Imaging, Measurement and Modelling of Fluid Flow in Rough Rock Fractures

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Aberdeen University Petrophysics Group

μ2M Natural Environmental Research Council

http://petrophysics.webhop.net

Aberdeen University Petrophysics Group

- Director - Dr. Paul Glover
- 8 Members of Staff & 8 Associate Members
- Comprehensive Petrophysics Laboratory Facilities
- 30 publications and 25 conference abstracts since 1997
- Wide Range of Petrophysics/Geophysics Research
- Worldwide Collaboration
- Effective Links with Industry

Current Projects I

- Integrated Reservoir Modelling
- Genetic Algorithms and Fuzzy Logic
- Quantitative Seismic Analysis Techniques
- The Effect of Faults on Reservoir Fluid Flow
- Mapping Trough Structures in the Subsurface
- Resonance Enhanced Vibration Drilling Techniques
- Lithospheric Modelling of the Lower Crust

Current Projects II

- Novel Techniques for k–ϕ Prediction
- NMR and PET Techniques for Micro-structural and Hydraulic Properties
- Measuring/Modelling the Effect of Rough Fractures on Fluid Flow
- Prediction of Permeability and Electrical Properties from Rock Microstructure
- Complex Electrical Conductivity and Electro-kinetic Properties of Rocks

Fluid Flow in Rough Fractures in Rocks

Structure

- Introduction
- Digital Optical Imaging
- High Fidelity Polymer Models
- Fracture Profiling
- Synthetic Fractures
- Flow Measurement
- Flow Modelling
- Novel Imaging Techniques
- Summary

Background: 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

Surface Roughness Profiling

- In absence of filling materials, flow of fluids controlled by roughness of fracture walls & physical separation
- Stress regime, mean aperture, fluid properties and flow rate etc. also affect fluid flow
- Fracture roughness profiles measured using mechanical profilometers and optical methods:
  1. Time consuming
  2. Expensive
  3. Low resolution

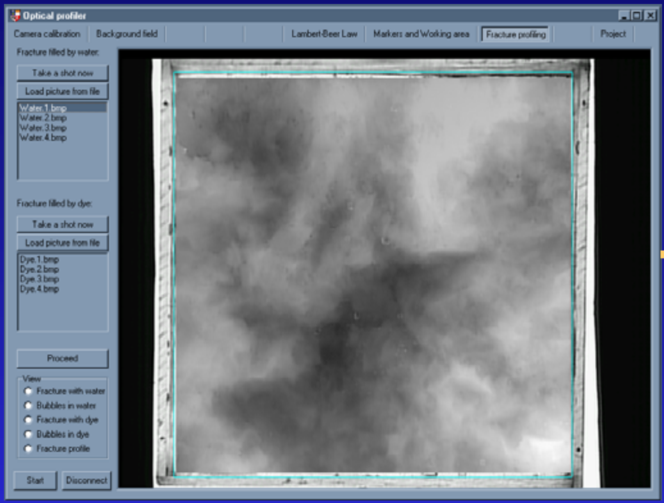
Rocks

1 Sandstone, 1 Limestone, 1 Granite, 1 Grano-diorite, 2 Syenites, 2 Chalks ...

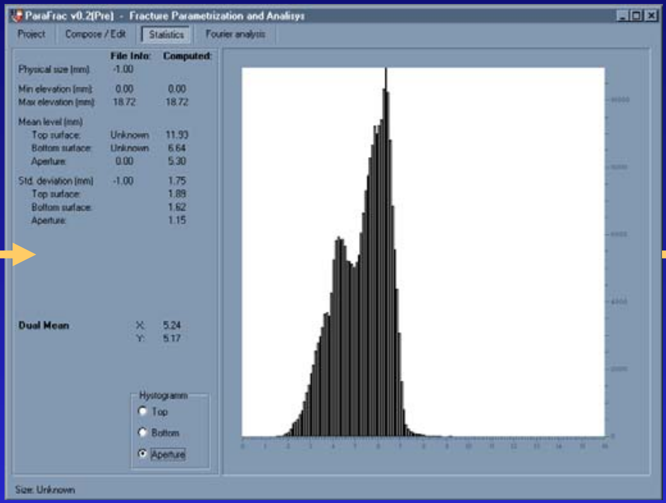
Petrophysical data:

- Porosity (effective & non-effective)
- Permeability (K_L)
- Grain density
- Water saturation
- Capillary pressure
- Composition

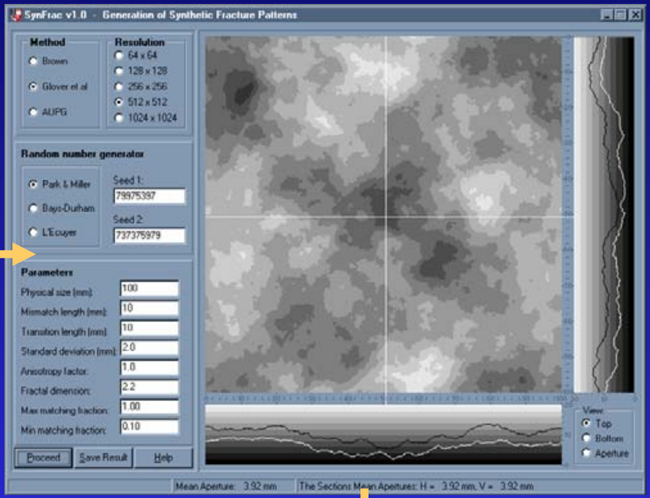
The Framework



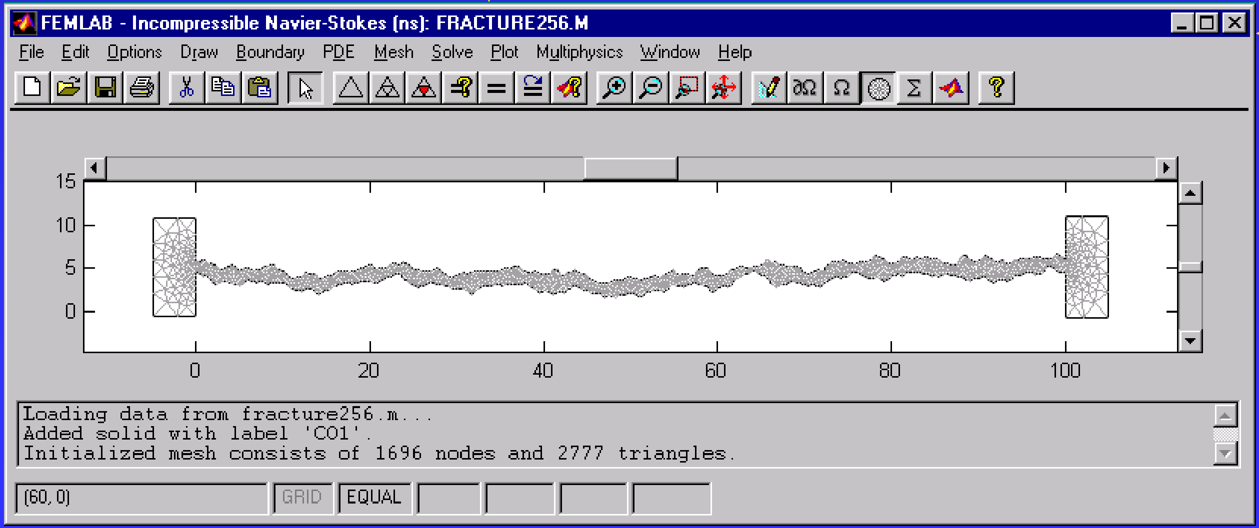
OptiProf (v.0.8)



ParaFrac (v.0.5)



SynFrac (v.1.0)



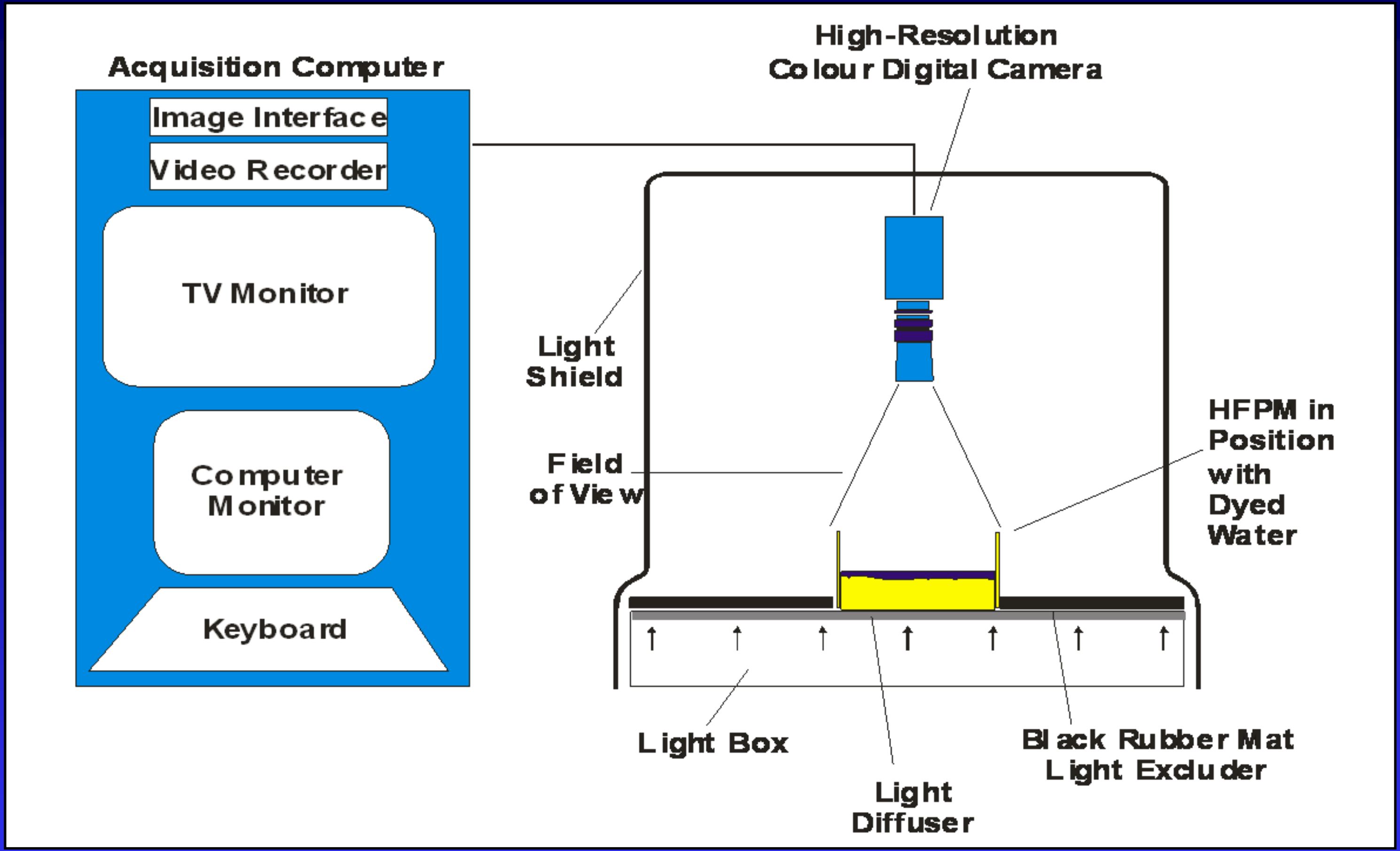
Comsol FEMLAB software for physical processes modelling

Digital Optical Imaging

Digital Optical Imaging Method

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

Camera records images directly onto TV monitor connected to a PC-based workstation.



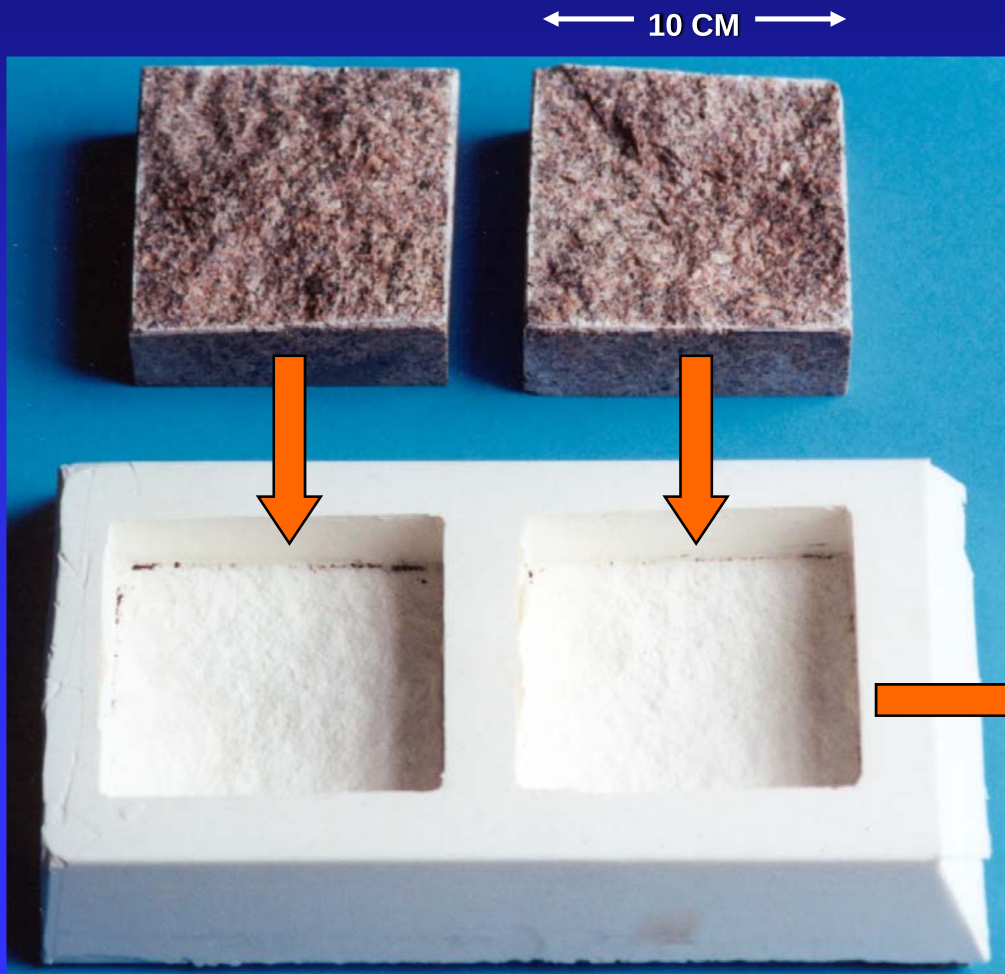
Resolution of Method:

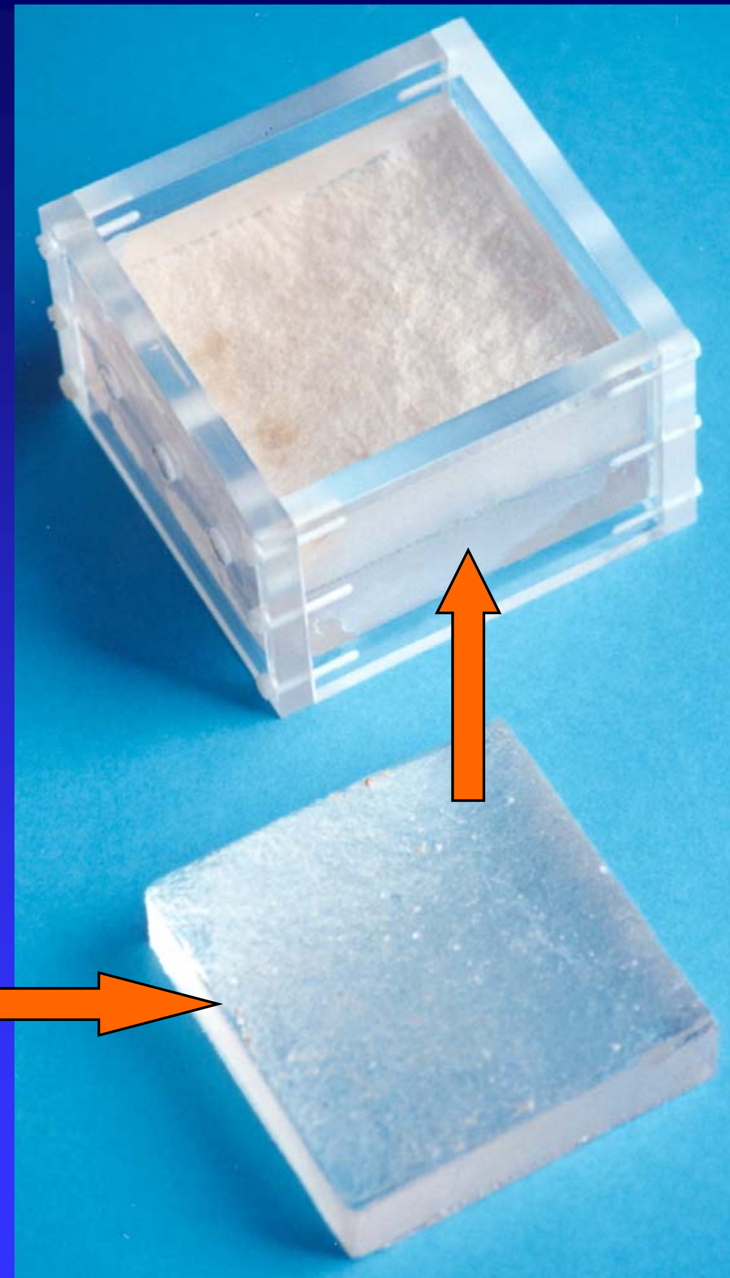
Camera pixel array: 640 x 480 (307,200 pixels)
Lateral Resolution(*xy*) 200 μm (Widest zoom: 100 x 100 mm)
Lateral resolution (*xy*) 15.6 μm (Highest zoom: 10 x 7.5 mm)
Vertical resolution (*z*) 15 μm (8-bit grey-scale depth)

High Fidelity Polymer Models of Fractures

HFPM Construction

HFPMs produced by casting from moulds of rock fractures



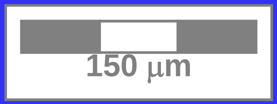


HFPM Resolution

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



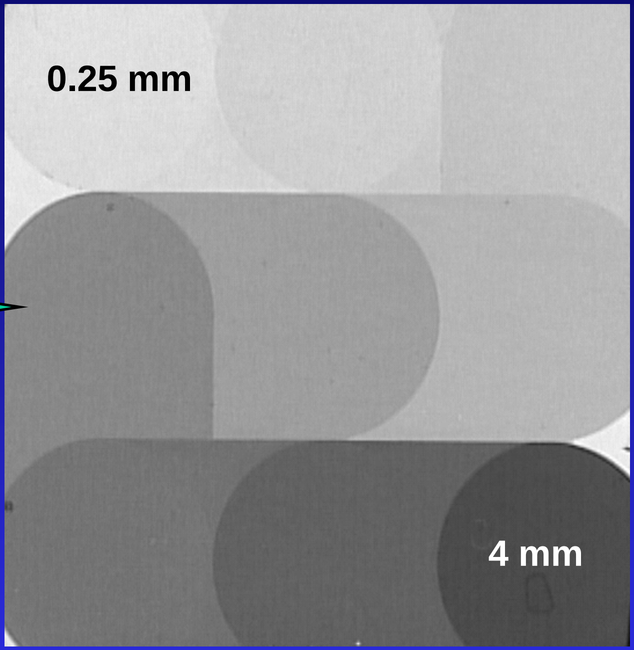
HFPM

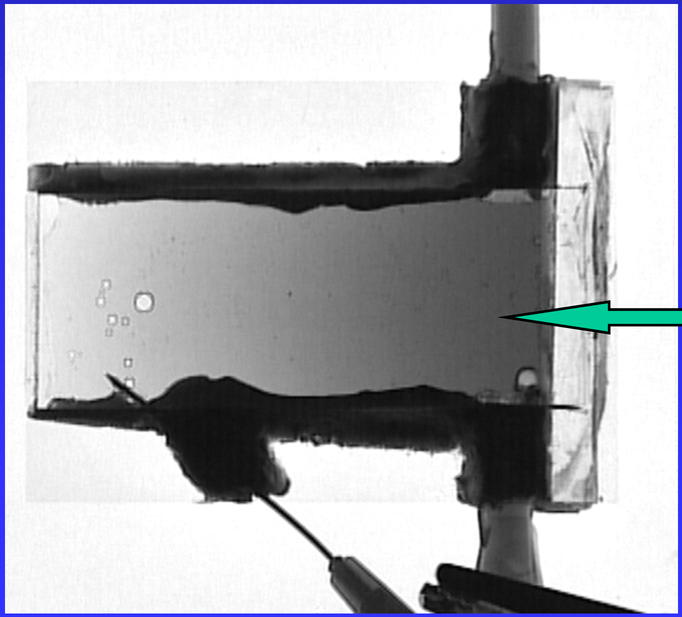
Fracture Profiling

Calibration Devices

Tile with pocket areas of known thickness filled with dye (1g/l).

Greyscale image obtained

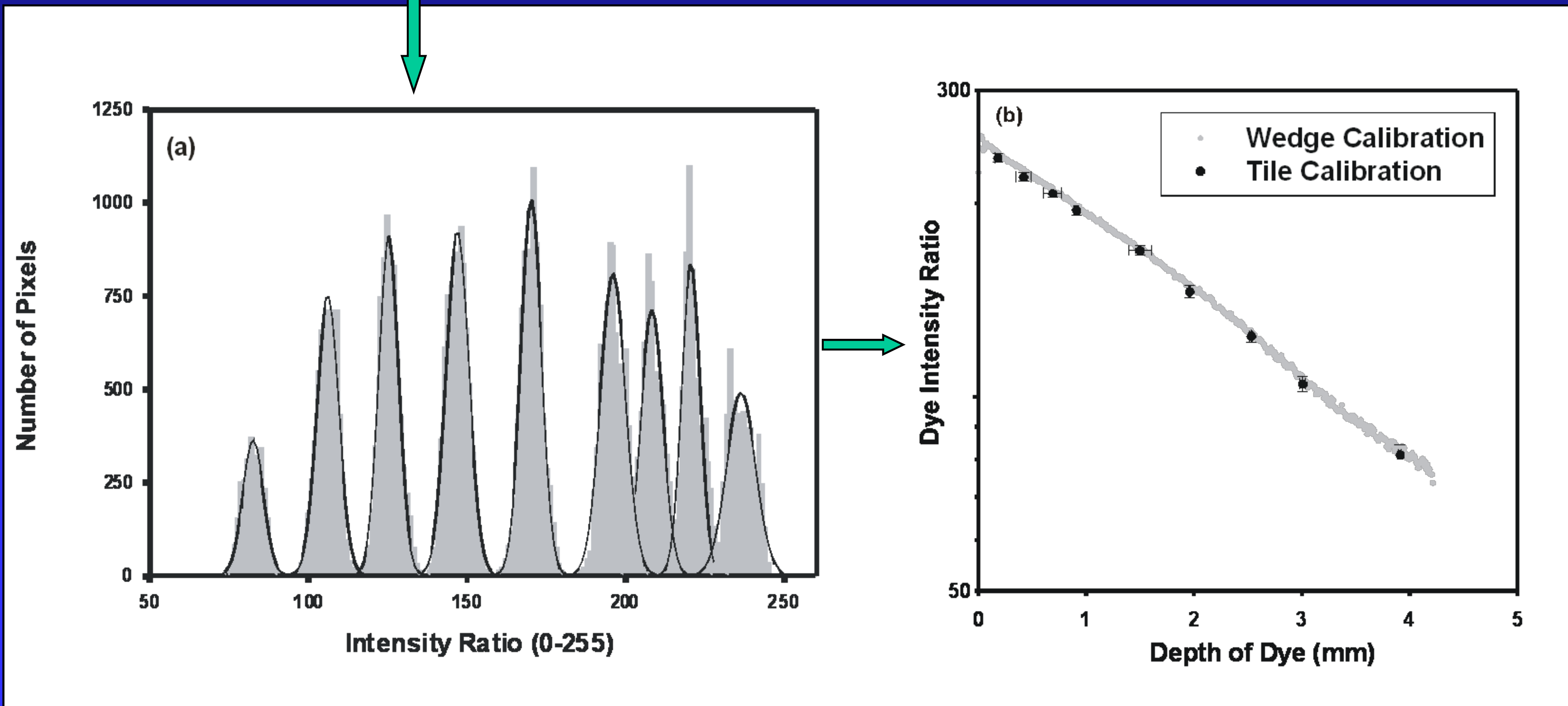




Supporting data from wedge with maximum thickness of 4.3 mm

Calibrating the Dye

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:

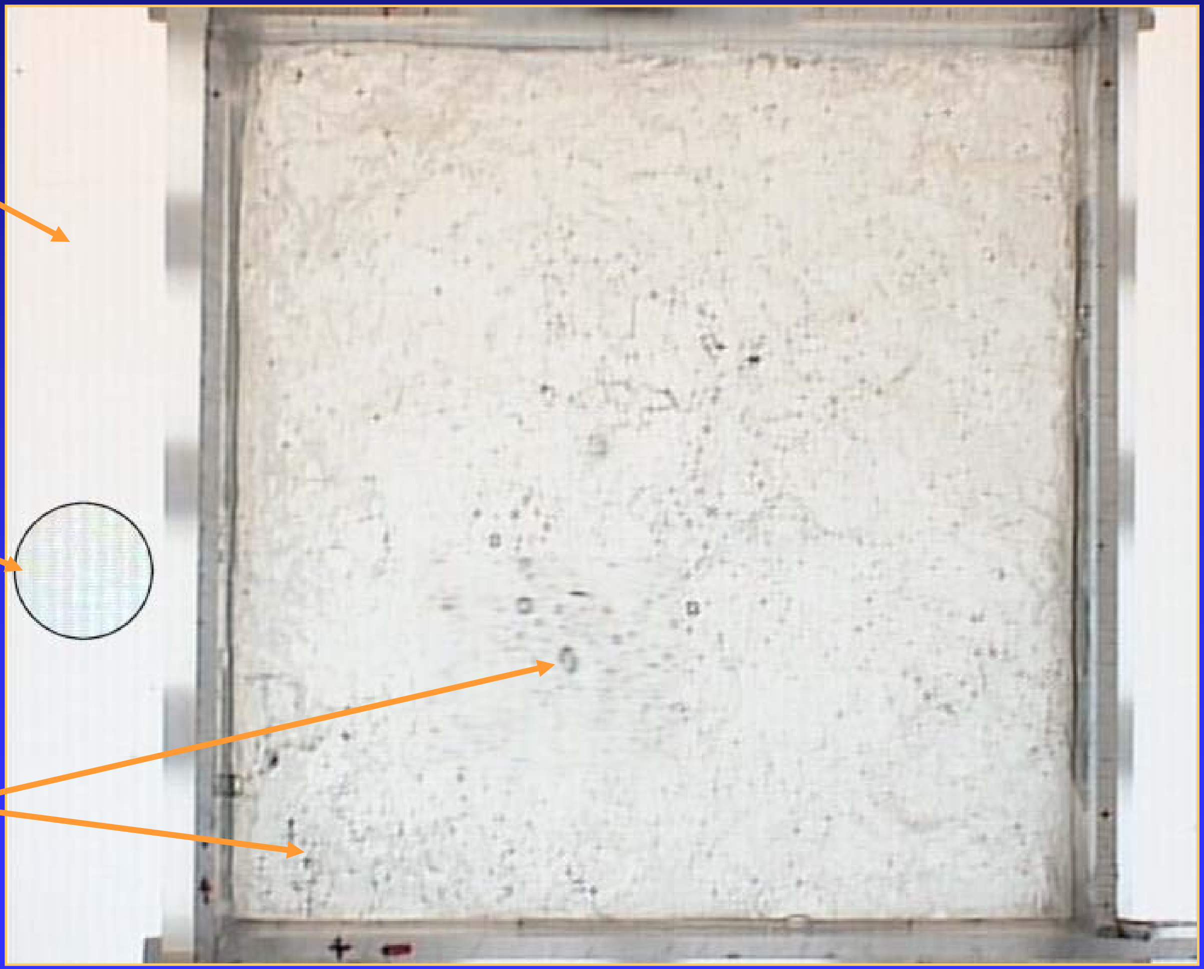
- **Cheap, does not require an expensive equipment**
- **Fast (relatively), whole fracture surface to be scanned simultaneously**
- **High *xyz* resolution**

Technical Reality

Non-uniform backlight

Video channel distortions:
Coarse structures
CCD noise

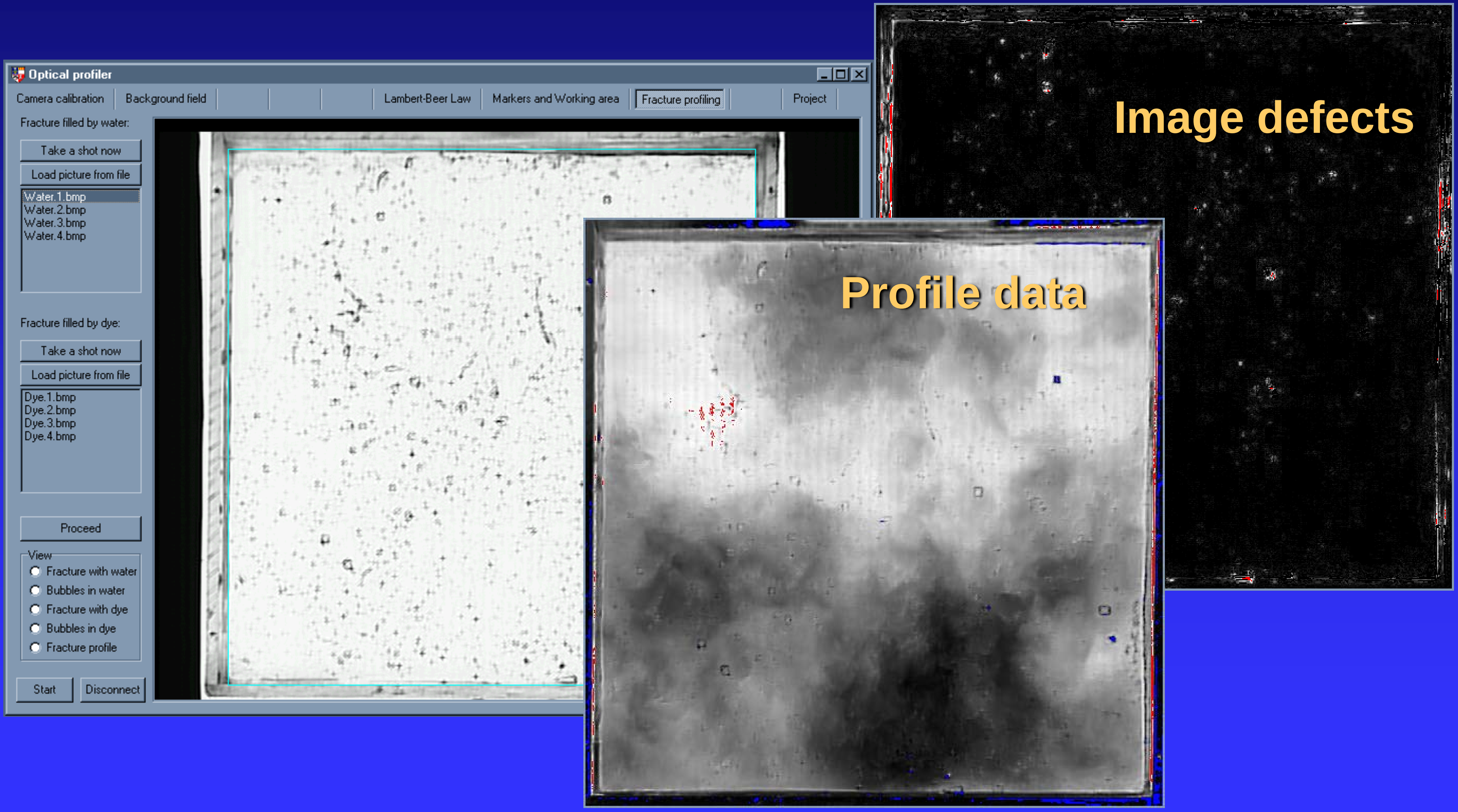
Bubbles and particles in the liquid (water or dye)



