Viscoacoustic Imaging: A High Resolution Depth Imaging Solution

Ruben D. Martinez (PGS) and Ernesto Lemos (PGS)

Abstract

We use viscoacoustic imaging to enhance the resolution of seismic depth images in complex geology areas. The combination of a tomographic approach to derive 3D Q models of the subsurface and viscoacoustic and anisotropic prestack depth migration yields images that are superior in resolution than those obtained without compensating for attenuation and dispersion during imaging. Results obtained using field datasets from the North Sea and Brazil demonstrate the advantages provided by the viscoacoustic depth imaging solution.

Introduction

Attenuation of seismic waves by the Earth causes a loss of high-frequency energy and a general distortion of the phase of the wavelet. Seismic attenuation and dispersion compensation is required for complex geology scenarios such as: shallow hydrates in the Gulf of Mexico (GOM), shallow gas clouds in the North Sea (Chen and Huang, 2010; Yu et al., 2002) or complex overburden overlying sub-salt and pre-salt exploration targets in the GOM and Brazil respectively. Under these conditions estimating the Q model using a tomographic approach (Brzostowski and McMechan, 1992, Valenciano and Chemingui, 2012) is necessary. The Q and anisotropic velocity models (VTI or TTI) can then be used to perform viscoacoustic anisotropic prestack depth migration (VAPSDM) to produce high resolution images of the subsurface. The viscoacoustic and anisotropic migration effectively accounts for the effects of the attenuation anomalies on the amplitudes and kinematics of the final image. Even a constant Q and anisotropic prestack depth migration produces significantly improved results in resolution. We demonstrate our solution using field datasets from the North Sea and Brazil.

Q estimation and compensation during prestack depth migration

It is widely accepted that Q varies with lithology types such as shale, sands, carbonates, salt, etc. therefore a 3D Q estimation is required (Figure 1).

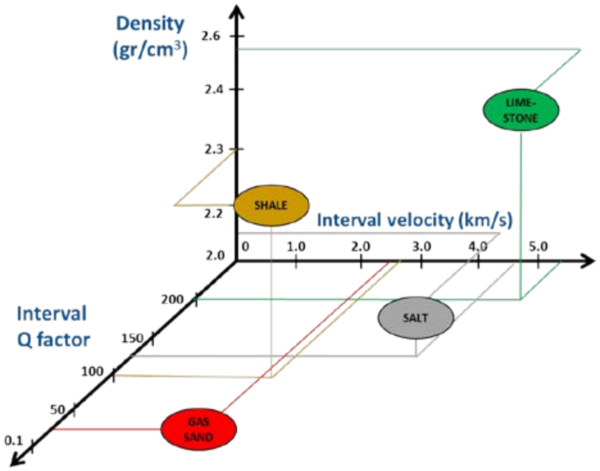

Figure 1: Relationship between key lithologies with rock properties such as velocity, density and Q.

Assuming that geometrical spreading, scattering, or other non Q-related factors have been removed from the data, Valenciano and Chemingui (2012) have implemented a workflow for a tomographic approach to estimate a 3D Q model. In this implementation for the Q estimation, they used the amplitude spectral ratios in a tomographic approach to compute the Q model as follows:

$$-\frac{2}{\omega}\ln\left[\frac{A_k}{A_o}\right] = \int_{rayk} Q^{-1}(x,y,z)v^{-1}(x,y,z)ds = t_k^* \qquad (1)$$

where A_k are the seismic spectrum measured at a seismic horizon, A_o is a reference seismic spectrum measured at a horizon not affected by attenuation, ω is the angular frequency, v is the velocity model, Q is the quality factor, and t^* is the attenuated travel time. Given a dataset consisting of spectral estimates at various times, equation 1 provides a linear system in Q^{-1}. A solution for this linear system is found to estimate the Q model (Valenciano and Chemingui, 2012).

For geologically complex areas, the estimation of the Q model as accurate as possible can render important improvements to the seismic resolution displayed in the depth seismic images. Even a constant Q migration - if the constant Q assumption is acceptable - can benefit the result over that obtained with the classical Q compensation in the time domain, where time variant inverse Q filters are applied to the seismic wavefield trace to trace.

