Characterization of Heterogeneities at the Reservoir Scale: Spatial Distribution and Influence on Fluid Flow

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Outline

- Definitions, Goals & Significance of Project
- Spatial Distribution of Fractures
  - Fracture Type (faults versus joints)
  - Mechanical Stratigraphy
  - Throughgoing Fracture Zones
- Characterization of Limestone Pore Geometry
  - Stratigraphic Controls
  - Influence on porosity trends
- Developing a Fracture Architecture for Layered Sedimentary Rocks

What are reservoir-scale heterogeneities?

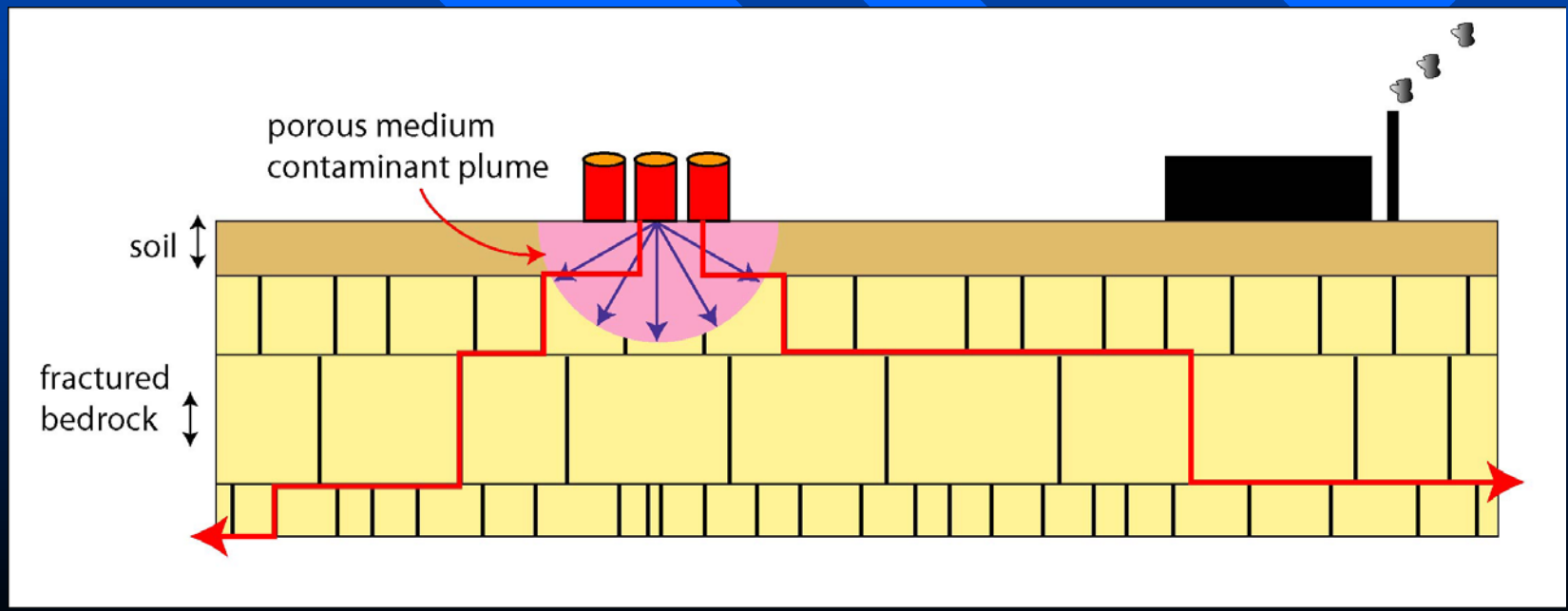
- Structural Discontinuities
  - Faults, Joints, Fracture Zones
- Sedimentological / Diagenetic Features
  - Facies changes, solution cavities, stratigraphic boundaries

Why are they important?

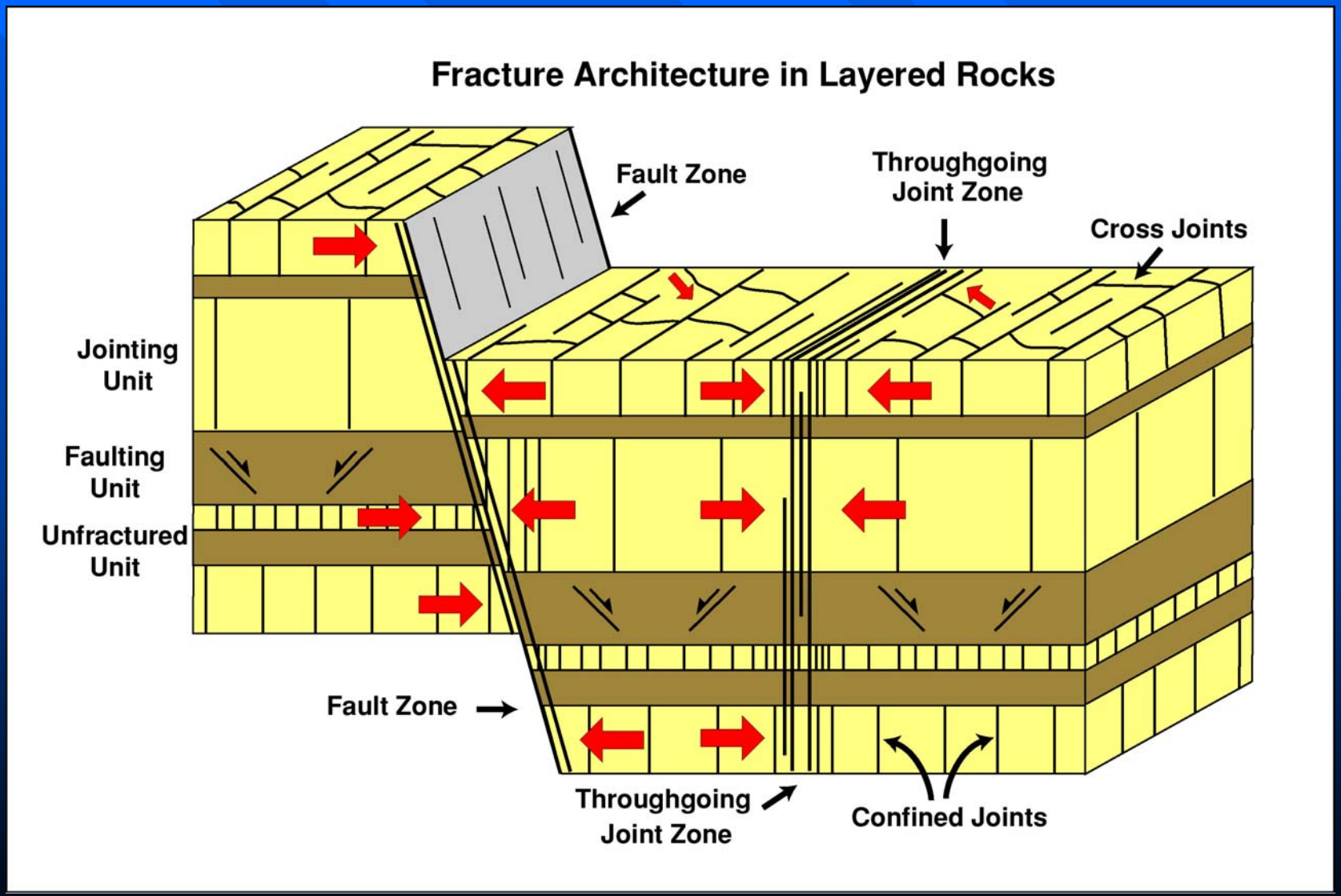
- They control velocity, direction and volume of fluid flow in the subsurface
- They can serve either as conduits or barriers to fluid flow
- They add complexity to oil & gas production, reservoir modeling, contaminant transport.

Why is the D.O.E. interested?

- Oil & Gas production from fractured (unconventional) reservoirs
- Enhanced / secondary recovery from mature oil fields
- Contaminant migration in the shallow subsurface
- Potential target for carbon sequestration