Profiling Methodology

- Individual calibration of the pixels of CCD matrix
- Stacked images to be taken with further averaging to neglect the camera noise
- Clearfield equalisation
- Comparison of several images allow to recognize effectively bubbles and particles in liquid
- The methodology is implemented as a software algorithm

Profiling Software



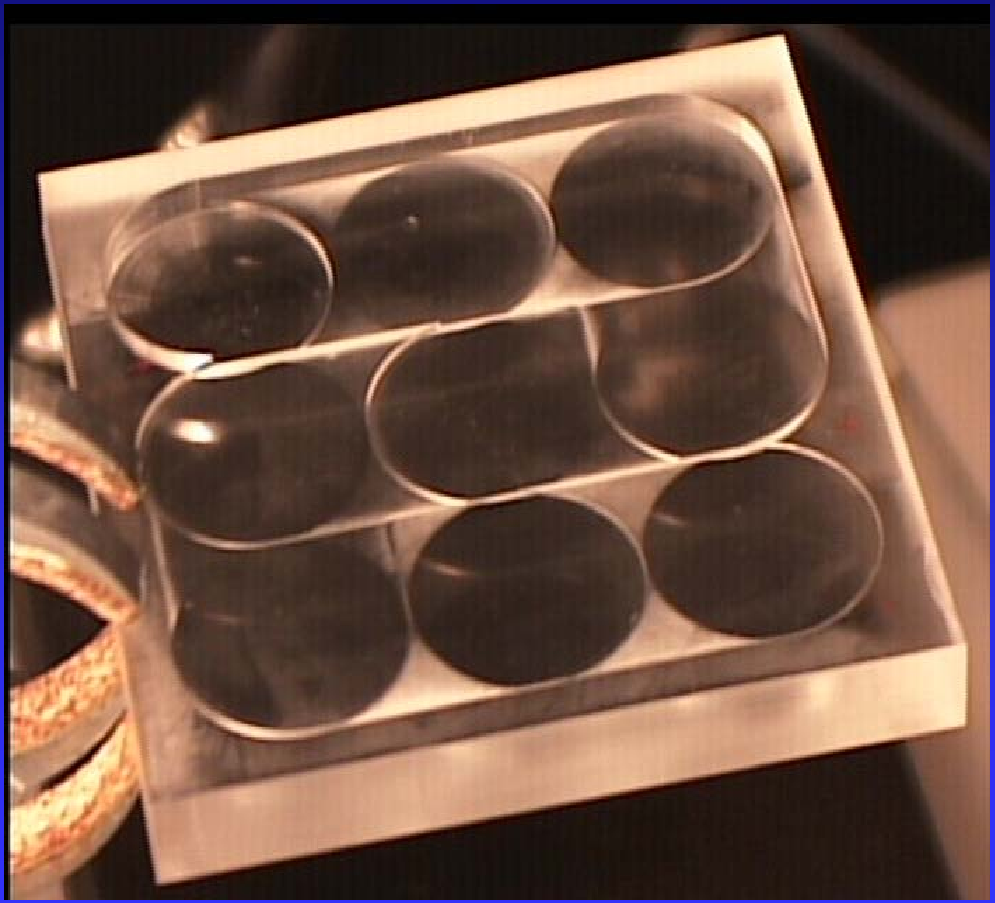
Automatic Defect Recognition

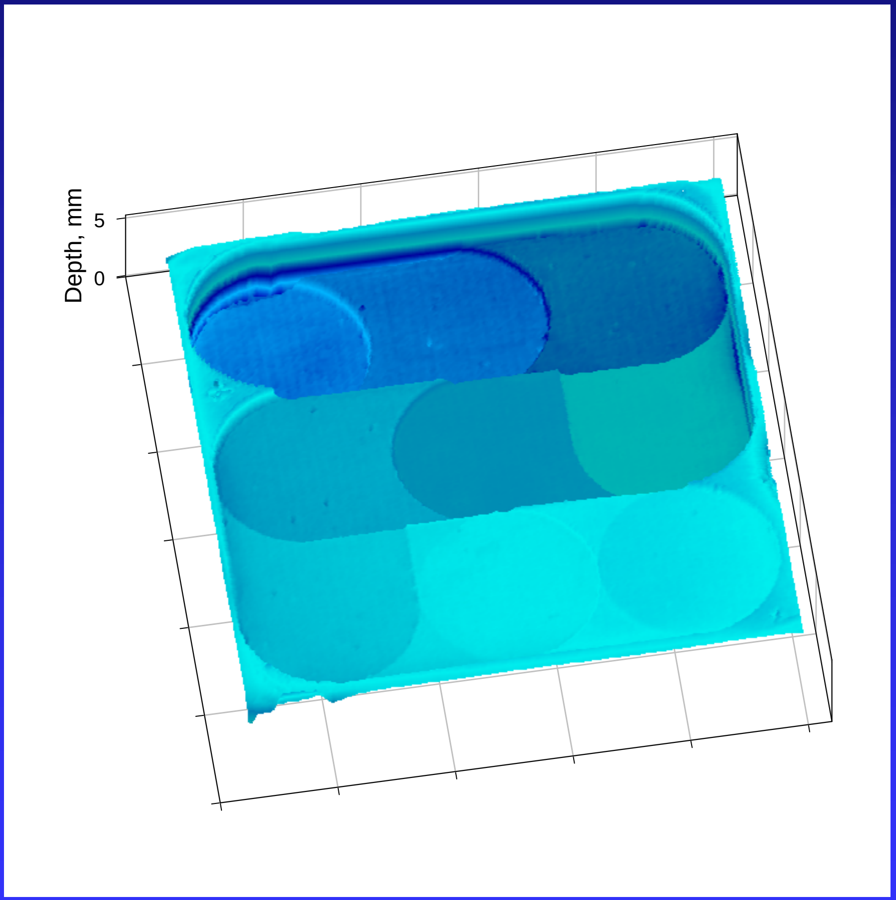
3 of >10

Resulting image

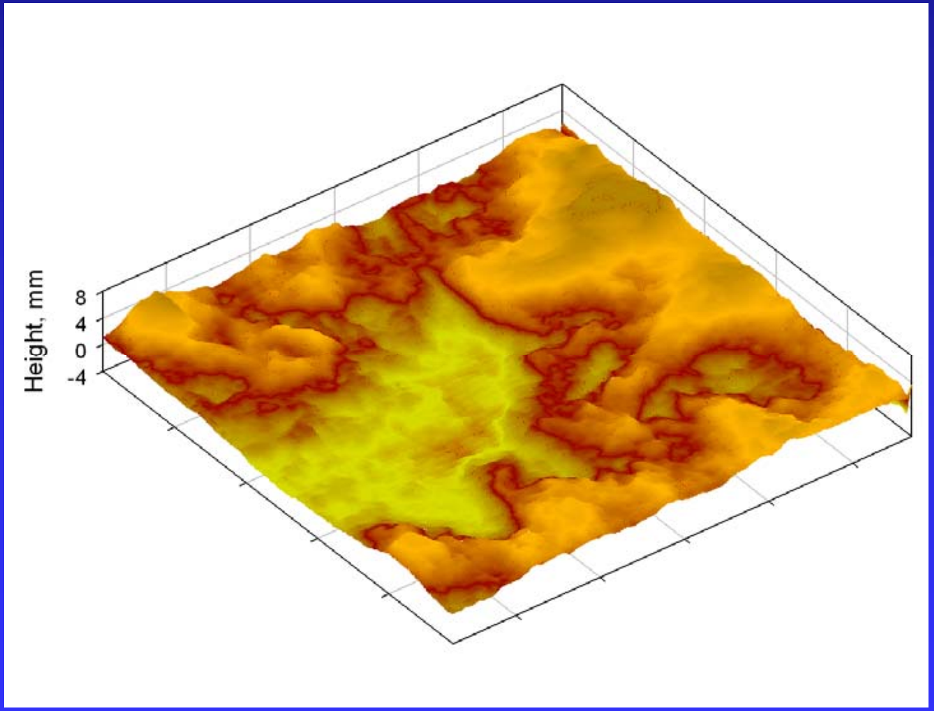
Defects map

Sample of Profiling Result



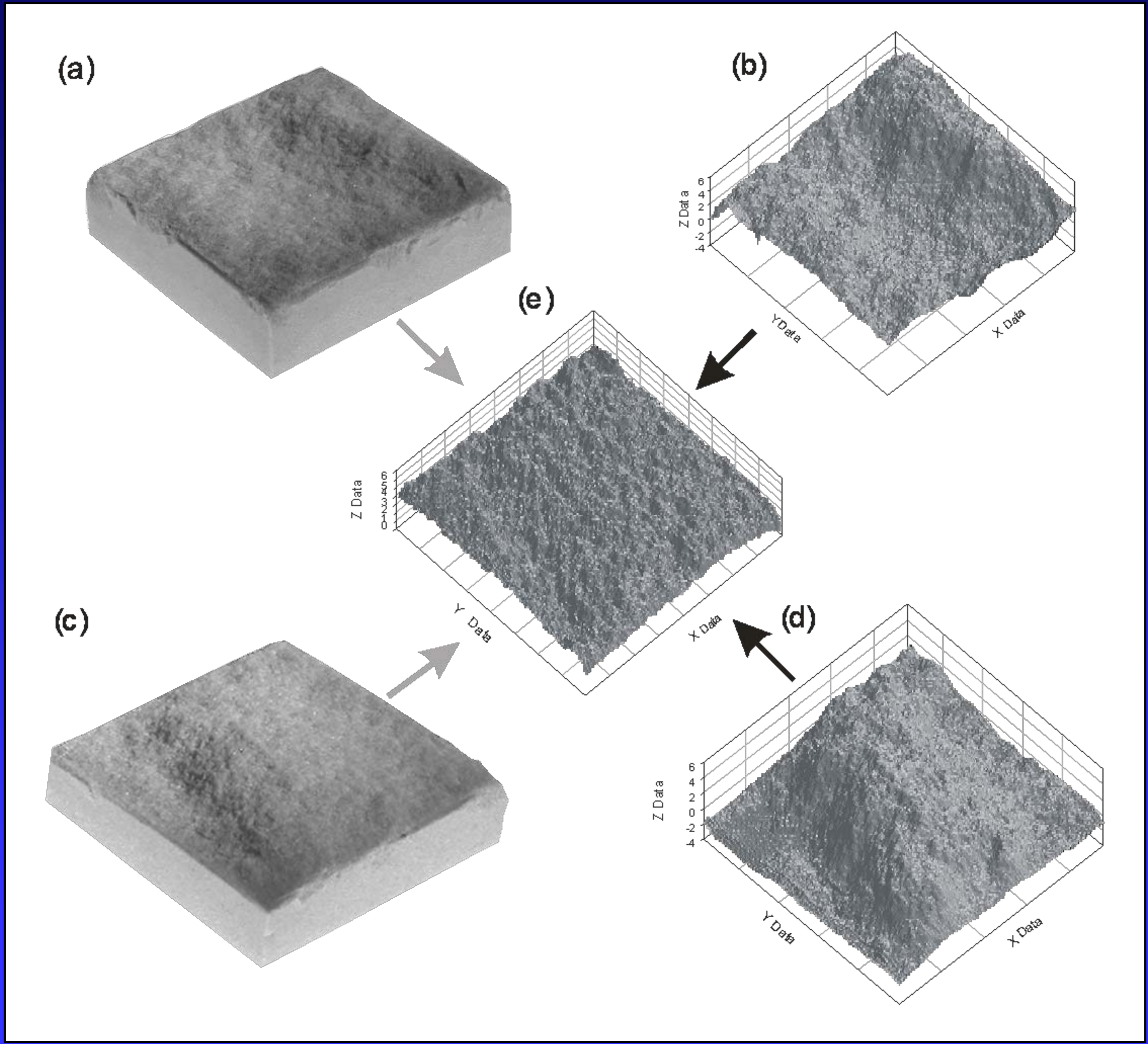


Profiling Sample: Pearly Granite

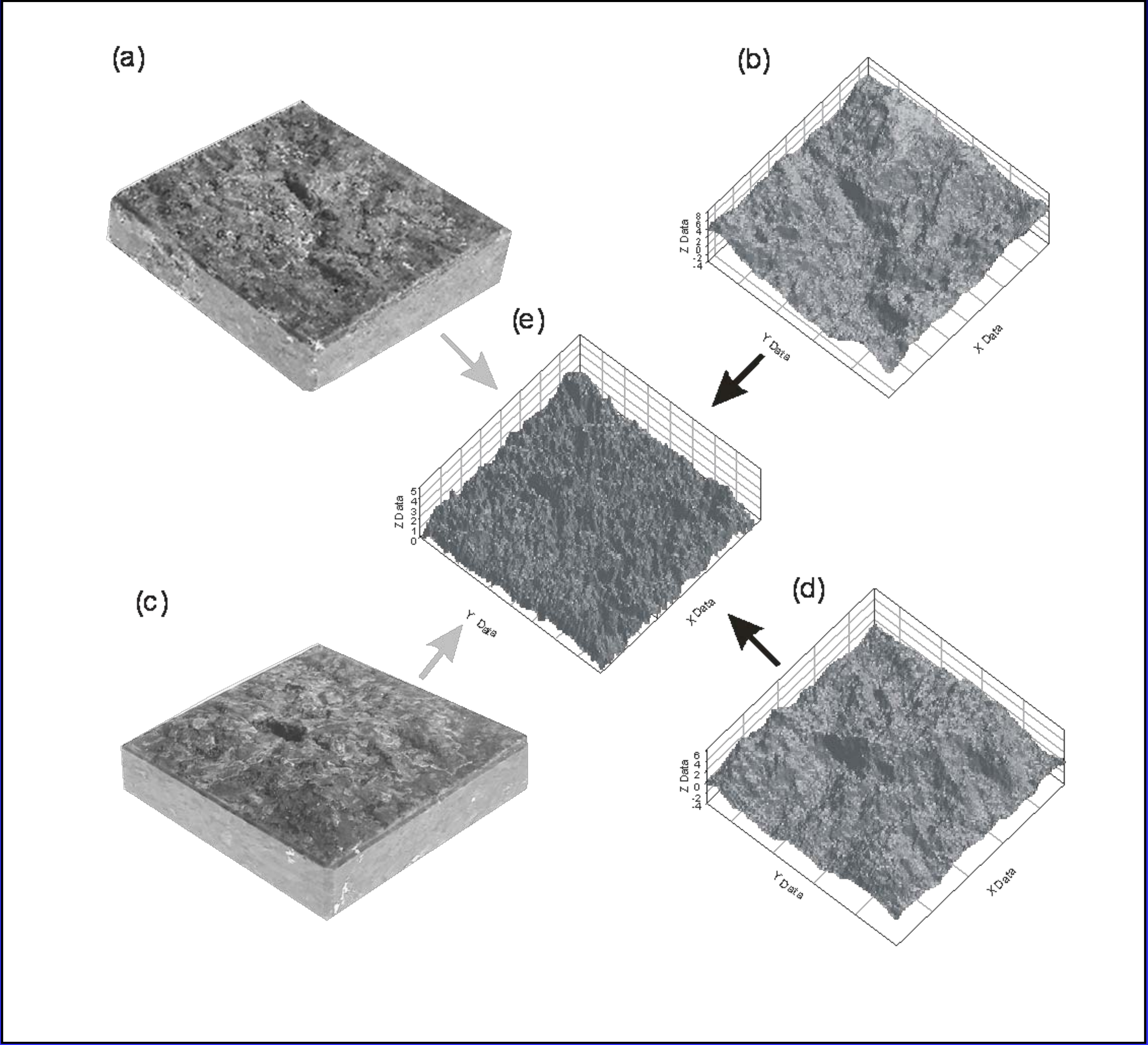


Fracture Profiles & Aperture Maps

Sandstone

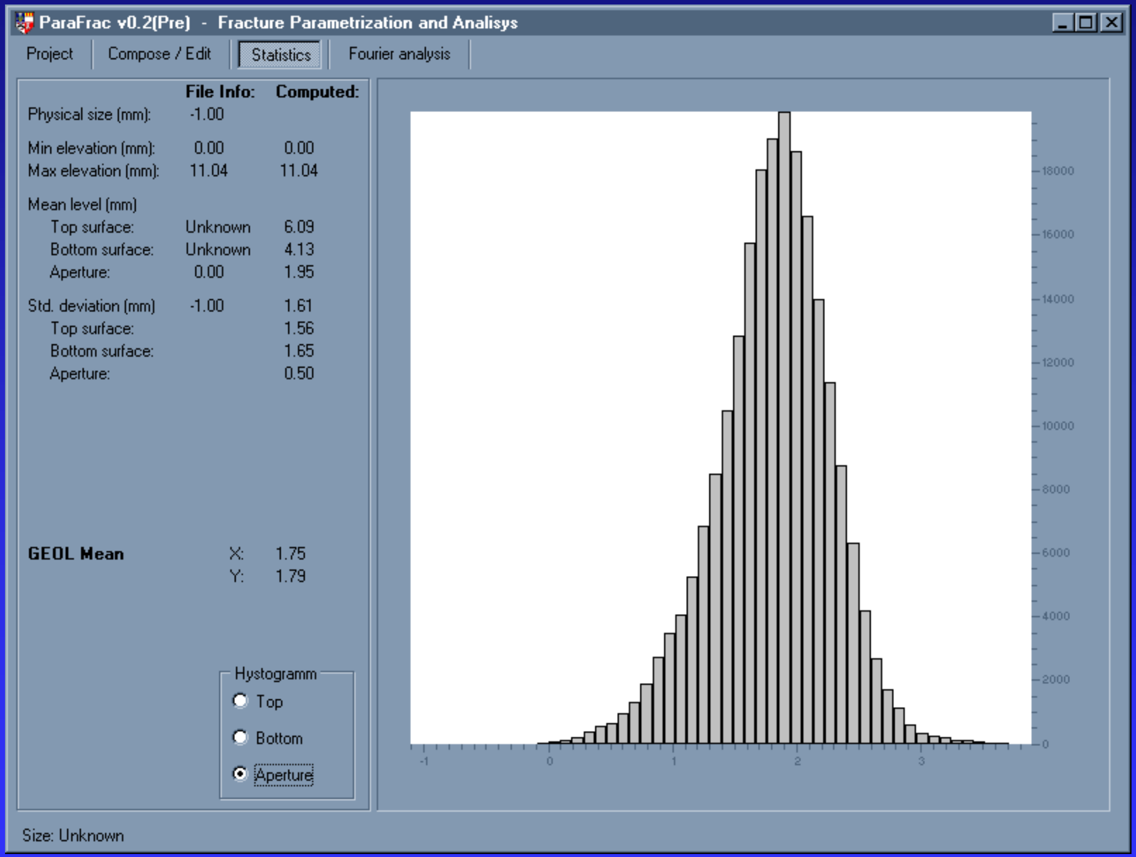


Granite



