High-resolution Structural and Stratigraphy Interpretation from Diffraction Energy

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Abstract

Small subsurface scale features, such as natural fractures, act as scattering sources to seismic waves 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 workflow is based on an imaging algorithm that can recover and separate specular and different types of diffraction energy from recorded seismic data.

Diffraction energy weighted stacks gives to geoscientists the possibility to extract from seismic data a high-resolution structural and stratigraphic interpretation for validating a better understanding of the reservoir based on improved structural framework and geophysical model, as well as controlling the decision-making process for economic risk analysis.

Introduction

The characterization of small-scale features is a challenge when dealing with conventional seismic methods. Seismic resolution has limitation to understand sub-seismic scale structural patterns, stratigraphic variations and reservoir heterogeneities.

Minor fault trends, stratigraphic edges and fractures, represent scattering sources for seismic wave propagation. The wavefield generated by those source points is identified as diffraction energy. This energy is always registered during seismic acquisition, but suppressed by standard processing sequences and algorithms of imaging. The method explained in this paper is based on an imaging algorithm that maps the recorded surface information into the local angle domain (LAD). The differentiator of this method is its capability to preserve wavefield through decomposition into reflection and diffraction energy. This paper describes the LAD technology and shows its benefits when applying it to the Eagle Ford play of South Texas and Barnett Shale of Fort Worth Basin, where seismic data can be of moderate quality, leading to accurate, high-resolution, and high-certainty seismic interpretation for risk-management of this field development.

Based on our experience, the methodology presented in this paper could be extended to any kind of geological environment, especially in carbonate plays, where the understanding of structural and stratigraphic complexity is a key factor for decision-making

Local Angle Domain imaging method

Imaging System

This imaging system attempts to preserve the integrity of the data recorded during the seismic acquisition, and looking for a more accurate subsurface geology interpretation. The system enables geophysicists to use seismic data in a continuous way directly in the subsurface local angle domain (LAD), resulting in two complementary common gathers systems: directional and reflection (Koren & Ravve, 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 (Figure 1).

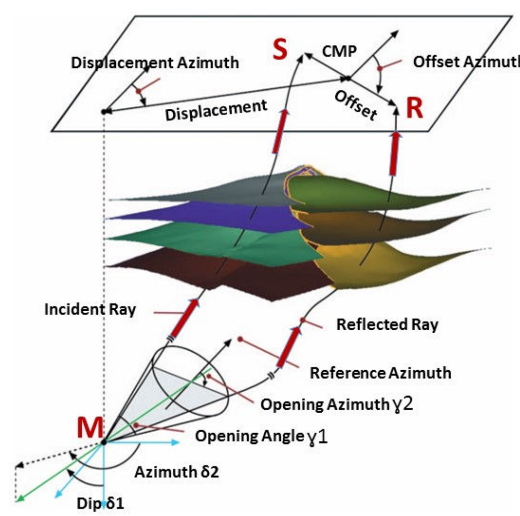


Figure 1 - The input seismic data are first mapped into a full-dimensional decomposition for each imaging point in four components of the LAD. A given subsurface point M and the four angles associated with the LAD: dip δ 1 and azimuth δ 2 of the ray pair normal, opening angle ɣ 1 and opening azimuth ɤ2. Adapted from Koren 2011.

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 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. Figure 2 shows an example of a cylindrical specularity directional angle gather, where the specular energy is emphasized. High values of specular energy along the vertical axis indicate the directivity changes of the reflectors in depth. Using this approach, we can generate two seismic stack products from filtering the energy of directional gathers: specular energy weighted stack to improve the continuity of the structural information, and diffraction energy weighted stack to attempt obtain a high-resolution image.

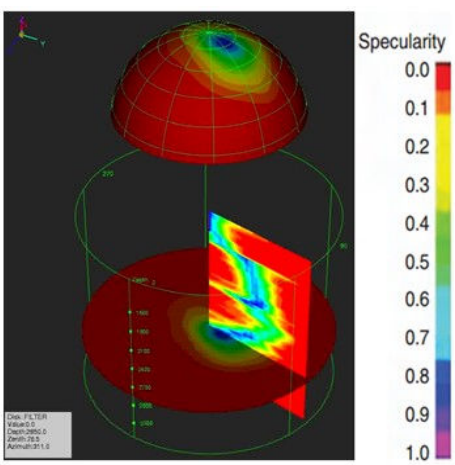


Figure 2- 3D specularity directional gather

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. 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 3).

