Tomography + pre-stack depth migration of *P-S* converted waves

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Summary

We show in this paper that *P*- and *S*-wave velocity models estimated by tomographic inversion of *P-S*, converted waves, traveltimes are adequate to perform pre-stack depth migration. Examples of velocities estimated directly from converted waves, field data exhibit lateral and vertical changes in both velocities (*P* and *S*) and Vp/Vs ratio. Even though the migrations results are sensitive to subtle changes in velocity models, smooth, velocity maps obtained from *P-S*, reflection tomography yield well focused, converted wave images. These results suggest that tomographic velocity estimation and pre-stack depth migration may be the way to image converted waves in cases when the conventional imaging techniques based in common conversion point gathering, dip moveout, and post-stack, time migration fail due to differences in resolution between *P* and *P-S* waves, lateral and vertical changes in both velocities and Vp/Vs ratios, or a combination of both.

Introduction

The use of *P-S* converted waves has increased over the last few years, after various studies have demonstrated their tremendous potential as a tool for fracture and lithology characterization (Ata and Michelena, 1995; Miller et al., 1995) imaging sediments in gas saturated rocks (Granli et al., 1995), and imaging shallow sediments with higher resolution than conventional *P-P* data. The reasons for the increased use of *P-S* converted waves over *S-S* surveys are two fold: converted waves cost less and are expected to contain the same information, in principle, as *S-S* reflections.

The asymmetry of the ray path with respect to the mid point between source and receiver makes the processing of converted waves an awkward task when compared to the processing of non converted waves. When the medium is horizontally stratified, conventional processing includes sorting the data into common conversion point (CCP) gathers which uses an exact (Tessmer and Behle, 1988) or approximated expression (Krey et al., 1985) for the conversion point in a homogeneous, horizontal layer. The accuracy of this expression decreases either as the reflector dip increases or as the Vp/Vs ratio changes both laterally and vertically along the ray trajectories. Smearing of the conversion point due to reflector dip can be solved in some cases by doing dip moveout (Harrison, 1992), but to account accurately for vertical and lateral changes in compressional and shear velocities, more complex reflector geometries, or both, CCP based imaging may be inadequate, and it may be necessary to image the data by using pre-stack depth migration.

The problem of estimating the *P*- and *S*-wave velocities models in depth that are needed to do pre-stack depth migration of converted waves is still an open question. When the medium is horizontally stratified, *P*-and *S*-wave, interval velocity models can be estimated from RMS velocities derived from *P* and *P-S* records (Ferguson and Stewart, 1995). These velocity models in time can be easily transformed to depth by using zero offset traveltimes. However, since *P* and *P-S* records do not necessarily have the same resolution, and not all boundaries in the medium necessarily produce both *P-P* and *P-S* reflected energy, interval, velocity models in depth derived from RMS velocities may not be adequate to do pre-stack depth migration of converted waves.

D'Agosto and Michelena (1997) developed a tomographic method to do velocity estimation directly from *P-S*, converted waves that does not have to honor traveltimes from *P-P* reflections, although it may need interval velocities derived from *P-P* data as starting model. We show in this paper that velocities estimated by this method are adequate to do pre-stack, depth migration of converted waves. Even though the method has been tested so far with field, converted wave data recorded in an structurally simple area, we believe the results are encouraging enough to continue doing research in velocity estimation and pre-stack, depth migration to solve imaging problems in more complex structures with *P-S* converted waves.

We start by showing the tomographic inversion yields prefect answers when testing it with synthetic, noise free, reflected traveltimes. Then, we show how the method works with field records and compare the estimated *P* and *S* velocities with dipole sonic, *P* and *S* velocities. Once the errors in the estimated velocities and depths have been quantified, we create 2D, *P*- and *S*-wave velocity models by inverting the radial component of selected shot gathers along a 6 km long seismic line recorded in south-west Venezuela. Finally, we used those velocity models to do pre-stack depth migration and analyze the sensitivity of the results to changes in the velocity model.

