Dip Constrained Migration Velocity Analysis and Interpretative processing

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Abstract

In pre-stack depth migration processing flow, there is the important step of velocity estimation. Migration velocity Analysis (MVA) is one of most used method in the seismic industry. In this work we describe the MVA workflow that takes into account the dip of layers to automatically increase geologic information as a regularization procedure in inversion. We apply the workflow in a real data set from Campos Basin detailing the shallow region. The experiment clearly shows the importance of interpretation team interacting during processing. Particularly for the studied area, MVA delivers velocity field consistent with geologic evolution of the site.

Introduction

Seismic workflow in oil industry is composed of three main phases: acquisition, processing and interpretation. Usually those phases have sharp limits. In pre-stack depth migration processing flow, there is the important step of velocity estimation. Migration velocity Analysis (MVA) is one of the most used method in seismic industry. The objective of MVA workflow (Figure 1) is the estimation of a velocity field for depth migration for best imaging.

Sometimes best imaging does not mean geologically feasible velocity model. This subject has been addressed by some authors. Delprat-Janaud and Lailly (1992) compute numerical uncertainties that approximate the physical uncertainties. They limit the study to Hilbertian model spaces and derive necessary and sufficient condition which yields the desired result - the norm chosen in model space has to bind the Frechet derivative of the forward map. Clapp et al. (2002) use nonstationary operators that tend to spread information along structural dips of layers in tomographic process. Costa et al. (2008) propose a reflection-angle-based kind of smoothness constraint as regularization in slope tomography. Santos et al. (2013) quantify the gradients differences of velocity and amplitude volumes in a parameter called Geological Incoherence Index (GII). Luo et al. (2017) propose anisotropic diffusion smoothing operators into the conjugate gradient algorithm to precondition tomography.

We developed and apply the structure tensor based regularization in MVA process using a workflow that includes available geological information. With an example of Campos Basin dataset we show advantages and limitation of this process.

Method

The objective of the Migration Velocity Analysis (MVA) workflow (Figure 1) is the estimation of a velocity field for depth migration for best imaging. In seismic reflection a point in underground may be sampled by different shot gathers. After migration, if we use the correct velocity field, the image point may be located at the same position (x, y, z). The difference of event positions may be measured comparing common offset gathers (COG) (Trier (1990) and Deregowski (1990)) or evaluating common reflection points (CRP) as published in Al-Yahy a (1989), Symes e Carazzone (1991) and Jin and Madariaga (1994). Events at CRP gathers become flat when we use correct velocity field or a kinematically equivalent velocity field (Santos et al, 2013).

A starting velocity field is used to migrate the seismic data. After migration, step 2, the data is organized in CRP-gathers. The flatness of the events are used as a metric for Stopping Criteria step. If the events are flat, the velocity field is accepted (Y) and the process stops delivering the suitable velocity field for imaging. Otherwise, if the events are not flat (N) the process continues.

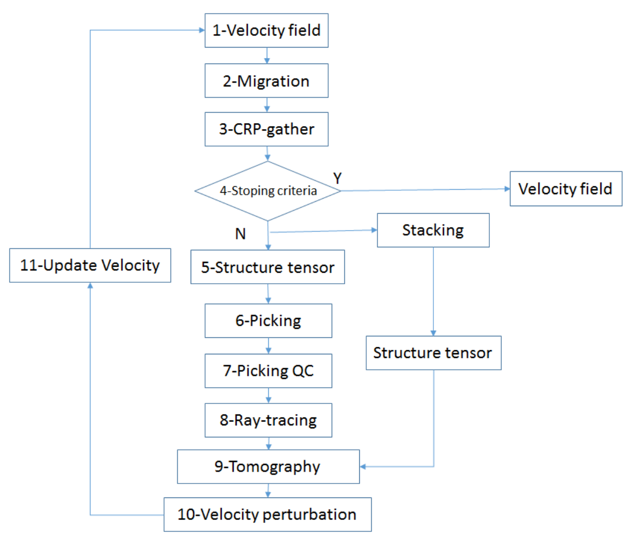

Figure 1: MVA workflow

In the main stream of the MVA process, in step 5, structure tensor (Fehmers and Christian, 2003) of CRP-gather are calculated. Picking makes use of CRP-amplitude gathers and CRP-gathers structure tensor (Silva, 2019). In step 7, picking QC, avoids non feasible pickings.