The accuracy of the Q model significantly benefits from broadband pre-processing in time. Specifically, wavelet processing is important to obtain a broadband spectrum rich in low and high frequencies like that obtained when deghosting using dual sensor data (Burren et al., 2013). The accuracy of the low frequency end has a significant positive effect on the accuracy of the Q estimation. The amplitude attenuation rate calculated from the amplitude spectral ratios is more accurate (Figure 2). Figure 2 shows that the deghosting process achieved with the dual sensor data provides an estimate of Q to be less than that estimated with the conventional data.

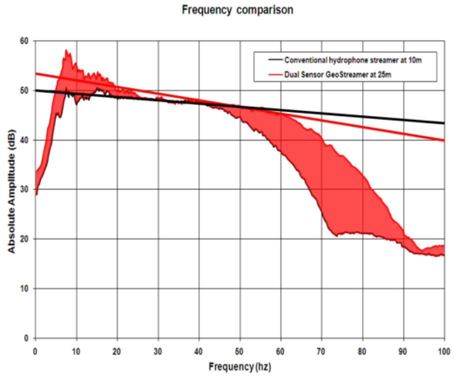

Figure 2: Amplitude spectra from conventional data (black line) and dual sensor data (red line).

Q prestack depth migration

Q prestack imaging can be achieved using methods either based on rays or the wave equation. The best known ray based method to compensate for Q during the migration is Kirchhoff PSDM. The Green's functions or traveltimes are different from those ordinarily computed for an acoustic Kirchhoff prestack depth migration. In the viscoacoustic case, the traveltimes are complex and no longer real. The imaginary part in the traveltimes incorporates the attenuation and dispersion effects. The implementation incorporates anisotropy; VTI (vertically transverse isotropy) or TTI (tilted transverse isotropy).

Imaging with Q compensation can also be performed using wave equation approaches (Valenciano et al., 2011). Implementations can be using the one-way wave equation (WEM = Wavefield Extrapolation Migration) or the two-way wave equation (Reverse Time Migration). For either approach a Q, anisotropic parameters and velocity models are required.

North Sea case study

Q tomography and the migration with Q compensation was applied to a 3D dataset from the North Sea. The data was acquired with dual-sensor streamers comprised of hydrophones and vertical geophones. The area is characterized by a gas chimney, which hampers the imaging of reflectors at the oil reservoir level, and by a significant VTI anisotropy. Therefore, a workflow that addresses both problems is necessary to image the reservoir.

Q tomography was used to derive the attenuation model using offsets up to 4000 m. Figure 3 shows the 3D Q model for 54 inlines for an offset of 200m. A low Q (high attenuation) anomaly is well resolved. Next, we performed a VTI wave equation migration with and without the Q compensation (Valenciano et al., 2011).

In Figure 4, a close up of the VTI migrations with and without the Q compensation is depicted. The Q compensation using the tomographic model greatly improves the continuity and resolution at the reservoir level.

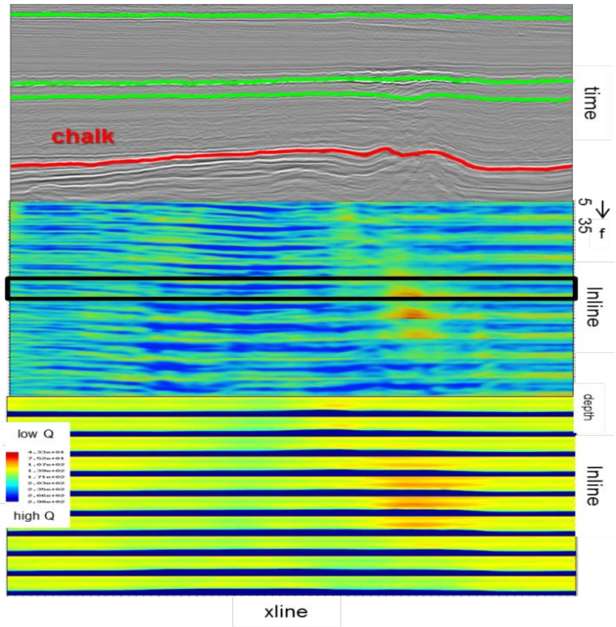

Figure 3: (Top) Migrated stack showing the horizons used in the Q tomographic step; (Middle) amplitude spectral ratios for 54 inlines used as input for the Q tomography, and (Bottom) the Q model for 54 inlines. Note the low Q anomaly related to the gas cloud,

