Natural Fracture Patterns and Attributes across a Range of Scales*

Julia F.W. Gale[1]

Search and Discovery Article #41486 (2014)**
Posted November 17, 2014

*Adapted from 2013-2014 AAPG Foundation Distinguished Lecture. Please refer to related article by the author, Search and Discovery Article #41487 (2014).

[1]Bureau of Economic Geology, University of Texas at Austin (julia.gale@beg.utexas.edu)

Abstract

Natural fractures are a prominent and dramatic feature of many outcrops and are commonly observed in core, where they govern subsurface fluid flow and rock strength. Examples from more than 20 fractured reservoirs show a wide range of fracture sizes and patterns of spatial organization. These patterns can be understood in terms of geochemical and mechanical processes across a range of scales. Fractures in core show pervasive evidence of geochemical reactions; more than is typical of fractures in many outcrops. Accounting for geochemistry and size and size-arrangement and their interactions leads to better predictions of fluid flow. Opening-mode fracture apertures commonly follow power-law size distributions with opening displacements ranging from approximately 1 µm to 1 m. A power law forms a straight line on a log cumulative frequency versus log aperture size plot. The slope of the line is the power-law exponent, reflecting the relative number of narrow and wide fractures in the set. The pre-exponential coefficient reflects the overall fracture intensity. We examine the variation in power-law exponent and coefficient for fracture sets in carbonate and siliciclastic rocks and analyze why such variation occurs. Fractures may open in a single event or may repeatedly open and seal. During an opening event the rate of opening competes with the fastest rates of precipitation to determine if the fracture will seal before the next strain increment. Small fractures completely seal with cement precipitated synchronously with opening, whereas large fractures may retain some porosity. The aperture size at which porosity is preserved varies, and it is controlled by the temperature of the ambient fluid, the composition and texture of the host rock and precipitating minerals, and the length of time the fracture wall is exposed to mineral precipitation, which is dependent on burial history and fracture timing. If the widest fractures are not completely sealed before the next strain increment, they may act as planes of weakness, causing strain to progressively partition into fewer fractures, which will grow wider. The extent to which this process happens should partly govern the exponent in the power-law distribution. Cements deposited while fractures are growing may cause fracture-size distributions to vary from those found in barren fracture arrays (including many of those in outcrop). Geochemical and fracture-size interactions may also affect fracture spatial arrangements. Fractures may be evenly spaced, but more commonly fractures occur in complex and, in some cases, fractal arrays of clusters. We have developed a method, based on a two-point correlation integral, to rigorously identify different types of spatial arrangement, including periodic, random, and clustered. Our method provides a measure of preferred spacing relative to that expected from a random ordering of spacings. I show examples from outcrop data sets and from fractures interpreted in image logs in shale gas wells.

Selected References

Gale, J.F.W., 2004, Self-organization of natural mode-I fracture apertures into power-law distributions, in 6th North America Rock Mechanics Symposium, Rock mechanics across borders and disciplines: ARMA/NARMS 04-488, CD-ROM, 13 p.

Gale, J.F., R.H. Lander, R.M. Reed, and S.E. Laubach, 2010, Modeling fracture porosity evolution in dolostone: Journal of Structural Geology, v. 32/9, p. 1201-1211.

Gale, J.F.W., Laubach, S.E., Olson, J.E., Eichhubl, P., and A. Fall, 2014, Natural fractures in shale: a review and new observations: AAPG Bulletin, v. 98/11, p. 2165-2216.

Hooker, J.N., L.A. Gomez, S.E. Laubach, J.F.W. Gale, and R. Marrett, 2012, Effects of diagenesis (cement precipitation) during fracture opening on fracture aperture-size scaling in carbonate rocks, *in* J. Garland, S.E. Laubach, J.E. Neilson, and K.J. Whidden, eds., Advances in carbonate exploration and reservoir analysis: Geological Society (London) Special Publication 370, p. 187–206.

Hooker, J.N., S.E. Laubach, and R. Marrett, 2013, Fracture aperture size—frequency, spatial distribution, and growth processes in strata-bounded and non-strata-bounded fractures, Cambrian Mesón Group, NW Argentina: Journal of Structural Geology, v. 54, p. 54-71.

Hooker, J.N., S.E. Laubach, and R. Marrett, 2014, A universal power-law scaling exponent for fracture apertures in sandstone: Geological Society of America Bulletin, v. 126/9-10, p. 1340–1362.

Marrett, R., O.J. Ortega, and C.M. Kelsey, 1999, Extent of power-law scaling for natural fractures in rock: Geology, v. 27, p. 799-802.

Twiss, R.J. and Moore, E.M., 1992, Structural geology, W.H. Freeman and Company, 532 p.

Natural Fracture Patterns and Attributes across a Range of Scales

Bureau of Economic Geology

Julia F. W. Gale

The University of Texas at Austin
Jackson School of Geosciences

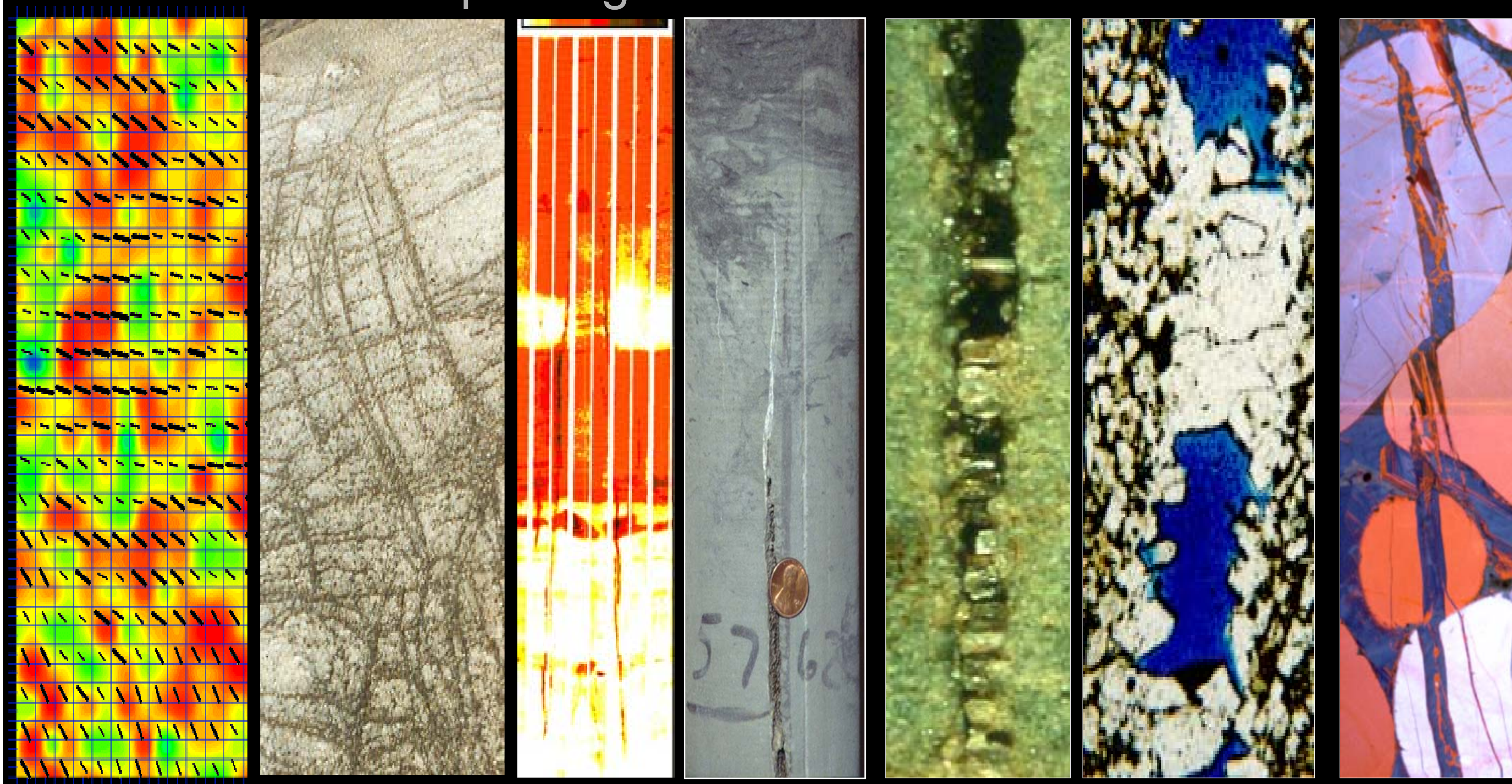
Randy Marrett, Steve Laubach, Jon Olson, Rob Lander, John Hooker, Peter Eichhubl, András Fall, Esti Ukar, Orlando Ortega, Leonel Gomez

FRAC Fracture Research & Application Consortium

"Dedicated to conquering the challenges of fractured and unconventional reservoirs by 2020"

