Characterization and Modeling of Naturally Fractured Reservoirs: The Role of Outcrop Analogues

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Characterization and Modeling of Fractured Reservoirs: the Big Picture

iReservoir's Integrated Approach

1. Create Equally Probable Geologic Models
   - *Quantify* spatial heterogeneity
   - Identify the *fracture indicators* (curvature, faults, strain, lithology, etc.)
   - Map crack density from fracture indicators
   - Create site-specific *equally probable scenarios*
2. Constrain Geologic Models using *Seismic, Log and Engineering Data*
3. Use *History Matching* to constrain and validate the geologic model

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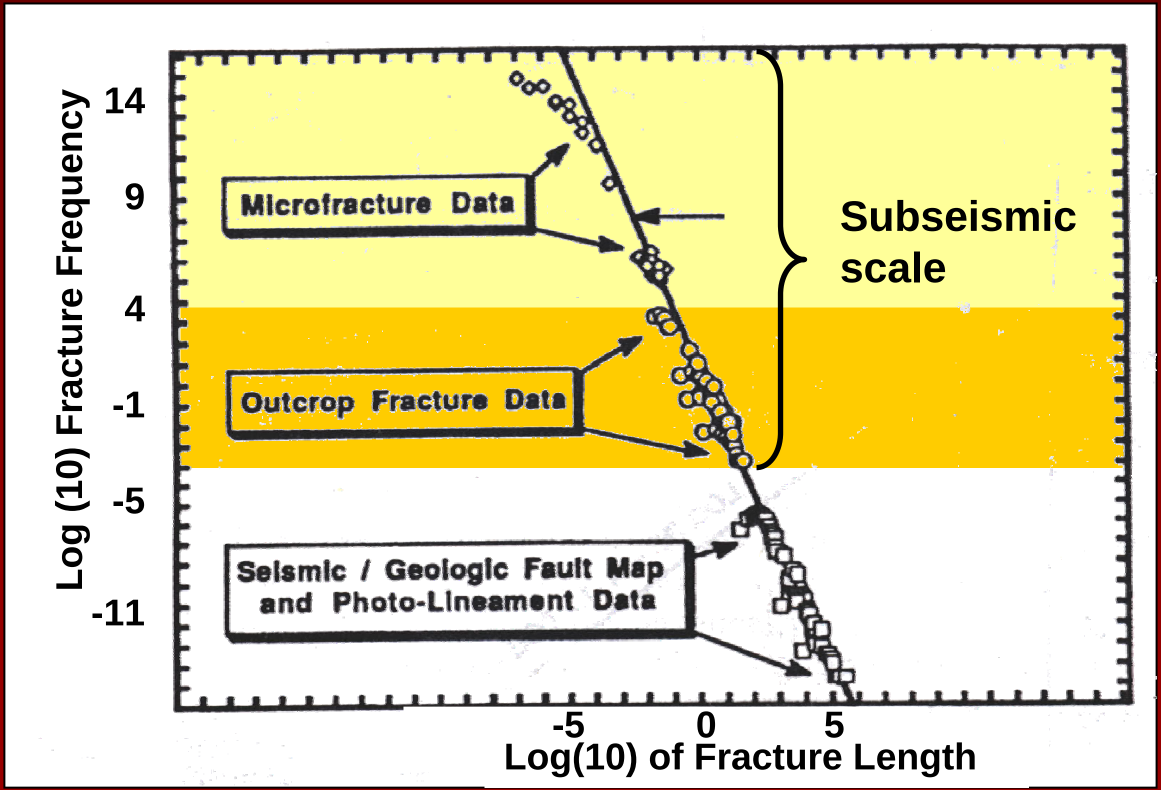
Why Outcrop Descriptions?

1. Spatial heterogeneity at subseismic scale
2. Deformation mechanisms and parameters controlling fracture distribution
3. Reservoir specific statistics



After Heffer & Bevan (1990)

Florez, 2006

Outline

1. Why outcrop analogues ?
2. Deformation mechanisms from outcrops
3. Example of faults and fractures systems fold and thrust belts:
    - Hierarchical shearing and progressive deformation,
    - Fracture hierarchies and stratigraphic architecture,
    - Factors controlling fracture distribution.
    - Comparison to subsurface.
4. The role of conjugate faulting on fracture localization.
5. Use of outcrop data for geostatistical modeling.
6. Conclusions.

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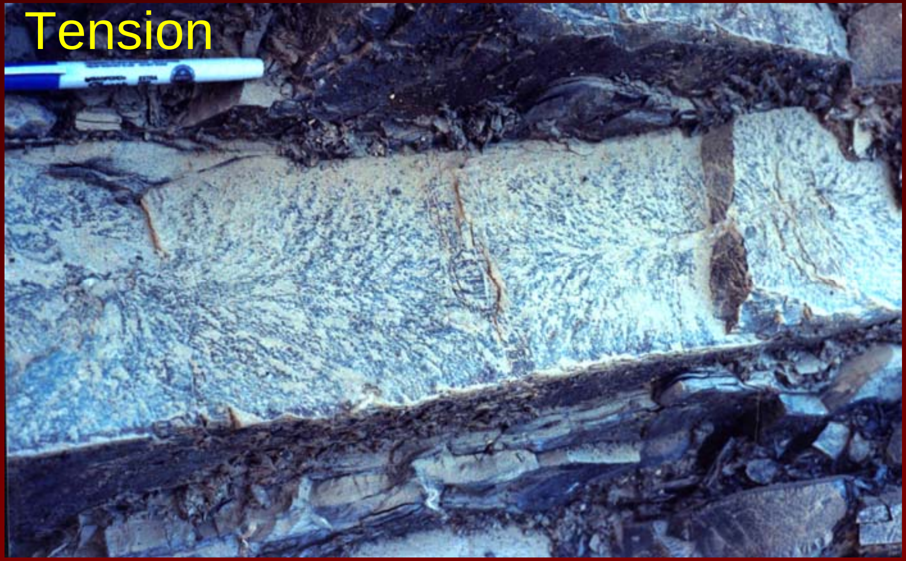
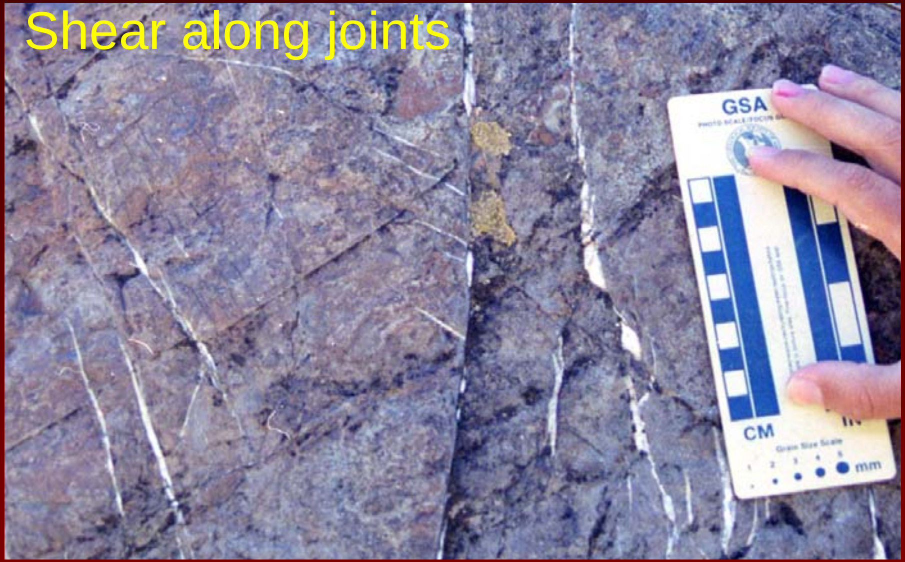
Deformation Mechanisms from Outcrops



Tension



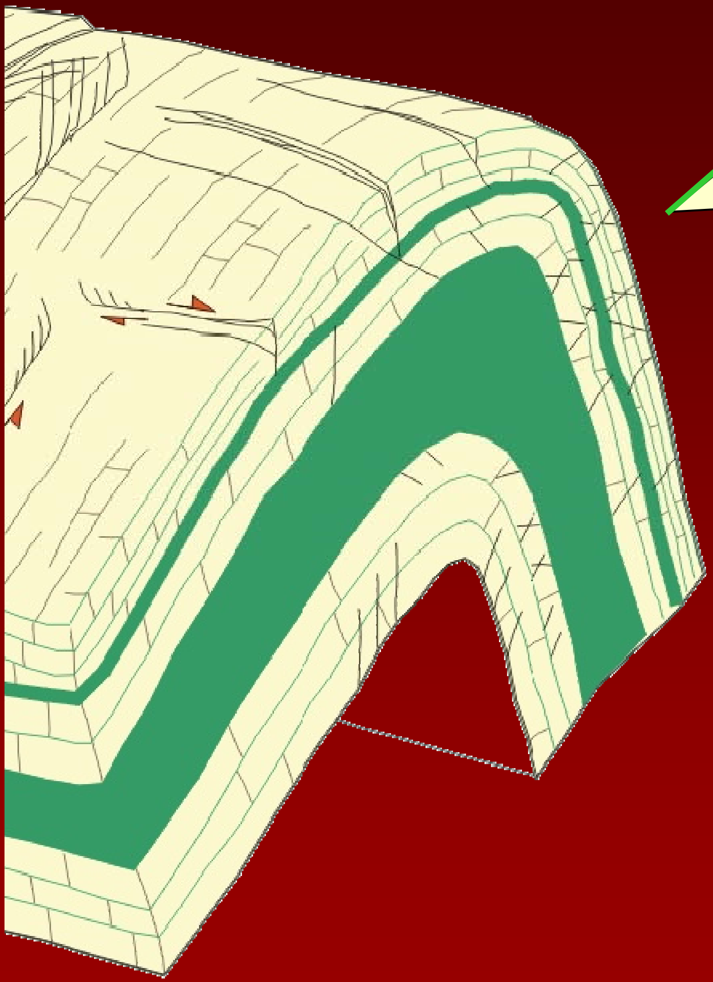
Shear along joints

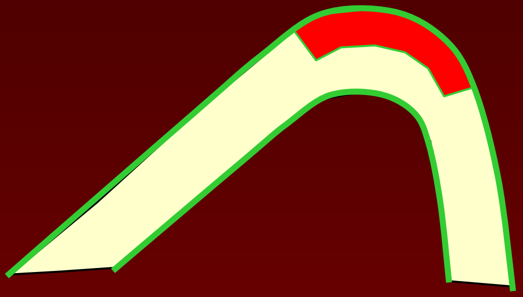
Tension and Compression

Flexural Slip

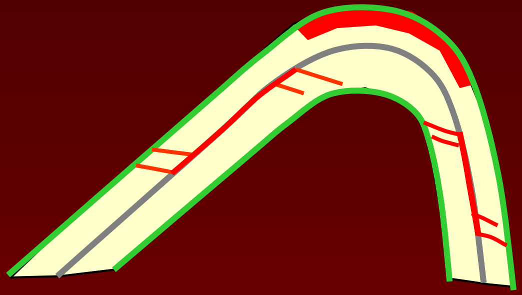
Florez, 2006

Fracturing Mechanisms





Bending



Flexural Slip

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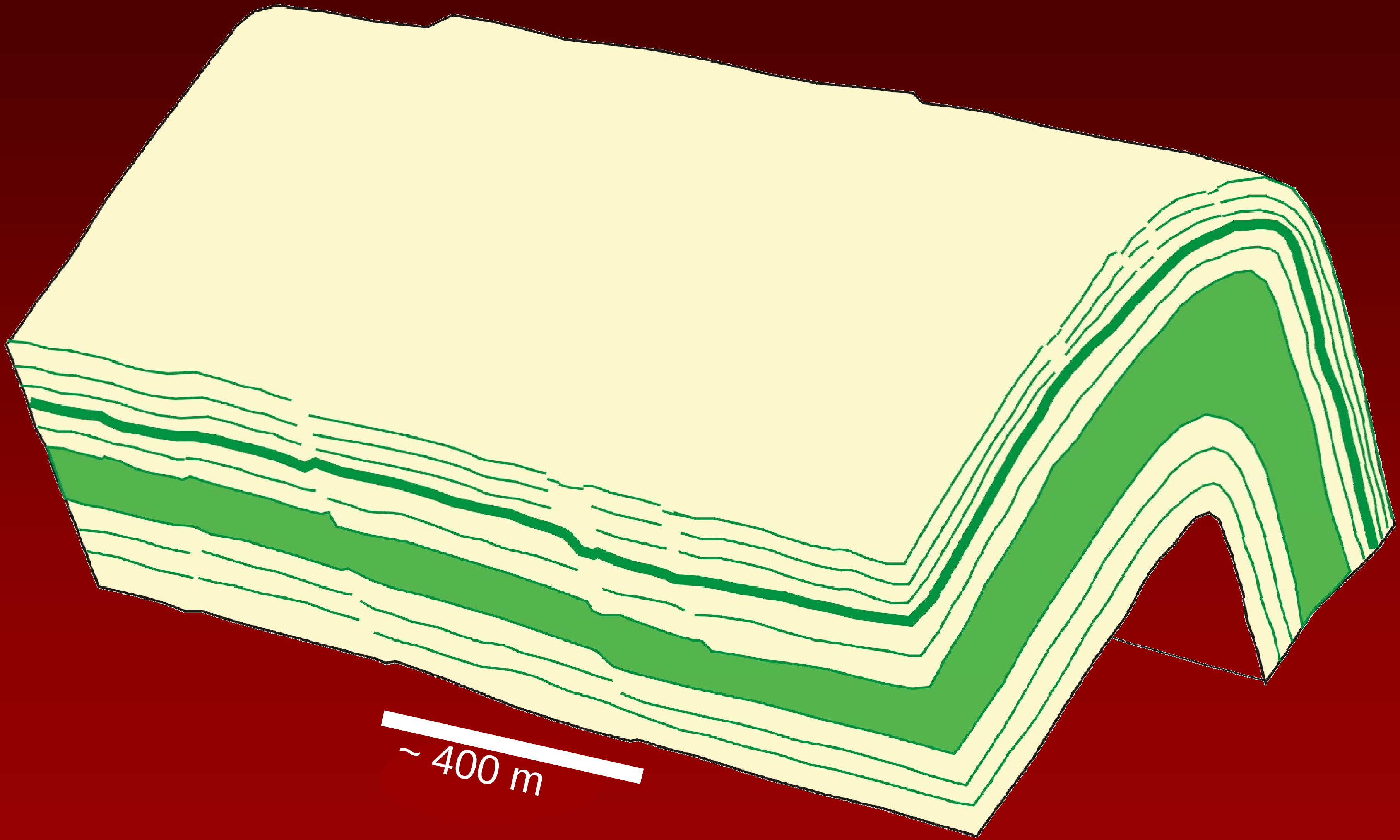
Faults and Fractures in a Fold and Thrust Belt



How are faults and fractures distributed in this Anticline?

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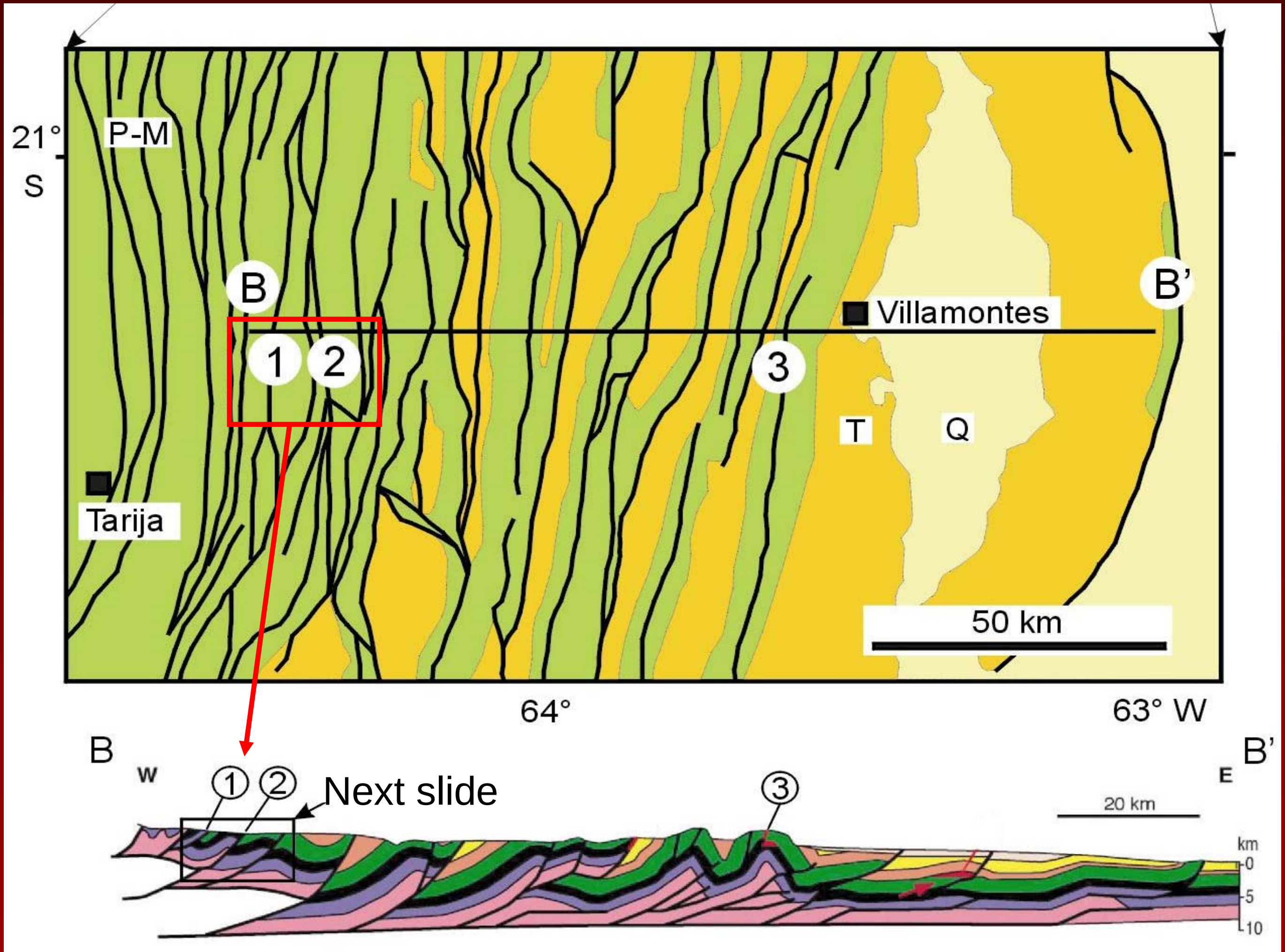
Bolivian Subandean Fold and Thrust Belt



After Labaume et al, 2001

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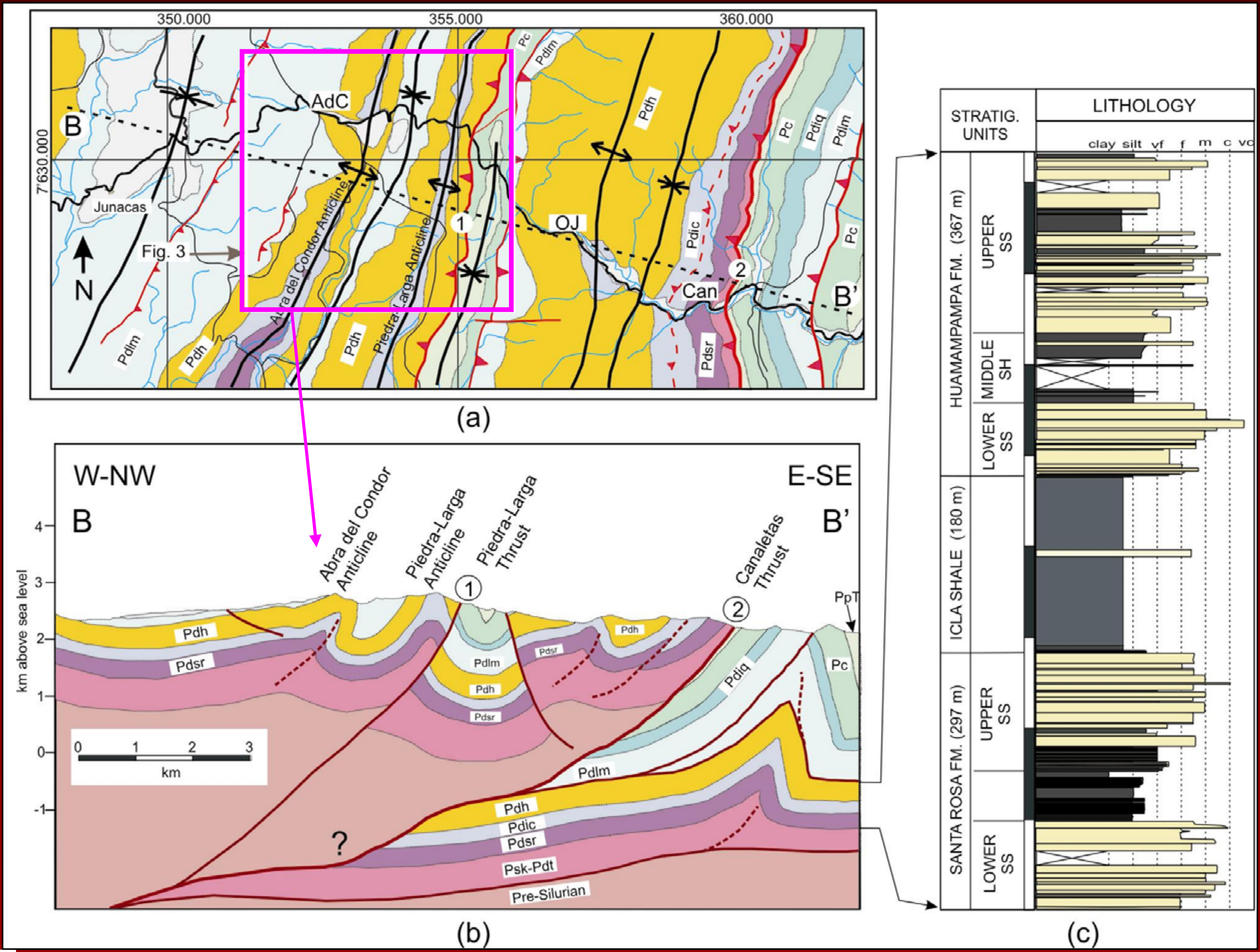
Faults and Fractures at the Abra del Condor Anticline



