experimental micro geomechanics

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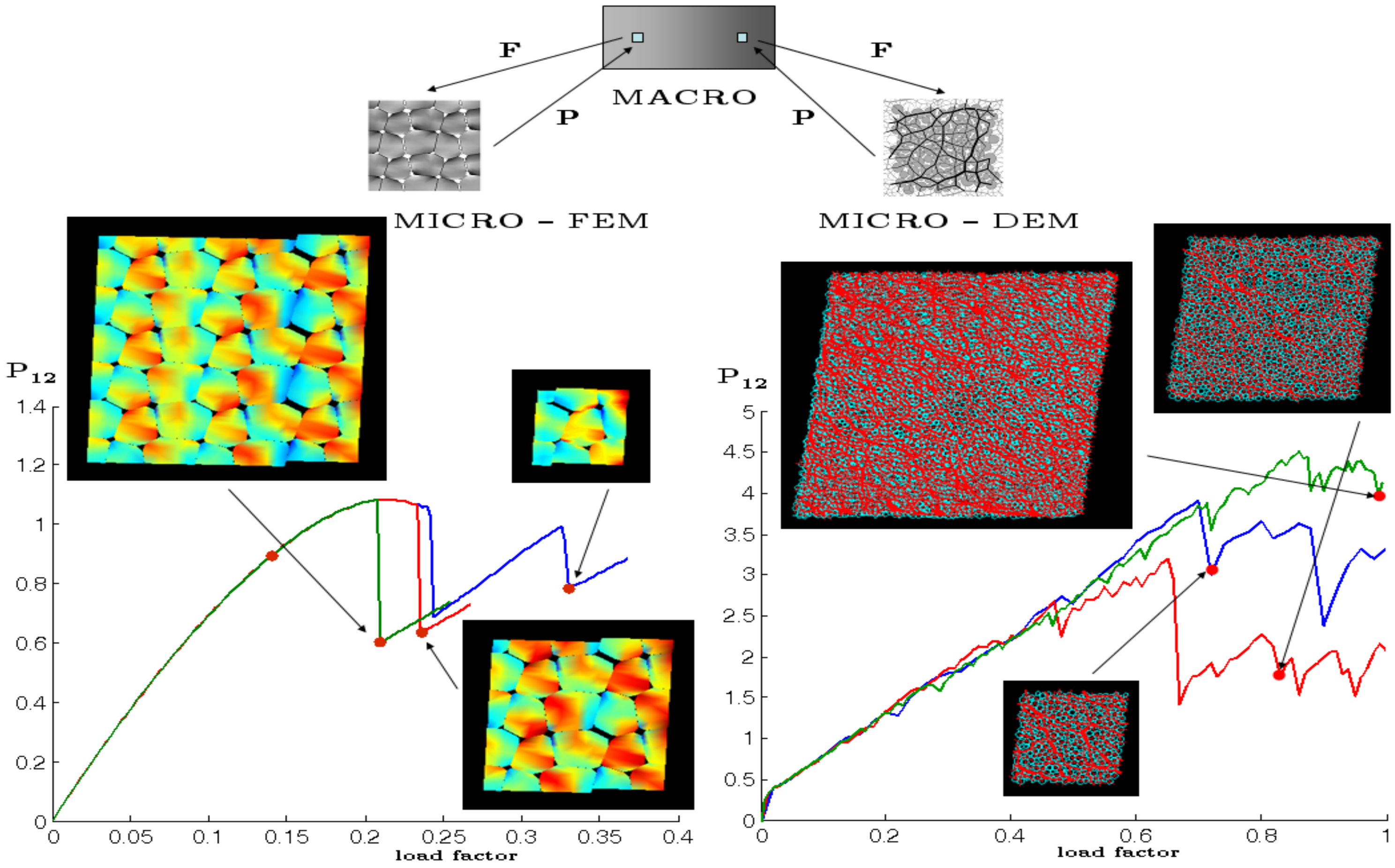
- why, what for
- the tools — full-field methods
  - camera + 2D DIC,
  - x-ray micro tomography + 3D DIC,
  - ID-Track
- examples of results — shear bands in sand, other ongoing work

the mechanical behavior of geomaterials (in particular: localized damage, localized strain and fractures) is inherently multi-scale

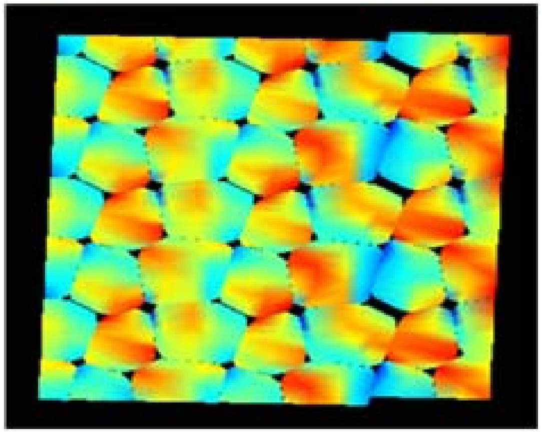
↓

adopt an explicit multi-scale (say two-scale) approach both in the modeling and in the experiments

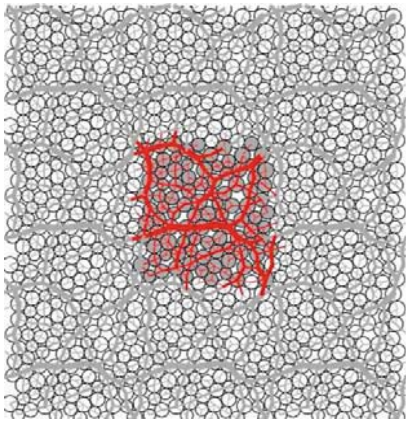
numerical homogenization



the key question: which "micro" structure?



PhD Jeremy Frey, 2010
PhD Nando Marinelli



PhD Michael Nitka, 2010
PhD Kien Trung Nguyen

→ for this approach to be effective, we need:

• an appropriate microstructure

• ideas as for how such microstructure evolves
material → process, i.e., understanding the mechanims

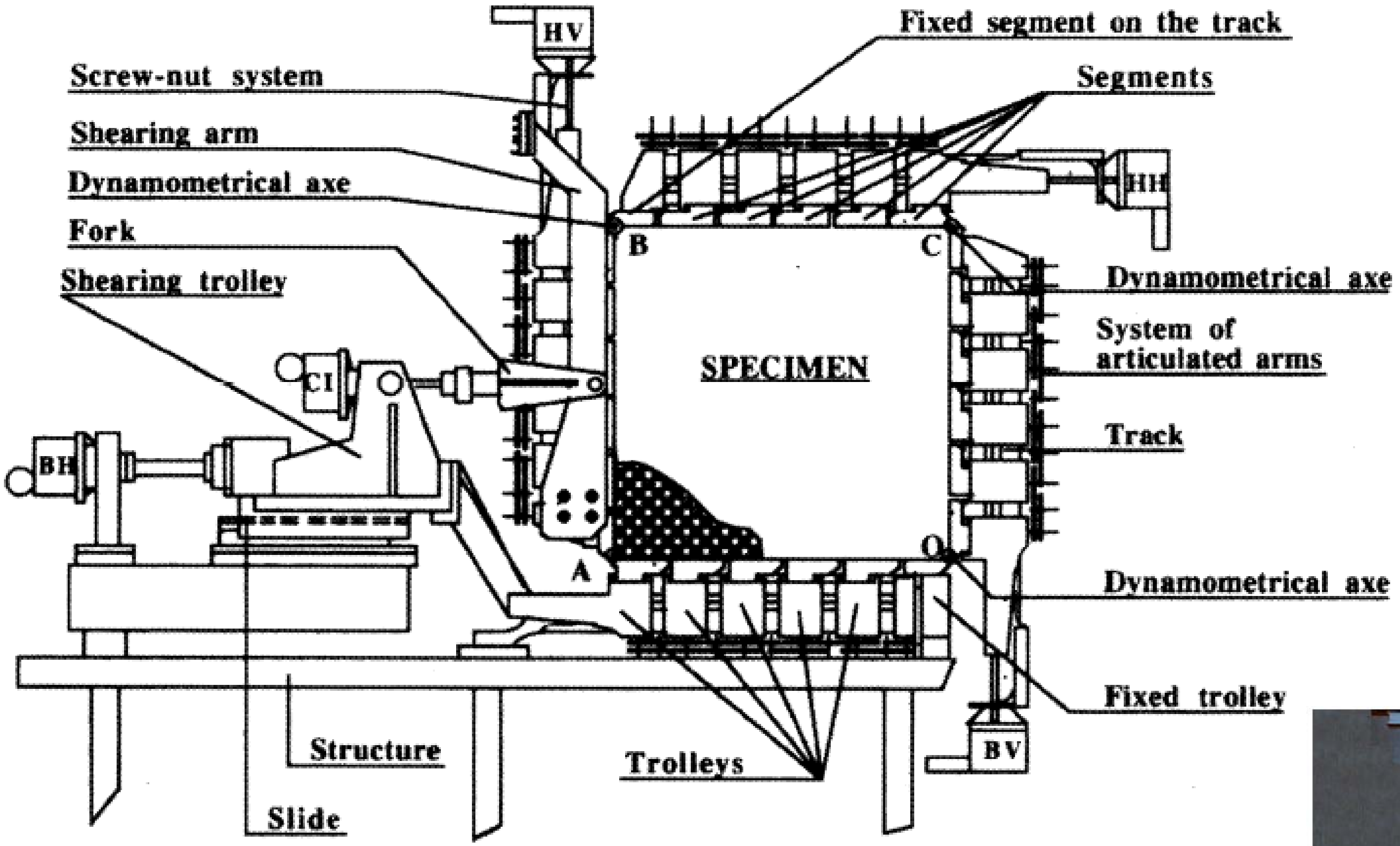
here come the experiments

The development of discrete element methods (DEM) provided powerful and flexible investigation tools. On the other hand, this has had the unfortunate effect that relatively few attempts have been made to develop finely-tuned experimental techniques for microscale investigations of granular materials. This has lead to the paradox of micromechanics of granular materials as a science based almost entirely on "virtual evidence".

Sibille & Froiio, Granular Matter 2007

the 1γ2ε apparatus in Grenoble

H. Joer, J. Lanier, J. Desrues and E. Flavigny, '1γ2ε: a new shear apparatus to study the behavior of granular materials', *Geotech. Testing J.*, **15**(2), 129–137 (1992).



assemby of rods: a 2D granular material

Schneebeli 1956: Une analogie mécanique pour les terres sans cohésion

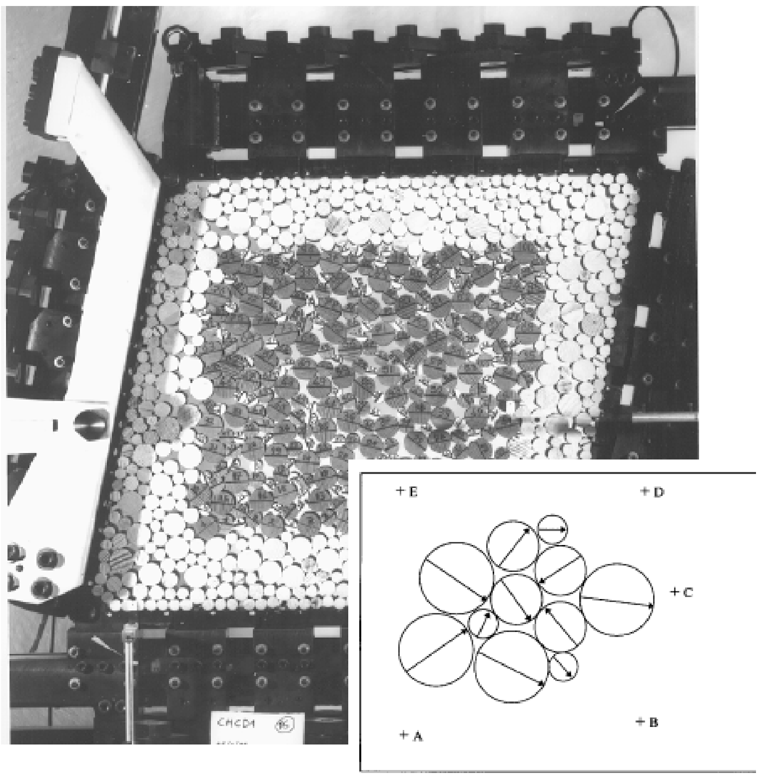
MECHANICS OF COHESIVE-FRICTIONAL MATERIALS, VOL. 2, 121–163 (1997)

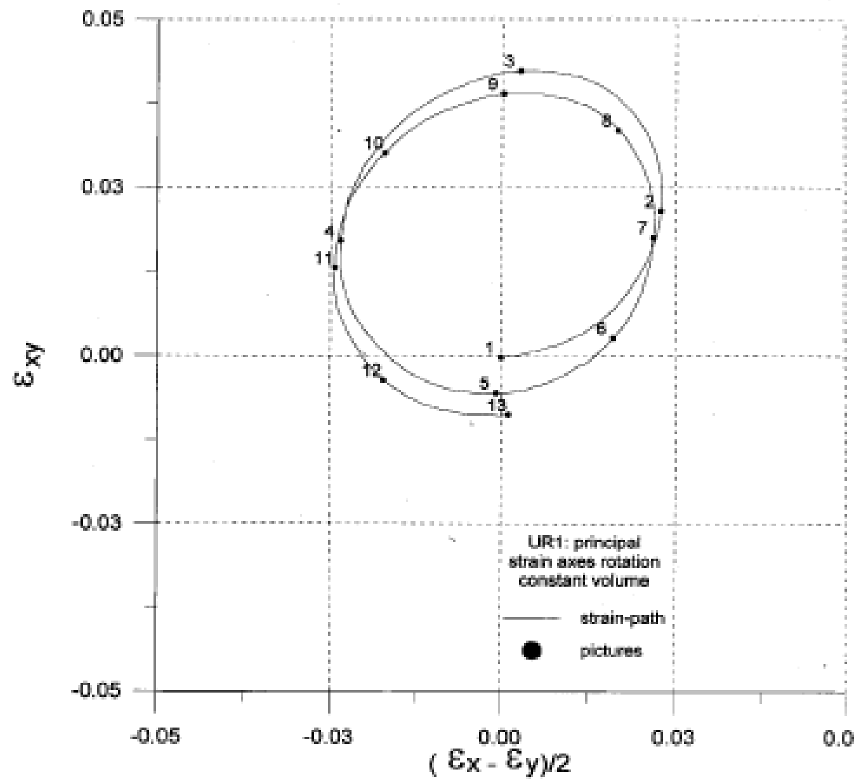
Experimental micromechanical analysis of a 2D granular material: relation between structure evolution and loading path

F. Calvetti[1], G. Combe[2] and J. Lanier[2]

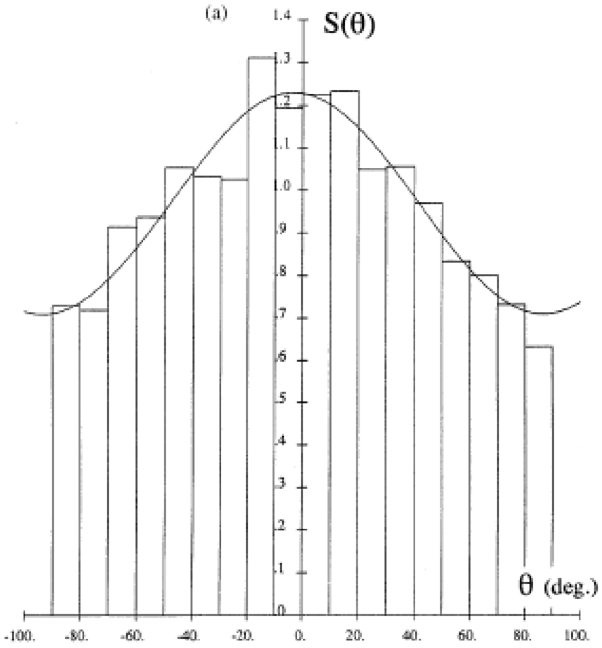
[1]*Politecnico di Milano, Milano, Italy*

[2]*Université J. Fourier, Grenoble, Laboratoire 3S-IMG, B.P.53, 38041 Grenoble, France*

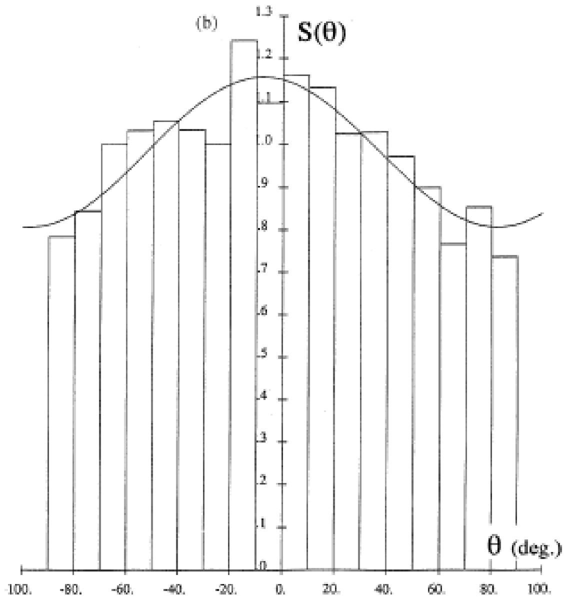




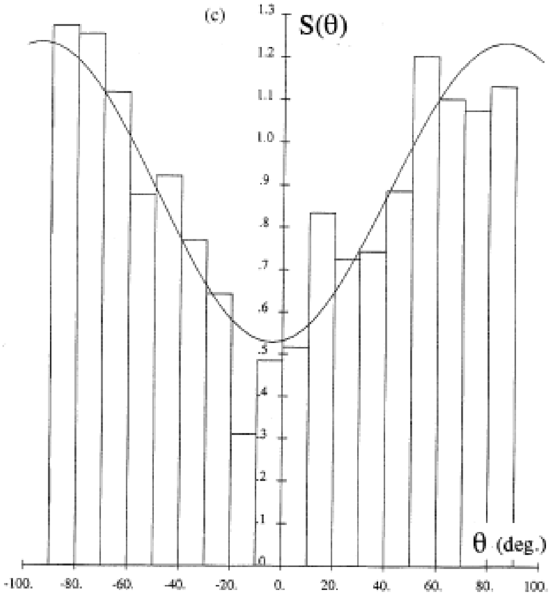
just one example from Calvetti et al. 1997



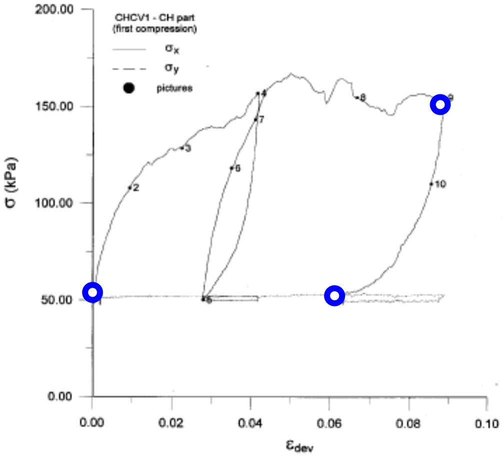
horizontal compression



unloading to isotropic stress



vertical compression

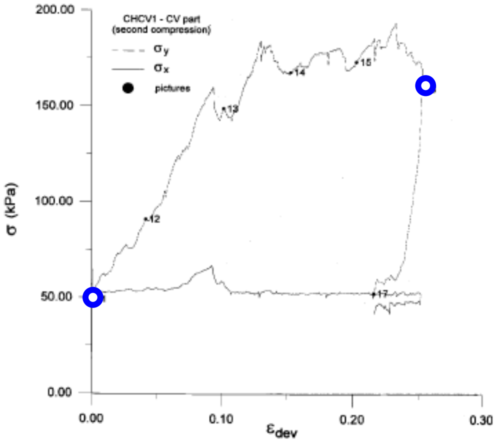


$$S(\theta) = \frac{N_j(\theta)}{N_i(\theta)} = 1 + \frac{\Delta N(\theta)}{N_i(\theta)}$$