Fractures Across a Range of Scales

Seismic | Outcrop | Logs | Core | Thin section | SEM

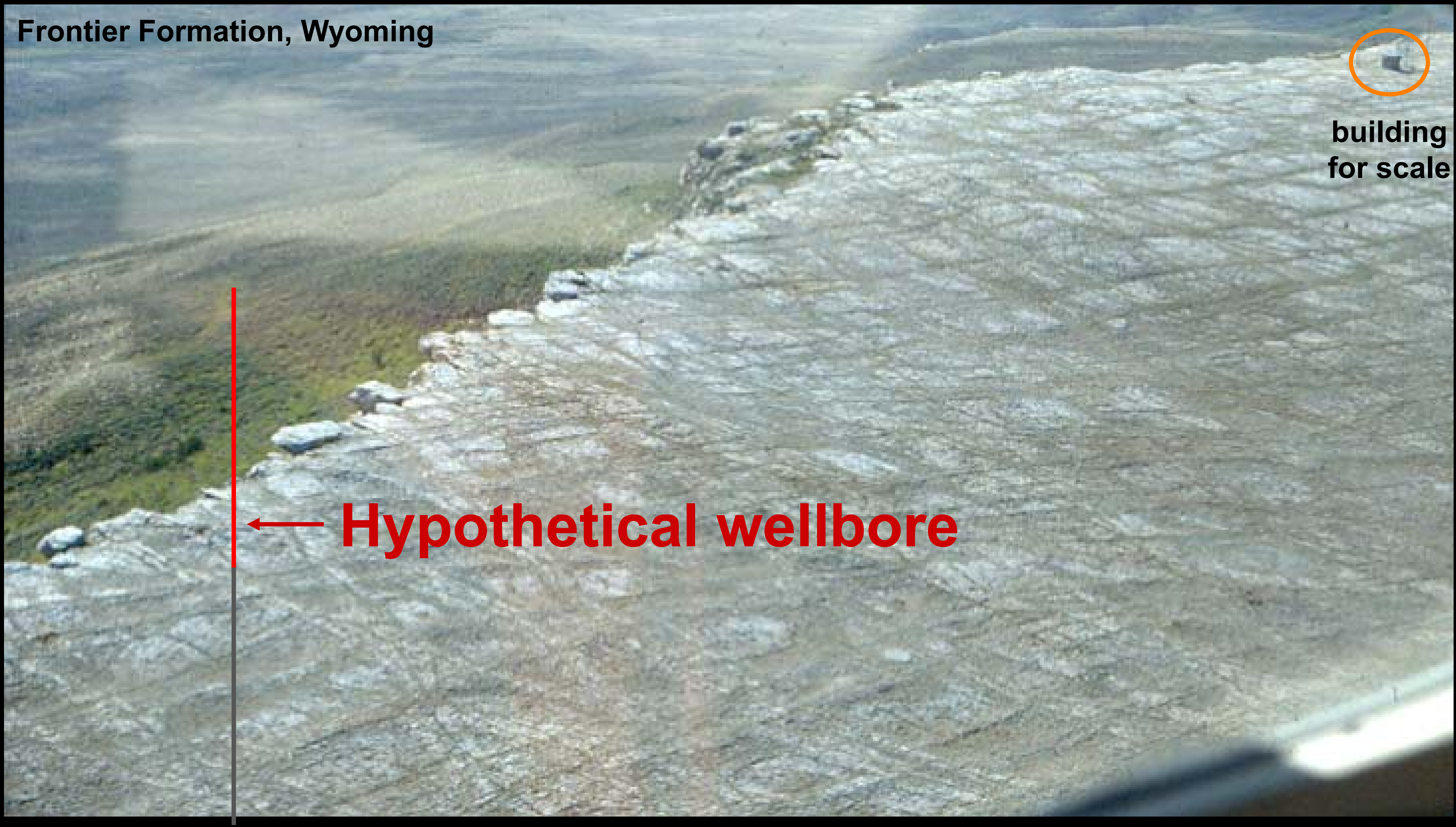


dm | m | cms | mm | < mm | 0.5 mm | μms

Scale Differences: Fractures vs Wellbores

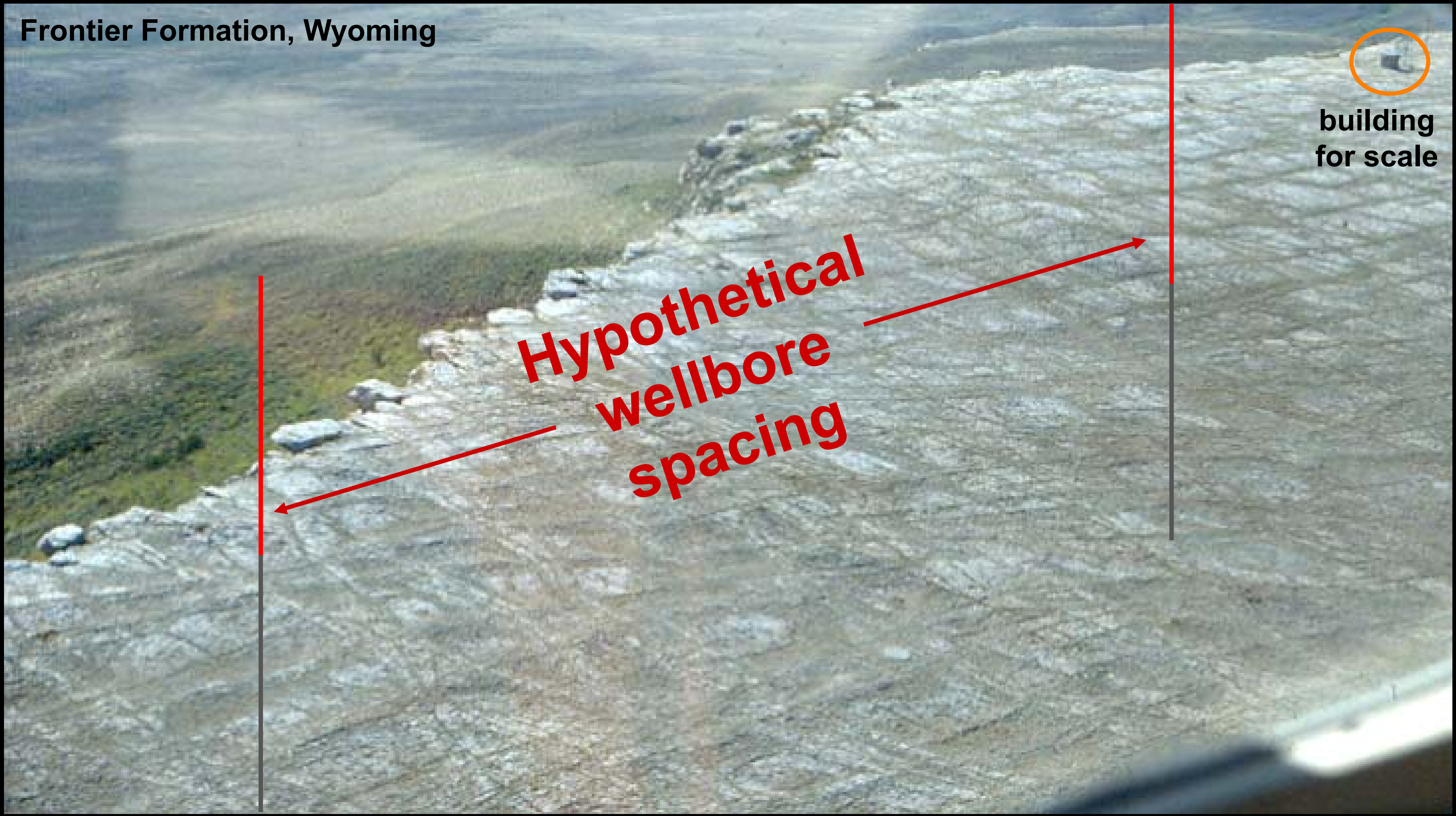
Slide courtesy Randy Marrett

Scale Differences: Fractures vs Wellbores



Slide courtesy Randy Marrett

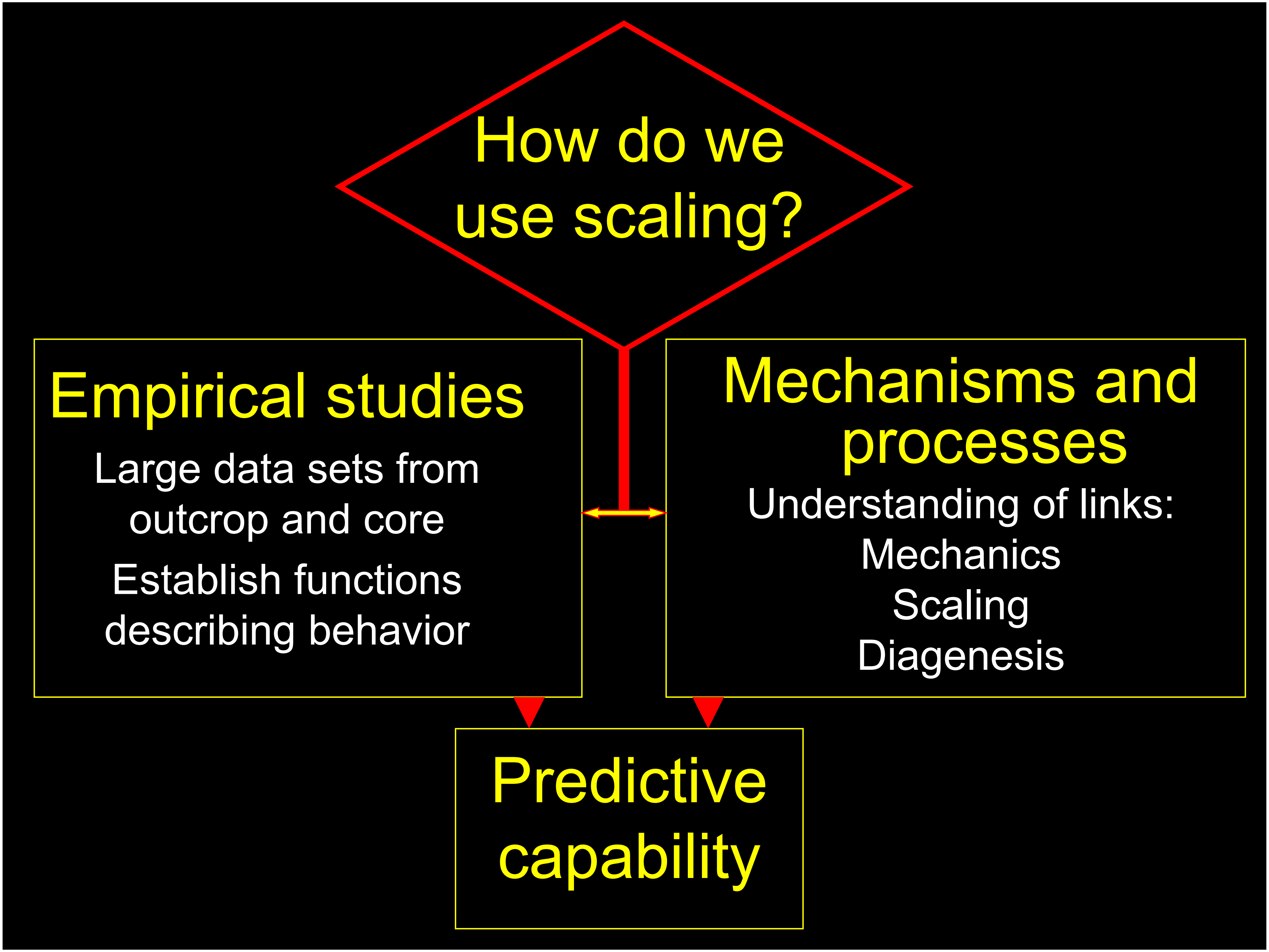
Scale Differences: Fractures vs Wellbores



Slide courtesy Randy Marrett

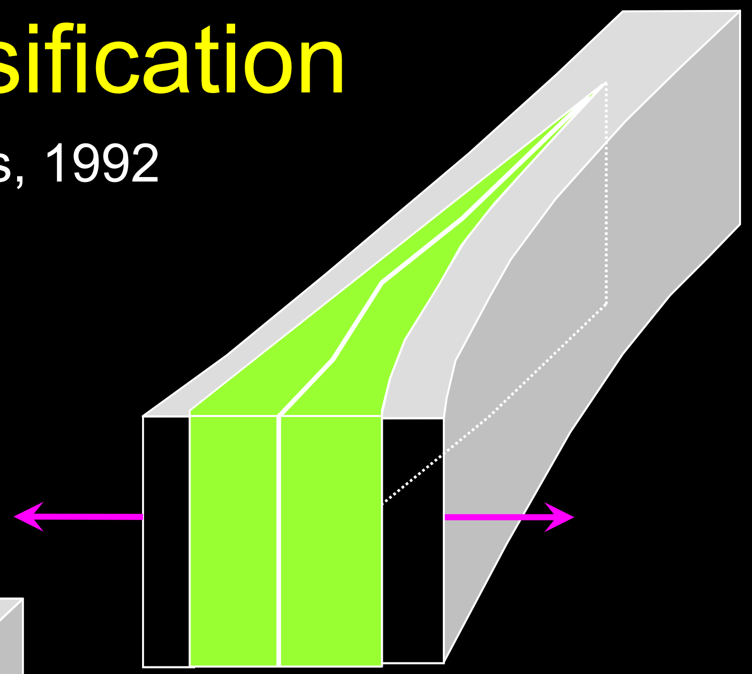
Scaling: Problem and Insight

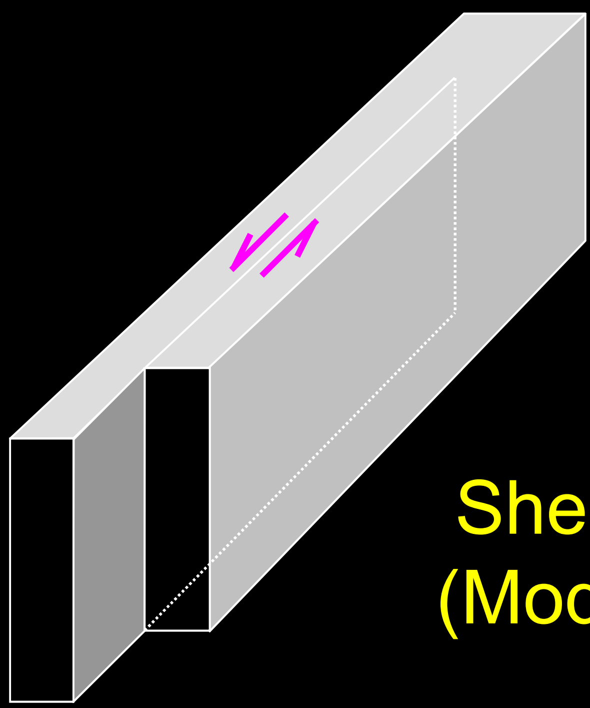
- Sampling problem for subsurface fractures
  - large fractures most conductive
  - but too sparse to sample adequately
  - commonly at low angles to borehole
- Insight
  - microfractures abundant in some lithologies
  - micro- and macrofractures are part of same fracture set
    - Share some characteristics
    - Quantitatively linked (scaling)

