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Are broad band, wide and multi-azimuth the new normals for 3D marine seismic?

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SUMMARY

In the last decade the seismic industry has seen ever increasing application of wide, multi-azimuth, and rich azimuth surveys. Additionally, in last half decade the industry has seen a much greater emphasis on broadband acquisition and processing methods with the goal of achieving a seismic spectrum that spans both low and high frequencies. But are these technologies used only in specialized cases or are they the new normals in acquisition and processing?

There are significant costs associated with these acquisitions styles. So, value must be achieved by the use of technologies that provide improved subsurface images. The paper discusses some of the issues and highlights key technologies. This includes: imaging and velocity inversion in complex regimes, preservation of bandwidth for reservoir characterization, and estimation of the anisotropic and azimuthal properties of the subsurface.

Key words: multi-azimuth, wide azimuth, dual-sensors, wavefield separation, illumination, prestack migration, reverse time migration, RTM, angle tomography

INTRODUCTION

In the last decade the maine seismic industry has seen an ever increasing use of wide and multi-azimuth surveys. These acquisition types have been achieved through combinations of multiple streamers, multiple sources, and typically with multiple tiles (sail line passes). The major purpose of these surveys is to provide greater illumination and azimuthal information. An example of the improved illumination capabilities of a wide azimuth survey over as standard narrow azimuth survey is shown in Figure 1 (Fromyr, et al, 2008).

The ever increasing need for increased illumination, wide and multi-azimuth acquisition methods have been combined to achieve “rich azimuth” (e.g. Howard, 2007) or “full azimuth” (e.g. Moldoveanu, 2009). A simple demonstration of the uplift obtained from rich azimuth can be seen in Figure 2, where 3 wide azimuth surveys of 0, 120 and 240 degrees were simulated over the SEG SEAM model and then imaged and combined to produce a rich azimuth depth imaging. While the single wide azimuth has very good image quality, the rich azimuth image has superior imaging quality both in illumination and amplitude balance.

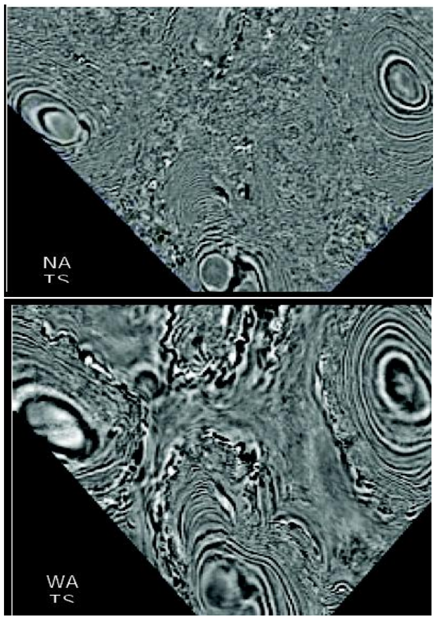


Figure 1. Prestack Migrated Depth slices from narrow azimuth and wide azimuth surveys in the Gulf of Mexico. Note the improved illumination of the wide azimuth survey.

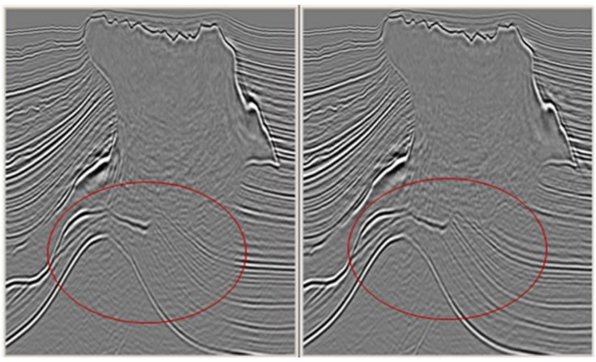


Figure 2. Prestack Migrated Depth images from a wide azimuth and rich azimuth model acquisition and imaging using the SEG SEAM model. Note the improved illumination and improved amplitude balance of the RAZ image.

The second major change in seismic marine exploration in the last half decade has been the emergence of acquisition and processing methods that produce broad band seismic signals. The ultimate goal of these technologies is to remove the degradation in the seismic spectrum from both source and receiver ghosts, which are caused by the interference between up-going and down-going wavefields near the free surface.