Fracture Characterisation & Synthetic Fractures

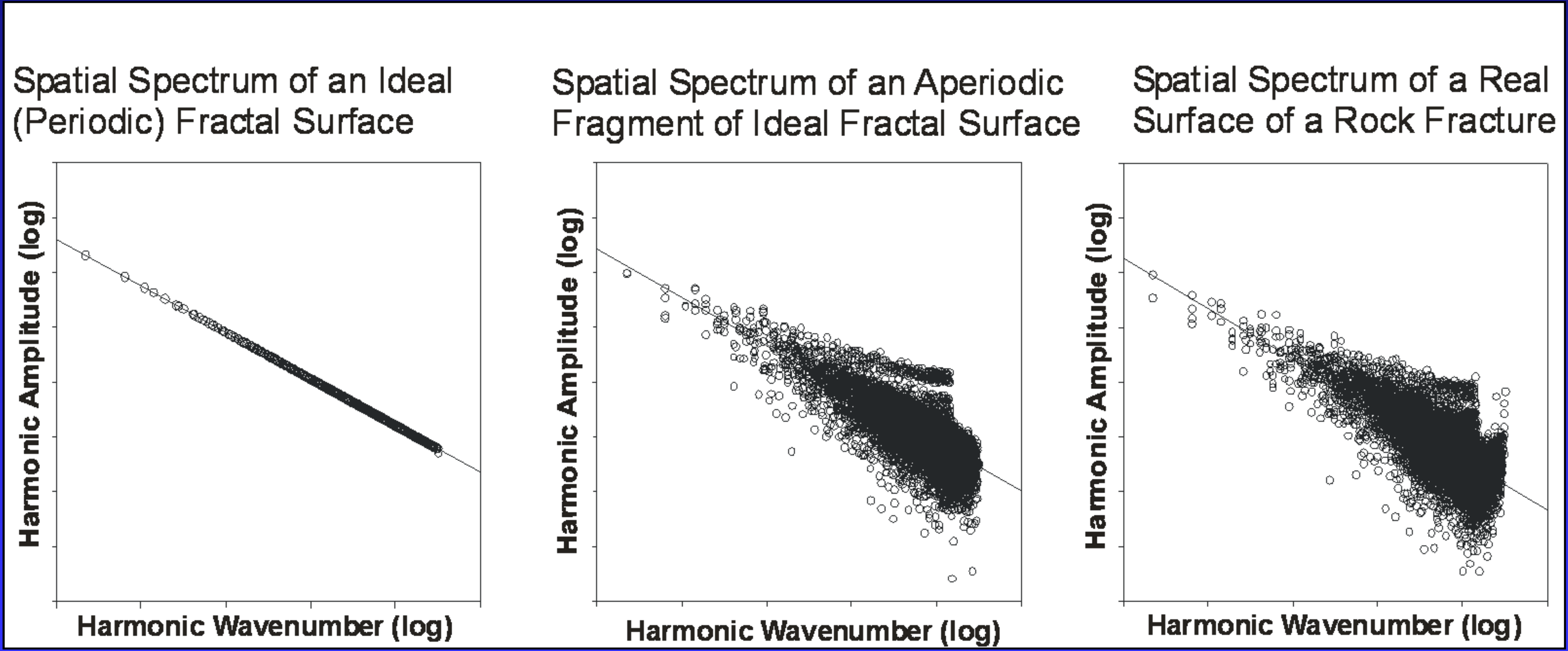
Fracture Parameterisation



- Statistical Analysis
- Spectral Analysis
- Fractal Analysis
- Correlative Analysis

Set of Fracture Parameters

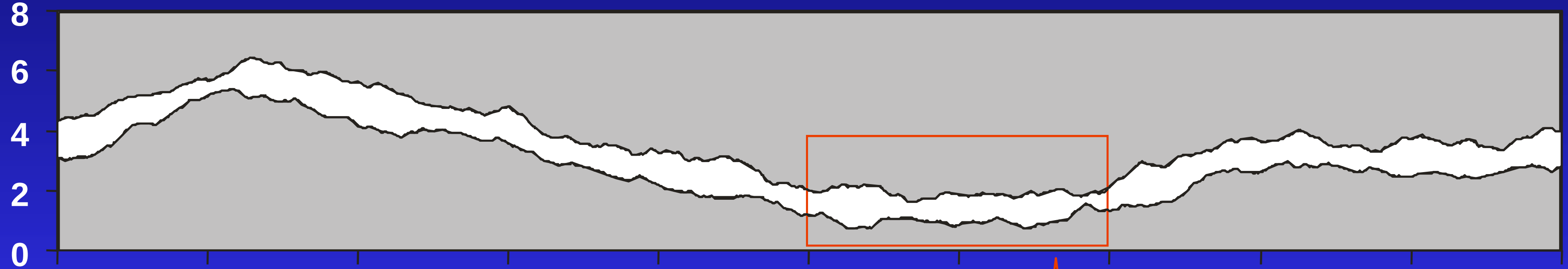
Fractal Spectrum Analysis



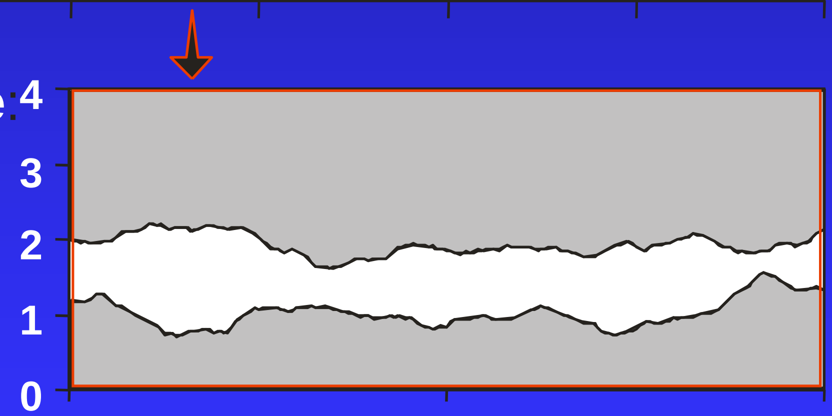
Numerical Synthesis of Fractures

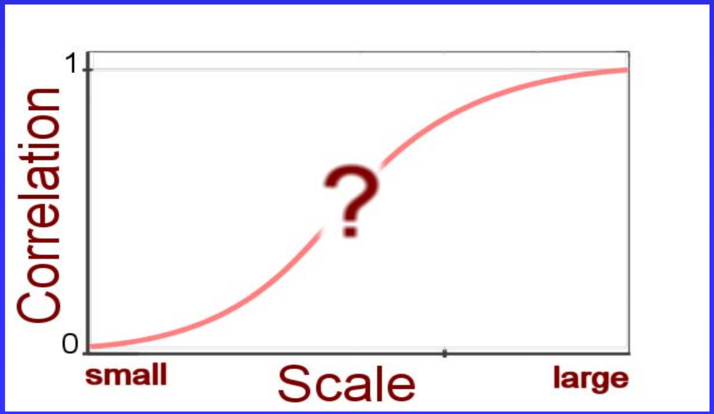
- **Fractal synthesis is used to generate fracture surfaces**

Fracture surfaces match at macroscale:

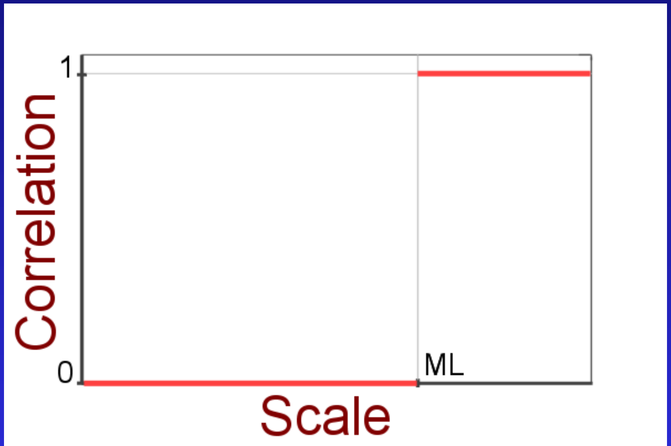


…And relatively independent at microscale:

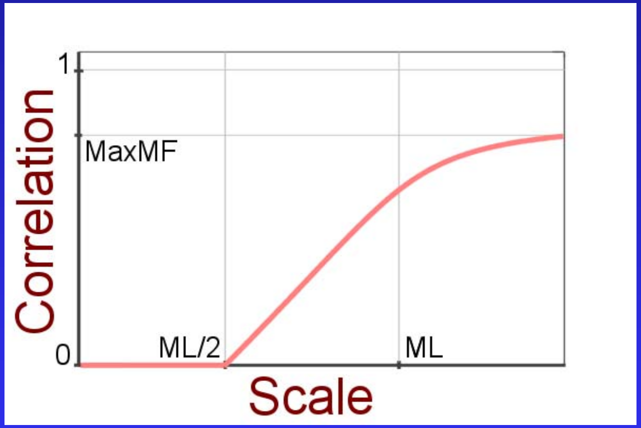




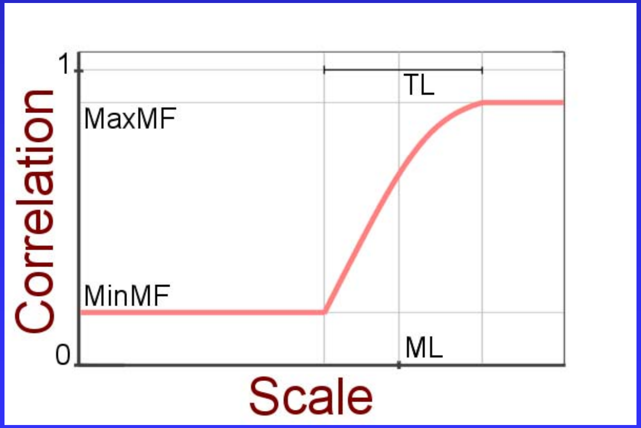
Synthesis Methods



Brown (1995)

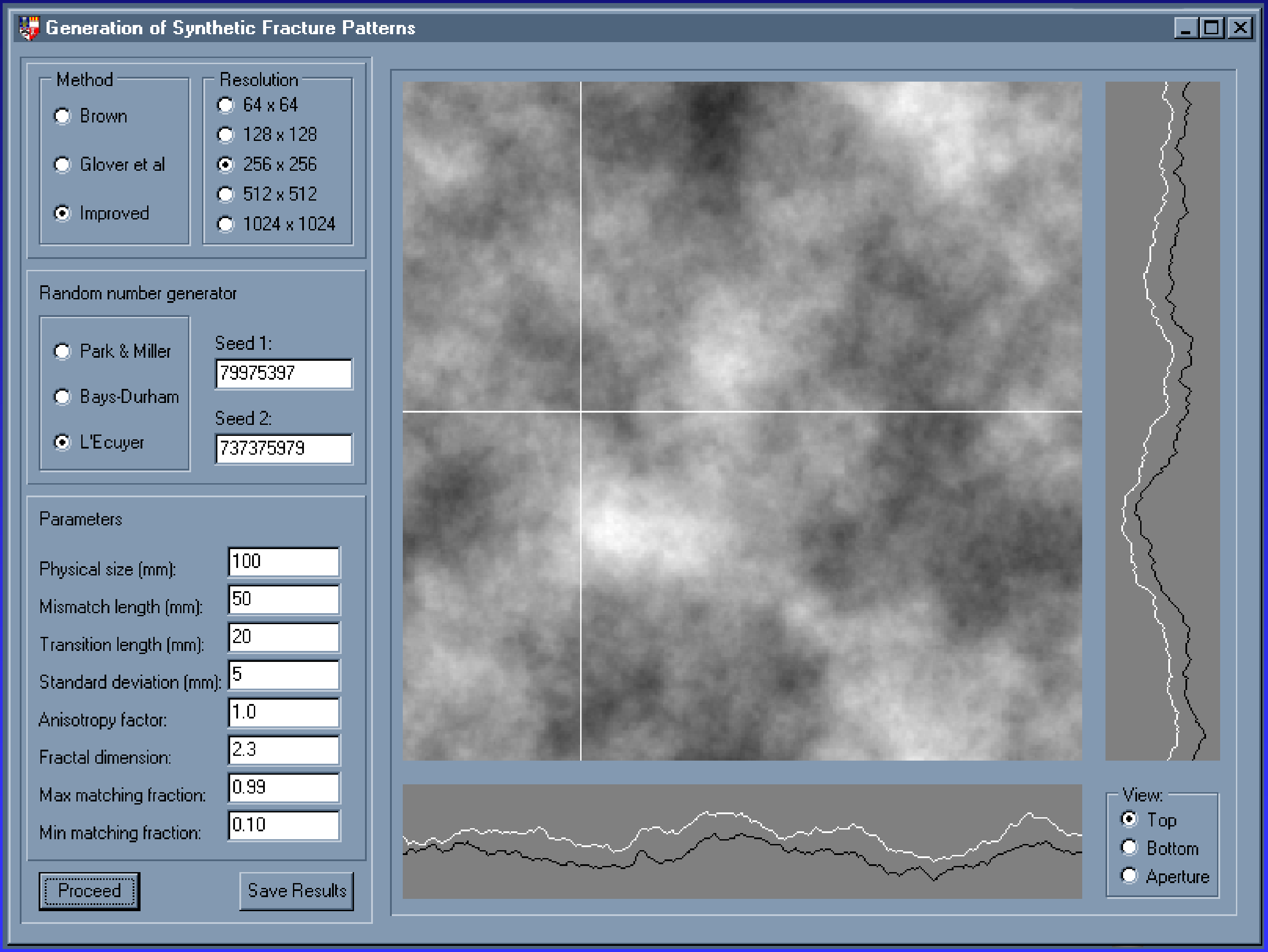


Glover *et al.* (1998)