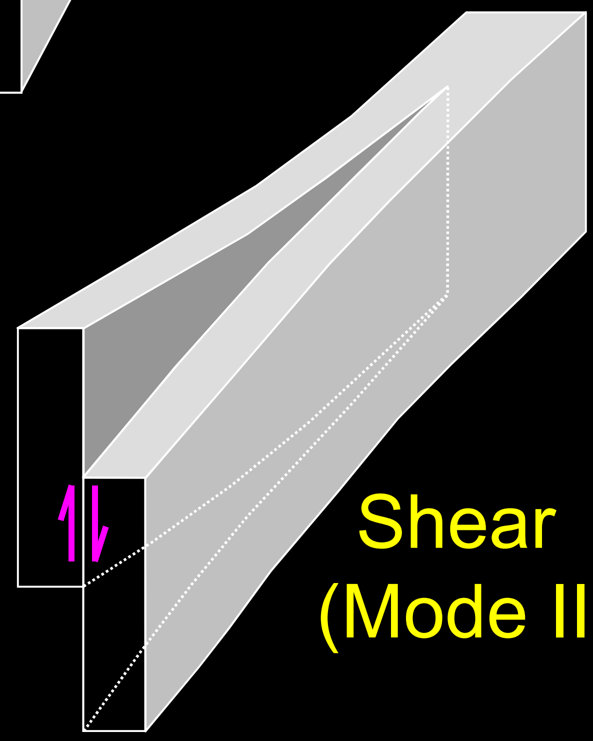

How do we use scaling?
Empirical studies
Large data sets from outcrop and core
Establish functions describing behavior
Mechanisms and processes
Understanding of links:
Mechanics
Scaling
Diagenesis
Predictive capability

