Characterizing Dynamic Stress Sensitive Fracture Apertures in A DFN Representation: An Example From the Island of Pag (Croatia)

Prabhakaran, Rahul; Bruna, Pierre-Olivier; Bertotti, Giovanni; Mittempergher, S.; Succo, A.; Bistacchi, A.; Storti, F.; Meda, M.

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PSCharacterizing Stress Sensitive Fracture Apertures in Discrete Fracture Network Representations: A Stress Based Method to Represent Fracture Aperture Heterogeneity as an Input for Fluid Flow from Realistic, Outcrop Derived DFN Fracture Representations*

Rahul Prabhakaran[1], Pierre-Olivier Bruna[1], Giovanni Bertotti1, Silvia Mittempergher[2], Andrea Succo[3], Andrea Bistacchi[2], and Fabrizio Storti[3]

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Abstract

Carbonate reservoirs contain nearly 60 percent of the world's conventional oil and gas reserves. Subsurface data and outcroppings indicate that they are intensely fractured. The subsurface distribution of natural fractures is often unknown due to their sub-seismic size and owing to difficulties in extrapolating 1D fracture information from available well data to 3D reservoir geomodels. Outcrop analogues is a method that one can resort to for constraining the 3D architecture of fracture networks. Outcrops represent a local snap shot of the current multiscale state of fracturing which is perhaps a net result of multiple events of stress reversals, burial and / or exhumation and tectonics. Outcrop data is still useful to calibrate mechanical and fluid flow models to predict the impact of fractures on storage and flow in the subsurface. The outcrop fracture data is used in building a Discrete Fracture Network (DFN) representation in which multiscale fractures are represented explicitly and hence honors the fracture intensity and topology. DFN representations can be used as input for flow and geomechanics numerical models.

In this work we utilize a combined outcrop based and numerical approach to characterize fracture patterns, fracture apertures and fluid flow sensitivities using a folded 'box-type' anticlinal structure example from the Pag Island, Croatia. Fractured folds often form prolific reservoirs owing to the structural closure they afford and the additional porosity and permeability due to the fold related fracturing. The fracture patterns are of specific interest owing to the complex geometries associated with folding. A 3D model of the Pag Island is created with slices of multiscale fracture traces which are interpreted and digitized from drone photogrammetry. We use 2D finite element modeling to quantify a stress sensitive fracture aperture and by incorporating these apertures into a conformal discrete fracture and matrix reservoir simulation model we can quantify the effect of stressed aperture on fluid flow. Our results indicate that the fluid flow behavior is variable spatially owing to the aperture heterogeneity across the area of the fractured fold.

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CHARACTERIZING STRESS SENSITIVE FRACTURE APERTURES IN DISCRETE FRACTURE NETWORK REPRESENTATIONS

A stress based method to represent fracture aperture heterogeneity as an input for fluid flow from realistic ,outcrop derived DFN fracture representations

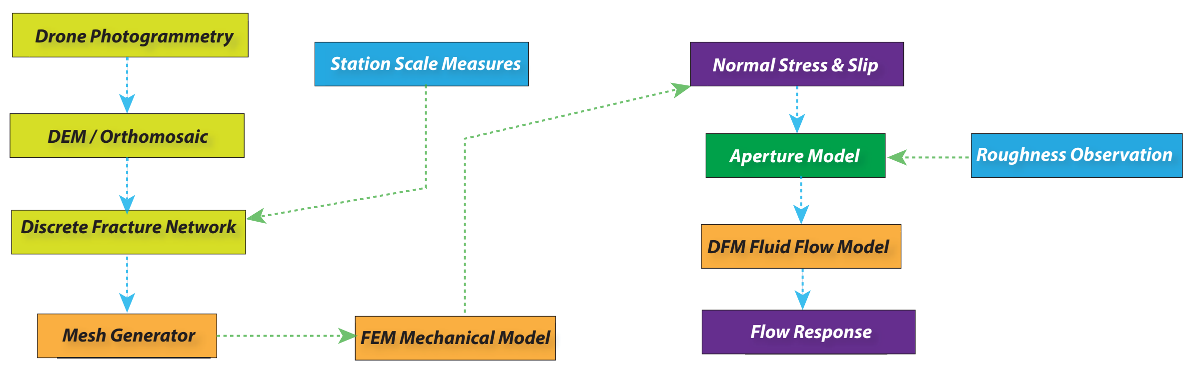
Rahul PRABHAKARAN, Pierre-Olivier BRUNA, Giovanni BERTOTTI, Silvia MITTEMPERGHER, Andrea SUCCO, Andrea BISTACCHI, Fabrizio STORTI*

ABSTRACT

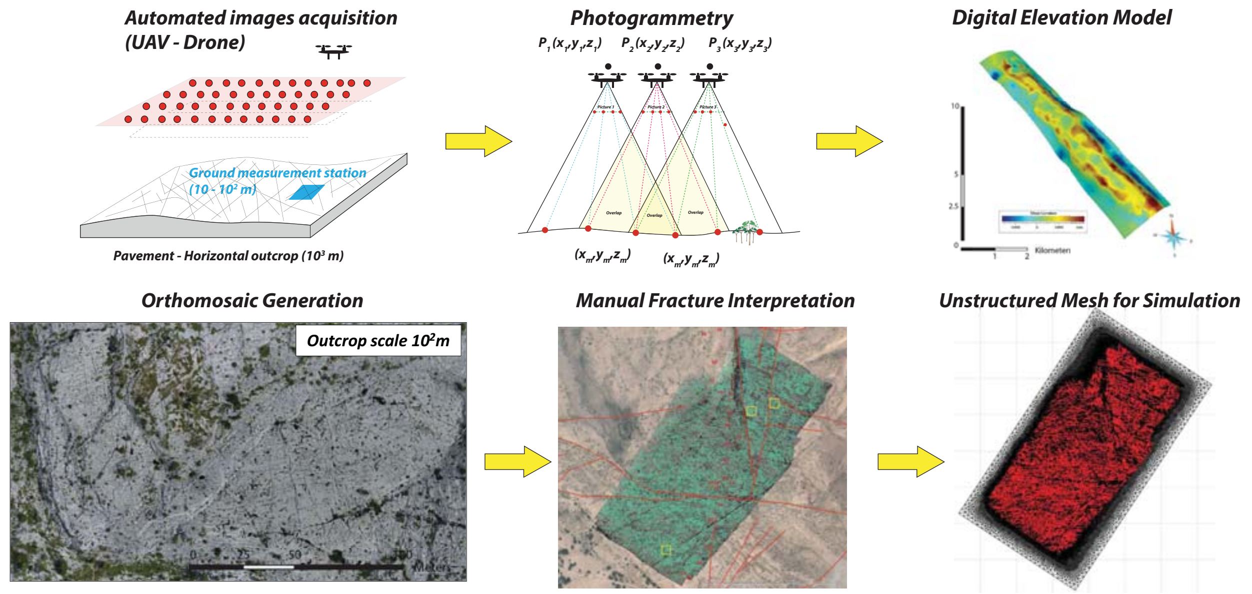
Carbonate reservoirs contain nearly 60 percent of the world's conventional oil and gas reserves. Subsurface data and outcroppings indicate that they are intensely fractured. The subsurface distribution of natural fractures are often unknown due to their sub-seismic size and owing to difficulties in extrapolating 1D fracture information from available well data to 3D reservoir geomodels. Outcrop analogues is a method that one can resort to for constraining the 3D architecture of fracture networks. Outcrops represent a local snap shot of the current multiscale state of fracturing which is perhaps a net result of multiple events of stress reversals, burial and / or exhumation and tectonics. Outcrop data is still useful to calibrate mechanical and fluid flow models so as to predict the impact of fractures on storage and flow in the subsurface. The outcrop fracture data is used in building a Discrete Fracture Network (DFN) representation in which multiscale fractures are represented explicitly and hence honors the fracture intensity and topology. DFN representations can be used as input for flow and geomechanics numerical models.

In this work we utilize a combined combined outcrop based and numerical approach to characterize fracture patterns, fracture apertures and fluid flow sensitivities using a folded 'box-type' anticlinal structure example from the Pag Island, Croatia. Fractured folds often form prolific reservoirs owing to the structural closure they afford and the additional porosity and permeability due to the fold related fracturing. The fracture patterns are of specific interest owing to the complex geometries associated with folding. A 3D model of the Pag Island is created with slices of multiscale fracture traces which are interpreted and digitized from drone photogrammetry. We use 2D finite element modeling to quantify a stress sensitive fracture aperture and by incorporating these apertures into a conformal discrete fracture and matrix reservoir simulation model we are able to quantify the effect of stressed aperture on fluid flow. Our results indicate that the fluid flow behavior is variable spatially owing to the aperture heterogeneity across the area of the fractured fold.

