Phase-shift anisotropic depth migration using controlled illumination: Stability in relation to addition of random noise

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This paper was prepared for presentation at the 9th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, 11-14 September 2005.

Abstract

The present work studies the stability of a depth migration for 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 exposed to noisy conditions created by a random noise generator. Even with lower signal to noise ratio (SNR) we can correctly migrate anticline structures under a thick anisotropic shale layer.

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 the 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 to image the interested 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.

In the present work we test the stability, in relation to random noise addition, of an algorithm for areal shot migration scheme applied to multicomponent seismic data in VTI media (Cetale Santos, et al 2005).

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 $P(k_x, z_0, \omega; x_j)$, where x_j is j^{th} shotpoint position at the surface, we compute the areal shots through the weighted sum of delayed shots,

$$P_{syn}(k_x, z_0, \omega; z = f(x)) = \\ = \sum_{j=1}^{N_s} A(x_j; z = f(x)) e^{i\omega\Delta t(x_j; z = f(x))} P(k_x, z_0, \omega; x_j) \qquad (1)$$

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.

$$\Delta t(x_j; z = f(x)) \quad \text{and} \quad A(x_j; z = f(x)) \qquad (2)$$

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.

Phase-shift depth migration for VTI Media

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

$$P_{syn}(k_x, z_0 + \Delta z, \omega; z = f(x)) = e^{ik_z\Delta z} P_{syn}(k_x, z_0, \omega; z = f(x)) \qquad (3)$$

For an upward solution, we use.

$$k_z = -\sqrt{\frac{w^2}{v^2} - {k_x}^2}, \qquad (4)$$

where k_x, k_z, ω 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 Δz with a negative sign. In the migration case Δz has a positive sign.

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

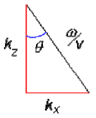
$$M_{syn}(x,z;z=f(x)) = \sum_{\omega} e^{-i\omega.TD(x,z)} P_{syn}(x,z,\omega;z=f(x)) \qquad (5)$$

where TD(x,z) denotes the direct arrival maximum amplitude traveltime, obtained from the areal 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:

$$\frac{k_x}{\omega} = \frac{\sin\theta}{v(\theta)} \quad and \quad \frac{k_z}{\omega} = \frac{\cos\theta}{v(\theta)}, \qquad (6)$$

the spatial frequency k_z is estimated through a table generated by varying θ between 0 and π rad, and by computing $\sin\theta / v(\theta)$ and $\cos\theta / v(\theta)$, which are related to the values of k_x/ω and k_z/ω. Once we have the values of k_x and ω it is possible to determine k_z from the table. For some values of k_x and ω, k_x/ω is outside the sin θ /v(θ) table. The evanescent waves were treated in a way similar to Rousseau, (1997), where the propagating angle is θ = π/2–iα, which leads to cos(θ) = isinh(α) and sin(θ) = cosh(α).

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

$$v_P^2(\theta) = \alpha^2\left[1 + \varepsilon \cdot \sin^2(\theta) + D(\theta)\right]$$

where

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

Discussion of the Results

In order to test the robustness of the migration algorithm, 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.

For the areal shots generation, we considered the wave-fronts defined by the curves in Figure 2a. The other curves in Figure 2a were used to generate some of the 25 areal shots. The curves can assume the shape that better illuminate the target. Figure 2b shows the areal shot for the wavefront defined by 1 in Figure 2a. Figures 2c and 2d shows the same areal shot with random noise added, with SNR of 10dB and -15dB, respectively. Note that in the last case only the direct wave stands above of the noisy signal.

Figure 3a show the results of the migration obtained for the areal shot defined by the curve 1 of Figure 2a. Figures 3b and 3c show the migration results of the data shown in Figures 2c and 2d, respectively.

Figure 4 presents the sum of 25 individual areal shot migrations. Figure 4a is the noiseless result, while Figures 4b and 4c are the results from data with 10dB and -15dB signal-to-noise ratios, respectively.

The stability with relation to the addition of noise was confirmed. The reflectors were correctly mapped in two different scenarios of noise addition, which are shown in the sequence of Figures 2c, 3b and 4b for SNR of 10dB and the sequence of Figures 2d, 3c and 4c for SNR of -15dB. The migration algorithm has a filtering behavior by increasing migrated sections SNR. In Figure 3b we can observe almost the same result as in Figure 3a, where there is no noise added. In Figure 3c, obtained by the migration of the areal shot in Figure 2d, we can not observe coherent events with the exception of the direct wave, but we can see the correct imaging of some reflectors.

