Challenges and solutions in wide azimuth seismic data processing and imaging for geologically complex areas

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Abstract

Over the last years, wide azimuth (WAZ) seismic data collection techniques have shown to provide improved seismic resolution and subsurface illumination than conventional narrow azimuth (NAZ) surveys. However, WAZ geometries pose processing challenges.

Proper WAZ compliant pre-processing is required to prepare the 3D seismic data for depth velocity model building and migration in order to produce useful seismic depth images for structural interpretation and prospect generation.

WAZ 3D tomography should be used to provide accurate velocity models accounting for velocity anisotropy. The estimation of anisotropic parameters is vital to tie the wells and it is still a challenge and the subject for significant research efforts. During the model building stage, WAZ Beam PSDM (prestack depth migration) is preferred; it is efficient and accurate. Implemented in an interactive environment, anisotropic depth models can be delivered in a short time allowing the interpreter to have more time for the geologic interpretation. After several iterations, WAZ compliant hi-end imaging algorithms, such as anisotropic prestack one-way wave equation migration or reverse time migration are employed to produce the final seismic image.

In this presentation, we will review and illustrate challenges and solutions in WAZ seismic processing and imaging using data sets from complex geology areas.

Introduction

The success of seismic imaging in depth greatly depends on the right choice of the data acquisition and processing technologies based on the right understanding of the geologic problem at hand. These choices are not trivial in geologically complex areas.

Over the last years, we have witnessed a significant evolution of 3D data acquisition designs, for example, the evolution from narrow azimuth (NAZ) in the 1990's to wide (WAZ) in the 2000's (figure 1)(Long, 2006). Presently, it is widely accepted that the azimuth component provided by WAZ geometries increase seismic resolution and illuminate better the subsurface in the presence of high geological complexity. However, these wide azimuth geometries pose new challenges on how the seismic data should be processed. In data processing, processes well accepted for years, e.g. binning, source designature, debubble, deghosting, demultiple (for surface, 'peg legs' and interbed multiples) are now a new challenge. Very sophisticated algorithms are required to address these effects in the presence of azimuth variations. If the azimuth and offset dependency is ignored at the pre-processing steps, depth velocity model building and depth migration algorithms could not possibly deliver useful seismic depth images for structural interpretation and prospect generation.

Seismic imaging in depth has also evolved. Velocity model building using true azimuth 3D tomography is used to provide not only accurate velocity models for migration but also be able to account for velocity anisotropy, in this case, TTI (tilted transverse isotropy). The estimation of anisotropic parameters is still a challenge and it is the subject for significant research efforts. To handle large volumes of data during the model building stage, a very reliable and fast imaging algorithm is required to iterate with tomography very efficiently and accurately. Beam PSDM (prestack depth migration) is one of the most efficient and accurate algorithms for model building (Sherwood et al., 2008). When it is implemented properly in a combined computer environment, anisotropic depth models can be delivered in a short period of time. This is advantageous as it allows the interpreter more time to make decisions about the geologic model. After several iterations, the final seismic imaging stage can be achieved using hi-end imaging algorithms such as anisotropic prestack one-way wave equation migration or reverse time migration (Crawley, S., 2010).

In this paper, we will review and illustrate challenges and solutions in processing and imaging using data sets from complex geology areas affected by salt tectonics for example.

WAZ data acquisition – A step change towards increasing seismic resolution

The advent of the wide azimuth (WAZ) method for seismic data acquisition has brought a number of new opportunities in complex geology areas. The increase in seismic resolution is significant. In the deep water of the Gulf of Mexico (GOM), we have seen exceptional examples (Figure 1). The added value incorporated by WAZ lies in the better seismic illumination obtained due to the wide azimuth sampling in addition to the other typical field parameters. However, WAZ data acquisition has posed new processing challenges which span from seismic signal processing through depth imaging.

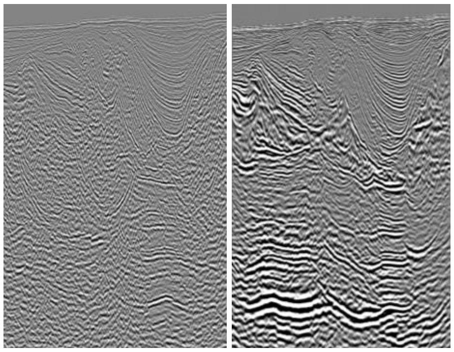

Figure 1: Seismic image in depth from the Gulf of Mexico obtained from seismic data acquired with narrow (left) and wide (right) azimuth field designs.