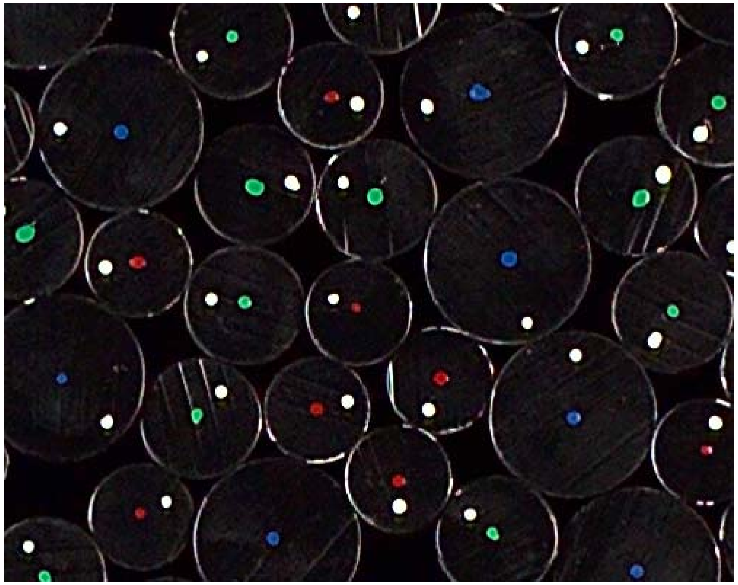
S(θ): evolution of structure

S(θ) < 1 more contacts lost

S(θ) > 1 more contacts gained



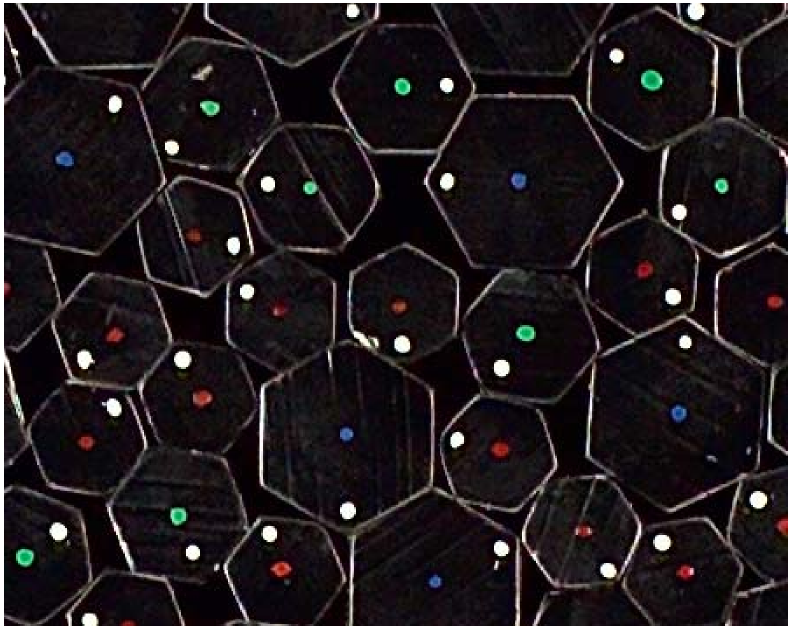
effect of particle shape: rotations and couple stresses



three sizes: 14 mm, 16 mm, 22 mm

two sections: circular, hexagonal

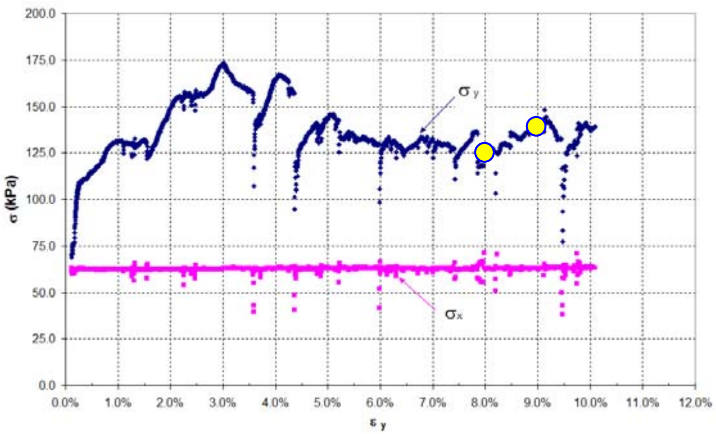
material: aluminium

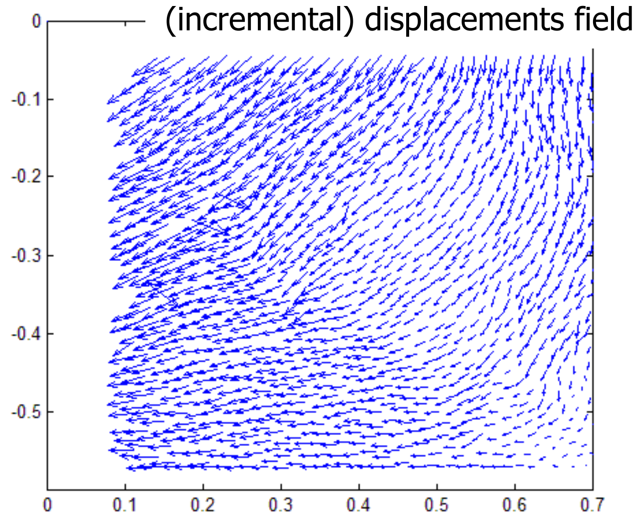


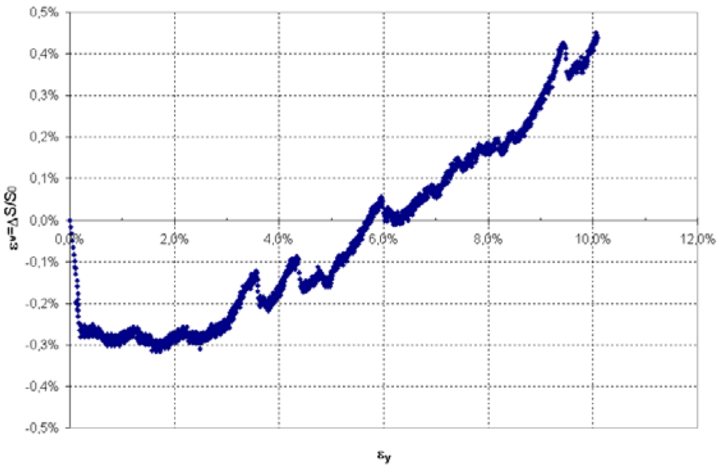
→ tracking particle displacements (including rotations) throughout a test

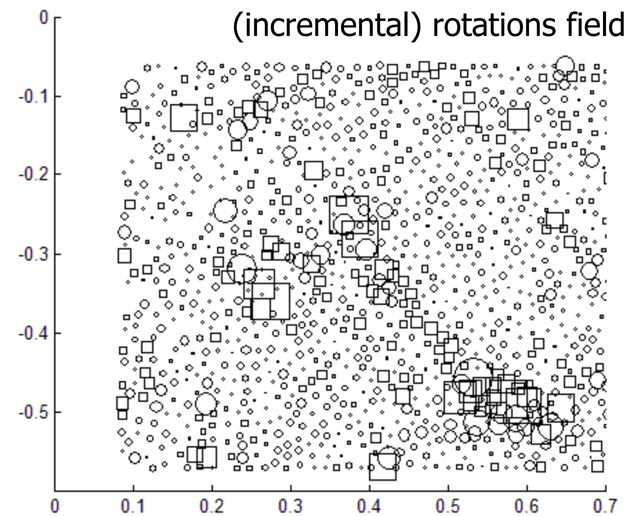
L. Sibille & F. Froiio (2007) - Numerical photogrammetry for translational and rotational field measurements on Schneebeli material

Lirer S., Flora A., Viggiani G., Lanier J. (2007) Proc. 18th Engineering Mechanics Division Conference (EMD2007)





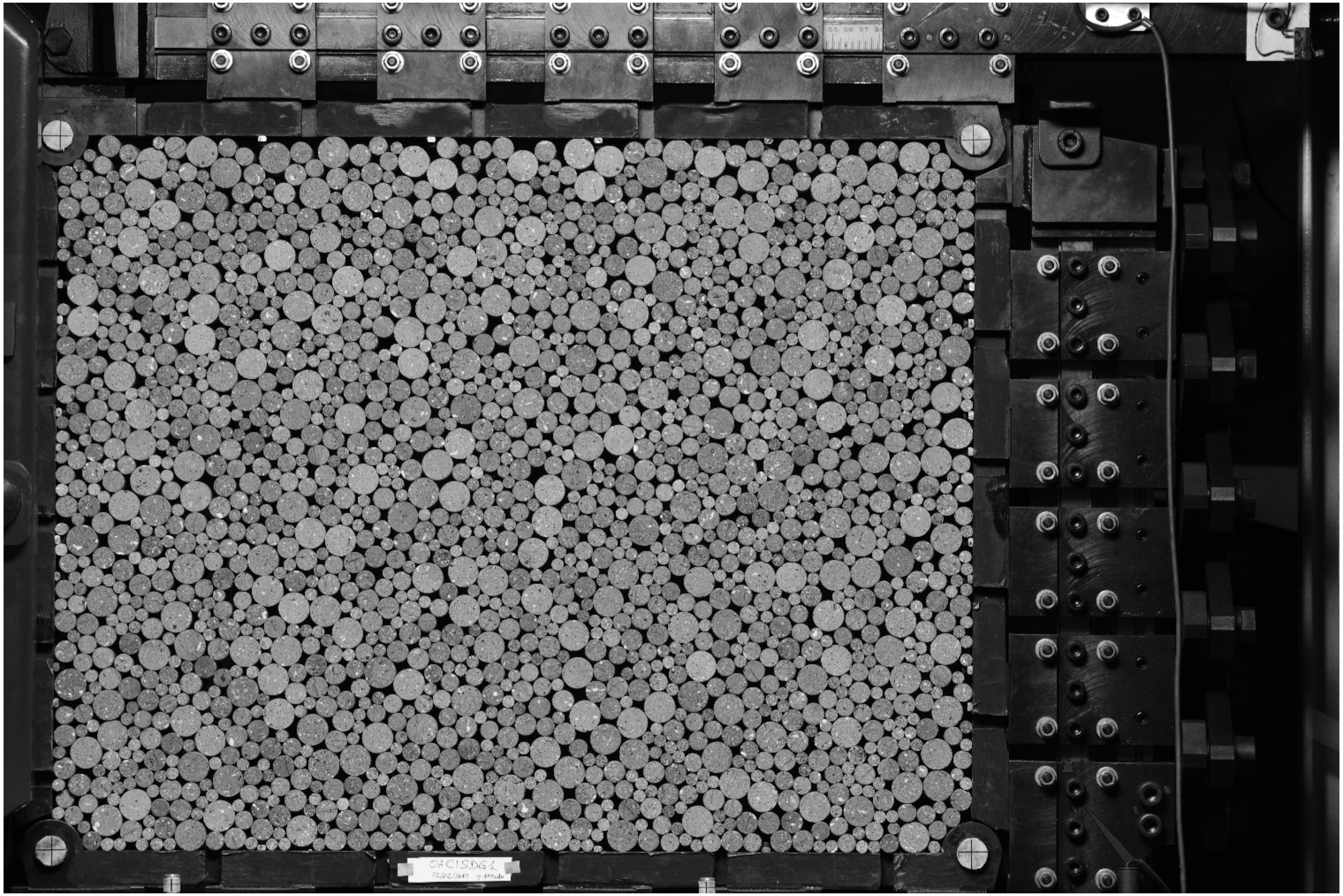




Lirer S., Flora A., Viggiani G., Lanier J. (2007) Proc. 18th Engineering Mechanics Division Conference (EMD2007)

“new" results – digital cameras + individual particle tracking

fluctuations in quasi-static deformation of granular media



Alessandro Tengattini’s Masters thesis (2010) – G. Combe, V. Richefeu, S. Hall

"new" results – digital cameras + individual particle tracking

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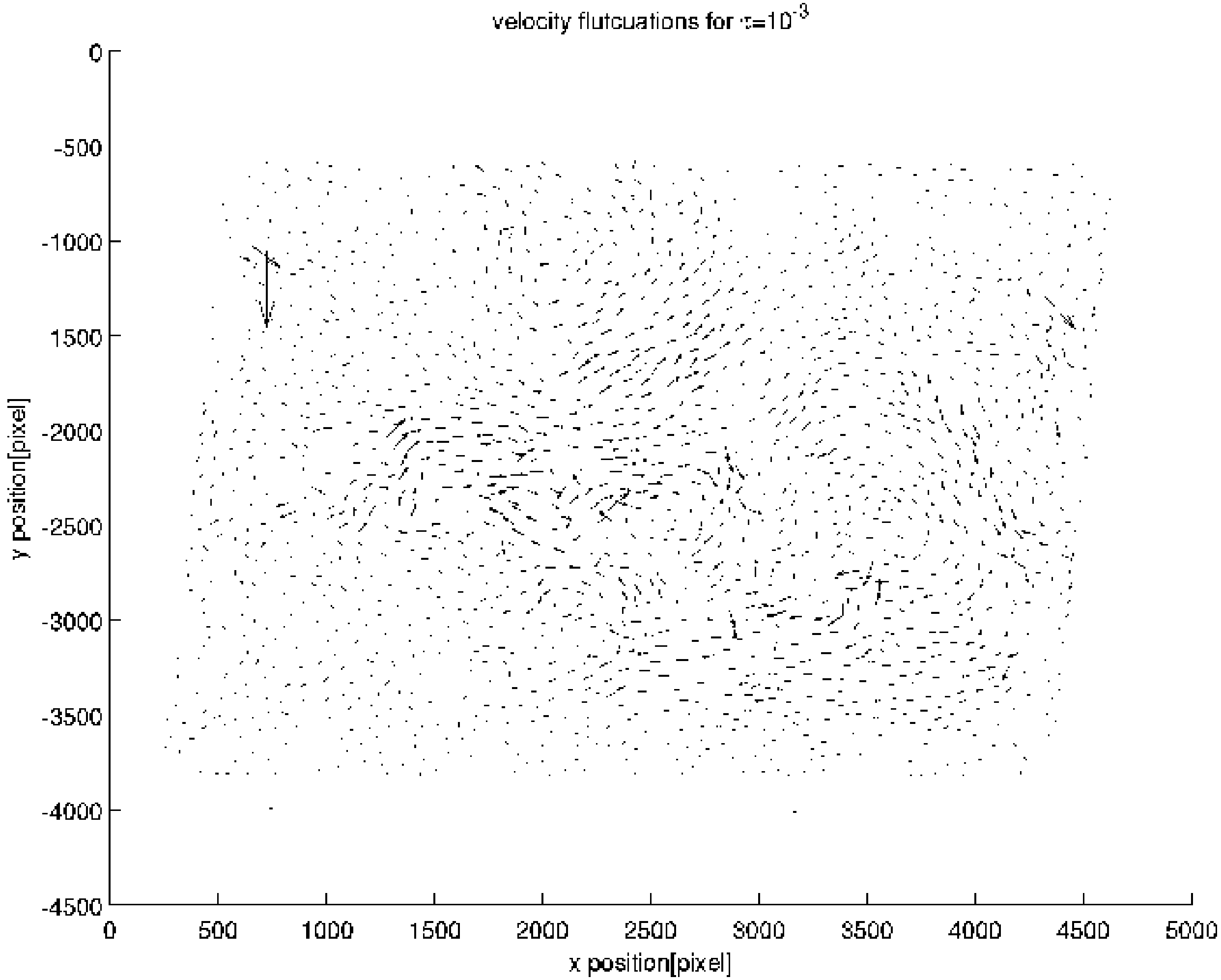


Alessandro Tengattini's Masters thesis (2010) – G. Combe, V. Richefeu, S. Hall

OK, but this is for 2D analogue granular materials…

can we look at the behavior of 3D real granular materials?

yes – for example by using x-ray micro tomography

flying into a sand specimen

digisens

voxel size = 16 μm mean grain size ≈ 0.3 mm

where do we get the x-rays?

synchrotron source

lab scanner

key advantages:

short scanning time

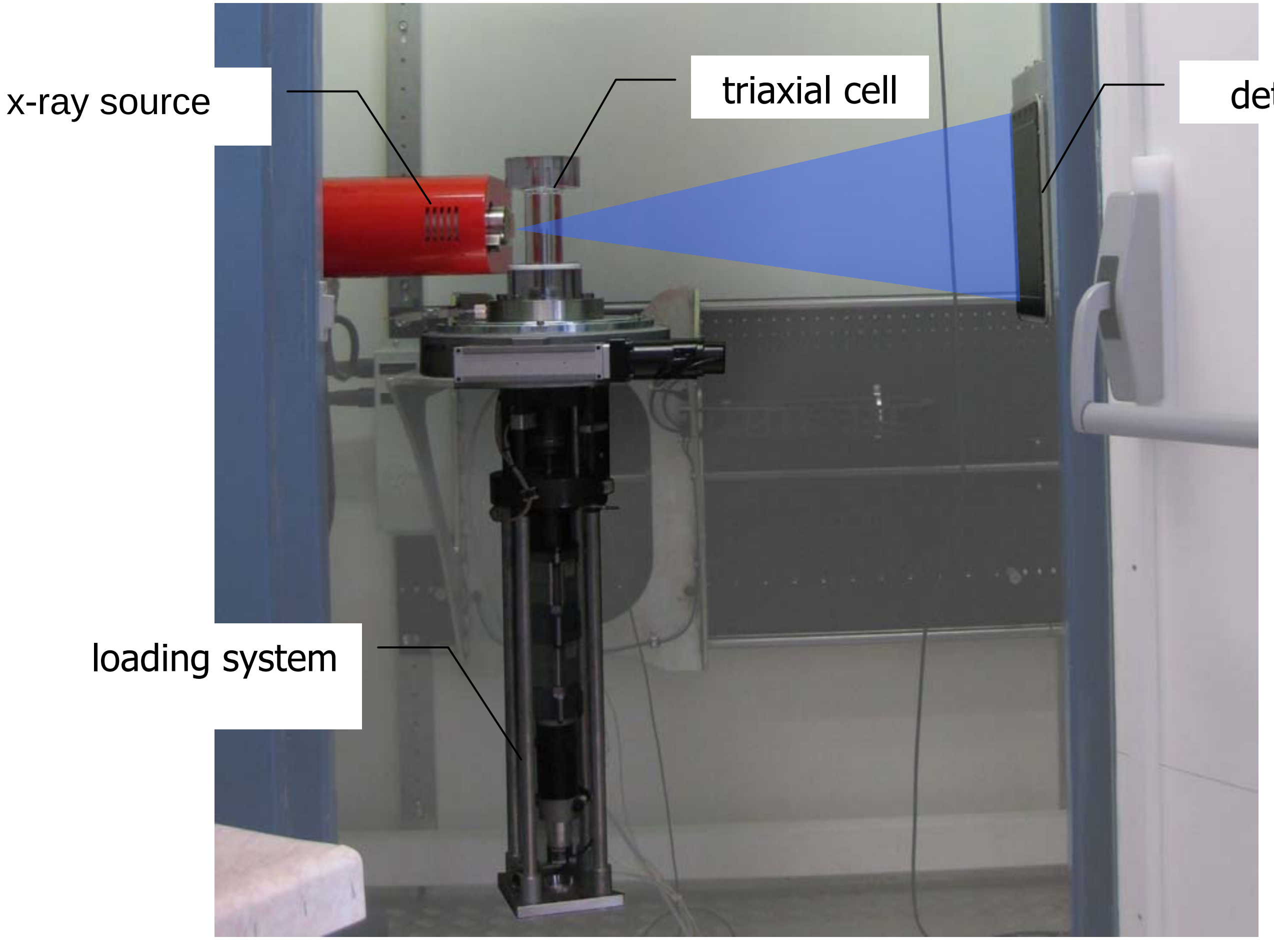
high resolution

spatial resolutions rivals the synchrotrons'

