Survey design for vertical cable seismic acquisition

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ABSTRACT

The vertical cable recording geometry is showing considerable promise as a seismic acquisition technique. It is especially suitable in marine areas where any of the following are present: 1) obstacles (e.g. platforms or buoys) for a vessel towing one or more streamers, 2) deep to very deep water, and 3) a complex subsurface geology. Vertical cables also overcome the problems of pipelines on the sea bottom, which may prohibit the use of ocean bottom cables (OBC). On land, use of vertical cables may be useful anywhere one would use a VSP survey.

This paper discusses the design of the surveys that can best image the target geology in the most economic way. Thus, we are interested in questions of source and receiver distribution and the resultant target coverage.

Analysis of coverage (fold) for regular grids of cells (bins) in vertical-cable acquisition was done for a straightforward, 2.5-D synthetic case. The model describes a passive continental margin environment in a Mesozoic basin. Acquisition geometries with a different numbers of vertical cables, hydrophones per cable, numbers of shot points and water depths are analyzed. Three-dimensional ray tracing was used to obtain the reflection point from a target layer. Converted (P-to-S) waves, offset and azimuth distribution and a land case are also analyzed.

The results show that good coverage can be obtained using only a single cable, a reasonable number of hydrophones per cable, and a modest shot point spacing. Azimuth and offset distributions are poor for a single bin with a single-cable geometry, but improve as more cables are used. Deeper water acquisition shows better fold homogeneity than shallow water when several cables are used on an optimized configuration. For converted-wave imaging, longer offsets are necessary, but higher fold is obtained close to cable positions.

INTRODUCTION

In conventional marine seismic acquisition, a ship tows both the source (a set of air-guns) and the receivers (pressure sensitive hydrophones, placed in a cable called streamer). For most 3-D surveys, two or more streamers are towed at the same time. In a typical configuration, each streamer has a length of 3,500 to 6,000 m and the minimum cable separation is 50 m. Due to water currents, these cables may have a ‘feathering’, or lateral movement, that can reach 45°, and even more. In areas with hydrocarbon production facilities, platforms and buoys become obstacles for the passing of the vessel towing these cables, making necessary the use of some alternative approach.

Among the techniques generally used to overcome this problem (e.g., undershooting and ocean bottom cables), the vertical-cable concept has been

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attempted. Very good results have been achieved in the Gulf of Mexico, mainly for sub-salt imaging (Krail, 1994b, 1997). The concept is close to 3-D VSP, but instead of sparsely located wells, a set of regularly spaced cables in the vertical position is used. Each cable has single hydrophones at different depths to record the wavefield generated by a shooting vessel. The cables are kept in the vertical position by the use of buoys at their top and anchors at their bottom.

The quality of seismic images often improves when high data redundancy is available: Stacking usually gives a higher signal-to-noise ratio and further enhancement follows from the use of different offsets and azimuths. The number of times a point (or a bin) is imaged for different source and receiver positions is called the coverage, fold or multiplicity. Adequate fold is required to achieve a good image, so pre-survey planning must be accomplished, based on geological and petrophysical information, to define the acquisition parameters.

The results of coverage, offset and azimuth distribution for some acquisition geometries and receiver configurations on different geological models using vertical cables are presented and discussed in this report.

OVERVIEW AND EXAMPLES

The basic idea of this technique is to use the receivers (piezoelectric sensor -- the hydrophones) in a vertical configuration, instead of horizontal, which is the usual case in marine seismic acquisition. On land, the use of 3-C receivers is an additional benefit, but the discussion in this section will be restricted to the marine case.

Instead of being placed in a cable (streamer) filled with a special low-density oil (called neroma), the vertical cable hydrophones are attached to the outside of a high-strength stress member. To reduce water current drag, a fairing is attached to the cable (Krail, 1993). Keeping electrical and mechanical integrity of the cables and hydrophones under high hydrostatic pressure is a significant issue (Krail, 1994b). The cables are kept in the vertical position through the use of buoys at their tops and an anchor at their bottoms. A vertical cable scheme, from Krail (1994a), is shown on Figure 1.

The vertical-cable genesis is in the marine walkway VSP, with the obvious difference – and advantage – of not being necessary to have a drilled well. It is also based on US Navy antisubmarine warfare technology. This method was patented by Texaco (Krail, 1994b), which some years ago allowed its use by PGS.

In general, 3-D pre-stack depth migration in the receiver domain is applied to the data. Using the reciprocity assumption, the relatively highly spaced hydrophones are considered as sources and the relatively closely spaced shot points are considered as receivers. In this way, good subsurface sampling is obtained and aliasing is less of a problem.

According to Leach (1997), the downgoing wavefield (water-surface ghost) can be -- after proper processing -- stacked to the upgoing (primary) energy to increase signal-to-noise ratio. Guimarães (1998) shows the direct (upgoing) energy gives a more dense sampling close to the cable and the ghost energy, although sparser, illuminates regions farther from the cables.

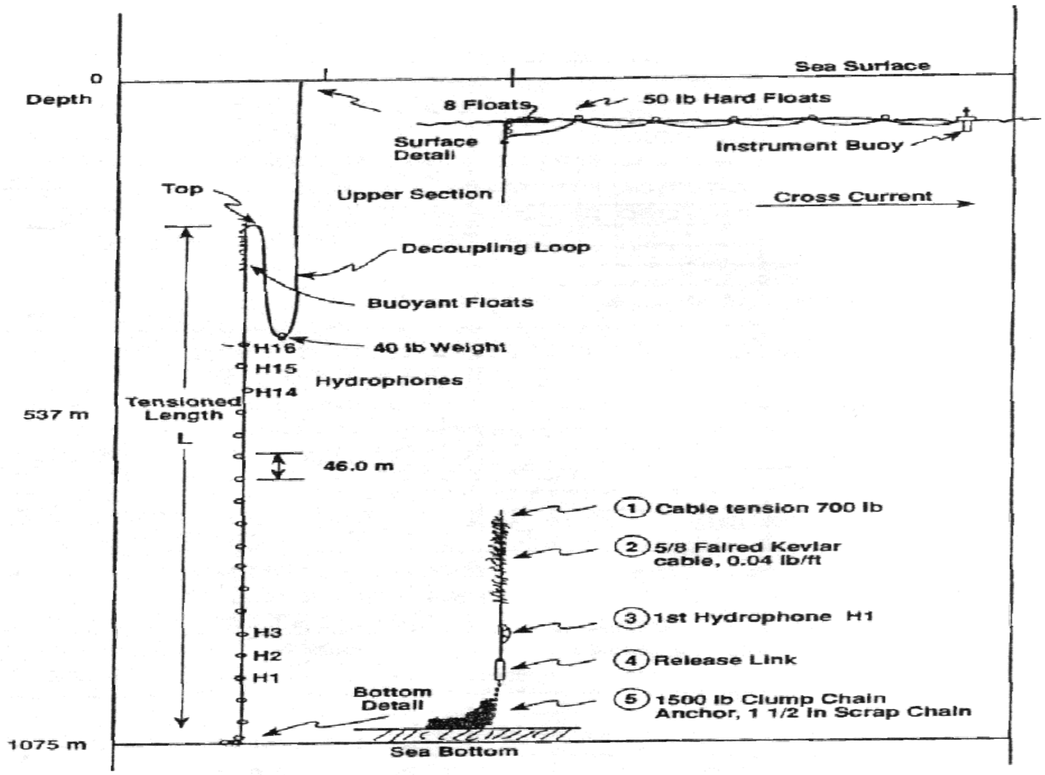


Figure 1 – Scheme of a vertical-cable (from Krail, 1994a).

