

Integrated AVAZ–AVA Analysis for Mapping Potential Sub-Seismic Fracture Corridors in Pre-Salt Carbonates, Santos Basin

Introduction

The Barra Velha Formation (BVF) is the main pre-salt carbonate reservoir of the Santos Basin, where sub-seismic fracture networks remain poorly constrained between wells and mapped faults. BVF is a lacustrine carbonate succession subdivided into three intervals BVE 100, BVE 200, and BVE 300. Previous studies show that fracture intensity is influenced by both fault proximity and lithological composition, particularly silica content (Mendes et al., 2024; Laubach et al., 2019). Seismic-attribute-based approaches have previously been used to characterise stratigraphic architecture and non-matrix porosity in the BVF (Bueno et al. 2014), while fracture abundance derived from image logs is itself sensitive to structural complexity along the wellbore.

Integrated Amplitude variation with azimuth (AVAZ) and Amplitude variation with angle (AVA) analysis offers a seismic-scale pathway to detect and characterise such sub-seismic fracture zones. AVAZ provides a fracture-sensitive seismic anisotropy proxy, while AVA helps separate lithological and fluid-related elastic effects (Shuey, 1985; Schoenberg and Sayers, 1995). This study integrates AVAZ and AVA attributes across BVE 100, BVE 200, and BVE 300 using four-azimuth stack data and 12 image-log wells, with the structural and lithological framework of Mendes et al. (2024) used as geological control.

Methodology

Azimuthal amplitude variation was decomposed using a second-order Fourier expansion (Downton and Roure, 2015), in which the amplitude A measured at azimuth φ is written as:

$$A(\varphi) = A_0 + C_2 \cos 2(\varphi - \varphi_2) \quad (I)$$

Least-squares inversion of the four azimuthal stacks returns A_0 , the isotropic amplitude, together with C_2 and φ_2 at each grid location (Rüger, 1998). C_2 is treated as a fracture-sensitive anisotropy magnitude rather than a direct measure of fracture intensity, and φ_2 gives the azimuth of the seismic anisotropy. AVA attributes were derived from the isotropic angle stacks using the three-term Shuey (1985) approximation:

$$R(\theta) = A + B \sin^2\theta + C (\tan^2\theta - \sin^2\theta) \quad (II)$$

where A , B , and C are the intercept, gradient, and curvature terms used to characterize lithological and fluid-related elastic contrasts independently of the azimuthal anisotropy analysis.

Probable sub-seismic fracture corridors were mapped using a composite score that combines normalized C_2 , φ_2 coherence, AVA anomaly, and fault-distance weighting. Corridor bodies were extracted using thresholding and morphological filtering, while PCA was used to estimate their elongation direction. The robustness of the maps was tested with 400 parameter combinations, and independent full-stack attributes, including Chaos, Variance, and Ant-Tracking, were used to compare seismic character inside and outside the mapped corridors.

Results and Discussion

C_2 magnitude decreases with distance from mapped fault traces at all three BVF intervals (Figure 1) (Pearson $r = -0.28$, -0.37 , and -0.43 for BVE 100, BVE 200, and BVE 300), broadly reproducing the fault proximal increase in fracture intensity reported from borehole scan-lines by Mendes et al. (2024). AVA intercept A follows a different spatial pattern, largely independent of fault distance and more strongly linked to lithology, with positive values at BVE 100 associated with reworked carbonates and negative values at BVE 200 associated with clay-rich intervals. In Figure 1 although mean normalized C_2 decreases away from mapped faults, the broad interquartile ranges indicate that additional controls beyond fault proximity influence the anisotropic response.