Fracture Classification

Twiss and Moores, 1992

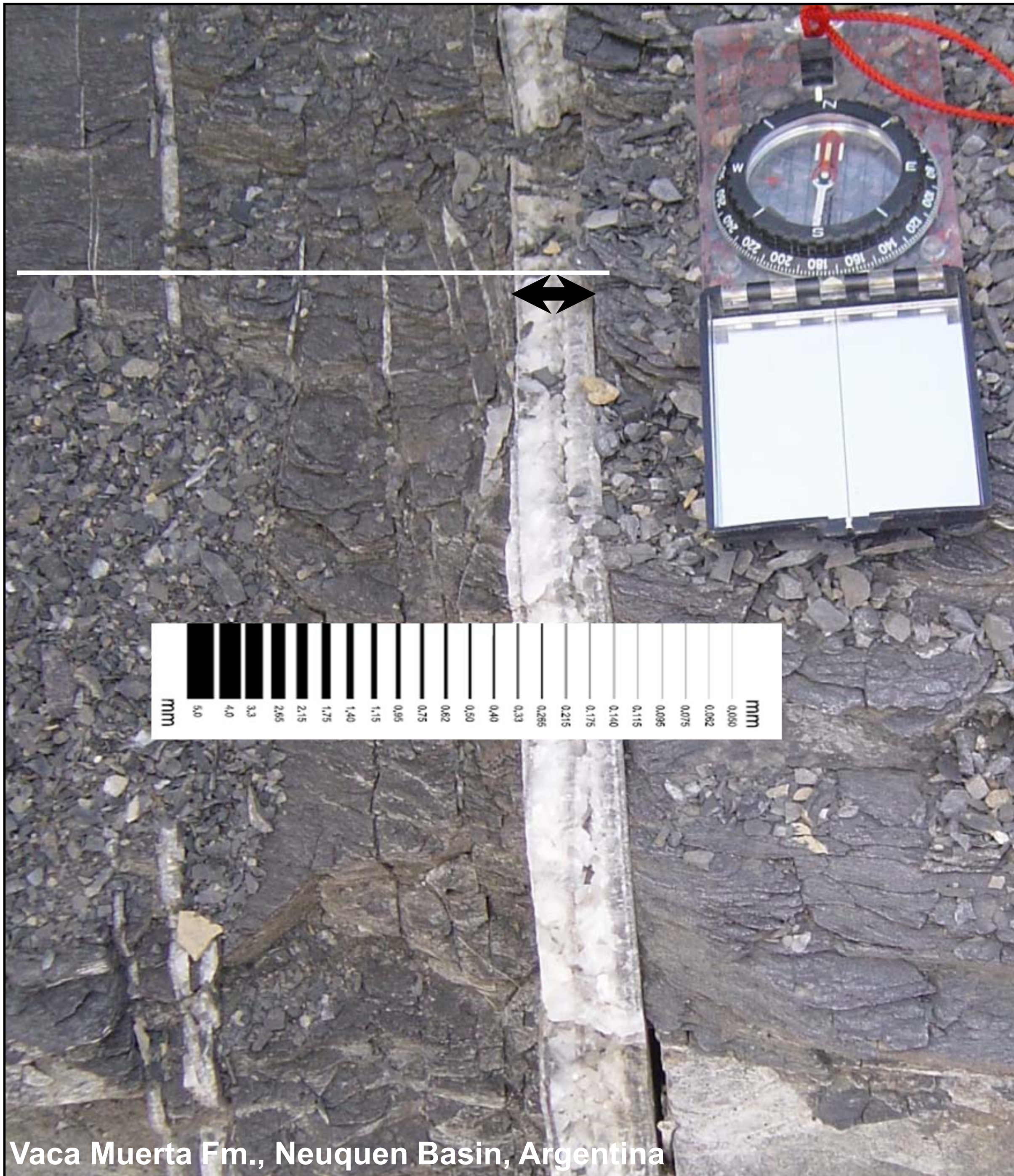






Attributes

- Aperture
- Openness
- Height
- Length
- Spatial Organization



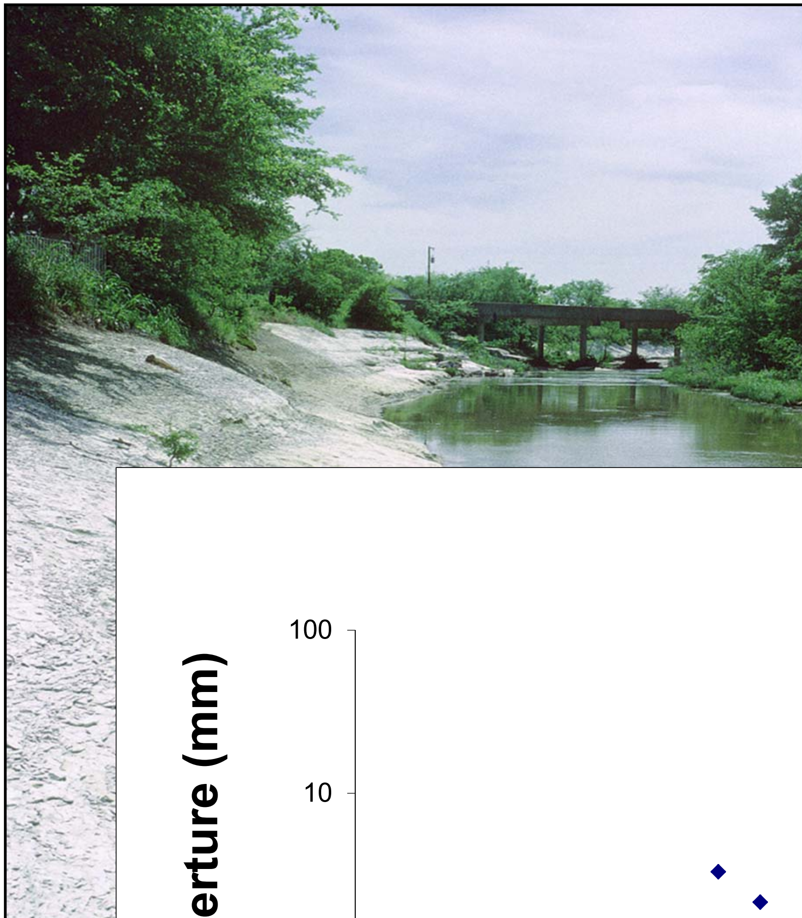
Fracture Kinematic Aperture

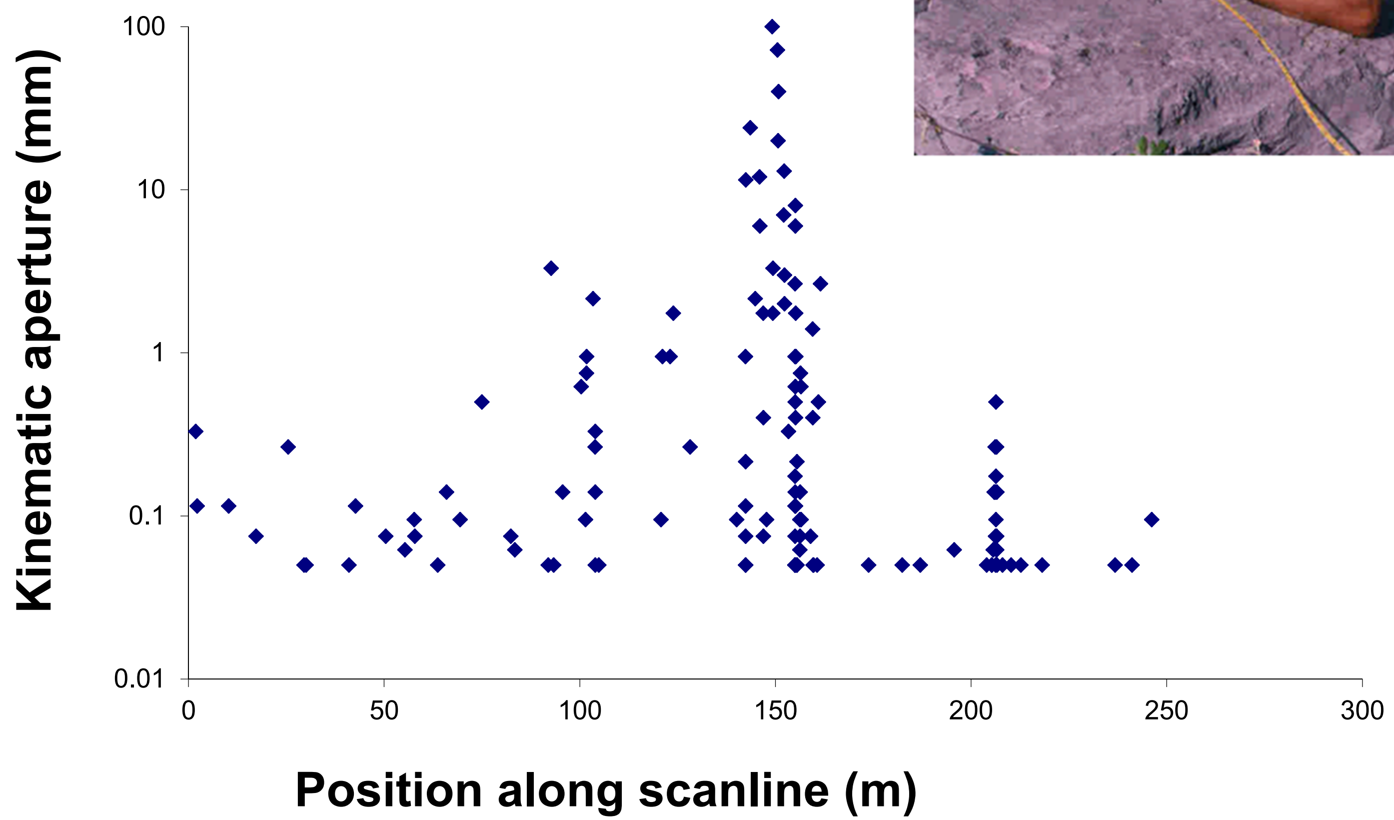
Includes cement and opening

Measured orthogonal to fracture walls

Fracture Frequency

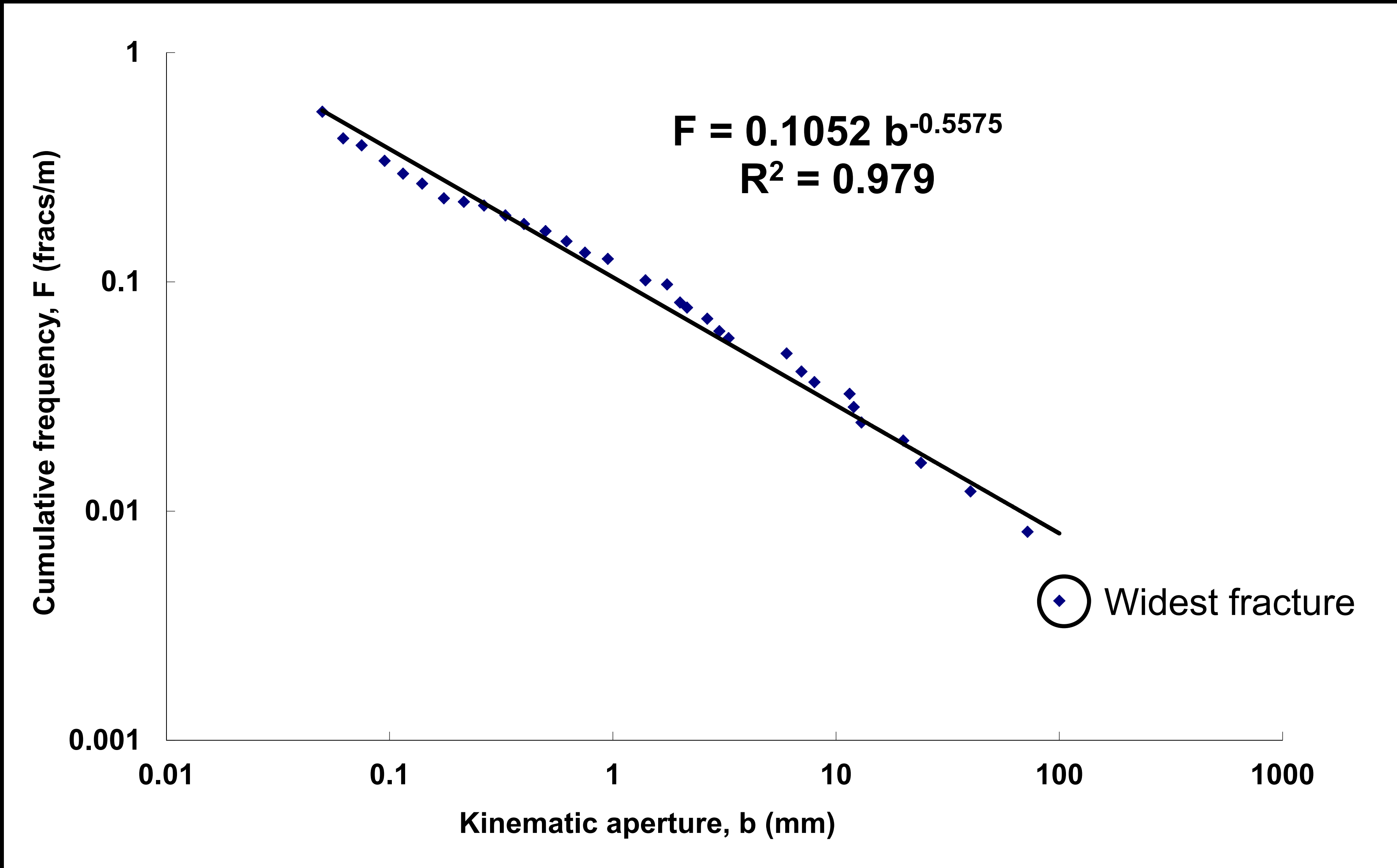
Austin Chalk, Grove Creek, Waxahachie, TX





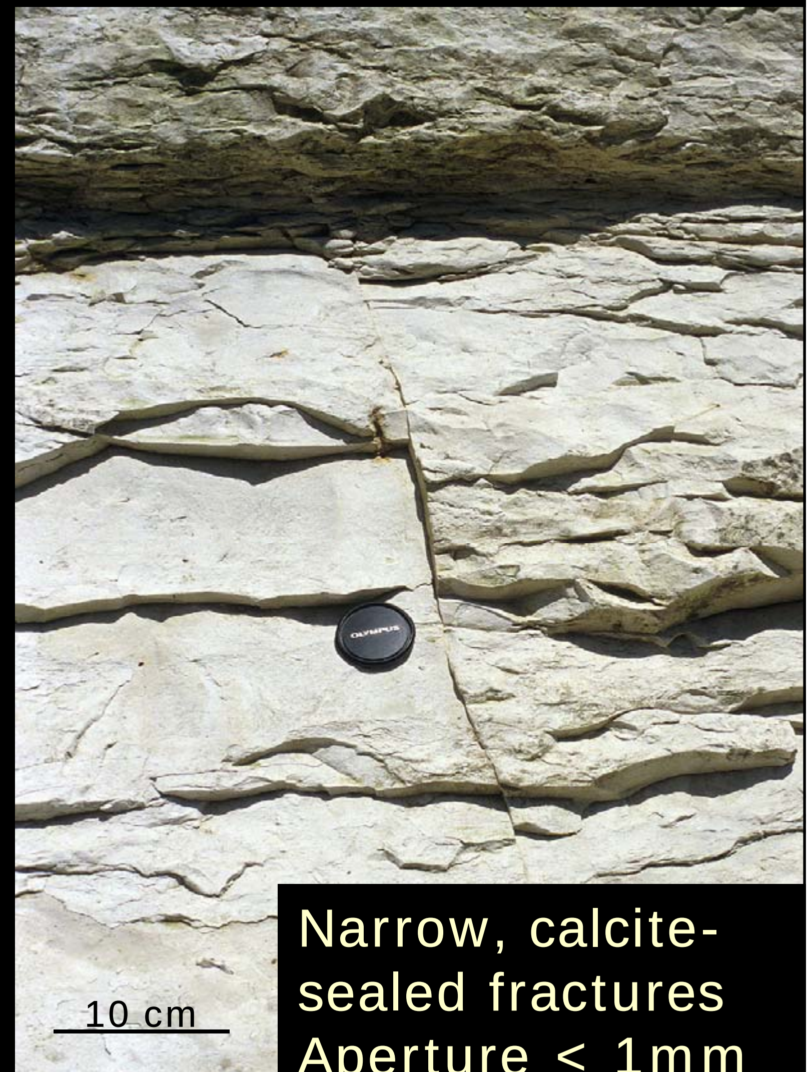
Aperture-Size Distribution

Austin Chalk, Grove Creek



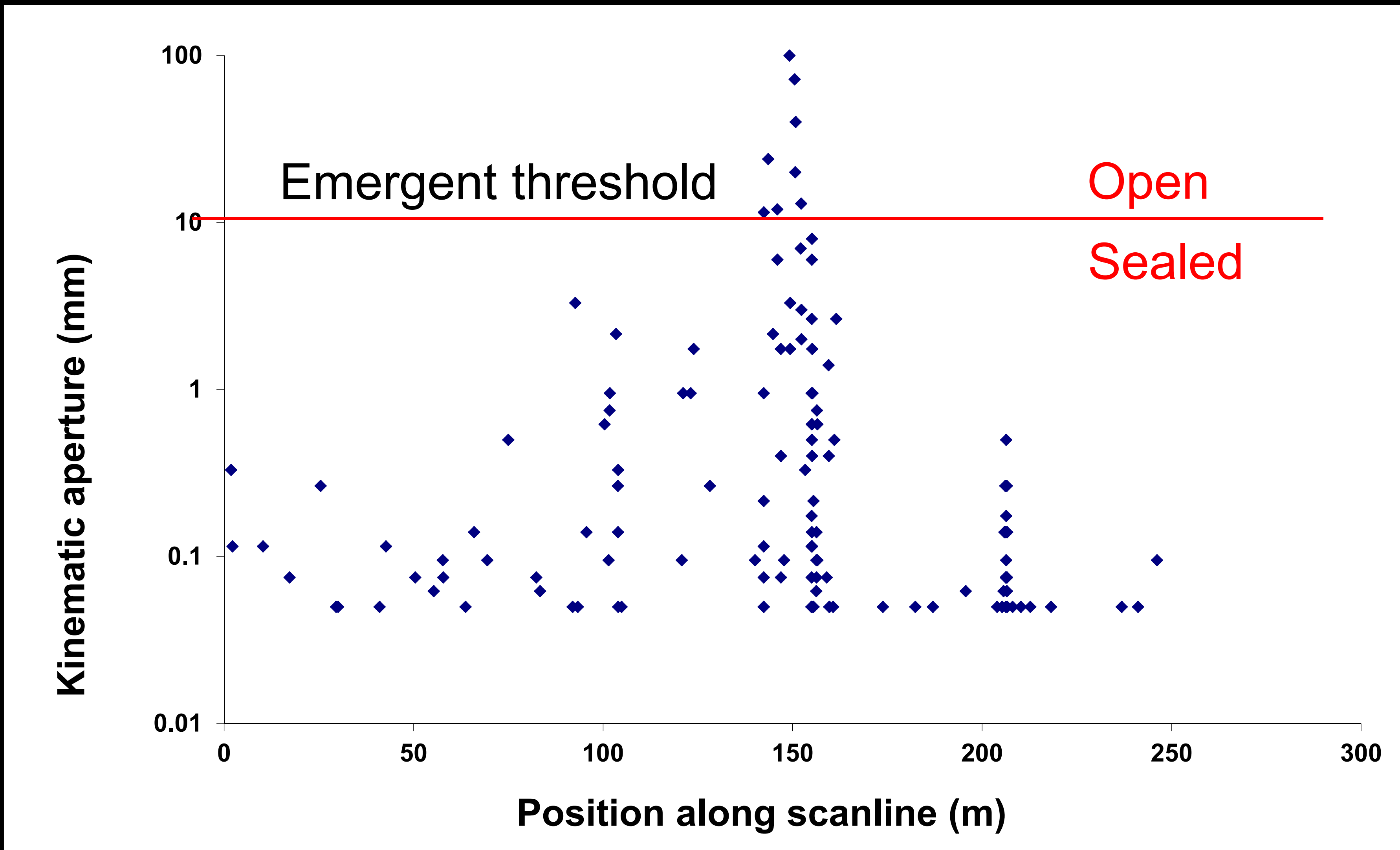
Which Fractures Are Open?