Challenges and solutions in seismic data pre-processing

Although processing steps such as signal processing, noise and multiple attenuation and regularization and interpolation are considered conventional, the correct application of the corresponding algortihms associated with these steps is challenging for WAZ data.

WAZ designature and debbuble are now more complicated. Directional designature will have to be performed in an offset and azimuth dependent manner. Emmission and emergency angles will have to be taken into account for an accurate deconvolution of the source wavelet and the bubble.

In noise attenuation, the main challanges are related to swell noise and seismic interference (SI). Techniques based on prediction error filtering have been used successfully to attenuate swell noise. These algorithms exploit the swell noise characterisitcs, such as low frequency and high amplitudes, to discriminate and attenuate the noise components. SI is similarly attenuated by trapping the noise components, which are typically high in frequency and amplitude, in a domain such as τ-p to then by editing accomplish the SI attenuation.

In order to have a successful depth imaging result, the attenuation of multiple reflections is necessary. In general and in the presence of complex geology, multiples can prevent the successful estimation of the velocity model and anisotropic parameters. Also, multiples will get smeared by the migration operators making the final image noisy. Therefore the challange is to attenuate the 3D multiples considering the WAZ nature of the data. There are many types of multiples contaminating the seismic data. Amongst these are: first and second order surface related, 'peg legs' and interbed multiples. All of them are complex and difficult to predict and remove. Although there are several methods for multiple attenuation, the model and data driven methods are popular and applied regularly in deep water seismic data sets. The model driven methods such as the wave equation based methods require a reflectivity model for prediciting the multiples (Andre, et al., 2010). The data driven methods such as 3D SRME (surface related multiple elimination), on the the other hand, require the data itself and a well spatially sampled wavefield.

3D SRME is applied considering the true azimuth and, in some cases, with dip corrections. The true azimuth characteristic of the algorithm is vital to obtain successful results when processing WAZ data sets (Aaron et al., 2011).

Figure 2 shows a comparison between the application of RTM (reverse time migration) using raw data (left) and RTM with designature, debubble, noise attenuation and true azimuth (TA) 3D SRME applied. Clearly, the left panel is noiser and ringy as a result of the multiple contamination.

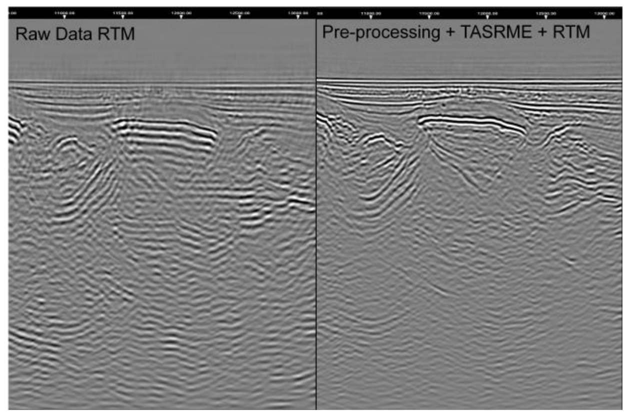

Figure 2: A reverse time migrated depth image from the Gulf of Mexico without (left) and with (right) preprocessing and true azimuth (TA) 3D SRME.

In some cases, enhanced high resolution Radon (EHRR) demultiple is applied after TA 3D SRME. Both processes are complementary; EHRR addresses well residual multiples for long to very long offsets, whereas TA 3D SRME is particulary powerful in the short to mid offsets where EHRR is not so effective due to the small moveout differential. In some other ocassions, diffracted multiple attenuation algorithms are also applied.

Other processes commonly applied are: water column statics and survey regularization and trace interpolation.

The success of time pre-processing is usually evaluated after prestack depth migration (PSDM) even with an initial or intermediate depth velocity model.

Challenges and solutions in seismic imaging

Once the time pre-processing has been accomplished another set of challenges in depth imaging should be faced and resolved. The first challenge is to estimate the TTI model. A TTI model is described by five parameters varying in 3D. The estimation of these parameters is challanging and ideally should be accomplished using true azimuth 3D traveltime tomography honoring the WAZ geometry (see figure 3). Figure 4 depicts the main steps of the TTI tomographic approach. When so much velocity model complexity is present, it is common to resort to the pragmatic approach of using fixed anisotropic parameters and solve for velocity perturbations (V_{tilt})(interval velocity perpendicular to an surface at a given image point).