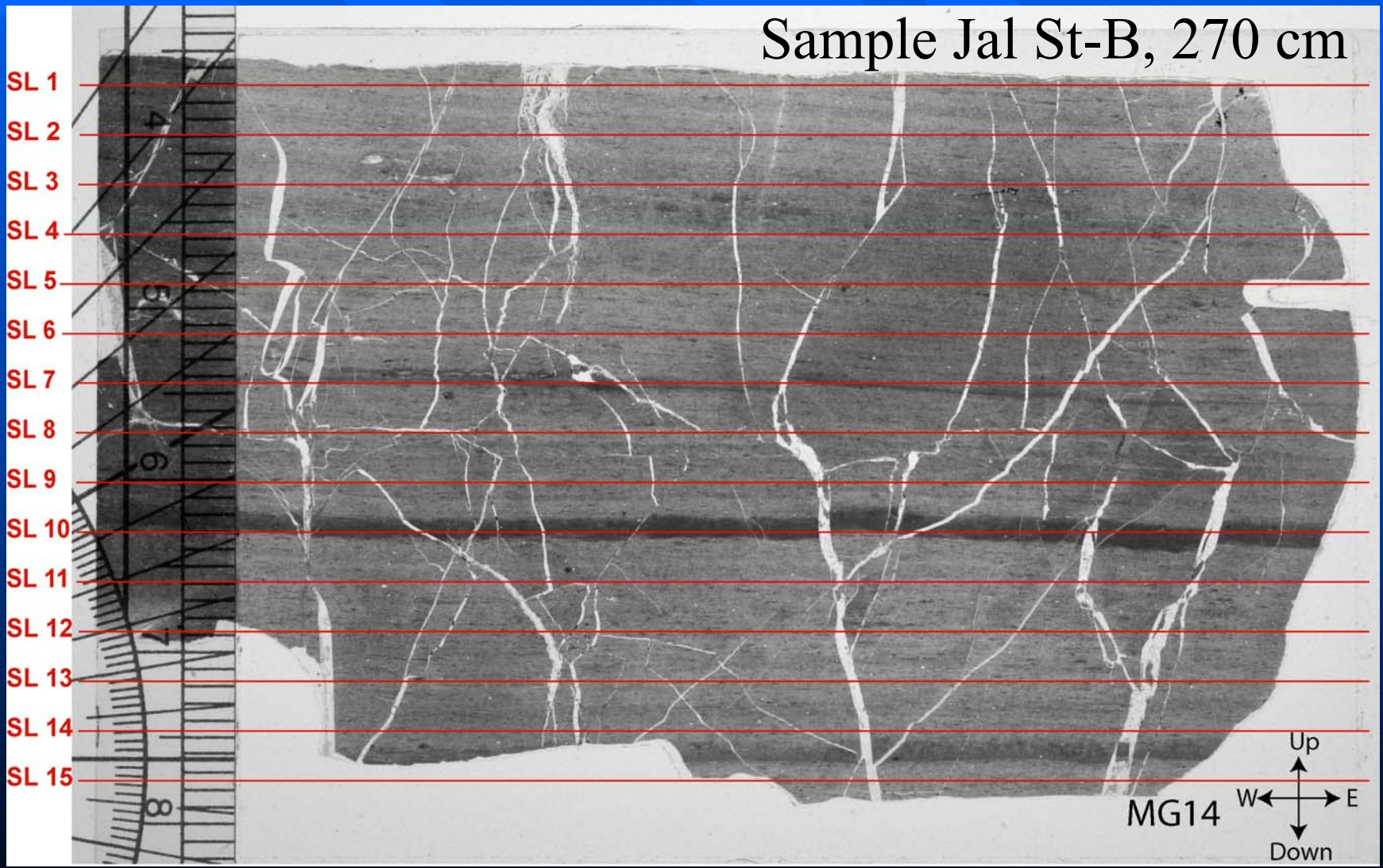


Schematic of Fracture Distribution

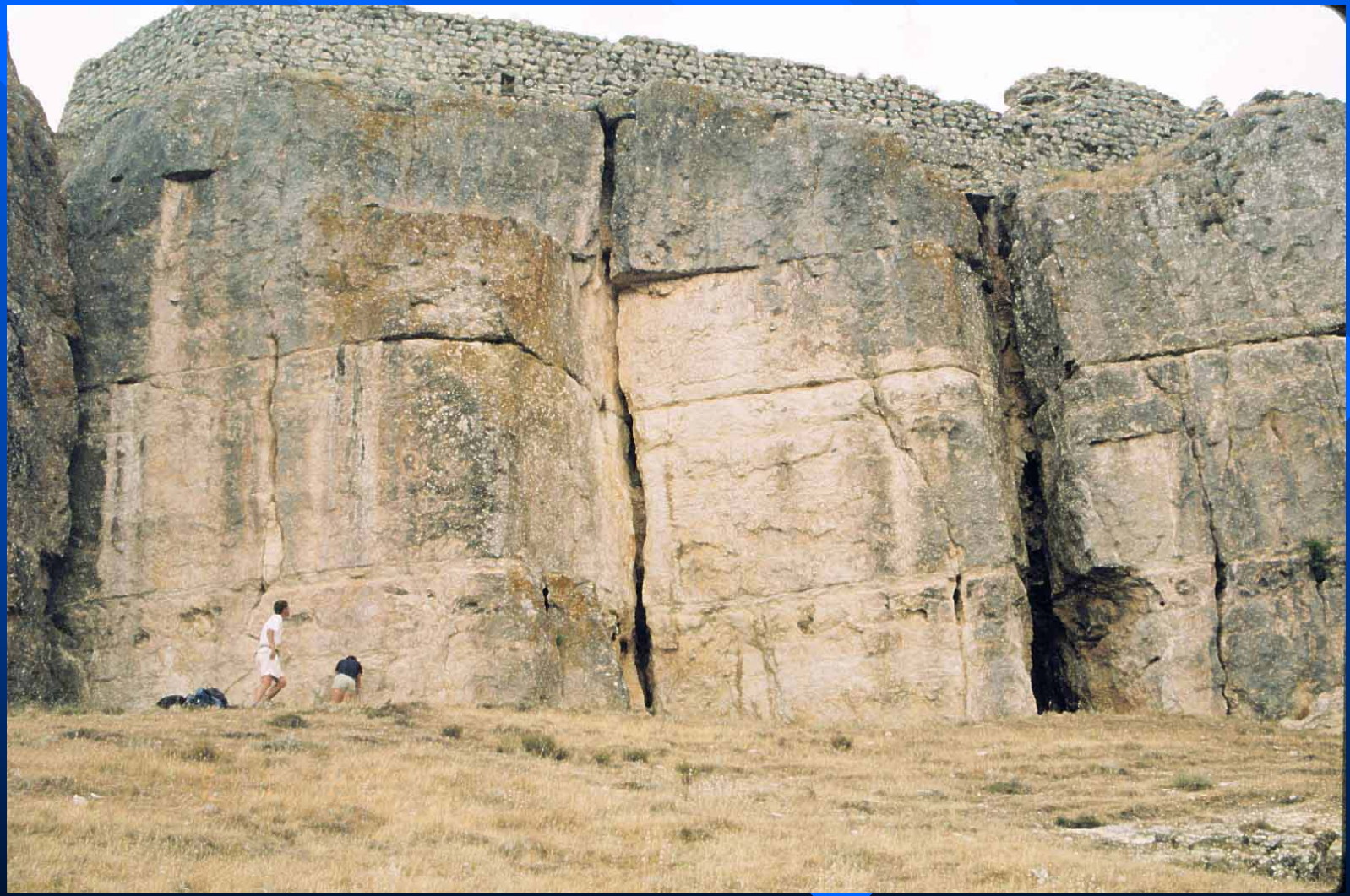


Integrated Mech Strat at Reservoir Scale

Fractures at the Microscale



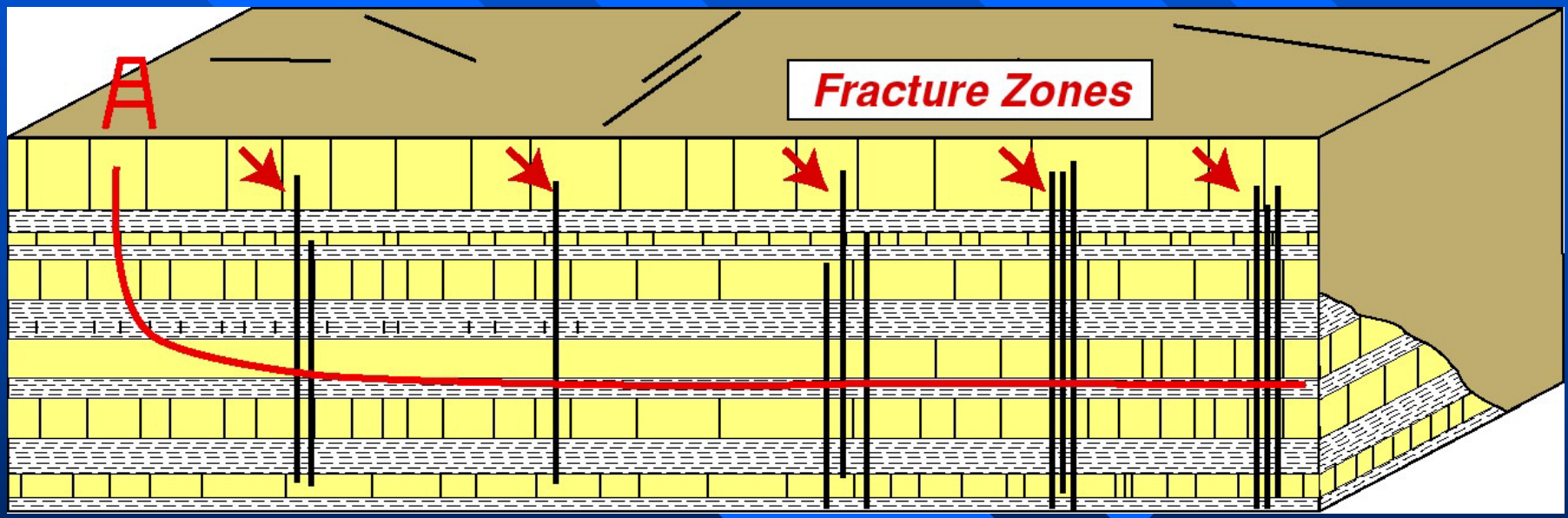
Fracture Zones at the Reservoir Scale



Fractured Limestone, Atienza (Spain)

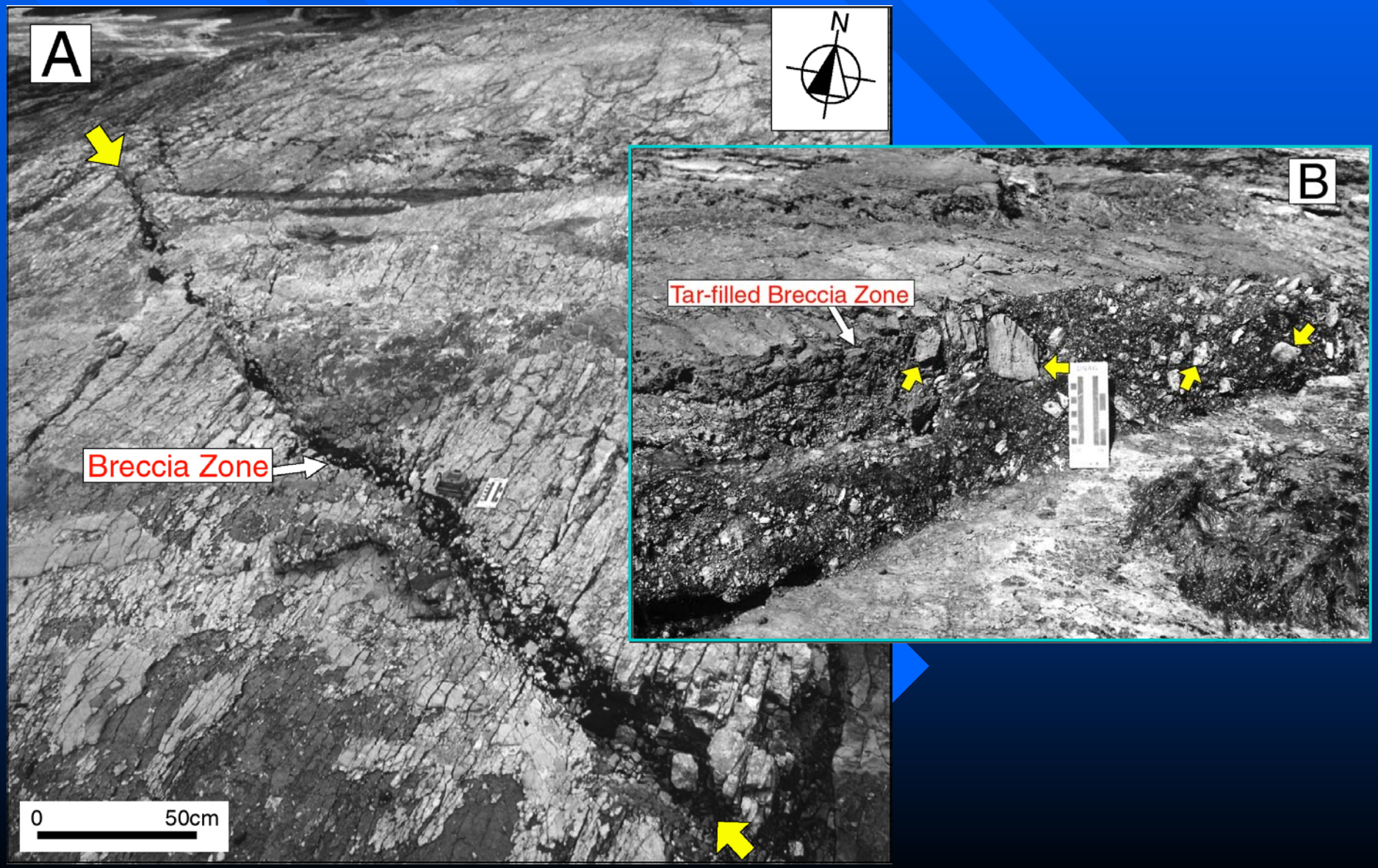
Why are fracture zones important?

… they serve as high-permeability conduits for fluid flow in the subsurface

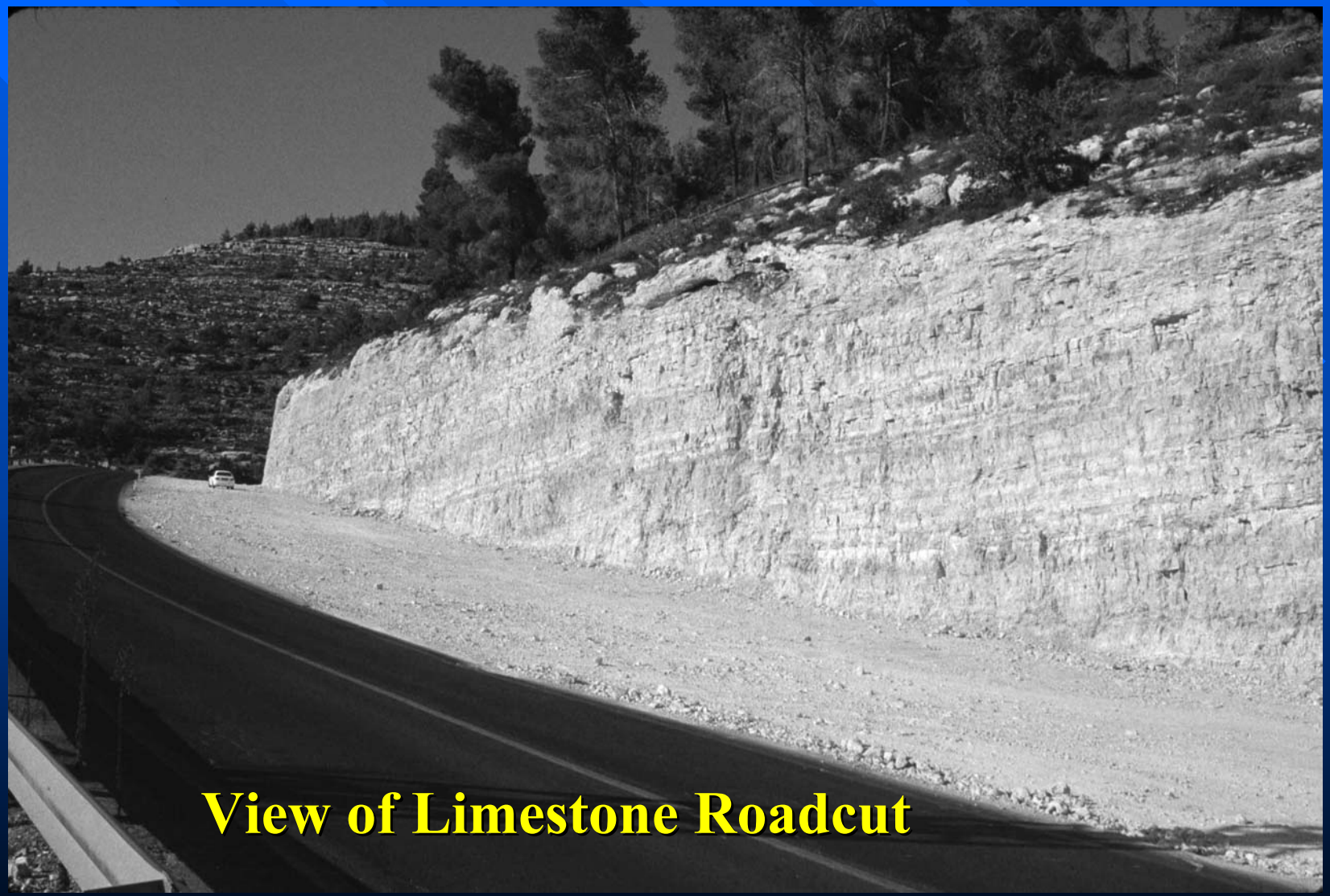


Horizontal wells target fracture zones in order to maximize oil & gas production from fractured reservoirs

Tar-filled Fracture Zones
Monterey Formation Reservoirs, California



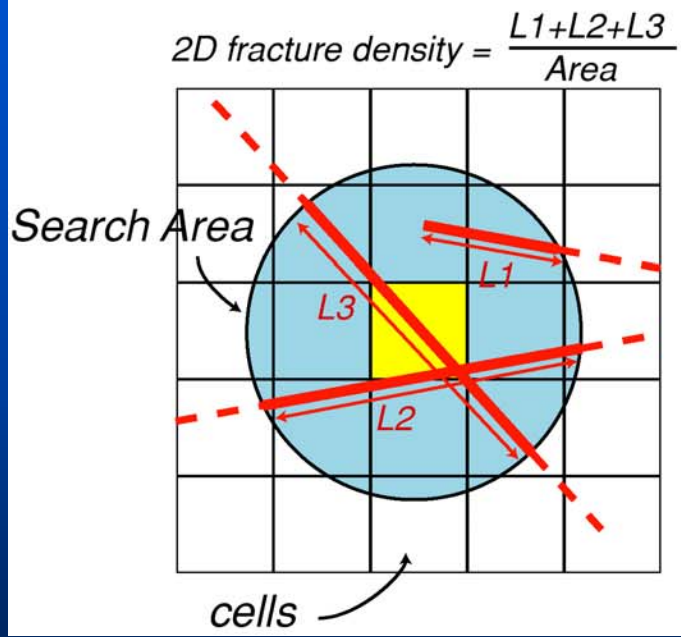
Fracture Zone Characterization Using GIS



