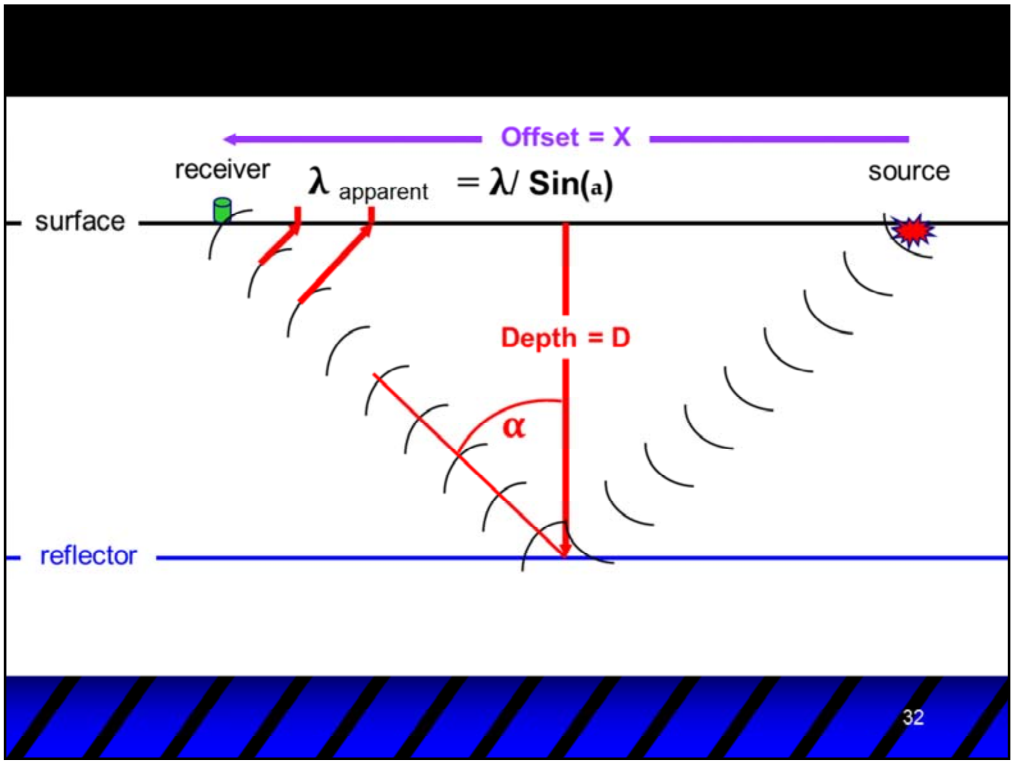
We can use the same data, but display it as a series of graphs connecting the data across the rows. This shows how the surface is changing in space at any one time. From these graphs we can measure apparent wavelength and apparent wavenumber (1 / λapp).
Toggle back and forth between the previous slide and this one to convince yourself that these are two representations of the same data set.



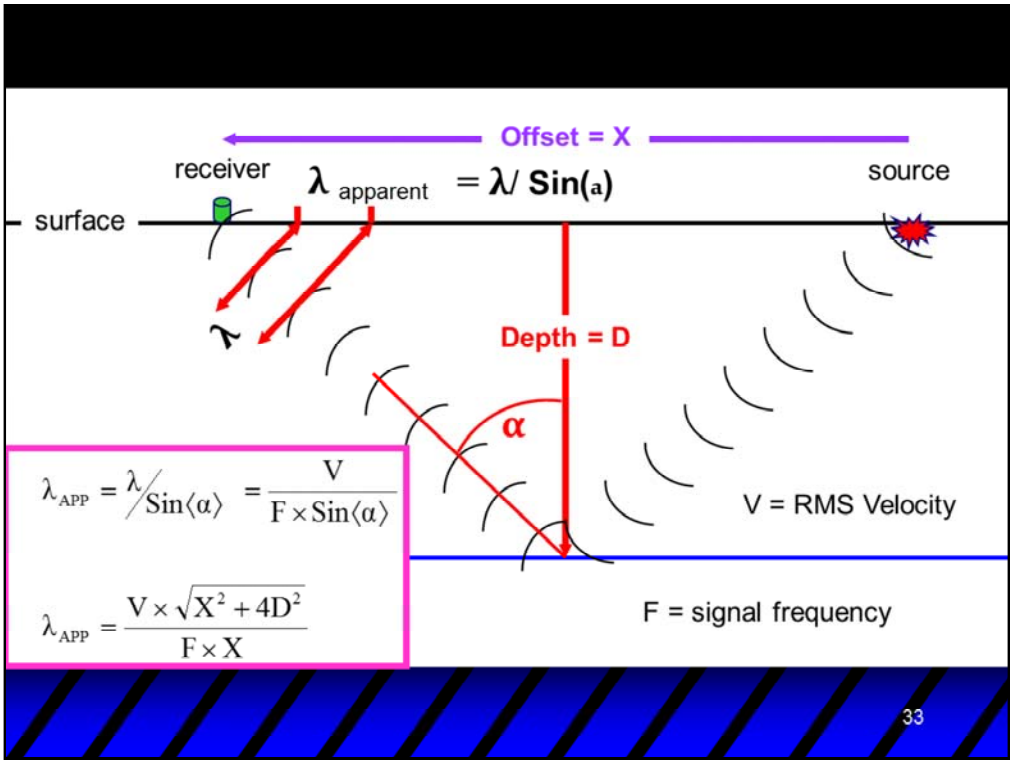
Let's derive an expression for apparent wavelength one more time. For a P-P wave (and a flat surface, flat reflector and homogeneous and isotropic medium), the reflection point will coincide with a point vertically below the mid-point of the source and receiver. The distance from the midpoint to the receiver is therefore X/2 and the depth of the reflector is D.



The true wavelength of the propagating P-wave is λ. This is V/F locally. On average it is λ= Vrms / F

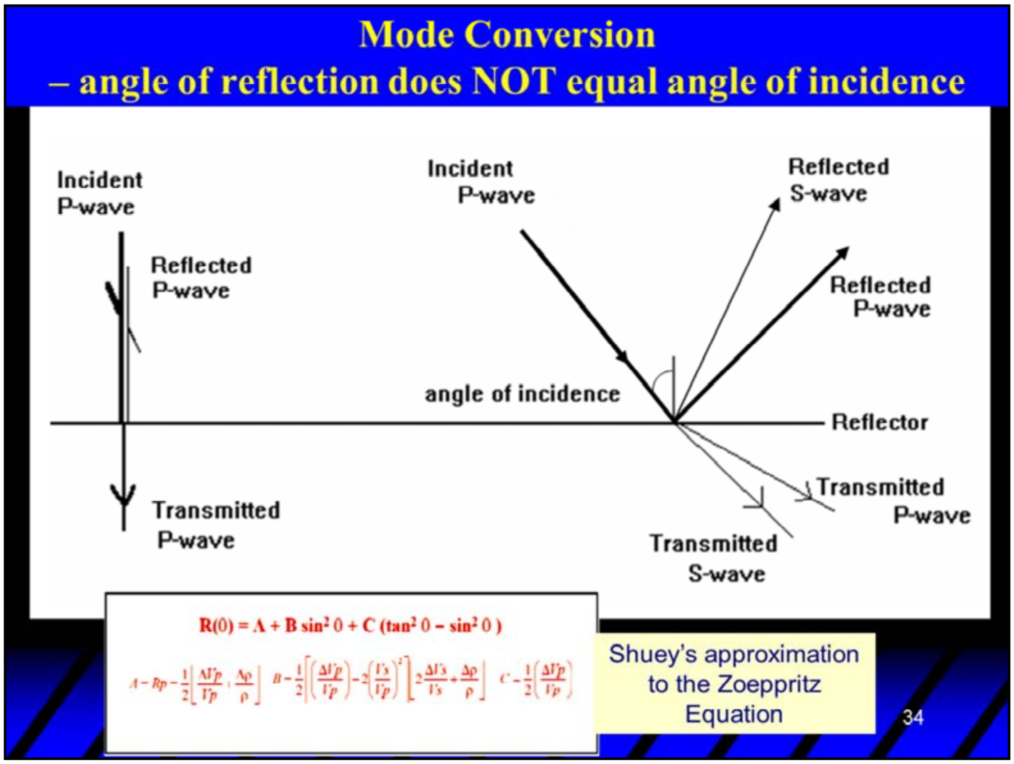


As the propagating wave emerges at the receiver, the apparent wavelength as measured across a horizontal surface will be $\lambda app = V / (F \sin(\alpha))$

