what actually happens when geomaterials fail: a look within

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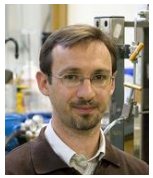
+ many colleagues and students, including:


Pierre Bésuelle

Jacques Desrues

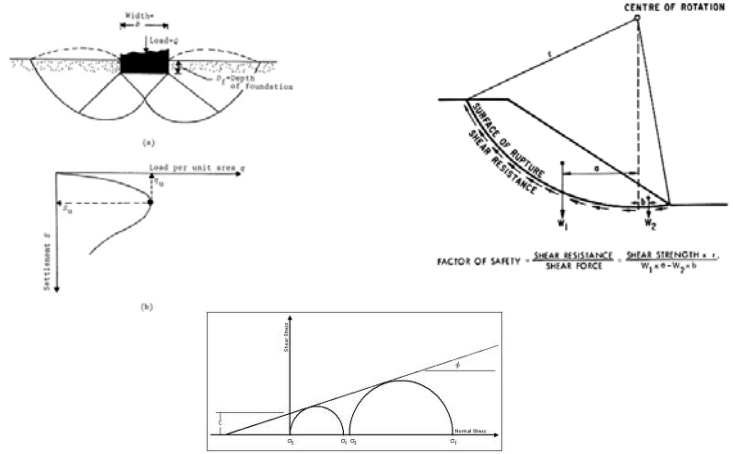
Steve Hall

Eddy Andò

when loaded, geomaterials not only peacefully deform

they may also (and often do) FAIL

are we good in modeling/predicting (i.e., understanding) failure?



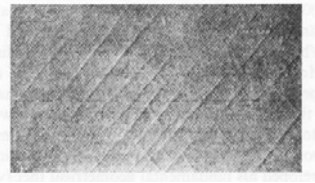
localized failure is quite a tricky phenomenon

plane strain compression (sand)

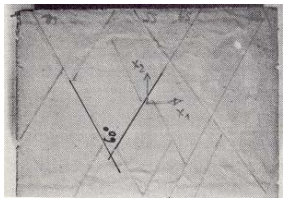
what is strain localization?

→ strain localization is the (more or less progressive) concentration of deformation into narrow zones of intense shearing (shear banding)

(material out of the shear band(s) stays essentially undeformed)

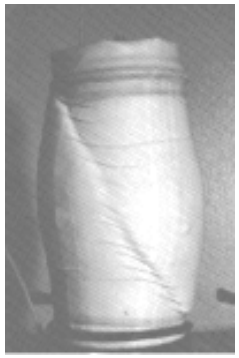


"fliessfiguren" in metals
(Mohr, 1900)



patterns of localized deformation in clay
(Kuntsche, 1982)

shear bands are commonly observed in the lab as well as in situ



triaxial compression on sand

railway tracks after a quake in Turkey

failure in soils and rocks is almost always associated with localized fractures and/or shear bands developing in the material

(natural or human-made slopes or excavations, unstable rock masses, embankments or dams, tunnels and mine galleries, boreholes driven for oil production, repositories for nuclear waste disposal)

why is strain localization / localized failure a “tricky phenomenon” ?

Geomaterials are composed of particles. However, when dealing with them, we often use *continuum models*, which ignore particles and make use of abstract variables such stress and strain

Continuum mechanics is the classical tool that geotechnical engineers have always used for their everyday calculations: estimating settlements of an embankment, the deformation of a sheet pile wall, the stability of a dam or a foundation, etc. History tells us that, in general, this works fine.

While we are happily ignoring particles, they will at times come back to haunt us. This happens when deformation is localized in regions so small that the detail of the soil’s (or rock’s) particular structure cannot safely be ignored. *Failure* is the perfect example of this.

Researchers in geomechanics have long since known that all classical continuum models typically break down when trying to model failure. All sorts of numerical troubles ensue – all of them pointing to a fundamental deficiency of the model: the lack of *microstructure*.

(the term microstructure doesn’t prescribe a dimension (*e.g.*, microns), but rather a scale – the scale of the mechanisms responsible for failure)

how to model localization? what do we wish to model?

