X-ray tomography for granular materials current trends and perspectives

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Eddy Andò

outline

- x-ray radiography, x-ray tomography
- x-ray tomography and image analysis
- trends, challenges, perspectives
    - individual grain kinematics
    - characterization of grain-to-grain contacts
    - production of fines by grain breakage
    - cemented granular materials (grain debonding)
    - partially saturated sand (menisci)
    - fine-grained geomaterials

x-rays

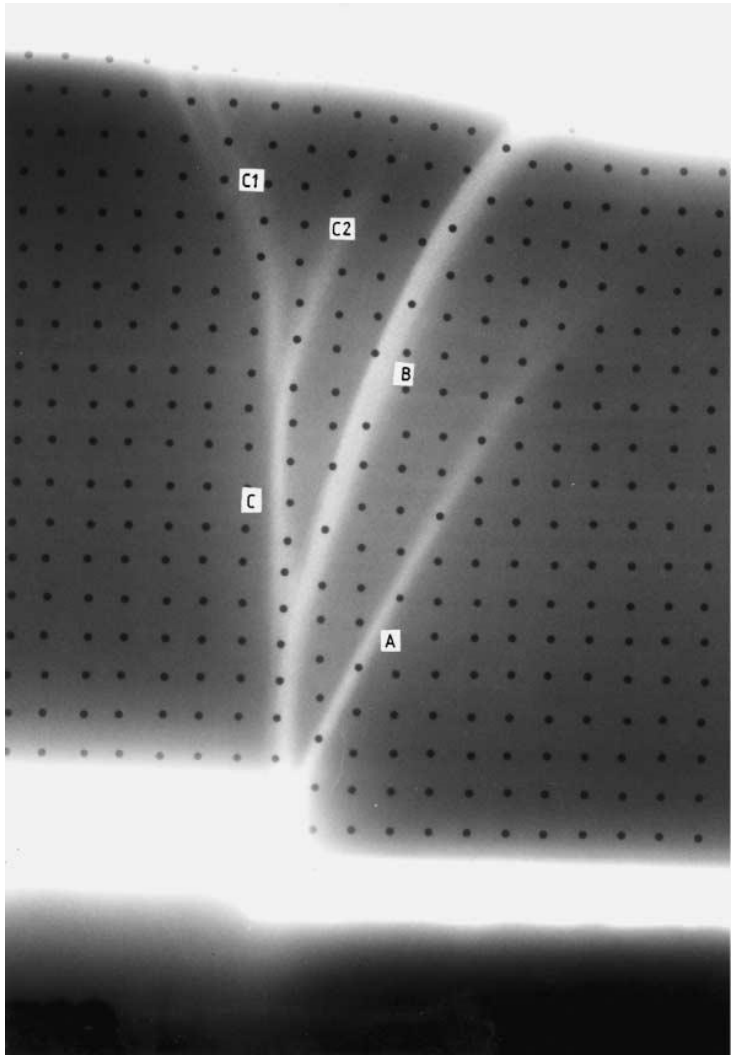
Hand with Ring: print of Wilhelm Röntgen's first "medical" x-ray, of his wife's hand, taken on 22 December 1895 and presented to Ludwig Zehnder of the University of Freiburg, on 1 January 1896

- discovery of x-rays by Wilhelm Röntgen
- first radiographies in 1895
- first ever Nobel prize in Physics in 1901

x-rays have been voted **the** discovery of the last 100 years

radiographs are maps in **2D** of the attenuation of the x-rays as they travel through the object being imaged

x-ray radiography and geomechanics



Roscoe and coworkers, Cambridge 1960s

radiography → tomography

when things must be seen in 3D, then radiography is not sufficient

radiography (2D) → computed tomography (3D)

in order to get a 3D image with x-rays we need:

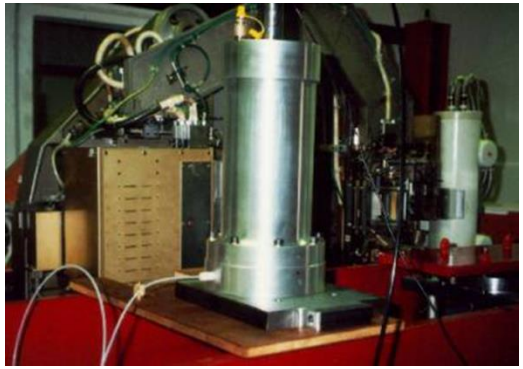
many radiographs (acquired at different angular positions)

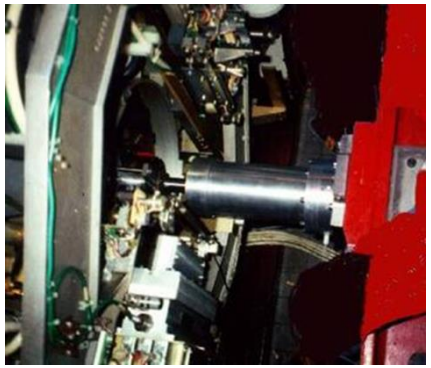
some mathematics (Radon transform)

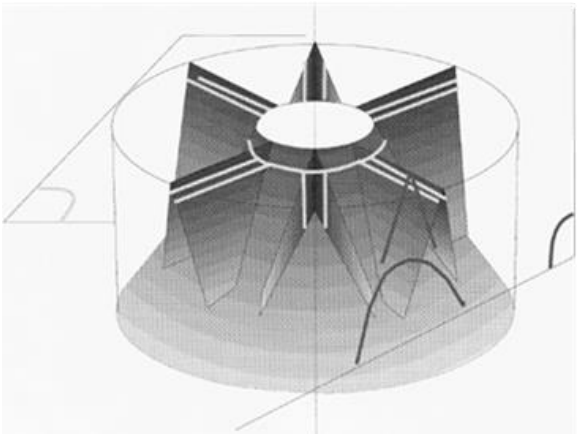
- tomography = "extension" of radiography
- original mathematical framework by Radon in 1917
- first x-ray CT scanner in 1972 by Hounsfield & Cormack
- Nobel prize in Medicine in 1979

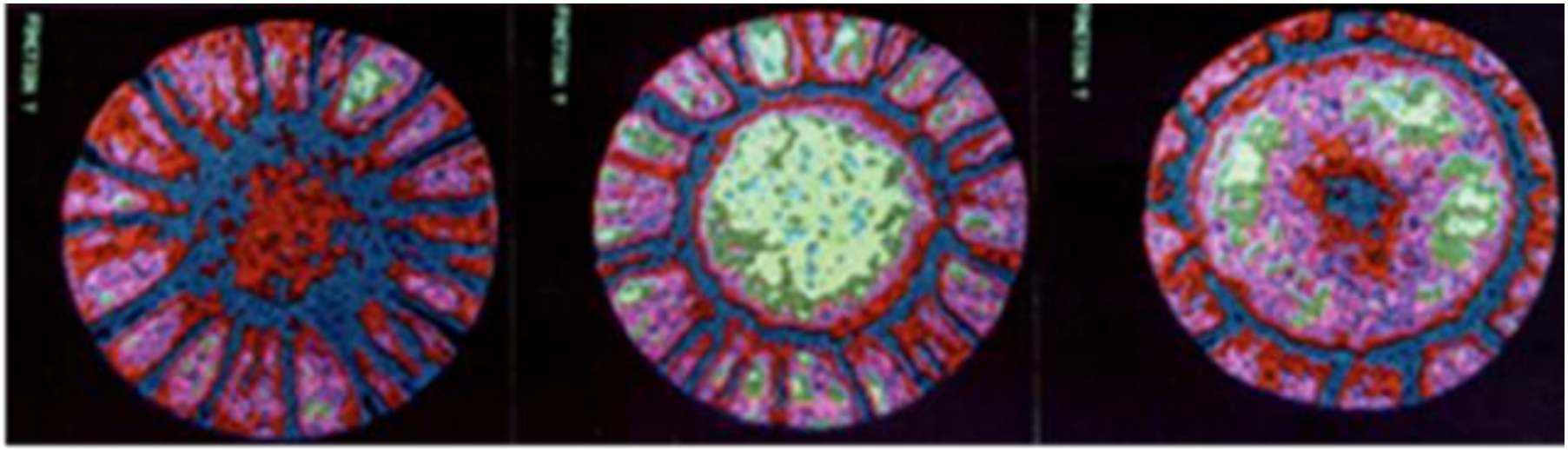
x-ray tomography and geomechanics

Jacques Desrues: using a medical CT scanner to hunt for strain localization in 3D in sand

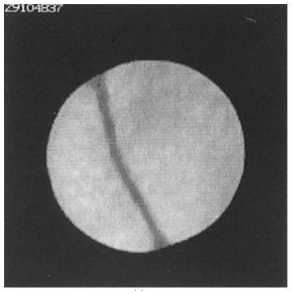


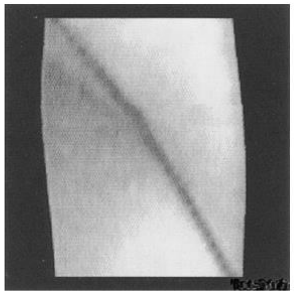






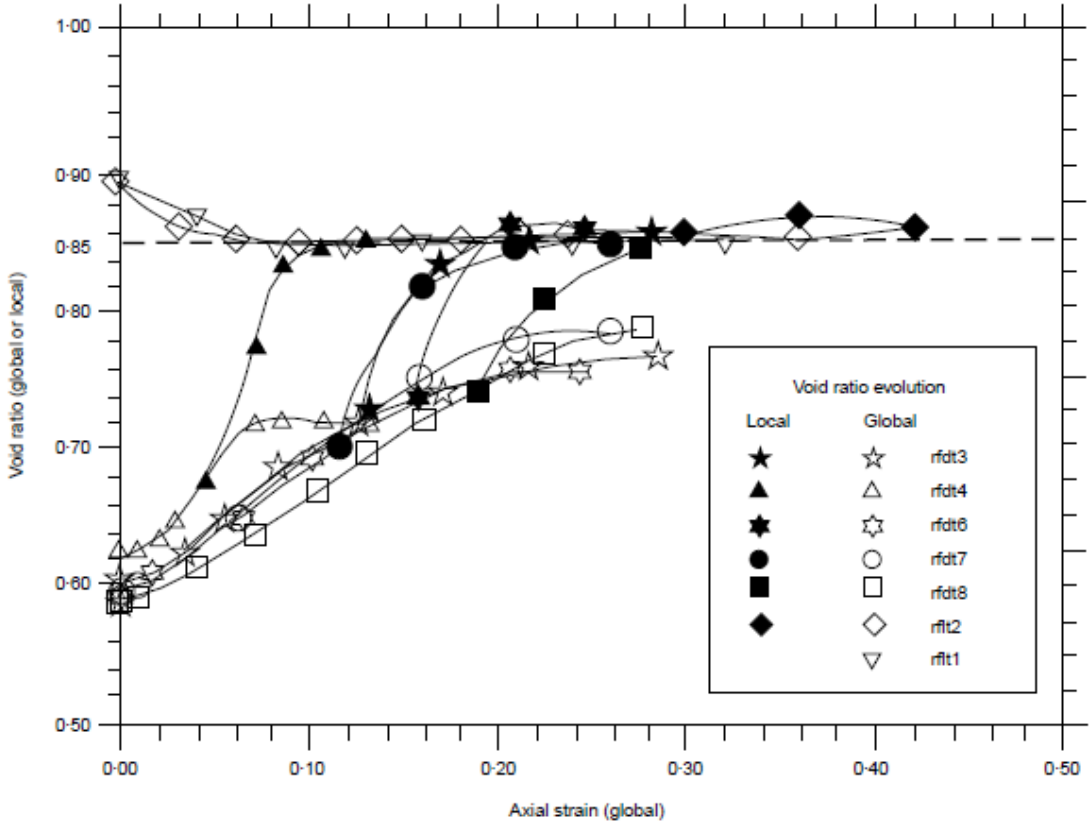
x-ray tomography as a quantitative tool



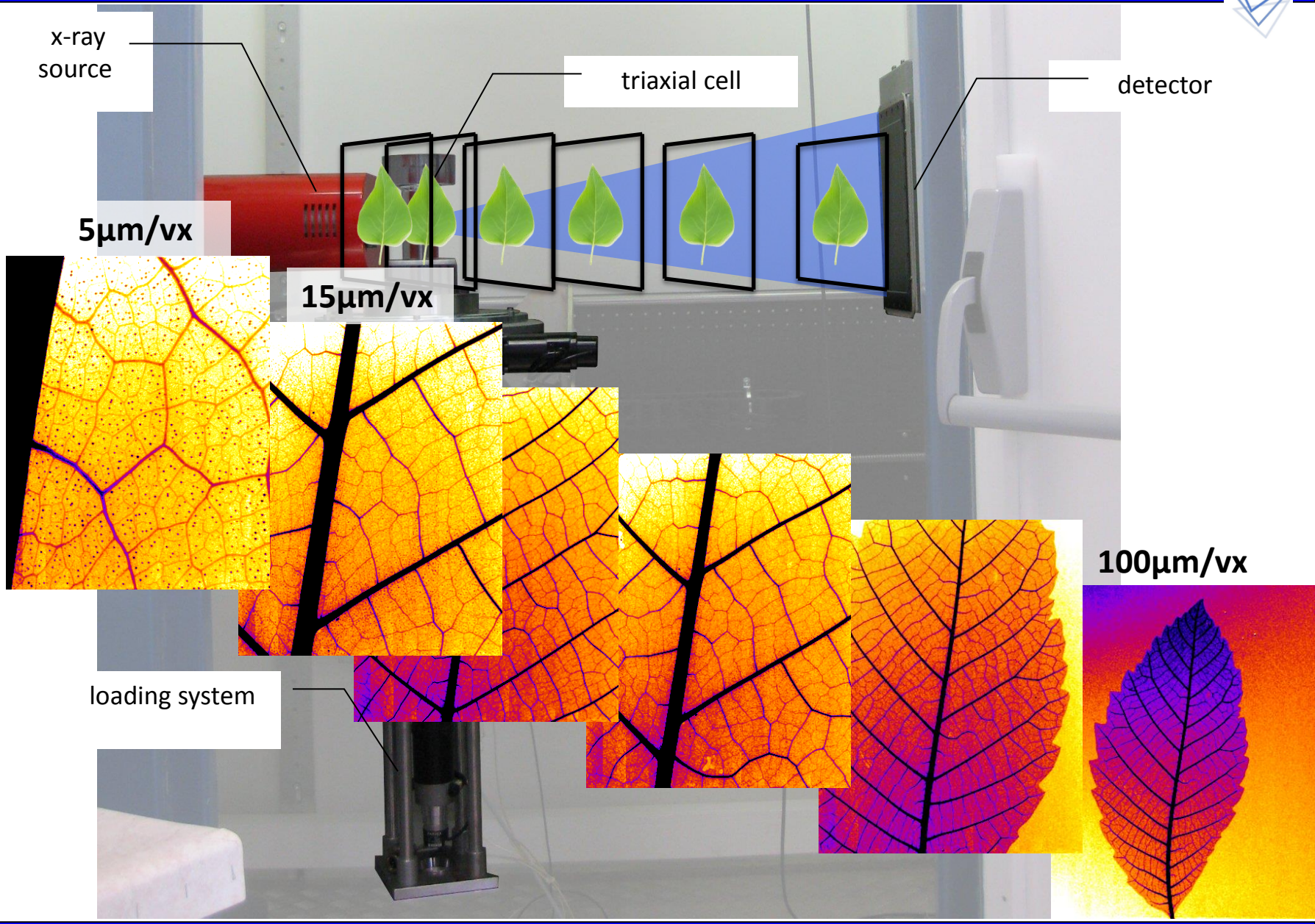


Desrues, J., Chambon, R., Mokni, M. & Mazerolle, F. (1996). *Géotechnique* **46**, No. 3, 529–546

Void ratio evolution inside shear bands in triaxial sand specimens studied by computed tomography



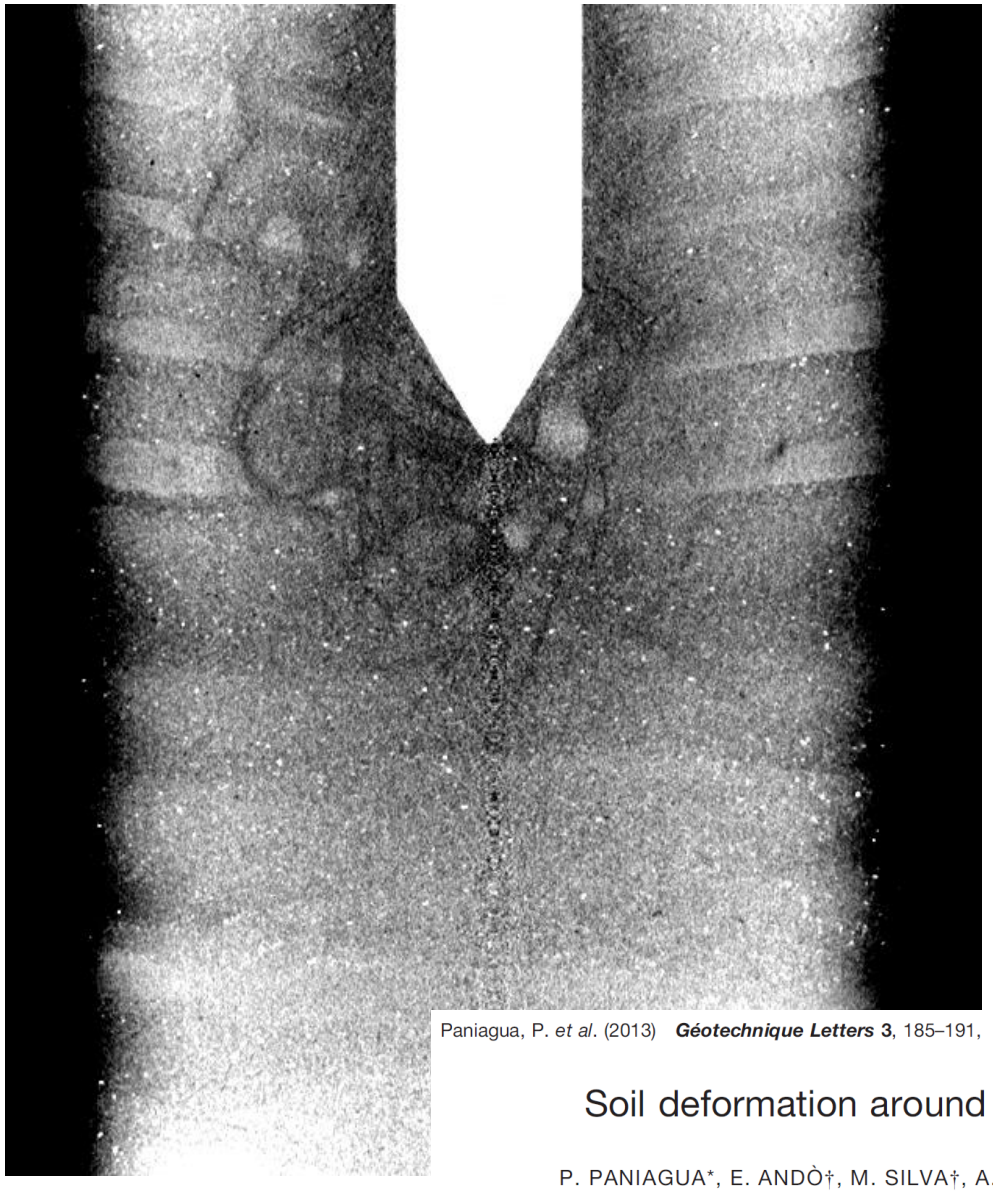
in a geomechanics lab in Grenoble…



imaging the physics at the pertinent scale(s)

imaging lab-scale CPT

Priscilla Paniagua
NTNU Trondheim



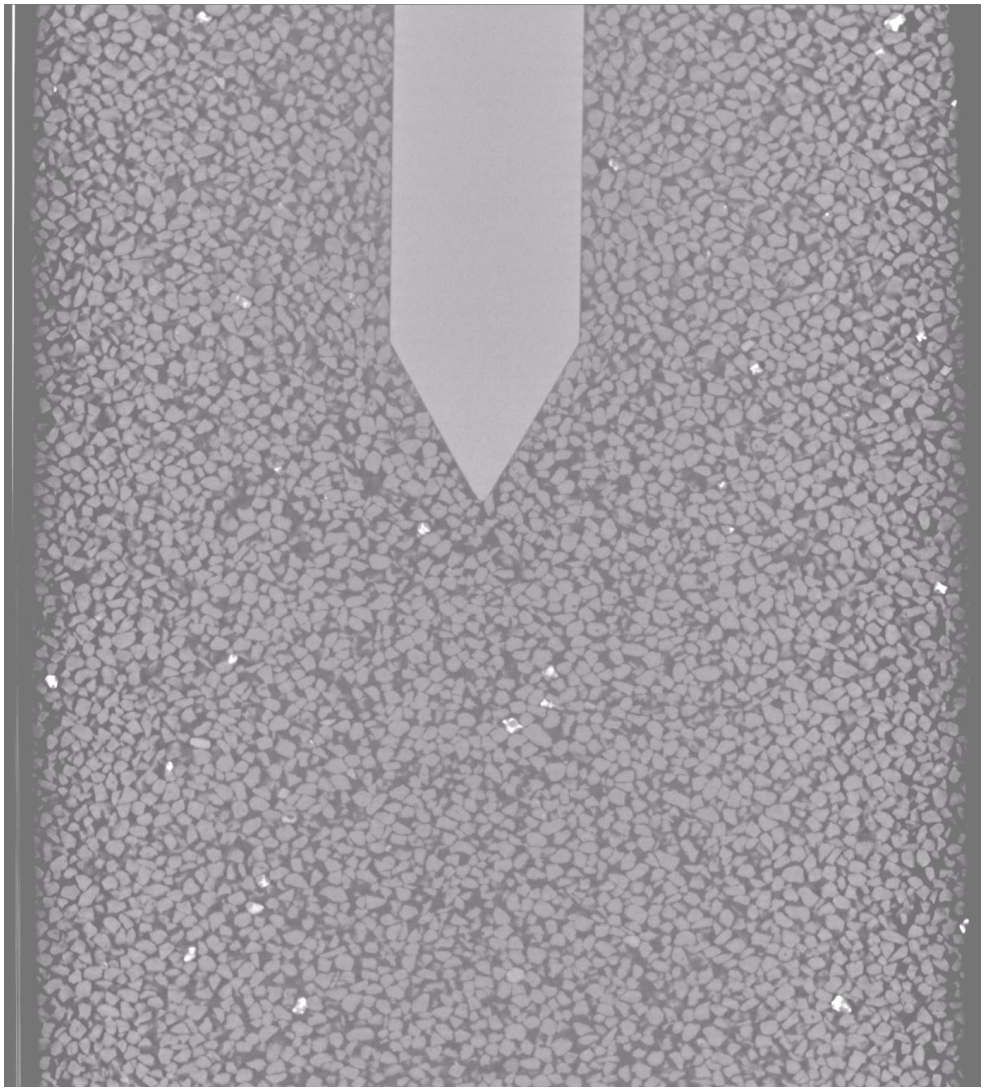
Paniagua, P. *et al*. (2013) ***Géotechnique Letters*** **3**, 185–191, http://dx.doi.org/10.1680/geolett.13.00067

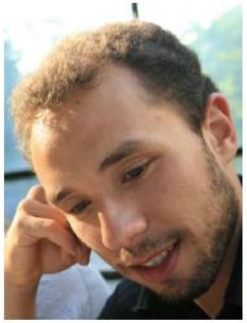
Soil deformation around a penetrating cone in silt

P. PANIAGUA*, E. ANDÒ†, M. SILVA†, A. EMDAL*, S. NORDAL* and G. VIGGIANI†

imaging lab-scale CPT (again, but with visible grains)

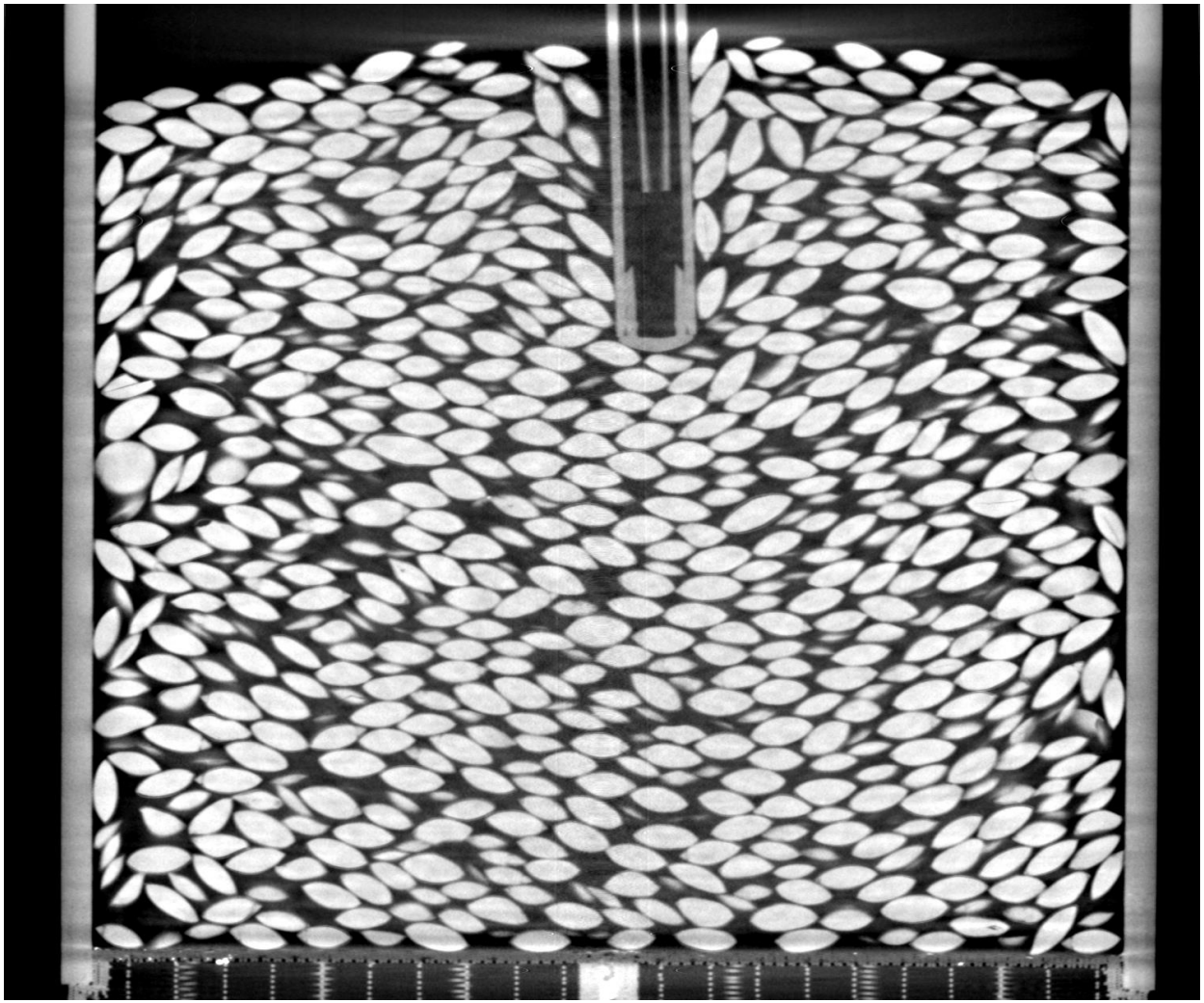
Matias Silva





Marios Gkiousas-Kapnisis

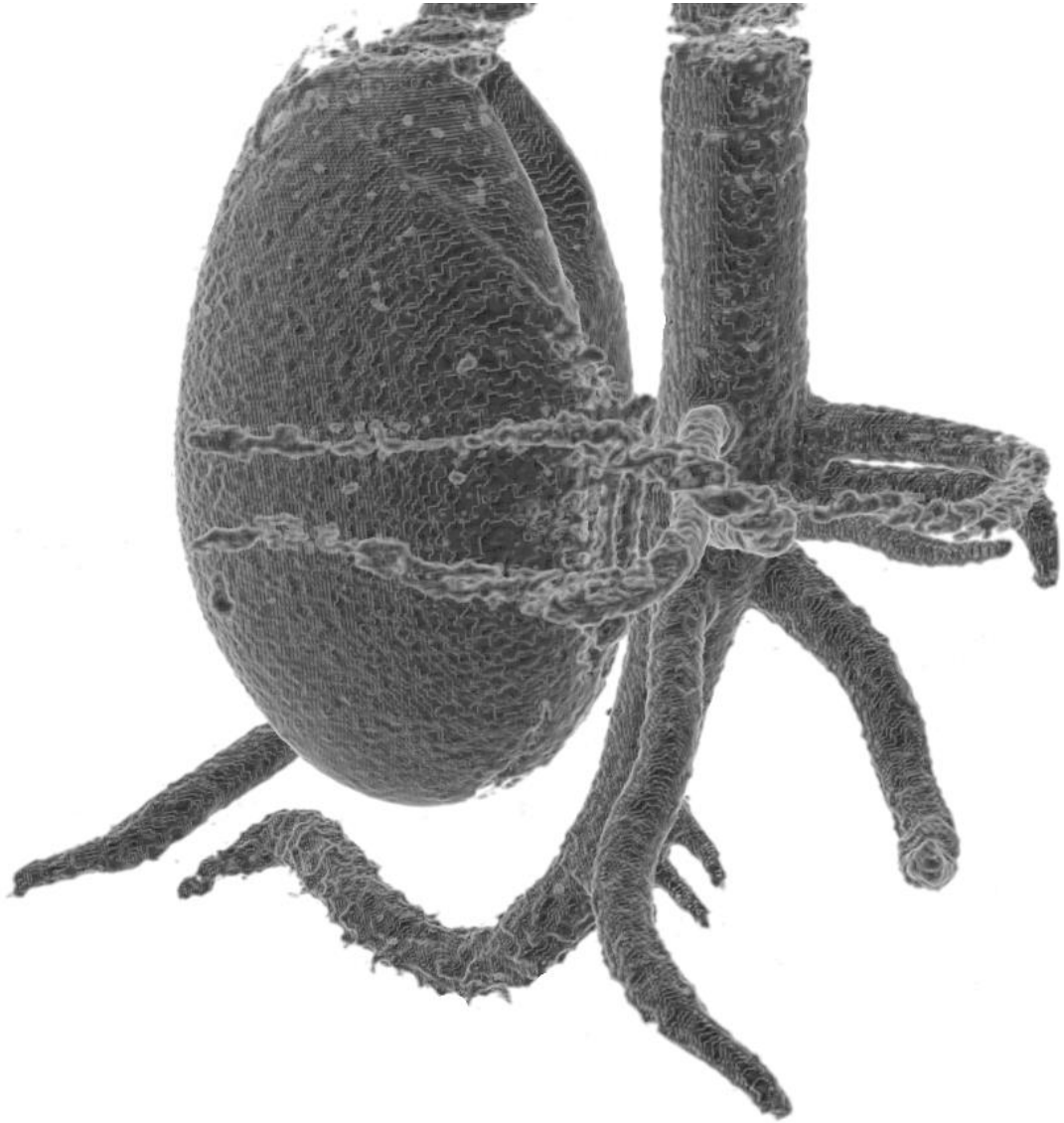
low tech "CPT" in flat "sand"