The migration algorithm also displayed its filtering behavior when it almost removed all the noise the migrated section in Figure 3b and make partially visible, in Figure 3c, the heavily suppressed reflections in Figure 3b.

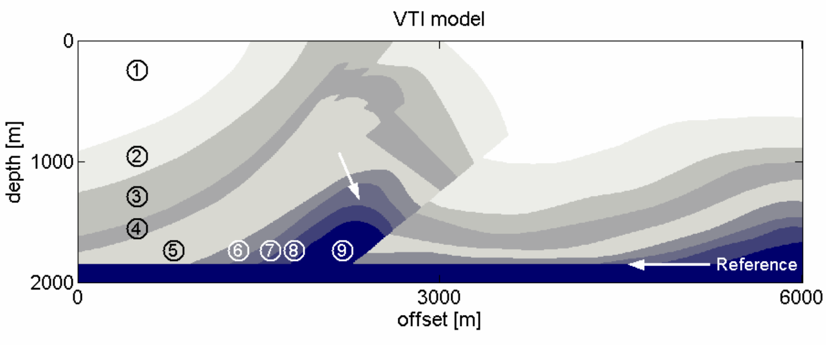
Conclusions

One of the main advantages of the migration algorithm (Cetale Santos et al. 2005) is that 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.

When we added random noise to the areal shots, we could observe, by the result in Figure 3, that the migration algorithm is very robust to additive noise, since it behaves like a filter removing the random noise.

Acknowledgments

The authors would like to thank PETROBRAS for the financial support through the PRAVAP 19 research program. We would like to thank PETROBRAS INTERNATIONAL, TOTAL and ANDINA for using a typical model of San Alberto field, Bolivia.



Medium	α	β
1	3000	1732
2	4000	2309
3	4500	2598
4	4800	2771
5*	4400	2540
6	4900	2829
7	5000	2887
8	5100	2944
9	5300	3060

Figure 1 – Structural cross section of the San Alberto model and its table of parameters. All media with ρ=2400 Kg/m^3.
* The medium 5 has anisotropic parameters ε = 0.1, δ = 0.01.