The first reported vertical-cable acquisition was done in the Gulf of Mexico, in 1987, using three cables, for a common geological problem in that area: imaging of sand reservoirs against flanks of a salt dome (Krail, 1994b).

In 1992, and again in the Gulf, it was used to image below the salt. In that survey, six cables were used at water depths greater than 1,000 m. The data, acquired in an 11 x 8-km^2 area, was processed using 3-D pre-stack migration. A comparison between this data and a conventional (streamer) 3-D data showed clearer images for subsalt reflections. However, this comparison may not be quite fair, as a poststack migration was used in the conventional data processing. The acquisition cost was said to be half of a conventional 3-D seismic, as the time to collect the data was drastically reduced. This happens because: 1) it is much easier for the source vessel to maneuver through obstacles without towing a streamer, and 2) no infill lines (to obtain the desired fold) are necessary (Krail, 1994b). No comments, though, are made about the time necessary to deploy and remove the cables.

Anderson et al. (1997) present an equal comparison between streamer and vertical cable (as both data had pre-stack depth migration applied) in the Gulf of Mexico. In this survey, 12 cables (16 hydrophones, spaced 45m, per cable) on a 1.6 x 1.8 km^2 spacing grid, were used to cover 99 different cable positions in a total area of 14 x 16 km^2. The shot point and shooting line interval were 50 m and 40 m, respectively. The streamer data was a 2-boat operation, both vessels proceeding along the inline direction with a 6-km distance between them. The authors found close results for both methods, even for complicated small-scale structures.

Another survey is reported to have been done in 1989, in water depth of 600 m, offshore Louisiana. A total of 180 shooting lines with a 9-km length, shot point and line spacing of 50 m, were acquired. A 12-channel cable was used. The recorded data was transmitted to the shooting boat through digital telemetry. Individual channels monitoring performed real-time quality control. The tilt from the vertical was less than 5° (Krail, 1991, 1993).

One use of vertical cable outside of the Gulf of Mexico is given by Leach (1997). This case is from Strathspey Field, North Sea (water depth approximately 145 m, or 440 feet). Twelve cables were deployed on a 3 x 4 grid, each cable holding 16 hydrophones spaced 8 m. Six swaths were planned, covering 8 x 6.4 km^2 in the subsurface. Storms during the acquisition moved cables and buoys as much as 200 m away from their initial sites. The whole processing cost was around US$ 700,000, compared to a estimation of US$ 8 to 10 million for a conventional dataset with the same number of traces (60 million traces). This was the second attempt on the world for a large-scale vertical-cable survey. According to the author, if 4 more cables were available, 4 swaths could be used instead of 6, significantly reducing cost.

Krail (1997) reports another survey in Gulf of Mexico deep water, which may be the same reported in Krail (1994b), as the area (80 km^2), water depth (1,200-1,500 m) are number of cables (6) were equal. The distance between cables was 1.6 km, and each cable had 16 hydrophones. Using a shot point interval of 25 m and 400 shot points per line, 40 lines with 40-m spacing were acquired. A receiver domain pre-stack migration was applied – so, 16 pre-stack migrations were done for each cable.

As for the winter of 1997/1998, the recording was done using tape drives inside the buoys. For every shot, a selected trace is sent to the shooting vessel through radio, for quality control purposes (OGJ, 1995; George, 1996).

Guimarães et al. (1998) present the results of a physical modeling (1:30,000 geometrical scale factor) data acquired using the vertical-cable technique on a model similar to the Salt Canopy 3-D SEG/EAGE numerical salt model, reported by Sekharan et al. (1997). Their main purpose was to verify both the merits and problems of this technique. The scaled acquisition geometry is 1,650-m cable distance, 8 cables, 8 hydrophones per cable and 100 m hydrophone distance. A brick-type-shooting pattern of 25 x 25-m was obtained after 8 swaths were combined. They obtained good results using upgoing (direct) and downgoing (reflected at water surface) data together.

Moldoveanu et al. (1997) presented a comparison, on two small 3-D surveys in the Gulf of Mexico (55 to 60 m water depth), between streamer and vertical hydrophone array with radio telemetry system. The processing flows were the same, except for downgoing attenuation through wavefield separation for the vertical data. The results show stronger water-layer reverberation attenuation, better signal-to-noise ratio and improved resolution on the vertical hydrophone array.

A major deep-water oil discovery is reported to occur through the use of vertical-cables in an area 150-km Southeast of New Orleans, at a 1,000 m water depth (OGJ, 1995; George, 1996). Conventional seismic data showed prospective zones, but apparently not large enough. However, with vertical-cable additional objectives were seen. A wildcat well (5,400 m deep) produced oil from a layer 870 m below a tabular salt formation.

In comparison to conventional acquisition, the vertical-cable advantages reported by Krail (1991, 1993, 1994b, 1997), Anderson et al. (1997), Leach (1997) and Sekharan et al. (1997) are:

- less background noise,
- the acquisition is less susceptible to weather conditions, what is very important in places like North Sea, off West Africa and the storm zone of Southeast Asia,
- up- and down-going waves may be separated,
- a less rigid and easier to reconfigure geometry is possible, which is especially interesting when 3-D pre-stack migration is used,
- as several azimuths are sampled, true 3-D imaging is possible (3-D marine data is in general obtained through the shooting of several 2-D closely spaced lines),
- no common mid-point assumption is used (this is a major concern in Gulf of Mexico sub-salt imaging), as the data is 3-D pre-stack migrated,
- on small 3-Ds, costs are considerably reduced, as smaller boats can pull the source, eliminating the large distances required for turning a vessel pulling long streamers,
- the coverage is better as the boats can get closer to any obstruction,
- 3-D pre-stack depth migration is much cheaper than on streamer data,
- for complex geologic structures, a more uniform distribution of reflection points from an interface can be obtained.

A higher resolution, when compared to streamer data, is claimed for this technique (OGJ, 1995; George, 1996; Leach, 1997), but the reason presented for this (less noise at higher frequencies) may not occur on some environments.

One great advantage, not mentioned in the literature, is the possibility of acquisition in areas where the sea bottom has oil and/or gas production line on it, which may cause the use of ocean bottom cables to be difficult, if not impossible. Reefs on sea bottom, including cold water carbonates (generally present on deep to very deep water) may also prohibit the use of bottom cables. Another potential advantage is for 4-D seismic, as a closer to constant receiver positioning and response can be obtained on time-lapse surveys, without the coupling concern that may be present for ocean bottom receivers.

Acquisition costs may have a wide variation, according to geographical area, time of the year, water depth and survey size. An 80 km^2 3-D survey offshore Brazil would be 2.5 times the cost of a conventional (streamer) 3-D.

GEOLOGICAL MODEL AND RAY TRACING

A straightforward 2.5-D geological model was created using the numerical modeling program GX 3D-VSP™, from GX Technology. No multiple reflections and downgoing reflected energy from the sea surface were considered for the ray tracing. Downgoing wavefield coverage contribution will be considered on future works.

