PS 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 ($\sigma H = 170^{0}$). Horizontal stylolite analysis indicates that after this tectonic event the rocks where buried to a depths of ± 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.

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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

Quinten Diede BOERSMA, Hilario BEZERRA and Giovanni BERTOTTI*

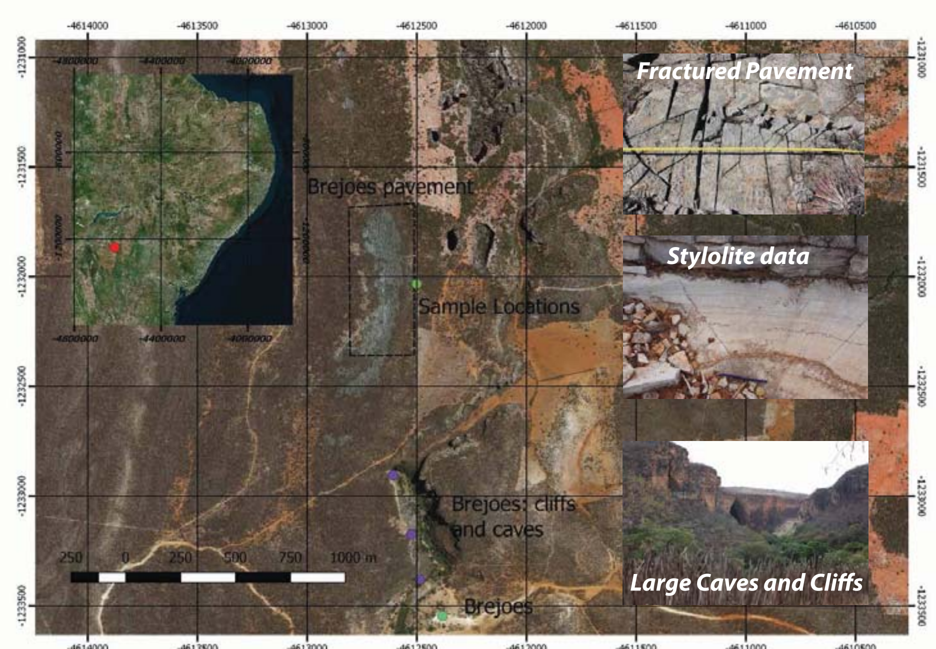
ABSTRACT

Natural fracture networks *within* ***subsurface rocks*** *often form a system* ***connected discontinuities*** *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.*

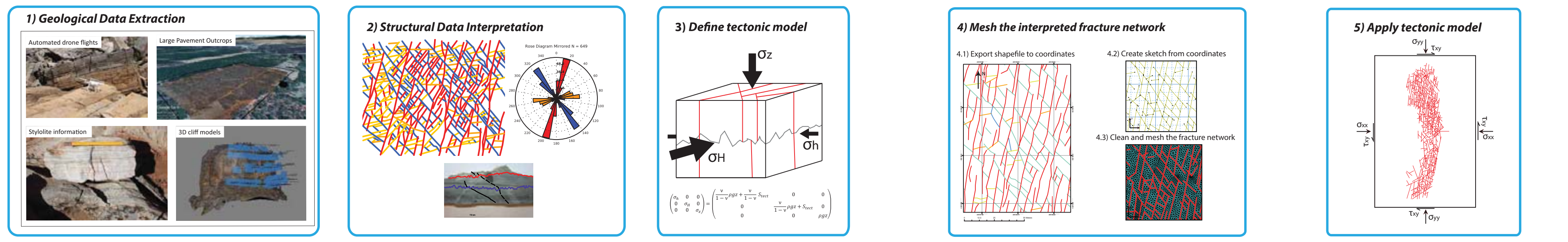
First of all, the ***field data*** *shows one* ***conjugate fracture pair*** *(****FSET1****,* ***FSET2****) and one* ***vertical stylite set*** *(****SSET3****), which formed as a results of* ***horizontal compression (σ_H = 170°)****.* ***Horizontal stylolite analysis*** *indicates that after this* ***tectonic event*** *the rocks where buried to a* ***depths*** *of* ***± 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, shows 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.*

BREJOES FIELD AREA



The ***fractured pavement, cliff outcrops*** *and* ***large cave systems*** *are located near the village of* ***Brejoes, Bahia NE Brazil*** *(see figure). The study area is located in the* ***Irece Basin*** *within* ***Northern part*** *of the* ***Sao Francisco Craton*** *which has been preserved from the* ***Brazilian Orogeny (740-580 Ma)*** *(Almeida et al., 2000). The studied* ***outcrops*** *are part of the* ***Salitre Formation (700-540 Ma)*** *and are mainly comprised out of* ***platform carbonate sediments*** *(Misi & Veizer, 1998). These carbonate sediments show large signs of* ***contractional structural deformation*** *such as, a* ***conjugate fracture set and sub vertical stylolites****. Finally,* ***bedding parallel stylolites are observed,*** *indicating* ***burial*** *of the carbonates.*

WORKFLOW



GEOLOGICAL DATA EXTRACTION AND INTERPRETATION

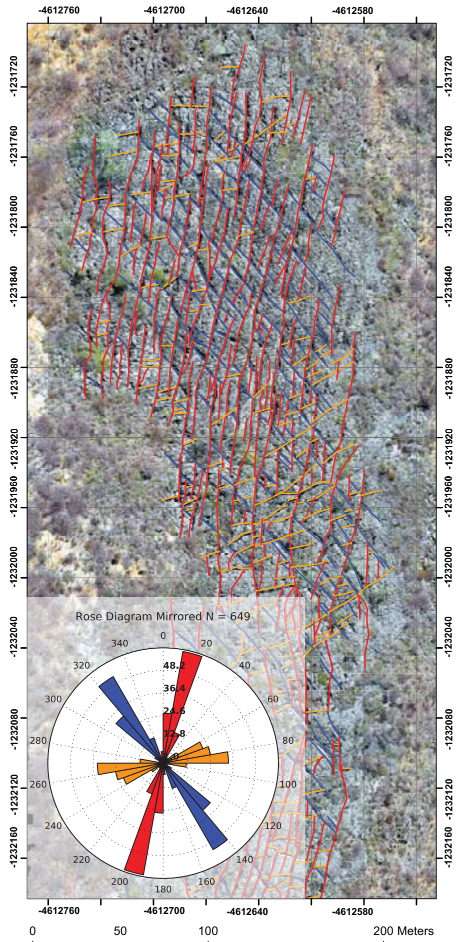
The large fractured ***pavement*** *and cliff* ***outcrops*** *are* ***imaged*** *using* ***drone flight missions*** *and* ***photogrammetry software****.* ***Several stylolite*** *samples where also acquired from the field and where used in order to* ***derive the maximum depth of formation*** *(Bertotti et al., 2017; Ebner et al., 2009) . Interpretation of the* ***geological data*** *was done using* ***GIS software*** *and* ***3D interpretation tools****, and these interpretations where used in order to derive a profound* ***tectonic model*** *of the area. This* ***tectonic model*** *will used in our* ***numerical modelling study****.*