P-S, reflection tomography

We estimate velocities in this paper by using a tomographic method (D'Agosto and Michelena, 1997). Such method yields *P* and *S* wave velocities in depth, assuming horizontally, stratified models, directly from *P-S* reflected arrivals. Figure 1 shows the result of the inversion synthetic, *P-S* reflected traveltimes calculated in a model that consists of seven horizontal layers. The estimated velocity model follows very accurately the given model regardless of the initial model (constant in this case). Noise introduces serious problems of non uniqueness in

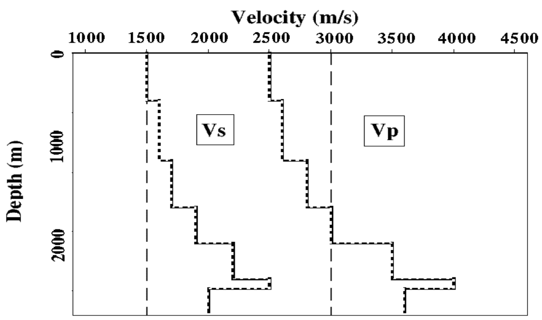

Fig. 1: Convergence of parameters v_p, v_s and h for the synthetic data. the continuous line denotes the estimated model, the dot line indicates the real model and the dash line shows the initial model.

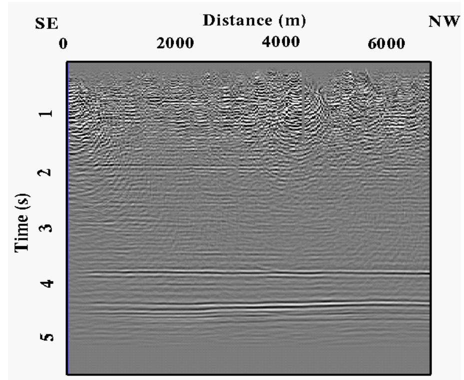

Fig. 2: *P*-*S*, post-stack time migration

the results. These problems can be alleviated by smoothing the data using a traveltime function that is consistent with the traveltime function of reflected arrivals in layered models. This procedure also smoothes out the effect of other minor changes of curvature in the picked traveltimes that are not consistent with the assumption of horizontally, stratified models, such as dips or lateral velocity variations. The smoothing procedure, however, is not explained in this paper.

The results of the inversion deteriorate, as expected, when the traveltimes are not consistent with the assumption of layered models. After performing various tests (not shown) with synthetic traveltimes calculated in models with dipping interfaces, we concluded that velocity and depth errors are less than 8% when reflector dips are less than 6 degrees. Greater dips require the use of inversion algorithms that consider the dip angle of each layer as another unknown of the problem.

P-*S*, pre-stack depth migration

We used a Kirchhoff type, pre-stack depth migration that was modified to handle different velocity models for upcoming (*S*) and down going (*P*) wave propagations. The computation of the traveltime tables is performed by paraxial, ray tracing on *P* and *S* velocity models estimated tomographycally . The accuracy of the migration algorithm was tested by migrating synthetic *P*-*S* shot gathers generated with an elastic finite differences algorithm over structurally complex models. When using the given velocity field, the geometry of reflectors (not shown) was retrieved accurately in the depth, migrated images of the horizontal component.

Field data example

We inverted and migrated *P*-*S*, field data recorded over the Maporal Field, in south-west Venezuela. Structurally, Maporal is a dome slightly extended in the NE direction. The geological setting is composed mainly of nearly flat-lying sediments, which dip towards the NE approximately 4 degrees. The target zone is the member "O" of the Escandalosa Formation, a 25 m thick, fracture limestone located at a depth of approximately 3000 m. In addition to the multicomponent seismic data, there were four dipole, sonic logs right above the target zone which were used to calibrate the results. In Figure 2 we can see a *P*-*S* time migrated section from the area.

Velocity model estimation

The portion of the data we used to test the algorithms consisted of 124 shot gathers with 216 channels each. The maximum offset for each shot was 3672 m. The distance between sources was 51 m. More details about the data acquisition, processing, and interpretation can be found in Ata and Michelena (1995). In Figure 3 we can see the *P* and *S* velocity models estimated from traveltimes generated for a shot located in the vicinity of one of the wells where a dipole sonic log was available. The discrepancies in *P* and *S* velocities are less than 3% when compared to velocities measured at the well. The discrepancies in reflector depths are less than 5%.

To construct 2D, *P* and *S*, velocity maps we selected 13 shot points, separated 500 m each. From each selected shot gathers, we picked the events of interest and then, inverted the corresponding traveltimes for *P* and *S* velocities. The results of each inversion where later interpolated and smoothed to generate the 2D, *P* and *S*, velocity functions shown in Figures 4 and 5. We can see lateral changes in velocities that seem to be stronger for the *S*-wave than the *P*-wave velocity model. Notice that Vp/Vs ratio changes both vertically and laterally.

