Structural Modelling of a Fractured Carbonate Reservoir Analogue: 
A Structural and Numerical Understanding of a Conjugate Fracture Network 
with an Application to Fluid Flow and Cave System Development

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Abstract

Natural fracture networks within subsurface rocks often form a system-connected discontinuity, which affects rock strength, effective permeability and local stress fields. If open, these connected systems can greatly enhance fluid flow and therefore productivity within tight reservoir rocks. One of the most commonly observed arrangements are the conjugate fracture networks, which often form interconnected systems with densely spaced fractures, and these networks are believed to have a large impact on fluid flow and karsification in carbonate reservoirs.

In this study, we will use quantitative field data, taken from fractured carbonates (Salitre Fm, NE Brazil), and implement it into a 2D finite element model. The acquired results are then used in order to assess tectonic stresses responsible for the fracture network development. Furthermore, the numerical and field results will be compared with a large cave system present in the area.

First of all, the field data shows one conjugate fracture pair (FSET1, FSET2) and one vertical stylite set (SSET3), which formed as a result of horizontal compression ($\sigma_H = 170^\circ$). Horizontal stylolite analysis indicates that after this tectonic event the rocks where buried to a depths of $\pm 500m$. Our numerical simulations indicate that smaller conjugate fractures (FSET1, FSET2) show localized behaviour and the smaller vertical stylolites (SSET3) are relatively homogenously distributed. This correlates with the small-scale field observations. Finally, our field data and numerical analysis show a clear correlation with the geometry of the cave system and the geometry and modelled shear of the fracture network. This implies that the fractures most likely acted as conduits for fluid flow.
References Cited


ABSTRACT

Natural fracture networks within subsurface rocks often form a system connected discontinuities which affect rock strength, effective permeability and local stress fields. Often, these connected systems can greatly enhance fluid flow and therefore productivity within reservoir rocks. One of the most commonly observed arrangements are the conjugate fracture networks, which often form interconnected systems with densely spaced fractures, and these networks are believed to have a large impact on fluid flow and karstification in carbonates. In this study, we use quantitative field data, taken from fractured carbonates (Salitre Fm, NE Brazil), and implement it into a 2D finite element model. The acquired results are then used in order to assess tectonic stresses responsible for the fracture network development. Furthermore, the numerical and field results will be compared with a large cave system present in the area.

First of all, the field data shows one conjugate fracture pair (FSET1, FSET2) and one vertical stylite set (SSET3), which formed as a result of horizontal compression (σH ≈ 170 MPa). Horizontal stylolite analysis indicates that after this tectonic event the rocks where buried to a depth of ±500m. Our numerical simulations indicate that smaller conjugate fractures (FSET1, FSET2) show localized behaviors and the smaller vertical stylolites (SSET3) are relatively homogeneously distributed. This correlates well with the small cave observations. Finally, our field data and numerical analysis, shows a clear correlation with the geometry of the cave system and the geometry and modeled shear of the fracture network. This implies that the fractures most likely acted as conduits for fluid flow.

BREJOS FIELD AREA

The structural framework, UHF outcrops and large cave systems is located over the village of Brejos, Bahia NE Brazil. This study area is located in the Ilheu Basin which is the western part of the Bahia Basin, which was formed as a result of basin spreading (Salitre Fm, NE Brazil). The studied northern part of the Salitre Formation (790-330 Ma) is well exposed at the quarry of Ilheu, Brazil (Diniz et al., 2000). The studied northern part of the Salitre Formation is a potash-rich formation with a thickness of approximately 1000 m. Several karstic features, such as large size, karstic depressions and small size, karstic dolines, are found in the region. The brejos field area is one of the most frequently observed arrangements of the conjugate fracture networks. These conjugate fractures are observed in the brejos field area, and are mainly comprised out of stratified chalk carbonates. The studied conjugate fracture network is a result of the tectonic event, which often form as a result of horizontal compression (σH ≈ 170 MPa). Horizontal stylolite analysis indicates that after this tectonic event the rocks where buried to a depth of ±500m. Our numerical simulations indicate that smaller conjugate fractures (FSET1, FSET2) show localized behaviors and the smaller vertical stylolites (SSET3) are relatively homogeneously distributed. This correlates well with the small cave observations. Finally, our field data and numerical analysis, shows a clear correlation with the geometry of the cave system and the geometry and modeled shear of the fracture network. This implies that the fractures most likely acted as conduits for fluid flow.

WORKFLOW

To acquire field data and perform the data analysis, a 3D geological model was used. This model is composed of a 2D plane stress element which follows the shear law. The tectonic model was used to assess the tectonic stresses responsible for the fracture network development. Furthermore, the numerical and field results will be compared with a large cave system present in the area.

GEOSTRUCTURAL MODELLING OF A FRACTURED CARBONATE RESERVOIR ANALOGUE

A structural and numerical understanding of a conjugate fracture network with an application to fluid flow and cave system development

Quinten Diede BOERSMA*, Hilario BEZERRA and Giovanni BERTOTTI

ABSTRACT

Structural modelling of a fractured carbonate reservoir analogue is often used in the oil and gas industry to understand the behavior and connectivity of the reservoir. This study is focused on a conjugate fracture pair and one bedding-perpendicular stylolite set, which forms the input for our numerical model. The numerical results show that fracture set 1 is more dominant on a large scale and that sets 2 and 3 are more frequent on a smaller scale. The acquired numerical results indicate that their structural features formed as a result of one compressional tectonic event (σH = 170 MPa). At the direction of tectonic stress is based on the biarc intersection plane and orientation of the stylolites. The resulting numerical results show similar behaviour with respect to observations taken from the pavement outcrop. Finally, we model and show the close correlation between the geometry of the Brejos Cave System and the geometry of the fracture network.

