Observe, explore, simplify and quantify.

The role of experimental physics in geology

Dag Kristian Dysthe

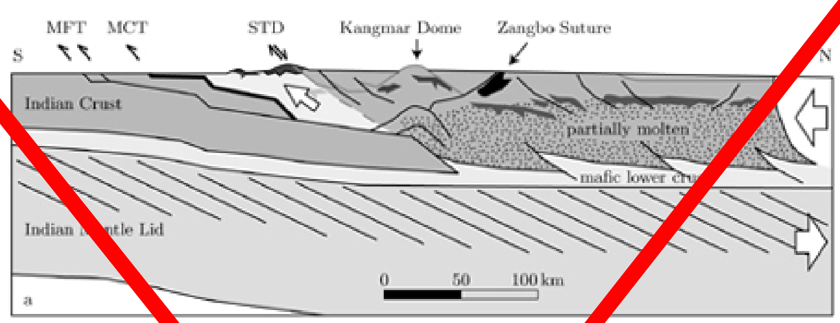
Experiments and geological processes

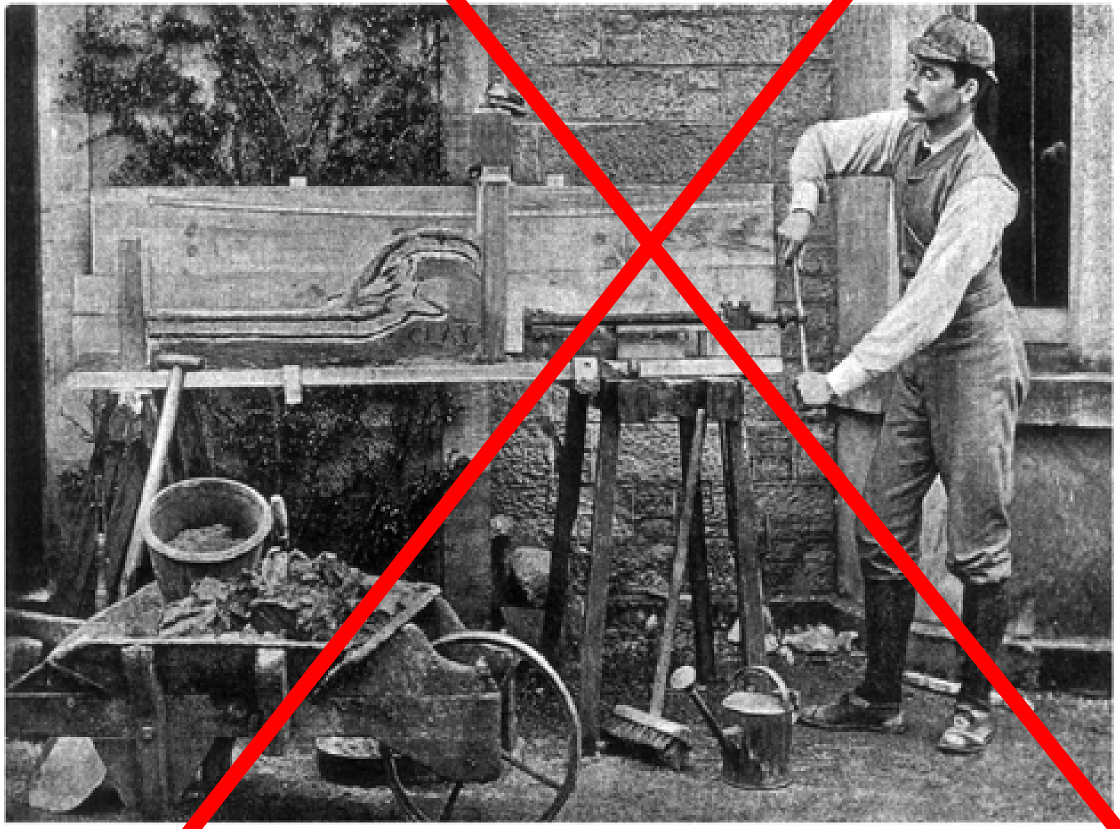
- Geological processes
  - Are slow: mountain building, basin subsidence, weathering, continental subduction
    - Leave only ”frozen states” for observation
  - Are explosive: Earth quakes, volcanoes, venting
  - Involve hard (large stresses needed) and hot materials
  - ~~Require heavy equipment and patience for direct experiments on real rocks~~

  Because 3D, confinement and high pressure impedes good experimental techniques

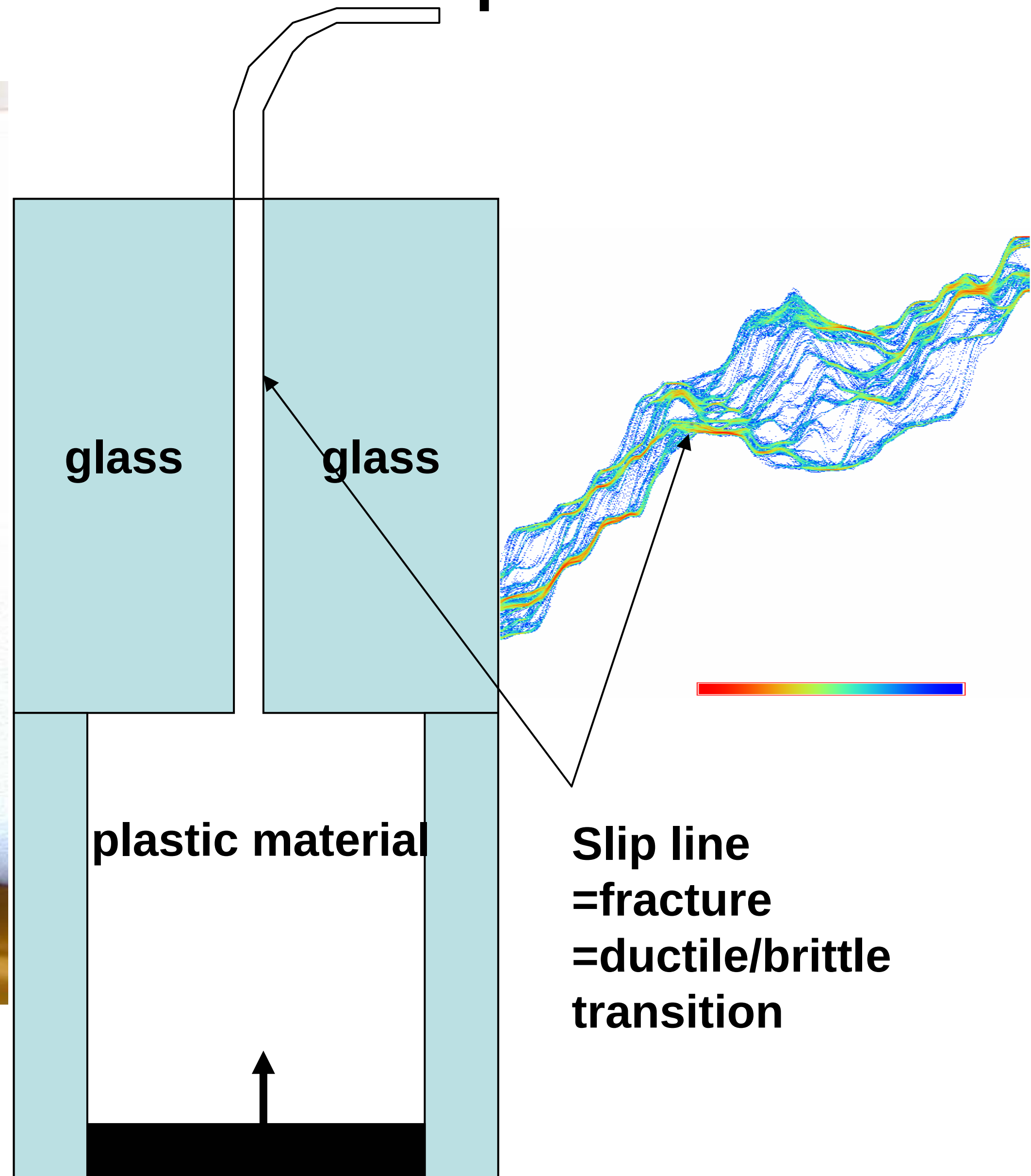
Experiments and geological processes

- Similarity and scaling
  - Geometrically similar models where governing parameters scale equally
- Complex, not complicated
  - Simplify complicated geology until only complexity remains





Extrusion simplified and quantified



COESQA

- Choose
  - Phenomena, patterns, processes to study
- Observe
  - Field work with a physicists glasses
- Explore
  - Perform simple experiments with different materials to explore possible processes and practical materials
- Simplify
  - Boundary conditions, materials, few processes
- Quantify
  - Use high resolution techniques for extrordinary data sets:
    - Control environment and excitation
    - Optical imaging, dilatometry, interferometry, stress imaging, infrared imaging, balances, Lego, Xray reflectometry, AFM, Raman
- Apply
  - Insights about processes to geological context. Modelling

Problem choice

- Choice criteria
  - What are the geologists
  - What problems can ou
  - Is there an application answer the questions t with)
- Application to a compl numerical simulation.
  - Boundary conditions
  - Instabilities

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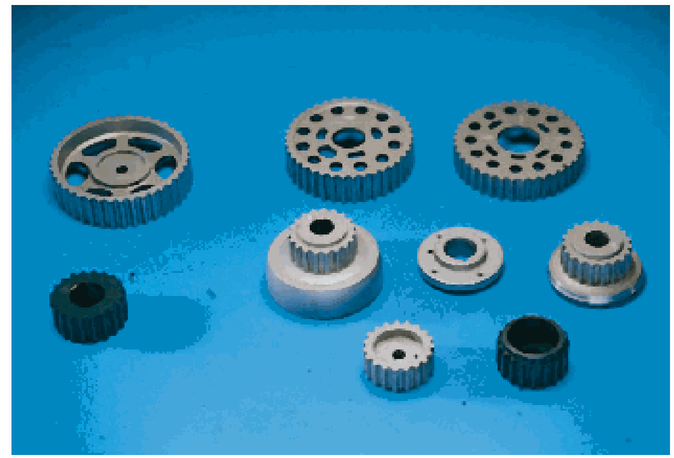
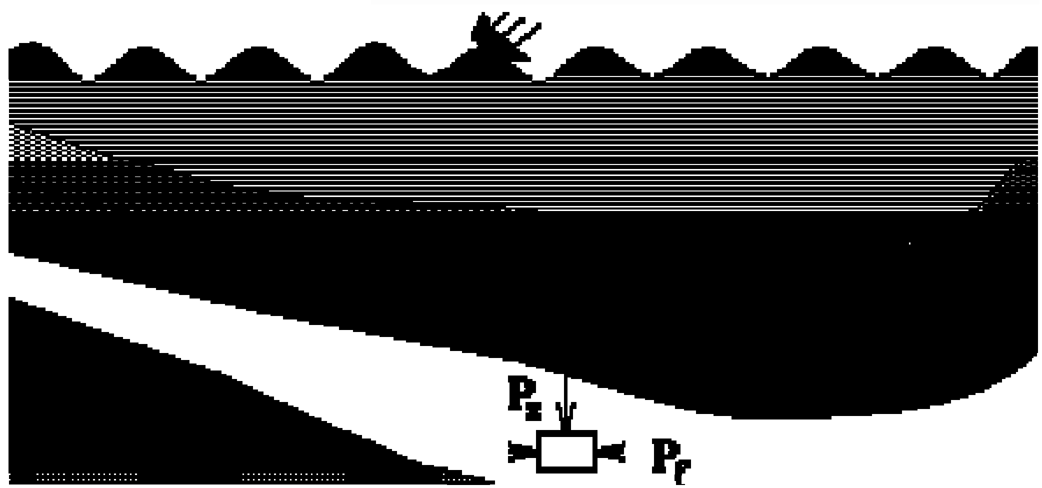
Compaction

Can an exceedingly booring subject become fun?