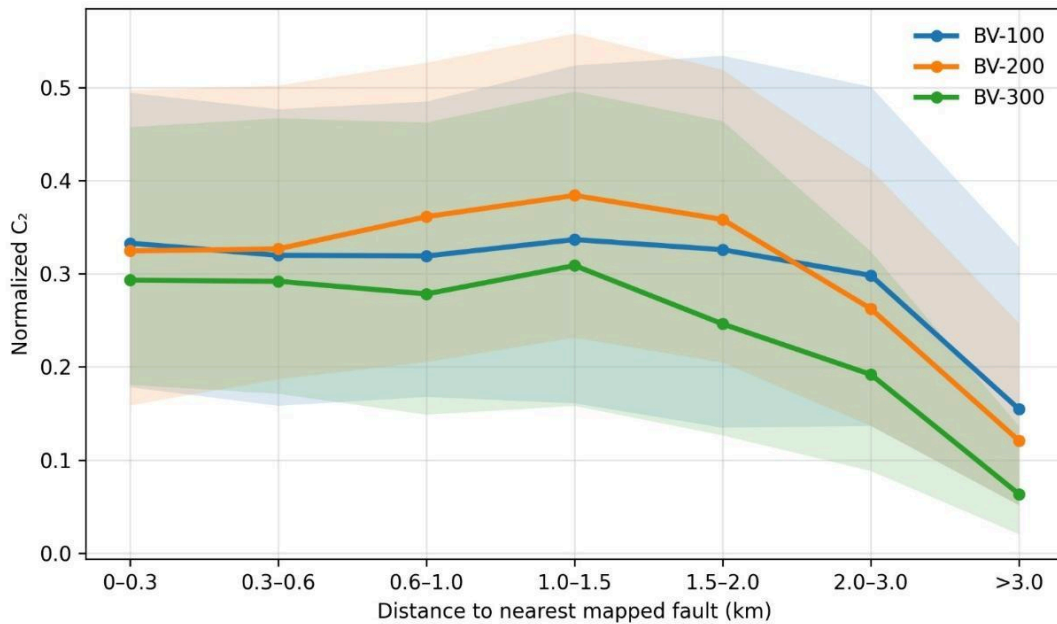


Figure 1 The overall negative trend in mean C_2 with increasing fault distance supports its interpretation as a fracture-sensitive seismic attribute. Shaded regions represent the interquartile range (25th–75th percentile) of normalized C_2 values within each fault-distance bin.

C_2 -weighted directional statistics show three distinct patterns across the BVE intervals. At BVE 100, ϕ_2 has a coherent NNW-SSE mean orientation (resultant $R = 0.60$), broadly consistent with the NW-SE and NE-SW fracture sets reported from image logs and with the NE-trending maximum horizontal stress inferred from borehole breakouts (Mendes et al., 2024). At BVE 200, the resultant falls to $R = 0.03$, indicating that ϕ_2 varies almost randomly in direction; this is consistent with the presence of several fracture sets of comparable strength in this interval, in line with the increase in ENE-trending structures noted from image logs at this level (Mendes et al., 2024), and is treated as a multi-family signal rather than a processing artefact. At BVE 300, ϕ_2 recovers a coherent N-S orientation ($R = 0.50$), aligned with the NNE-SSW F2 fault trend and with the discordant non-matrix porosity that characterizes this deeper, more structurally active interval. The seismic-derived orientations were not constrained by the borehole data during processing, so their agreement with the image-log fracture sets at BVE 100 and BVE 300 supports the use of ϕ_2 as a meaningful, if indirect, indicator of fracture orientation at these levels.

Seventy-nine probable sub-seismic fracture corridors were mapped across the three horizons (19, 34, and 26 at BVE 100, BVE 200, and BVE 300), with mean C_2 values comparable to those within the mapped fault damage zone (Figure 2), despite lying at mean distances of roughly 950–1030 m from mapped fault traces, within or close to the 1.2 km fault influence width reported by Mendes et al. (2024). PCA of the corridor bodies gives mean elongation azimuths of 47° – 54° (NE-SW) at all three horizons, oblique to the mapped fault strikes by roughly 17° – 25° . NE-SW corridors linking adjacent NNW-SSE fault segments are consistent with the geometry expected of relay-ramp linkage zones (Peacock and Sanderson, 1994), and obliquities of this order are also typical of secondary shears developed during fault reactivation (Kim and Sanderson, 2005). The 400-parameter sensitivity test identified a stable corridor core, with 2,207, 1,672, and 5,083 pixels retained in at least 70% of the tests for BVE 100, BVE 200, and BVE 300, respectively. About 20–25% of these pixels occur near fault tips or relay zones, while the rest are more likely influenced by lithological controls, especially silica content, as suggested by Mendes et al. (2024) and Laubach et al. (2019).