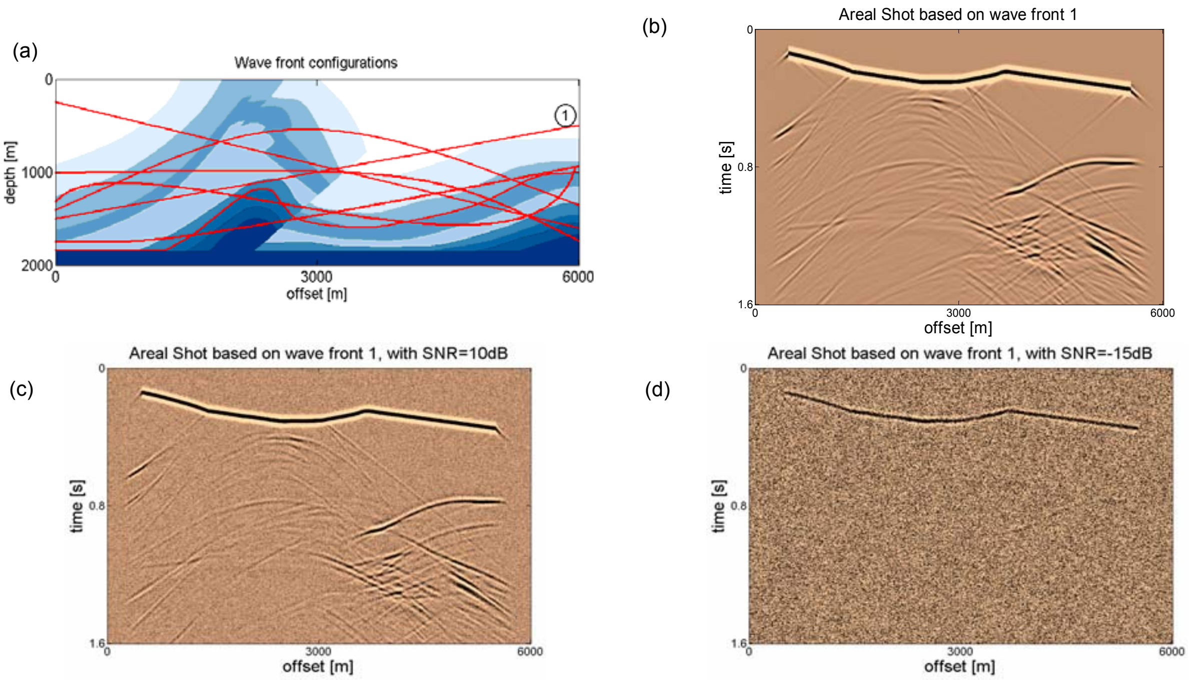


Figure 2: (a) Wavefront configurations. (b), (c) and (d) Areal shots related to wavefront 1, with varying degrees of noise added.

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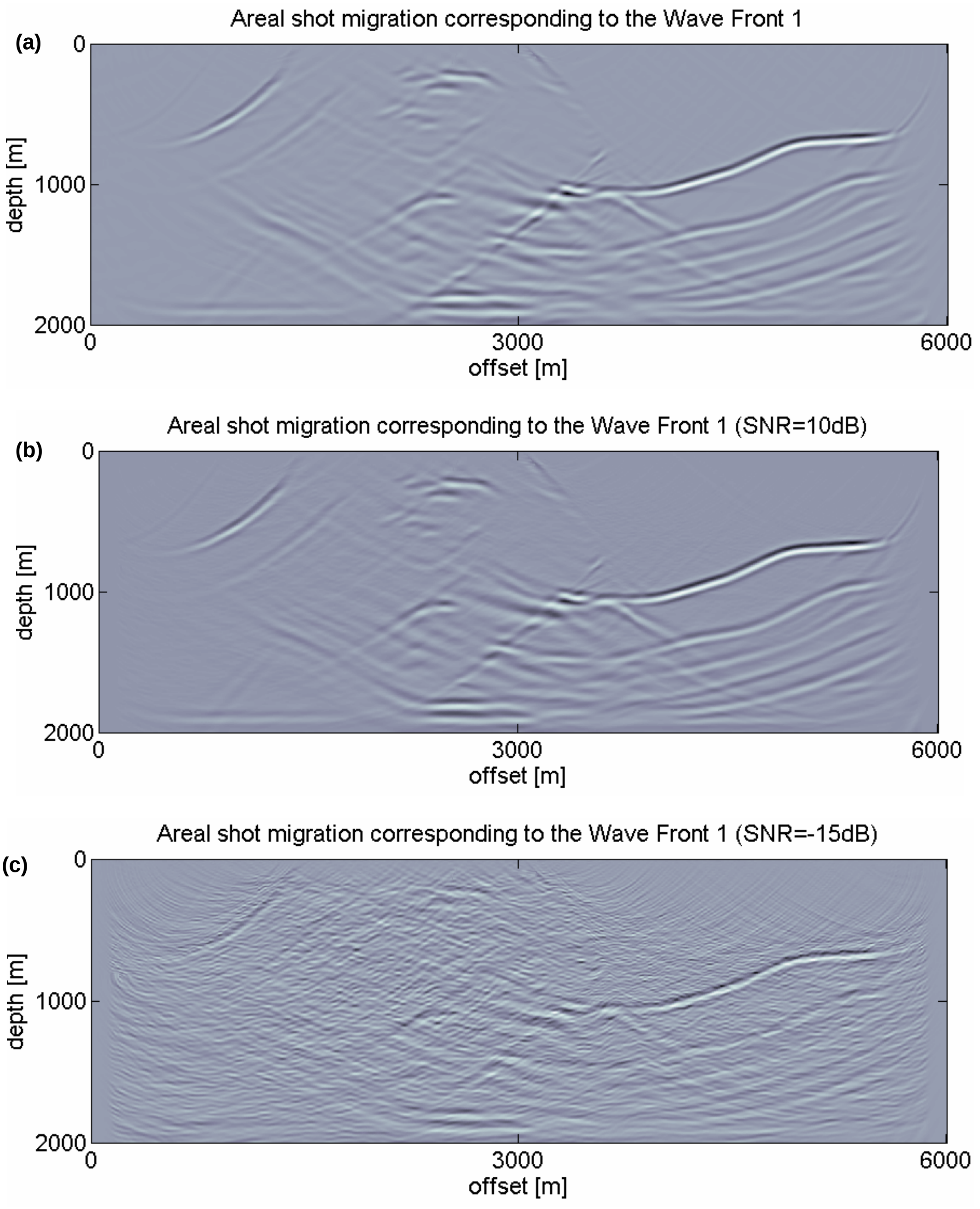

