Effective design for full-wave three-dimensional land and marine seismic surveys

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Abstract

While many of the same basic principles apply, designing full-wave 3D seismic surveys is considerably more complicated than designing conventional P-wave 3Ds or even pure S-wave 3Ds. With faster down-going (P-wave) energy and slower up-going (S-wave) reflections, common midpoint analysis fails for converted wave data. These data must be analyzed in the common conversion point (CCP) domain. Since Vp/Vs ratios vary with depth and lithology, estimating converted wave fold coverage depends strongly on knowledge of the subsurface geology. Because of the asymmetry of converted wave ray paths, a survey design that acquires uniform P-wave (or S-wave) fold coverage will result in non-uniform converted wave fold coverage. Filling gaps and reducing variability in the CCP fold coverage can be a complex exercise. Several land and marine (OBC/OBS) survey design types (wide and narrow azimuth, orthogonal and parallel, slant and variable line spacing) are examined using different bulk Vp/Vs ratios for estimating converted wave fold coverage for targets at different depths. Additional comparisons are conducted using converted wave ray tracing through a layered model with variable Vp/Vs ratios.

Due to offset mutes, shallow fold coverage is more difficult to acquire in all 3D survey design problems and requires denser source and receiver line spacings. Because of the asymmetry of ray paths for converted wave data and the typically high Vp/Vs ratios encountered in shallow sedimentary sequences, this shallow imaging problem is even more dificult for converted wave data, requiring even higher density receiver line spacings on the surface. Slanted shot lines and variable receiver and source line intervals will help to reduce CCP fold variations. Wide-azimuth survey designs will allow more subsurface overlap and will improve the cross-line fold coverage of converted wave surveys.

For the purposes of this paper, full-wave 3D survey design will focus on P-wave and converted-wave (PS-wave) acquisition. The main design factors involved in including the pure S-wave ray paths would be the addition of shear wave sources in orthogonal polarizations.

Introduction

The goal of full-wave seismic acquisition design is to simultaneously record both P-wave and converted wave (PS-wave) seismic data with the same acquisition geometry. One way to approach this issue is by using basic design principles and determining the constraining factors derived from P-wave and PS-wave criteria simultaneously. A great deal of knowledge and experience has developed around 3D seismic survey design primarily associated with P-wave acquisition. The ocean-bottom environment tends to make unique demands on the survey design process, mostly because of the different types of recording instruments and configurations available for use in that environment. However, the fundamentals of seismic survey design remain very consistent for land, OBC and even marine streamer data. By assuming that the same fundamentals apply to PS-wave acquisition as well, a systematic design approach to simultaneous P-wave and PS-wave acquisition can be accomplished.

Fundamental to the survey design process is the understanding of the seismic imaging goals for the prospect. To fully appreciate the constraining factors for a survey design, we will assume a very demanding and strict set of imaging goals.

- We want to record P-wave and PS-wave data simultaneously with the same recording geometry.
- The P-wave data and the PS-wave data should be comparable from an interpretation viewpoint. We will assume this means similar subsurface coverage and similar resolution.

If we review the fundamentals of the design equations and the factors controlling the decision making process, we can easily reduce the design problem to three simple categories: bin size calculations, offset calculations, and survey size and orientation. Availability of recording equipment (such as number of cables) and environmental or operational issues usually dictate the specific survey acquisition geometry. Other factors also impact final design, but, in most cases, few factors impact the resultant geometry more than these basic geophysical parameters.

Method

An example of using the constraining design factor is shown using the well-known bin size equation:

$$BinSize = \frac{Velocity}{4 * Frequency * \sin(dip)}.$$

This equation relates wavelength of the seismic event to sampling theory. The velocity used in the numerator is commonly the interval velocity for the seismic wave at the objective horizon, although the RMS velocity to the objective is also often used. The frequency value in the denominator is the maximum recoverable (unaliased) frequency for the target event. The "dip" term is structural dip, but is generally recommended to use a minimum dip value of 30^o to allow for the proper sampling and migration of diffraction events. This equation is routine for most survey design exercises because it ties the survey design to the geological target properties from a seismic sampling point of view. The PS-wave is generally the constraining factor for bin size calculations because the shear wave propagation velocity is always slower than that for the P-waves, and it predicts a smaller bin size. This equation also illustrates the relationship between spatial sampling and the recoverable frequency. While the recoverable frequency for the PS-wave data will often be lower than that for the P-wave data, the difference will usually be less than the ratio between the P-wave and S-wave velocities (Vp/Vs). This will impact the P-wave recording by over-sampling, but it will also ensure that the acquisition parameters are adequate for both types of seismic events. Similar logic can be applied to offset requirement calculations, aperture calculations, and record length. Generally, near offsets and bin size will be constrained by PS-wave parameters (particularly the lower S-wave velocities), while far offset and migration aperture calculations are usually constrained by the P-wave parameters (generally higher velocities). If one utilizes an migration aperture equation that includes velocity, P-wave parameters will always predict a larger aperture for subsurface sampling.

Strict conformity to the imaging goals prescribed previously produces a survey geometry the same size as a standard P-wave design geometry but more densely sampled. Another issue that gets a great deal of attention in PS-wave design is conversion point shift at depth. This is commonly called the CCP or common conversion point. This point predicts the subsurface sampling point for a given source-receiver pair. It is always shifted towards the receiver station due to the slower upward-traveling shear wave velocity after conversion. Depending on the depth and ratio between the P-wave and S-wave velocities (Vp/Vs), this will impact the uniformity of the subsurface coverage for the two types of recording. Shallow reflections and/or high Vp/Vs ratios will always be more challenging, requiring closer receiver line spacing to maintain consistent fold coverage.

Land Full-Wave 3D Designs

Converted wave binning responses for four survey design types are compared in this study. The four land survey types are Narrow Azimuth Swath, Orthogonal, Slant, and Variable Line Spacing Slant. Orthogonal and slant designs are generally wide azimuth designs, in this case with nearly equal in-line and cross-line offsets. To minimize variations due to other design parameters, the three wide azimuth designs use identical receiver templates: 12 lines with 96 stations per line on 50-meter group intervals and 400-meter receiver line spacing. These designs also use similar shot salvos with salvos of 8 shots on a 50-meter cross-line shot interval centered in the recording patch and 400-meter shot line spacing. These parameters allow the acquisition of uniform 36-fold mid-point data in 25-meter CMP bins with consistent (but not identical) offset distributions. For the Variable Line Spacing design, the receiver and source line spacing averages 400 meters, varying between 350, 400, and 450 meters. The patterns of line spacing variations are designed to acquire uniform 36-fold coverage. The narrow azimuth design uses 6 lines with 96 active stations per line on 50-meter group intervals and 100-meter receiver line spacing. With two sources separated by 50 meters between the center two receiver lines, a 200-meter in-line shot spacing, and a 100-meter cross-line roll, this design will also acquire uniform 36-fold data. These designs are only presented as examples to illustrate the coverage characteristics of different designs and are not proposed to solve any specific geophysical imaging problem.

Marine OBC/OBS Test Designs

Converted wave fold coverage is also compared for three examples of marine Ocean-Bottom Cable (OBC) and Ocean-Bottom Seismometer (OBS) survey designs. These three designs represent common designs currently used in the marine environment: an in-line design with shot lines parallel to long receiver cables deployed on the sea floor, a cross-line design with shot lines perpendicular to the cables, and a node-type design with relatively sparse bottom sensor stations and dense shots.

Because of the relatively high cost of deploying and positioning cables on the sea floor and the relatively low cost and high repeatability of marine airgun shots, OBC survey designs tend to have a rather low density of receiver stations and a very high density of shots. In today's OBC market, most seismic surveys are acquired utilizing two (though sometimes three or four) long parallel cables. The data are generally shot either with the source boat sailing along multiple shot lines parallel to and between the cables (acquiring narrow-azimuth P-wave data with trace distributions analogous to conventional to streamer data) or along relatively long shot lines perpendicular to (and crossing) the cables (acquiring wide-azimuth data distributions analogous to land survey designs). For multicomponent (PS-wave) data acquisition, it is absolutely critical for the source lines to extend beyond the active receiver lines in both design cases (parallel and perpendicular) in order to collect continuous sub-surface PS-wave coverage. This, of course, is necessitated by the shifting of the CCPs toward the receiver stations, which causes gaps in the subsurface coverage that can only be filled by overlapping the subsurface coverage from adjacent shot lines and swaths. For PS-wave acquisition with parallel OBC shooting, this phenomenon requires shooting as many as three (or even more) times more shot lines parallel to the cables, depending on the shallow Vp/Vs ratio.