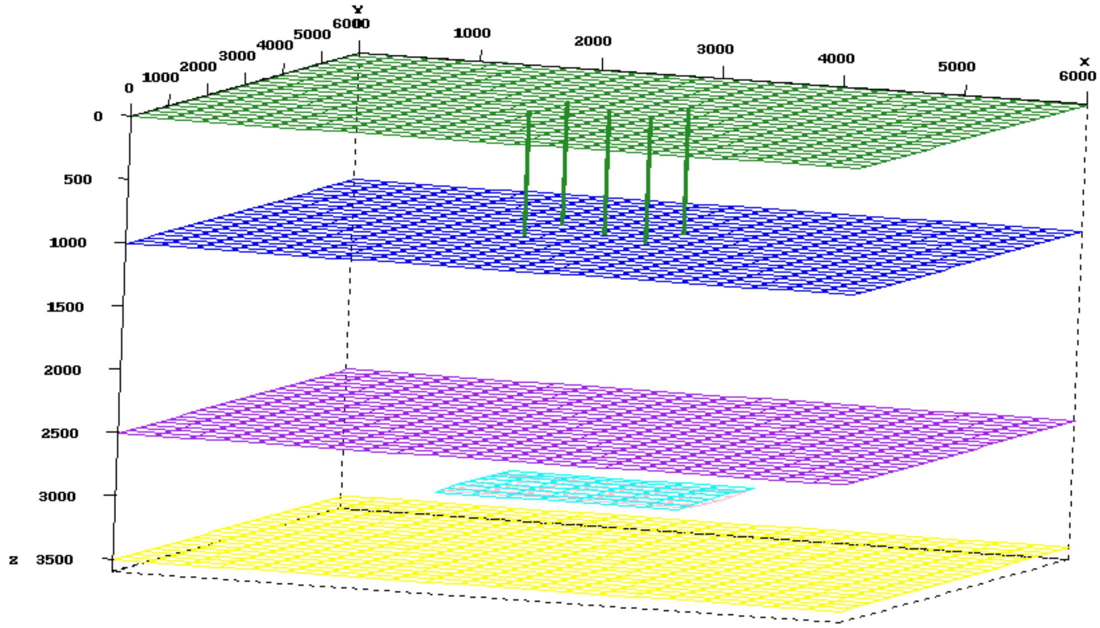
The model intends to represent an area of passive continental margin. It consists of four layers, including a target (figure 2a). The shallowest layer is the water or a weathering layer. Below it there are two layers of Tertiary age, representing sand and shales deposited in a shallow to deep-water environment. They are separated by an unconformity. The target, inside the lower Tertiary layer, has top and bottom slightly curved (see figure on Appendix I). It petrophysically represents an unconsolidated sandstone turbidite. Only the reflection points from the top of target interface were used for analysis. On some models a 6% dip on X direction was applied to all layers.

The total area of the model is 4 x 4 km^2, and the target has 2 x 2 km^2. All layers below the water are elastic. All layers but water, weathering and target have a constant linear increase of velocity with depth. Density was obtained using Gardner's relationship (except for water) and shear wave velocities using Poissons' ratio. A table with elastic parameters and thickness for each layer is presented in Appendix II.

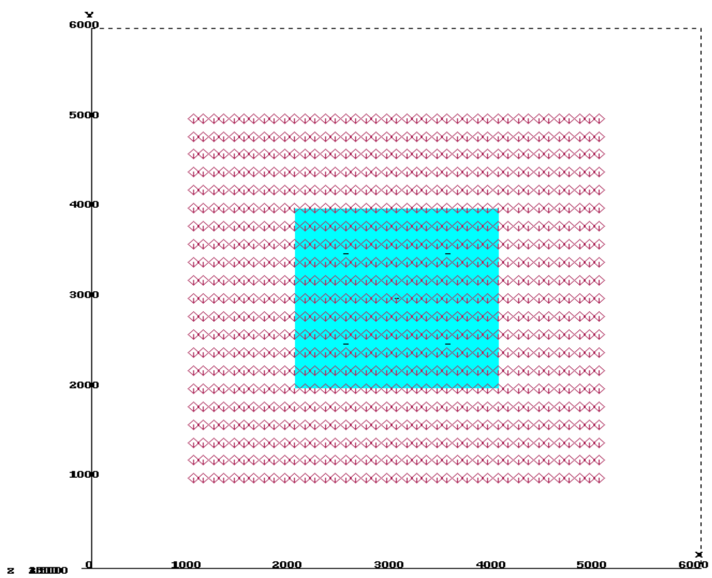
Two shot points configurations were used: 1) 100 m shot point distance (along X axis) and 200 m shooting line spacing (along Y axis, figure 2b); and 2) 50 m for shot point distance and 100 m shooting line spacing. The later, although more realistic, was in general avoided due to the long computer time. As these parameters are underestimated for marine acquisition, one can consider that on a real situation greater values for coverage will be obtained. Both shooting configurations are 3 x 3 km^2, so there is a 1-km aperture to all sides of the target (Figure 2b).

One cable at the center of the model (3.0 km X and Y coordinates) was used for most ray tracing. Some examples with 2 and 4 cables were also tested. In general, 16 hydrophones per cable were used, as this is close to the maximum possible number of receivers that can currently be placed on a cable.

The computer time for the ray tracing varied from 4 to 50 hours, depending on receiver and shot point numbers, on a Sun Ultra 1/140 MHz workstation.



(a)



(b)

Figure 2 – (a) 3-D view of the geological model (1,000 m water depth). Target is the fourth layer from top, around 3,000 m. Five cables are also shown; (b) map view of shot point grid (outer square, from 1,000 to 5,000 m) and target (inner square, 2,000 to 4,000 m). Distances are in metres.

The ray tracing method used by 3D-VSP™ is presented in Pereyra (1988, 1992). It consists of a global (bending) two-point ray tracing technique, which works in complex media. A simple shooting algorithm provides starting rays for the two-point module, which then uses receiver continuation to generate coherent ray families. The representation of many geological unconformities (e.g., normal and reverse faults, pinchouts and salt domes) is possible on this method.

The most important ray tracing parameters (GX, 1994, 1997) used in GX 3D-VSP™ were:

- *propagation mode*: P-wave only or P-to-S conversion at target; in marine cases, for P- to S- conversion, the energy was converted back to P- at the sea bottom

- *ray shooting mode*: 2-point continuation. Once a shot-to-receiver path has been found, the other receiver reflections are obtained using receiver continuation; this fastener the ray tracing

- *search control*: a value of two was used for primary, inline and crossline. These parameters – which vary from 1 to 100 – specify the density of searching used during ray tracing. The *primary* field controls how dense the search is on the horizon during the first and final passes of ray tracing. It should increase according to the model complexity (GX, 1997). *Inline* (along the longest axis of receiver pattern) and *crossline* (perpendicular to inline) control how searching is performed on the receiver array. The bigger they are, the more precise (and slower) the ray tracing procedure is. A technical support geophysicist at GX, Ms. Susan Collins, recommended the value of two.

The coverage, offset and azimuth distributions were calculated using a simple Matlab function, presented in Appendix III. Matlab plot function *pcolor* were used to plot the fold, azimuth and offset for the whole survey for each specific acquisition geometry.

TARGET IMAGING: RESULTS AND COMMENTS

A map for the shot-point configuration used when the shooting direction is along the X-axis is presented in figure 2b. Most models used this pattern. On all figures, the maximum fold achieved for one case was used as a value for fold normalization for all other cases, to permit a comparison between different acquisition geometries. A bin size of 100 x 100 m was used on all analysis.

Figure 3 shows the fold results for the geological model of Figure 2a when the water depth is 500 m and one cable at the center of the model (3.0 km for X and Y coordinates) is used. Four different situations are analyzed: 16 hydrophones (from 30 to 480 m at 30 m interval) with a 100 x 200 m shot point (SP) grid (100 m on X direction), 32 hydrophones (15 to 480 m at 15 m interval) and 100 x 200 m SP, 16 hydrophones with 50 x 100 m SP grid and P-S-P mode (P- to S- at target and S- to P- at water bottom) with 16 hydros and 100 x 200 m SP grid.