→ onset and progression (in time and space) of localization

→ overall behavior in the presence of multiple regions of localized strain, possibly interacting with each other

→ hydro-thermo-mechanical coupling

modeling strain localization requires advanced, non conventional models

a similar statement can be made for experimental methods

studying strain localization in the lab requires advanced, non conventional methods

a fantastic tool: x-ray μ-tomography

flying into a sand specimen

voxel size = 16 μm 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)

imaging a process, not just the material

- we can/wish to look inside
- we can/wish to track heterogeneous response during a test

qualitative and quantitative characterization of heterogeneities in both material properties and processes during a test

italian coffee maker

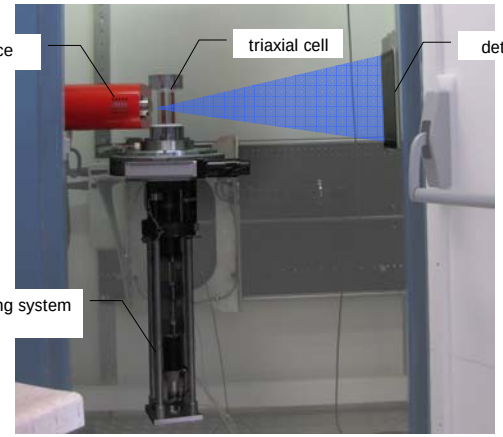
neutron radiography

in situ x-ray tomography at lab 3SR

multiscale (variable magnification):

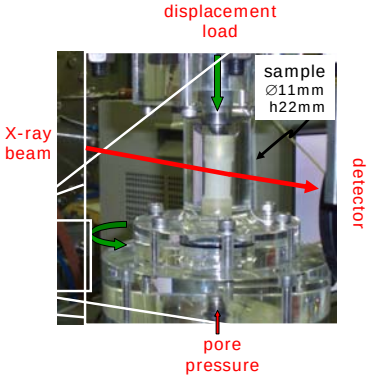
Ø 4 mm ⇨ ≈ 5 µm voxel width Ø 210 mm ⇨ ≈ 220 µm voxel width

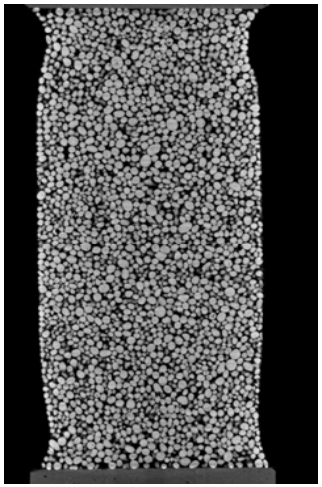
→ adaptability to image the physics of materials at the pertinent scale(s)



imaging a process, not just the material

in situ µtomography triaxial system

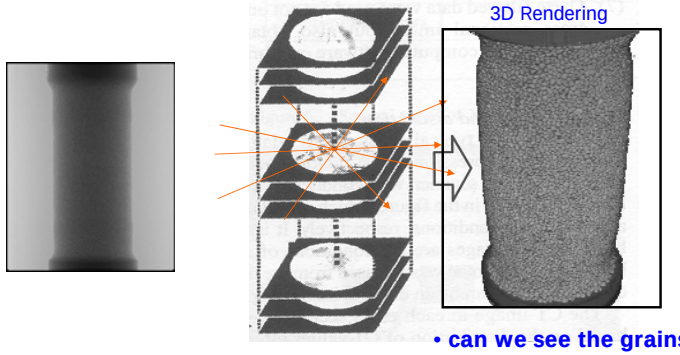




Caicos Ooid from the Bahamian archipelago (provided by ExxonMobil)

x-ray tomography (more than just radiography)

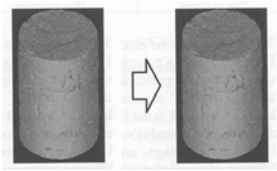
- recording attenuation profiles through a specimen, at different angular positions
- reconstructing a 3D image of the internal structure of the specimen (in fact, the spatial distribution of the linear attenuation coefficient)



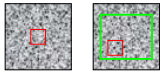
- **can we see the grains?**
- **do we want to see the grains?**

comparing one x-ray image to another: DIGITAL IMAGE ANALYSIS

... adding 3D DIC (mapping one digital 3D image onto another)



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



search in 3D for best correlation displacement vector (integer - pixel)

