

Fracture Characterization in the Barra Velha Formation Using Geometric Seismic Attributes, PCA and SOM

Introduction

Brazilian pre-salt carbonate reservoirs represent some of the most significant hydrocarbon discoveries of the past two decades, with the Santos Basin containing several giant hydrocarbon accumulations hosted within the Aptian Barra Velha Formation (Moreira et al., 2007). These carbonate reservoirs exhibit pronounced heterogeneity resulting from the combined effects of depositional processes, diagenetic modification, and structural deformation. Among the factors controlling reservoir performance, natural fractures play a critical role in enhancing permeability, improving reservoir connectivity, and influencing fluid-flow behaviour within complex carbonate systems (Nelson, 2001).

The characterization of fracture systems in the Barra Velha Formation remains challenging because fracture networks commonly occur below seismic resolution and are expressed as subtle structural discontinuities within seismic data. While well observations provide valuable local information, they are insufficient for delineating fracture corridors at the reservoir scale. Geometric seismic attributes such as similarity and curvature have proven effective for highlighting discontinuities, fault-related deformation, and fracture-prone zones that may not be readily identifiable on conventional seismic amplitude data (Chopra and Marfurt, 2007). Consequently, seismic attribute analysis provides a valuable framework for seismic-scale fracture characterization in complex carbonate reservoirs.

The interpretation of multiple seismic attributes is often complicated by redundancy and the high dimensionality of attribute datasets. Principal Component Analysis (PCA) provides an objective approach for dimensionality reduction by extracting the dominant modes of variation within the attribute space while preserving the most significant structural information. Self-Organizing Maps (SOM), an unsupervised machine-learning technique, can subsequently classify seismic responses into spatially coherent groups while preserving topological relationships within the data (Kohonen, 2001). The integration of PCA and SOM has been successfully applied to seismic facies analysis and reservoir characterization in a variety of geological settings (Roy et al., 2010; Roden et al., 2015; Zhao et al., 2015), yet their application to seismic-scale fracture corridor characterization in the Aptian pre-salt carbonates of the Santos Basin remains limited.

This study presents an integrated workflow combining geometric seismic attributes, PCA, and SOM to delineate fracture corridors within the Barra Velha Formation in Santos Basin, Brazil. The objective is to identify structurally controlled fracture zones and evaluate the effectiveness of unsupervised machine-learning techniques for improving seismic-scale fracture characterization in highly heterogeneous pre-salt carbonate reservoirs.

Method

A seismic-attribute-based workflow was implemented to identify and characterize fracture corridors in the Barra Velha Formation (Figure 1). The methodology consisted of four consecutive steps: conditioning of the seismic dataset, extraction of geometric attributes, reduction of attribute dimensionality through PCA, and unsupervised pattern recognition using a SOM clustering classification.

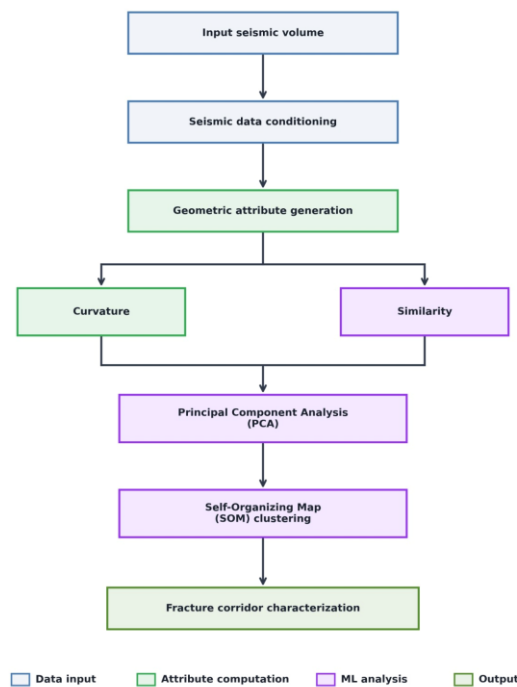


Figure 1. Integrated seismic attribute workflow for fracture corridor characterization

Data conditioning: Prior to attribute extraction, the 3D post-stack seismic volume was conditioned to enhance structural continuity and suppress noise. Structural smoothing was applied to improve the signal-to-noise ratio while preserving geologically significant discontinuities associated with fracture zones.

Attribute computation: Two categories of geometric attributes were computed from the conditioned volume. Curvature attributes most positive (k^+) and most negative (k^-) were extracted to highlight zones of structural bending and deformation. Broadband similarity was computed to delineate lateral discontinuities and fault-related features not readily visible on conventional amplitude data (Chopra and Marfurt, 2007).

PCA: The computed attribute volumes were subsequently input into a Principal Component Analysis to reduce dimensionality and remove redundancy within the multi-attribute dataset. The first three principal components (PC1, PC2, PC3), which capture the dominant modes of structural variation, were retained as input to the classification stage.

SOM: The principal components were classified using a Self-Organizing Map, an unsupervised machine learning algorithm that preserves topological relationships within the input data (Kohonen, 2001). The SOM output delineates spatially coherent seismic facies representing distinct structural and fracture-related responses within the Barra Velha reservoir unit.

Results

The integrated workflow was applied to the 3D seismic volume across the study area, spanning the BVE100, BVE200, and BVE300 intervals of the Barra Velha Formation. Two key outputs are presented to demonstrate the effectiveness of the approach.