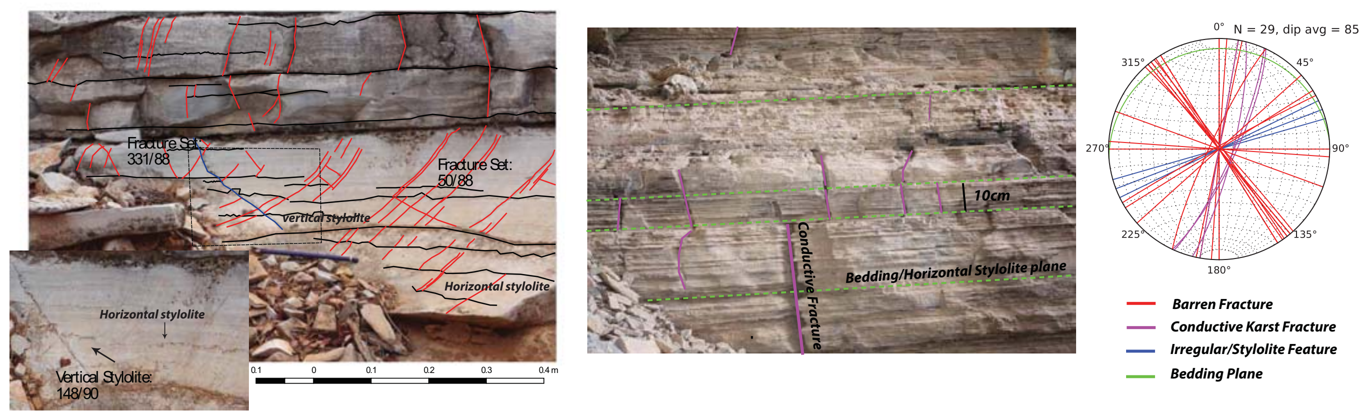
NUMERICAL MODELING

The ***acquired field data*** *forms the input for our* ***geological models****. Fracture data* ***(shapefiles)*** *is imported in to the numerical model. These features will be* ***meshed*** *and assigned as* ***crack seams****, so that they behave and perturb the stress field following* ***LEFM****. This is done using the* ***workflow*** *from Bisdom et al., 2017, which allows us to* ***mesh*** *and* ***model complex intersecting fractured systems****. The* ***mesh*** *is comprised out of* ***2D plane stress elements*** *which follow* ***Hooke's law*** *of* ***linear elasticity*** *and the* ***horizontal principal stresses*** *will be applied to the boundaries of the models as normal and shear stresses.*

GEOLOGICAL DATA: INTERPRETATION AND RESULTS

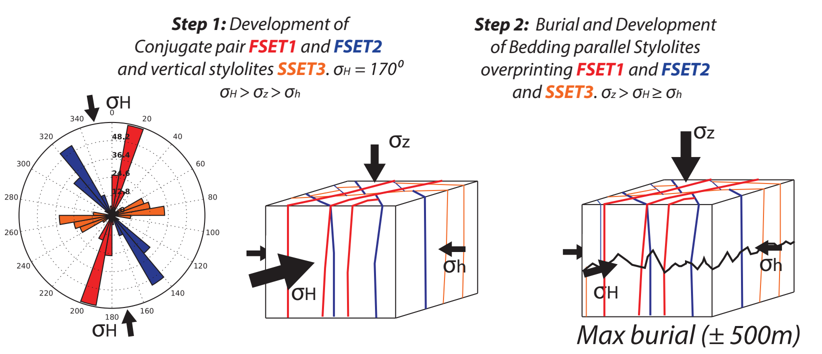
GEOLOGICAL DATA ANALYSIS





Detailed Interpretation of Brejoes Pavement on the poster to left

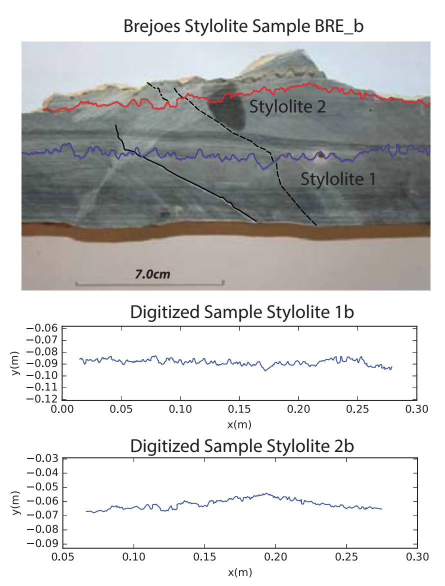
GEOLOGICAL DATA: INTERPRETATION AND TECTONIC MODEL

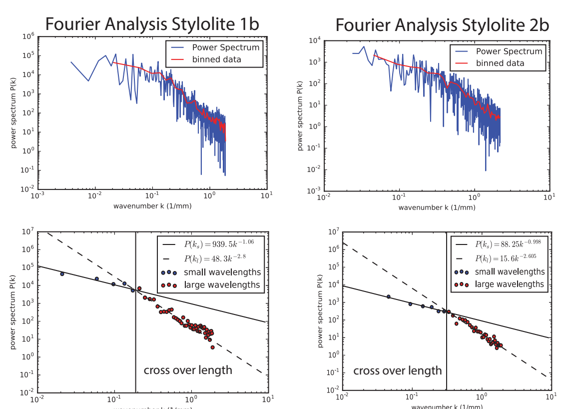


$$\begin{pmatrix} \sigma_h & 0 & 0 \\ 0 & \sigma_H & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} = \begin{pmatrix} \frac{\nu}{1-\nu}\rho g z + \frac{\nu}{1-\nu} S_{tect} & & 0 \\ & \frac{\nu}{1-\nu}\rho g z + S_{tect} & \\ 0 & & \rho g z \end{pmatrix}$$

The acquired ***structural data*** *indicates four main structural features (****FSET1****,* ***FSET2****,* ***SSET3****,* ***Horizontal stylolites****), where the* ***first three features*** *formed as a result of* ***horizontal tectonic compression*** *(see figure). We assume that* ***direction*** *of this* ***tectonic stress*** *can be represented by the* ***biaxial intersection plane*** *of the two conjugates (****FSET1****,* ***FSET2****). The magnitude of the applied stress is* ***19.5 MPa*** *((σ_H - σ_h) =* ***10MPa****). The* ***vertical stylolite set*** *(****SSET3****) is* ***perpendicular*** *to this maximum* ***compression direction****. Horizontal stylolite data suggests that after this tectonic event, the rocks where* ***buried*** *to a depth of roughly* ***500m****.*

GEOLOGICAL DATA: STYLOLITE ANALYSIS AND RESULTS





Sample	Power-law $P(k_L)$ (long wavelengths)	Power-law $P(k_s)$ (short wavelengths)	Wavenumber (k) (mm^{-1})	Cross-over Length L_c (mm)
BRE_1a	$P(k_l) = 33.9\,k^{-2.607}$	$P(k_s) = 1153\,k^{-0.807}$	K = 0.140 (mm^{-1})	L_c = 7.09 (mm)
BRE_2a	$P(k_l) = 42.7\,k^{-1.727}$	$P(k_s) = 87.36\,k^{-1.09}$	K = 0.325 (mm^{-1})	L_c = 3.07 (mm)
BRE_1b	$P(k_l) = 48.3\,k^{-2.8}$	$P(k_s) = 939.5\,k^{-1.06}$	K = 0.182 (mm^{-1})	L_c = 5.48 (mm)
BRE_2b	$P(k_l) = 15.6\,k^{-2.605}$	$P(k_s) = 88.25\,k^{-0.998}$	K = 0.340 (mm^{-1})	L_c = 2.94 (mm)

		Average data	Data range (Monte Carlo simulation)
Surface Tension (J m^{-2})	γ	0.27	0.27 (Bertotti et al. 2017)
Young's Modulus (GPa)	E	30	15 - 45
Poisson's ratio	ν	0.25	0.2 - 0.3
Rock density (kg m^{-3})	ρ	2500	2250 - 2750
Crossover-length (m)	L_c	From FPS	From FPS

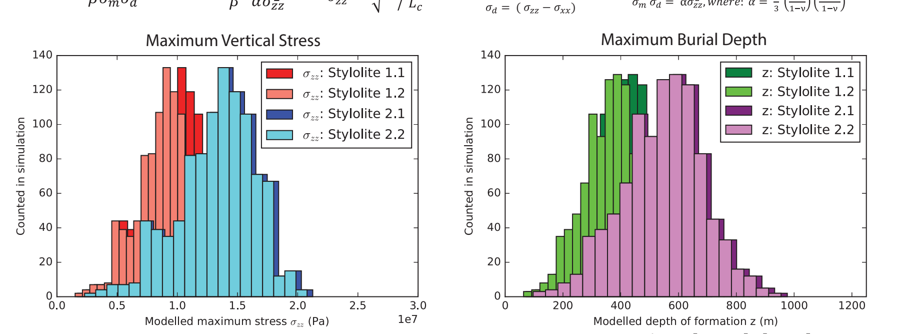
$$L_c = \frac{\gamma E}{\beta \sigma_m \sigma_d} \quad (1) \qquad L_c = \frac{\gamma E}{\beta}\frac{1}{\alpha \sigma_{zz}^2} \quad (2) \qquad \sigma_{zz} = \sqrt{\frac{\gamma E / \beta\alpha}{L_c}} \quad (3)$$