WORKFLOW

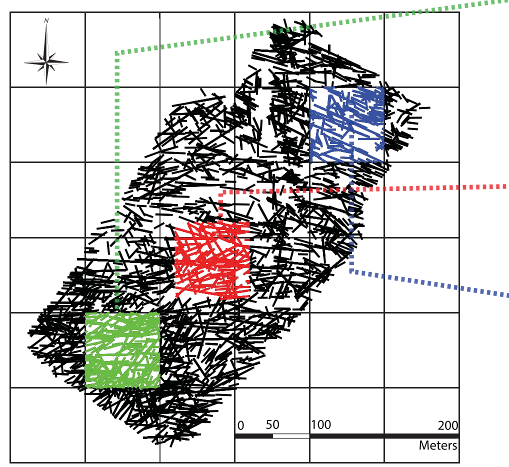


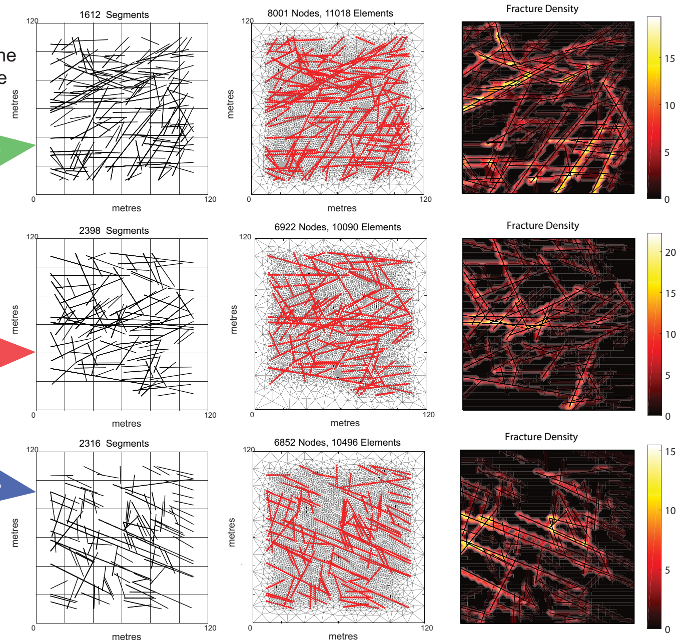
FROM PHOTOGRAMMETRY TO DIGITIZED DISCRETE FRACTURE NETWORK



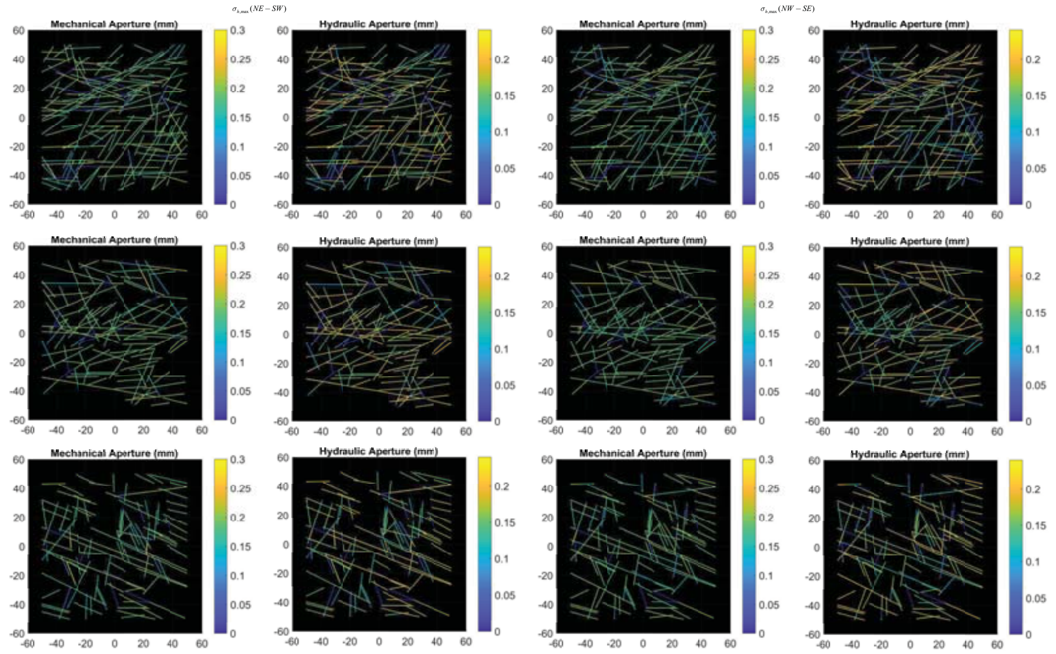
SAMPLING DFN FROM REGIONS OF FOLD

Detailed quantification indicate that fracture intensity and orientations vary along the fold. Owing to the complex nature of the fracture sampling and for computational reasons, we choose to analyze the fracture dataset in 3 boxed samples, one on the limb of the fold (traces in green), one on the hinge (traces in blue) and one sample in between (traces in red). We generate a unstructured, conformal mesh for the three samples and these are also depicted. Fracture density heat maps highlight the variation in orientations of the fractures in the samples.



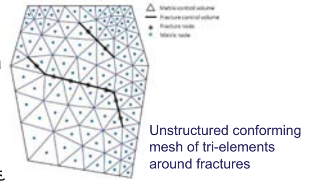


APERTURE HETEROGENEITY VARIATION WITH STRESS



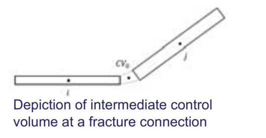
FRACTURED RESERVOIR FLUID FLOW MODEL

The fluid flow reservoir simulation model uses the same unstructured mesh as that of the mechanical finite element model. For the fluid slow simulation, we use the ADGPRS (Automated Differentiation General Purpose Research Simulator) which is a discrete fracture and matrix (DFM) approach. In the 2D case, the fractures are represented explicitly as lower dimensional fracture elements with the matrix elements (triangles) forming a conformally unstructured configuration around the fractures.



Unstructured conforming mesh of tri-elements around fractures

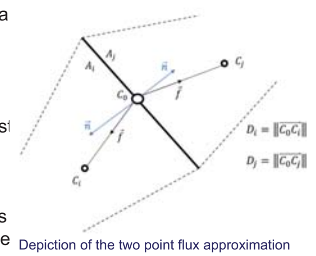
The DFM approach of Karimi Fard et al (2003) whereas two point flux approximation is applied between control volumes is used. The mean properties of the grid block as well as the evaluated variables are defined at nodes which are the centroids of the control volumes.The parallel plate model of flow through a fracture is used where fracture walls are separated by an aperture 'h'. The thickness of the fractures is not represented in the grid domain but only on the computational domain.



Depiction of intermediate control volume at a fracture connection

The transmissibility for a connection between two fractures is achieved by introducing an intermediate control volume that redirects flow. For multiple fracture intersections, the star-delta transformation is used to simplify the transmissibility computation. For a fracture intersection with 'n' connections, transmissibilities are computed using the equation: $T_{ij} \simeq \frac{\alpha_i \alpha_j}{\sum_{k=1}^{n} \alpha_k}$

For the fluid flow simulations on three fractured samples, we run three cases. The first two are scenarios when the fracture aperture is heterogenous and varies with stress directions. The third case is when the fracture aperture is set constant and when the aperture is not heterogenous (or stress sensitive). The matrix properties are set as 20 % porosity and 0.01875 mD permeability. The fracture porosity is set as 1. The model is initialized with a pressure of 300 bar with a dead oil model. Hence the fluid flow is incompressible and single phase. Wells are set on depletion with bottom-hole pressure constraint of 1 bar.



Depiction of the two point flux approximation between two control volumes.

FRACTURE APERTURE CALCULATION

Fracture aperture plays a dominating role in determining fluid flow efficiency and fluid storage in fractured reservoirs. Fracture aperture measurements from outcrop is a poor proxy for use in a reservoir simulation model as the apertures have been opened up owing to release of stress during exhumation and may also be subject to karstification by meteoric waters or may have been weathered. Fracture aperture may be obtained from well data, either measured from cores or from borehole imagery data i.e FMI logs The Barton - Bandis empirical aperture model defines an aperture which is conductive to flow owing to the intrinsic fracture roughness and shear displacement. The aperture is dependent upon local stresses, shear displacement, initial roughness , initial mechanical aperture and the mechanical properties of the rock. A set of empirical functions were defined by Barton and Bandis (1980), Barton (1982). These functions were expanded for cyclic loading by Asadollahi et al (2010). Olsson and Barton (2001) defined the hydraulic aperture as a function of the mechanical aperture.

