Reverse Time Migration Velocity Analysis with Plane Waves

Luiz Alberto Santos*, André Bulcão, Djalma M. Soares Filho, Bruno Pereira Dias, Felipe Prado Loureiro, Paulo E. M. Cunha, Alan A. V. B. Souza, Fernanda F. Farias, Gustavo C. Alves - PETROBRAS

Abstract

In this work we present an alternative migration velocity analysis strategy that uses pairs of delayed stacks to estimate velocity field. The method involves the migration of two delayed stacks (p and –p slowness), using the reverse time migration as the migration tool, and scan for the velocity function that maximize the correlation between corresponding migrated events. Synthetic examples and preliminary field results has shown the feasibility of the method.

Introduction

Migration is an inversion operation that maps reflections and diffractions on their true position since the kinematics of subsurface is correctly described by the velocity field or the corresponding Green function (Sheriff, 2002).

Cunha and Palermo (2003) present the multi-point reverse time migration (RTM) as an alternative strategy for conventional RTM. A typical seismic survey has thousands of shots and, conventional RTM involves the migration of each shot gather, application of image condition and stacking. So the process and all stability needs, turned the process particularly expensive for the processing power of 2000's years. Cunha and Palermo (2003) stack few shot-gathers with different delays composing families of plane wave surveys that are migrated and stacked. Tens of migrated delayed stacks suffice to generate images comparable to conventional RTM. So, the imaging process becomes much cheaper. Boechat (2007) employs synthesis operator, wave fronts more complex than planes, to better illuminate targets in depth also optimizing the RTM imaging.

Schultz and Claerbout (1978) employ plane waves to estimate the velocity field. The non-coincidence of events at different migrated panels measures the error in the velocity field. Corresponding events should focus in the same position.

In this paper we conjugate the delayed stack RTM forming pairs of plane waves to estimate the velocity field. The process is useful only for complex regions.

Flow for reverse time migration velocity analysis with plane waves

Seismic surveys are designed to sample an event at depth several times as such procedure improves subsurface images. Migration velocity analysis principle estates that an event at different gathers (shot-gather, receiver-gather, common offset-gather, angle-gather) may focus at the same position after migration whenever the velocity field is correct.

The process presented here involves the depth migration of one pair of symmetrically delayed stacks and evaluation of migrated panels through a layer stripping strategy. The flow is straightforward and contains the following steps:

1- Choice of p parameters - corresponding to time delays between shot-gathers- suitable for the depth of the target layer i. The time delay $T(x_{s_j})$ for each shot gather position x_{s_j} is given by equation 1:

$$T(x_{s_j}) = p x_{s_j} \qquad (1)$$

where p is the slowness that define the plane wave dip.

2- Low pass filter to enhance more expressive and laterally continuous horizons, bottom of layer i;

3- Choice of suitable functions to describe the velocity of layer i;

4- Perform the RTM of the pair of sections/volumes p and –p for each velocity using a maximum excitation time image condition. The wave equation for multi-source is:

$$\nabla^2 u(\vec{x},t) - \frac{1}{v(\vec{x})^2}\frac{\partial^2 u(\vec{x},t)}{\partial t^2} = \sum_{j=1}^{N_s} f\left(\vec{x}, t - T(x_{s_j})\right) \qquad (2)$$

where $u(\vec{x},t)$ is the wave field, $v(\vec{x})$ is the velocity field, t is time and f is the multi-point source or plane like source. We call the migrated image in depth as $I = I(\vec{x}, v(\vec{x}), p)$;

5- Cross-correlate along axis z the pair of sections/volumes obtained with the same velocity model $v_{i,k}(\vec{x})$ through equation 3:

$$C(x, y, z_{lag}, v_{i,k}(\vec{x}), p) = I(\vec{x}, v_{i,k}(\vec{x}), p) \otimes_z I(\vec{x}, v_{i,k}(\vec{x}), -p) \qquad (3)$$