There are a number methods in acquisition to address receiver side ghosts – streamers towed at multiple depths, variable depth cables (e.g. Soubaras and Dowle, 2010) and multi-component (hydrophones and geophones) acquisition systems (Carlson, et al., 2007, Robertsson, et al, 2008)

One such method of addressing the receiver side ghost is dual-sensor streamer acquisition and processing, where hydrophone and geophone measurements can be used to separate the total wavefield into up-going and down-going wavefields at the acquisition surface (Carlson, et al, 2007). This allows for deeper tow depth of the seismic streamer, which reduces noise and improves the pass band at lower frequencies. This improves operational efficiency. These lower frequencies are important for both reservoir inversion and full waveform inversion.

More recently we have seen variable depth source arrays combined with source designature to remove both the effects of the source ghost and signature. This dual-sensor acquisition combined with wavefield separation gives a full broadband solution, where the effects of signature and ghosts have been removed (e.g. Parkes, et al., 2011) – see Figure 3.

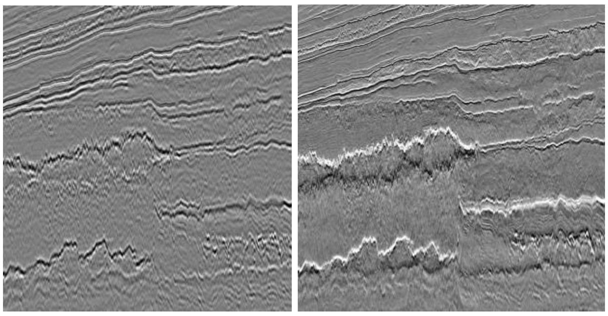


Figure 3. Comparison between conventional acquisition and broadband seismic using dual-sensor and distributed source technology. Note the improvement in stratigraphical detail and bandwidth.

Given the advances both in multi-azimuth and broadband acquisition technologies, a question arises as to whether these technologies will become the new normals for towed marine seismic technology. Certainly in many cases cost will be the determining factor in answering this question. Provided the present demand for 3D seismic is maintained or increased, it likely that most major acquisition companies will continue deploy these acquisition methods and combine them, obtaining data that is both azimuth rich and broadband.

However, in many cases the answer will be dependent on whether we can obtain value from the data. To derive full value from these acquisition methods, processing and imaging technologies need to be advanced enough to take full use of the data provided. Beyond the sheer volume of data that these systems produce, it is critical that processing and imaging technologies are up to the task.

IMAGING TECHNOLOGIES

So what are the technology requirements for taking advantage of these advances in acquisition? Because there are so many options on the acquisition side, the challenge is to provide a full suite of seismic processing, velocity and imaging methods that address the complexities that are introduced.

So, what are the some of the processing and imaging technologies? Below is only a partial list:

1. Source designature
2. Separation of simultaneous sources and source side deghosting.
3. Wavefield separation or imaging conditions to address receiver side ghosts and separate the total wavefield into up and down-going wavefields This allows for for deeper tows, and provides bandwidth at both low and high frequencies.
4. Spatial data interpolation or regularization
5. Wide azimuth multiple removal
6. Advanced velocity estimation: multi-azimuth tomography, including the potential of fast imaging (e.g. beam), to accelerate velocity model updating
7. A suite of advanced seismic imaging methods, that allow for both high resolution imaging, including the effects of Q and anisotropy
8. Imaging in complex velocity, anisotropy, structure, (wave equation migration, RTM).
9. Migration based inversion (e.g. least squares migration)
10. Full waveform inversion
11. Imaging the full wavefield, including the use of multiples.

Certainly subsets of these technologies are applicable to more traditional narrow azimuth acquisition. However, the inclusion of azimuth increases the complexity and volume of information that must be addressed.

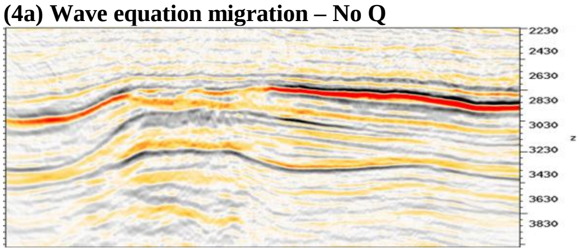
TECHNOLOGY EXAMPLES

It is beyond the scope of this abstract to cover each of the technologies listed above or in any specific one in detail. So, in this abstract I discuss a subset of these technologies that focus on prestack depth imaging that makes use of broadband data and imaging that is required for complex structures, making used of azimuth for illumination and advanced velocity updating through angle tomography.

