Seismic Survey Designs for Converted Waves

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ABSTRACT
Designing converted wave 3D surveys is considerably more complicated than designing p-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 fold coverage will result in non-uniform converted wave fold coverage, and filling gaps in the CCP fold coverage can be quite complex. Several land and marine (OBS/OBC) 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 a target at depth. Additional comparisons are conducted using converted wave ray tracing through a layered model with variable Vp/Vs ratios.

As in all 3D designs, shallow coverage for converted wave data is more difficult than deeper coverage and requires denser line spacing. Slanted shot lines and variable receiver and source line intervals will help to reduce CCP fold variations. Because of the shift of the conversion points toward the receiver lines, wide-azimuth survey designs will allow more subsurface overlap and will improve the cross-line coupling of converted wave surveys.

Land Test 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. The orthogonal and two slant designs are relatively wide azimuth designs, 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 8 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 100-meter in-line shot spacing, and a 200-meter cross-line roll, this design will acquire uniform 48-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

Additionally, converted wave fold coverage for different objectives are 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 the 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. Typically, it is much more economical to fire marine airgun array shots than it is to deploy multi-component sensors on the sea floor. For that reason, most, if not all, marine designs will have a much higher density of shots than receiver stations.

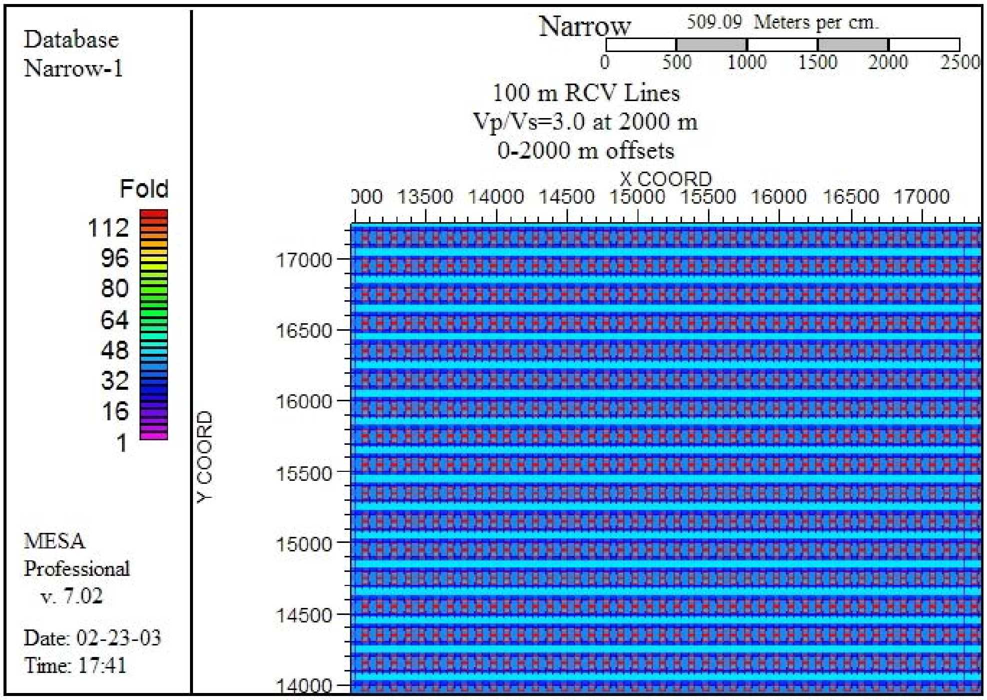
The two OBC designs use two long parallel cables with 50-meter group spacings and 400-meter cable spacings. Four seismic components are recorded at each receiver station; three orthogonal geophones and one hydrophone. The hydrophone sensor is added to allow removal of the receiver ghost and water column reverberations. The node design, with a 200-meter grid of receiver stations on the sea floor, also uses four seismic components at each station.