6- Stack the correlation panel of each velocity function:

$$S(z_{lag}, v_{i,k}(\vec{x}), |p|) = \iint_{x,y} C(x, y, z_{lag}, v_{i,k}(\vec{x}), |p|)dxdy \quad (4)$$

7- Evaluate the lag zero of correlation panels. The highest value at lag zero corresponds to the most suitable velocity function for layer i. This operation is represented as follow:

$$v_i(\vec{x}) = v_{i,k}(\vec{x}) \text{ for } \max[S(z_{lag}, v_{i,k}(\vec{x}), |p|)] \quad (5)$$

8- Update the velocity model and bottom horizon for layer i;

9- Perform steps 2 to 8 until the deepest horizon.

Synthetic application of RTMVA-PW:

A synthetic model with a single diffractor immersed in a homogeneous velocity field, v=1000 m/s, is surveyed by a pair of plane waves delayed with p=0,0006 s/mand p=-0,0006 s/m.

The resulted seismograms were migrated with three velocities: 750 m/s, 1000 m/s and 1500 m/s. Due to comparison reasons, the six migrated sections ($I(\vec{x}, v(x), \pm p)$) are stacked in Figure 1 and the diffractor position after migration are enhanced on points A1, A2, O, B1 and B2.

The migration of the two seismograms with velocity of 1000 m/s collapses the diffraction at position O in Figure 1. The focusing occurs because the migration velocity is correct:

$$I(\vec{x}, v = 1000, p) \approx I(\vec{x}, v = 1000, -p) \quad (6)$$

The points A1 and A2 of Figure 1 represent the locations of the migrated diffraction with the velocity equal to 750 m/s. As the velocity field is 250 m/s lower than the correct, migrated points do not coincide and occur at a shallower position.

$$I(\vec{x}, v = 750, p) \neq I(\vec{x}, v = 750, -p) \quad (7)$$

The velocity of 1500 m/s wrongly locates the diffractor at position B1 for p=-0,0006 and B2 for p=0,0006. In this case the velocity is 500 m/s higher than the correct one and that locates migrated points deeper than point O. The horizontal distance between B1 and B2 is twice longer than A1 and A2, as the error in velocity is also twice.

$$I(\vec{x}, v = 1500, p) \neq I(\vec{x}, v = 1500, -p) \quad (8)$$

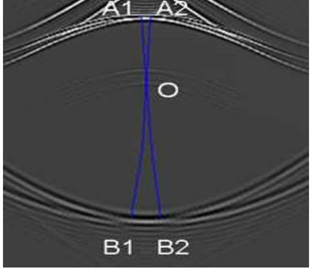


Figure 1: Overlay of migrated sections. A1 and A2 are the difractor migrated position with velocity equal to 750 m/s and respectively p=0,0006 s/m and p=-0,0006 s/m. At point O there is focusing with v=1000 m/s, the correct velocity. B1 and B2 are the diffractor position migrated with v=1500 m/s respectively of the seismograms stacked with p=-0,0006 s/m and p=0,0006 s/m.

The above experiment was extended to a series of point diffractors composing a sinusoidal surface. The correct background velocity is also 1000 m/s and the seismograms were migrated with three velocities, 750 m/s, 1000 m/s and 1250 m/s. Following the flow for RTMVA-PW previously described, the resulting correlation panel of step 5 ($C(x, y, z_{lag}, v_k(\vec{x}), |p|)$) is presented at Figure 2. For each velocity the horizontal axis represent the x coordinate of the surveyed area and the vertical axis is the lag of the correlation.