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

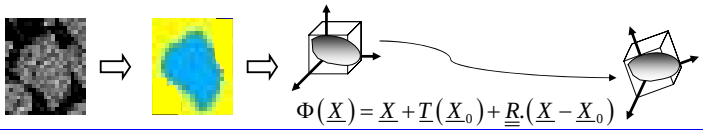
mean grain size ≈ 20 voxels

volume of a grain ≈ 5500 voxels

also available in a discrete version

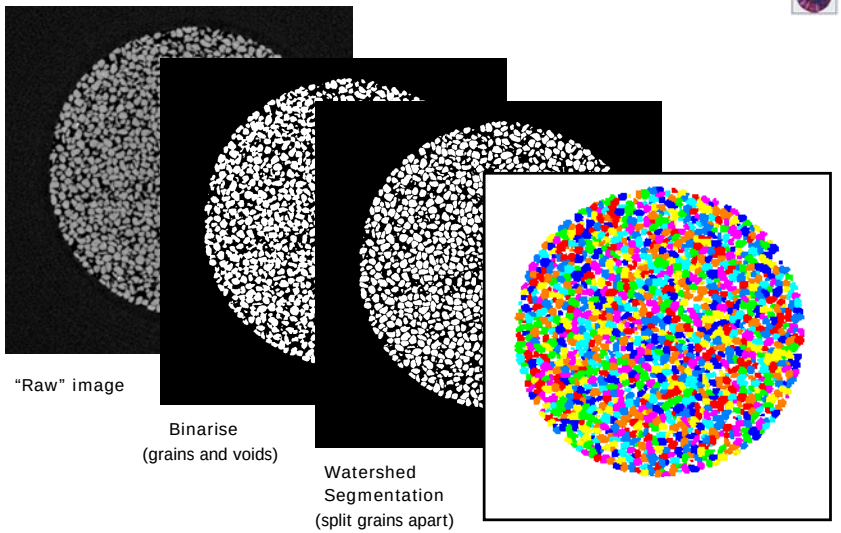
"grain shape" correlation domain centered on each grain

full grain kinematics for each grain (3 displacements + 3 rotations)



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

how do we see/identify the grains?



"Raw" image

Binarise (grains and voids)

Watershed Segmentation (split grains apart)

Label Individual Grains

processing flow

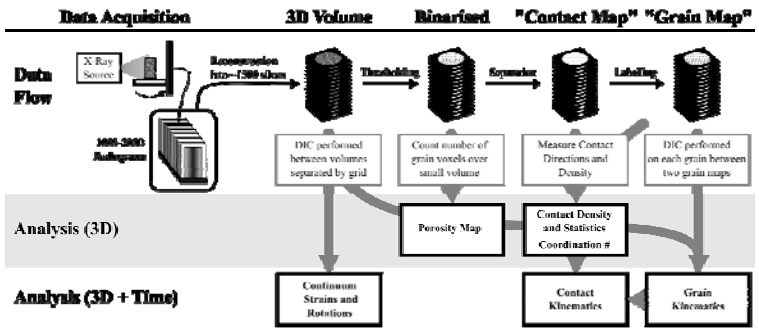
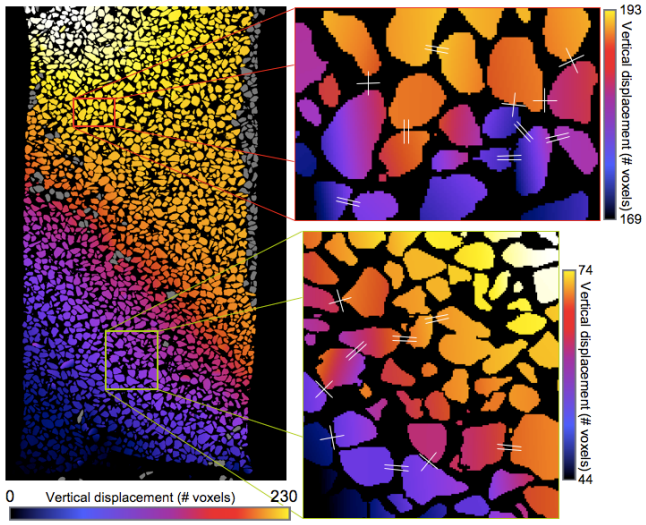


Image: E. Andò (Andò et al., 2010)

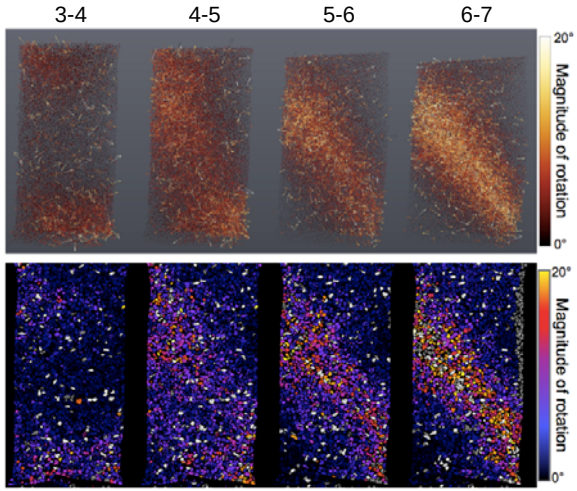
grain displacements – they can be locally discontinuous