View of Limestone Roadcut

Mapping Fracture Density (Intensity) in GIS

Line Density routine in ArcInfo

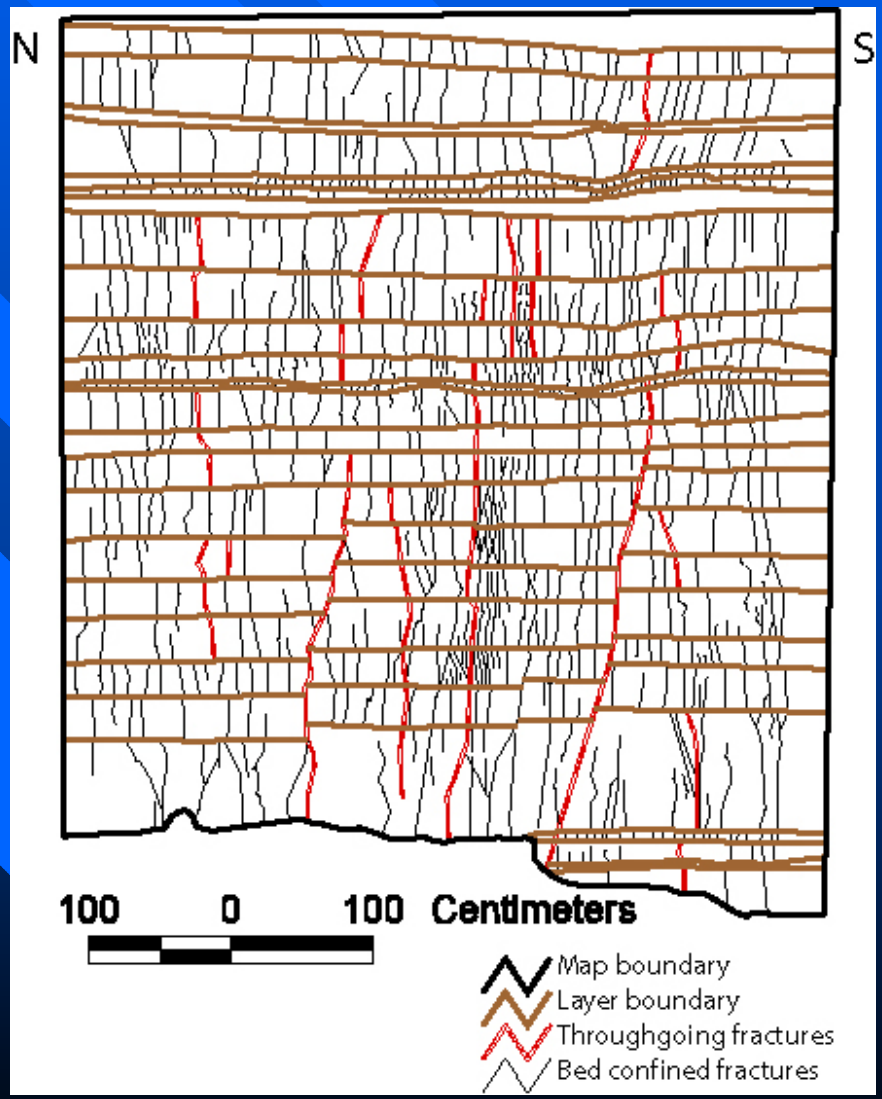


Calculates a two-dimensional fracture density for each cell in the map grid. The sum total of all fracture lengths within a prescribed search area is divided by the search area.

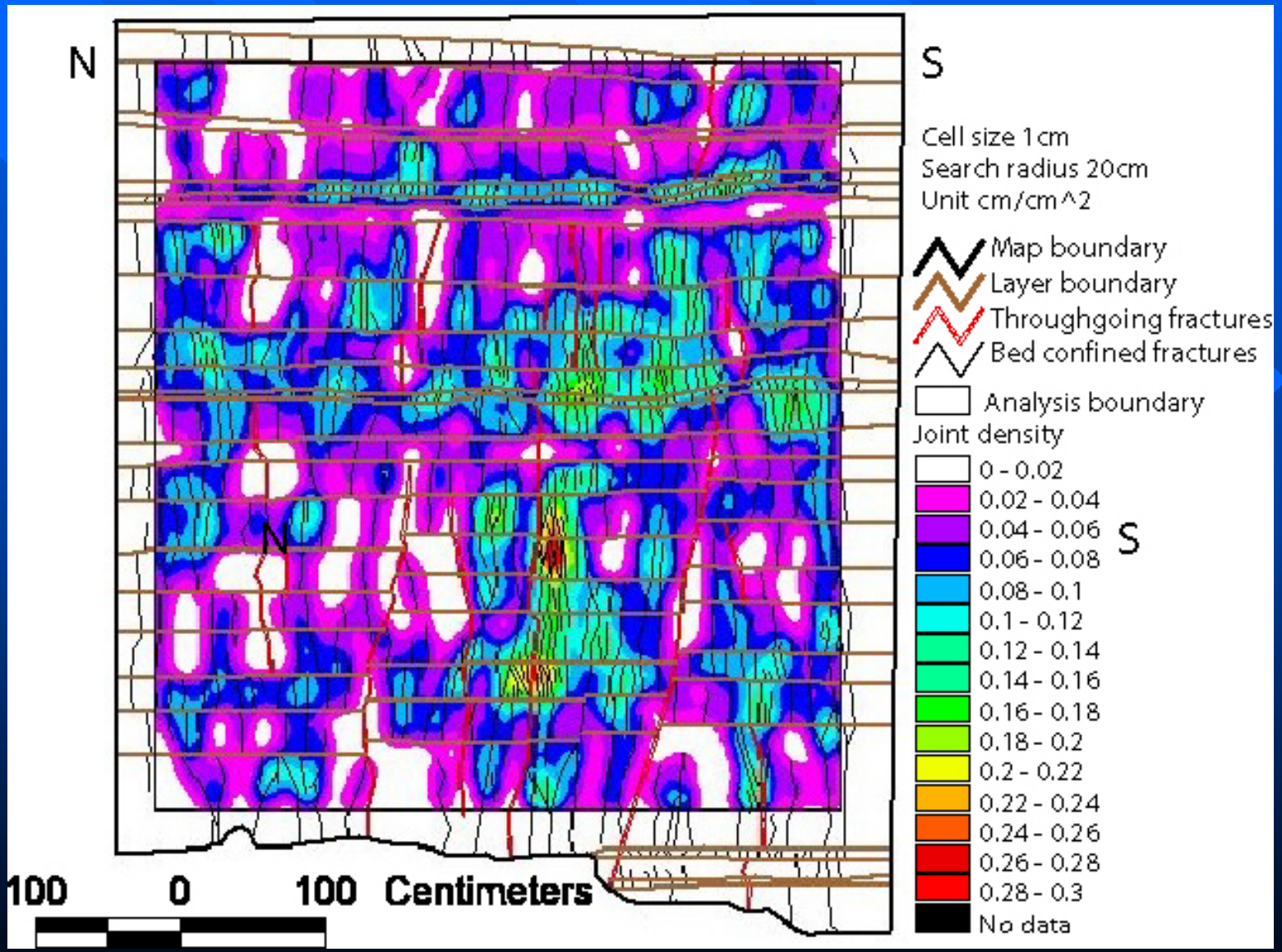
Example 2 - Fractures in well-bedded limestone

Outcrop photo

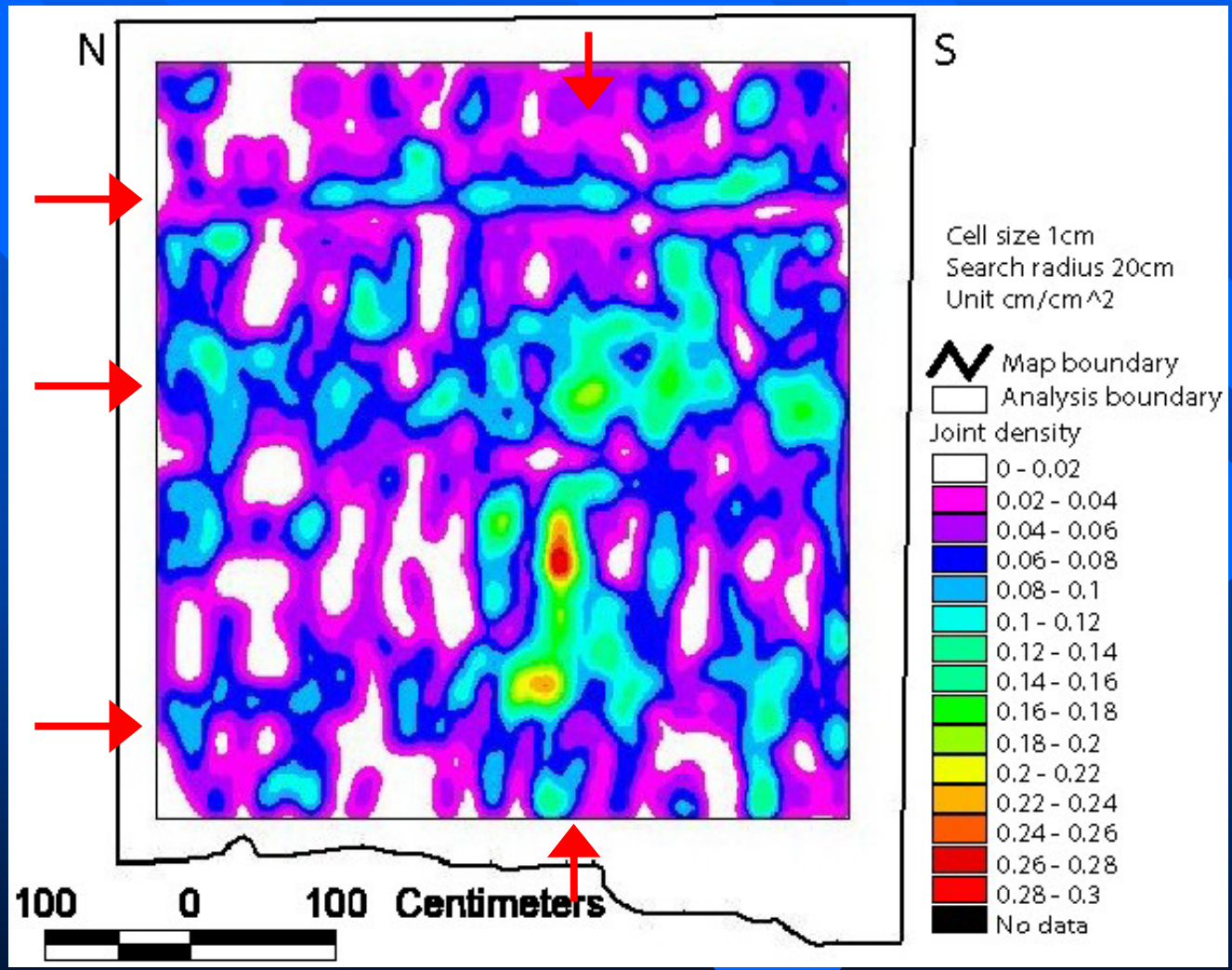
Outcrop sketch



Example 2 – Fracture Density Map

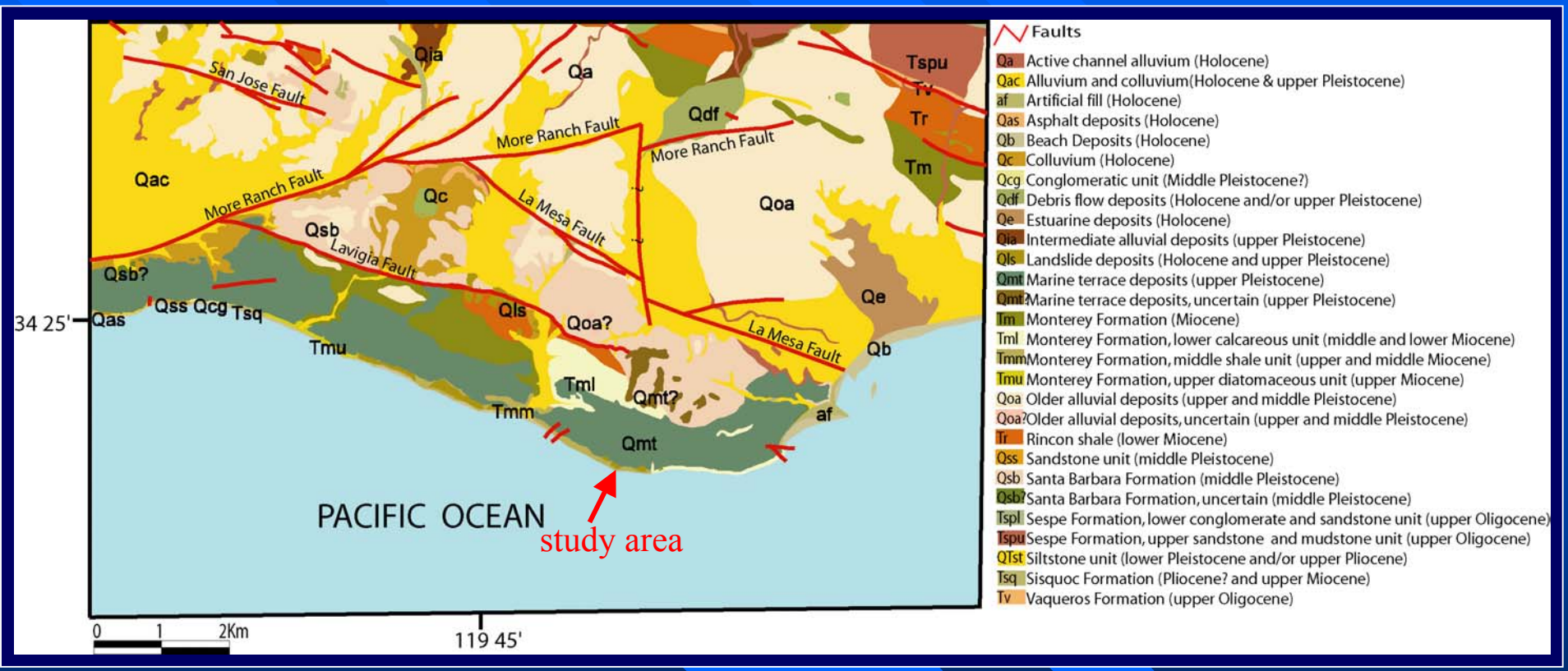


Example 2 – Fracture Density Trends



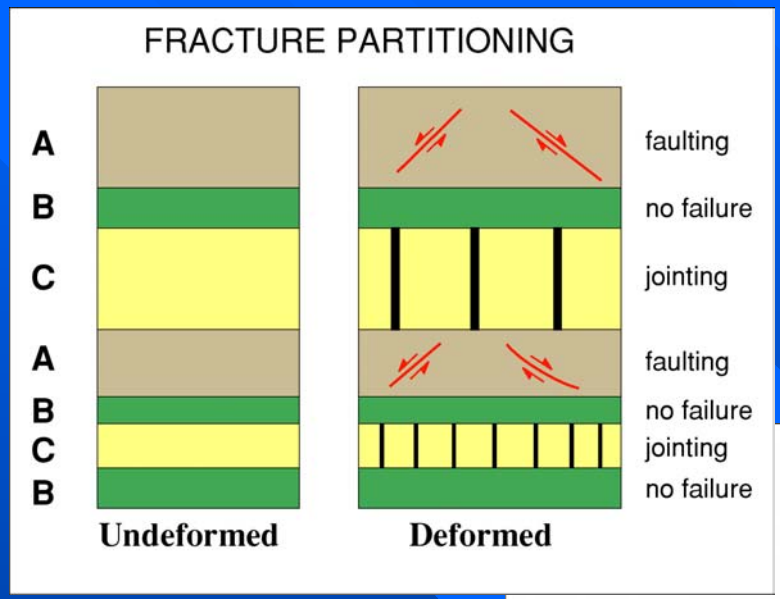
Summary: method identifies FZ as vertically aligned, linear trends of high fracture density across bedding