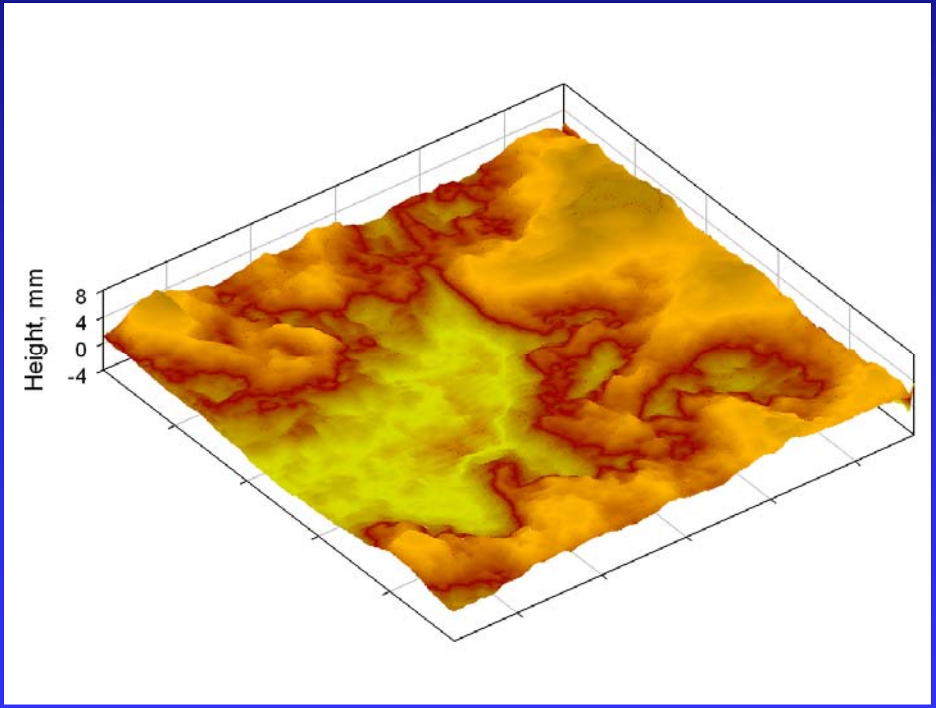


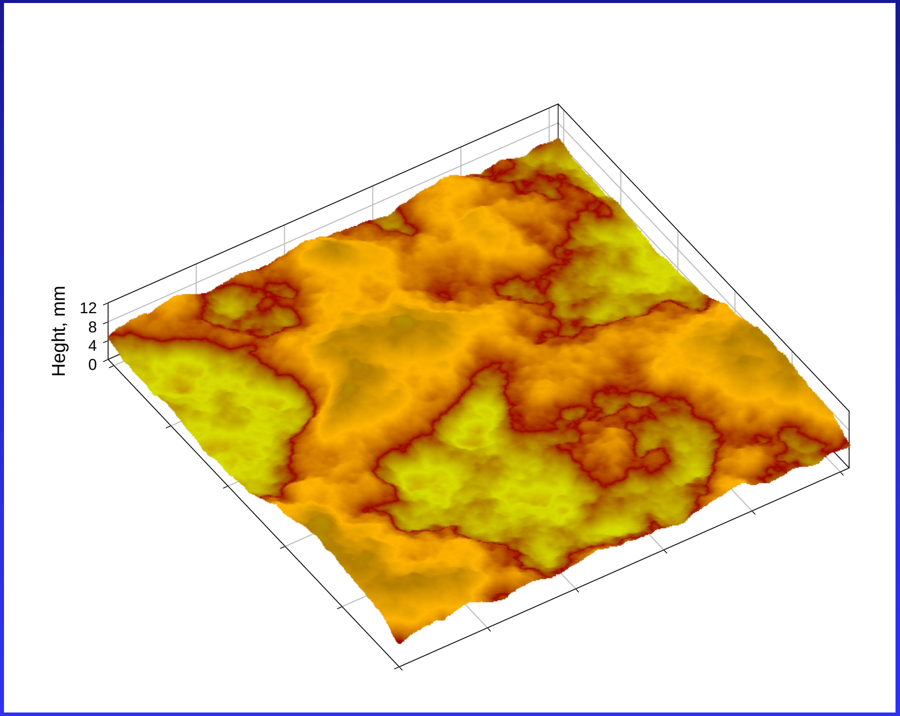
Present method

Software for Numerical Synthesis



Result of Numerical Synthesis

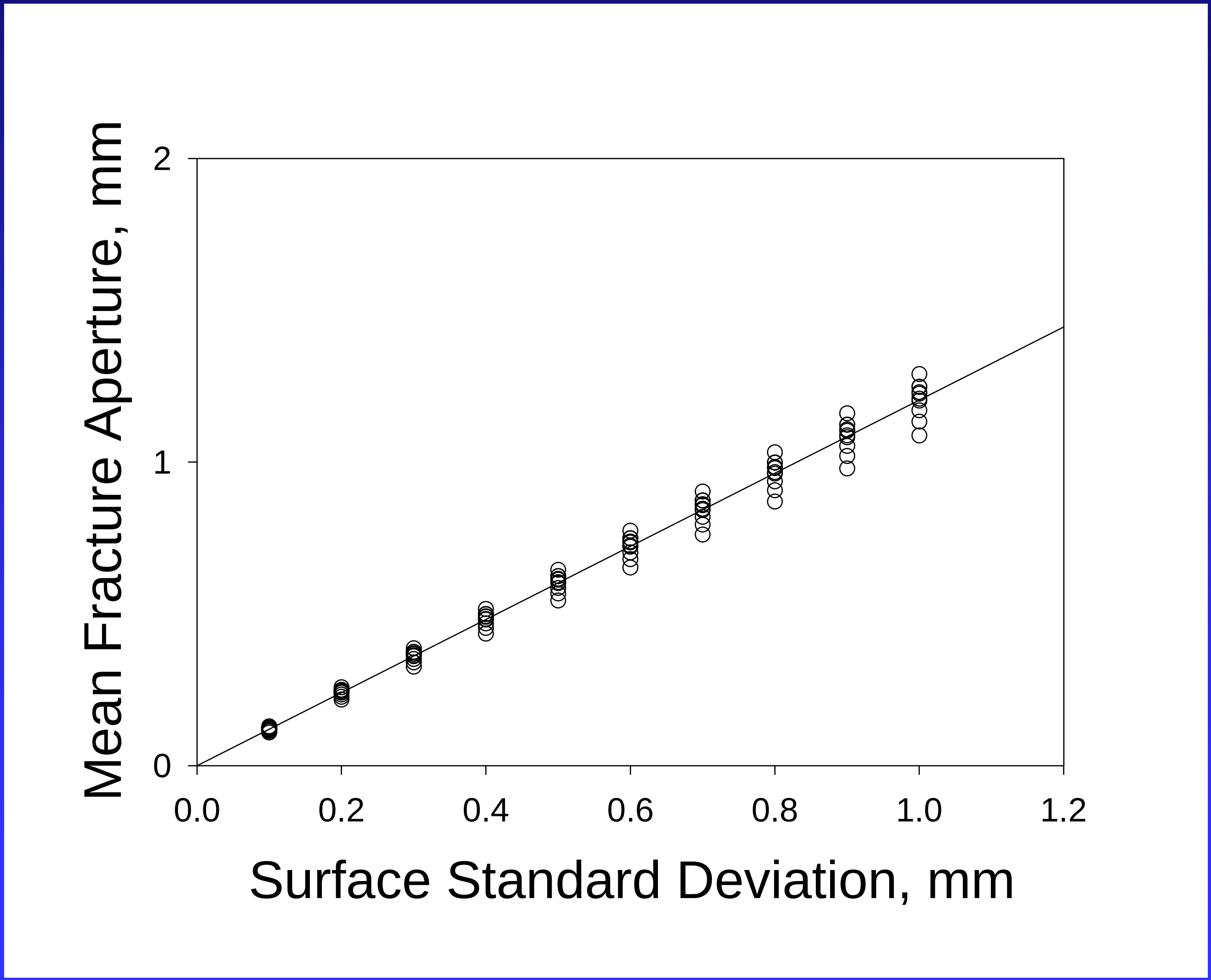




Granite fracture surface **Synthesized fracture surface**

Analysis of Synthetic Fracture Apertures

Surface Asperity Heights



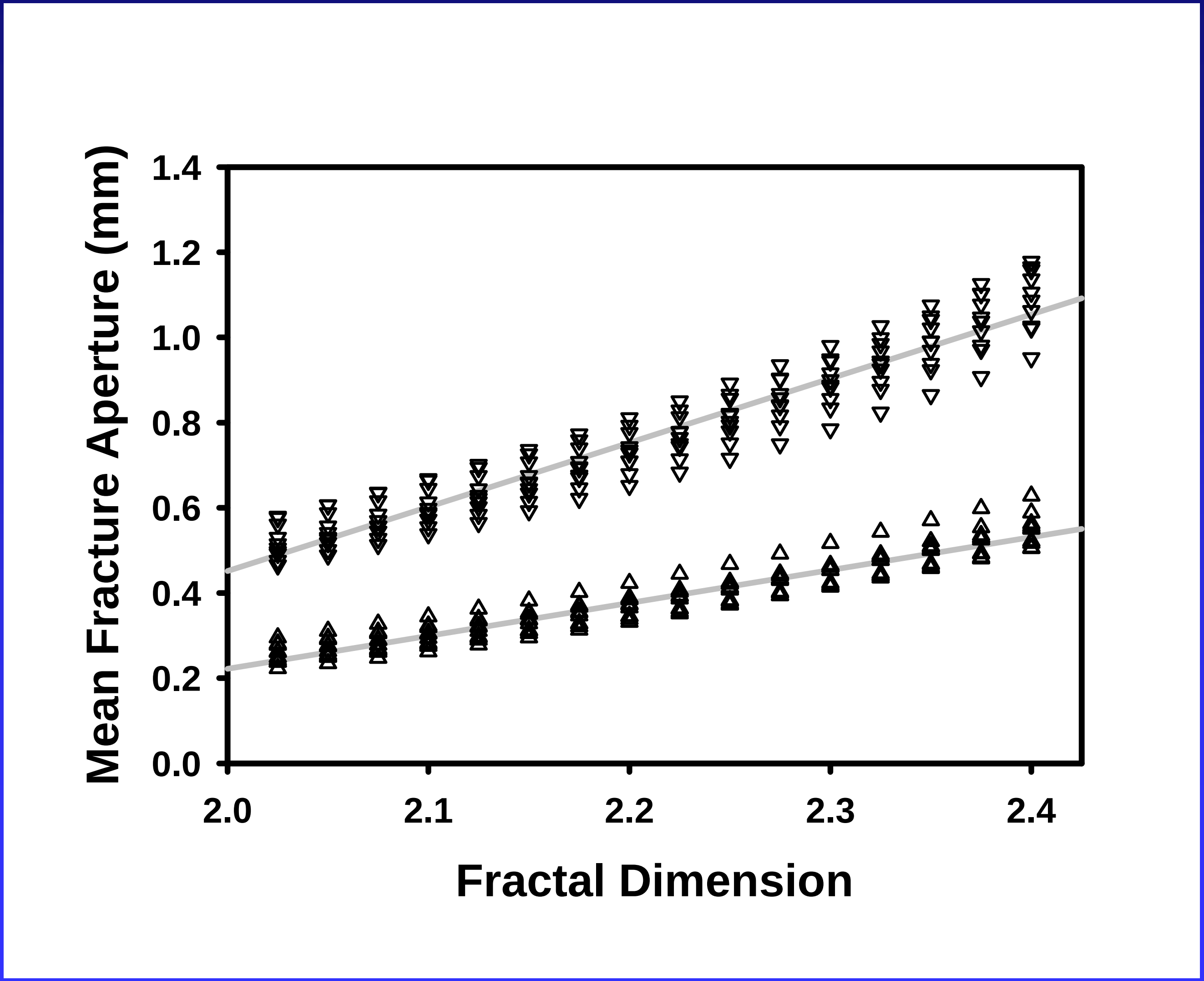
Method: AUPG

ML = 10 mm

TL = 20 mm

FD = 2.2

Fractal Dimension



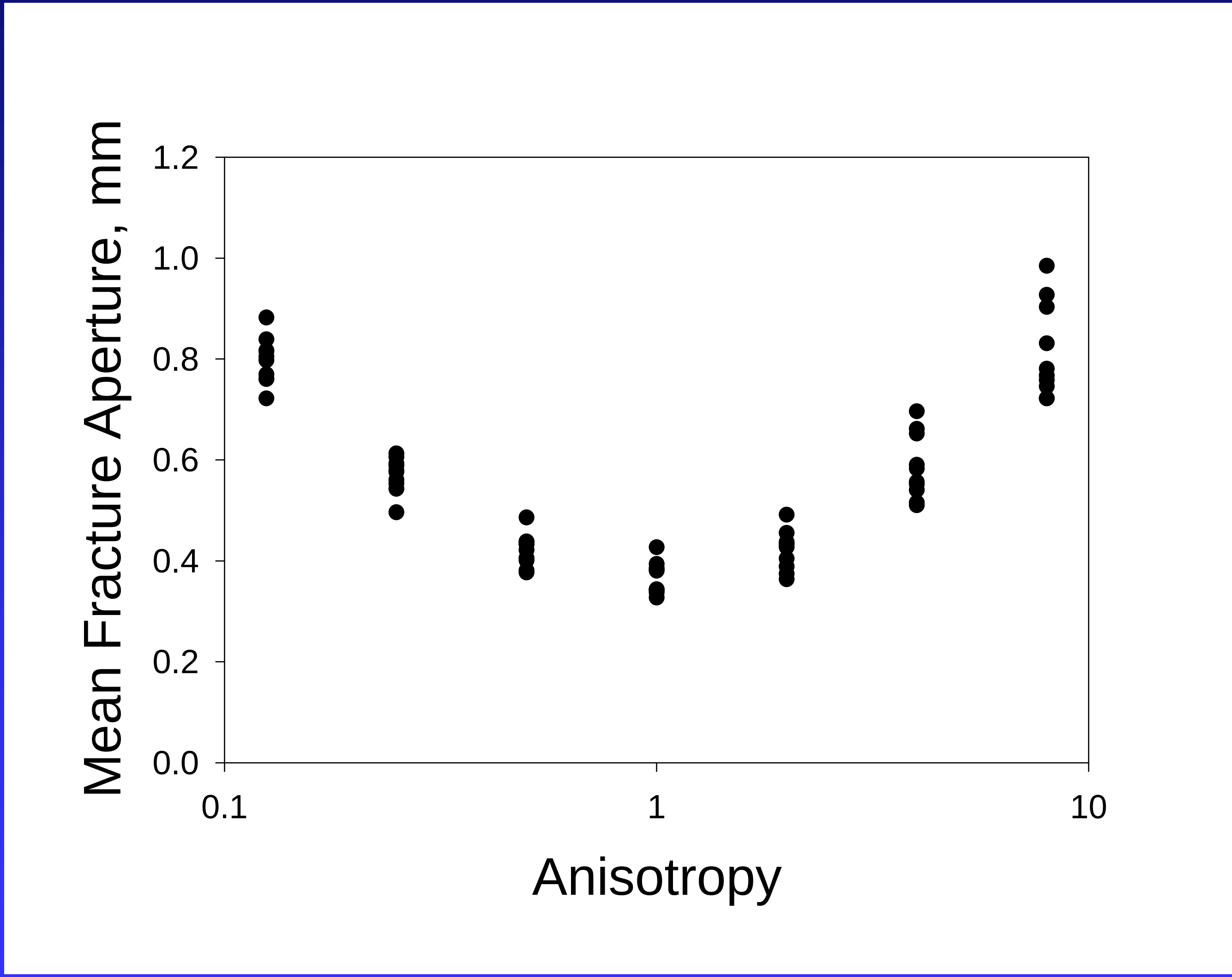
Method: AUPG

ML = 10 mm

TL = 20 mm

StD = 0.3; 0.6 mm

Surface Anisotropy



Method: AUPG

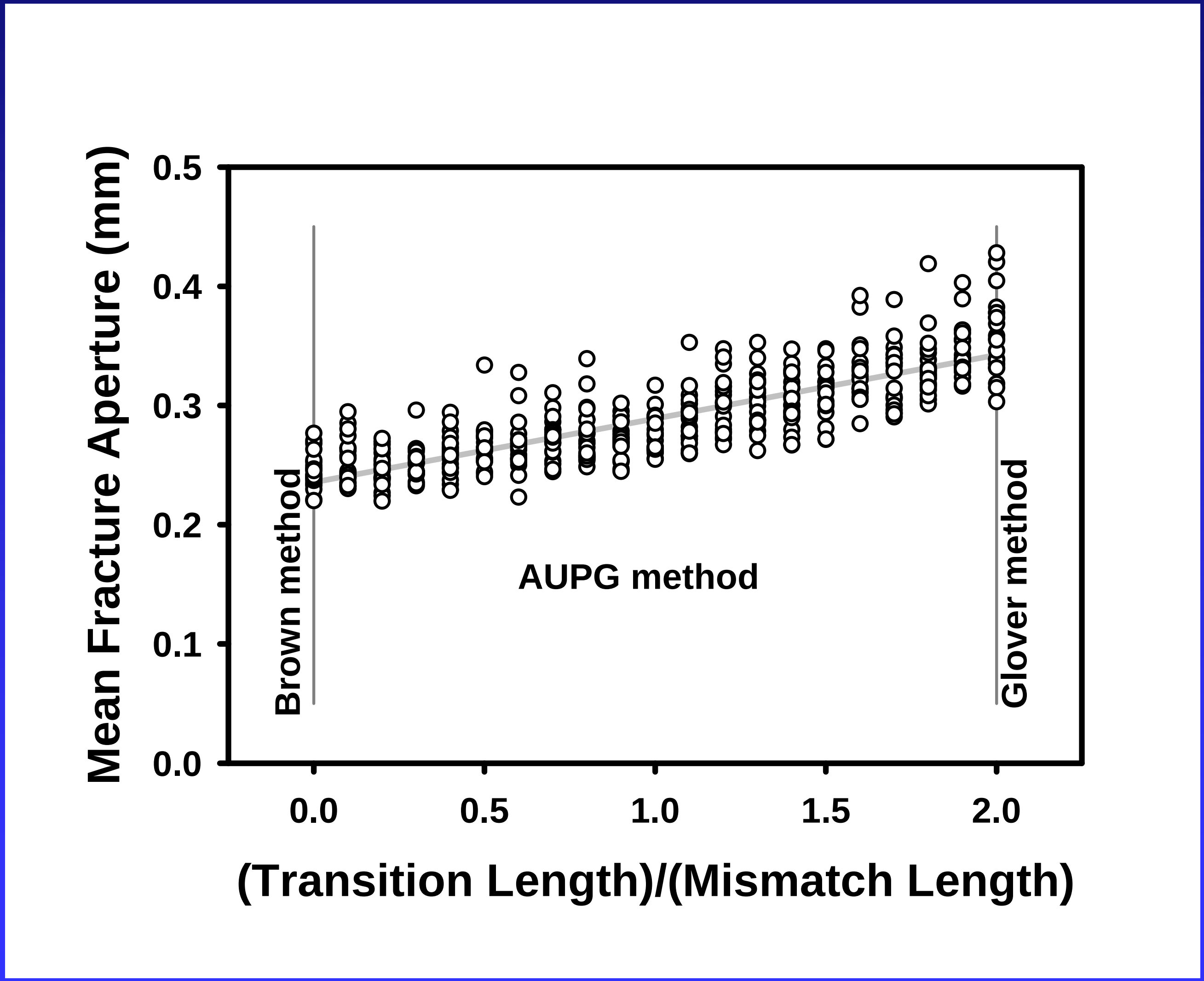
ML = 10 mm

TL = 20 mm

StD = 0.3 mm

FD = 2.2

Comparison of Different Methods



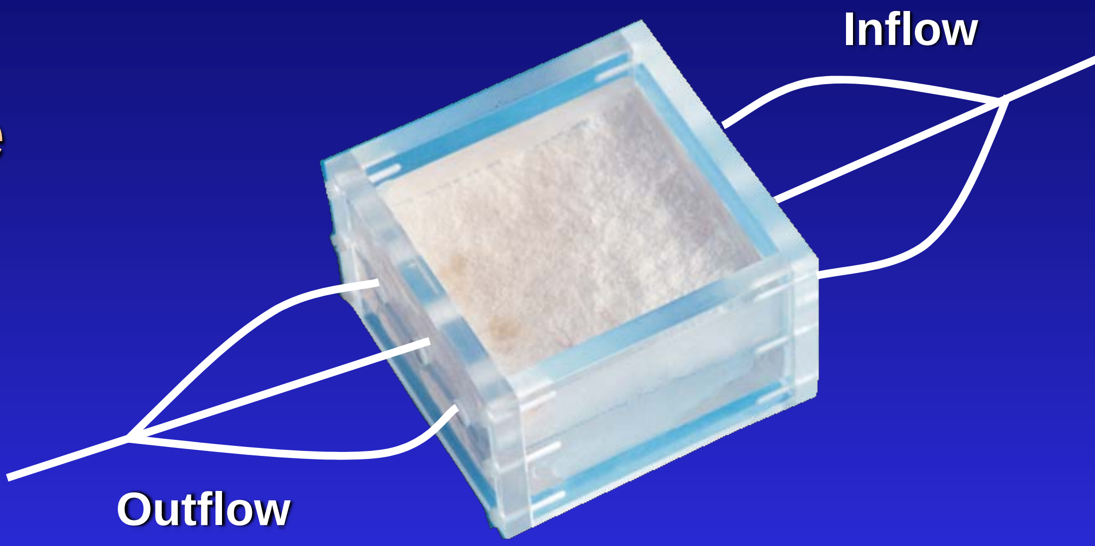
Flow Measurements

Flow Conditions

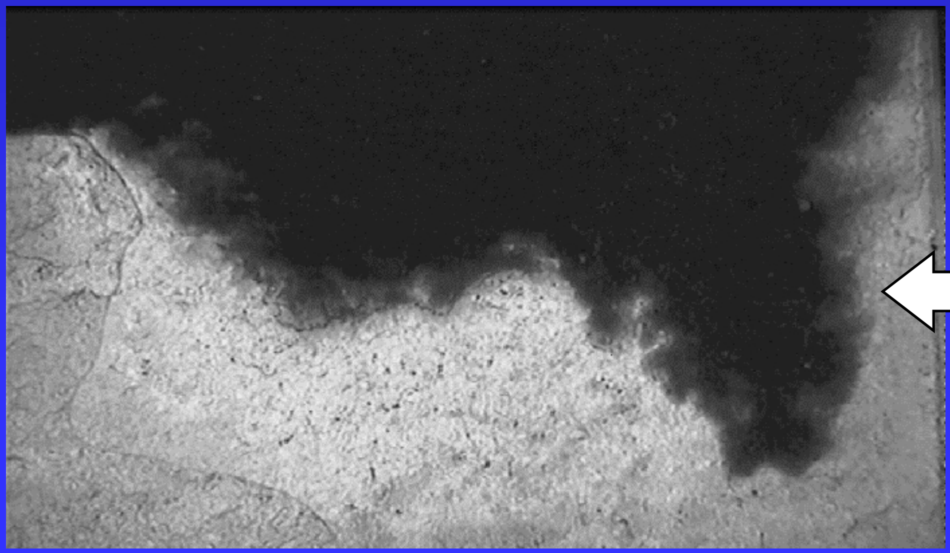
- HFPM cleaned with detergent & dried using compressed air
- Black dye (5g/l) pumped through HFPM using peristaltic pump
- Also performed at 90º to original HFPM
- Variable flow rates, fluid viscosities & densities
- Pressure gradient set-up across HFPM

