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Multiscale Structural Analysis Integrating Azimuthal Seismic Attributes and Borehole Image Logs in a Pre-Salt Carbonate Reservoir, Santos Basin, Brazil

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The Santos Basin, located along the passive continental margin of southeastern Brazil, is the most prolific offshore petroleum basin in the country and hosts one of the most significant pre-salt reservoirs, developed within the lacustrine carbonates of the Barra Velha Formation. These reservoirs are marked by high geological complexity, characterized by natural fracturing and pronounced stratigraphic and structural heterogeneity. Composed primarily of Aptian-age carbonate rock cycles, they exhibit seismic facies typical of mounded platforms, onlaps, slopes, and structural highs. Faults and fractures, expressed in seismic data as discontinuous reflections with linear to curvilinear geometries, represent fundamental structural controls on reservoir behavior. Fracture characteristics such as orientation and density are typically inferred from borehole image logs, which provide high-resolution but spatially limited information. To estimate fracture properties in interwell areas and map fault distribution, seismic data are commonly used. Although conventional stacked volumes provide useful structural information, they tend to average directional content, which may reduce sensitivity to anisotropic features associated with aligned fractures or segmented fault networks. Azimuthal seismic volumes acquired at different illumination angles preserve wavefield directionality, enhancing the detection of structural anisotropy and enabling the extraction of attributes sensitive to orientation-dependent discontinuities. This directional sensitivity improves the imaging of subtle features, such as aligned fractures and subtle fault patterns, that are often undetectable in conventional stacked seismic volumes. Comparison of volumes acquired at azimuths of 40°, 140°, 220°, and 320° allows assessment of variability in the seismic expression of discontinuities.

This study applies a multiscale structural analysis integrating azimuthal seismic attribute interpretation with borehole image log analysis to characterize fault and fracture patterns and their spatial distribution. The dataset comprises four post-stack 3D seismic volumes and sixteen wells with borehole image and conventional logs, covering approximately 206.4 km². Most Positive Curvature (MPC) was calculated to support the identification of convex structures and subtle flexures. Subsequently, the Thinned Fault Likelihood (TFL) attribute was calculated through dip scanning, capturing and delineating both faults and fractures. This attribute provides high-resolution fault imagery in three dimensions and enables direct estimation of fracture density and proximity. Ant Tracking was then applied as a fault enhancement method to highlight laterally continuous fault frameworks. Borehole interpretations provided fracture density logs and rose diagrams of orientation for multiscale comparison and validation.

A comparative analysis between seismic and borehole derived fracture patterns was conducted to evaluate their spatial consistency. The combination of MPC, TFL, and Ant Tracking significantly improved imaging of discontinuities, enabling the identification of distinct fault and fracture families. Fracture families observed in seismic data (NW–SE, N–S, NE–SW, and E–W) showed strong correlation with borehole-derived orientations. Higher fracture densities were observed in the lower intervals of the Barra Velha Formation, whereas the upper intervals showed lower densities, indicating reduced anisotropy. Major NE trending faults, better resolved in the 140° and 320° volumes, exhibit greater lengths in the deeper sections of the reservoir and decrease toward the top. Minor N–S faults, linked to half-graben structures, were more clearly imaged in the 40° and 220° volumes and mostly affect the middle reservoir interval. A qualitative correlation was observed between areas of high fracture intensity and zones of elevated seismic anisotropy, both supported by borehole image data. These results highlight the effectiveness of integrating azimuthal seismic attributes and borehole image data to improve fault and fracture characterization and support structural interpretation in reservoir analysis.