(albeit with significantly slower scanning times) multiscale (variable magnification):

Ø 4 mm ⇨ ≈ 5 µm voxel width   Ø 210 mm ⇨ ≈ 220 µm voxel width

→ adaptability to image the physics of materials at the pertinent scale(s)



tremendous possibilities now available in experimental geomechanics

↓

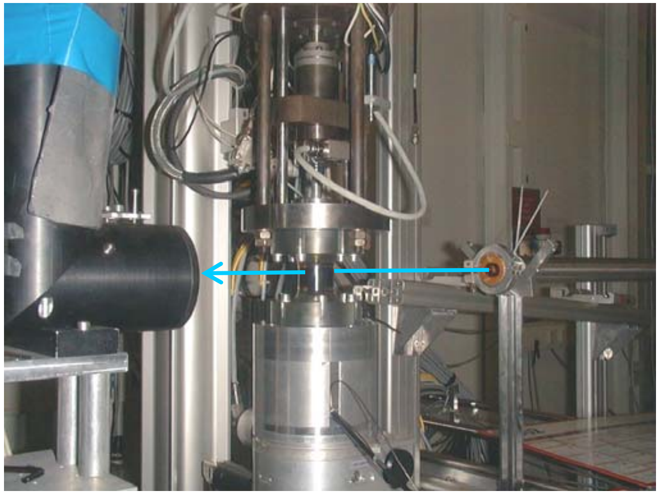
access to behaviour at unprecedently small scales

what is the scale that can be looked at?

vs.

what is the scale we want to look at?

moreover, we can look
inside a specimen (at an appropriately small scale)
while it deforms under load



in-situ x-ray micro tomography

+

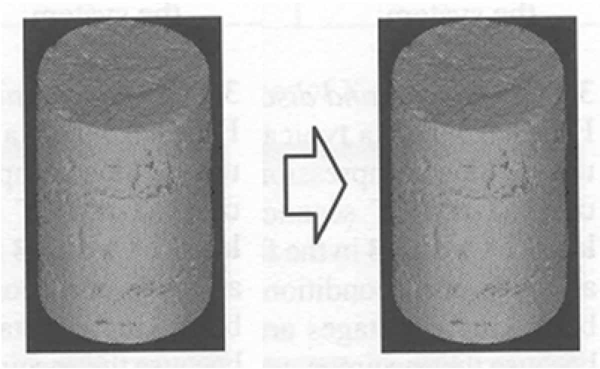
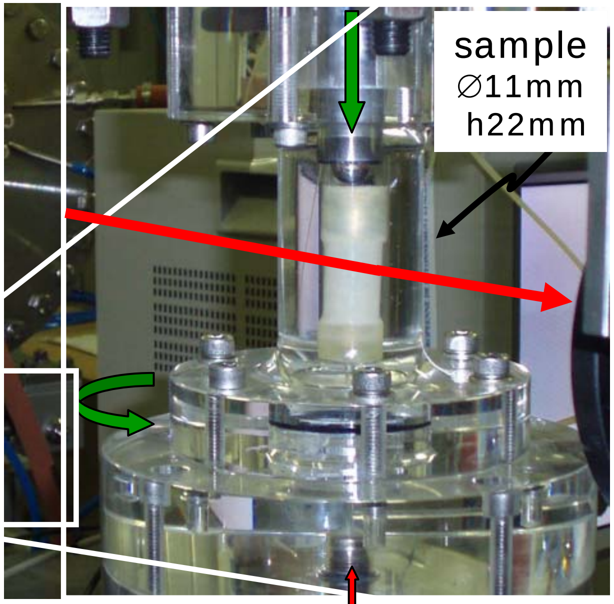
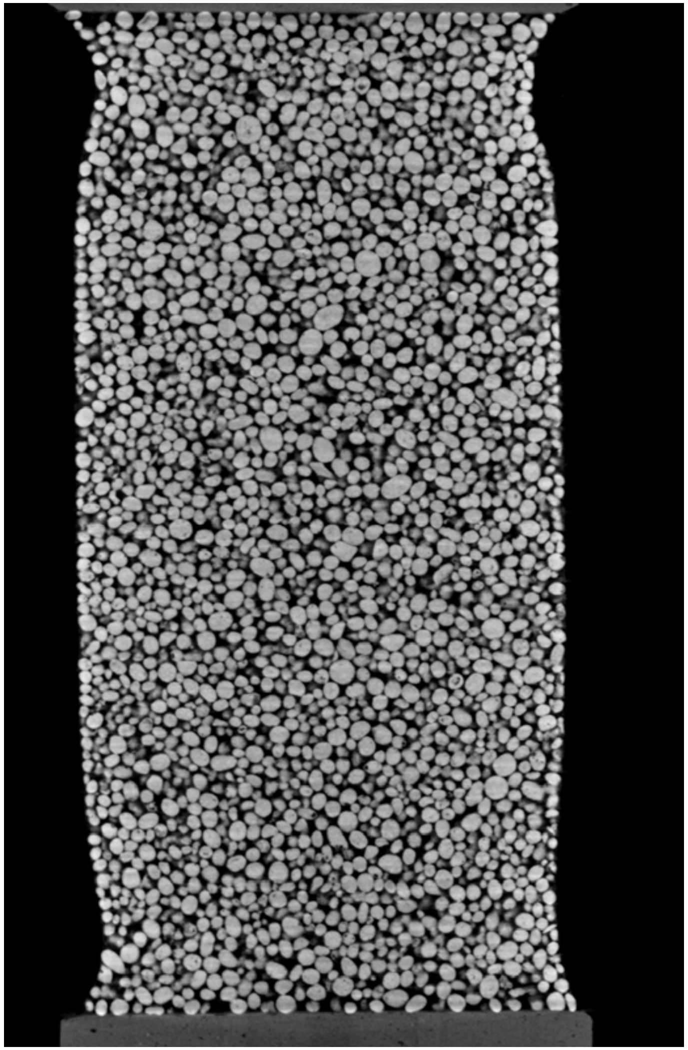


image analysis
(3D volume DIC, Particle Tracking)

→ how small is "small" ?

for sand, we need to see the individual grains





example 1

strain localization in sand

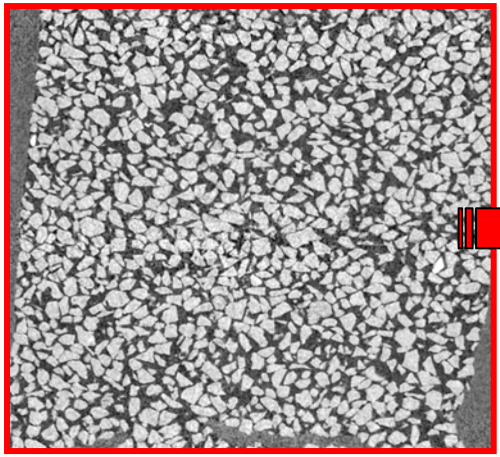
(down to the grain scale)

imaging

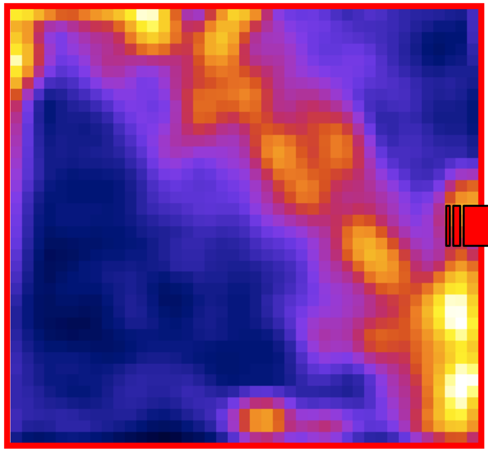
evolution (both in space and time) of deformation with grain-scale resolution for a sand undergoing triaxial compression

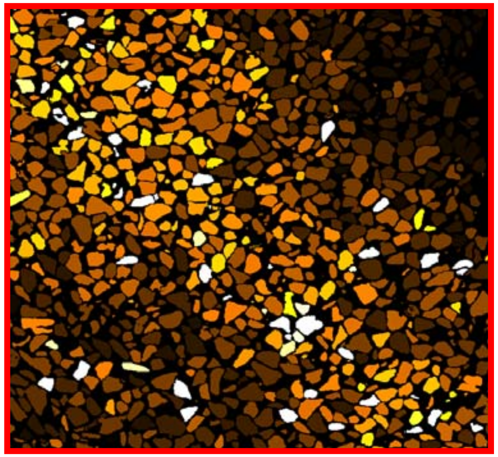
combining

- 3D *in-situ* synchrotron X-ray micro tomography
- 3D-volumetric digital image correlation (DIC)
  - ➢ Continuum approach (strain)
  - ➢ Discrete approach (full 3D grain kinematics)



3D *in-situ* synchrotron X-ray micro tomography





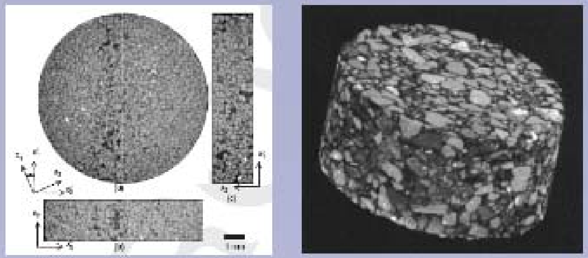
• 3D-volumetric DIC

➢ shear strain fields

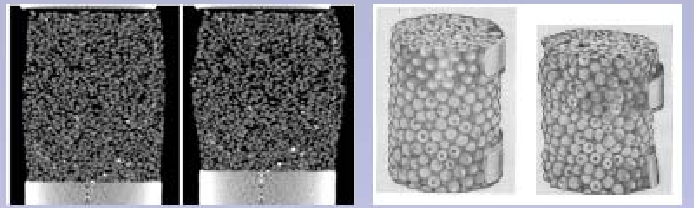
➢ grain kinematics

previously with x-rays...

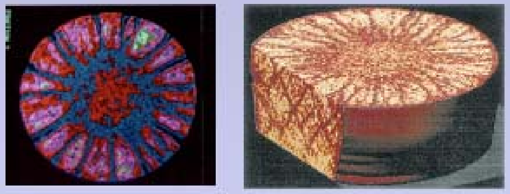
x-ray imaging of the grain-scale detail of granular materials (e.g., Oda et al. 2004, Wang et al. 2004, Matsushima et al. 2006)



in-situ grain-scale imaging during deformation
(e.g., Matsushima et al. 2006, Alshibli & Alramhi 2006)

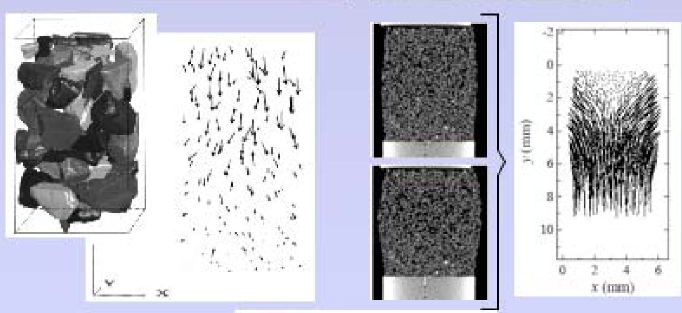


low resolution x-ray tomography dilatant bands without grain-scale detail (e.g., Desrues et al. 1996, Alshibli et al. 2000, 2003)

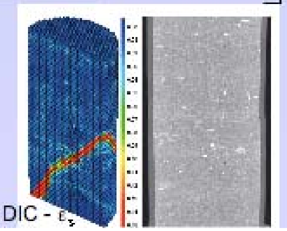


characterisation of particles' kinematics from in-situ x-ray CT

- "man-made" materials (e.g., Alshibli & Alramhi 2006, Chang et al. 2003)
- large grains (e.g., Fu et al. 2008)
- 2D-PTV for slice through a 3D volume (Matshushima et al. 2006)



X-ray CT + 3D-DIC for fine-grained geomaterials
clay rock (Lenoir et al. 2006)



… let's go high tech: synchrotron radiation micro tomography!

high-energy beamline ID15A at the ESRF in Grenoble (European Synchrotron Radiation Facility – collaboration w/ M. di Michiel)

key advantages:

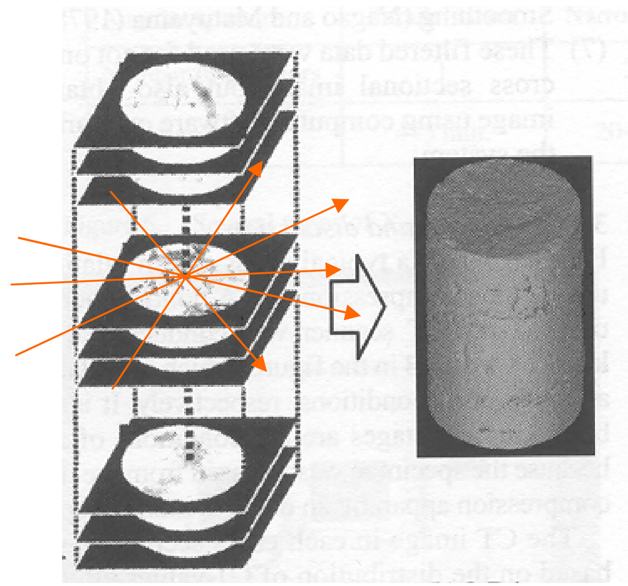
- ⇨ short scanning time
- ⇨ high resolution

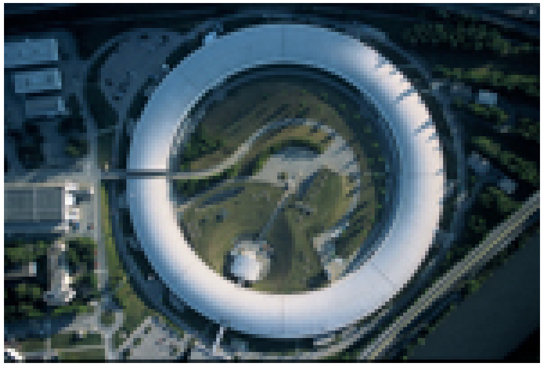
acquisition of the entire specimen takes about 12 mins (4 scans of overlapping vertical sections)

voxel size in the reconstructed volume is $14 \times 14 \times 14\ \mu m^3$

basic principle

- recording attenuation profiles through a specimen slice, under different angular positions
- reconstructing a radiograph of the slice
- repeating to get a complete set of slices over the specimen
- reconstructing a 3D image of the internal structure of the specimen from the spatial distribution of the linear attenuation coefficient



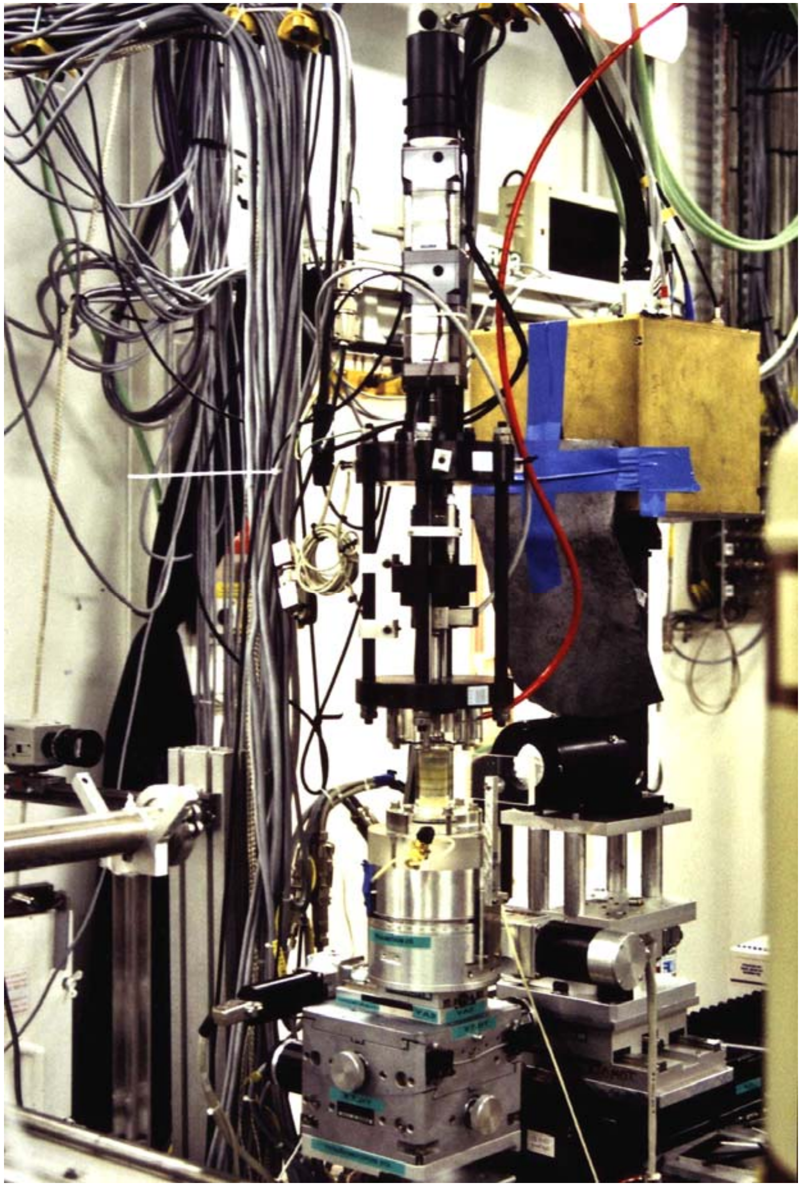


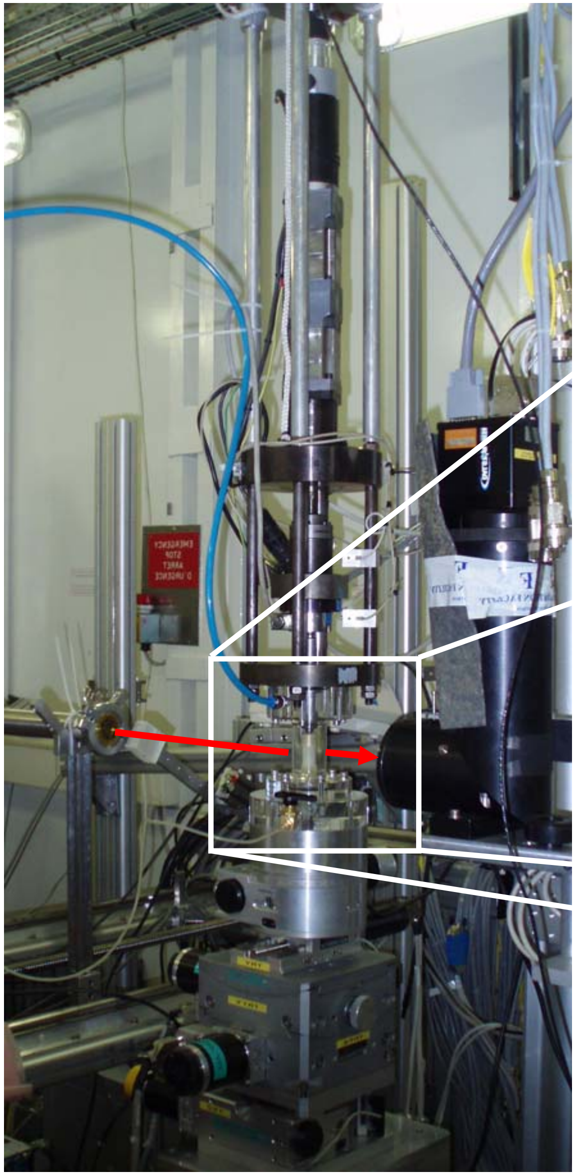
ESRF, Grenoble (France)

