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Impact of large-scale structures on fracture network connectivity: Insights into the Vaca Muerta unconventional play, Neuquén basin, Argentina

Correa-Luna, C., Yagupsky, D. L., Likerman, J., & Barcelona, H., 2025. *Tectonophysics*, **898**, 230640.

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Introduction

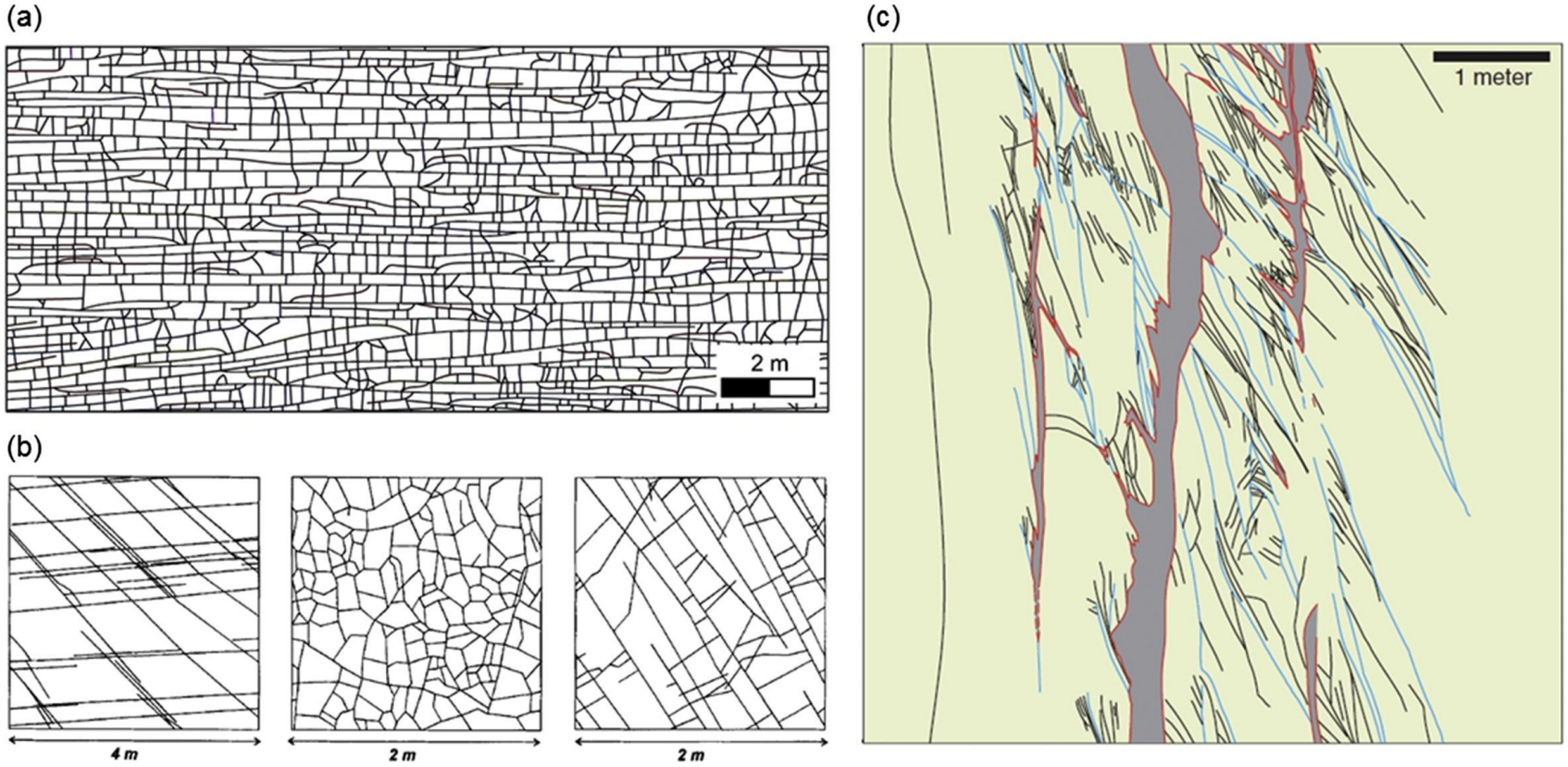
Natural fracture networks in rock masses are crucial due to their significant impact on mechanical behavior and fluid flow dynamics.

Understanding fracture networks contributes to managing hydrocarbon production, geothermal energy, groundwater flow and contaminant transport, CO_2 storage, and engineering projects, among others.

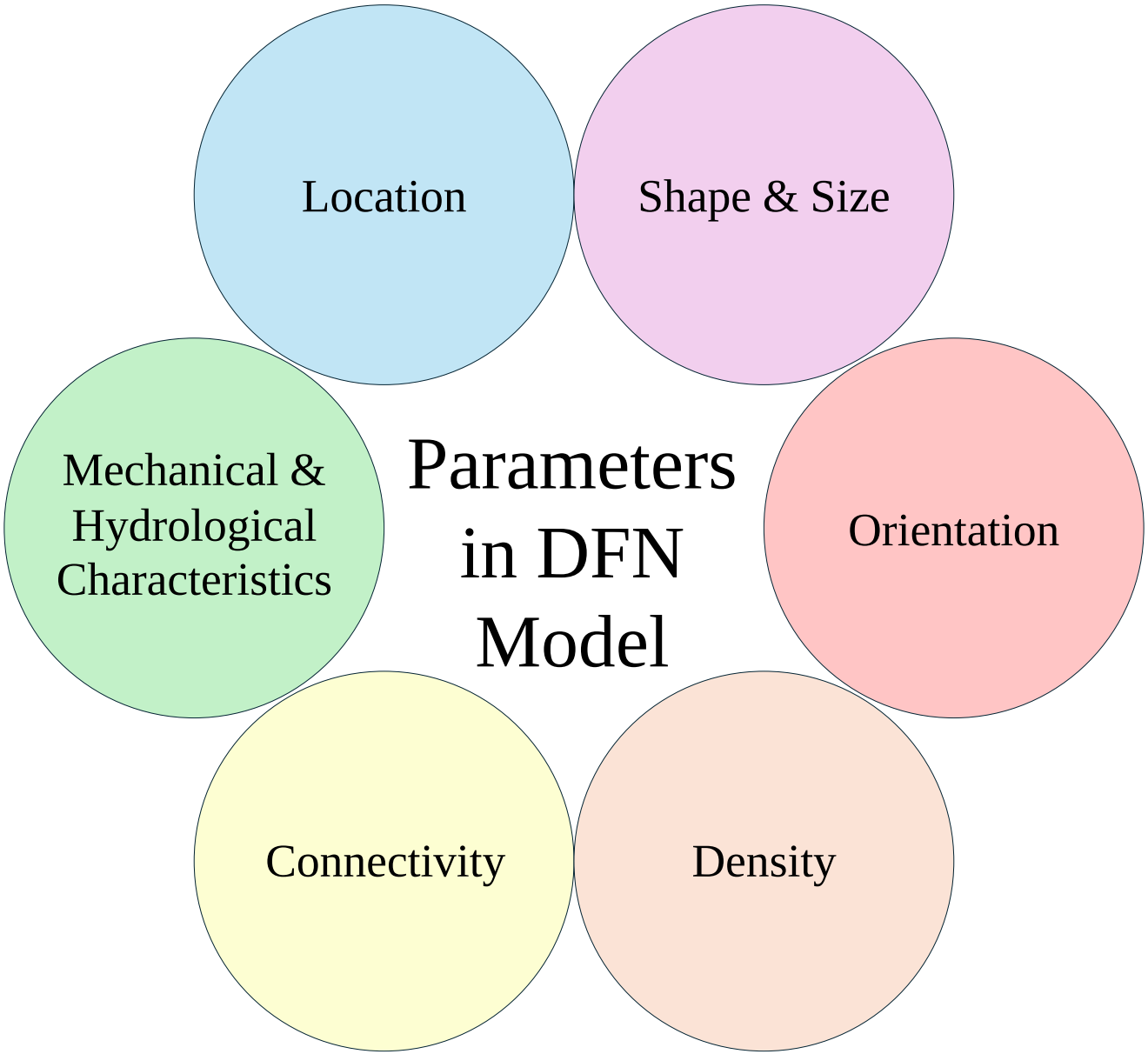
Discrete Fracture Network models allow for the assessment of the role of natural fracture networks as pathways for Fluid Flow.