PCA of the multi-attribute dataset reveals that PC1 accounts for 67.09% of the total explained variance, with energy-based and outer product attributes contributing most significantly to the first principal component (Figure 2). This confirms that the dominant structural signal within

the seismic data is effectively captured by a reduced set of components, providing a robust input for unsupervised classification.

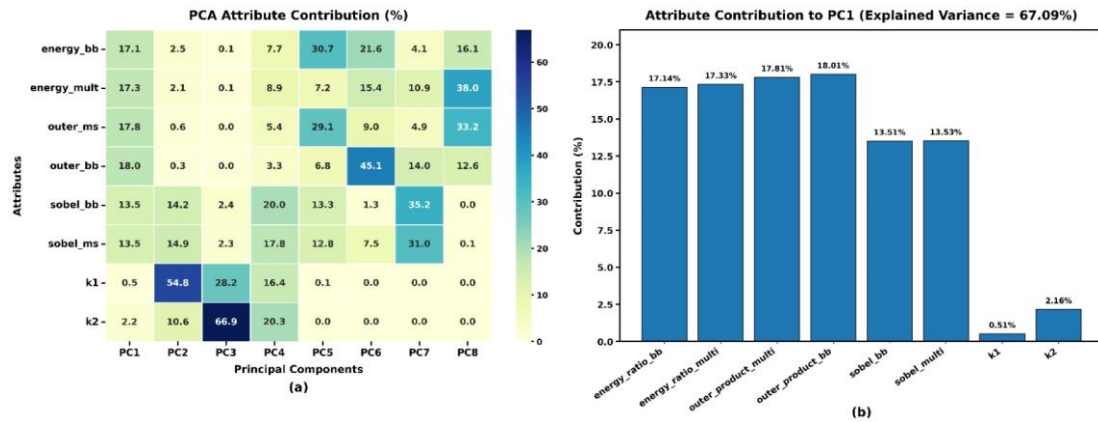


Figure 2. Principal Component Analysis results: (a) PCA attribute contribution matrix (%) across eight principal components; (b) individual attribute contributions to PC1 (explained variance = 67.09%), showing that energy ratio and outer product attributes dominate the first principal component.

SOM classification of the principal components delineates spatially coherent seismic neurons interpreted as fracture corridors across the BVE100, BVE200, and BVE300 intervals of the Barra Velha Formation (Figure 3). The BVE200 interval exhibits the highest fracture corridor density, identifying it as the primary sweet spot for natural fracture development within the study area. The corridor pattern observed across all three intervals is consistent with the regional Cabo Frio fault system, confirming that fracture distribution within the Barra Velha Formation is structurally controlled rather than randomly distributed.

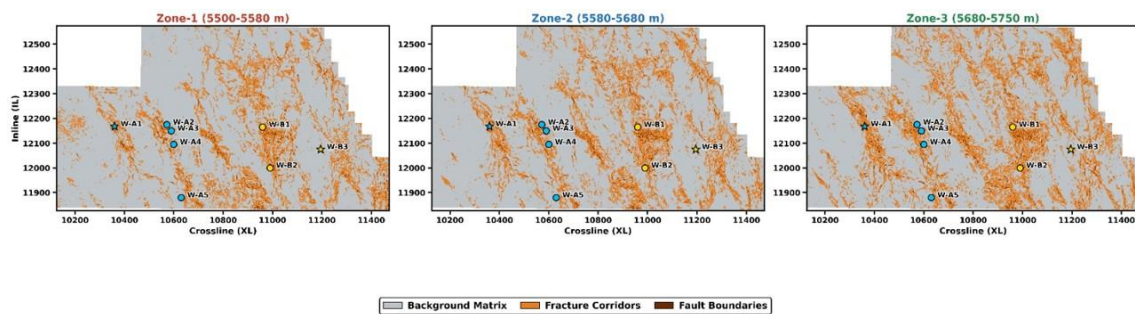


Figure 3. Self-Organizing Map classification for the (a) BVE100, (b) BVE200, and (c) BVE300 intervals of the Barra Velha Formation showing interpreted fracture corridors (orange) and fault boundaries.

Conclusions

This study presents and validates an integrated multi-attribute workflow for the characterization of natural fracture corridors within the pre-salt carbonates of the Santos Basin. The principal conclusions are as follows. PCA applied to eight geometric discontinuity attributes demonstrates that three principal components account for 93.97% of the total variance, with PC1 (67.09%) dominated by coherence

attributes representing the primary fracture signal and PC2 (14.11%) dominated by K1 curvature, reflecting structural geometry. A 3×3 SOM classifier applied to the PCA-reduced attribute space delineates a dominant structural fabric with secondary cross-cutting lineations consistent with the rift-related stress regime of the Santos Basin, despite the absence of geological constraints during classification. Among the analyzed intervals, BVE200 exhibits the highest seismic-scale fracture corridor intensity. The integrated five-attribute composite sweet-spot score identifies zones of elevated fracture intensity characterised by high fracture probability and enhanced structural discontinuity. These zones define the principal fractured corridor intervals within the Barra Velha reservoir and constitute priority targets for discrete fracture network (DFN) modelling in the companion study. More broadly, the results demonstrate that the integration of seismic geometric attributes, PCA dimensionality reduction, and SOM clustering provides a robust and transferable framework for fracture corridor characterization in pre-salt carbonate reservoirs.

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