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Seismic Diffractions for Fault Interpretation: An Example Using OBN Data in Ultra-Deep Waters of the Santos Basin

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Abstract

Fault interpretation in complex geological environments using standard seismic data is a challenge. It demands previous knowledge or special/particular datasets. This study describes a processing workflow for seismic diffractions extracted from azimuth-rich data acquired using nodes distributed across an ultra-deepwater region of the Santos Basin. The dataset was processed using the Local Angle Domain methodology, which enabled effective separation of diffraction energy from reflected waves. The resulting images were interpreted to delineate the structural framework, and the analysis presented here pays special attention to the post-salt section. This interpretation incorporates supplementary seismic attributes to enhance fault plane mapping. The outcomes are compared with those derived from conventional reflection-based interpretation, emphasizing the complementary value of integrating both approaches.

Introduction

Diffraction typically occurs during wave propagation when waves encounter geological discontinuities such as faults, karsts, unconformities, and others. Although diffraction is present in all seismic data, it is often considered as "undesired noise" in most cases. Consequently, its use for structural mapping is not common, mainly due to the difficulty in distinguishing it from reflections. However, the effort to separate this information is worthwhile, as diffraction can provide additional information about these features related to their genesis, enabling a more detailed understanding of geological structures in seismic mapping.

The processing challenge lies in distinguishing these diffractions from reflections, which are the primary focus of conventional workflows. Diffraction waves naturally scatter in all directions at discontinuities within the medium and typically have much lower amplitudes—about one-tenth of the energy of the compressional wave (Khaidukov et al., 2004).

Because they are a distinct type of wave, diffractions can provide valuable additional information for structural mapping, highlighting specific geological features (Khaidukov et al., 2004; Koren et al., 2010). They are easier to interpret in horizontal slices or layered views across horizons. Unlike reflection amplitudes, which are positive or negative relative to a seismic horizon, diffractions do not have a straightforward amplitude polarity.

To make it easier to interpret the data and enhance the continuity of vertical section analysis, we also employed attributes that highlight the energy of these events. For example, using an energy envelope can significantly aid in identifying and interpreting fault planes. This approach improves the visualization and understanding of the underlying geological structures, providing clearer insights into the subsurface features. The results will illustrate the efficiency of this proposed approach.

Energy separation

The seismic imaging technique employed is designed to extract high-resolution, angle-dependent reflectivity information from the subsurface. Operating in the Local Angle Domain (LAD), the method utilizes full-azimuth common-angle image gathers. Data processing occurs in two domains: the reflection domain and the directional domain (Fig. 1a). The imaging process and its mathematical framework are detailed by Koren and Ravve (2011).

The LAD integrates seismic events generated by pairs of rays that share a common orientation of the apparent reflection surface but differ in opening angles through a weighted summation scheme.

Directional gathers facilitate the separation of specular reflection and diffraction components and preserve directivity-dependent seismic responses. It is created by integrating data along the axes of directional dip angle and directional azimuth. For the separation of waves, a diffraction filter is applied that either preserves or removes the specular energy, depending on the desired volume. Figures 1b and 1c illustrate an example of a gather dip/azimuth in this scheme.

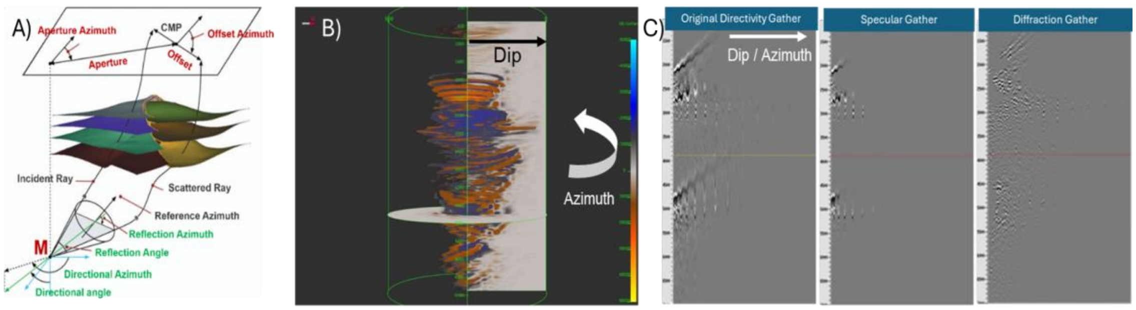

Figure 1: a) Subsurface-to-surface and surface-to-subsurface ray-based mapping. Each ray pair maps a specific seismic data event recorded on the acquisition surface, into a 4D local angle-domain space in the subsurface — dip and azimuth of the ray pair normal, opening angle and opening azimuth (Koren & Ravve, 2011). b) 3D cylindrical directional angle gather. c) 2D view of full directivity gather, specular energy gather and diffraction gather, varying with directional dip and azimuth.