Discrete Fracture Network (DFN)

A model that represents the geometrical properties of each fracture and the topological relationships between individual fractures and fracture sets.

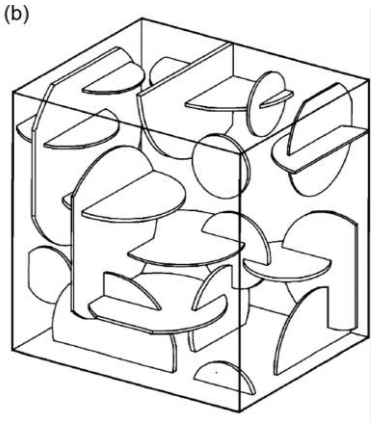


Geologically-mapped DFN patterns. (a) A limestone outcrop at the south margin of the Bristol Channel Basin, UK. (b) Sandstone exposures in the Dounreay area, Scotland. (c) Fault zone structures in the Valley of Fire State Park of southern Nevada, USA. (Lei et al., 2017)

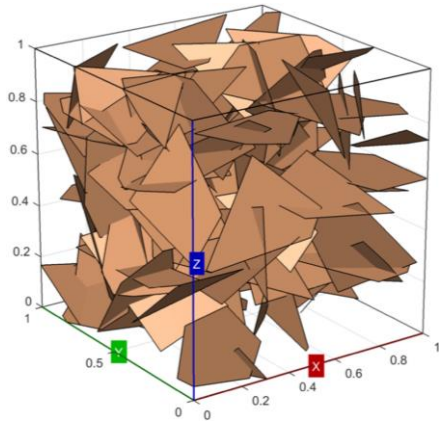

Location
Shape & Size
Mechanical & Hydrological Characteristics
Parameters in DFN Model
Orientation
Connectivity
Density

Parameters in DFN Model

1. Location：3D spatial coordinate
2. Shape & Size： Fracture can be different Shape and Scale
3. Orientation： Fracture's Attitude（Strike & Dip）
4. Density： Fracture's Length or Quantity in unit area
5. Connectivity： Intersection of Fracture
6. Mechanical & Hydrological characteristics： Permeability, Shear Strength, Aperture size etc.）。

