Improving seismic resolution of prestack time-migrated data

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Abstract

Seismic resolution significantly affects the quality of seismic interpretation. Processing parameters that affect resolution such as picking velocities in the presence of interbed multiples benefit from an understanding of the underlying geology. Three-dimensional migration is almost always performed by an external service company or internal specialty processing group, with the “final” product being migrated gathers and the final migration-stack section. In the Chicontepec Basin, Mexico, we have evaluated improvements in data quality made after 3D prestack time migration. By first mapping shallow volcanics that generated strong interbed multiples, we performed a new velocity analysis to better image the weaker, underlying primaries of interest. We remove the local migration stretch through an inverse NMO correction, followed by a nonstretch NMO correction and prestack structure-oriented filtering. Such compensation for migration stretch improves the vertical resolution and preserves far-offset data valuable to subsequent prestack inversion that would otherwise need to be muted. Because S-impedance inversion depends heavily on the farther offsets, the resulting S-impedance images have resolution that is in general equivalent to and, in the target area of rapid S-impedance seen in the well logs, exceed that of the P-impedance images. Attributes such as coherence and curvature show improved fault resolution, whereas noisy areas look more chaotic because of the increased frequency content.

Introduction

For reasons of specialized expertise, cost efficiency, and computational resources, 3D migration is almost always performed by an external service company although several of the larger oil companies have an internal or colocated specialty processing group. Ideally, the migration velocity model and key components of time processing parameters are defined and/or quality controlled by the interpreter. The final product is usually a suite of migrated gathers and a final stack of the migrated data.

In some cases, geologic features of interest become clear only after the data have been migrated, as was the situation for the survey described here, which justified the remigration of the data using a different algorithm and different service company. Further interpretation may illuminate more subtle limitations in the original processing — in this case study, the presence of overlapping extrusive volcanic flows and intrusive igneous sills. In almost any 3D migrated data volume, the interpreter may wish to maximize the bandwidth, filter noise that crosscuts the structure, and further flatten the gathers prior to attribute analysis or impedance inversion. Our case study on data conditioning starts with a large, good-quality 3D time-migrated data volume supplied by a professional processing group to illustrate the value that can be added by additional postmigration processing.

Chicontepec Basin, discovered in 1925, is one of the most productive basins in Mexico. Commercial production in the basin began in 1952. The original oil in place (OOIP) is equal to 140 BBO, whereas only 0.1% of the OOIP (140 MBO) has yet been recovered. The basin is about 25 km wide (east–west), and 123 km long (north–south) (Abbaszadeh et al., 2008). The Chicontepec play is characterized by thin turbidite and fan reservoirs that are surrounded by shales. These sand reservoirs have very low porosity and permeability. In addition, the sand reservoirs are occasionally multistoried, and are cut by mass transport complexes and mud slumps (Sarkar, 2011). The Chicontepec turbidite reservoirs have been altered by complex diagenetic processes, including extensive cementation. Because these reservoirs are tight and have low porosity and permeability, the wells are usually hydraulically fractured to improve production (Sarkar, 2011). Shallow volcanics exist in the area, and give rise to reverberating refractions and interbed multiples that mask deeper reflectors of interest.

This study focuses on a structurally complex 3D “Amatitlán” seismic survey acquired in 2003 on the northern part of the Chicontepec Basin, Mexico. The data were originally acquired and processed by Petro-
leos Mexicanos (PEMEX). However, acquisition obstacles such as human settlements, dense forest, and sensitive archeological sites gave rise to anomalies in the shallow section of the data. Therefore, to obtain better shallow imaging and to attenuate low-frequency noise, the Amatitlán survey was reprocessed by PEMEX Exploration and Production in 2007. The following processing steps were applied before providing the data for this study:

- careful deconvolution to detect and eliminate some of the reverberations, multiples and ghosts
- refraction statics to remove the irregular terrain effects on the data
- detailed velocity analysis
- coherent noise suppression to filter out coherent shot-generated noise
- trace mutes, datum corrections, aliased noise suppression, and azimuth moveout corrections
- 3D amplitude-friendly Kirchhoff prestack time migration into 60 offset bins ranging from 50 to 3000 m at 50 m increments.

