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Multi-dimensional Seismic Data Decomposition for Improved Diffraction Imaging and High Resolution Interpretation

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SUMMARY

Small subsurface scale features, such as natural fractures, act as scattering sources to a seismic wave propagating through the subsurface. The wavefield generated by those source points is identified as diffraction energy. This type of energy, recorded during data acquisition, is then suppressed by conventional processing and standard imaging algorithms, where summations and averaging processes are applied. We propose an innovative approach of a seismic imaging and inversion system carried out in depth, in which data events are imaged and decomposed in the Local Angle Domain into two complementary full-azimuth angle gather systems with fully sampled directivities and reflectivities. If specular reflections carry the highest energy and facilitate the interpretation of large scale geological events, diffraction energy carries information of any small scale heterogeneity with respect to the seismic wavelength (Moser 2008) like small scale faults. The objective of this paper is to describe the method and to illustrate its benefits by applying it to a set of shales reservoirs (Eagle Ford and Barnett) leading to accurate and high-resolution, high-certainty seismic interpretation for risk-managed field development.

Introduction

Small subsurface scale features, such as natural fractures, act as scattering sources to a seismic wave propagating through the subsurface. The wavefield generated by those source points is identified as diffraction energy. This type of energy is recorded during data acquisition, but suppressed by conventional processing and standard imaging algorithms, where summations and averaging processes are applied. The technique applied in this paper is based on an imaging algorithm that maps the recorded surface information into the local angle domain. The differentiator in this system is its ability to preserve wavefield for decomposition into reflection and diffraction energy. This paper describes the technology and illustrates its benefits when applying it to the Eagle Ford and Barnett shale reservoirs, where seismic data can be of moderate quality, leading to accurate, high-resolution, and high-certainty seismic interpretation for risk-managed field development.

Method

Imaging System

This imaging approach retains the integrity of the collected data in a form that can be used to achieve an unambiguous interpretation of the subsurface geology. The input seismic data are first mapped into a full-dimensional decomposition for each imaging point, in four components of the local angle domain (LAD) (Koren & Rave, 2011). A point diffractor ray tracing operator has been designed that shoots rays from the imaging point equally in all directions, and stores the required ray properties for all the rays that succeed in reaching the surface. The permutations of the individual diffracted rays form a system of reflection ray pairs (incident and scattered) that enable the decomposition (binning) of the migrated seismic events into the in situ 4D LAD table at each subsurface point. The in situ 4D LAD table comprises two polar angles representing the directivity of the ray pairs (the sum of the incident and scattered slowness vectors) and two additional angles representing the opening angle and opening azimuth between the two slowness vectors at the image points.

The imaging system outputs two complementary full-azimuth angle gathers: Reflection and Directional. Reflection gathers are used for reliable velocity analysis (VVAZ) and amplitude inversions (AVAZ) to determine fracture and stress orientation and intensity. Full-azimuth directional angle gathers are organized into dip/azimuth angle bins at the subsurface and can be interpreted as a seismic dipmeter. The full wavefield is mapped along all dips and azimuths, and the work presented in this paper is based on the ability to retain the full wavefield along the directional angle gathers.

Wavefield Separation along Directional Angle Gathers

After the initial mapping, the different wavefields are stored in the directional angle gathers in their relevant bins. How are the different types of energy recognized along directional angle gathers? Reflection energy along directional gathers manifests itself as curve shape events, where the true dip is always at the bottom of the curve carrying the maximum energy (Figure 1). Diffraction energy from small-scale heterogeneity (point diffraction) is scattered across all dips and azimuths; therefore, this type of diffraction energy is exhibited as flat, constant and weak. Edge diffraction and corner waves typically associated with the presence of faults will exhibit energy at different dips, but always at the plane (azimuth) of the fault (Figure 1).

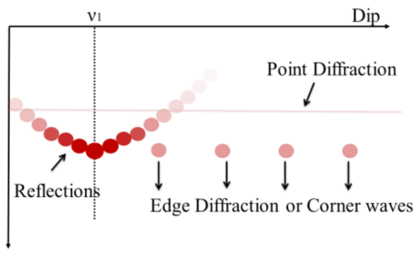

Figure 1 *Illustration of the different wavefields along directional gathers for the 2D case.*

Stacking procedure

Stacking is always required; in this case, two different types of stacking procedures were applied in order to generate different stacks (specular energy and diffraction). To discriminate between the different wavefield types, as diffraction energy is typically weaker than specular reflection energy (Berkovitch, 2009), we apply weights during the stack process to attenuate the specular reflection energy and enhance the diffraction energy (Koren & Rave, 2011). A second approach uses structural separation by stacking along different dips or azimuths applying different mutes. In a simple structural environment, edge diffractions from faults can be discriminated from specular reflections by stacking higher dips.

Results

Eagle Ford Shale – South Texas

Figure 2 illustrates the resolution of diffraction energy, where high energy reflections from flat events were removed. Energy from reflections is significantly stronger than diffraction energy. Therefore, energy scattered from edge diffractions or corner waves at the fault location is masked by the strong reflection energy (left image). The image on the right shows a diffraction stack upon removal of the reflection energy. Fault lineaments are clearly highlighted and present better continuity.