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Joints and Sheared Joints

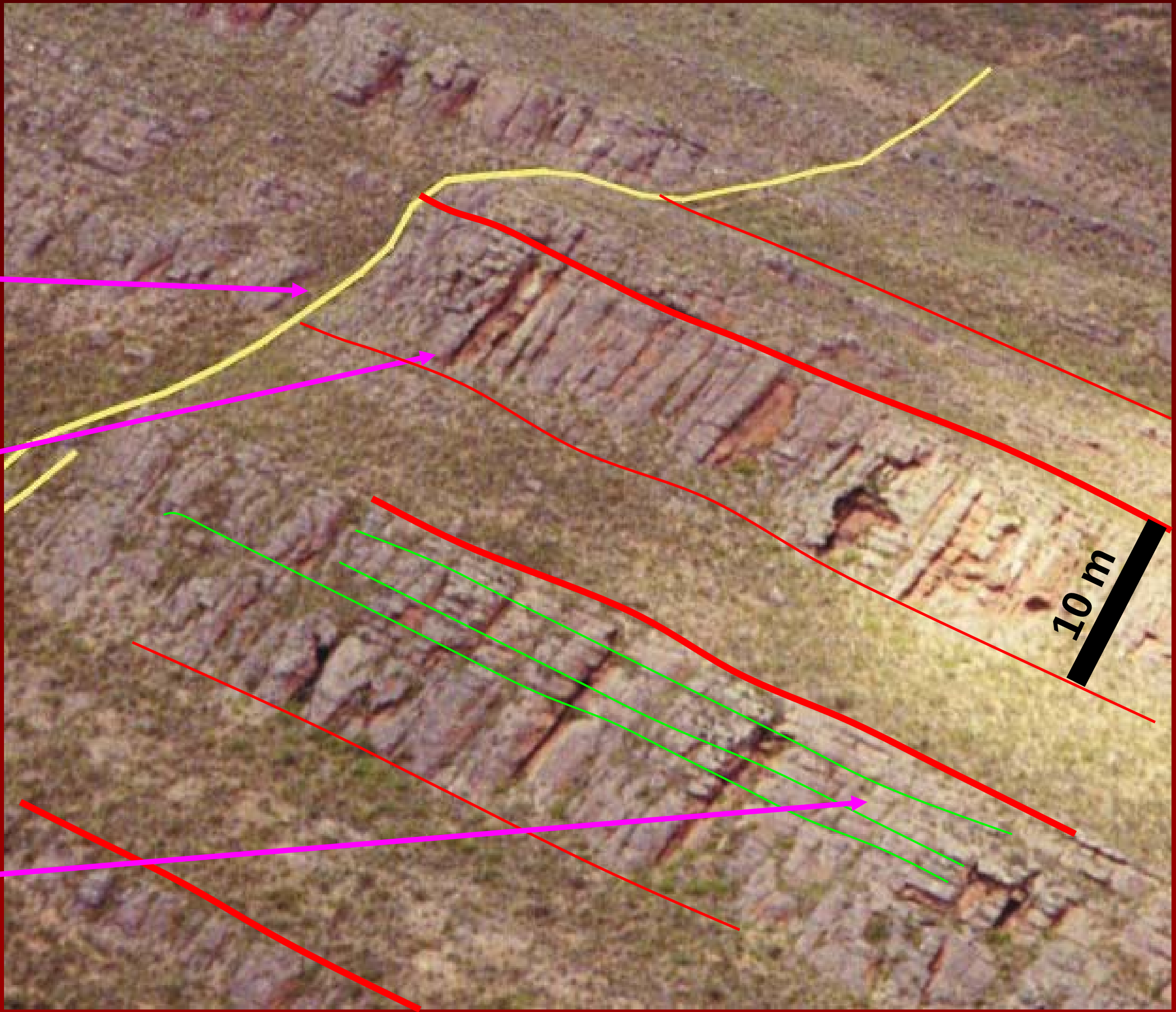
Joints

Sheared Joints

Florez, 2006

Small and Intermediate Faults

Faults and fractures in this case are the result of hierarchical shearing and progressive deformation. Four main hierarchies identified: (1) joints, (2) small faults, (3) intermediate faults, (4) fault zones.



Intermediate Fault

Sheared Joints or Small Faults

Joints :

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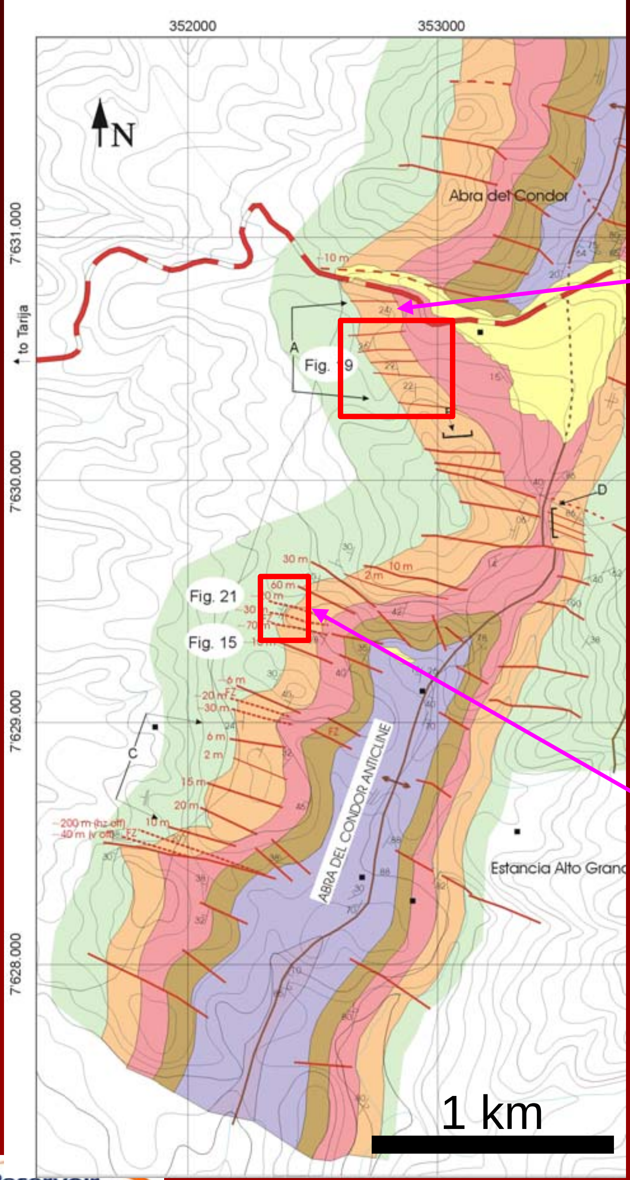
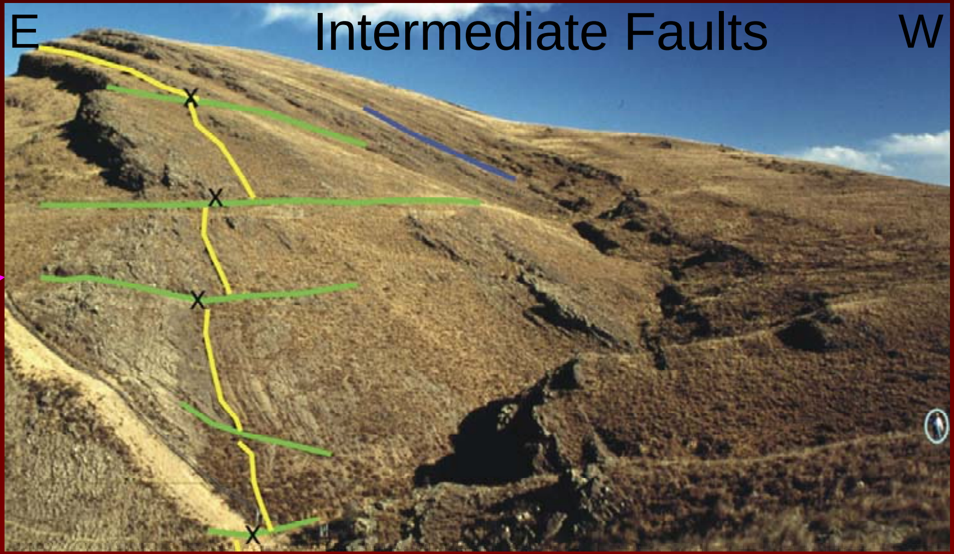
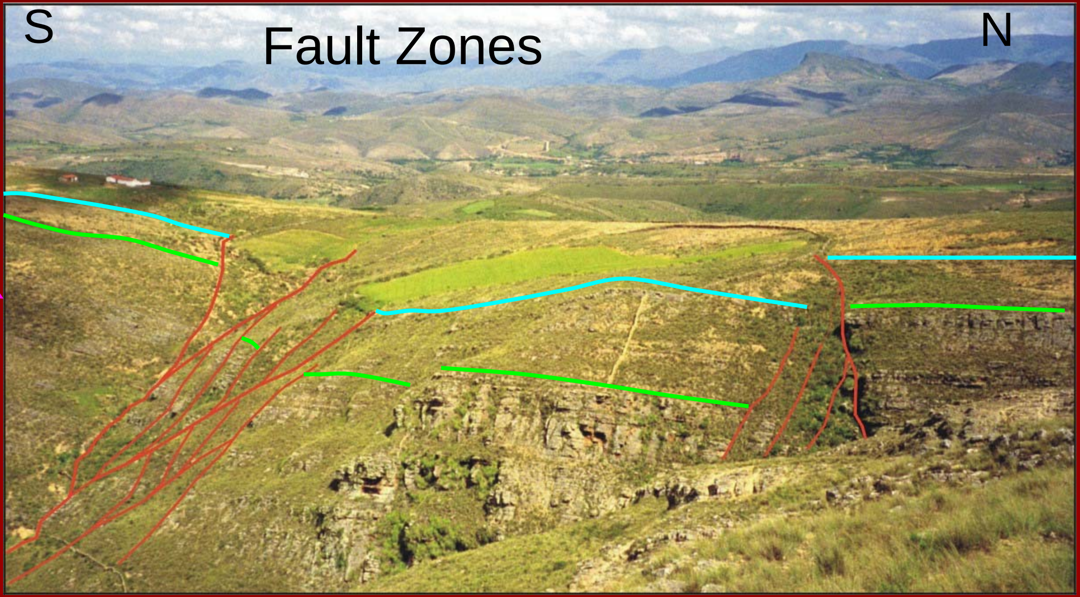
Fault Zones and Intermediate Faults







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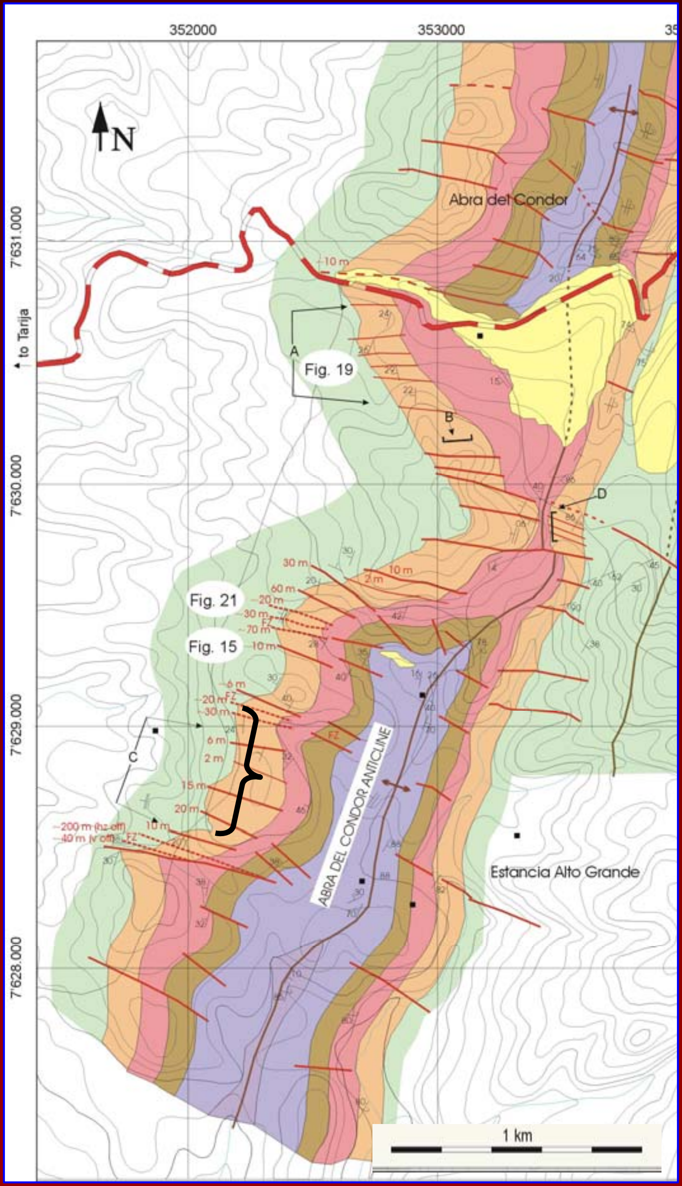
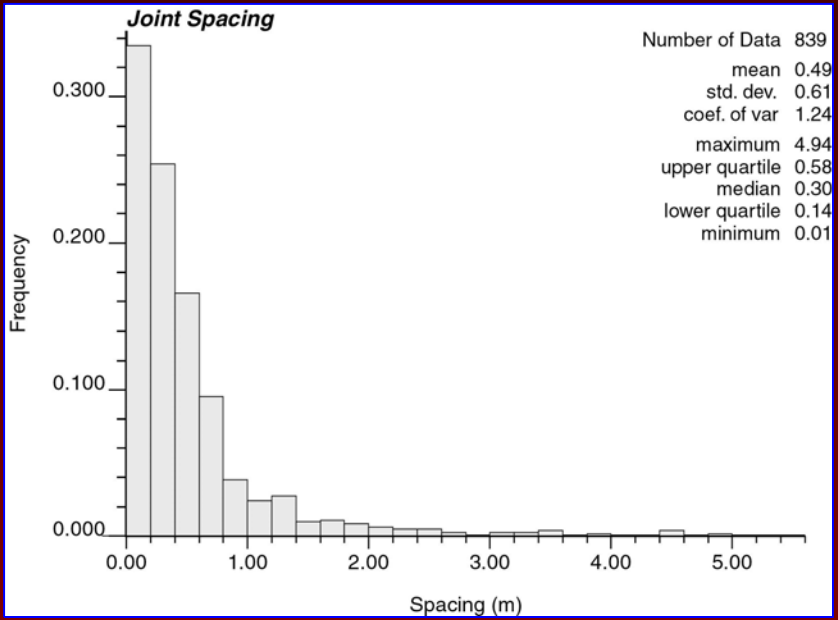
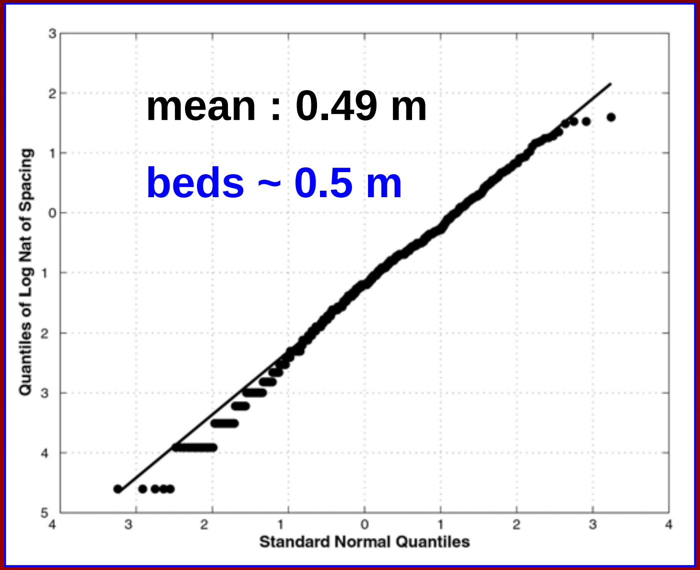
Spacing of Joints







mean : 0.49 m

beds ~ 0.5 m

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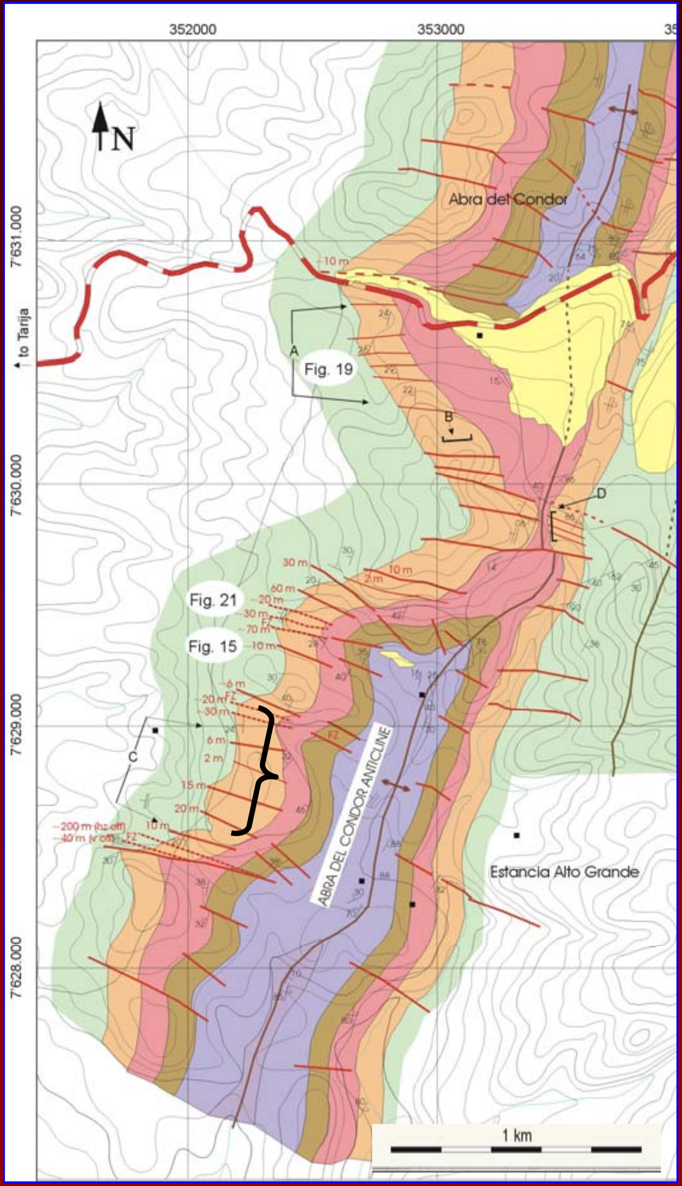
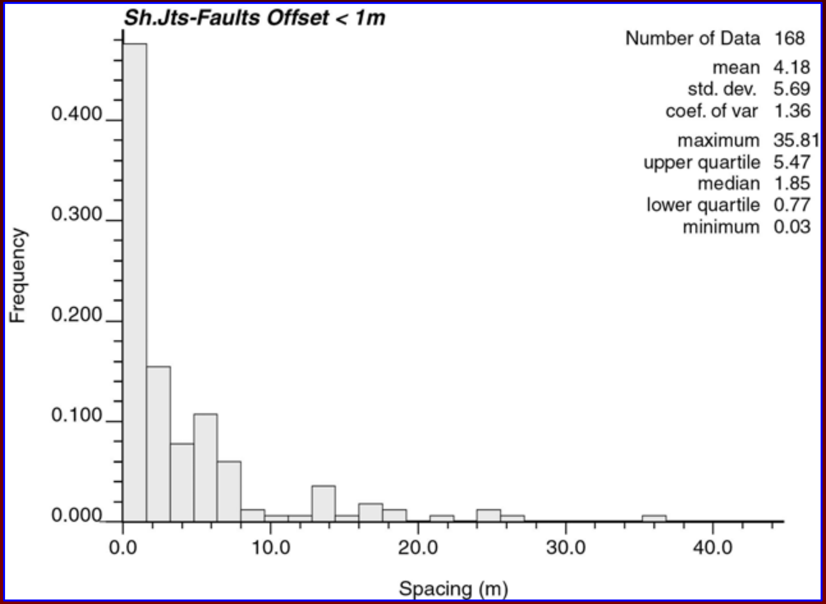
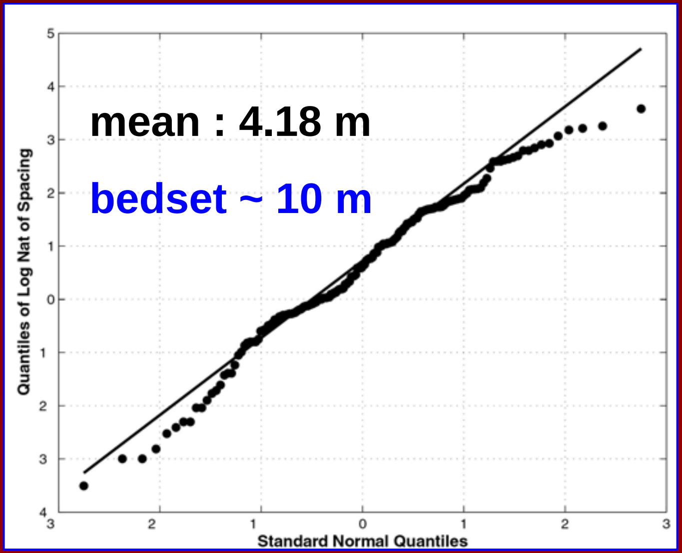
Spacing of Small Faults