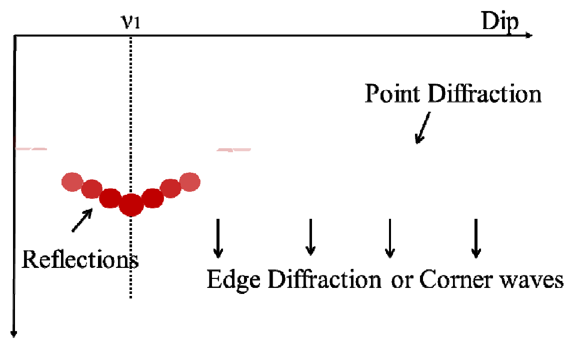


Figure 3 - Illustration of the different wavefields along directional gathers for the 2D case.

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 4 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 (Image above). The image below shows a blending between specular energy stack with a diffraction stack upon removal of the reflection energy. Fault lineaments are clearly highlighted and present better continuity.

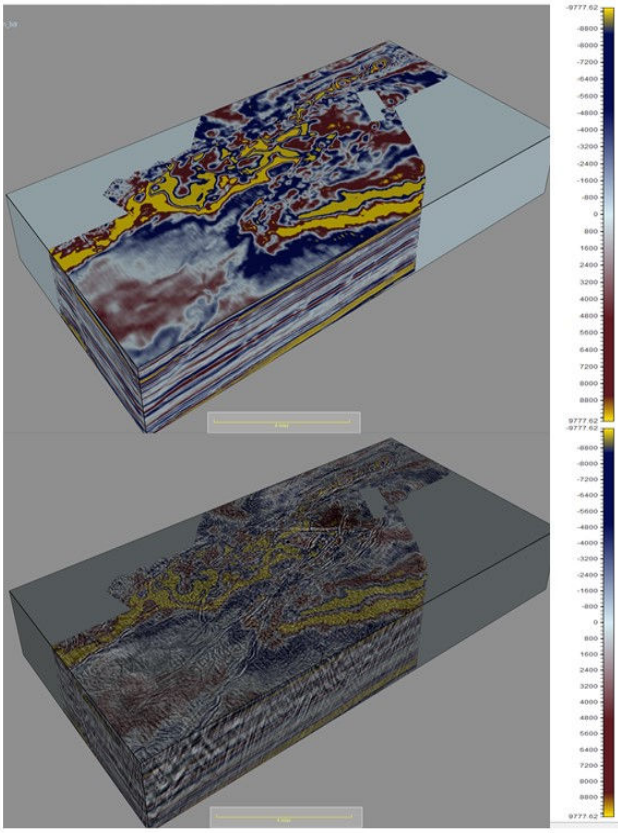


Figure 4 - Specular reflection stack (above) and volume blending between diffraction and specular stack (below) – Data Courtesy of Seitel.

Natural fractures in shale formations can provide a pathway for higher permeability; therefore, they need to be characterized. Geometrical attributes such as coherence and curvature 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 5, red to blue palette) than on the coherence cube (Figure 5, 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. New potential fault lineaments 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.

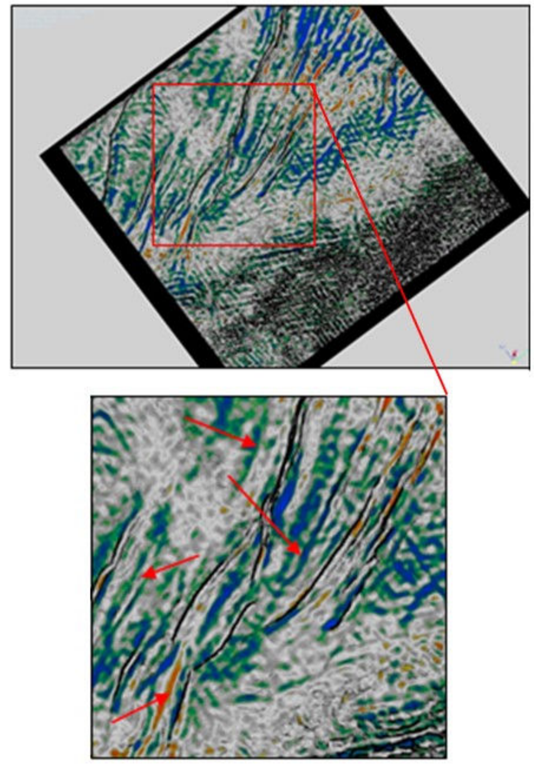


Figure 5 - Depth slice, merge of extracted diffraction and coherence volumes. Enlarged area corresponds to red square. Red arrows indicate improvements in the fault definition (continuity, extension and potential) - Data courtesy of Seitel.