Isotropic depth imaging is typically the first step in the flow in order to estimate the most accurate isotropic NMO interval velocity (V_{nmo}) model possible.

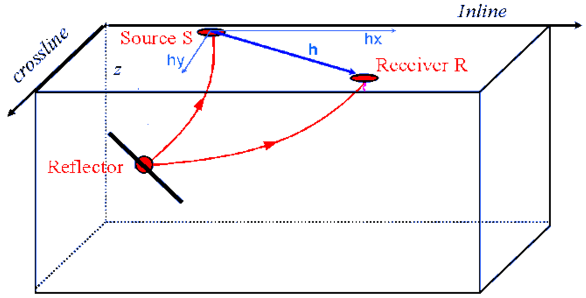

Figure 3: True azimuth implementation of the 3D traveltime tomography.

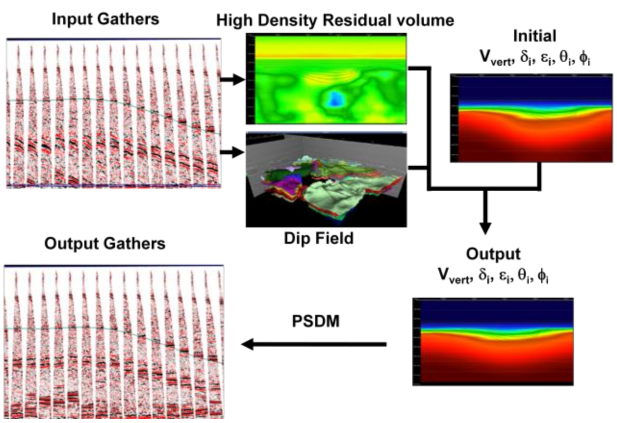

Figure 4: Schematic form of the main steps for 3D TTI traveltime tomography.

Several iterations are necessary to incorporate information about structural details in the model and thus obtain V_{nmo} interval velocities with geologic meaning. Other steps following the isotropic V_{nmo} interval velocity estimation include tomographic iterations to optimize other parameters such as ε and δ, which are known as the Thomsen parameters (Thomsen, 1986). Alternatively, some approximations for ε and δ are assumed to solve only for V_{tilt}. With the V_{nmo}, ε and δ a VTI (vertically transverse isotropy) medium is defined. But to describe a TTI medium, two more parameters are required and defined with *apriori* information about the azimuth (ϕ) and dip (α) of the interpreted surfaces, which describe the structural framework.

In the presence of weak reflectivity, like in the sub-salt cases, other methods to estimate the velocities are used. These are usually based on interval velocity scanning using wave equation PSDM algorithms (Jiao et al., 2008). To date this represents one outstanding challenge in the industry.

At every iteration, a prestack depth migration (PSDM) step is performed. It is essential to have an efficient and accurate PSDM algorithm available for this purpose, since the results from each iteration should be made available to the interpreter for the adjustment of the prior structural model. Beam PSDM has shown to be a very efficient and accurate algorithm in the presence of very complex geology. Beam PSDM allow the geophysicist to solve the challenge of imaging very steep and overturned dips with precision. This yields useful common image gathers (CIG) for picking the residuals and supply the tomography with information to adjust the model in the presence of complex geology.

After the TTI model has been estimated using tomography and Beam PSDM, the final seismic image may be obtained using either Beam PSDM, Wave Equation Extrapolation methods (WEM PSDM) or a higher end imaging algorithm such as reverse time migration (RTM) (figure 5). The challenges with wave equation based approaches are related with algorithmic efficiency aspects. This forces the requirement to have a well validated model available.