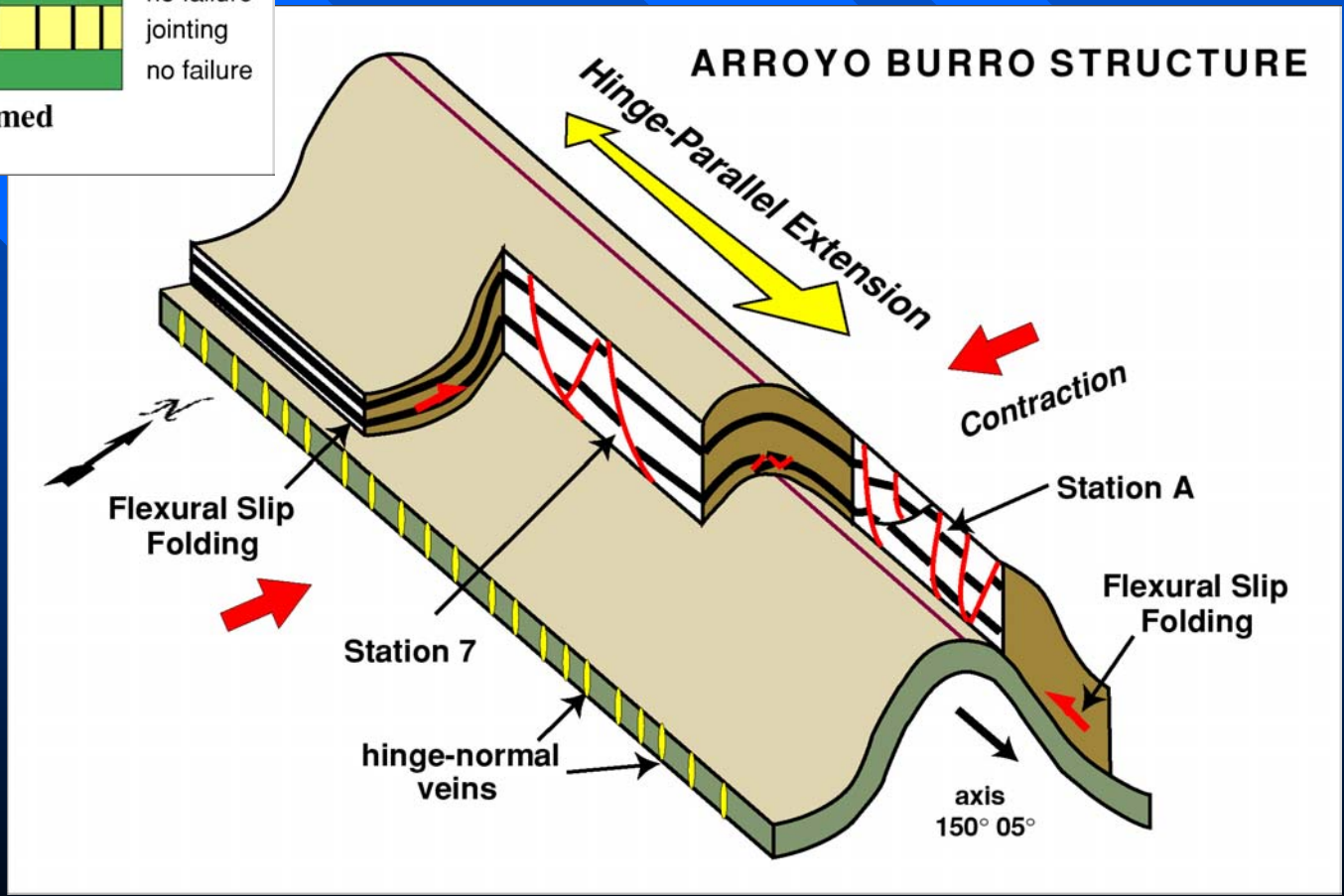
Geologic Map of Study Area



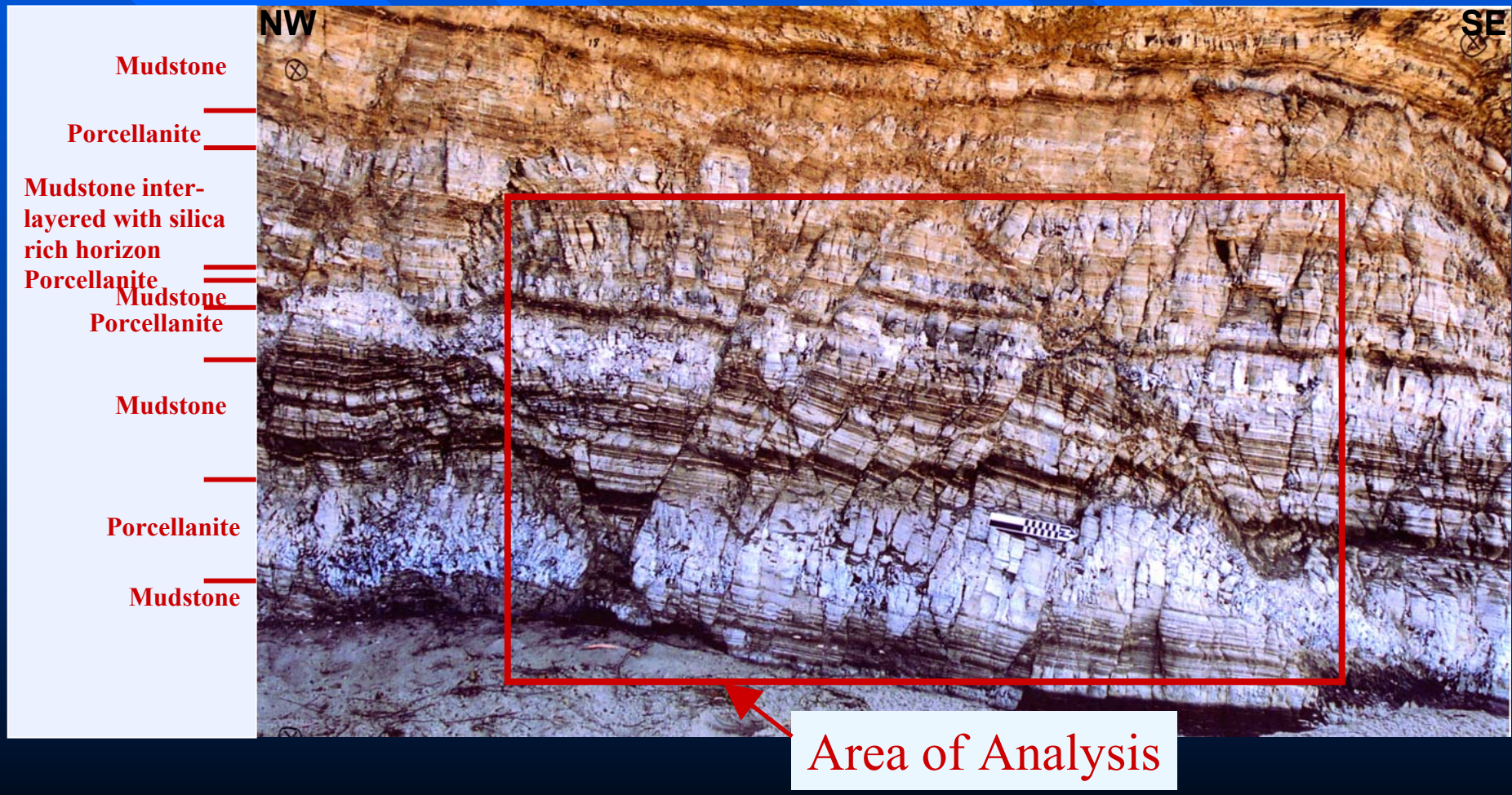
Geologic map of the Santa Barbara Coastal Plain Area, Santa Barbara county, California. By: Scott A. Minor, Karl S. Kellog, Richard G. Stanley, Paul Stone, Charles L. Powell, II, Larry D. Gurrola, Amy J Selting and Theodore R. Brandt

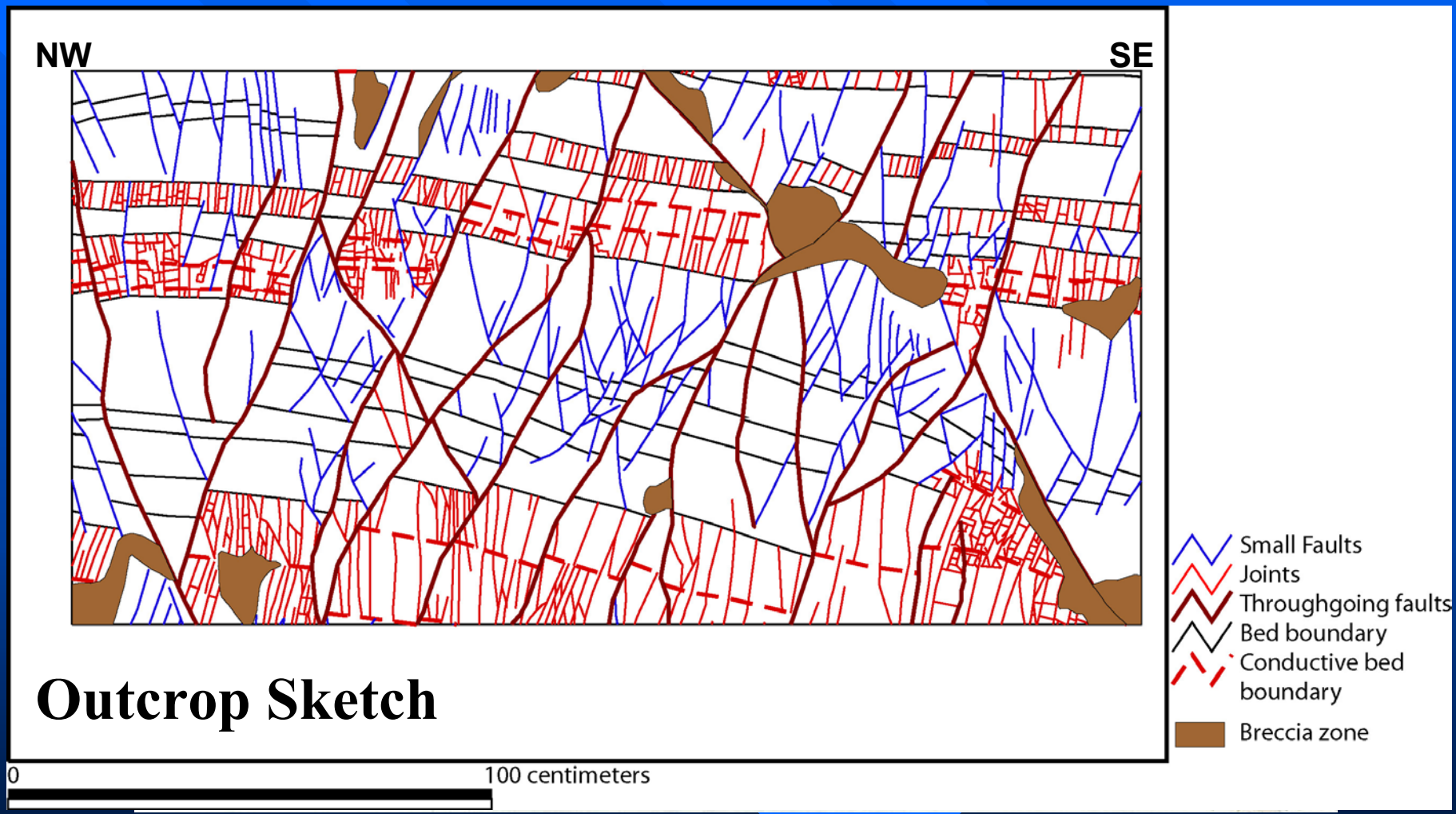
Dependence of Fracture Style on Lithology (Rock Type)