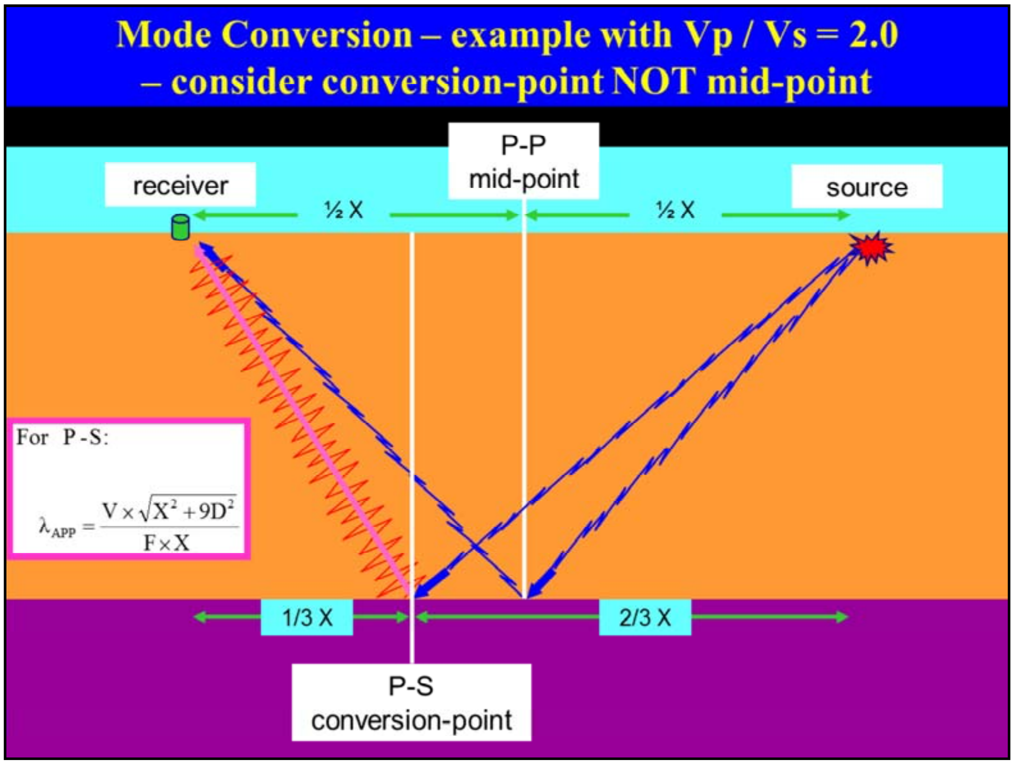


But what is sin(α)? It is the ratio of the side opposite to the reflection angle (X/2) divided by the length of the hypotenuse, which is SQRT(D^2 + (X/2)^2) or sin(α) = X / SQRT(X^2 + 4 D^2)

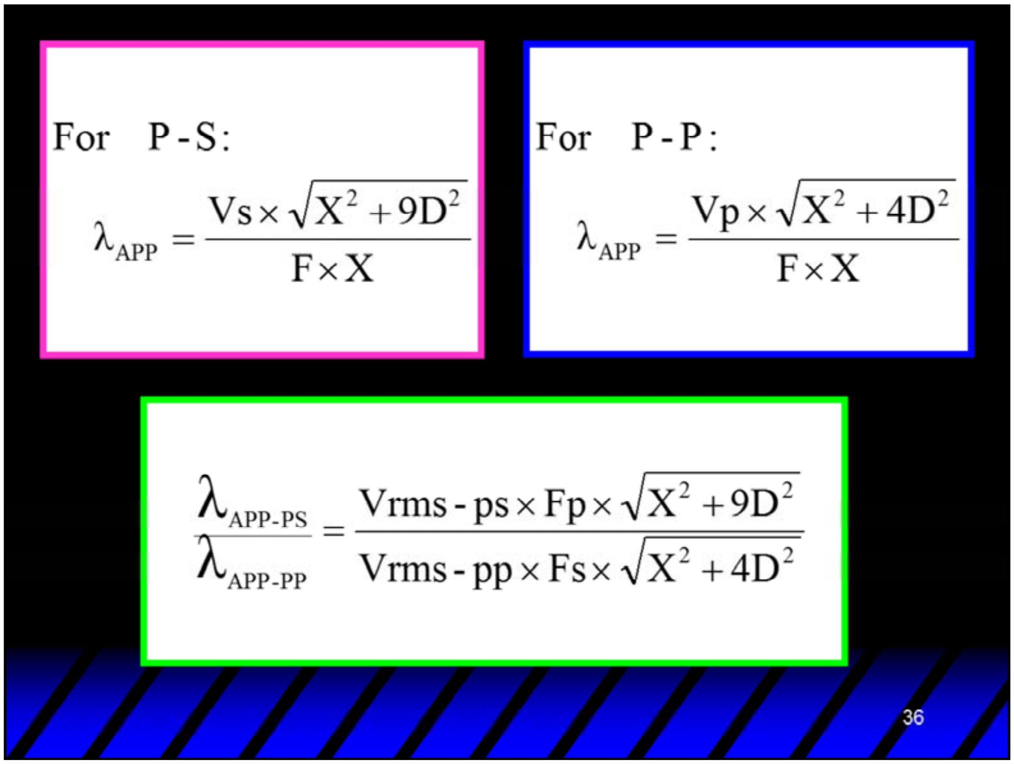
So now we can express apparent wavelength in terms of Vrms, F, X and D without concern for angles.



However, when we consider a converted-wave experiment where our down-going wave propagates as a P-wave and then converts to a reflected shear wave at a boundary of interest, we must recognize that the reflection angle of the shear wave is less than the incident angle of the P-wave. Of course, for the P-P conversion, the angle of reflection is equal to the angle of incidence.



So for P-S data, the reflection does not occur at the midpoint between the source an receiver. Depending on the depth of the reflector and the Vp/Vs ratio, the reflection point (now called a conversion point) is located closer to the receiver than to the source. For a VP/Vs ratio of 2.0, the asymptotic conversion point lies vertically below a point that is 2/3 of the way from the source to the receiver. This changes the geometry of the emergent angle and therefore of apparent wavelengths. Note that the equation is similar to the P-P case, but with a factor of 9D^2 as opposed to 4D^2.



Let’s consider the ratio of P-S apparent wavelengths versus P-P apparent wavelengths for a source and receiver at the same offset (X) and targets at the same depth (D). Here we use Fp to represent the dominant frequency of P waves and Fs to represent the dominant frequency of shear waves.

For $X = D$ and $Vp / Vs = 2$:

$$\frac{\lambda_{\text{APP-PS}}}{\lambda_{\text{APP-PP}}} = \frac{2 \times Fp \times \sqrt{10}}{3 \times Fs \times \sqrt{5}} = 0.94 \times \frac{Fp}{Fs}$$

For $X = 0$ and $Vp / Vs = 2$:

$$\frac{\lambda_{\text{APP-PS}}}{\lambda_{\text{APP-PP}}} = \frac{2 \times Fp \times 3D}{3 \times Fs \times 2D} = \frac{Fp}{Fs}$$