Another example is showed in the figure 6, where we combined the most positive curvature in rainbow palette and the diffraction energy weighted stack in gray scale. Fault and lineaments taking a polygonal appearance on most positive curvature attribute, the magnitude of lineaments is preserved but not the shape (Roberts, 2001), and then the merge with diffraction energy weight stack helps to improve the understanding of the structural setting.

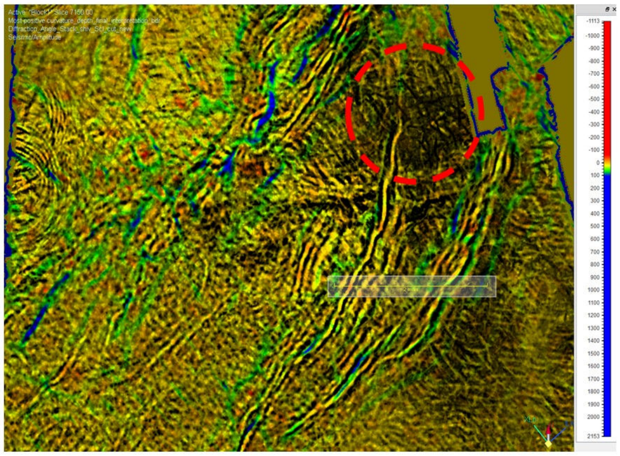
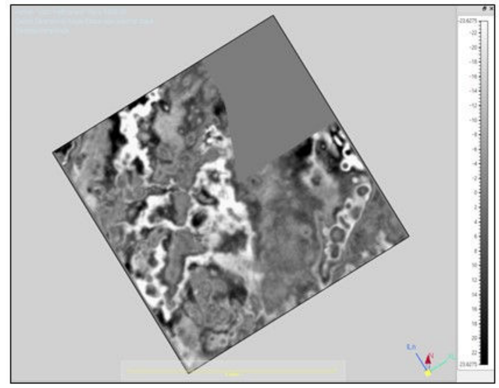


Figure 6 - Depth slice, merge of most positive curvature and diffraction energy weighted stack. There are zones where diffraction energy volume brings high-resolution structural information (red circle) - Data courtesy of Seitel.

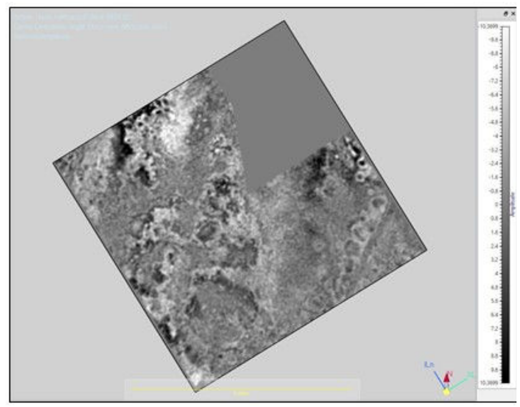
Barnett Shale – Fort Worth Basin

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. The specular analysis was applied to this dataset (Figure 7). On the high-resolution diffraction energy weighted volume, we can observe small-scale features that help to construct and validate the geophysical model of this area. The interpretation to determine faults extension, fractures trends and karsts detection is considerably improved.

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 8 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.