**Geologic setting**

The Sierra Madre Oriental, formed during the Late Cretaceous-Early Tertiary Laramide Orogeny, is one of the major fold and thrust belts in Mexico (Morán-Zenteno, 1994). The Chicontepec Basin is a subbasin of the Tampico-Misantla Basin located in east central Mexico (Figure 1). The tectonic evolution of the Tampico-Misantla Basin can be divided into four main stages: (1) Late Triassic-Callovian rifting, graben development, and opening of the Gulf of Mexico (GOM); (2) Late Jurassic-Early Cretaceous drift stage, development of passive margin, and widespread marine transgression; (3) Late Cretaceous marine connection of the GOM Basin to the Pacific Ocean; and (4) Late Cretaceous-Early Tertiary Laramide Orogeny; uplift of the Sierra Madre Oriental in eastern Mexico and the Sierra Madre de Chiapas in southeastern Mexico, and associated foredeep development (Morán-Zenteno, 1994; Cantu-Chapa, 2001; Goldhammer and Johnson, 2001; Díaz, 2008).

During the Triassic-Jurassic graben development, first the volcanic deposits and then during Middle Jurassic the extensive salt deposits were accumulated in the GOM (Díaz, 2008). The Late Jurassic-Early Cretaceous passive margin development and marine transgression led the seawater to enter the basin from the Pacific Ocean across central Mexico, and a large inland sea was developed. Taman and San Andrés shales and carbonates were deposited during this time in the Tampico-Misantla Basin (Salvador, 1991; Goldhammer and Johnson, 2001; Díaz, 2008).
Johnson, 2001; Diaz, 2008). During the Late Paleocene-Early Eocene, partly turbiditic, and fine-grained clastic sediments of the Chicontepec Formation were deposited in submarine canyons within the east-migrating foredeep (Diaz, 2008). During the Oligocene, coarse-grained nonmarine and shallow marine clastics (Palma Real and Meson Formations) and marine shales (Horcones and Alazan Formations) were deposited. Clastic shelf systems were swiftly formed and were strongly progradational across the whole basin (Horbury et al., 2003; Diaz, 2008). The Paleocene section consists of the Velazco, Lower Chicontepec, and Middle Chicontepec Formations. The Lower Eocene section is composed of the formations Aragon and Upper Chicontepec Channel. The Guayabal Formation was deposited in the Middle Eocene, and the Tantoyuca and Chapopote Formations were deposited in the Upper Eocene (Figure 2).

The Chicontepec Formation is primarily composed of shales and thin-bedded sandstones (Bermúdez et al., 2006). The average thickness of the Chicontepec Formation in the study area is about 300–400 m, whereas the maximum thickness of the formation in the western GOM Tampico-Misantla Basin is about 2000 m (Bitter, 1993). The Chicontepec reservoir facies are highly compartmentalized and have very low porosity (1%–10%) and permeability (0.01–5 mD) (Bermúdez et al., 2006).

Methods
Like NMO, migration maps the input data to the output image sample by sample and thereby stretches the far-offset traces. Residual velocity analysis using semi-automatic modern scanning techniques can better flatten these events but will not significantly change the amount of stretch. Instead, we go back to an older, less elegant flow commonly called the Deregowski (1990) loop whereby we first remove most of the effect of migration velocity by applying a vertical reverse NMO (RNMO) correction to each gather. From the interpreter’s perspective, migration does three important things to these RNMO-corrected gathers. First, migration reduces the CMP smear associated with dipping reflectors such that the newly picked velocity will more accurately approximate a root-mean-square velocity based on flat-layer assumptions. Second, migration implicitly forms a “supergather” in that all of the data that fall within the migration aperture are used to construct the migrated image, thereby improving the signal-to-noise ratio (S/N) of subsequent velocity scans. Third, unlike the unmigrated data, the current version of the migration stack provides a very good, if suboptimal, image of the geology. Using this image, the interpreter can shift velocity analysis locations to avoid faults and other zones in which the NMO assumptions break down and to be alerted to areas where overlying multiple generators can contaminate the primary reflectors of interest. In this paper, we apply RNMO followed by velocity analysis and nonstretch NMO to the migrated gathers. We then apply prestack structure-oriented filtering (SOF) to the prestack seismic gathers to improve the pre-stack data quality throughout the survey. This method is simple but effective, because it improves the data quality without remigrating the data.