(yes, snowballs are made by compacting snow!)

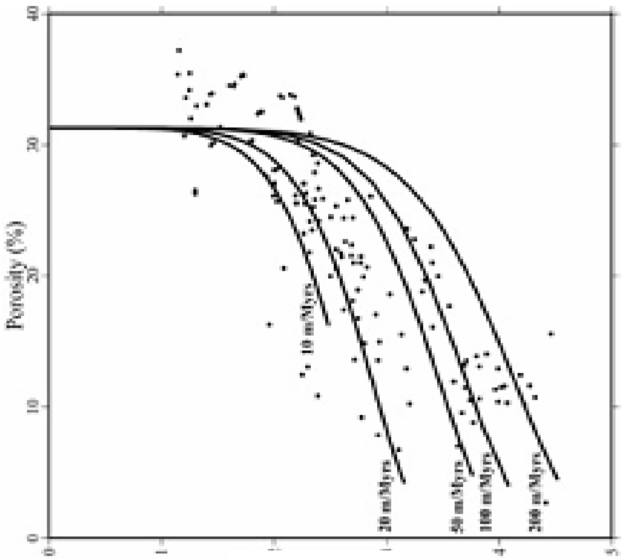




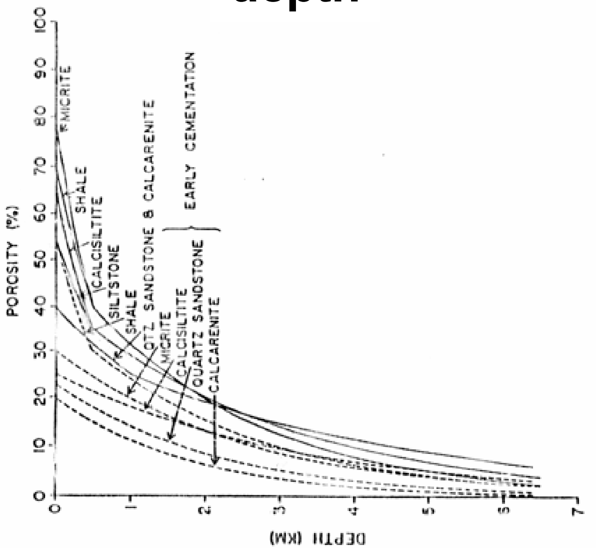
Demonstration

Compaction

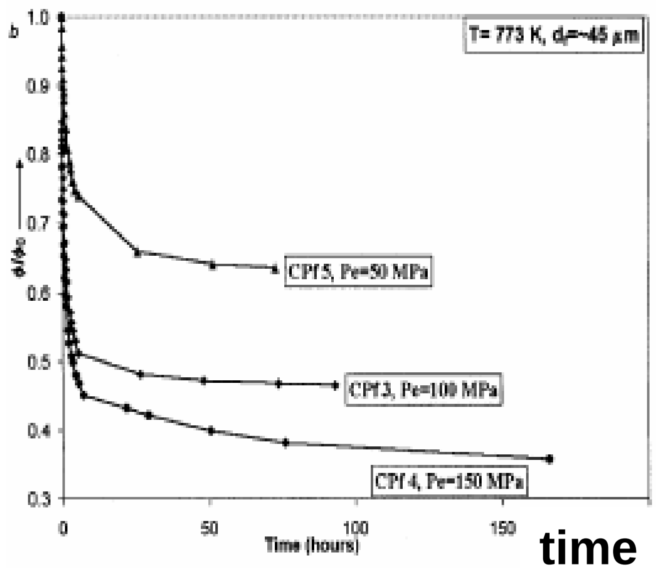
φ(z)



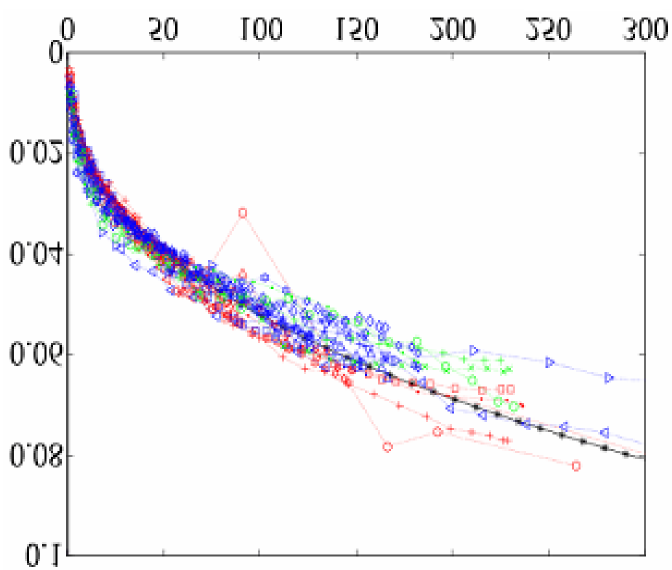
depth



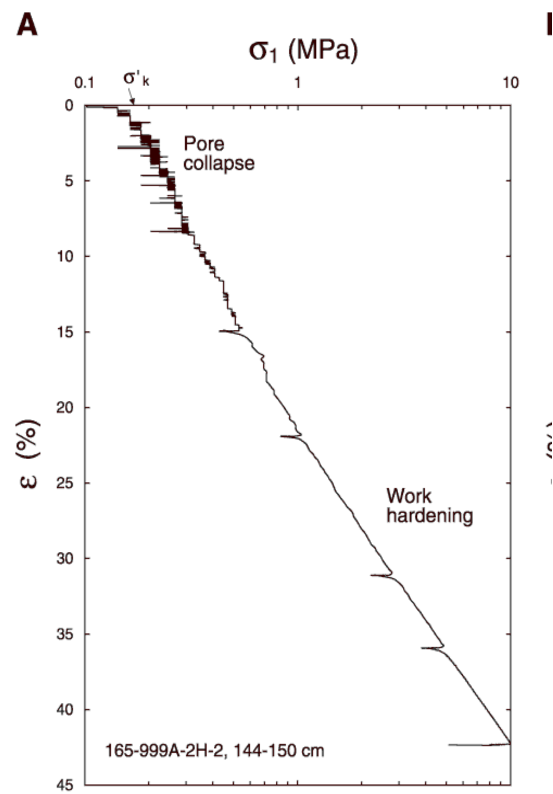
φ(t)



time



φ(σ)

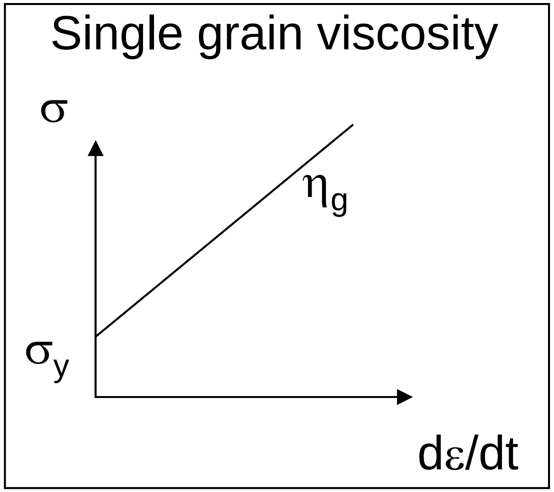


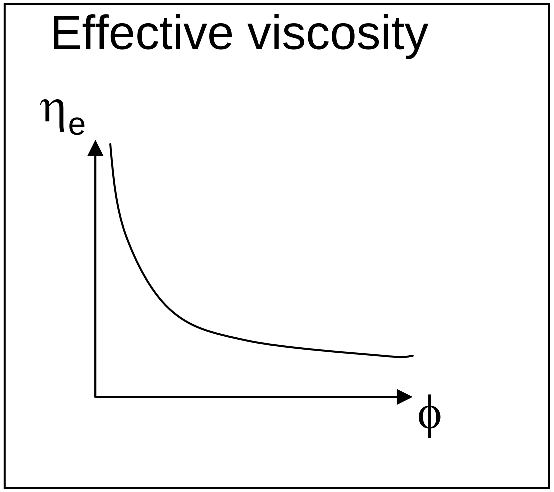
Simplify

- Uniaxial compaction, viscous round grains
- Parameters:
  - ϕ porosity
  - σ stress
  - t time or $d\phi/dt$ strain rate
  - η_g grain viscosity
  - μ friction coefficient
- Dimensional analysis:
  - $\phi=\phi_0+f(\sigma t/\eta_g,\mu)$
  - $\phi=\phi_0+f'(\sigma/(\eta_g d\phi/dt),\mu)$
  - $d\phi/dt= (\sigma/\eta_g)\ f''(\phi,\mu) = \sigma/\eta_e(\phi,\mu)$
- Grain viscosity variability factor 10^{19}

=> experiment with any size and stress that is practical

Does there exist a universal compaction curve, $\eta_e(\phi,\mu)$?





Dimensional analysis

- Dimensions: LMT: $[\rho]_{LMT}=ML^{-3}$, LFT: $[\rho]_{LFT}=K^{-4}FT^2$
- What is to be determined? $\phi-\phi_0$
- Find governing parameters $\sigma, \eta_g, \mu, t, d\phi/dt$
- Dimensions of governing parameters:

  $[\sigma] = MLT^{-2}$, $[\eta_g] = MLT^{-1}$, $[t] = T$, $[\mu] = 1$, $[d\phi/dt] = T^{-1}$
- Number of independent dimensional gov. par.:

  $[\eta_g]= [\sigma t]$ => 2 independent
- Π teorem:

No. indep., dim. gov. par. = no. gov. par. – no. gov. par. with indep. dim.