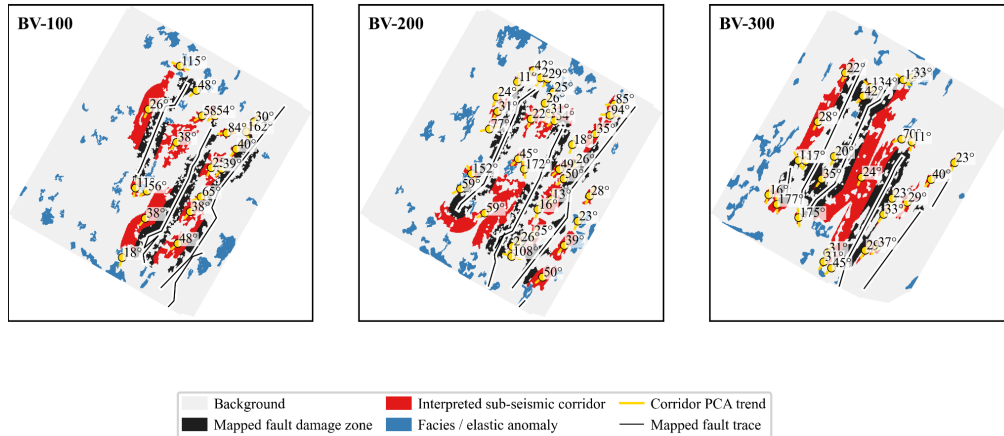


Figure 2 Probable sub-seismic fracture corridors mapped from the composite score combining normalized C_2 , ϕ_2 coherence, AVA anomaly, and fault-distance weighting. The mapped corridors show coherent NE-SW elongation from PCA analysis and are spatially consistent with fault-linkage or relay-zone geometries.

The independent full-stack attributes provide generally supportive evidence for the mapped corridors. Trace-to-trace Variance and Ant-Tracking are consistently higher inside the corridors across all three horizons, with the strongest Variance contrast observed at BVE 200, where ϕ_2 coherence is weakest. This suggests that the probable corridors correspond to zones of increased lateral seismic heterogeneity rather than artefacts of the AVAZ workflow (Figure 3). Seismic Chaos shows a weaker and less consistent response and is therefore treated only as secondary supporting evidence.

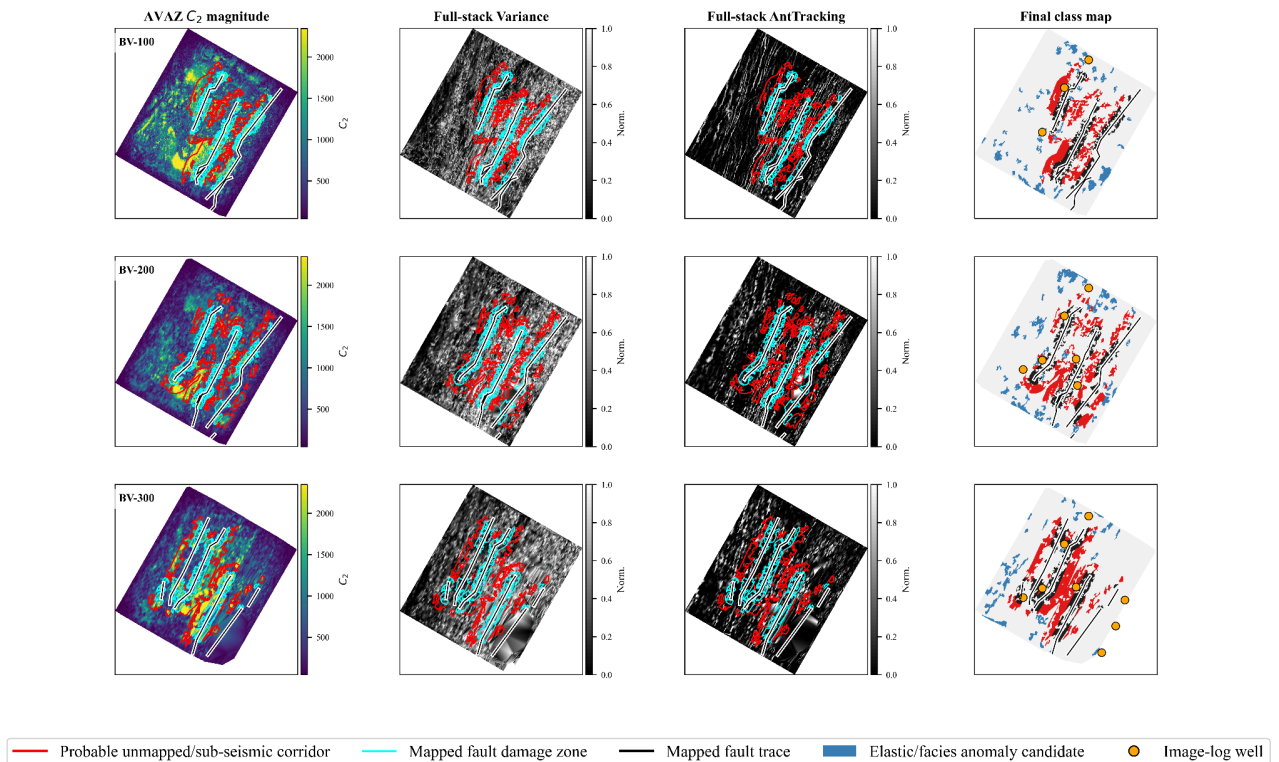


Figure 3 Comparison between the AVAZ-derived corridor maps and independent full-stack seismic attributes. Variance and Ant-Tracking are generally higher within the mapped corridors than outside them, providing supporting evidence that the corridors correspond to real seismic lineaments rather than artefacts of the AVAZ scoring workflow.