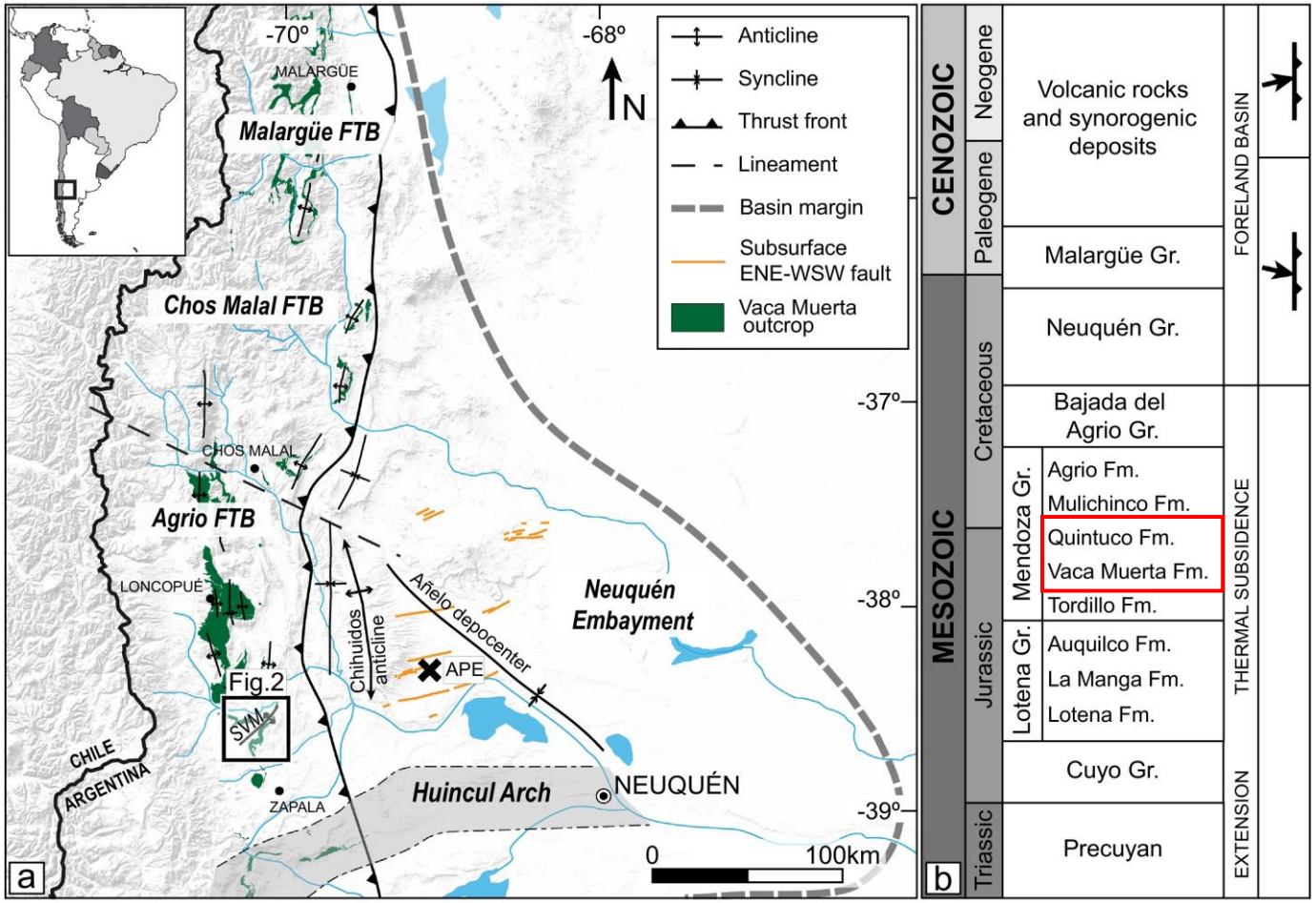


Long et al., (1985)

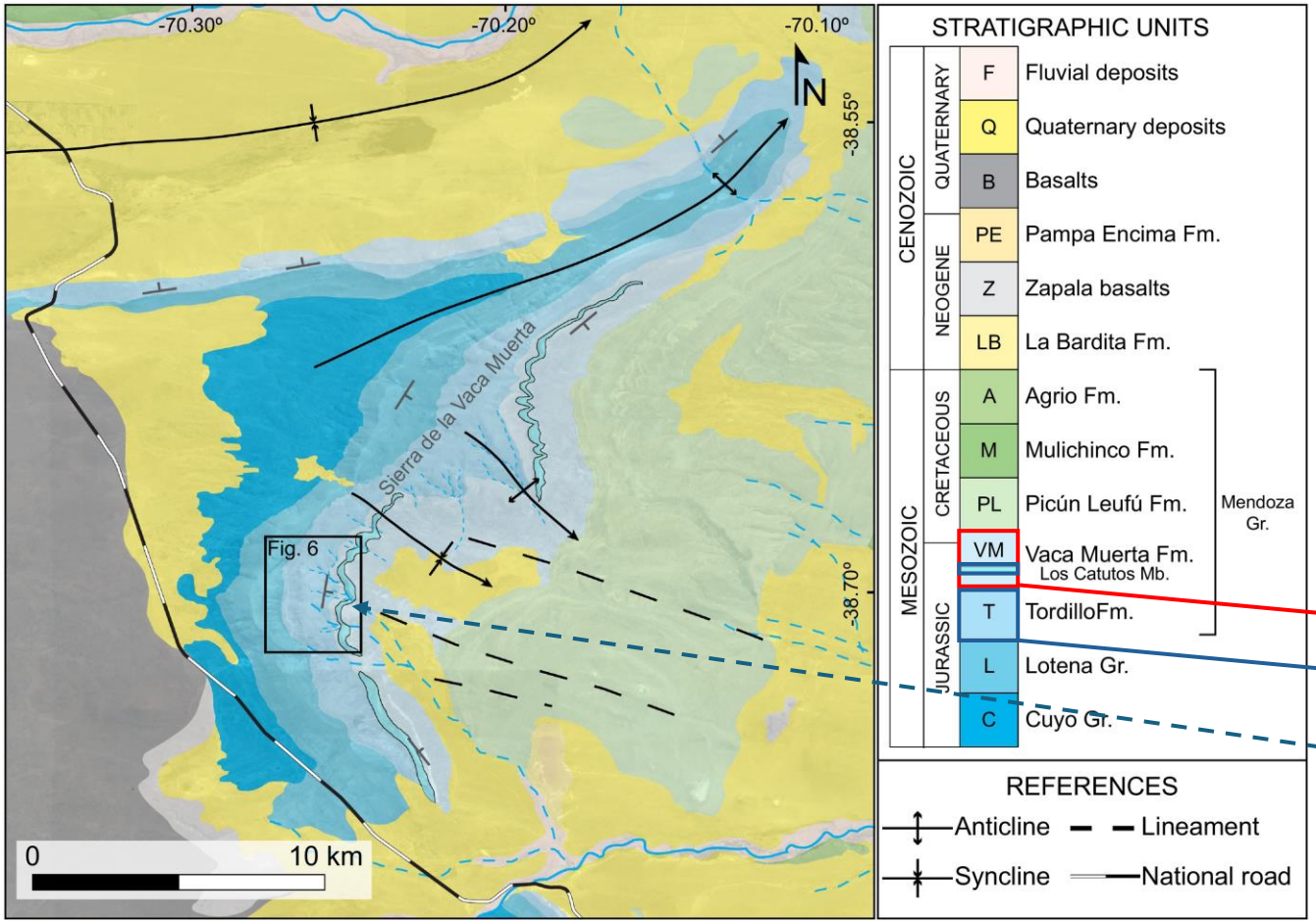


Alghalandis (2017)

Regional Geology



(a) The main morphostructural units of the Neuquén Basin.
(b) Mesozoic and Cenozoic tectonostratigraphic column and basin stages for the Neuquén Basin, with convergence direction variations from the Late Cretaceous to the Cenozoic.



In Vaca Muerta, this study investigates how large-scale structures influence fracture network connectivity there.

