High Resolution Petrophysical Measurements of Deformation Bands

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Background: Fractures

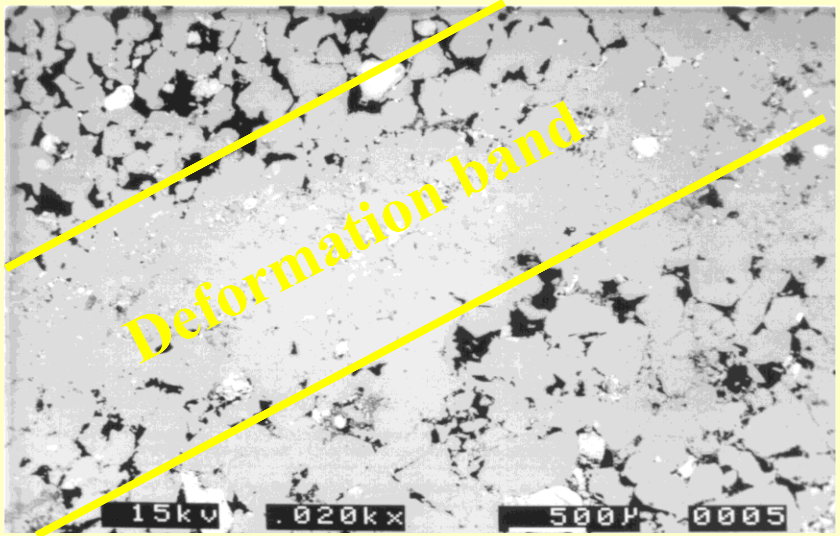
- Fractures are common in Earth's crust & exist on wide range of scales. 2 types: Open & Closed
- Mechanical properties of host rock play important role in determining hydraulic properties of fractures
- The impact of fractures upon fluid flow has many practical applications:
  - Flow channelling and compartmentalisation in hydrocarbon & water reservoirs
  - Control of contamination by domestic & chemically toxic industrial waste, & remediation
  - Design of safe repositories for nuclear waste
  - Hot dry rock/Geothermal energy projects

Deformation Bands (*Aydin*, 1978)

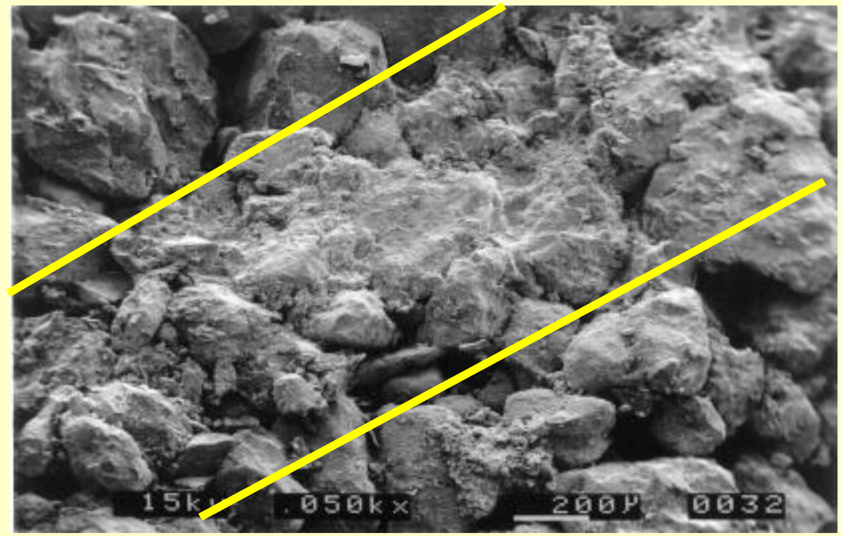
- Large impact upon flow properties of reservoir, in sub-seismic domain
- Downscaling; L & D related through power-law & fractal in nature. Scaling varies with lithology
- Use of lithology in prediction; clean vs. impure sandstones
- Must understand spatial distribution & *internal structure* to remove uncertainty in role in fault seal analysis
- Information from core material/outcrop

MICRO-STRUCTURAL ANALYSIS

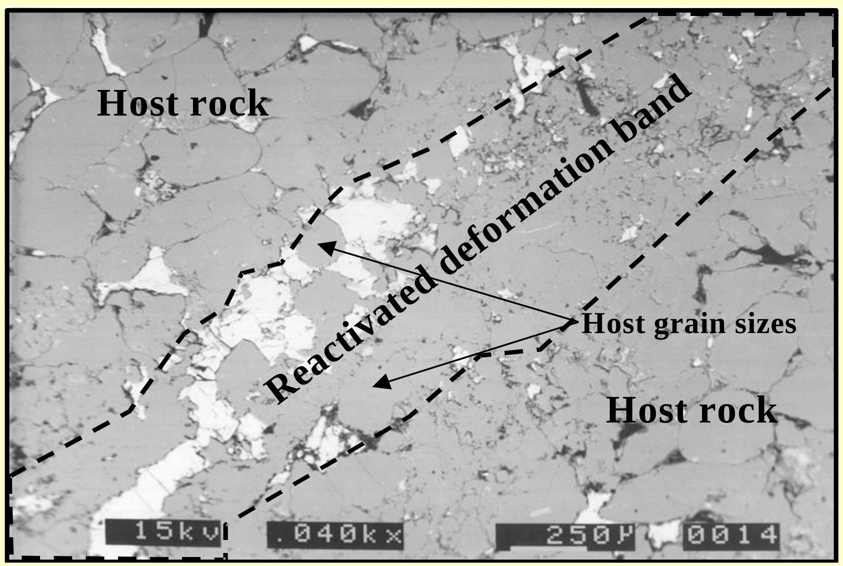
SEM-BSEI



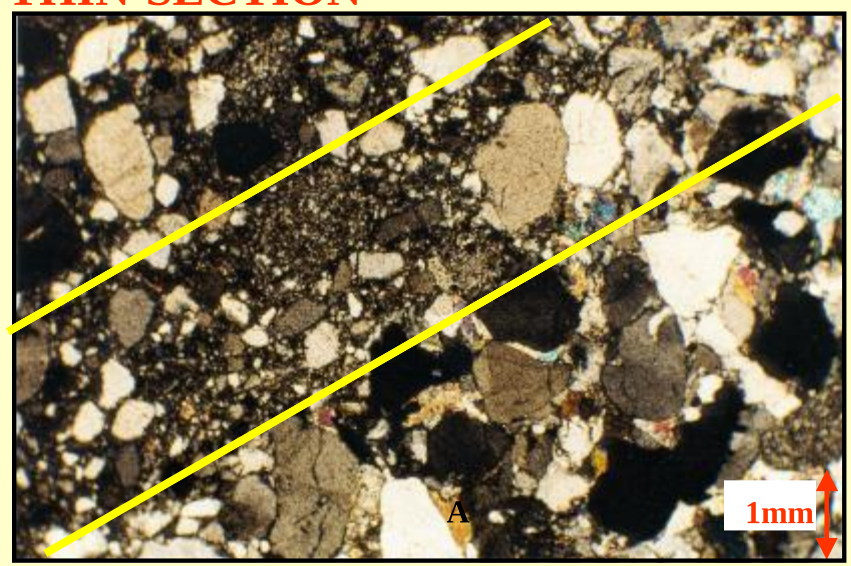
SEM-SE



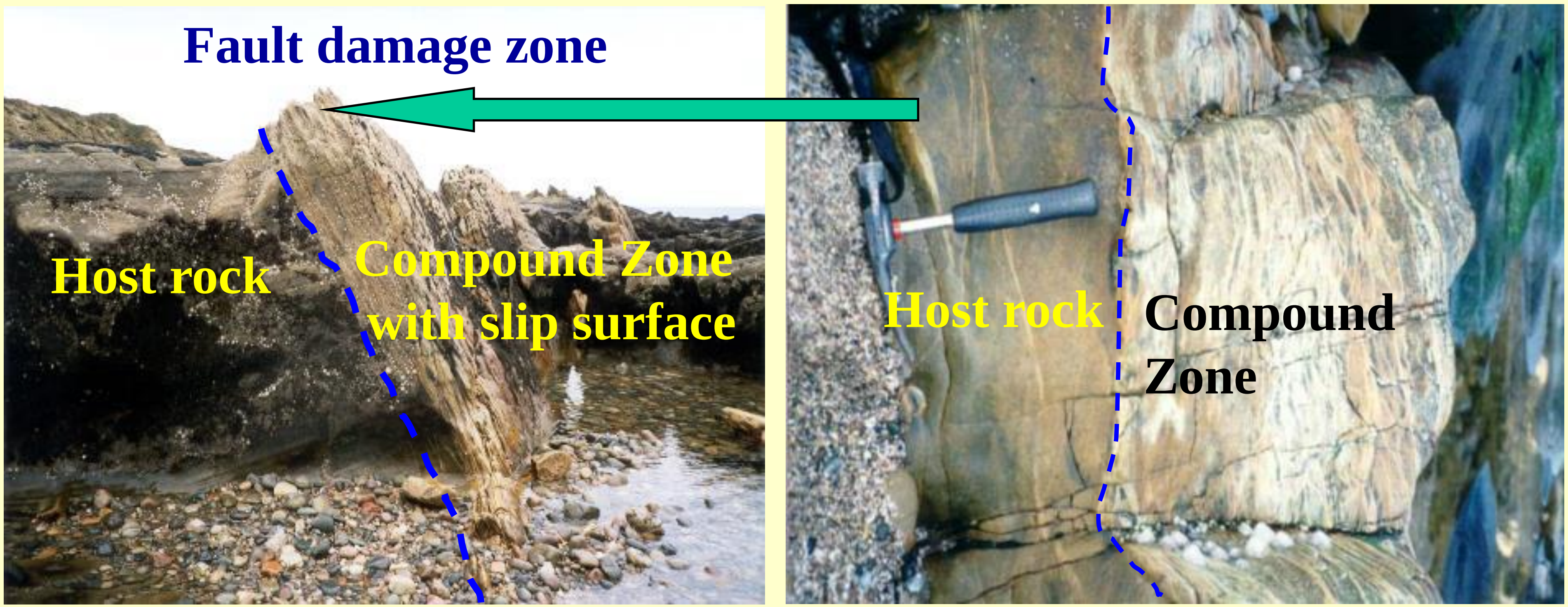
POROSITY CHANGES



THIN-SECTION



SEQUENTIAL DEVELOPMENT OF DEFORMATION BANDS



Formation of Deformation Bands

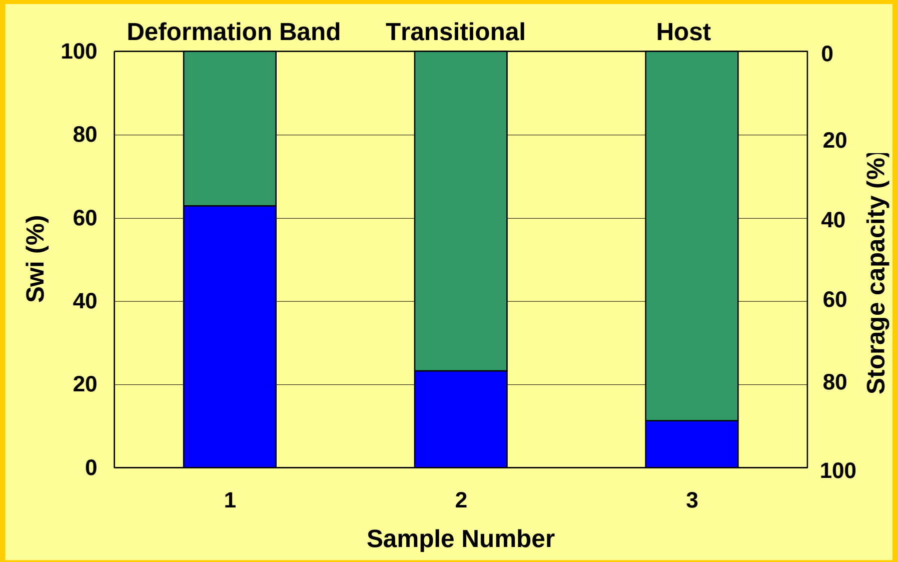
- Strain hardening (localisation) mechanism
- Wider fault zone > axial strain
- Granulation initially intense, closely associated with slip but levels off with further slips having little effect on comminution (Engelder, 1974)
- Gouge strands = matrix supported, large grains surrounded by smaller particles.
- Sammis et al. (1987), probability of fracture decreases as size of neighbour decreases

CONVENTIONAL CORE ANALYSES

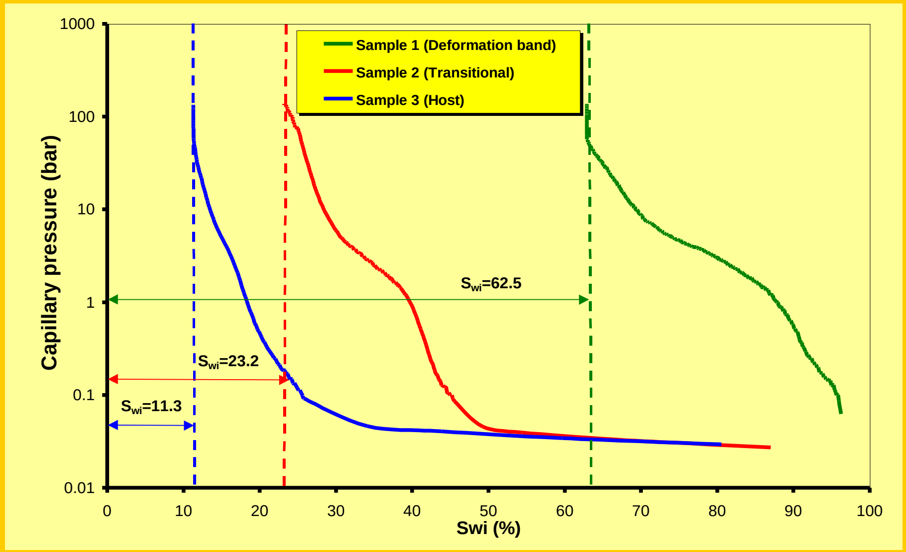
Petrophysical Properties

Sample number	Sample Location	Swi (%)	Porosity (%)			Klinkenberg Permeability (mD)	
		MICP	Helium	MICP	Image analysis	Kn	PDPK
1	Deformation band	62.5	13.3	9.01	4 - 10	555	0.0034 - 397
2	Transitional	23.2	20.5	18.35	10 - 15	677	29.6 - 899
3	Host rock	11.3	25	19.95	15 - 21	1750	397 - 3080