Depth migration

We used the velocity models obtained in the previous section to migrate all shot gathers from the selected portion of the line. Figure 6 shows the result of the pre-stack depth migration. As we can see, the geometry of the reflections follows very closely the geometry of the interfaces in the velocity models for both *P*- and *S*-waves (Figures 4 and 5). Velocities from tomography needed

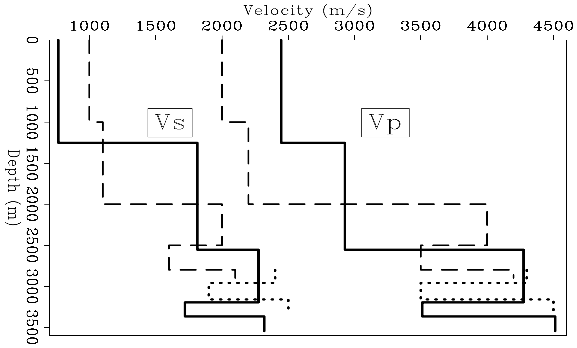

Fig. 3: Estimated P- and S-wave velocities in depth considering an initial guess (dashed) obtain from P-waves The continuous line corresponds to the estimated model; the dotted line denotes an average sonic log obtained from four differents sonic logs recorded in the field.

to be smoothed to achieve better focusing. Additionally, to enhance the focusing, minor modifications of the tomographic velocities in selected parts of the models were also necessary. This means that even though the tomographic velocities honor very accurately the kinematics of the reflections, such velocities are not good enough yet to optimize the focusing in the migrated images.

To check the sensitivity of the result to the velocity model, we migrated the same data using a velocity model that was laterally homogeneous for both P- and S-waves, and equal to the velocity model obtained by inverting the first shot record (Figures 7 and 8). The average velocities and positions of the interfaces in the laterally, heterogeneous models (Figures 4 and 5) and laterally, homogenous models are roughly the same. However, as Figures 6 and 9 show, the migrated images are completely different, which gives an idea about the sensitivity of the migration to lateral changes in the velocity model. The image obtained by using the laterally, homogenous models is severely over-migrated. This result gave us more confidence in the accuracy of the velocities estimated by P-S, reflection tomography, since with those models we could obtain well focused, migrated images that are consistent with the reflector geometry expected in the area (Figure 2).

However, work needs to be done to understand differences and similarities between structures and amplitudes of the pre-stack depth migration (Figure 3) and post-stack time migration results (Figure 2) presented in this study.

Conclusions

We have presented the results of pre-stack, depth migration of P-S, converted waves using velocity models estimated by doing P-S, reflection tomography. The application of the procedure to field data from south-west Venezuela show that pre-stack, migrated images are very sensitive to lateral changes in P and S velocities. Velocity images from the same area also show vertical changes in the Vp/Vs ratio.

These results suggest that the combination of tomography (for more complex velocity models) and pre-stack, depth migration can be the way to image converted waves in structurally complex areas, in areas where P and P-S resolutions are so different that velocity models derived from one data set are not be consistent with the other, or in areas with lateral and vertical changes in velocities and Vp/Vs ratios. In all these situations, conventional imaging techniques based on common conversion point gathering, dip moveout, and post-stack, time migration may fail or yield inaccurate results.

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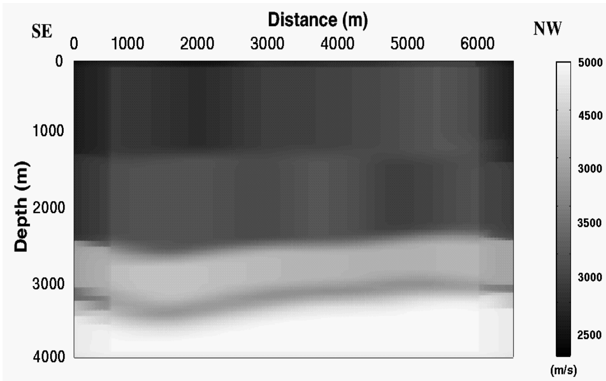

Fig. 4: Compressional wave velocity model estimated by P-S, reflection tomography.