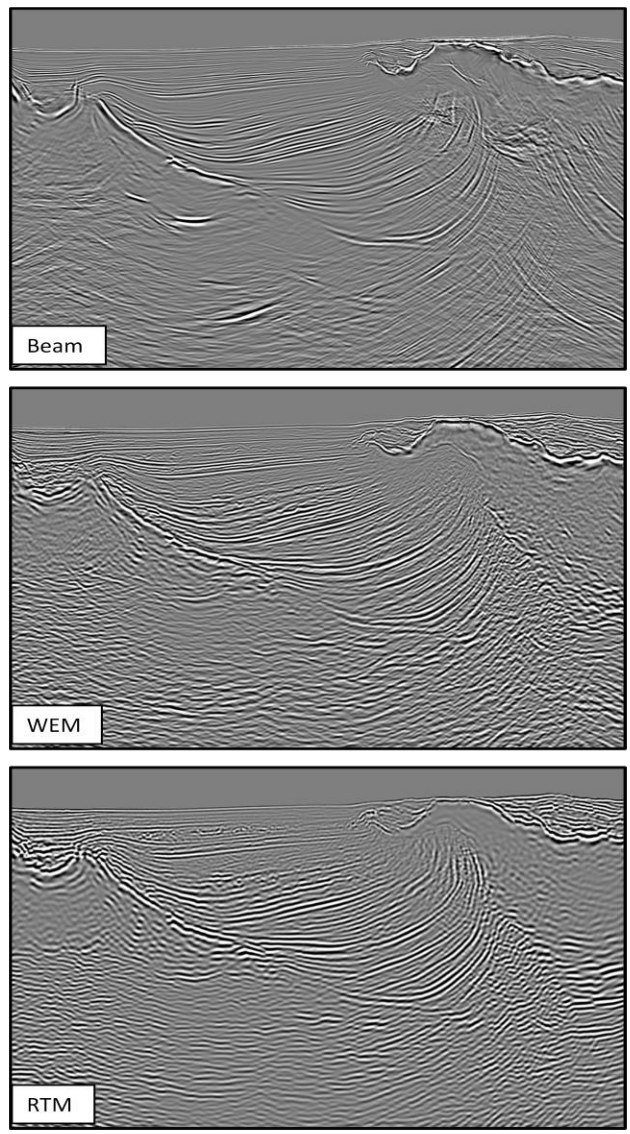

Figure 5: Comparison of depth images obtained from a WAZ data set using three different PSDM algorithms.

Emerging technology for high resolution velocity model building

As high performance computing evolves, methods such as full waveform inversion (FWI) become more viable to produce high resolution velocity models. 3D FWI is available and current efforts are in the expansion of these methods to account for velocity anisotropy.

To achieve FWI successful results, some data conditions must be satisfied. The classical requirement of large offsets is one key parameter to obtain highly resolved velocity contrasts in depth and space.

It is well known that high seismic resolution implies broad temporal and spatial bandwidth. However, an important parameter for FWI is the low frequency content in the seismic spectrum. Low frequencies will constrain better the velocity field obtained during the inversion process. To satisfy this requirement, dual sensor technology to acquire high resolution data has proved to be successful (Fromyr et al., 2011 and Kelly et al., 2010).

Figure 6 illustrates the application of full waveform inversion (FWI) using dual sensor data collected in the Gulf of Mexico. It is noticeable the details introduced in the velocity field obtained after several iterations of FWI. Much of the velocity resolution comes from the low seismic frequencies present in the P_{up} (up going pressure) which results from the dual sensor wavefield after processing.

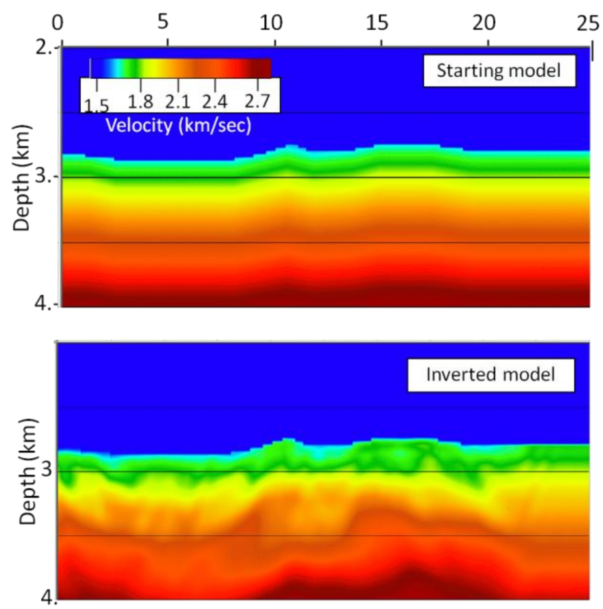

Figure 6: Full waveform inversion (FWI) result using real dual sensor seismic data aquired in the Gulf of Mexico (after Kelly et al., 2010).

Conclusions

Wide azimuth (WAZ) acquisition geometries undoubtedly provide higher seismic resolution but have prompted significant innovations in data processing. Time and depth processing algorithms had to be expanded to exploit the azimuth component and provide the expected uplift from the WAZ seismic data quality. The uplift is consistent in all WAZ data sets. It is expected that the inclusion of WAZ dual sensor recording will further increase the opportunities to obtain seismic images with even better seismic resolution and enhance the results of processes such as full waveform inversion (FWI).

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