Wide,
partly open
fractures

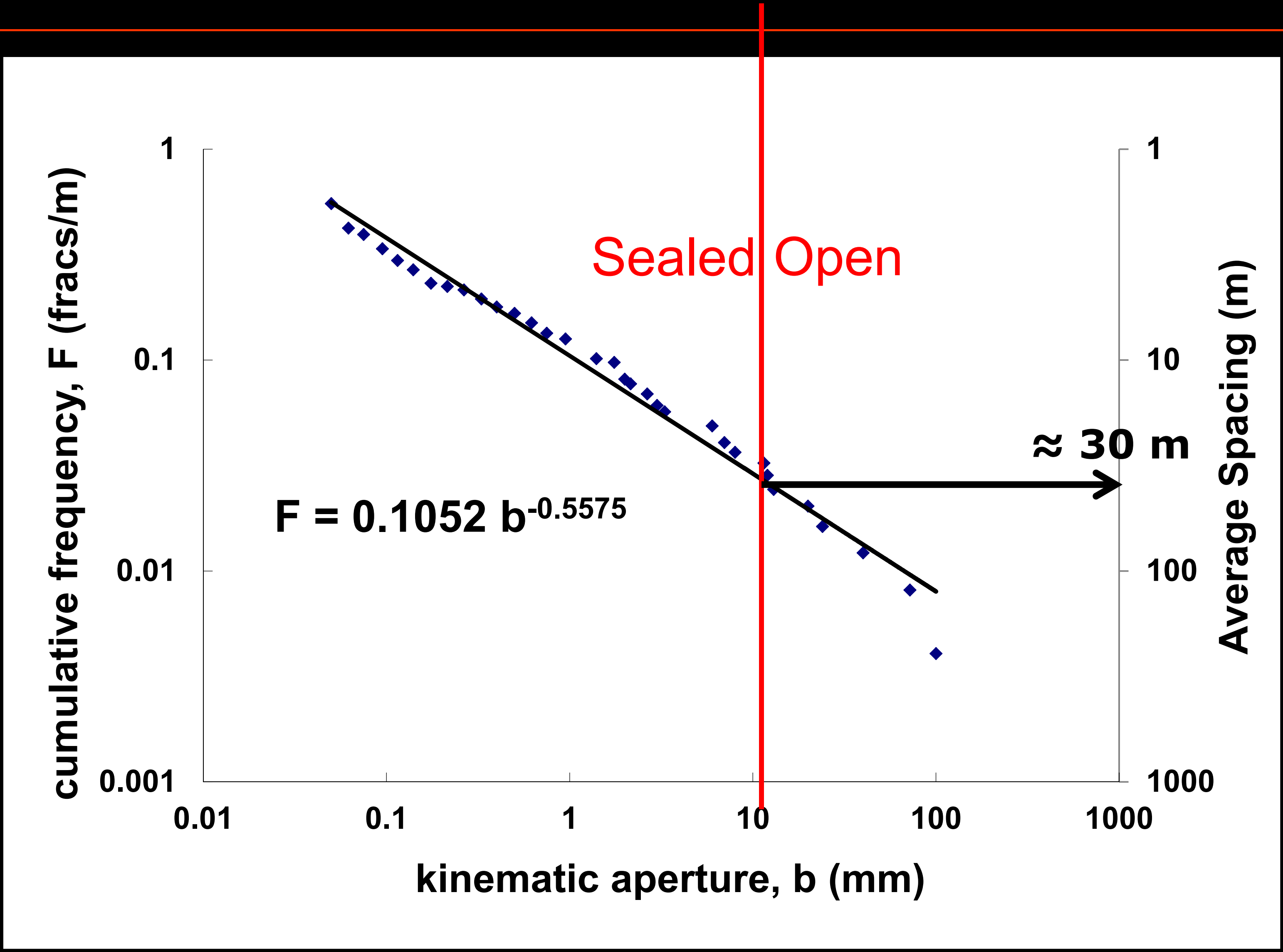


Narrow, calcite-
sealed fractures
Aperture < 1mm

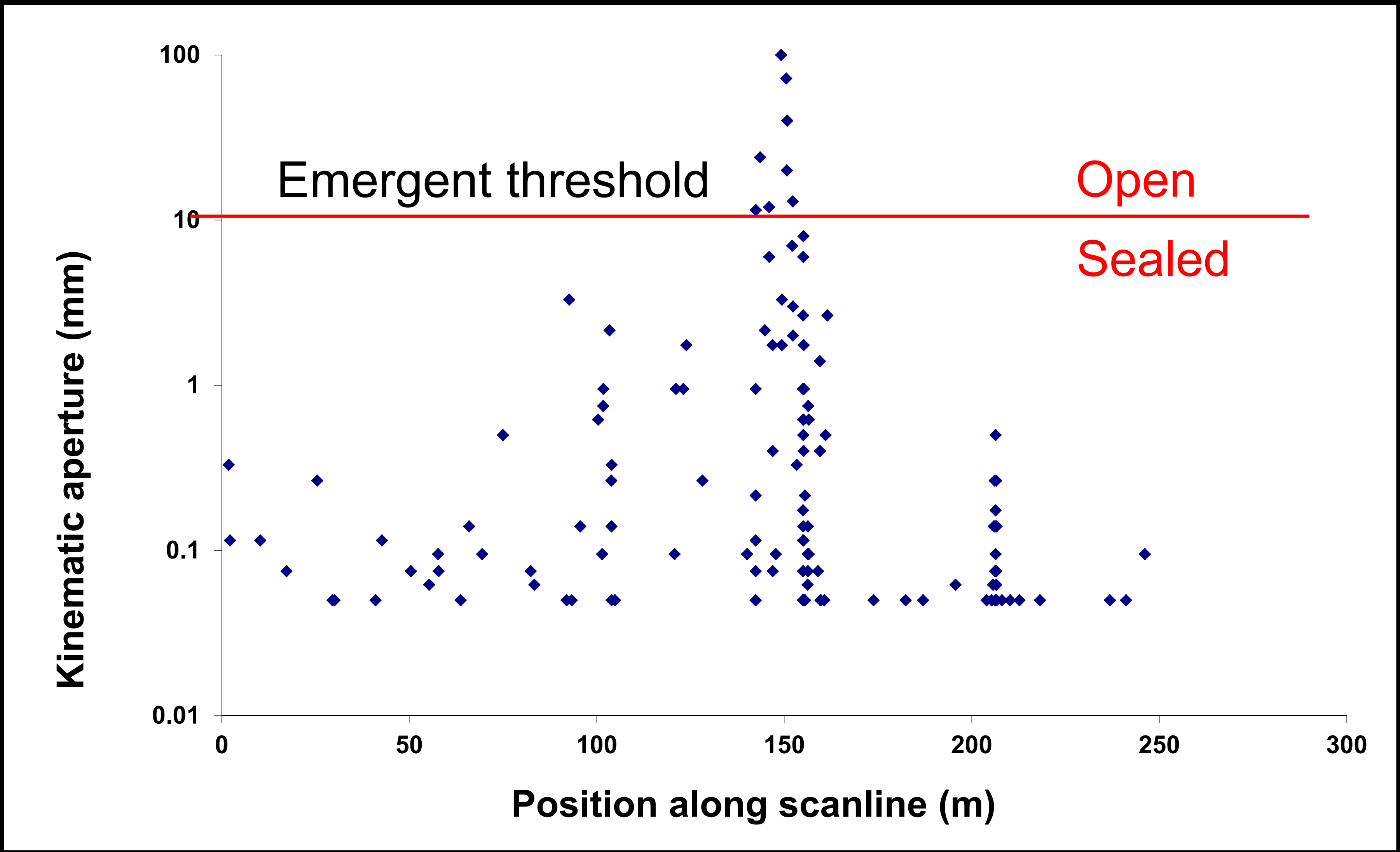
Which Fractures are Open?



Which Fractures are Open?



Which Fractures are Open?

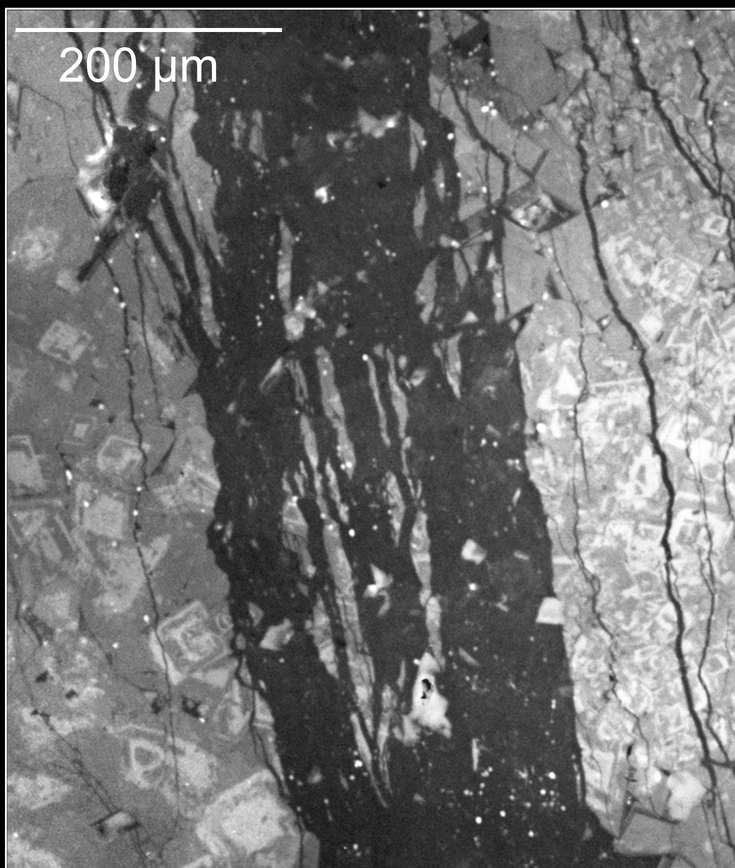


Opening Rate and Diagenesis

- Competition between opening rate and cement precipitation
- Rate determines whether fracture is open
- Collaborative work with Rob Lander and Rob Reed (Gale et al., 2010, Modeling fracture porosity evolution in dolostone, Journal of Structural Geology)