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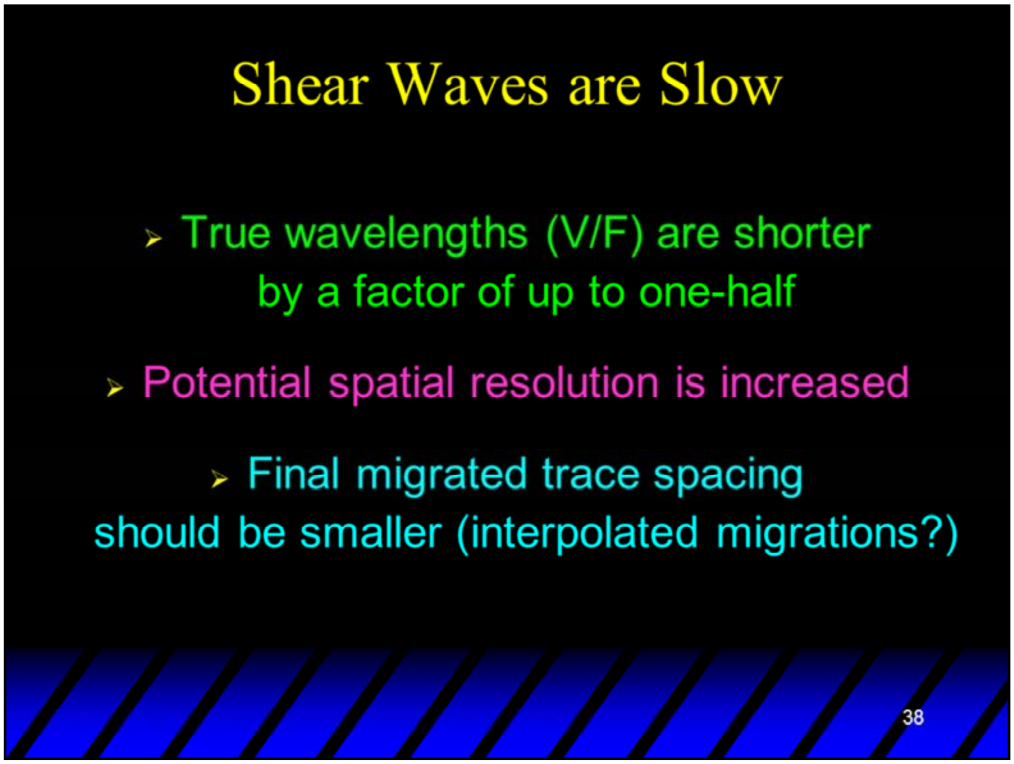
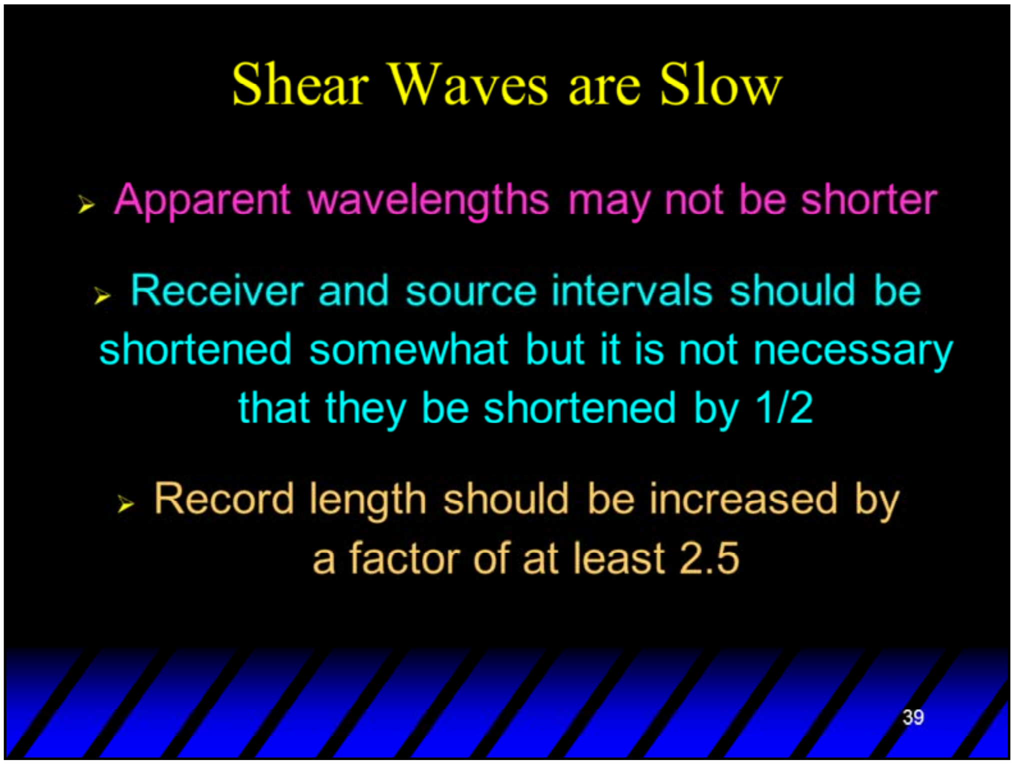
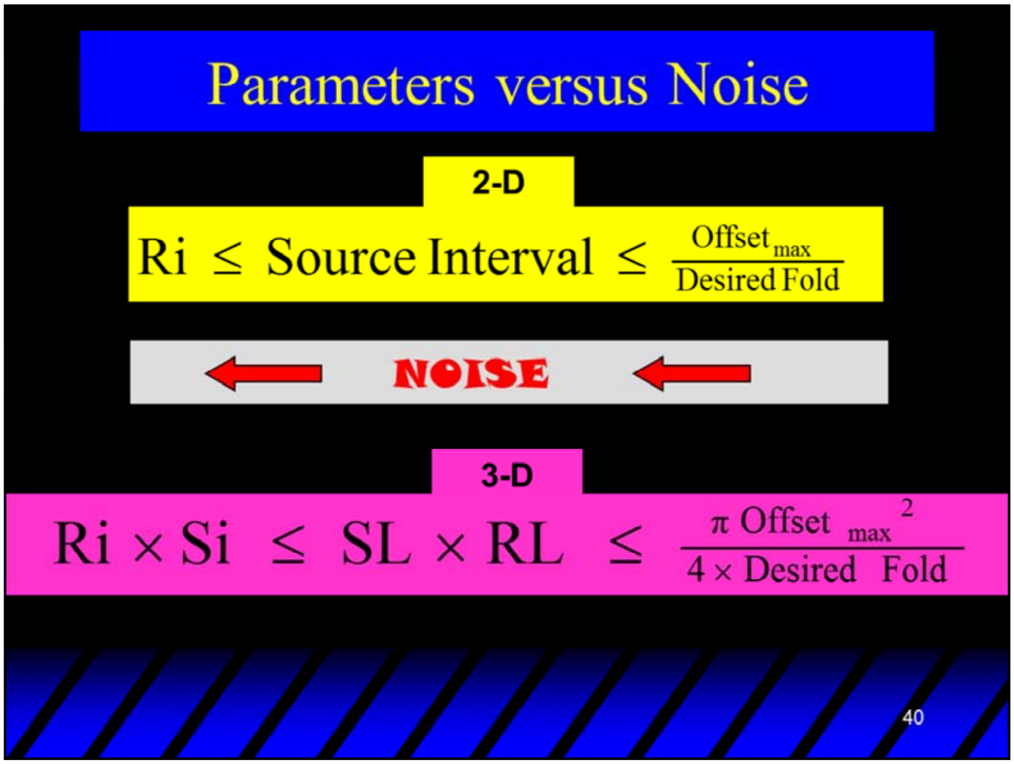
For a Vp/Vs ratio of 2.0, then Vrms for the P-S data will be about 2/3 of the Vrms for the P-P data. We find that for near offsets the ratio of apparent wavelengths depends only on the ratio of the frequencies of P and Shear data. For far offsets the ratio of apparent wavelengths is nearly equal (94%) to the ratio of frequencies. For the same frequencies, shear wave true wavelengths are much shorter that P-wave true wavelengths. But (for the same frequencies), shear wave apparent wavelengths are about the same as P-wave apparent wavelengths. The fact is that shear wave data is often much lower frequency than P-Wave data and therefore the apparent wavelengths of shear-waves are longer than P-waves and are therefore easier to measure.



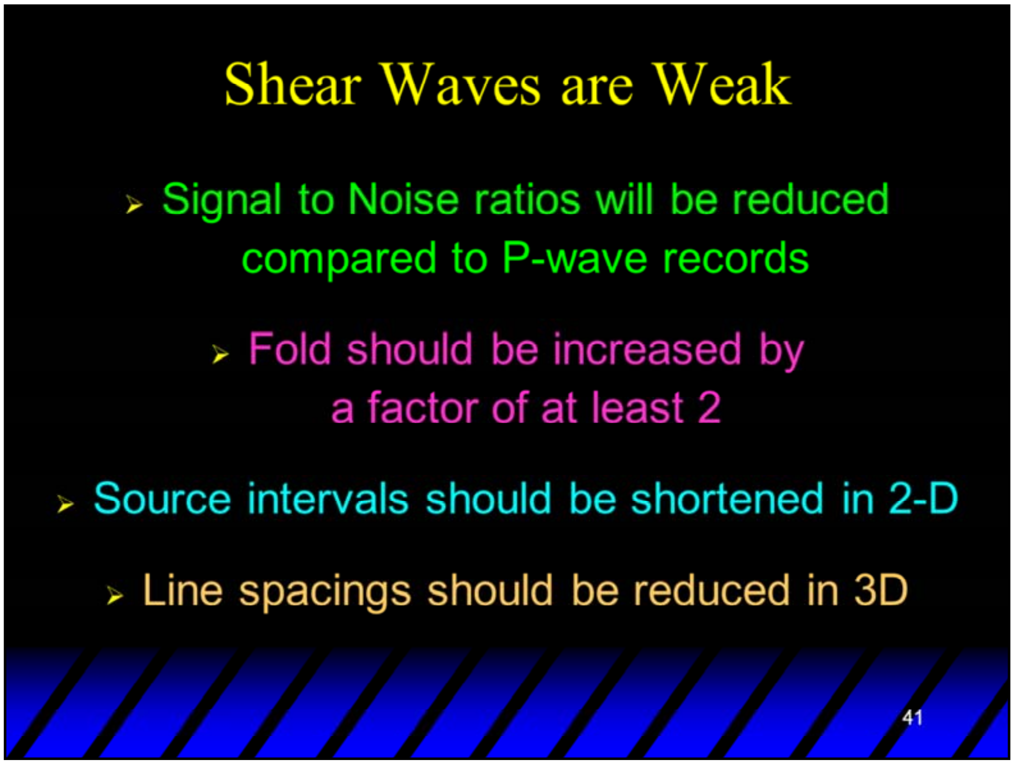
Since true wavelengths of shear waves will be shorter than P-waves (for similar frequencies) it is recognized that they have greater potential resolving power. In civil engineering and environmental geophysics, we use shear waves almost exclusively in order to obtain improved resolution. However, for deep targets, shear waves experience a greater amount of absorption and we lose frequency content rapidly with depth. Therefore, some of the above statements may not be as true for deep oil exploration as they are for shallow engineering applications.



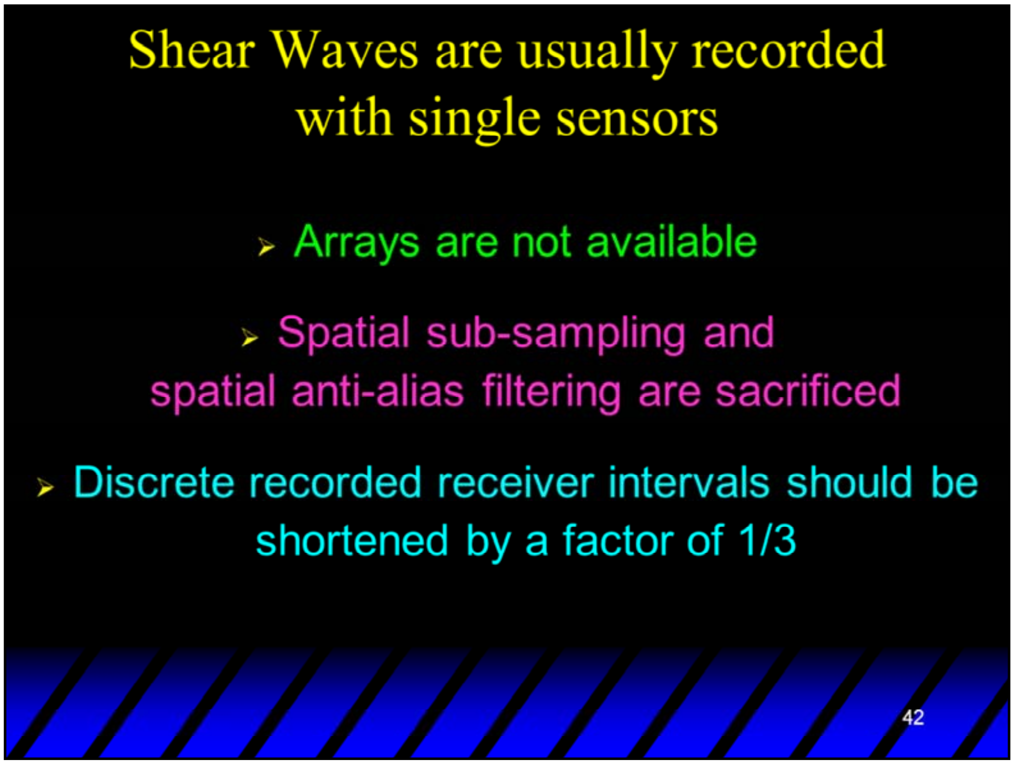
Apparent wavelengths of shear waves may, in fact, be longer than P-waves, so the second comment above is not necessary for sampling shear waves. However, we most often measure shear waves with single discrete receivers as opposed to an array of sensors as is more common for P-waves. This means that we give up the sub-sampling of short noise wavelengths that we get in conventional P-wave recording. In order to regain this, we recommend that single sensors be deployed at no more than 1/3 of the normal array intervals. Note that this is a general spatial sampling consideration for single sensors versus arrays and the recommendation is not a consequence of shear wave recording.