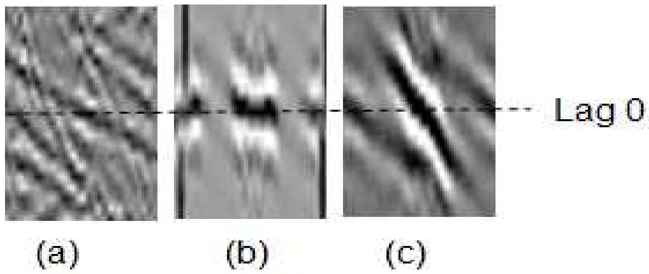


Figure 2: Cross-correlation $C(x, y, z_{lag}, v_k(\vec{x}), |p|)$ panels of migrated delayed sections with velocities of 750 m/s, 1000 m/s and 1250 m/s respectively at a, b and c. The horizontal axis is the x coordinate of surveyed area and along the vertical the lag (z_{lag}) of correlation. Lag 0 is enhanced with the dashed line.

In step 6 each panel is stacked delivering a trace per velocity model. At lag 0, the panel b at Figure 2 is the one with more events in phase. So, among the other two, panel b, with the correct velocity of 1000 m/s, will deliver highest value at lag 0.

The process, nevertheless, failed when the target horizon is not complex. For plane and horizontal interface the velocity estimation procedure is non-conclusive. All migrated horizons fall in level z according to the employed velocity model. So, all correlations panels show similar values at lag zero. The method is suitable only for complex, despite continuous, structures.

Synthetic application in a realistic model

A synthetic model inspired in the geology of Lula field in Santos Basin (Brazil), called Tupi model (Figure 3), is used to test the RTMVA-PW technique. Over Tupi model two synthetic seismograms were run with plane waves formed with p=0,00004 s/m and p=-0,00004 s/m. The delayed seismograms are shown in Figure 4(a) and 4(b).

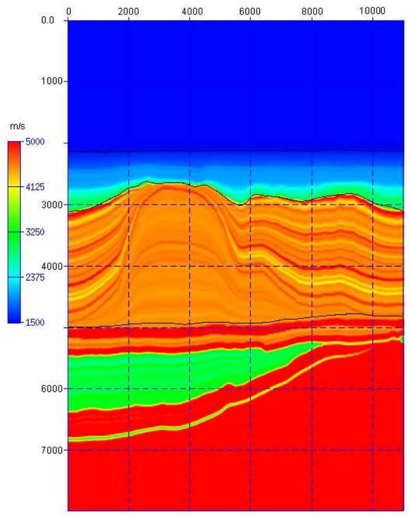
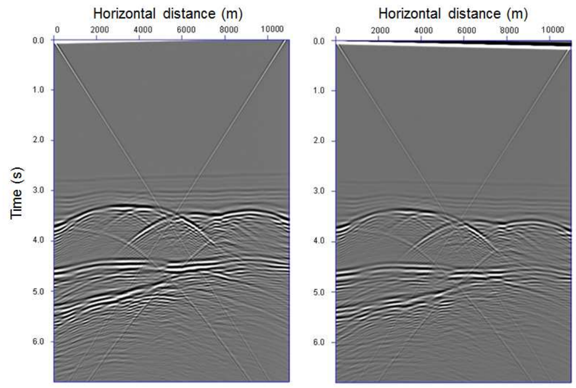


Figure 3: Tupi Model with compressional velocity in m/s. The horizontal and vertical axis are in meters.



(a) (b)

Figure 4: (a) Seismogram obtained with p=0,00004 s/m; (b) Seismogram obtained with p=-0,00004 s/m.

We've chosen the reflections with greater lateral continuity giving four main layers:

1- water layer;

2- Drift (mainly clastic) section;

3- Salt layer;

4- Pre-salt layer (sag and rift) and;

For each layer we defined a simple velocity function simulating a low level of knowledge about the surveyed area. Then, for the water layer it was defined a constant function. For the drift section we adopt a linear function to represent a top-concordant compaction curve. For the salt and pre-salt layers we use constant functions.

Because the sea bottom is smooth and almost horizontal we do not apply the RTMVA-PW for the first layer. Conventional velocity analysis (semblance) worked perfectly for the water layer delivering a constant velocity of 1500 m/s.