Outcrop Photo



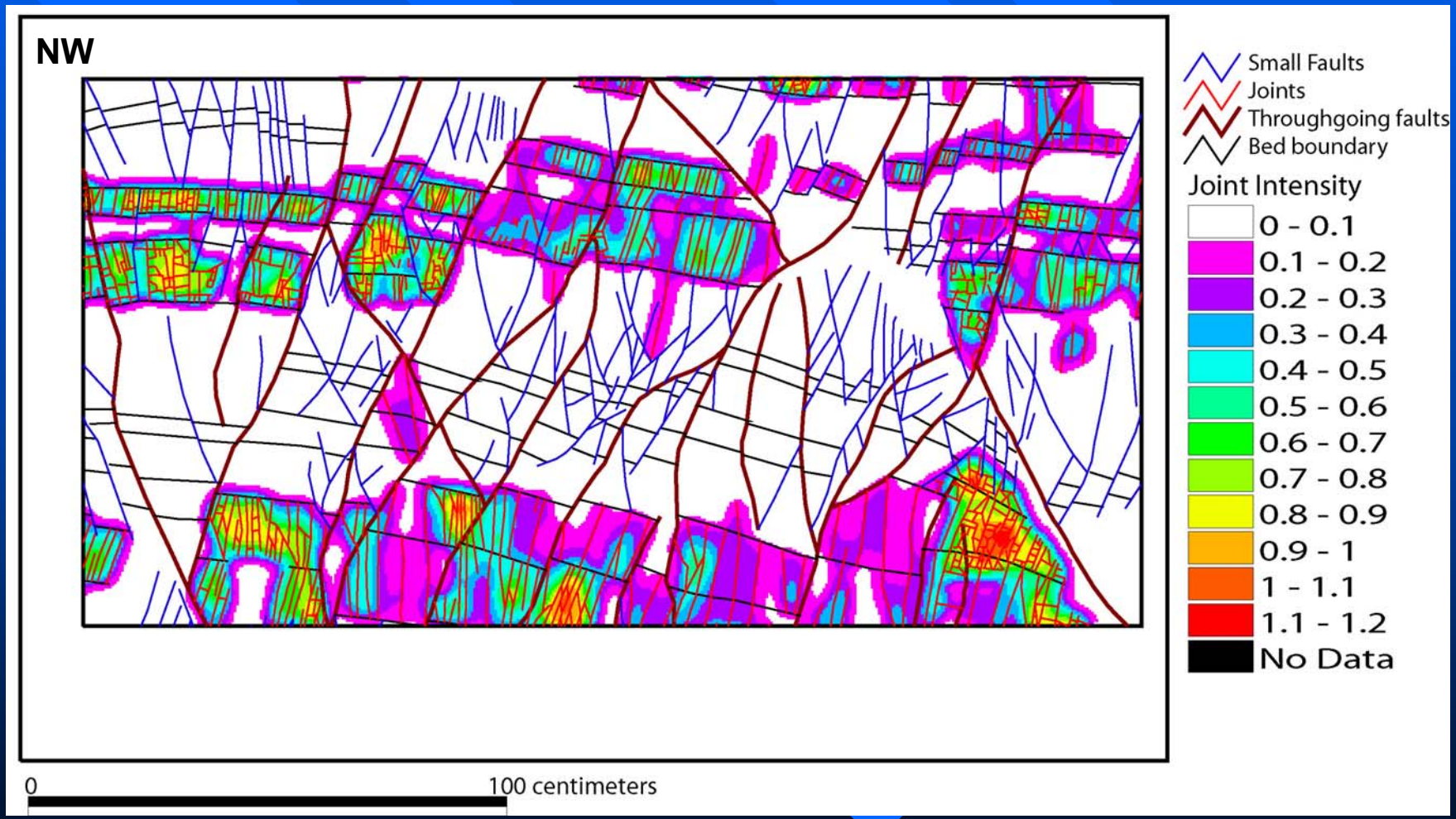


Outcrop Sketch

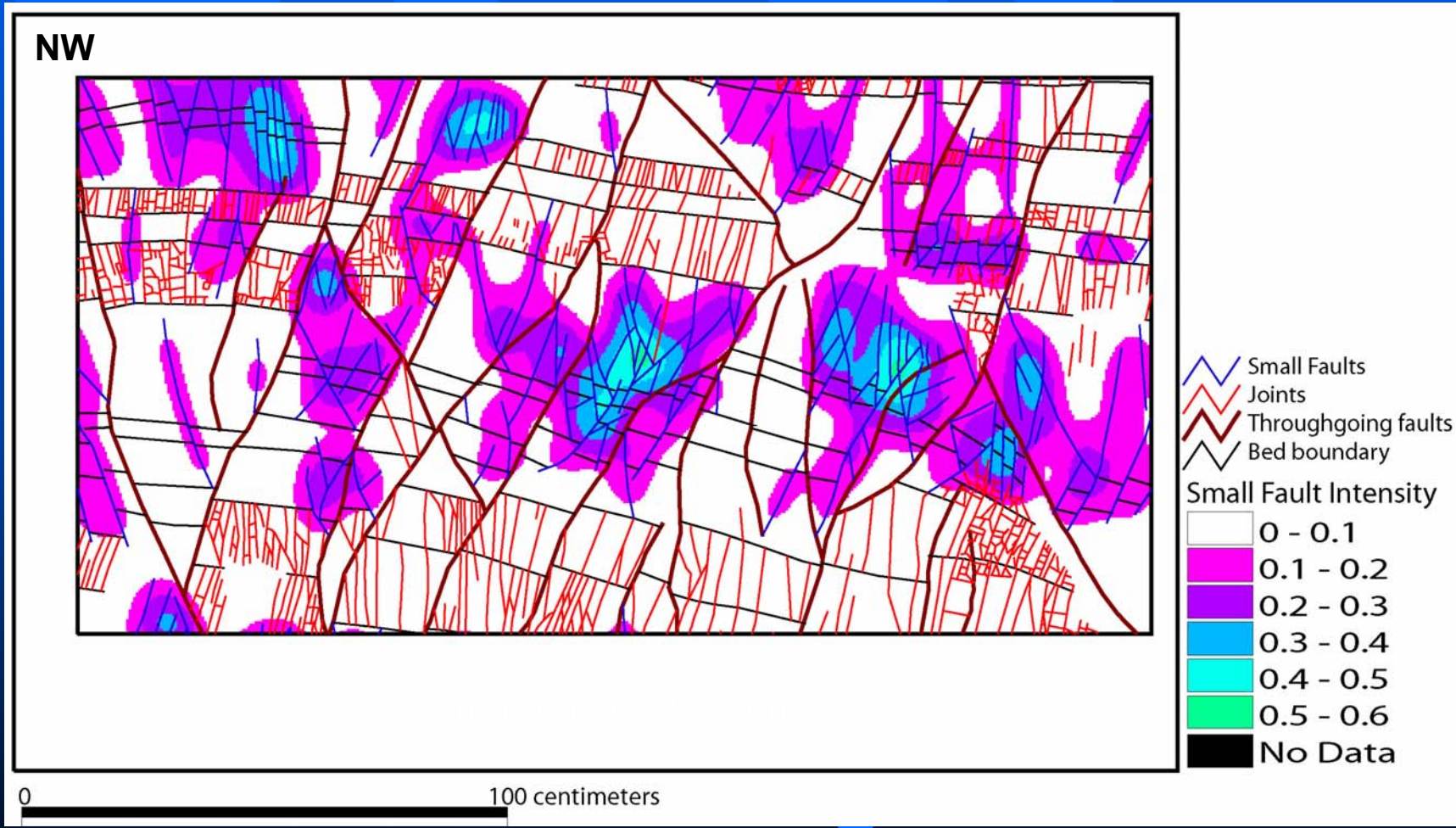
Spatial Analysis Comparing Distribution of Joints vs. Faults

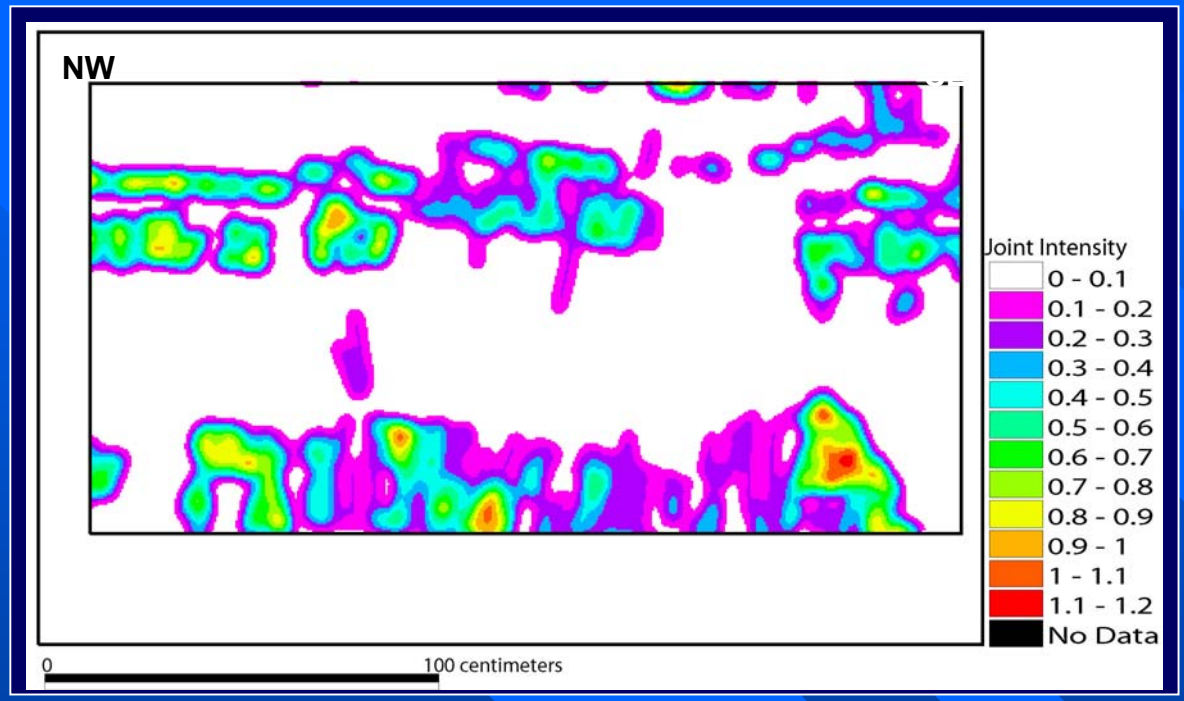
- Fracture Spacing
- Fracture Clustering
- 2D Fracture intensity
- Fracture Partitioning
- Fractal Dimension
- Fracture connectivity