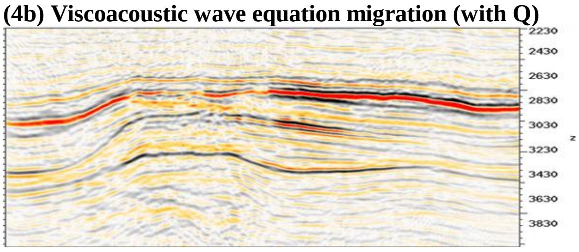
Viscoacoustic imaging solutions to correct for attenuation:

Reservoir characterization requires not only amplitude fidelity, but the largest bandwidth possible. Broad band acquisition, may treat source signature estimation and deghosting technologies, but only consider the spectral issues at the acquisition datum. However, seismic attenuation and transmission alters both the amplitude and phase of the wavefields travelling in the subsurface. To make corrections for these effects, imaging technologies must both estimate Q and include Q in the imaging algorithm with the goal of removing the effects of attenuation as much as possible. Both the amplitude and phase distortion of the seismic waves as they travel through the subsurface must be treated. The real cause of this distortion is due to propagation in depth, therefore, the appropriate domain for the prestack imaging is depth. The imaging needs to be Q compliant and inversion is required to estimate Q. A natural domain for implementation of Q migration is an anisotropic viscoacoustic wave equation migration (QWEM), where the frequency dependent phase and amplitude corrections are built into Fourier finite difference depth extrapolators (Valenciano, et al, 2012). An example of this is shown in Figure 4, where a Q model was estimated from inversion and 3D QWEM was applied to dual-sensor data acquired in the North Sea. Beyond the value obtained by the capabilities of anisotropic viscoacoustic imaging, this method is also applicable for imaging in complex media and is much more affordable for imaging at high frequencies than reverse time migration and therefore can take greater advantage of the higher end of the broad band spectrum. This displays below shows stacks, spectra and subsurface angles without Q compensation and with Q compensation. Note also that the dual-sensor processing is enabling for this technology and Q inversion is necessary.

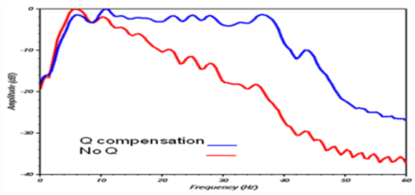
(4a) Wave equation migration – No Q



(4b) Viscoacoustic wave equation migration (with Q)



(4c) Spectra at reservoir level (after z to t conversion)



(4d) Subsurface angle gathers: No Q and with Q

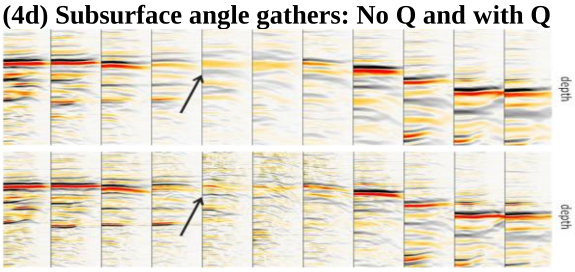


Figure 4. 3D anisotropic wave equation depth images from dual-sensor data in the North Sea. Figure 4(a) is the WEM image no, Figure 4(b) is a QWEM image with Q, where the Q model was estimated from prestack Q inversion. Figure 4(c) is a spectral comparison for both cases (after mapping to time) are select angle gathers with no Q compensation and with Q compensation. Note the improved resolution phase and amplitude enhancement at the crest of the structure, which is that area most affected by attenuation.

Imaging in complex velocity and structural regimes and imaging through salt:

Many of the large potential untapped reservoirs in the world are in areas with structural or velocity complexity, below salt or areas with very steep dip. This almost always translates into the major exploration risks to be illumination and accurate imaging of reservoirs. This has been one of the major drivers for the rapid evolution of seismic with rich azimuth distributions. In these regimes we use a collection of tools to address the imaging challenges. Ray based methods - including fast beam migration and prestack Kirchhoff depth migrations - can address many of the imaging challenges and provide input to multi-azimuth tomographic velocity inversion and salt interpretation for the construction of velocity models. However, when the velocity variability is large, these ray based imaging procedures are not typically accurate enough to be used for final depth migrations. In those cases wave equation migration solutions must be are employed. If the dips not extremely large, say less than 60 degrees, depth extrapolation methods (e.g. Fourier finite difference) can be used. However, in areas with complex salt geometries, and where strong velocity variations create extreme focusing problems and/or turning waves, then reverse time migration (RTM) is often the imaging tool of choice. This is often true in the final stages of velocity model construction. Figure 5 shows an extracted line from a 3D prestack depth migration of the wide azimuth Crystal III survey in the western Gulf of Mexico using TTI RTM depth migration (Crawley, et al., 2010)