We can differentiate between diffracted and specular waves by analyzing their energies: typically, specular energy shows up as events with higher amplitude, while diffracted energy tends to appear at the edges with lower amplitude. The specular energy is concentrated around the dip values of geological features and can be isolated either by applying a diffraction filter during data processing or directly on the raw data through filtering of the relevant dips.

Method and Dataset

The LAD was applied to a subset of full-azimuth seismic data acquired in an ultra-deep portion of the Santos Basin using ocean-bottom node (OBN) technology. The original data are very dense, enabling high-quality imaging. In the present study, particular emphasis was placed on the directional gathers, given their effectiveness in enhancing structural interpretation

To further enhance feature visibility, a principal component analysis (PCA) was performed on the diffraction volume, improving signal-to-noise ratio and sharpening structural outlines. Additional seismic attributes, such as the pseudo deconvolution using the ridges of the wavelet transform (Matos et al., 2014) and the seismic energy (Matos, 2018), were applied to enhance vertical continuity and improve the delineation of major fault systems observed in the raw directional seismic amplitude volume.

For comparing the diffraction results with the standard approach to reflection data interpretation, we also used the raw directivity amplitude (which includes specular energy) to calculate various structural attributes. These included high-resolution eigenvalue-based coherence and multiple curvature measures. The eigen-coherence attribute has proven especially effective in identifying faults and fractures, while curvature attributes helped highlight folding patterns and other regions susceptible to structural deformation (Chopra and Marfurt, 2007).

Results

The diffraction data were loaded into the workstation and analyzed alongside other standard volumes derived from reflections, as shown in Figure 2. While the study primarily focuses on fault interpretation, several discontinuity features, such as channels and landslides, were also identified within the diffraction data. These key geological features are clearly visible at the same depth slice in the high-resolution eigen coherence, further supporting the effectiveness of the depth imaging technique.

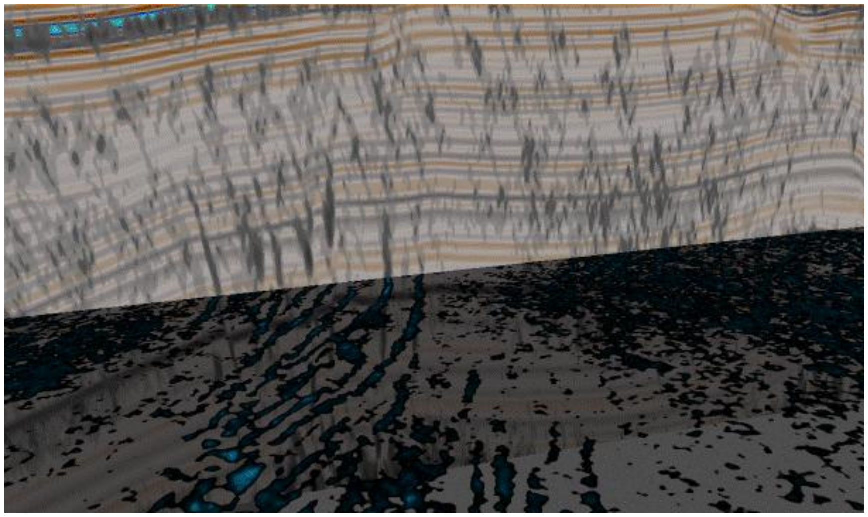

Figure 2: Corended **d**iffractions and conventional amplitude reflection section and a depth slice with diffractions only. There is a clear correlation between faults and the presence of diffraction, even for events below or at the limit of seismic resolution.