Storage Capacity

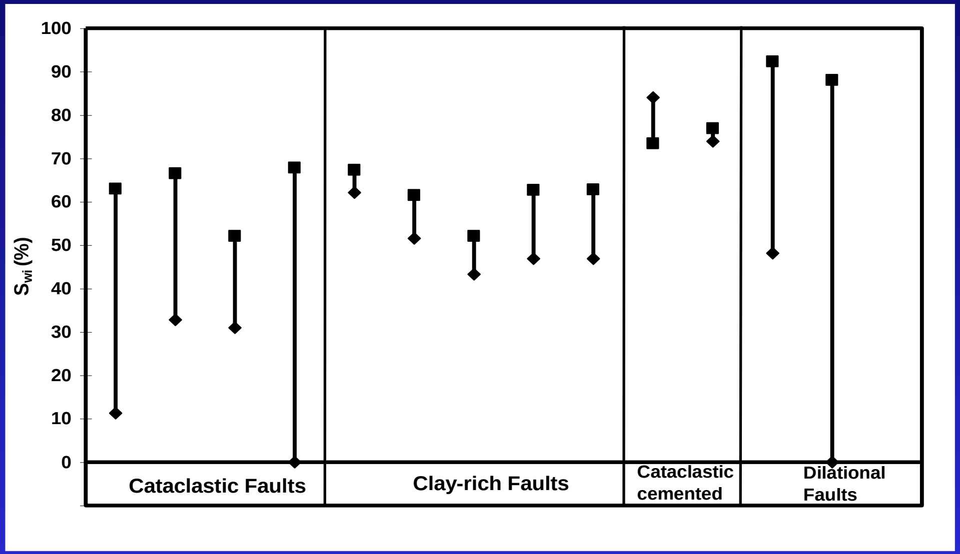


Capillary pressures

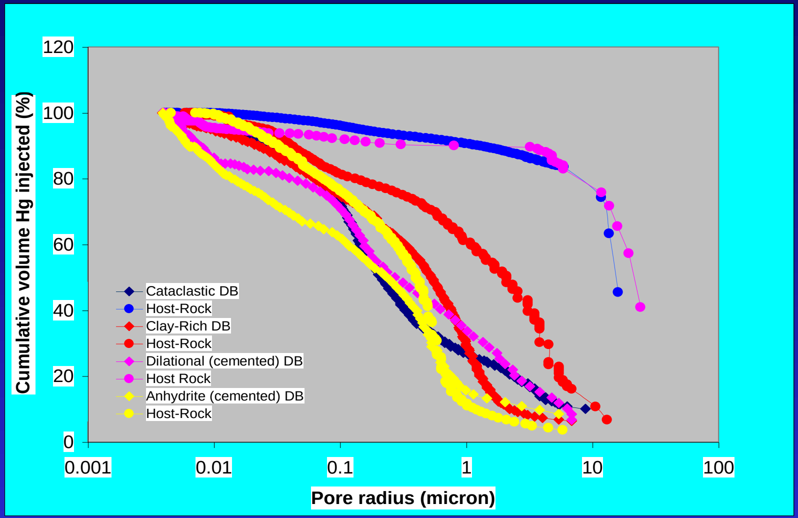


MERCURY INJECTION DATA

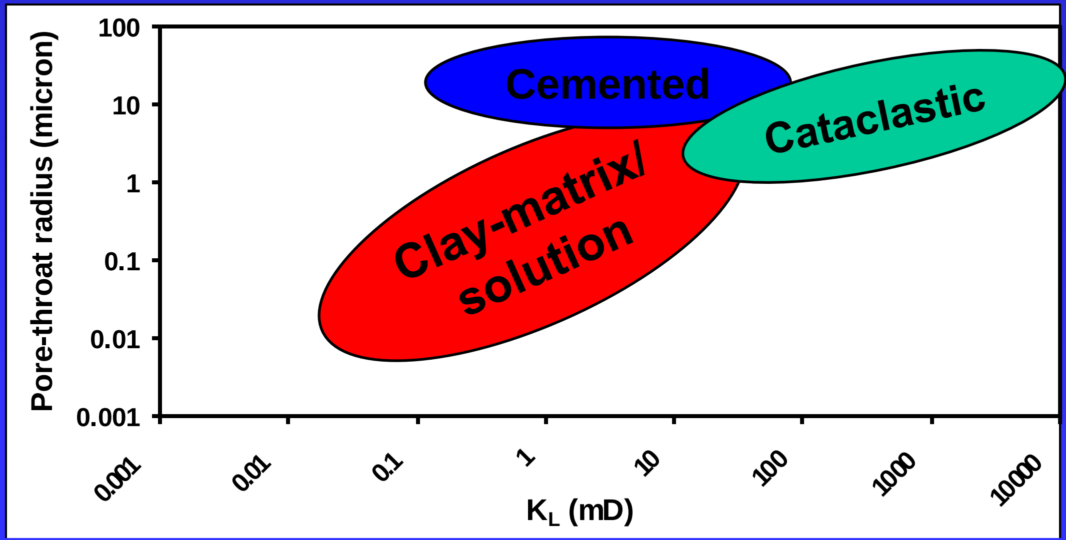
S_{wi} variation



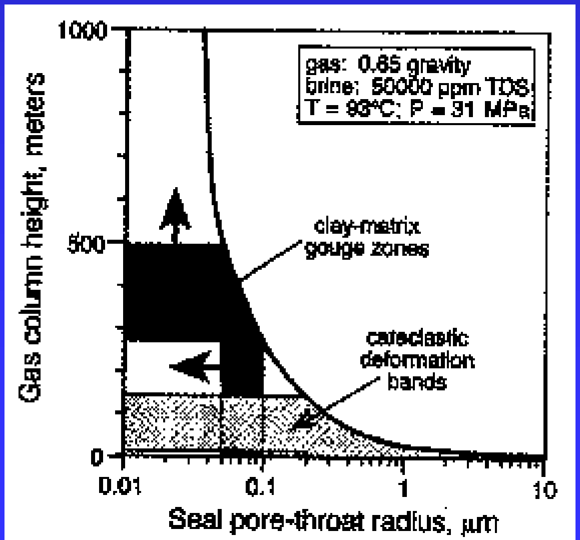
Pore radii distribution

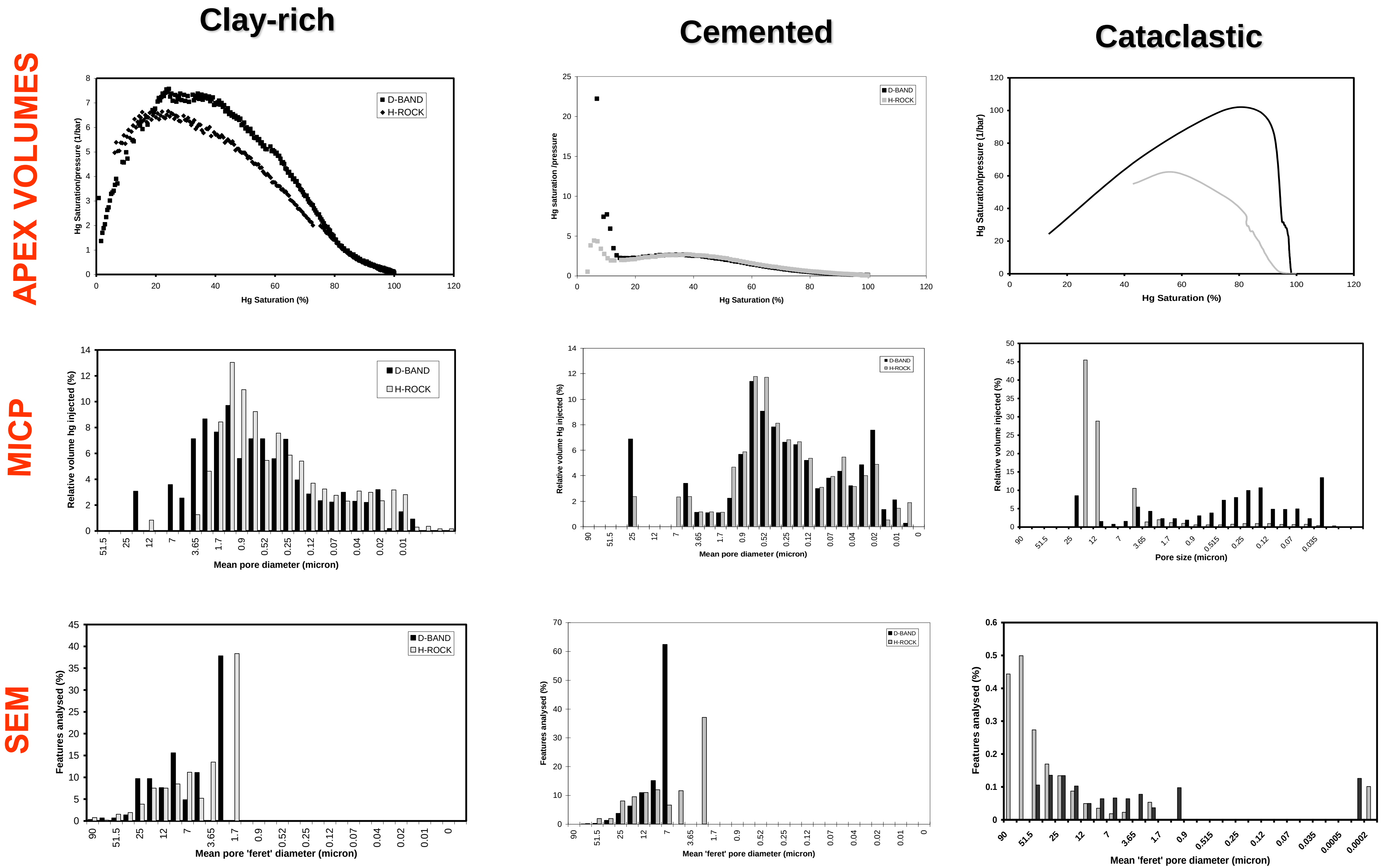


Ranges of pore radii & permeability



Max. sealable gas col height vs. pore radius

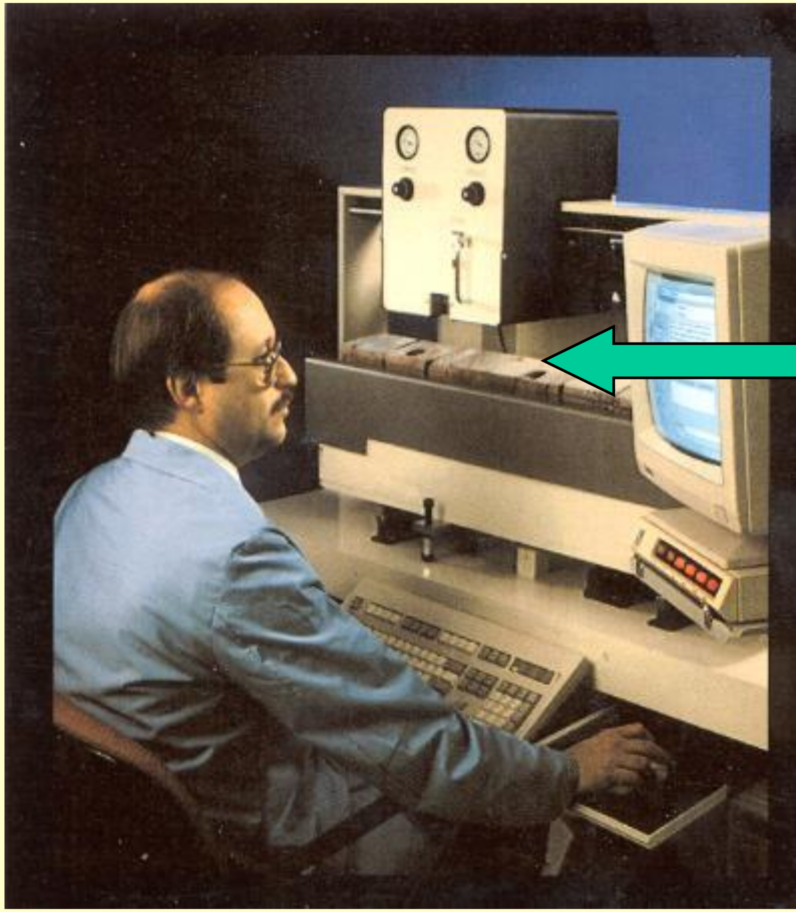



Clay-rich
Cemented
Cataclastic
APEX VOLUMES
MICP
SEM
D-BAND
H-ROCK
Hg Saturation/pressure (1/bar)
Hg saturation /pressure
Hg Saturation (%)
Relative volume hg injected (%)
Relative volume Hg injected (%)
Relative volume injected (%)
Mean pore diameter (micron)
Pore size (micron)
Features analysed (%)
Mean pore 'feret' diameter (micron)
Mean 'feret' pore diameter (micron)

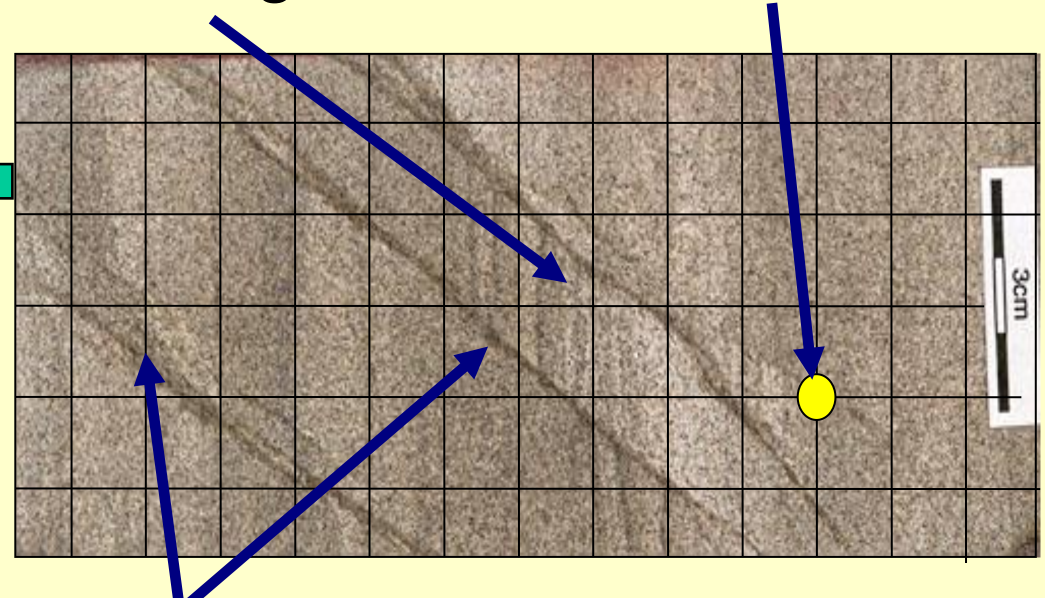
PRESSURE-DECAY PROFILE PERMEAMETRY (*Jones*, 1992)

- High resolution (0.001 mD) K_L -corrected measurements
- Probe technique; pressure decay used to measure permeability
- High Resolution permeability images
- 2D measurement therefore a fraction of the volume measured using conventional permeametry