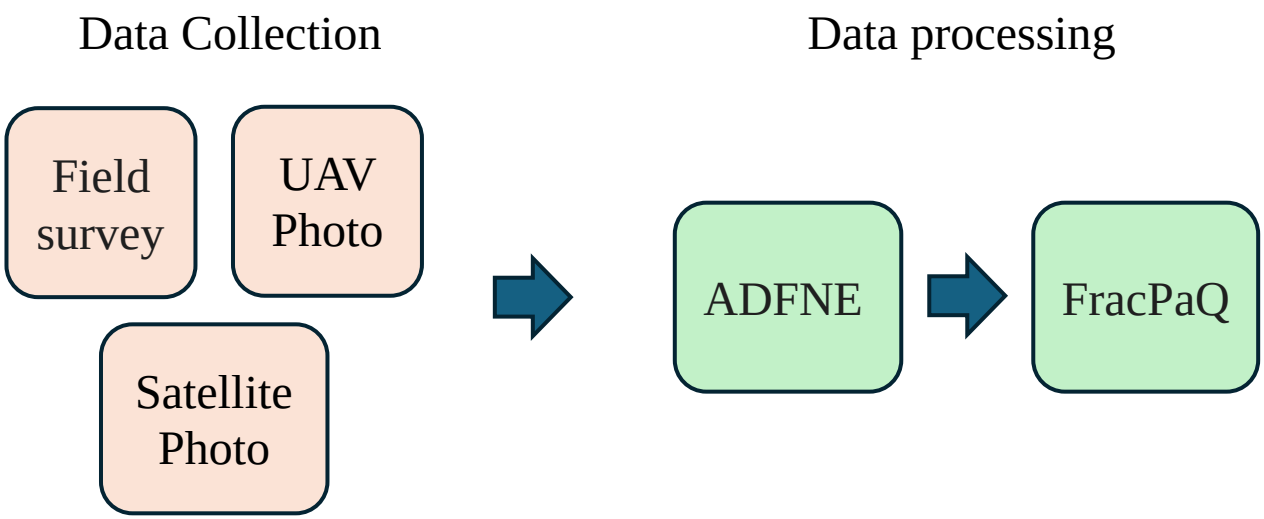
Methodology

1. Data Collection:

- Field fracture survey
- Georeferenced orthophotos from Unmanned Aerial Vehicle (UAV) aerial photography.
- Satellite Photography (Tracing the large-scale fracture)

2. Data processing – Two-dimensional DFN:

- ADFNE (Model Building)
- FracPaQ (Permeability Anisotropy analysis)



Methodology

ADFNE

- Open source software for discrete fracture network engineering.
- Based on the UAV survey area, ensuring inclusion of the large fracture corridors mapped in Tordillo Formation outcrops.
- Each fracture set was characterized by mean azimuth, Fisher's *k* parameter, minimum, maximum, and mean fracture trace lengths, and its length distribution law.
- Calculating Intersection Points & the Number of Clusters between fractures.

FracPaQ

- FracPaQ is a MATLAB toolbox for the quantification of fracture patterns.

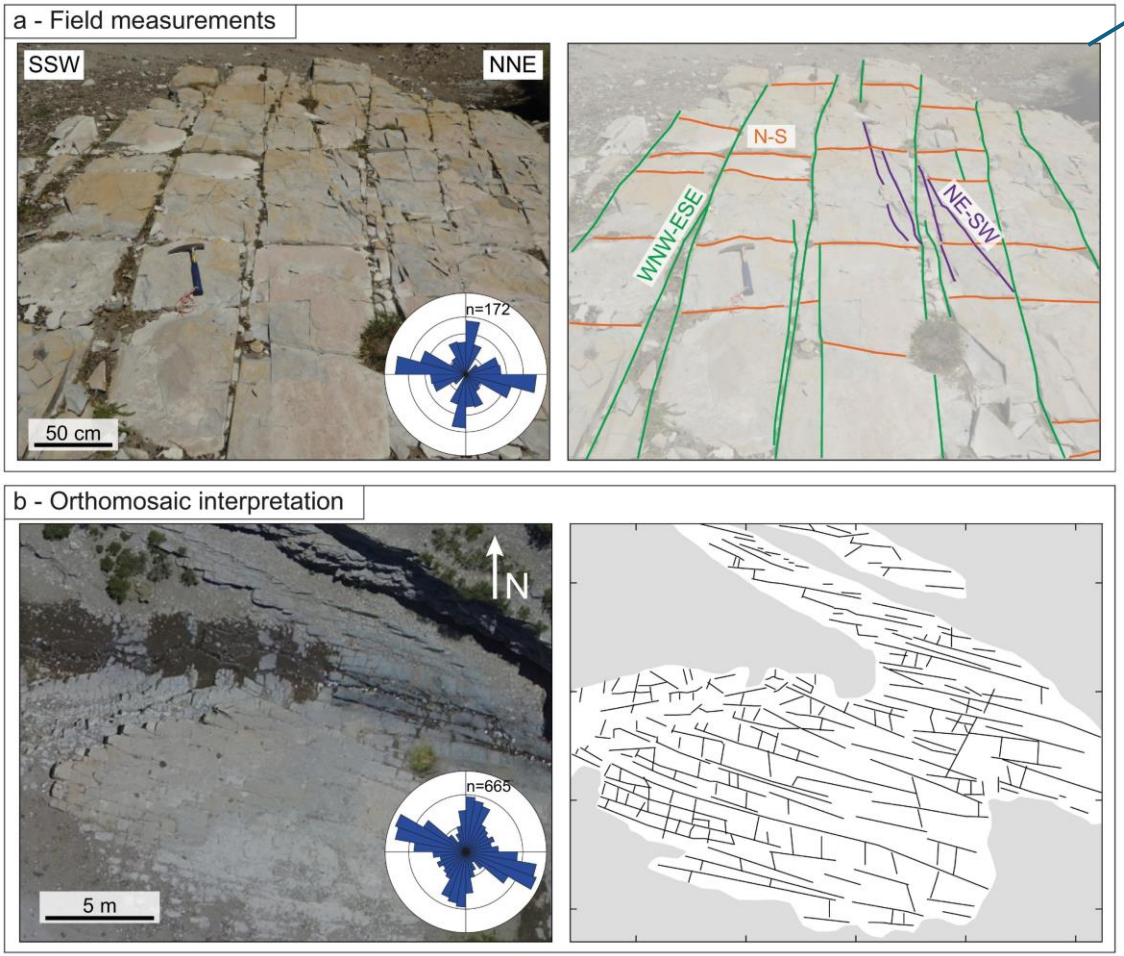
- 120 simulations were conducted, summarized in cluster mass frequency and proportion histograms, and in the permeability anisotropy results.

Result

Crack Network of Los Catutos:

The equal-area rose diagram summarizes fracture orientation for each case. Consisting primarily of a set of fractures with a WNW-ESE trend, accompanied by a set of minor orthogonal fractures (N-S trending).

'ladder-like' Pattern



The equal-area rose diagram: WNW-ESE trend with a set of N-S trending minor orthogonal fractures.