Joint Intensity Map



Small Fault Intensity Map

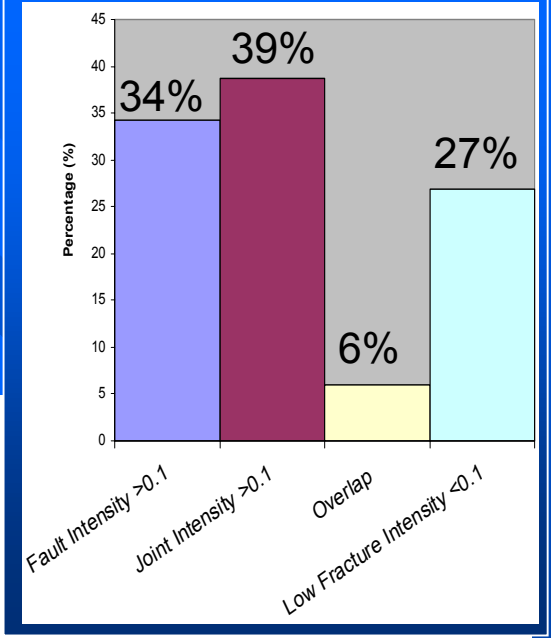


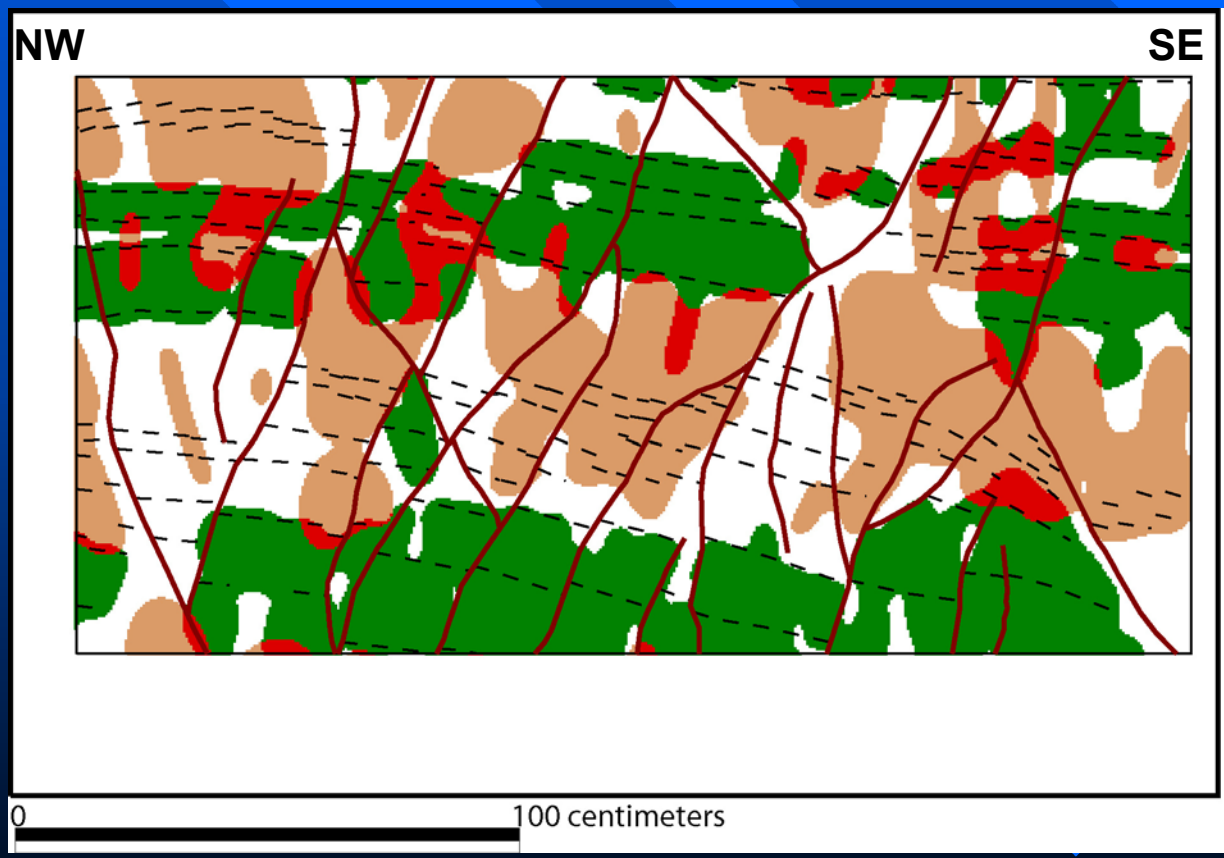


Joint Intensity Map

Small Fault Intensity Map

Quantifying Spatial Heterogeneity of Fracture Partitioning

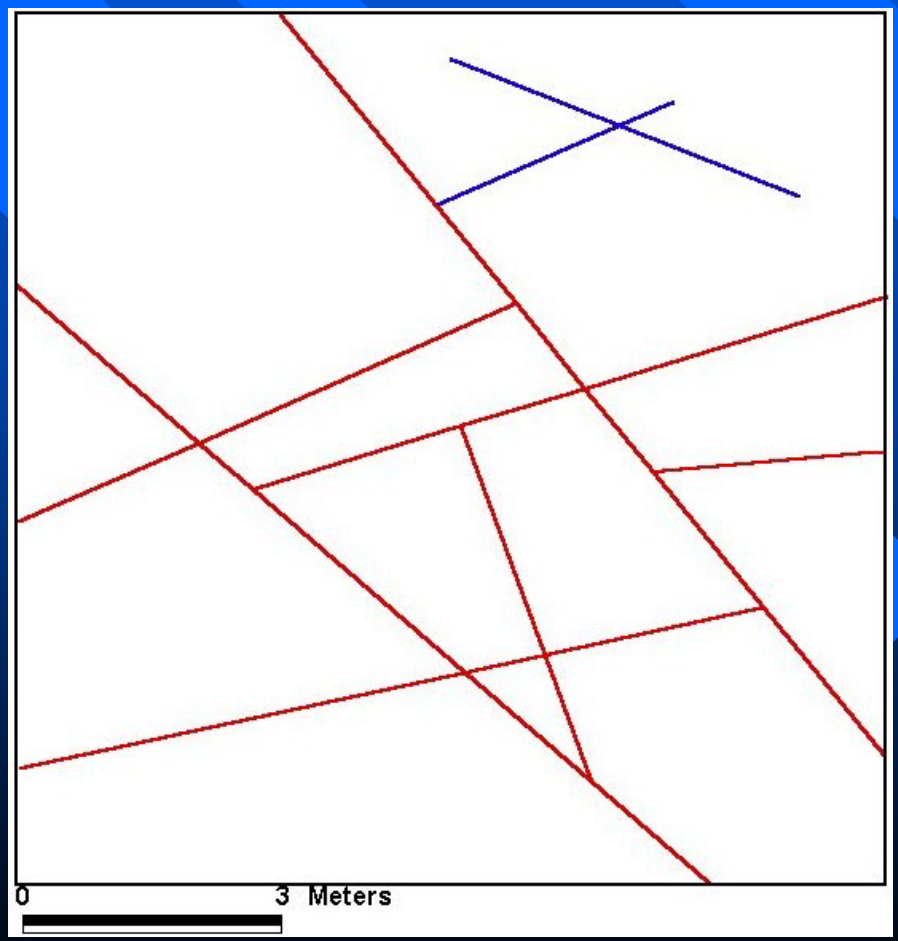




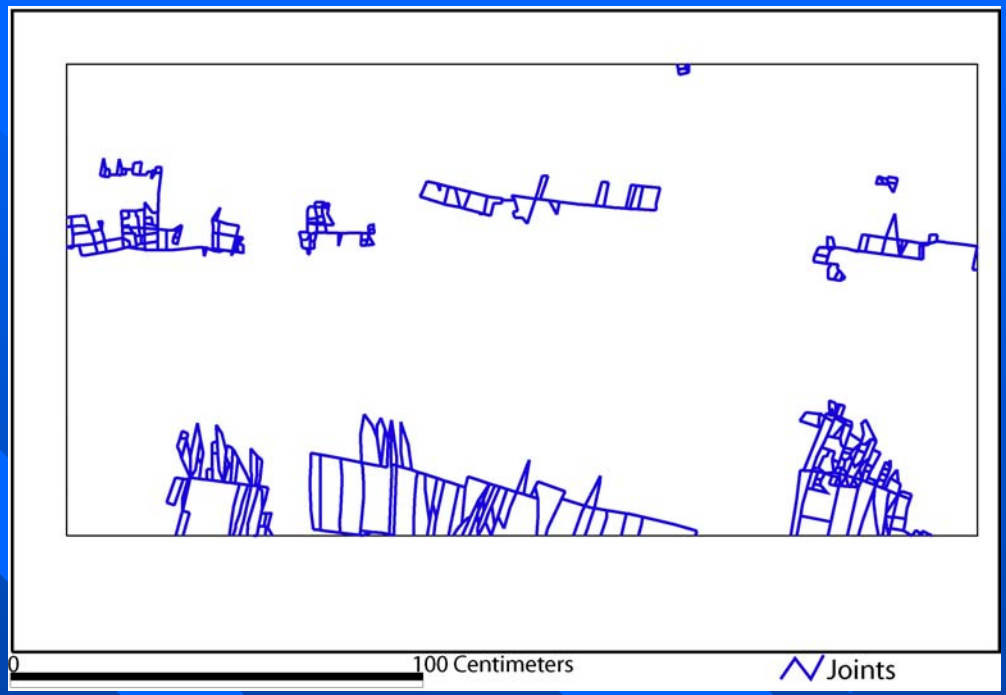
Boundary
Area of analysis
Layer Boundary
Throughgoing Faults
Region of small fault intensity >0.1/cm
Region of joint intensity >0.1/cm
Region of small fault and joint intensity >0.1/cm
Region of fracture intensity <0.1/cm

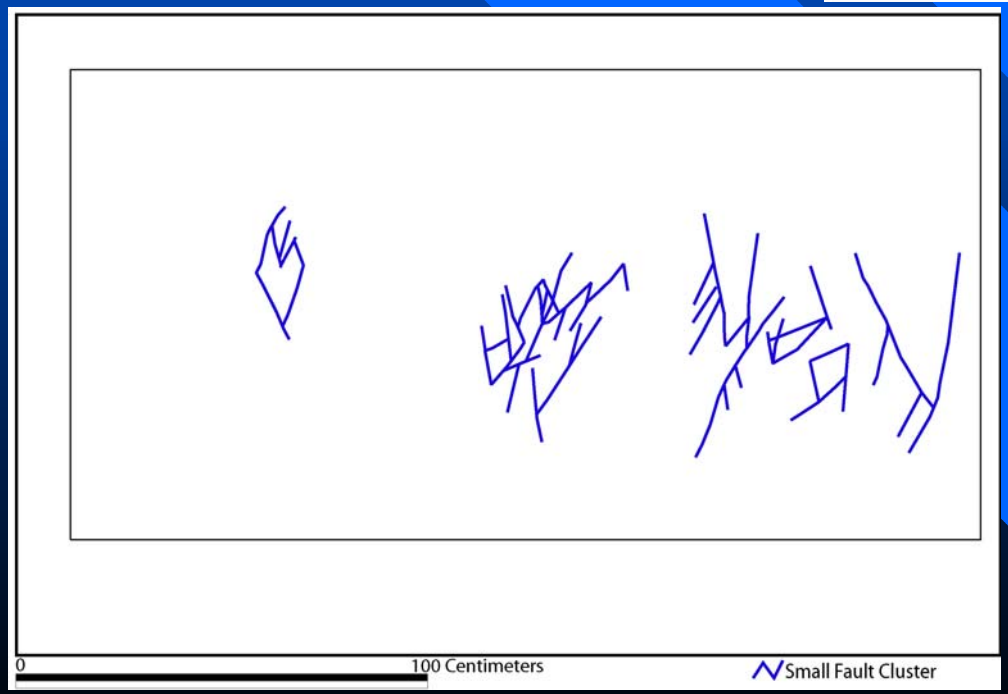
Percolation Theory

- Ensemble of percolating fracture segments within the fracture system is called the *Backbone Network*



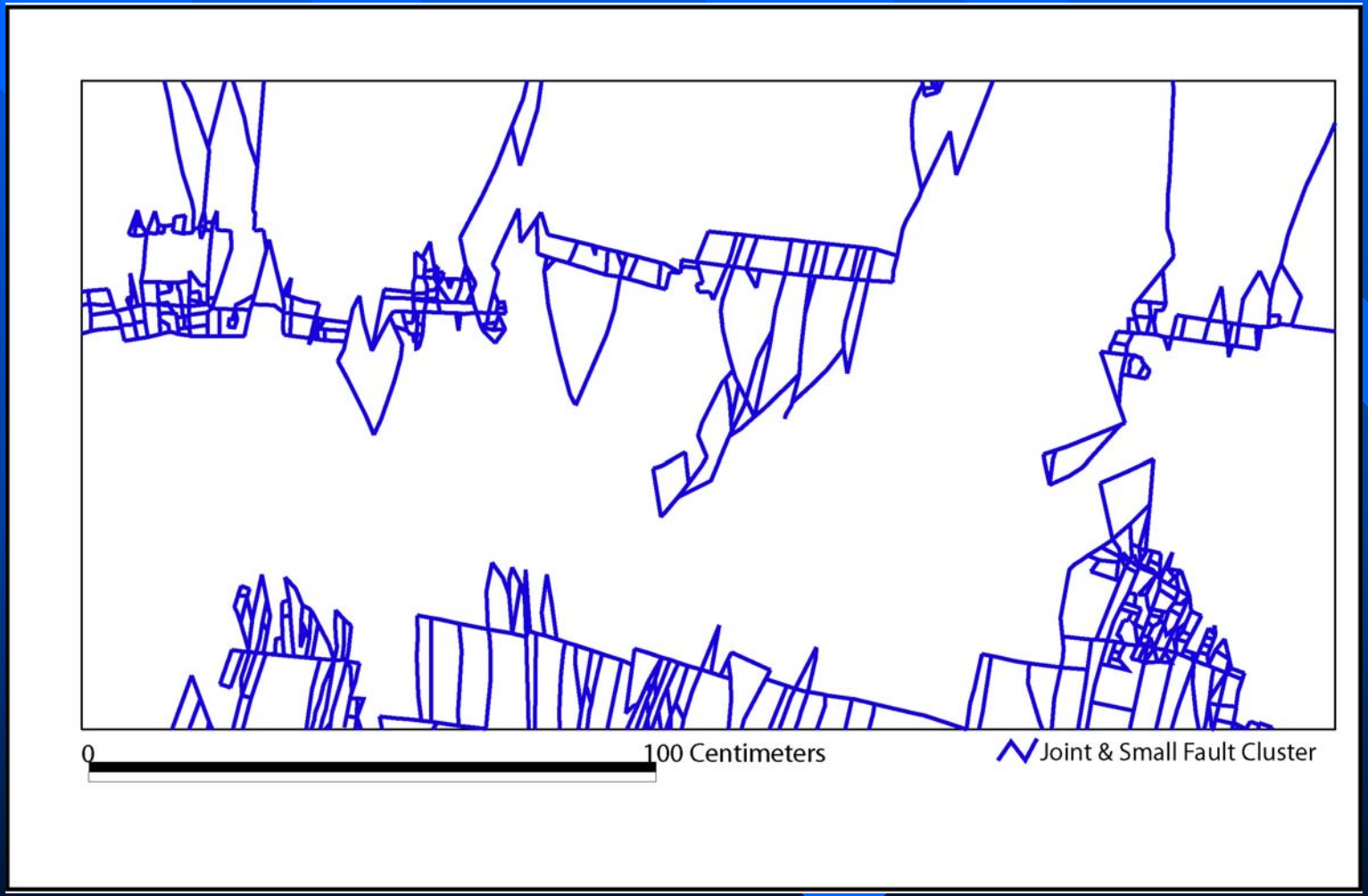
Joint cluster map
Cluster length = 613 cm
Cluster size = 0.14





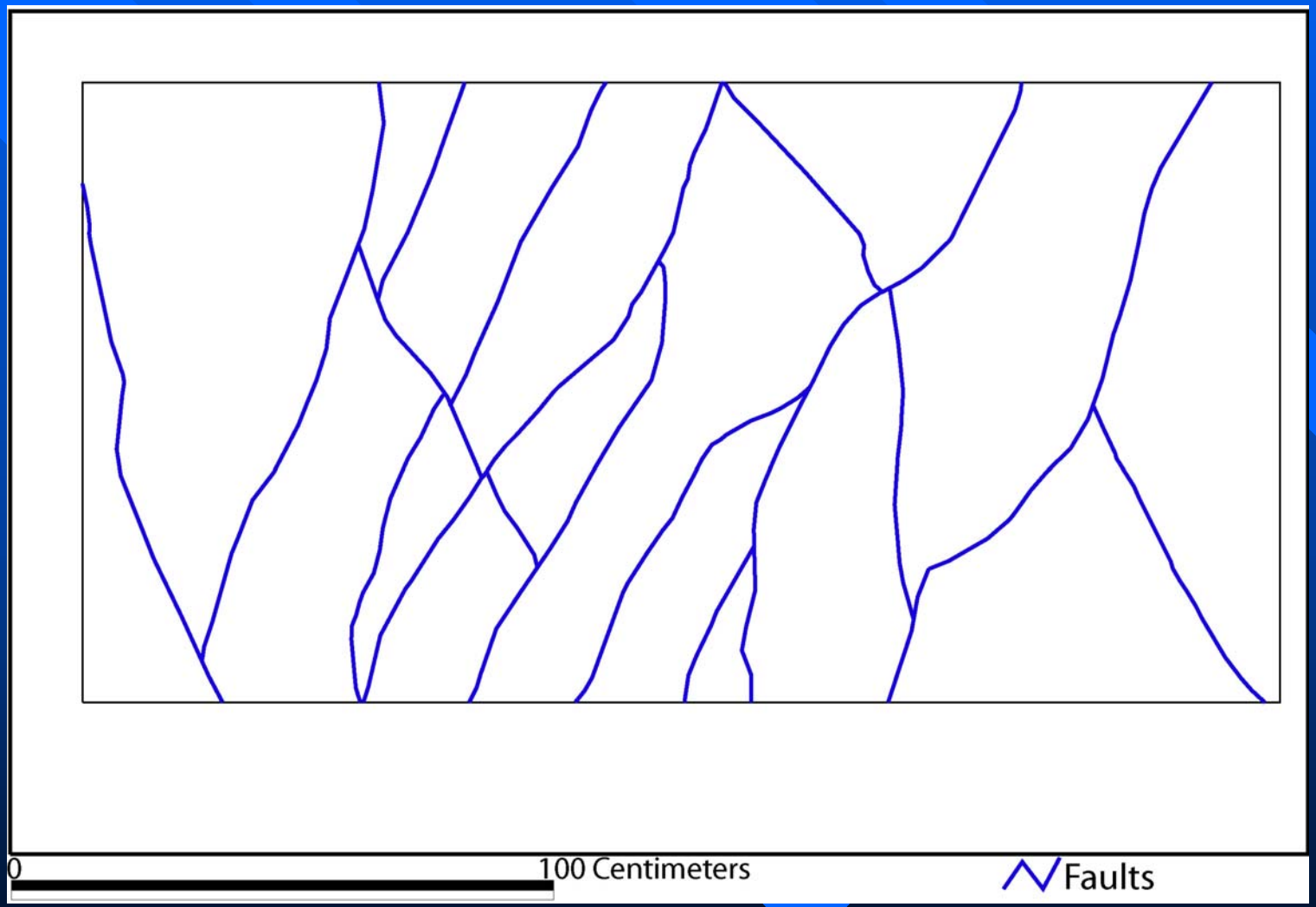
Small Fault cluster map
Cluster length = 212 cm
Cluster size = 0.093