Sample	Modelled maximum stress: σ_{zz} (Pa)	Modelled maximum depth: z (m)
BRE_1a	$8.69 \cdot 10^6 \pm 2.07 \cdot 10^6$	$3.57 \cdot 10^2 \pm 0.906 \cdot 10^2$
BRE_2a	$1.32 \cdot 10^7 \pm 3.14 \cdot 10^6$	$5.42 \cdot 10^2 \pm 1.38 \cdot 10^2$
BRE_1b	$9.89 \cdot 10^6 \pm 2.36 \cdot 10^6$	$4.06 \cdot 10^2 \pm 1.03 \cdot 10^2$
BRE_2b	$1.35 \cdot 10^7 \pm 3.22 \cdot 10^6$	$5.55 \cdot 10^2 \pm 1.41 \cdot 10^2$

Expressing mean and differential stresses in σ_{zz}

$$\sigma_m = \frac{1}{3}(\sigma_{zz} + 2\sigma_{xx}) \qquad \sigma_{xx} = \sigma_{yy} = \frac{\nu}{(1-\nu)}\sigma_{zz}$$

$$\sigma_d = (\sigma_{zz} - \sigma_{xx}) \qquad \sigma_m \sigma_d = \alpha\sigma_{zz}^2, \text{where: } \alpha = \frac{1}{3}\left(\frac{1+\nu}{1-\nu}\right)\left(\frac{1-2\nu}{1-\nu}\right)$$

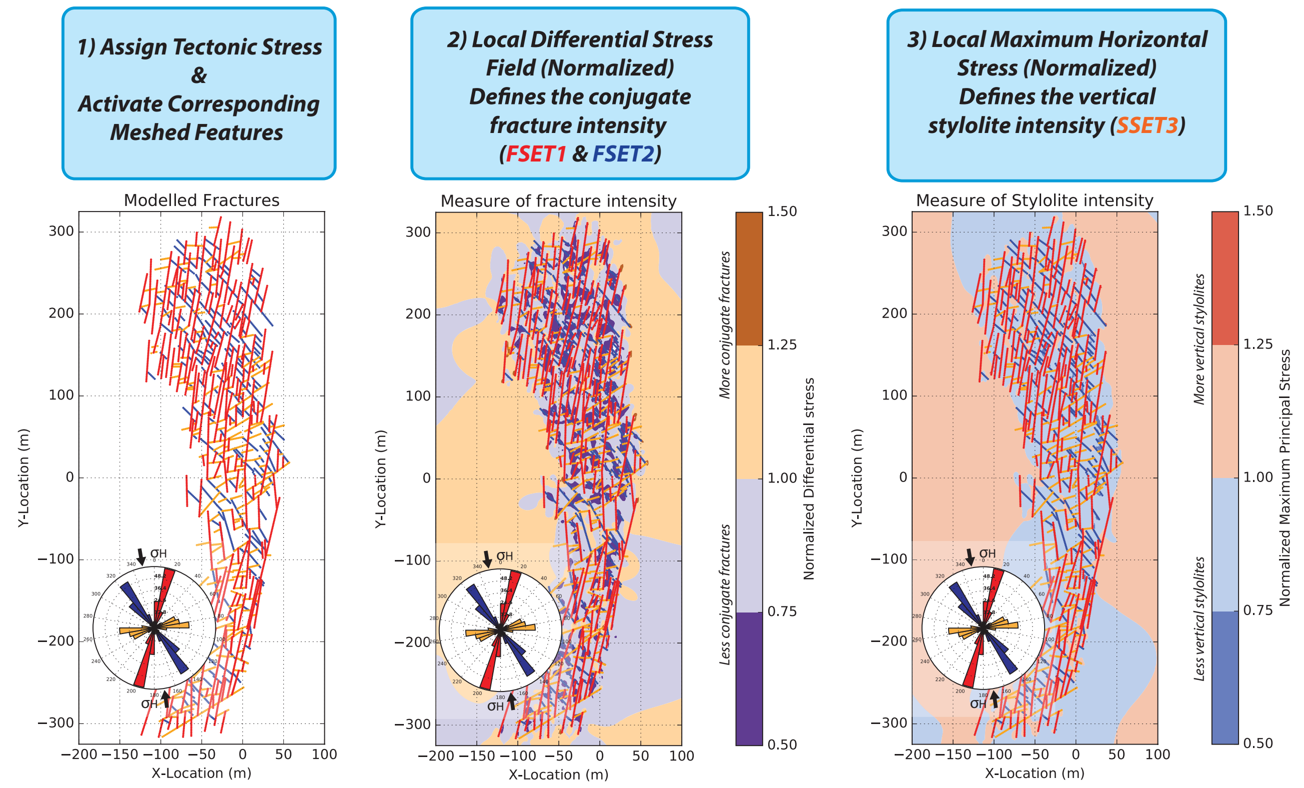


Monte Carlo Simulations on stylolite results

Avarage simulated depth of formation z = ± 500m

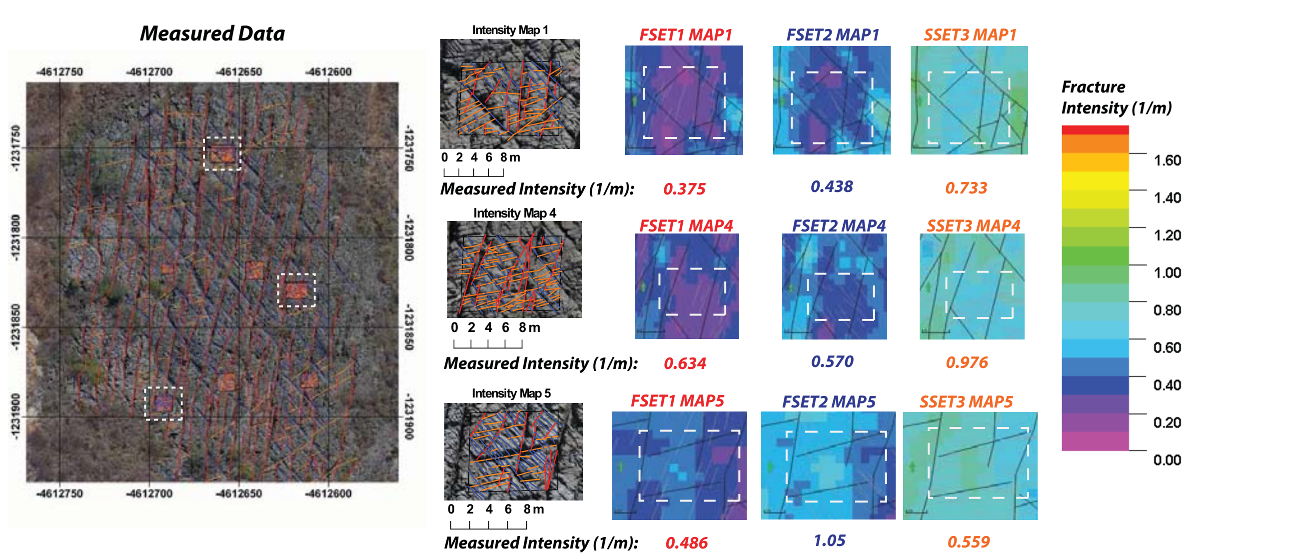
NUMERICAL MODELING: PROCESS AND RESULTS

FINITE ELEMENT ANALYSIS: APPLYING THE TECTONIC MODEL



The ***structural*** *features (****FSET1****,* ***FSET2****,* ***SSET3****) and the derived* ***tectonic model*** *we form the basis for our numerical simulation of the local* ***driving stresses*** *and* ***shear*** *on the fracture planes, and these elements are shown in figure 1. Figure 2 shows the* ***normalized local differential stress field*** *and which is, following from Mohr Coulomb theorem, is a measure of* ***conjugate fracture density*** *(****FSET1****,* ***FSET2****). Figure 3 shows the* ***normalized maximum horizontal stress****, which we use as a measure of* ***stylolite density*** *(* ***SSET3****). The results indicate that the* ***differential stress field*** *show a high* ***degree of localization*** *and the maximum* ***horizontal stress field*** *is relatively* ***homogenously*** *distributed.*