mean : 4.18 m

bedset ~ 10 m

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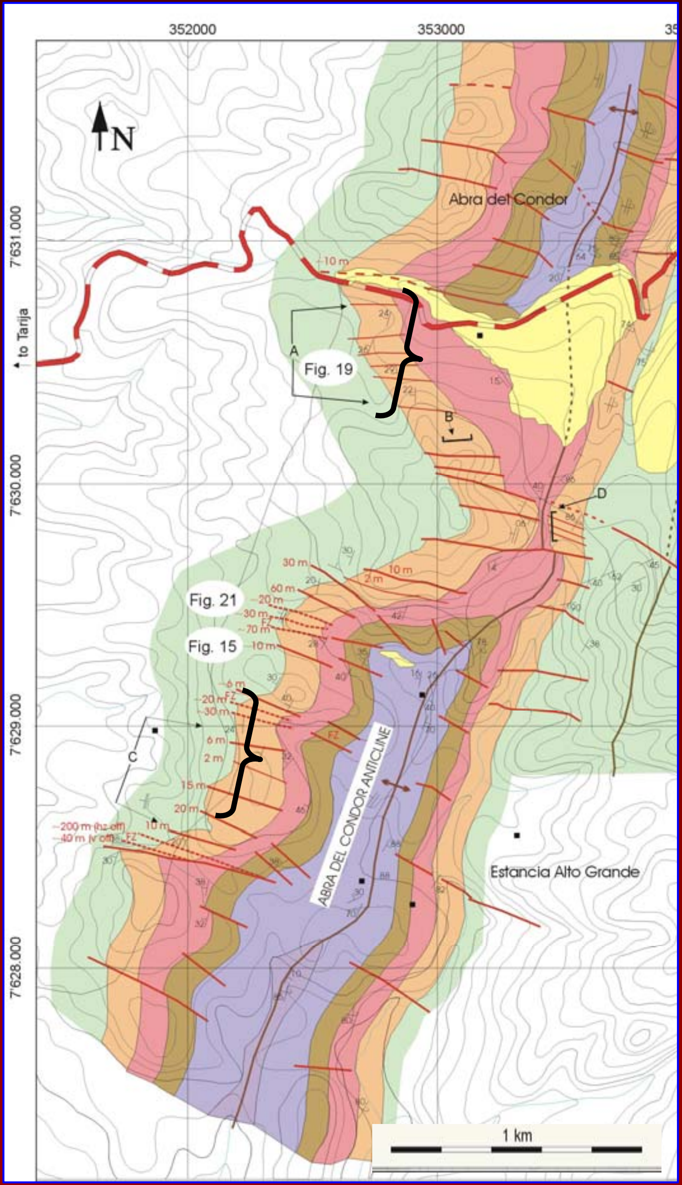
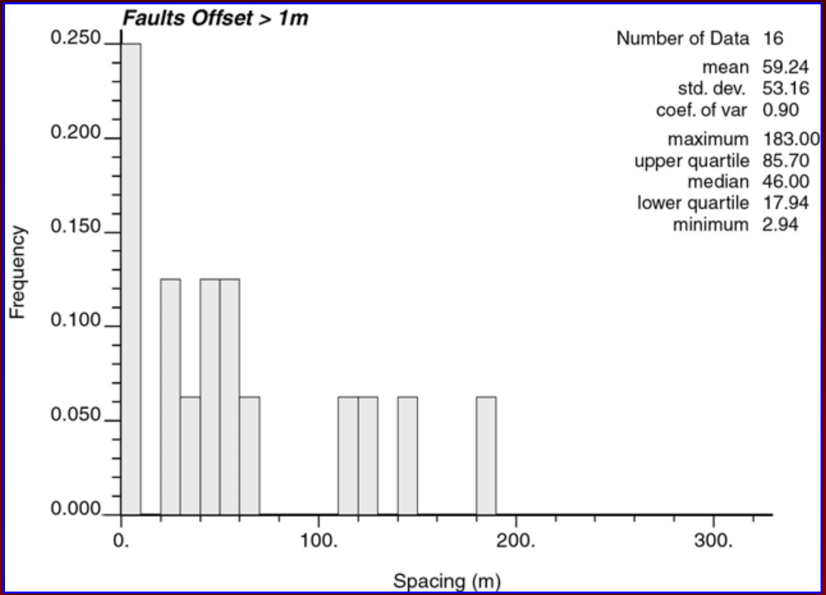
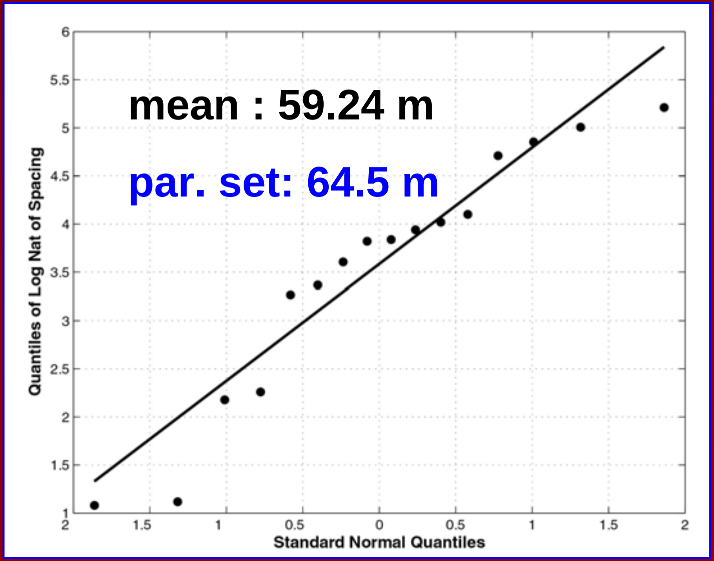
Spacing of Intermediate Faults







mean : 59.24 m

par. set: 64.5 m

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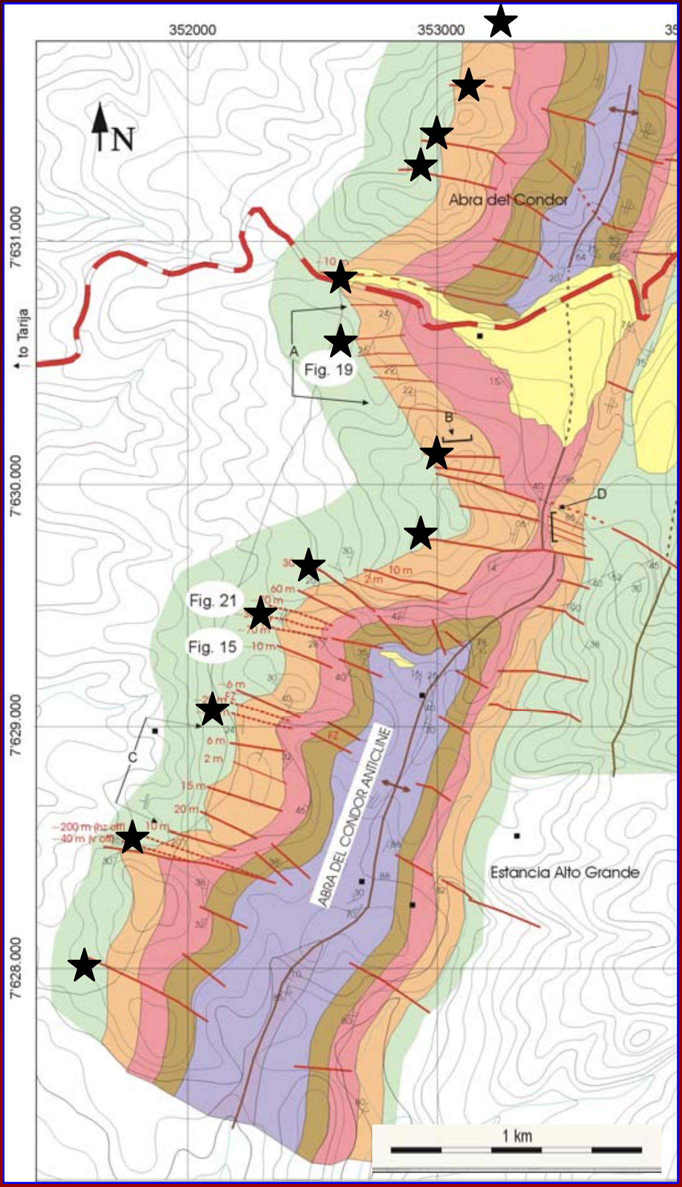
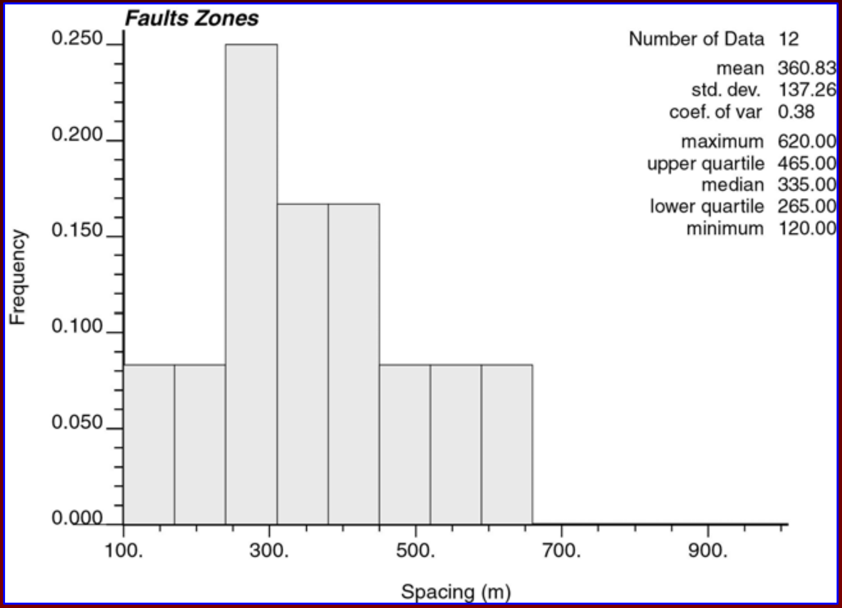
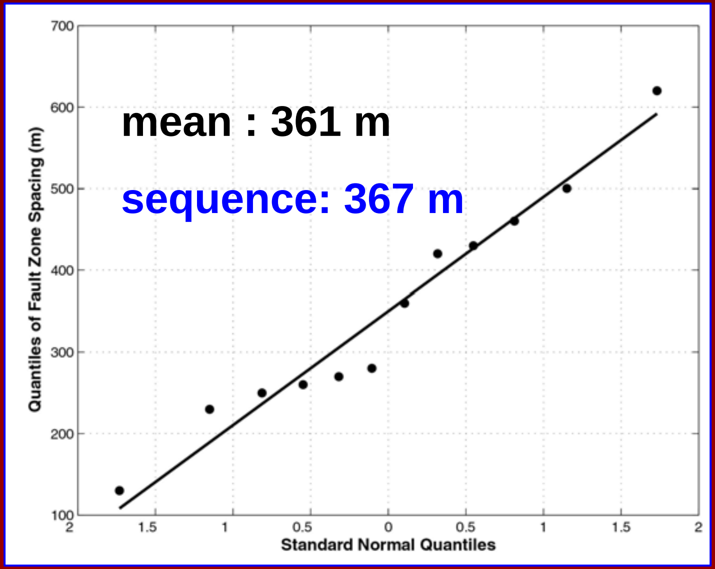
Spacing of Fault Zones






mean : 361 m

sequence: 367 m

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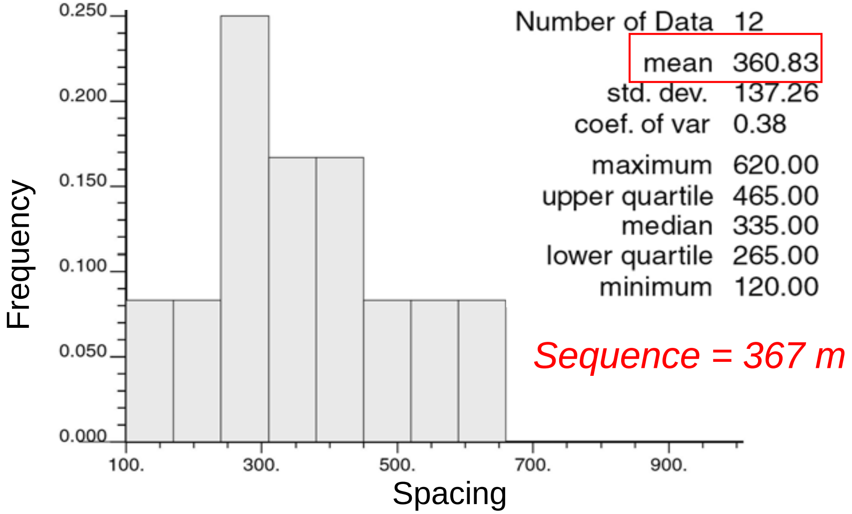
Fracture Spacing and Stratigraphy

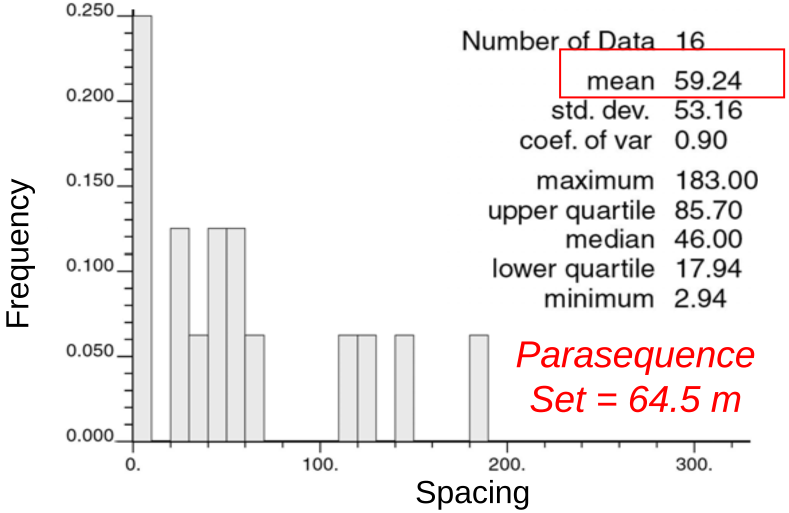
Fault Zones



Number of Data	12
mean	360.83
std. dev.	137.26
coef. of var	0.38
maximum	620.00
upper quartile	465.00
median	335.00
lower quartile	265.00
minimum	120.00

Sequence = 367 m

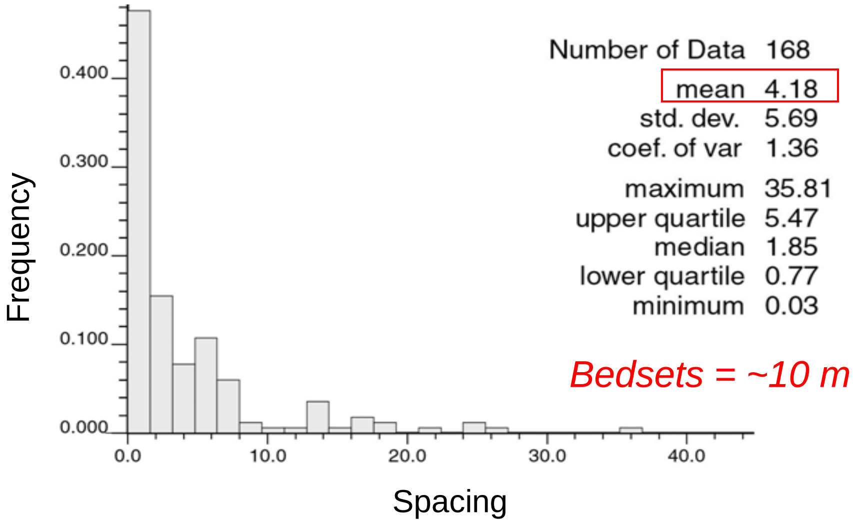
Intermediate Faults



Number of Data	16
mean	59.24
std. dev.	53.16
coef. of var	0.90
maximum	183.00
upper quartile	85.70
median	46.00
lower quartile	17.94
minimum	2.94

Parasequence Set = 64.5 m

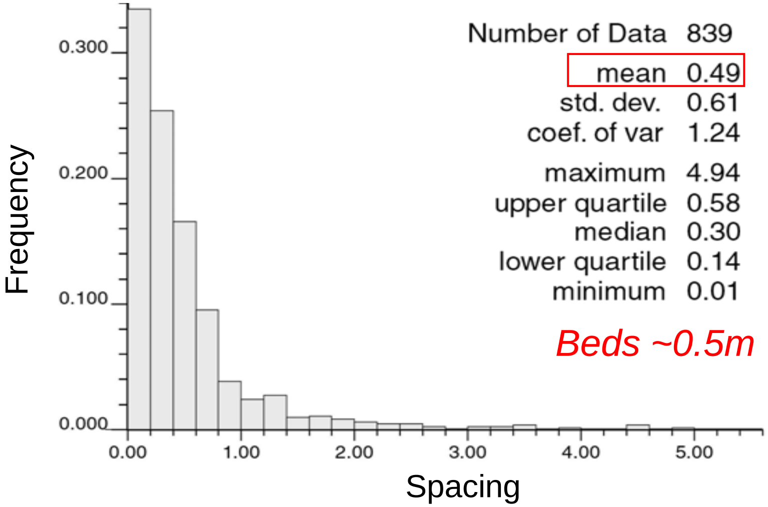
Small Faults (offset < 1m)



Number of Data	168
mean	4.18
std. dev.	5.69
coef. of var	1.36
maximum	35.81
upper quartile	5.47
median	1.85
lower quartile	0.77
minimum	0.03

Bedsets = ~10 m

Joints



Number of Data	839
mean	0.49
std. dev.	0.61
coef. of var	1.24
maximum	4.94
upper quartile	0.58
median	0.30
lower quartile	0.14
minimum	0.01

Beds ~0.5m

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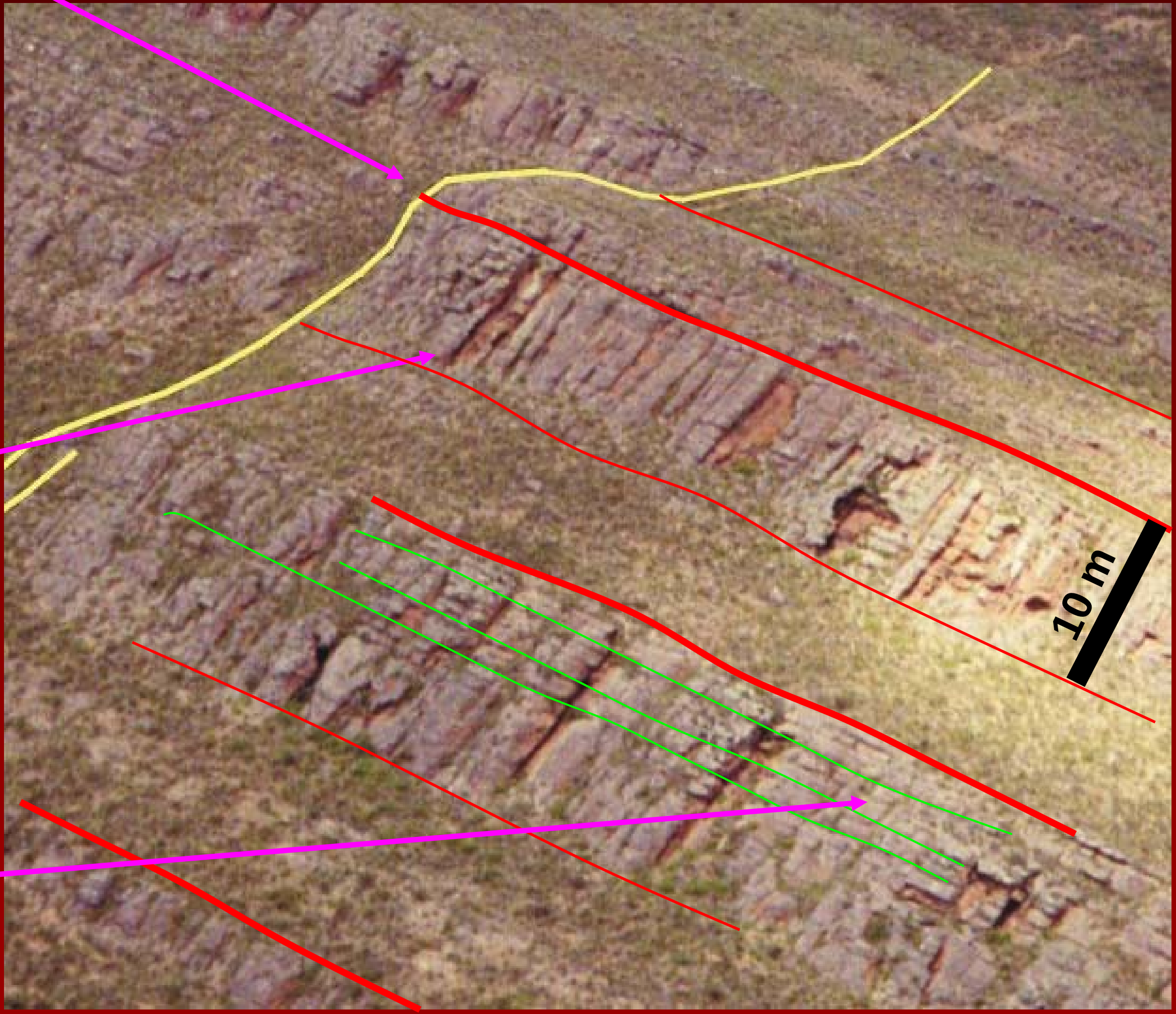
Factors Controlling Fracture Distribution: Stratigraphy and Lithofacies