Joint and Small fault cluster



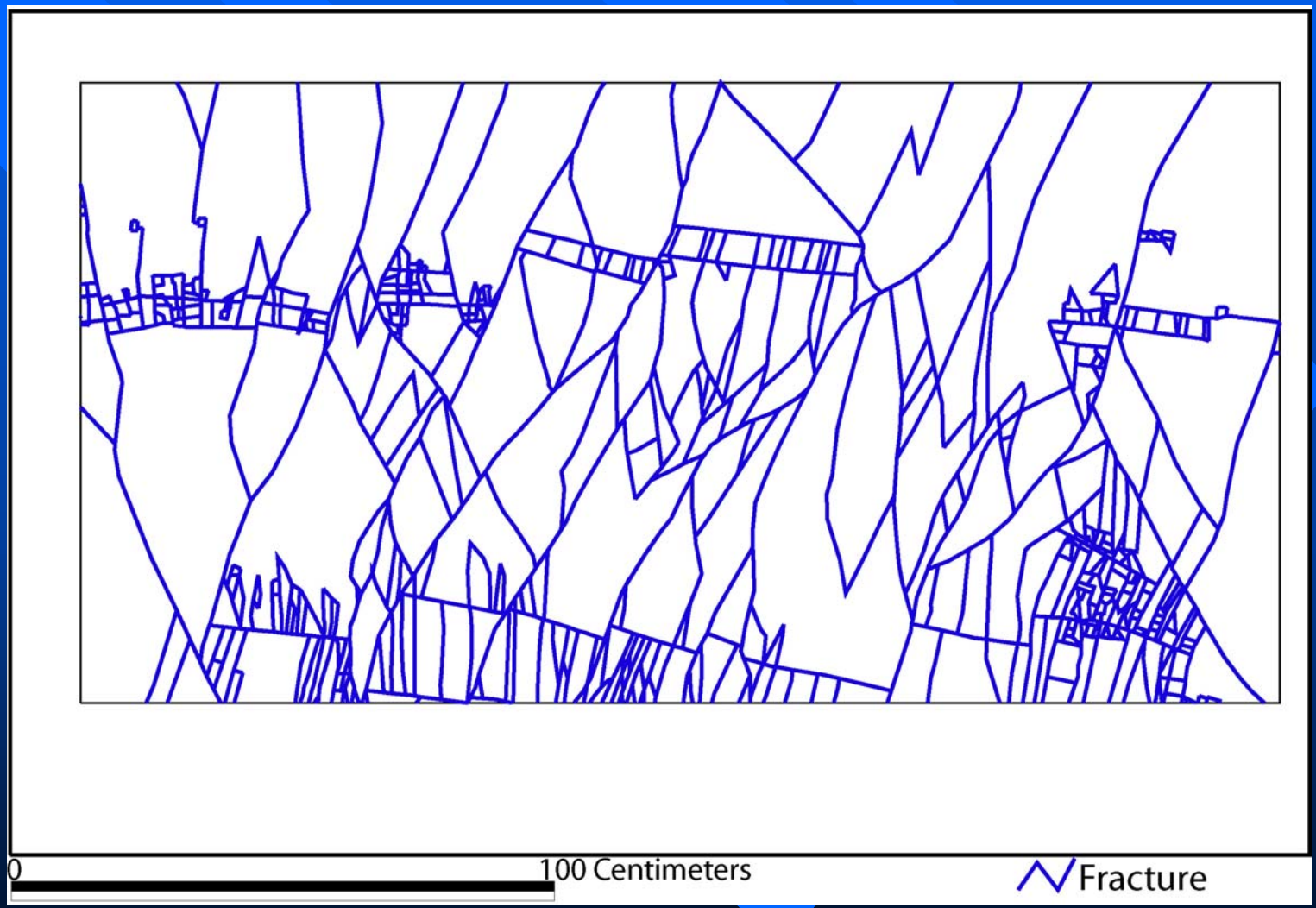
Cluster length = 1592 cm; Cluster size = 0.24

Fracture Backbone with Throughgoing Faults



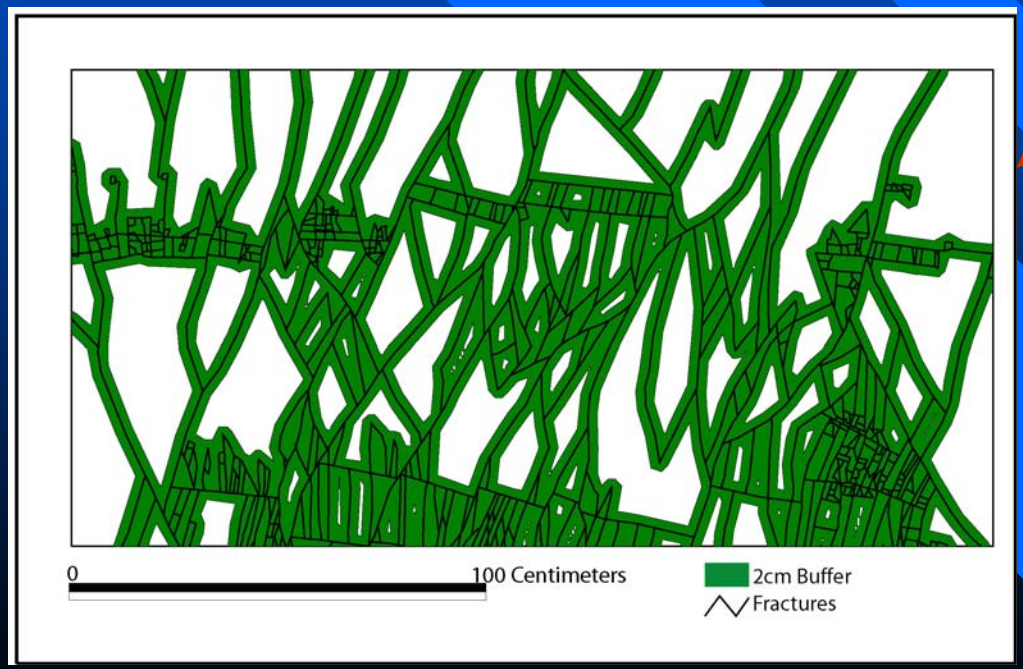
Cluster length = 1271 cm; Cluster size = 0.86

Fracture backbone



Cluster length = 5672.93; Cluster size = 0.7

Rockmass within 2cm buffer zone around the backbone



Increased by 37%

Importance of small fractures in network

Buffer size (cm)	Big faults		All fractures	
	Area covered (sq. cm)	Percentage area (%)	Area covered (sq. cm)	Percentage area (%)
1	2927.517	11.571	10268.904	40.589
2	5107.574	20.188	14576.469	57.615
3	7368.899	29.126	17710.602	70.002
4	9314.843	36.818	19784.241	78.199
5	11374.064	44.957	21542.550	85.148

- Throughgoing fractures ensure continuous pathway through the fracture network (i.e. provides the backbone).
- Abundant small fractures (joints and faults) dramatically increase the volume of rock matrix in contact with the percolating fracture system.
- Reservoir quality is enhanced by having fractures at both scales (single and multi-layer).

Quantitative Characterization and Distribution of pores in Carbonate Rocks

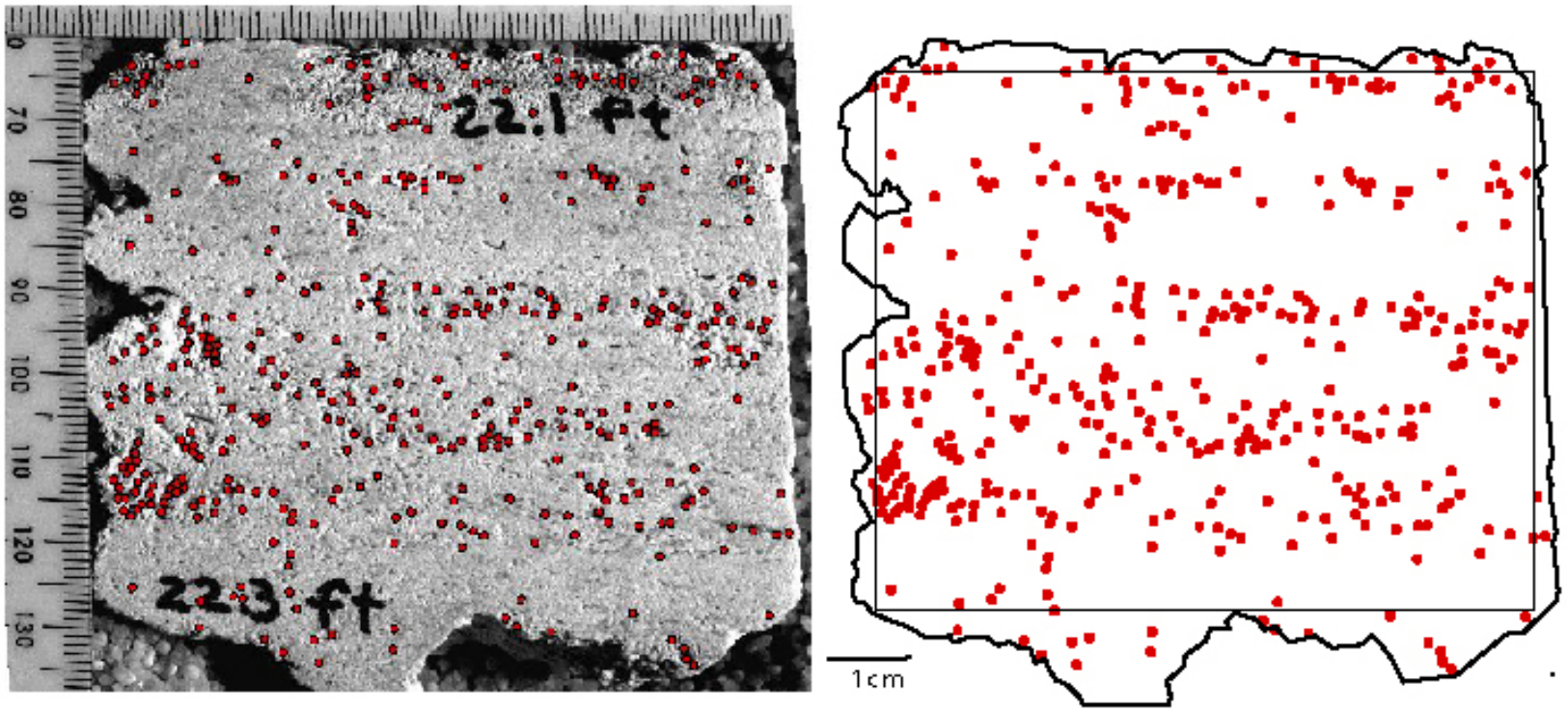
- Characterize distribution, size and geometry of solution-enhanced pores
- Identify pore facies
- Relate porosity to hydrologic properties
- Test Hypothesis: Horizontal flow channels develop as a result of macro pore coalescence