The two OBC designs discussed in this study use two long parallel cables with 50-meter group intervals and 400-meter cable spacings. Four seismic components are recorded at each receiver station; three orthogonal geophones and one hydrophone. The hydrophone sensor is added to allow removal of the receiver ghost and water column reverberations via PZ summation. The node design example, with a 400-meter grid of receiver stations on the sea floor, also uses four seismic components at each station.

An important advantage of OBC recording over conventional marine streamer recording is the decoupling of the source boat from the recording cables. This allows efficient acquisition of split-spread data, which allows higher fold coverage, better offset distributions and stack responses, and reciprocal ray-paths for refraction statics corrections.

CCP Binning

While P-wave CMP binning of all of the tested land and marine designs yields uniform fold coverage, converted wave binning results in variable CCP fold coverage. The asymmetry of the fast down-going P-wave and slow up-going S-wave ray paths causes the converted wave reflection data to "shift" toward the receivers. This results in a cross-line shift of the subsurface coverage toward the receiver lines (causing high and low fold stripes parallel to the receiver lines) and "stretches" the trace distribution parallel to the receiver lines (causing low fold stripes perpendicular to the receiver lines). Historically, such converted wave fold analysis has been computed asymptotically for a given Vp/Vs ratio, assuming a very (infinitely) deep target. However, in this study, CCP fold coverage is computed for specific target horizons at different depths with different bulk Vp/Vs ratios above the target. This allows a general analysis of the effects of depth and Vp/Vs on the CCP fold coverage.

CCP fold coverage for the Narrow Azimuth, Orthogonal and Variable Line Spacing Slant designs are shown below (in Figures 1a, b and c) for a Vp/Vs ratio of 3.0 at a target depth of 2000 meters. The wider azimuth designs smooth out the "high-frequency" bin-to-bin CCP fold variations in Figure 1a and the variable line spacing and slanted shot lines (in Figure 1c) further reduce the CCP fold variations.

Alternative processing techniques can also be used to reduce CCP fold variations. Flexible binning and interpolation techniques have been successfully applied to reduce CCP fold variations in some cases. However, the large gaps in CCP fold coverage observed for very shallow horizons and/or for very high values of Vp/Vs can only be filled in by reducing the receiver line spacing in the field acquisition.

Marine OBC CCP Design Analysis

Figure 2 shows a typical wide-azimuth OBC design. Figures 3, 4a and 4b show some subsurface fold comparisons for this wide-azimuth survey design. In this example, the two receiver cables are deployed on the sea floor with a line spacing of 500 meters and the shots lines are 300 meters apart. The active cable lengths are 9000 meters, with the shot line centered across the cables to allow long offset data for a deep reflection target (~4500 meters deep). There are 80 shots on each shot line to provide moderately long cross-line offsets (~2000 meters) and good cross-line fold overlap for both the P-wave and C-wave data.

This design will acquire uniform P-wave subsurface coverage with 60-fold multiplicity for a target at depth of 4500 meters. Figure 3 shows the corresponding converted wave CCP fold coverage for the same deep target, assuming a Vp/Vs ratio of 2 above the reflection horizon, which is not unreasonable for a relatively deep sedimentary target. Note that while the P-wave fold is uniform, the CCP fold coverage varies with stripes of higher and lower fold coverage oriented parallel to the receiver lines. In this case, the CCP fold varies between about 37 and 84 at the target. This is caused by the shifting of the CCP reflection points away from the shots and toward the receiver lines. For different values of Vp/Vs and for different target depths, the CCP fold coverage will also vary. The width of the fold coverage stripes parallel to the receiver lines can be made narrower by reducing the receiver line spacing on the sea floor.