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REFERENCES


NUMERICAL MODELING

This study used quantitative field data as input for a 2D finite element model, allowing us to mechanically model fractured reservoir analogue. Our finite element analysis showed that the fractures in the network are not affected by the conjugate fracture pair and one bedding-perpendicular stylolite set. The results show that fracture set 1 is more dominant on a large scale and that sets 2 and 3 are more frequent on a smaller scale. The acquired numerical results indicate that their structural features formed as a result of one compressional tectonic event (σH = 170 MPa). At the direction of tectonic stress is based on the biarc intersection plane and orientation of the stylolites. The resulting numerical results show similar behaviour with respect to observations taken from the pavement outcrop. Finally, we model and show the close correlation between the geometry of the Brejos Cave System and the geometry of the fracture network.

CONCLUSIONS

This study used quantitative field data as input for a 2D finite element model, allowing us to mechanically model fractured reservoir analogue. Our finite element analysis showed that the fractures in the network are not affected by the conjugate fracture pair and one bedding-perpendicular stylolite set. The results show that fracture set 1 is more dominant on a large scale and that sets 2 and 3 are more frequent on a smaller scale. The acquired numerical results indicate that their structural features formed as a result of one compressional tectonic event (σH = 170 MPa). At the direction of tectonic stress is based on the biarc intersection plane and orientation of the stylolites. The resulting numerical results show similar behaviour with respect to observations taken from the pavement outcrop. Finally, we model and show the close correlation between the geometry of the Brejos Cave System and the geometry of the fracture network.

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The Brejoes fractured pavement is dominated by one conjugate fracture pair namely: a NNE-SSW striking fracture group (FSET1), a NW-SE striking fracture group (FSET2), and one E-W striking Stylolite Set (SSET3), perpendicular to the biaxial intersection plane of the conjugate pair. On a larger scale, FSET1 is clearly the dominant fracture group and this fracture group also shows the longest fractures. However, on a smaller scale, fracture set 2 and Stylolite Set 3 are more pronounced, and this dominance is homogenously distributed throughout the pavement. This is also observed in the fracture intensity results. The length data indicates nested behaviour, at which, smaller features are more frequent at all scales, with the smallest measurable scale being 1cm.

This data is used in the DFN Simulations.
**LINK BETWEEN FRACTURES, TECTONICS AND THE CAVE SYSTEM**

**SATELITE IMAGE AND CAVEMAP BREJOES AREA**

**BREJOES PAVEMENT DATA**

**ORIGIN OF THE BREJOES CAVE SYSTEM**

The Brejoes caves are resembled out of a system of interconnected tunnels which extend 2.5 kilometres northward from the entrance near the village of Brejoes (see map). The origin of the caves remains a subject of debate and could be of epigenic (surface) or hypogenic (deep seated) origin. A recent study on similar rocks and caves 250 km North of our study area by Klimchouk et al., 2016 found a large cave system having hypogenic origins. Their chemical analysis showed that the cave system formed due to circulating hydrothermal fluids, roughly 520 Ma, hence post tectonic deformation. Furthermore, the geometry of these caves is largely controlled by the orientation and topology of the fracture network.

**CORRELATION BETWEEN FRACTURES AND CAVE SYSTEM**

The quantitative geometrical data from both the fractured pavement and the cave system show a clear correlation. Both systems are dominated by the NNE-SSW and NW-SE fracture groups and show an exponential length distribution. These two fracture groups also show the most opening in our numerical analysis (more shear is more hydraulic aperture) (see figures). Furthermore, field data analysis showed that several NNE-SSW fractures showed signs of conductivity. Therefore, our results indicate that these fracture groups most likely acted as dominant conduits for fluid flow, hence, controlling the geometry of the cave system, either at deep seated (hypogenic) or surface conditions (epigenic).

**STRESS INDUCED OPENING**

Barton & Bandis (1980) indicated that fractures can also show opening under compressional conditions, where, the opening ($E_n$) is a function of the roughness of the fracture plane ($JRC$), the Joint Compressive strength ($JCS$), an initial aperture ($E_0$), the normal stress ($\sigma_n$) and the shear displacement ($\mu_s$).

$$E_n = E_0 - \left( \frac{1}{\nu_m} + \frac{K_{CS}}{\sigma_n} \right)^{-1}$$

$$\sigma = \frac{E_n}{JRC^2} \begin{cases} \frac{\mu_s}{\nu_{peak}} & \text{for} \quad \frac{\mu_s}{\nu_{peak}} \leq 0.75 \\ \sqrt{E_n/JRC_{E0}} \quad \text{for} \quad \frac{\mu_s}{\nu_{peak}} \geq 1 \end{cases}$$

**NUMERICALLY MODELLED DATA**

**BREJOES CAVE SYSTEM DATA**

**Figure from Bisdom et al., 2016**

Map taken from internal UFRN report 2018 on Brejoes Caves

Rose diagram and histogram are based on a polyline interpretation of the Cave system (see figure)