bean seed growth in sand

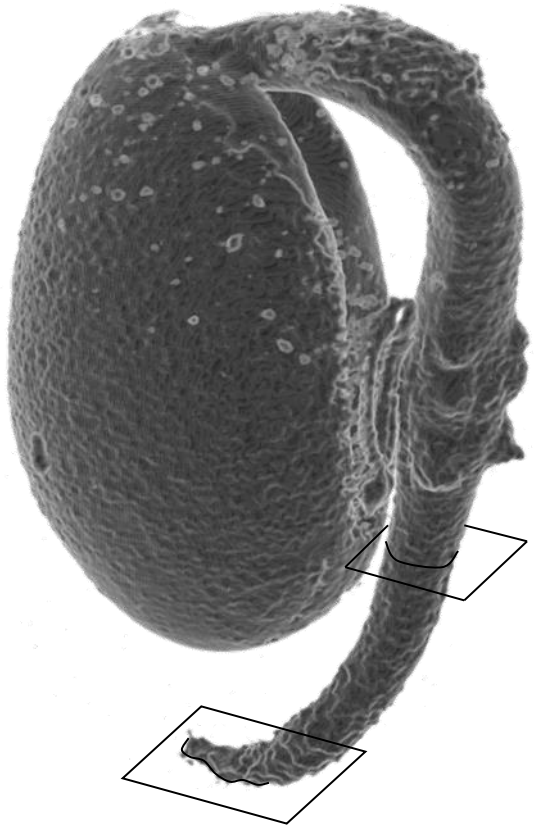
Carlos Santamarina
Georgia Tech

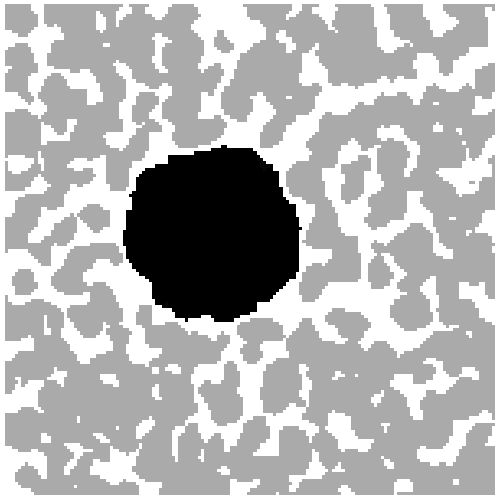
Daiki Takano
PARI Yokosuka

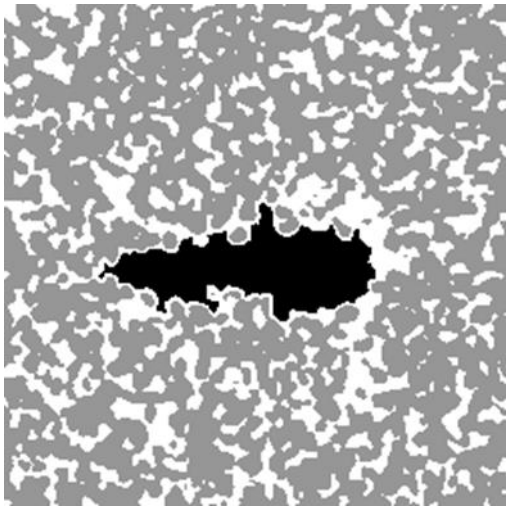


Viggiani *et al.* (2014) - Laboratory x-ray tomography: a valuable experimental tool for revealing processes in soils

bean seed growth in sand







Viggiani *et al.* (2014) - Laboratory x-ray tomography: a valuable experimental tool for revealing processes in soils

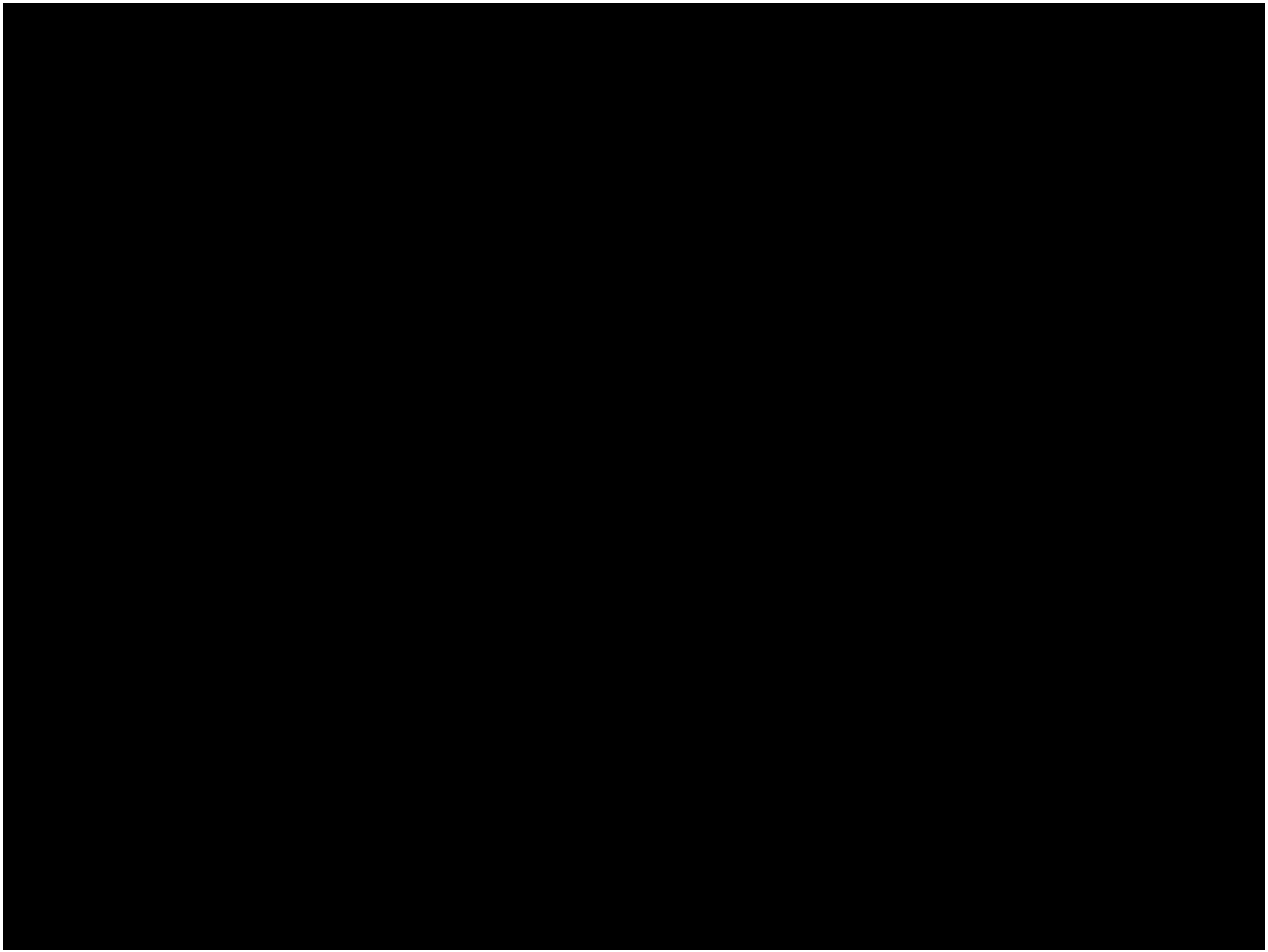
even more exotic x-imaging (unleash your imagination!)

massive ice lensing in bentonite

radial growth of ice lenses in kaolinite

Viggiani *et al.* (2014) - Laboratory x-ray tomography: a valuable experimental tool for revealing processes in soils

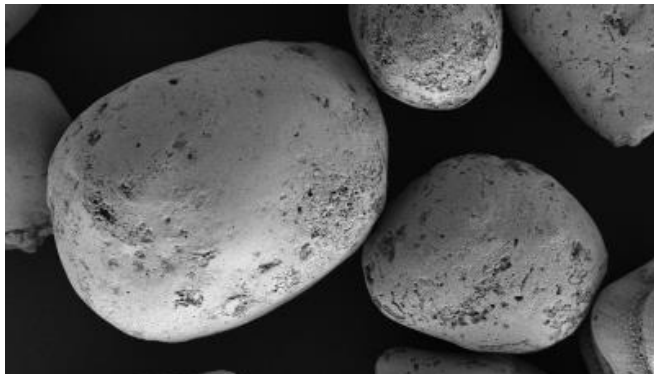
grain-scale imaging a sand specimen while it deforms under load

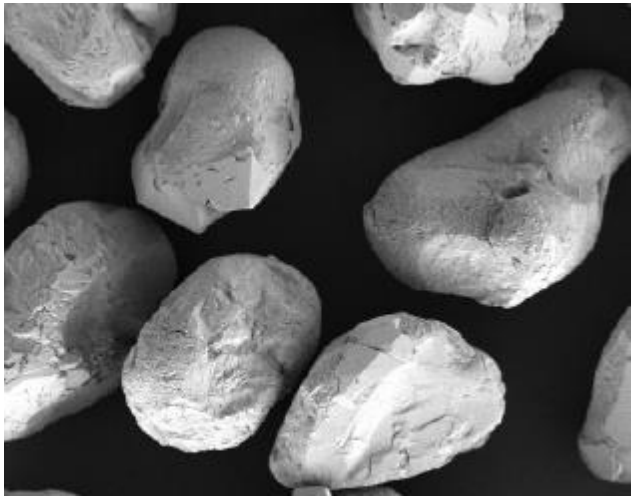


Caicos Ooid

Calcite, D_{50} = 350μm

very rounded





Ottawa 50/70 Sand

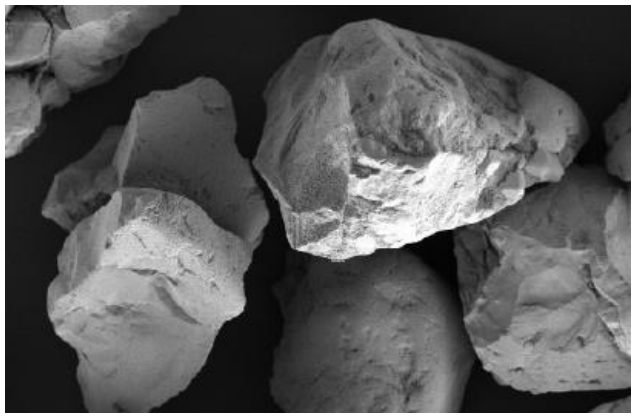
Quartz, D_{50} = 250μm

rounded

Hostun HN31 Sand

Quartz, D_{50} = 338μm

angular

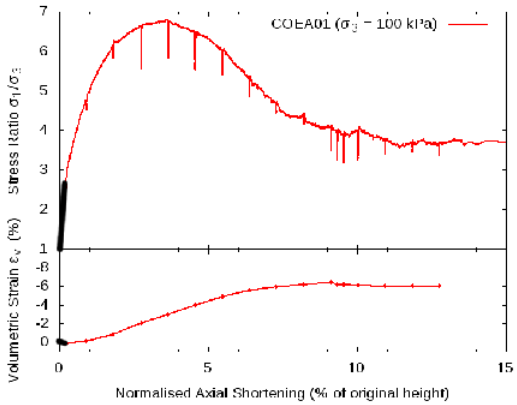


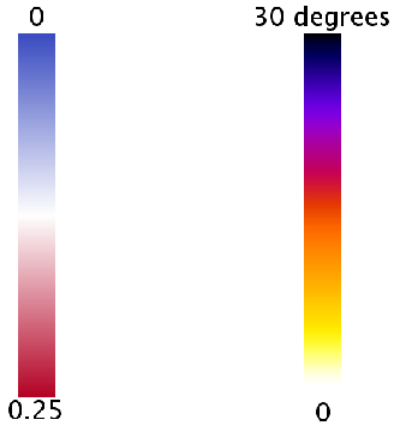
individual grain kinematics

Hall et al., Géotechnique 2010
Andò PhD 2013
Andò et al. Acta Geotechnica 2012
Andò et al. Géotechnique Letters 2012
Andò et al. Géotechnique Letters 2013

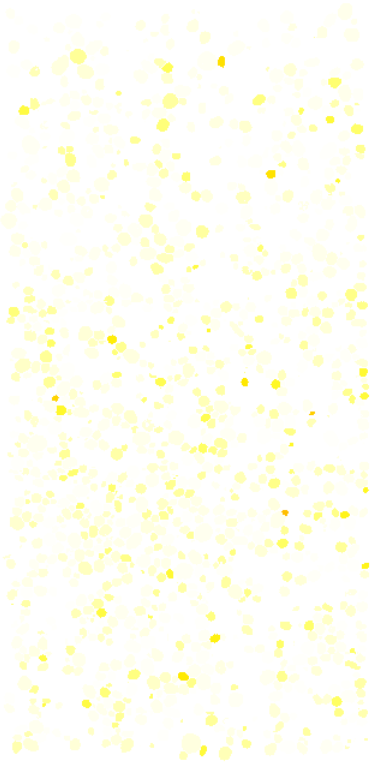
Grain-scale kinematics for test COEA01

Deviatoric Strain





Intensity of Rotations



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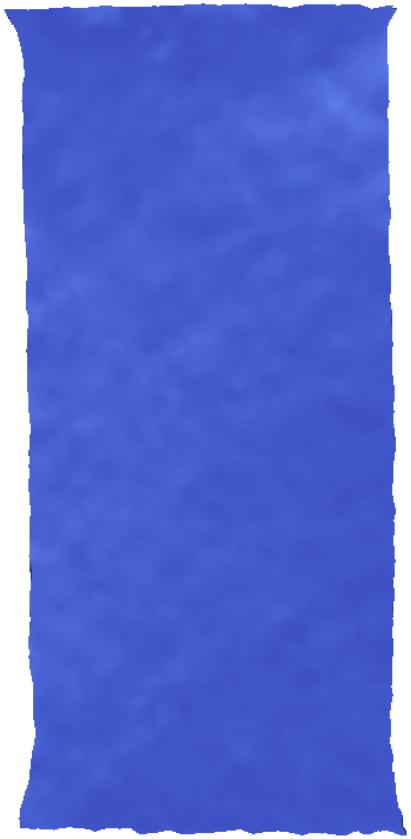

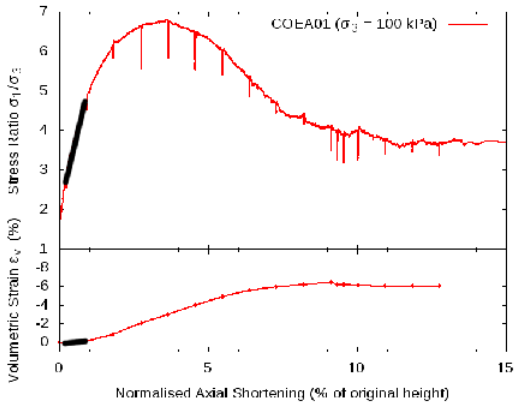

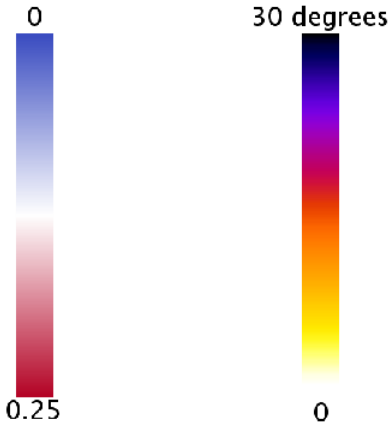

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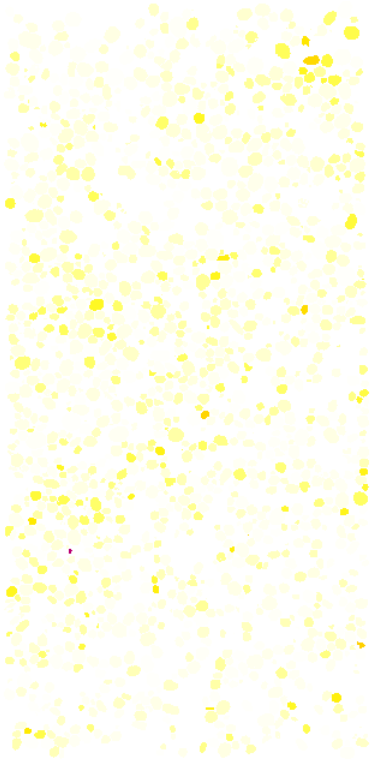

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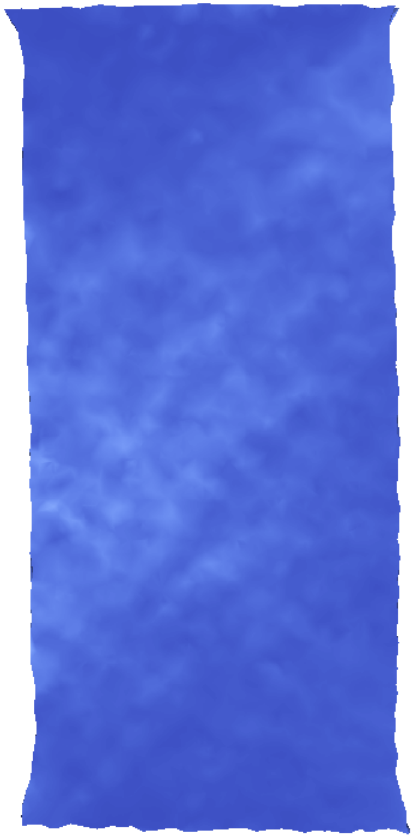

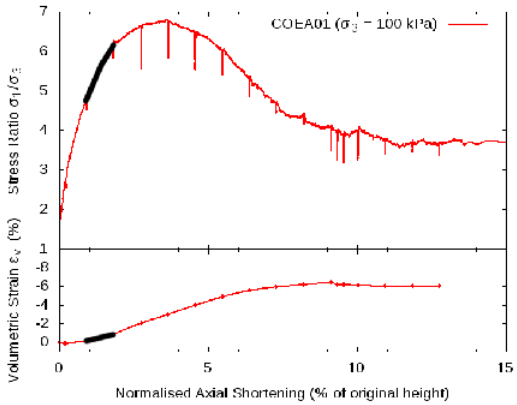

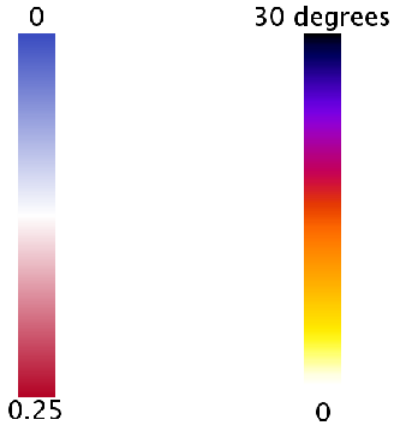

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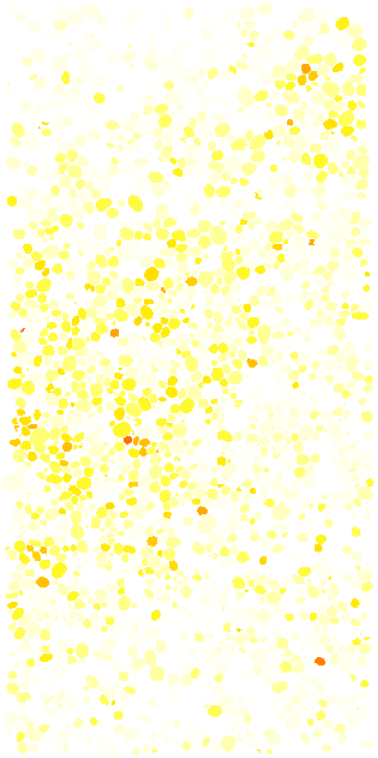

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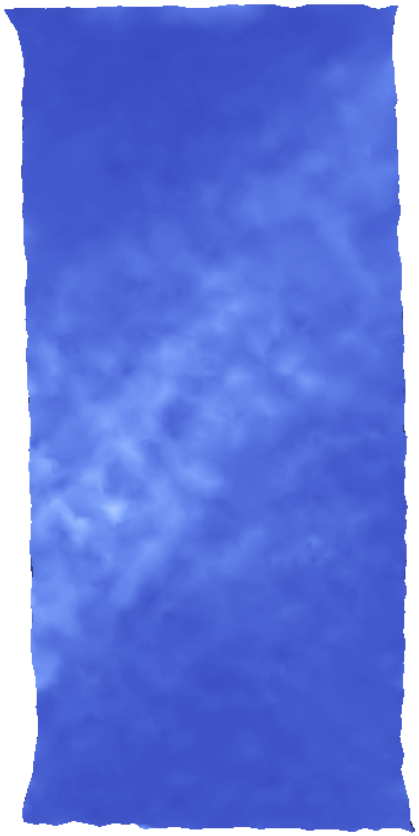

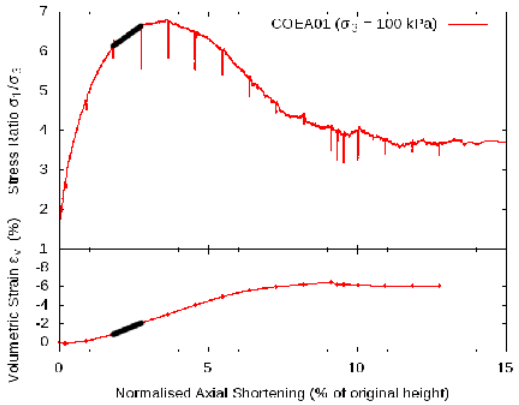

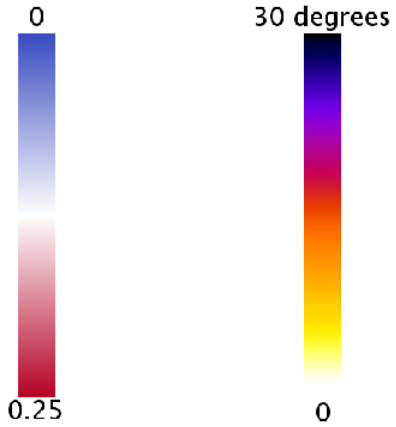

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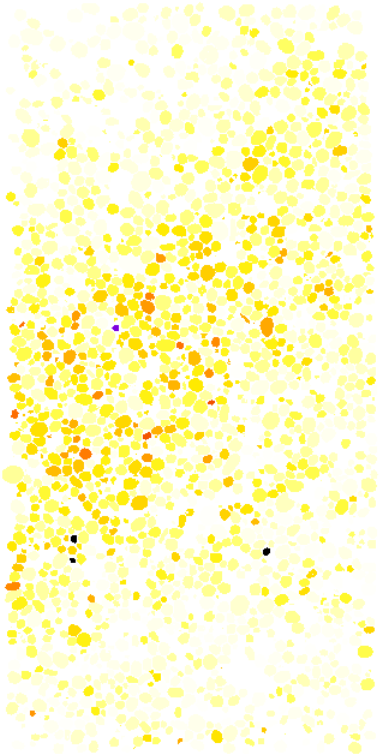
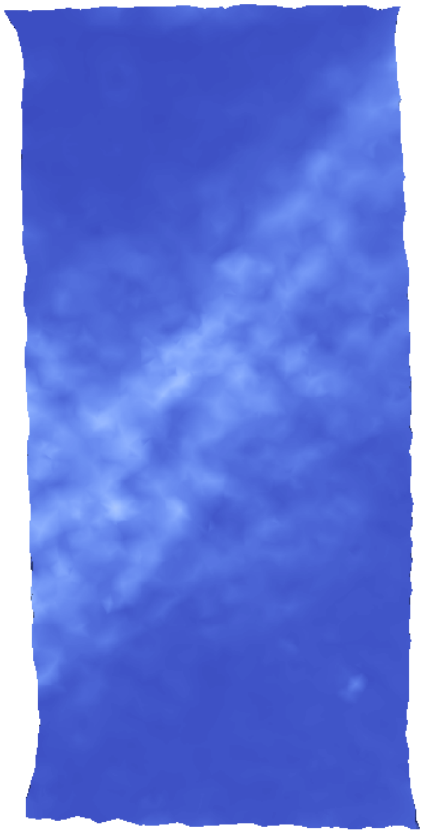
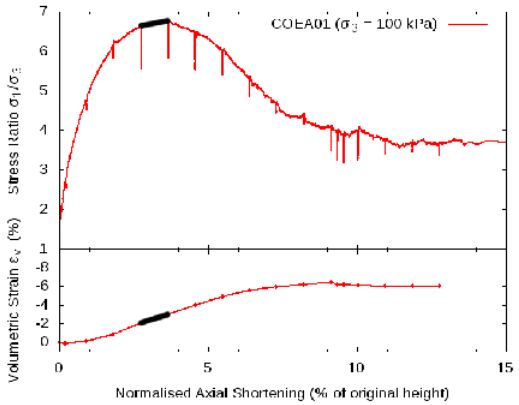
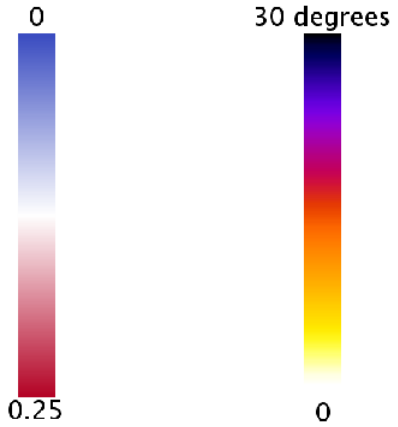