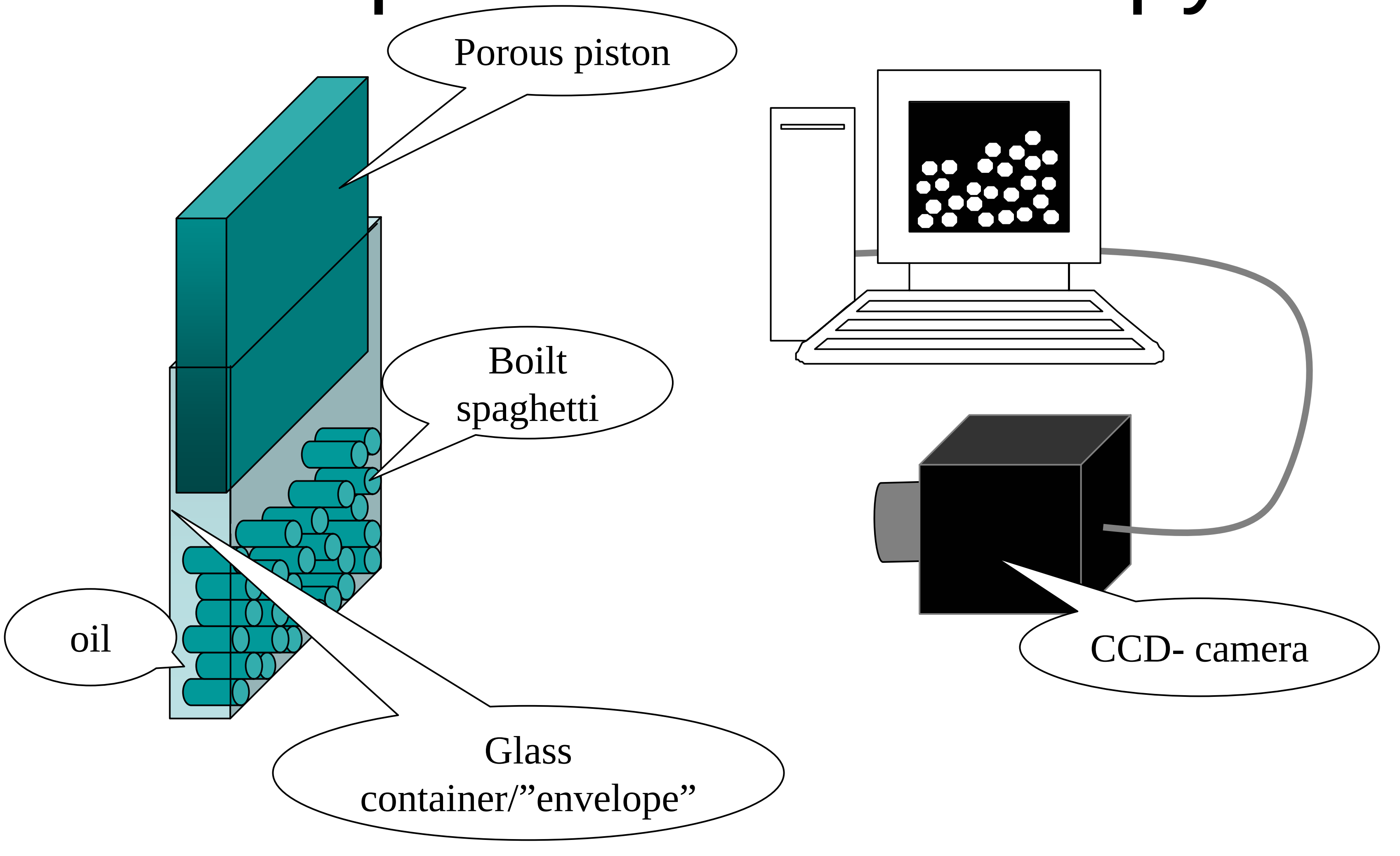
= 4 – 2

=> $\phi-\phi_0=\Pi(\sigma t/\eta_g,\mu)$

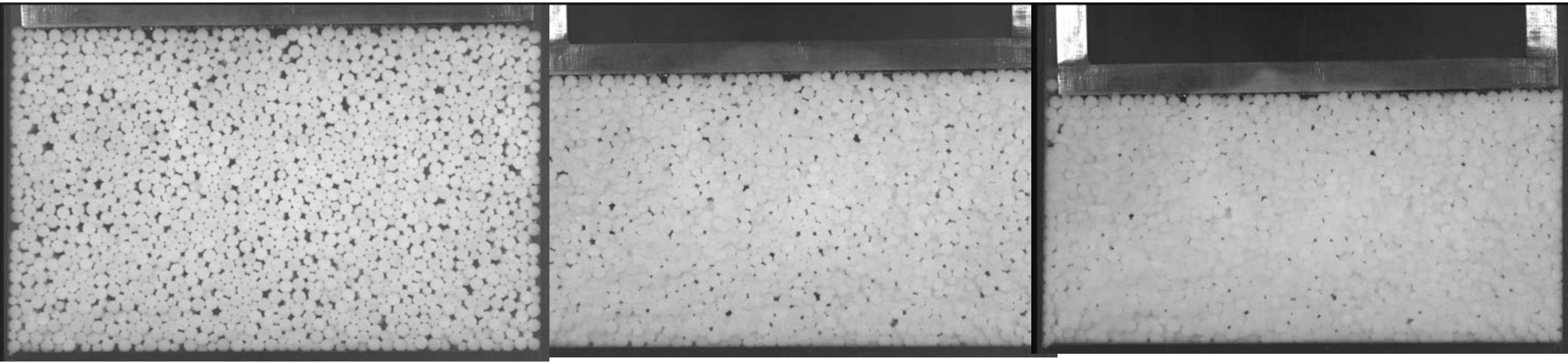
Scaling

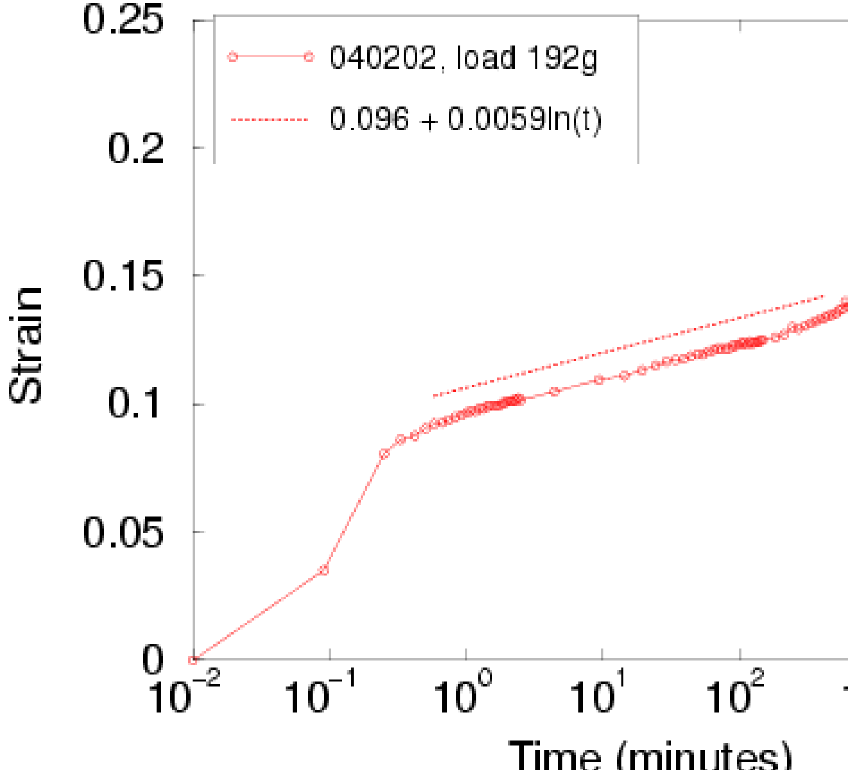
- Scale bound: Process with governing parameter that does not scale or with limited range of scaling
  - Chemical processes (no scaling)
  - Diffusion (in liquids: factor 10-100)
- Scaling: Process with governing parameters that scale over a large range
  - Viscosity (14 orders of magnitude)
- Scale free: Self similar patterns e.g. fracture

Compaction “microscopy”