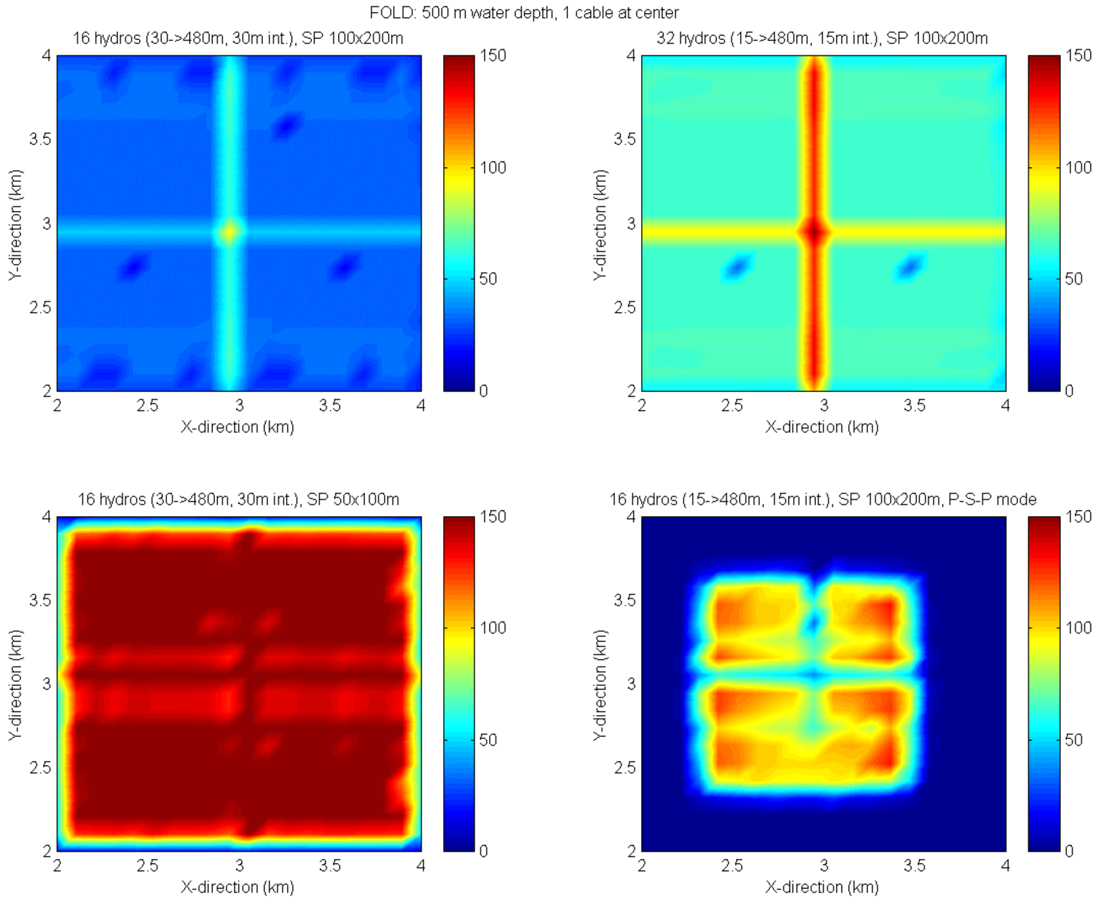


Figure 3 – Fold for 1 cable at center and 500m water depth; upper left: 16 hydros, SP 100X200m; upper right: 32 hydros; lower left: SP 50x100m; lower right: P-S-P mode.

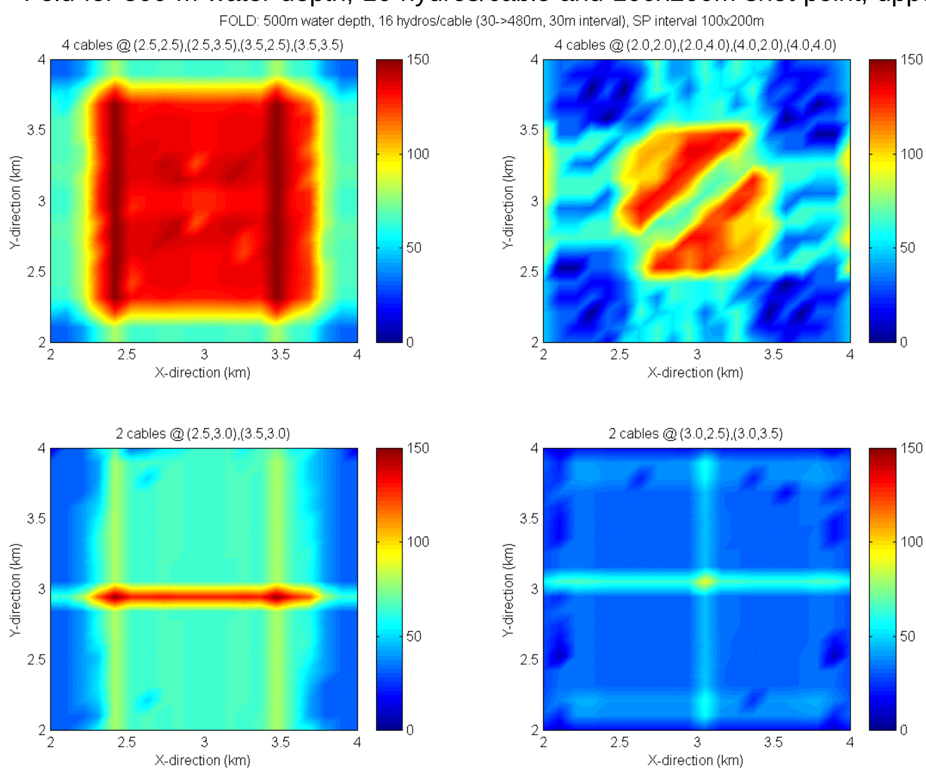
The simplest case in Figure 3 (upper left) is 16 hydrophones at a 30 m interval, the shallowest receiver at 30 m and the deepest at 480 m. We see that the fold has a very homogeneous and smooth distribution over the target, except close to the cable position (center of the model). The average values for fold (around 30) can be considered only modest for a marine 3-D. When twice the number of receivers are used (upper right on Figure 3), the average fold more than duplicates (from around 30 to around 80), which shows how important the use of shorter hydrophone distance may be. Another very effective way to increase the coverage is to reduce by two the shot point and shooting line intervals (lower left on figure 3), as when the number of shot increases by four, the average fold roughly increases by the same amount (from 30 to around 140).

Besides a more homogeneous fold distribution, the use of more shot points has two other advantages over the use of more receivers: 1) currently it is unlikely that more than 20 receivers/cable are available to be used, which limits the minimum receiver distance; and, 2) the closest shot point grid used here (50 x 100 m) is still very wide compared to conventional shooting values.

The imaging for converted wave – P- to S- at target and S- to P- at water bottom – is also presented (lower right of Figure 3). We see that a high (around 100) and homogenous fold is obtained, but for a smaller area than the P-P image. This result is expected, as most conversion points are located closer to receiver than source. Some ways to overcome this problem may include: 1) the use of longer offsets, but how big this offset increase has to be was not checked here, and/or 2) consider downgoing energy reflected from sea surface. The first option, although more expensive, may be necessary due to difficulties on ghost identification of P-S-P mode in the data.

The results for more cables are presented in Figure 4. A realistic number of receivers per cable (16) and a larger than realistic shot point – due to computer time – grid (100 x 200 m) were used. A centered and equally-spaced 4-cables ("internal") geometry – cables coordinates (2.5,2.5), (2.5,3.5), (3.5,2.5) and (3.5,3.5) – shows a high (over 120) and relatively homogenous fold over most of the target (upper left on Figure 4). The fold decreases on both directions from the center, this being more drastically at corners. When the same number of cables is used on an "external" configuration – cables positioned on target corner limits, coordinates (2,2), (2,4), (4,2) and (4,4) – the fold both decreases and looses homogeneity in the distribution. So we see that to deploy the cables in an "internal" configuration is better than an "external".