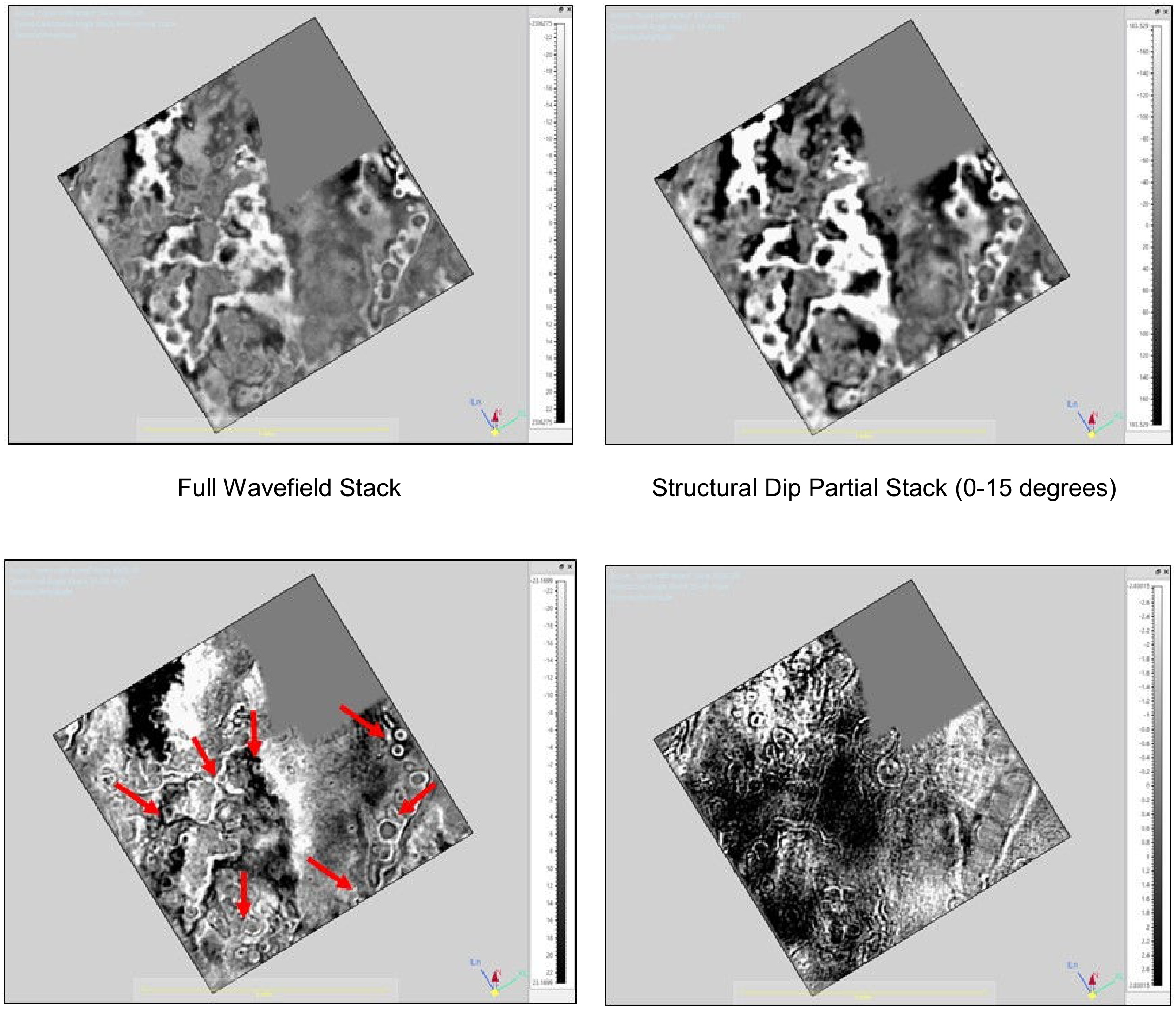
Full Wavefield Stack



Diffracted Energy Stack

Figure 7- 4500 ft. Depth slice: Full wave stack and diffracted energy weighted stack. Small-scale discontinuities are observed, this image helps to understand the compartmentalization of this heterogonous reservoir.

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 to 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 9), before drilling survey design begins.



Full Wavefield Stack

Structural Dip Partial Stack (0-15 degrees)

Structural Dip Partial Stack (15-30 degrees)

Structural Dip Partial Stack (30-45 degrees)

Figure 8 – 4500 ft. Depth slice, different ranges of dip were stacked. As we separate reflections from diffraction energy, karsts are revealed with higher resolution. Red arrows on 15-30 degrees structural dip partial stack indicate seismic anomalies interpreted as karsts. The characterization and validation of these features is important to support the analysis for risk-management of this field development.

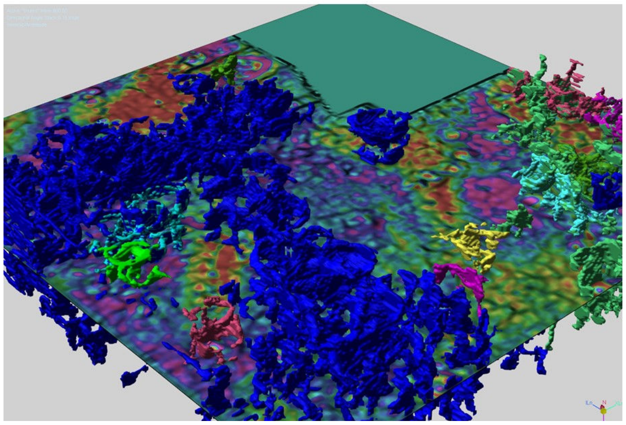


Figure 9 - Depth slice with merged diffraction and amplitude volumes – detected geobodies on the diffraction volume.

Conclusions

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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