Conclusions

AVAZ-derived C_2 and ϕ_2 show three fracture-related anisotropy responses across the Barra Velha Formation: a coherent NNW–SSE trend at BVE 100, a weak and dispersed multi-family response at BVE 200, and a coherent N–S trend at BVE 300. These patterns are broadly consistent with the image-log structural framework of Mendes et al. (2024). The difference between C_2 and AVA intercept A also shows that fracture-related anisotropy and lithological variation should be interpreted together rather than from a single attribute. In total, 79 probable sub-seismic fracture corridors were identified, with a consistent NE–SW elongation and average distances of about 950–1030 m from mapped faults. Their agreement with Variance and Ant-Tracking attributes supports the interpretation that these probable corridors represent real seismic features rather than artefacts of the AVAZ-based workflow. These results provide useful spatial inputs for future fracture-orientation and likelihood modelling in the BVF reservoir.

Acknowledgements

This research was supported by the Energy Production Innovation Center (EPIC), hosted at the University of Campinas (UNICAMP) and funded through the partnership between Equinor Brasil and FAPESP (Grants 2017/15736-3 and/or 2025/04182-3). Further recognition is extended to the ANP for their support via the R&D levy regulation. The authors also acknowledge the contributions of the Center for Petroleum Studies (CEPETRO), the School of Mechanical Engineering (FEM), and the Institute of Geosciences (IGe) as well as Luiza de C. Mendes for image log interpretation. Emilson Leite is also grateful to CNPq for the Research Productivity Fellowship, grant 310571/2022-7.

References

- Bueno, J.F., César, B., Kuroda, M.C., Vidal, A.C. and Leite, E.P. [2014] Structural and stratigraphic feature delineation and facies distribution using seismic attributes and well log analysis applied to a Brazilian carbonate field. *Interpretation*, 2(1), SA83–SA92.
- Downton, J.E. and Roure, B. [2015] Interpreting azimuthal Fourier coefficients for anisotropic and fracture parameters. *Interpretation*, 3(3), ST9–ST27.
- Kim, Y.S. and Sanderson, D.J. [2005] The relationship between displacement and length of faults. *Earth-Science Reviews*, 68(3–4), 317–334.
- Laubach, S.E., Lander, R.H., Criscenti, L.J., Anovitz, L.M., Urai, J.L., Pollyea, R.M., Hooker, J.N., Narr, W., Evans, M.A., Kerisit, S.N., Olson, J.E., Dewers, T., Fisher, D., Bodnar, R., Evans, B., Dove, P., Bonnell, L.M., Marder, M.P. and Pyrak-Nolte, L. [2019] The role of chemistry in fracture pattern development and opportunities to advance interpretations of geological materials. *Reviews of Geophysics*, 57(3), 1065–1111.
- Mendes, L.C., Basso, M., Villacreces Morales, J., Chinelatto, G.F., Blanco, J.M., Correia, U.M.C., Ponte, J.P., Matheus, G.F., Camargo, M.M., Gavidia, J.C.R., Medeiros, R.S.P. and Vidal, A.C. [2024] The influence of major faults and fractures on the development of non-matrix porosity system in a pre-salt carbonate reservoir, Santos Basin, Brazil. *Journal of Structural Geology*, 189, 105271.
- Peacock, D.C.P. and Sanderson, D.J. [1994] Geometry and development of relay ramps in normal fault systems. *AAPG Bulletin*, 78(2), 147–165.
- Rüger, A. [1998] Variation of P-wave reflectivity with offset and azimuth in anisotropic media. *Geophysics*, 63(3), 935–947.
- Schoenberg, M. and Sayers, C.M. [1995] Seismic anisotropy of fractured rock. *Geophysics*, 60(1), 204–211.
- Shuey, R.T. [1985] A simplification of the Zoeppritz equations. *Geophysics*, 50(4), 609–614.