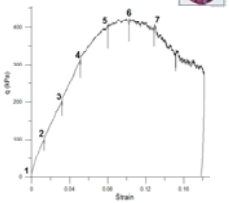


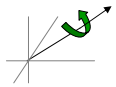
what about grain rotations ?

incremental grain rotation angles obtained by “discrete” approach

large rotations after peak localized with shear strain

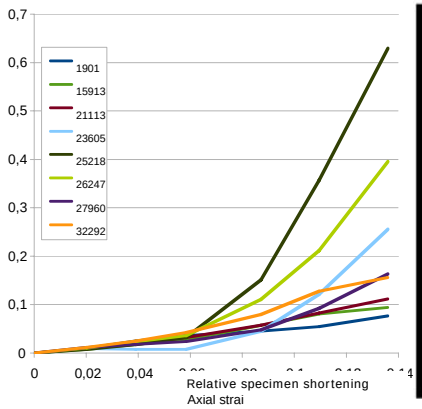


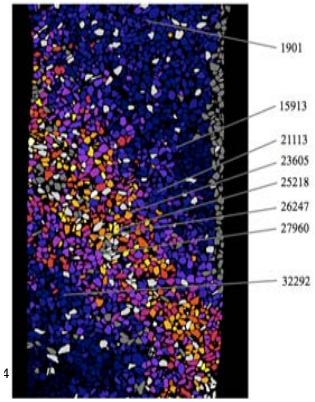




grain rotation histories

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





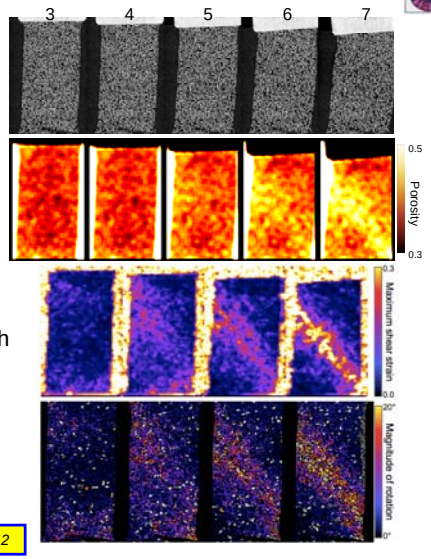
an example of what one can get (TXC on Hostun sand)

in-situ x-ray micro tomography

porosity distribution/evolution

classic (continuum) DIC approach

discrete DIC approach



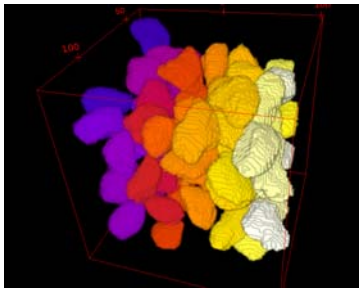
***Hall et al. (2010) - Géotechnique**, 60, 5, 315-322*

from discrete DIC to ID-Track

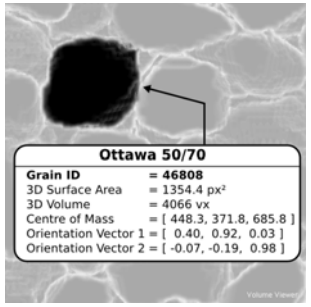
track grains – based on relevant characteristics that can be measured in a 3D volume

each grain is represented by this single measurement. This differs radically from Image Correlation, which relies on the "image" of a grain (i.e. the grayscale information of the several thousands of voxels which makes it up)

two lists of grains with their positions and measurements can be processed, instead of the two whole tomographic volumes



now each grain can be analyzed...



For each Grain in Reference Volume:

a) Search in Deformed Volume for any Grain within search window

b) For each matching Grain, keep only those within ±10% of Original Grain's Volume

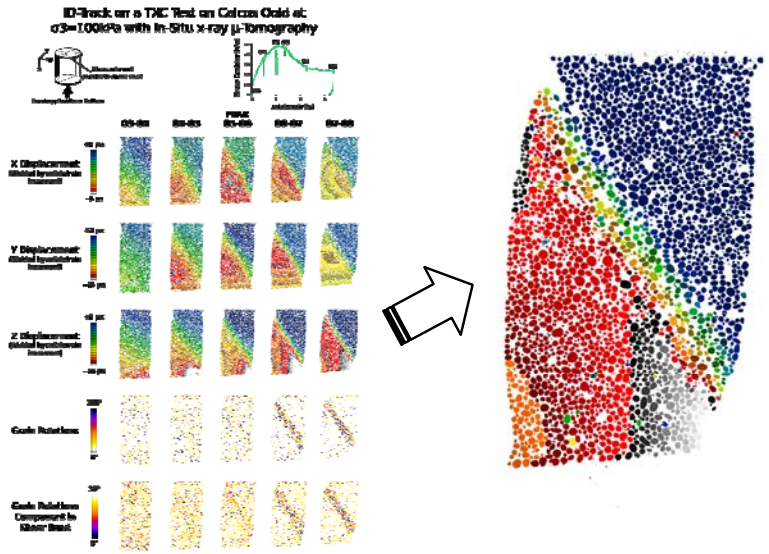
c) **If first pass:**
- Select Grain with Closest Volume
- Update Grain Tracking: Ref. Grain → Def. Grain