Velocity analysis
One of the more important steps in processing is velocity analysis, which consists of calculating NMO or migration velocities by aligning traces measured at different offsets, thereby flattening the hyperbolic events in the prestack gathers. In time migration, if the velocity is too low, the reflection is overcorrected, and it curves upward. If the velocity is too high, the reflection is undercorrected, and it curves downward.

The original data were prestack time migrated using a Kirchhoff algorithm into 50-m offset bins ranging between 50 and 3000 m. The original migration velocities were then removed using a simple RNMO correction. We then perform a dense residual velocity analysis on a 250 × 250 m grid (every 10th inline and crossline) to flatten the gathers, scanning velocities ranging from 1000 m/s to 7000 m/s. Figure 3a shows the semblance panel computed from the RNMO-corrected gather shown in Figure 3b.

Nonstretch normal moveout (matching-pursuit normal moveout) correction
The next step after velocity analysis is to apply NMO corrections to flatten the prestack seismic gathers (Figure 3c). Matching-pursuit normal moveout (MPNMO), introduced by Zhang et al. (2013), is a matching-pursuit-based normal moveout correction...
used to minimize NMO stretch effects in long-offset data, thereby increasing the frequency content of the data. Zhang et al. (2015) showed how such corrections can improve subsequent prestack inversion to map geomechanical properties in an unconventional Fort Worth Basin, Texas, shale play. Kazemi and Siahkoohi (2012) propose an alternative method to minimize migration stretch. To avoid stretching the non-zero offset traces, the moveout correction needs to be constant for all samples that form part of a reflection event. MPNMO processes the data wavelet-by-wavelet rather than sample-by-sample, thereby avoiding wavelet stretch effects at far offsets. The standard NMO correction causes wavelet stretching at far offsets that lowers the frequency content of the seismic data. The part with severe stretching is usually muted from the data, resulting in reduced leverage against multiples.

**Figure 3.** (a) Velocity semblance scan of the migrated gather shown in (b) after reverse moveout using the migration velocity. (c) The nonstretch NMO-corrected gather.

**Figure 4.** (a) Original migrated data with a 30% stretch mute. (b) The same gather after RNMO followed by MPNMO showing the increase in far-offset information.
and reduced accuracy of the shear impedance estimates. By reducing stretch, MPNMO obviates the need to mute the long-offset data. As a result, frequency content is preserved and resolution is increased (Zhang et al., 2013).

Figure 4a shows a prestack gather with a 30% stretch mute applied. Figure 4b shows the corresponding MPNMO-corrected gather, preserving the longer offsets. Figure 5 shows the frequency spectrum of the original prestack time-migrated data compared to the frequency spectrum after performing postmigration velocity analysis and MPNMO, with the latter showing significant frequency enhancement and improved resolution compared to the original data.

**Prestack structure-oriented filtering**

After MPNMO correction, we apply a prestack SOF to the prestack time-migrated common offset gathers. In prestack SOF, reflector dip and coherence computed
from the stacked volumes are used to guide the prestack data filter. For these data, we use an edge-preserving mean filter along reflector dip to remove random noise, thereby preserving lateral discontinuities. Figure 6a and 6b shows common reflection point gathers before and after applying prestack SOF to common offset volumes. Figure 6c shows the rejected signal plotted at the same scale. Most of the incoherent and cross-cutting coherent noise is removed resulting in cleaner data amenable to prestack inversion and attribute computation.

**Results**

Figure 7a shows the original vertical seismic amplitude section corresponding to line AA’. Figure 7b shows the same section after performing residual velocity analysis, MPNMO correction, and prestack SOF revealing a broader bandwidth and an improved S/N.

After we precondition and stack the data, we compute coherence and curvature attributes. Figure 8 shows time slices through coherence and two vertical slices through the original seismic amplitude corendered with the most-positive and most-negative curvatures, with the attributes computed from this same amplitude volume. Yellow arrows indicate two shallow volcanic sills on one of the vertical slices. Green arrows indicate faults. Figure 9 shows the same slices but now with the preconditioned amplitude data volume and its attributes. Preconditioning has sharpened and amplified fault and flexure anomalies that were previously smeared. The incoherent area to the west is associated with complex faulting, and the circular and arcuate anomalies in the center of the survey are due to low fold due to the surface conditions. The vertical slices in Figure 10 through the preconditioned amplitude data and its amplitudes show the improved resolution of the faults, giving rise to curvature and coherence anomalies (green arrows). Yellow arrows show the relationship of the low-coherence anomalies at this time slice continuing all the way to the surface and should be considered to be noise. Original and preconditioned vertical seismic amplitude sections corendered with coherence (in yellow) are shown in Figure 11. Sharper fault discontinuities are observed on coherence computed from the preconditioned data.