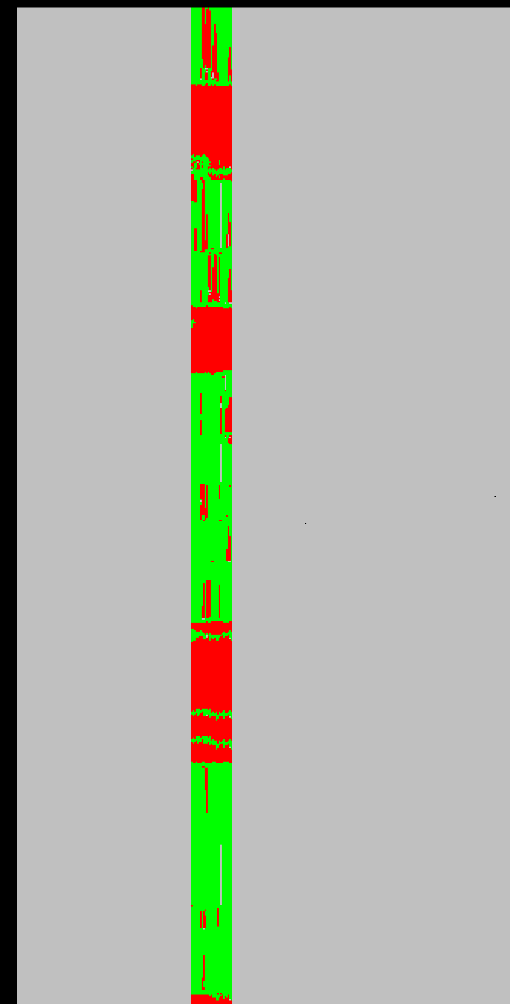
Slow Opening: Sealed Fractures

Crack-seal mechanism



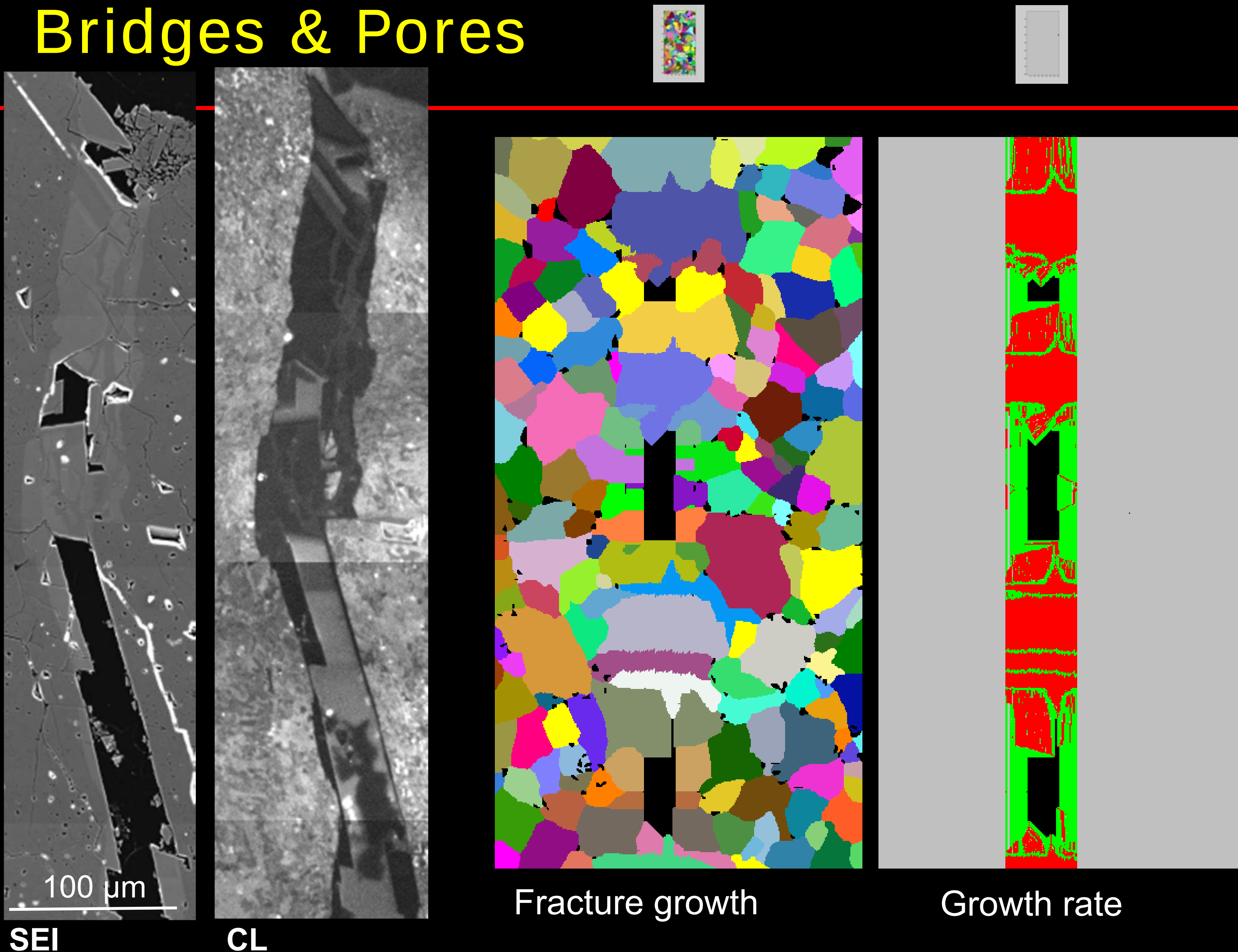
Example, Ellenburger

Crystal growth



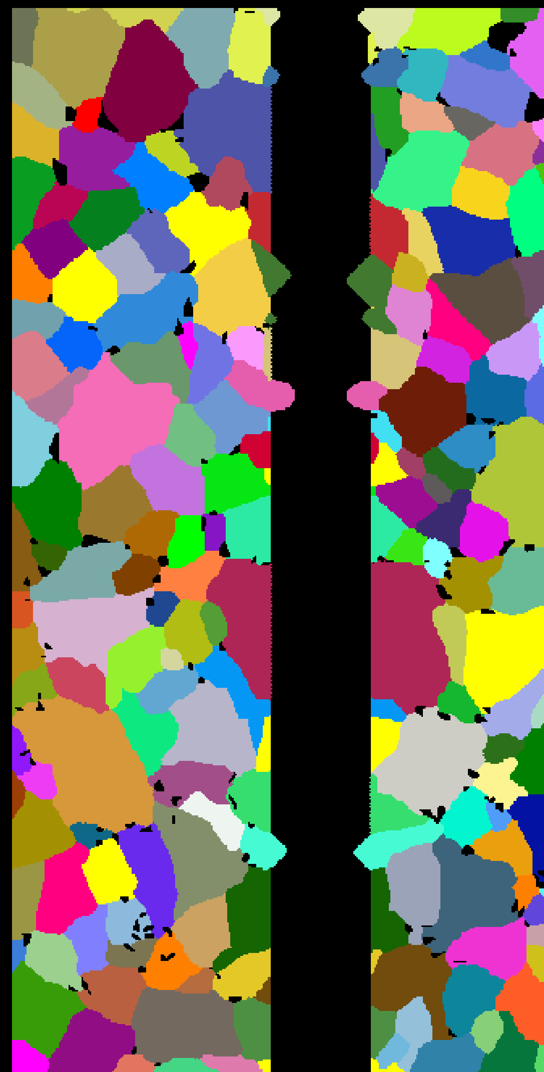
Growth rate

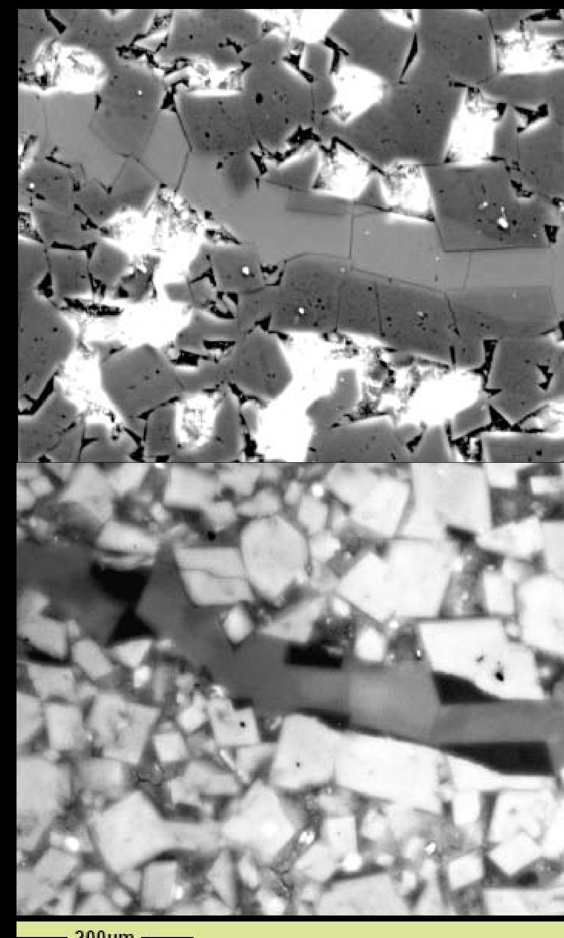
Moderate Opening:
Bridges & Pores



Fast Opening with respect to growth rate: Open Fractures

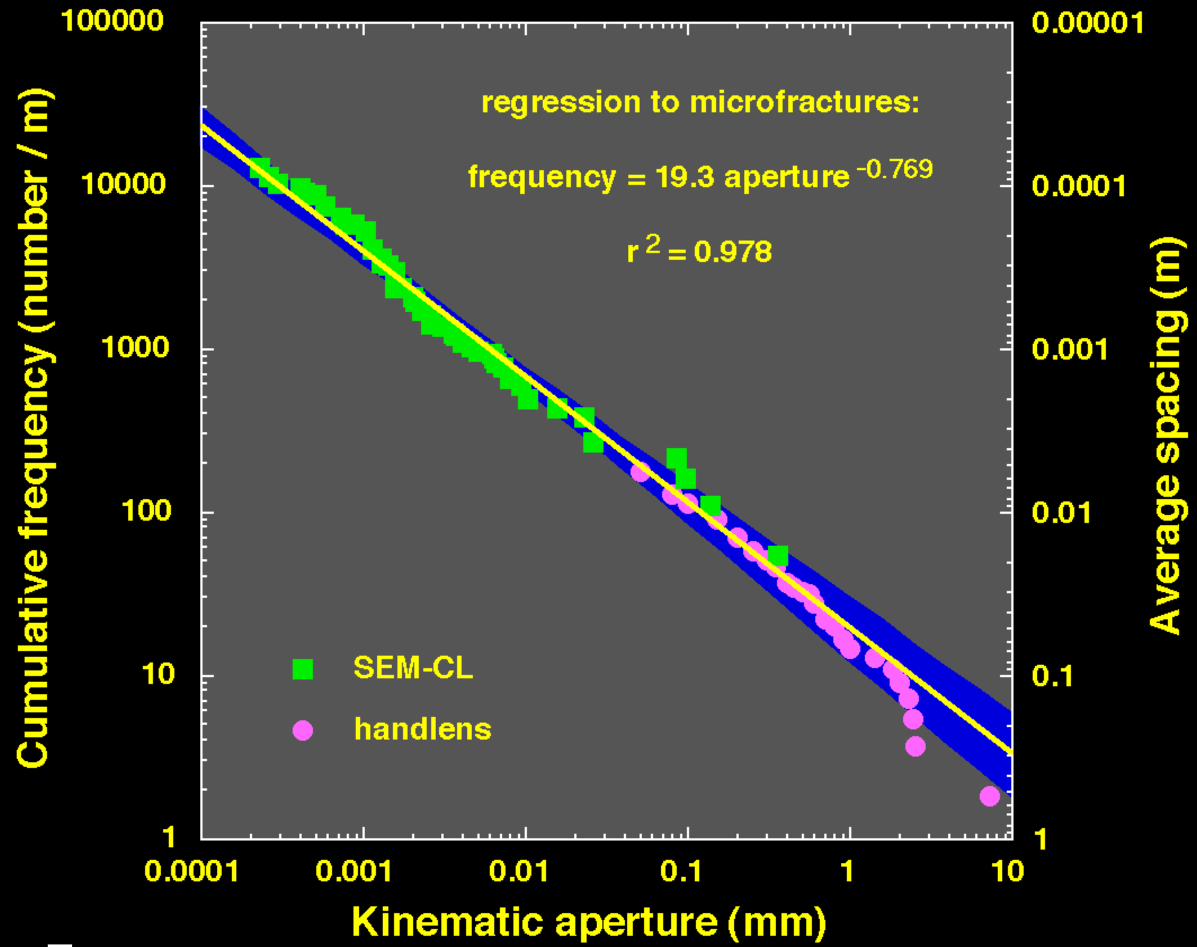
Fracture growth





Example: Ellenburger

Aperture-Size Distribution Micro- and Macrofractures



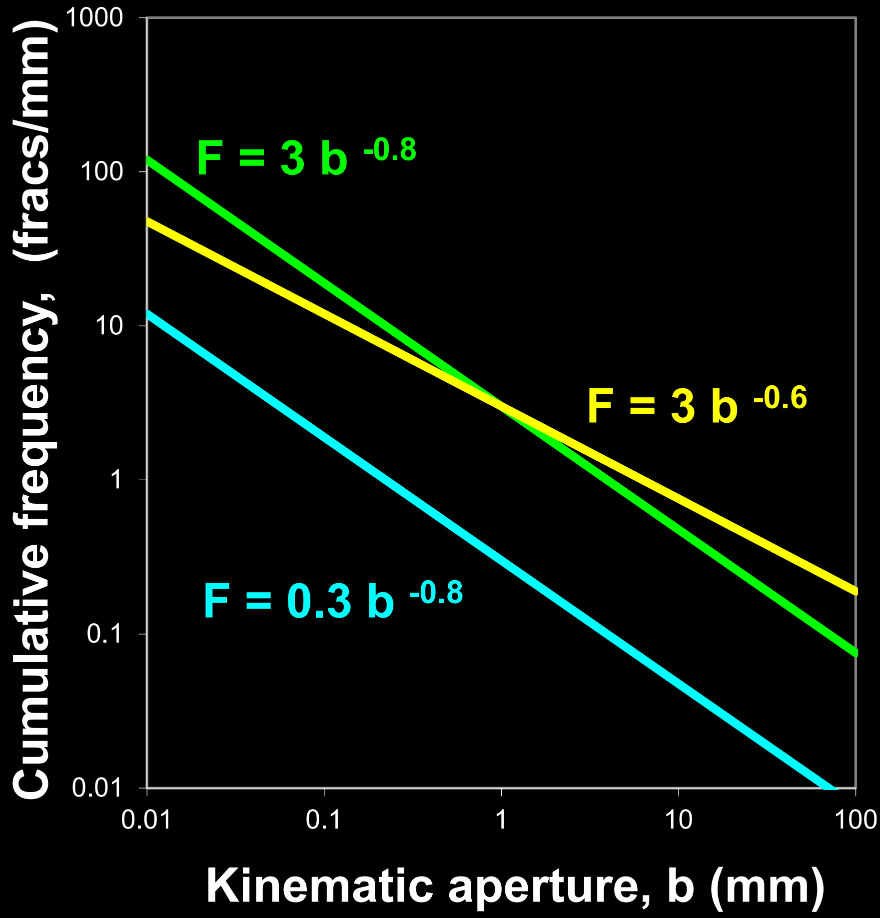
Ozona Sandstone, Texas
Blakeney-Krueger #1 Well

Marrett, Ortega, & Kelsey, 1999. *Geology* 27: 799-802

Aperture-Size Distribution
Power Law Variables

$F = \text{coefficient } b^{-\text{exponent}}$

- Coefficient: measure of fracture intensity at a given aperture size
- Relative intensities of small and large fractures constant (green and blue curves)
- Exponent: slope of curve, reflecting relative numbers of narrow and wide fractures (green and yellow curves)



What Factors Control Aperture-Size Distribution?