PDPK SETUP



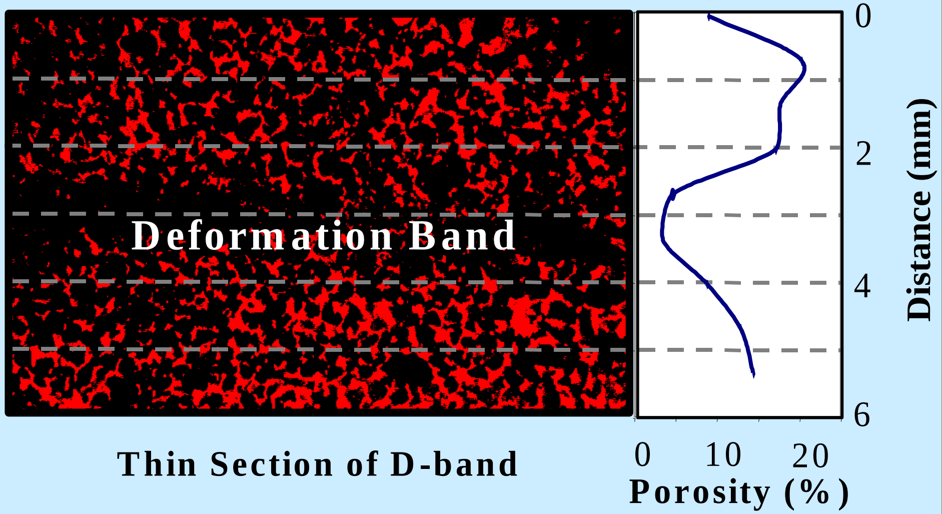
Sandstone core with fractures

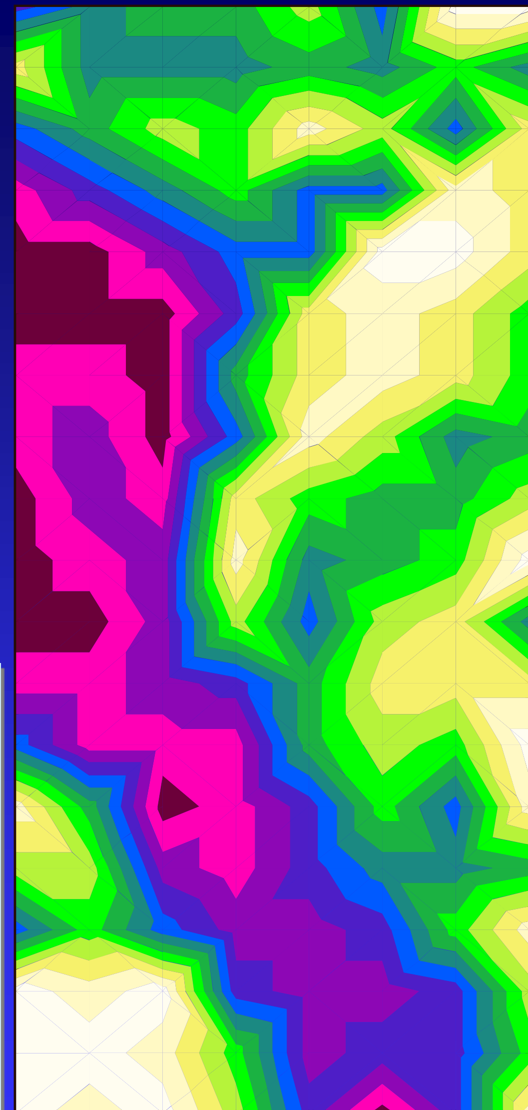


Cataclastic DB in a porous sandstone

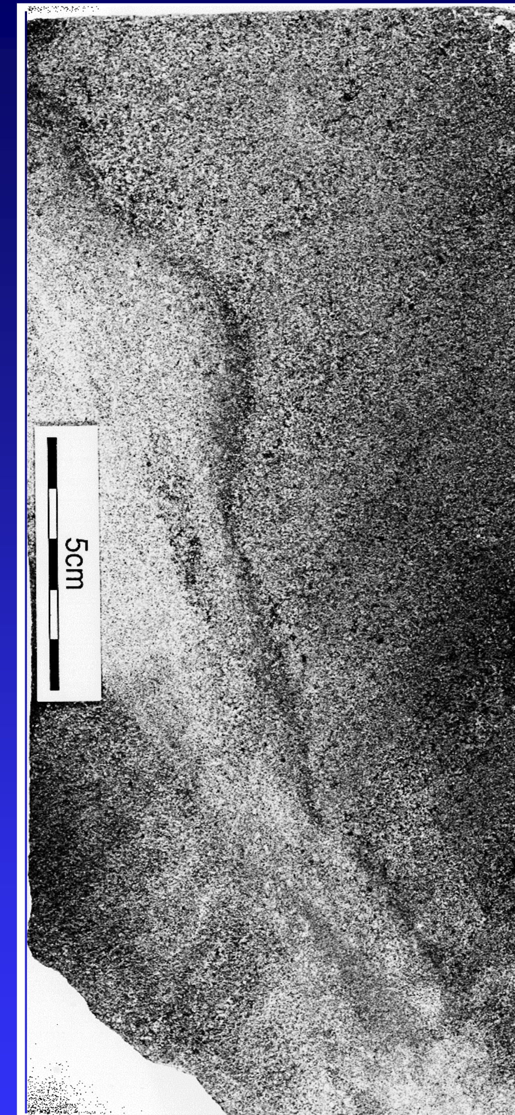
Legend

	0.0034	to	2.35
	2.35	to	29.6
	29.6	to	192
	192	to	397
	397	to	682
	682	to	785
	785	to	899
	899	to	1090
	1090	to	1220
	1220	to	1420
	1420	to	1850
	1850	to	3080





1 cm grid resolution

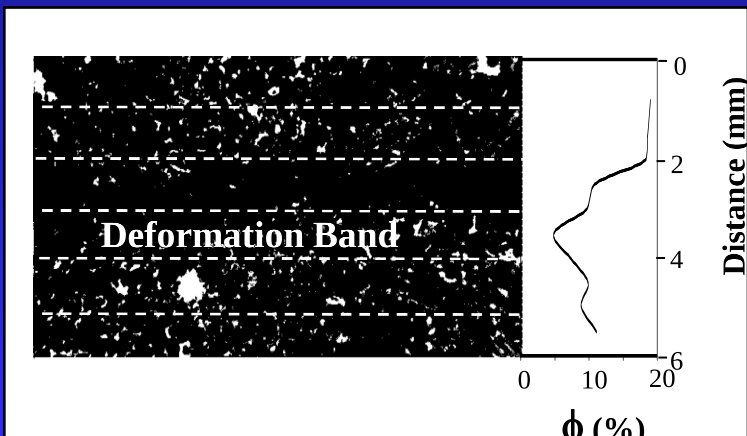


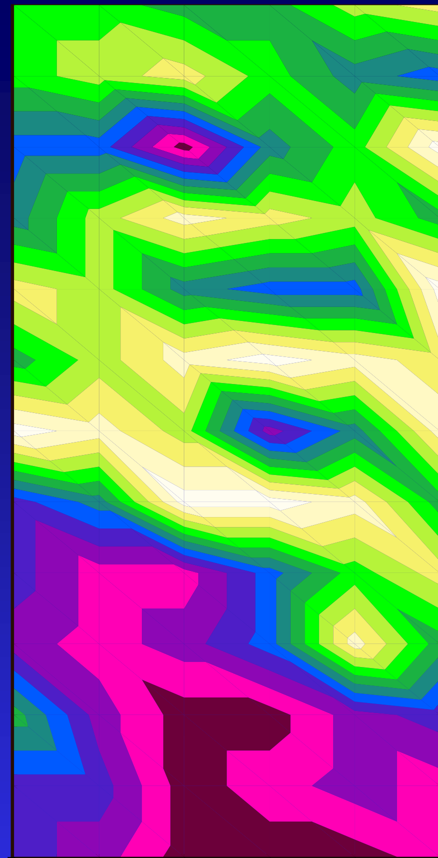
Highly porous sandstone

Clay-rich DBs

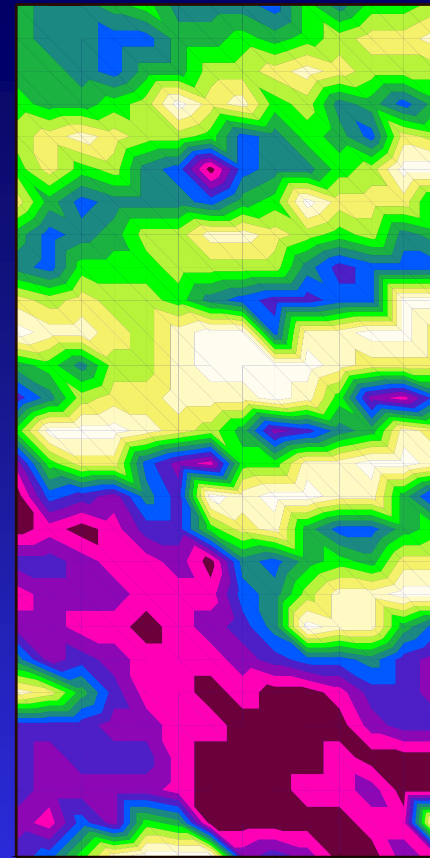
Legend

	0.00026	to	1.22
	1.22	to	2.52
	2.52	to	4.46
	4.46	to	6.87
	6.87	to	11.5
	11.5	to	13.6
	13.6	to	16.5
	16.5	to	20.7
	20.7	to	25.1
	25.1	to	30.7
	30.7	to	39
	39	to	1070

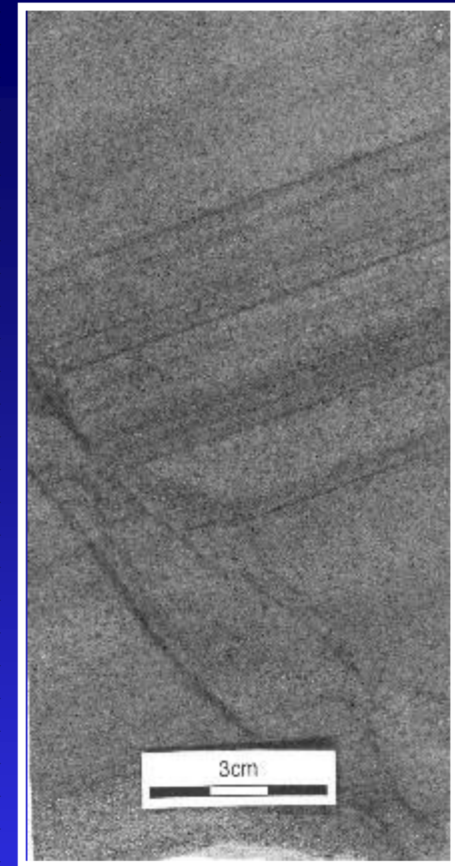




1cm grid resolution



5 mm grid resolution

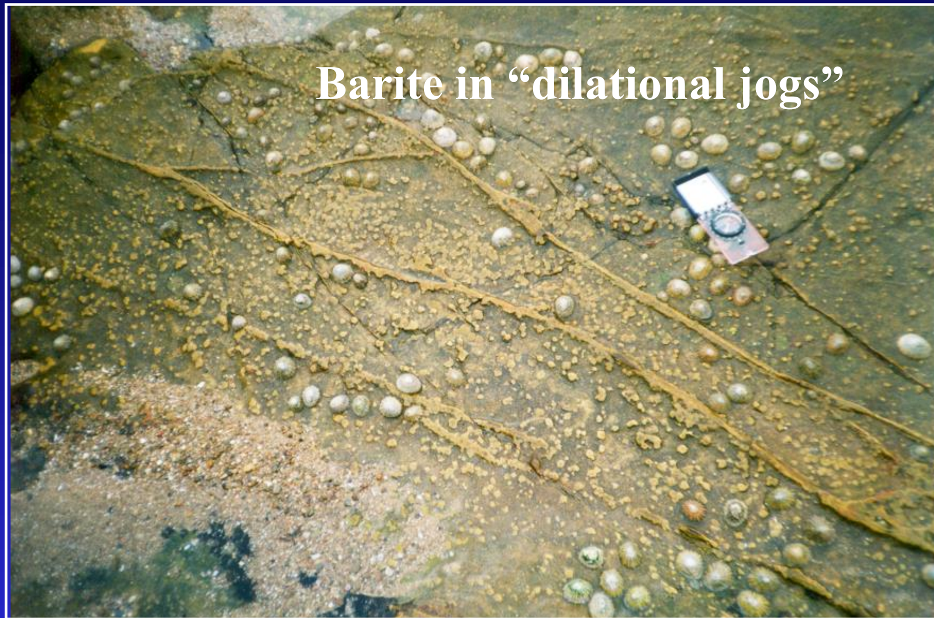


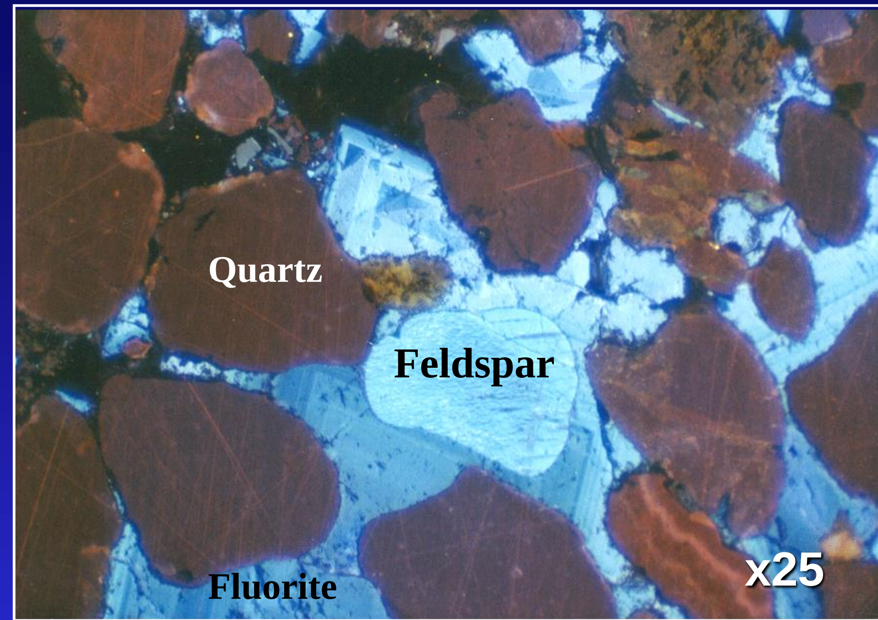
Clay-rich sandstone

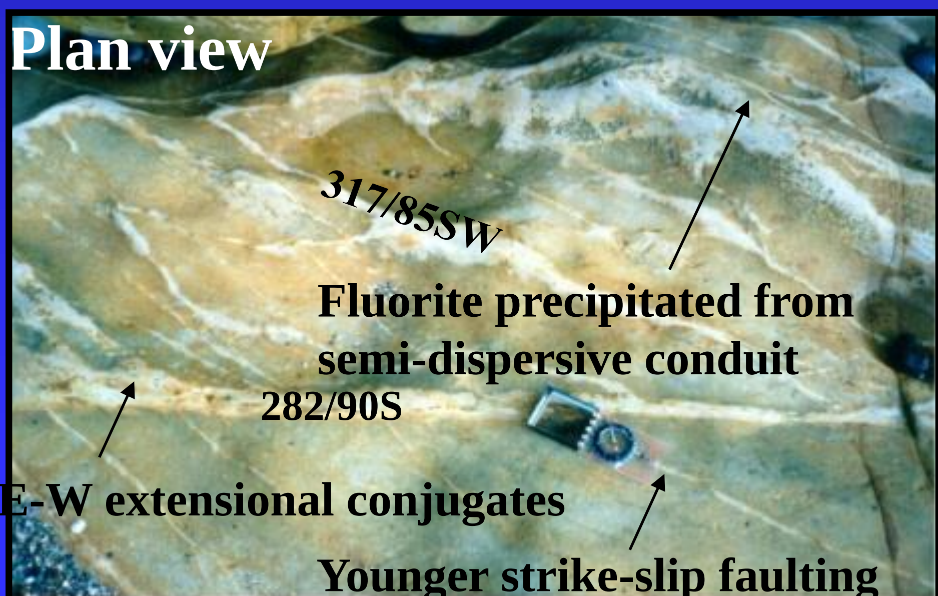
Critical role of clay content in fault rock development can be assessed accurately if phyllosilicate content logs are generated from sedimentary analysis of reservoir stratigraphies