In step 8, rays are traced in the current velocity field. Ray trajectories are used to build the sensitivity matrix. In step 9, Tomography, sensitivity matrix and the misfit of picked events are used to calculate velocity perturbation employing a Gauss-Newton based algorithm. This perturbation is algebraically added to current velocity field in step 11. Then, back to step 1, the workflow runs again until the stopping criteria is reached.

The main branch of the workflow does not assure an estimation of a feasible velocity field, even in a convergent inversion process. In practice, the main branch makes use of a simple objective function $\Phi(m)$ (equation 1).

$$\Phi(m)=\left\|d-F(m)\right\|_2^2 \ , \qquad (1)$$

In MVA d is the depth of the event at offset zero. The objective function measures the misfit between the calculated depth in the migration process at each offset, $F(m)$, and its depth at offset zero.

The iterative solution, so far, may converge to an unfeasible velocity field. This subject has already been discussed and treated by some authors (Delprat-Janaud and Lailly (1992), Clapp et al. (2002), Costa et al. (2008), Santos et al. (2013) and Luo et al. (2017)).

In this work, a parallel branch of MVA workflow is performed to regularize and guide the convergence to a solution more feasible geologically. This secondary branch (Figure 1) starts just after the Stopping Criteria step. CRP-gathers are stacked delivering a seismic volume. Then, Structure tensor of this volume is calculated and the results are used to regularize the inversion in the Tomography step.

The structure tensor is performed to calculate an operator D_R to use for regularization in objective function:

$$\Phi(m)=\left\|d-F(m)\right\|_2^2+\lambda_r\left\|D_R(m-m_r)\right\|_2^2. \ , \qquad (2)$$

where λ_r weight the regularization and m_r is a reference model vector.

This parallel flow is paramount to estimate velocity field that follows layering and secondary structures of underground.

All the routines used in the described workflow, Figure 1, are proprietary programs developed in Petrobras.

Application

We apply the described workflow, Figure 1, in a dataset surveyed in a sector of Campos Basin. The data were previously processed using post-stack time migration flow. As there are sea bottom canyons in the surveyed area, the available starting velocity for MVA is not suitable. It was derived from a NMO velocity cube, whose the premises are corrupted by the lateral velocity contrast at canyons. Then, we needed to build another velocity field.

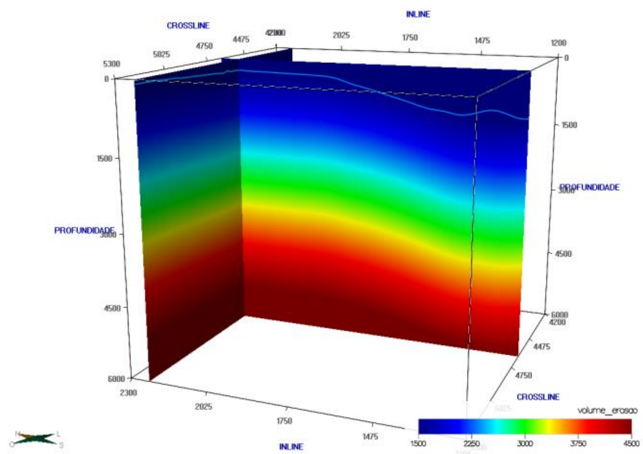

Figure 2: Starting velocity field built in V3O2 system.