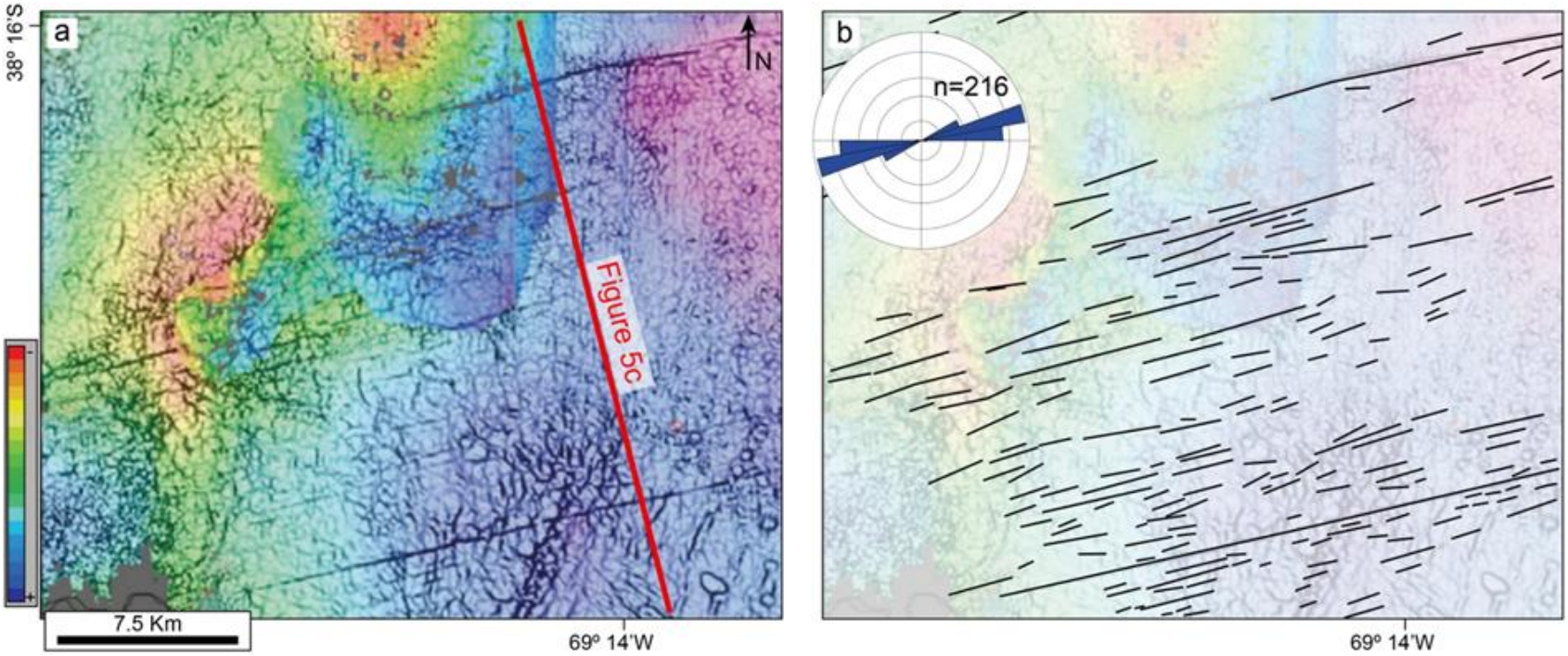
Field:
Mean spacings: 0.36 - 0.58 m
Traces: 0.22 - 9.92 m
mean trace length = 2.36 m
median = 1.99 m (SD = 1.52 m).

UAV:
Mean spacings: 0.15 - 0.21 m
Traces: 0.2 - 4.57 m
mean trace length = 0.85 m
median = 0.67 m (SD = 0.61 m).

Result

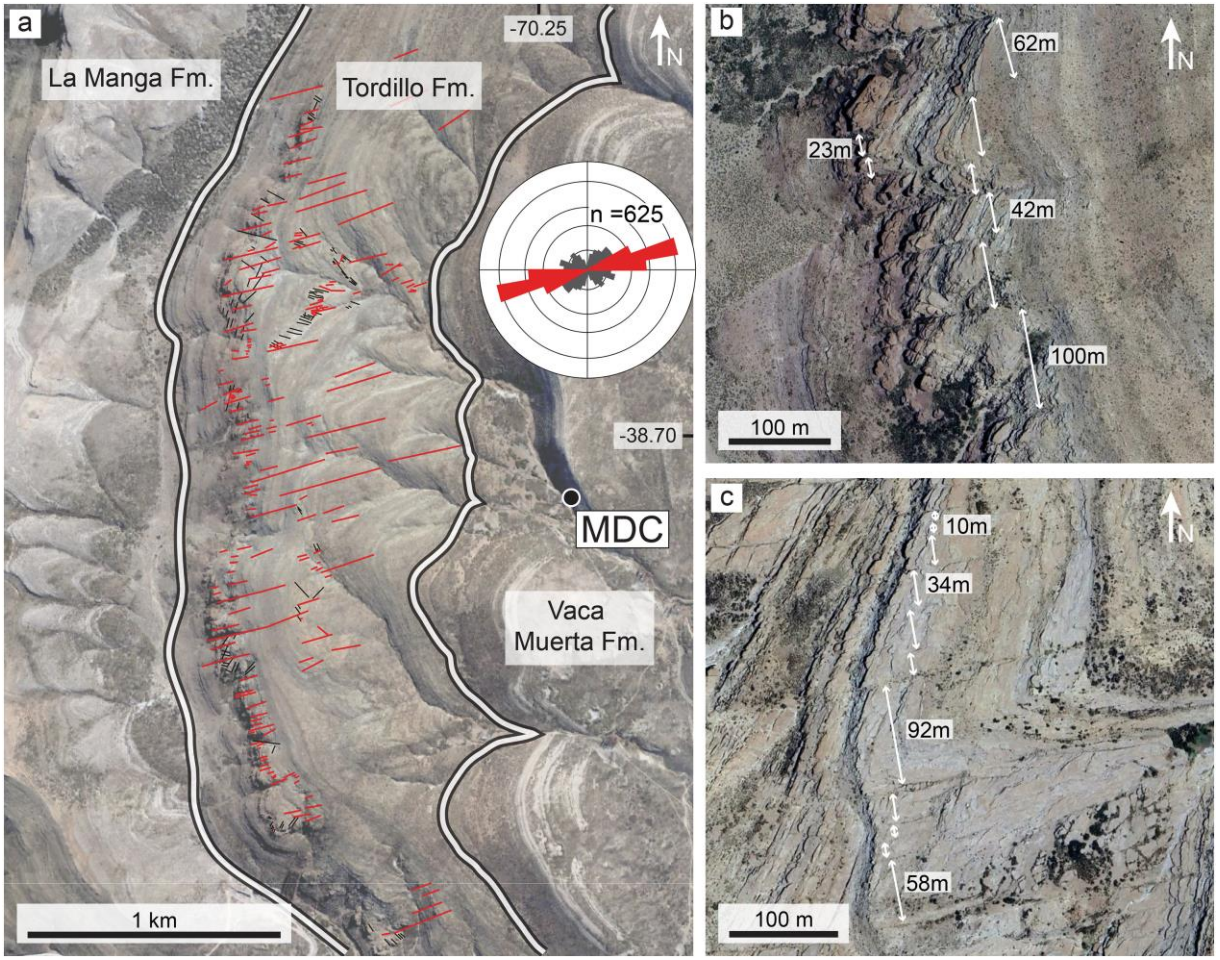
Large-scale Fracture:

From the outcrop survey, GPS, and seismic profiles, it was observed that large-scale cracks trended ENE-WSW, had a nearly vertical dip, and ranged in length from a few meters to hundreds of meters.