Fluid Flow through Rough Fracture

Fracture surface halves are mated and secured in a fluid - flow rig



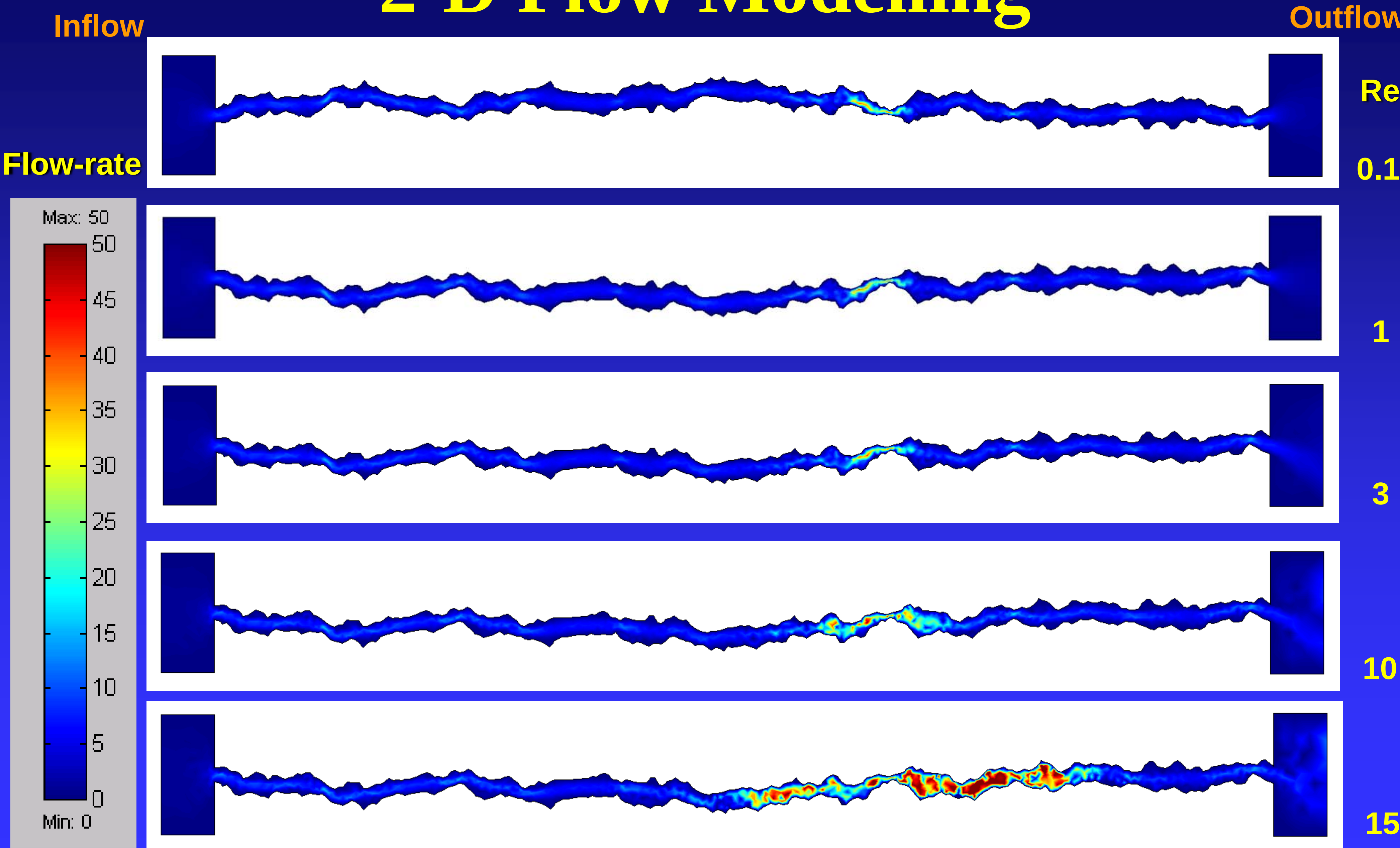
Flow manifolds at input & output ports

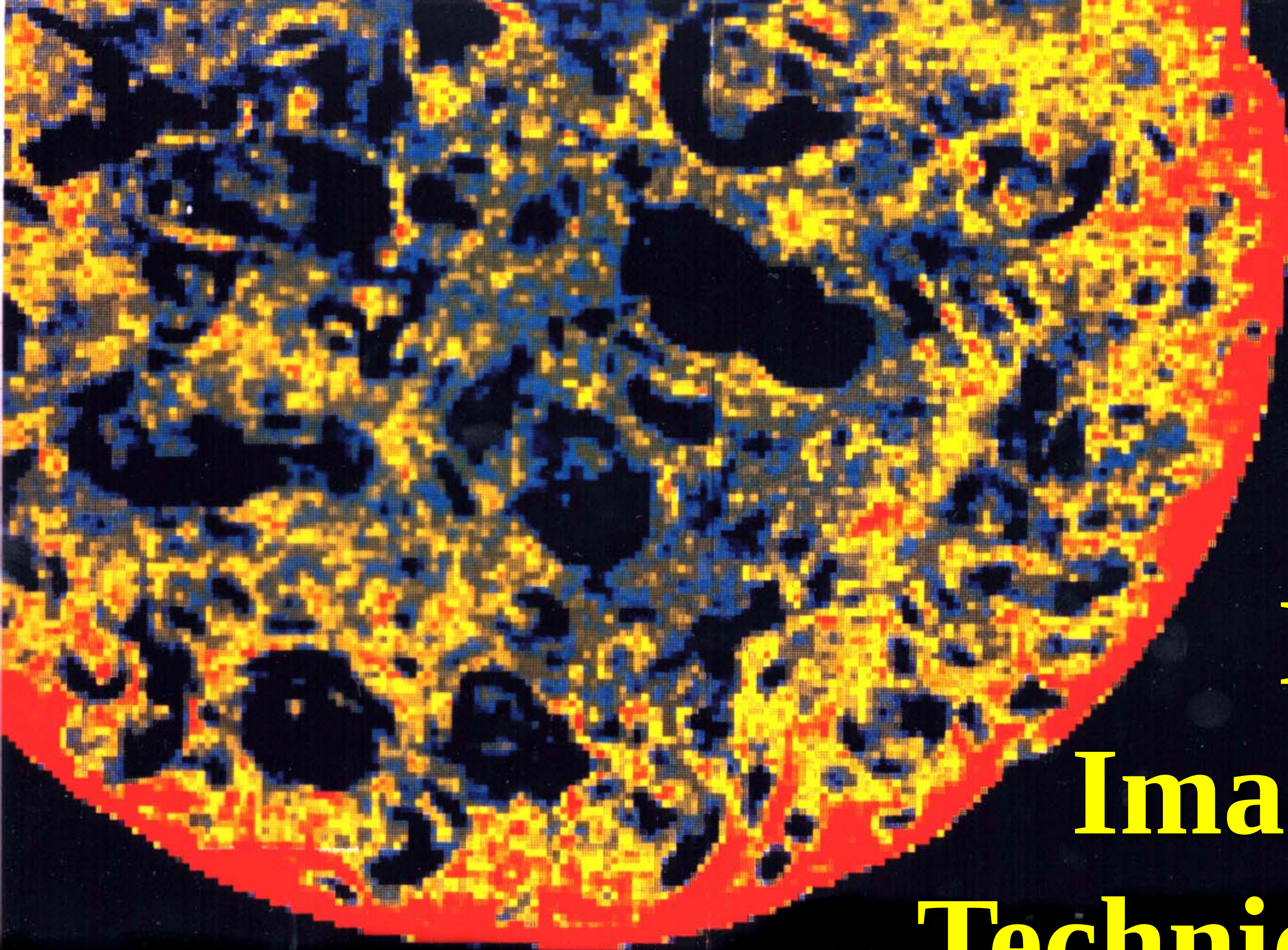


Clear water is replaced by dyed water in the flow through a rough fracture

Flow Modelling

2-D Flow Modelling





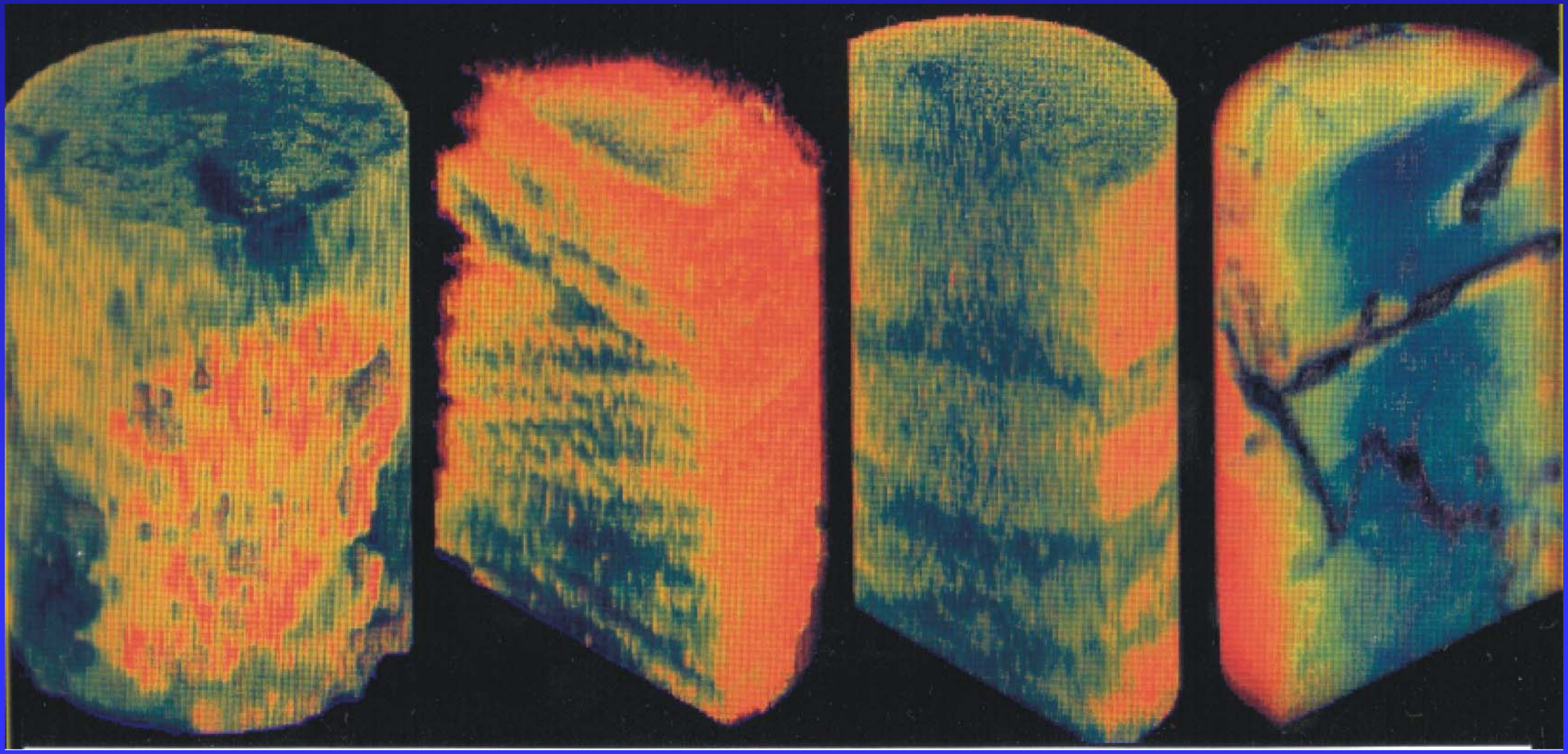
New Imaging Techniques

Novel Techniques

- DOI Imaging
- CT Scanning
- NMR Measurements
- PDPK Imaging
- PET Imaging
- Image Analysis