FINITE ELEMENT ANALYSIS: CORRELATION WITH FIELD DATA



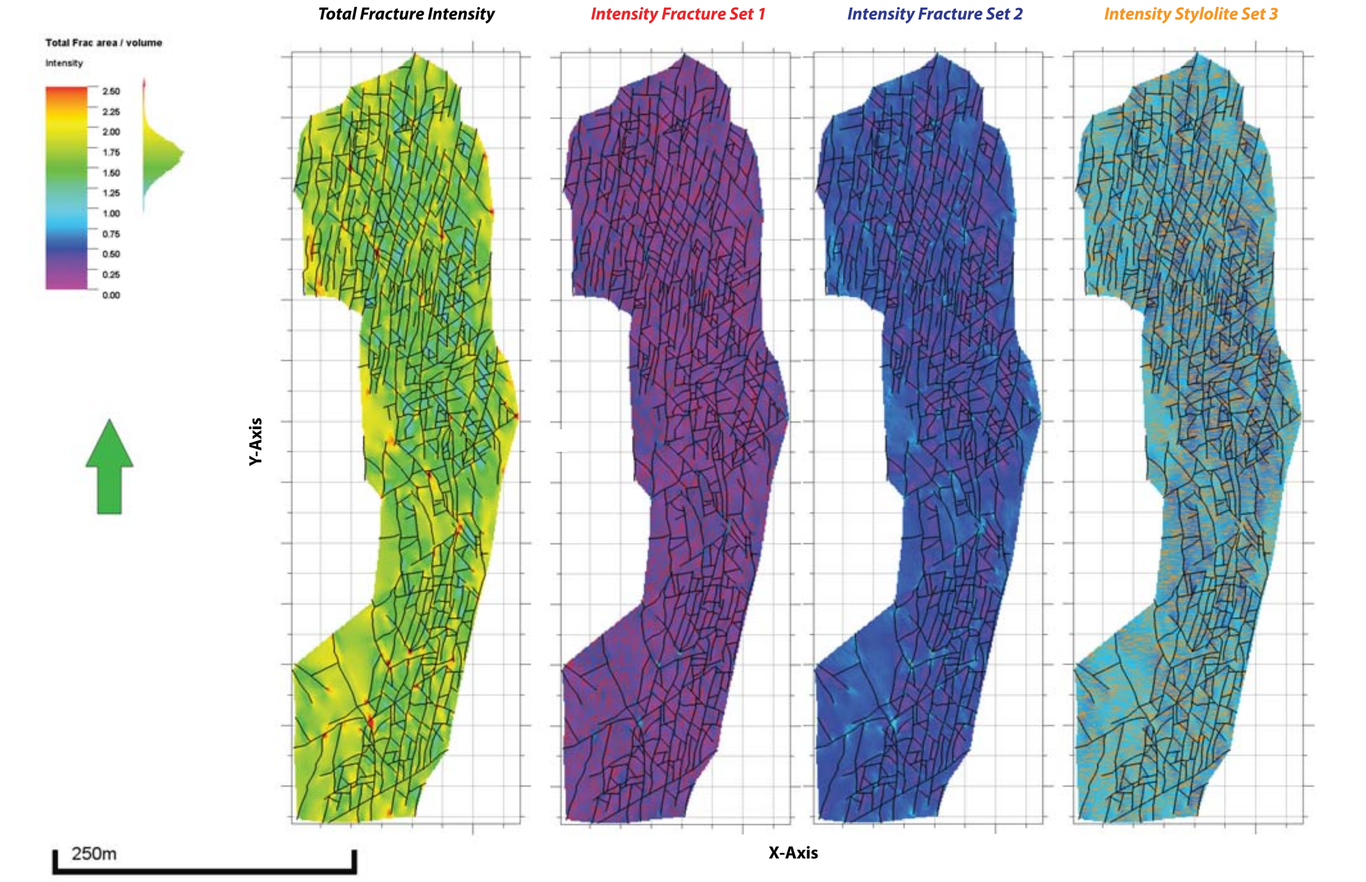
Modelled data shows correlation with the measured data, especially in terms of fracture intensity. However, some differences do occur locally (see figure)

FINITE ELEMENT ANALYSIS: COMBINING FIELD AND NUMERICAL DATA

Using the ***measured field data*** *(intensity results) and the* ***acquired local driving stresses*** *((σ_H - σ_h)local & σ_H local), the* ***fracture intensity*** *for the* ***smaller features*** *(background) can be calculated (see equations). The results a depicted below and show quite a* ***good correlation*** *with the* ***observations*** *from* ***UAV imagery****. However some* ***detailed observations cannot be replicated*** *(see below).*

$$I_{FSETi} = \frac{(\sigma_H - \sigma_h)_{local}}{(\sigma_H - \sigma_h)_{applied}} \cdot I_{FSETi}\,[measured] \quad \textbf{Fracture Intensity}$$

$$I_{SSET_i} = \frac{(\sigma_H)_{local}}{(\sigma_H)_{applied}} \cdot I_{SSET_i}[measured] \quad \textbf{Stylolite intensity}$$



Detailed study on the correlation between field, numerical and cave data can be found on the poster to the right

CONCLUSIONS

This study used ***quantitative field*** *data as input for* ***2D finite element models****, allowing us to* ***mechanically model fractured reservoir analogue****. Our field data* ***analysis*** *showed that the fracture network can be subdivided into* ***one 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 these structural features formed as a result of one* ***compressional tectonic event*** *(****σ_H = 170°****), at which the* ***direction*** *of* ***tectonic stress*** *is based on the* ***biaxial 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* ***Brejoes Cave System*** *and the* ***geometry of the fracture network****.*