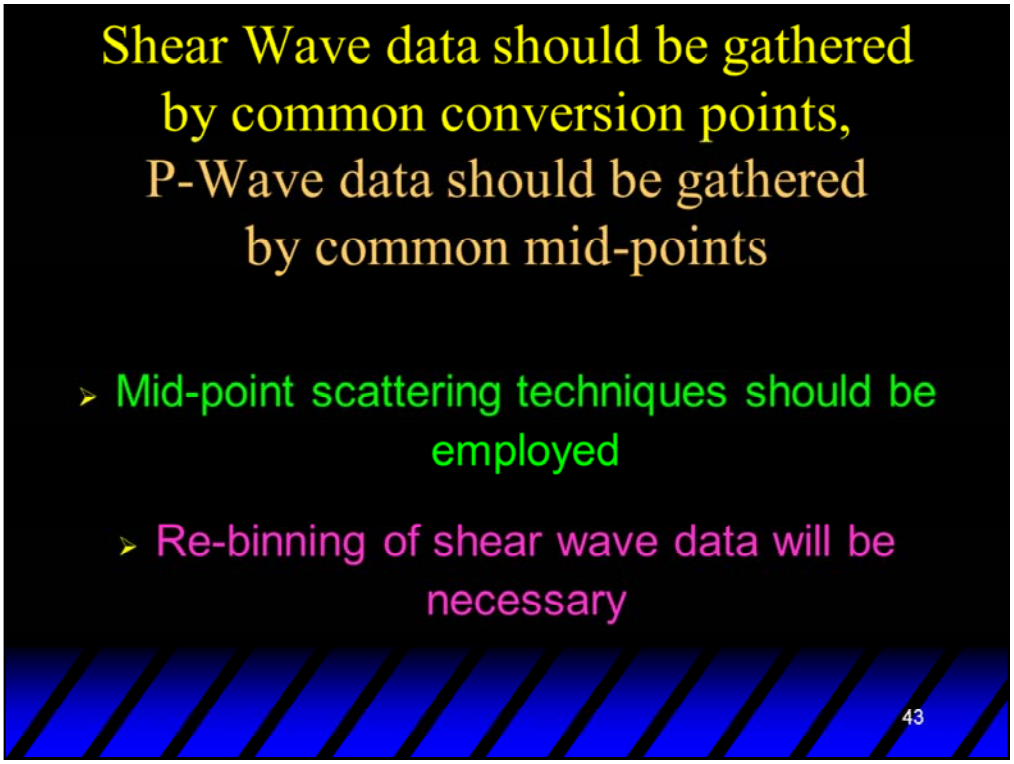
One significant problem is the shear waves are weak. Therefore, the signal-to-noise ratio of shear wave data is much less than for P-wave data. This means we must build more robust designs for shear waves. In 2-D, this means reducing our source interval. In 3-D, this means reducing our line spacings.



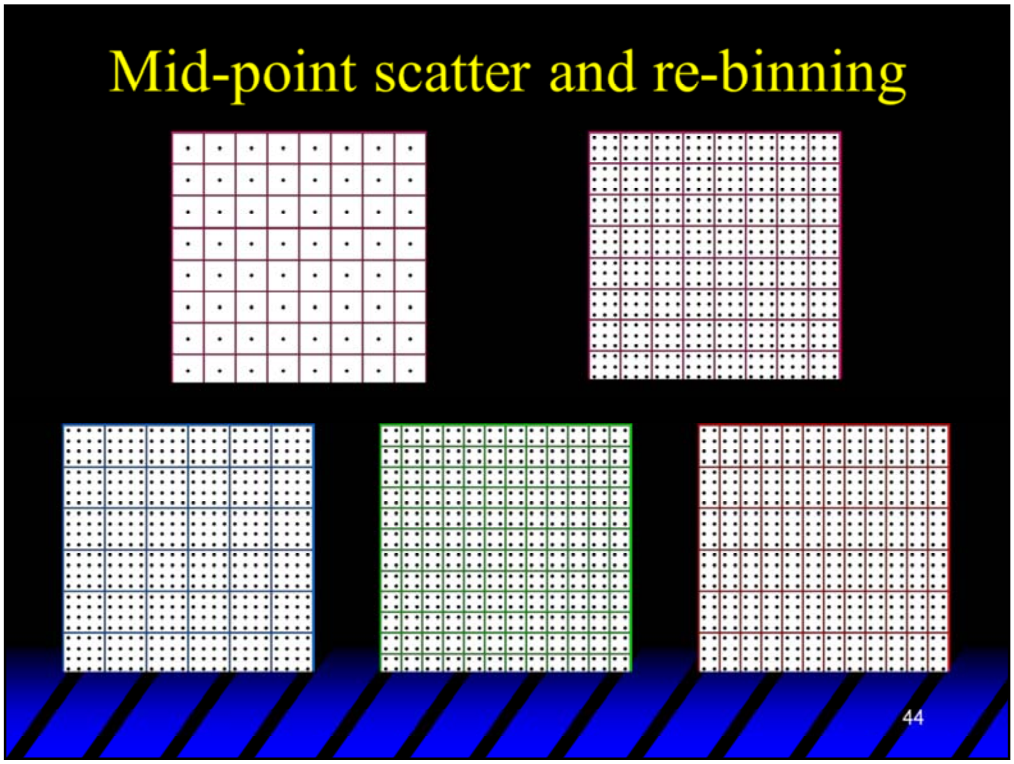
We should be prepared to spend more money if we are serious about making use of the shear-wave data.



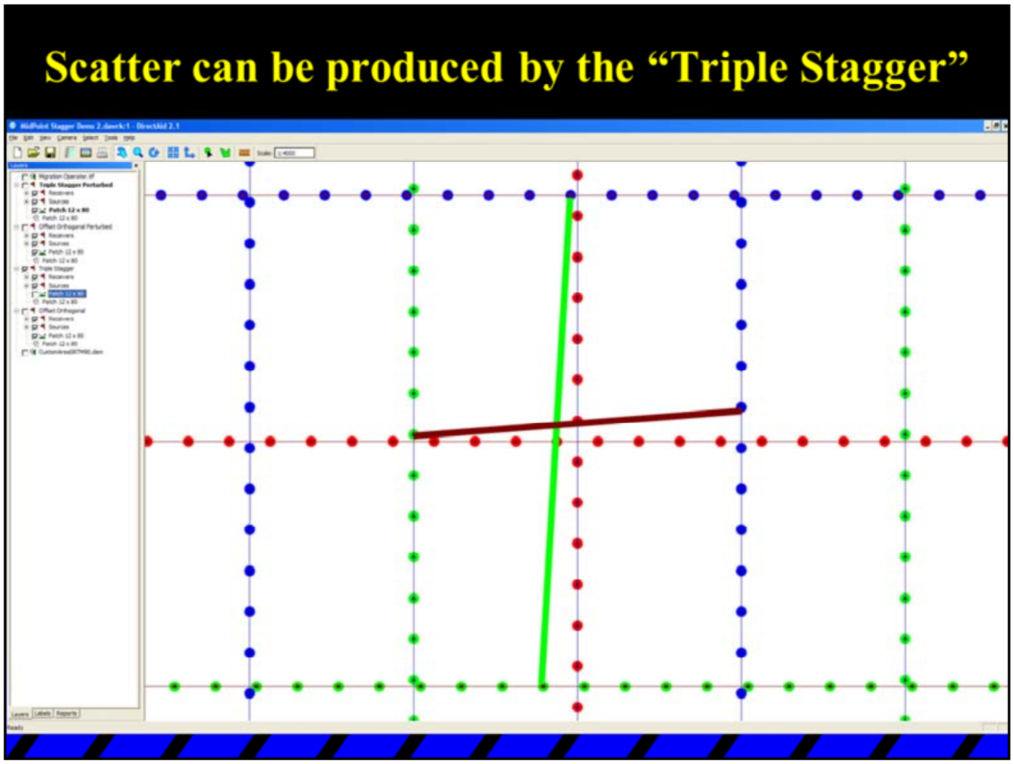
Arrays have been branded with a bad reputation. However, it is clear in noisy areas that arrays are a very important part of dealing with noise. The short spacing between array elements pushes the Nyquist wavenumber to higher values (allows us to measure short-wavelength noise without aliasing). The summing of the array elements forms a filter that is an effective anti-alias filter when forming large receiver intervals. This sub-sampling for shorter wavelength noise (such as scattered surface waves, for example) is not available when single discrete receivers are used unless receiver intervals are shortened. Recording discrete point receivers can be a good thing provided the spatial separation of the sensors is not much greater than the separation of elements in a typical analog array. We strongly recommend that single-sensor spacing be 1/3 or less of a conventional program designed to use arrays.