Grain-scale kinematics for test COEA01

Deviatoric Strain







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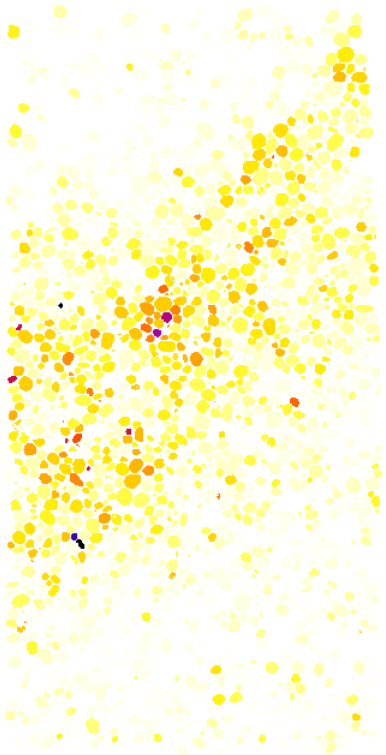

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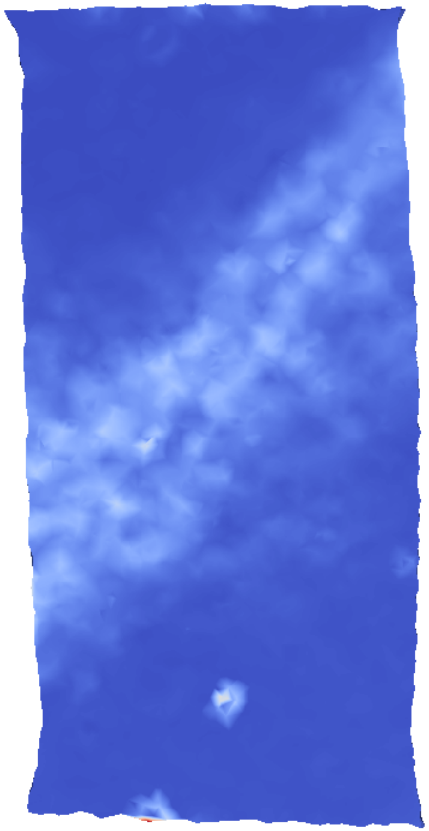

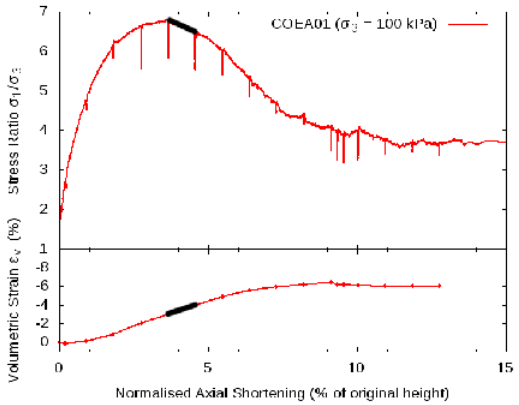

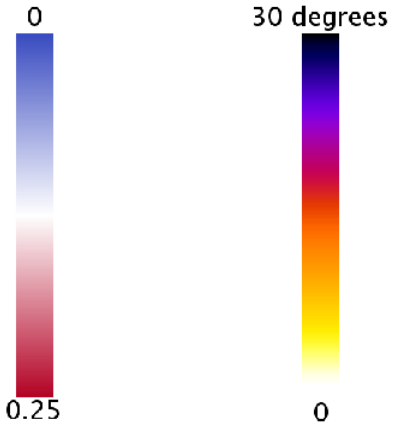

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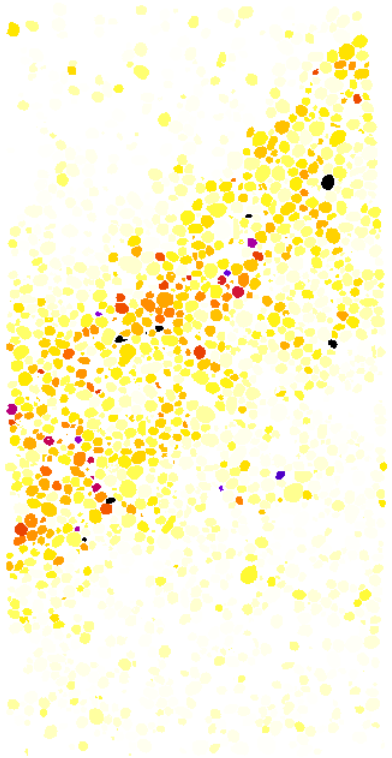
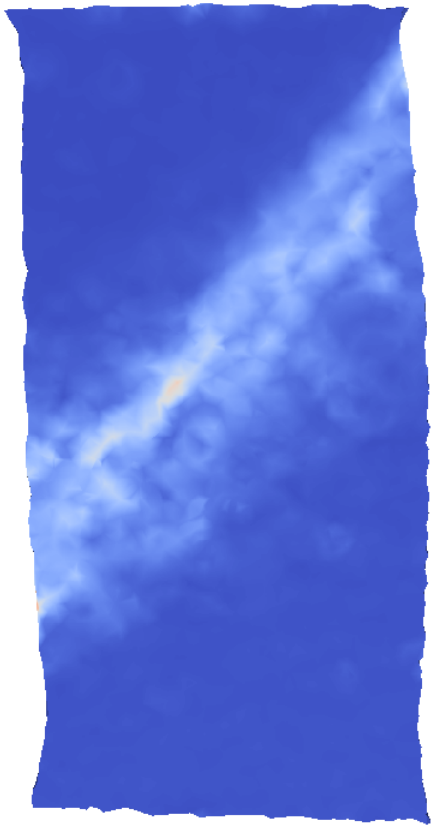
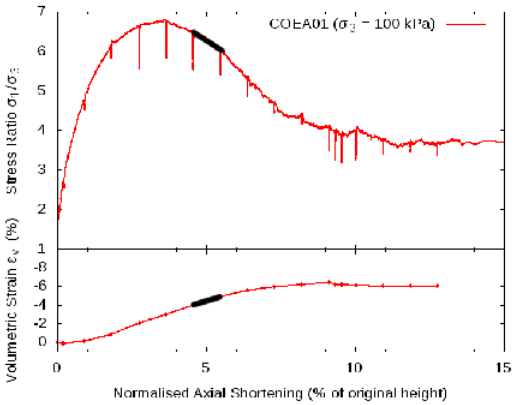
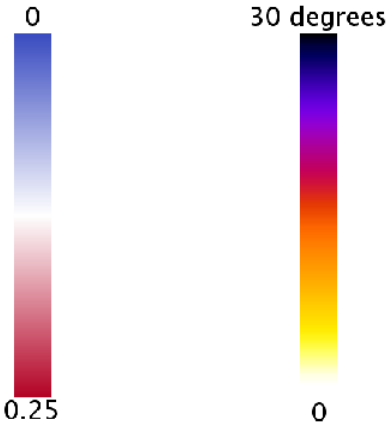


Grain-scale kinematics for test COEA01

Deviatoric Strain







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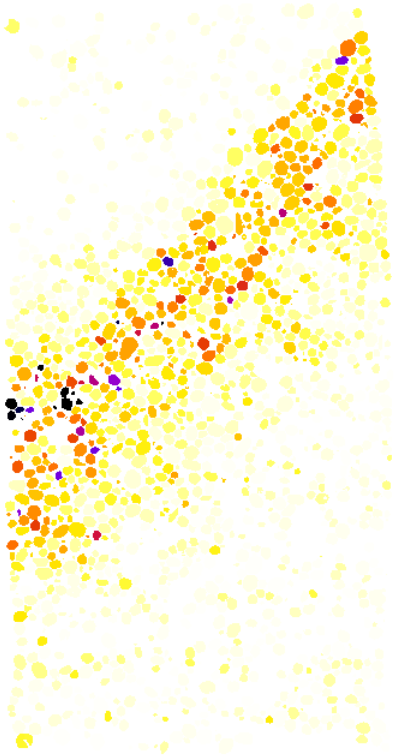

Grain-scale kinematics for test COEA01

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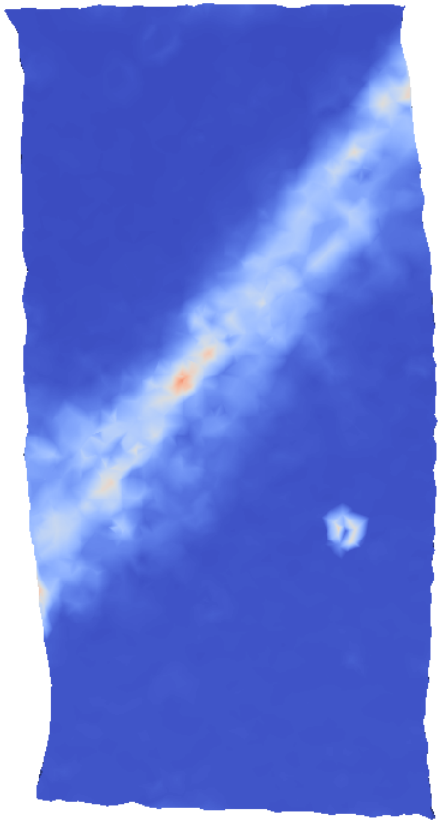

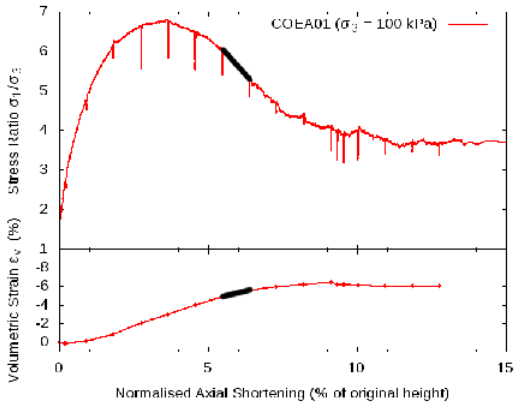

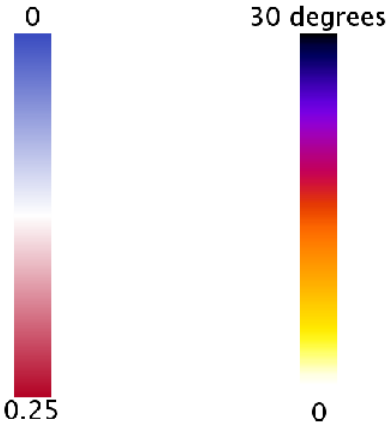

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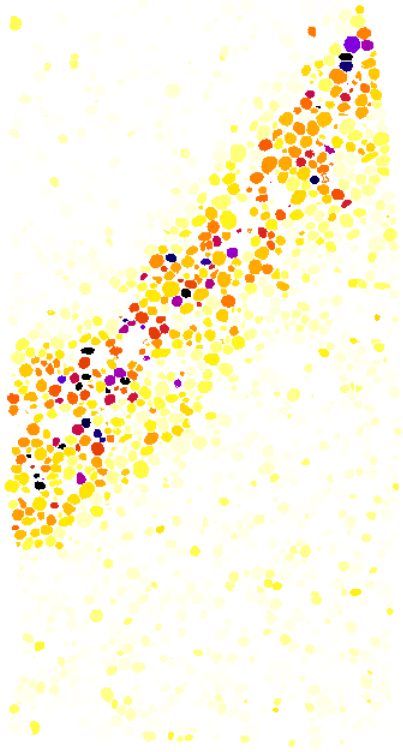

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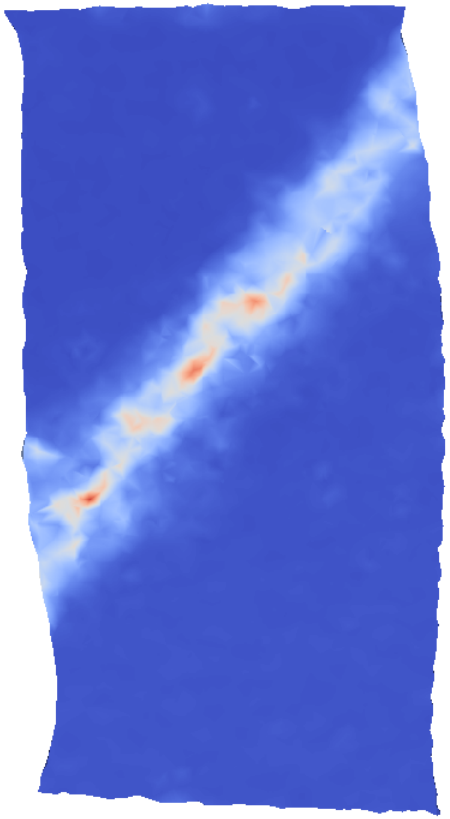
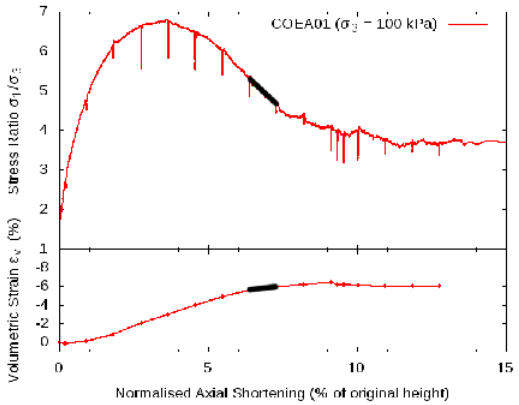
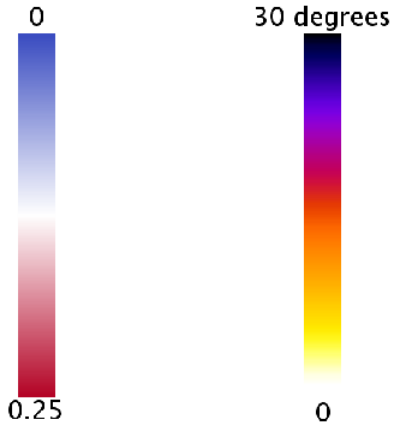
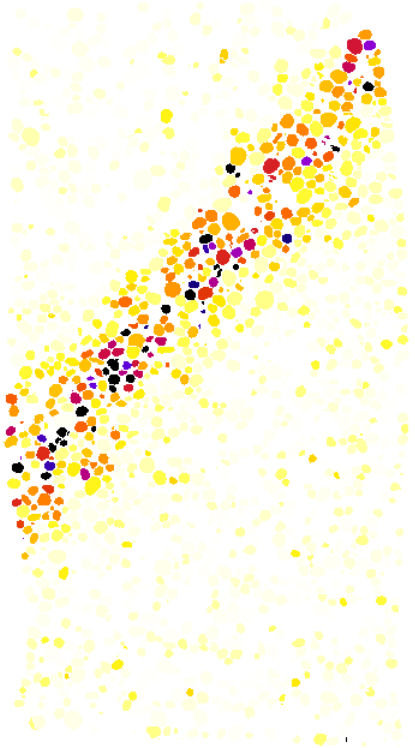
Deviatoric Strain