For the second layer, the post-salt section, the model is described by equation 9below:

$$v_{i=2,k} = 1500 + g_k(z - h(x)) \quad (9)$$

where g_k is the vertical gradient, z is the depth and h(x) is sea bottom depth. Six different gradients were used and the steps 4, 5, 6 and 7 were done.

Figure 5 shows the function $S(z_{lag}, v_{i,k}(\vec{x}), |p|)$ at lag zero for layer 2. The highest energy for $S(z_{lag} = 0, v_{i,k}(\vec{x}), |p|)$ occurs at model $v_{2,3}$ with g_k = 1,5 s^{-1}.

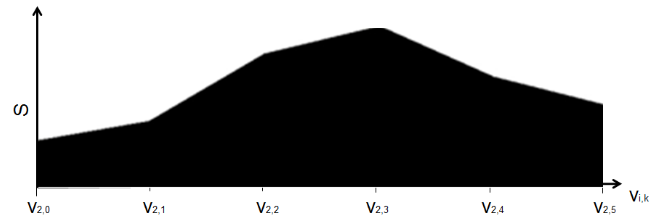


Figure 5: Function $S(z_{lag} = 0, v_{i,k}(\vec{x}), |p|)$ as a function of velocity model $v_{2,k}$ for layer 2.

The function S for the third layer points to model $v_{3,8}$ as the best one to describe salt velocity ($v_{3,8}$ = 4200 m/s) - Figure 6.

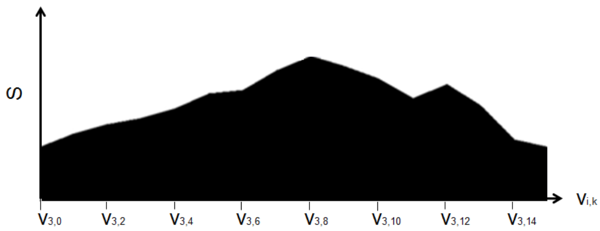


Figure 6: Function $S(z_{lag} = 0, v_{i,k}(\vec{x}), |p|)$ as a function of velocity model $v_{3,k}$ for layer 3.

For the pre-salt there is a loss of resolution because of the used |p| (0,00004 s/m). The best model $v_{4,10}$=4400 m/s is a bit higher than the second highest value – Figure 7. A higher |p| should be used to overcome this ambiguity.

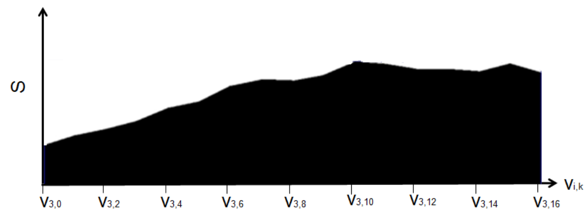


Figure 7: Function $S(z_{lag}=0, v_{i,k}(\vec{x}), |p|)$ as a function of velocity model $v_{4,k}$ for layer 4.

The estimated model is ilustrated at Figure 8 plotted together with the migrated section.

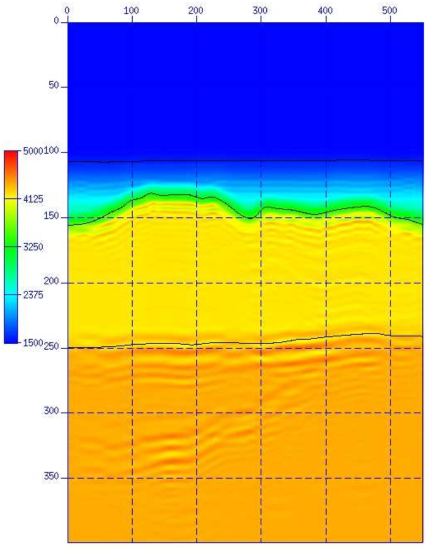


Figure 8: Velocity model estimated with RTMVA-PW for Tupi model. The horizontal and vertical axis are in meters.

Figures 9a and 9b show the migration result with estimated velocity field with RTMVA-PW and the correct velocity field respectively. The top of salt is correctly migrated as it is the top of basement (Figure 9). The base of salt, however, is a bit above the expected position pointing to a low velocity employed for the salt layer.