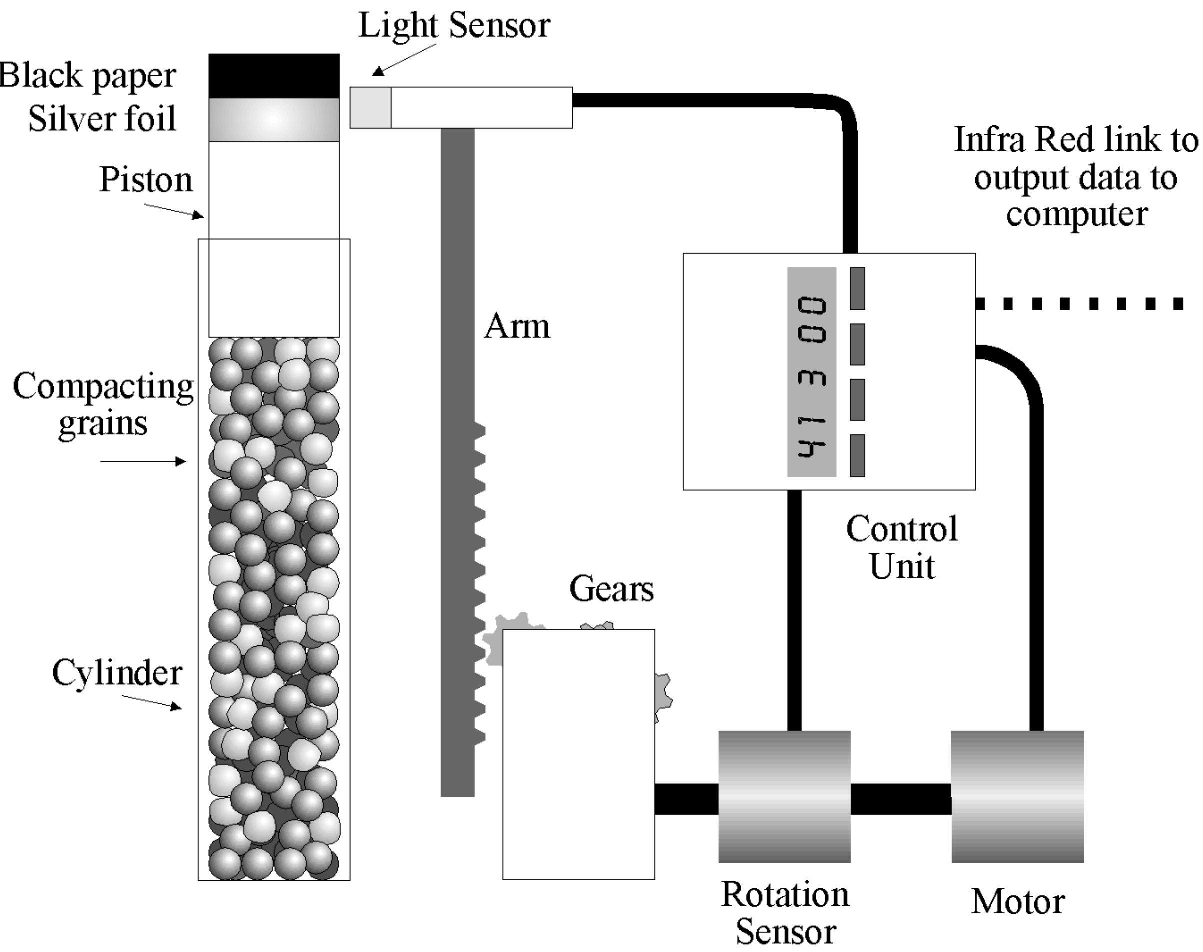


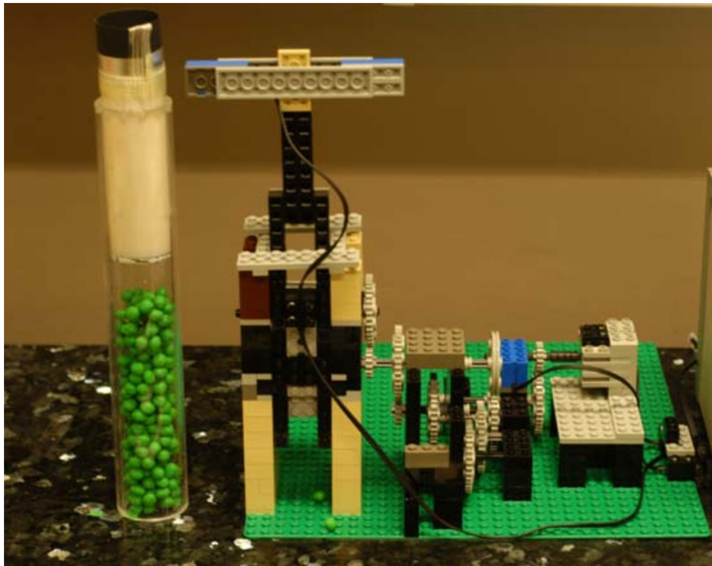
Compaction of spagetti, constant load



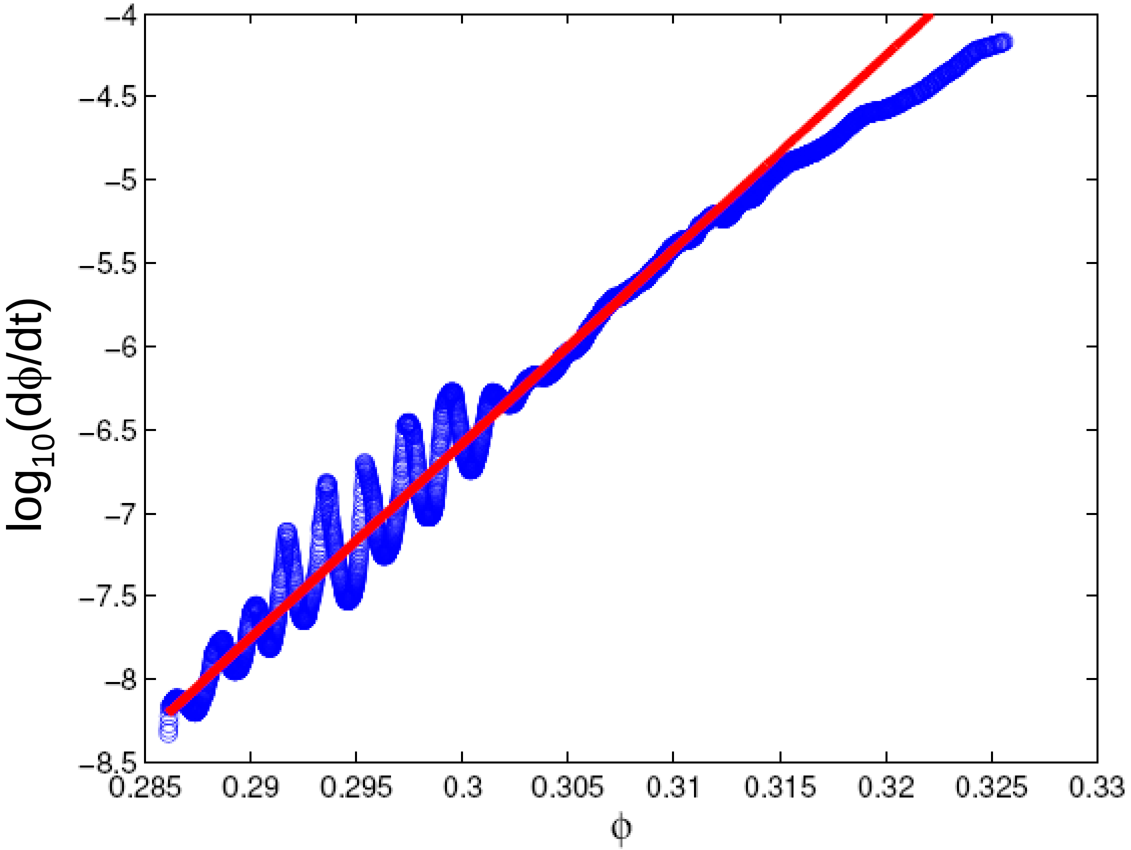


Compaction of Play-Doh, constant load, (Lego sensor)

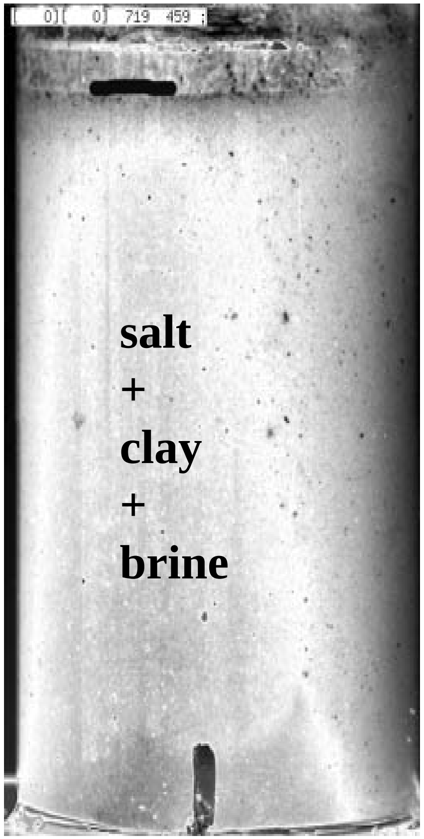


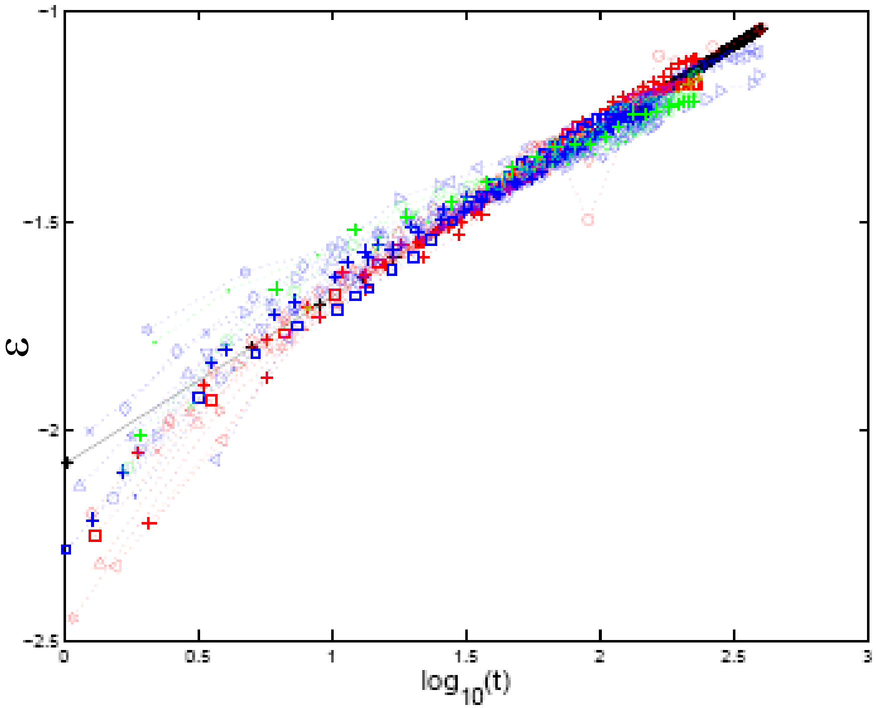


Compaction of Play-Doh, constant load



Compaction of salt and clay in brine, constant load

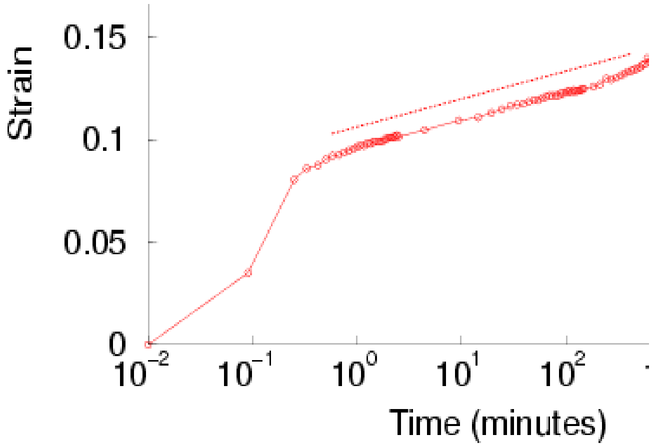




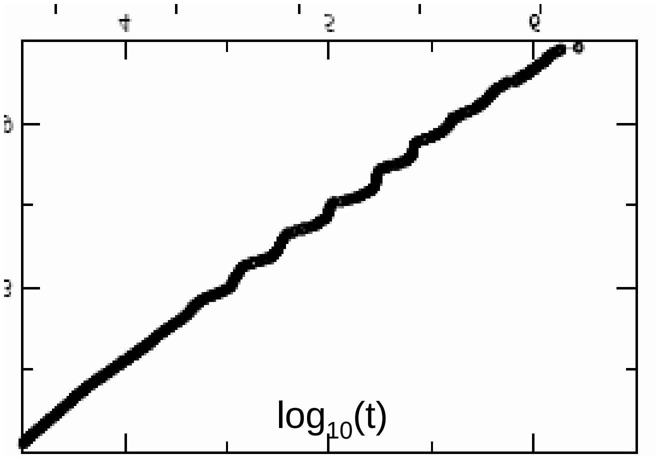
Data collaps of different loads, grain sizes and clay content

Universal compaction curve?