x-ray characteristics

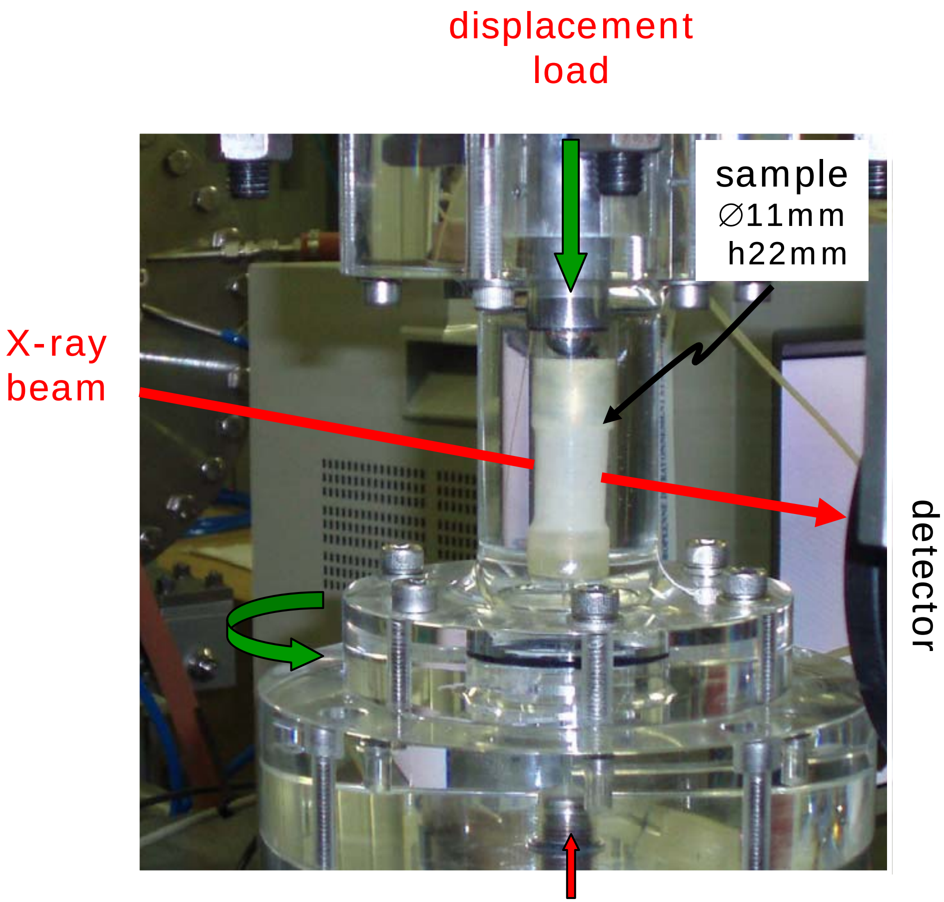
- x-ray white beam to have a high photon flux
- x-ray energy: 50 to 70 keV
- spatial resolution: 14 μm (voxel size)
- time for scanning: 12 to 15 minutes

experimental setup





in situ μtomography triaxial system



- confinement cell in plexi, capacity 1 MPa
- axial loading, max 7.5kN, min 1μm/min
- capable of drained/undrained conditions

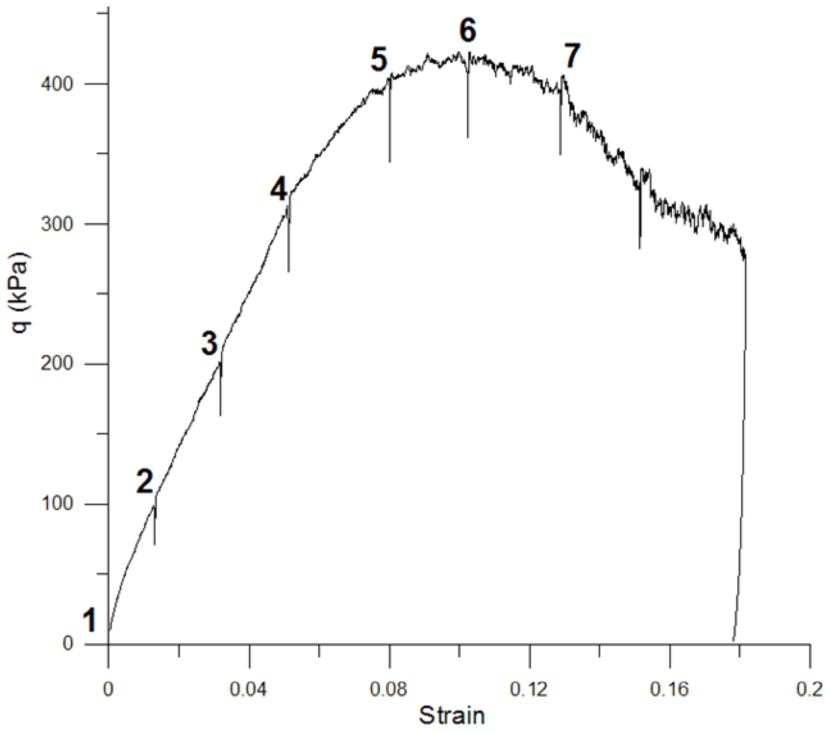
triaxial compression of Hostun sand

- fine-grained, angular siliceous sand
  $D_{50} \approx 300\ \mu m$

- dry specimen
- initially dense (e_0 about 0.65)
- cell pressure = 100 kPa

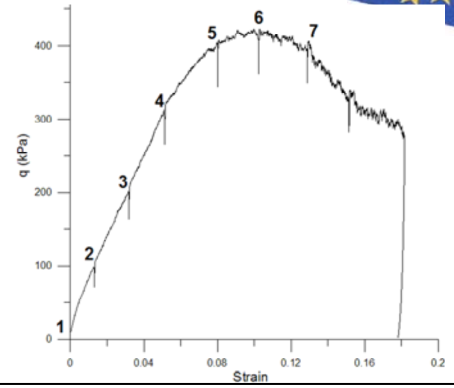
- sample dimensions: Ø11 x h22 mm
- total number of grains ≈ 50 000

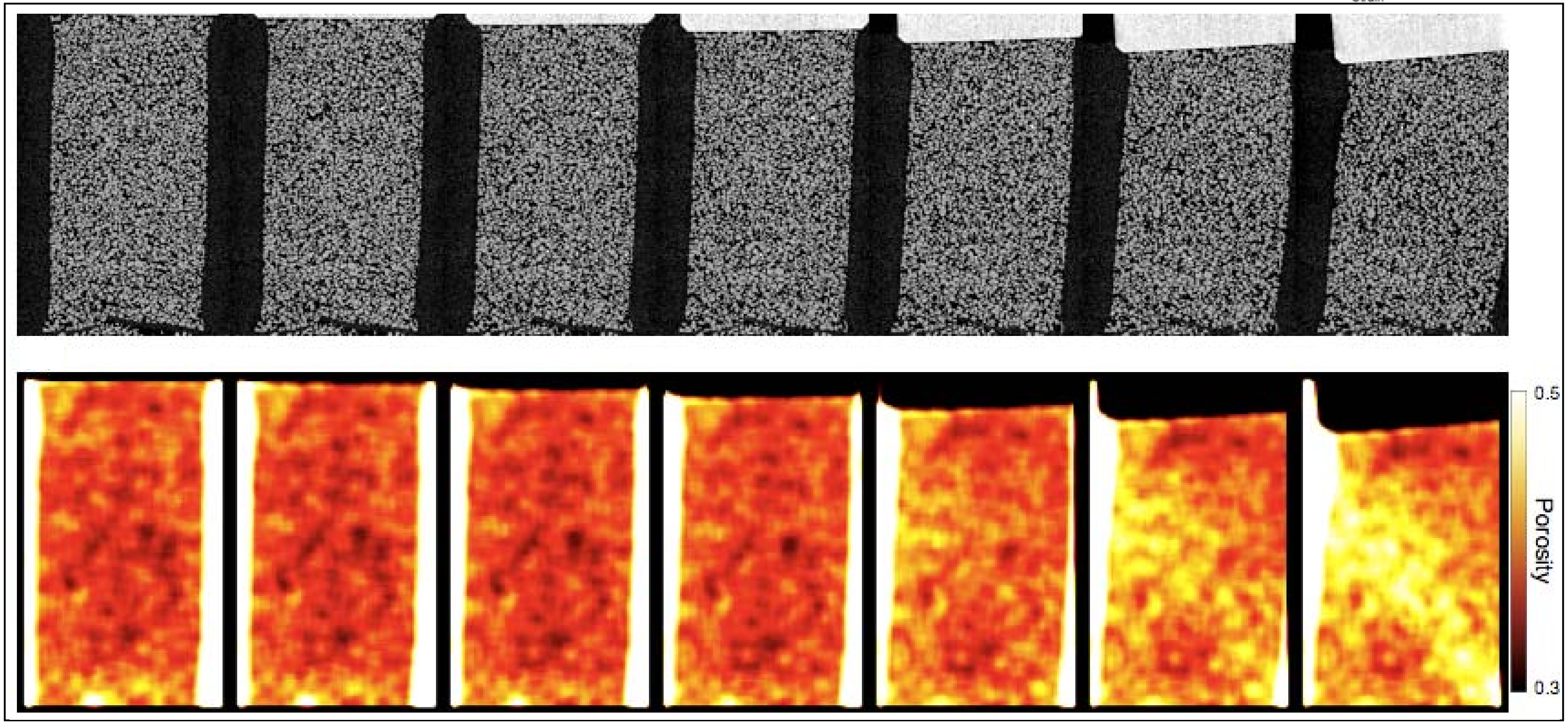
⇨ small but remains mechanically pertinent



X-ray tomography scans during loading: 1-7

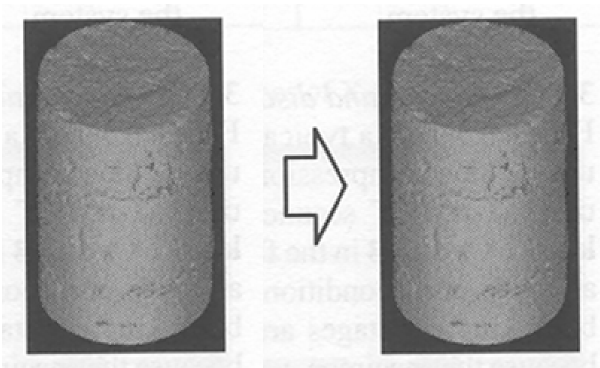
- x-ray tomography scans: 1-7
  - spatial resolution : 14 x 14 x 14 μm^3
    - mean grain size ≈ 20 voxels
    - volume of a grain ≈ 5500 voxels





vertical slices through middle of volume roughly perpendicular to localization

“classic” DIC (continuum approach)



two 3D images of specimen at different loading/deformation levels

displacement field with sub-pixel accuracy [dx, dy, dz])

strain field

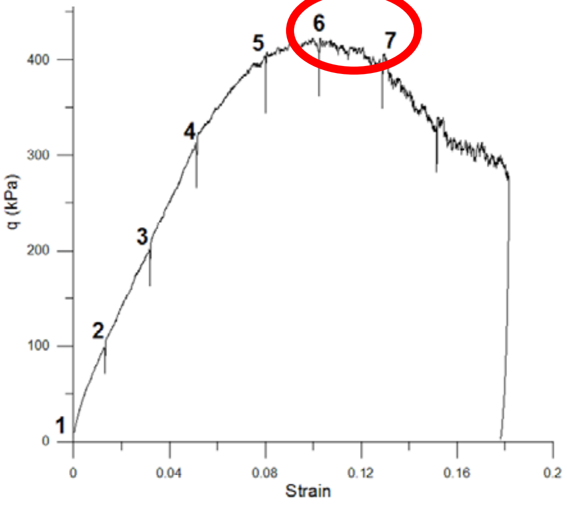
(in-house 3S-R codes “*TomoWarp*” / “*PhotoWarp*” - 3D/2D, S. Hall))

3D-DIC applied over entire specimen

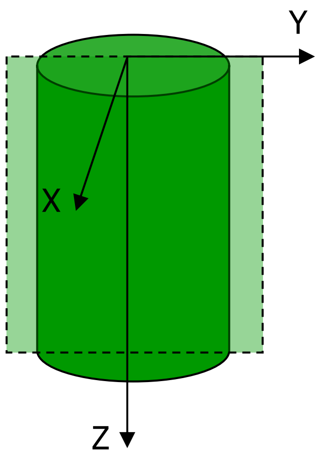
- spacing of DIC grid = 20 voxels
- correlation domain = 21 voxels^3 ≈ mean grain size

incremental analysis

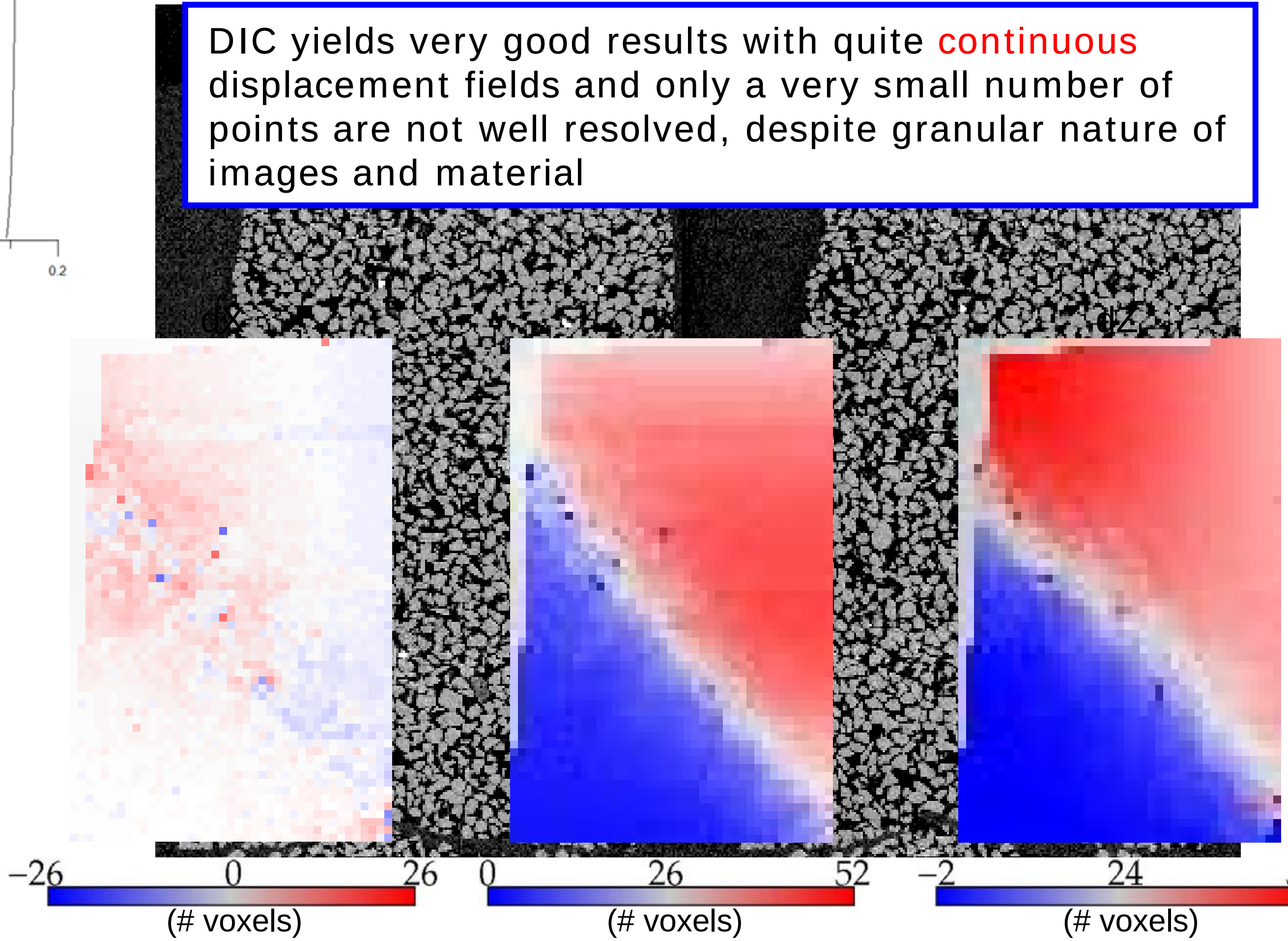
look at deformation at different stages of the test and thus identify development of strain localization

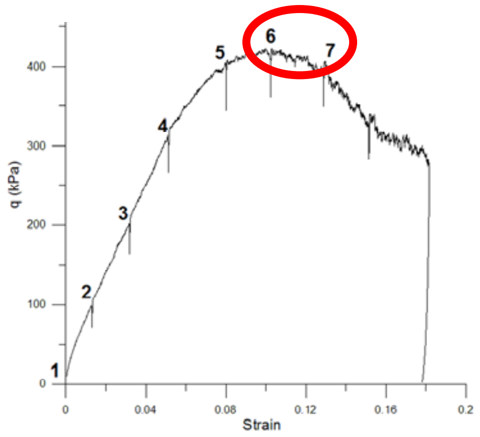


DIC yields very good results with quite continuous displacement fields and only a very small number of points are not well resolved, despite granular nature of images and material

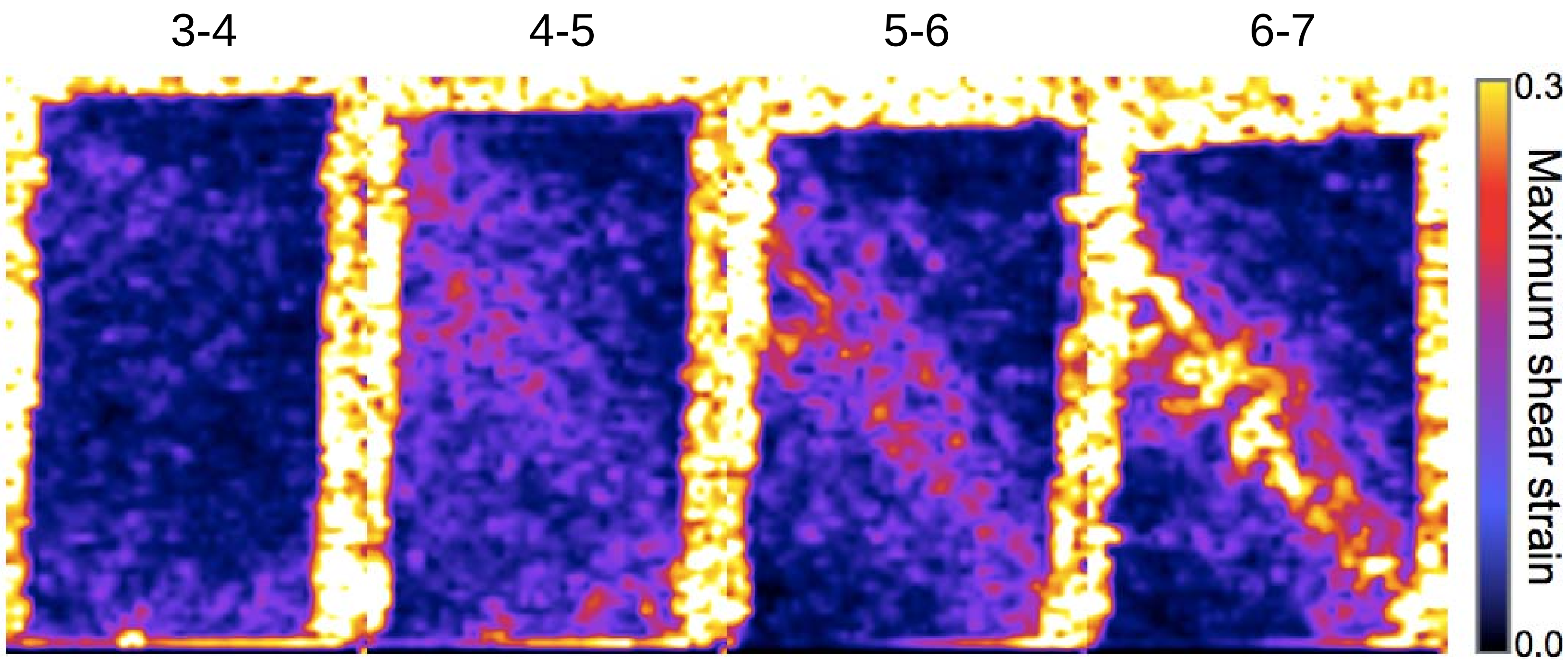


(vertical slices through middle of volume roughly perpendicular to localization)