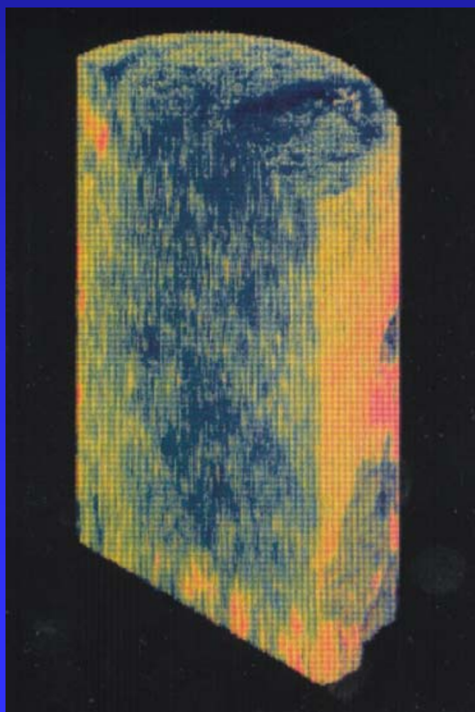
CT Scans

- **Rock Structure**

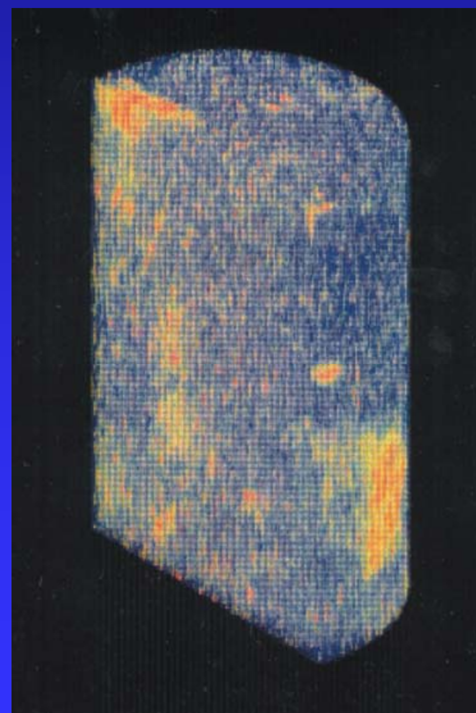


CT Scans

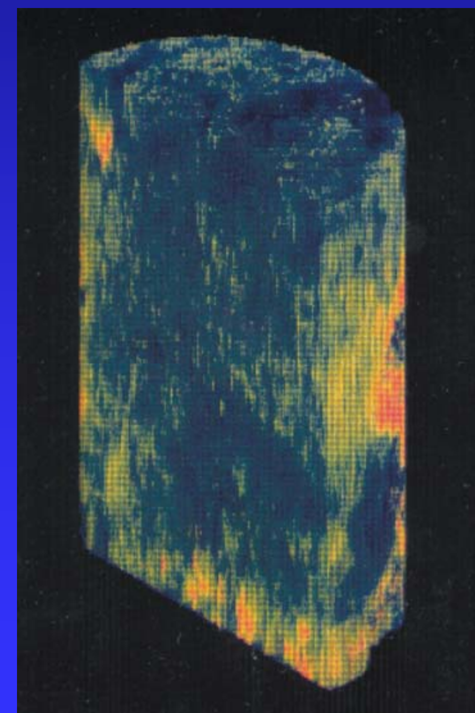
- **Rock Properties - Porosity**



Scan Xenon Saturated



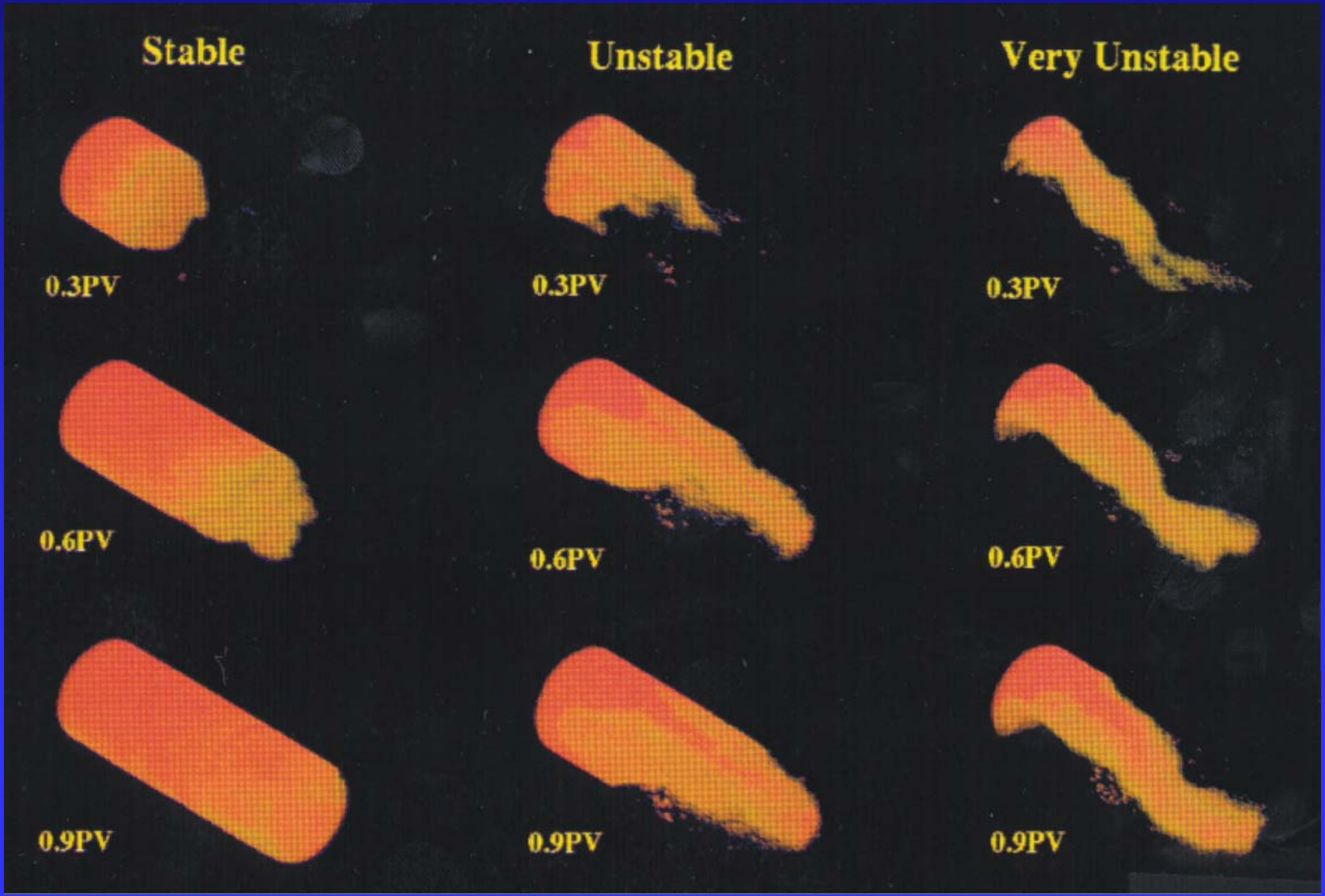
Porosity Map



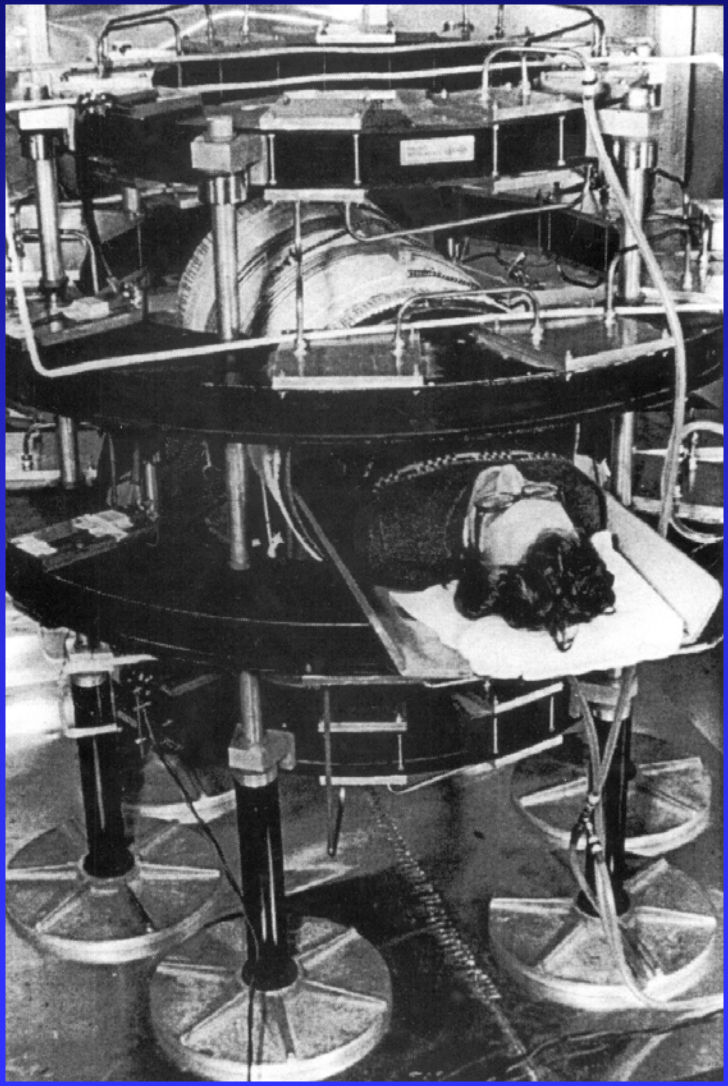
Scan Evacuated

CT Scans

- Fluid Flow



NMR Scanners



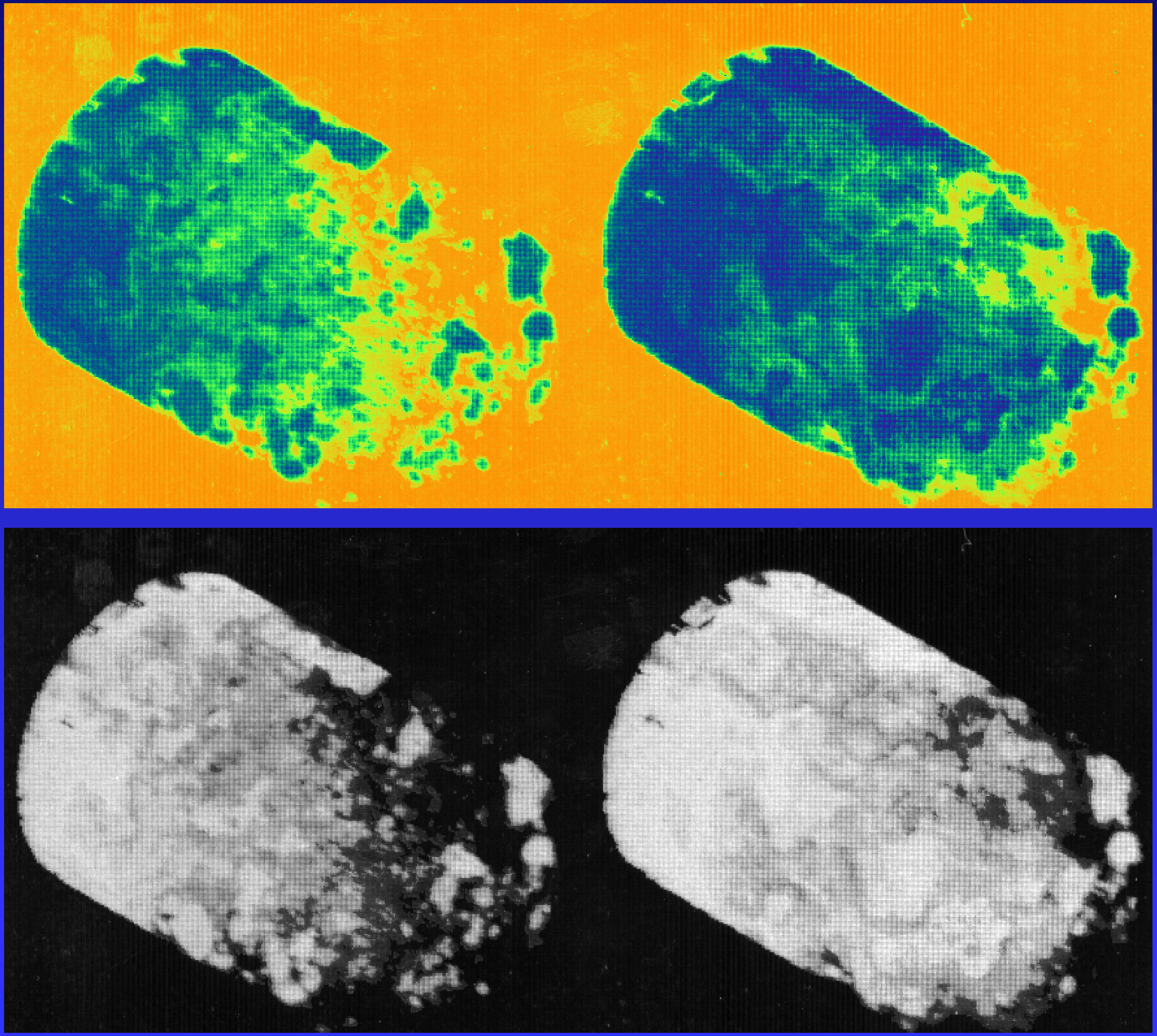
Initially developed

in Aberdeen in 1979

by J.M.S. Hutchinson

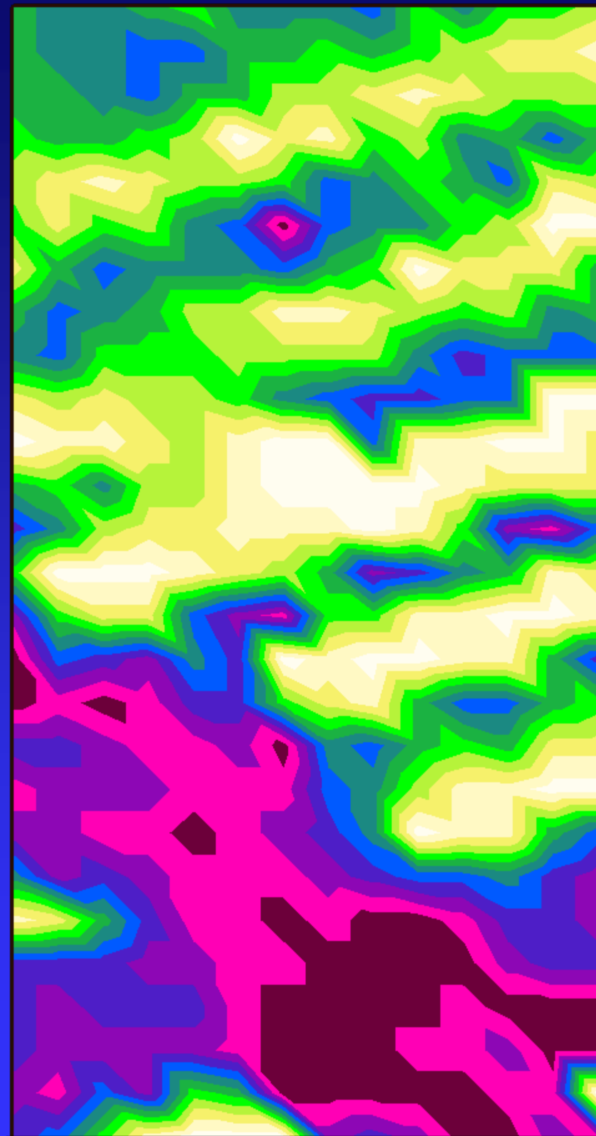
NMR Scanning of Rocks

- NMR images the fluids only
- But can trace fluid flow and bound fluids well

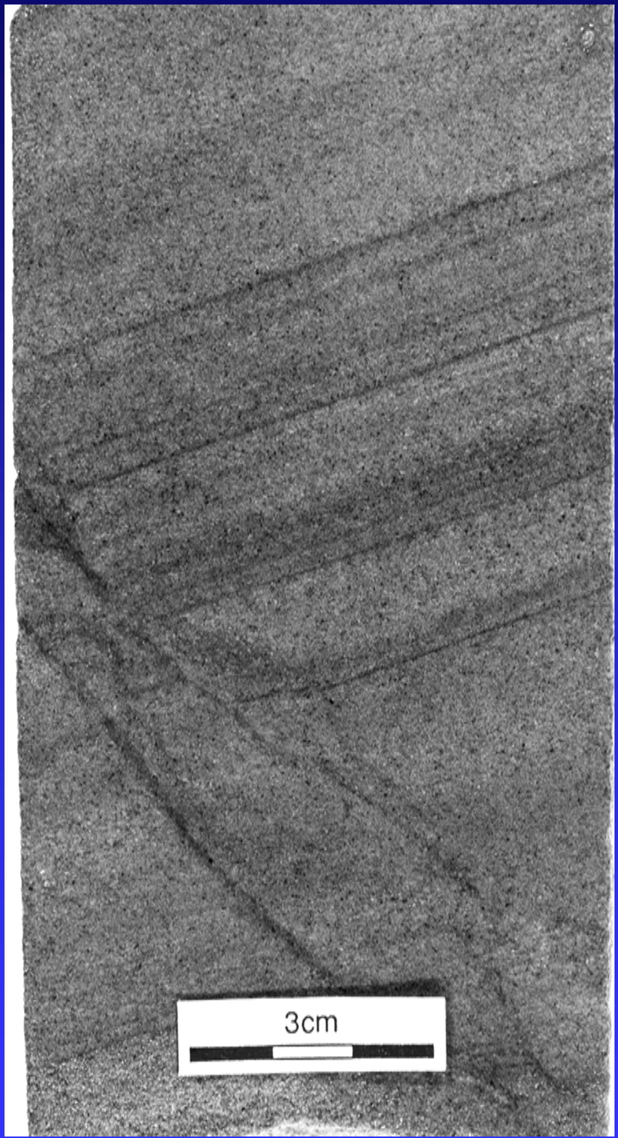


PDPK Permeability Imaging

K (mD)			
	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



5 mm grid resolution

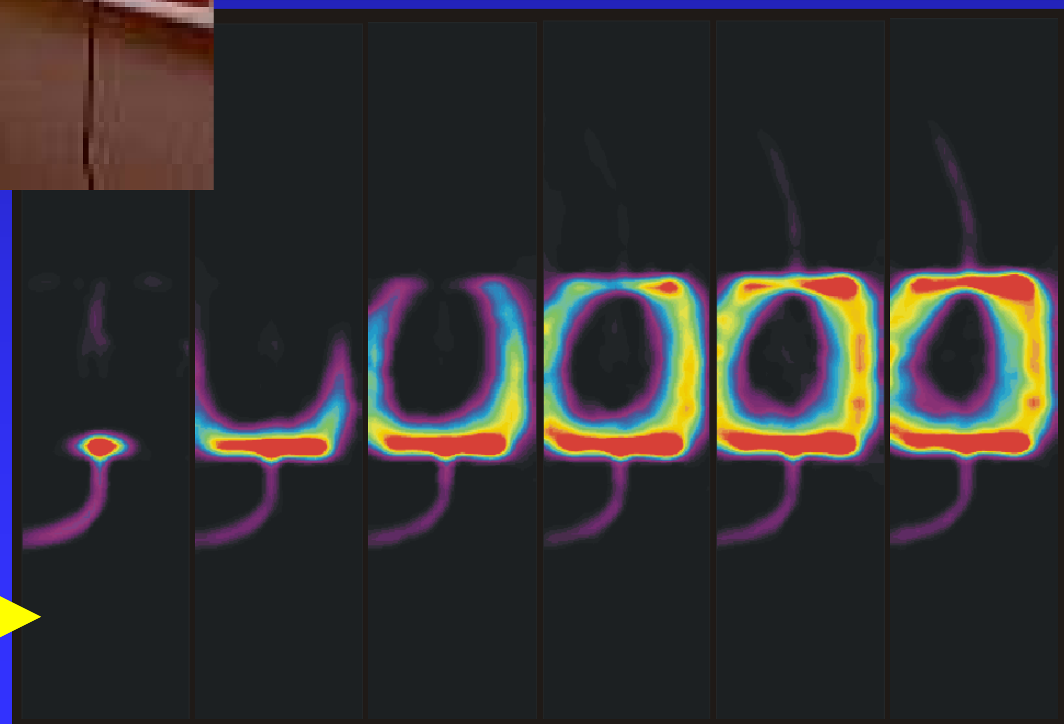


Clay -rich sandstone

PET Imaging

A Modern
PET Imager

Example flow of water
through a HFPM



PET Imaging

- **Example**

  Flow of water through a core containing deformation bands

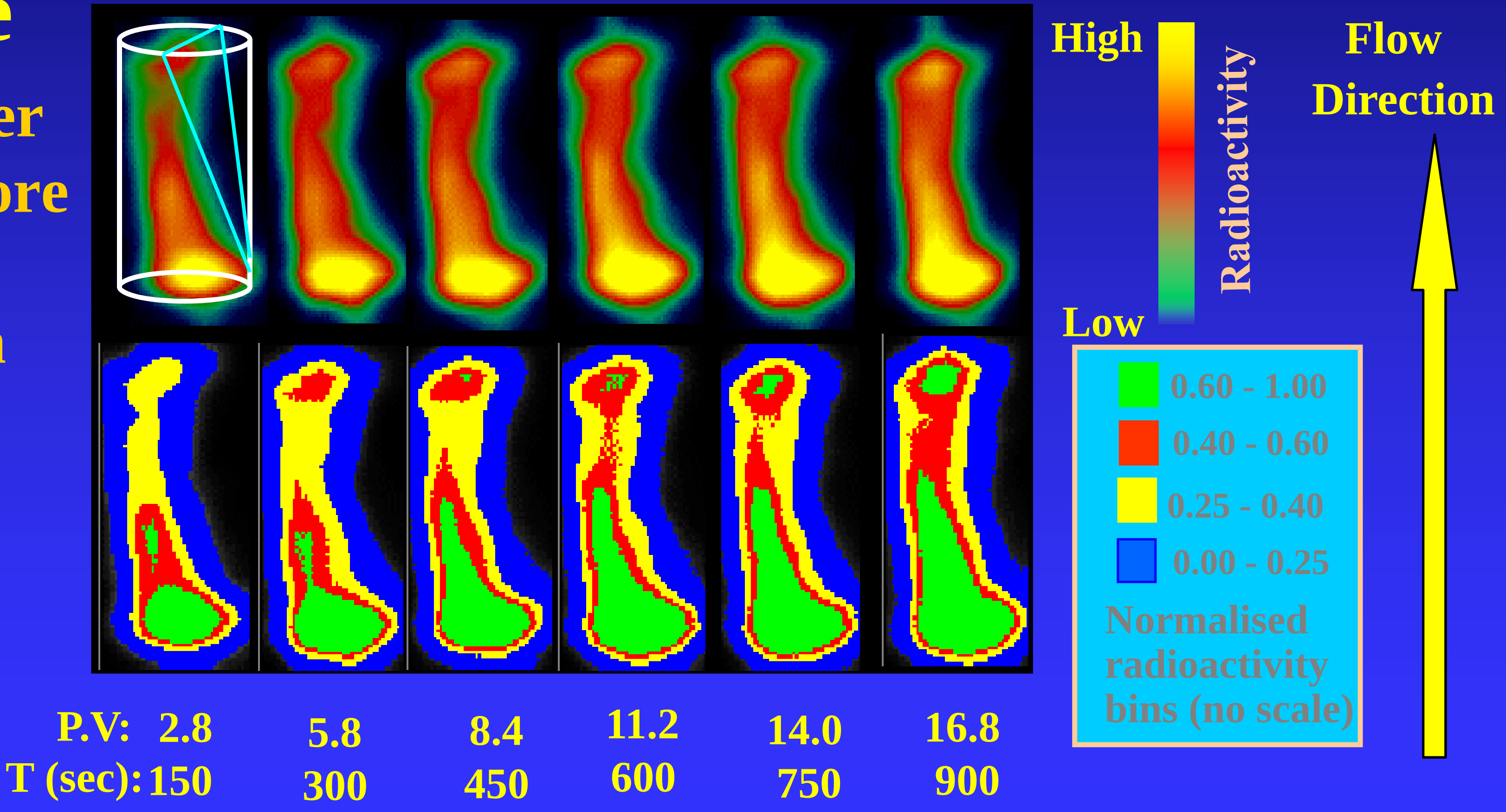
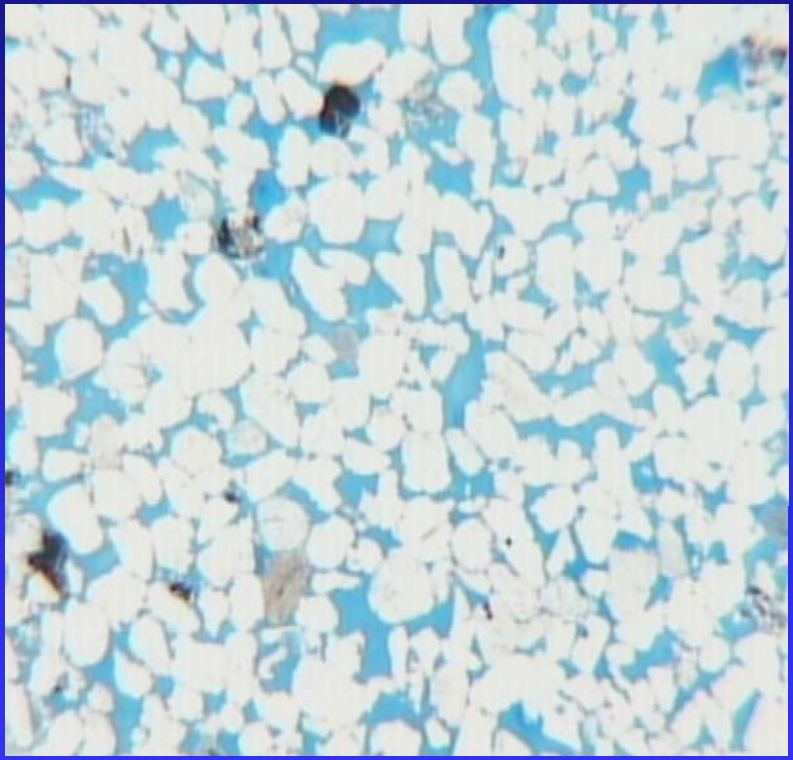


Image Analysis



Thin Section