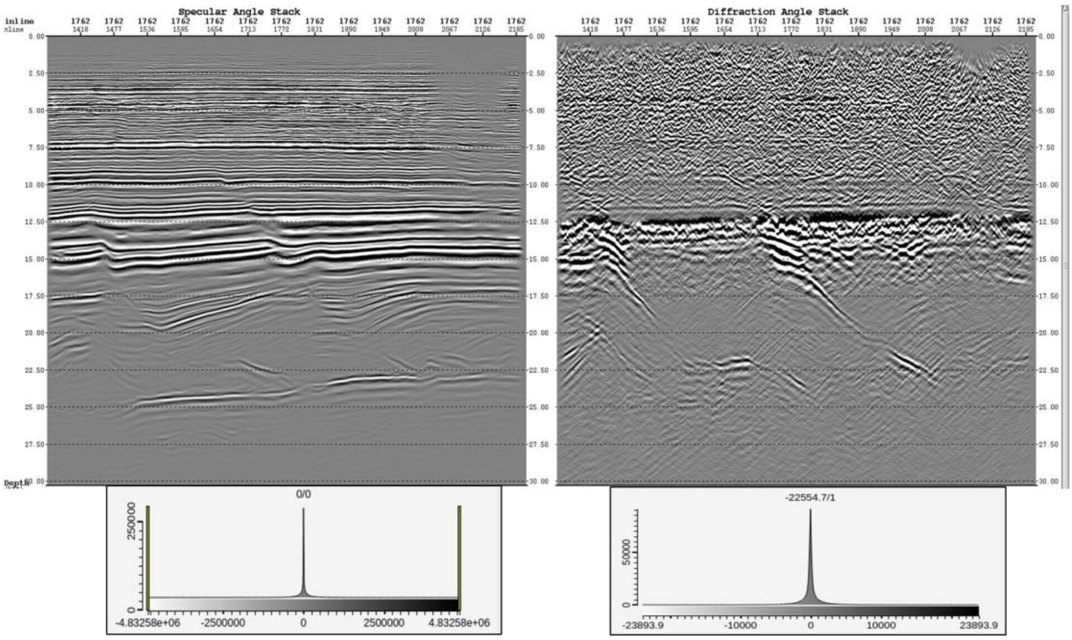

Figure 2 *Specular reflection stack (left) and diffraction stack (right) with their respective values range – Data Courtesy of Seitel.*

Natural fractures in shale formations can provide a pathway for higher permeability; therefore, they need to be characterized. Geometrical attributes such as coherence are commonly used for mapping fault/fracture lineaments. The most appropriate process for reviewing diffraction volume results is to compare them with geometrical attributes from conventional poststack attributes. To understand the benefit of interpreting the diffraction volume along with other poststack seismic attributes, an extraction of both attributes onto a depth slice, at the depth of the zone of interest, and merged into a single view, represents a good approach in the case of the Eagle Ford. It is clear that more continuous lineaments are visible on the diffraction volume (Figure 3, red to blue palette) than on the coherence cube (Figure 3, black and white palette). The position and trend of fault lineaments are consistent between the two attributes. From the diffraction volume, faults lineaments can be extended (Figure 3). New potential fault lineaments (Figure 3) are visible on the extracted diffraction attribute depth slice, which allows the interpretation of a high-definition structural pattern at the limits of the seismic vertical resolution.

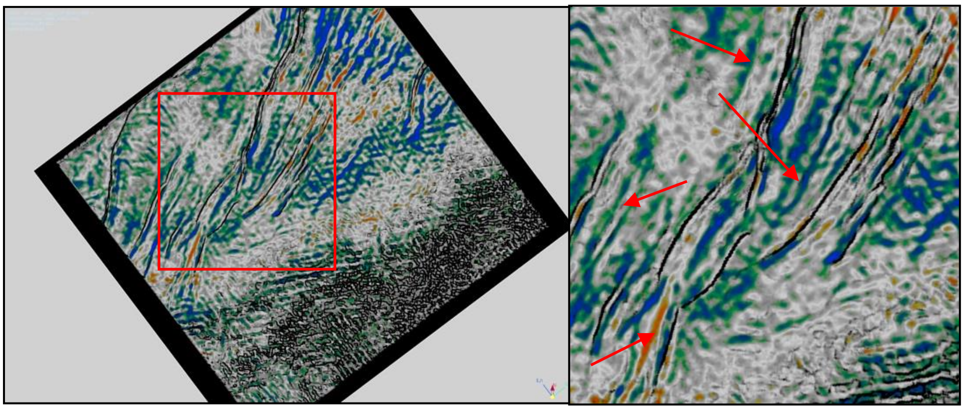

Figure 3: *Depth slice, merge of extracted diffraction and coherence volumes. Enlarged area corresponds to red square. Red arrows indicate improvements in the fault definition (continuity, extension and potential) - Data courtesy of Seitel.*