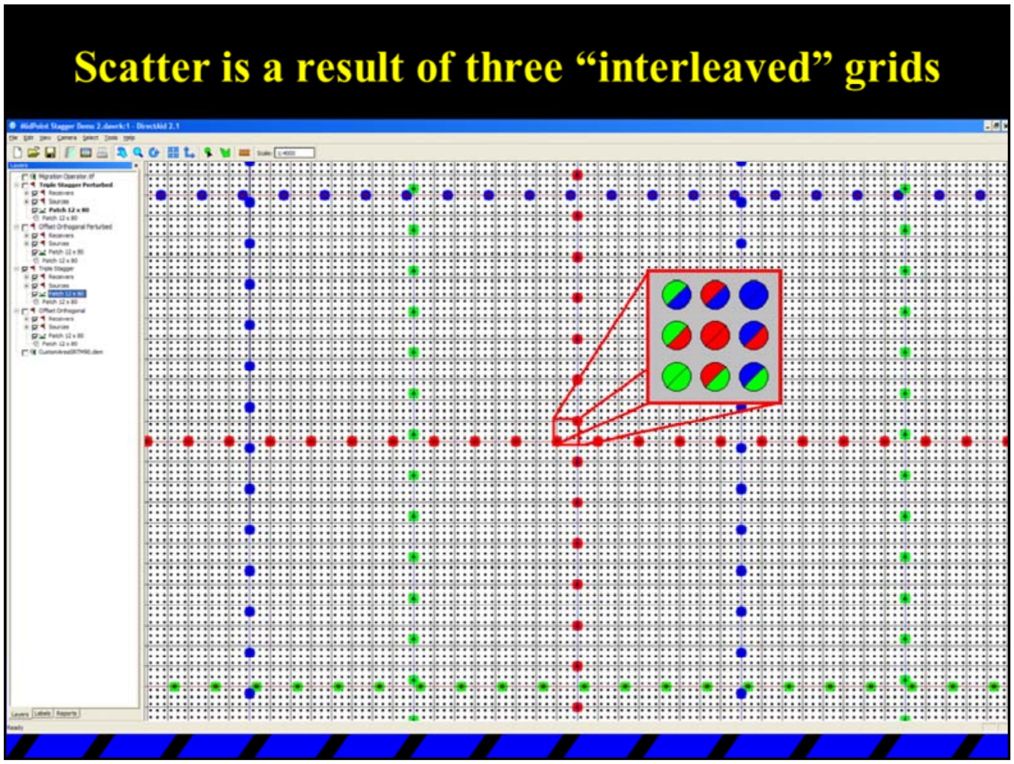
Due to different reflecting/conversion points and due to differing wavelengths, shear-wave data must be collected differently than P-wave data. The binning of data prior to stack must be based on conversion points rather than mid-points.



We recommend that some scheme of mid-point scattering be used to provide the flexible binning options that are necessary for converted-wave data. Re-binning options are not available with so-called mid-point focused designs.
There are many powerful reasons for designing mid-point scattered programs. The re-binning option is just one such reason. More powerful reasons are related to statistical diversity, sampling of pre-stack migration operators, and 5-component COV Cazdow data interpolations.

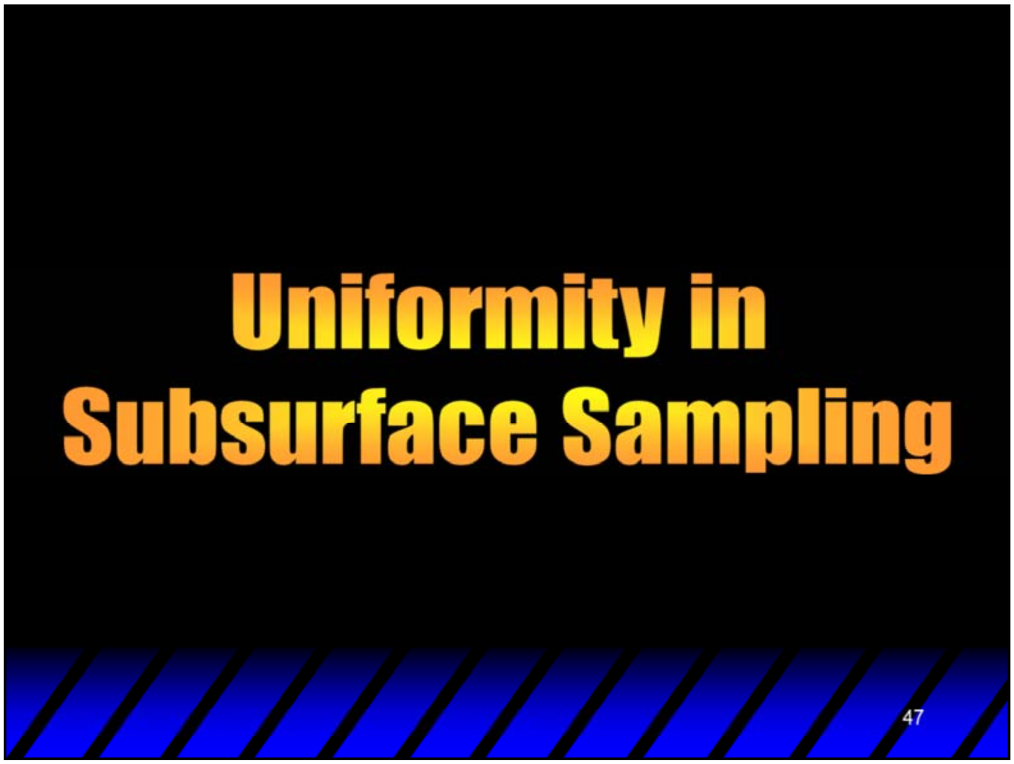


Forced midpoint scatter can be easily produced by relative shifts of point positions along adjacent lines of sources or receivers.
For a triple stagger that produces 9 midpoint centers per bin (3 x 3), the relative shift from line to line should be 1/3 of an interval.
We usually ensure that no intersections produce coincident sources and receivers by using relative point shifts of 1/6, 3/6 and 5/6 of a source or receiver interval.

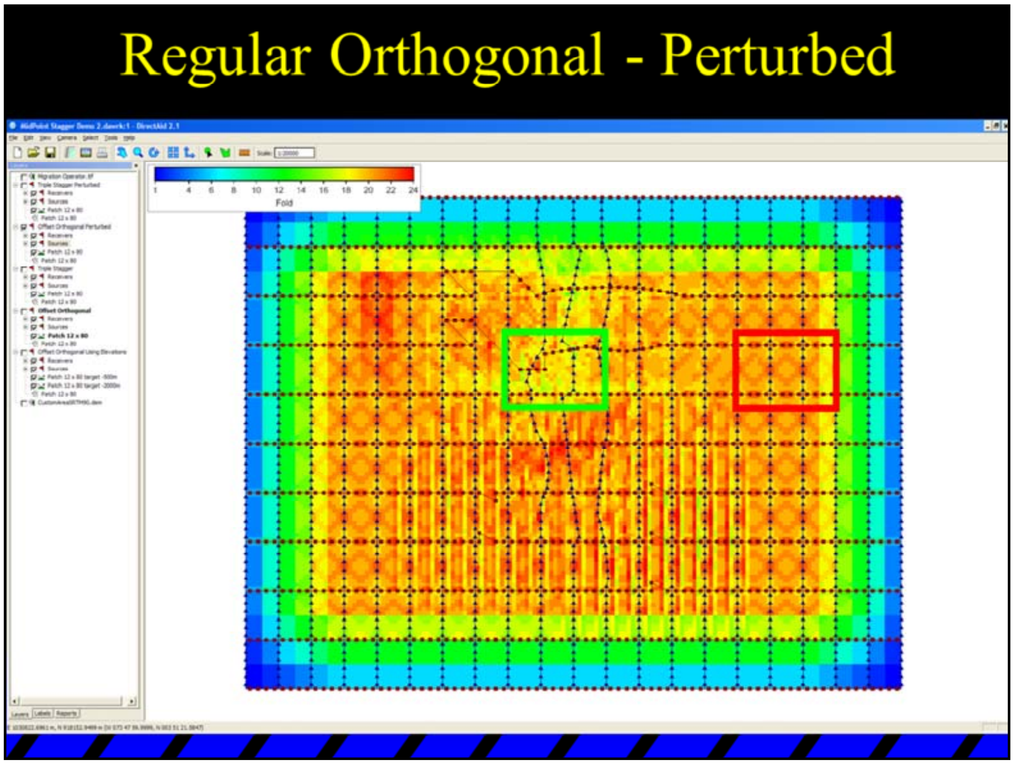


This, in effect, produces three interleaved grids that together produce the desired midpoint scatter.

We have observed many advantages to midpoint scatter. The greatest advantage that will be described in terms of improved spatial sampling of pre-stack migration operators.