d) Calculate Neighbourhood Displacements and restart

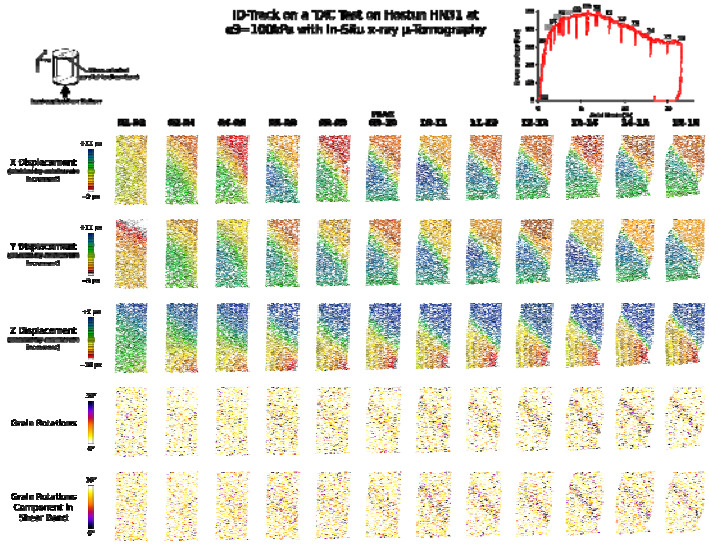
If second pass:
- Select Grain with Closest Volume AND with Smallest Deviation from displacement of neighbours
- Update Grain Tracking: Ref. Grain → Def. Grain
- Stop.

note/choice: if we can't follow a grain we leave it blank – but we are aware

ID-Track results on Caicos Ooid – PhD Eddy Andò



ID-Track results on Hostun Sand – PhD Eddy Andò



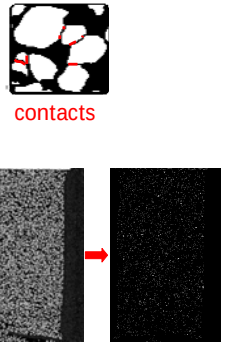
we get huge amounts of data for each test

(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)

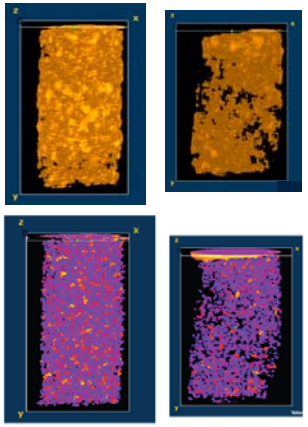
looking at other issues: e.g., contacts – distribution and evolution



contacts

volume from x-rays

contacts

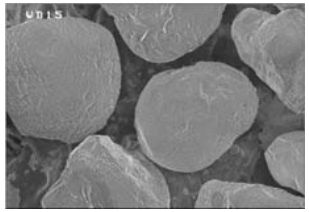


contacts density

coordination number

exploring other mechanisms – example #1

microbially induced cementation of Ottawa sand



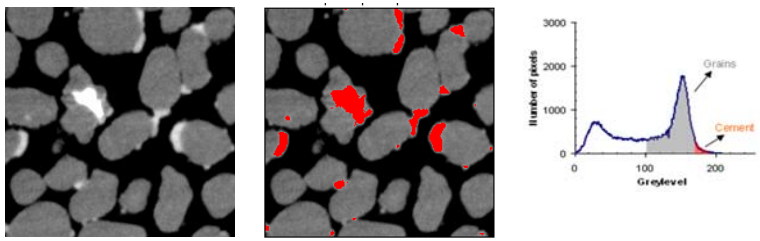
Bacillus Pasteurii , non – pathogenic, naturally occurring microorganism

provide calcium and urea

metabolism in acid environment

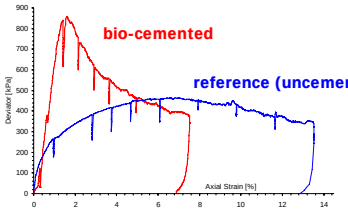
calcite cement precipitation $Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \downarrow$