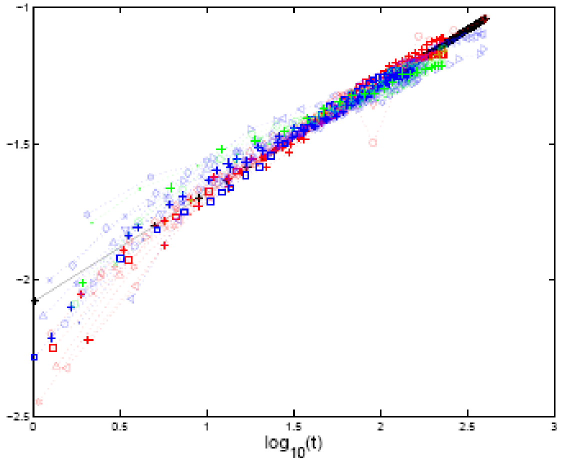
Spagetti



Play-Doh



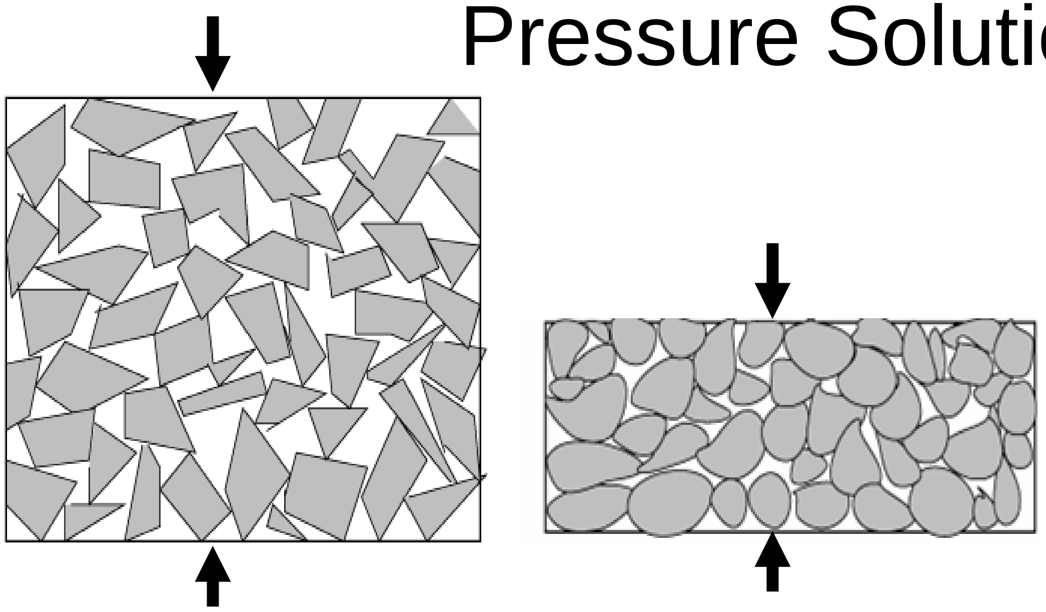
Salt+clay



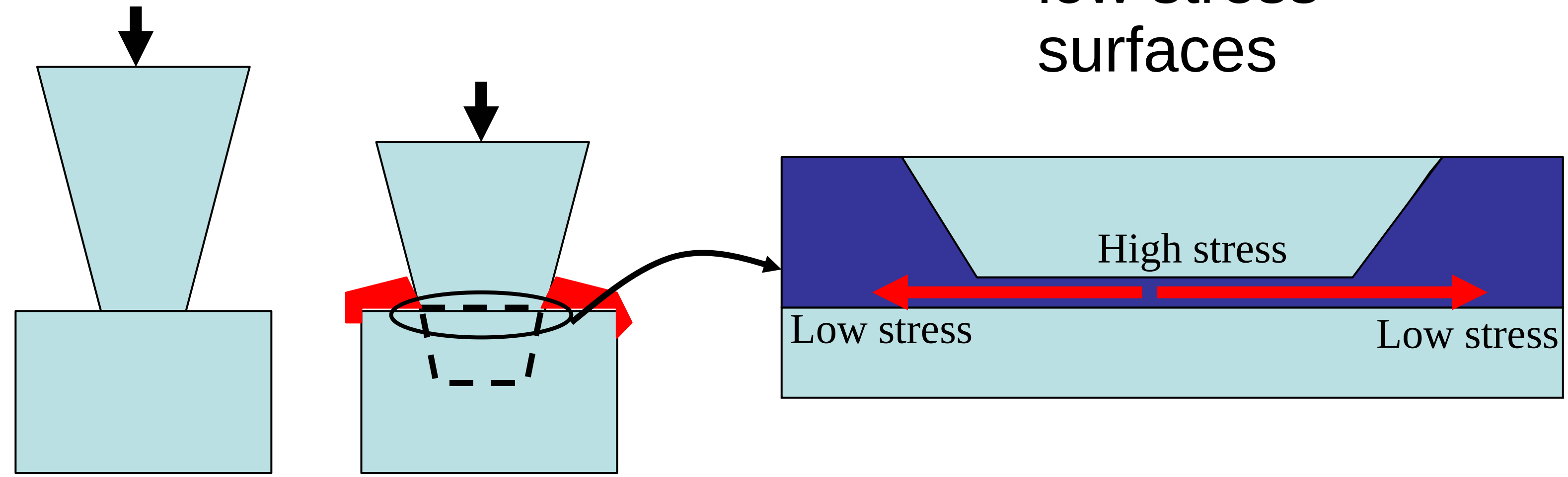
$\varepsilon \sim \log(t)$ => Dramatic work hardening: $\eta_e = \eta_g \exp(\alpha/\phi)$

Revealed by high resolution measurements!

Pressure Solution Creep



- Dissolution at high stress surfaces
- Mass transport in fluid
- Precipitation at low stress surfaces



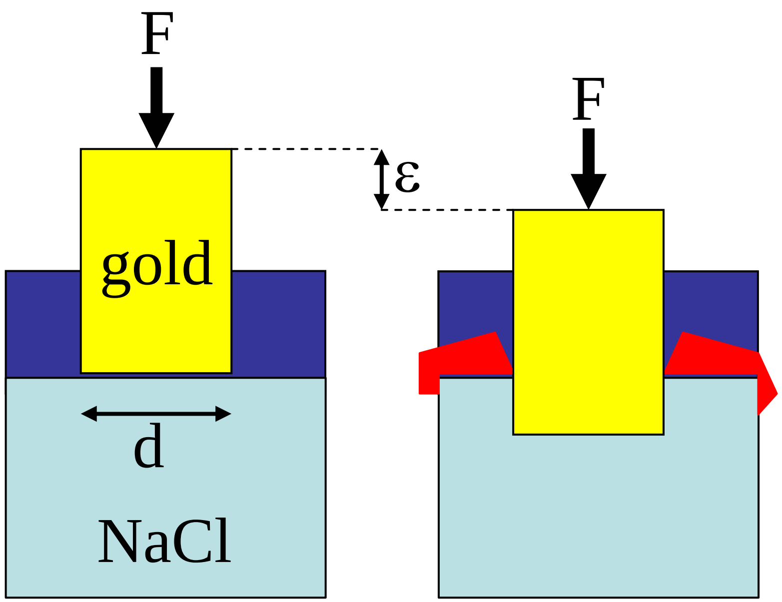
Mechano-chemical processes

- Chemical potential depends on stress
- Viscosity governed by pressure solution creep (PSC)
  - $d\varepsilon/dt = (dz/dt)/L_g = s\,\alpha\,(\Delta D/L_g^3)\,(\sigma-\sigma_f)/\sigma_f$

	variation
• Δ – thickness of confined fluid	10?
• s – solubility of mineral in water	10^4
• D – diffusion coefficient	10
• $(\sigma-\sigma_f)/\sigma_f$ – effective stress	100
• $\alpha = \sigma\, ds/d\sigma$ – stress sensitivity of solubility	1

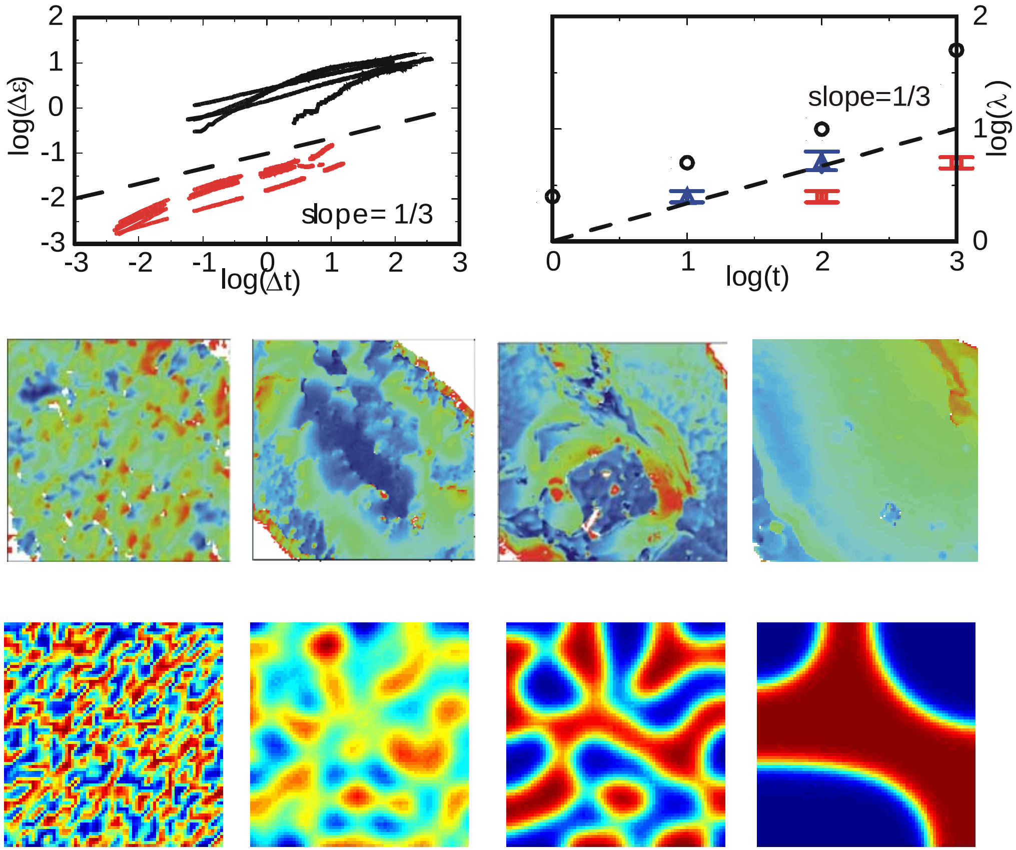
    - L_g^{-3} -> use small contacts and measure small displacements!
  - Max solubility and stress, 100μm contacts: dz/dt = 3 nm/h
- => Diffusion limited mechano-chemical processes require microscopic or nanoscopic methods

