Phase-shift anisotropic depth migration using controlled illumination applied to a model of the San Alberto field – Bolivia.
Marco Antonio Cetale Santos*, DEE/PUC-Rio, Djalma Manoel Soares Filho, PETROBRAS, Paulo Léo Manassi Osório, DEE/PUC-Rio, Felipe Prado Loureiro, DEE/PUC-Rio

Summary
We introduce a new scheme for depth migration in elastic vertical transverse isotropic media (VTI), using the concept of controlled illumination. In the proposed method the areal shots obtained from multicomponent records are extrapolated using phase-shift techniques. Through the weighted addition of delayed shots we synthesize appropriate areal shots, which increases the accuracy of the seismic imaging in the area of interest. The computational cost of the present method is much lesser, when compared to the cost of migrating all the records, since only a few areal shots are necessary to image the area selected by the interpreters. The proposed method was tested on a typical numerical 2D model from the San Alberto field in Bolivia. It was possible to correct image an exploration target located underneath a thick highly tectonic deformed anisotropic shale layer, using only 3% of the computational time necessary to migrate all the shot records.

Introduction
One of the great challenges in the search for new oil and gas fields has to do with seismic imaging underneath intensively tectonic deformed areas. This includes areas underneath thick salt layers, such as the coastal basins in east of South America and areas subjected to great compressional efforts, like some coastal basins in the west of South America.

In this context, the wave equation migration based methods have played a fundamental role. In fact, its simplicity and the generality of their premises render its superiority in terms of accuracy when compared to asymptotic approximation based methods. On the other hand, wave equation depth migration usually demands a computational effort that is several times superior to the capacity of most computer centers, which turns many projects unfeasible.

Many propositions aim at the wave equation migration optimization. Most of them are based in the concept of wave synthesis, as initially proposed by Taner (1976) and by Schultz and Claerbout, (1978). In these works, the synthesized waves were positioned near the surface, which in many instances, were very far from the exploration targets. Berkhout (1992) proposed a method in which the synthesized waves were positioned closer to the targets, that allowed the image of interest areas more precisely.

Recently, among the several works in this area, we can cite Cunha (2002), who generalizes the concept of reverse time migration for areal sources, and Wang et al. (2001) who introduced the concept of multi controlled illumination.

Methodology
The proposed methodology has five steps:
1. The input consists of the wavefield horizontal and vertical components.
2. Computation of the compressional wave seismograms.
3. Generation of areal shots related to the desired wavefronts located at the target proximities.
4. Migration of each areal shot.
5. Summation of all migrated areal shots.

Areal shots from multicomponent data
Once we have the field seismograms for the horizontal and vertical wavefield at the surface, derived from a multicomponent 2D survey, we compute the compressional wavefield seismograms by applying the divergent operator at a datum located near the surface (Sun and Wang, 1999).

From the compressional wave seismograms, represented by $\mathbf{P}(k, z_0, \omega; \mathbf{x})$, where $\mathbf{x}_j$ is the position of the $j$th shotpoint on the surface, we compute the areal shots through the weighted sum of delayed shots,

$$
\mathbf{P}_{\text{syn}}(k, z_0, \omega; z = f(x)) = \sum_{j=1}^{N_s} A(x_j; z = f(x)) e^{i\omega \Delta t(x_j; z = f(x))} \mathbf{P}(k, z_0, \omega; \mathbf{x}_j)
$$

Where, $N_s$ is the number of seismograms in the sum; $z = f(x)$ defines a wavefront to be used in the vicinity of the interest area; $\Delta t(x_j; z = f(x))$ represents the delay to be considered in the seismogram traces regarding the $j$th shotpoint; $A(x_j; z = f(x))$ is the weight to be assigned to the seismogram relative to the shotpoint located in $x_j$.

$$
\Delta t(x_j; z = f(x)) \text{ and } A(x_j; z = f(x))
$$

are computed through the upward propagation of the wavefield generated in all the points along the curve $z = f(x)$. $A(x_j; z = f(x))$ is given by this wave largest amplitude at the point $x_j$. $\Delta t(x_j; z = f(x))$ is the difference between the maximum value of the arrival traveltime along the surface and the value of this time at $x_j$. 


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Phase-shift depth migration for VTI Media

In the depth migration process we can use the scalar wave equation in the frequency domain:

\[ P_{\omega}(k_x, z_0 + \Delta z, \alpha z, z = f(x) = e^{i \omega \eta} P_{\omega}(k_x, z_0, \alpha z, z = f(x)) \] (3)

For an upward solution, we use:

\[ k_z = \sqrt{\frac{w^2}{n^2} - k_x^2}, \] (4)

where \( k_x, k_\omega, \omega \) and \( v \) are the spatial frequencies, the temporal frequency and velocity, respectively.

In modeling, the solution in equation (3) only propagates waves from the reflectors up to the receivers, using a \( \Delta z \) with a negative sign. In the migration case \( \Delta z \) has a positive sign.

We depropagate each area shot separately and use the image condition which is given by the direct arrival maximum amplitude traveltimes at each medium point and the migration results is given by \( M_{\omega}(x,z) \).

\[ M_{\omega}(x,z;z = f(x)) = \sum_\omega e^{\omega TD(x,z)} P_{\omega}(x,z, \alpha z, z = f(x)) \] (5)

where \( TD(x,z) \) denotes the direct arrival maximum amplitude traveltimes, obtained from the area shots forward modeling. (Cetale Santos et al, 2003).