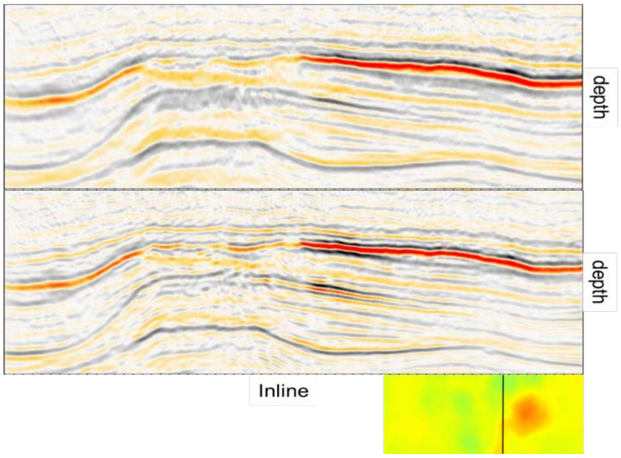

Figure 4: WEM (Wavefield Extrapolation Migration) without Q compensation (Top) and with Q compensation during migration (Bottom).

For this example, Kirchhoff PSDM was also performed without and with Q compensation with very similar results. The Kirchhoff PSDM result showed a little more noise than the WEM PSDM result.

The amplitude spectra corresponding to the data set shown in Figure 4 are depicted in Figure 5. The uplift in resolution is significant. At 36 Hz approximately, an improvement of about 10 dB is achieved at the zone of interest (reservoir level).

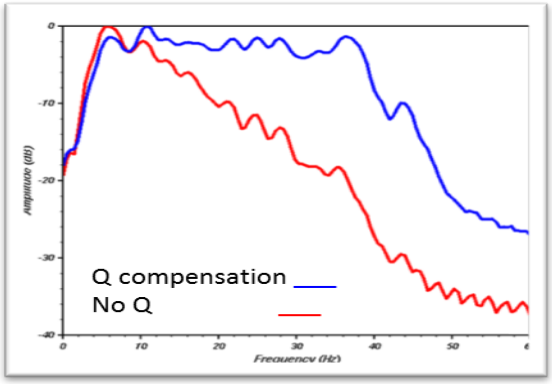

Figure 5: Amplitude spectra shows the resolution enhancement achieved after wavefield extrapolation migration (WEM) without (red) and with (blue) Q compensation applied during the migration.

Santos Basin case study

Using a portion of a 3D survey from the Santos Basin, Brazil, Q migration was evaluated and resulted in resolution improvements at the pre-salt depth levels. Kirchhoff PSDM was used to perform the migration without and with Q.

Figure 6 illustrates a comparison between Kirchhoff PSDM with and without Q compensation applied during migration. The resolution obtained at the top of salt level is slightly better when correcting for Q. The same applies to the base of salt case. Significant improvements in resolution are observed at the pre-salt levels as well; the amplitudes are brighter as a result of higher frequency content and subtle faulting is observed. In general, the Q Kirchhoff migration result is de-blurred.

The improvements in resolution observed in the seismic depth images can be confirmed by computing amplitude spectra in the depth domain for two windows; one shallow and one deep (see Figure 7). The resolution enhancement in the vertical wavenumber domain is close to 5 dB at 70 cycles / meter in the shallow window and about 3 dB at 40 cycles / meter in the deeper window. The deeper window corresponds to the pre-salt sediments (see Figure 8).

Figure 9 further illustrates the seismic resolution enhancements achieved for the pre-salt sediments. Note the resolution improvement at the base of salt, fault planes and geologic blocks.