(a) Isochronous map and minimum curvature (Cmin) of Sequence 11 (Upper Tithonian) on the Aguada Pichana Este block (from Gangui and Grausem, 2014).

(b) Interpretation of ENE-WSW lineaments from this study. Inset equal-area, length-weighted rose diagram of the interpreted lineaments summarizes their orientation.



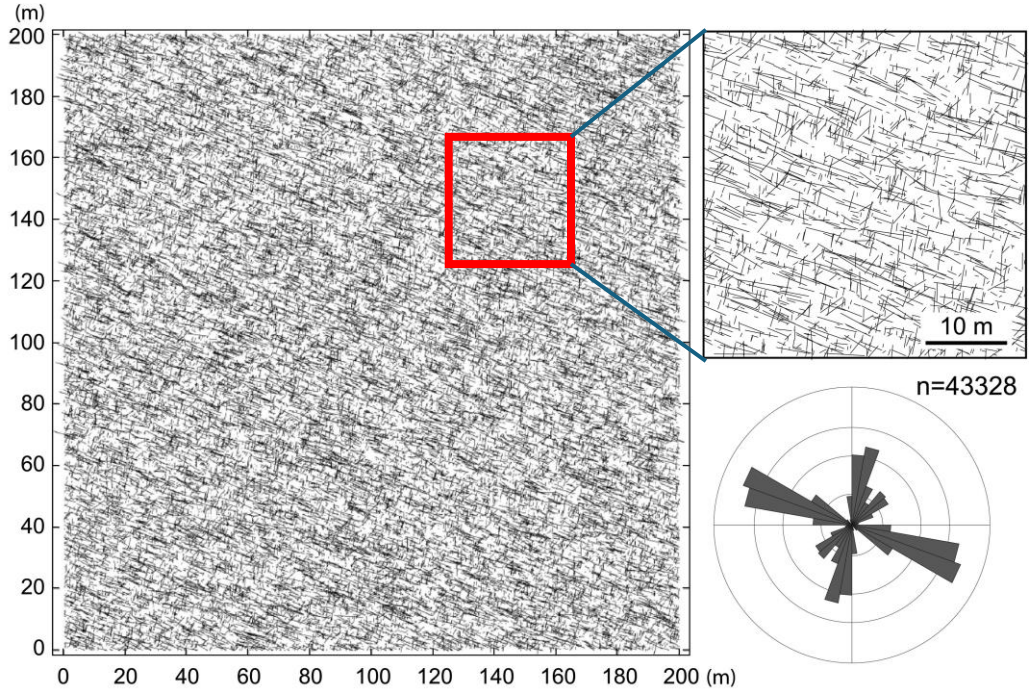
(a) Lineaments interpretation from a satellite image of the Tordillo Formation outcrops. The sampling site, Mallín de los Caballos (MDC).

(b) & (c) Zoom-in of the satellite image highlighting the pattern and spacing of ENE-trending lineaments.

Result

Discrete Fractures Network(DFN):

Results show that the fracture network in the Mallín de los Caballos outcrop is poorly connected. Although clusters show extension in the WNW-ESE direction, they only account for a small part of the network. The overall system is largely segregated, with small clusters and high permeability anisotropy driven by the orientation of fracture clusters and the longest fractures.

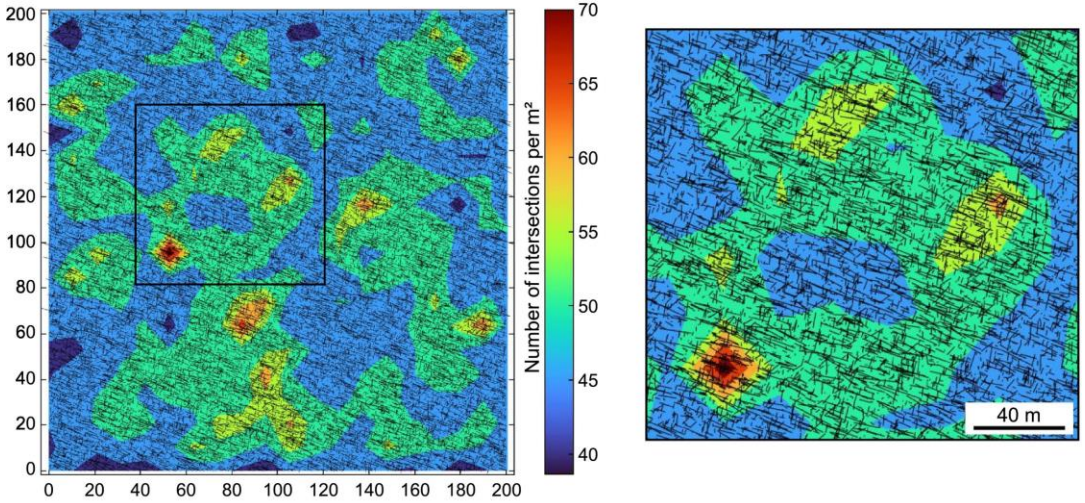


Base DFN model (left) and zoom-in (right) with the equal-area, length-weighted rose diagram of the generated synthetic fractures.