In this way, for the isotropic grid points, \( k_z \) will be computed according to equation (4). On the other hand, for the TI grid points, \( k_z \) will be estimated by the following algorithm. In doing this, we created a hybrid method.

Given the dispersion relation:

\[ \left(\frac{\omega}{v}\right)^2 = k_x^2 + k_z^2, \]

and taking into account the following trigonometric relations:

\[ \frac{k_y}{\omega} = \sin \theta \quad \text{and} \quad \frac{k_z}{\omega} = \cos \theta \]

the spatial frequency \( k_z \) is estimated through a table generated by varying \( \theta \) between 0 and \( \pi \) rad, and by computing \( \sin \theta / v(\theta) \) and \( \cos \theta / v(\theta) \), which are related to the values of \( k_z/\omega \) and \( k_z/\omega \). Once we have the values of \( k_z \) and \( \omega \) it is possible to determine \( k_z \) from the table. For some values of \( k_z \) and \( \omega \), \( k_z/\omega \) is outside the \( \sin \theta / v(\theta) \) table. The evanescent waves were treated in a way similar to Rousseau, (1997), where the propagating angle is \( \theta = \pi/2 - i\delta \), which leads to \( \cos(\theta) = \sinh(\alpha) \) and \( \sin(\theta) = \cosh(\alpha) \).

We compute the phase velocity field using the following (Thomsen, 1986):

\[ v_e^2(\theta) = \alpha^2 \left(1 + \frac{\sin^2(\theta)}{\sin(2\theta)} + D(\theta)\right) \]

where

\[ D(\theta) = \frac{2}{\alpha^2} \left(1 + \frac{4\delta^2 \sin^2 \theta \cos^2 \theta}{\sin^2(2\theta)} + \frac{4(f+\epsilon)}{f\delta} \sin^2(\theta) - 1\right) \]

Discussion of the Results

In order to test the proposed method we depth migrate several areal shots obtained by finite differences modeling on VTI media (Cetale Santos et al, 2004). The chosen seismic model was based on the San Alberto field in Bolivia (Soares Filho et al, 1997). This field presents high velocity contrasts, steep dip interfaces and a thick anisotropic shale layer (assumed VTI), which is located above the exploration targets (Figure 1). In this figure the horizontal reflector located at the bottom is used as a reference reflector.

We simulated a seismic survey with 501 shot records, with consecutive shotpoints separated by 10m. We spread 1200 receptors 5m apart from each other along the model surface. Figure 2 shows the migration result of the shot record relative to the source located at \( x=3000 \)m.

For the areal shots generation, we considered the wavefronts defined by the curves in Figure 3a. Figure 3b shows the areal shot for the wavefront defined by 1 in Figure 3a. Figure 4 shows a sequence of snapshots obtained during the imaging condition traveltimes generation relative to wavefront 3. Figure 5 shows the results obtained for each areal shot defined by the curves of Figure 3a. Figure 6 presents the sum of 15 individual areal shot migrations.

The time required to migrate one areal shot or to migrate a single shot gather was the same. The areal shot migration results offered the possibility of more regional interpretations, when compared to the migration of a single shot gather. Besides a better global illumination, the areal shot migration exhibits specific details of the model. Comparing Figures 5a and 5b we can see that the wavefront defined by 1 (Figure 3a) favors the imaging of the interfaces with similar slopes. The wavefronts defined by 3 and 4 (Figure 3a) exhibit good results in the target area, indicated by the arrow in Figure 1a. Figure 6 shows the 15 areal shot migration sum, which exhibits besides the exploration target correct imaging, the plane interface used as reference.
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Conclusions

We presented a robust method for depth migration of areal shots generated in a multicomponent seismic survey, for elastic anisotropic media with VTI symmetry. Appropriate areal shots are synthesized through the weighted sum of delayed shot gathers, after the compressional field separation. Its application to a numerical model based on the San Alberto field shows the numerical robustness with regard to high lateral velocity variations and VTI anisotropy.

As in the case of any other migration techniques, the proposed method does not require the exact velocity model, but a reasonable outline of the main structures, that can be obtained through focus analysis, tomography, etc, besides of a clear understanding of the exploration targets.

This method can easily be extended to cope with transverse isotropic media.

References


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Figure 1 – Structural cross section of the San Alberto model and its table of parameters. All media with $\rho=2400$ Kg/m$^3$.

* The medium 5 has anisotropic parameters $\varepsilon = 0.1$, $\delta = 0.01$.

Figure 2: (a) Common Shot Gather, and (b) its depth migration.
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Figure 3: (a) Wavefront configurations. (b) Areal shot related to wavefront 1.

Figure 4: Sequence of snapshots obtained during the generation of the imaging condition traveltimes relative to wavefront 3

Figure 5: Migrated sections relative to the wavefront configurations shown at Figure 3(a): (a), (b), (c), (d) results for wavefronts 1, 2, 3 and 4, respectively.

Figure 6: Sum of 15 migrated sections.