Intermediate Fault:
Parasequence set

Sh-Joints/SF :
Bedsets and Parasequences

Joints :
Beds

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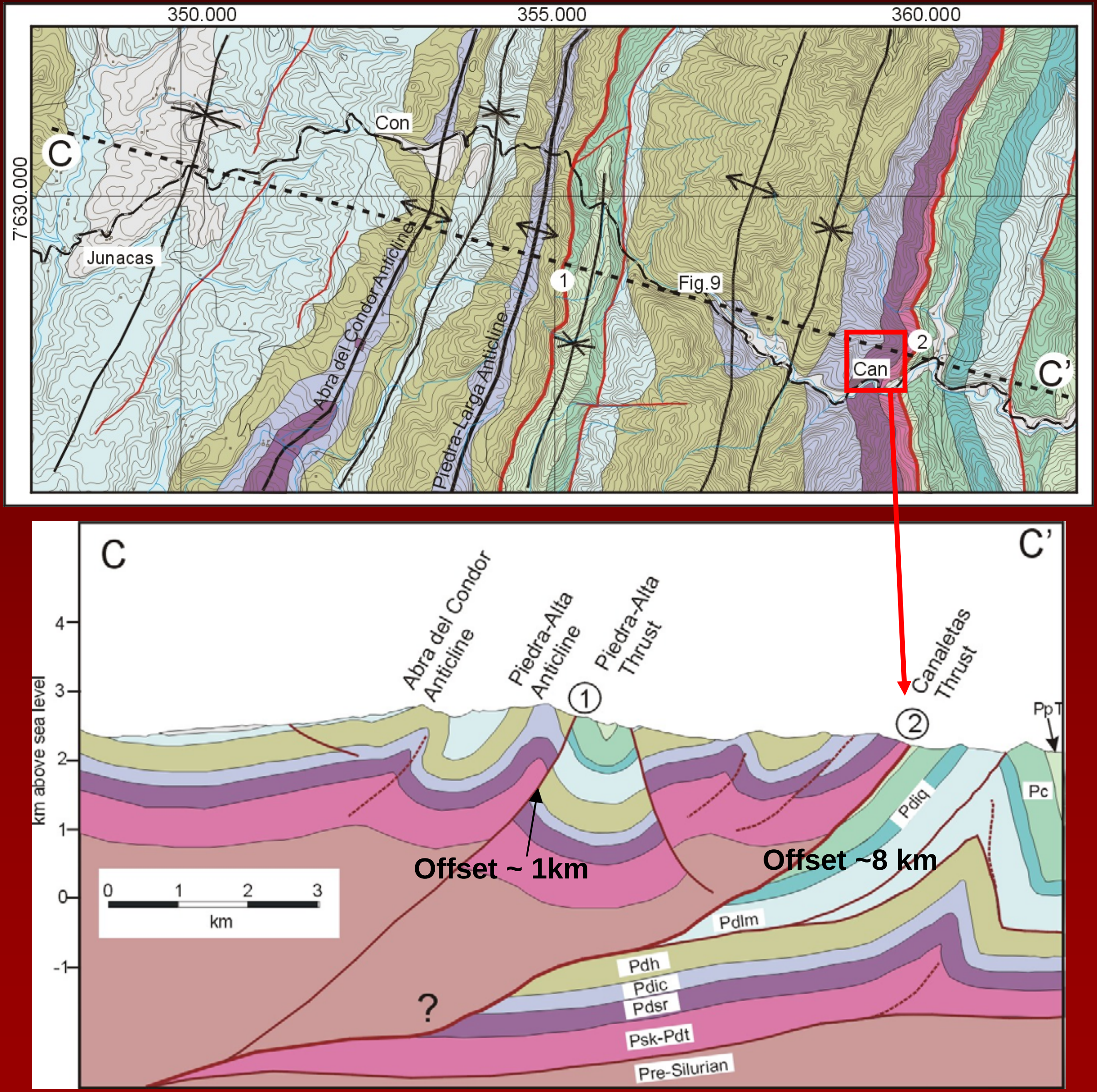
Fracture Spacing and Shear Strain



Offset ~ 1km

Offset ~8 km

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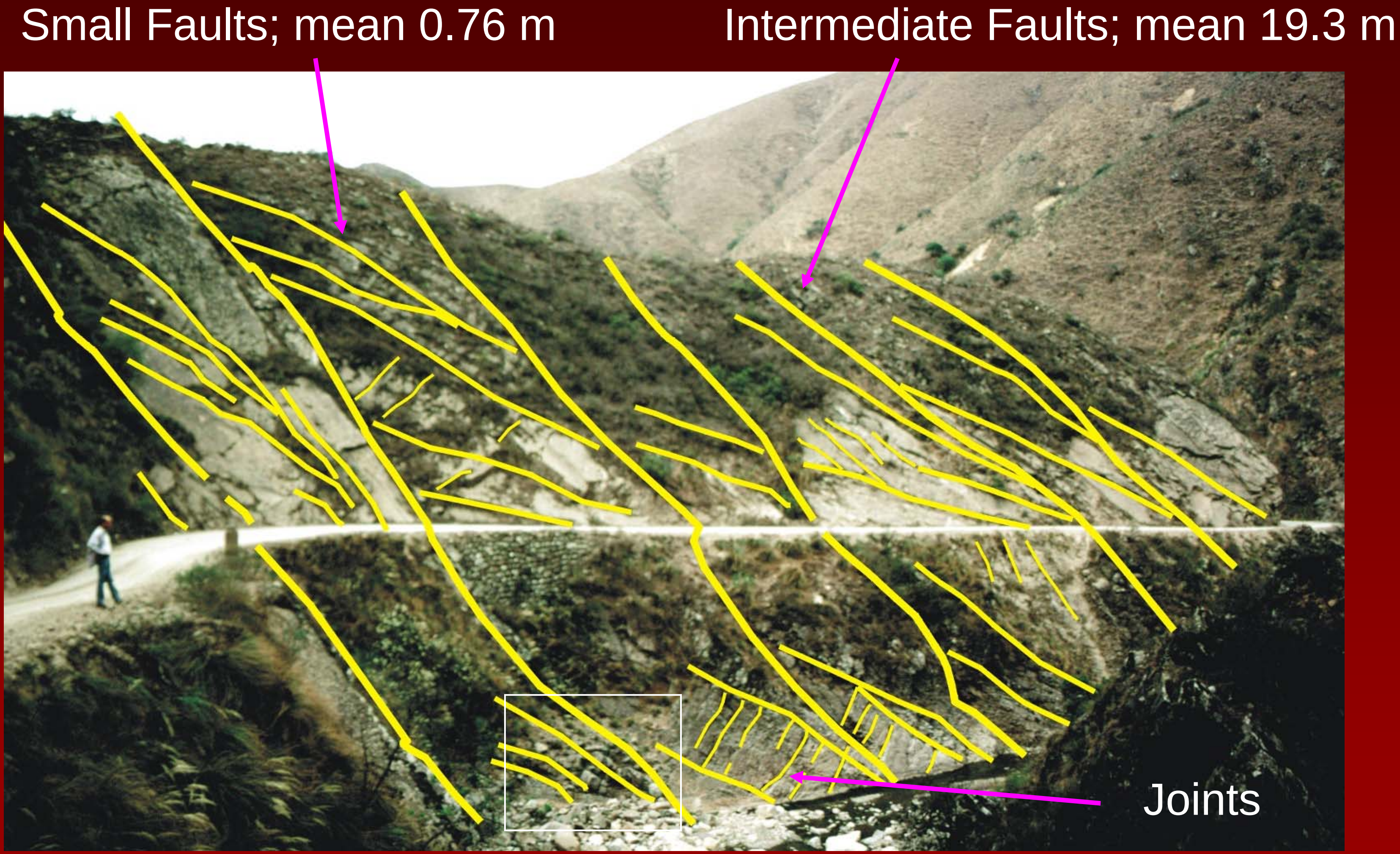
Fracture Spacing and Shear Strain



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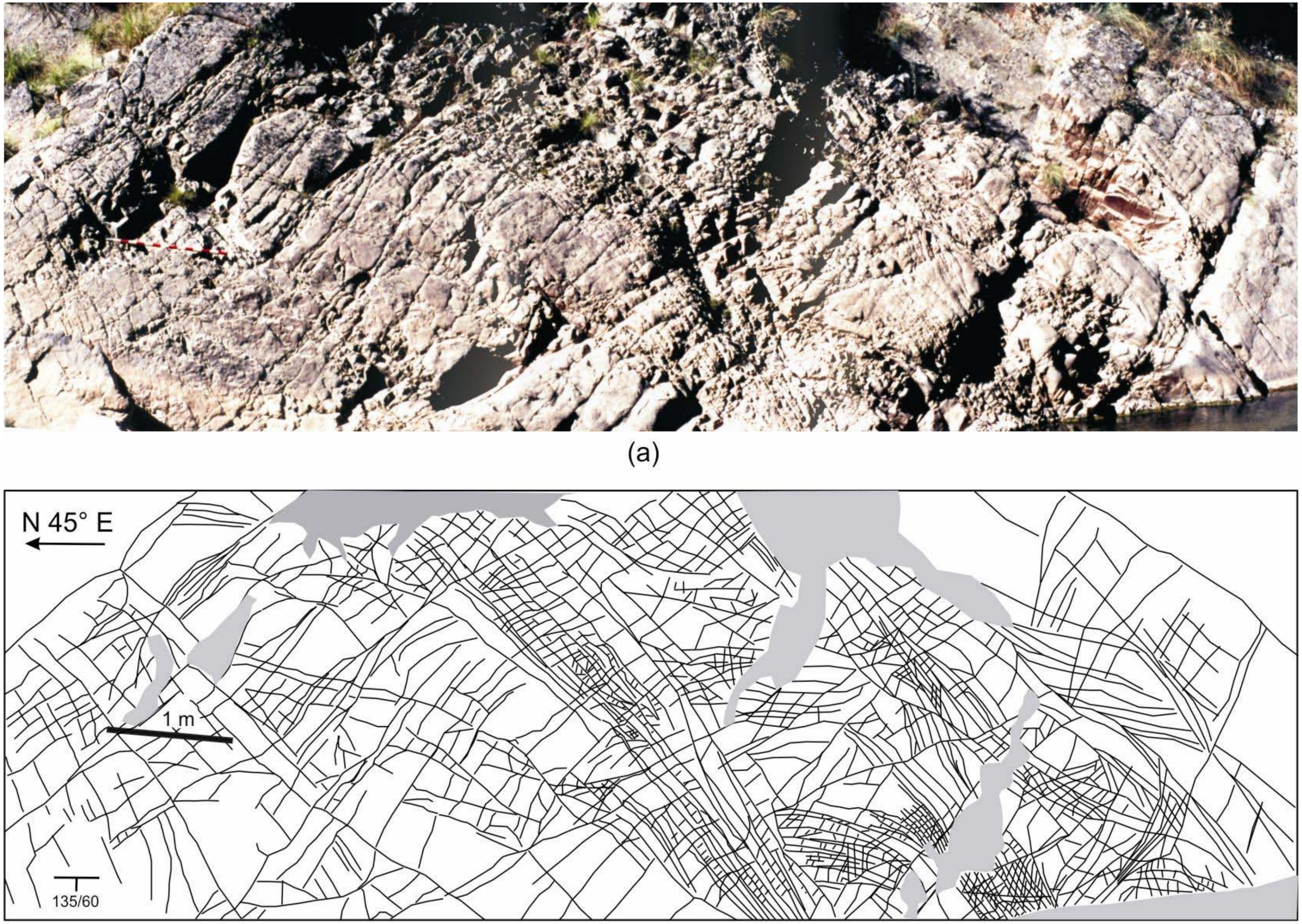
Complex Fracture Pattern near Canaletas Thrust



(a)

(b)

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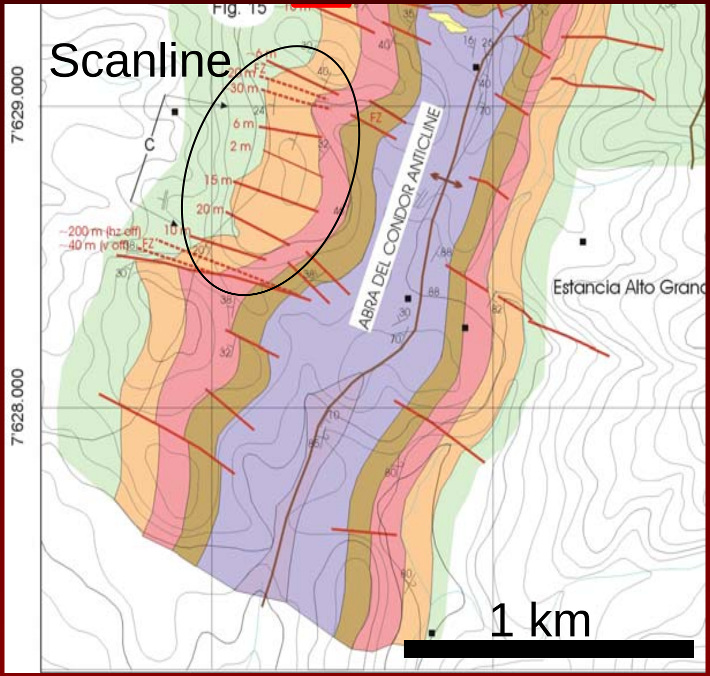
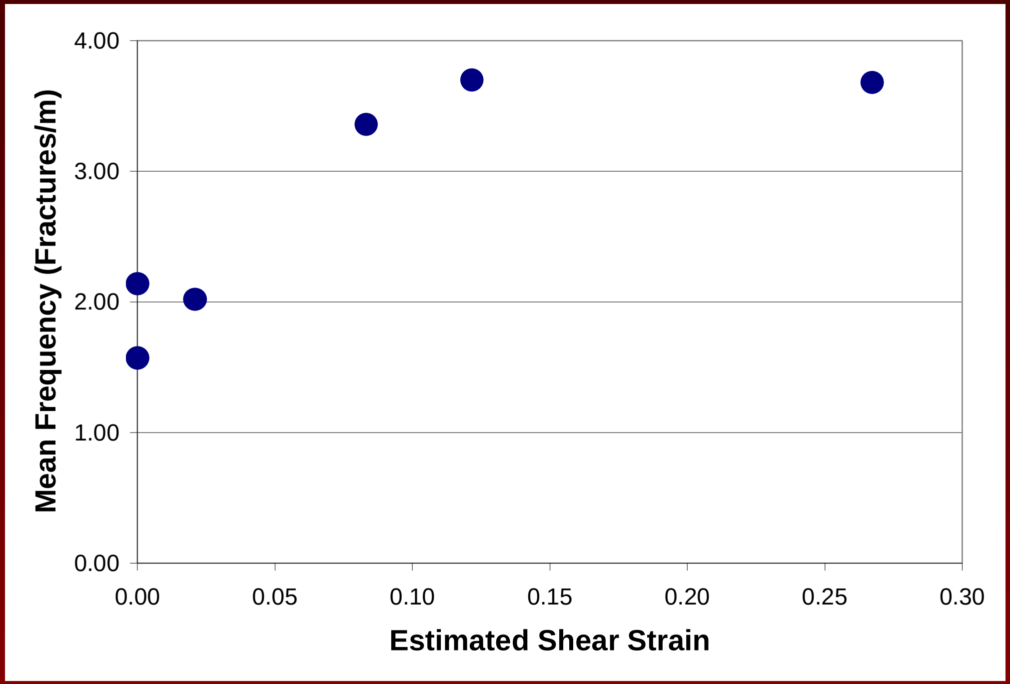
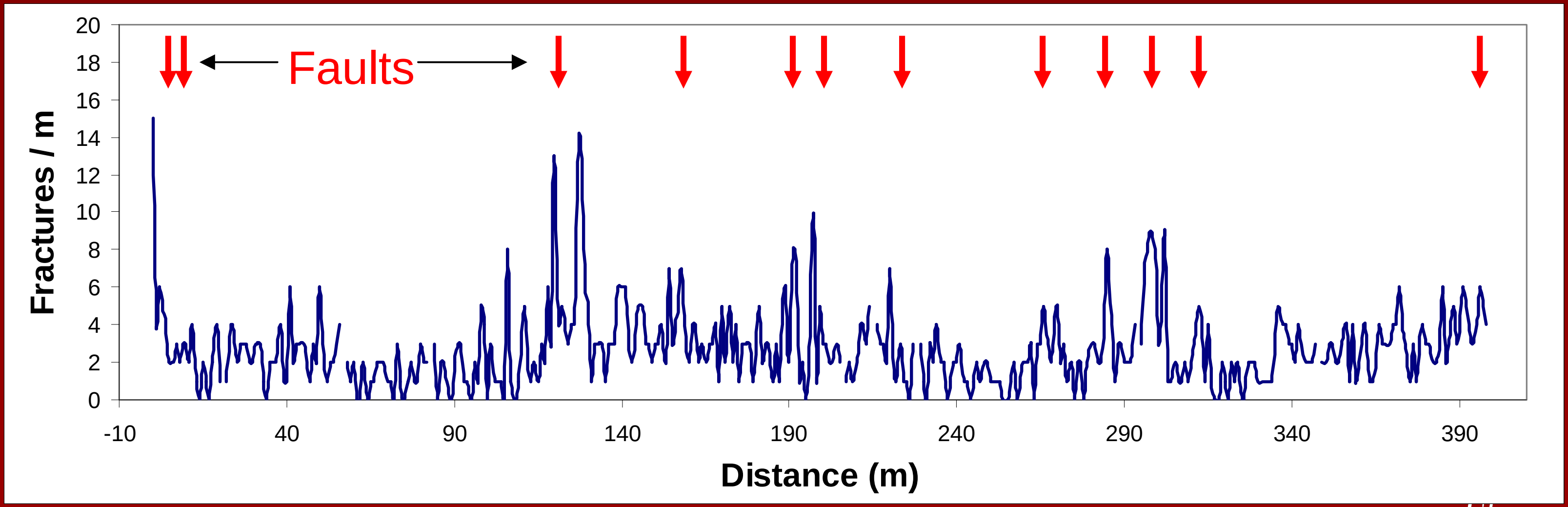
Shear Strain and Fracture Density







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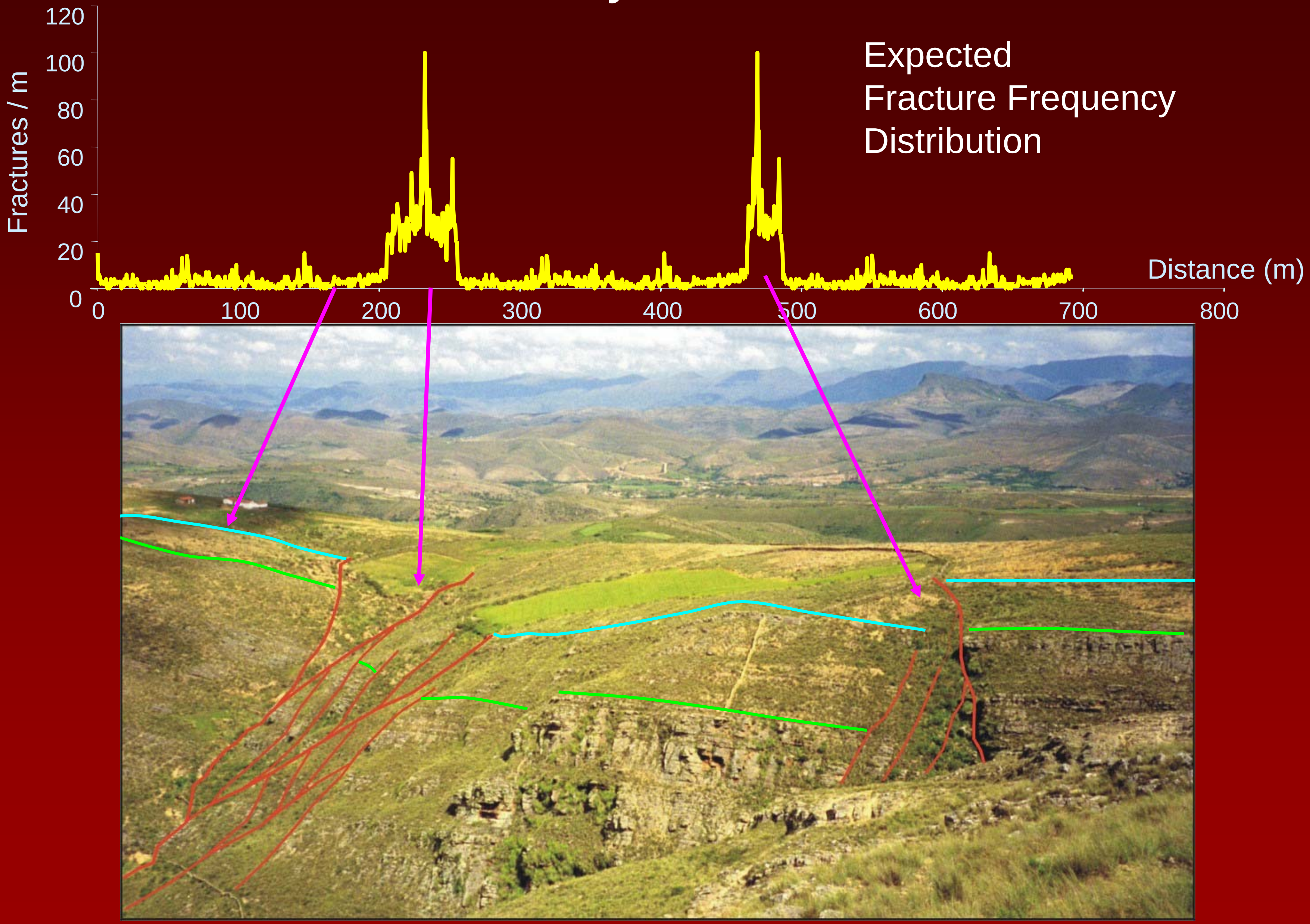
Fracture Density and Fault Zones