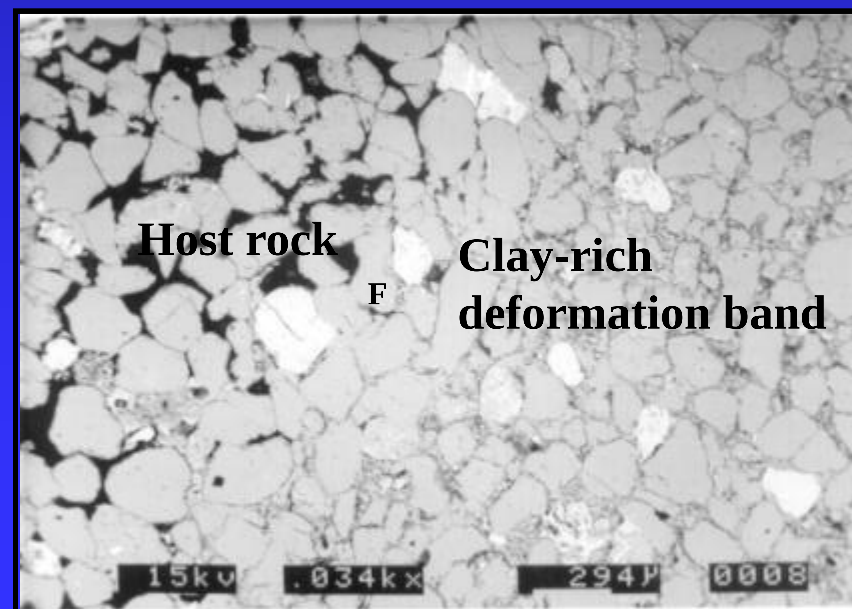
Juxtaposition of reservoir against low permeability units & shale smear not only sealing mechanisms

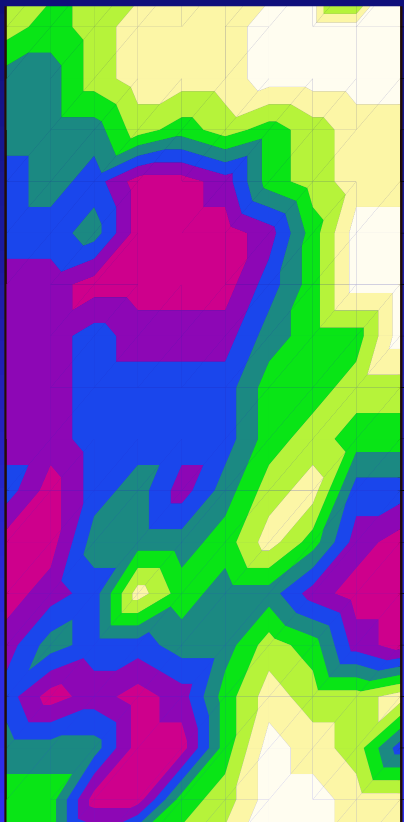
Cemented Deformation Bands







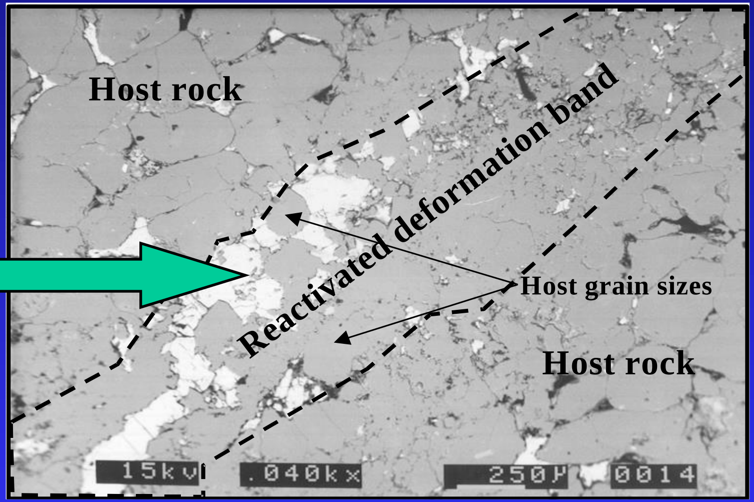




1cm grid resolution

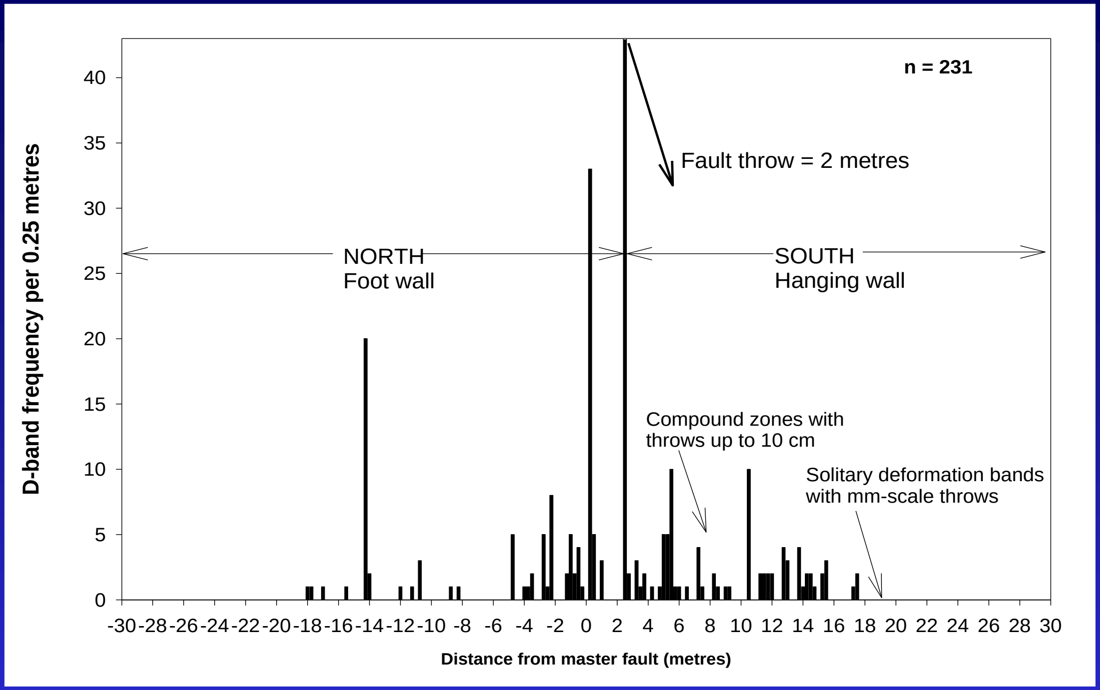
5 mm grid resolution

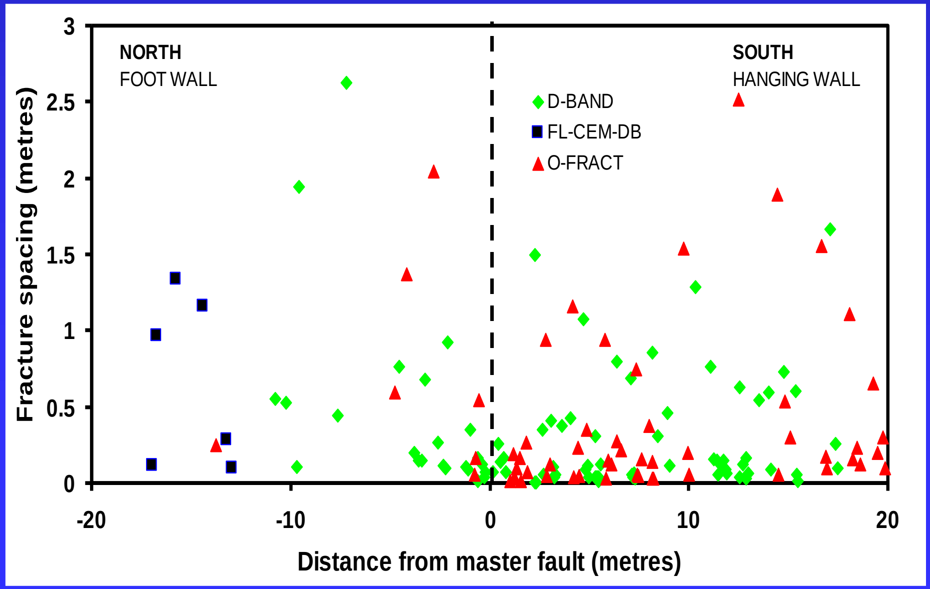
Cemented D-bands

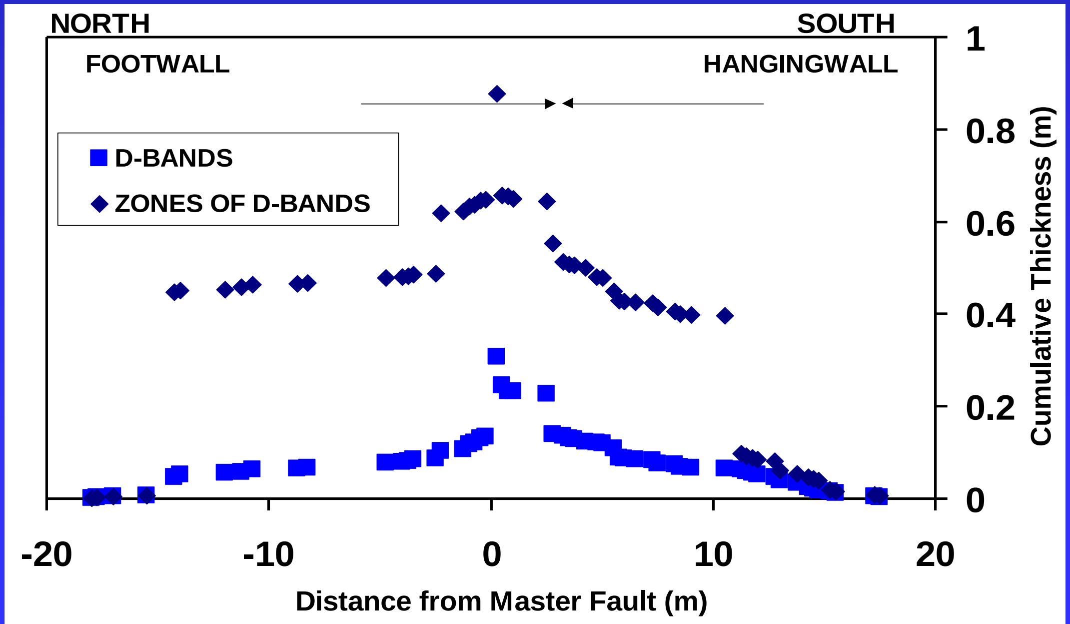


Integration with macro-properties

Critical elements; Damage zone dimensions, fault clustering, offset populations, orientations, total thickness.

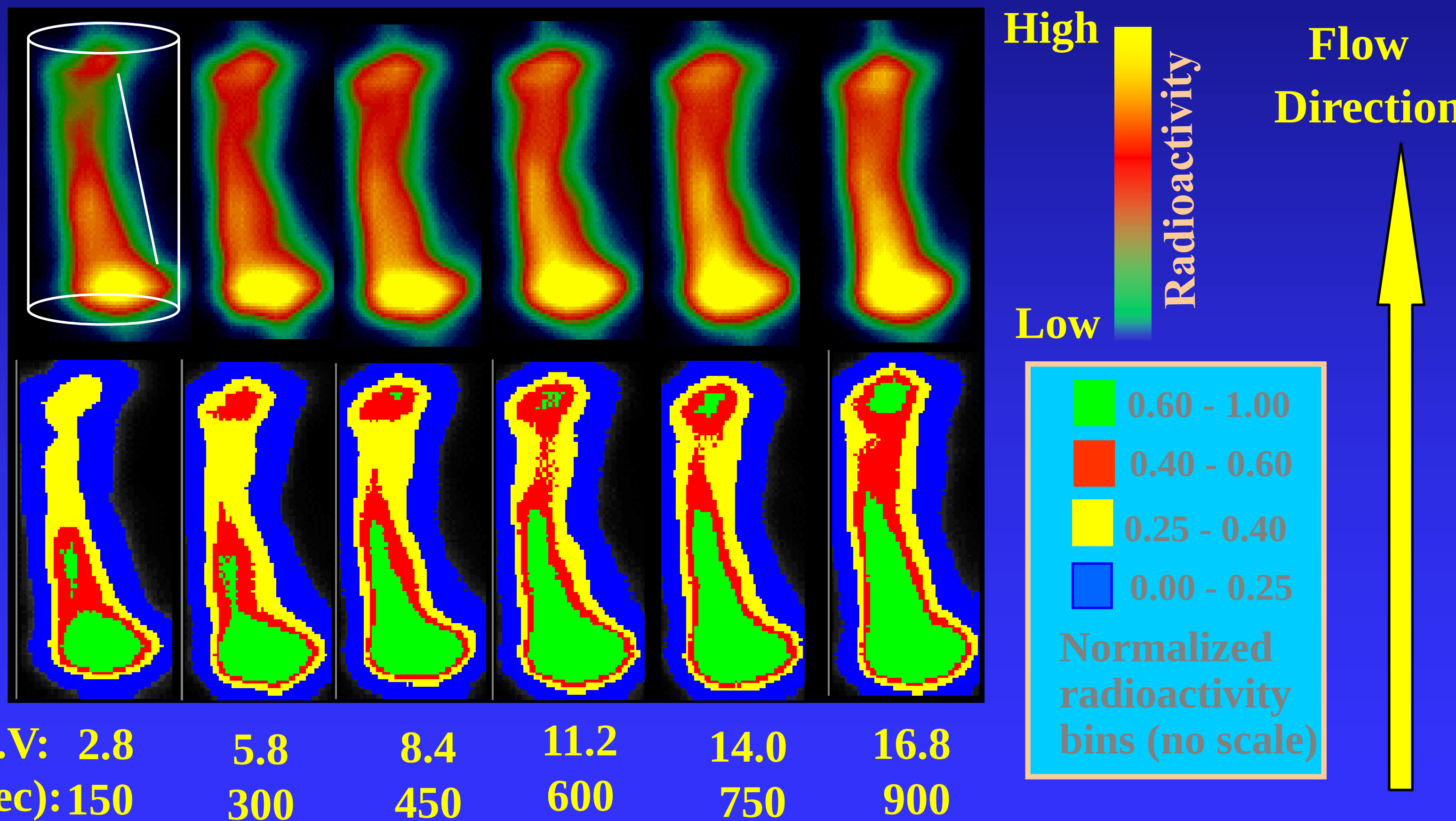






PET – scanning: to visualise d-bands as influence to fluid flow by tracing mobile chemicals in sandstone plug containing d-bands

- Flow rate
  15 ml/min
- 30 PET scans
  over 15 minutes



Summary

- Role of d-bands in fault seal through integrated geometrical & microstructural studies
- Microstructure characterisation; influences fault rock distribution & juxtapositions- but geohistory critical !
- Formation dependant upon protolith
- Higher resolution measurements of smaller rock volumes reduces uncertainty in role in fault seal.
- Downhole tool information on fault contents require validation against core material as the detection of some materials (e.g., kaolinite) may not be a simple process.