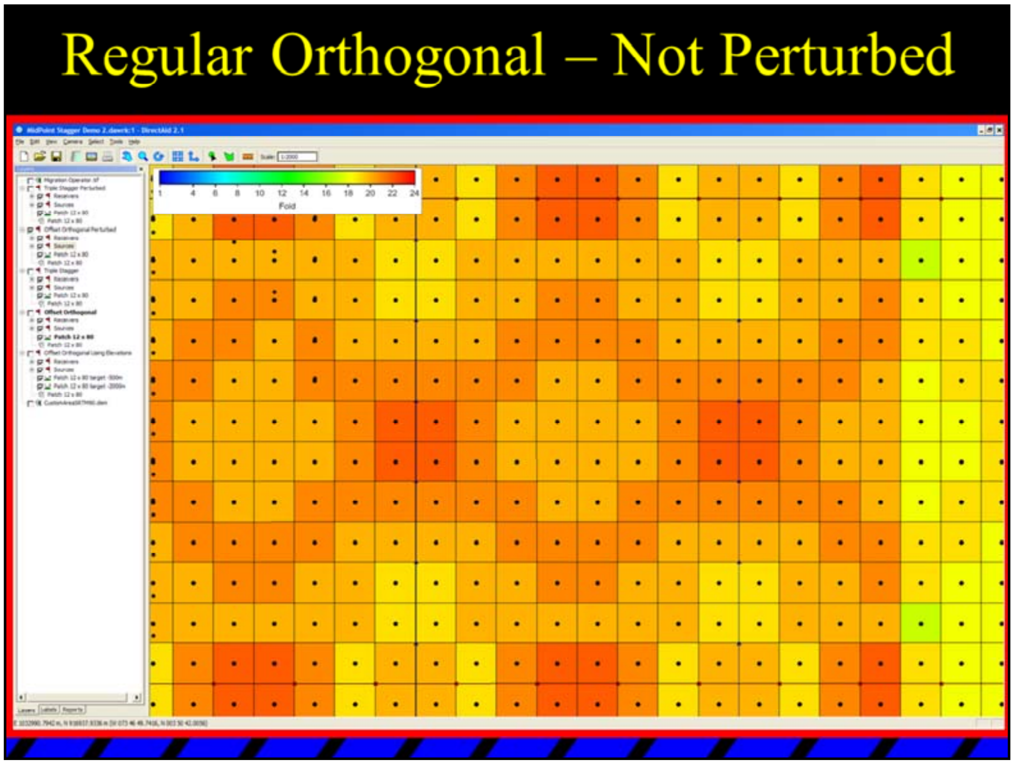


Do we ever have Mid-Point Focused surveys in reality? What happens when designs become perturbed during implementation?

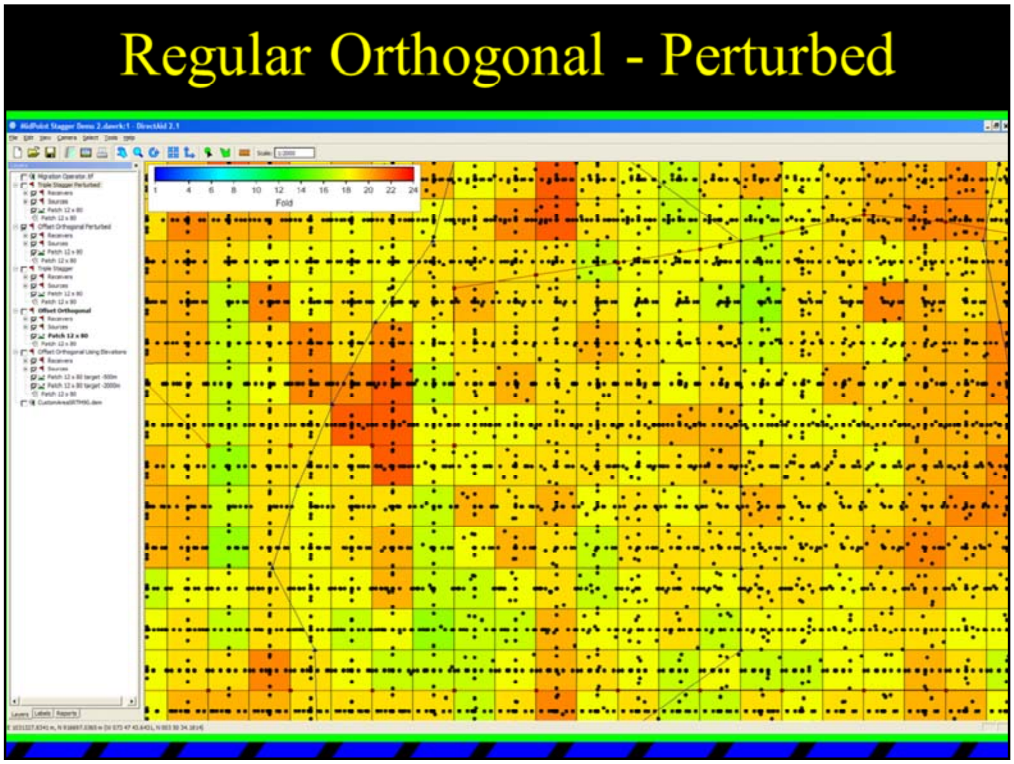


Here is a Regular Orthogonal design (mid-point focused) showing a fairly regular area (red square) and an area where sources and receivers have been moved (perturbed – green square).

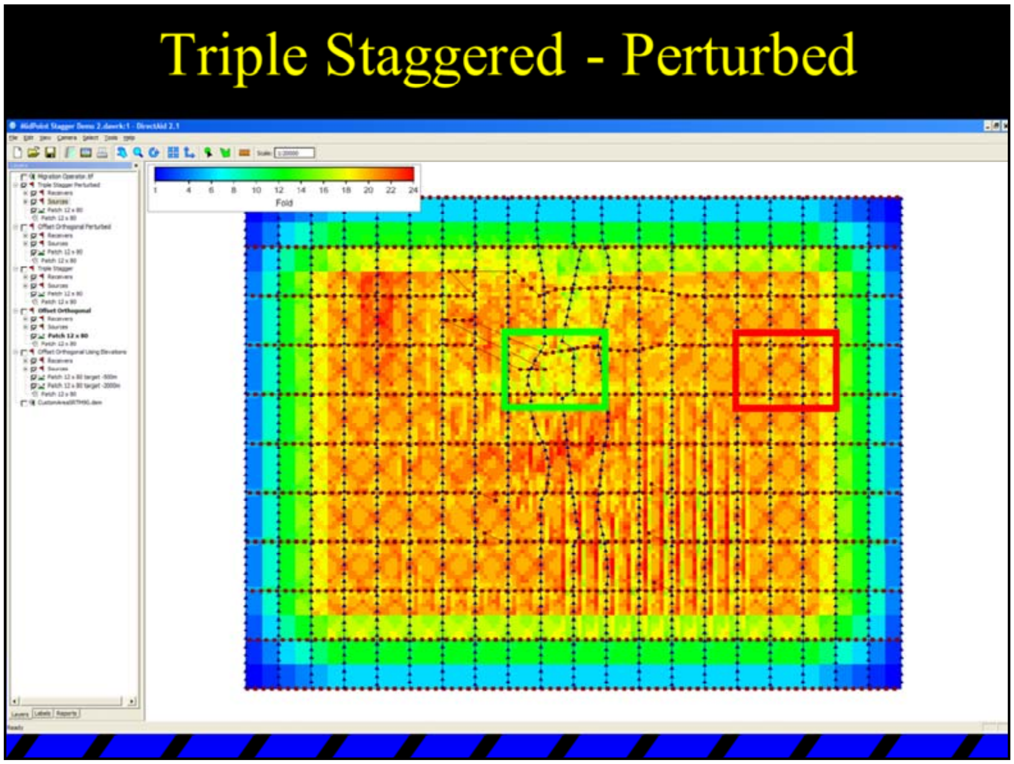
Notice that regular fold patterns (and patterns of other more important statistics) are disrupted by perturbation.



A detail of the un-perturbed area of the regular orthogonal 3D shows the mid-point focused nature of the design.

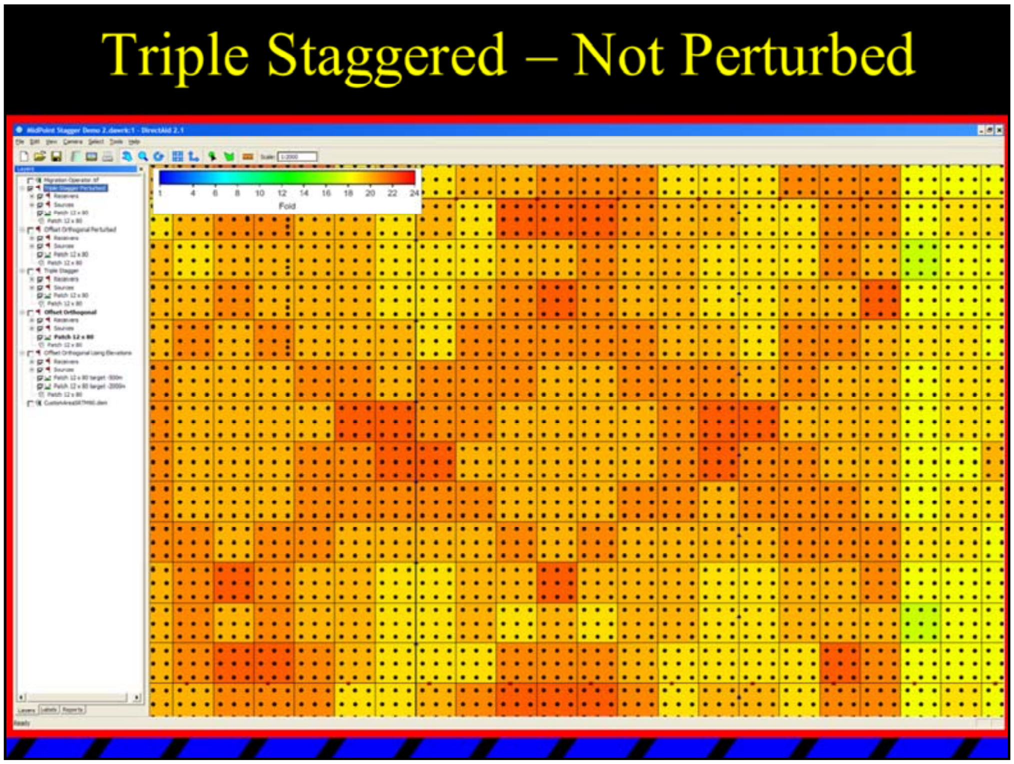


A detail of the perturbed area of the regular orthogonal 3D shows that mid-points are no longer focused in this area. Typical perturbations produce mid-point scatter.