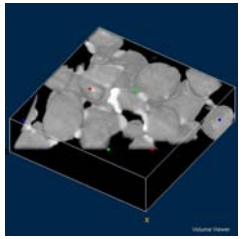
99.9 % pure quartz / rounded grains, D_{50} = 120 μm

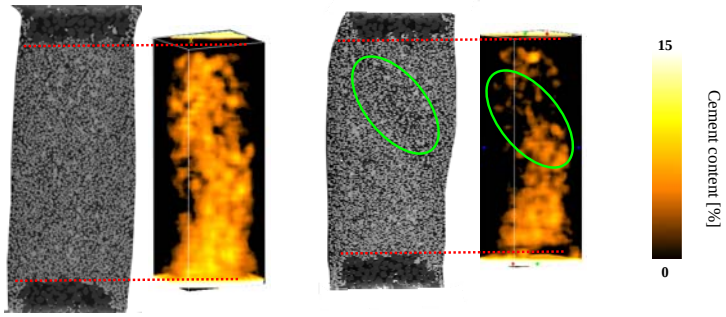


calcite and *quartz* have **different attenuation** to x- rays → **segmentation** → pores/grains/cement

evolution of cement distribution during loading and failure

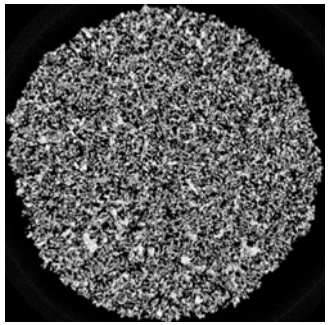


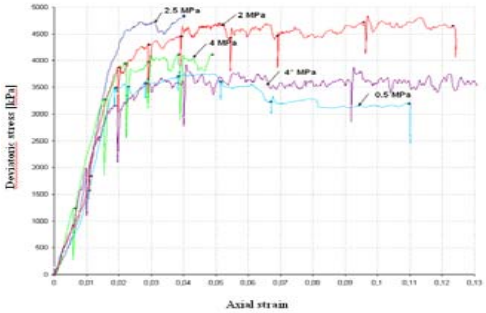




exploring other mechanisms – example #2

compaction bands in a porous rock (calcarenite)





Tuffeau de Maastricht

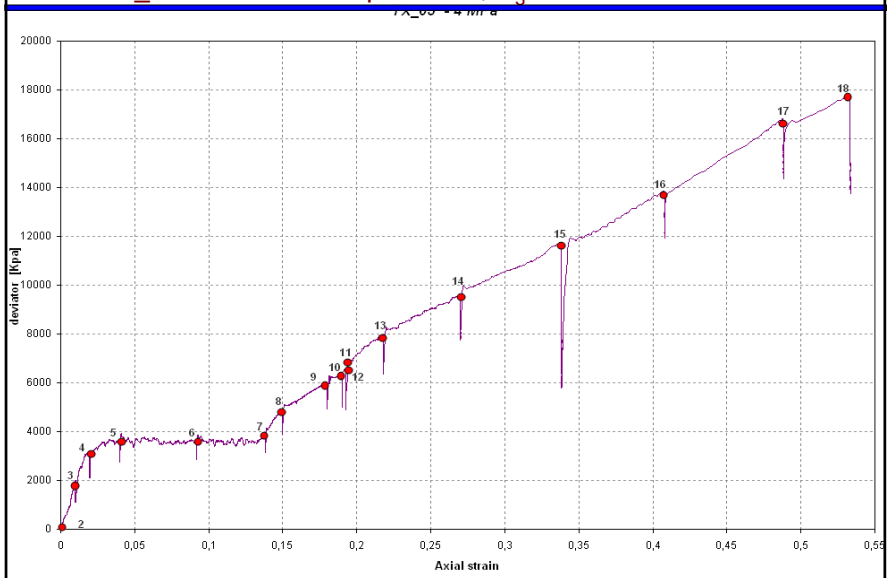
a sedimentary siliceous limestone

1~2 % quartz, the rest calcite

porosity ~ 50 %

mean grain size: ~ 0.1 - 0.2 mm

test TX_05: triaxial compression, σ_3 = 4 MPa



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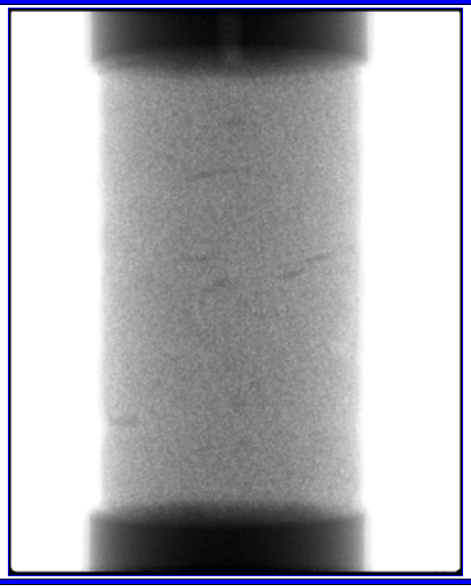