Figure 4 – Fold for 500 m water depth, 16 hydros/cable and 100x200m shot point; upper left:



4 "internal" cables; upper right: 4 "external" cables; lower left: 2 cables along X-axis (constant Y); lower right: 2 cables along Y-axis (constant X).

As the top target is slightly curved (10 m depth difference on 1,000 m distance along Y direction, figure on Appendix I), when 2 cables are used on orthogonal alignments, some differences will occur. When 2 cables (1 km apart) are along Y center (coordinates (2.5,3.0) and (3.5,3.0)) of the model, a fair fold (around 80) is obtained for most of the target (lower left on figure 4). However, if the 2 cables are used along a constant X (coordinates (3.0,2.5) and (3.0,3.5)), the average fold has a strong decrease (less than 50, lower right on figure 4). The conclusion is when curved interfaces are present, the cables should be aligned on the longitudinal axis of the structure rather than on the transverse.

For dipping layer (profile shown in Appendix I), besides the expected loss of coverage along the dipping direction, the best shooting direction is also a concern. Figure 5 shows the results for two orthogonal shooting directions: parallel to dip (left) and strike (right) directions. A slightly more homogeneous and higher fold is obtained for shooting along strike. One has to remember that the analyzed interface has not only the dip, but also some curvature, which causes some scattering on reflected energy.

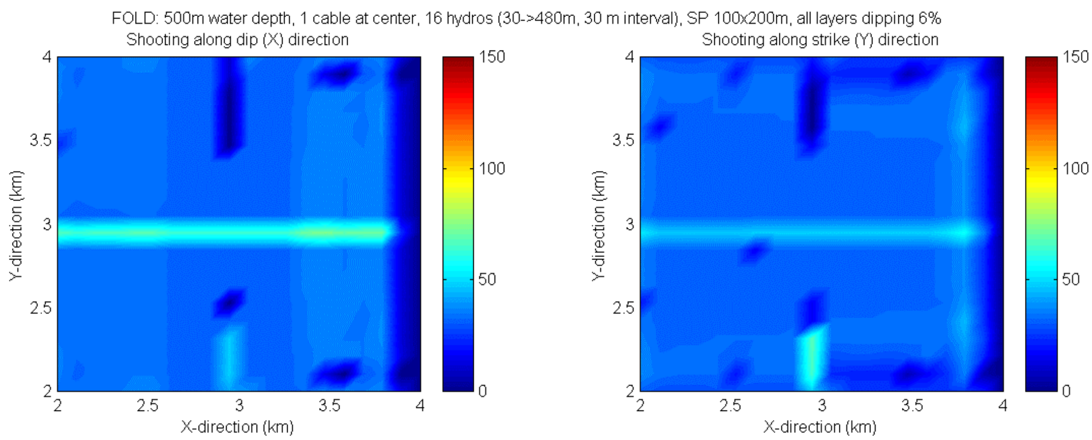


Figure 5 – Fold for dipping layers (6% dip to the right), water depth 500m, 1 cable at center. Shooting along dip (left) and strike (right) directions.

The behavior for deeper water (1,000 m) is now considered. Figure 6 presents results when one cable is used with different receiver configurations. For 16 hydrophones 60 m apart (from 60 to 960 m depth), shown on upper left, a high fold is not obtained (coverage is under 50) over most of the target. The target top curvature causes less coverage to be present towards the center (along a constant X). Using twice receivers (upper right) increases the fold roughly by two, keeping the same imaging distribution.

If we have a limited number of receivers per cable and a great water depth, we may ask which is the best option: use of a regular receiver distribution, or concentration of most hydrophones in the shallow or deep section of the cable? The first choice (regular receiver distribution) has already been presented (upper left on Figure 6). The second (Figure 6, lower left) and third (Figure 6, lower right) are discussed now.

When the receivers are placed in the shallow part of the cable (30 to 480 m at 30 m apart, lower left on Figure 6), a slightly better fold distribution is obtained than if a regular spacing is used along the whole cable, but a small decrease on fold content also occurs over some areas. If the receivers are used in the deeper part (530 to 960 m, 30 m apart, lower right on Figure 6), the fold increases without apparent changes on fold distribution. These results may have an impact when real data using vertical cable (or 3D-VSP) is going to be acquired.

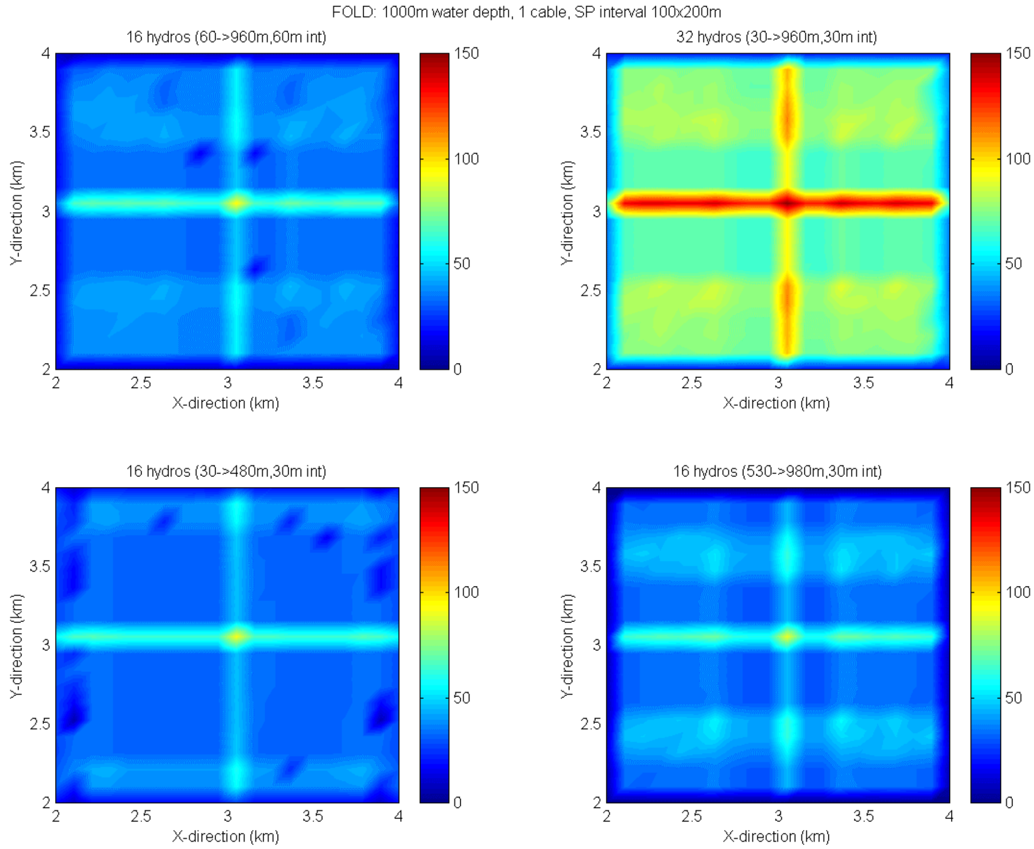


Figure 6 – Fold for 1000 m water depth, 1 cable at center; upper left: 16 hydrophones (60m apart) from 60 to 960m; upper right: 32 hydros (30m apart) from 30 to 960m; lower left: 16 hydros (30 m apart) from 30 to 480m; lower right: 16 hydros (30m apart) from 530 to 980m.

As for 500 m water depth, one obtains more homogeneous and higher coverage using smaller grid size on shot point geometry (results on upper left of figure 7) than increasing the numbers of receivers (figure 6, upper right). This conclusion may be even more important for deeper waters, where it can be more difficult to handle a larger number of hydrophones in the cable.