Strain & strain rate

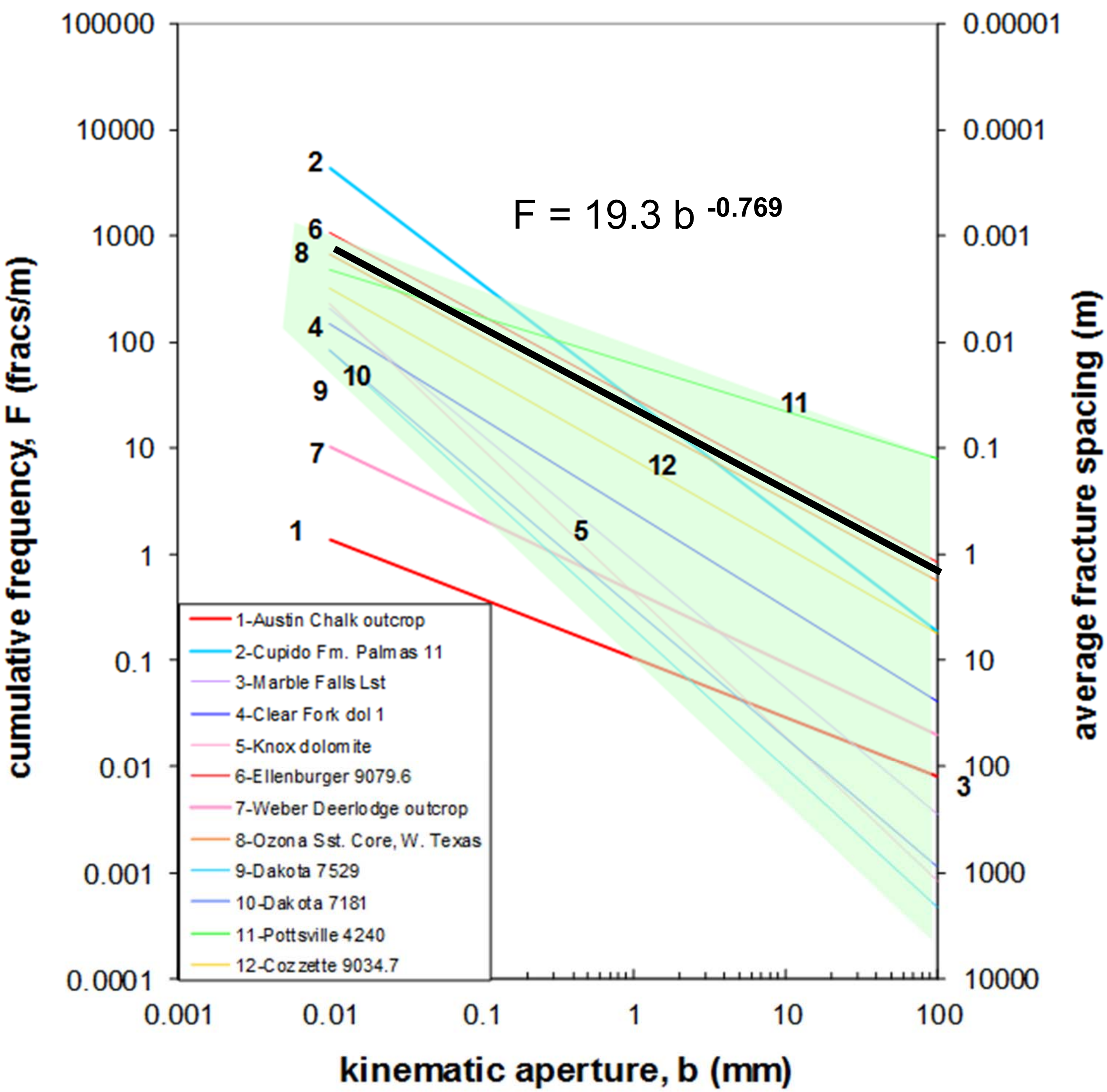
Diagenesis

Mechanical layer thickness

Strain

Does increase in strain reflect

- New fractures at the small scale?
  - Increase in coefficient and exponent
- More large fractures as fractures link?
  - Decrease in exponent and coefficient
- A combination of these?
- Does strain partition onto open (larger) fractures?
  - Decrease in exponent



Variation in Power-Law Exponent

6 of 12 exponents ≈ - 0.8

Green envelope: shallow slopes go with high intensity and vice versa

3 exceptions

Gale, J. Self-organization of natural mode-I fracture apertures into power-law distributions. ARMA, Houston 2004.

Strain Rate + Diagenesis

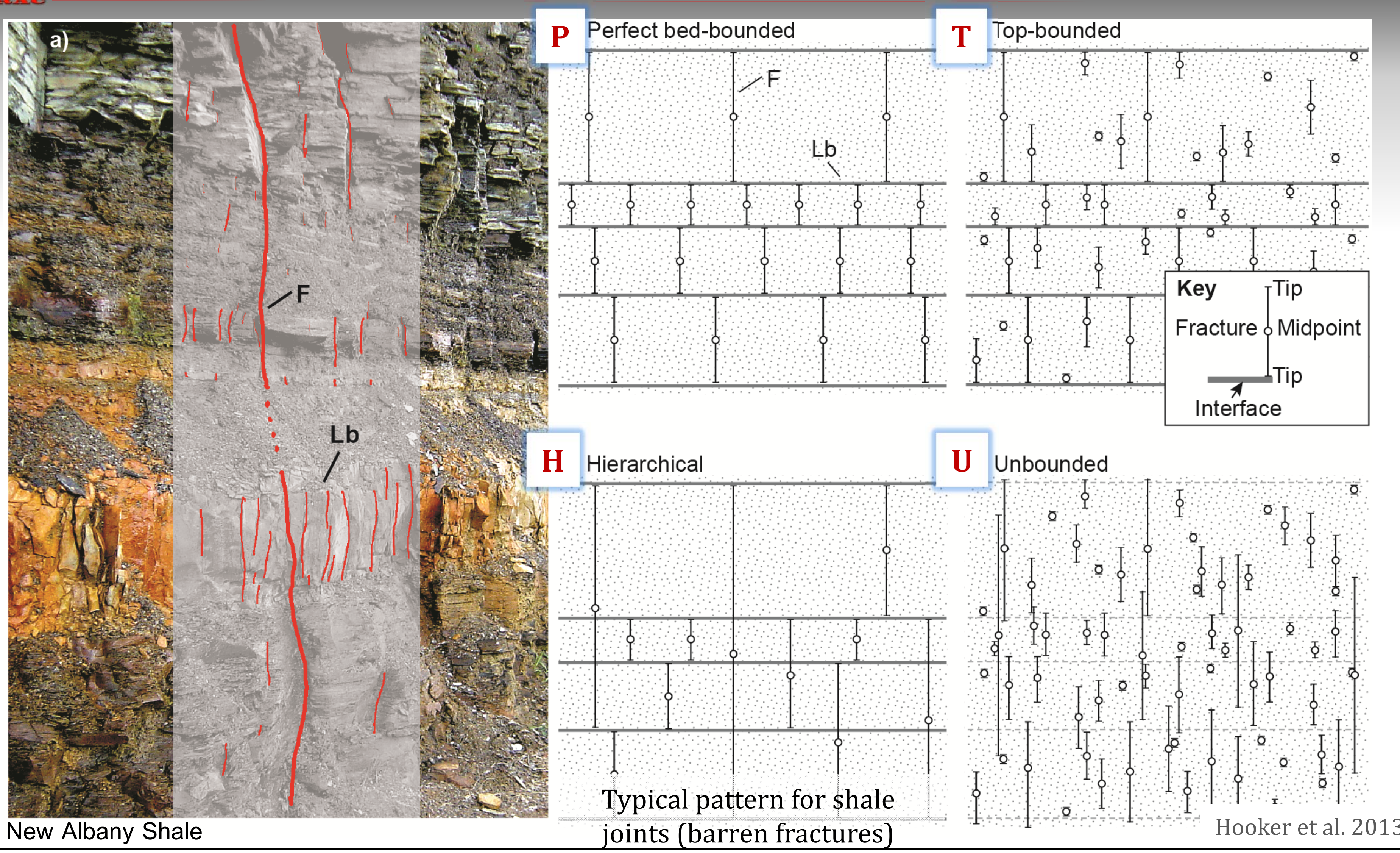
- Once open, fractures do not close
- Opening rate
  - Competition between opening rate and cement precipitation rate determines whether fracture is open (Lander et al.)
  - Partly open fractures might continue to grow more readily than sealed fractures
  - Opening rate might vary with time

Factors Affecting Aperture-Size Distribution
Mechanical Layer Thickness

- Mechanical layer thickness
  - May control height
  - Aperture growth of layer-confined versus unconfined fractures
- Is there a hierarchy of mechanical layers for different width fractures?

Hierarchical Example

New Albany Shale



Hooker et al. 2013

Attributes

- Aperture
- Openness
- Height
- Length
- Spatial Organization

Non-random natural fracture architecture

Evenly spaced fractures

Frontier Fm. Muddy Gap, WY

Clustered fractures

Cupido Fm. Sierra Madre Oriental, Mexico

Spatial Organization Terminology

Random: Lack of organization among fractures; clustering exists but lacks statistical significance

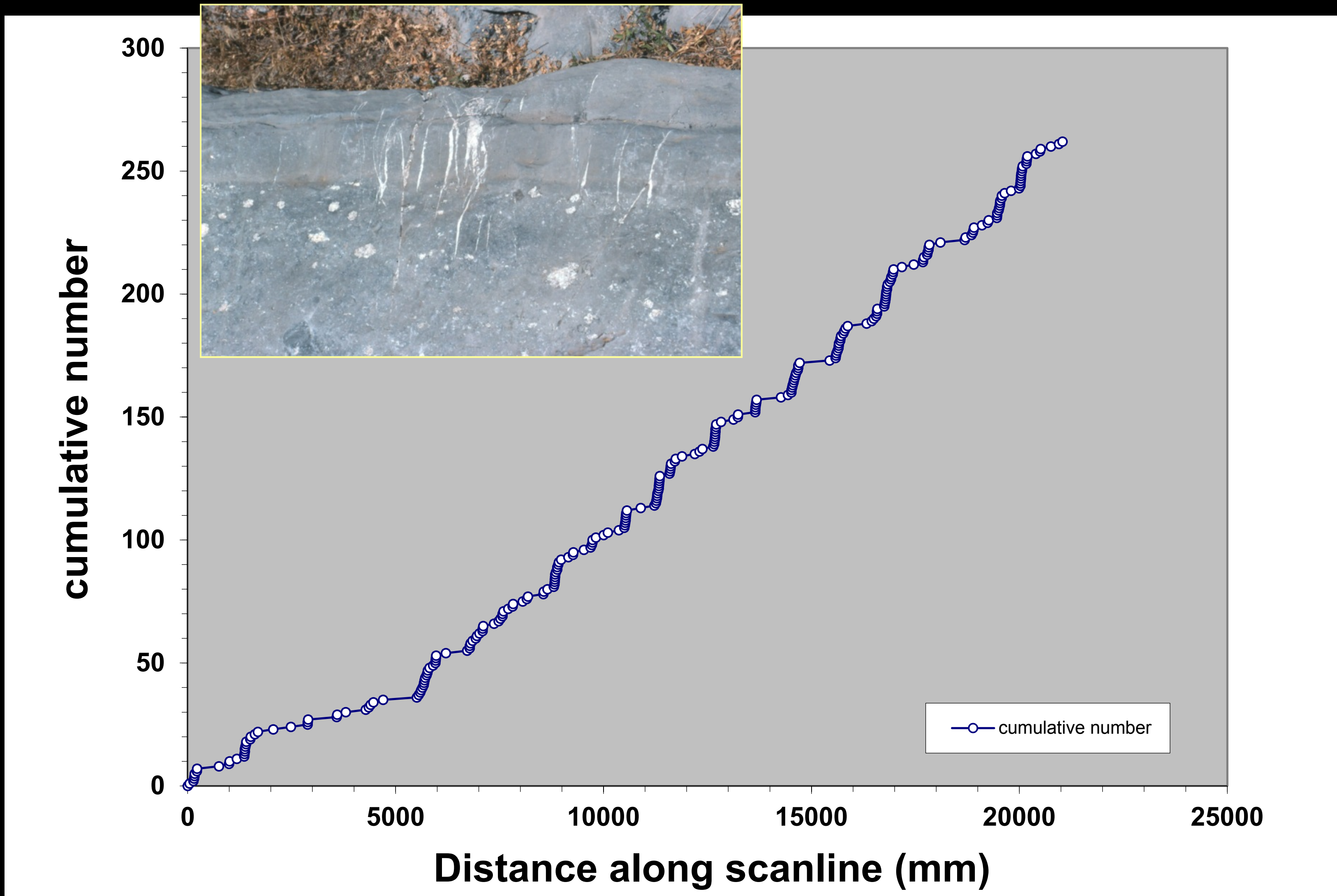
Harmonic: Evenly spaced; statistically significant absence of clustering

Clustered: Stronger clustering than random, with statistical significance

Fractal: Clustering that is systematic (follows power law) across a broad range of scales