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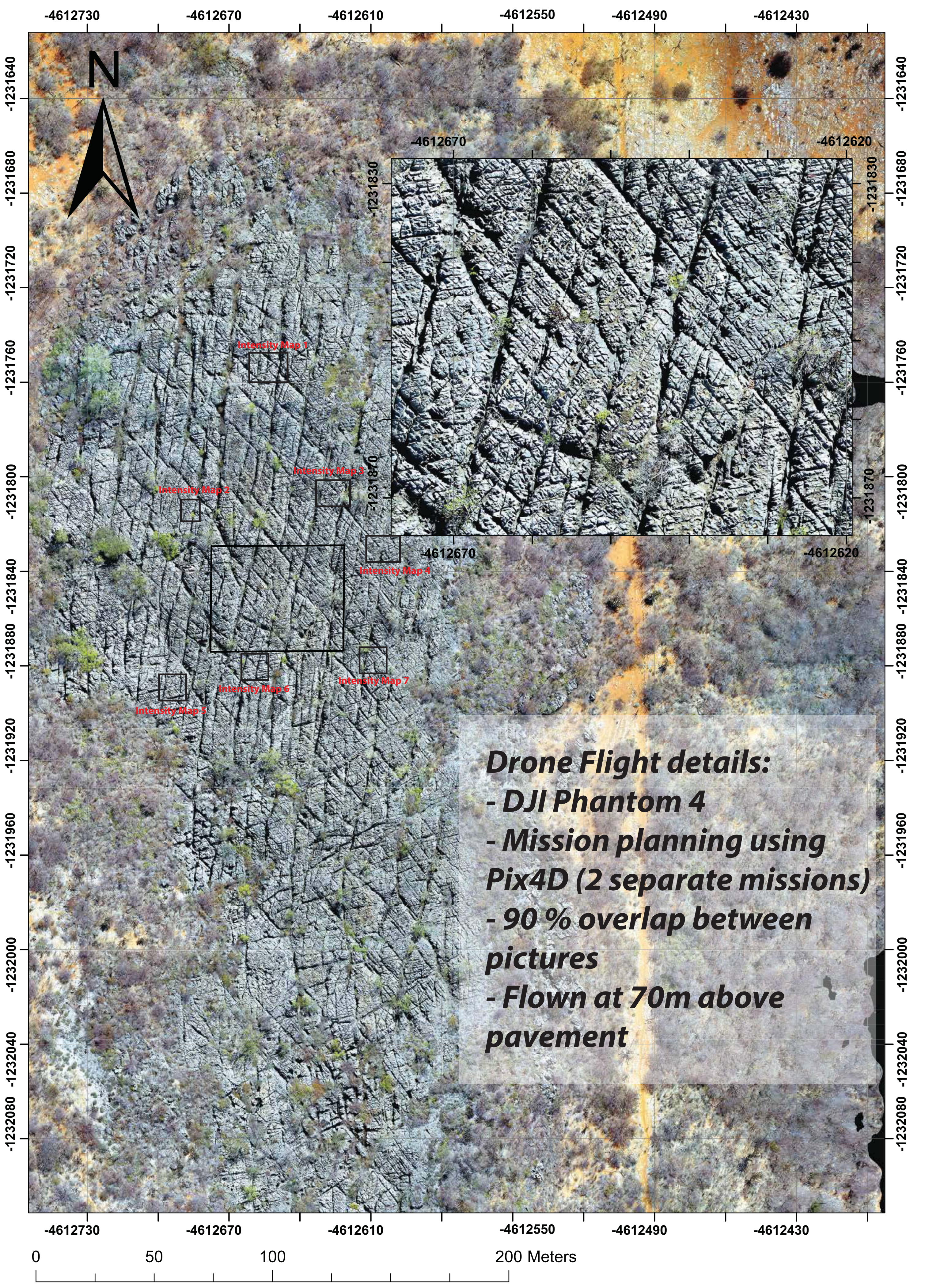
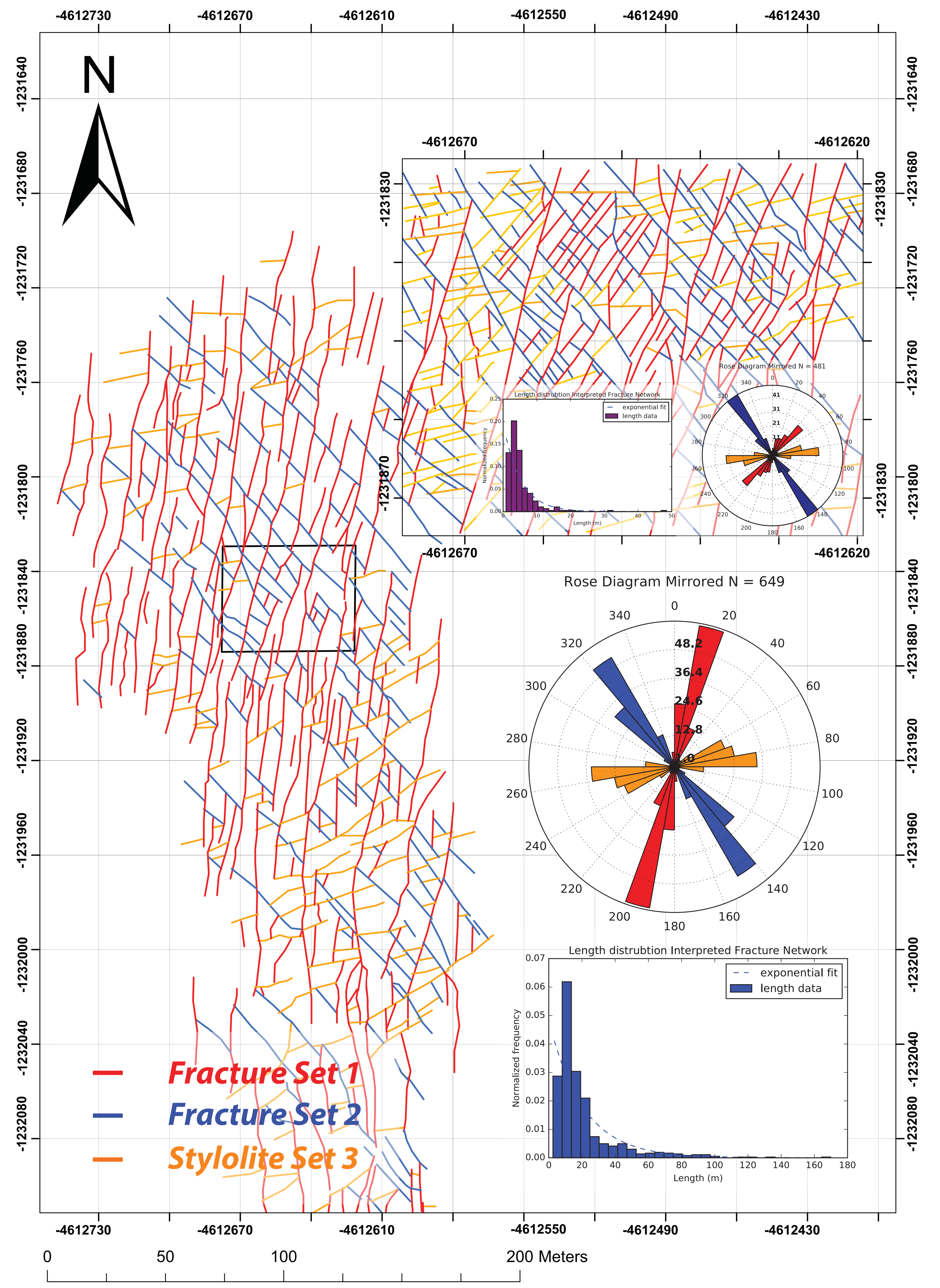
STRUCTURAL DATA FROM HIGH RESOLUTION DRONE IMAGES