For a shallow objective at a depth of 1500 meters, the effective P-wave fold coverage will be considerably lower than that at deep horizons because the long offsets will not record reflection data for very shallow targets. For the wide-azimuth design described above, the effective P-wave fold for a horizon at a depth of 1500 meters will be about 20 to 25. Figure 4a shows the CCP fold coverage for the same shallow target for a Vp/Vs ratio of 2. Note that the variations in the CCP fold coverage caused by the shifting of the converted wave traces toward the receiver stations is more pronounced for the shallow objective than for the deeper objective shown in Figure 3. The CCP fold varies between about 10 to 30 in Figure 4a, which is a variability of a factor of about 3 times, while it varies between 37 and 84 in Figure 3, which is a factor of just over 2 times. Figure 4b shows the CCP fold coverage at 1500 meters for a higher Vp/Vs ratio of 3. This velocity ratio is perhaps more representative of shallow sedimentary objectives because as rocks become more unconsolidated (as is typical for shallower sedimentary sequences), the Vp/Vs ratio typically increases as the shear wave velocity of the rocks decreases rapidly. In this case, the CCP fold varies from about 9 to 36. The bands of lower fold coverage (the blue areas) affect a wider area and the higher fold areas (in red) are more concentrated than in Figure 4a. For shallower horizons, the CCP fold coverage patterns are even more sensitive to the effects of higher Vp/Vs. The only effective way to improve the CCP fold coverage for such objectives is to reduce the receiver line spacing.

Converted Wave Ray Tracing

Since the Vp/Vs ratio is generally not constant in the geologic section of the real earth, a more robust analysis of CCP fold can be made by computing the converted wave ray paths through a geologic model with Vp/Vs ratios varying between layers, representing our best estimate of the lithology in a survey area, and calculating the CCP fold on a target horizon.

Diagnostic plots of CCP fold coverage on different horizons with different Vp/Vs ratios for the various designs are compared. As expected, the CCP fold variations on the shallow horizon are more prominent than on the deeper horizon. As in all 3-D designs, the shallow data coverage is most sensitive to line spacing. Such analysis can be used to estimate the maximum acceptable receiver line spacing for an expected target depth and Vp/Vs model. If the line spacing is too large for a given target, the CCP fold coverage on that horizon will exhibit larger variations and possibly even coverage gaps that are not easily filled in with flexible binning or interpolation. In general, CCP fold variations on deeper targets are less extreme for any design, but using designs with variable line spacing and slanted shot lines can result in less distinct CCP fold variation patterns.

Figure 5 shows an example of the resulting converted rays from a shot into the recording patch through two layers with different Vp/Vs ratios. Shots are shown in red and receiver stations in blue. Note the asymmetry of the down-going and up-going rays and the bending of the rays at the interface between the layers. The banded colored surface represents the CCP fold coverage on the target horizon, showing the banding of the converted wave fold coverage parallel to the receiver lines for this example.

Conclusions

In general, designing full-wave 3D seismic surveys to simultaneously acquire optimal P-wave and PS-wave data requires an appropriate level of knowledge of the seismic objectives and characteristics of the geology. The concept of constraining parameters will help determine which parameters are most critical for each aspect of the data. For instance, due to typically low shear wave velocities, the acquisition bin size (which controls source and receiver station intervals) should be computed based on the shear wave velocity. Similarly, due to typically high P-wave velocities at depth (and the fact that the PS-wave ray paths that correspond to a given P-wave reflection point are recorded with shorter offsets than the P-wave ray paths), long offsets are constrained by the P-wave velocity.

A survey design that would normally acquire uniform P-wave fold coverage will result in non-uniform converted wave fold coverage (often with strong fold PS-wave fold lineations) due to the asymmetry of the down-going (P-wave) and up-going (S-wave) wave fields. As in all 3D design problems, shallow data coverage is more difficult than deeper data coverage, and requires smaller line spacings. This is further complicated for converted wave studies because the Vp/Vs ratio for shallow, unconsolidated sedimentary rocks can be much higher than for deeper formations, resulting in a greater degree of CCP shift toward the receiver lines for the shallow horizons, requiring even smaller receiver line spacing. The only effective way to reduce this effect is to acquire PS-wave data for shallow objectives with relatively small receiver line spacing. Unfortunately, this generally increases the cost of such data acquisition.