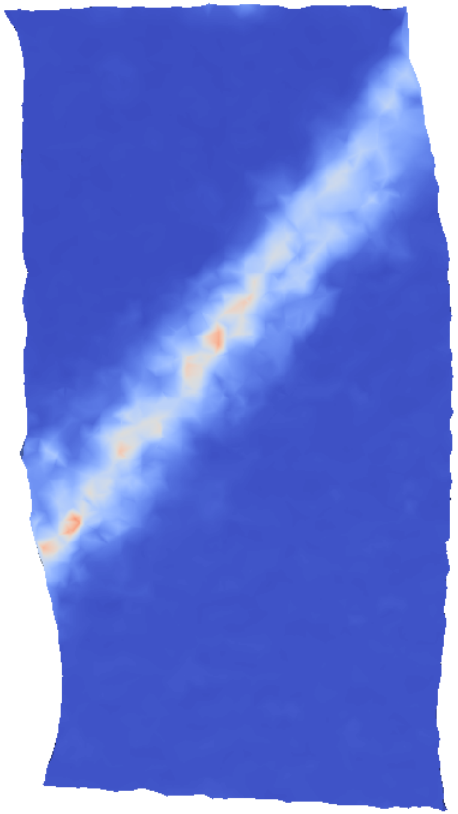


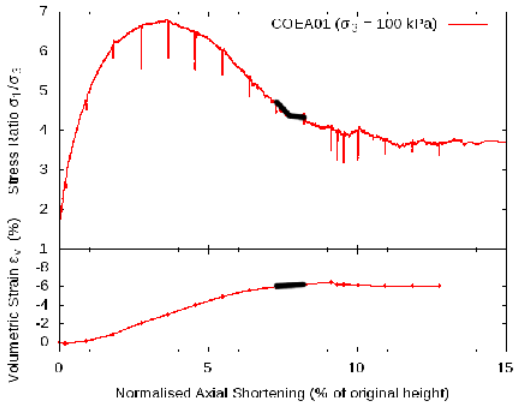
Intensity of Rotations

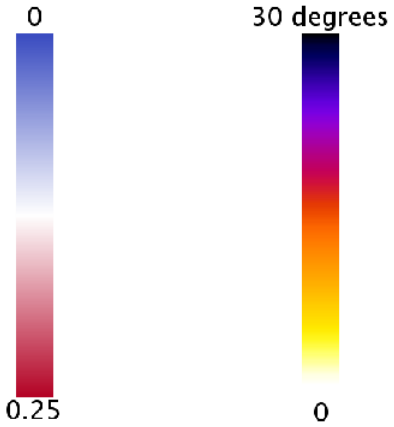


Grain-scale kinematics for test COEA01

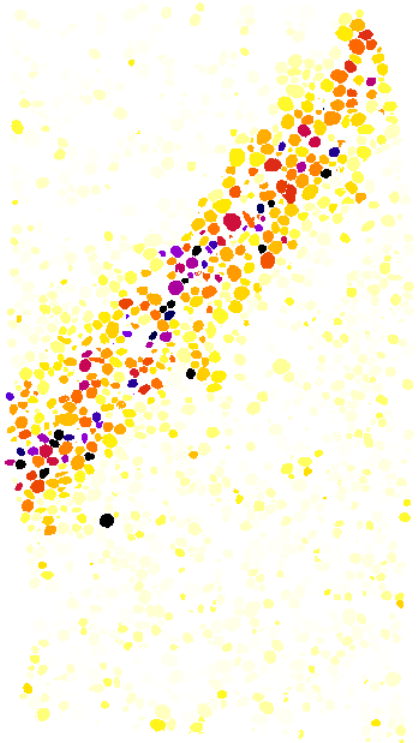
Deviatoric Strain





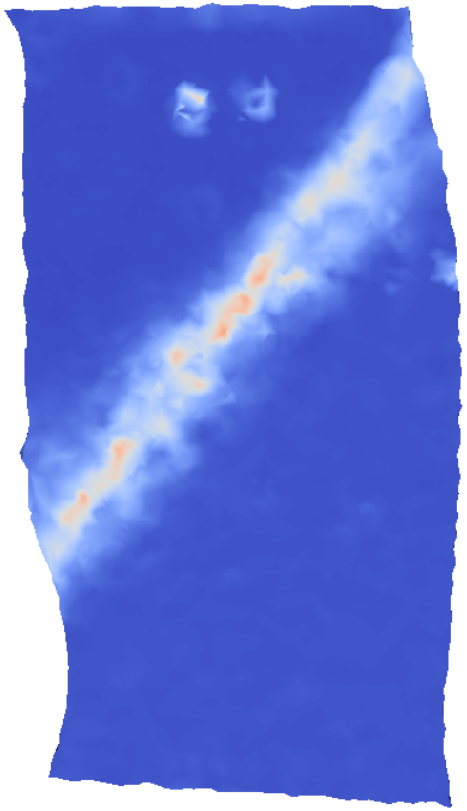


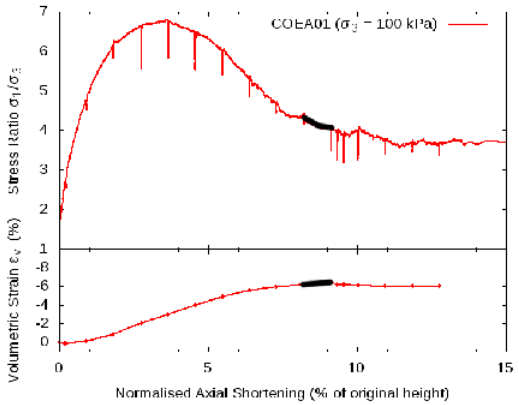
Intensity of Rotations

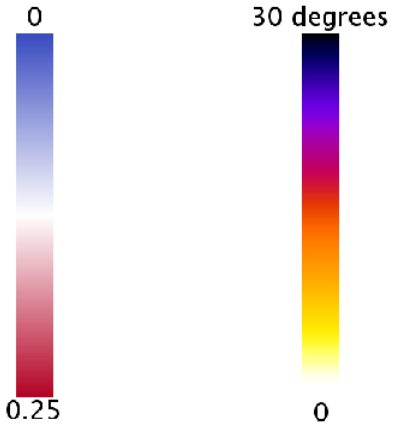


Grain-scale kinematics for test COEA01

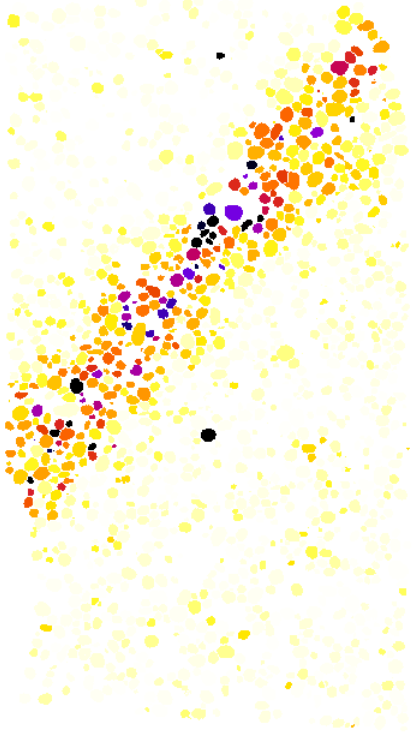
Deviatoric Strain





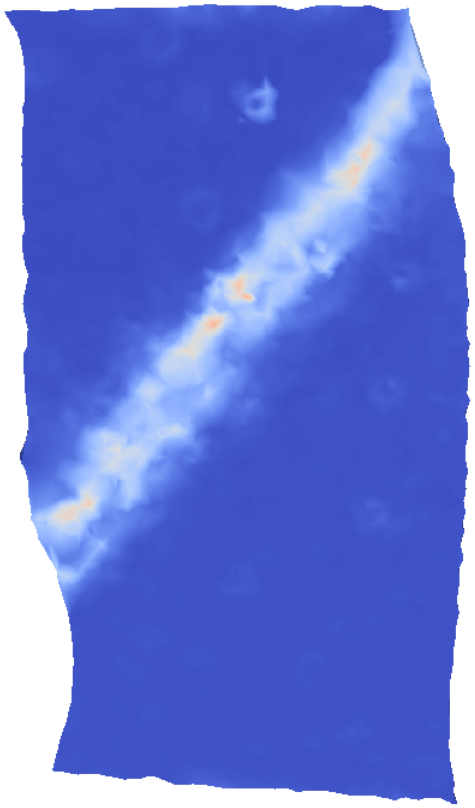


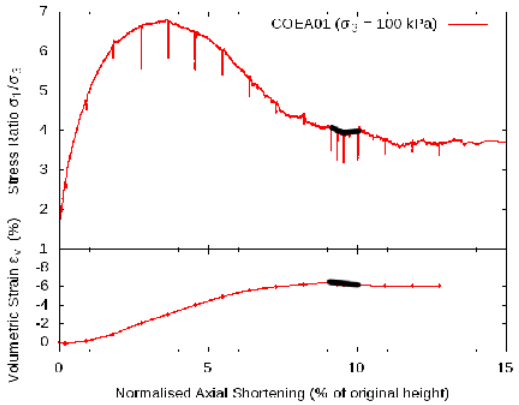
Intensity of Rotations

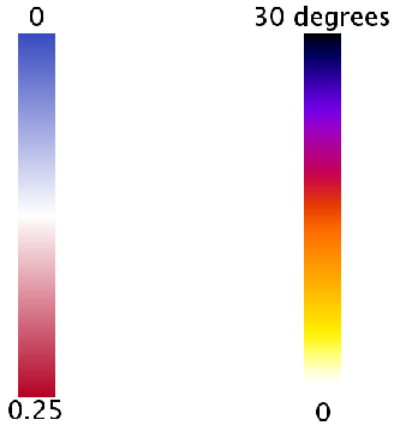


Grain-scale kinematics for test COEA01

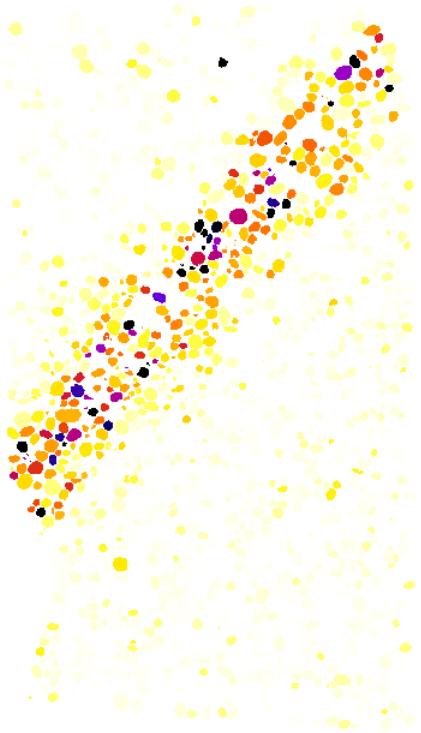
Deviatoric Strain





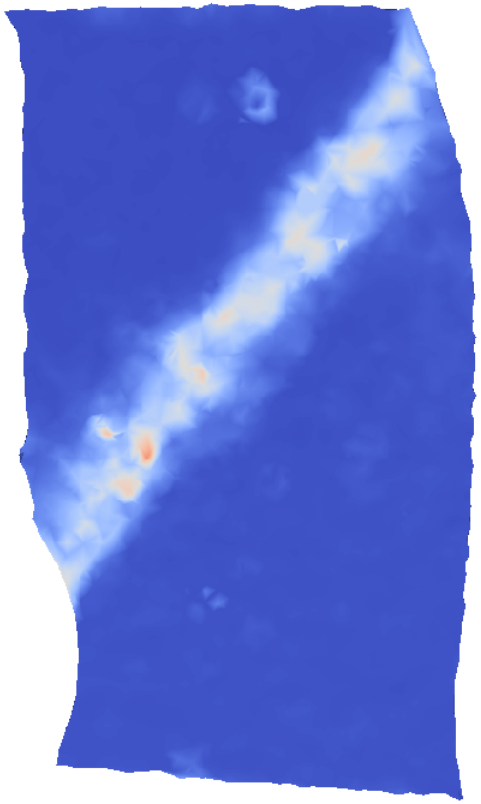


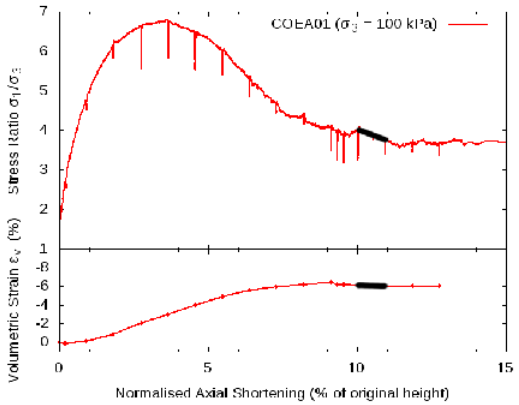
Intensity of Rotations

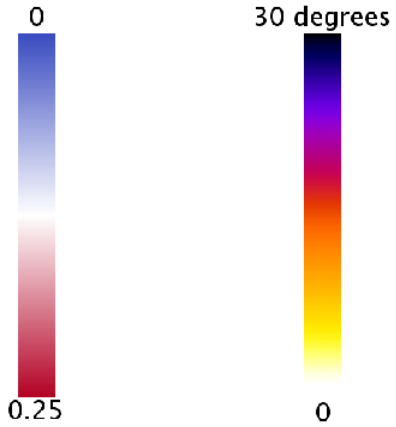


Grain-scale kinematics for test COEA01

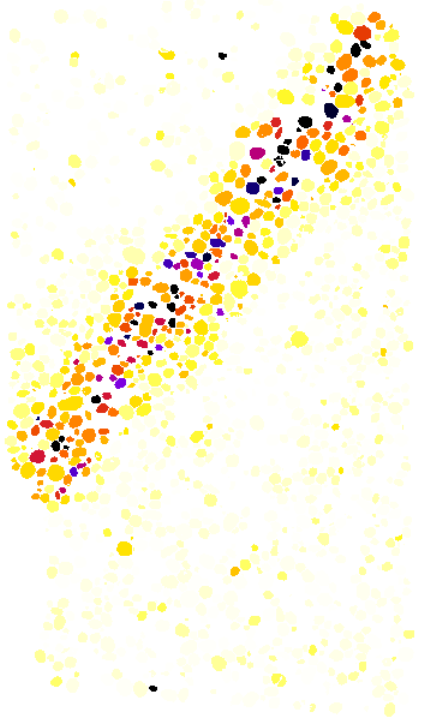
Deviatoric Strain





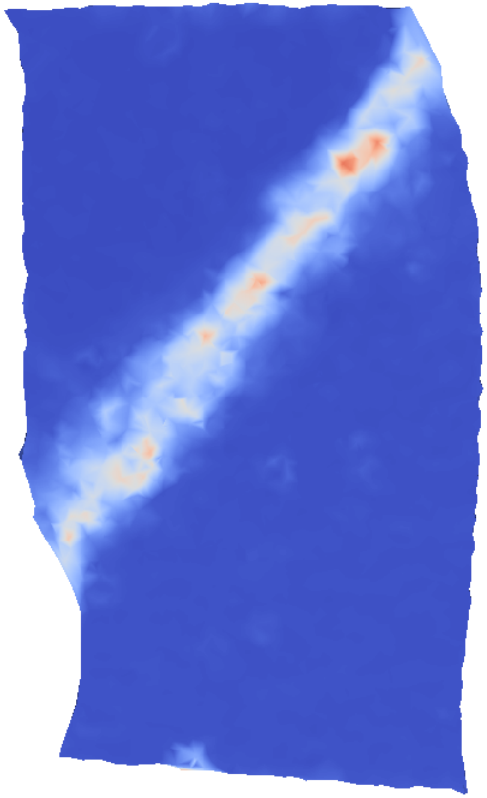


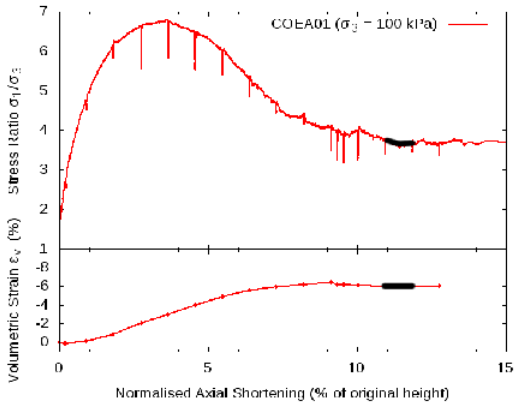
Intensity of Rotations

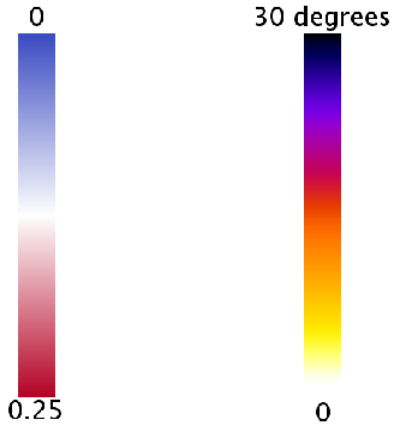


Grain-scale kinematics for test COEA01

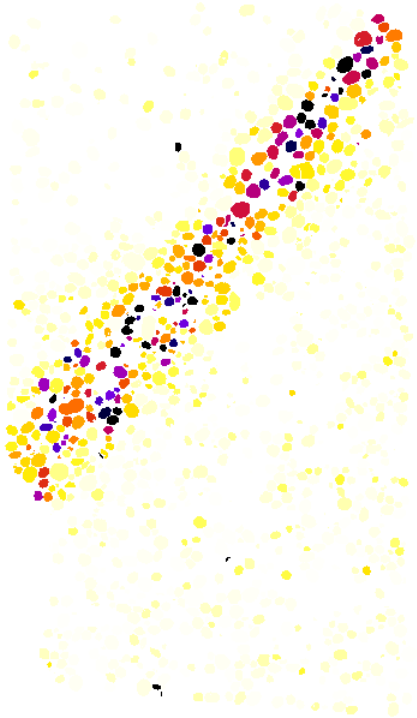
Deviatoric Strain



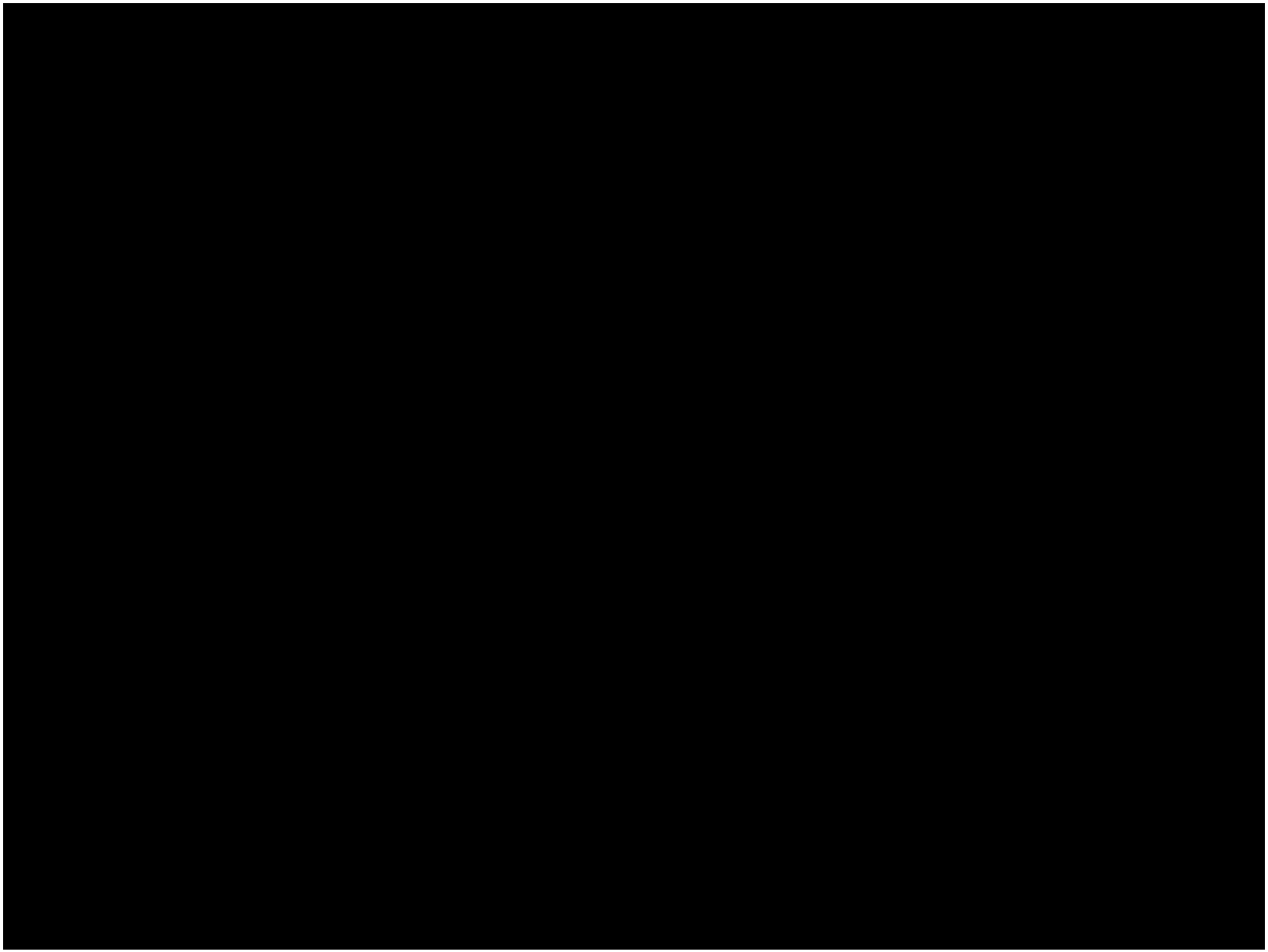




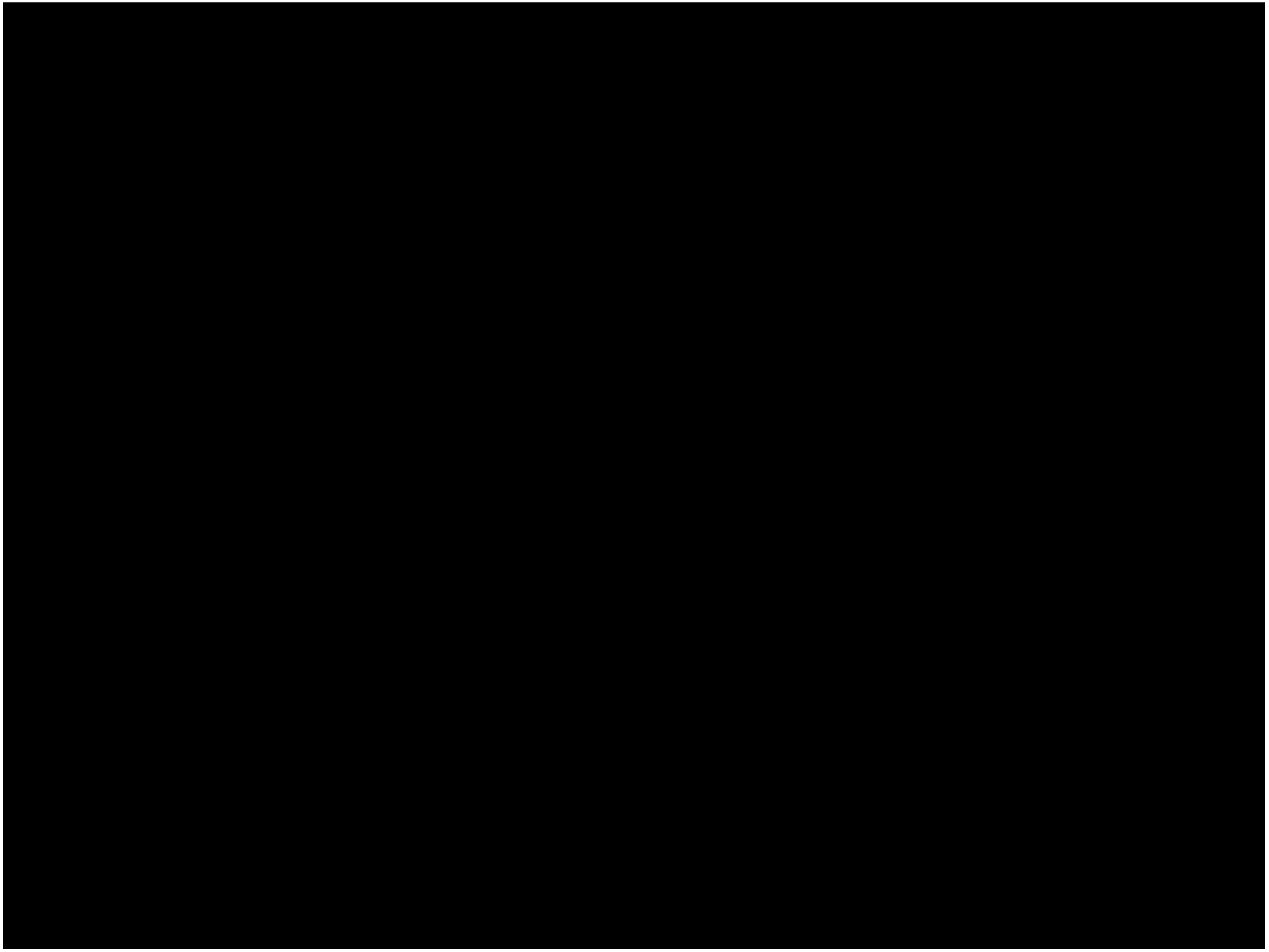
Intensity of Rotations



don’t forget these are 3D data



don’t forget these are 3D data



are we happy with what we can measure? Beyond grain kinematics

in-situ x-ray tomography combined with advanced image processing now allows **experimental micro-(geo)mechanics**

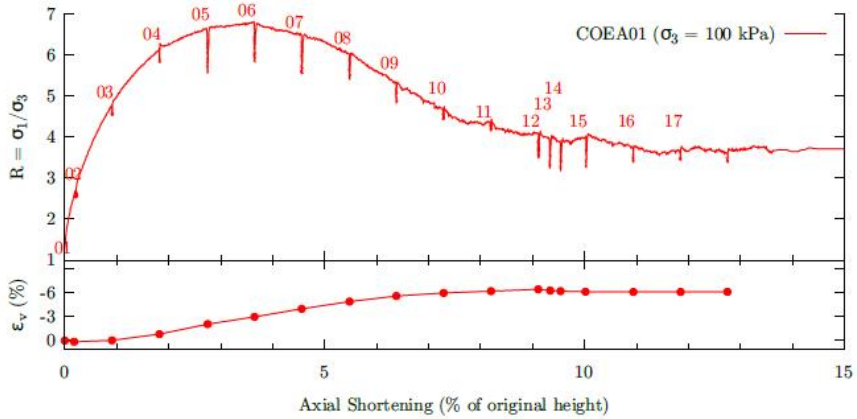
e.g., high-quality kinematical measurements are possible on all (say 50000) grains in a sand specimen deforming under load

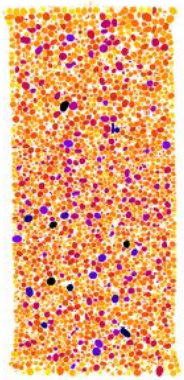
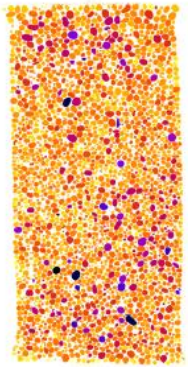
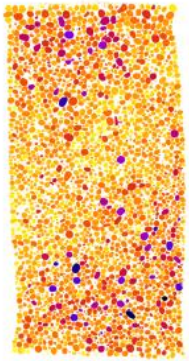
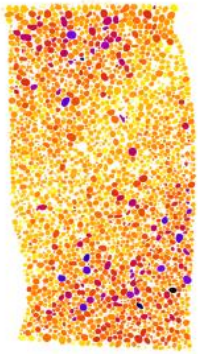
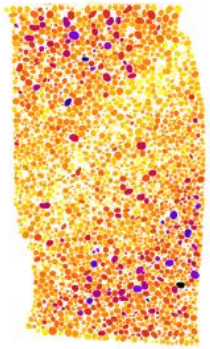
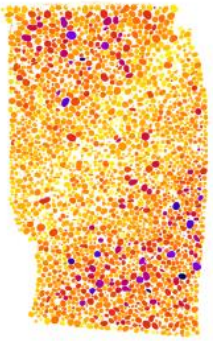
but, different scales of interest exist

challenges arise when smaller-than-grain-scale measurements are required

- characterization of grain-to-grain contacts (orientations and evolution)
- production of fines by grain breakage
- cemented granular materials (grain debonding)
- partially saturated sand (menisci)
- …

grain-to-grain contacts: detection

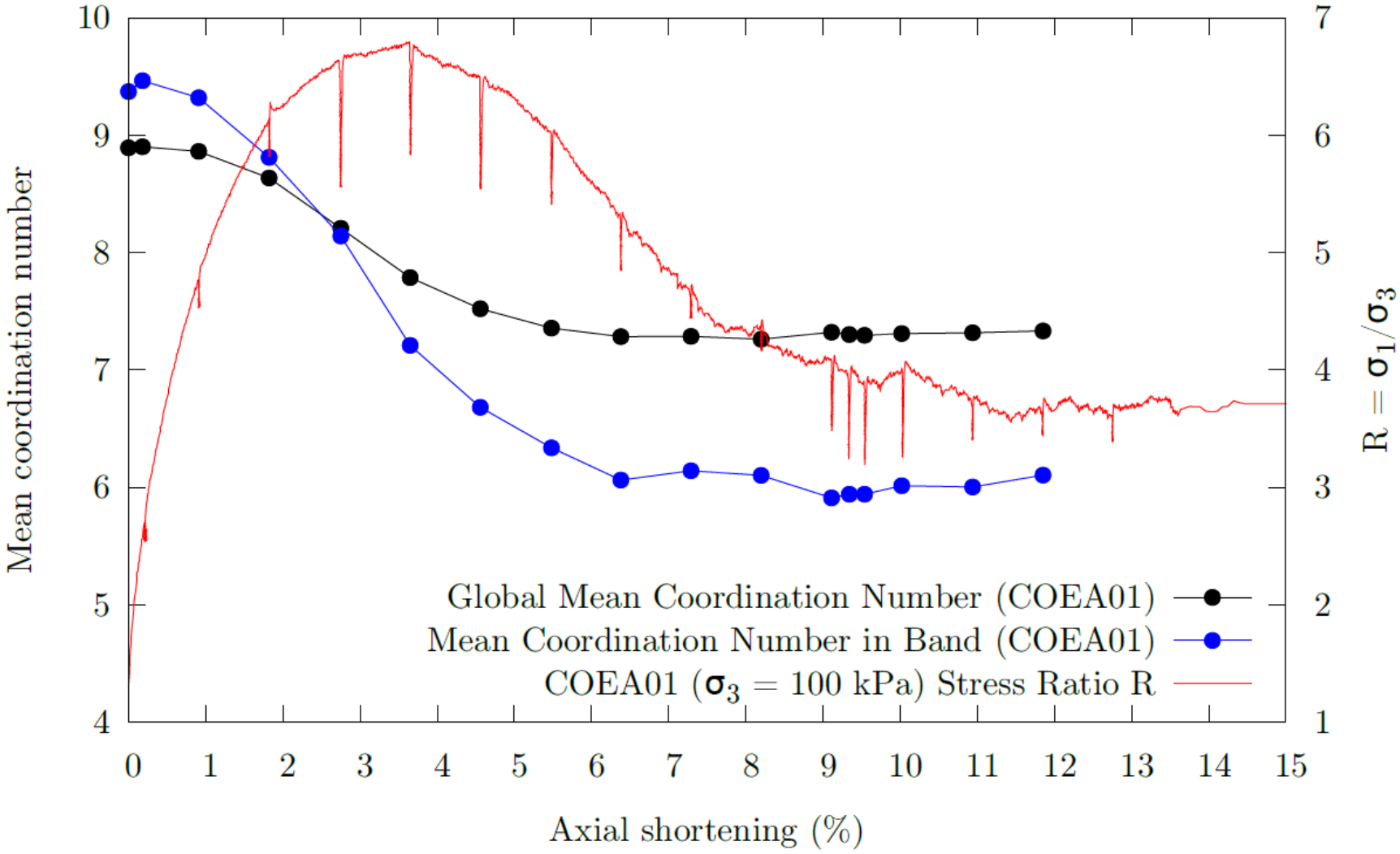


COEA01-01	COEA01-05	COEA01-07	COEA01-10	COEA01-12	COEA01-17
					

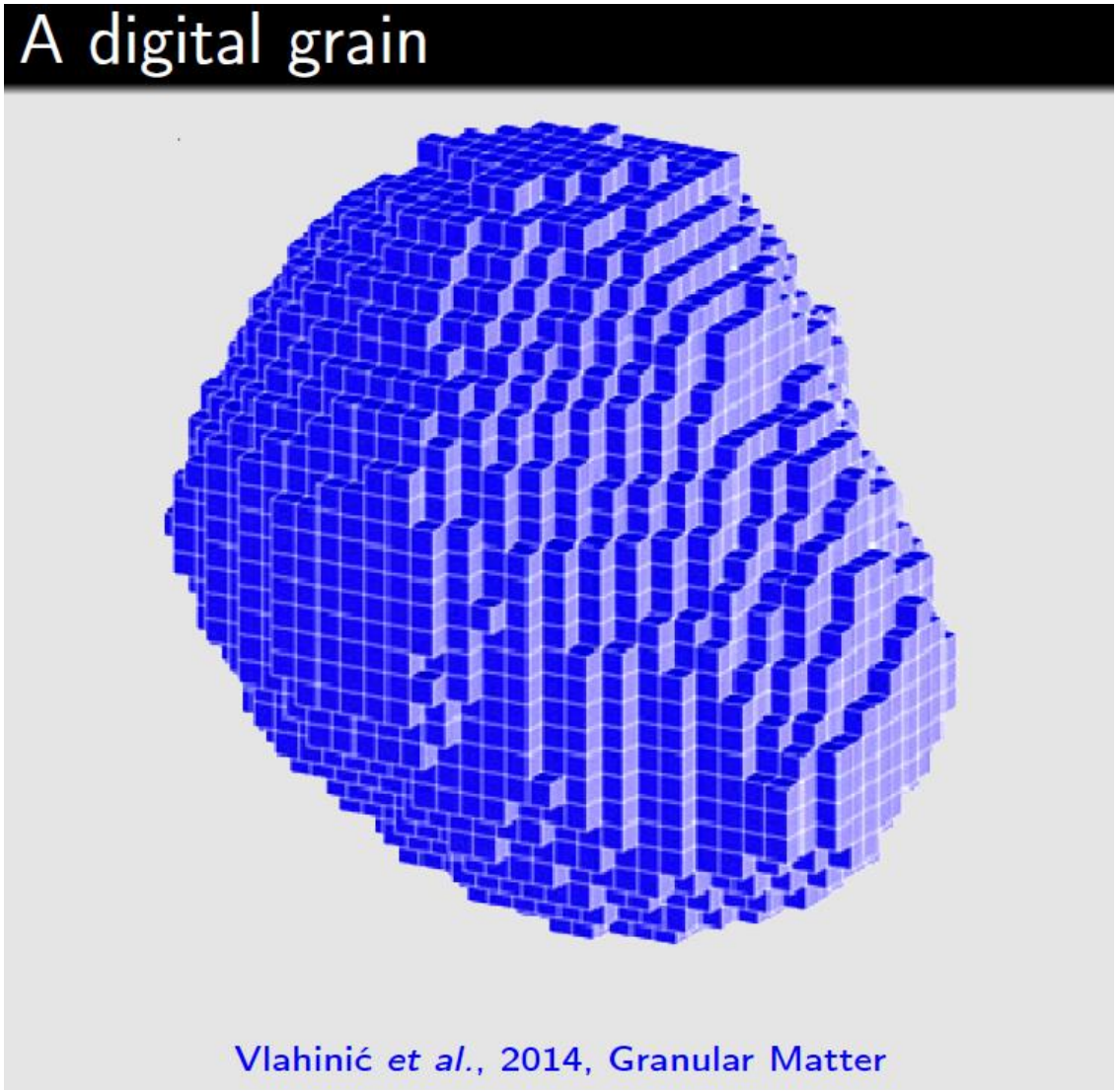
Coordination Number

0  **> 22**

grain-to-grain contacts: detection



grain-to-grain contacts: orientation



a "grain" is in fact an assembly of voxels

grain-to-grain contacts: orientation

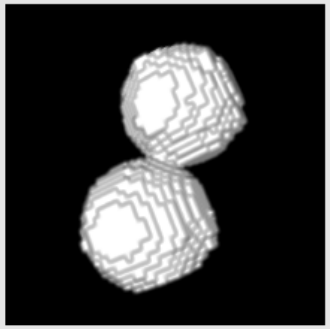
Pairs of digital grains

Glass Ballotini

Contacting grains 2D

Hostun Sand

Contacting grains 2D



Contacting grains 3D

Contacting grains 3D

Andò *et al.*, 2013, Géotechnique Letters

how well resolved is a contact between such voxelated objects?

Pair of Mathematicians

Hugues Talbot

Clara Jaquet

$\Rightarrow$ Contact orientation algorithm

Jacquet *et al.*, 2013, Proceedings ISMM

Viggiani et al., Powders and Grains 2013

grain-to-grain contacts: orientation

evolution of contact network – why do we care?

→ measuring fabric and fabric evolution – talk to Yannis D.