High Resolution Aperture Determination of Rough Fractures

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Structure

1) Experimental work on fracture modelling

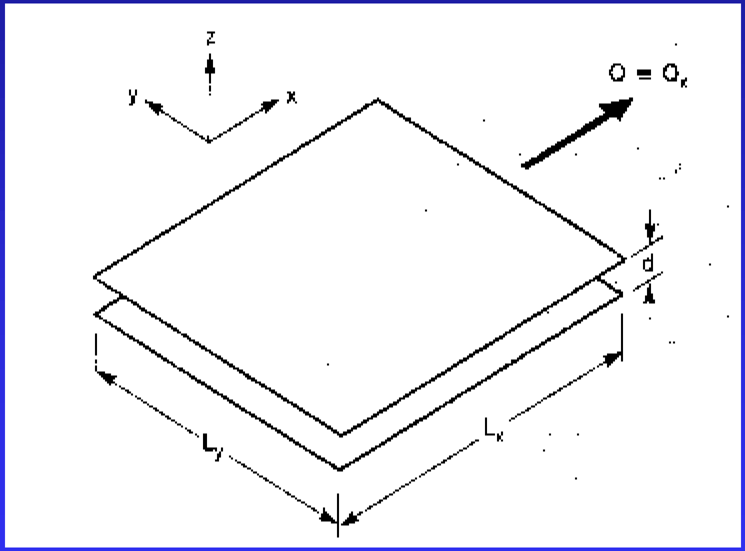
- Importance of surface roughness
- Flow experiments
- Construction of physical models & development of high resolution optical method to determine fracture apertures

2) Computer modelling

- “In house” profiling software
- Numerical synthesis of fractures

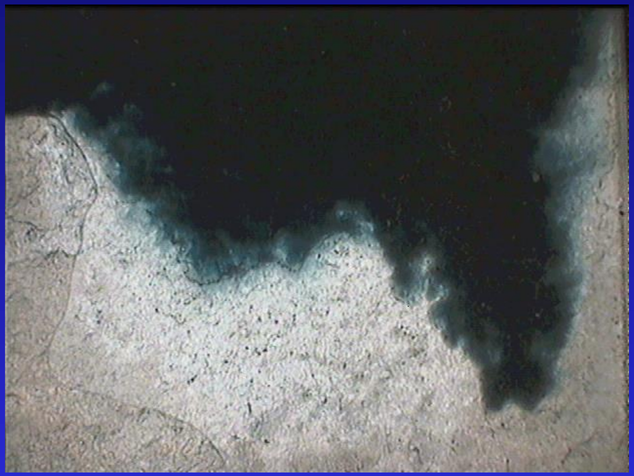
Importance of Surface Roughness

- In absence of filling materials, flow of fluids controlled by roughness of fracture walls & physical separation
- Variation in roughness associated with rock type & texture
- Hence replacement of parallel plate assumption, central to all multi-fracture network flow models.



- Stress regime, mean aperture, fluid properties and flow rate etc. also affect fluid flow

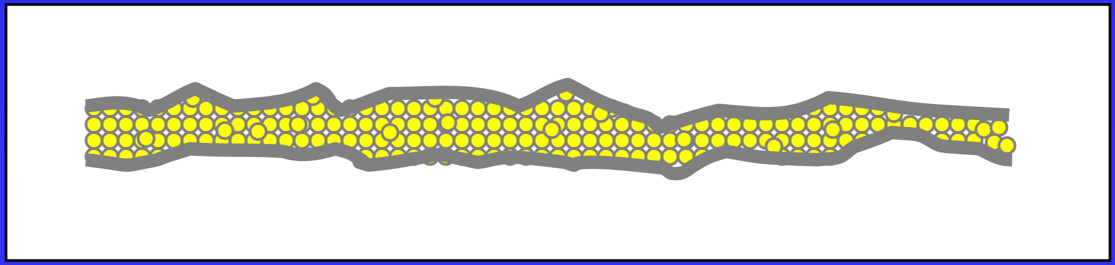
Flow Imaging of HFPMs



- Measurement of fluid flow through synthetic rough fractures using DOI

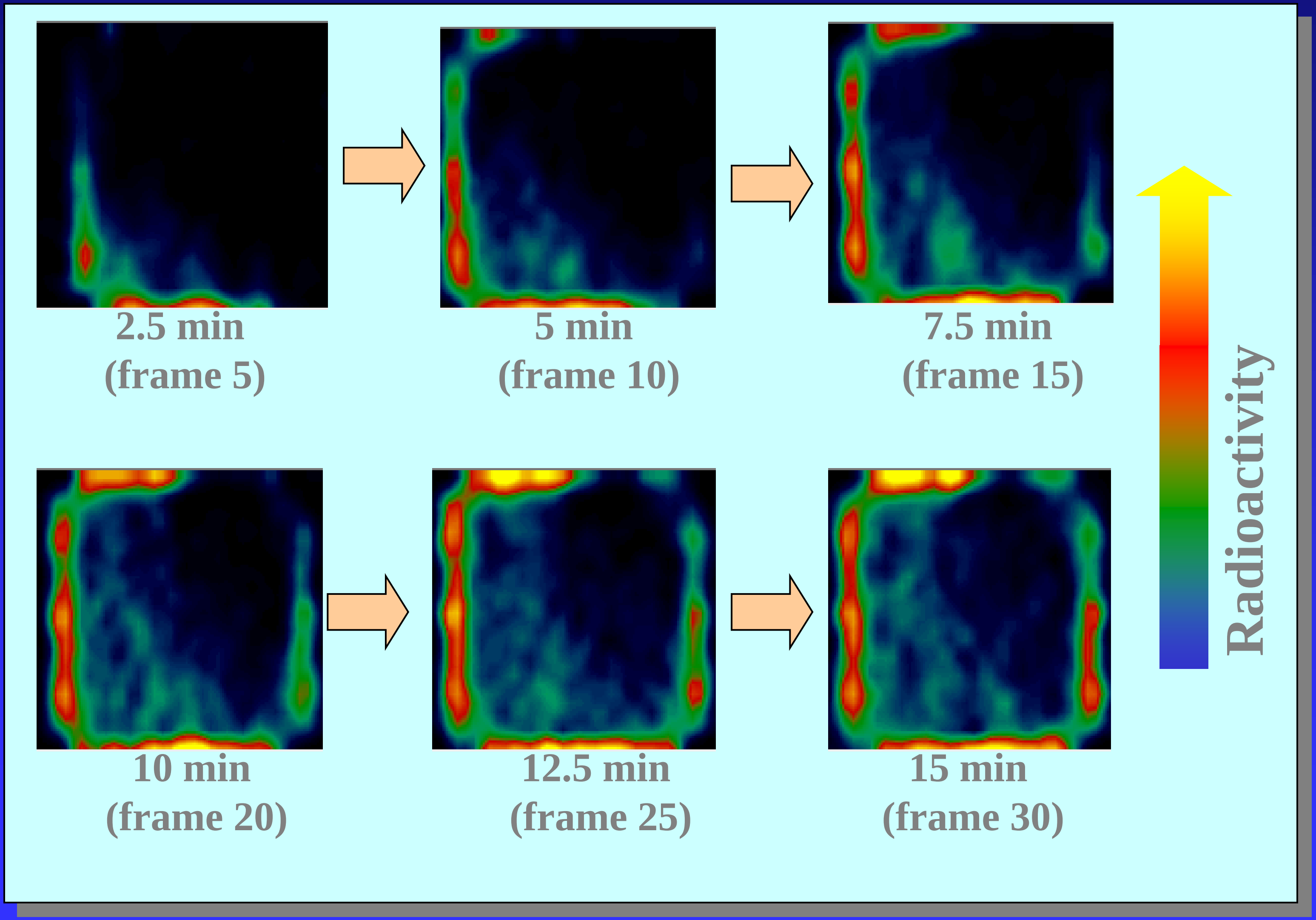
- Fluids may be miscible or immiscible for a range of flow rates viscosities and densities

- Sample may contain analogue gouge material



PET-Scanning of Fluid Flow

Low resolution but many fluid flow applications



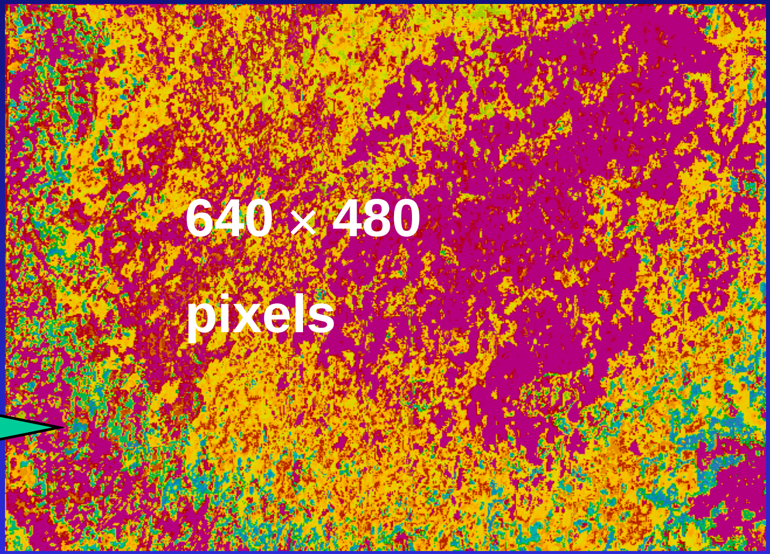
Development of Optical Method

- Fracture roughness profiles measured using mechanical profilometers/ photogrammetry/ shadow profilometers etc
- Time consuming & low resolution due to nature of measurement.
- Quantitative descriptions of fracture geometry e.g., application of statistical methods to estimate asperity height characteristics/ spatial distributions

Optical Method for Imaging Apertures

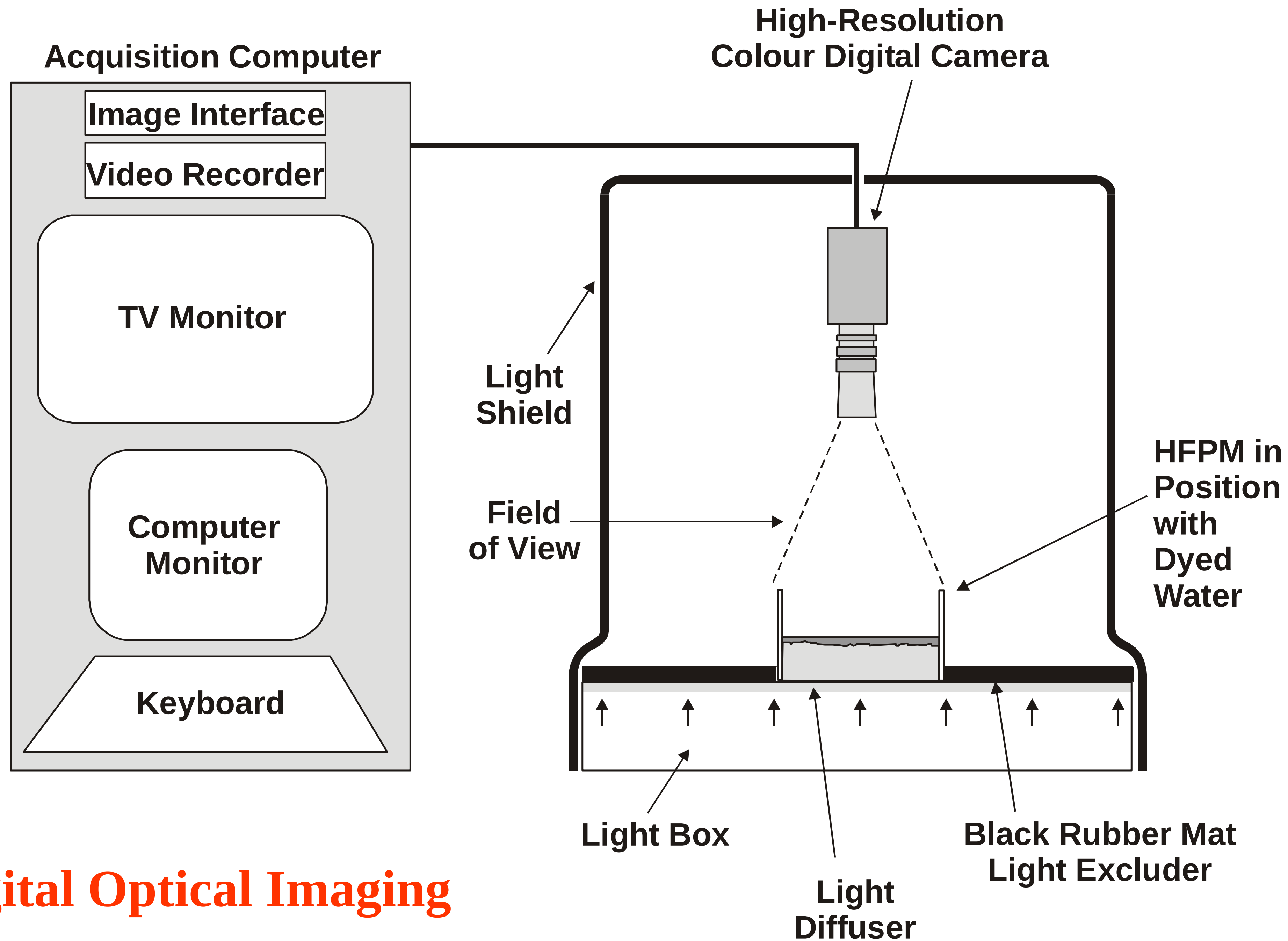
- High-resolution optical method to determine synthetic fracture apertures in a suite of rocks.