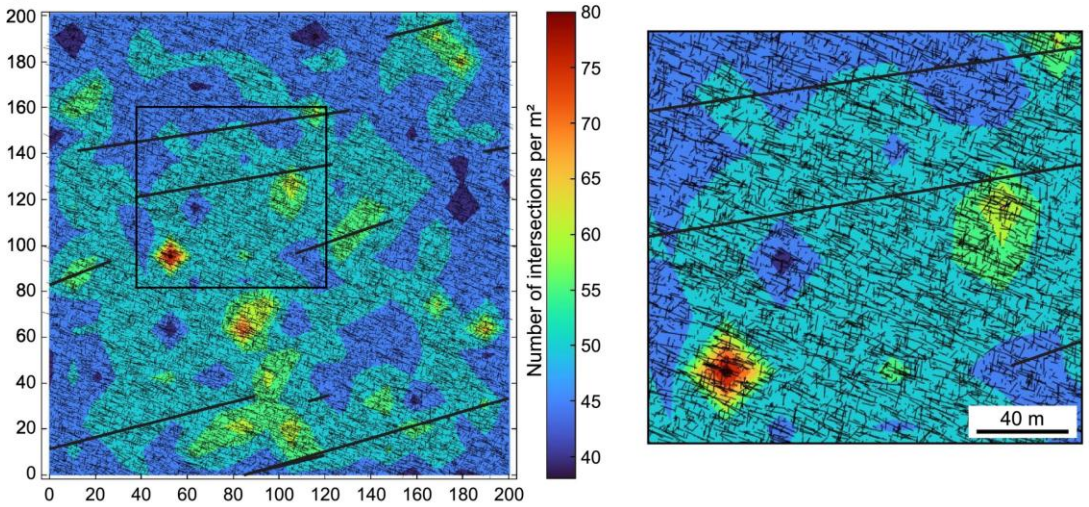
Discussion

1. Fracture intersection density: without or with fracture corridors

a Without fracture corridors



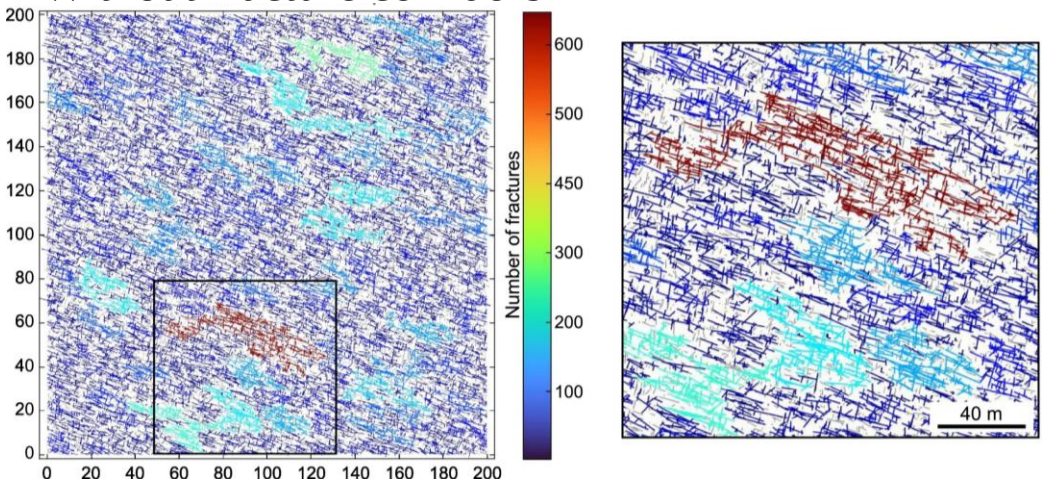
a With fracture corridors



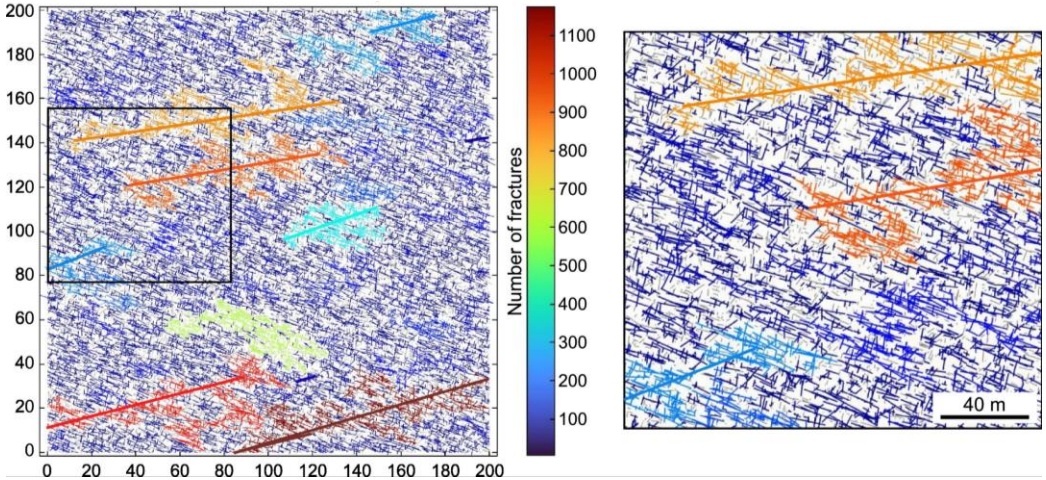
Fracture corridors increase the average fracture intersection density. The connectivity of the fracture were increased by the large scale ENE-WSW fracture.

2. Number of Fracture Clusters: without or with fracture corridors

b Without fracture corridors



b With fracture corridors



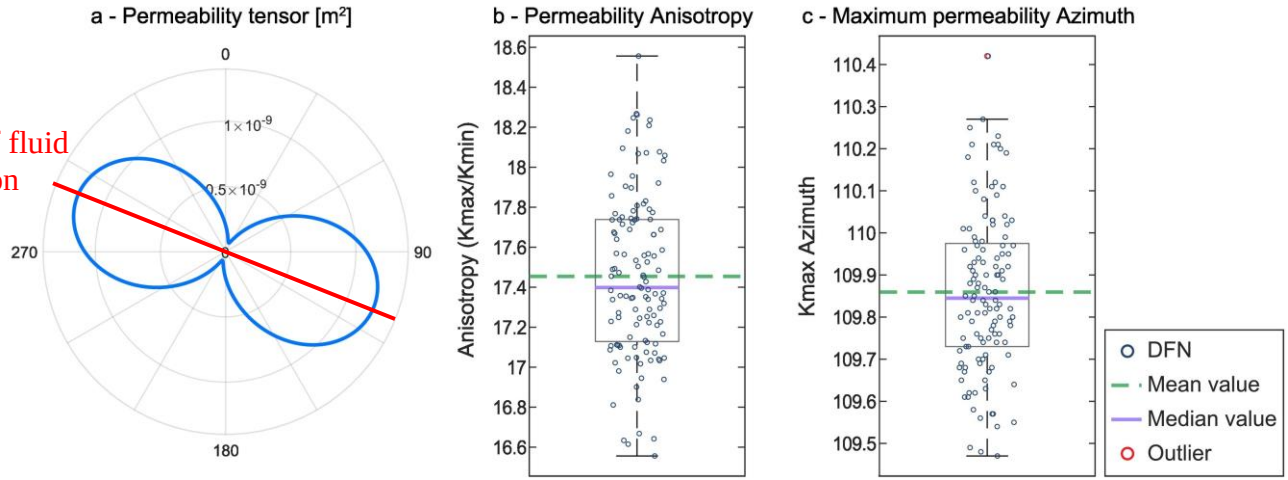
The figure shows connected fracture clusters colored according to the number of members.

Fracture corridors increase the Number of fracture clusters. That's another piece of evidence that shows that the fracture corridors increased the connectivity of the fracture.