According to Rosa (2010), Campos Basin vertical velocity gradient for clastic section is 0,6 s^{-1}. For the target area, the starting velocity just below sea bottom is unknown. For such shallow region, it depends on the sedimentation and erosive episodes. In the absence of feasible information, we used 1500 m/s as the sediment velocity at the sea bottom.

The starting velocity model is created with 1500 m/s for the water column and a sea bottom concordant gradient of 0.6 s^{-1} – Figure 2. The model is created in V3O2 – a Petrobras proprietary system for seismic interpretation, data integration and seismic inversion. In this procedure, we used a smooth version of sea bottom to avoid sharp marks in the initial velocity field and to simulate the effect of erosion in the initial velocity field. Erosion exposes deeper sediments with higher velocities. Using a smooth version of sea bottom to calculate velocity gradient and updating the model above actual sea bottom with water velocity (1500 m/s) simulates erosion effect. After this procedure, we create the first velocity model – m_0 - Figure 2.

Depth migration is performed with narrow aperture, 2 Km, to resolve shallow depths. After migration with m_0 model, we obtain the result of Figure 3.

The resulted migrated volume and CRP (Figure 3) point to under-estimation of the velocity field m_0. So, in Step 4 current velocity field was not accepted and inversion process continued.

Structure tensor (step 5) is calculated over each CRP-gather and, then, picking process starts (step 6). Picking tracks events on CRPs using the method described in Silva (2019). After picking, during QC step, complex curves are avoided and the remaining ones are stored. Over the current velocity field, rays are traced to build sensitivity matrix employed in Tomography, step 9. In this step, the misfit between each stored curve and the expected behavior, flat event in CRP, is used to compute the first term of equation 2. Also, parallel calculation of structure tensor is done over the migrated volume to be used in regularization – second term right hand side of equation 2. In this application we employ the current model as the reference one ($\mathbf{m}_r$).

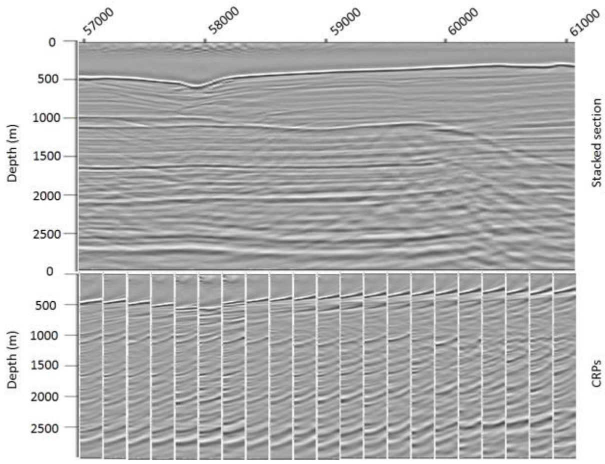

Figure 3:Top: Migrated section with m_0 and; Bottom: Corresponding CRPs migrated with the starting velocity field (Figure 2).

The perturbation in velocity field in this first iteration shows structures of underground, due to the employed regularization – equation 2. Layering of thicker strata is imposed in the perturbed velocity model. The calculated incremental velocity shows mainly positive values close to sea bottom that average 15 to 30 m/s. (Figure 4). Finally, it is remarkable that higher positive values are below and along the borders/shoulders of canyons ranging from 35 to 50 m/s.

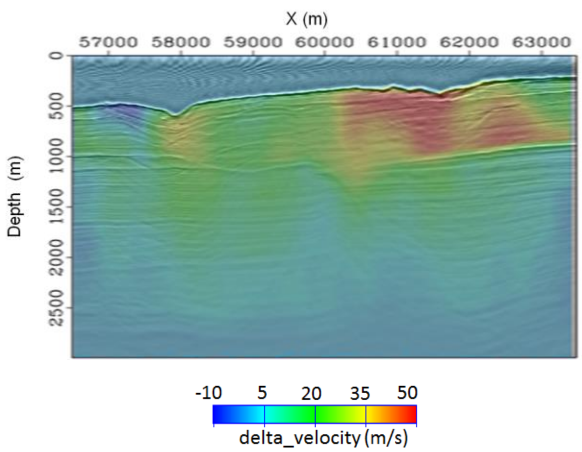

Figure 4: Overlay of the perturbation of velocity after the first iteration.