Xia Li · Hai-Sui Yu

Fabric, force and strength anisotropies in granular materials: a micromechanical insight

Acta Mech 225, 2345–2362 (2014)
DOI 10.1007/s00707-014-1120-6

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Matthew Coop


Jeff Wang

grain breakage – production of fines

University of Sydney


Alessandro Tengattini


Itai Einav

Uni CIPR Bergen


Reza Alikarami


Anita Torabi

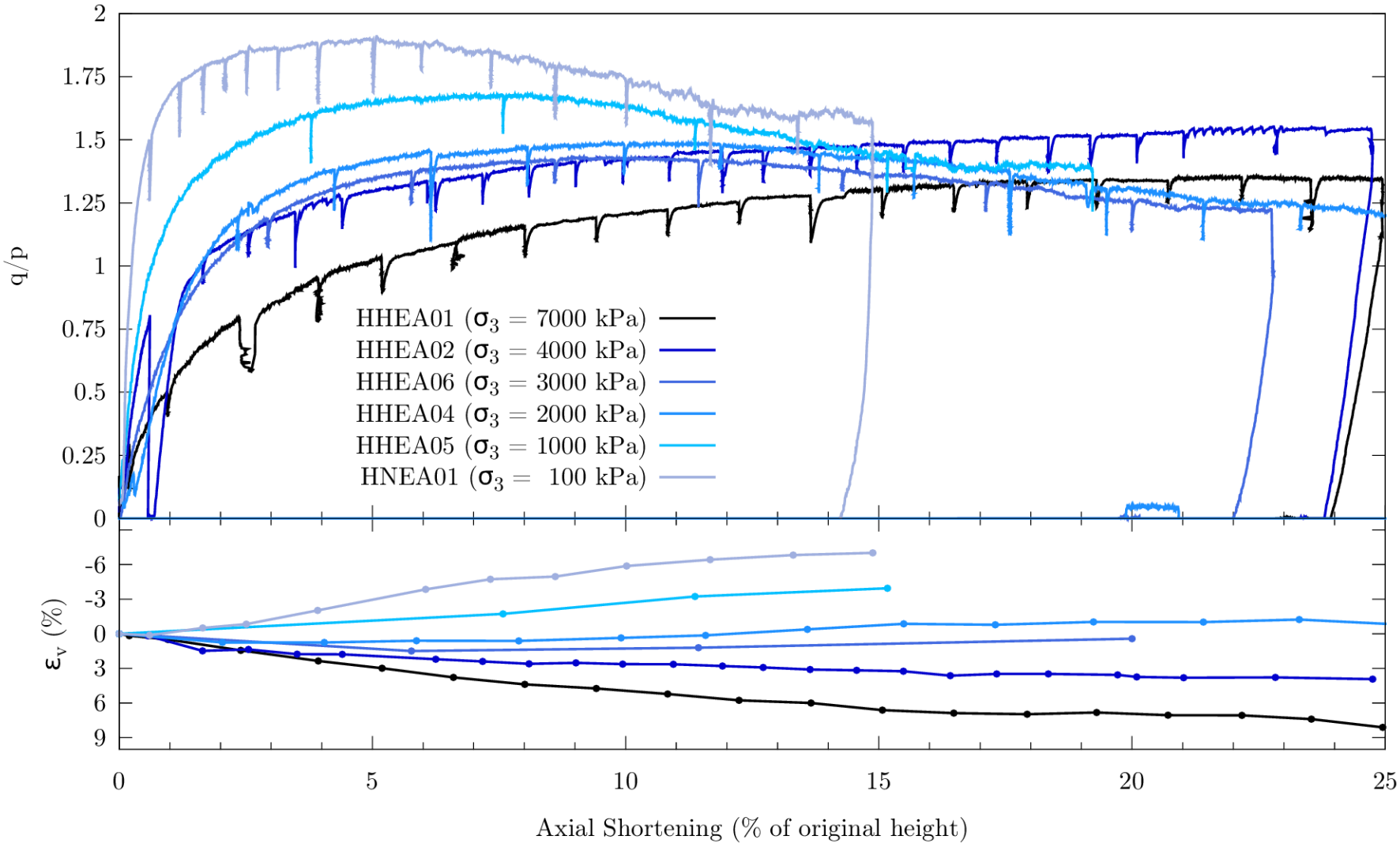
University of Edinburgh


Zeynep Karatza


Stefanos Aldo Papanicolopulos

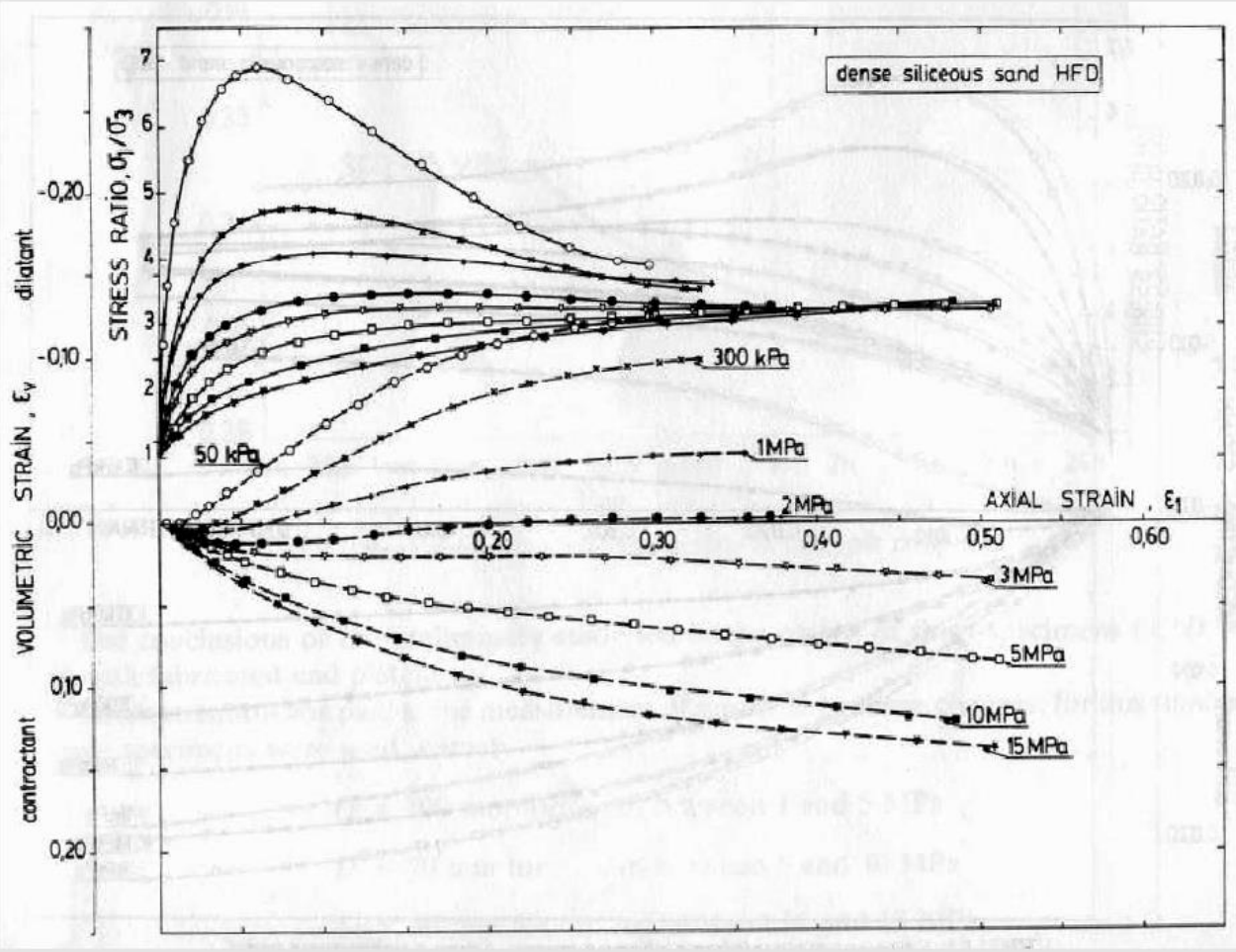

Jin Ooi

triaxial compression tests on angular Hostun sand



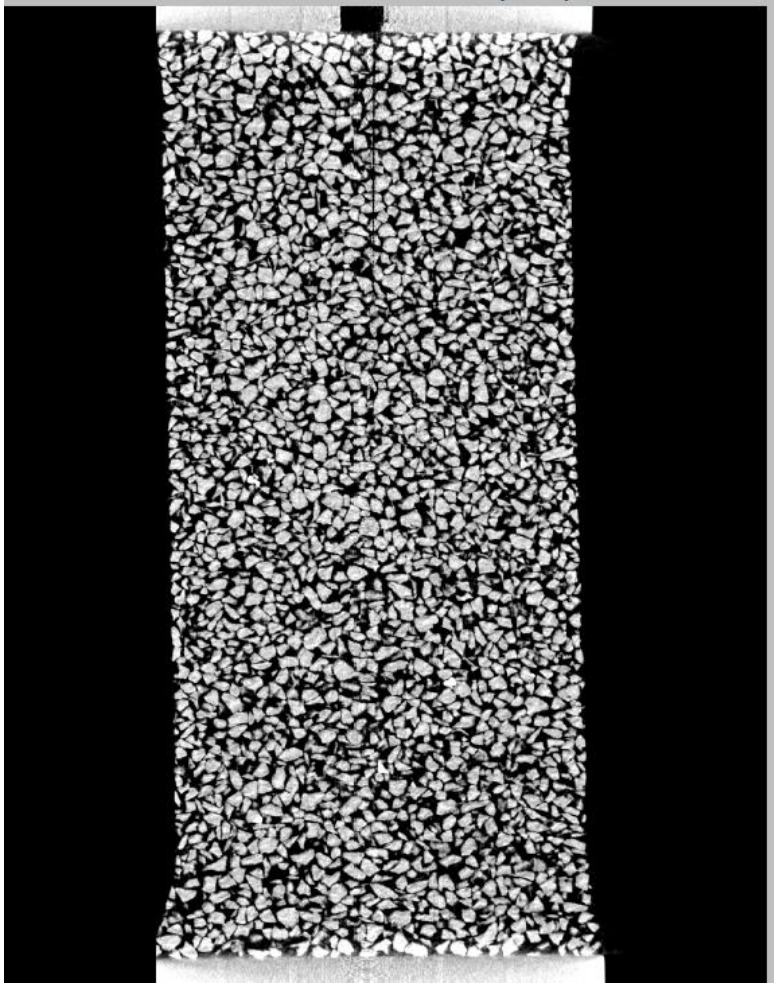
Alikarami *et al.*, Acta Geotechnica 2014 (submitted)

previous work



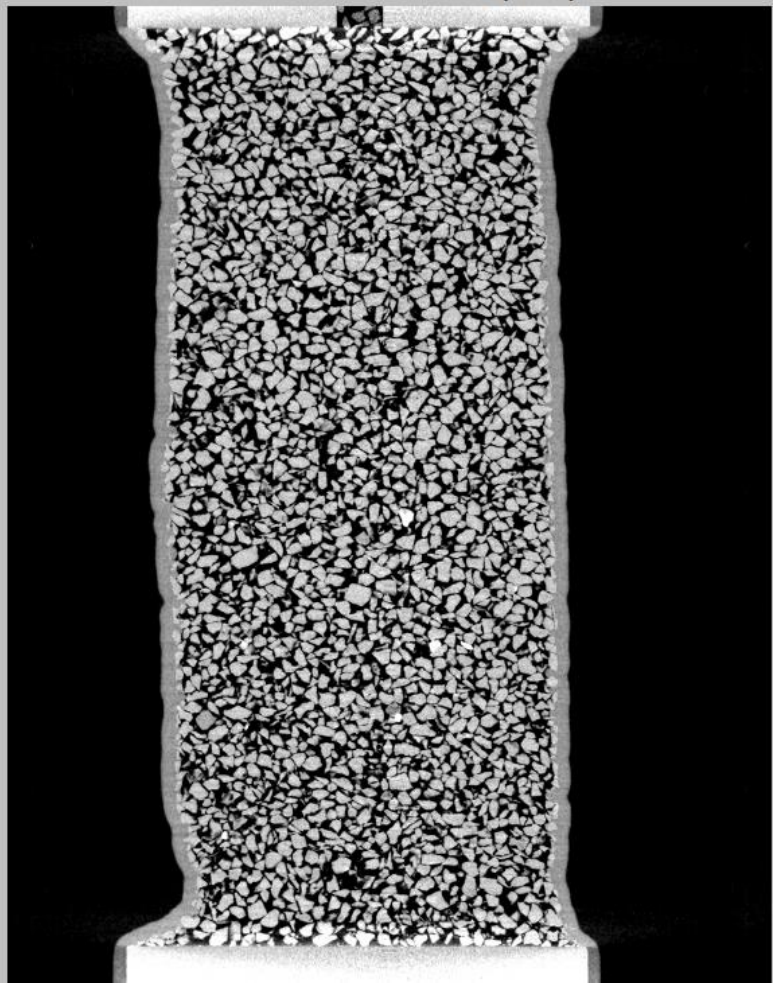
Colliat-Dangus *et al.*, 1988, ASTM

Hostun sand (01)



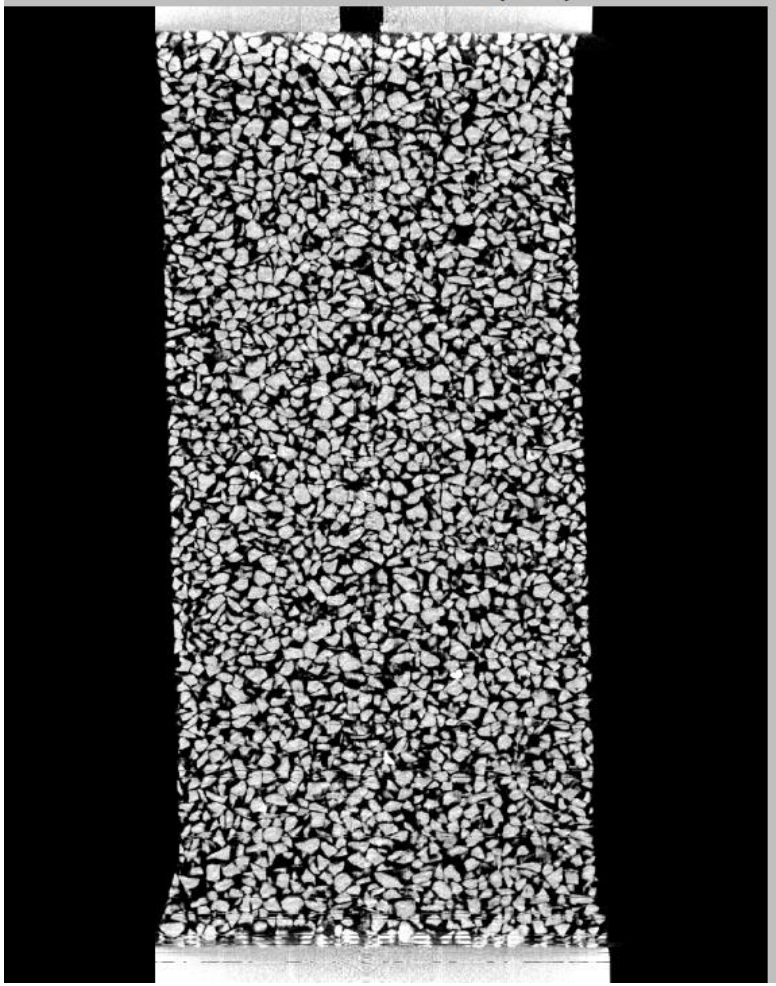
$\sigma_3 = 100$ kPa

Hostun sand (01)



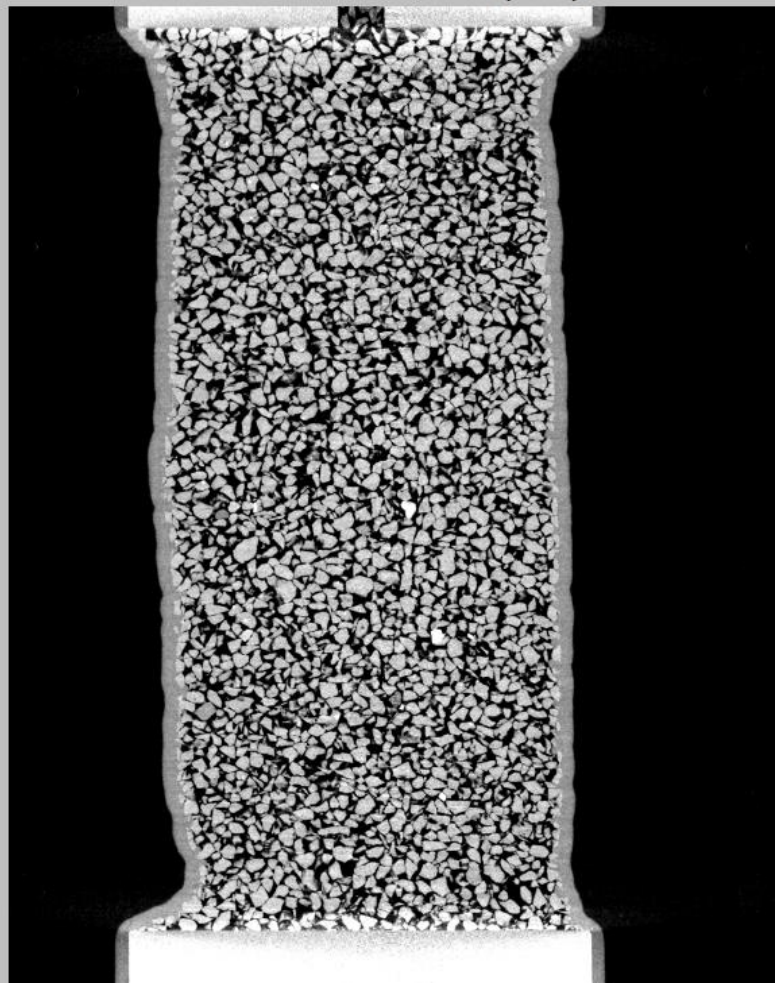
$\sigma_3 = 7000$ kPa

Hostun sand (02)



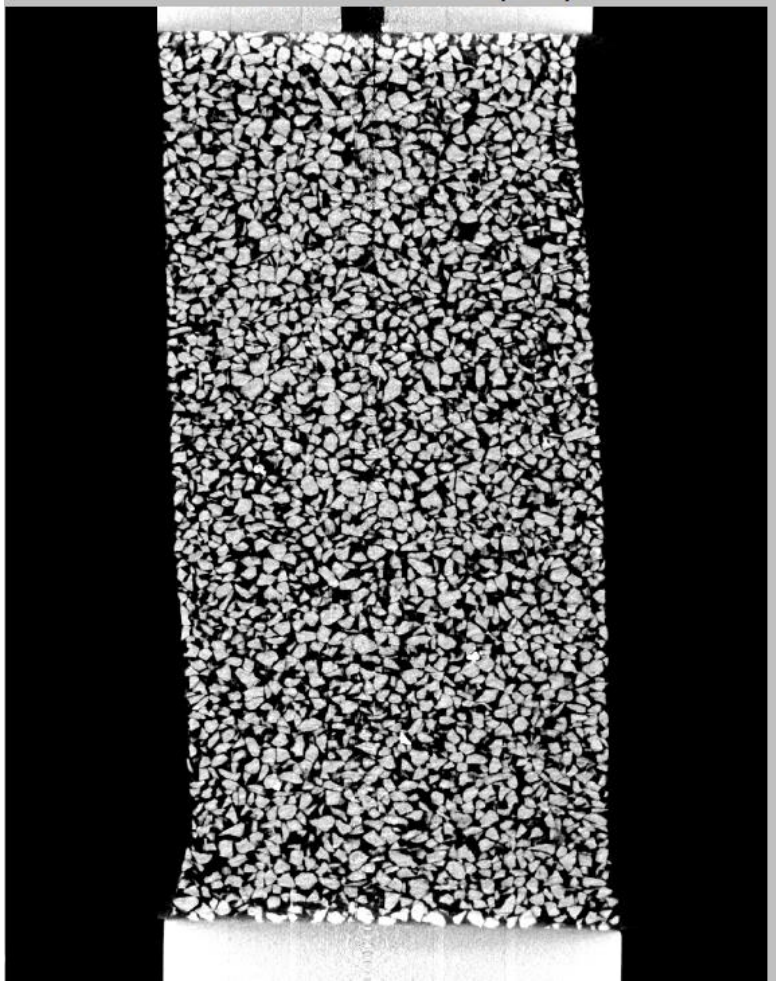
$\sigma_3 = 100$ kPa

Hostun sand (02)



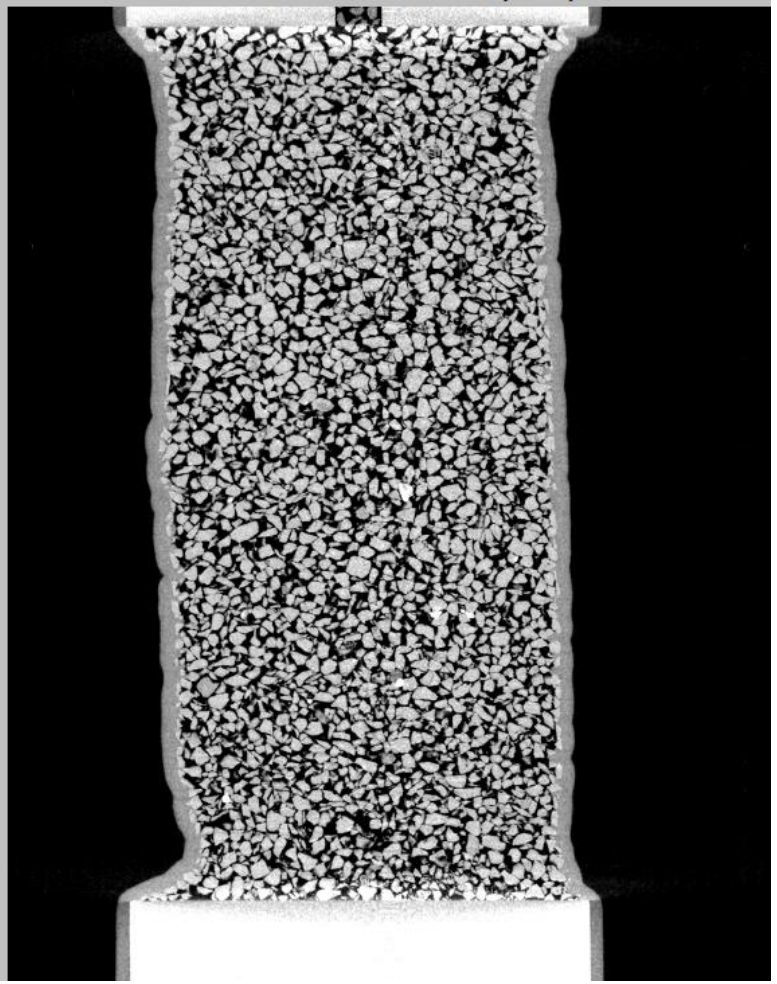
$\sigma_3 = 7000$ kPa

Hostun sand (03)



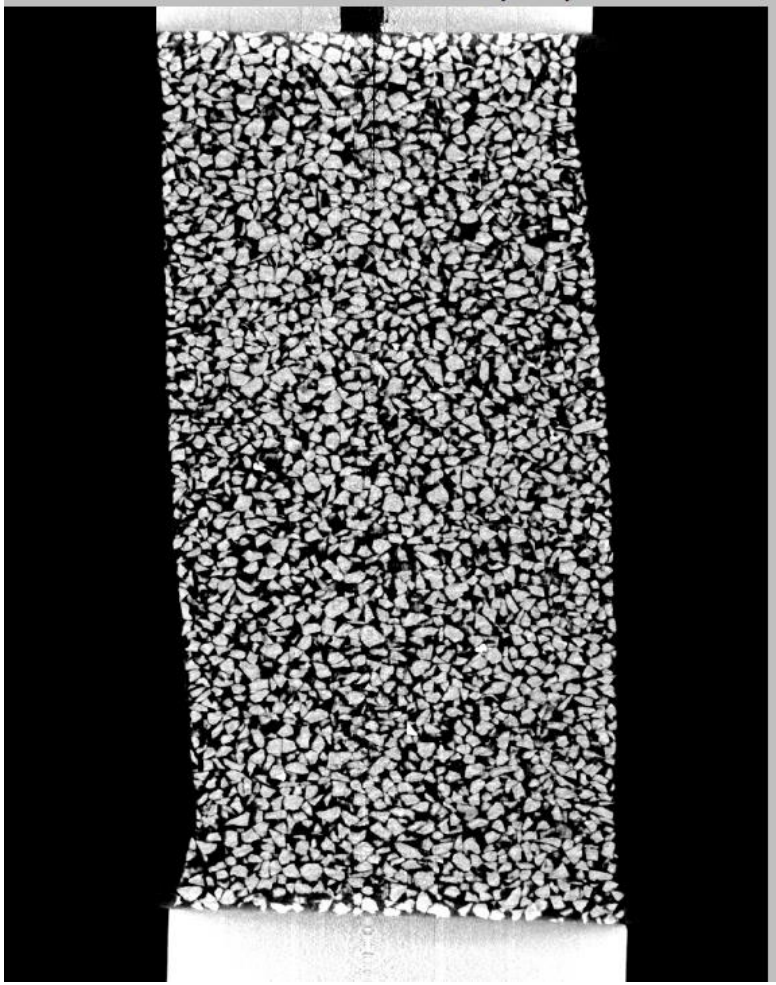
$\sigma_3 = 100$ kPa

Hostun sand (03)



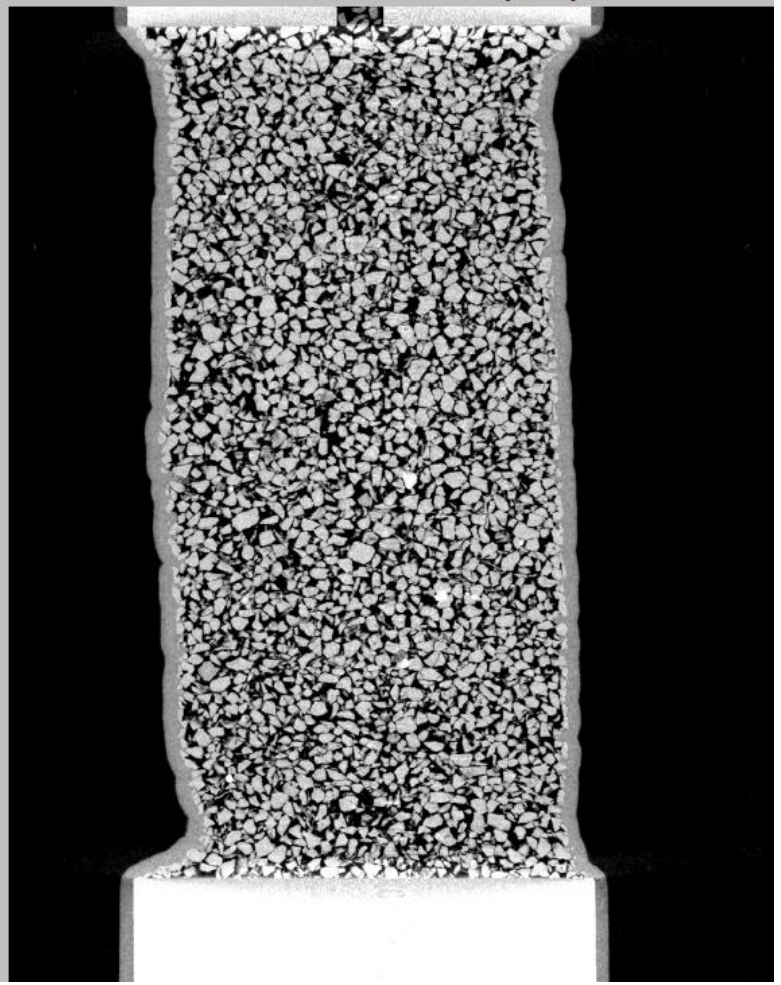
$\sigma_3 = 7000$ kPa

Hostun sand (04)



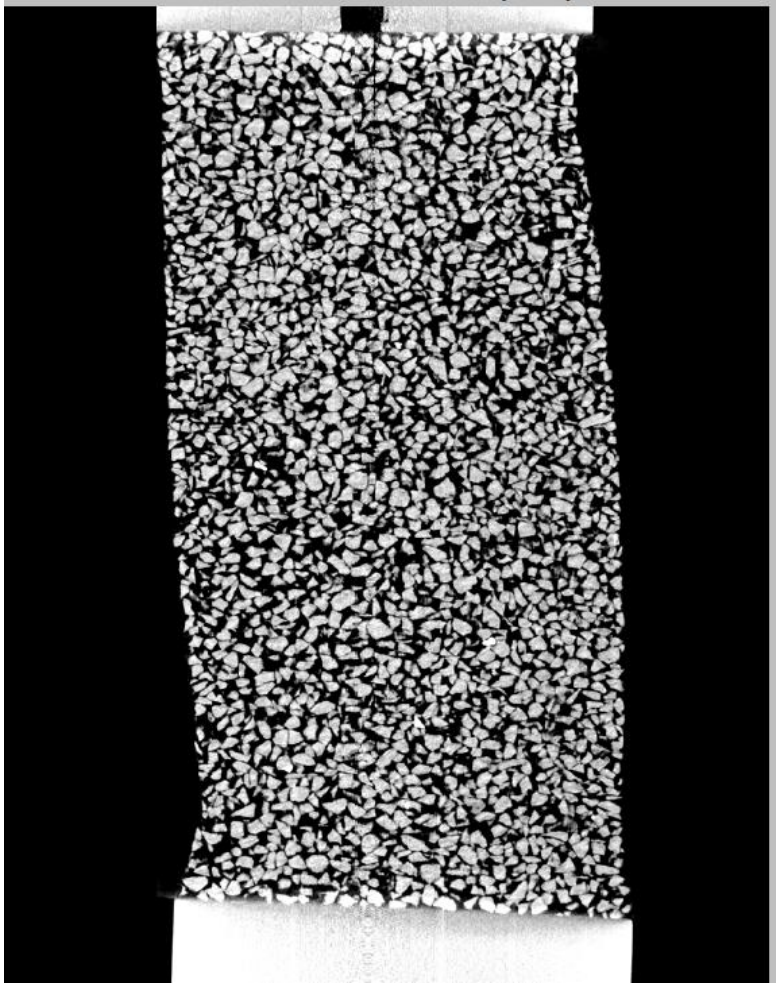
$\sigma_3 = 100$ kPa

Hostun sand (04)



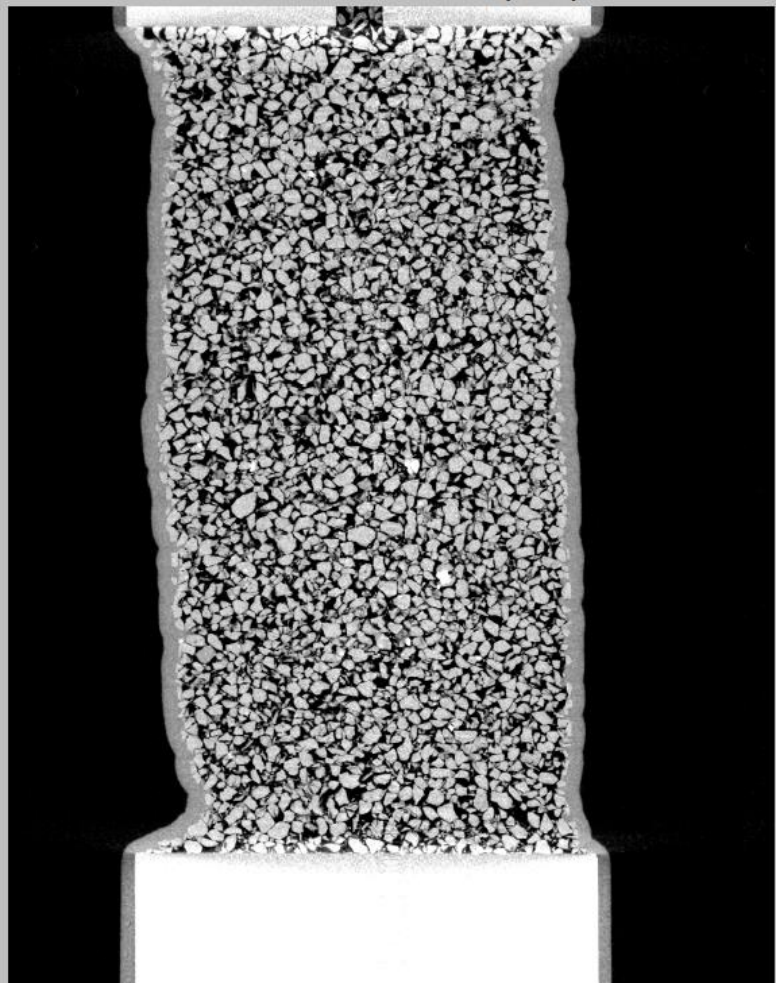
$\sigma_3 = 7000$ kPa

Hostun sand (05)