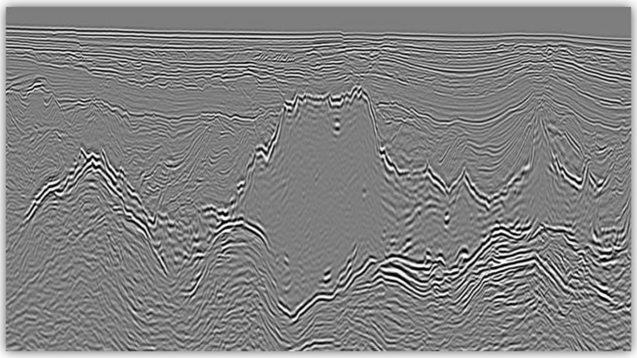


Figure 5. TTI RTM depth imaging of the Crystal III wide azimuth survey in the Gulf of Mexico. Note the complex salt geometries, which can limit subsalt illumination a complicate model construction.

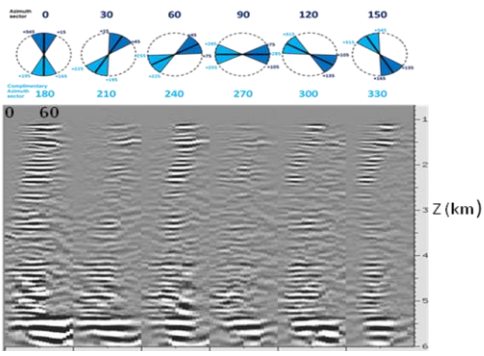


Figure 6. A single angle - azimuth gather from the TTI RTM Crystal III image. These can be produced at any or every subsurface image point, allowing for multi-azimuth tomography and optimized stacking.

In an RTM project it is important to not only to image and stack the data, but also to obtain prestack images. These prestack images are in the form of subsurface angle and azimuth gathers. These gathers can be generated at each subsurface image point (Crawley, et al, 2012) and thus be used both for optimized stacking and as input to angle and azimuth based tomography Figure 6 is a display of a single angle azimuth gather at one spatial x,y location. If we consider the whole image, it's dimension is to nx*ny*nz*nang*naz, which can be an enormous volume. So, combining or extracting meaningful subsets of the data is a critical.

Tomographic inversion with angle gathers:

Note from above that 3D WEM, QWEM and 3D RTM procedures can output subsurface angle gathers, which can then be used for angle based tomography. Figure 9 shows a tutorial demonstration of this using the SEG SEAM model. By starting with a model that was purposely in error, a full azimuth RTM image and angle gathers were produced. The angle gathers were picked and angle gather tomography was performed. The process was repeated to create second update. While only a tutorial, two iterations produce a reasonably good result. Shown in Figure 8 is the true velocity model, the purposely incorrect starting velocity model and two iterations showing the velocity model and resultant RTM gathers. In practice, this technology can be critical to complete the full imaging task.

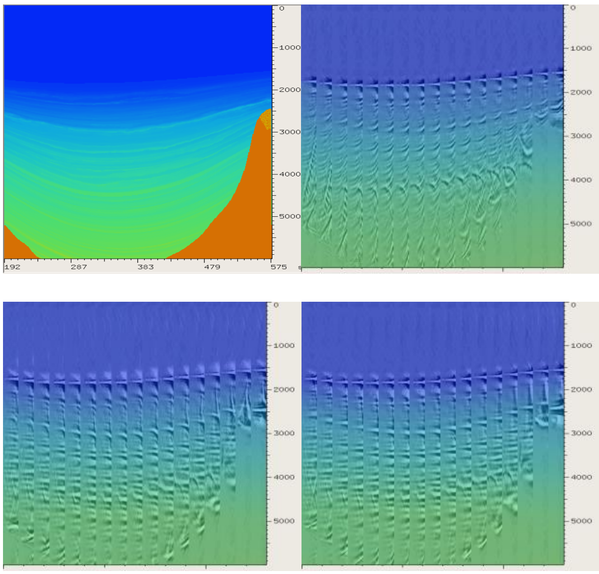


Figure 6. A tutorial of RTM imaging and angle tomography. The top row is the correct velocity and a purposely wrong starting velocity model. The bottom row shows two iterations of the process.

CONCLUSIONS

The question posed in this paper is whether multi-azimuth, wide azimuth (rich or full azimuth) and broad band acquisition are the new normals for marine seismic. More complex acquisition systems are continually being deployed by major contractors. This is certainly in response to the critical drivers for subsurface exploration - improved illumination, resolution and bandwidth. At the same time these acquisition styles require more complex and sophisticated processing and imaging technologies. Some of the key technologies are noted and examples are highlighted.

In the end the combinations of cost and value will determine how much of the overall marine seismic market these technologies occupy. But the trend is clearly increasing.

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