Barnett Shale – Fort Worth Basin

Producing hydrocarbons in a karsted and fractured zone has always been a high-risk procedure. This is the case in the Barnett Shale formation, which overlies the karsted and fractured aquifer limestone of the Ellenburger Group. The success of a well completion needs to take into account the risk of connecting the Ellenburger formation, through faults and karsts, with water. In the example below, we show how to use high-resolution diffraction images in order to accurately delineate the extension of the karsts (Grasmueck 2012). In this case, different ranges of dips were stacked. The objective is to separate the strong energy from primary reflections at low dips from secondary reflections at higher dips combined with diffraction energy which energies are lower and masked by primary reflection energy, such as within the karsts vicinity. Figure 4 shows the same depth slice at the karsts depth level. Stacks were generated in four different dip ranges: 0°-15°, 15° to 30°, 30° to 45° and 0°-45° (all dips) which we associate with the full wavefield stack.

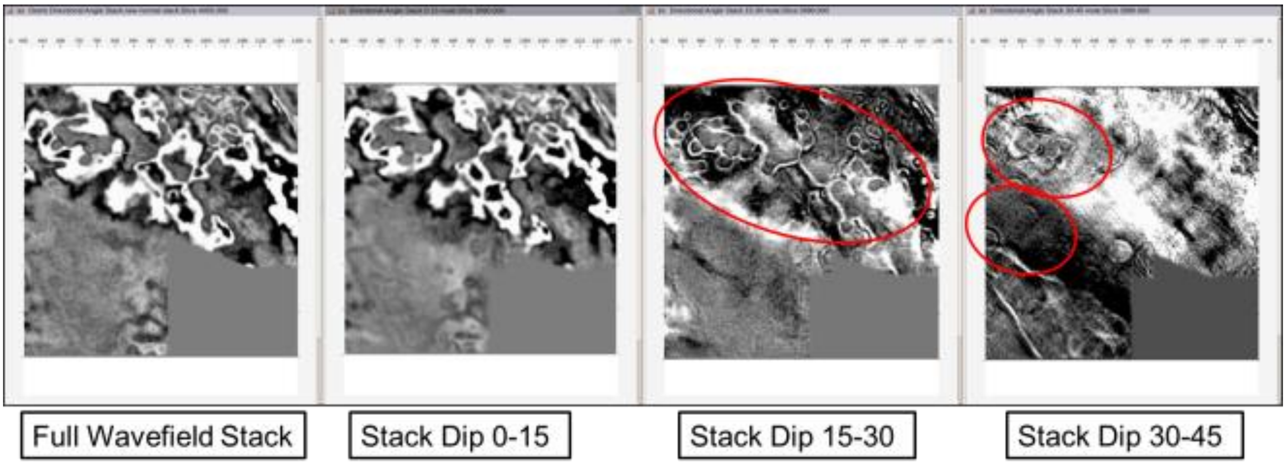

Figure 4 *Same depth slice, different ranges of dip were stacked. As we separate reflections from diffraction energy, karsts are revealed with higher resolution.*

At the depth of the Barnett Shale formation, the diffraction volumes highlight the karst features differently; the most precise delineation is in a dip stacking range of 15 - 30 degrees. As those features intrude from the Ellenburger formation into the Barnett Shale, detecting the corresponding geobodies will help us understand their extension (Figure 5), before drilling survey design begins.

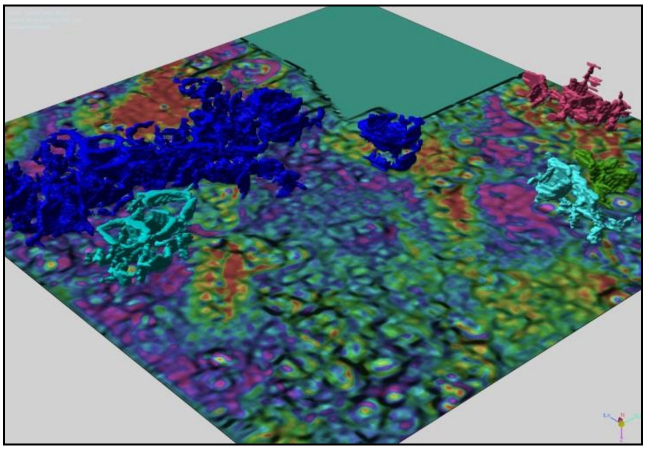

***Figure 5** Depth slice with merged diffraction and amplitude volumes – detected geobodies on the diffraction volume.*

Conclusion

In this paper, we use two examples to demonstrate the use of diffraction stack images to generate a seismic image that can be interpreted with more confidence. A conventional workflow adopted by the industry and designed to increase resolution and delineate geological features is the computation of geometrical attributes like coherence and curvature from migrated stacks. When comparing coherence and/or curvature to diffracted images, it is shown that the resolution obtained from depth migrated diffraction stacks is superior to that obtained using a conventional approach. Diffraction stacks can be integrated as an additional stack that can be incorporated into conventional workflows, to complement the image of the subsurface.

Acknowledgments

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