Conclusions

The compensation for attenuation and dispersion effects is best achieved during either 3D anisotropic Kirchhoff or WEM (Wavefield Extrapolation Migration) prestack depth

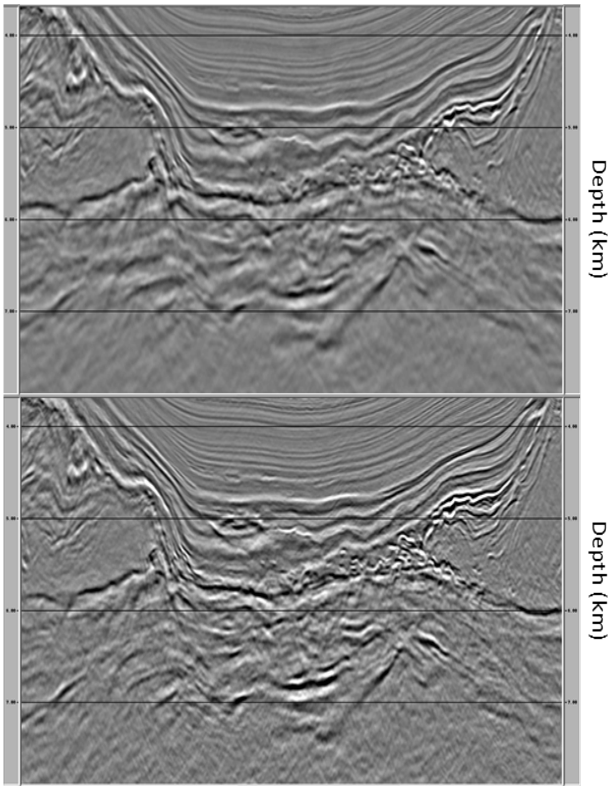

Figure 6: Kirchhoff PSDM without (Top) and with (Bottom) Q compensation during migration.

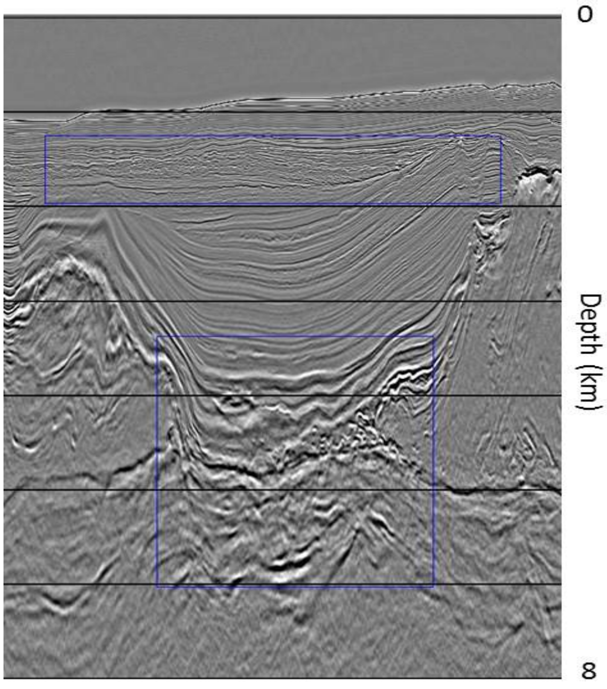

Figure 7: Kirchhoff PSDM with Q compensation applied during migration. The blue windows were used to compute the amplitude spectra shown in Figure 7.

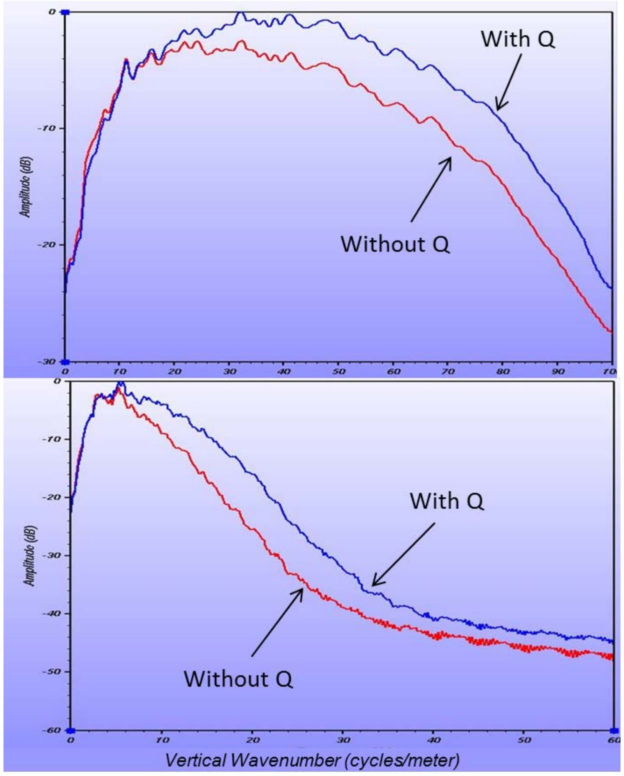

Figure 8: Amplitude spectra for the two depth windows shown in Figure 7. The spectra depict the result of Kirchhoff PSDM without and with Q compensation applied during migration.