Aperture map

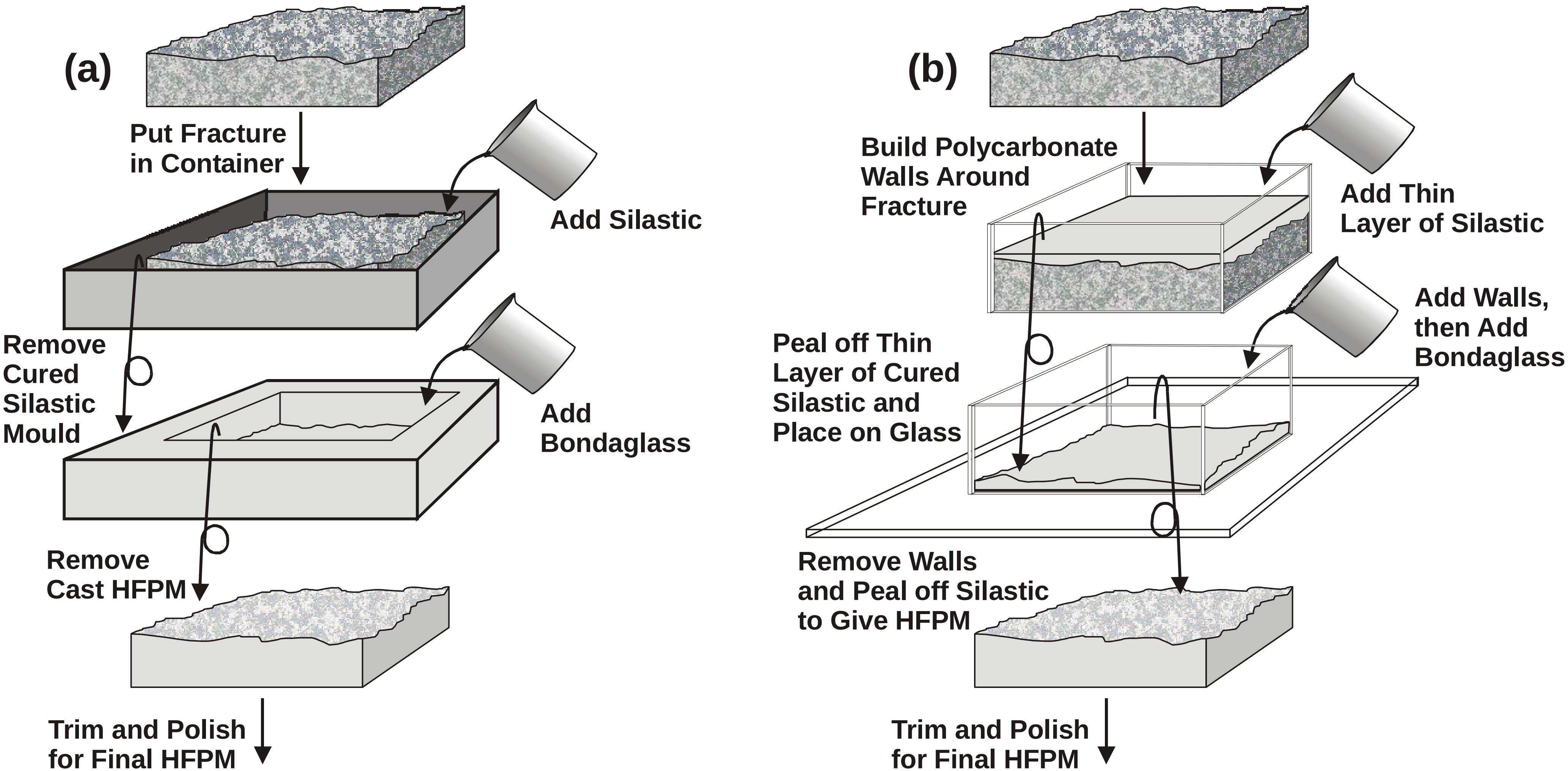


- The absorption of light passing through the fracture filled with dye can be used to derive the 2D aperture distribution using *Lambert-Beer Law*

$$Ix = I_o e^{-KcT}$$

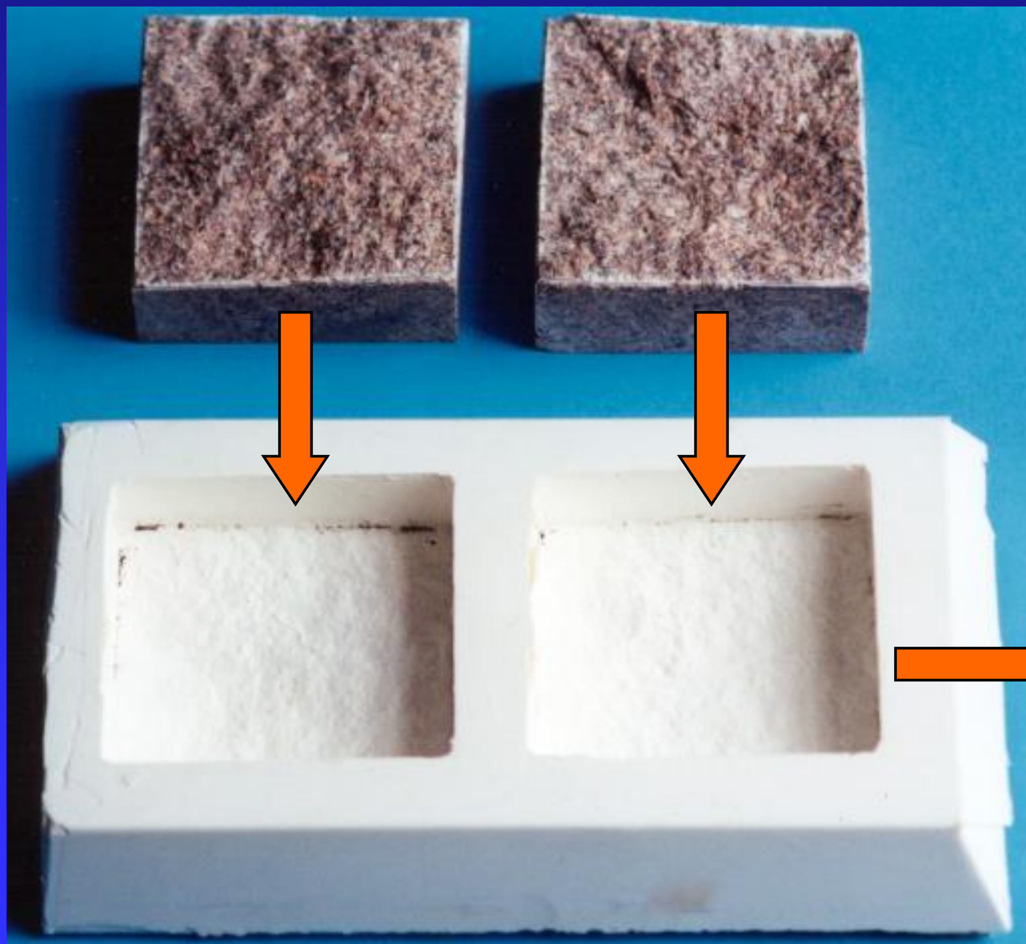


Digital Optical Imaging


(a)
Put Fracture
in Container
Add Silastic
Remove
Cured
Silastic
Mould
Add
Bondaglass
Remove
Cast HFPM
Trim and Polish
for Final HFPM
(b)
Build Polycarbonate
Walls Around
Fracture
Add Thin
Layer of Silastic
Add Walls,
then Add
Bondaglass
Peal off Thin
Layer of Cured
Silastic and
Place on Glass
Remove Walls
and Peal off Silastic
to Give HFPM
Trim and Polish
for Final HFPM

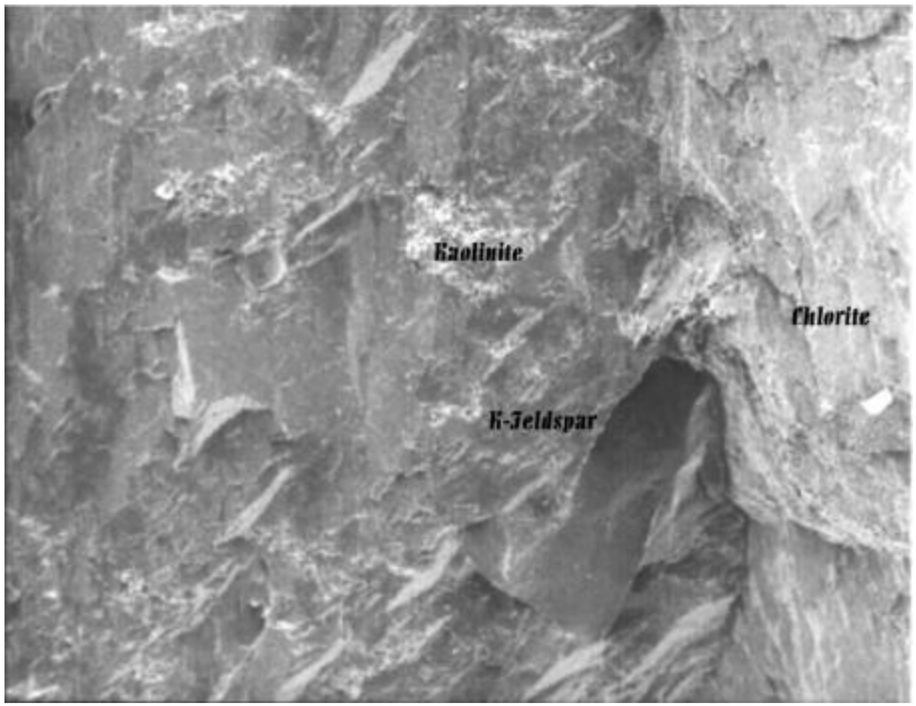
HFPM Construction

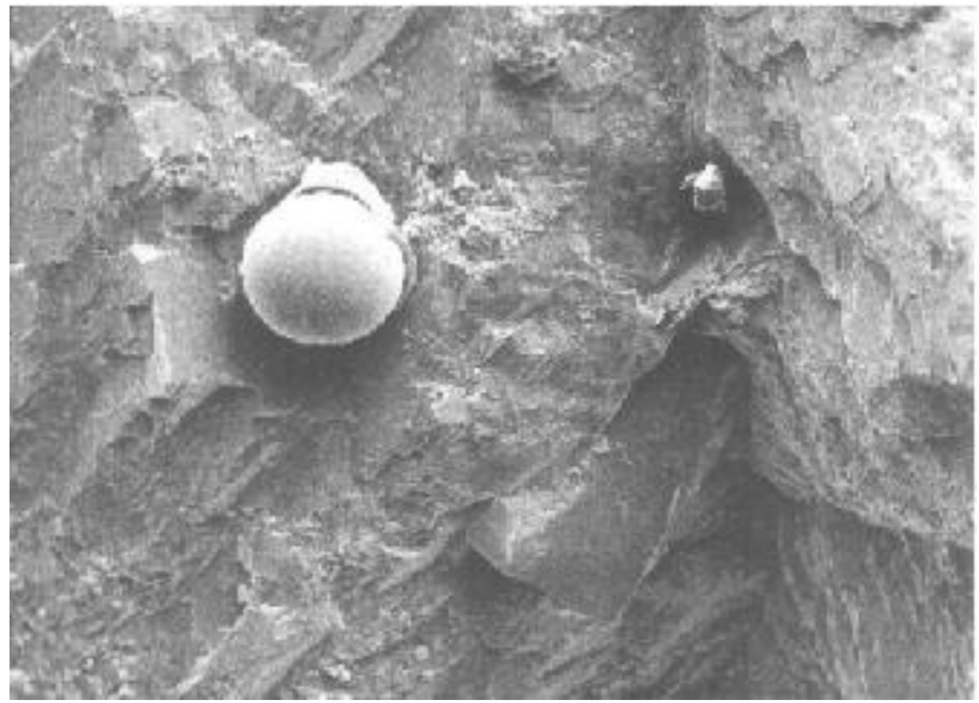
HFPMs produced by casting from moulds of rock fractures



HFPM Resolution

SEM used to see how well and to what scale the original rock has been reproduced in the epoxy resin replica. Resolution < 1 micron





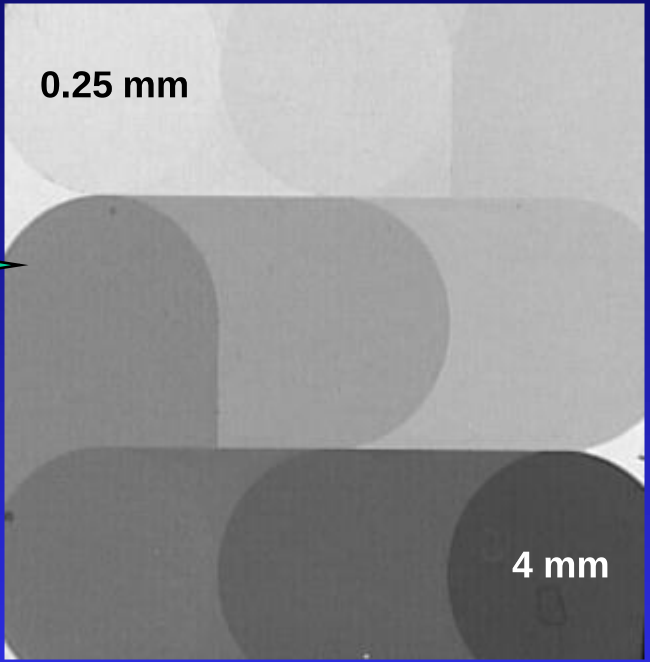
- Original Fracture

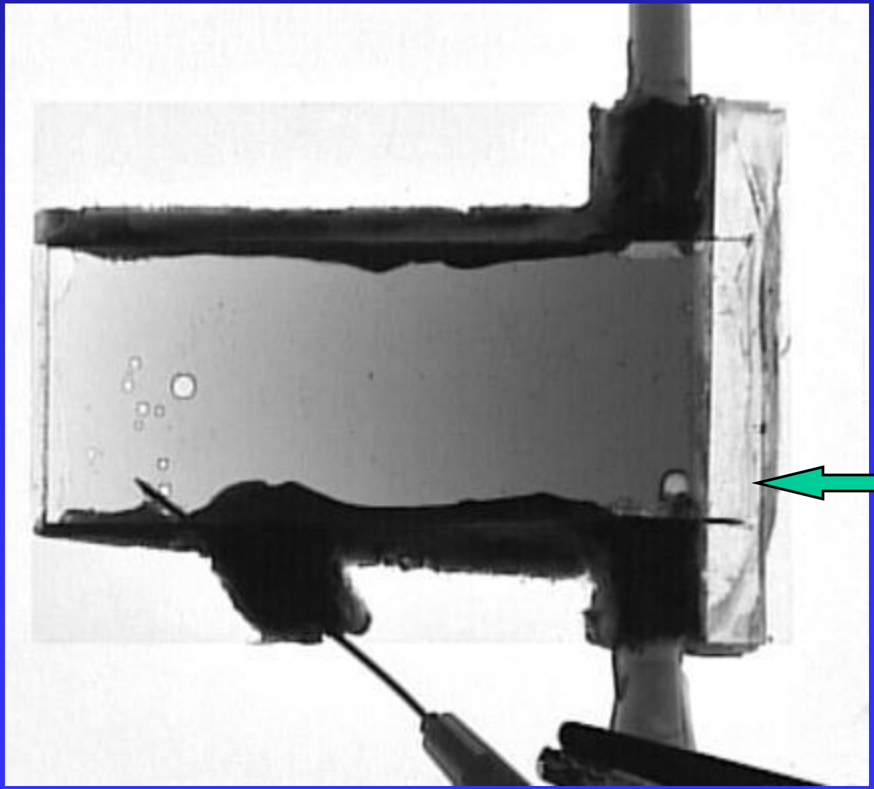
150 µm

- HFPM

Calibration Devices

Tile with pocket areas of known thickness filled with dye (1g/l). 8 bit greyscale image obtained