Indentation experiments



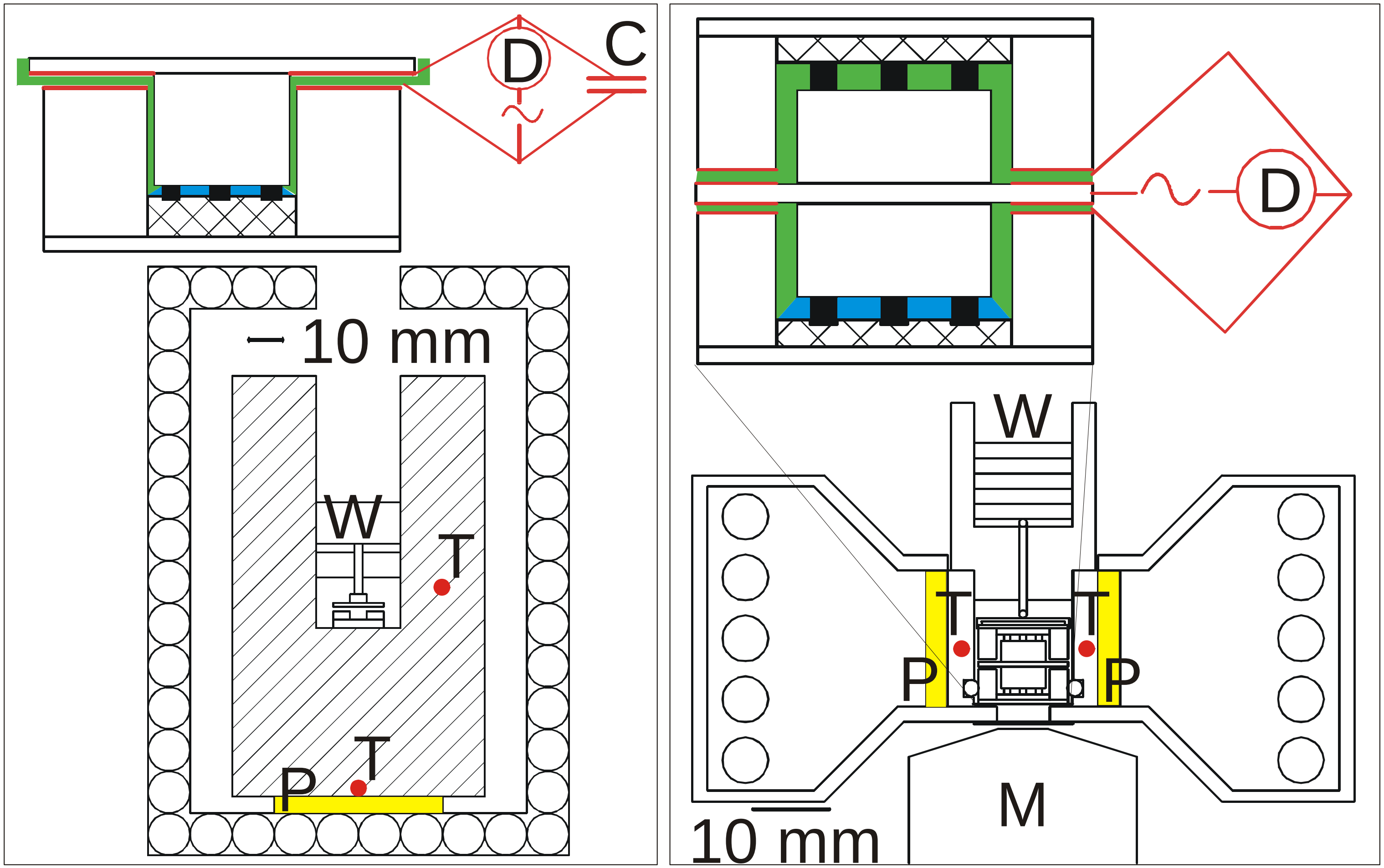
- Inert indenter
- Constant load, F
- Constant contact area, d^2
- Constant temperature, T
- Sensitive and stable displacement, ε, measurements
- Expected result: dε/dt constant, i.e. ε ~ t
- Goal: study dε/dt as function of F, d, T, crystal, where does it precipitate…

Interface evolution in fluid transport controlled creep

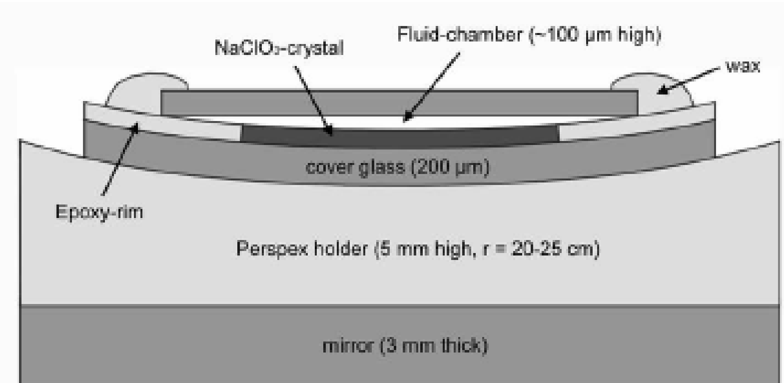


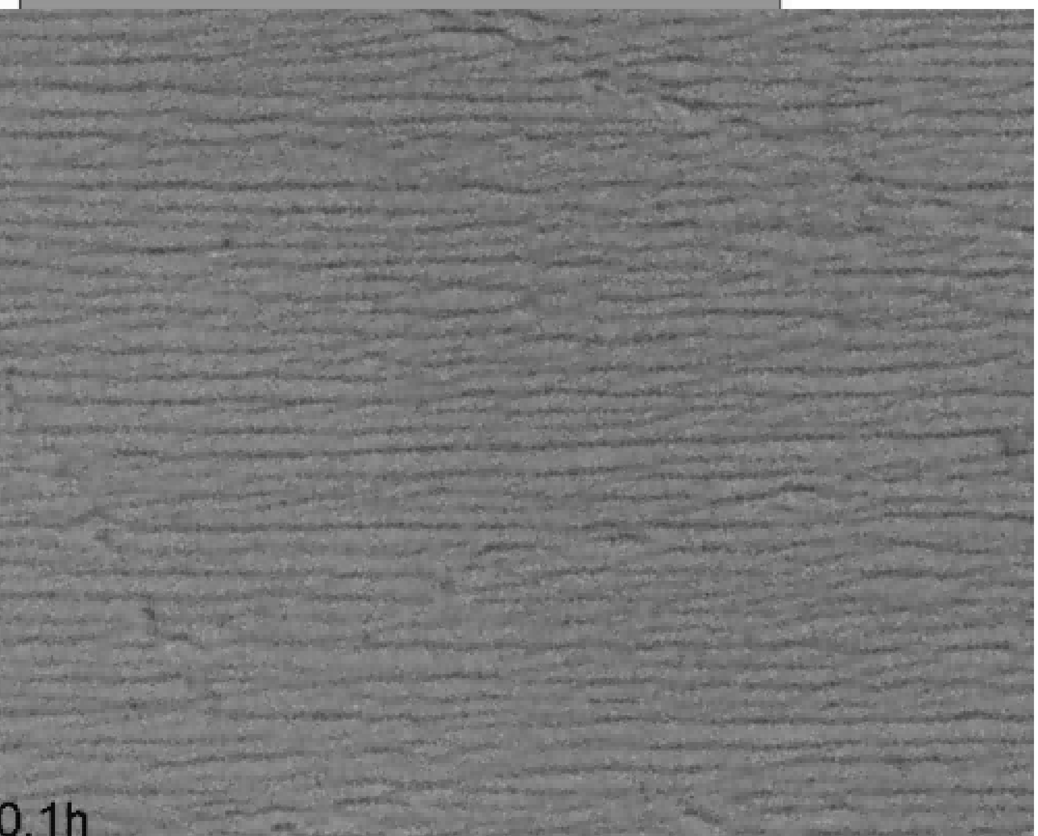
- Measurements of indentation by Pressure Solution Creep (PSC): $\varepsilon \sim t^{1/3}$
- Measurements of interface structure in PSC: $\lambda \sim t^{1/3}$
- Coarsening in time as spinodal decomposition: $\lambda \sim t^{1/3}$
- Consistent power law behaviour in diffusion limited model