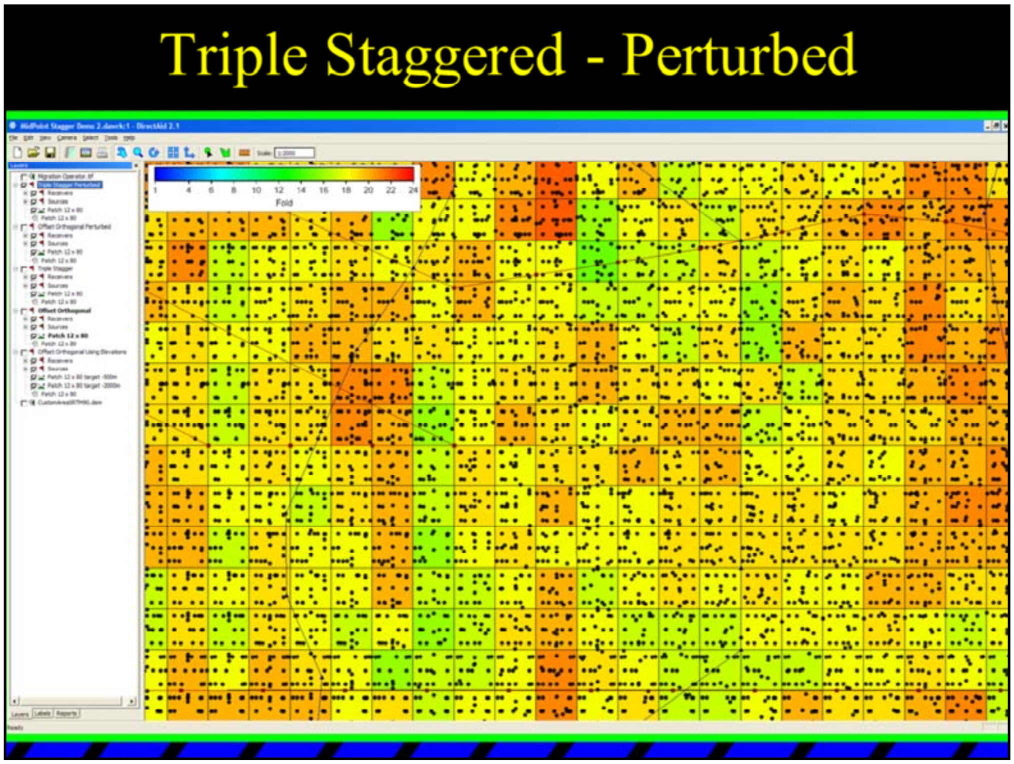


Here is a Triple Staggered design (mid-point scattered) showing a fairly regular area (red square) and an area where sources and receivers have been moved (perturbed – green square).

Notice that regular fold patterns (and patterns of other more important statistics) are disrupted by perturbation.

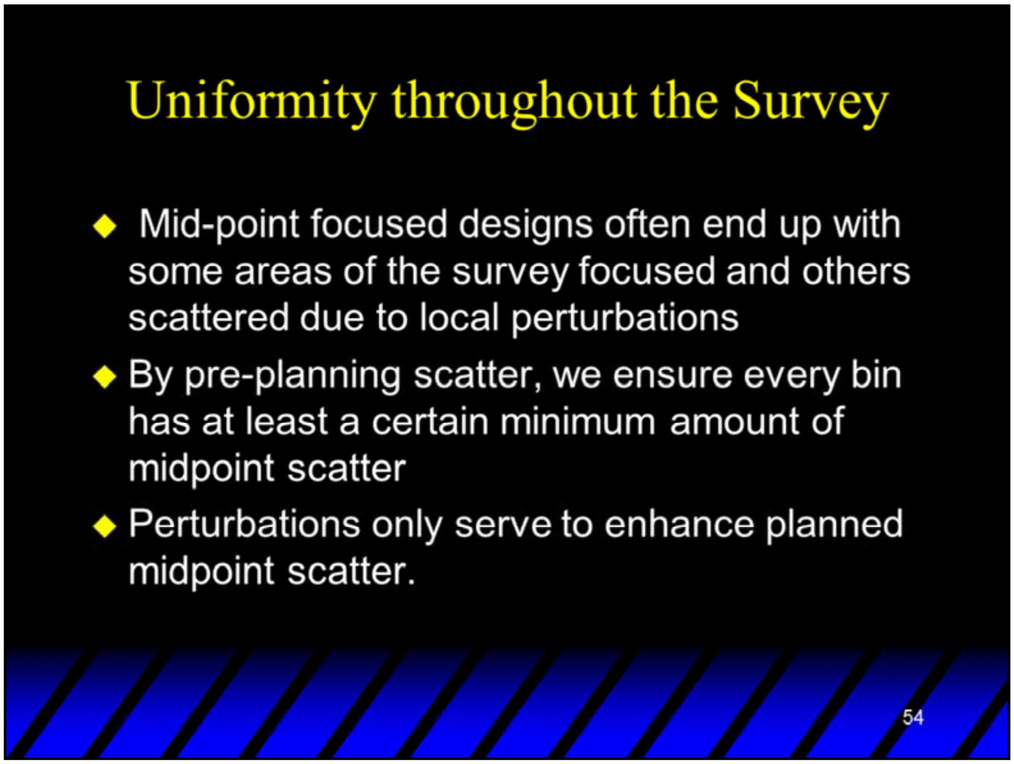


A detail of the un-perturbed area of the triple staggered 3D shows the mid-point scattering.

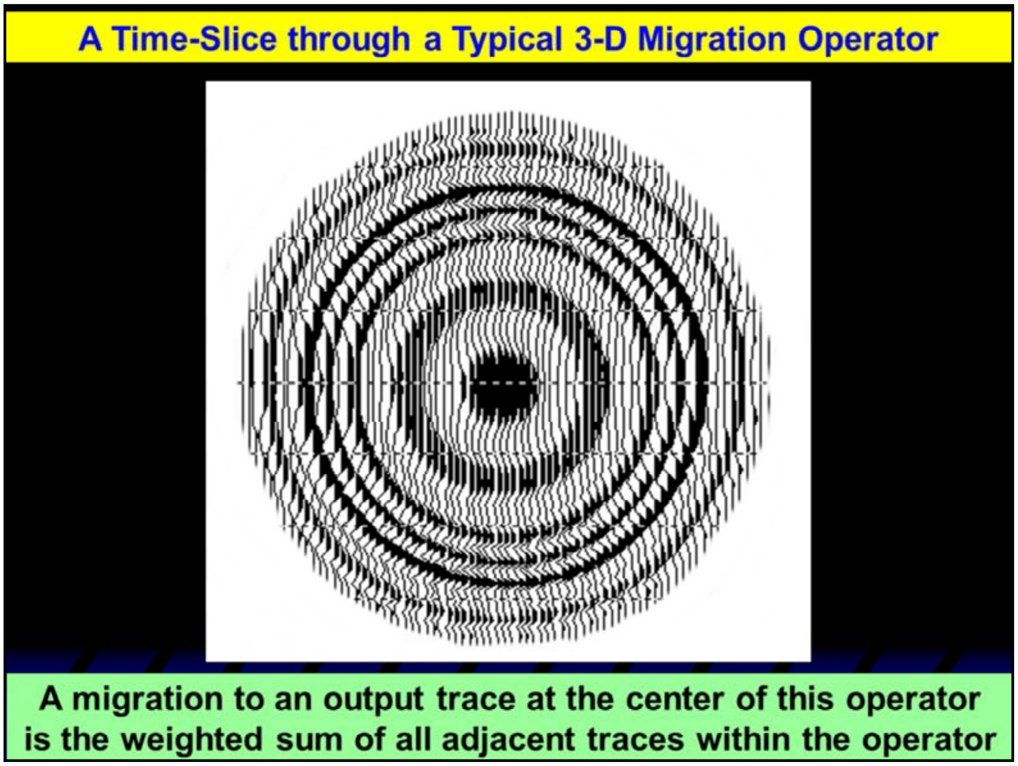


A detail of the perturbed area of the triple staggered 3D shows the mid-point scattering is further enhanced by perturbation.

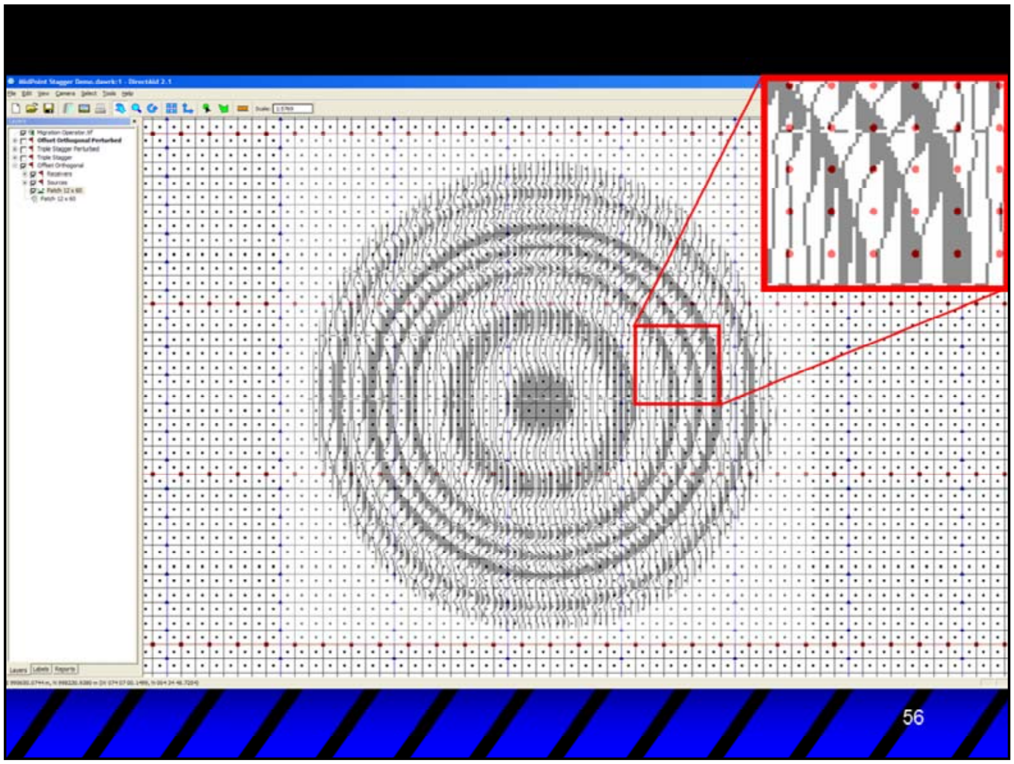
The regular pattern of mid-points is disrupted (possibly a problem for the flexible binning concept), but this is actually desirable for most of our identified advantages of scattering.