Discussion

The velocity analysis performed with Tupi synthetic data set simulates the same limitations observed in real field data. The use of simple functions (constant and linear) to describe the layers suffices as a first approximation. For exploration and reservoir characteriztion purposes, much effort must be spent to increase the spatial frequency contente of the velocity field. The results is a first step for input in a more detailed tomographic inversion or Full waveform inversion procedure.

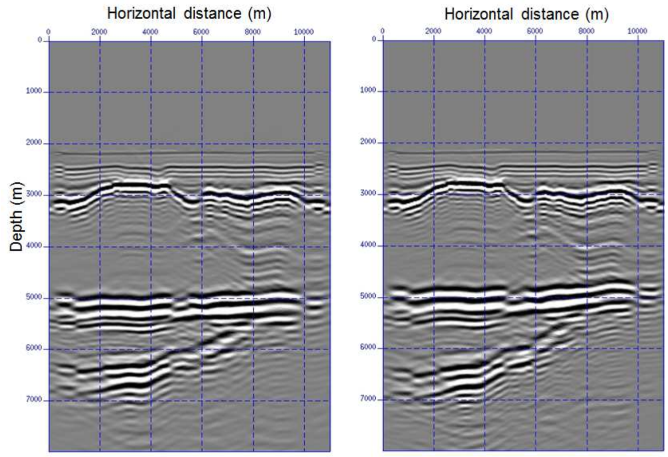
The process allows fast access to the velocity field framework in a 11 Km wide area in a very early stage of processing flow.

The linear function used for the post-salt layer gives good results as the top of salt is correctly migrated (Figure 9a).

The salt layer estimated velocity (4200 m/s) is lower than the real kinematics. This under evaluation, about 200 to 300 m/s below the expected values, caused the pull-up observed on the base of salt (Figure 9a).

Constant function is very simple to describe the layer 4 (pre-salt). However the $v_{4,10}$=4400 m/s compensates the low velocity of the salt layer, so the migrated horizons are correctly located (Figure 9).

Te layer stripping strategy has shown that, deeper layers and interface ask for steep p parameters or time delays. In the Tupi data set example, there is a progressive loss of resolution from layer 2 to layer 4 (Figures 5, 6 and 7). Steeper p for layer 4 should be employed to reduce the ambiguity.



(a) (b)

Figure 9: (a) Migrated section with the correct velocity model (at Figure 3). (b) Migrated section with estimated velocity field (at Figure 8).

Conclusion

We present a feasible migration velocity analysis technique using RTM as the migration tool. It is suitable for velocity framework estimation along large areas. The method is not suitable for smooth and sub-horizontal structures. The method is effective for diffractions, high curvature horizons and complex structures.

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References

Boechat, J.B.T, 2007. Migração reversa no tempo 3D orientada ao alvo por síntese de frentes de onda, PhD thesis.

Carvalho, P.M., Silva, F. B., Santos, L.A., Ruthner, M.P., Thedy, F.A.C., Cunha, C.A., Theodoro, C.E., Paula, L., Boechat, J.B.T., 2012. Aplicação de modelagem numérica elástica nos carbonatos microbiais da bacia de Santos. In Simpósio de Geofísica. Petrobras.

Cunha, P. E. M. e Palermo, L. A. C. 2003. A "Multi Source"version of the Reverse Time Migration (RTM). In Resumos Expandidos, 8o. Congr. Intern. da SBGf, volume 1, Rio de Janeiro. SBGf, Brazilian Geophysical Society, Soc. Expl. Geophys.

Schultz, P. S. e Claerbout, J., 1978, Velocity estimation and downward continuation by wavefront synthesis. Geophysics, vol. 43, n.4, p. 691-714.

Sheriff, R. E., 2002, Encyclopedic dictionary of xploration geophysics: Society of Exploration Geophysicist, 1.