Figure 3: Migrated sections relative to the areal shots of Figure 2: (a) without noise; (b) 10dB; (c) -15dB

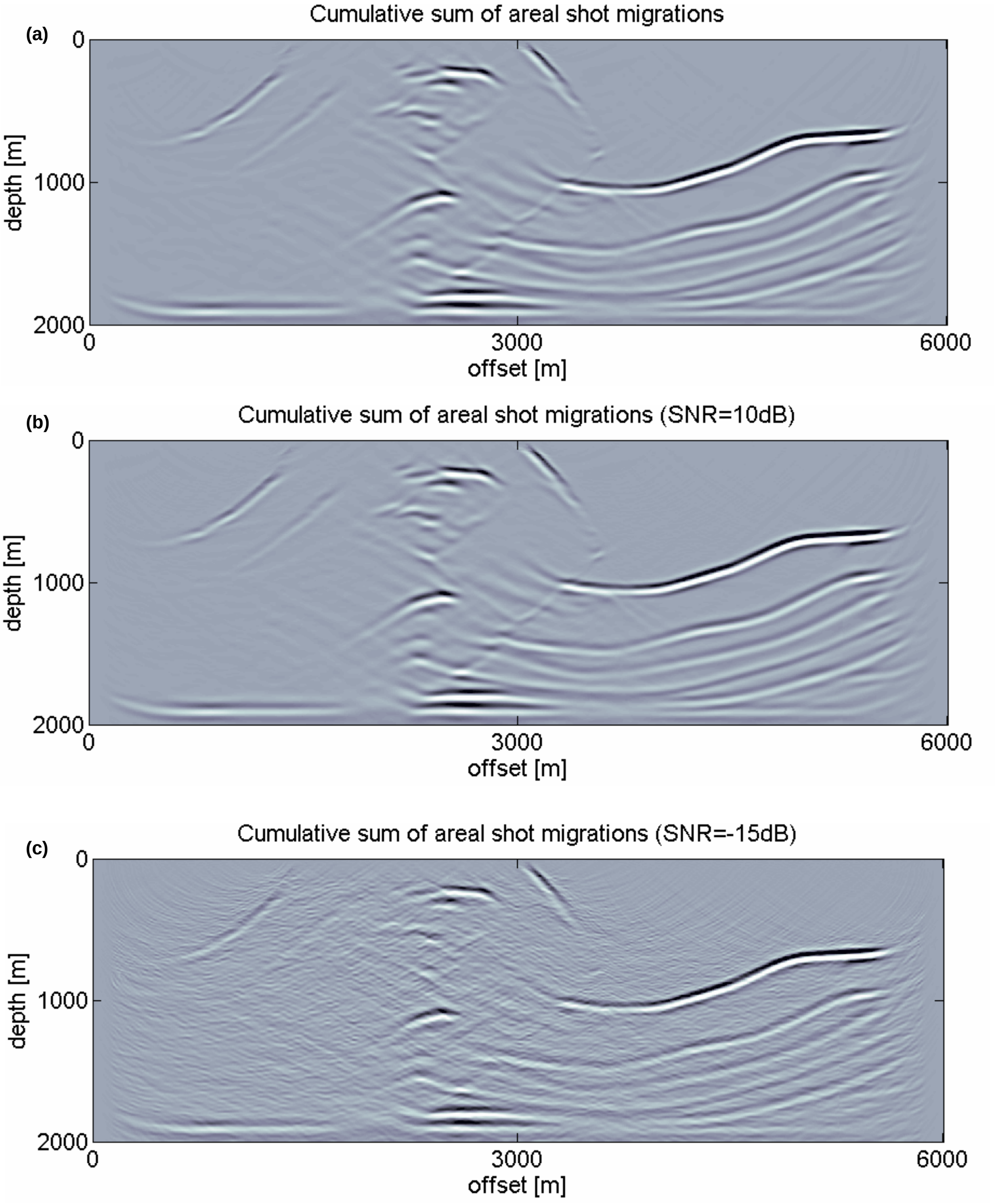

Figure 4: Sum of 25 migrated sections. (a), (b), (c) results from seismograms with varying degrees of noise added.