Cumulative Fracture Distribution

Palmas 11 dolostone



Scanline Data for Spatial Analysis

Measure aperture and spacing sequence along scanline

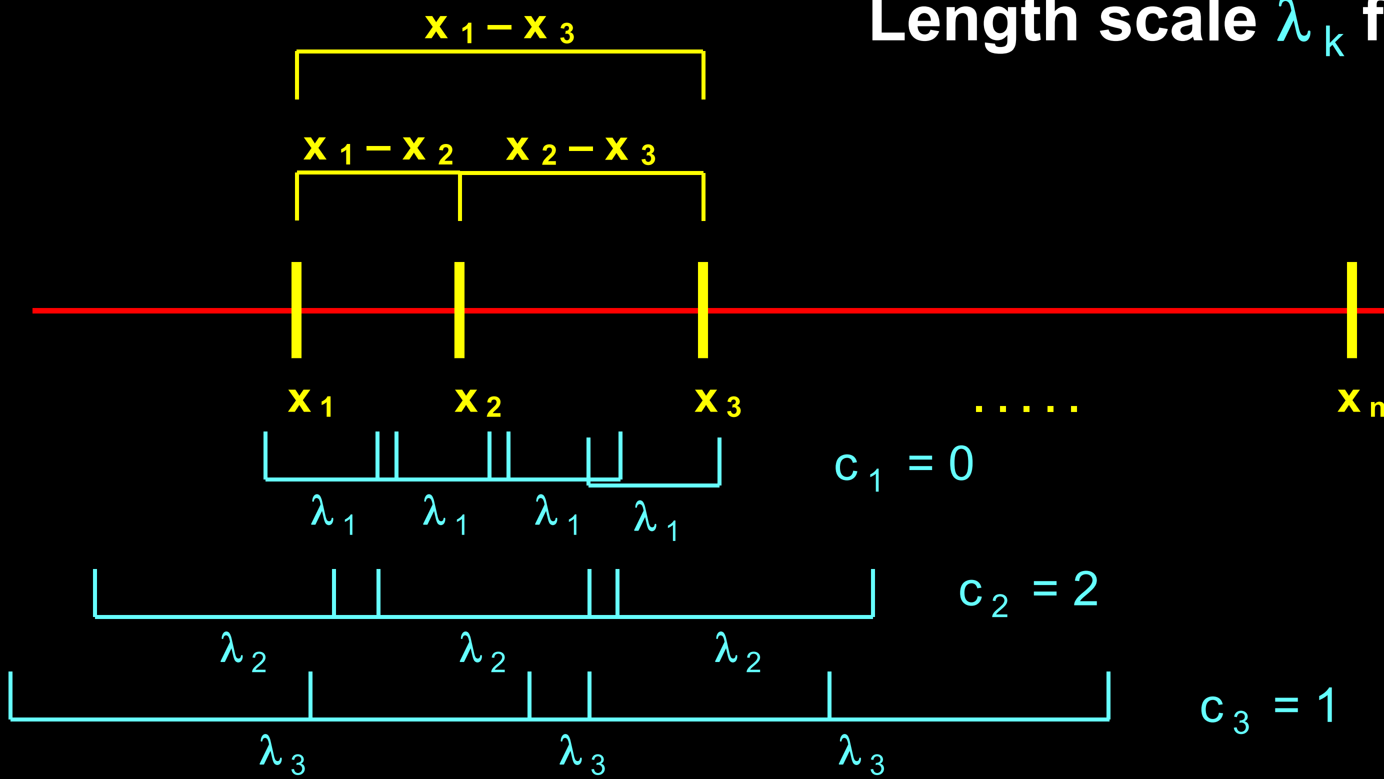
Number of fractures: n

Spacing of fracture pairs, including non-nearest neighbor fractures

Marrett et al.

Measuring Correlation Count

Length scale λ_k for analysis



Correlation count c_k is the number of fracture pairs for which

$x_i - x_j < \lambda_k$ and $x_i - x_j > \lambda_{k-1}$

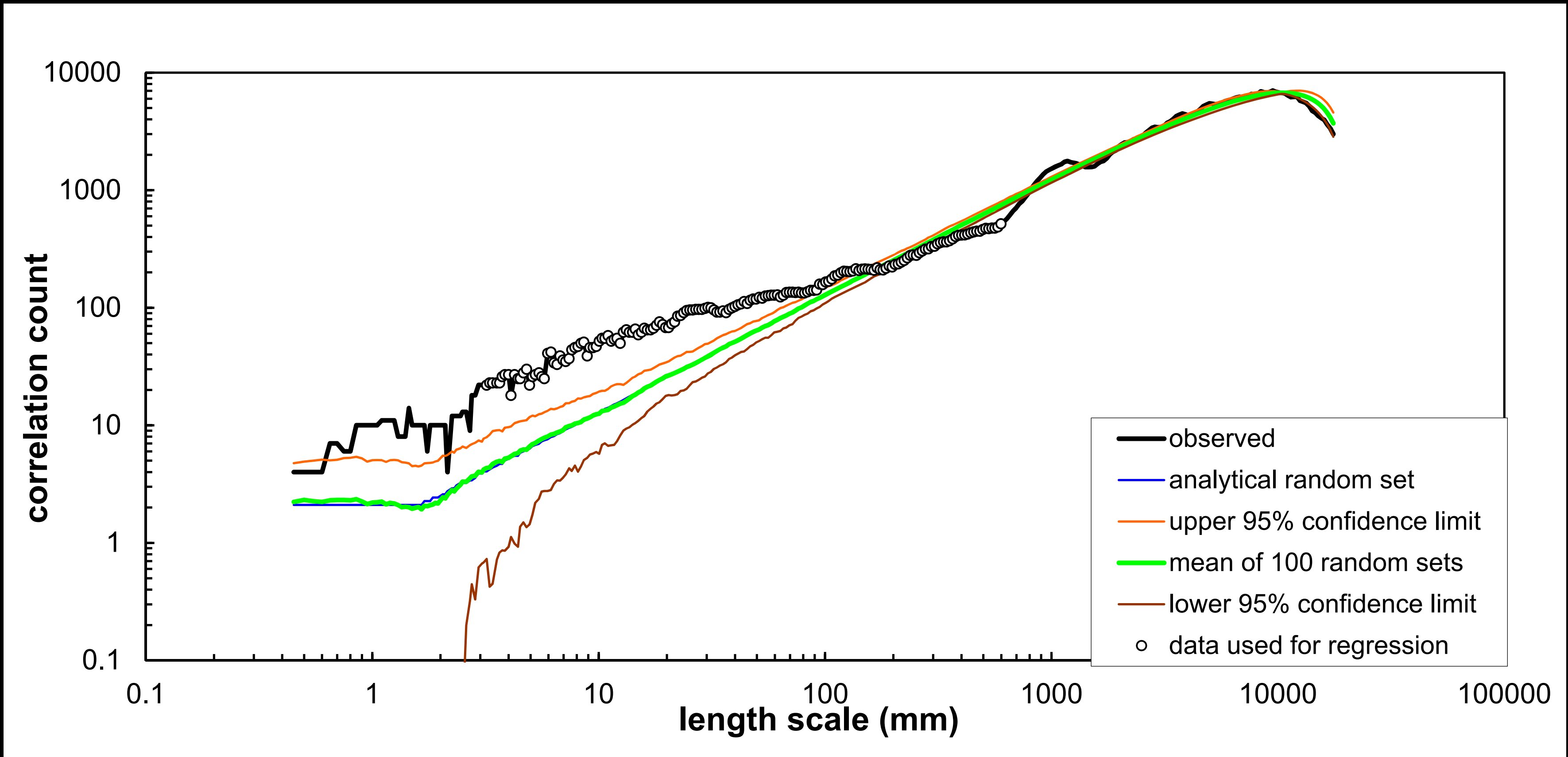
Marrett et al.

Spatial Correlation

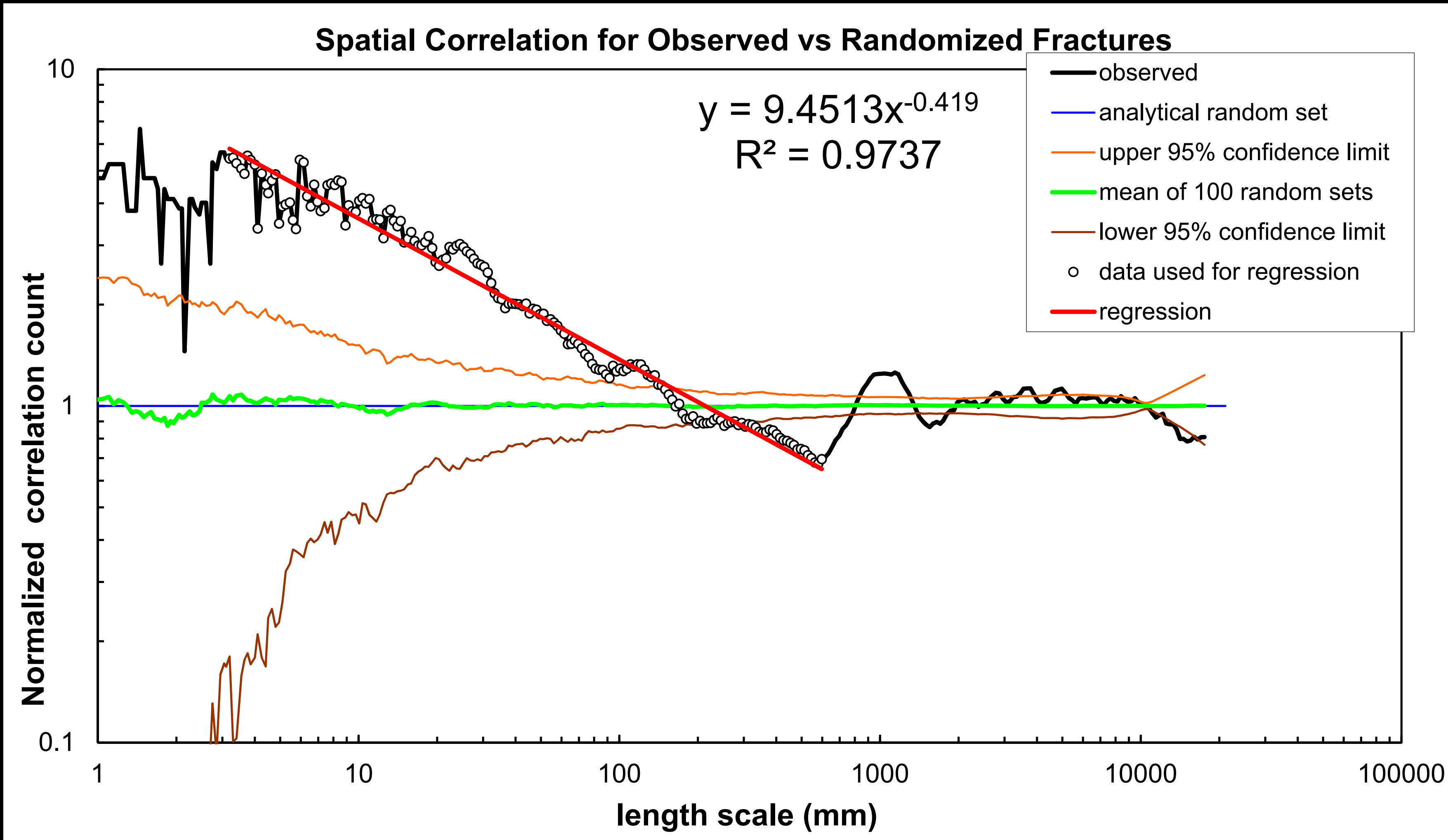
Measure of difference between data & random

c_k for random spacing calculated analytically (blue)

c_k for random spacing generated from randomized data (green = mean of 100 iterations)



Normalized Correlation Count



Marrett et al.

Conclusions

- Fracture aperture-size varies in a predictable way across a range of scales
- Aperture-size and openness during growth are linked
- Empirical data allow us to attempt models of growth
- Spatial organization of fractures can be quantified and compared with random cases

Bureau of Economic Geology

Acknowledgments

BUREAU OF ECONOMIC GEOLOGY

Funding

- Fracture Research and Application Consortium (FRAC)
- RPSEA (Funding for New Albany and Marcellus studies)
- GDL Foundation

Samples and collaboration

- Fracture Research and Application Consortium (FRAC)
- Kentucky & Indiana Geological Survey, Noble Energy, NGas, Daugherty Petroleum, Range Resources, Pioneer Natural Resources
- Terry Engelder