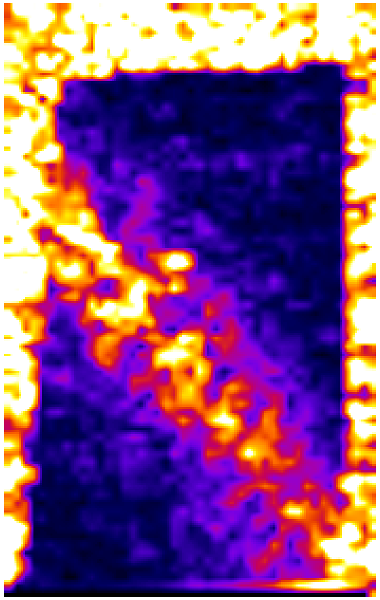


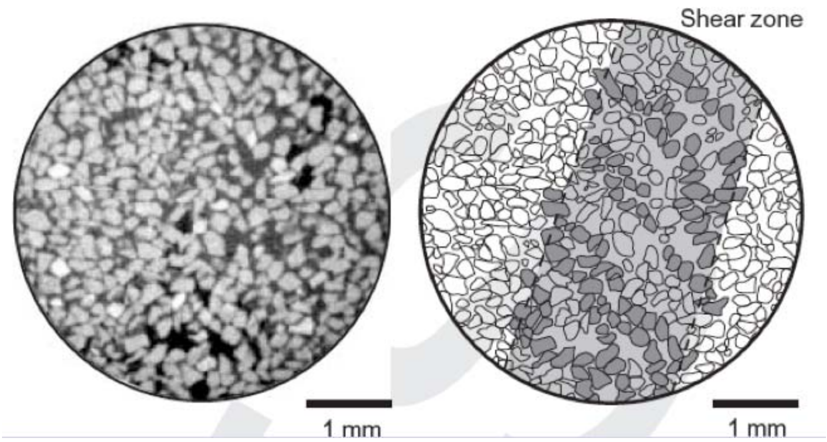
- shear strain localization initiated well before stress peak (step 4-5) and is well localized before peak (step 5-6)
- in step 6-7, strain is highest in the central part of the band: is it a “condensation” from a very diffuse, wide band in step 4-5 to a very focused band in step 6-7 ?
- band width is around 5 mm (17 D_{50}) in step 6-7 , but with a narrower, high strain core (convergence over the increment to the “true” final width?)



a few observations

- localization zone is not uniform (it shows a degree of "structure")
- aligned zones both of reduced and elevated strains: conjugated bands to the main band ?
- is it consistent with "columns" of aligned grains in a shear band ?



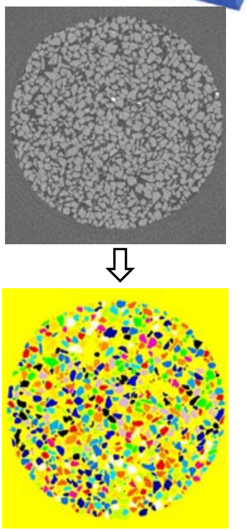


Oda et al. [2004]

- "continuum" DIC analysis works
  what about the relative displacements and rotations between individual grains
  ⇨ grain-focused, discrete DIC

❶ “classic” DIC
→ initial estimate of a displacement *[dx,dy,dz]* for each grain

❷ image segmentation
→ grain-mask to define grain-shape correlation domains (3 voxels expansion to capture grain boundary)



discrete DIC (collaboration w/ LMS, Palaiseau)

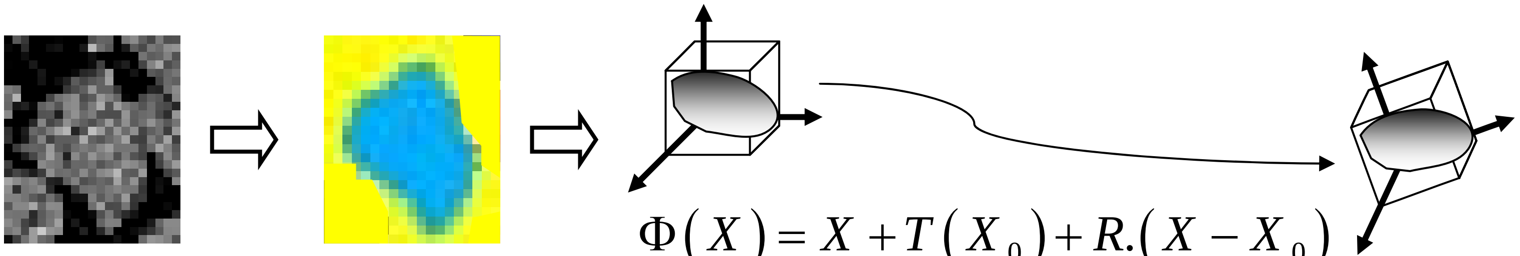
- “grain shape” correlation domain centered on each grain (from ❷)
- initial estimate of displacements from classic DIC results (from ❶)

⇩

sub-voxel refinement
(6 parameters: 3 displacements + 3 rotations)

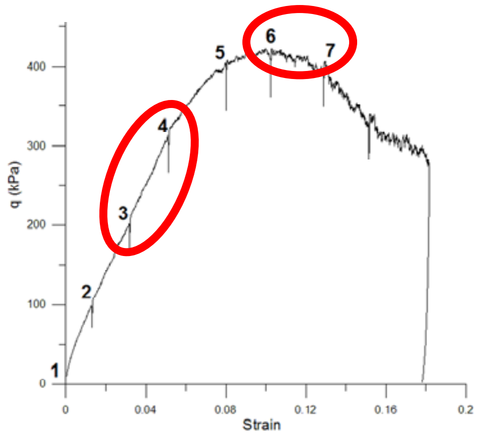
⇩

full grain kinematics for each grain

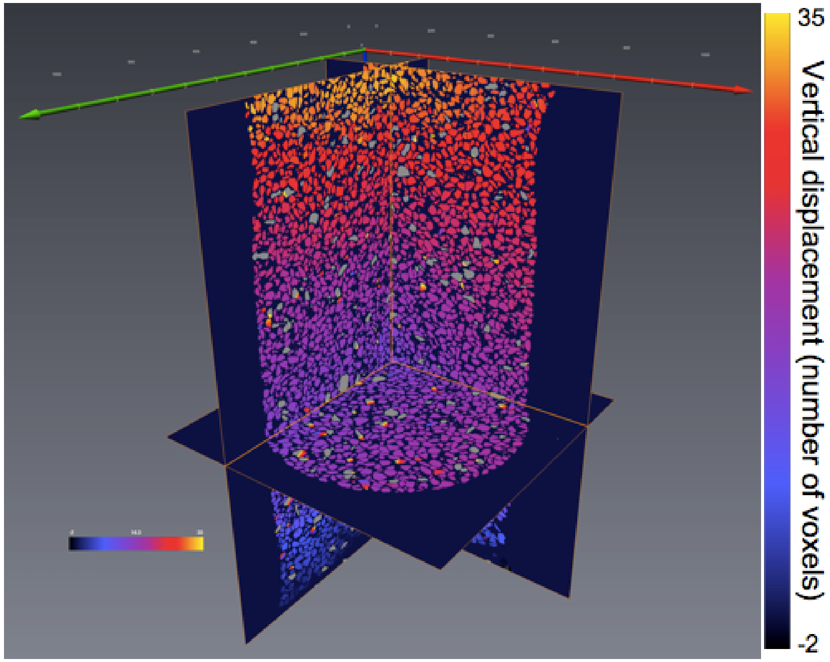


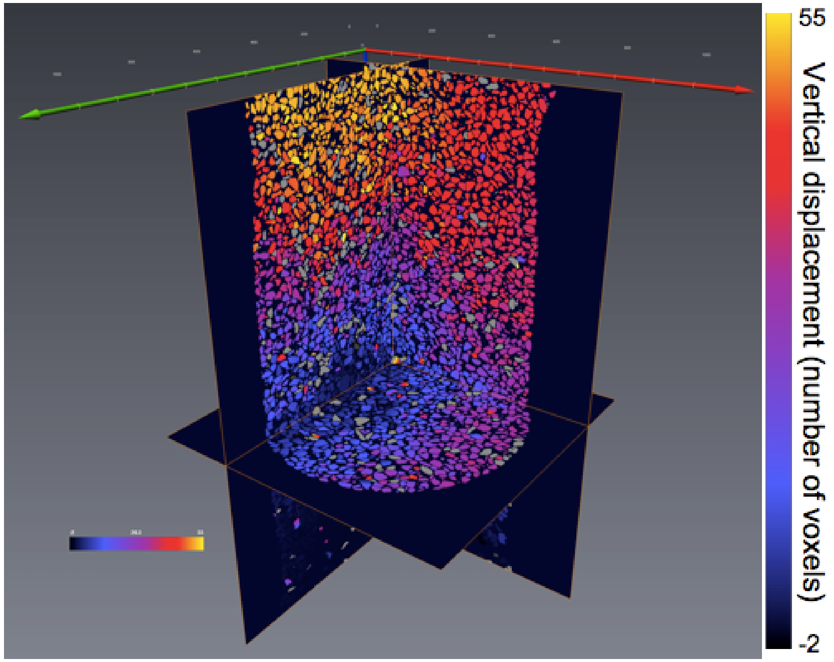
$$\Phi\left(\underline{X}\right) = \underline{X} + \underline{T}\left(\underline{X}_0\right) + \underline{\underline{R}}.\left(\underline{X} - \underline{X}_0\right)$$

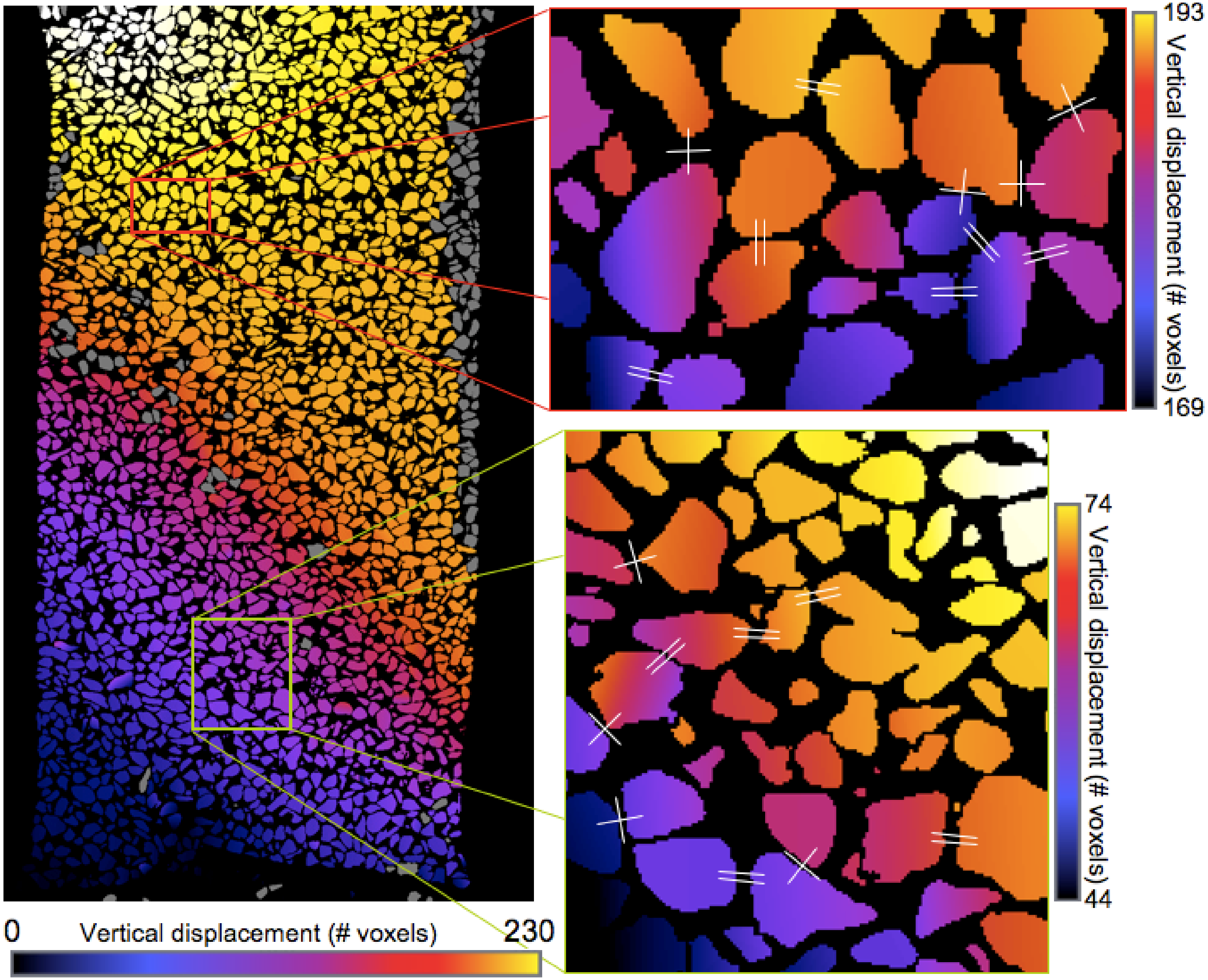
3D grain displacement field



Despite these results having been derived from a discrete analysis, they indicate a relatively continuous field of displacements, even in the presence of strain localization, which explains why continuum V-DIC performs well



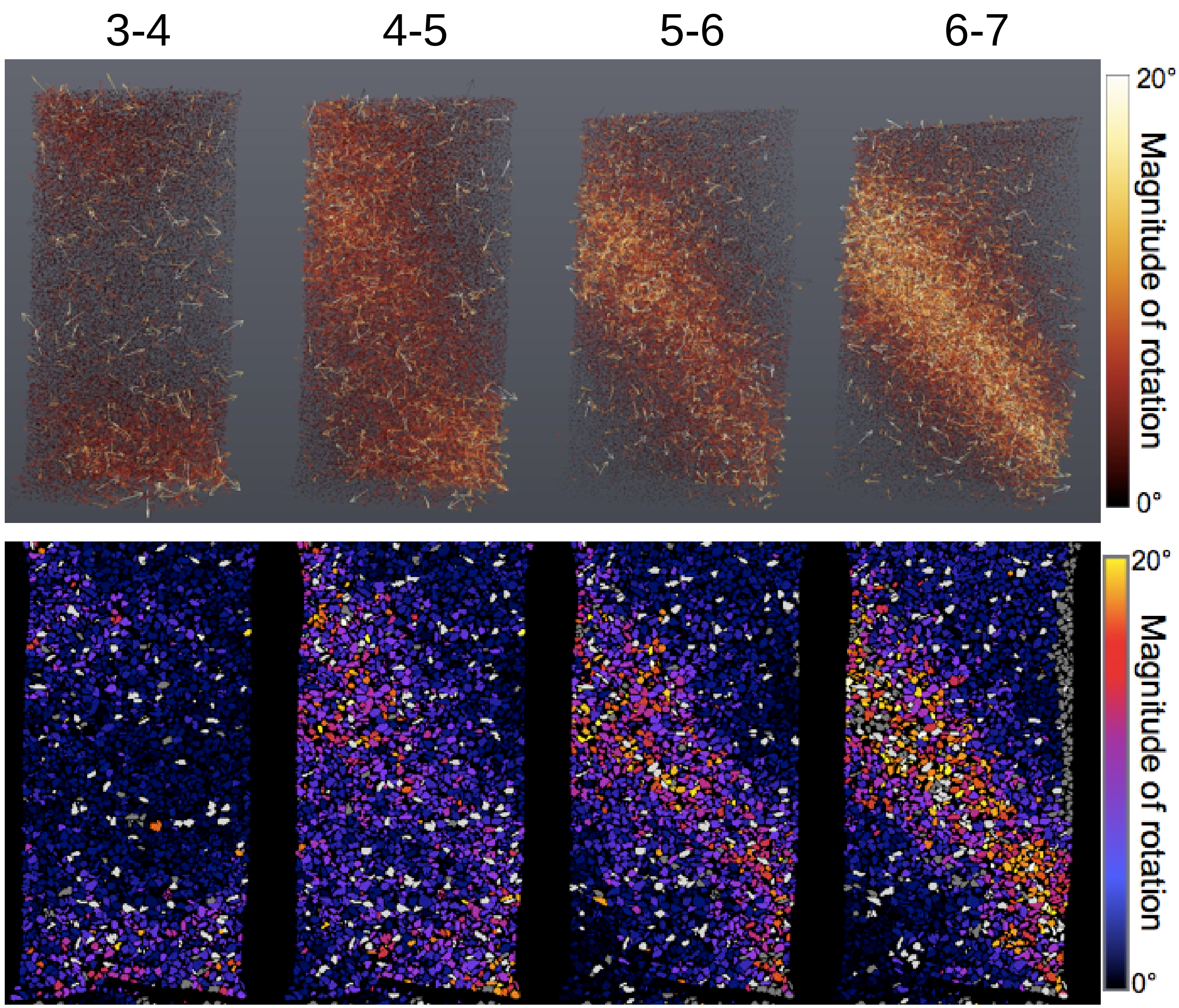


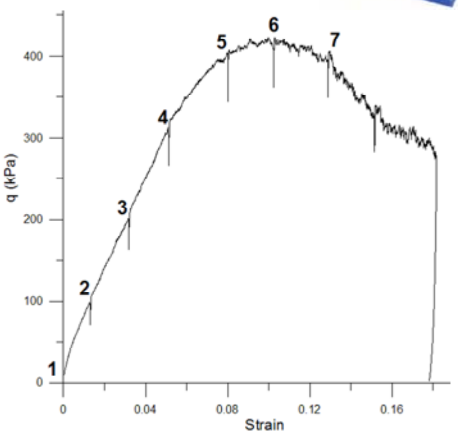

193
Vertical displacement (# voxels)
169
74
Vertical displacement (# voxels)
44
0
Vertical displacement (# voxels)
230

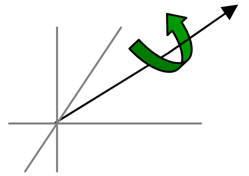
what about rotations ?