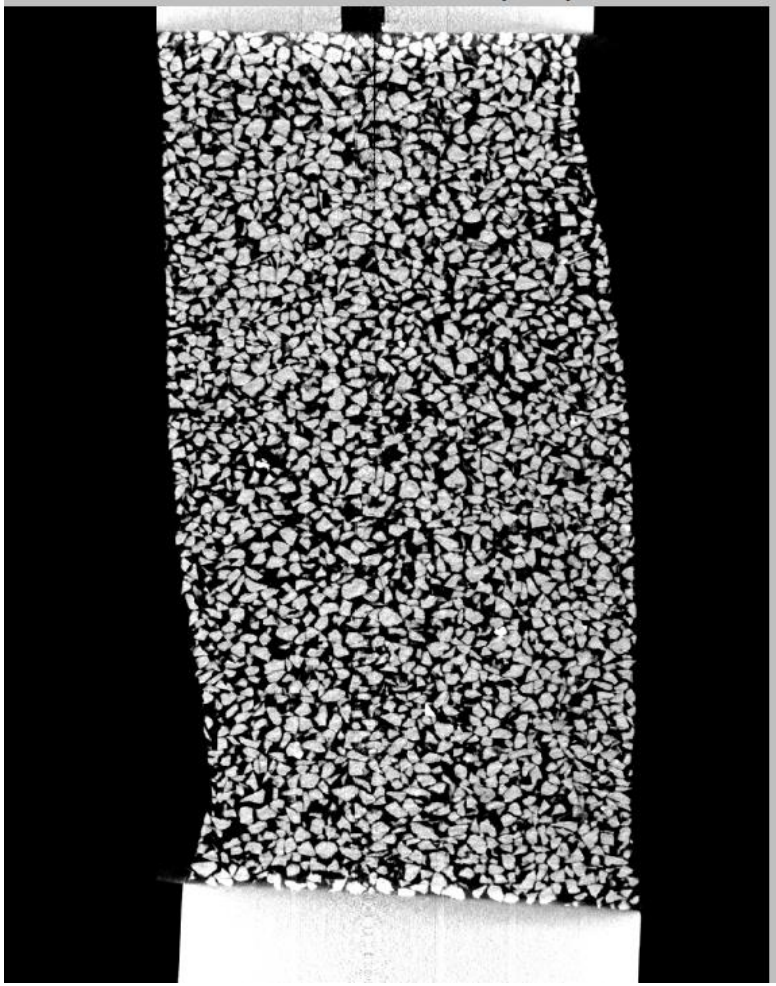
$\sigma_3 = 100$ kPa

Hostun sand (05)



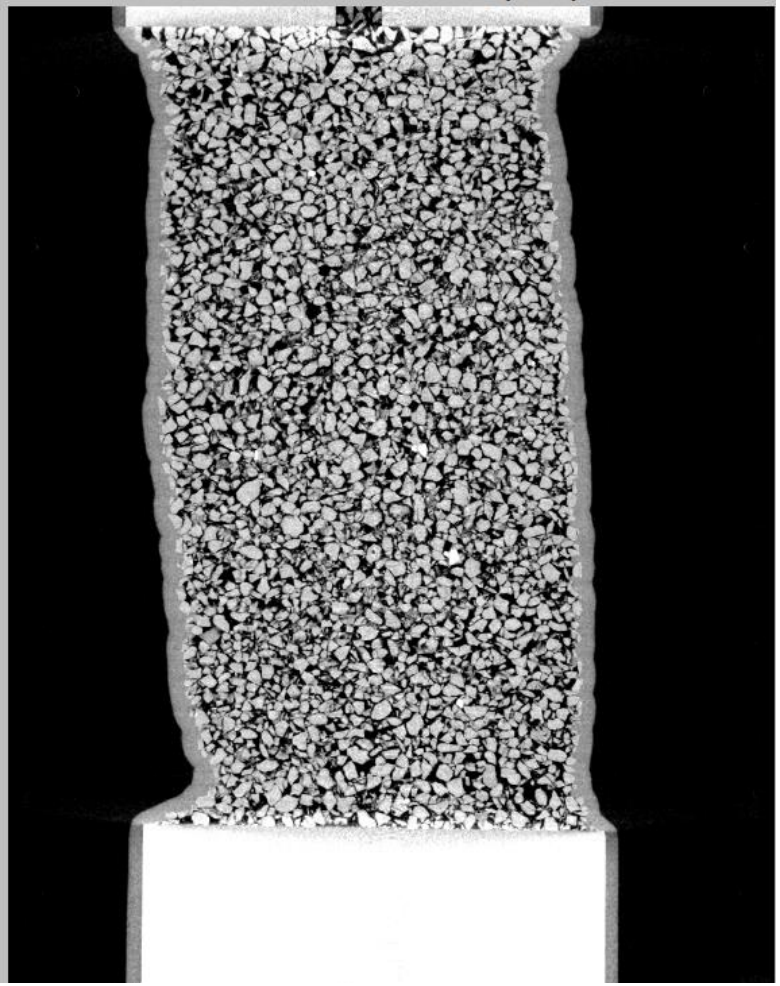
$\sigma_3 = 7000$ kPa

Hostun sand (06)



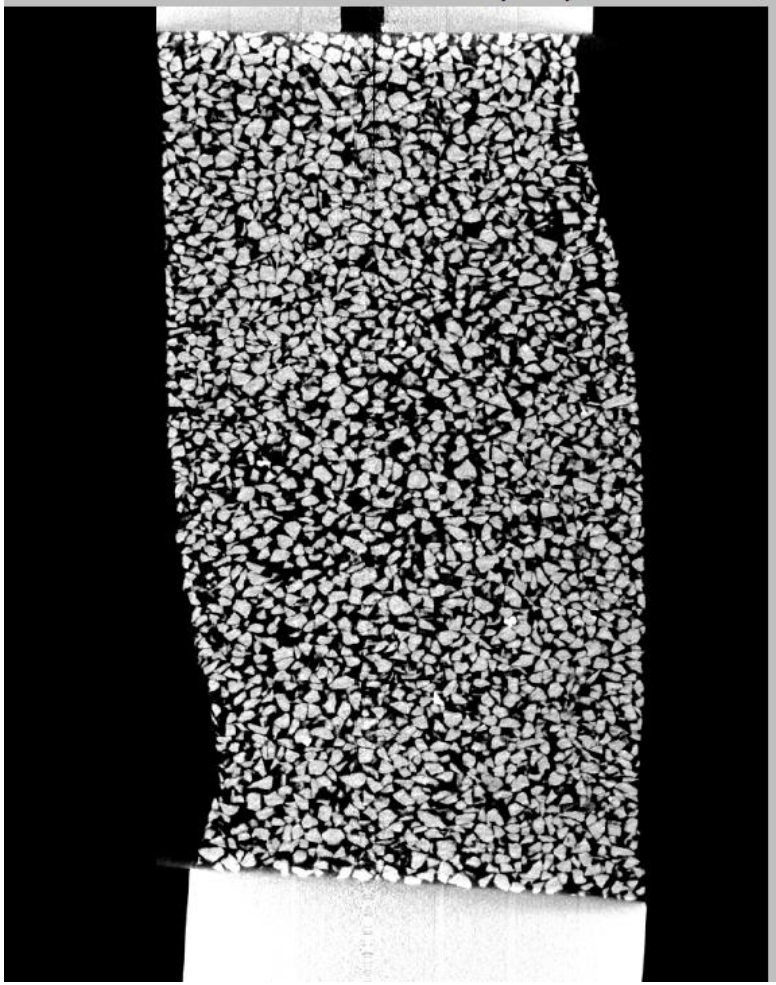
$\sigma_3 = 100$ kPa

Hostun sand (06)



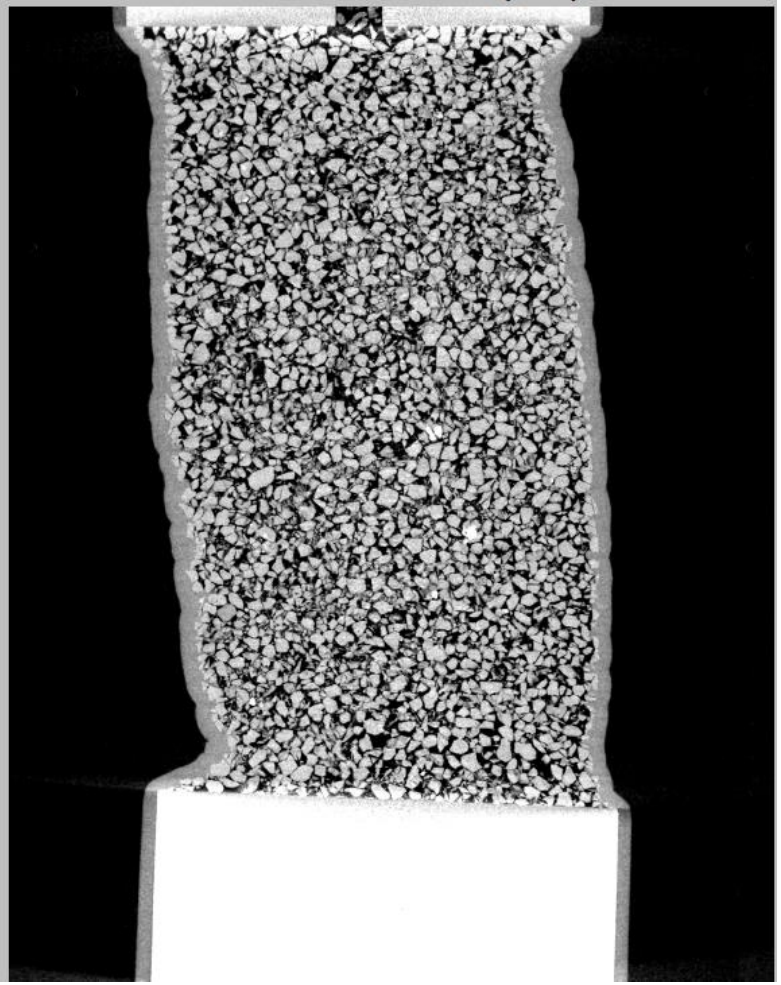
$\sigma_3 = 7000$ kPa

Hostun sand (07)



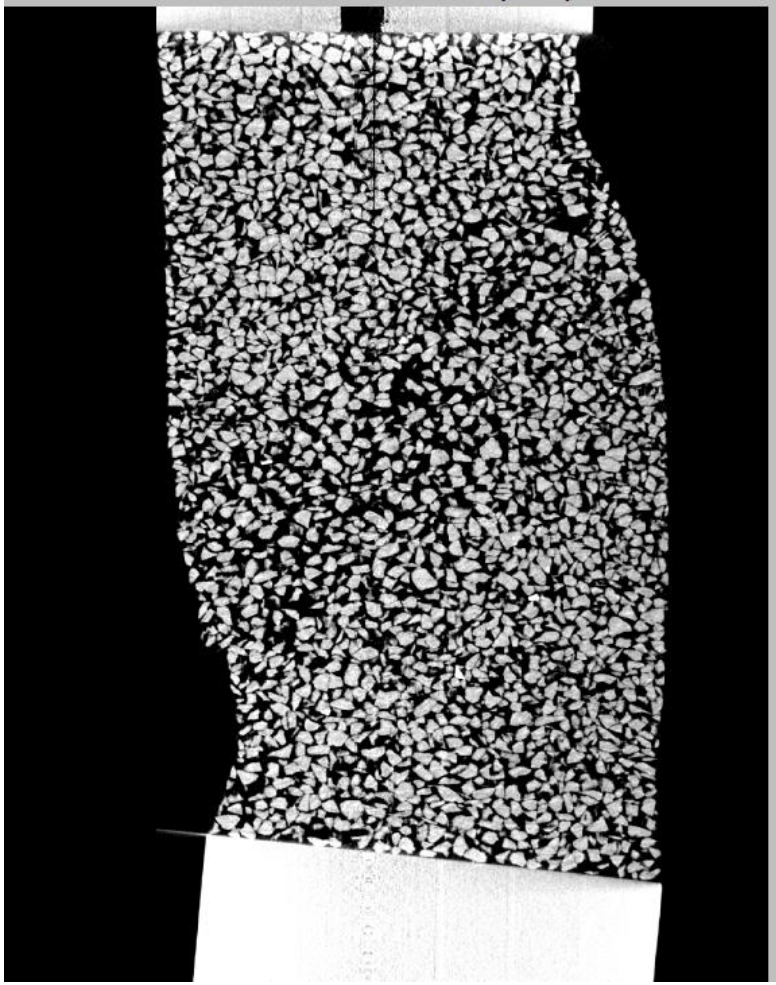
$\sigma_3 = 100$ kPa

Hostun sand (07)



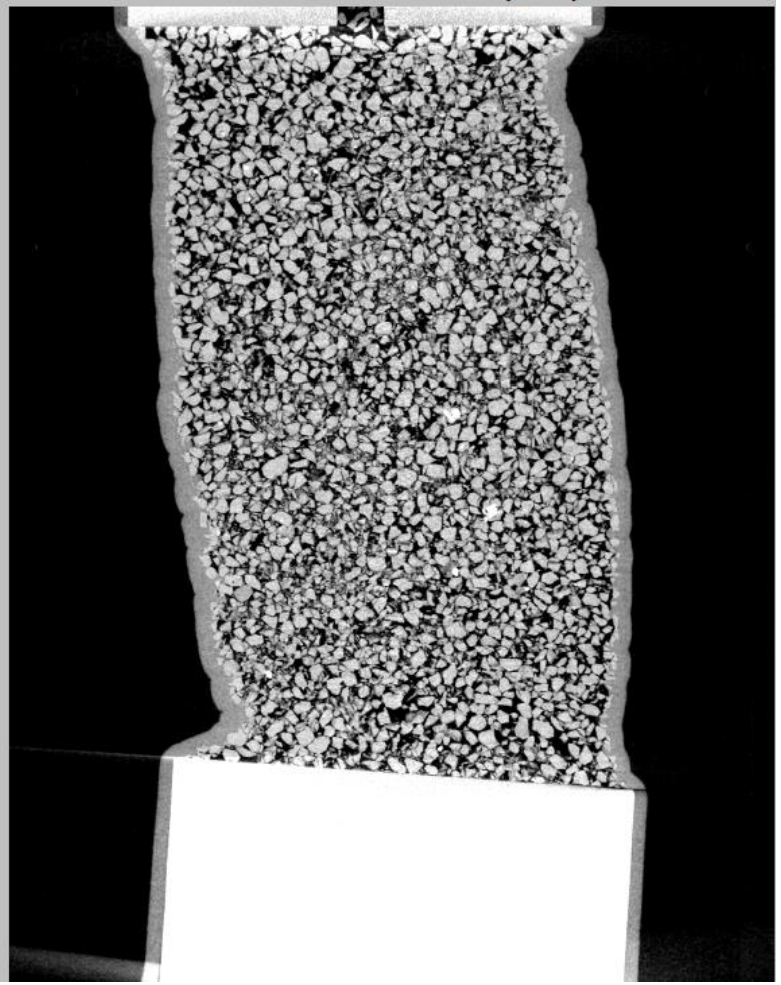
$\sigma_3 = 7000$ kPa

Hostun sand (08)



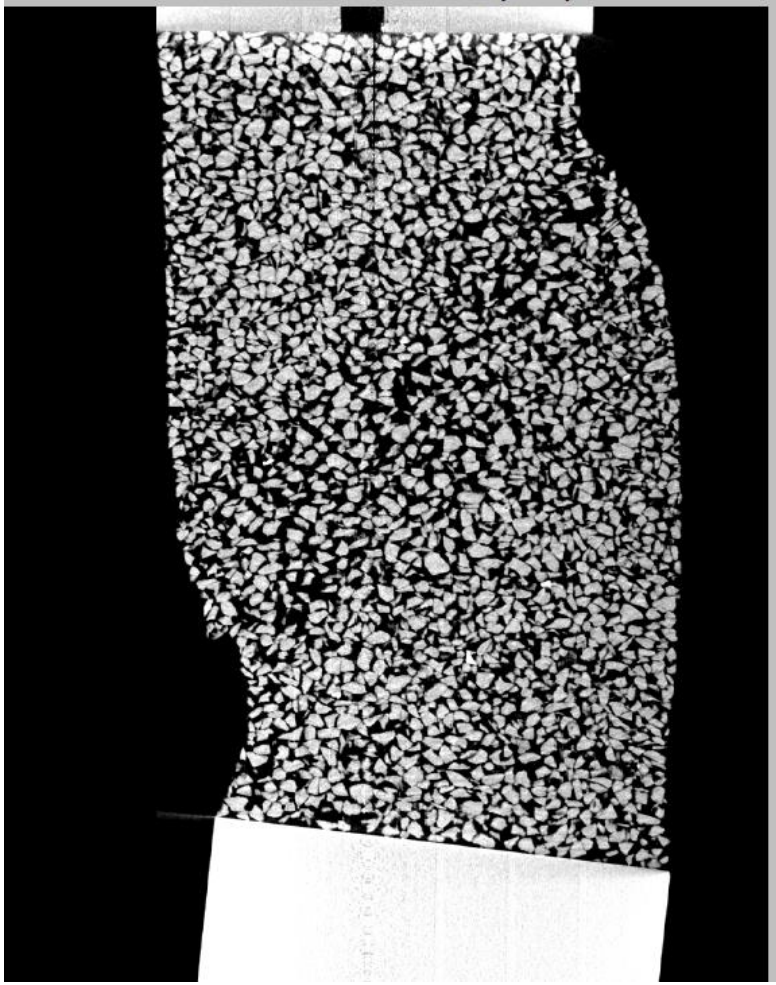
$\sigma_3 = 100$ kPa

Hostun sand (08)



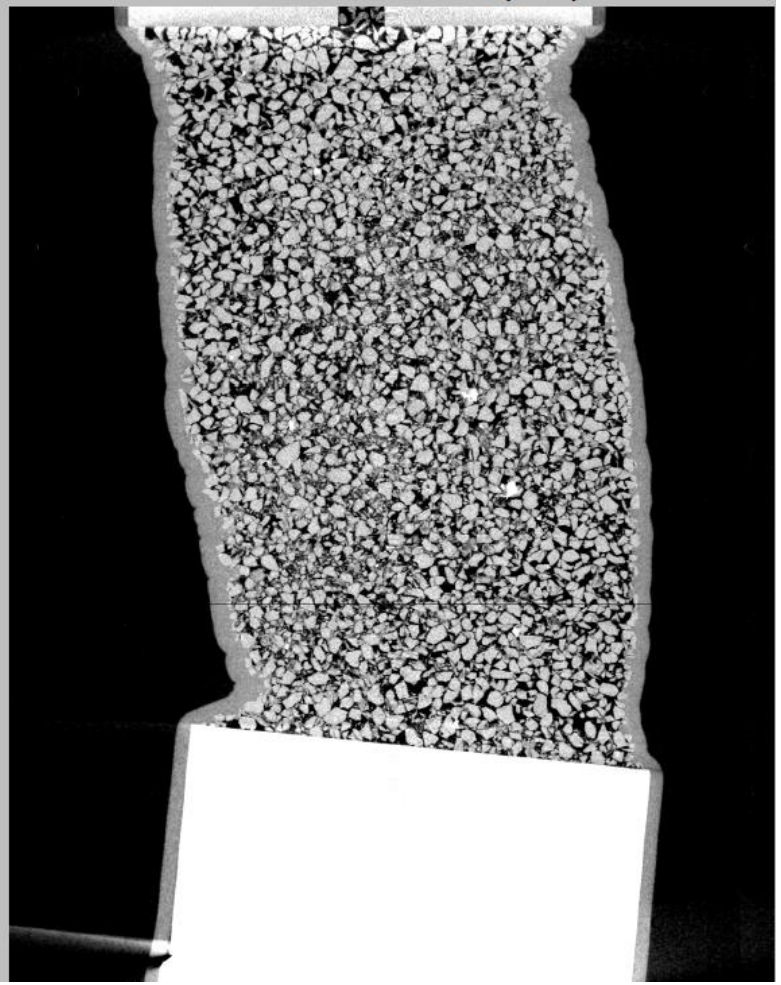
$\sigma_3 = 7000$ kPa

Hostun sand (09)



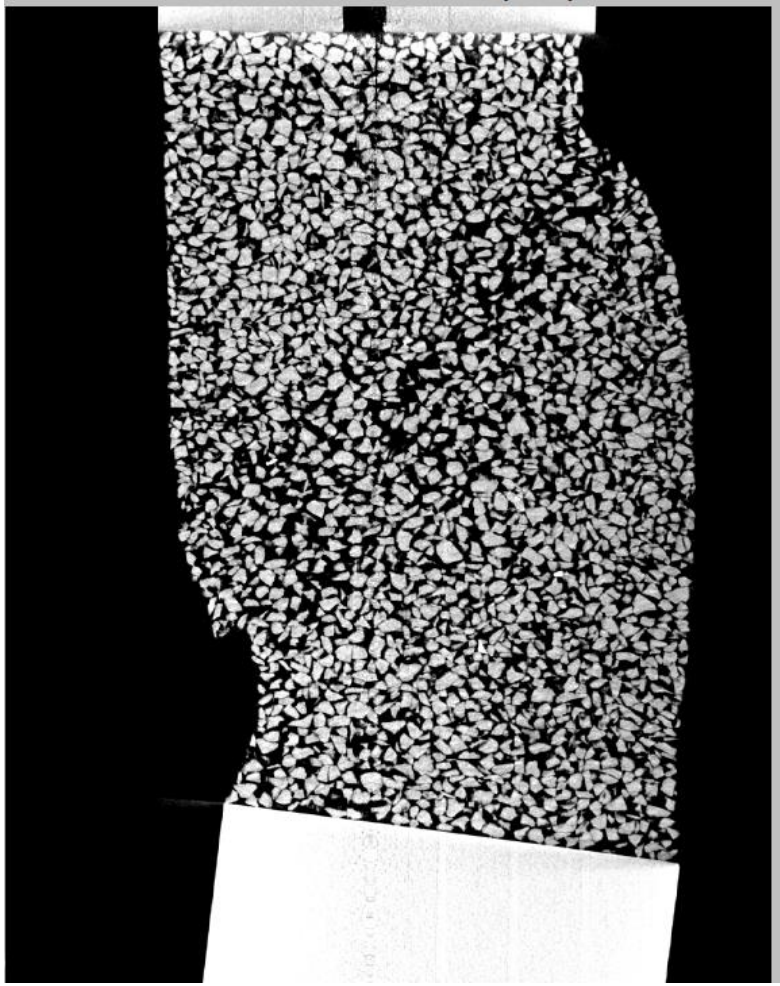
$\sigma_3 = 100$ kPa

Hostun sand (09)



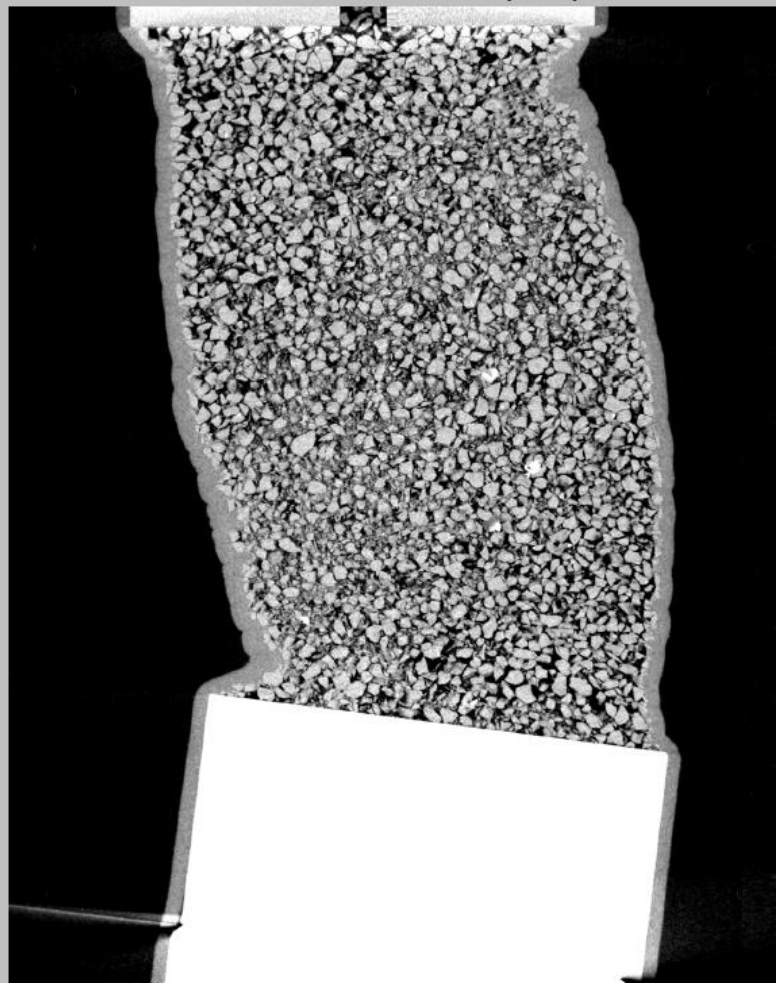
$\sigma_3 = 7000$ kPa

Hostun sand (10)



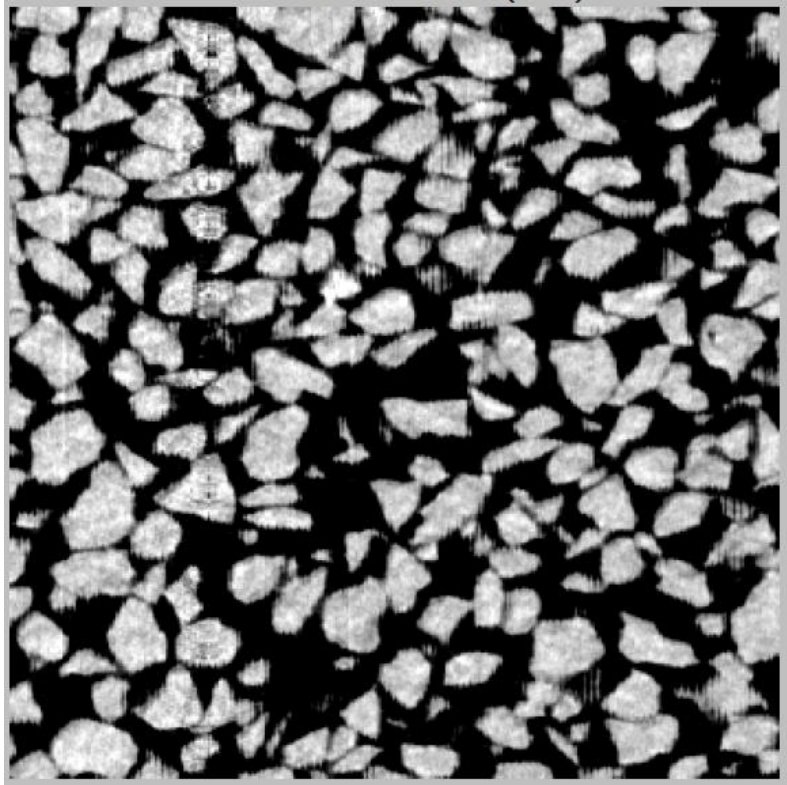
$\sigma_3 = 100$ kPa

Hostun sand (10)



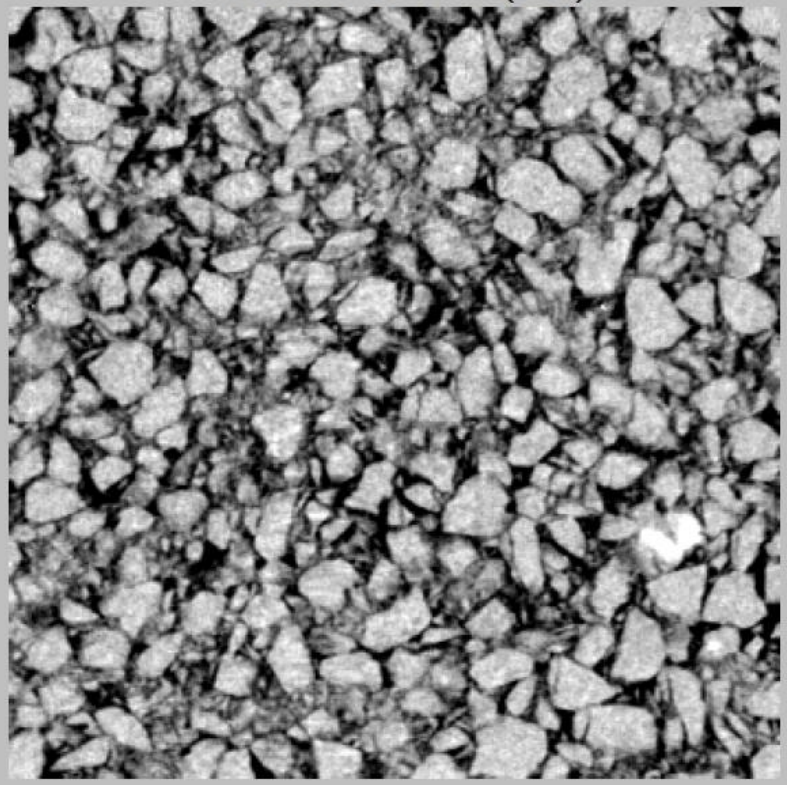
$\sigma_3 = 7000$ kPa

Hostun sand (11)



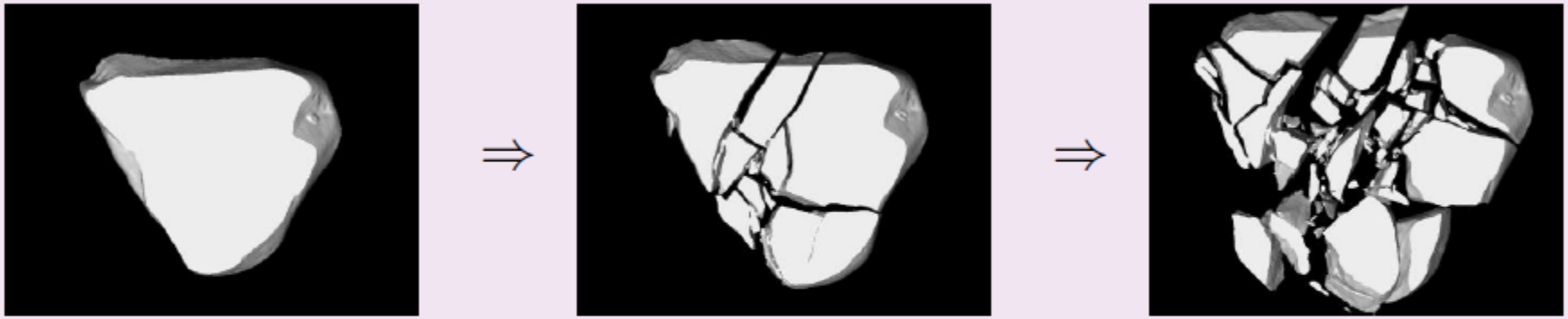
$\sigma_3 = 100$ kPa

Hostun sand (11)



$\sigma_3 = 7000$ kPa

So... what's happening?