The initial mechanical aperture is a function of the Joint Roughness Coefficient (JRC) and a mechanical property of the rock, the Joint Compressive Strength (JCS) and uniaxial compressive strength.

$$E_0 = \frac{JRC}{5}\left(0.2\frac{\sigma_c}{JCS} - 0.1\right)$$

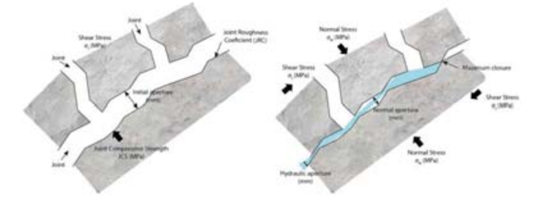
The mechanical aperture En is a function of the normal stress, initial stiffness and the maximum closure. The initial stiffness is a constant defined as below:

$$E_n = E_0 - \left(\frac{1}{v_m} + \frac{K_{ni}}{\sigma_n}\right)^{-1} \qquad K_{ni} = (-7.15) + 1.75 JRC + 0.02\left(\frac{JCS}{E_0}\right)$$

The maximum closure is dependent on JRC, JCS and the initial mechanical aperture

$$v_m = A + B\,(JRC) + C\left(\frac{JCS}{E_0}\right)^D$$

The maximum closure fitting parameters have been experimentally obtained by Asadollahi et al (2010) for different loading cycles. The hydraulic aperture for fluid flow is a function of shear displacement, normal stress, peak displacement and a parameter called mobilized fracture roughness and is given as:



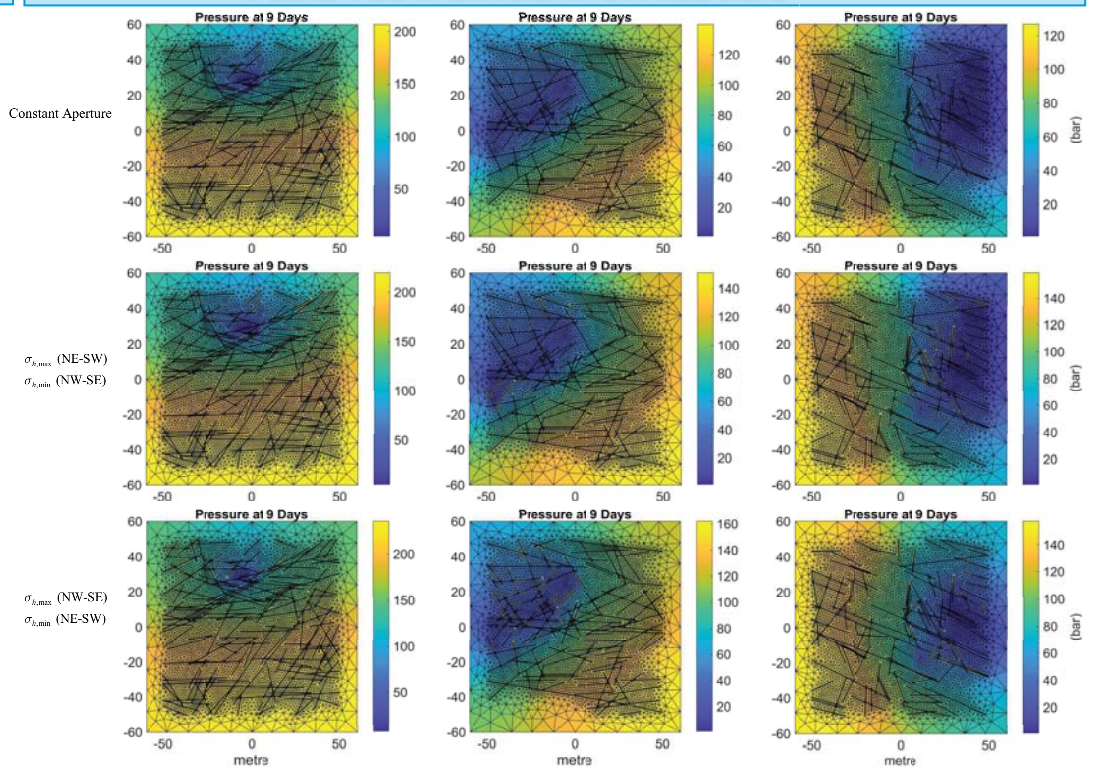
Constant	1st Cycle	2nd Cycle	3rd Cycle
A	-0.2960 ± 0.1258	-0.1005 ± 0.0530	-0.1032 ± 0.0680
B	-0.0056 ± 0.0022	-0.0073 ± 0.0031	-0.0074 ± 0.0039
C	2.2410 ± 0.3504	1.0082 ± 0.2351	1.1350 ± 0.3261
D	0.2450 ± 0.1086	-0.2301 ± 0.1171	-0.2510 ± 0.1029

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

We use the Finite element package ABAQUS for the stress calculations. The fractures are represented as seams with a plane strain continuum. We model the mechanical behavior as elastic. The mesh shown for the 3 samples are contained within a surrounding square geometrical area which is also meshed (not depicted) on which maximum and minimum horizontal loads are applied. This is to prevent any boundary stress perturbations within the fractured syste. Dsiplacement boundary conditions are applied on the boundaries to prevent model rotation and to ensure symmetrical deformation. Two stress scenarios are applied, one in which the maximum horizontal stress is perpendicular to the axis of the fold and the second when it is in the direction of the fold axis. With such a setup, the local stress field is computed and within each element abutting a fracture, the principal stresses and fracture strike yield the normal stress. The parameters used for the simulations are as follows:

$$Sh_{max} = 30MPa \qquad \nu = 0.3\ (-) \qquad JRC = 15\ (-)$$
$$Sh_{min} = 10MPa \qquad E = 35\ GPa \qquad JCS = 120MPa$$

FLUID FLOW SIMULATION RESULTS



COMPARISON OF FLUID FLOW RESPONSE

The fluid flow pressure response in the three scenarios highlight certain important issues in fractured reservoir behavior. Firstly the connectivity of the fractures have a huge impact on the depletion behavior. Sample 1 has the largest fracture density but still shows a lower pressure drop in the same time period owing to the placement of the wells on a relatively isolated fracture. Secondly, the constant aperture model seems to overestimate production as compared to the heterogenous aperture model. The difference in production is dependent on the exact well position.

The regions of smaller aperture constrain the depletion in all 3 cases, even as the exact pressure drop is dependent on the well position (on matrix / on well connected fracture / on large aperture fracture / on well connected large aperture fracture. The third key takeway is the relation of the larger fractures with respect to the stresses acting upon the system. From the aperture heterogenity plots of the three samples, fractures which are longer and connected with many intersections and are at an angle to the horizontal stresses have more open apertures.and are hence more conducive to flow.

CONCLUSIONS

We present a workflow that applies a stress based numerical method to derive heterogenous, sub-millimeter fracture apertures to a realistic outcrop derived 2D Discrete Fracture Network. The derived aperture is variable even along single fractures. Aperture is a function of normal stress, shear displacement and the initial roughness of the rock fracture. The method does not consider the effects of precipation and dissolution on the effective aperture. Moreover the effects of fracture propagation when stresses are applied (or when fluids are injected) are not considered. The heterogenous fracture aperture is also assumed to be constant on fluid depletion (no fracture closure owing to poroelastic effects are considered in the fluid model).

The Pag outcrop is an example of a highly complex fracture network with at least 6 clearly identifiable fracture sets. In such a multiscale network, the intensity, topology of the system is variable spatially and hence the fluid response varies greatly across the network which is obvious from our results. Stochstic fracture generators commonly used to model fractured reservoirs, do not capture this variation. Our stress based approach helps to identify bottlenecks in the network given that there is sufficient data to characterize fracture roughness (measured from cores, FMI) and knowledge of the current day stress field. An additional implication is that, even though there are multiple sets of fractures, only the preferentially oriented fractures would be conductive to flow. In future work, we will attempt to extend the workflow to coupled flow and geomechanics on the DFN in order to quantify the aperture dilation and closure that takes place owing to pressure changes (stress changes) in fractured reservoirs.