incremental grain rotation angles obtained by “discrete” approach

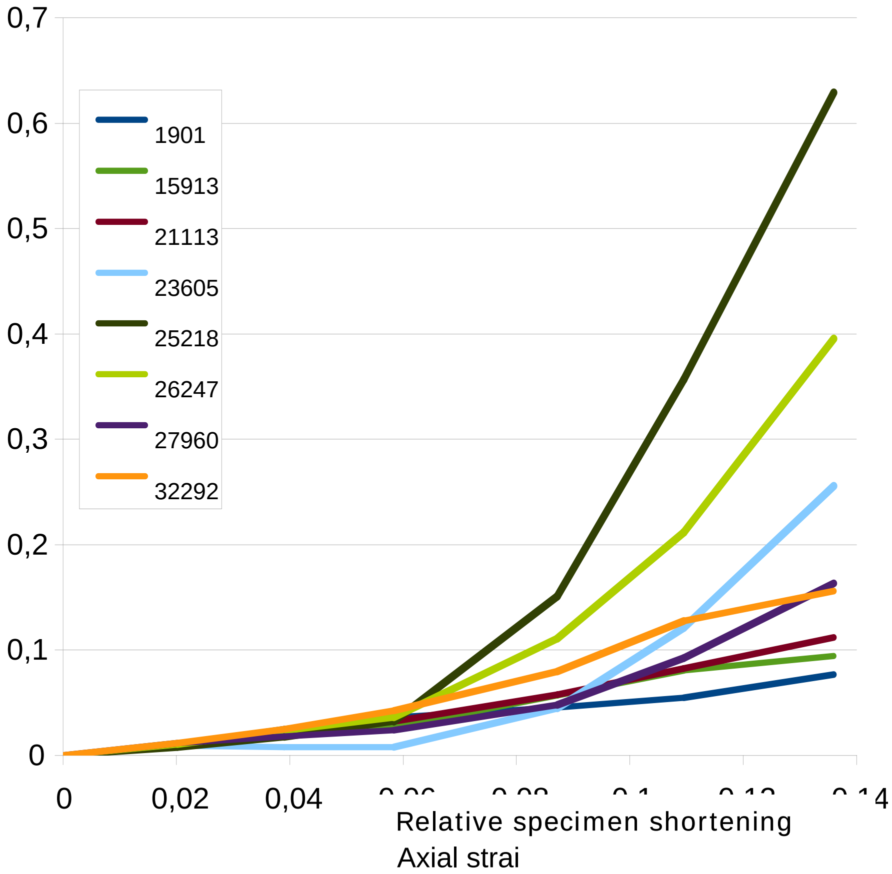
large rotations after peak localized with shear strain

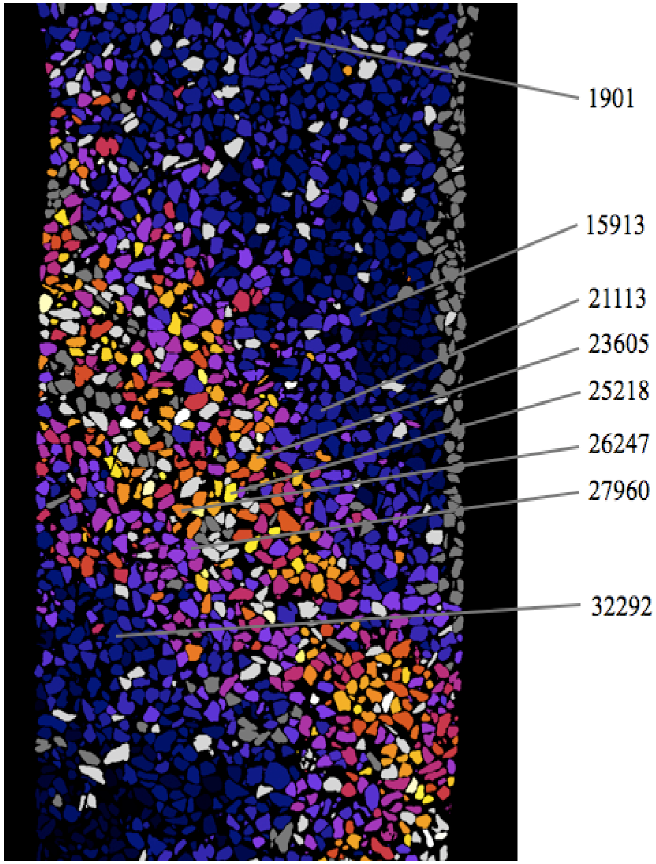






total grain rotation histories obtained by “discrete” approach for a few grains



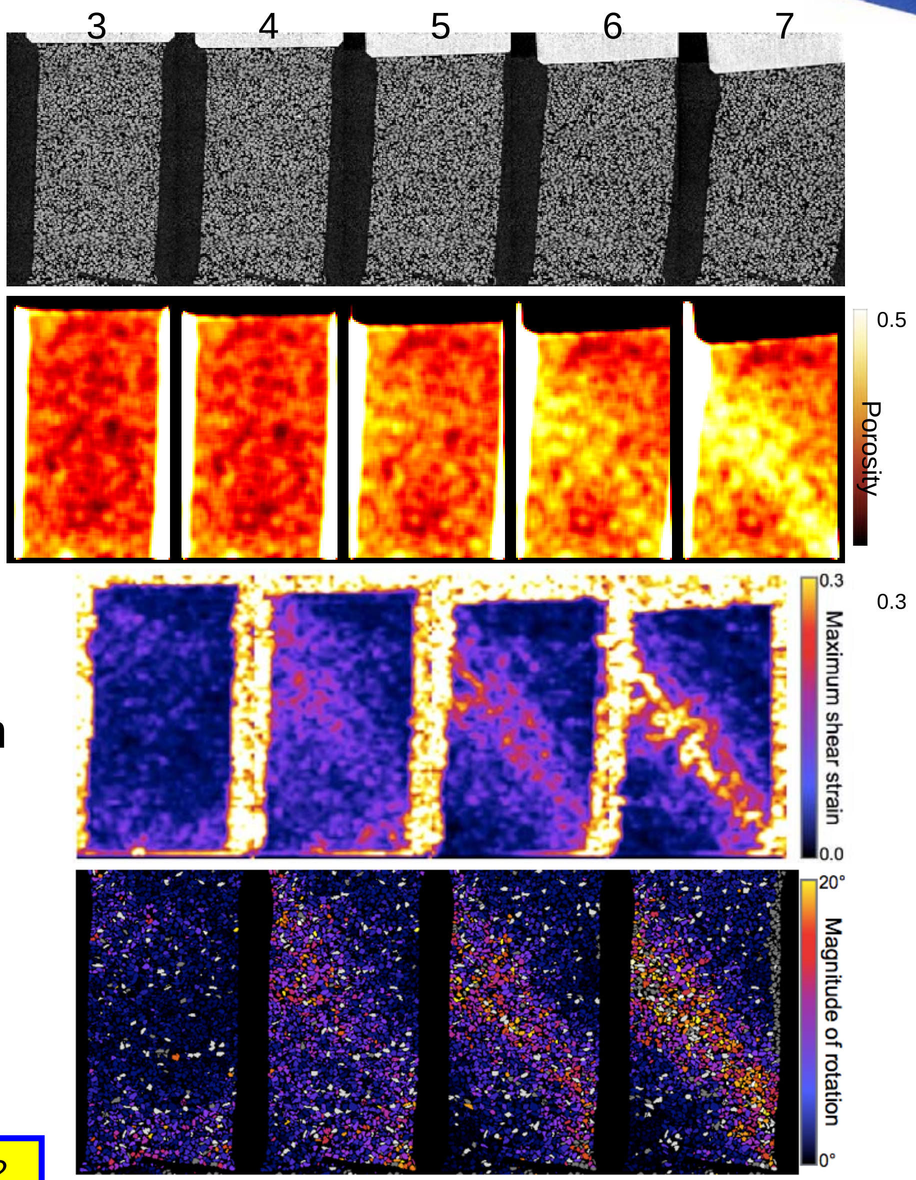


in-situ x-ray micro tomography

porosity distribution/evolution

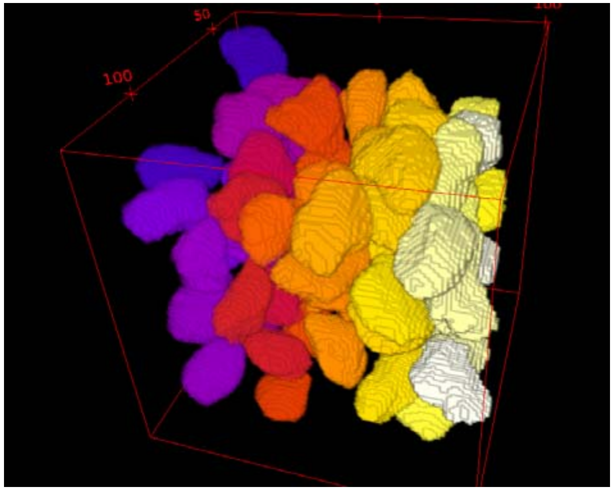
classic (continuum) DIC approach

discrete DIC approach



***Hall et al. (2010) - Géotechnique**, 60, 5, 315-322*

from DIC to ID-Track



▶ presentation given by Edward Andò one month ago at the 9th IWBDG

we get huge amounts of data for each test

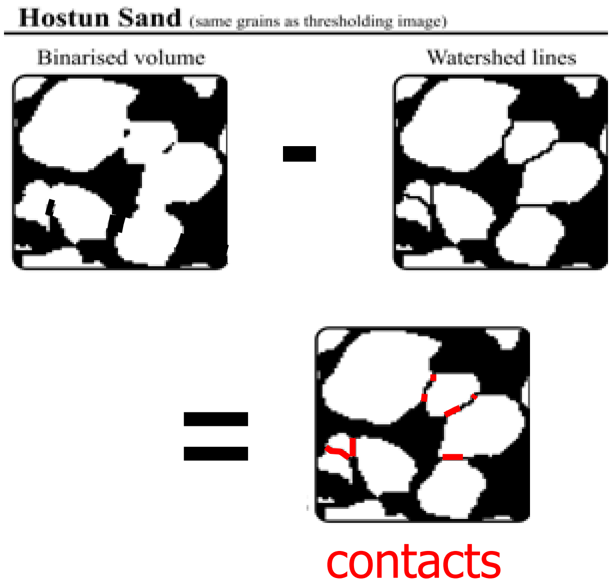
(one 3D volume from the x-rays is about 10 Gb)

what else can we do with these data?

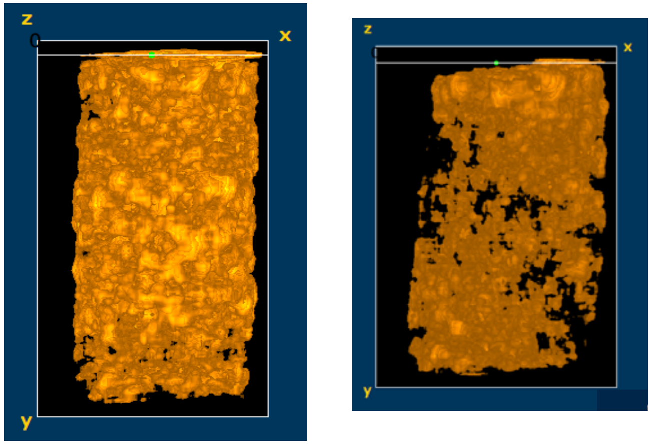
(apart from buying more and more hard disks!)

Calvetti, Combe, Lanier (1997)

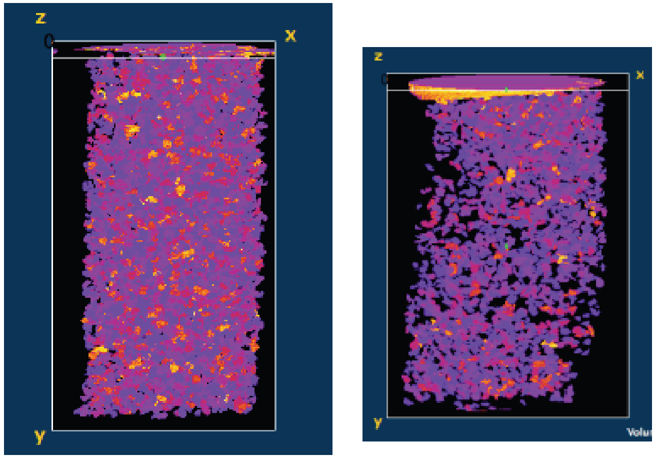
1. Description of the structure, that is to say, position of grains and contacts between them.
2. Description of the kinematics evolution: displacements, rotations, evolution of contacts.
3. Description of intergranular forces.



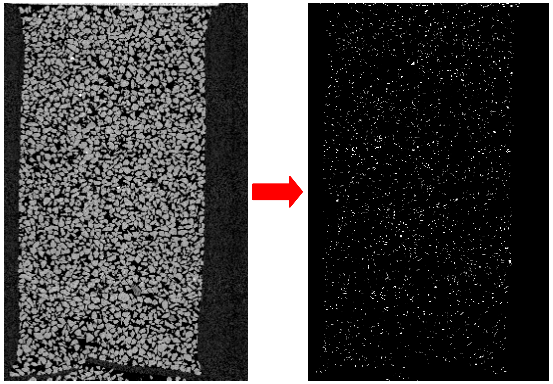
Eddy is working hard on this !



contacts density



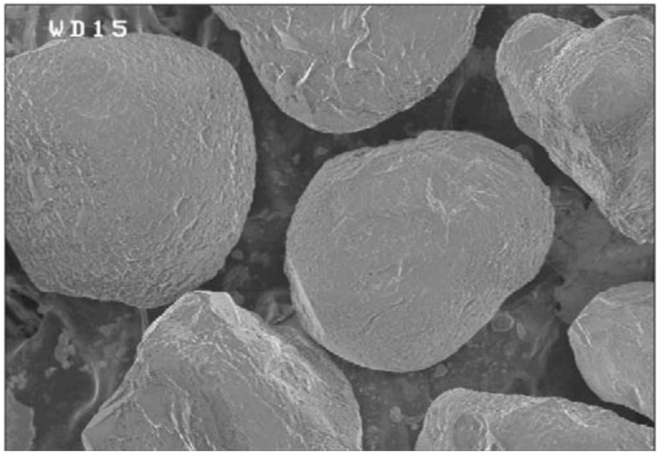
coordination number



volume from x-rays

contacts

microbially induced cementation of Ottawa sand



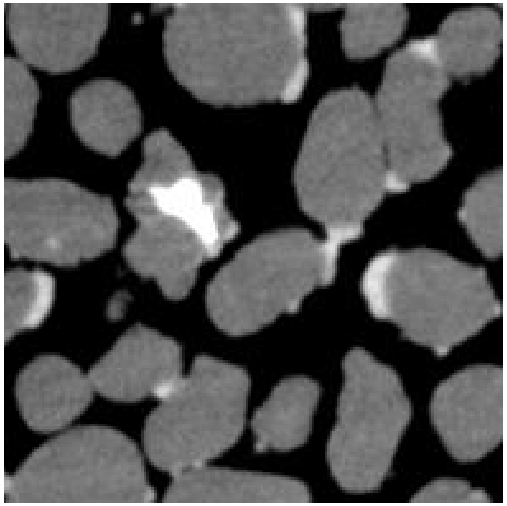
99.9 % pure quartz / rounded grains, D_{50} = 120 μm

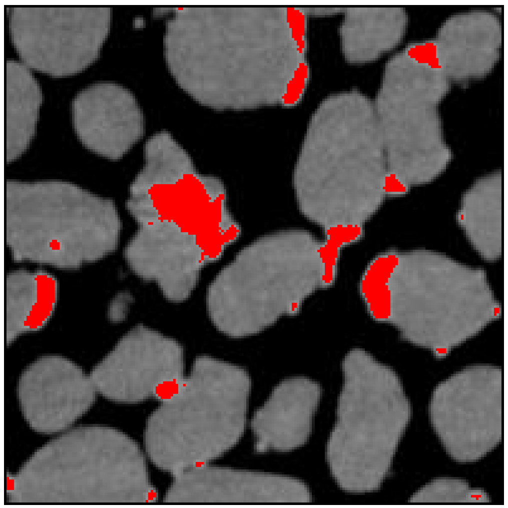
Bacillus Pasteurii , non – pathogenic, naturally occurring microorganism

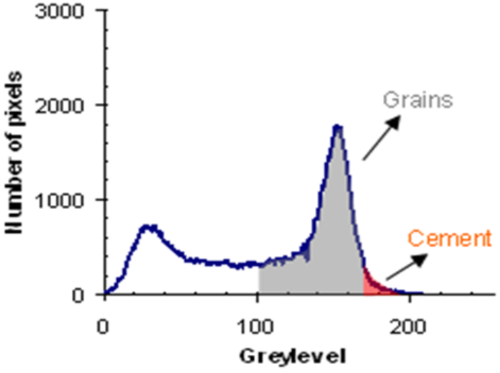
provide calcium and urea

metabolism in acid environment

calcite cement precipitation $Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \downarrow$