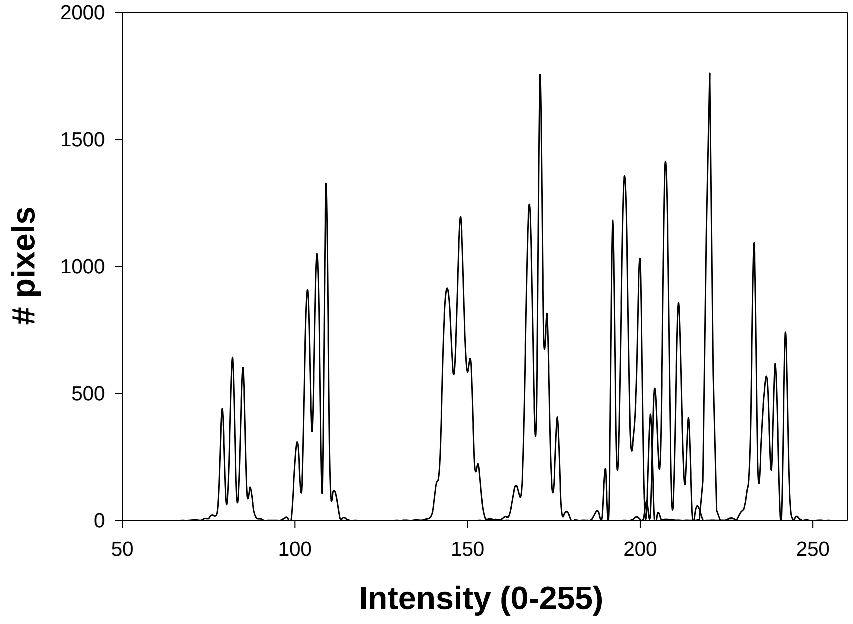


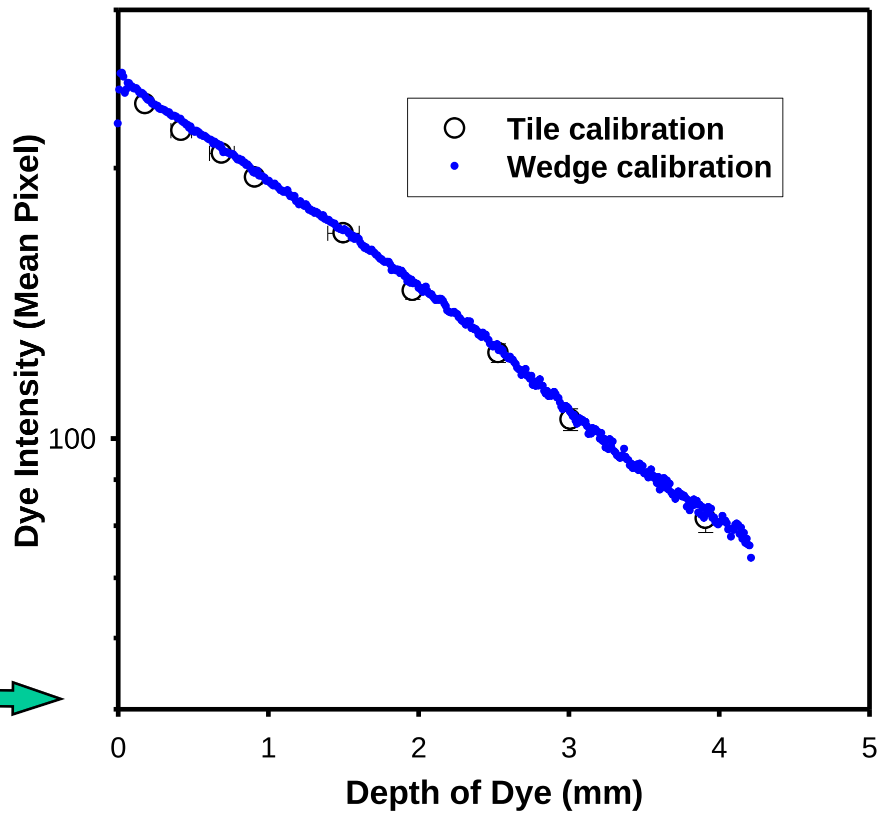


Supporting data from wedge with max. thickness of 4.3 mm

Lambert-Beer Law

Individual tile pocket intensities





Optical Profiling of Fractures

Computational Flow Models require the geometry of flow channel to be prescribed. An optical method was chosen to explore the fracture surface profiles.

Features of the choice:

- Cheap, does not require an expensive equipment.
- Fast (relatively), whole fracture surface to be scanned simultaneously.
- Accuracy of the method is subject of particular technique to be used.

Technical Reality

Non-uniform backlight

Video channel distortions:
- Coarse structures
- CCD noise

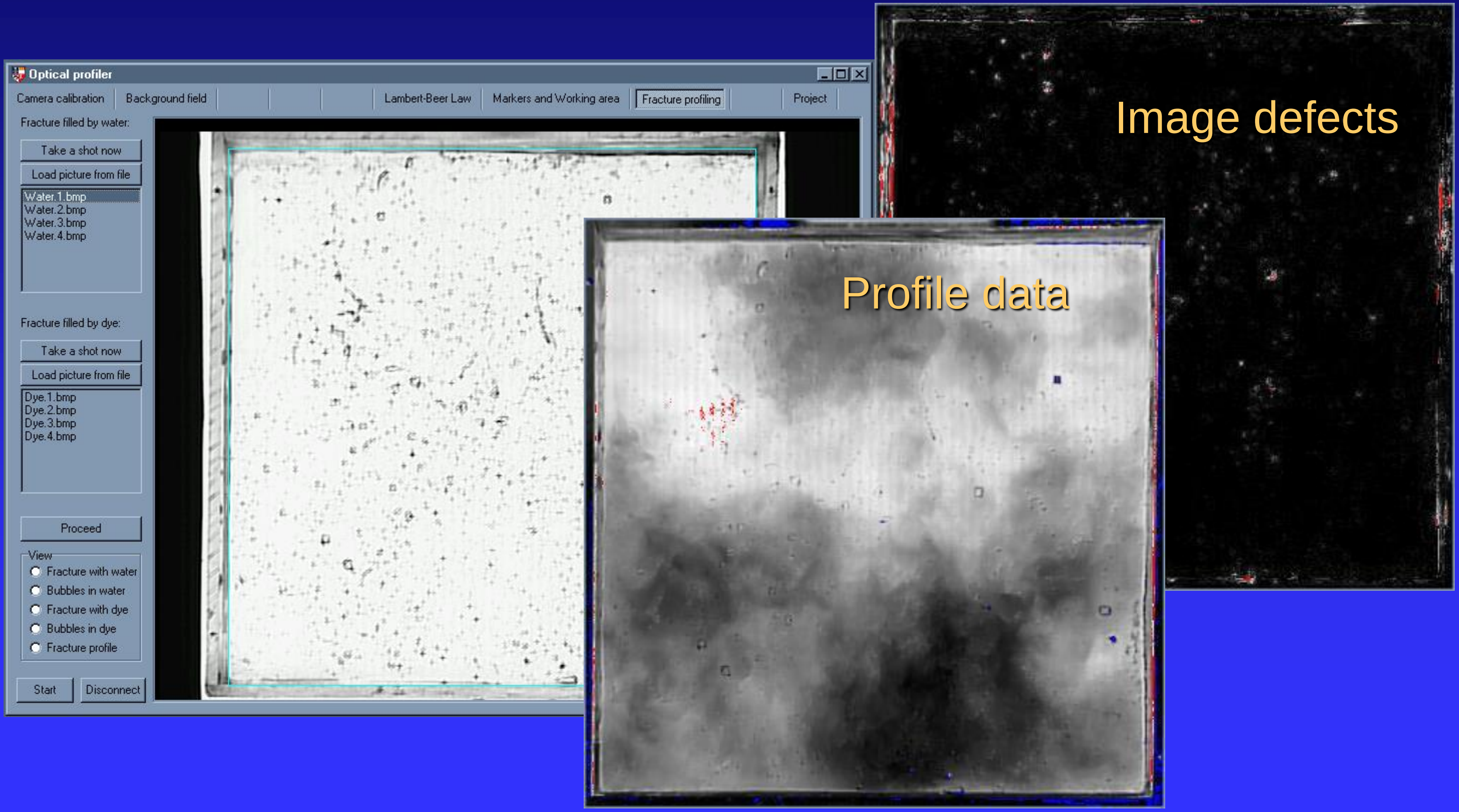
Bubbles and particles in the liquid (water or dye)

Profiling Methodology

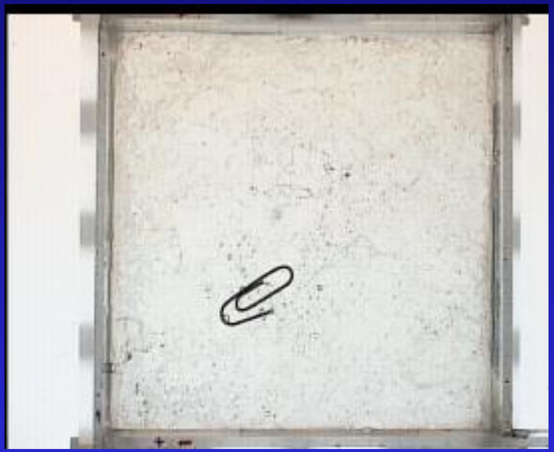
- Individual calibration of the pixels of CCD matrix.
- Stacked images to be taken with further averaging to neglect the camera noise.
- Clearfield equalization.
- Comparison of several images allow to recognize effectively bubbles and particles in liquid.

The methodology is implemented as a software algorithm.