When four cables are used on the same "internal" configuration explained before, the result is an excellent sampling, regarding both fold values and distribution, except for the target corners (Figure 7, upper right). A comparison to 500 m water depth (Figure 4, upper left) shows deeper water is favorable for vertical cable use when more than one cable is used on an optimized configuration, as the subsurface sampling obtained is superior in the 1,000 m case.

Converted wave imaging – primary P-to-S reflection at subsurface interfaces and converted back to a P wave at the sea bottom – results in a high and well distributed fold, but restricted around the center (lower left on Figure 7). The response here is close to the one from 500-m water depth (Figure 3, lower right).

If we had the target 500 m above the previous example (1,000 m water depth), a slightly higher fold would occur (Figure 7, lower right, compared to Figure 6, upper left), but no significant difference is present. So we see the results obtained here can be extrapolated, to some extent, for shallower target depths.

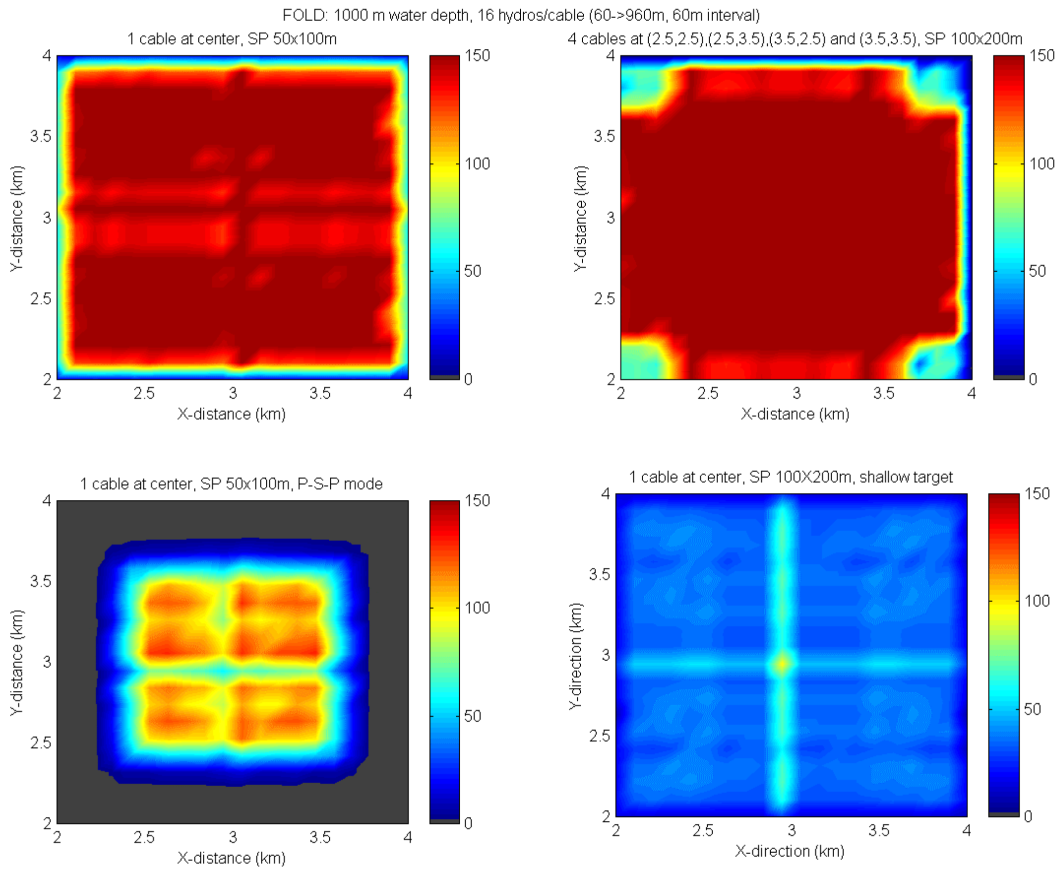


Figure 7 – Fold for 1,000 m water depth and 16 hydrophones/cable (from 60 to 960 m, at 60 m interval); upper left: SP grid 50x100m; upper right: 4 "internal" cables; lower left: P-S-P mode; lower right: target 500 m shallower.

The last analysis is for shallow water (50 m) and land environment (Figure 8). For the marine case (left on Figure 8), a comparison with 500 m (Figure 3, upper left) and 1,000 m (Figure 6, upper left) shows that, *when only one cable is used*, the thickness of the water layer is not very important on the target fold. This means the vertical cable technique can also be applied to shallow water, at least in a geological environment similar to the one tested here.

The last exercise regarding fold was in the land environment. The results (right on Figure 8) show a very homogeneous and relatively low fold. Using more shot points on land is much more expensive than offshore, at first glance the use of vertical cables may not give as good results as can be expected from the marine case.

A brief analysis of offset and azimuth behavior was also done. When a single cable is used, the results are straightforward, as no complex geological structure is present: the offset distribution is pretty close to concentric circles for different ranges (left column on figure 9). The same conclusion is true for azimuths: the ranges which contribute to subsurface sampling are the ranges obtained as if azimuth measures were done for the cable at the center of a hypothetical circle (left column on figure 10).

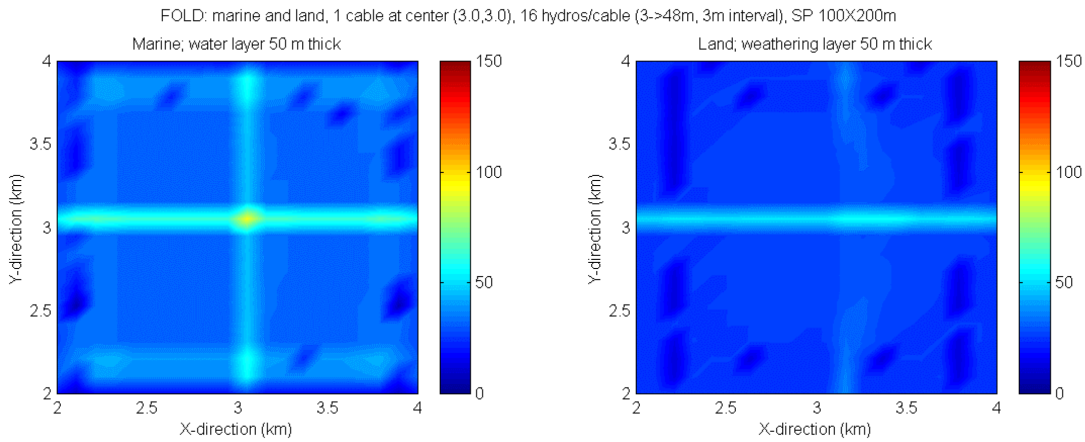


Figure 8 – Fold for 50m water (left) and 50m weathering thickness on land (right).