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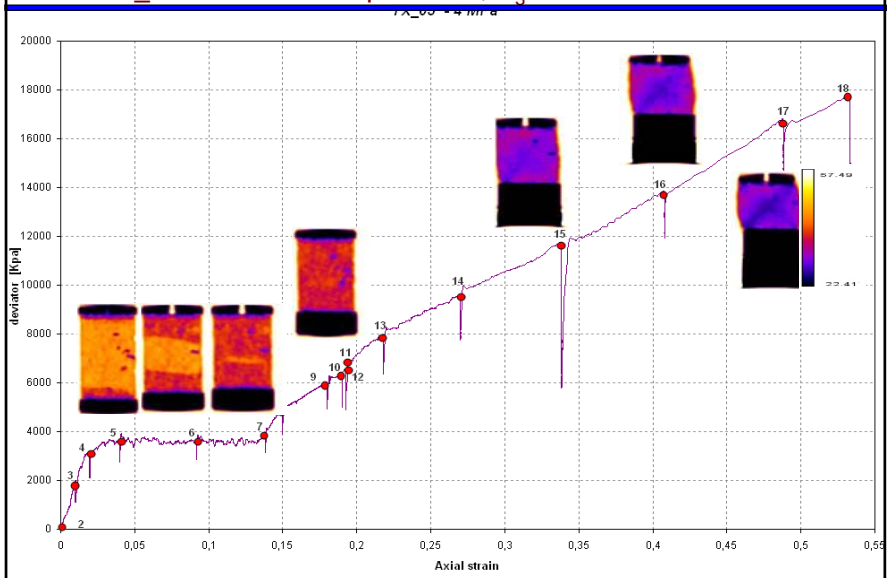
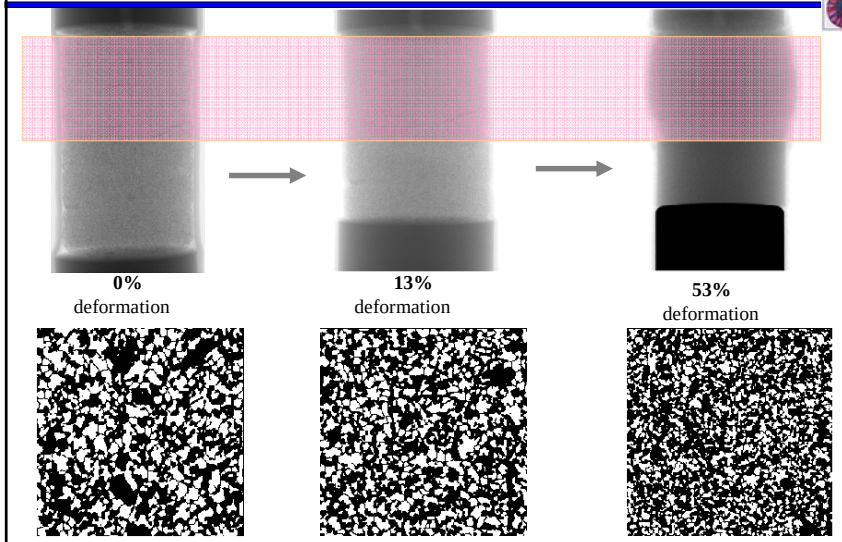


what is happening to the material?