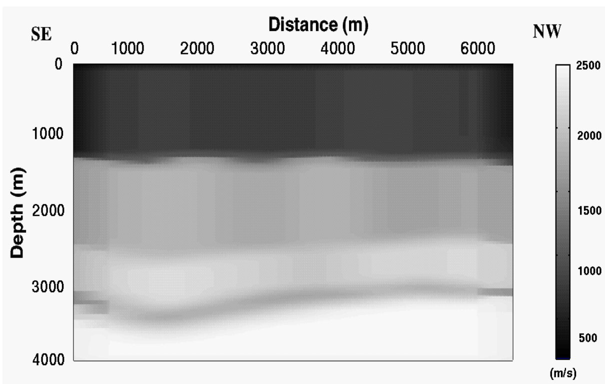

Fig. 5: Shear wave velocity model estimated by P-S, reflection tomography.

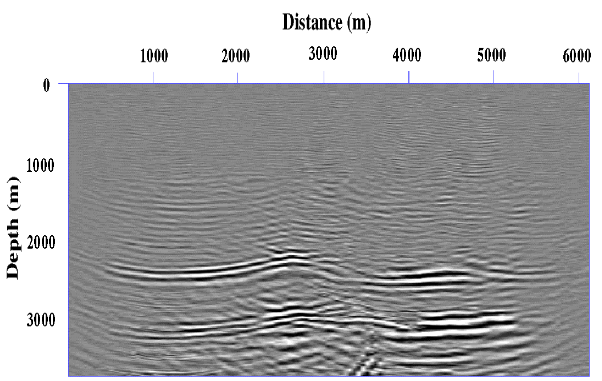

Fig. 6: P-S, pre-stack, depth migrated section obtained using the velocity maps shown in Figure 4 and Figure 5. Compare this image with the post-stack time migrated section shown in Figure 2.

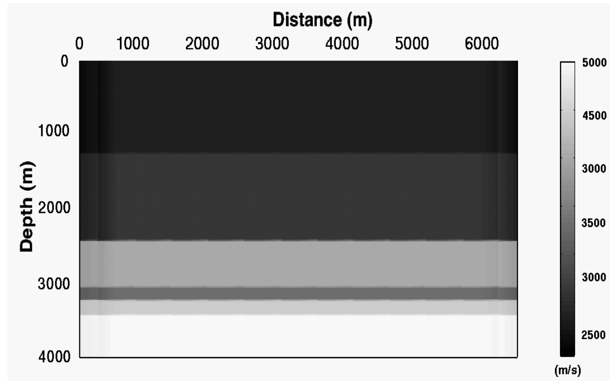

Fig. 7: Layered, compressional wave velocity model obtained by inverting the first shot gather in the SE.

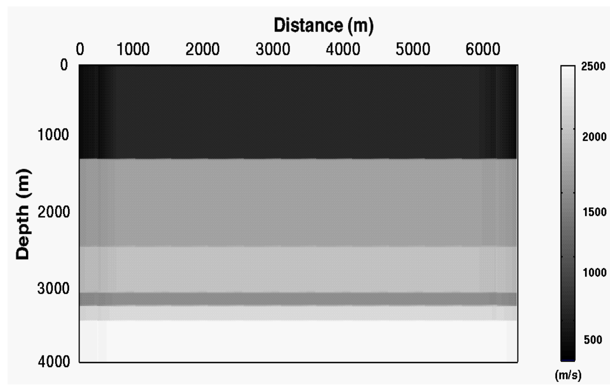

Fig. 8: Layered, shear wave velocity model obtained by inverting the first shot gather in the SE.

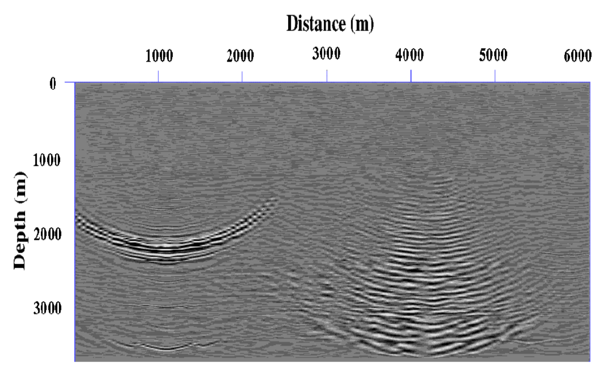

Fig. 9: P-S, pre-stack, depth migrated section obtained using the velocity maps shown in Figures 7 and 8.