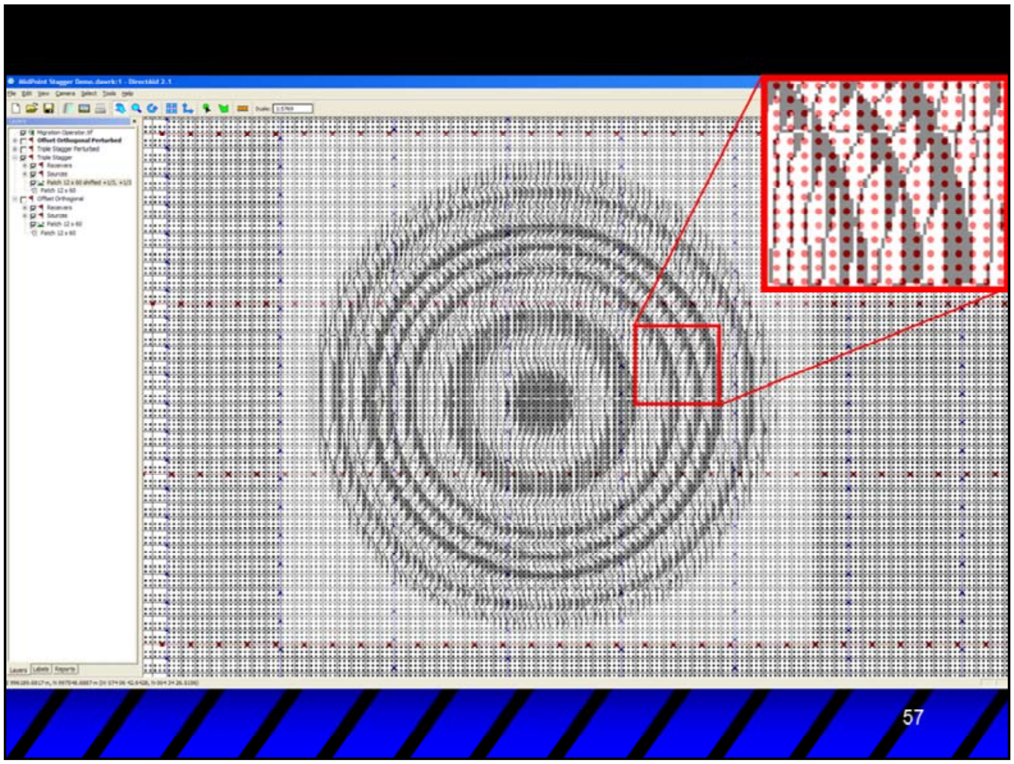
Planned mid-point scatter in a design ensures that no local area in a survey has substantially different mid-point scatter than other areas.



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.

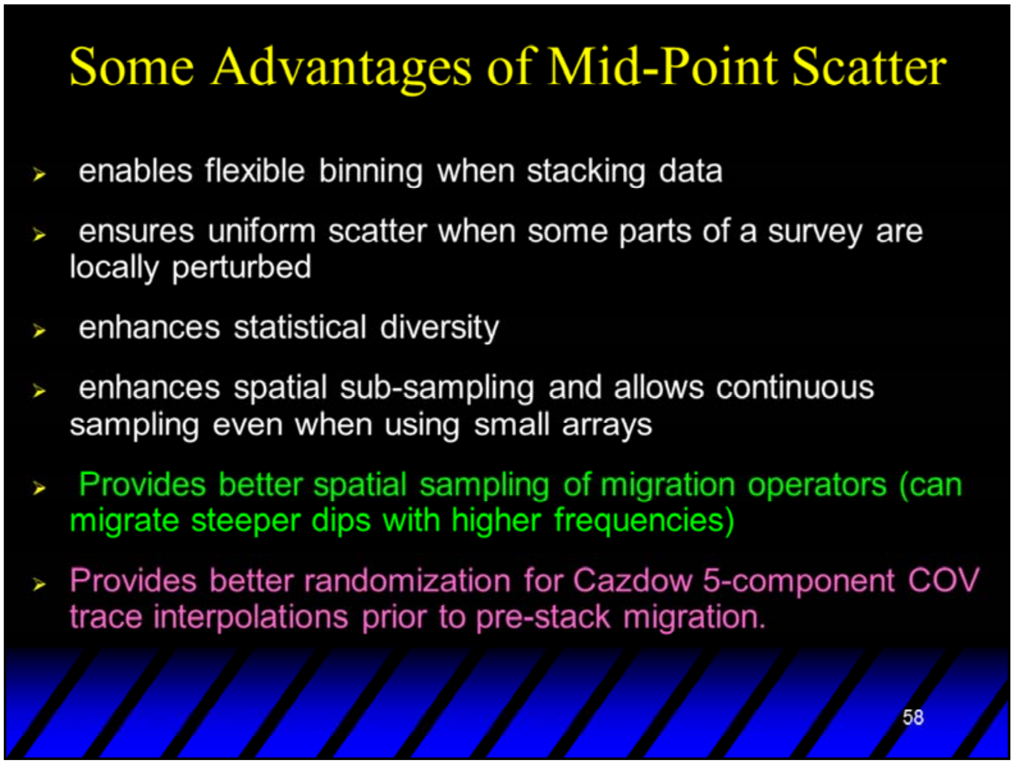


This migration operator has an aperture (radius) of about 480 meters, corresponding to a very shallow reflector. The model is a normal orthogonal with no forced midpoint scatter. Note that we have traces represented by mid-point indexes separated by the natural bin size. Notice that some of the shorter 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.



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 migration operator becomes larger and the migration becomes more powerful and focusing signal and attenuating noise.



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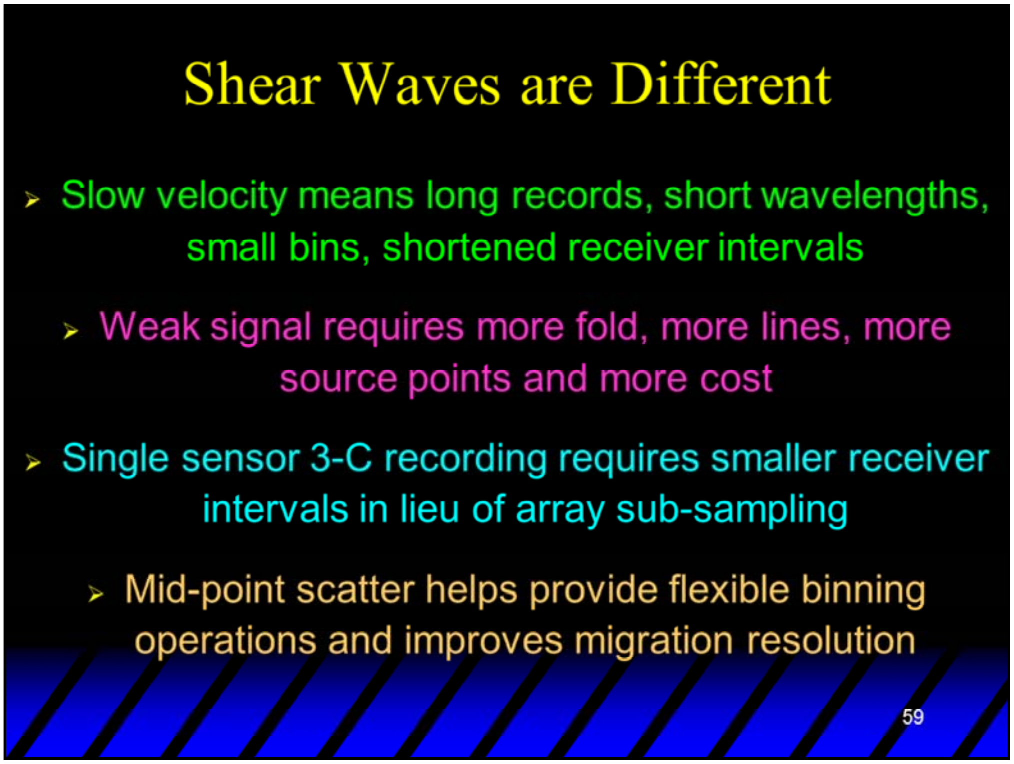

Many surveys are currently recorded with the attitude that only vertical components will be processed for now and the horizontal components will be stored for processing at some later date. If shear wave data is to be useful now or at any time in the future, it is important that we make certain adjustments to our program designs in order to ensure that the shear-wave data will be useful.


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