Recent single-grain (d=3mm) uniaxial compression x-ray work from Hong Kong

B. Zhao, J. Wang, M. Coop

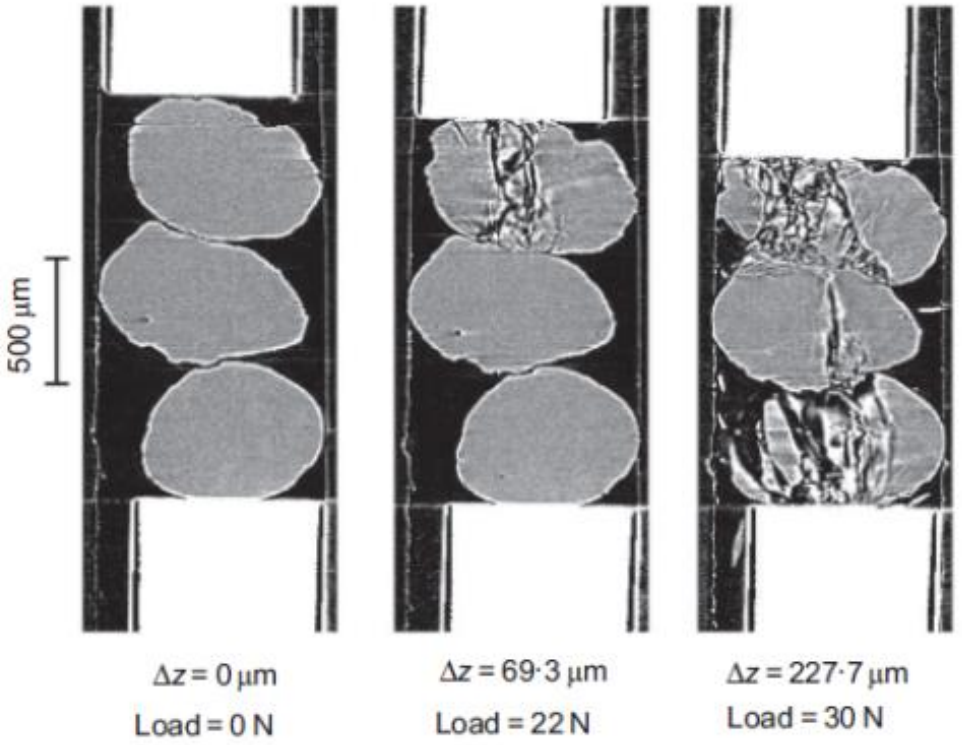
...at our scale...

Recent single-grain (d=3mm) uniaxial compression x-ray work from Hong Kong

B. Zhao, J. Wang, M. Coop

experimental observation of grain breakage mechanisms

Rock on Top of Another Rock by Fischli/Weiss (Serpentine Gallery, London – March 2013)

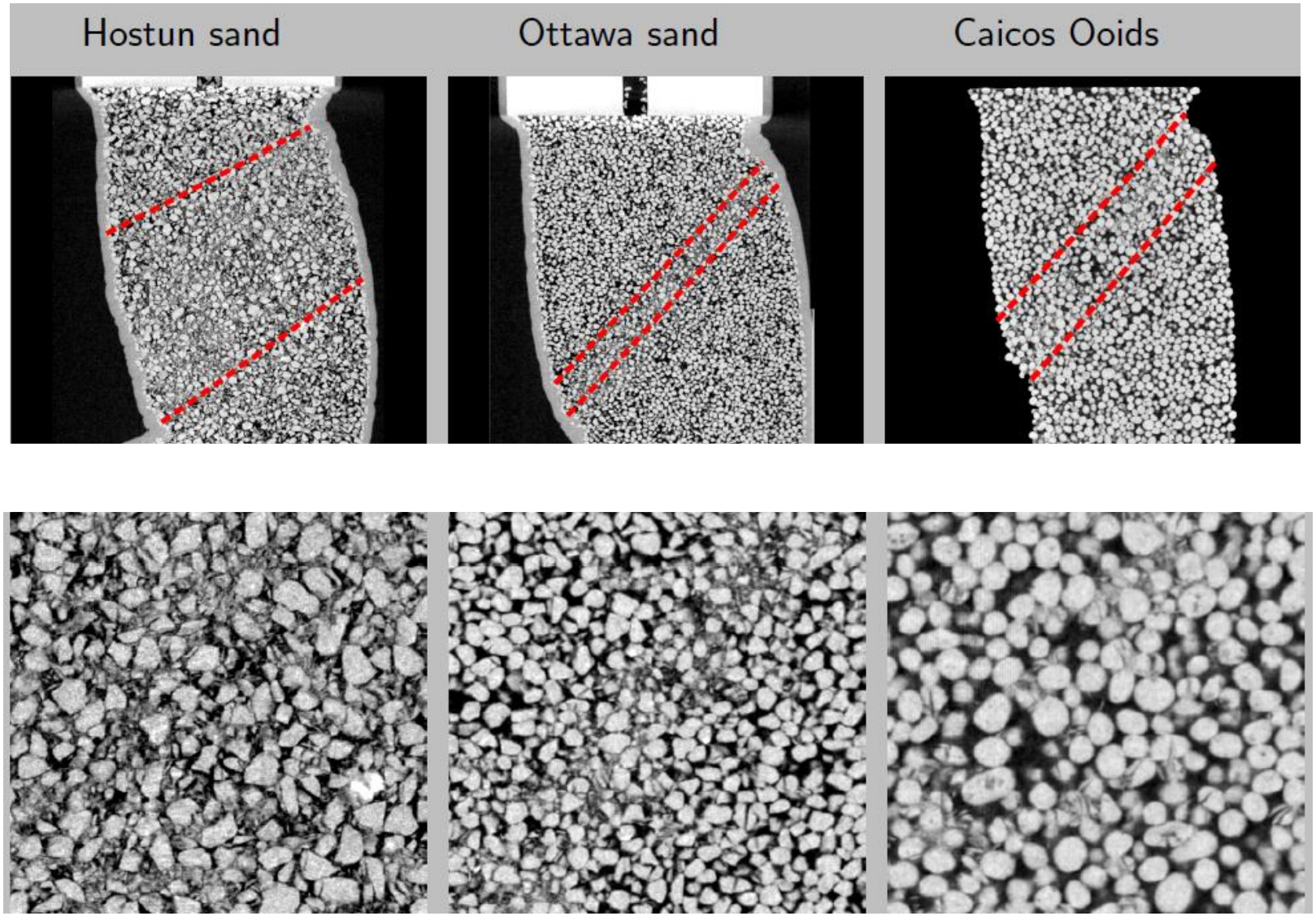


Cil, M. B. and Alshibli, K. A. (2012) ***Géotechnique Letters* 2**, 161–166, http://dx.doi.org/10.1680/geolett.12.00024

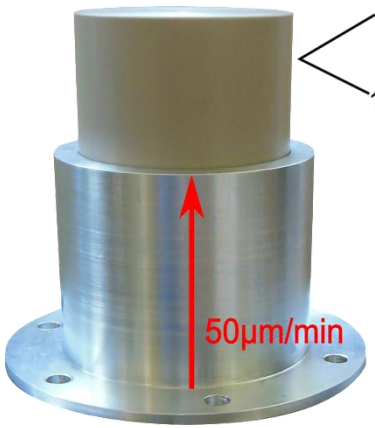
3D assessment of fracture of sand particles using discrete element method

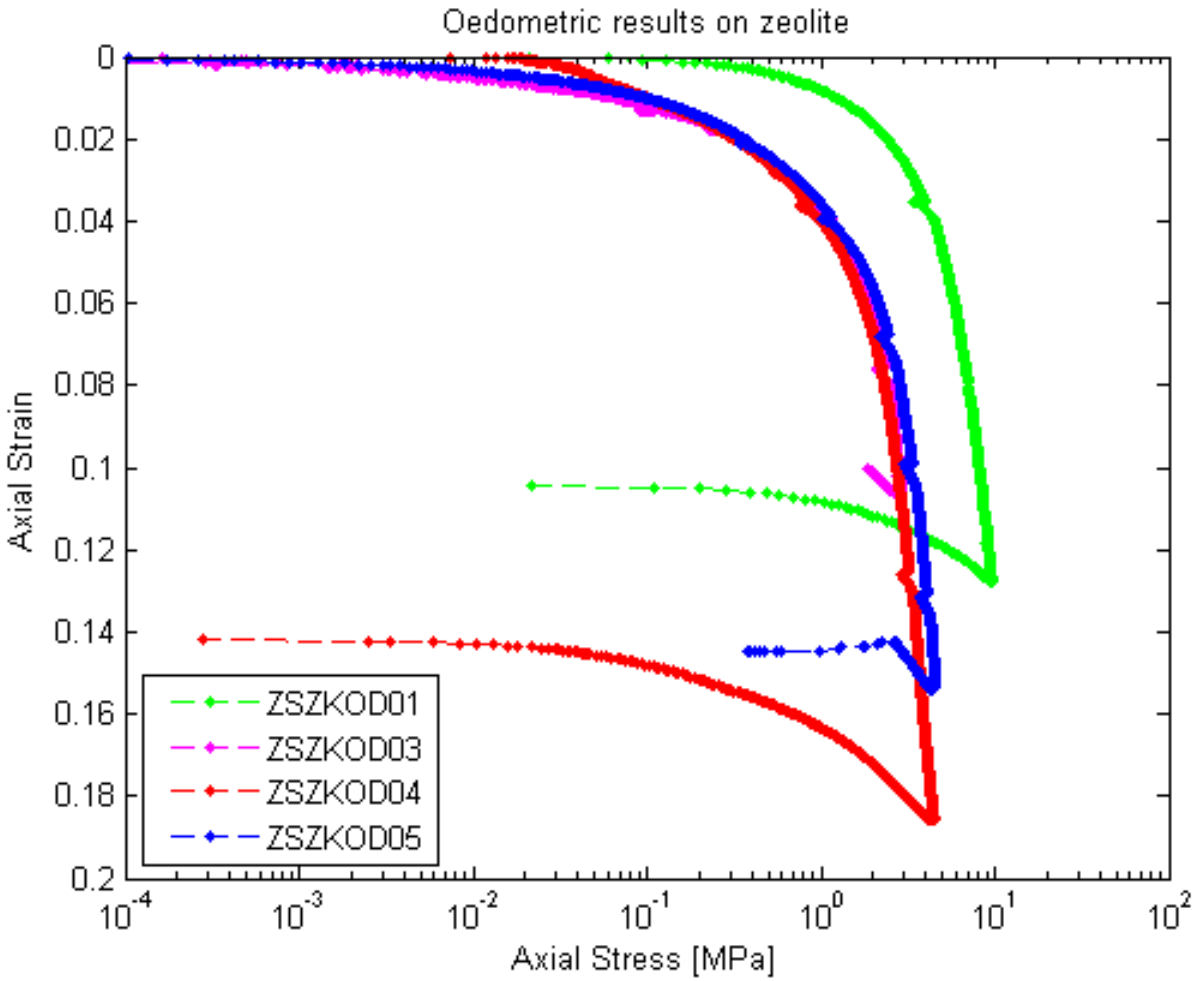
M. B. CIL* and K. A. ALSHIBLI*

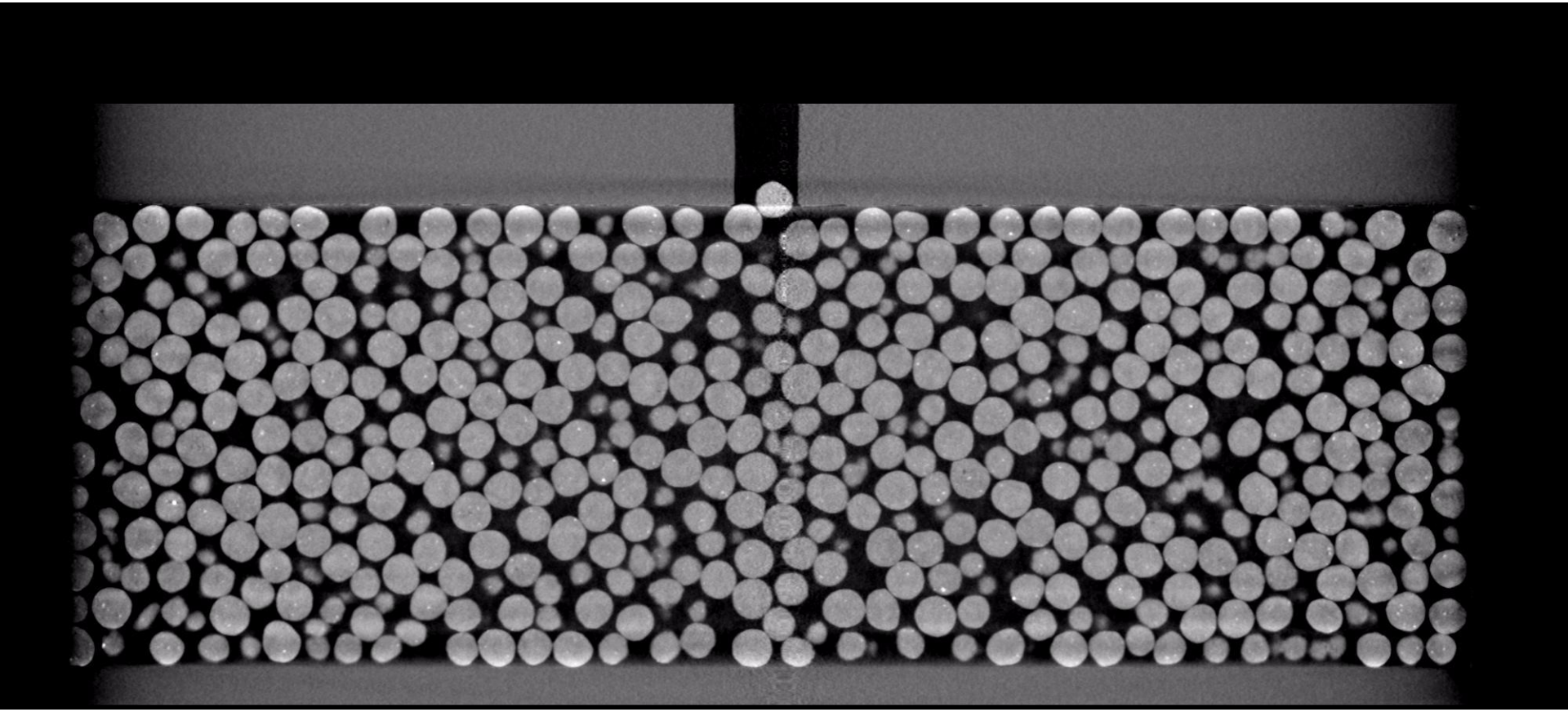
triaxial compression tests at high pressure (s3 = 7 Mpa)



recent results from 1D compression of zeolite (D_{50} = 1.2 mm)







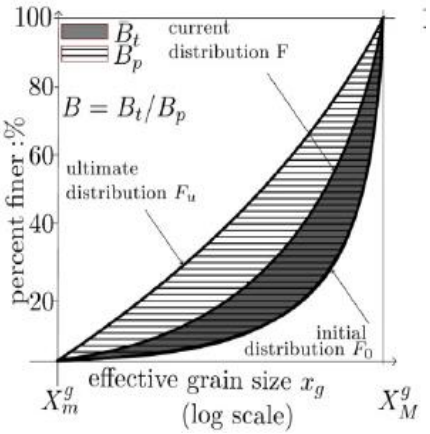
grain breakage: quantifying evolution of grainsize distribution

- grains do break
- fine material fills up the pore space
- coarser grains are visible but surrounded by finer material
- as it is, the final state image cannot be segmented

a challenge for image analysis – why do we care?

→ measuring evolution of breakage B – talk to Itai E.

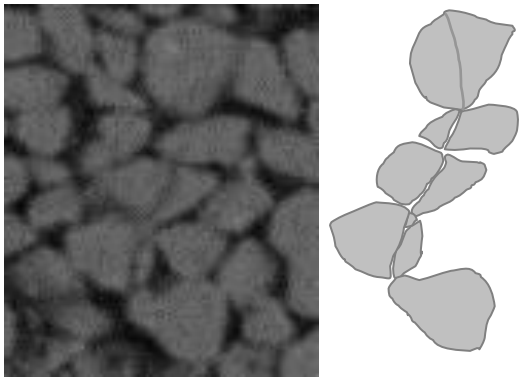
Breakage Mechanics model by Einav (JMPS 2007a, 2007b)

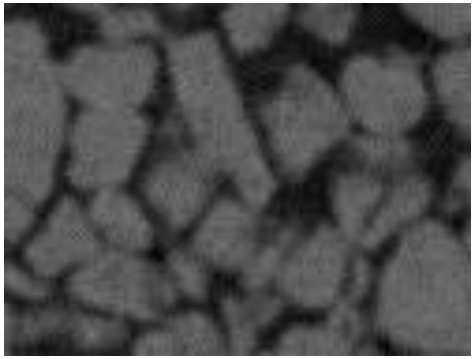


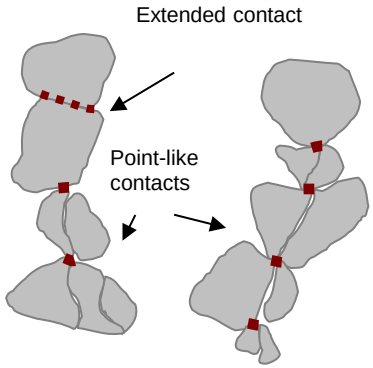
cemented granular materials – both grains and bonds can break

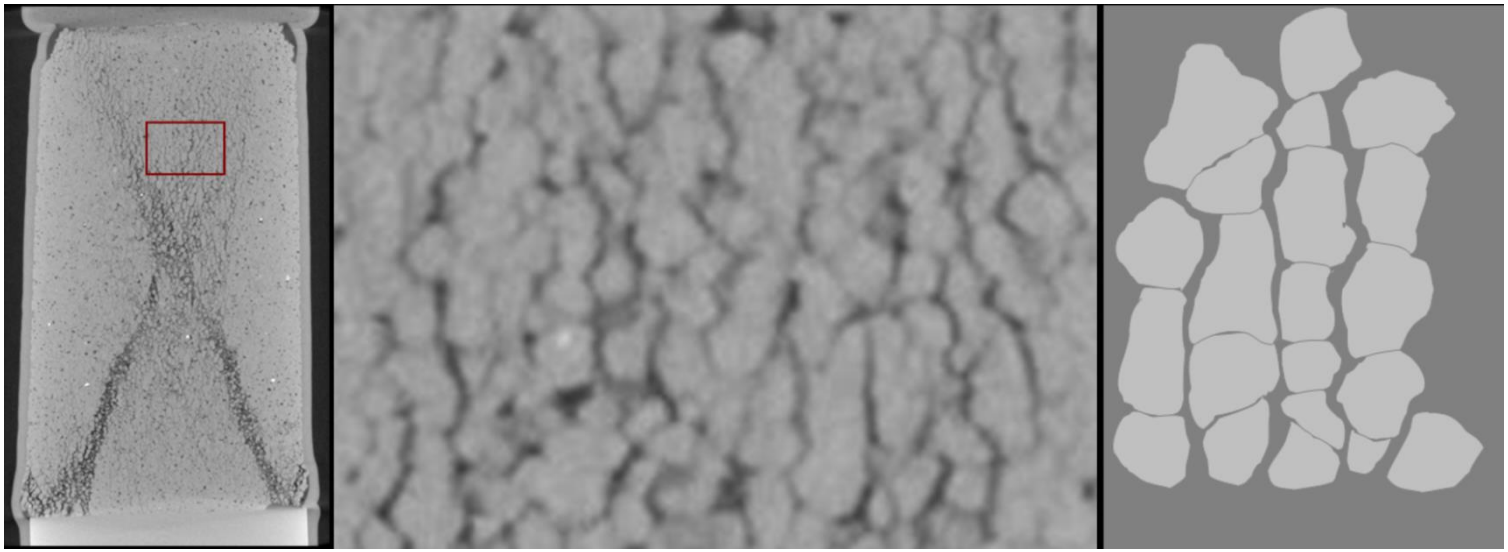
TXC on "soft" and "stiff" Fontainebleau sandstone

grain cementation by quartz overgrowths







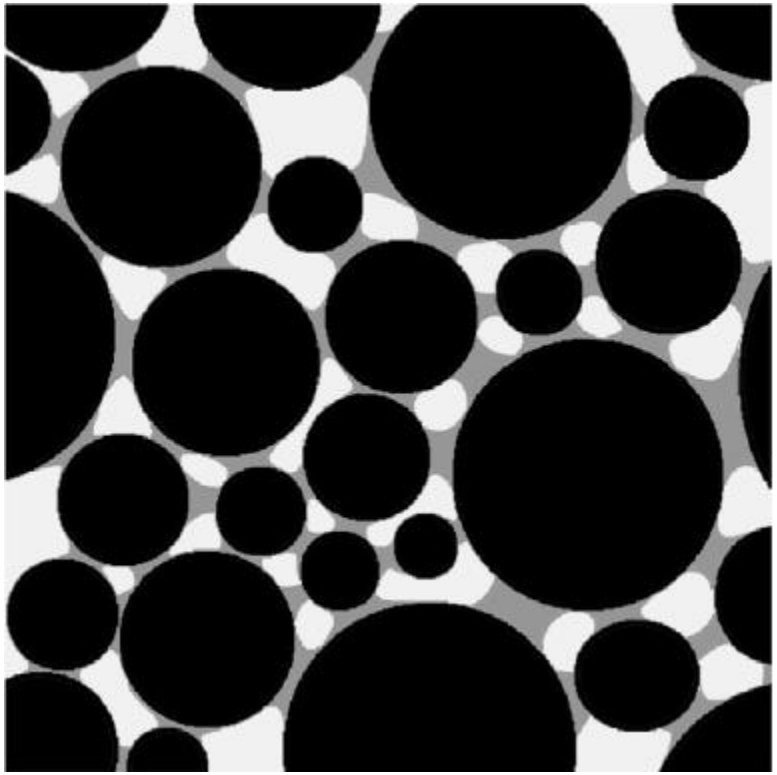


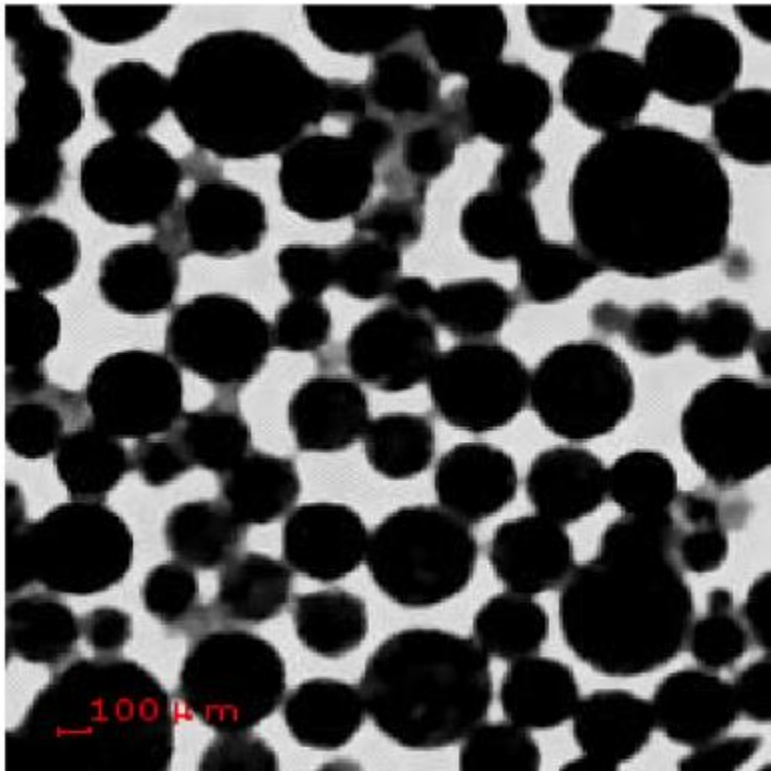
Joana Fonseca
City Univ. London

J. Fonseca, P. Bésuelle and G. Viggiani, Géotechnique Letters 2013

the quantitative grain-scale study of bonded granular materials is very challenging
grain-scale processes involve grain rearrangement + debonding + grain breakage