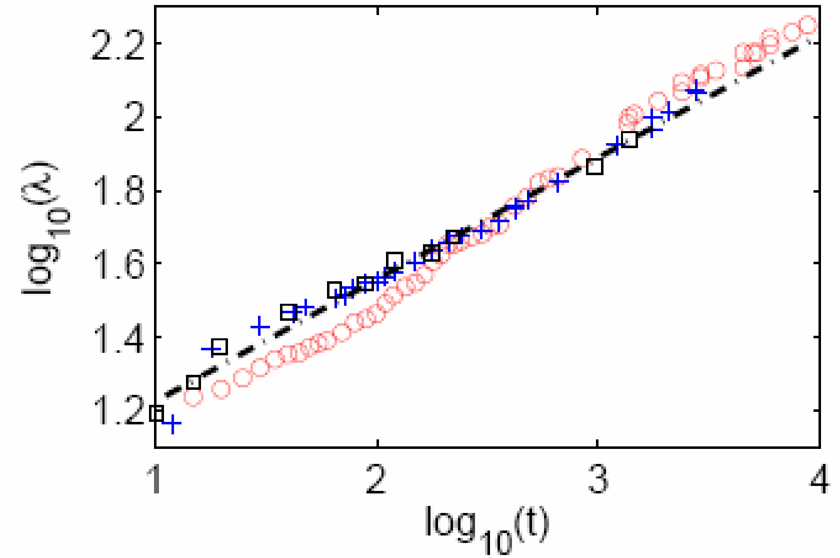
Measurement of PSC indentation rate

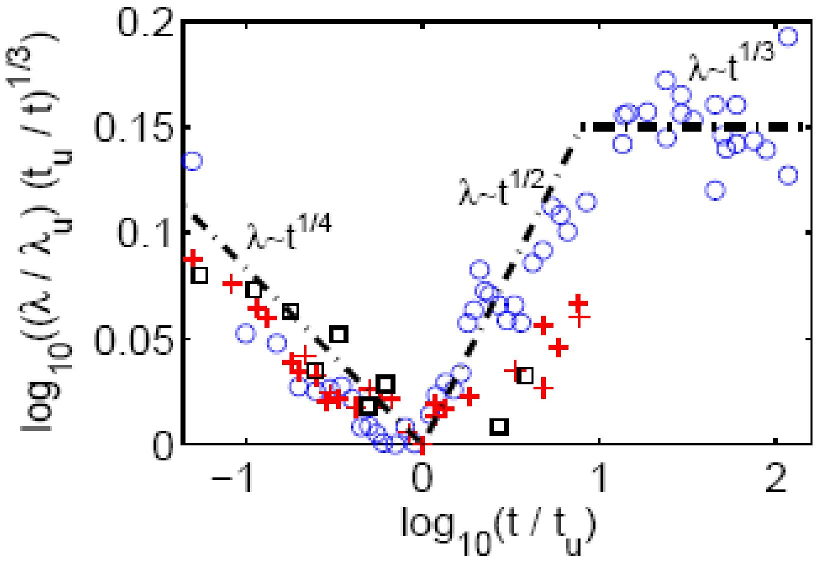


Stress roughening –> coarsening –> new equilibrium?



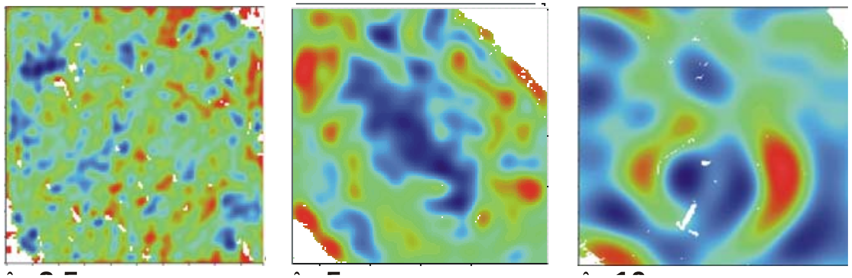




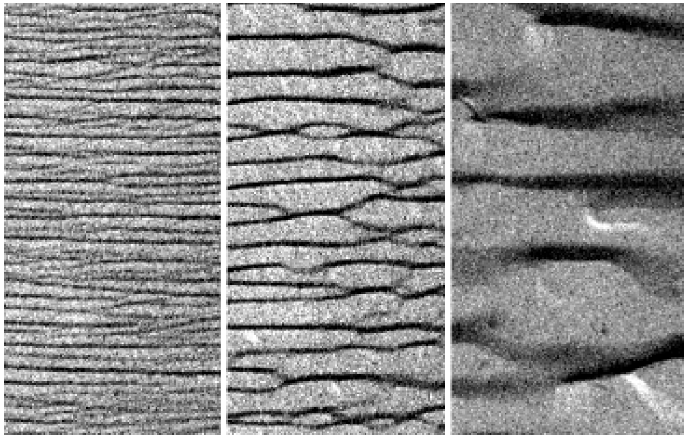


Unexpected phenomena revealed by high resolution data sets

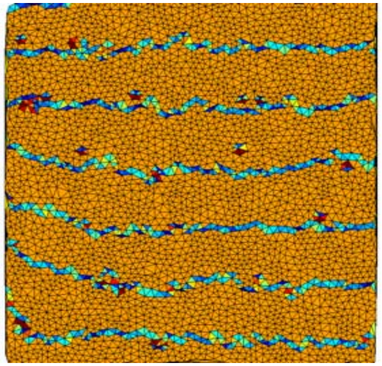
- Universal scaling in transient creep



- Roughening and coarsening towards stressed equilibrium



- Compaction bands



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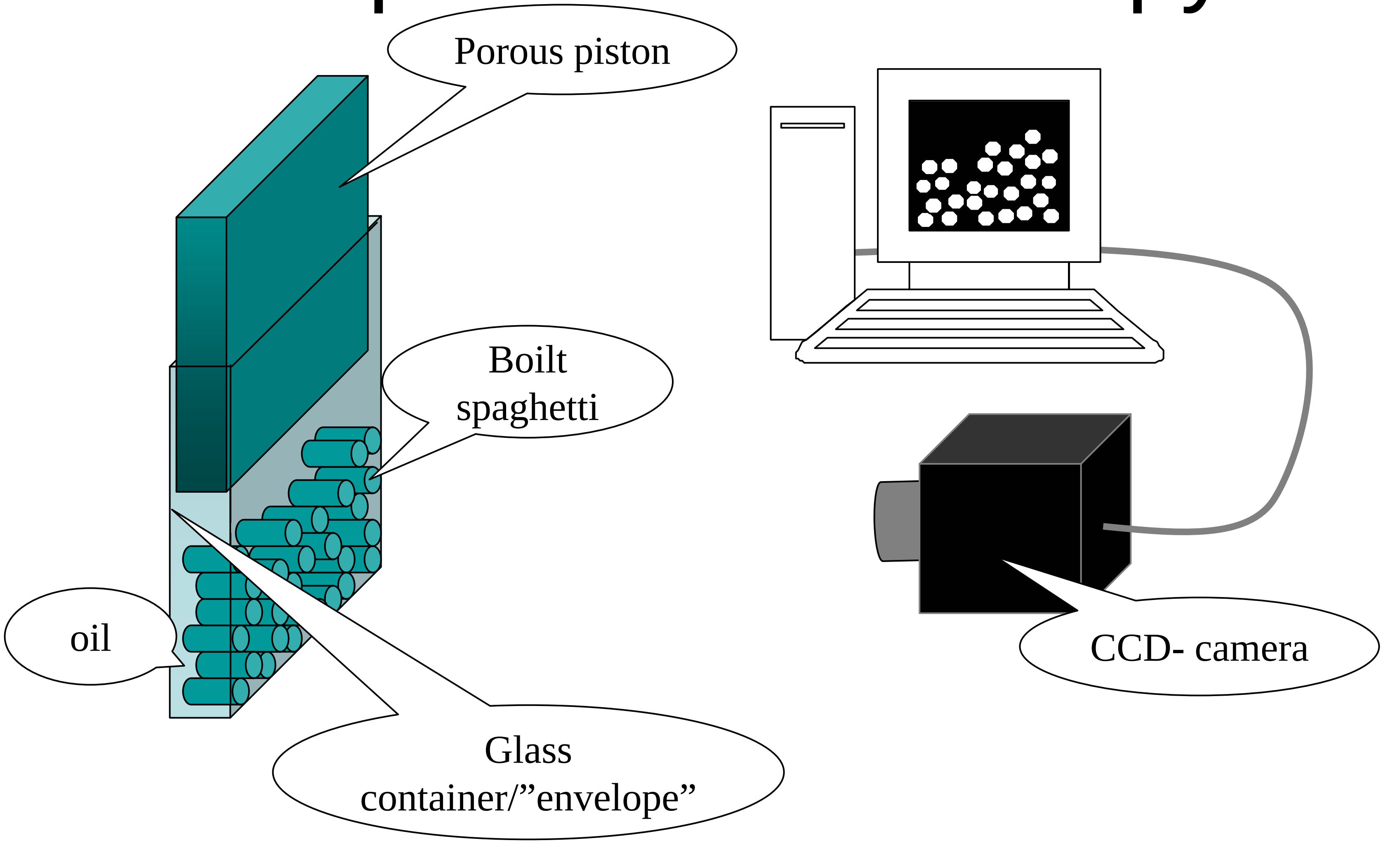