Slanted shot lines and variable receiver and source line spacing will help to reduce CCP fold variations. Flexible binning schemes applied in processing, allowing overlap of CCP bins, will also smooth many of the CCP fold variations observed, but cannot solve the difficulty encountered for shallow objectives. Because of the shift of the conversion points toward the receiver lines, wider azimuth survey designs with longer cross-line offsets will allow more overlap from swath to swath and will improve the cross-line coupling of converted wave surveys.

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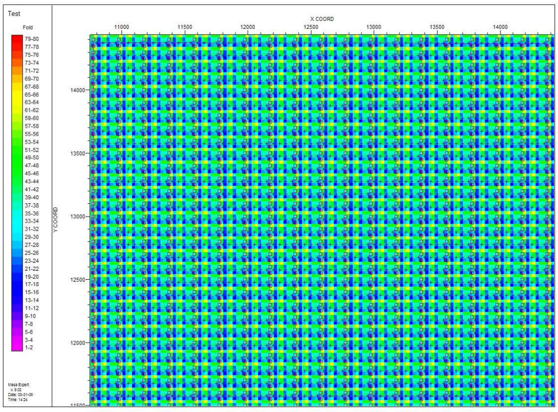

Figure 1a – Converted-wave fold coverage for a narrow-azimuth swath land shooting design for Vp/Vs = 3 at a reflection depth of 2000 meters.

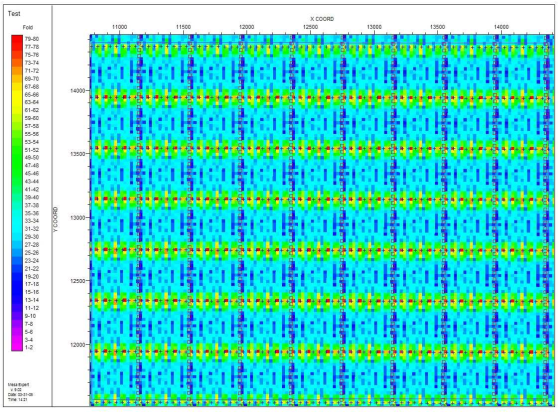

Figure 1b – Converted-wave fold coverage for a wide-azimuth orthogonal land shooting design for Vp/Vs = 3 at a reflection depth of 2000 meters.

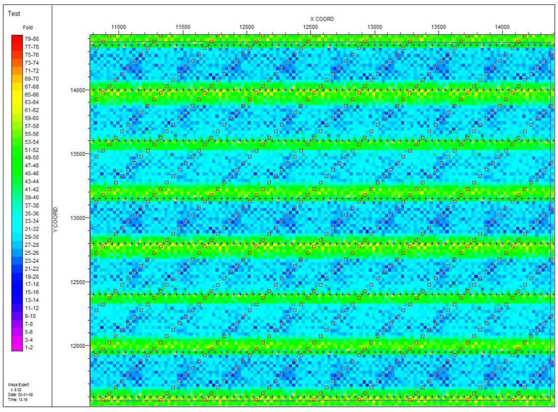

Figure 1c – Converted-wave fold coverage for a wide-azimuth slanted shot line land shooting design with variable receiver line spacings for Vp/Vs = 3 at a reflection depth of 2000 meters.

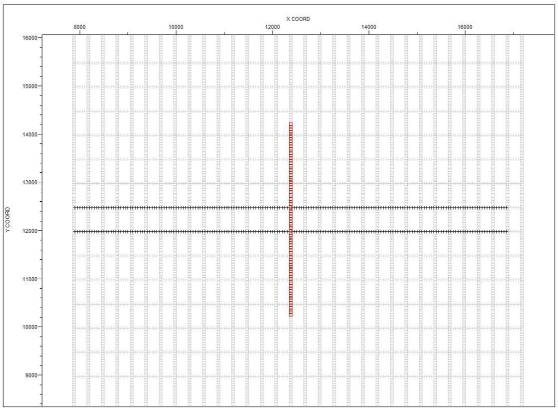

Figure 2. Wide-azimuth marine OBC design for simultaneously acquiring compressional- and converted-wave data.