Expected
Fracture Frequency
Distribution

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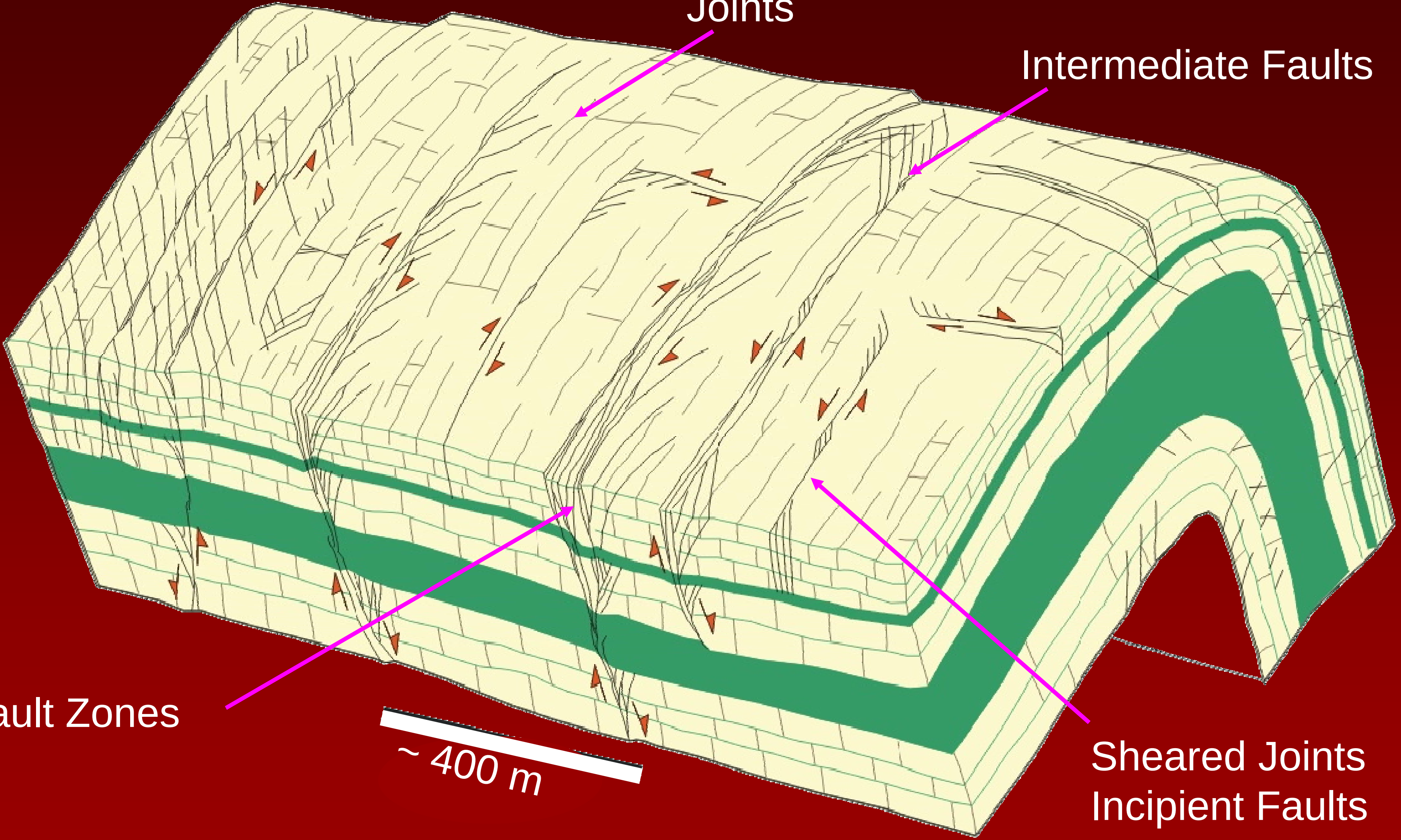
How are Faults are Fractures distributed?



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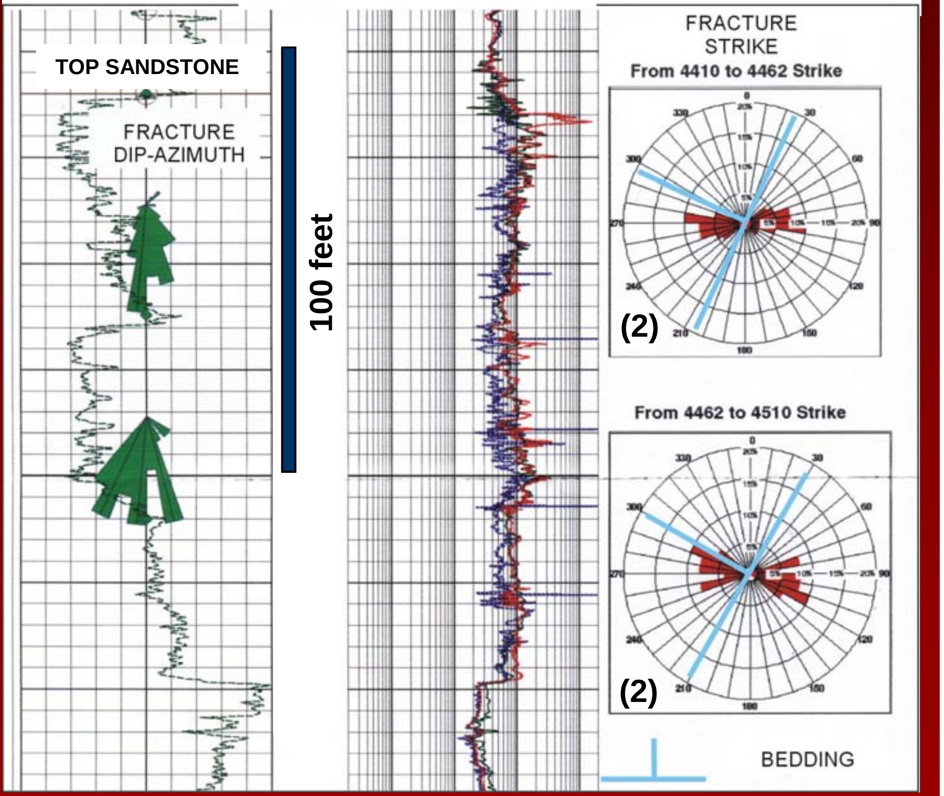
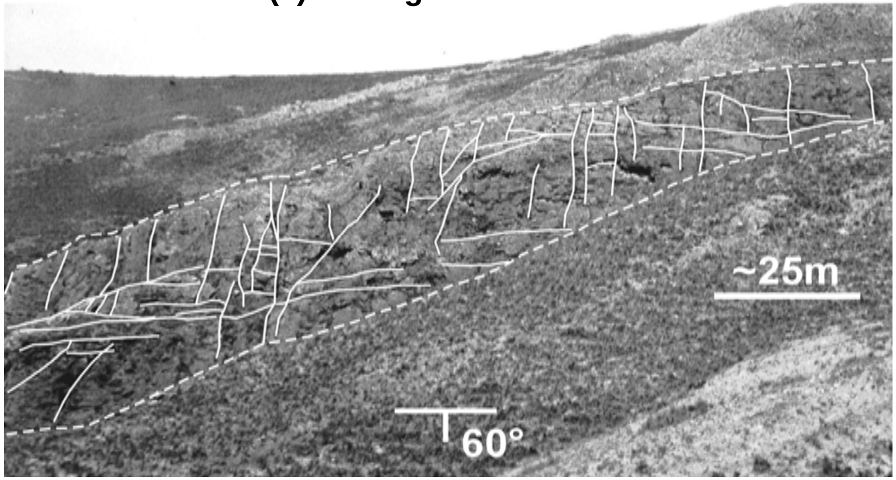
Comparison to Subsurface: Orientation

SUBSURFACE DATA

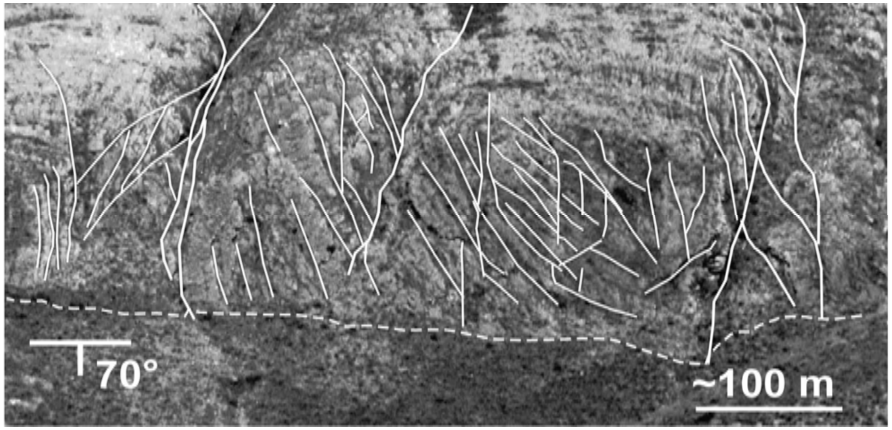


OUTCROP OBSERVATIONS

(1) Orthogonal Fracture Sets



(2) Dip-Parallel Faults and Oblique Splays



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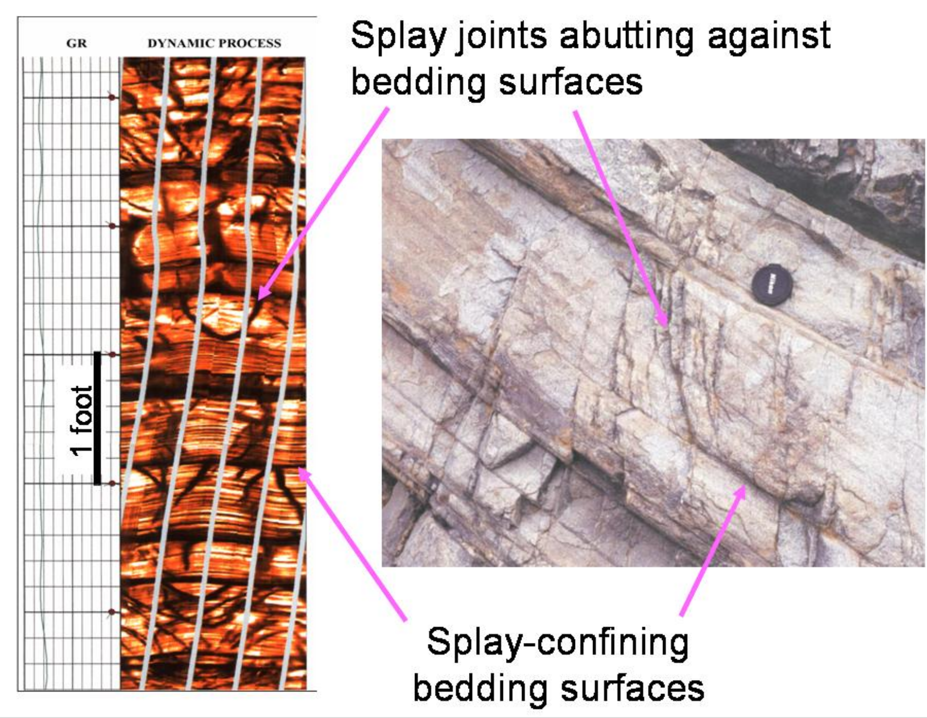
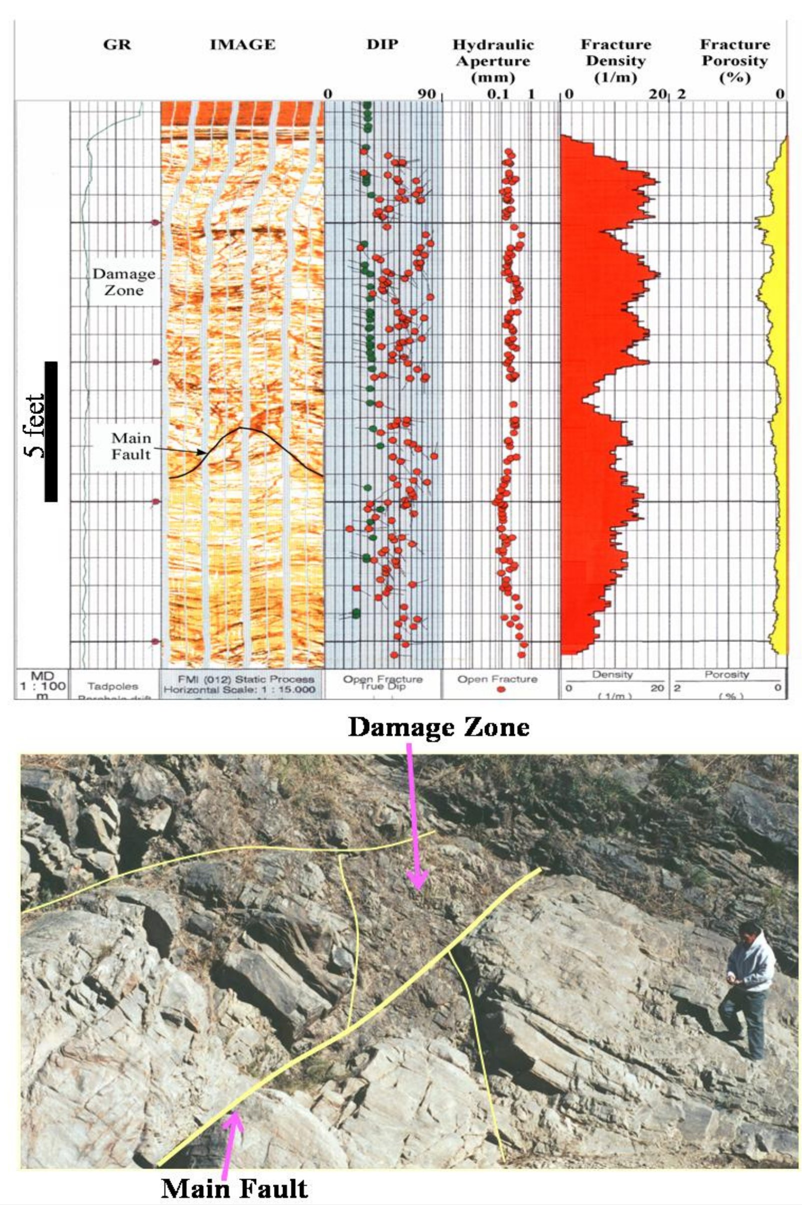
Comparison of Fracturing Mechanisms

Flexural Slip



Fracture Localization ⟶



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Comparison with other Areas (Zagros, Iran)

NASA World Wind

iReservoir.com e-solution for global energy

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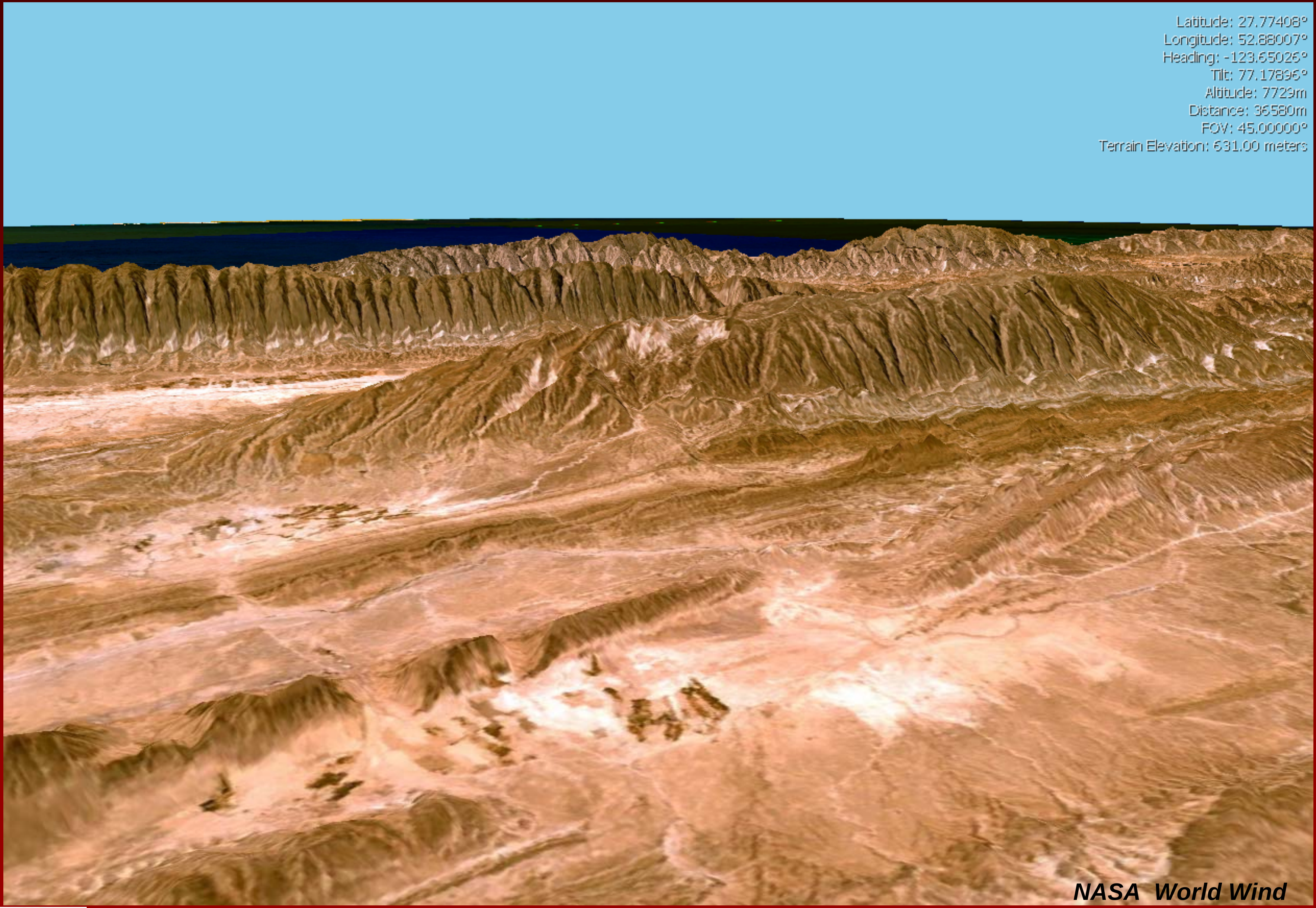
Oblique and Dip-Parallel Fracture Trends



NASA World Wind

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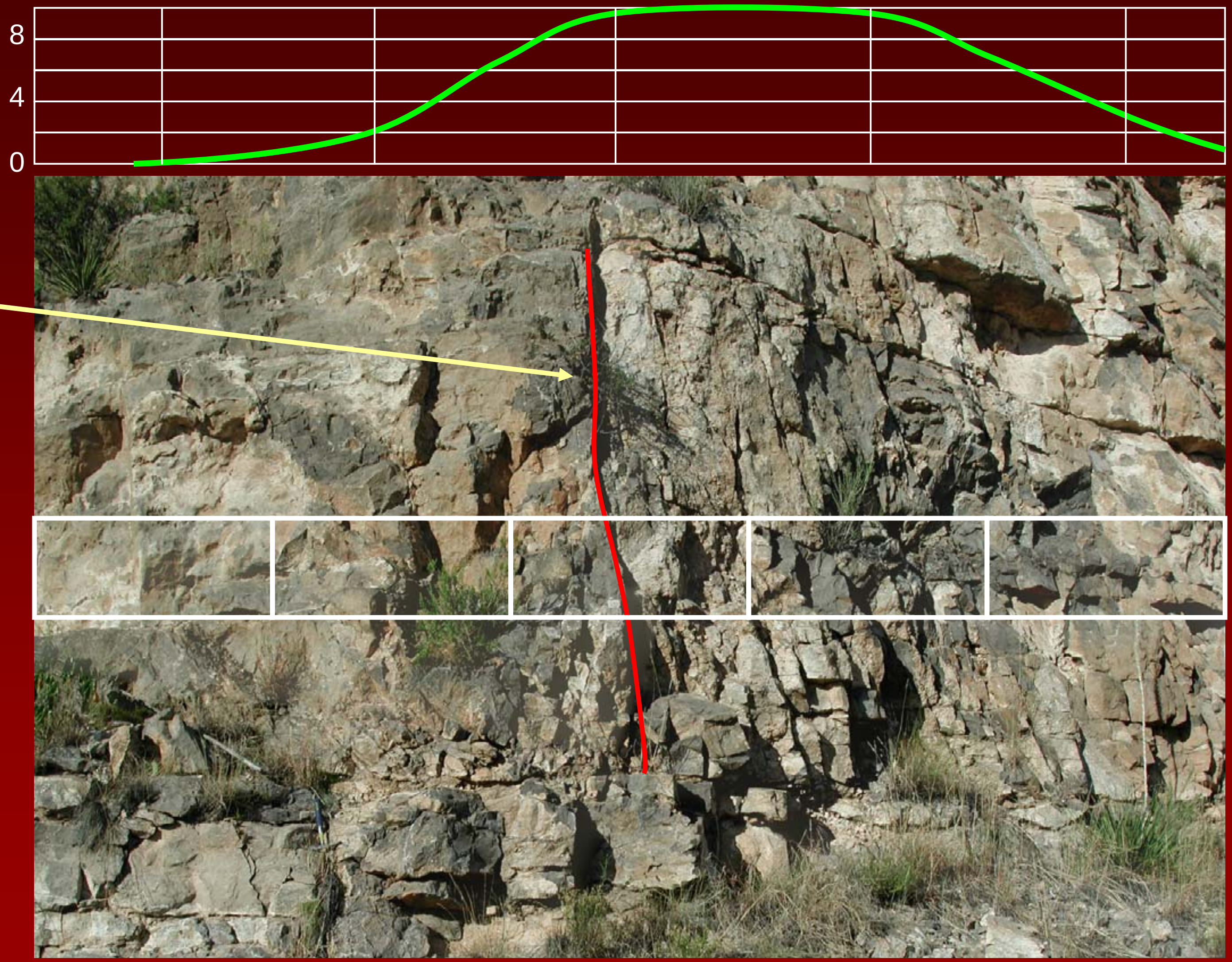
Conjugate Faults and Fracture Swarms