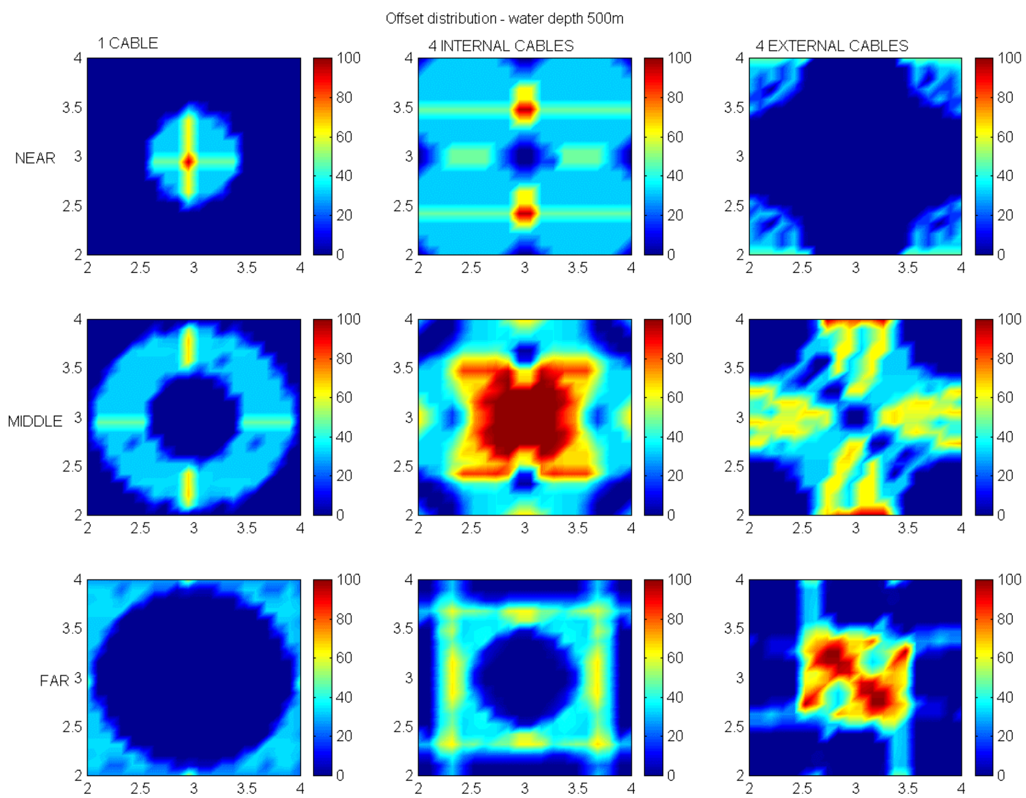


Figure 9 – Offset distribution: near (upper line), middle (central line) and far (lower line) for 1 cable (left column), 4 “internal” cables (middle column) and 4 “external” cables (right column). Water depth 500 m.

One can then conclude that a poor offset and azimuth sampling will occur if few cables are used, or if they are very far apart.

When more cables are available, the results for offset and azimuth are determined by just summing the values from each individual cable. The final result can have a complex shape, as can be seen on figures 9 and 10 for 4 cables configuration (middle and right columns). In the specific example shown here, we see that, regarding offset and azimuth sampling, the use of four cables in the “internal” configuration is more desirable than the “external”. We should remember that for fold the “internal” configuration is also better.

Offsets ranges were defined according to maximum offset: near offsets means offsets from zero to one third of the maximum offset, middle from one to two thirds and far from two thirds to maximum offset. Azimuths were grouped on 60^0 interval and the opposites groups added on plot.

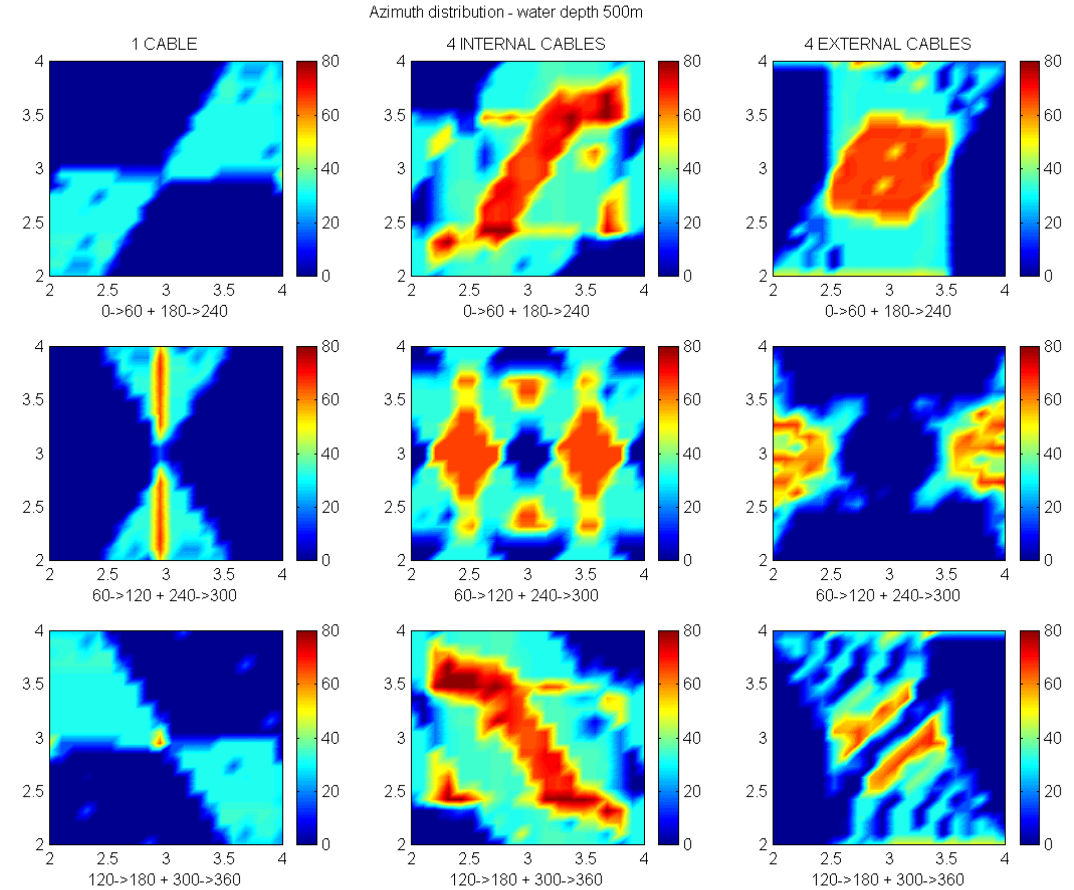


Figure 10 – Azimuth distribution: 0^0 to 60^0 plus 180^0 to 240^0 (upper line), 60^0 to 120^0 plus 240^0 to 300^0 (central line) and 120^0 to 180^0 plus 300^0 to 360^0 (lower line) for 1 cable (left column), 4 “internal” cables (middle column) and 4 “external” cables (right column). Water depth 500 m.

CONCLUSIONS

Using a single cable, good fold and lateral coverage can be obtained with the use of a reasonable number of receivers per cable and shot points. However, poor offset and azimuth per bin occurs. When more than one cable is used, offset and azimuth distribution can be drastically improved through the use of optimized cable positioning.

If converted (P- to S-) waves are to be acquired, larger offsets are necessary for a given target area. When dipping layers are present, shooting direction can be important. Different water depths give different fold when several cables are used. Concentrating receivers on cable deeper section may give better results than regular receiver distribution along the whole cable. On land environments, shallow cables may give poor results, and economic analysis comparing number of shot points *vs.* use of more cables and/or receivers per cable must be done. The results obtained here could be extrapolated for a target at least 15% shallower.

Future work includes: 1) comparison with streamer and OBC acquisition; 2) expand converted-wave analysis; 3) take into account downgoing energy, including effects on converted wave; 4) analysis of azimuth and offset contributions with different cables number and configuration, and 5) analysis for deeper target.

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Appendix I

Profiles showing target curvature and dipping interfaces.