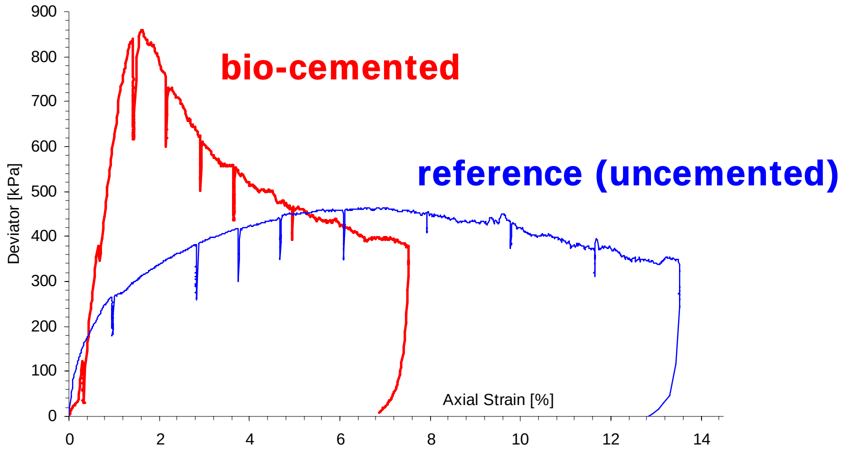


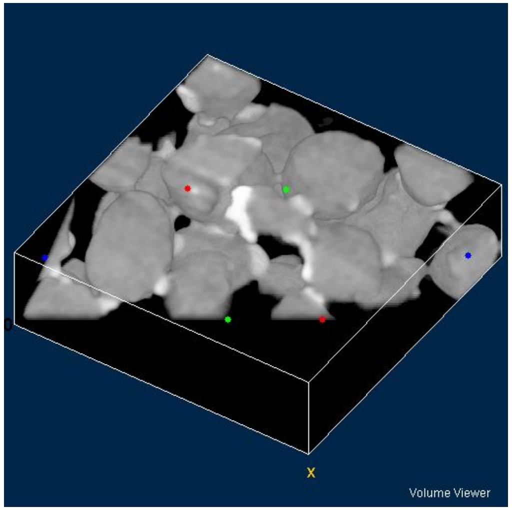


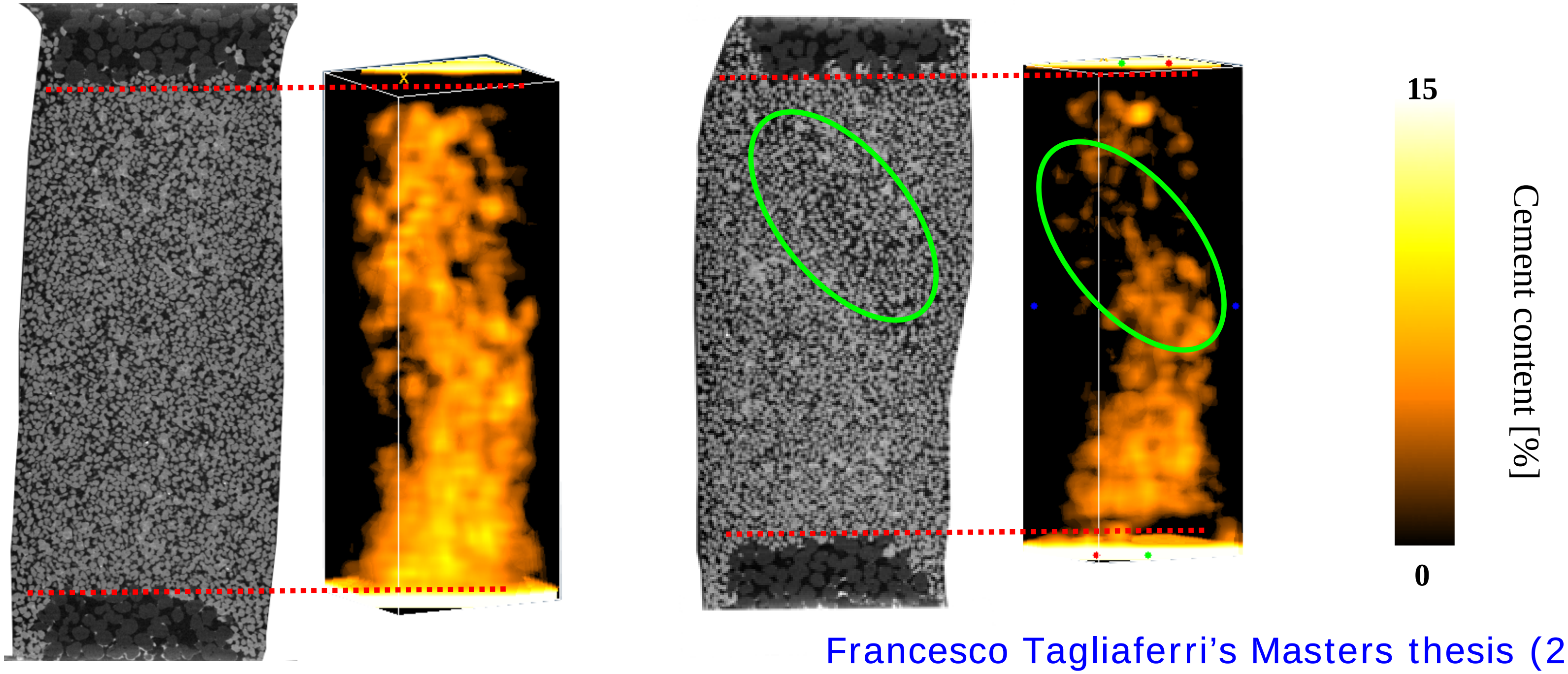


calcite and *quartz* have **different attenuation** to x- rays → **segmentation** → pores/grains/cement

evolution of cement distribution during loading and failure

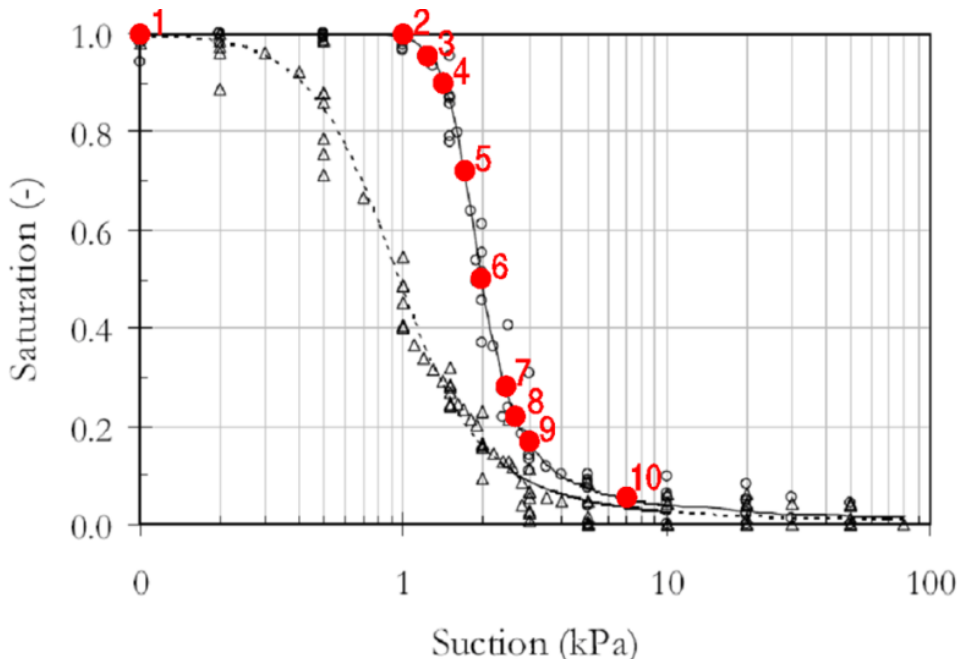


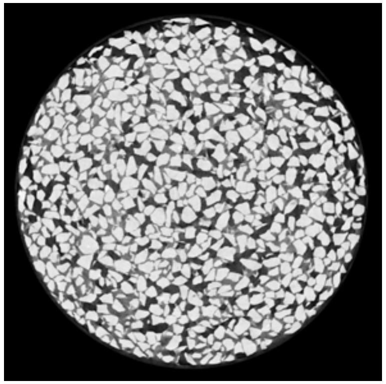


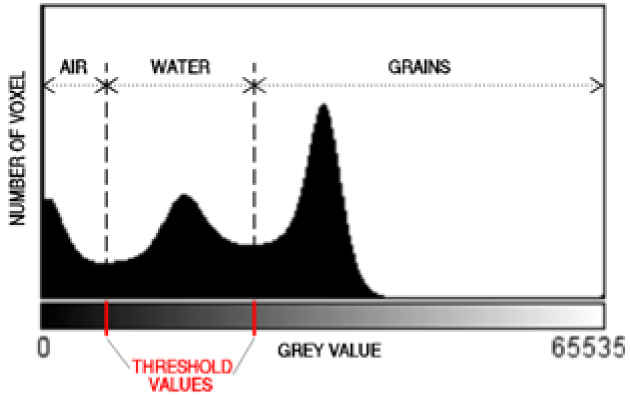


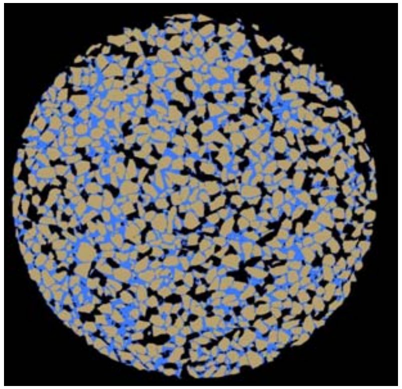
Francesco Tagliaferri's Masters thesis (2010)

micro scale characterization of water retention curve (Hostun sand)







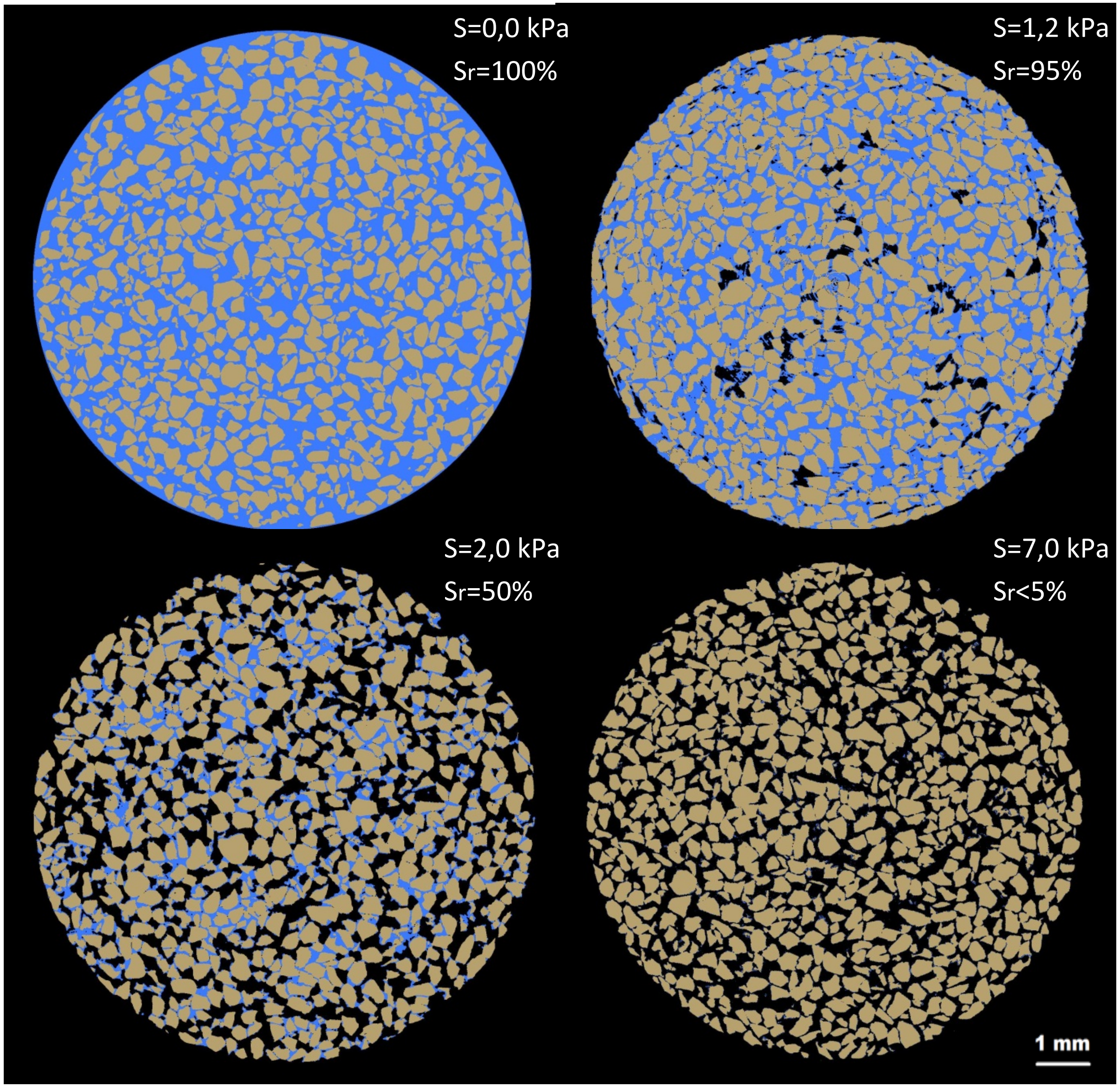


Ismael Riedel's Masters thesis (2011) – S. Salager, P. Bésuelle, E. Andò

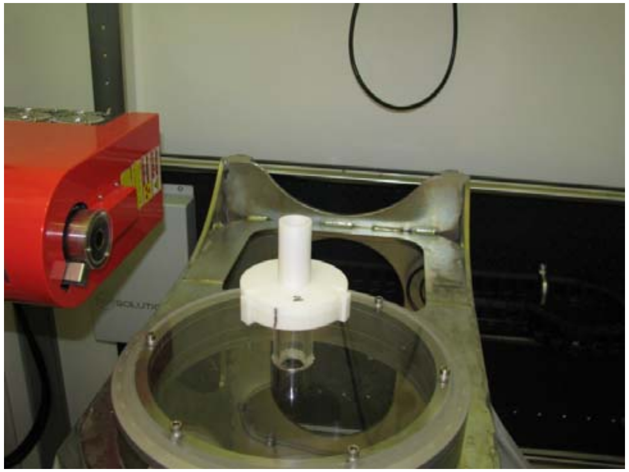
exploring other mechanisms – example #2

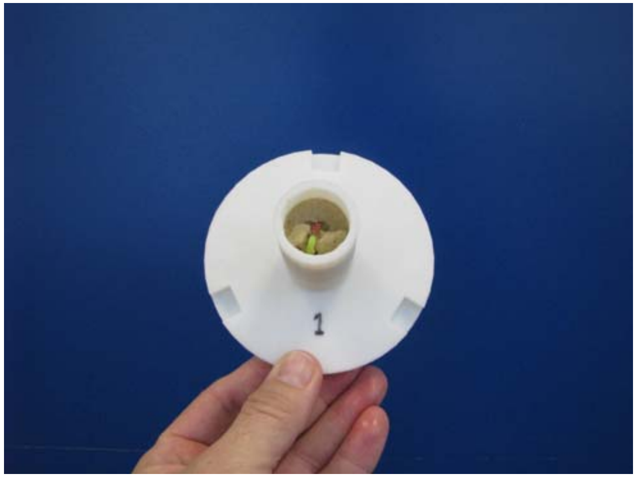
water retention domains

- complete saturation
- funicular domain
- pendular domain
- hygroscopic domain



micro scale characterization of bean germination in (Ottawa) sand

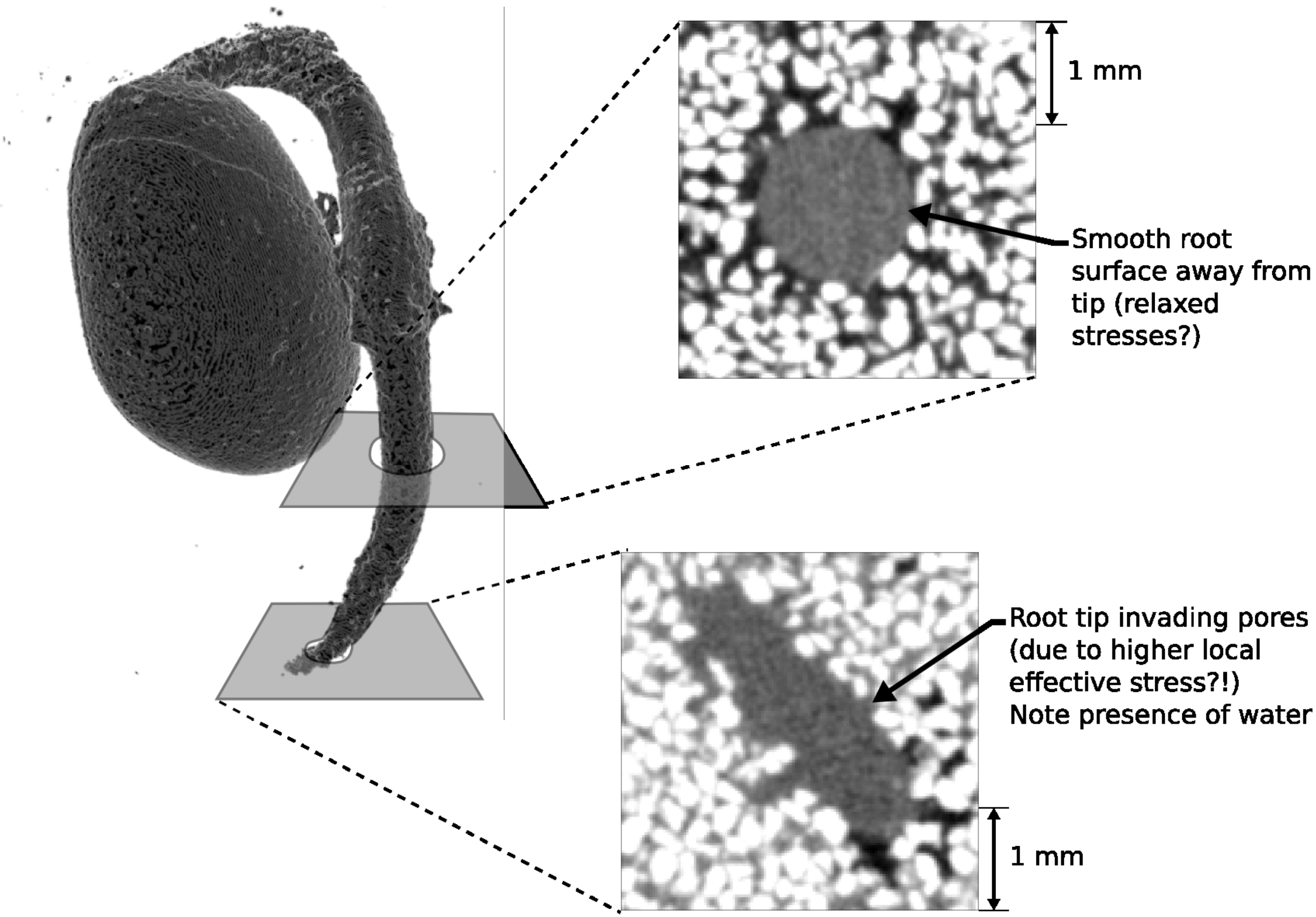




tomographic images (30 μm voxel size) were obtained every 24 hours

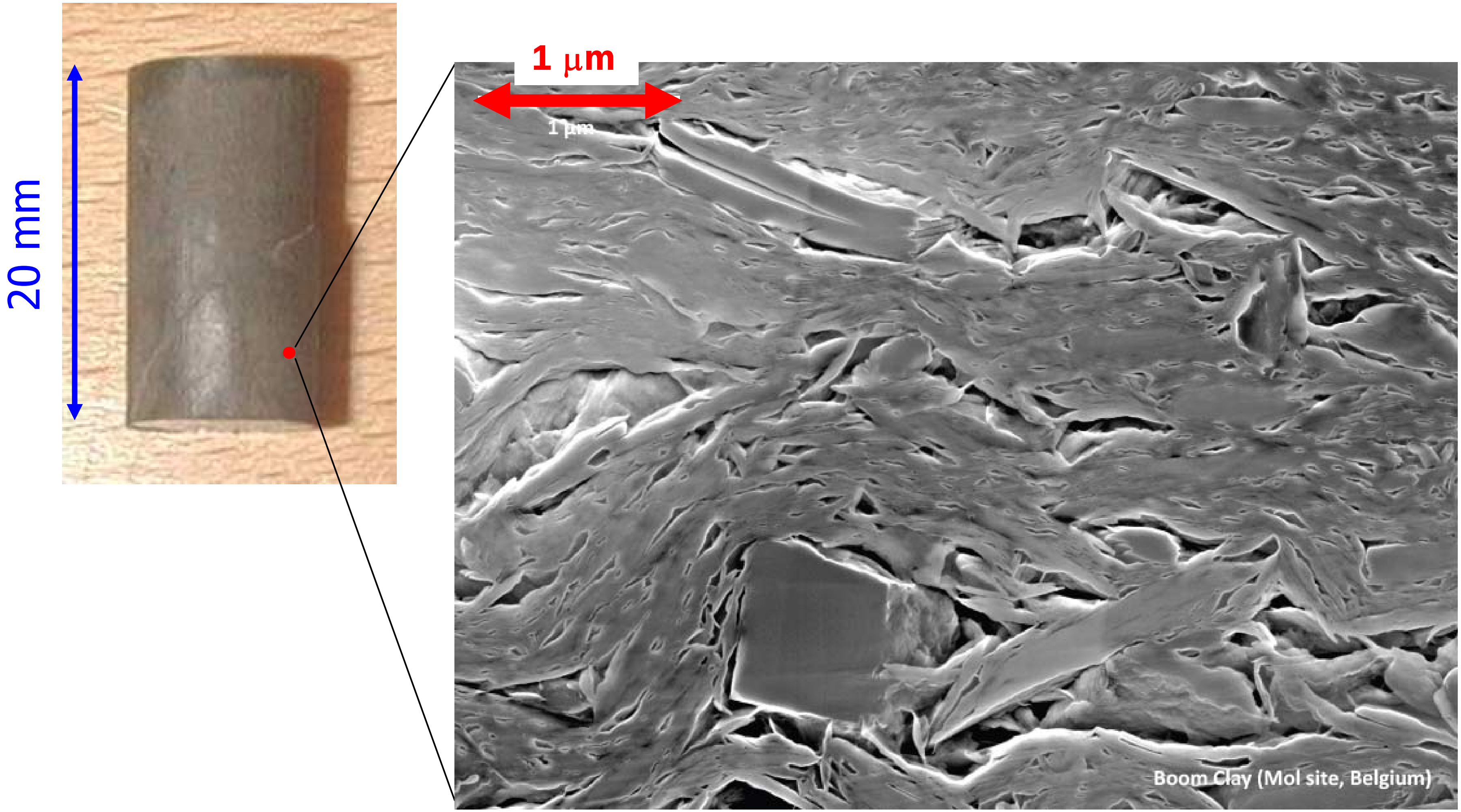
ongoing project (Carlos Santamarina, Daiki Takano, Eddy Andò, Cino Viggiani)

micro scale characterization of bean germination in (Ottawa) sand



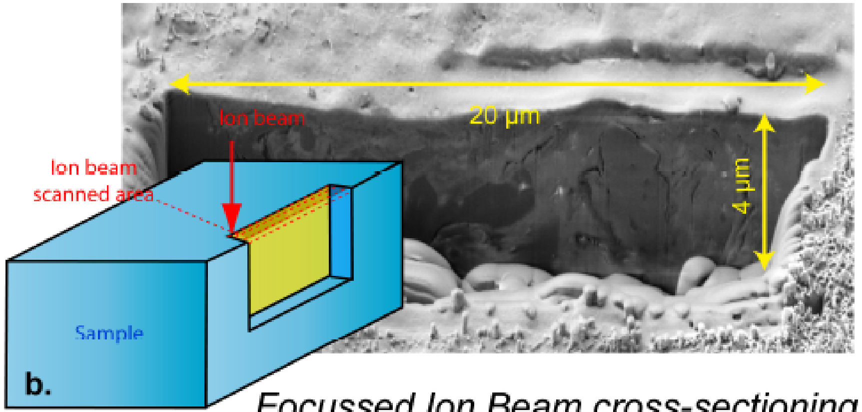
a few remarks on fine-grained geomaterials

how small is "small" for a clayrock ?