Small Fault

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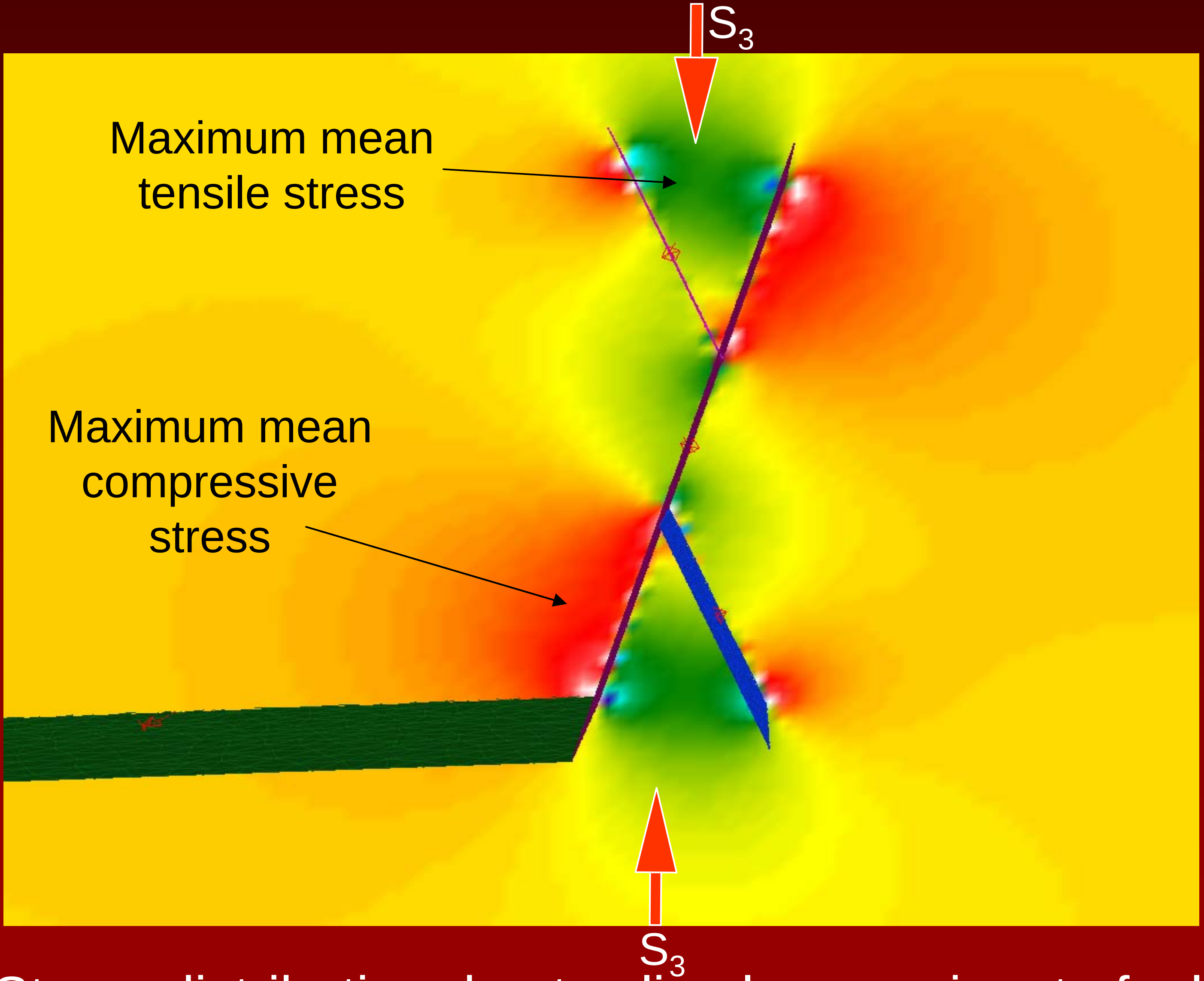
Conjugate Faults May Localize Tension



Stress distribution due to slip along conjugate faults

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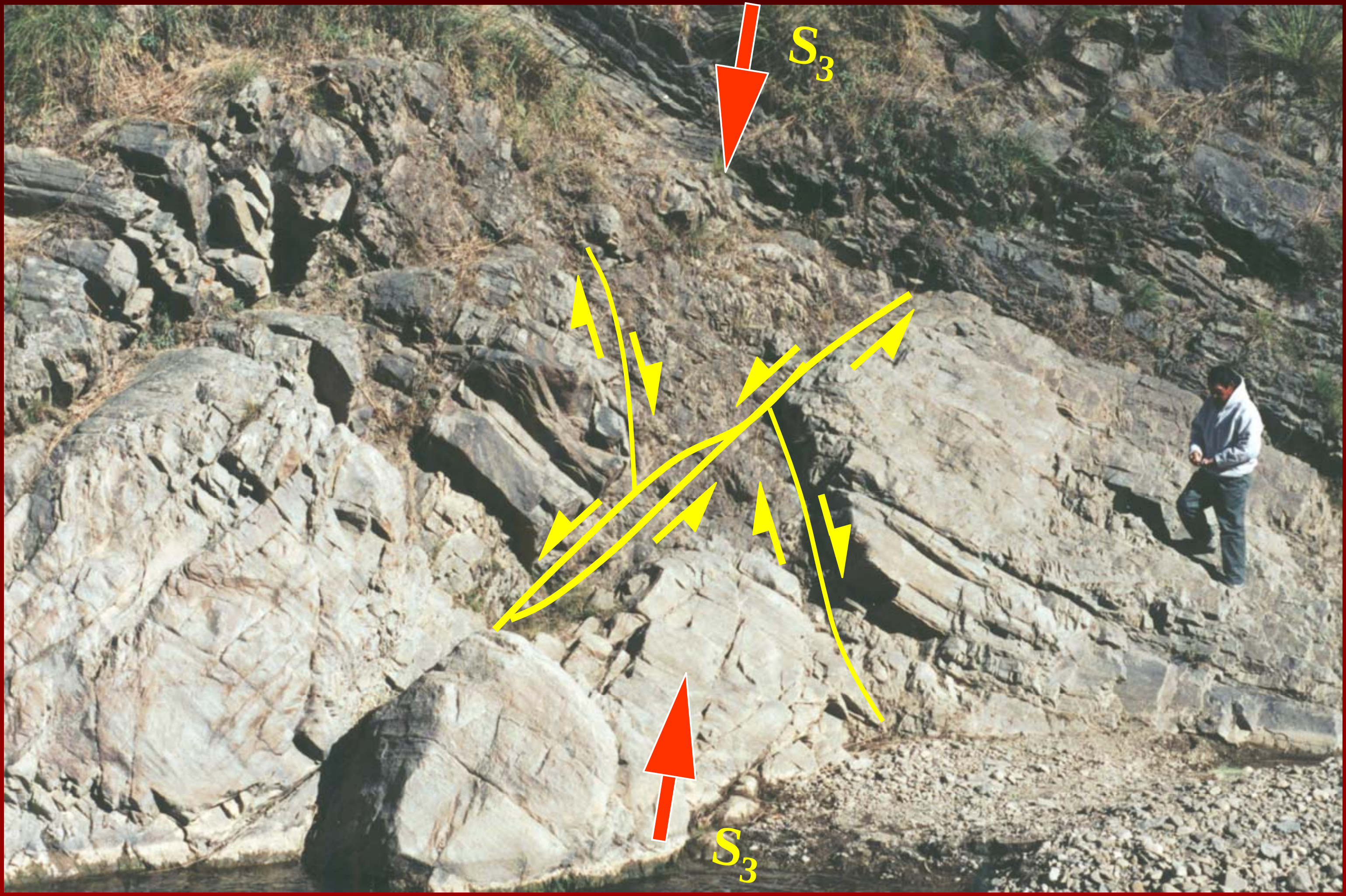
Fracture Swarm within Conjugate Faults



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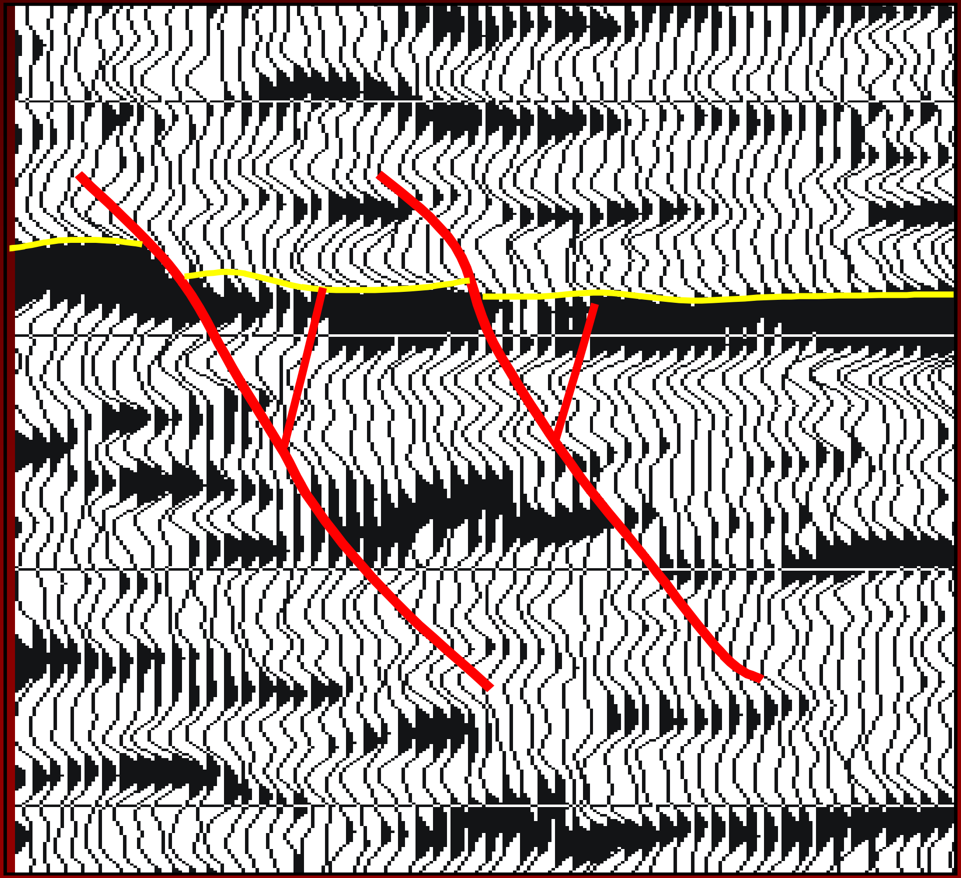
Implications for Seismic Interpretation



Asymmetric amplitude dimming around normal faults

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What we have learned so far:

1. Fractures occur at different scales as a result of hierarchical shearing and progressive deformation.
2. The spacing and dimension of different fracture hierarchies can be linked to stratigraphy
3. Shear strain and lithofacies are among the main factors controlling fracture density
4. Antithetic conjugate faults create fracture swarms

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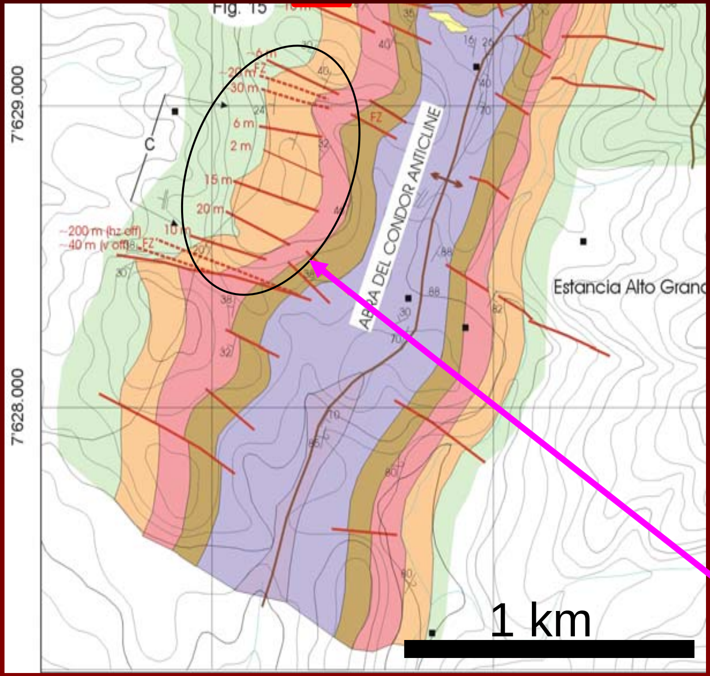
Fracture Modeling



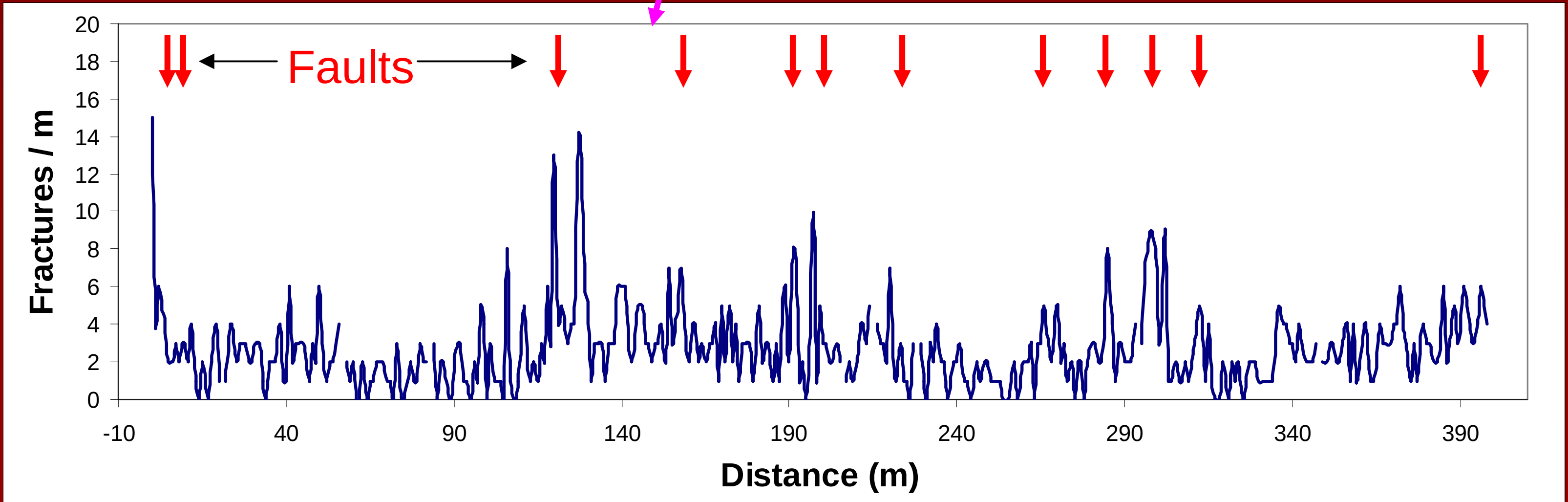
Fracture Density = Fractures / m

Fracture Density = 1 / Spacing

Low Shear-Strain = Low Fracture Density

High Shear-Strain = High Fracture Density

Scanline at Low Shear-Strain Area



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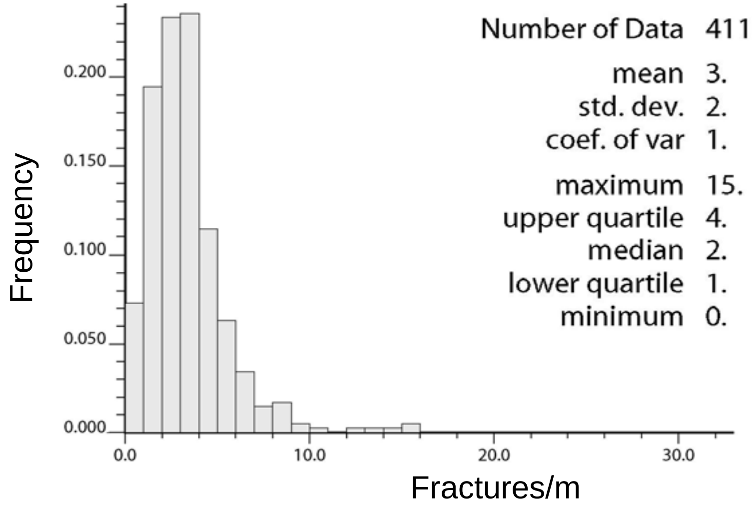
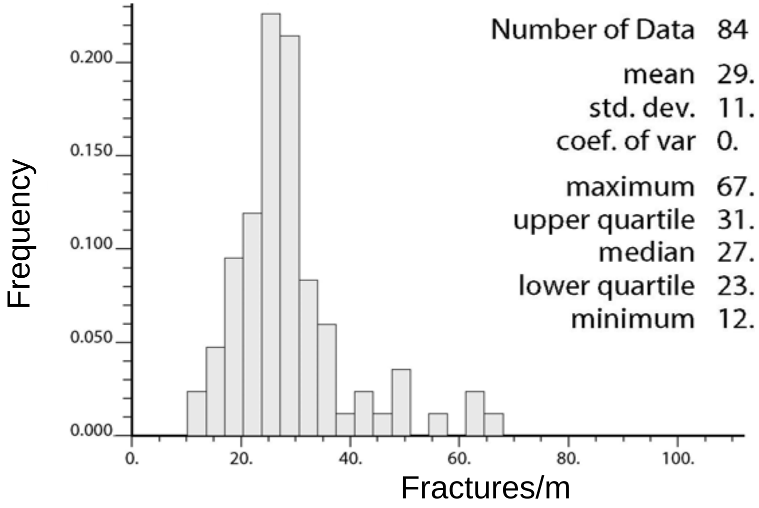
Fracture Density Distributions

Low Shear-Strain Area
Lognormal Distribution



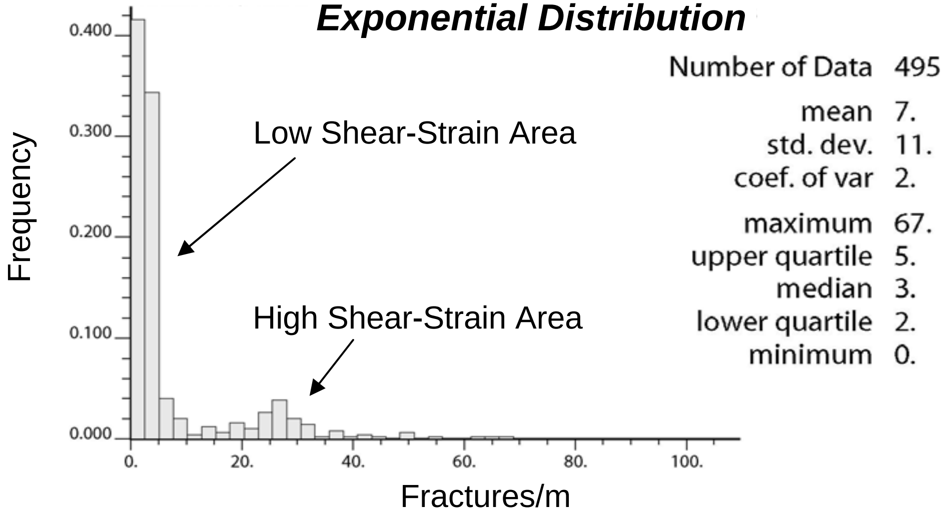
Number of Data	411
mean	3.
std. dev.	2.
coef. of var	1.
maximum	15.
upper quartile	4.
median	2.
lower quartile	1.
minimum	0.

High Shear-Strain Area
Normal Distribution



Number of Data	84
mean	29.
std. dev.	11.
coef. of var	0.
maximum	67.
upper quartile	31.
median	27.
lower quartile	23.
minimum	12.

Combined Data
Exponential Distribution



Number of Data	495
mean	7.
std. dev.	11.
coef. of var	2.
maximum	67.
upper quartile	5.
median	3.
lower quartile	2.
minimum	0.