Ccp Binning

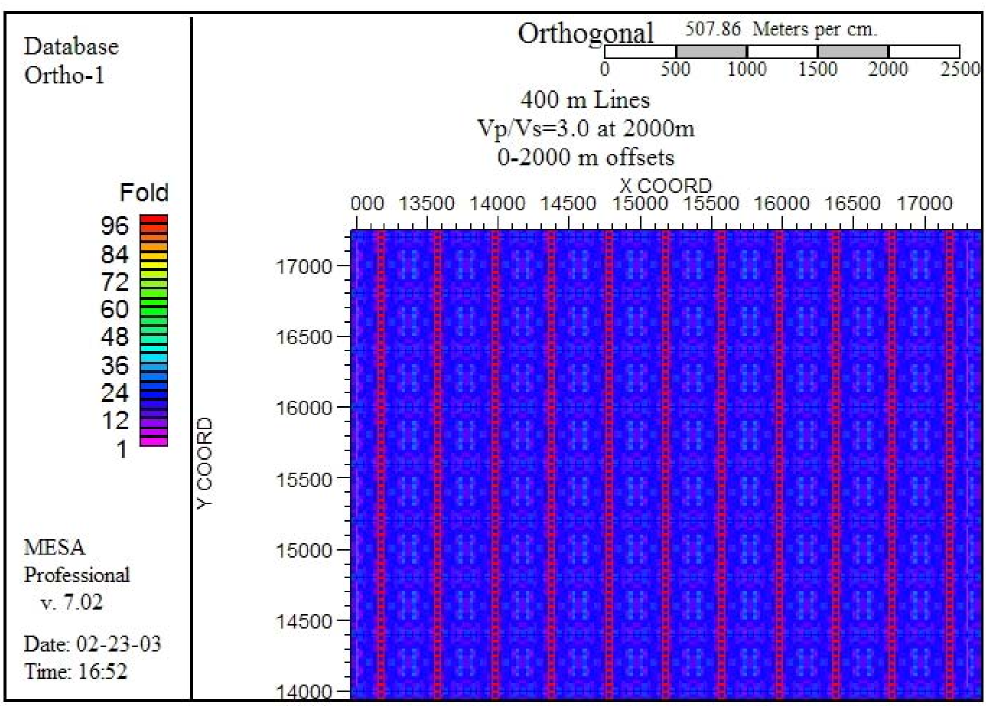
While p-wave CMP binning of all of the tested land and marine designs yields uniform fold coverage, converted wave binning results in variable CCP fold coverage. The asymmetry of the fast down-going and slow up-going ray paths causes the converted wave reflection data to “shift” toward the receivers. This causes 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 lower 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 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 for a Vp/Vs ratio of 3.0 at a target depth of 2000 meters. The wider azimuth designs smooth out cross-line variations and the variable line spacing and slanted shot lines further reduce or randomize CCP fold variations.

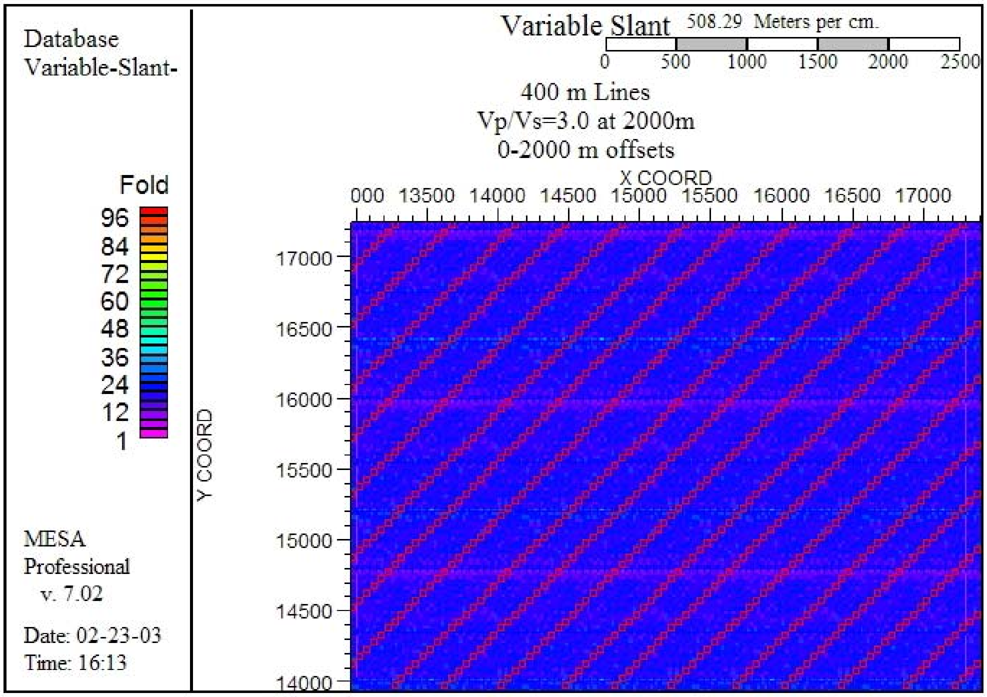
Narrow Azimuth Design – Vp/Vs = 3.0 at 2000 m depth



Orthogonal Design – Vp/Vs = 3.0 at 2000 m depth



Variable Line Spacing, Slante Shot Line Design – Vp/Vs = 3.0 at 2000 m depth



Alternatively, 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.