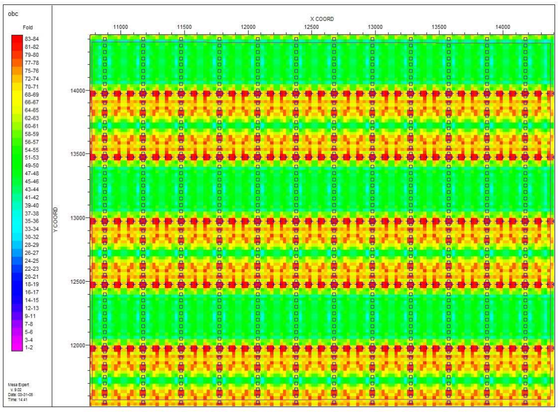

Figure 3. CCP fold coverage for wide-azimuth OBC design for a converted-wave reflection target at a depth of 4500 meters with nominal Vp/Vs = 2.

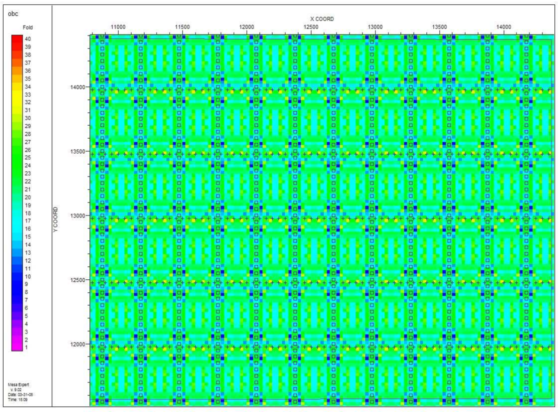

Figure 4a. Wide-azimuth converted-wave fold coverage for a target at 1500 meters with nominal Vp/Vs = 2.

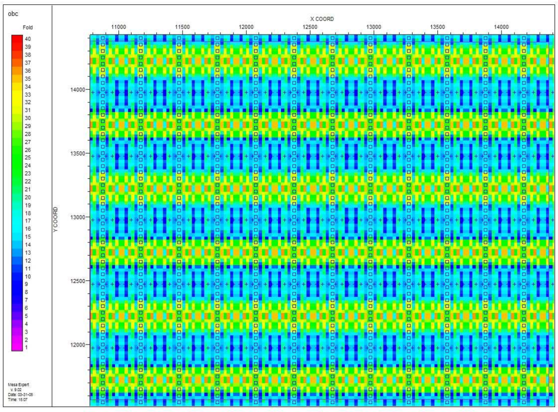

Figure 4b. Wide-azimuth converted-wave fold coverage for a target at 1500 meters with nominal Vp/Vs = 3.

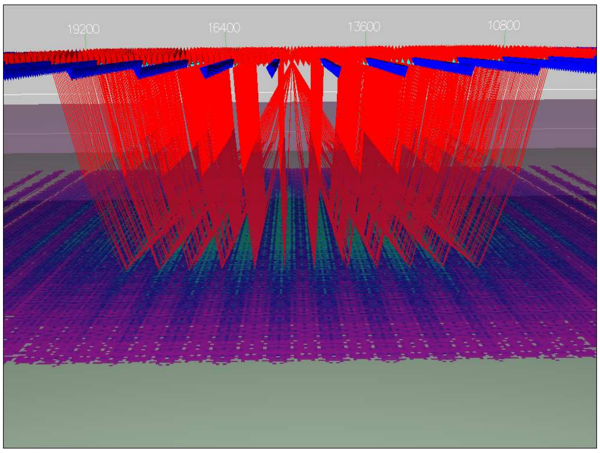

Fig. 5. Ray-tracing example for converted-wave rays in a layered-earth model.