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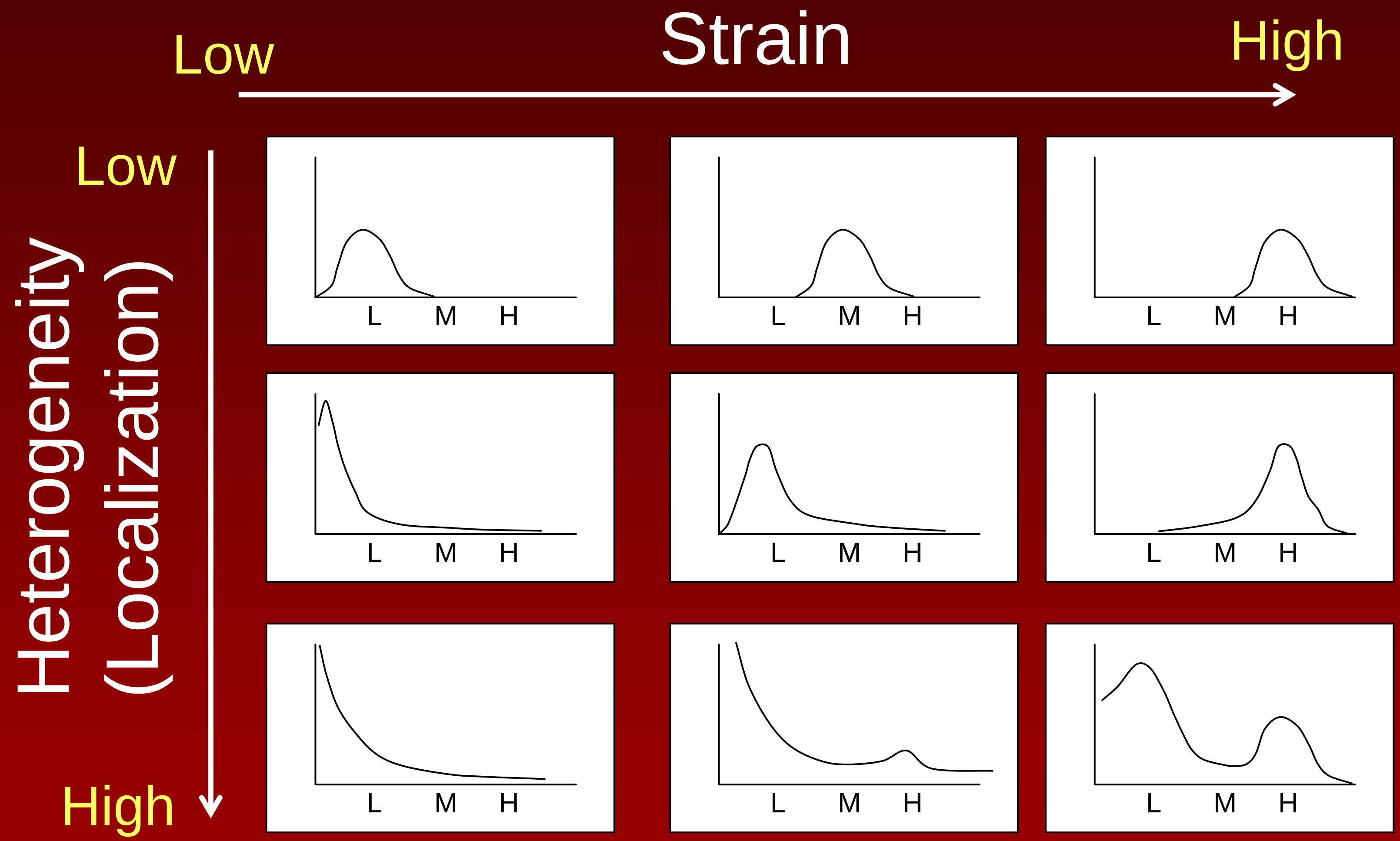
Conceptual Variation of Fracture Density Distributions



Low Strain High

Low Heterogeneity (Localization) High

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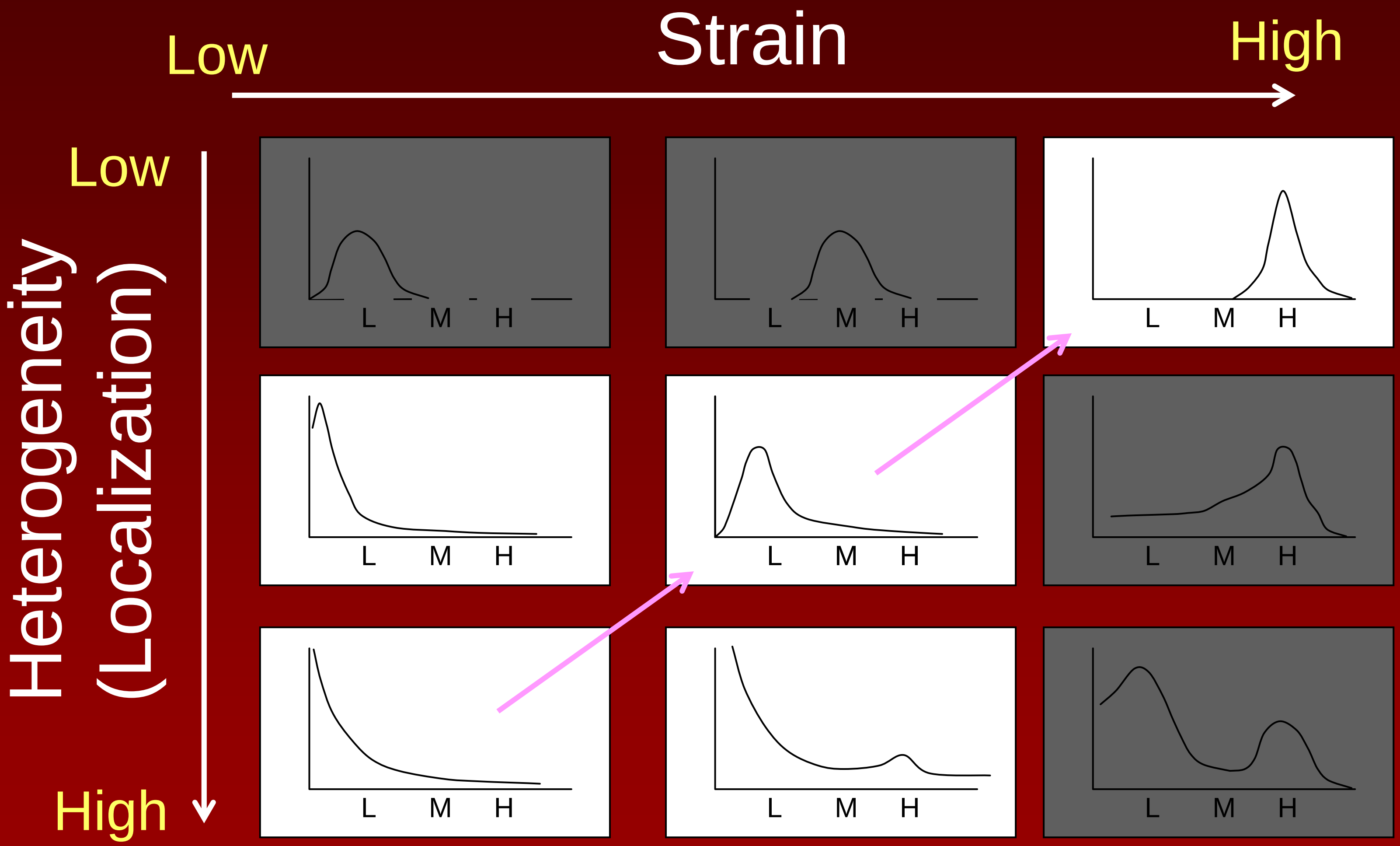
Conceptual Variation of Fracture Density Distributions



Strain

Low

High

Heterogeneity (Localization)

Low

High

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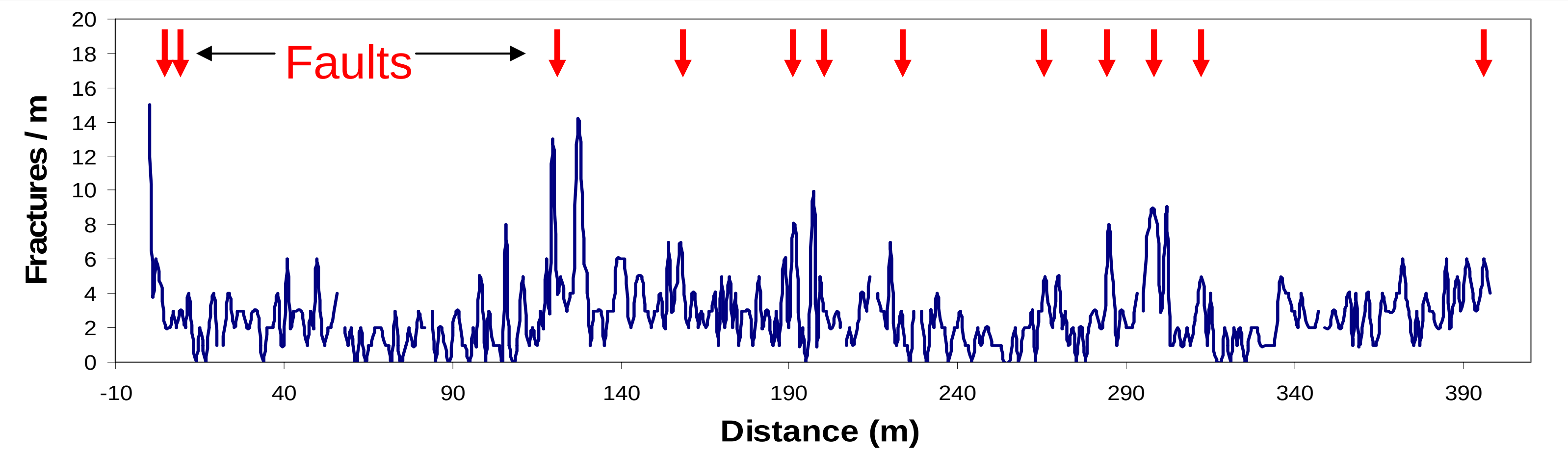
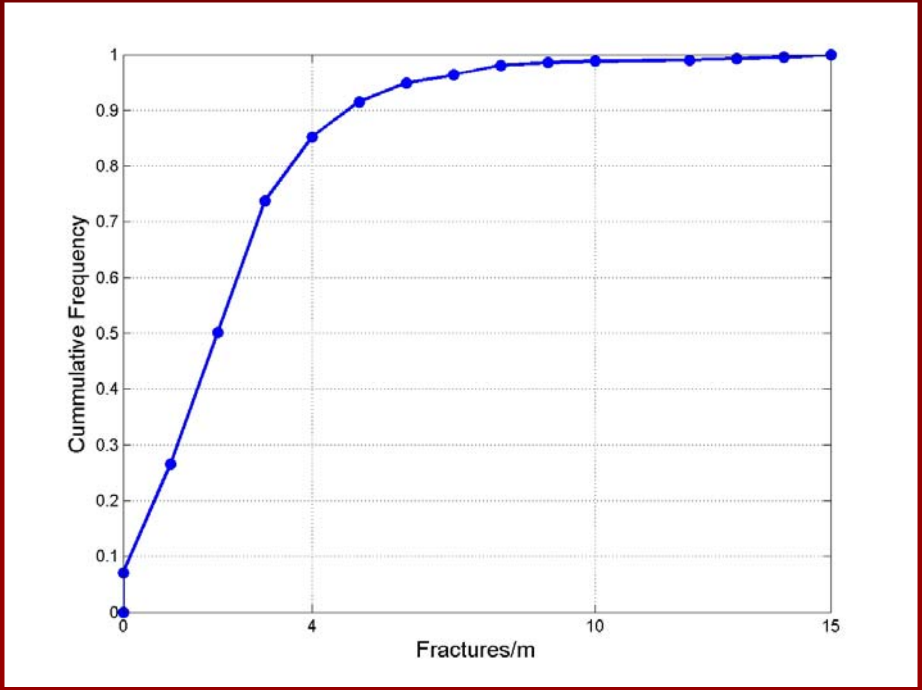
Empirical CDF for Simulation





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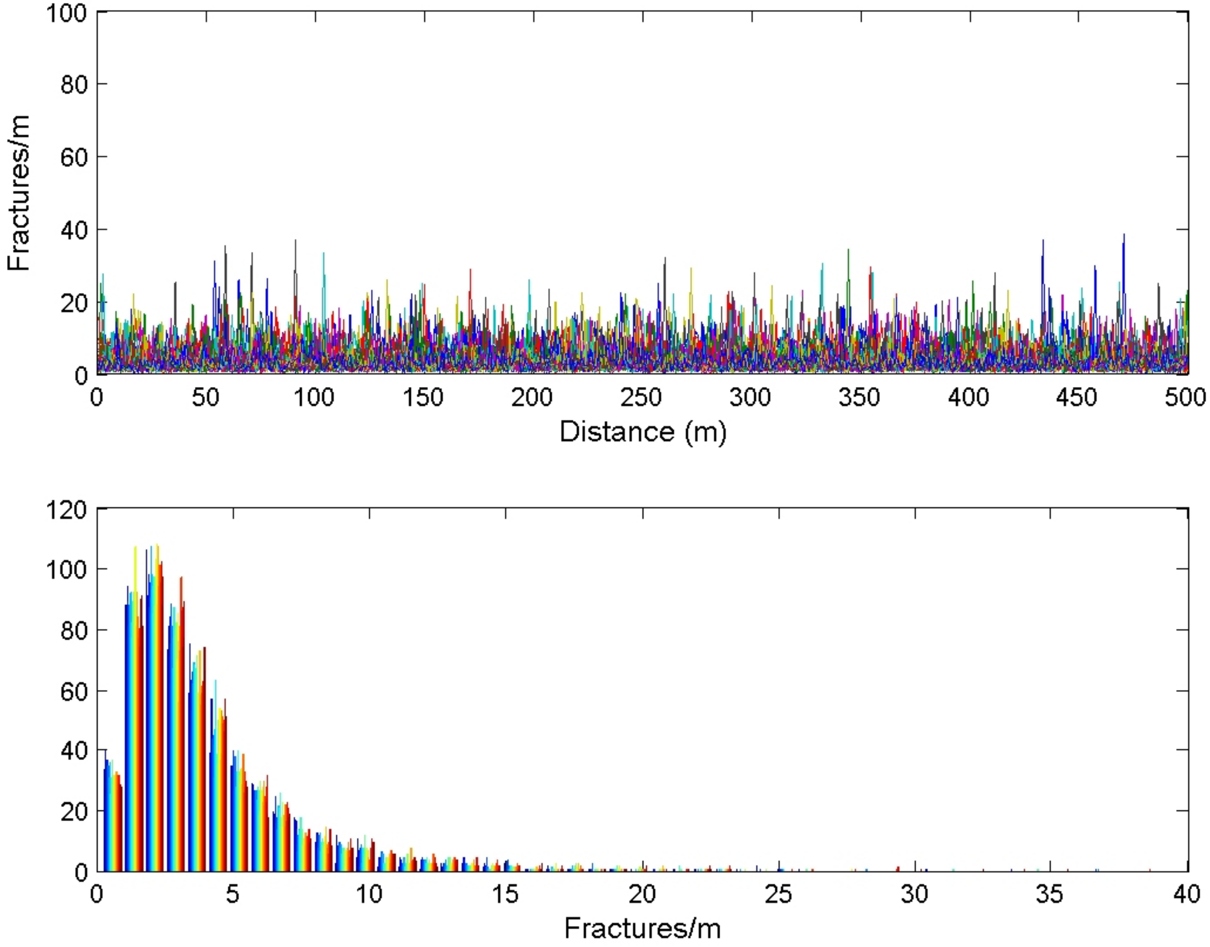
Equally-Probable Realizations



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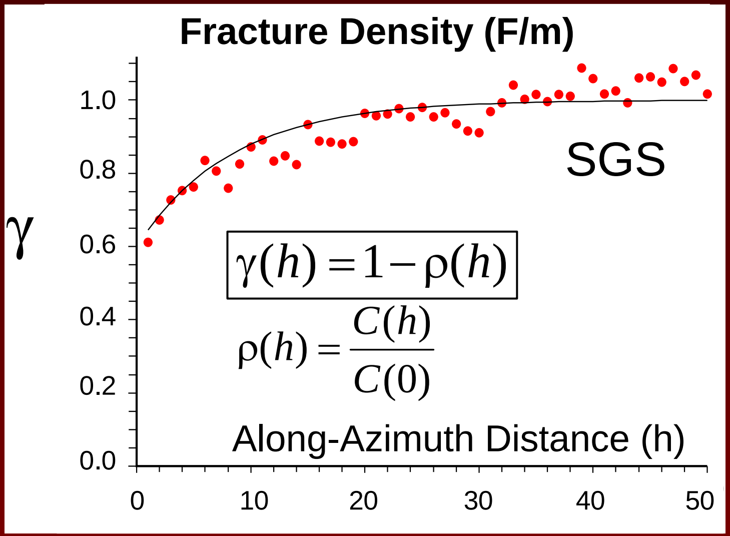
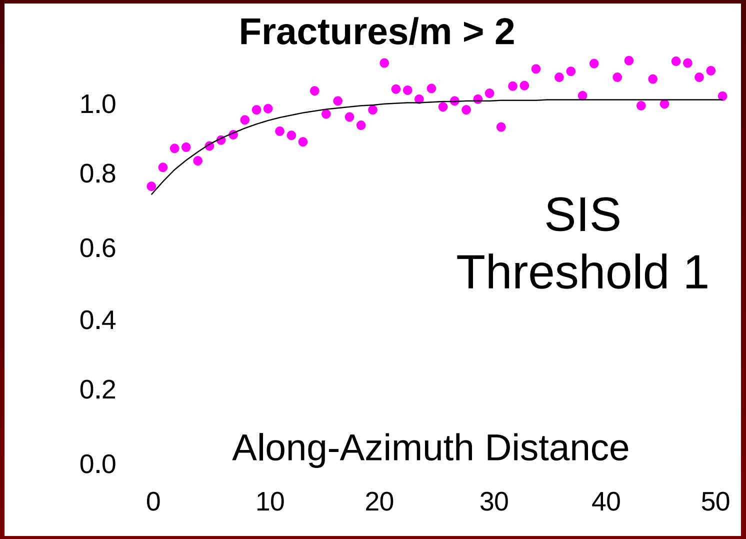
Spatial Correlation of Fracture Frequency



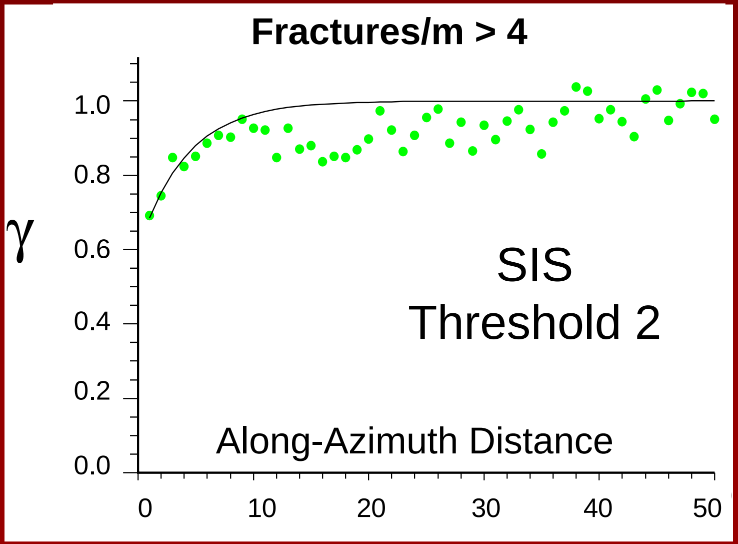
Fracture Density (F/m)

$$\boxed{\gamma(h) = 1 - \rho(h)}$$

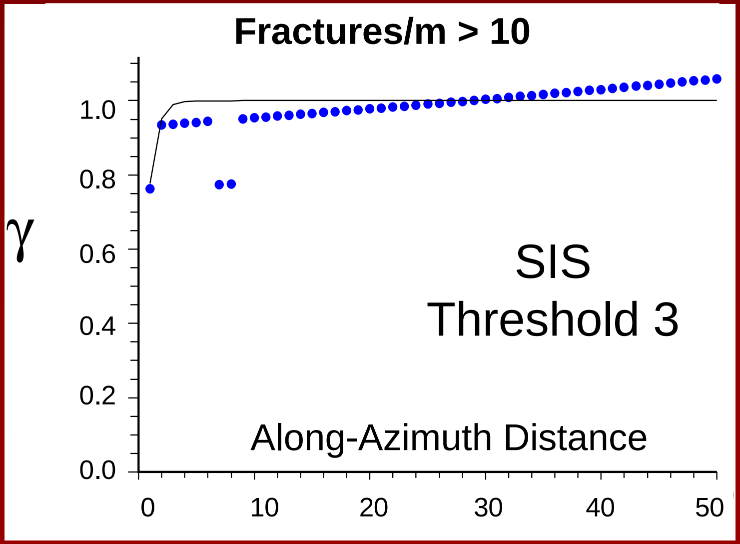
$$\rho(h) = \frac{C(h)}{C(0)}$$



Fractures/m > 2



Fractures/m > 4



Fractures/m > 10

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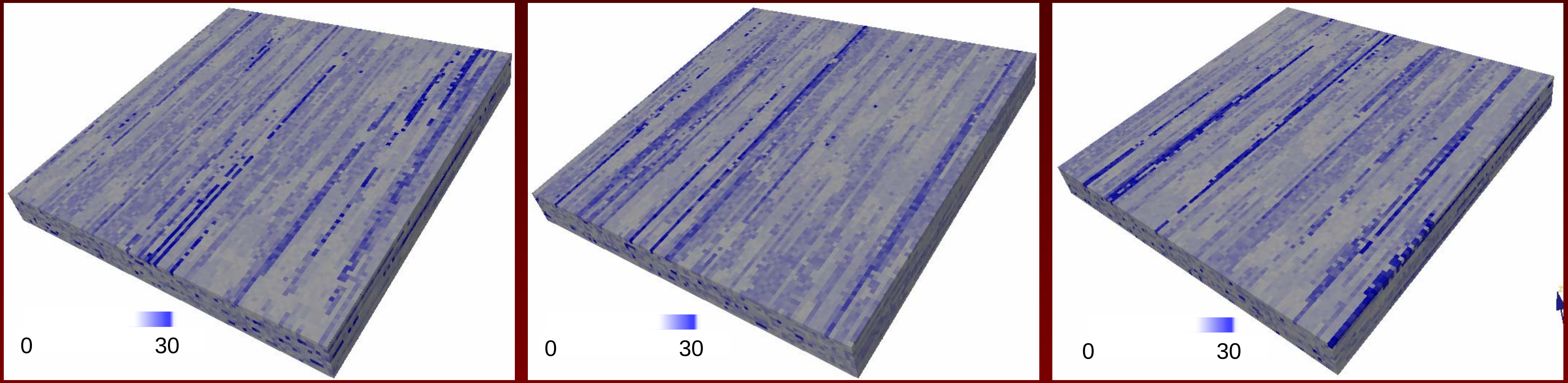
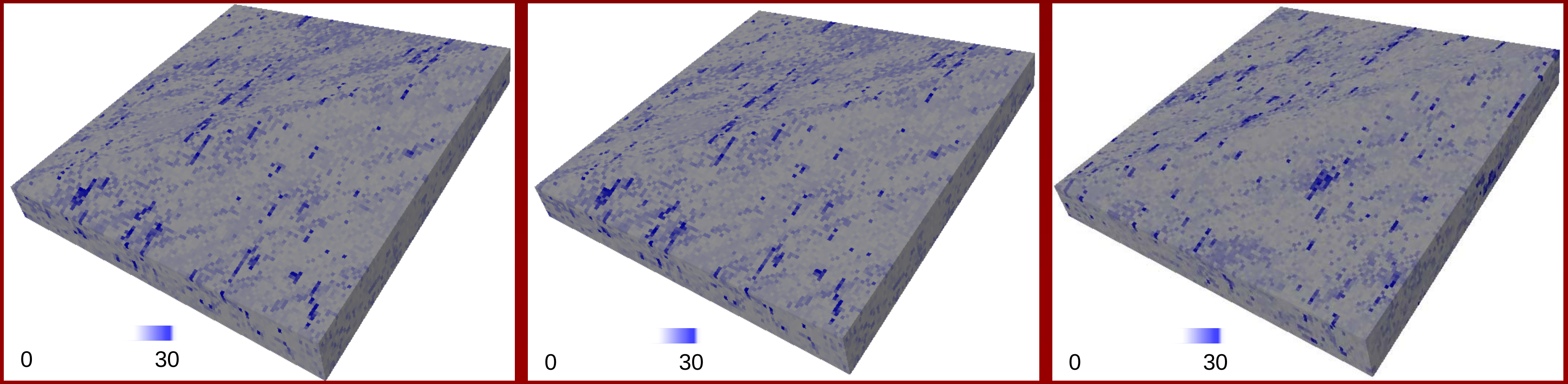
Variogram- Based Sequential Indicator