BIB image of Boom Clay -- courtesy of J.L. Urai, Aachen University

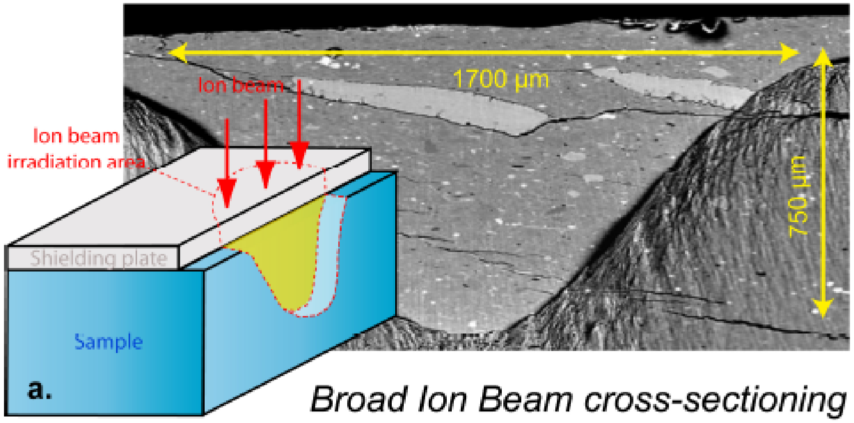
(ion beam sectioning)



Focussed Ion Beam cross-sectioning

- Ga source
- Polished up to 500 µm²

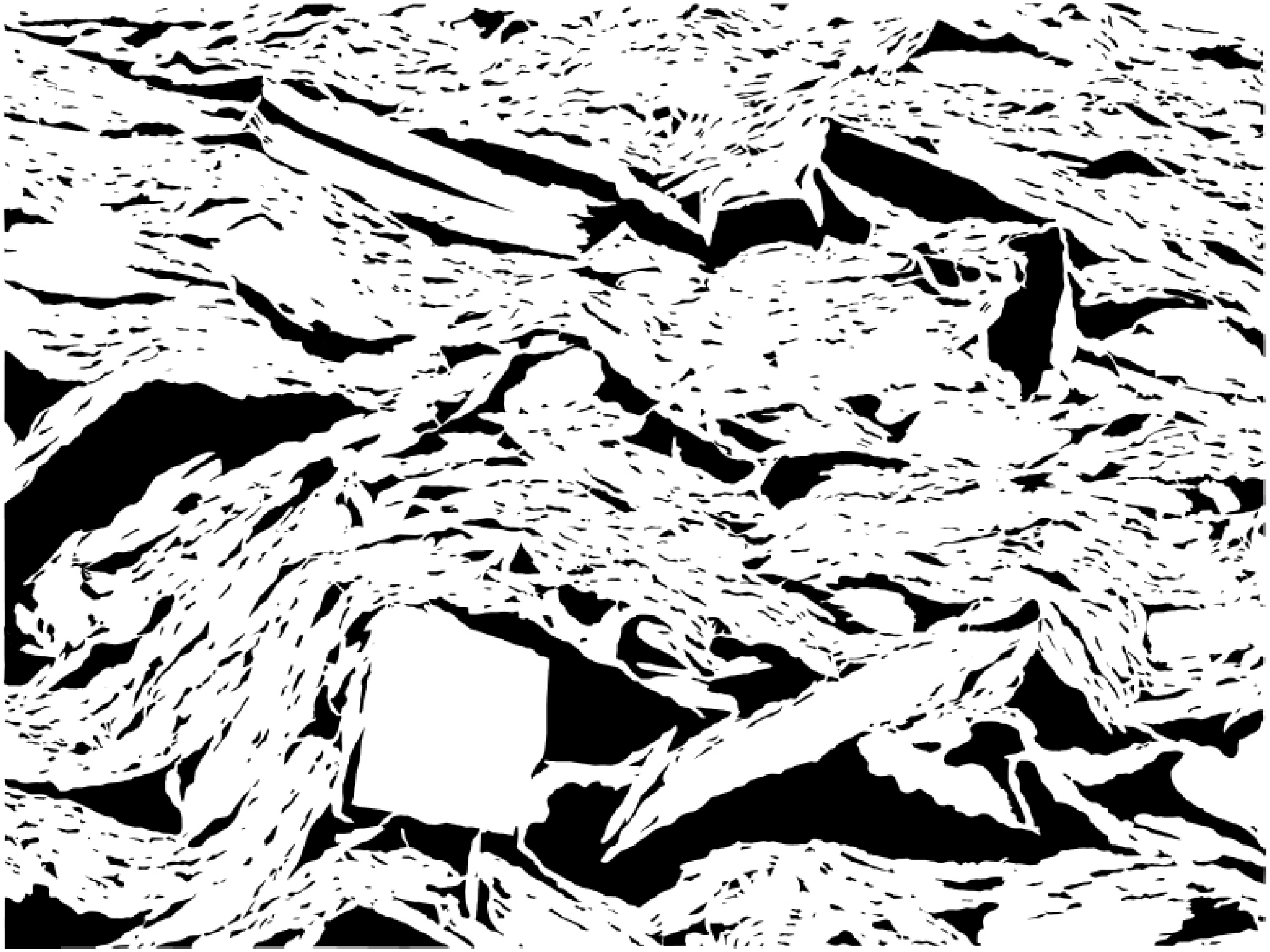
- Ar source
- Polished surface up to 2 mm²



Broad Ion Beam cross-sectioning

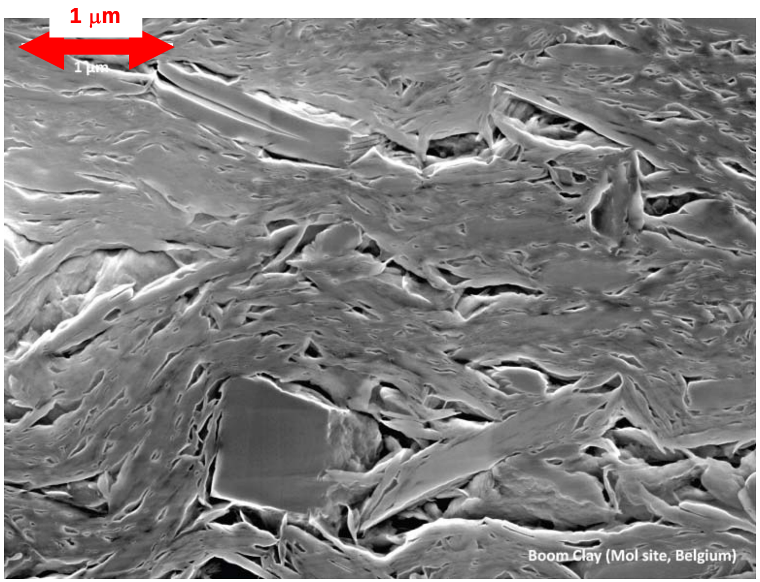
courtesy of J.L. Urai, Aachen University

looking at Boom clay at an extremely small scale



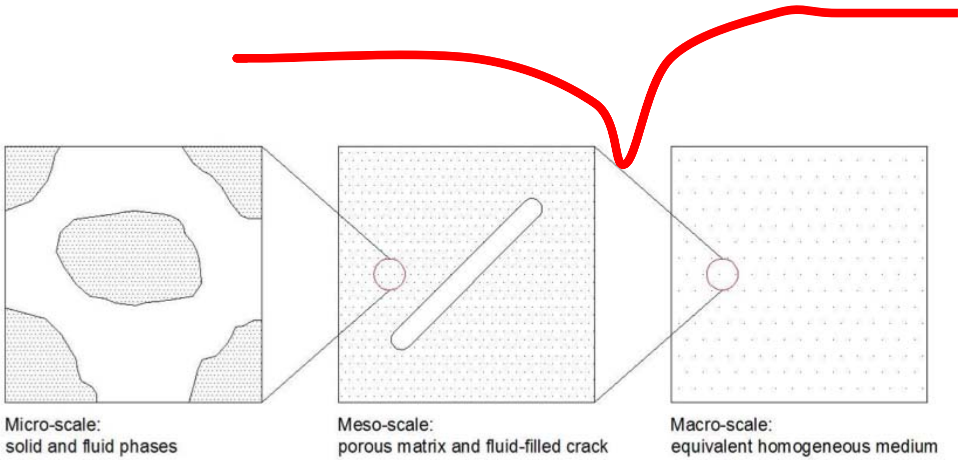
courtesy of J.L. Urai, Aachen University

how small is "small" for a clayrock ?

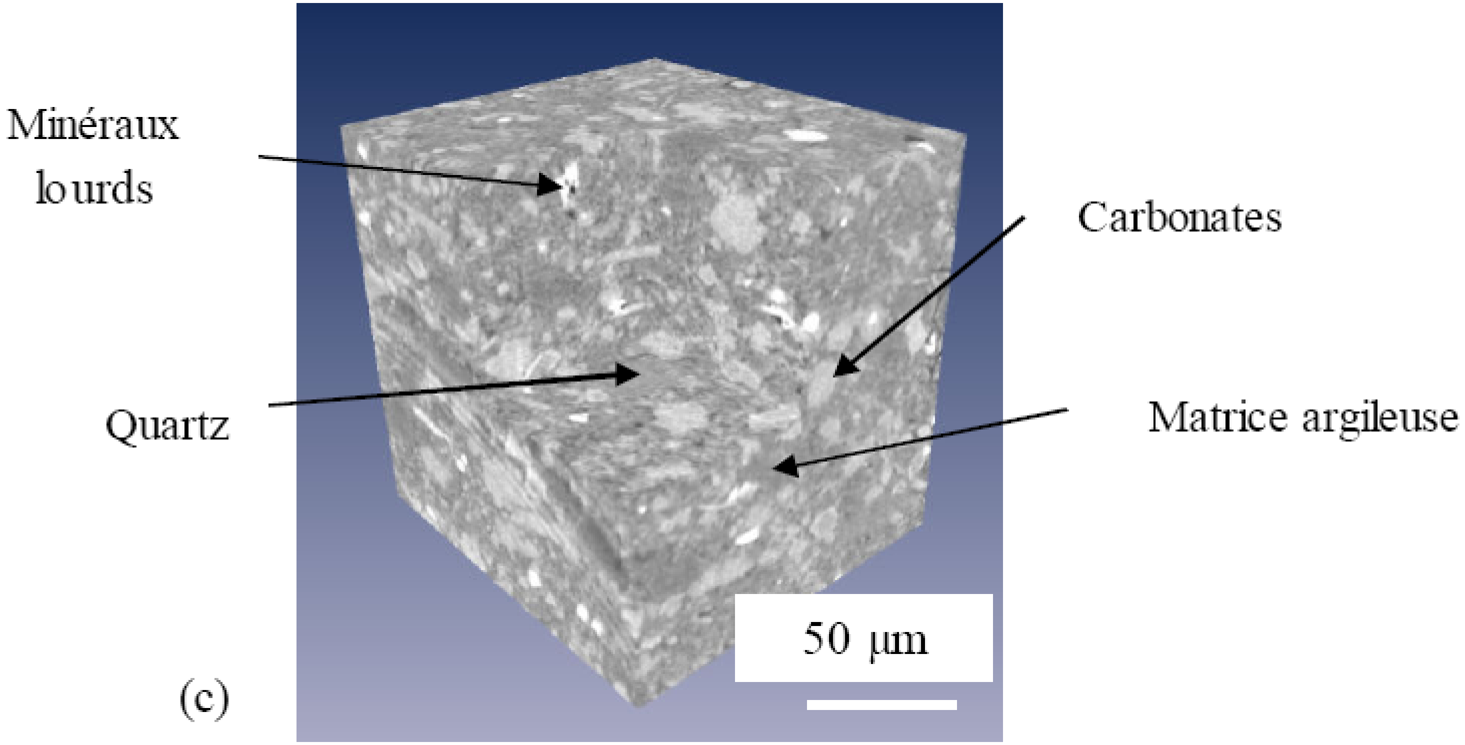


we believe this is too small (i.e., the interesting physics of the phenomena we wish to model are possibly taking place at a larger scale)

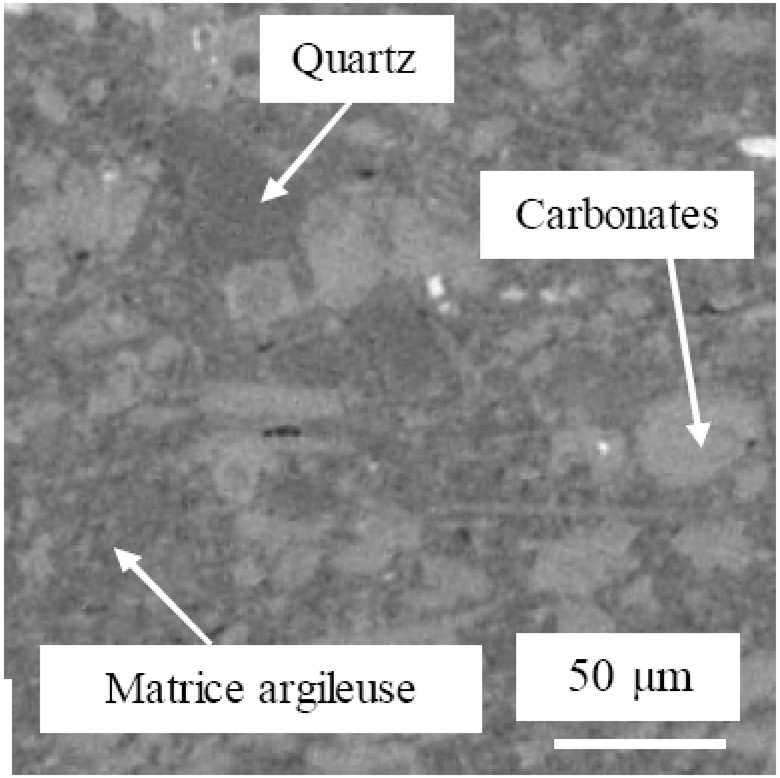
there are very many interesting scales in between



Jean-Charles ROBINET (2008) Thèse de doctorat de l'Université de Poitiers



Les volumes 3D ont été acquis a partir de cylindres de 1,4 mm de diamètre micro-carottes a sec a partir de l'échantillon imprégné. Les analyses micro tomographiques ont été réalisées sur la ligne ID 19 de l'European Synchrotron Facility Radiation (ESRF). Une énergie de faisceau incident de 20,5 keV et une résolution de 0,7 x 0,7 x 0,7 µm3/voxel ont été utilisées



there is plenty of things to see!

we wish to see and understand mechanisms at this scale

→ two types of TXC tests:

- ϕ 10 mm voxel size 7 μm (3SR)
- ϕ 1 mm voxel size 0.7 μm (ESRF)

the challenge: specimen preparation

non-conventional techniques (e.g., ion beam thinning, focused ion beam)

"what" and "how", but also "why" (i.e., what for)

new technologies clearly bring with them new questions. In addition, they also bring the ability to look back and give new answers to "old" questions

phenomena such as

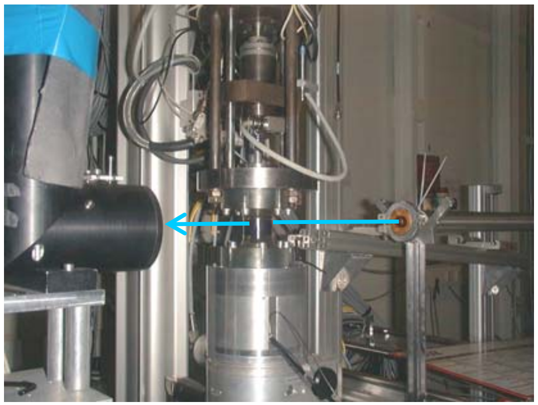
- strain localisation
- plastic dilatancy
- critical state
- grain crushing ▶
- evolution of grain contacts and force chains ▶
- water menisci
- ...
- mechanisms of plastic deformation
- ...
- the effect of soil sampling or sample preparation
- ...

can be reappraised in light of these new tools

time to conclude…

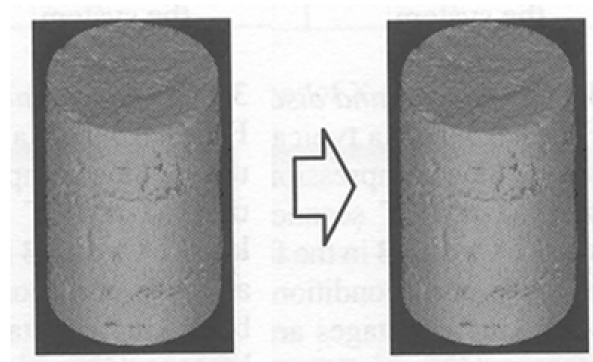
looking inside a geomaterial (at an appropriately small scale) while it deforms under load

in-situ x-ray micro tomography



+

image analysis (3D DIC, Particle Tracking)



tremendous possibilities, but tremendous challenges as well

quantitative analysis of (lots of) data

extend data processing: grain and **<u>contact</u>** morphology/distribution/evolution

other mechanisms at the grain scale: pores collapse, grain crushing, …

the dream of measuring also intergranular forces the key feature of multi-scale models is that one can inject the relevant physics at the appropriate scale

the success of such models crucially depends on the quality of the physics one injects: ideally, this comes directly from experiments

this is what I've shown you today

combining various advanced experimental techniques, we are able to image, in three dimensions and at small scales, the deformation processes accompanying inelastic deformation in geomaterials

this allows us to understand these processes and subsequently to define models at a pertinently small scale