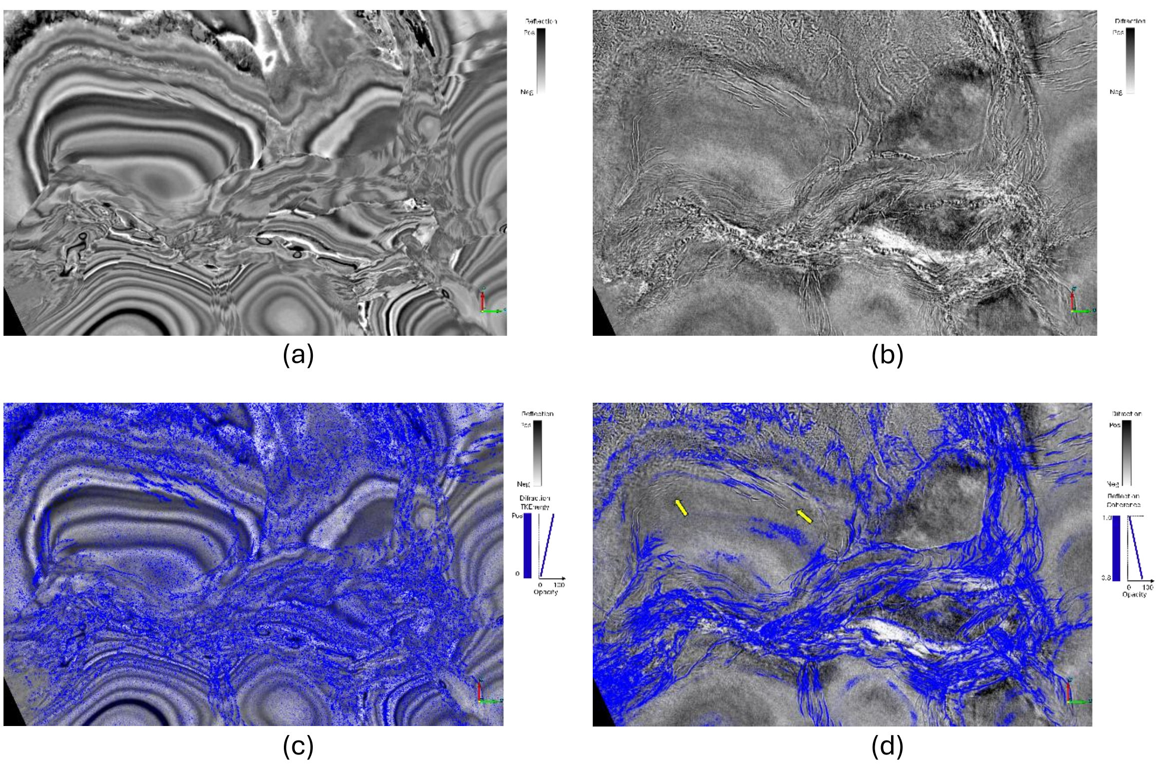

Figure 3: A depth slice presented with Specular (a), Diffraction (b), (Corended Reflection and Diffraction TK Energy (c) and Corended Diffraction and Reflection Coherency volumes (d). Panel (c) demonstrates how this attribute reveals the fault position, closely corresponding with corended amplitude. Panel (d) shows a combined rendering of diffraction and reflection coherence. Notably, in the areas marked by the arrows, there is increased geological detail, and the diffraction images tend to be more accurate.

Stronger specular signals often overshadow weaker diffraction signals, potentially obscuring important geological details. However, the diffraction volume holds the potential to offer improved resolution, uncovering additional geological information and finer subsurface features that might otherwise remain hidden.

When comparing the diffraction data with the structural attributes generated, we observe that they tend to complement each other. In certain areas, the diffractions are clearer and provide more geological insight, while in other regions, both datasets are quite similar. It is important to note that the processing of diffractions is likely to have significant room for improvement and further advancements, especially as this technology becomes more widely adopted. In contrast, conventional reflection processing is already well established. Nonetheless, the diffraction data have already demonstrated strong potential for structural interpretation in the evaluated area.

Figure 3 presents a depth slice illustrating the separation of specular (a) and diffraction (b) energies. The specular component closely resembles the original full-volume data. The observed diffractions are associated with discontinuities linked to fault planes. To enhance and facilitate structural mapping, the diffraction energy attribute was applied, with its maximum amplitude aligning with the fault planes. This aids fault interpretation, particularly since diffractions lack the conventional polarity seen in reflections.

Panel (d) displays a combined rendering of diffraction energy and reflection coherence—an attribute commonly used in traditional interpretation. Diffractions can be interpreted in a complementary way to reflection-derived structural attributes, contributing additional detail and insights. Notably, in the areas indicated by arrows, geological detail is significantly enhanced, and the diffraction images tend to be more precise. However, in other regions, the improvements are less marked, and in some cases, coherence images offer greater clarity.

Conclusions

Diffraction interpretation is an emerging technique that can reveal subtle geological structures previously obscured by dominant specular energy. The LAD processing flow is a methodology that effectively allow the filter of the diffraction energy from the full seismic wavefield, providing a reliable result. The stacked diffraction image adds higher resolution and enhances structural features detailing, improving data interpretation when used together with other structural attributes based on the reflection volume. The additional structural insights provided by this method are particularly valuable for well location decisions and for gaining a deeper understanding of the geological environment.

Acknowledgments

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