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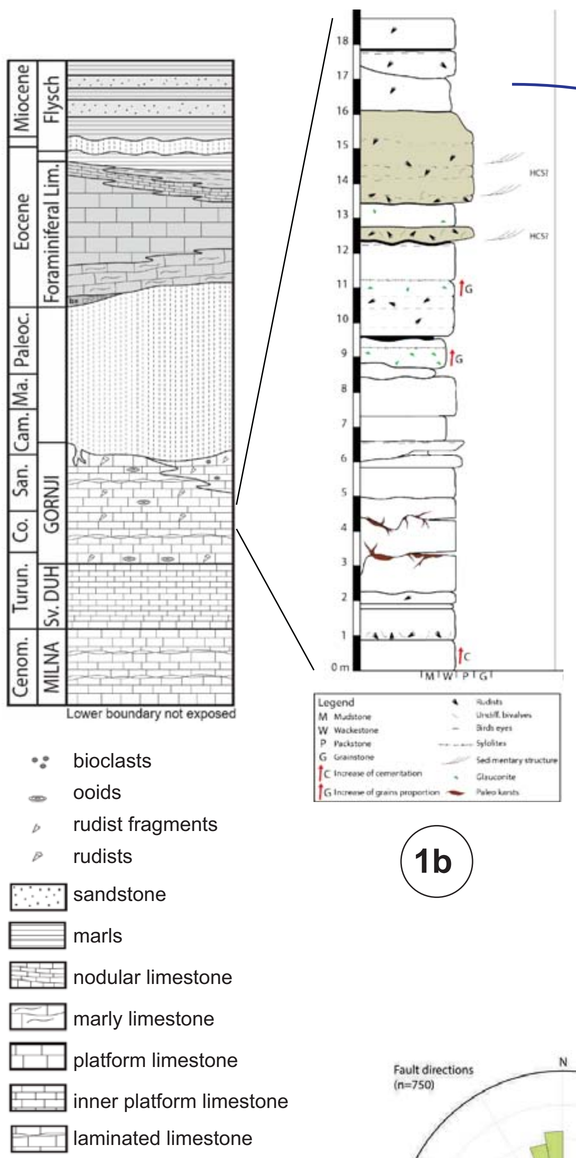
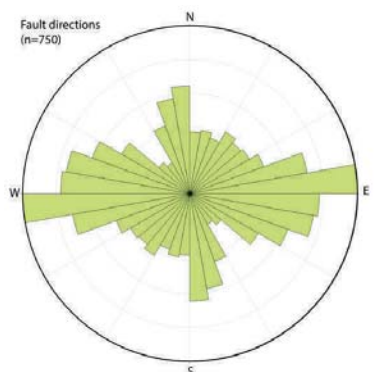
FOLDED AND FRACTURED RESERVOIR ANALOGUE : Pag Island, Croatia

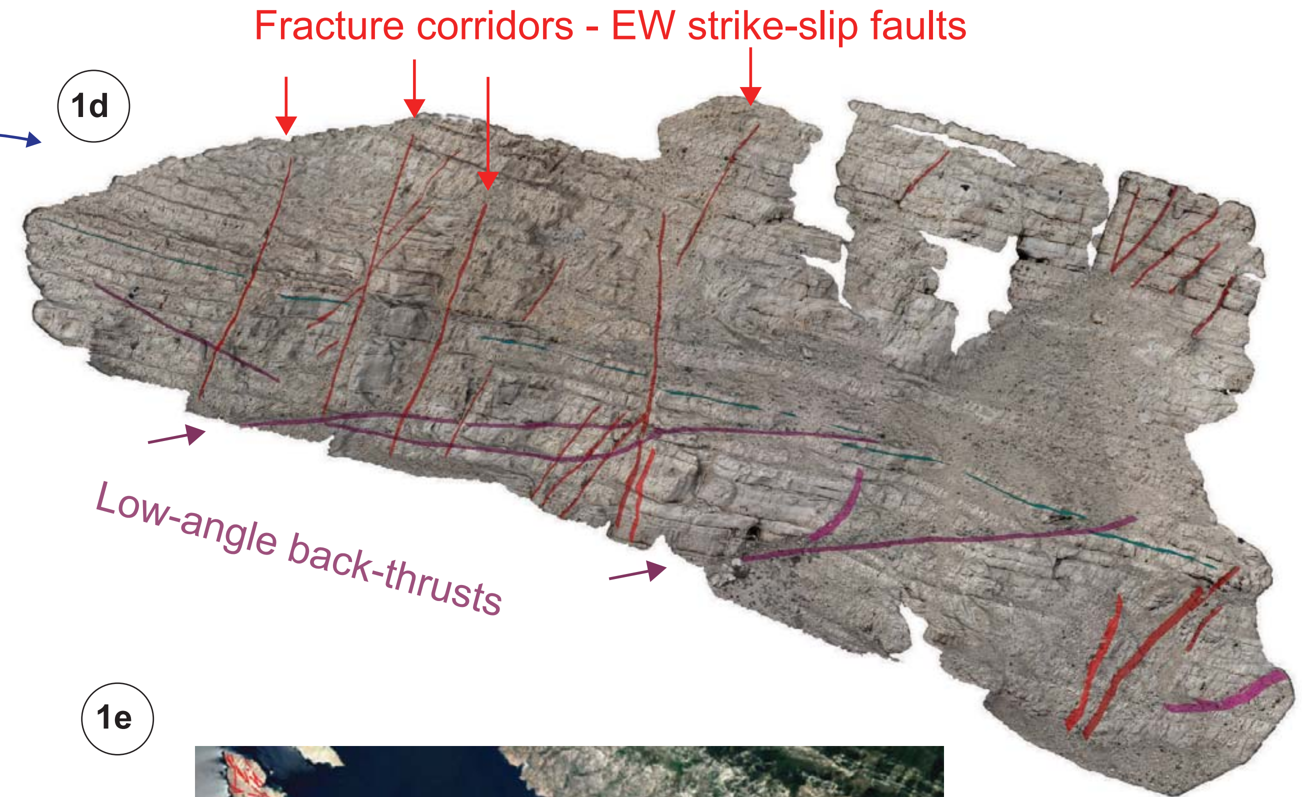
GEOLOGICAL SETTING AND DEFORMATION STYLE

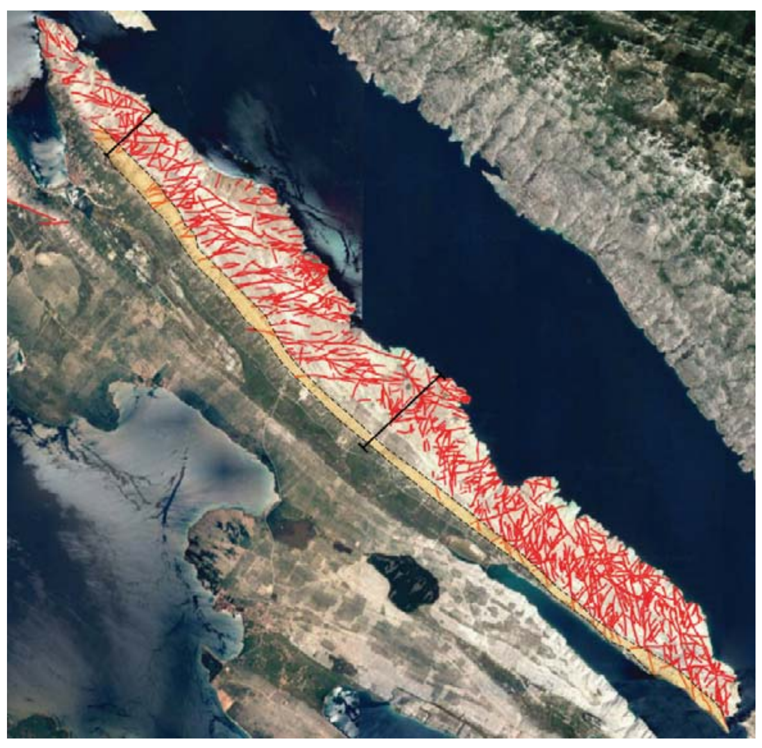
The External Dinarides are a fold and thrust belt characterized by general SW vergence [e.g., Tari, 2002]. The Pag anticline involves about 1 km of Cenomanian-Santonian rudist-bearing limestones overlain, through an unconformity, with transgressive Foraminiferal limestones of Eocene age (1b) [Korbar, 2009]. At the km-scale, the fold is continuous along-axis for ca. 30 km between the NW and SE periclinal terminations. In cross section, the fold has box geometry, with sub-vertical to overturned forelimb and a gently undulating hinge zone (1c). The fold is crosscut by minor thrust faults verging both to NE and SW, and by sub-vertical strike-slip faults striking either NS or EW. Thrust and strike-slip faults determine local increases in fracture intensity (1d, 1e).