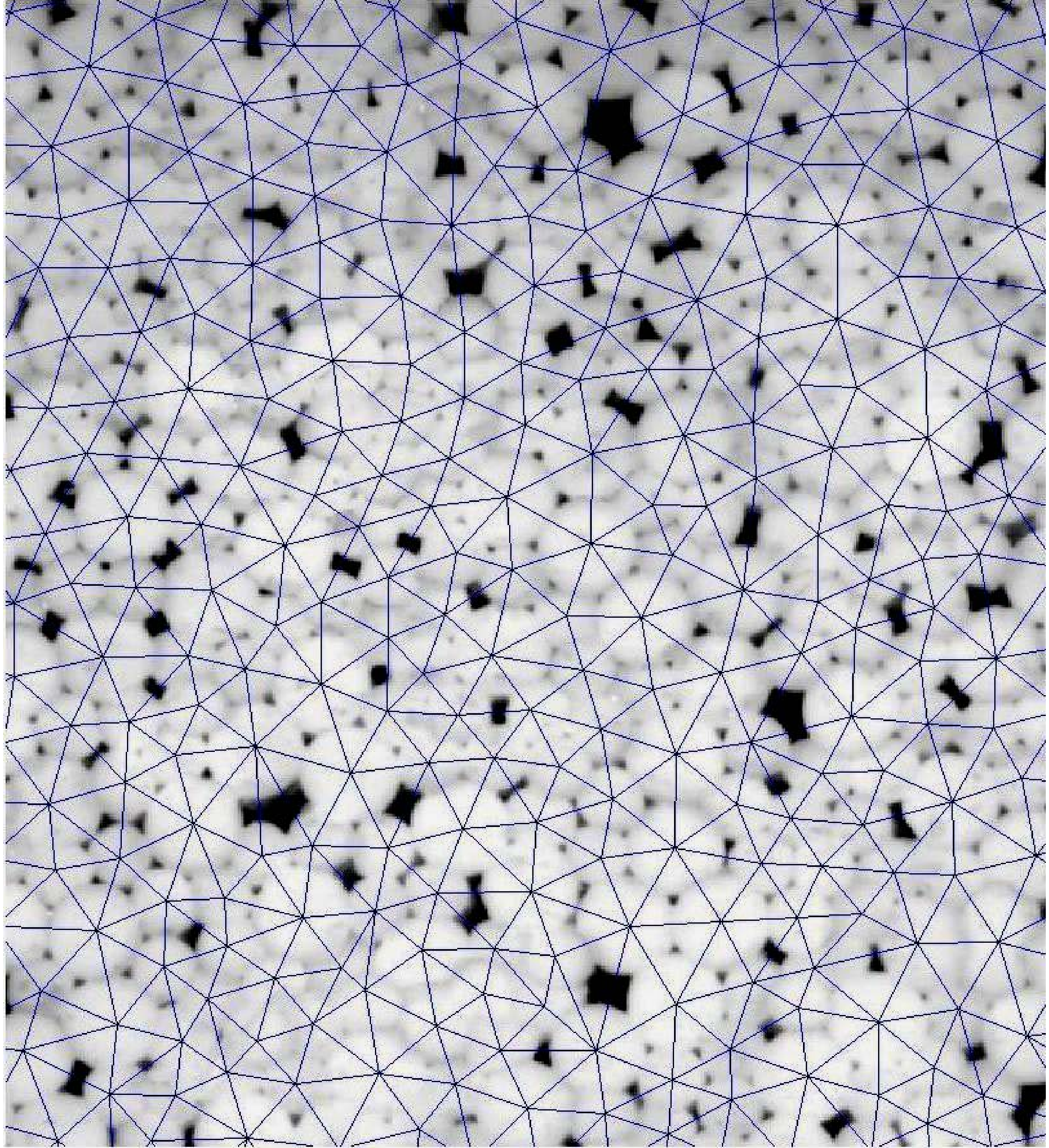

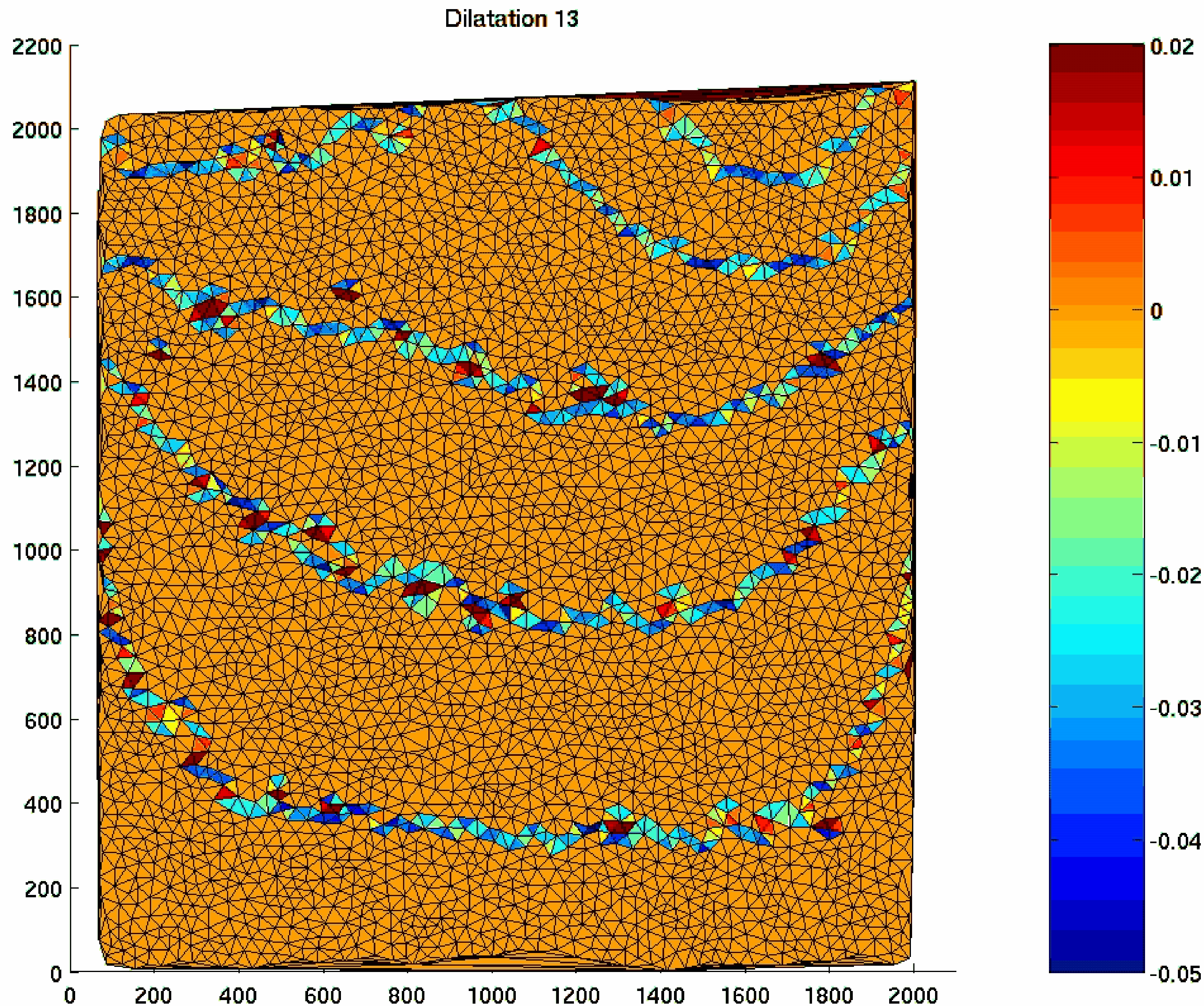
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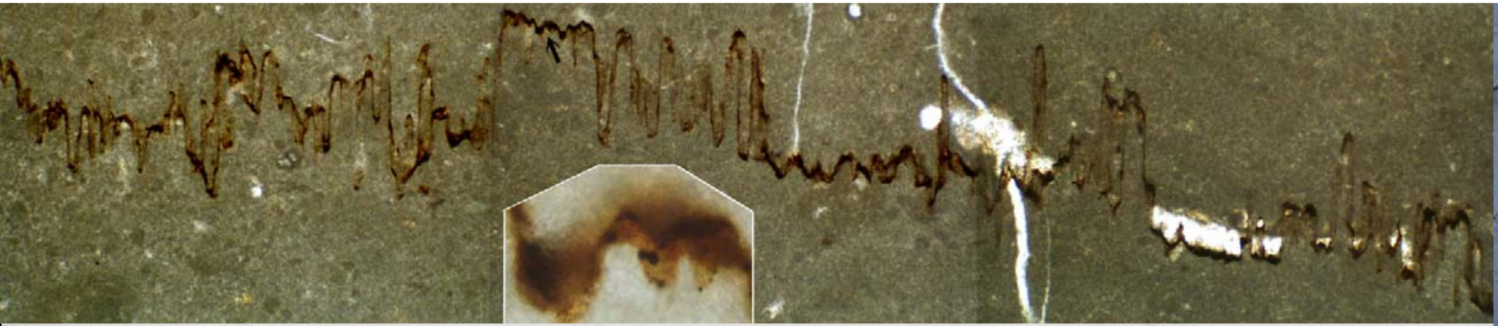
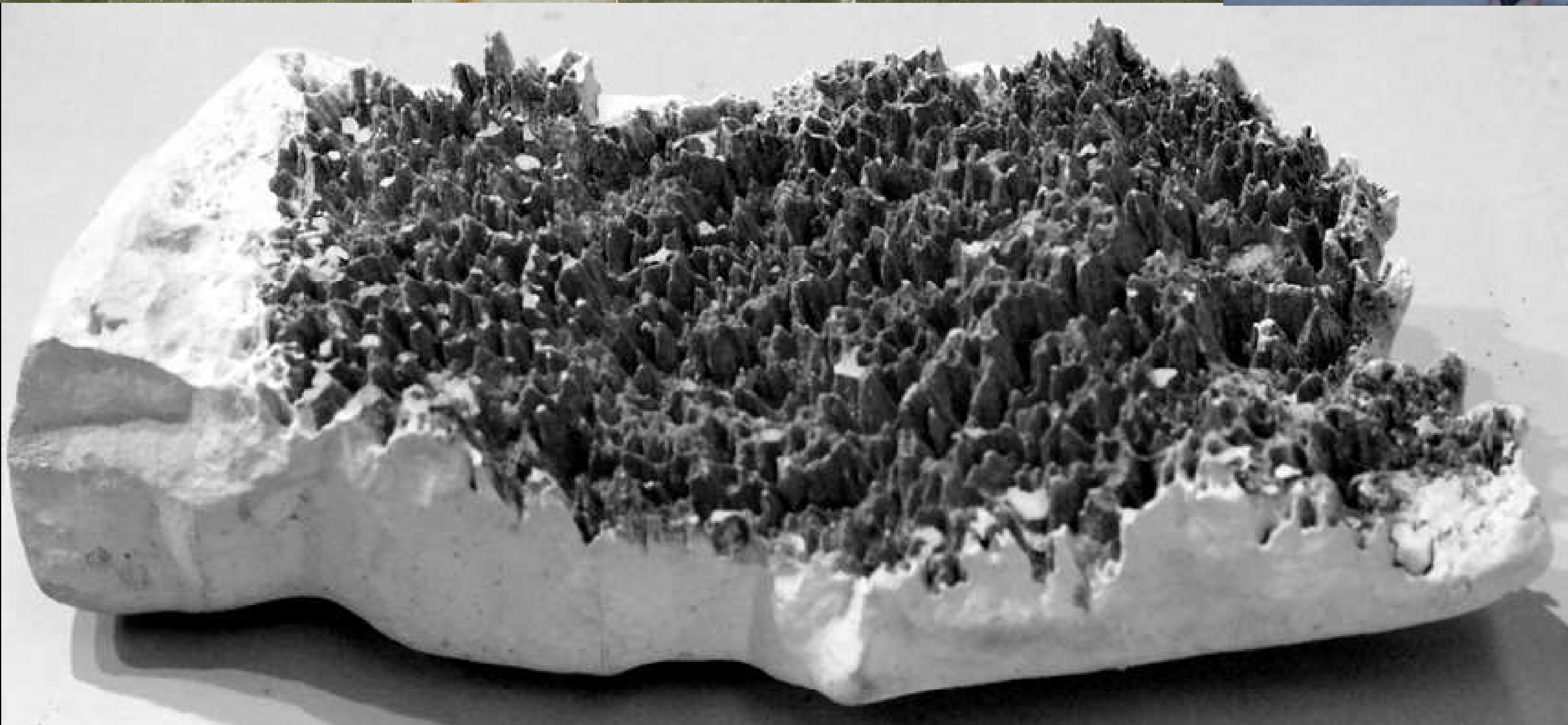
Stylolites





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