Seismic ties to the original data were good, but those to the conditioned data were excellent (Figure 12a), with correlations between the Top Eocene Chicontepec and Top Cretaceous carbonates ranging between 0.7 and 0.8. The data were converted to 17 angle-limited bins and wavelets tied for near-, mid-, and far-angle sections. The wavelets are remarkably similar, showing little stretch (Figure 12b). The spectra of the near- and far-angle wavelets are nearly identical, while that of the far-angle has the same bandwidth, but with reduced

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**Figure 7.** Line AA’ through (a) the original prestack time-migrated vertical seismic amplitude section and (b) the same section after prestack data conditioning. Note the better definition of the units and improved resolution within the Chicontepec reservoir interval after prestack data conditioning. Location shown in Figure 8.
Figure 8. A 3D view of the original seismic data and their attributes. A time slice at $t = 1.6$ s and two vertical slices through seismic amplitude corendered with the most-positive and most-negative principal curvatures. Yellow arrows indicate two shallow sills. Green arrows indicate faults that commonly show positive-curvature, coherence, and negative-curvature patterns corresponding to an upthrown block, fault, and downthrown block. The low-coherence zone to the west is highly faulted. The three semicircular low-coherence areas are associated with low fold due to surface conditions reported by Pena et al. (2009).

Figure 9. The same slices shown in Figure 8, but corresponding to the preconditioned data. Note that the faults indicated by the green arrows are better delineated and give rise to stronger anomalies. The low-coherence zone to the west is now even less coherent. Careful inspection of Figure 10 will show that these areas are highly faulted and now better resolved after data conditioning.
high-frequency content (Figure 12c). Prestack inversion for P- and S-impedance show an excellent tie to the well log impedance computed from P-wave sonic, S-wave sonic, and density logs (Figure 13). There is greater discrimination between sandstone and shale layers in the S-impedance than in the P-impedance seen on the well logs, which is the primary reason for the higher vertical resolution of the S-impedance section. However, this resolution was preserved during the nonstretch correction. In conventional analysis, the S-impedance inversion is usually of lower resolution, because it has a stronger contribution from stretched far-angle traces than P-impedance inversion, which has a stronger contribution from the near-angle traces.

Figure 10. The same time slice shown in Figure 9 through the preconditioned data and its attributes, where the two vertical slices show details of poor data areas (yellow arrows) and tight faulting (green arrows).

Figure 11. Line BB’ through (a) original prestack time-migrated data and (b) conditioned data, both corendered with their respective coherence volumes. Faults are better imaged on the coherence attribute computed from the preconditioned data, whereas noisy areas look more chaotic. The location is shown in the inset in Figure 7.
Conclusions

Seismic migration maps data acquired on the earth’s surface to approximate a suite of geologic cross sections, allowing a processor or interpreter to identify shallow multiple generators. Such identification is key to picking velocities that image the weaker reflectors of interest and to avoiding those associated with the stronger multiples. The improved gather alignment provided by such postmigration velocity analysis not only suppresses multiples but improves the bandwidth of the stacked volume. By following such velocity analysis with nonstretch NMO, we preserve broader bandwidth at larger offsets, further improving the frequency spectrum and avoiding the need to mute otherwise overly stretched events. Prestack SOF further improves the S/N by removing random and cross-cutting noise. For most conventionally processed seismic surveys, S-impedance volumes that depend heavily on the far-off-
set stretched amplitude data exhibit a lower resolution than the P-impedance volumes that more heavily weight the near-offset unstretched amplitude data. In this data volume, our preconditioning workflow avoids such stretch and provides an S-impedance volume that exhibits slightly higher resolution than the P-impedance volume, consistent with the corresponding reflectivity in the well logs. Volumetric curvature and coherence volumes computed from the preconditioned data show faults that are sharper and can be more easily identified than those computed from the original data.

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