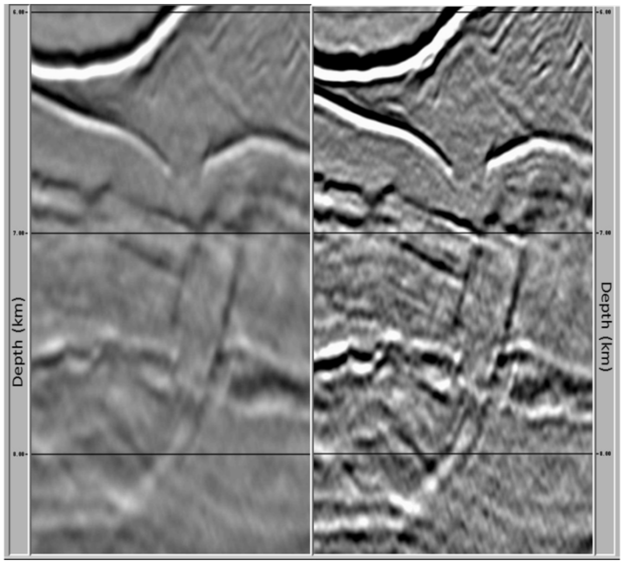

Figure 9: Anisotropic Kirchhoff PSDM images: without (Left) and with (Right) Q compensation during migration.

migration. In addition to the anisotropic parameters and velocities, a Q model is required for viscoacoustic imaging. The 3D Q model can be effectively estimated using a tomographic approach.

The real data examples demonstrate visible resolution enhancements when the Q effects are compensated for during PSDM as shown in the amplitude spectra before and after Q PSDM.

Q PSDM should be applied when high resolution solutions are required for seismic inversion. If ADCIG's (Angle Dependent Common Image Gathers) are output from the Q PSDM, they can be used for AVA (Amplitude vs. Angle) analysis.

Acknowledgments

The authors thank our colleagues from Petroleum GeoServices (PGS) that were involved in preparing the case studies presented in this paper. Special thanks go to Alejandro Valenciano Mavilio and Nizar Chemingui for the original work performed some years ago on viscoacoustic imaging.

We would also like to acknowledge PGS Multiclient for the North Sea and Santos Basin data sets that were used to illustrate the application of Q modeling and migration. Finally, we thank PGS for the permission to publish this work.

References

Brzostowski M. A., and G. A. McMechan, 1992, 3D tomographic imaging of near-surface seismic velocity and attenuation: Geophysics, **57**, 396.

Burren J., Comeaux, L., Jangeleme, G., Melo, R.,2013, A MAZ case study from the Jequitinhonha basin, Brazil; Combining legacy conventional with dual-sensor towed-streamer data: Presented at the 13th International Congress of the Brazilian Geophysical Society.

Chen, Y., and Y. Huang, 2010, Use Q-RTM to image beneath gas hydrates in Alaminos Canyon, Gulf of Mexico: 80th Annual International Meeting, SEG, Expanded Abstracts, 3165–3170.

Valenciano A. A., N. Chemingui, Whitmore, D. and Brandsberg-Dahl, S., 2011, Wave equation migration with attenuation and anisotropy compensation: 81st Annual International Meeting, SEG, Expanded Abstracts, **30**, 232.

Valenciano, A.A. and Chemingui, N., 2012, Viscoacoustic imaging: tomographic Q estimation and migration compensation: 73rd Annual International Meeting, SEG, Expanded Abstracts, 1-5.

Yu, Y., Lu, R. S. and Deal, M.M., 2002, Compensation for the effects of shallow gas attenuation with viscoacoustic wave-equation migration: 72nd Annual International Meeting, SEG, Expanded Abstracts, **21**, 2062–2065.

Valenciano, A.A. and Chemingui, N., 2012, Viscoacoustic imaging: tomographic Q estimation and migration compensation: 73rd Annual International Meeting, SEG, Expanded Abstracts, 1-5.