Dip-parallel Faults and Background Joints



Dip-parallel Faults and Oblique Background Joints (Splays)



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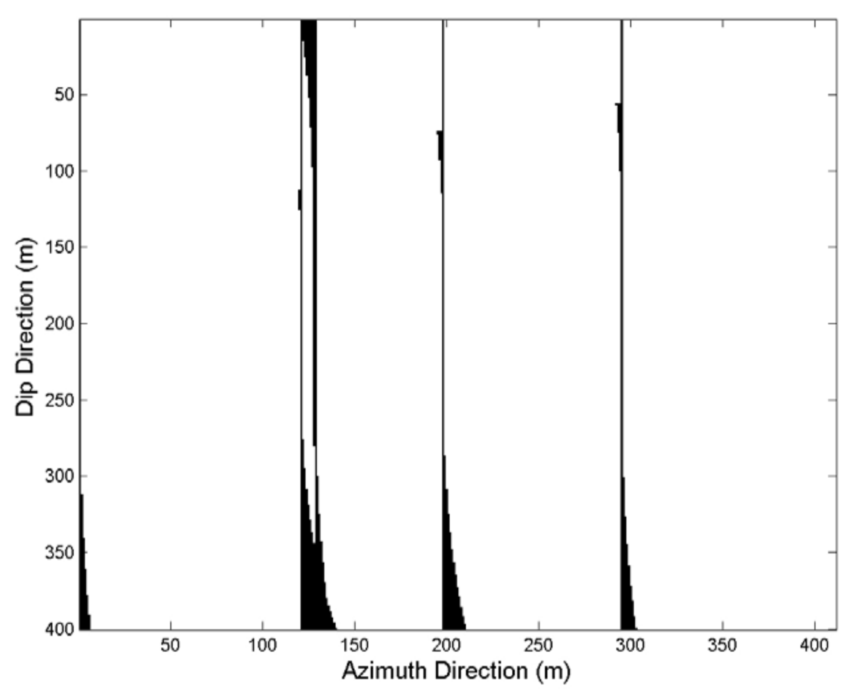
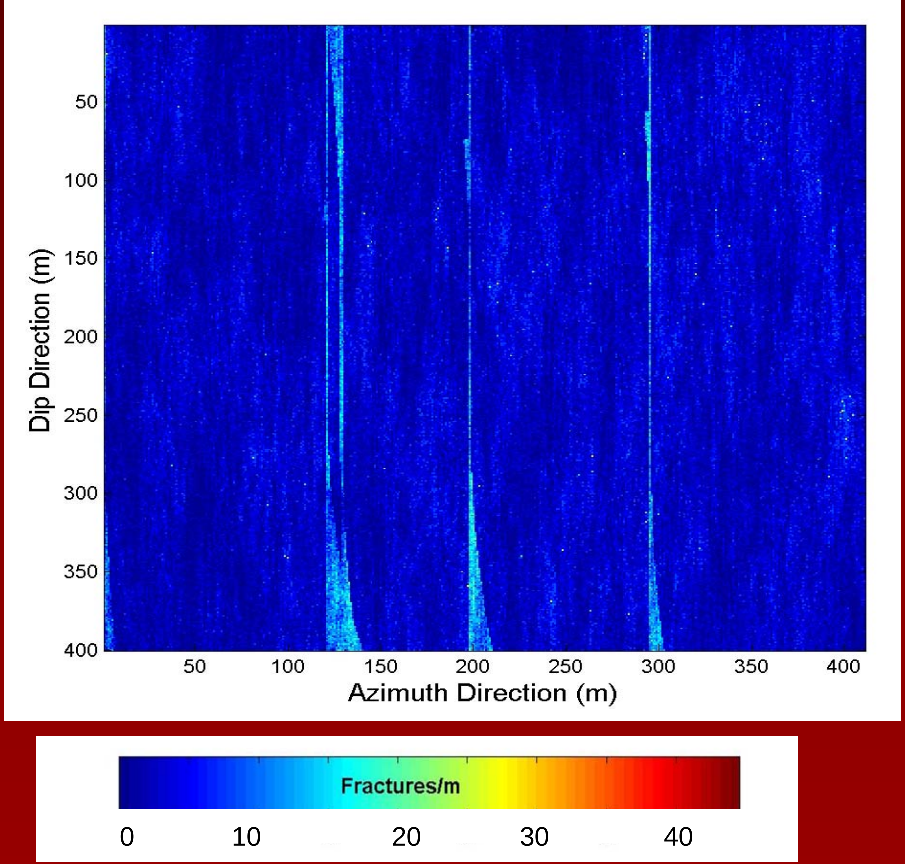
Stochastic Fault Modeling (SFM) and SGS: Object-Based Indicator

Low Shear-Strain Area

Dip-parallel faults and parallel joints



Stochastic Modeling of Fault Distribution and Architecture



Combination of SFM and SGS: Cookie-cutter Technique

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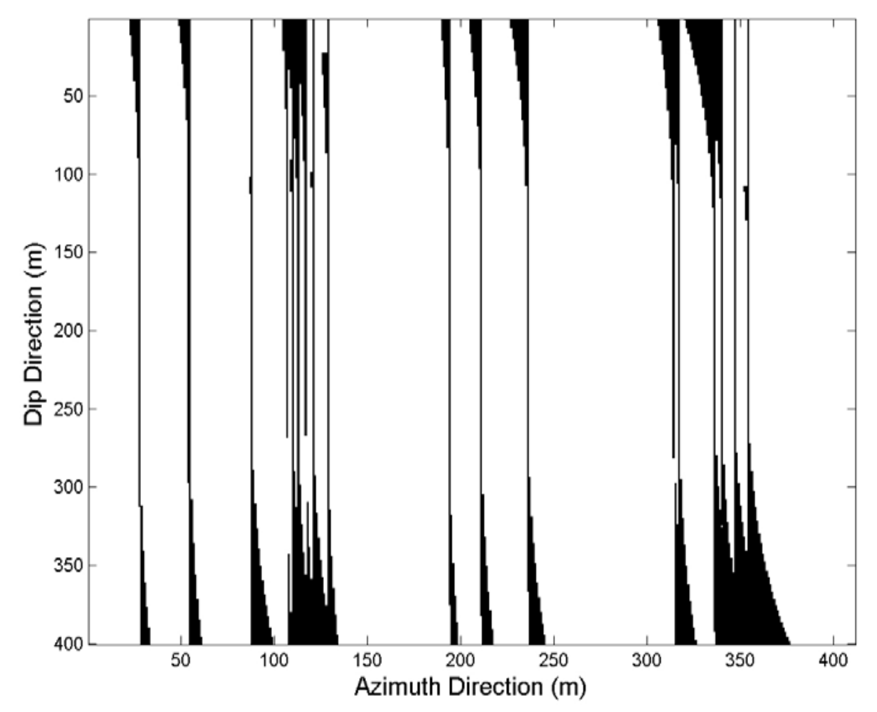
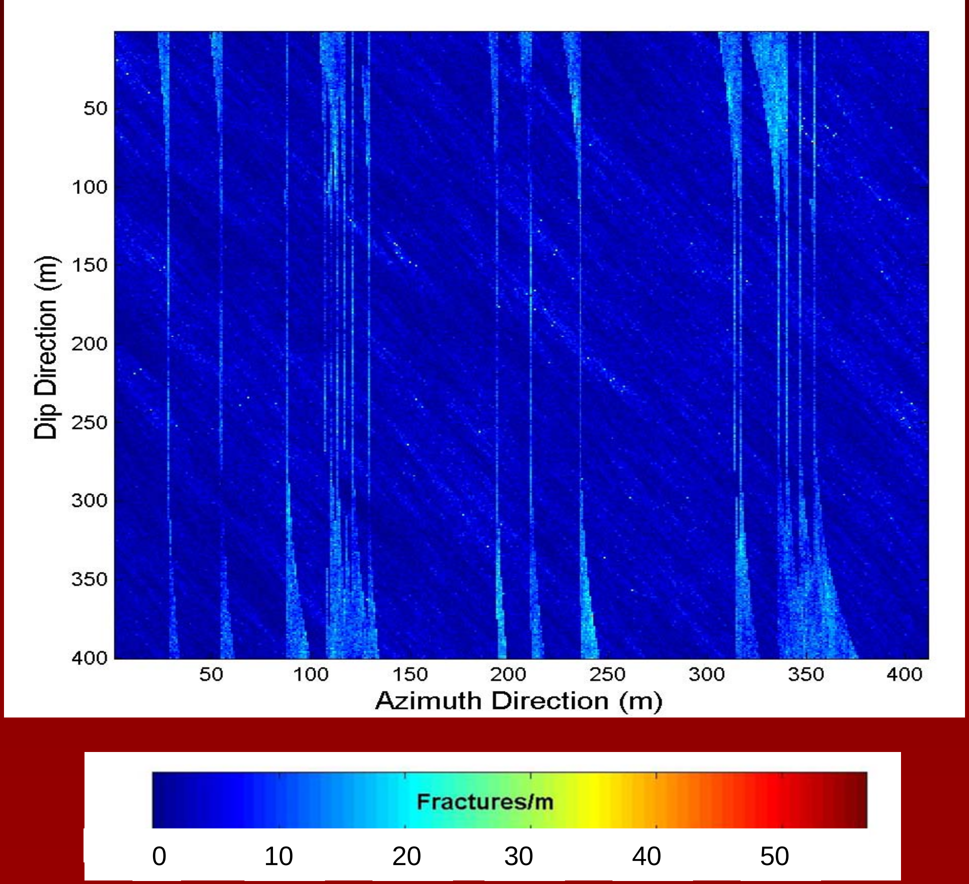
Object-Based Sequential Indicator Simulation (SIS)

Intermediate Shear-Strain Area

Dip-parallel faults and oblique splay fractures



Stochastic Modeling of Fault Distribution and Architecture



Combination of SFM and SGS: Cookie-cutter Technique

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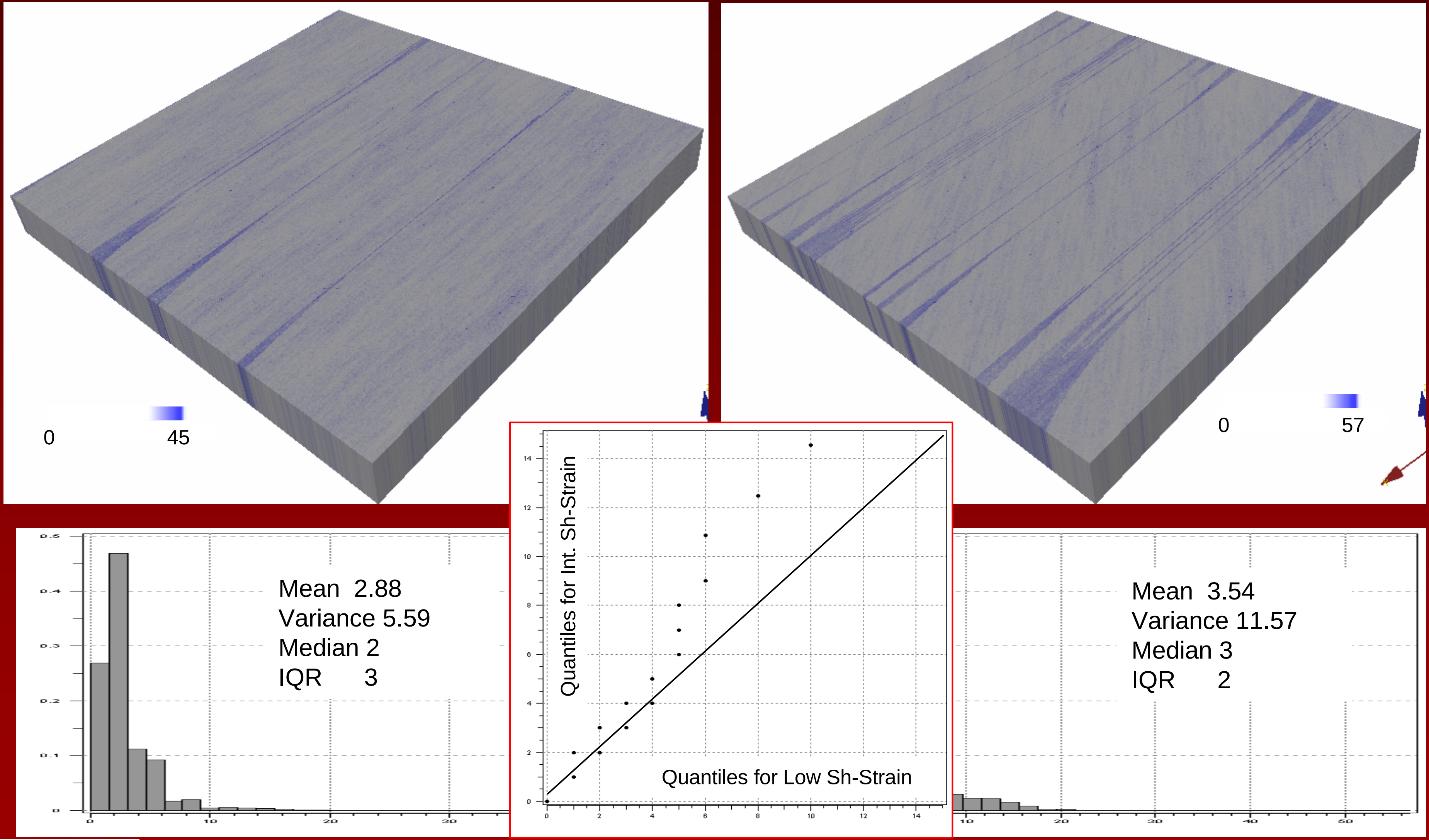
Results from Object-Based Indicator Simulation



Low Shear-Strain Area

Intermediate Shear-Strain Area

Mean 2.88
Variance 5.59
Median 2
IQR 3

Mean 3.54
Variance 11.57
Median 3
IQR 2

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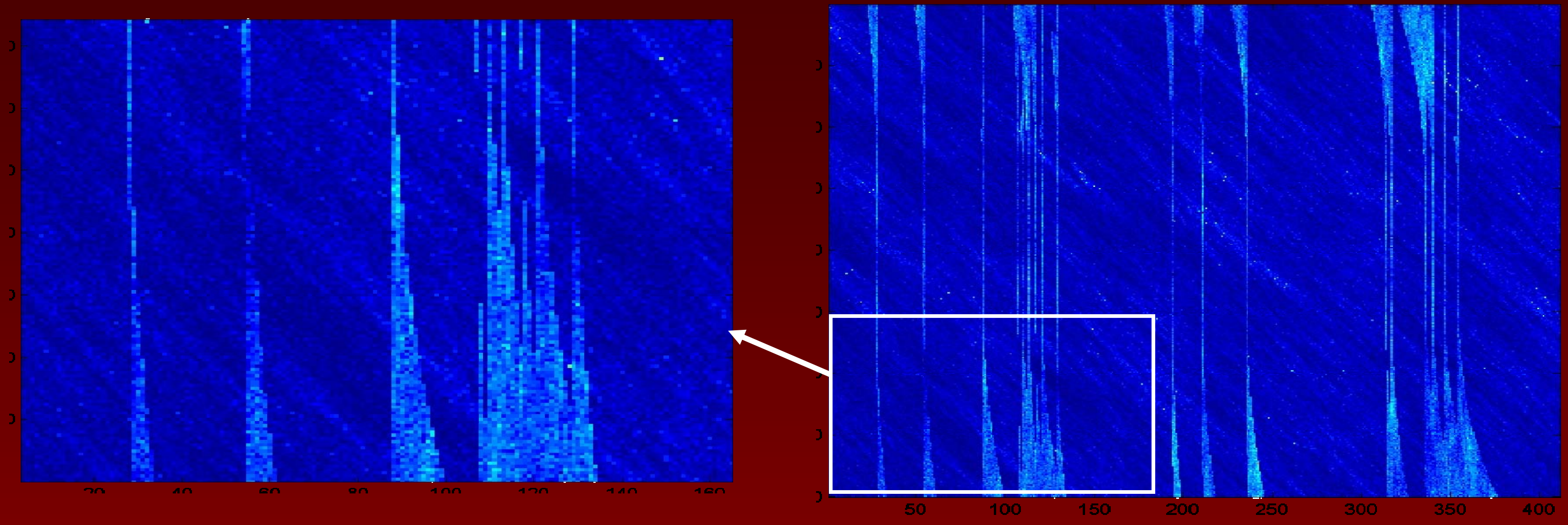
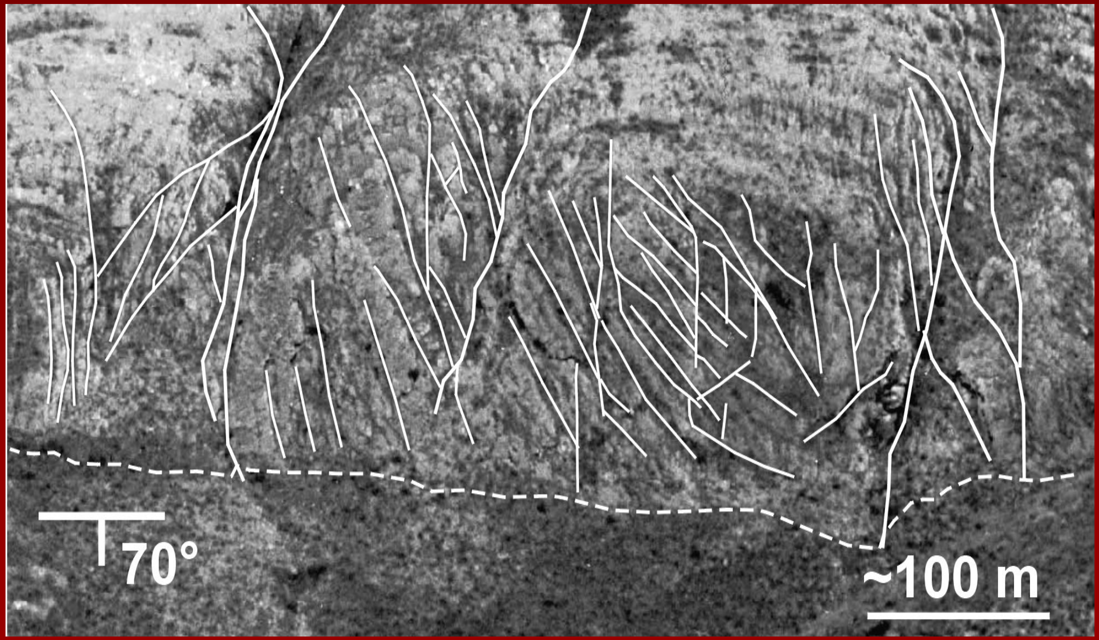
Reproducing the Spatial Heterogeneity



Intermediate Shear-Strain Area:

Dip-parallel faults, and oblique splay fractures



Florez, 2006

Conclusions

1. Outcrops provide key information about orientation, deformation mechanisms and spatial heterogeneity of fault and fracture systems.
2. In fold and thrust belts fracture systems evolve as the result of hierarchical shearing and progressive deformation, creating different fracture hierarchies.
3. There is a 1st order relationship between fracture spacing and stratigraphic architecture.
4. Shear strain and lithology are key factors controlling fracture density.
5. Antithetic conjugate faults can produce fracture swarms.
6. Object-based SIS can be used to model NFR.

Florez, 2006