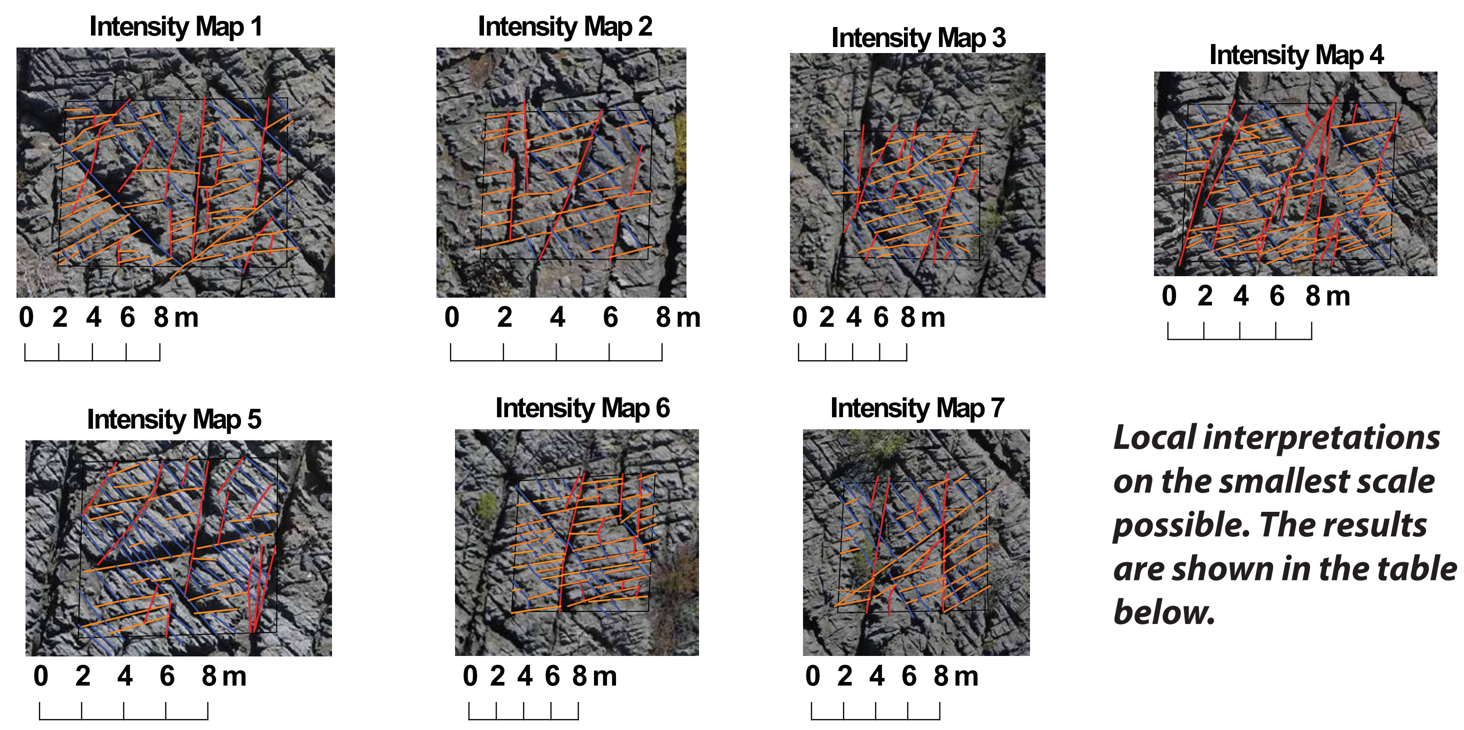
HIGH RESOLUTION PAVEMENT OUTCROP



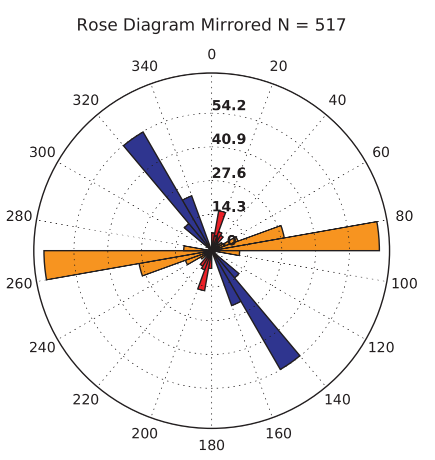
INTERPRETED FRACTURE NETWORK

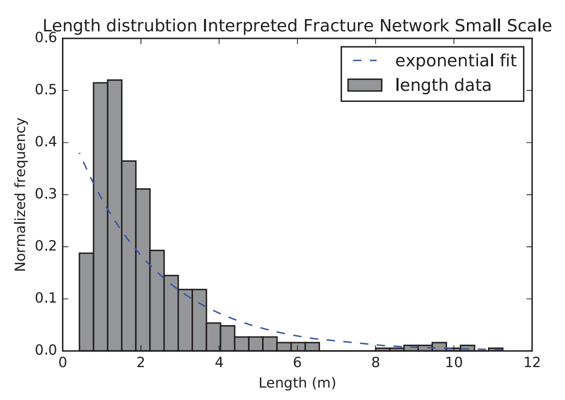


STRUCTURAL DATA ON THE SMALLEST SCALE



Local interpretations on the smallest scale possible. The results are shown in the table below.



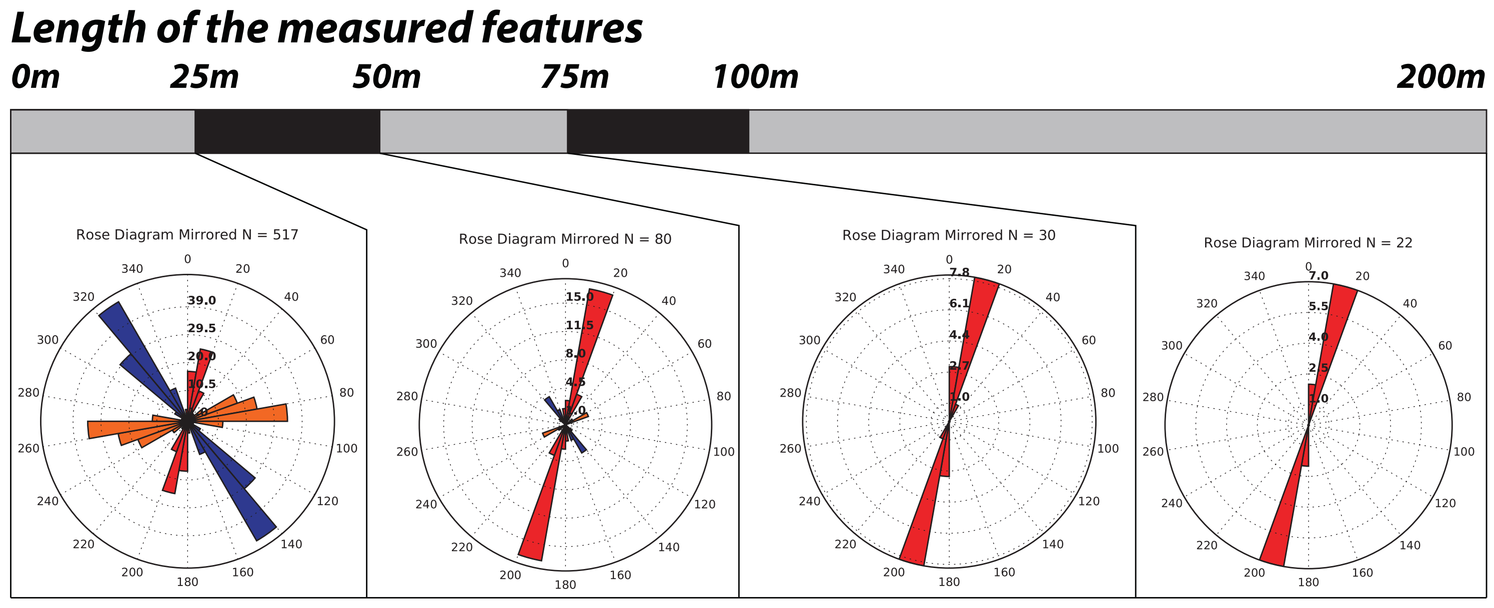


On a smaller scale, Fracture Set 2 and Stylolite Set 3 are more dominant wrt Fracture Set 1. This is also seen in the measured Intensity results.
IFSET1 < IFSET2 < ISSET3

Name	Map ID	FracSet1 (Intensity) (m^{-1})	FracSet2 (Intensity) (m^{-1})	StySet3 (Intensity) (m^{-1})	Total Intensity (m^{-1})
North 1	1	0.375	0.438	0.734	1.547
Mid 1	2	0.480	0.498	0.980	1.959
Mid 2	3	0.432	0.480	0.760	1.672
Mid 3	4	0.634	0.570	0.977	2.181
South 1	5	0.486	1.052	0.559	2.098
South 2	6	0.299	0.419	0.948	1.666
South 3	7	0.336	0.595	0.788	1.719
	Average intensity	**0.451**	**0.576**	**0.826**	**1.854**