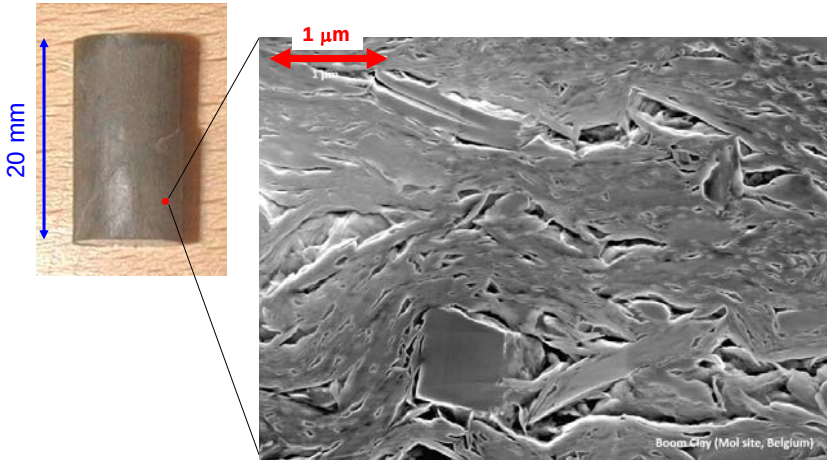


what about clayey (i.e., fine-grained) geomaterials?

plane strain compression (clay)

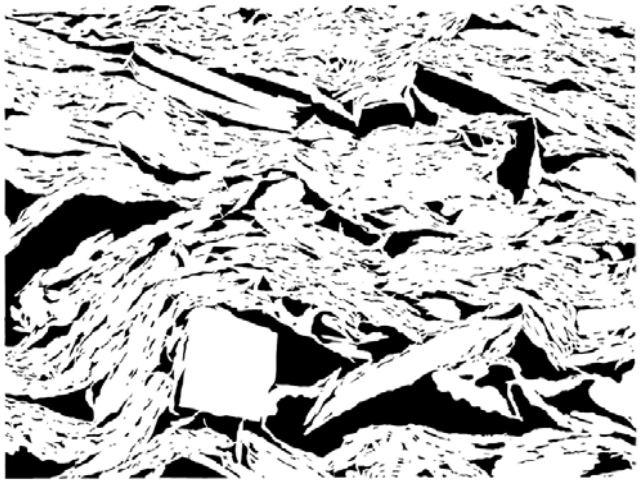
fine-grained geomaterials

how small is "small" for a clayrock ?



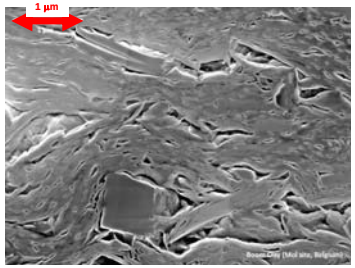
BIB image of Boom Clay -- courtesy of J.L. Urai, Aachen University

looking at Boom clay at very small scale



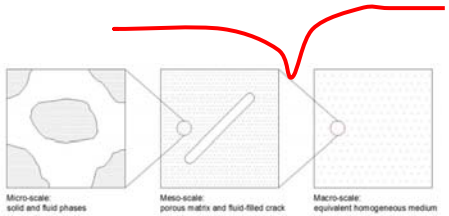
courtesy of J.L. Urai, Aachen University

how small is "small" for a clayrock ?

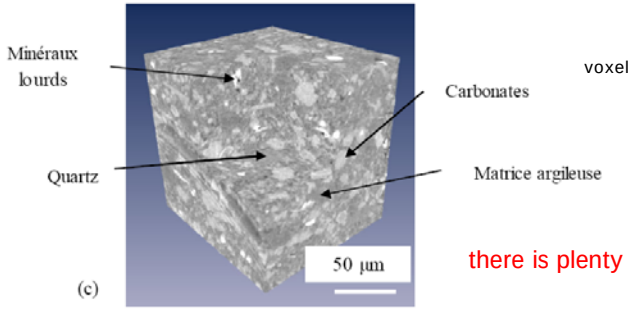


we believe this is too small (i.e., the interesting physics of the phenomena we wish to model are possibly taking place at a larger scale)

there are very many interesting scales in between



x-ray 3D images recently obtained / what we plan to do



voxel size 0.7 mm (ESRF)

there is plenty of things to see!

PhD JC ROBINET (2008) Poitiers

we wish to observe/understand/quantify failure mechanisms at this scale

we're currently planning two types of TXC tests:

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

I have a dream (measuring interparticle forces?)

Granular Matter
DOI 10.1007/s10035-011-0251-x

ORIGINAL PAPER

Can intergranular force transmission be identified in sand?

First results of spatially-resolved neutron and X-ray diffraction

Stephen A. Hall · Jonathan Wright · Thilo Pirling · Edward Andò · Darren J. Hughes · Gioacchino Viggiani

geometry, kinematics WHAT ABOUT FORCES/STRESSES?

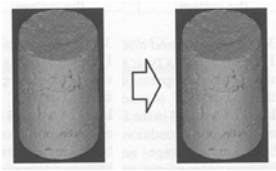
time to conclude...

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 **contact** morphology/distribution/evolution

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

closure: multi-scale modeling

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 failure in geomaterials

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