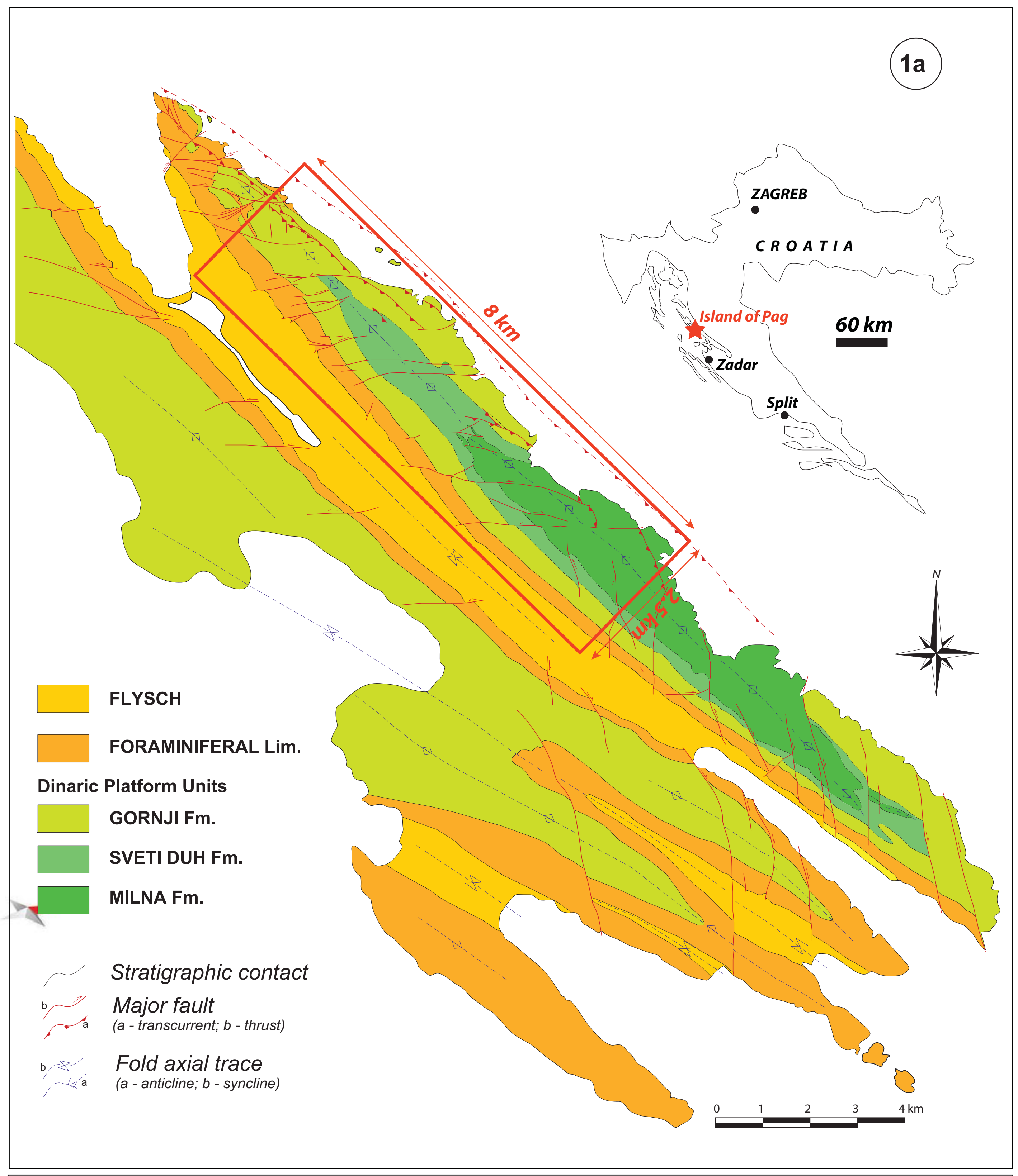


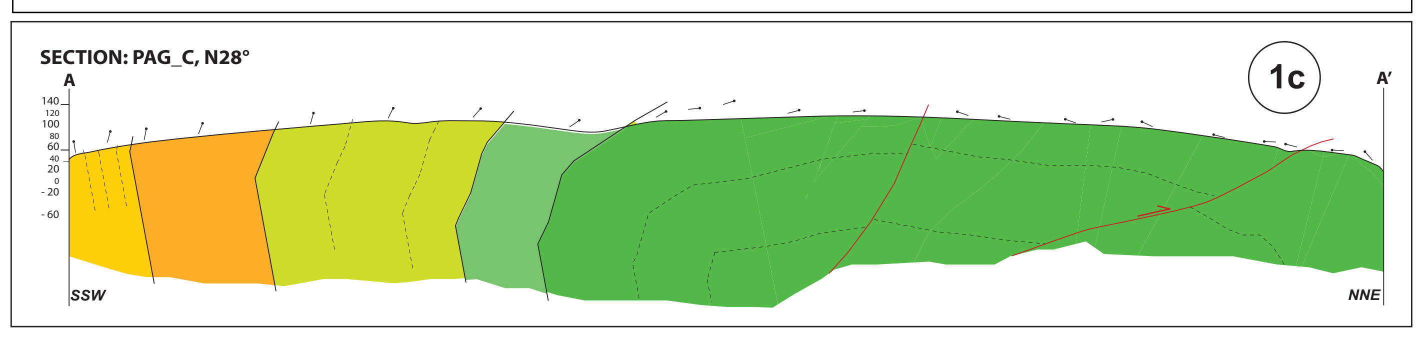
1b



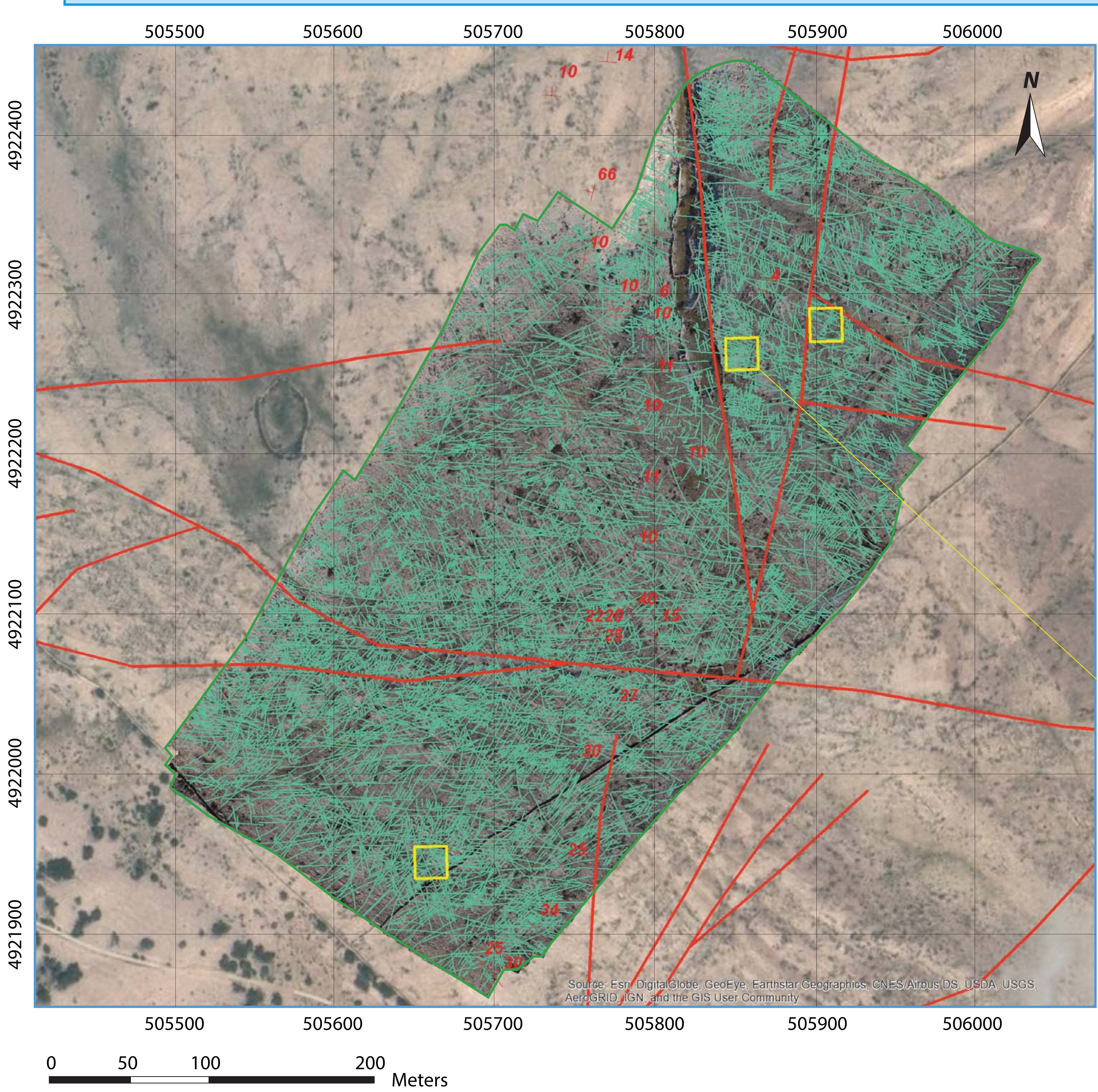


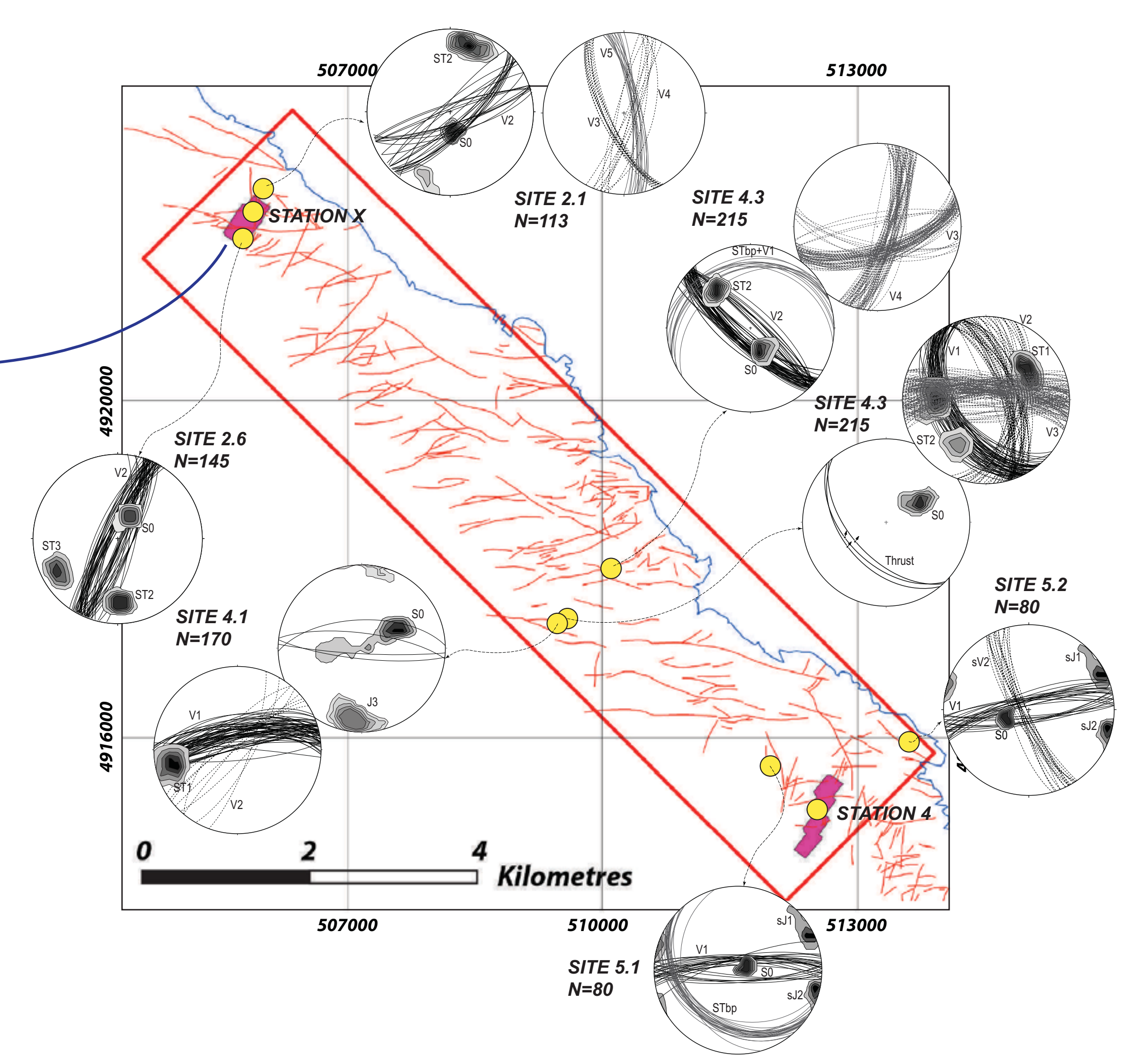


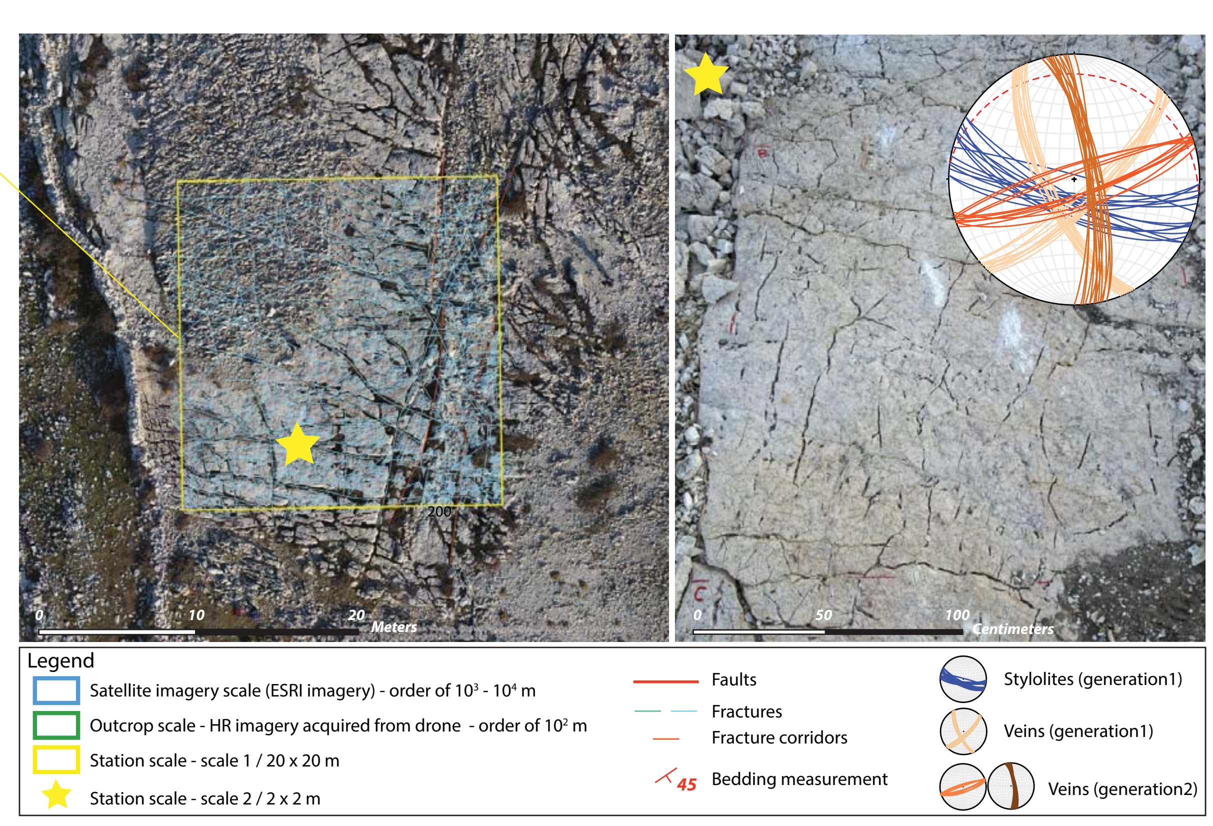




MULTISCALE FRACTURE CHARACTERIZATION AT DIFFERENT SCALES USING DRONE PHOTOGRAMMETRY