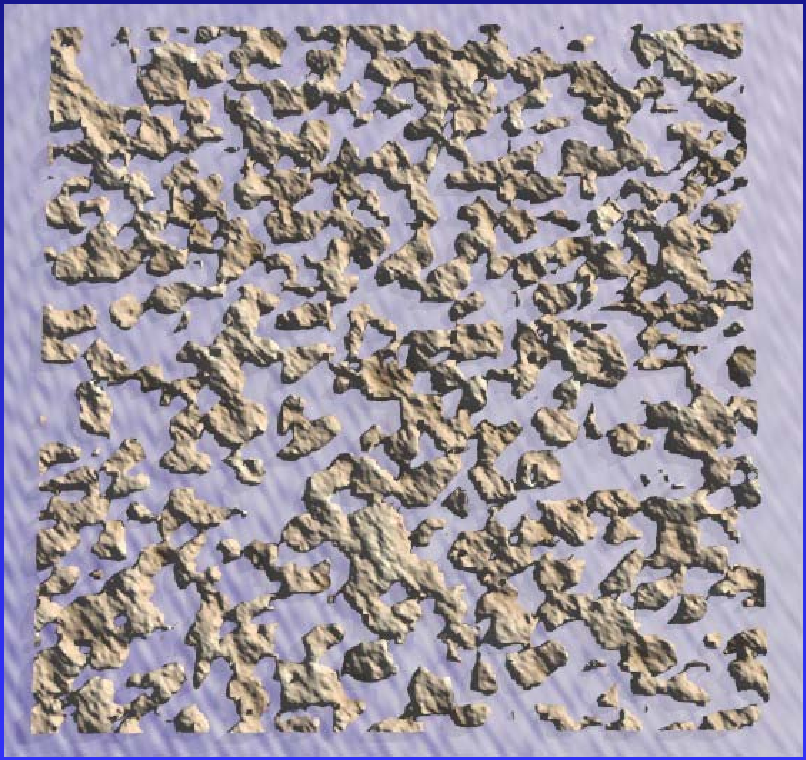


Image Analysed Section

Summary

Summary I

- The optical technique 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 modelling

Summary II

- A new methodology was developed to generate a synthetic numerical models of rough fractures in rocks
- The technique allows the parameterisation of surfaces of real fractures in rocks
- After tuning parameters of the numerical model, the synthetic numerical fracture surfaces have properties, which are identical to the real ones
- Both numerical and real fracture surfaces can be used in computational flow modelling

Summary III

- Fluid flow in rock fractures can be measured using the DOI method
- This flow can also be modelled effectively using FEM based methods
- Fluid flow and saturation can also be imaged directly using novel imaging techniques
- We can now quantitatively address fluid flow in rock fractures

Acknowledgements

- **Steven Ogilvie**

  Measurement of fluid flow in rough fractures (PDRF)

- **Evgeny Isakov**

  Modelling fluid flow in rough fractures (PDRF)

- **Colin Taylor**

  Petrophysics technician