This data is used in the DFN Simulations

LENGTH VS ORIENTATION BIG FRACTURES AND FAULTS



NNE-SSW and E-W Group are more dominant

NNW-SSE Fracture group is dominant

STRUCTURAL ANALYSIS OF THE ACQUIRED DATA

*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.*

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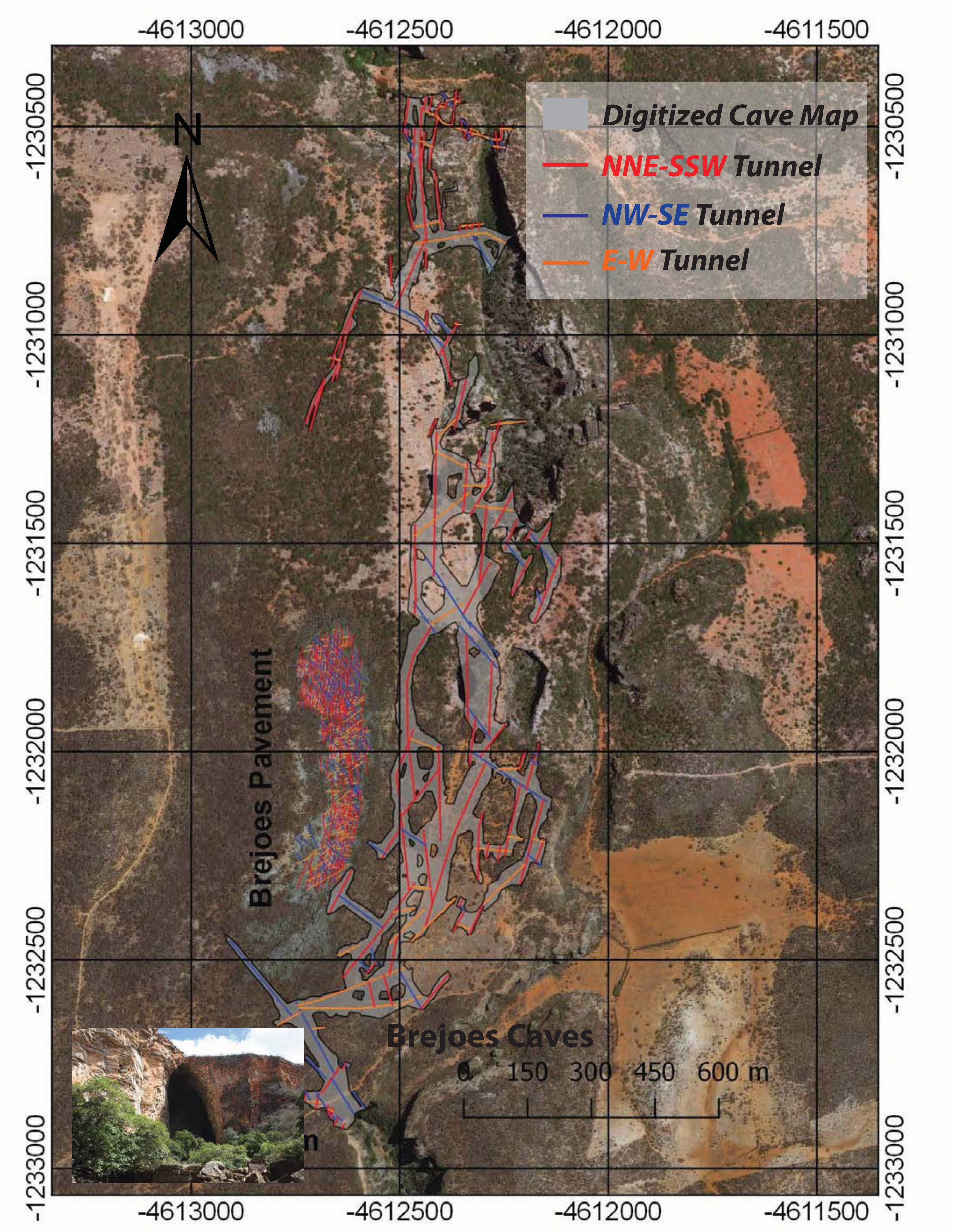
LINK BETWEEN FRACTURES, TECTONICS AND THE CAVE SYTEM

SATALITE IMAGE AND CAVEMAP BREJOES AREA



Map taken from internal UFRN report 2018 on Brejoes Caves

STRESS INDUCED OPENING

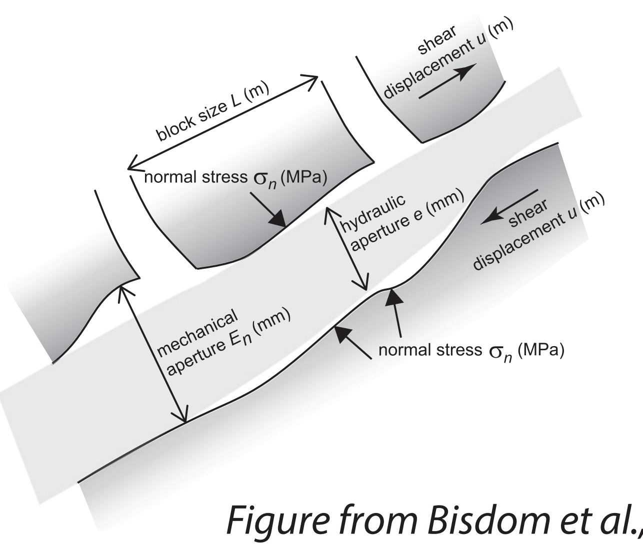


Figure from Bisdom et al., 2016

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

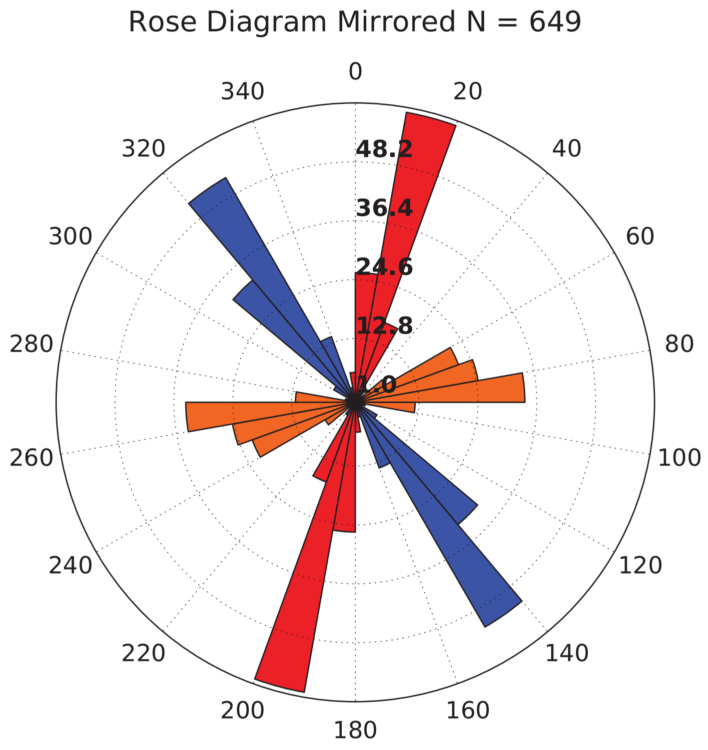
$$e = \begin{cases} \dfrac{E_n^2}{JRC^{2.5}} \; for \; \dfrac{u_s}{u_{peak}} \leq 0.75 \\ \sqrt{E_n} JRC_{mob} \; for \; \dfrac{u_s}{u_{peak}} \geq 1 \end{cases}$$

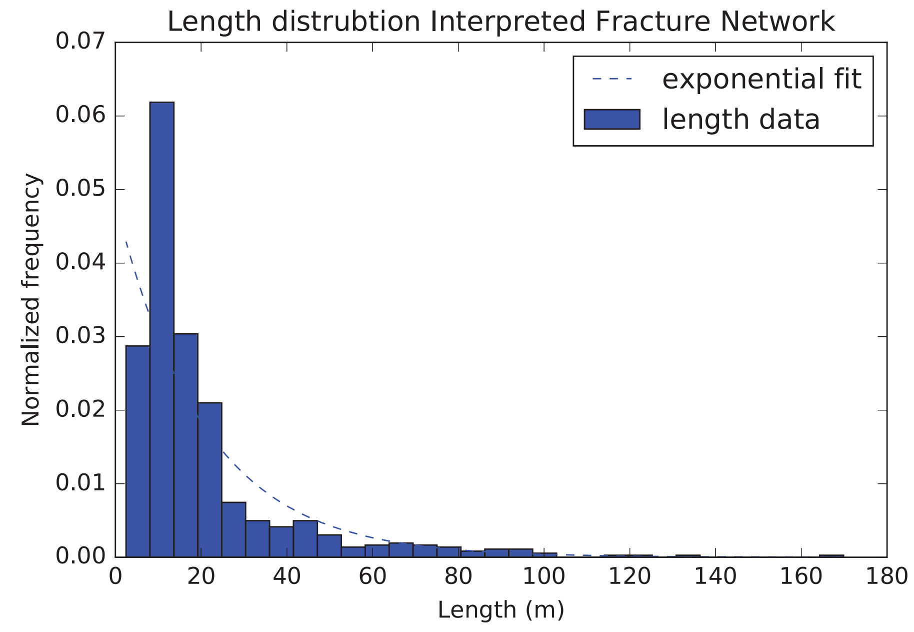
*Barton & Bandis (1980) indicated that **fractures** can also show **opening** under **compressional conditions**, where, the **opening (e: hydraulic aperture (m))** is a **function** of the **roughness** of the fracture plane (**JRC**), the **Joint Compressive strength** (**JCS**), an **initial aperture (E_0)**, the **maximum closure (v_m)**, the **normal stress (σn)** and the **shear displacement (μ_s)**. Recent modelling studies and geometrical studies have shown that this stress induced opening can have significant impact on the **effective permeability** and fluid flow in **naturally fractured rocks** (Bisdom et al., 2017; Bisdom et al., 2016).*