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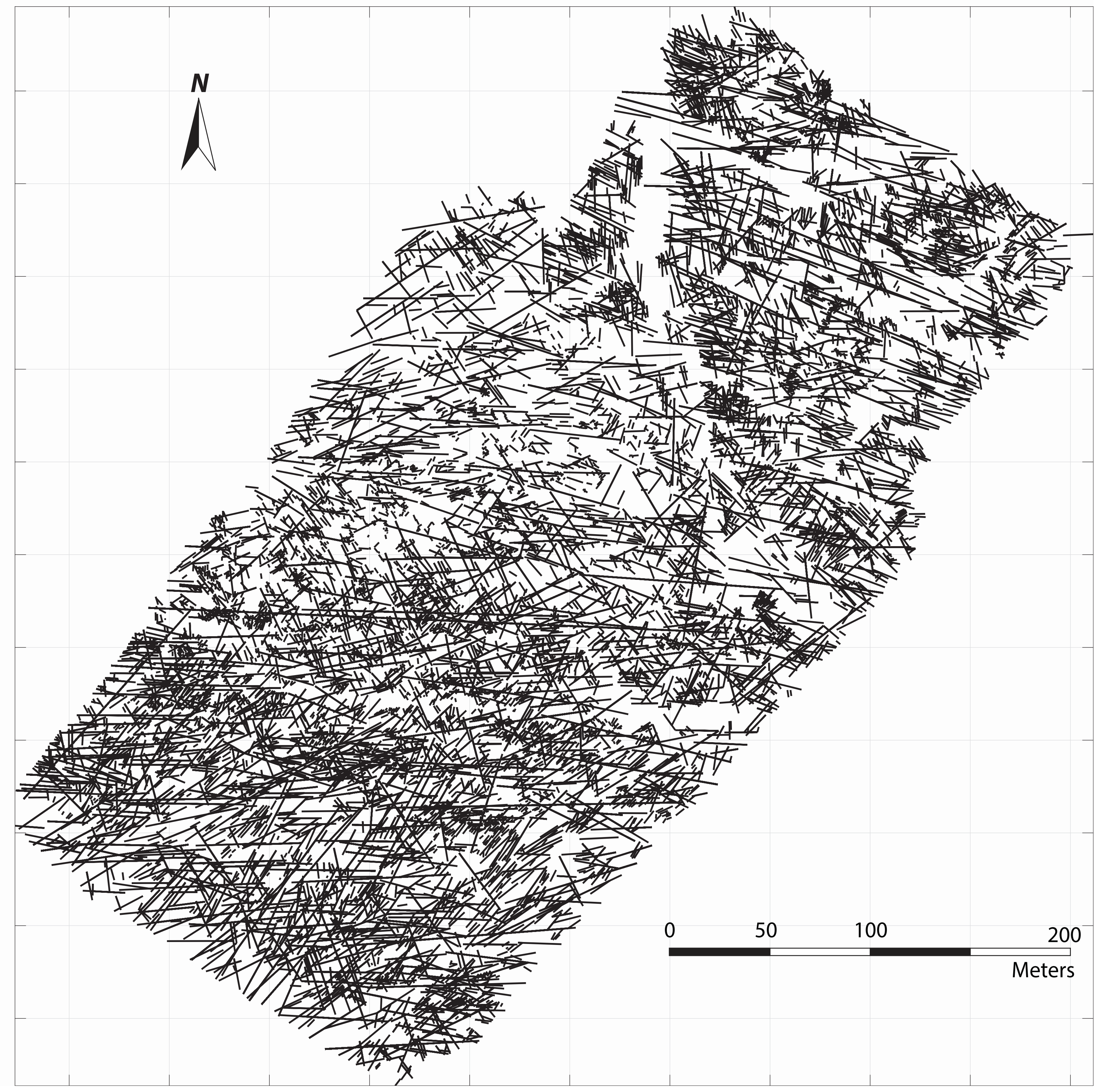
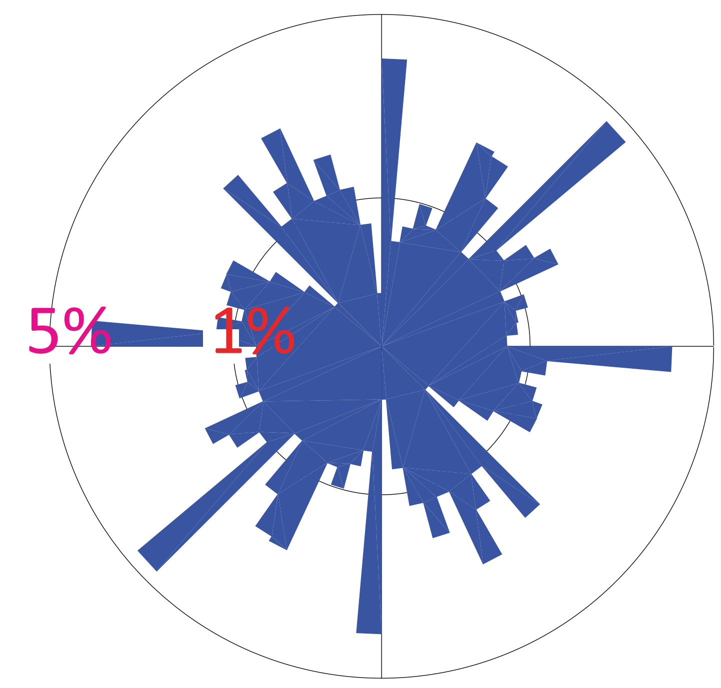
QUANTITATIVE ANALYSIS OF THE MULTISCALE FRACTURE DATASET

Rahul PRABHAKARAN, Pierre-Olivier BRUNA, Giovanni BERTOTTI, Silvia MITTEMPERGHER, Andrea SUCCO, Andrea BISTACCHI, Fabrizio STORTI, Marco MEDA*

DIGITISED FRACTURE NETWORK