After the second iteration the pattern of the velocity structure perturbation resembles the one in the first iteration (Figure 4) in the shallow part, shallower than 1000m. This pattern of progressive increase of velocity field at each iteration means we underestimate sediment velocity at sea bottom.

Results

The MVA process converged to a model showing more complexities in the shallow part of the volume (Figure 5). Those complexities, once the velocity is well estimated, promotes better imaging at deeper depths. Beyond imaging, the inversion process, as a phase in the seismic processing macro-workflow, brings important inputs for interpretation.

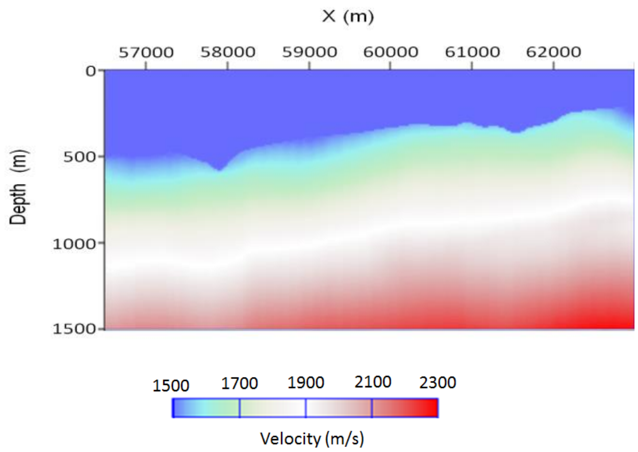

Figure 5: Final velocity model for the shallow region (shallower than 1000 m).

The inversion system show that the initial velocity is underestimated. Along the entire inverted volume, velocity at sea bottom is higher than 1520 m/s. Sea bottom velocities inside canyons are even higher, which increases the velocity gradient from the water layer to sediment pile and locally reaching 1600 m/s. This characteristic brings information about canyon evolution. Considering velocities proportional to compaction of sediment pile and age, in this region, there was no recent filling episode of both canyons. They are just excavating the sea bottom and exposing old and more compacted sediments.

Geometry of shallow events in migrated seismic data agrees with the information provided by MVA process. The regularization using structure tensor – second term of right hand side of equation 2 – calculate geologically feasible velocity field.

Discussion

The described process shows the inclusion of geologic information in MVA. Geologic information about compaction gradient is successfully used giving an initial velocity able to converge to reasonable solution.

The absence of information – the sediment velocity at sea bottom – is corrected during the tomographic process and it shows the robustness of the inversion system. The inversion process also brings geological valuable information by the velocity structure, indeed enhanced by using structure tensor guided regularization.

We confine our analysis along the shallow section of the data volume. We reach such good results because we do not ask to the data, more than it really can bring. As the migration aperture is 2Km, we restricted confidence in the results up to 1000 m. CRPs below that depth are not flat.

Despite estimated velocity field is brought in low spatial frequency, it is the first elastic property to reveal underground characteristics for exploration and/or production purposes. The MVA process needs and delivers geologic information that claims interpreters interaction. Quantitative interpretation during processing.

Conclusions

Convergence is reached using geological knowledge of underground. It is better than the velocity field from PSTM processing flow because of canyons damaging velocity semblance analysis in time domain.

Structure tensor is a very important step to estimate geologically feasible velocity field.

Interpretation needs to start during MVA as it brings and receives valuable information about subsurface reliable compressional velocities.

Particularly for this area, the canyons show no recent episode of sediment filling. They are still in an erosive phase. Geological knowledge and inversion process reach coherently the same conclusion.

Acknowledgments

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