3. Permeability Tensor & Anisotropy

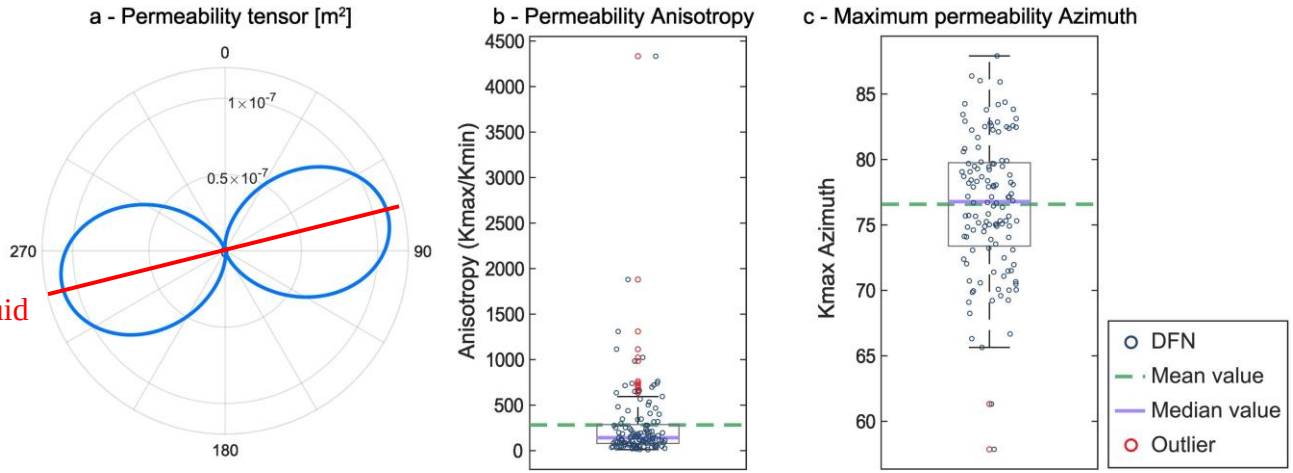
Without Fracture Corridors :

Direction of fluid migration



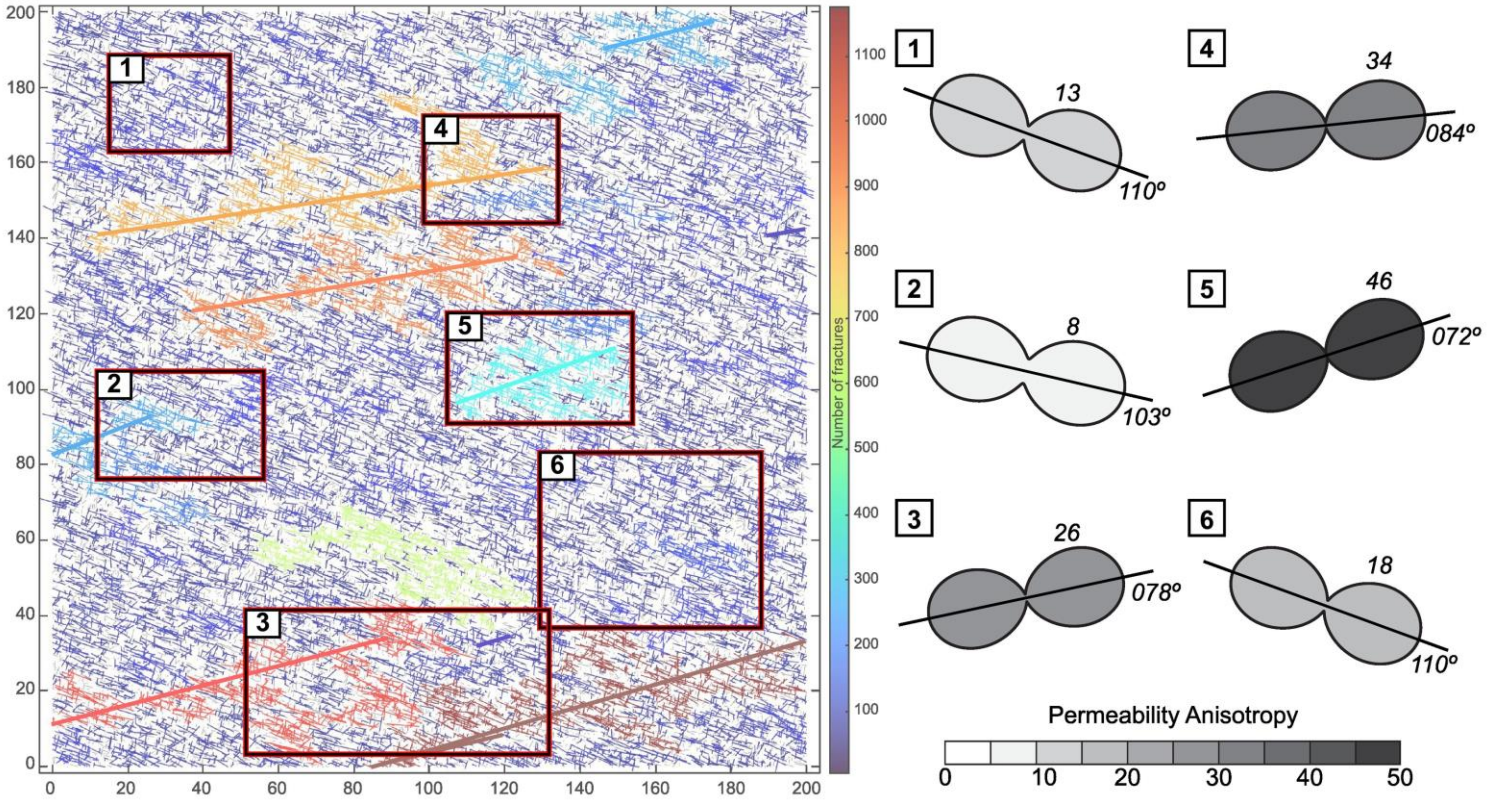
With ENE-WSW Corridors :

Direction of fluid migration



Changes in permeability anisotropy may affect the hydraulic fracturing process.

4. Base DFN with corridors cluster map and 2D permeability tensors for six selected sampling sites.



The right panel shows the permeability tensors for each sampling area, with anisotropy (K_{max}/K_{min}) values, and the orientation of the tensor's long axes indicating the direction of maximum permeability. These structures may serve as major pathways for fluid migration, affecting the reservoir's productivity.

Conclusion

1. A discrete fracture network (DFN) model is developed using a multi-scale approach that combines field data, UAV-derived orthomosaics, and satellite imagery.

2. ENE-oriented large-scale structures observed near this site within the Tordillo Formation outcrops were characterized and interpreted as fracture corridors.

3. In the absence of large-scale structures, the fracture network connectivity of the Vaca Muerta reservoir is low, and fluid flow is restricted.

4. Fracture corridors significantly improve the connectivity of the fracture network, increase permeability, and change the direction of fluid migration(anisotropy), which is crucial to the development of shale oil reservoirs.

Thank you for your attention.