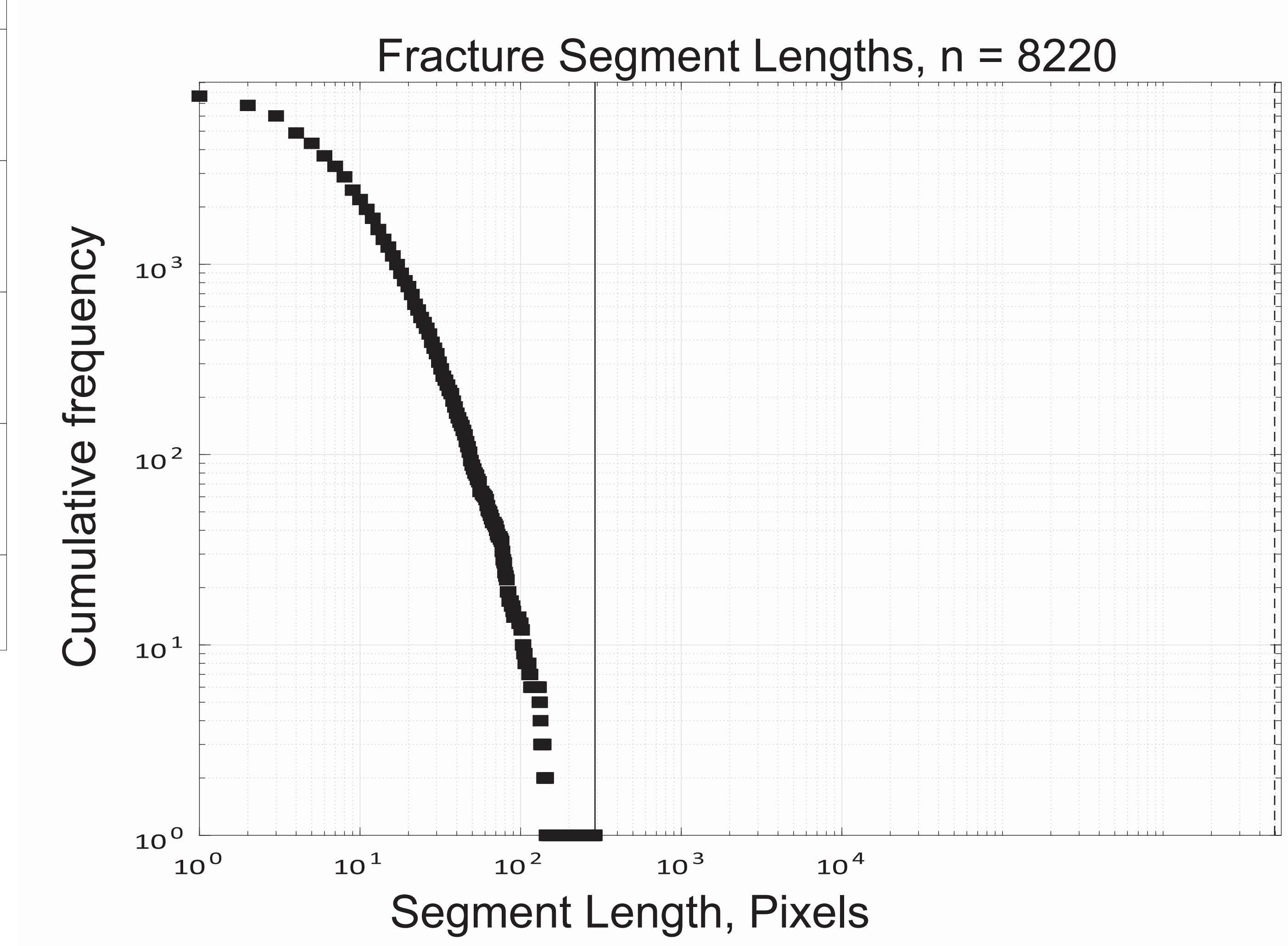
FRACTURE SETS ANALYSIS



Large Scatter in fracture azimuths are observed that indicate the structural complexity associated with folding related fracturing. Combining analysis of the fracture traces digitized from photgrammetry alongwith station scale measurements, the traces are classified into the following 6 major sets.