Drilling the Biscayne Aquifer
Dade County, FL

Limestone Core

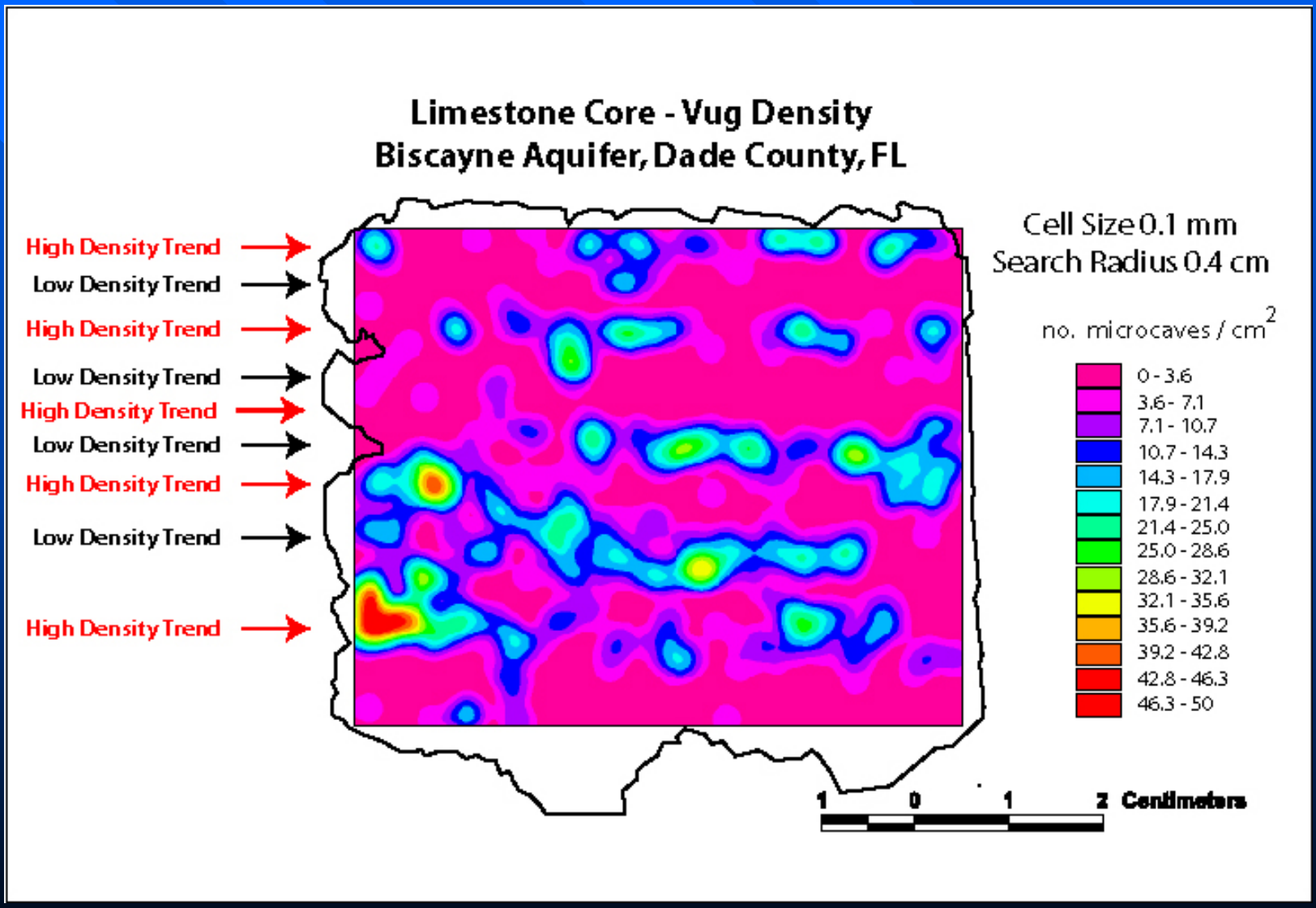
Digitized Pores

Limestone Core
Biscayne Aquifer, Dade County, FL
Digitized Secondary Porosity

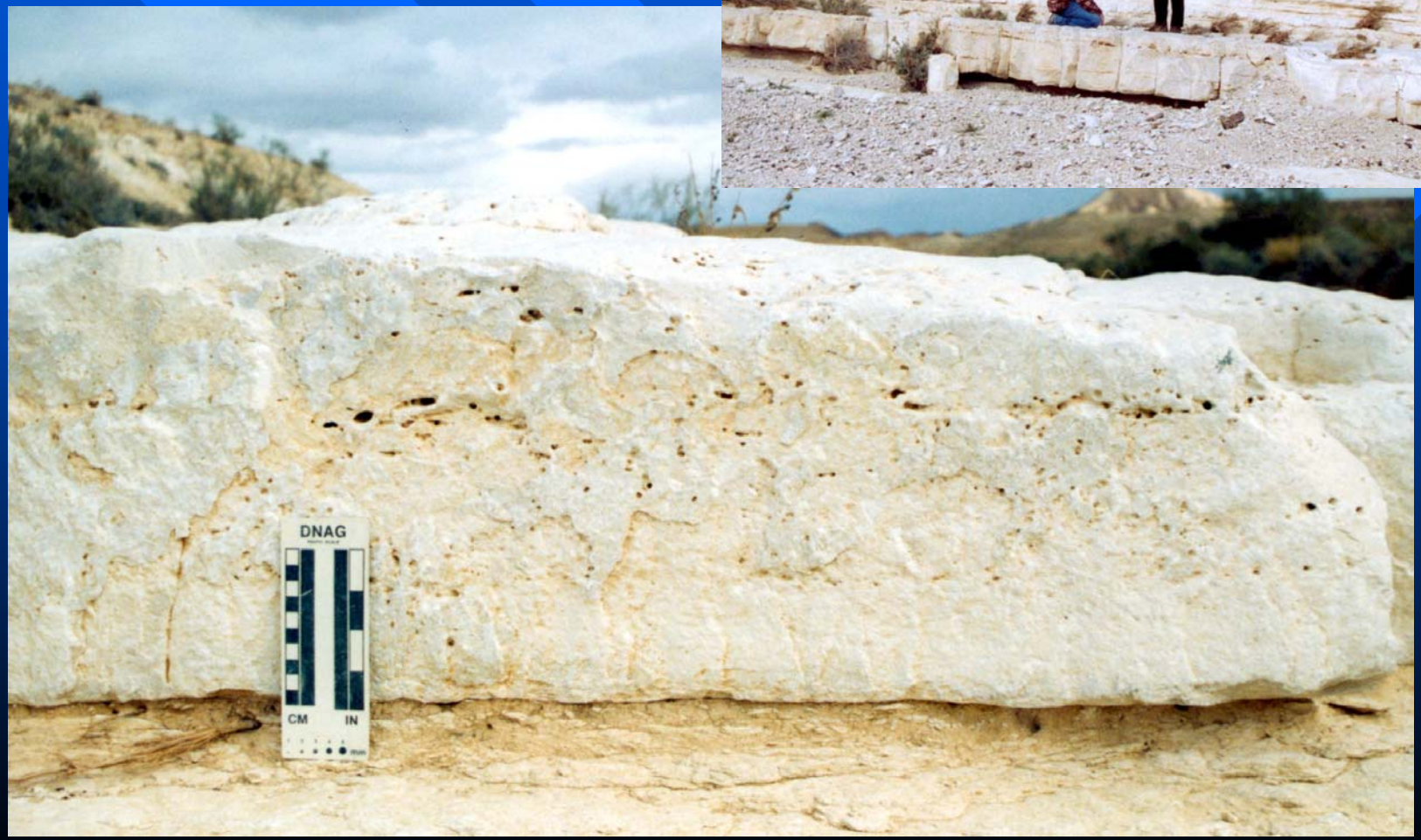


note zones parallel to layering with abundant pores, and other zones where pores are absent

Pore Density Map

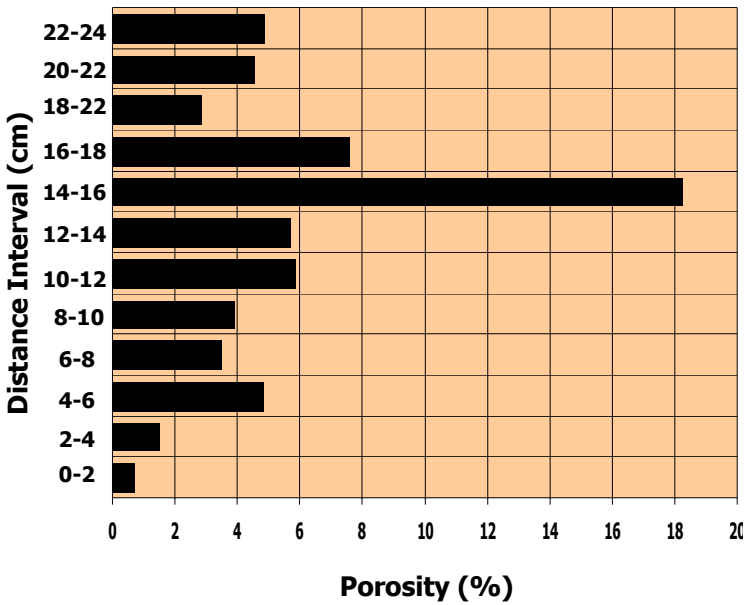


Outcrop photos of solution-enhanced Limestone

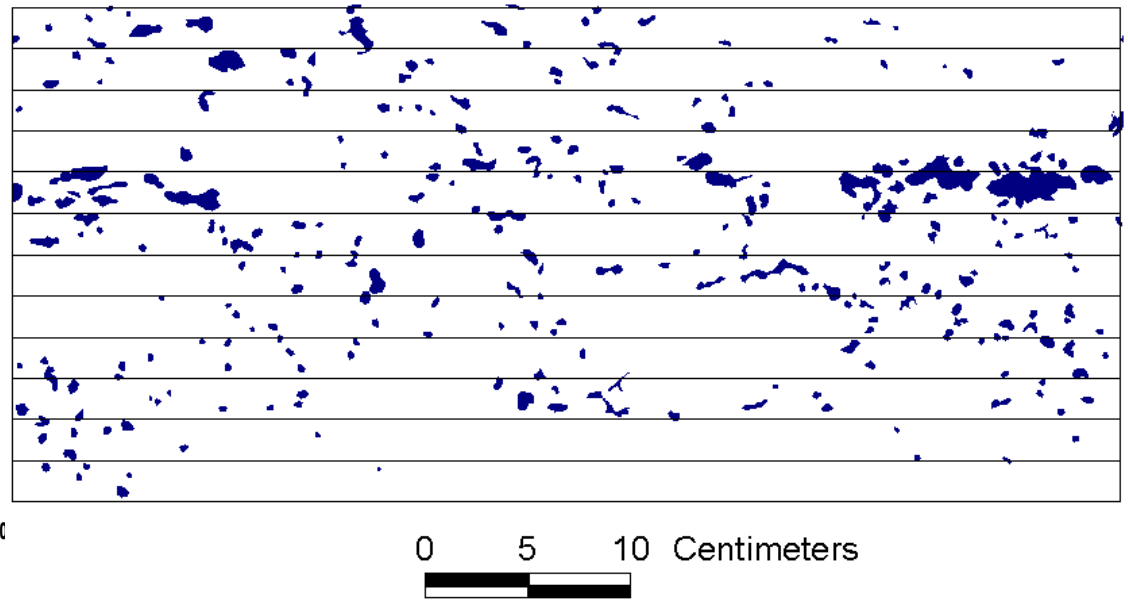


GIS-Image Analysis to Identify Zones of Preferential Dissolution

Interval Porosity



Digitized Pores

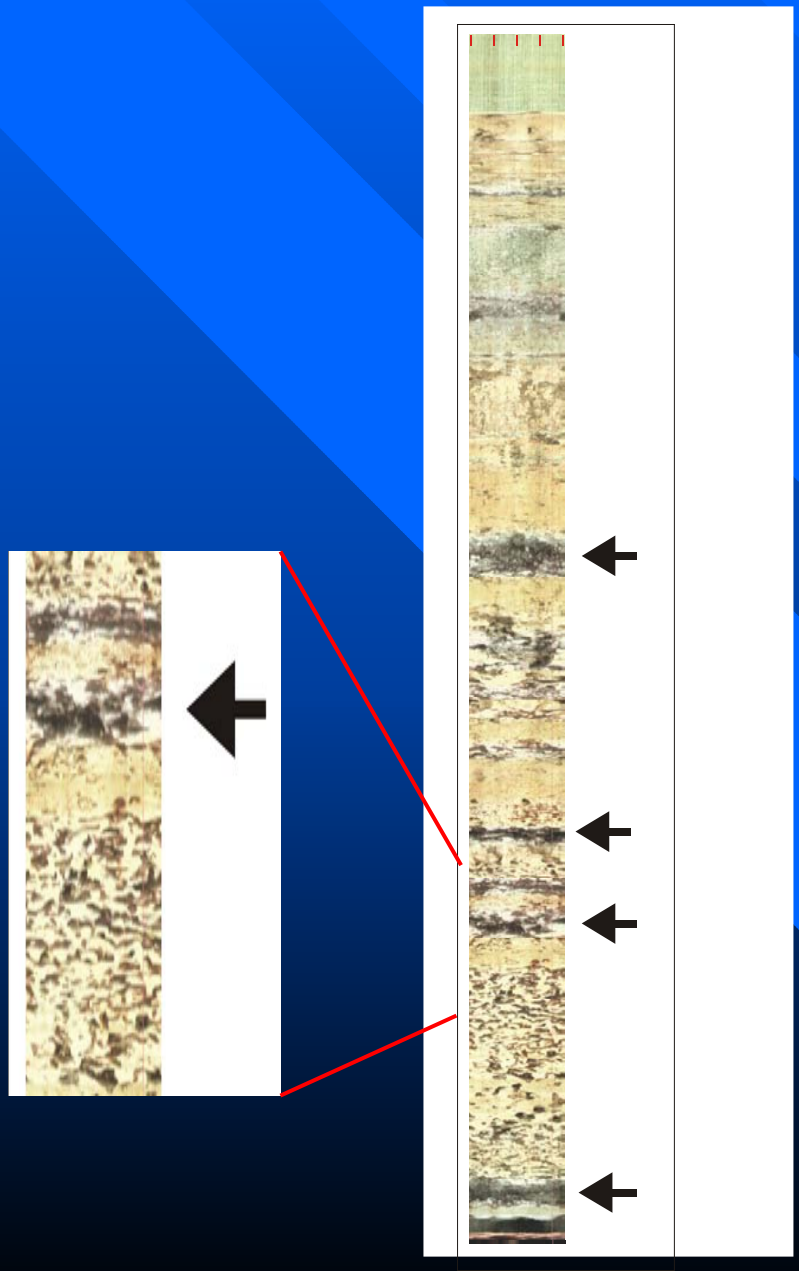


Logging

OBI 40 Optical Televiewer & Image

53 ft

Horizontal Flow Channels

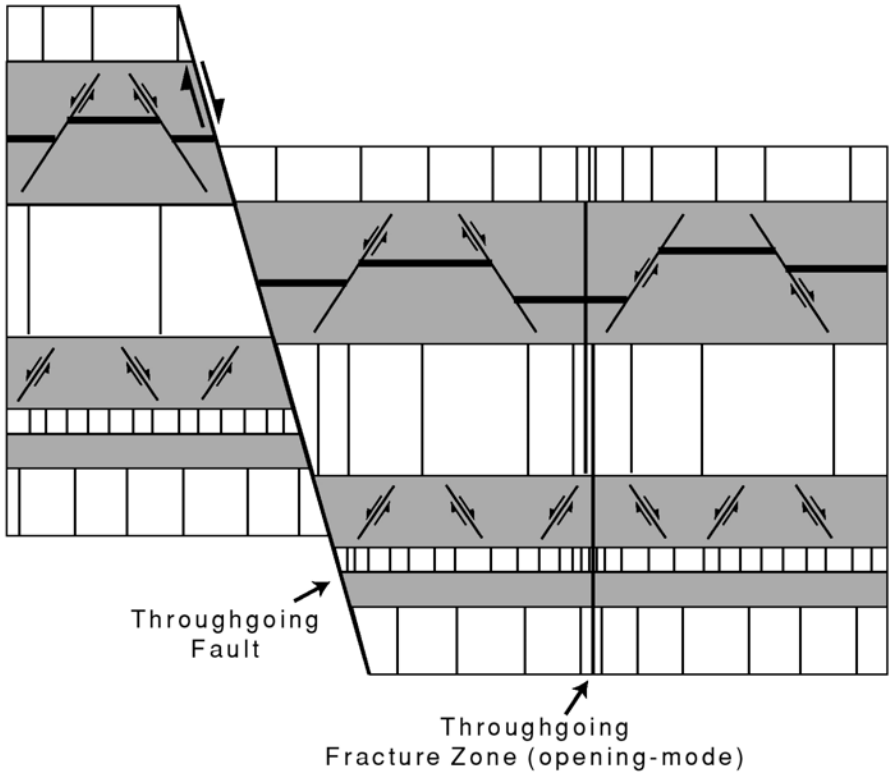


OBI 40 Televiewer Image

Black arrows are horizontal flow channels

Image is 55 feet in length

Fracture Architecture for Reservoir Characterization



Mech Unit	Scaling Relations (observed)	Throughgoing Scaling Relations (observed)	Physical Properties, P (predicted)	
7	FSR_7, $(A/L)_7$		P_7	
6	$(D/L)_6$, $(G/D)_6$	FSR_{1-7} $(A/L)_{1-7}$	P_6	fracture density
5	FSR_5, $(A/L)_5$	$(D/L)_{1-7}$	P_5	fracture porosity
4	$(D/L)_4$, $(G/D)_4$	$(G/D)_{1-7}$	P_4	permeability
3	FSR_3, $(A/L)_3$		P_3	
2	unfractured		P_2	
1	FSR_1, $(A/L)_1$		P_1	

single-layer structures + multi-layer structures ⇨ overall fracture architecture

Research in Fractured Bedrock at FIU Department of Earth Science