ORIGIN OF THE BREJOES CAVE SYSTEM

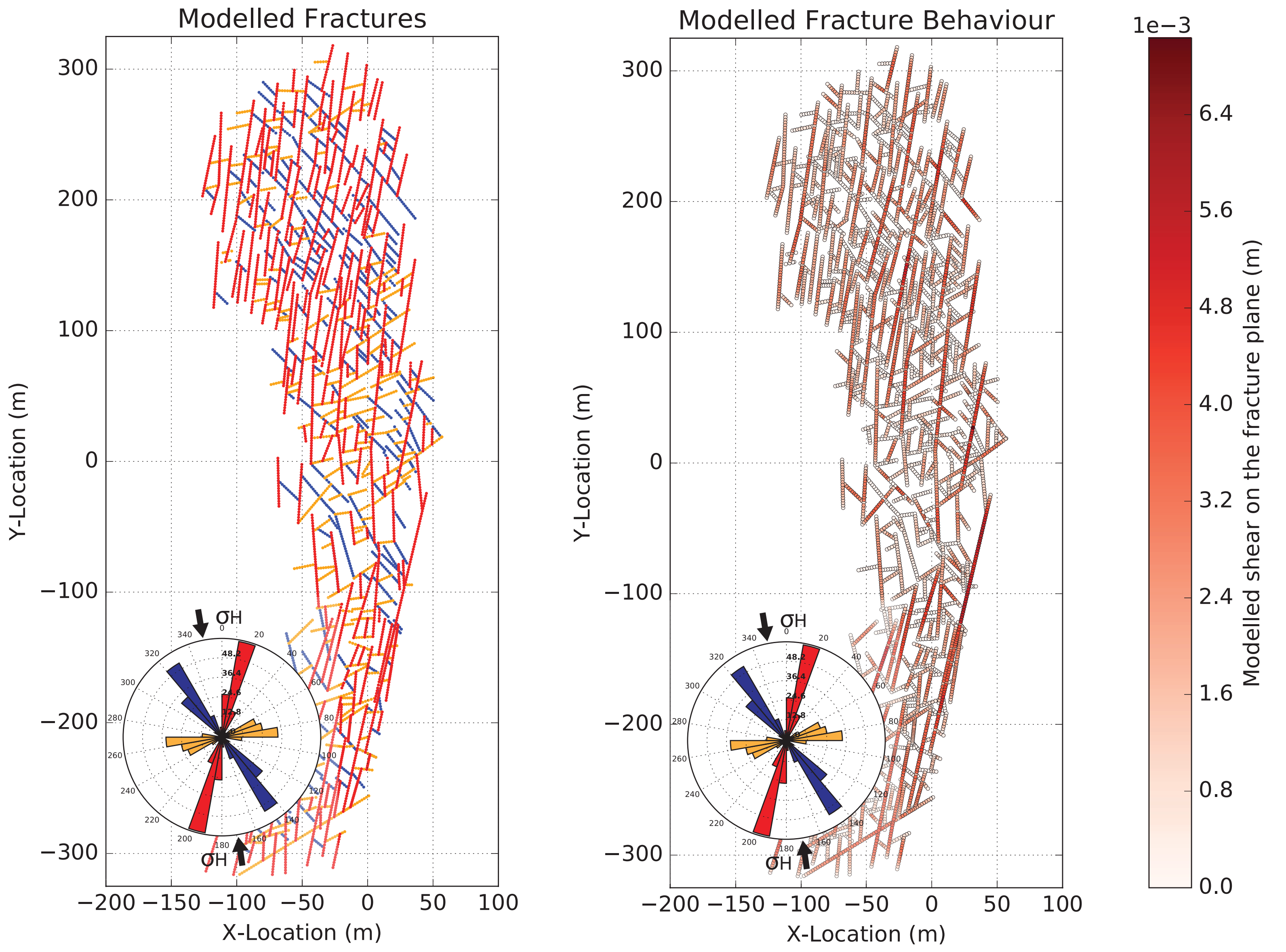
*The **Brejoes caves** are resembled out of a **system** of **interconnected** tunnels which extend **2.5 kilometres northward** from the entrance near the village of Brejoes (see map). The **origin** of the caves remains a subject of **debate** and could be of **epigenic (surface)** or **hypogenic (deep 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**.*

BREJOES PAVEMENT DATA

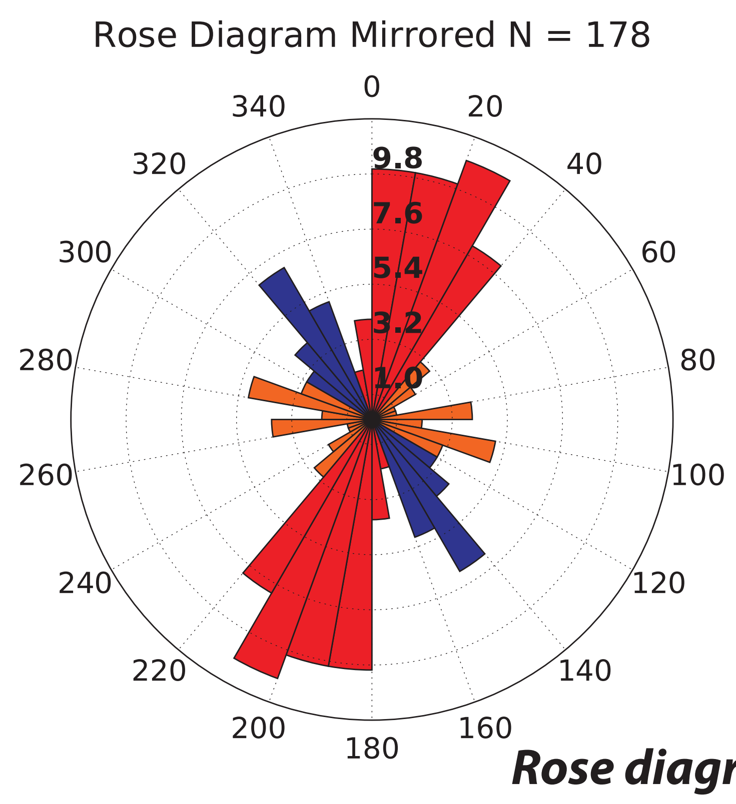


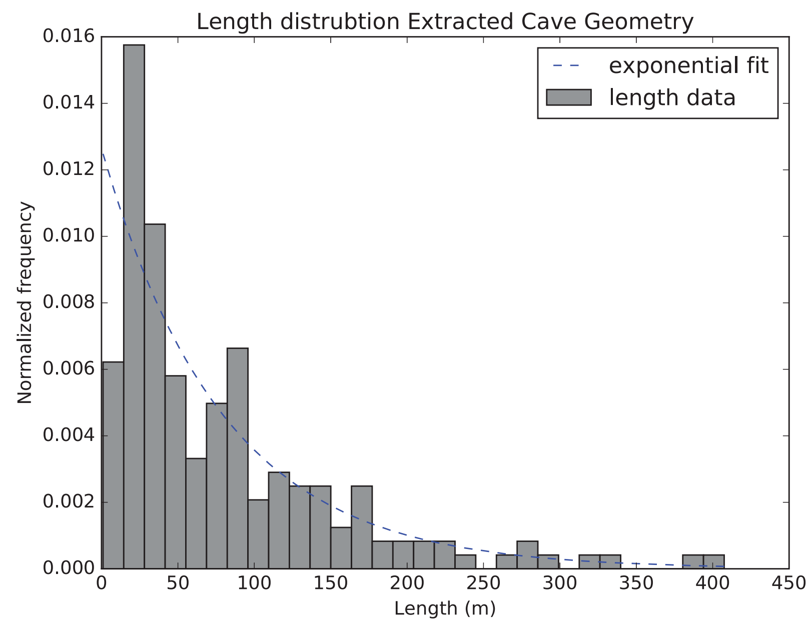


NUMERICALLY MODELLED DATA



BREJOES CAVE SYSTEM DATA





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

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).*

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