1. EW Tectonic Stylolites N 080 - N 110
2. Conjugated Veins N 030 - N 050
3. Conjugated Veins N 130 - N 150
4. NS Tectonic Stylolites N 010 - N 020 & N 160 - N 180
5. NE - SW Veins & Joints N 050 - N 070
6. NS Veins & Joints N 000 - N 030

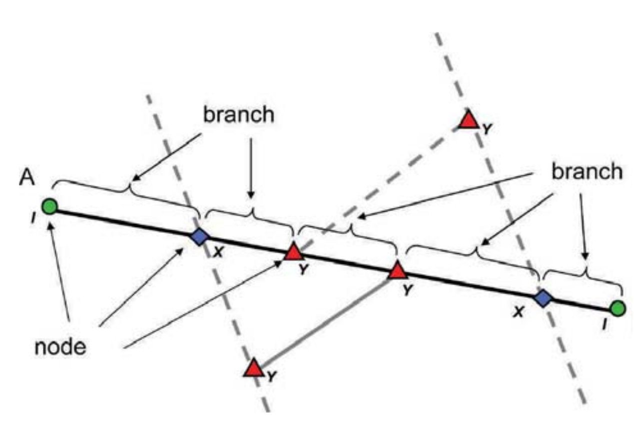
FRACTURE LENGTH STATISTICS



FRACTURE TOPOLOGY ANALYSIS

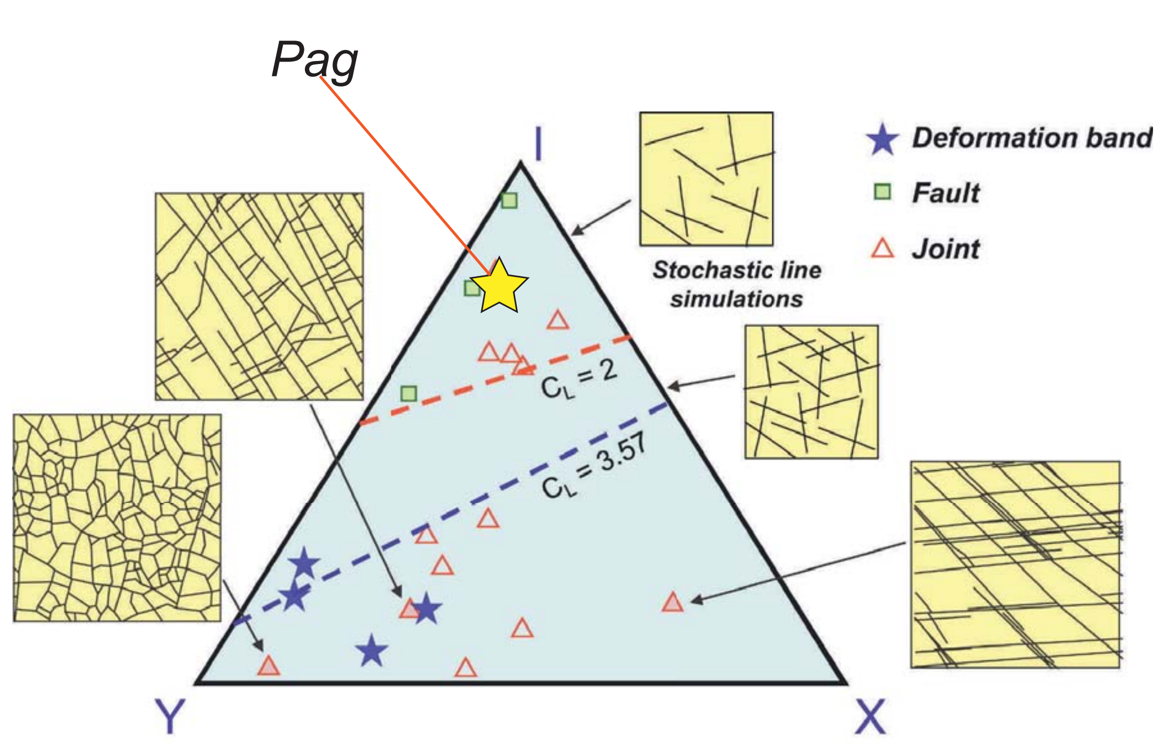
In 2D fracture networks, the fractures maybe considered to be a system of branches and nodes (Sanderson & Nixon, 2015). Fracture topology refers to the relationship between the elements of the network. The behavior of the fracture network to flow and stress depends not only upon the geometrical features of the fractures but also upon these connecting relationships. The nodes may be divided into isolated (I) nodes, abutting or terminating (T) or (Y) nodes and crosscutting (X) nodes. The proportion of these nodes define the topology (Manzocchi, 2002; Mäkel, 2007) and can be used to characterize the fracture system. We perform such a topological analysis of the nodes and derive the node metrics for the Pag fracture network.

Type	Count	%
I	16492	63
Y	2889	11
X	6659	26



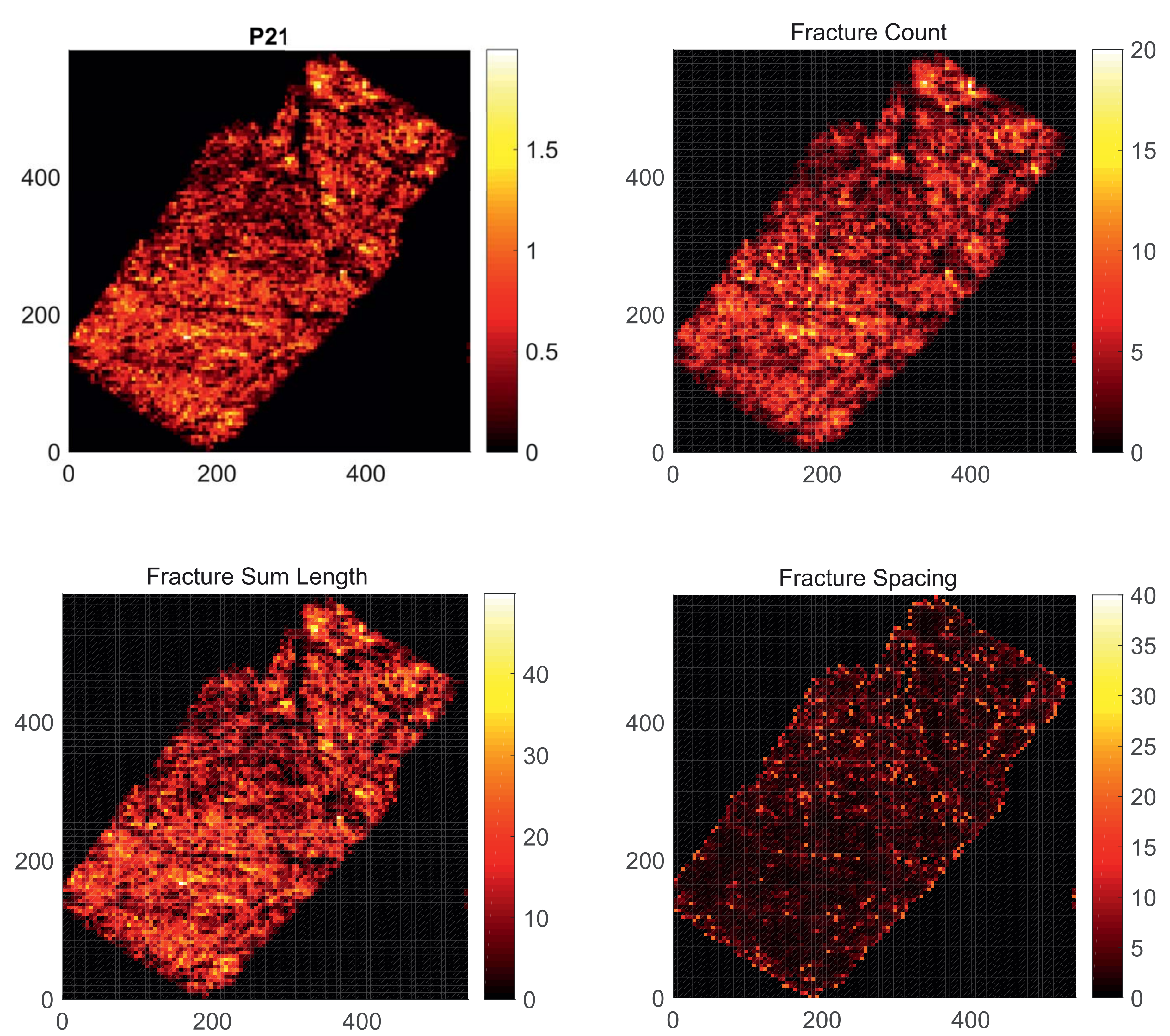
(adapted from Sanderson and Nixon, 2015

The proportion of nodes may be represented on a ternary plot. Sanderson anc Zhang (1999) compared three natural fracture networks with stochastic line simulations (fig below). The Pag system is juxtaposed on this ternary plot and it has an isolated topological character for the system as a whole.



(adapted from Sanderson and Nixon, 2015)

FRACTURE INTENSITY MEASURES



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