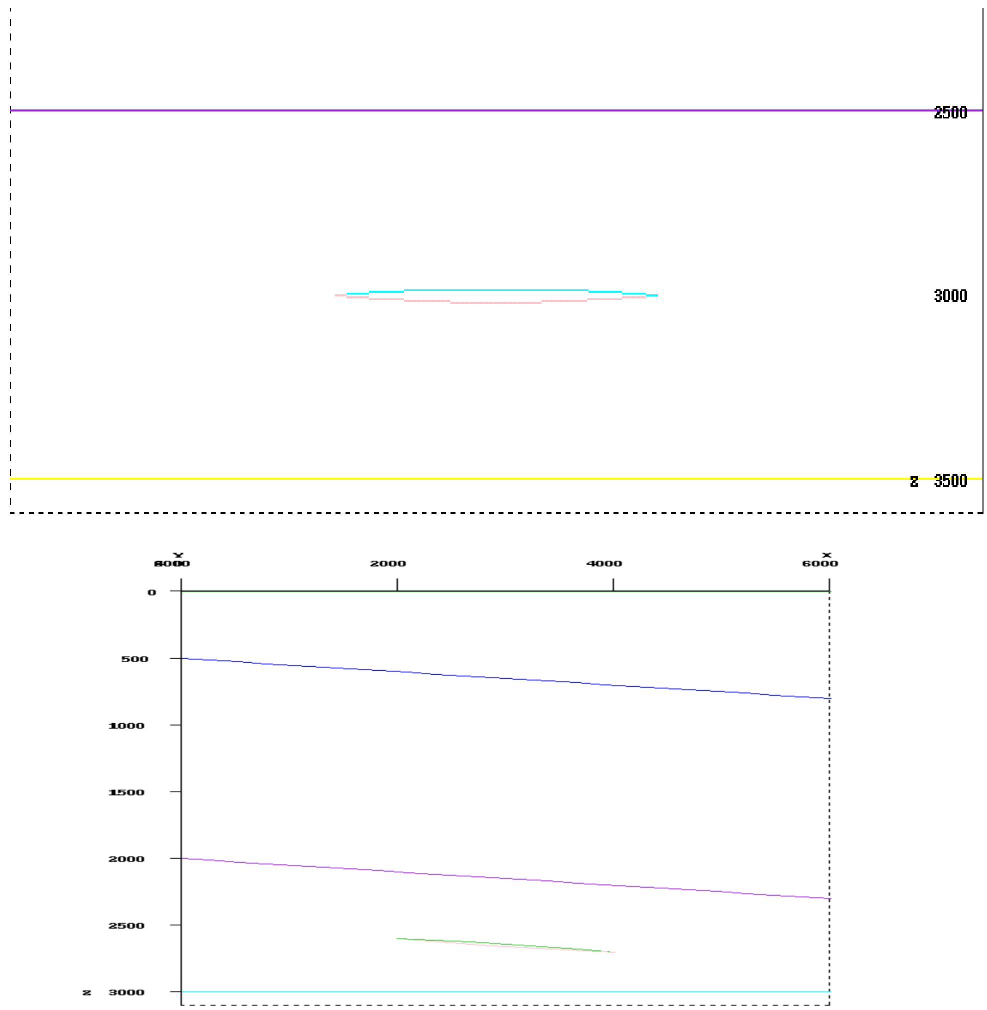

Figure A.1 – Lateral view of model showing target (around 3,000) top and bottom curvature (top) and dipping interfaces (bottom). Not to scale. Maximum target thickness 20 m.

Appendix II

Model elastic parameters and thickness

LAYER	$V_P = V_O + AZ$ (M/S)	POISSON RATIO	THICKNESS (M)
Water/ Weathering	Vp=1500; a=0/ Vp=1500,a=0	0.5/ 0.43	50,500,1000/ 50
Tertiary I	Vo=1600, a=0.5	0.4	1000,1500
Tertiary II	Vo=2350, a=0.4	0.36	1000
Target	Vp=2100, a=0	0.39	0-20 (curved)

Appendix III

Matlab function used to obtain bin fold, azimuth and offset distribution

```
function[fold,maxoffset,nearoffset,middleoffset,faroffset,azi060,azi60120,azi120180,azi180240,azi240300,azi300
            360]=bin11(xref,yref,xsou,ysou,xrec,yrec,binx,biny,maxnbinsx,maxnbinsy,azi)
%
%[fold,maxoffset,nearoffset,middleoffset,faroffset,azi060,azi60120,azi120180,azi180240,azi240300,azi300360]=
            bin11...
%     (xref,yref,xsou,ysou,xrec,yrec,binx,biny,maxnbinsx,maxnbinsy,azi);
%
% obtains fold, offsets (near, middle and far) and azimuths (6 sectors) for each bin in a 3D seismic survey
%
%input: xref,yref,xsou,ysou,xrec,yrec: x,y coordinates of reflection point,
%     source and receiver
%     binx, biny: bin dimensions in x and y
%     maxnbinsx,maxnbinsy: maximum number of bins in x and y
%     azi: source-receiver azimuth
%
% Carlos Rodriguez, oct/98 (based on nov/97 bin.m)
%

% sizing variables

x1=maxnbinsx;
y1=maxnbinsy;
  fold(x1,y1) = 0;
  nearoffset(x1,y1) = 0;
  middleoffset(x1,y1) = 0;
  faroffset(x1,y1) = 0  ;
  azi060(x1,y1) = 0;
  azi60120(x1,y1) = 0;
  azi120180(x1,y1) = 0;
  azi180240(x1,y1) = 0;
  azi240300(x1,y1) = 0;
  azi300360(x1,y1) = 0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% the first loop obtains offset and corrects for negative azimuths

n1=1;
while(n1<=length(xref))
 deltax = xsou(n1) - xrec(n1) ;
 deltay = ysou(n1) - yrec(n1) ;
 offset(n1)= sqrt(deltax*deltax + deltay*deltay);

% this loop is for data (e.g.,GX) where positive (0=Y+ axis,90=X+ axis) and
% negative azimuths are present; it also checks for azimuth=0
 if azi(n1)<=0
  azi(n1) = azi(n1) + 360 ;
 end

 n1=n1+1;
end

maxoffset=max(offset)
n2=1;

% the second loop obtains fold,near,middle and far offsets
% and azimuth distribution for all bins

while(n2<=length(xref))
 nbinx = ceil((xref(n2)-2000)/binx);    % 2000 used as origin for model1
```

```
 nbiny = ceil((yref(n2)-2000)/biny);    % (target min x and y)

  if nbinx<=0          % check if x or y reflection point is below min x or y
   nbinx=1;            % or over max x or y (this may be necessary due to
  elseif nbinx>maxnbinsx % internal Matlab approximations)
   nbinx=maxnbinsx;
  elseif nbiny<=0
   nbiny=1;
  elseif nbiny>maxnbinsy
   nbiny=maxnbinsy;
  end

 fold(nbinx,nbiny) = fold(nbinx,nbiny) + 1;

 if (offset(n2)<(maxoffset/3))
  nearoffset(nbinx,nbiny) = nearoffset(nbinx,nbiny) + 1;
 elseif (offset(n2)>(maxoffset*0.6667))
  faroffset(nbinx,nbiny) = faroffset(nbinx,nbiny) + 1;
 else
  middleoffset(nbinx,nbiny) = middleoffset(nbinx,nbiny) + 1;
 end

 if (azi(n2)<60)
  azi060(nbinx,nbiny) = azi060(nbinx,nbiny) + 1;
 elseif (60<=azi(n2)&azi(n2)<120)
  azi60120(nbinx,nbiny) = azi60120(nbinx,nbiny) + 1;
 elseif (120<=azi(n2)&azi(n2)<180)
  azi120180(nbinx,nbiny) = azi120180(nbinx,nbiny) + 1;
 elseif (180<=azi(n2)&azi(n2)<240)
  azi180240(nbinx,nbiny) = azi180240(nbinx,nbiny) + 1;
 elseif (240<=azi(n2)&azi(n2)<300)
  azi240300(nbinx,nbiny) = azi240300(nbinx,nbiny) + 1;
 else
  azi300360(nbinx,nbiny) = azi300360(nbinx,nbiny) + 1;
 end
n2=n2+1;
end
```