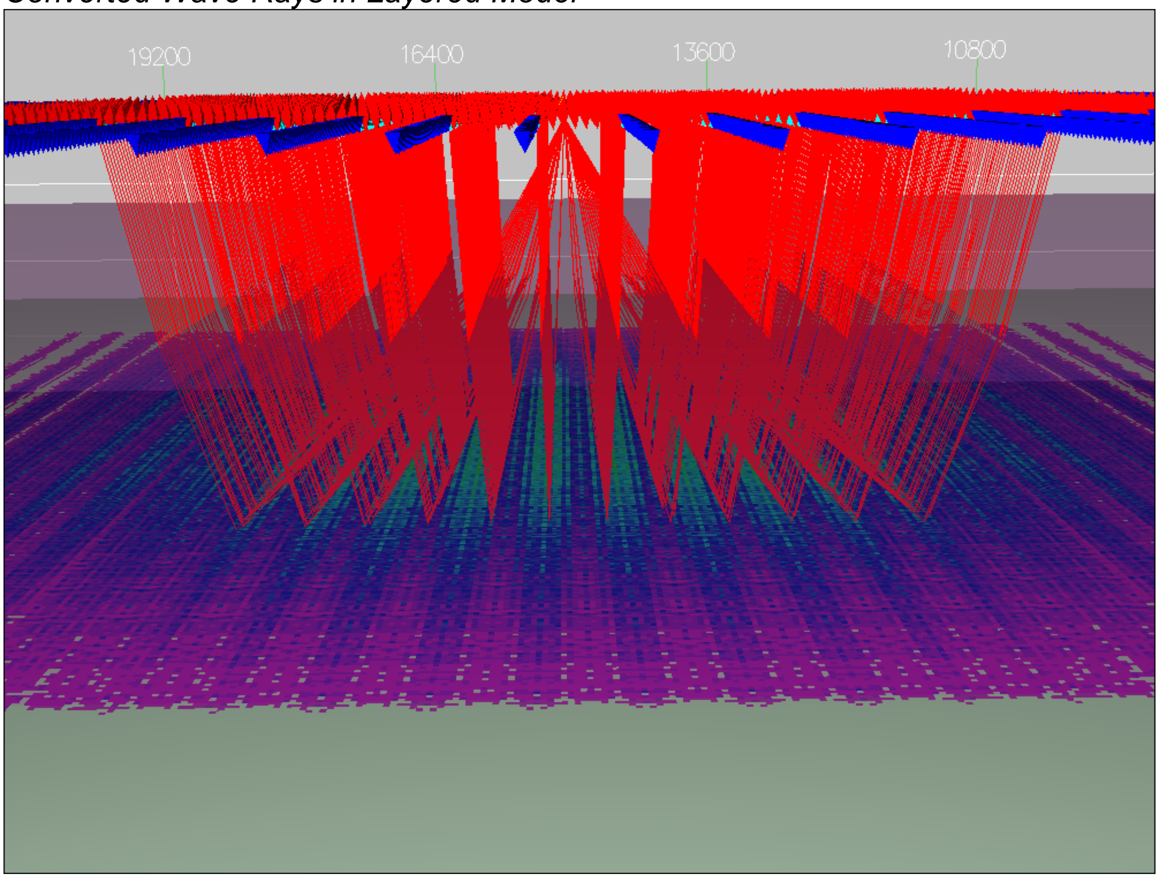
Converted Wave Ray Tracing

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 variable Vp/Vs ratios in each layer, representing our best estimate of the lithology in our 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 very sensitive to line spacing. In some cases, 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.

The following figure 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.

Converted Wave Rays in Layered Model



Conclusions

A survey design that would normally acquire uniform p-wave fold coverage will result in non-uniform converted wave fold coverage due to the asymmetry of the down-going (p-wave) and up-going (s-wave) wave fields. In order to estimate CCP fold coverage, knowledge of the Vp/Vs ratios in the survey area are required. As in all 3-D 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 for the shallow horizons, requiring even smaller receiver line spacing. 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.