Profiling Software



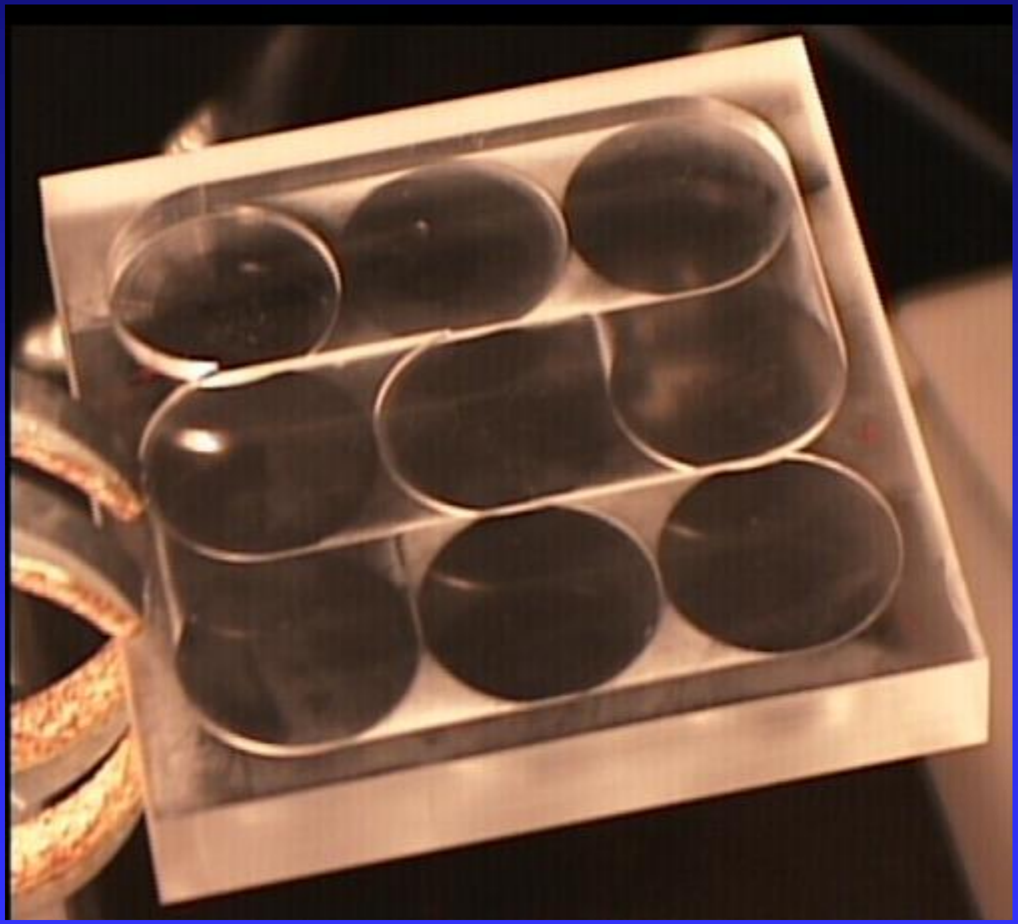
Automatic Defect Recognition

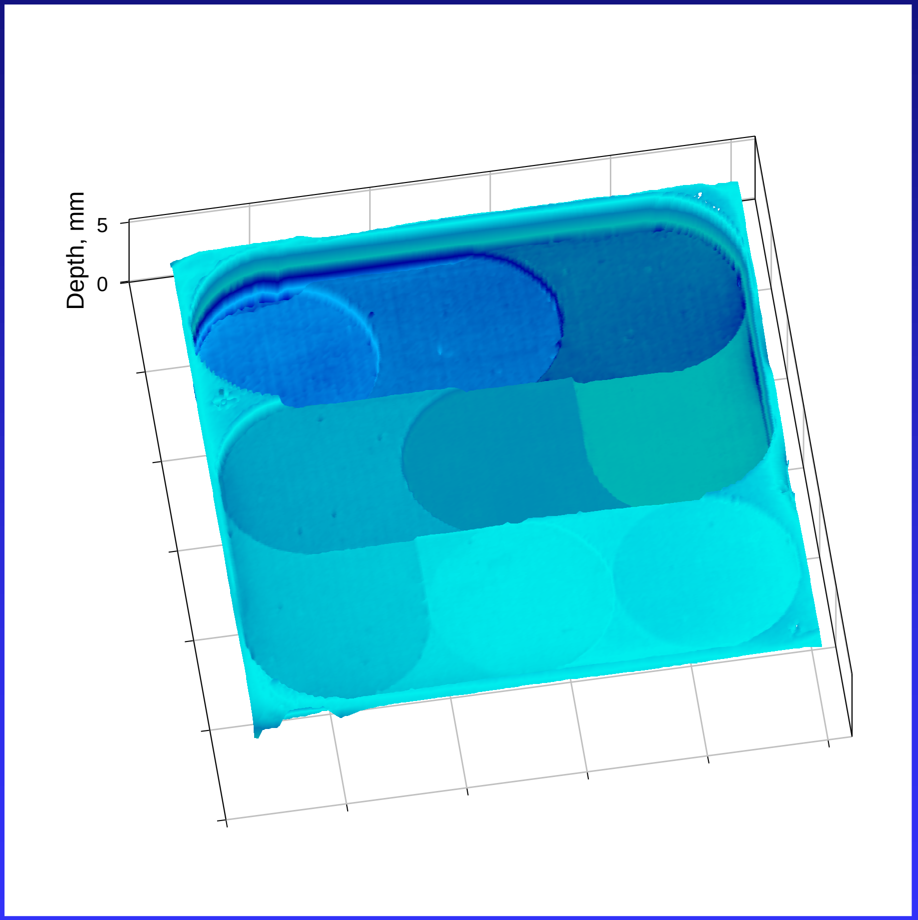


Resulting image

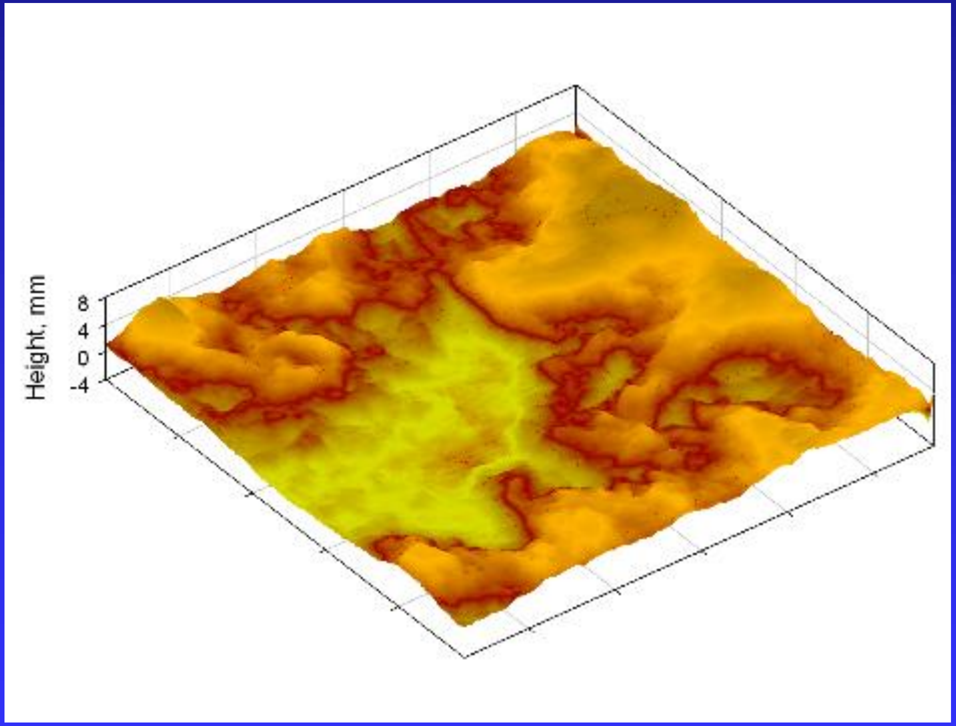
Defects map

Sample of Profiling Result





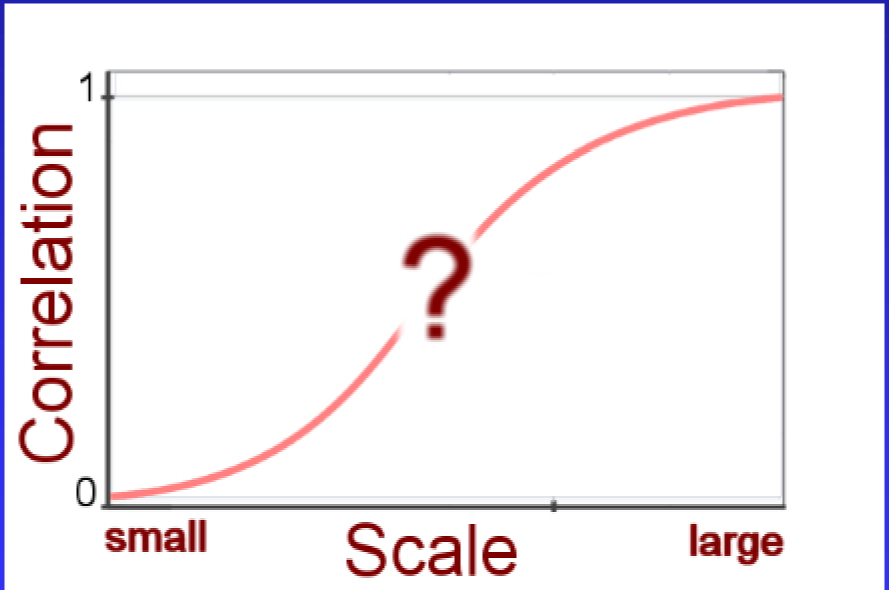
Profiling Sample: Red Granite



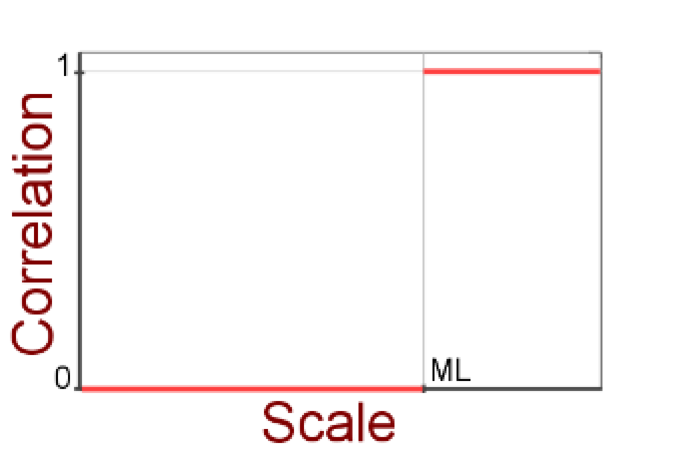
Numerical Synthesis of Fractures

- Fractal synthesis is used to generate fracture surfaces.

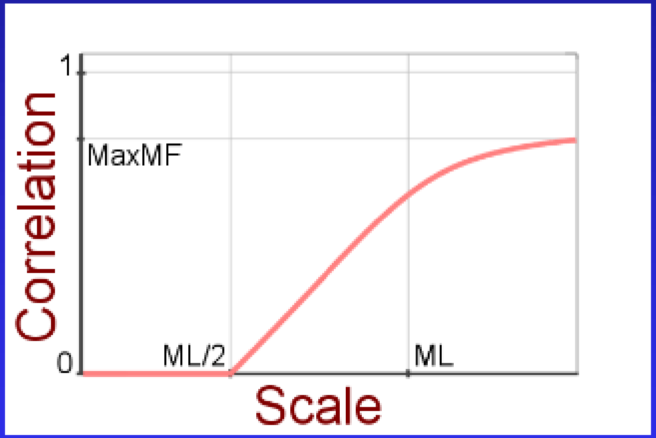
- The fracture surfaces should be similar in large scale of view and relatively independent at micro-scale.



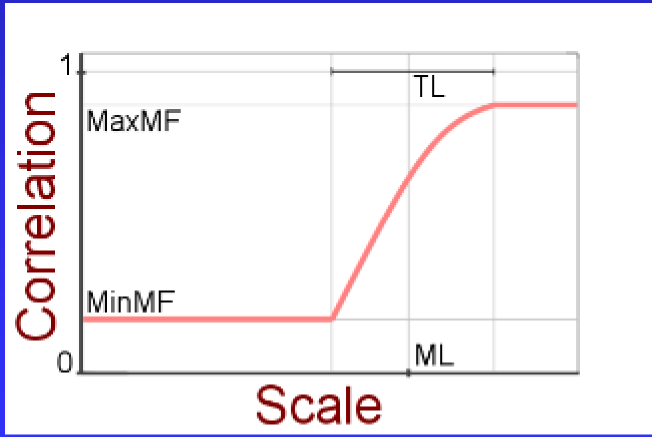
Synthesis methods



Brown (1995)

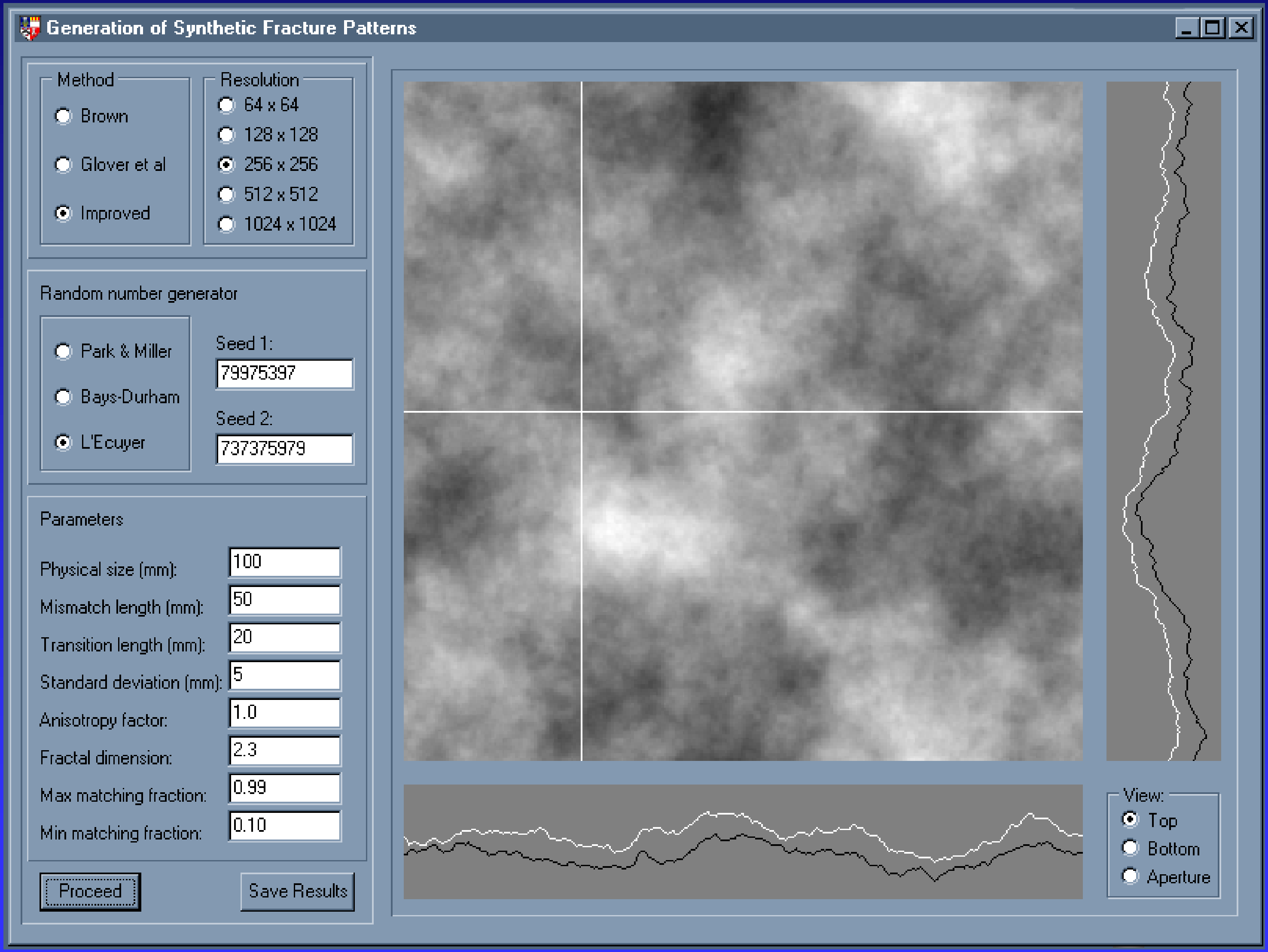


Glover et al. (1998)

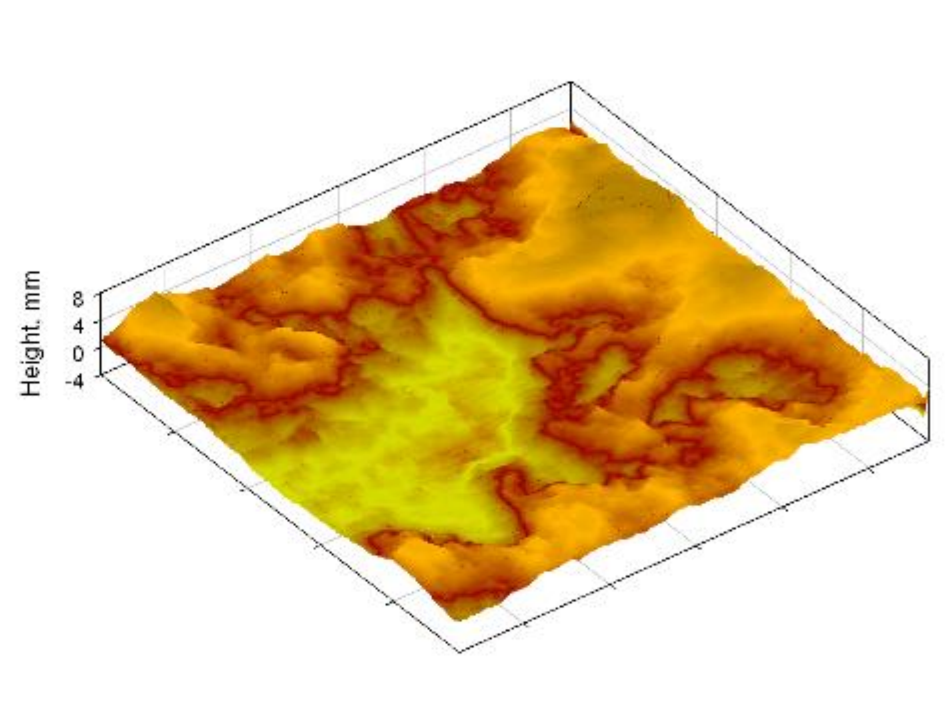


Present method

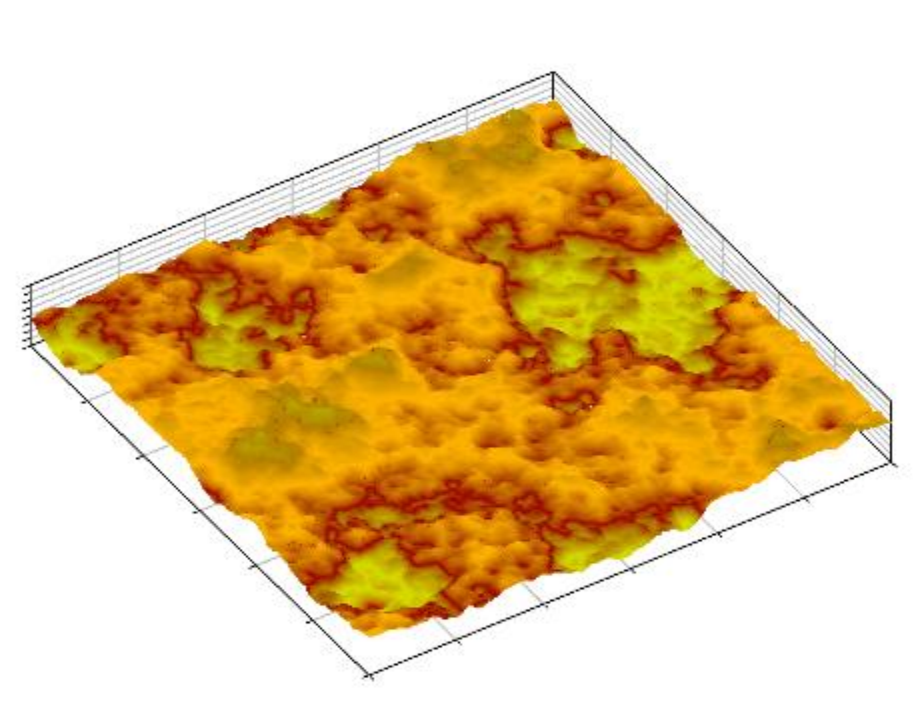
Software for Numerical Synthesis



Result of Numerical Synthesis



Pearly granite fracture surface



Synthesized fracture surface

Summary

- An optical technique developed in this study has provided high-resolution aperture determinations of rough fractures.
- Quicker & cheaper than PET/NMR techniques & also used to observe and monitor fluid flow through fractures
- Rough fractures be profiled, and numerical synthetic fractures can be produced to high precision
- Valuable results for 3D fluid flow modeling

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GRAIN-SIZE ANALYSIS