→ from natural materials to model materials





x-ray scan of calcite-cemented Glass Ballotini

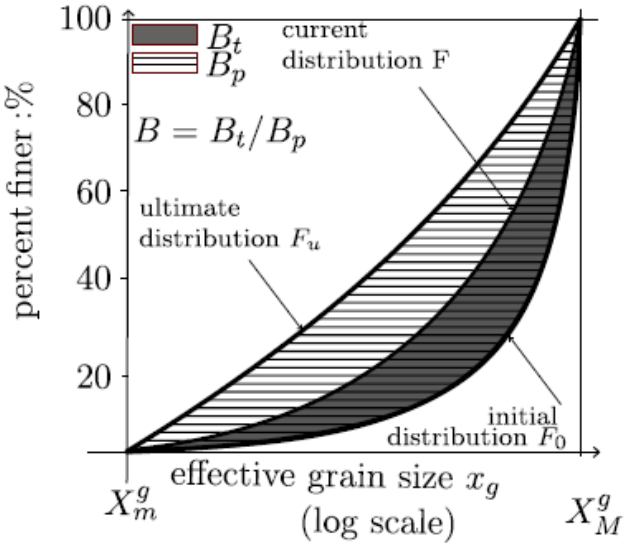
(PhD Alessandro Tengattini)

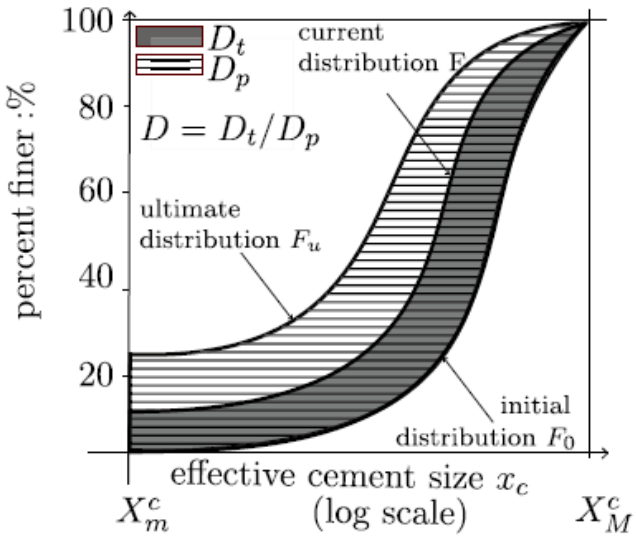
building up continuum models with micro mechanical roots

grain crushing
breakage mechanics

+

cement fracture
damage mechanics





A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables. Part I—Theory

Alessandro Tengattini [a,b], Arghya Das [a], Giang D. Nguyen [c], Gioacchino Viggiani [b], Stephen A. Hall [d], Itai Einav [a,*]

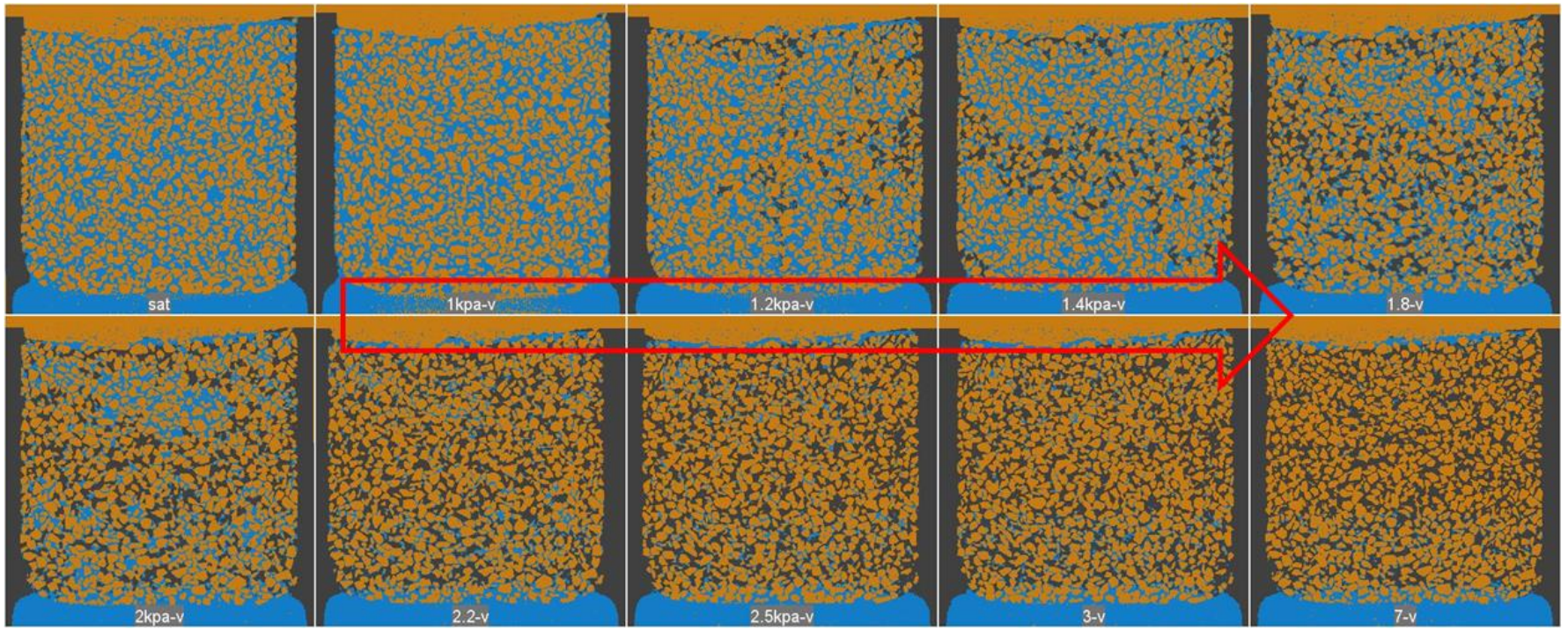
A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables. Part II – Validation and localization analysis

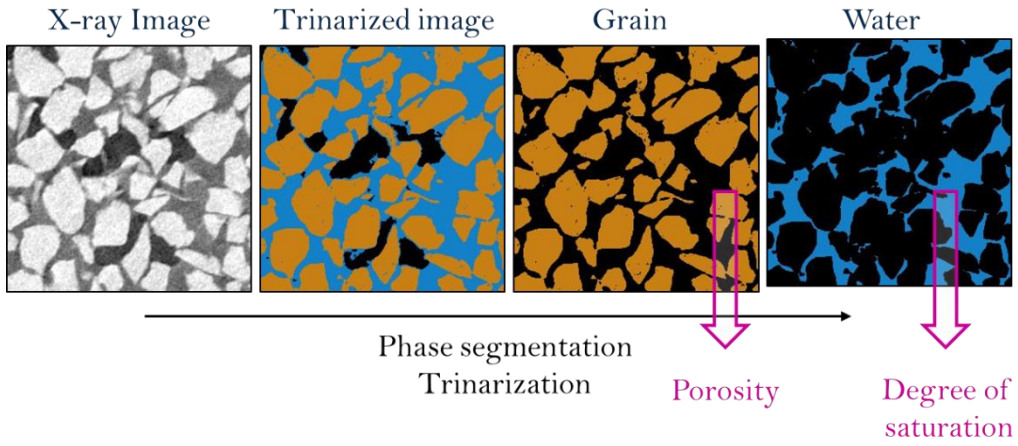
Arghya Das [a], Alessandro Tengattini [a,b], Giang D. Nguyen [c], Gioacchino Viggiani [b], Stephen A. Hall [d], Itai Einav [a,*]

Journal of the Mechanics and Physics of Solids

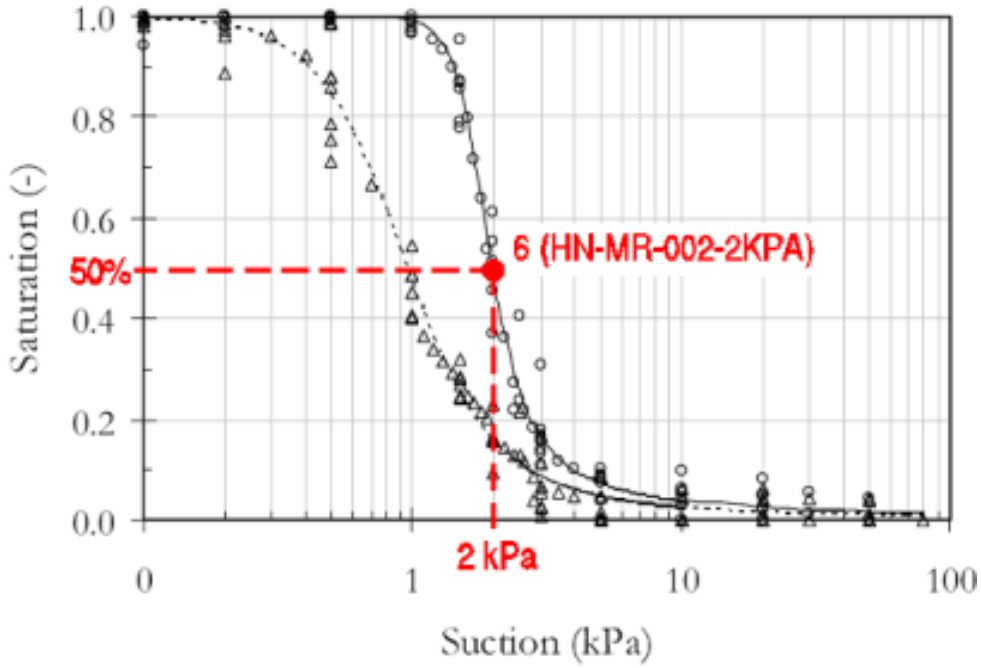
granular materials – more than two phases

partially saturated sand





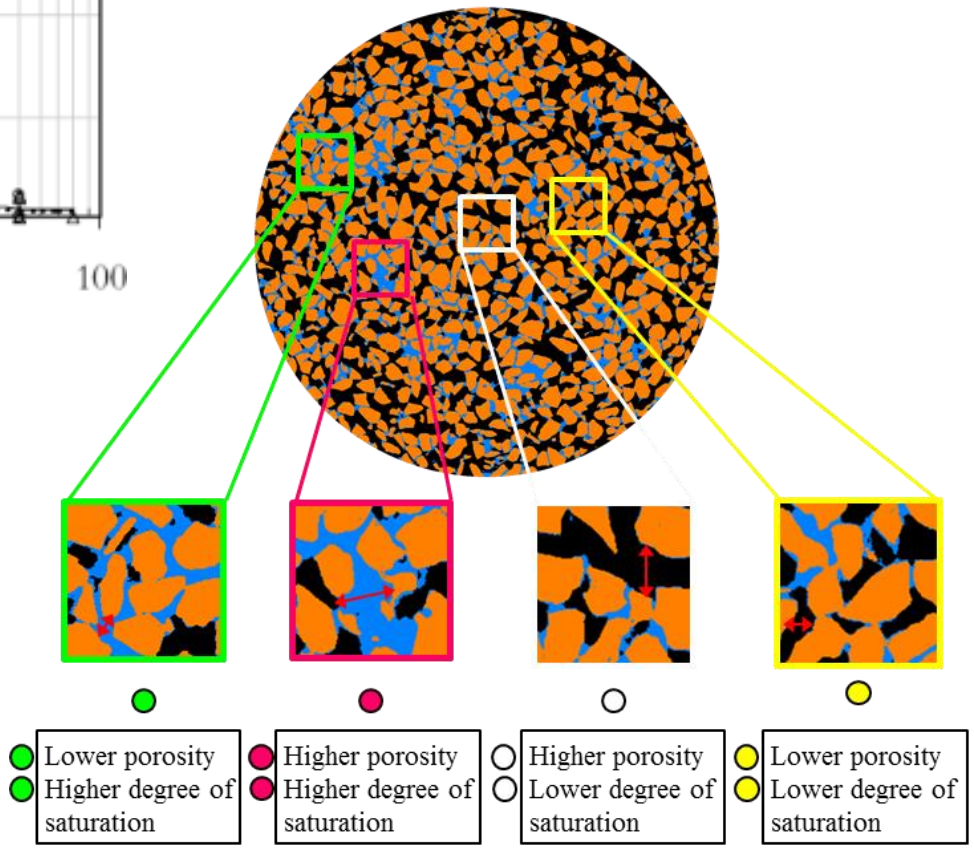
characterizing water retention behavior at the grain scale



Ghionwa Khaddour

Simon Salager

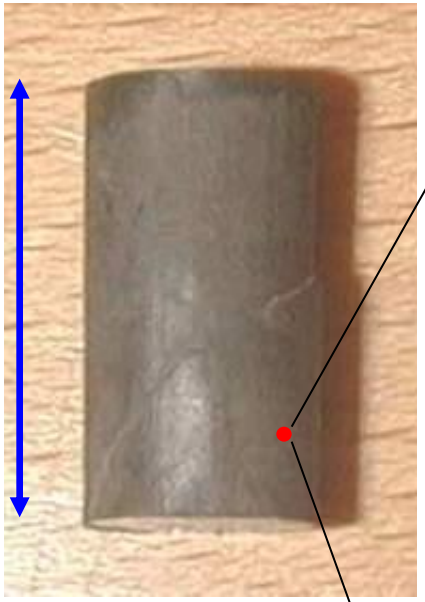
Yosuke Higo

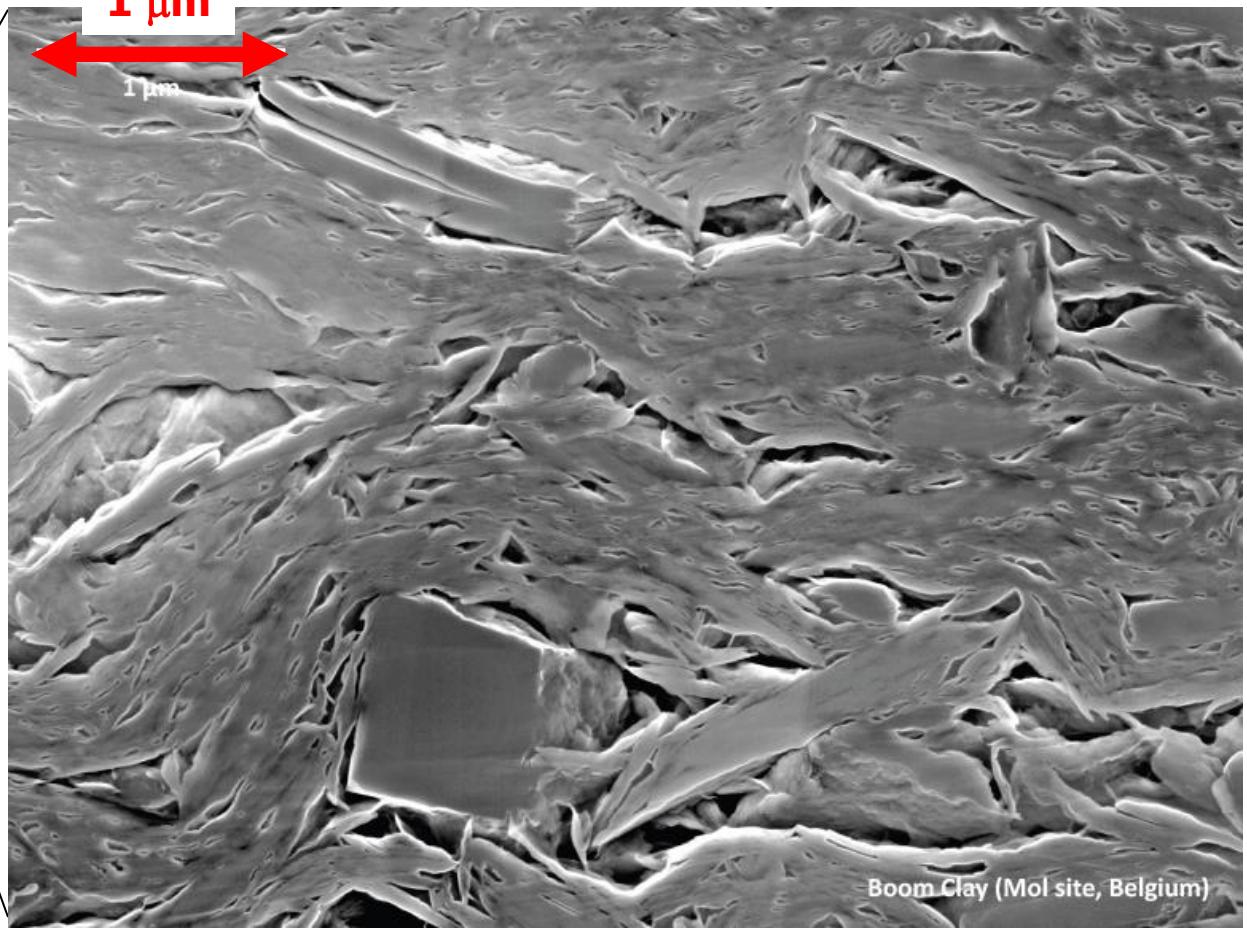


what about fine-grained geomaterials?

we would like to see the deforming micro structure!

how small is "small" for a clay?

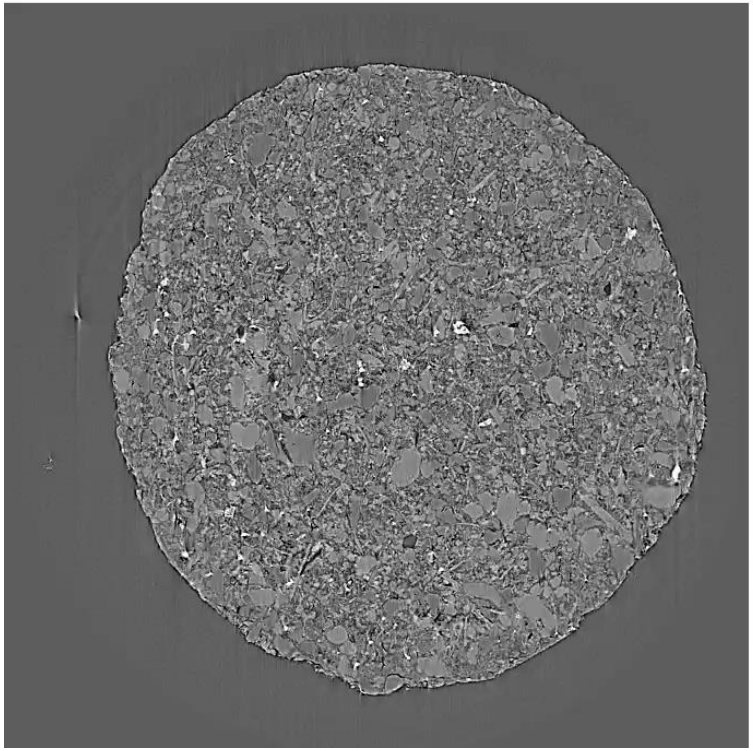


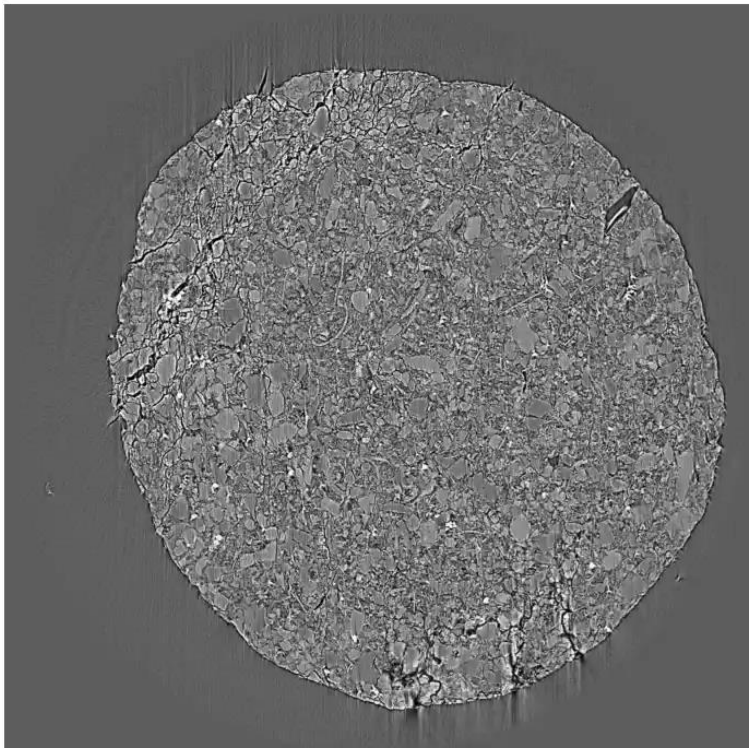


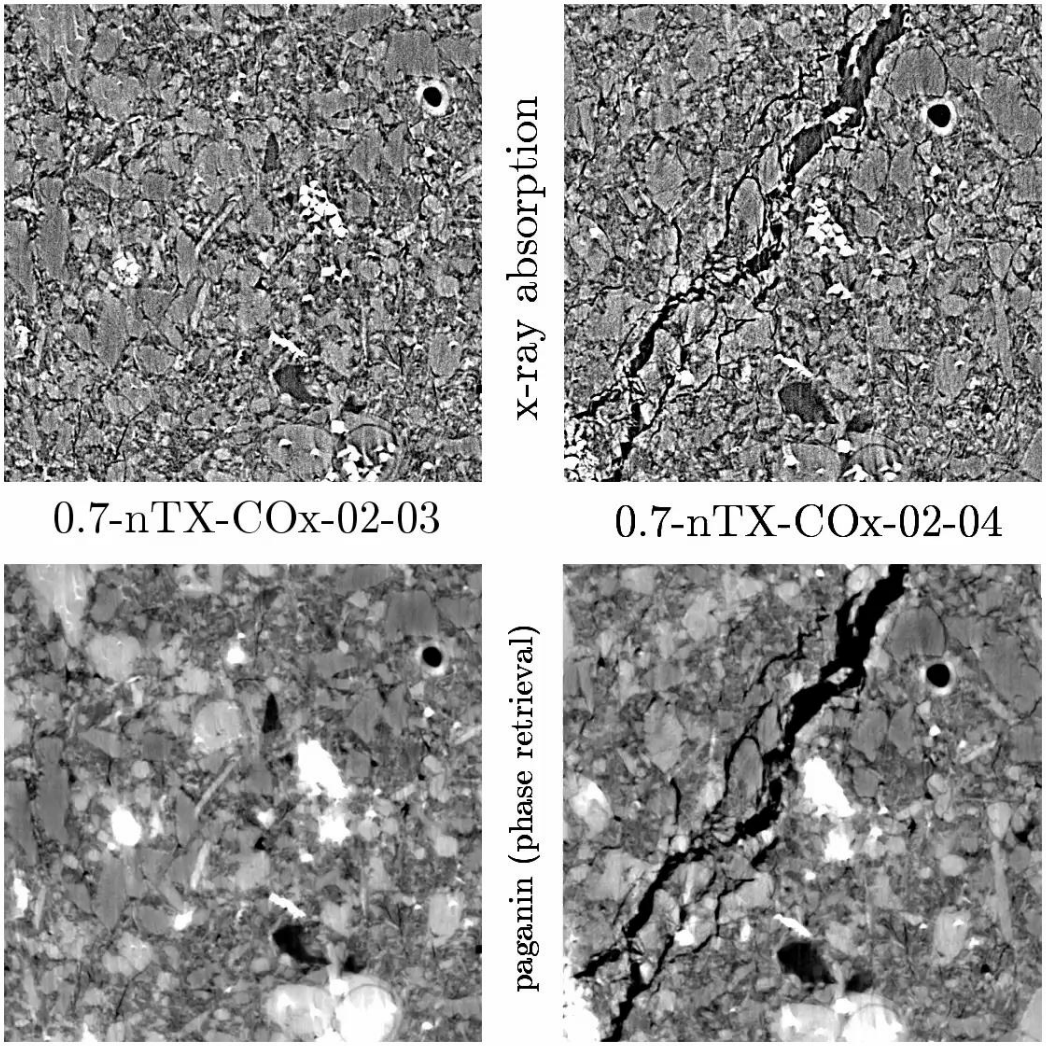
BIB image of Boom Clay -- courtesy of J.L. Urai, Aachen University

0.7-nTX-COx-02-03

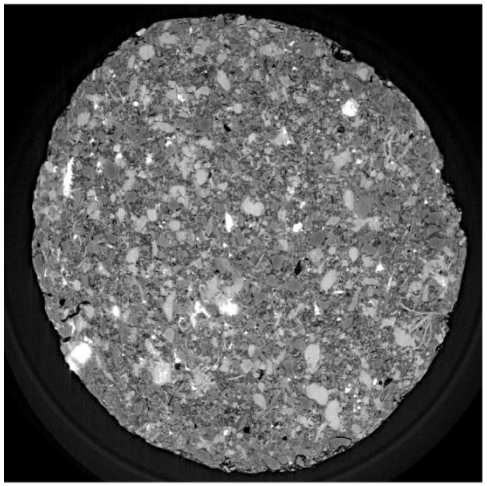
0.7-nTX-COx-02-04



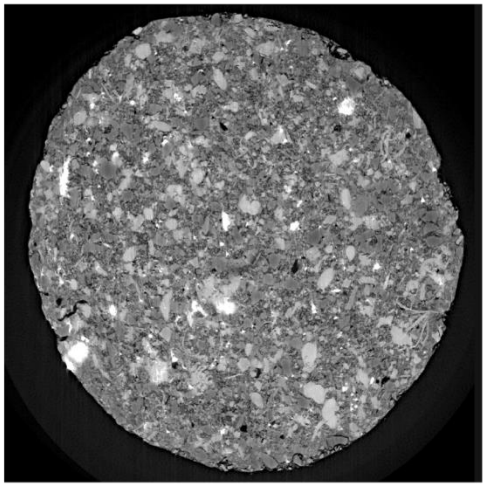



x-ray absorption
0.7-nTX-COx-02-03
0.7-nTX-COx-02-04
paganin (phase retrieval)

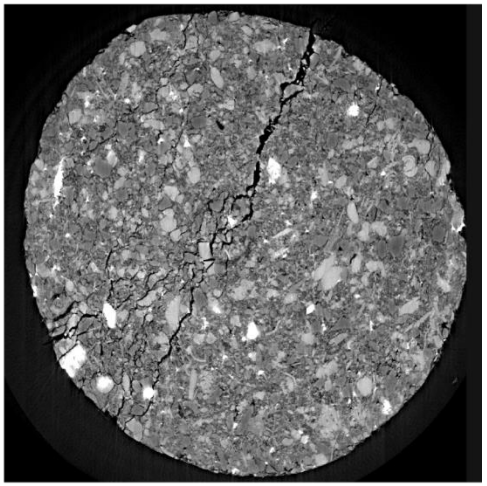
State 02



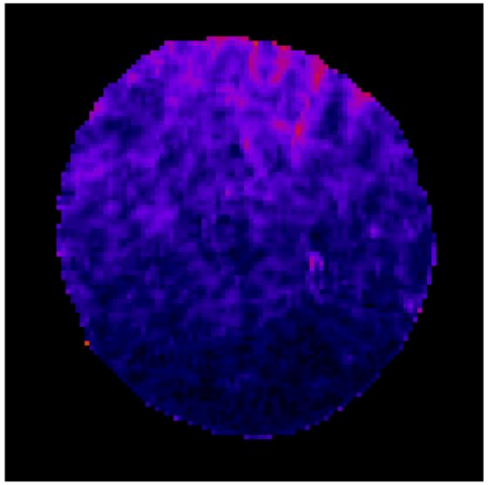
State 03



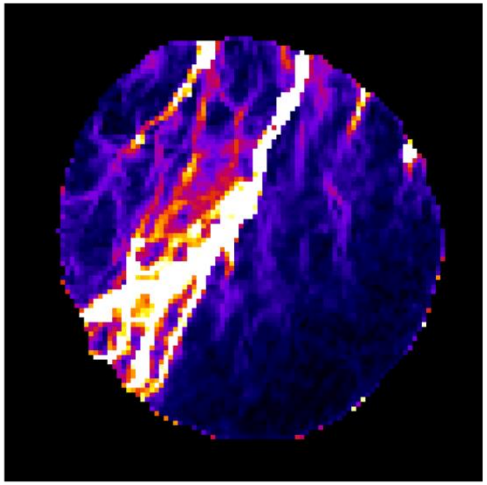
State 04



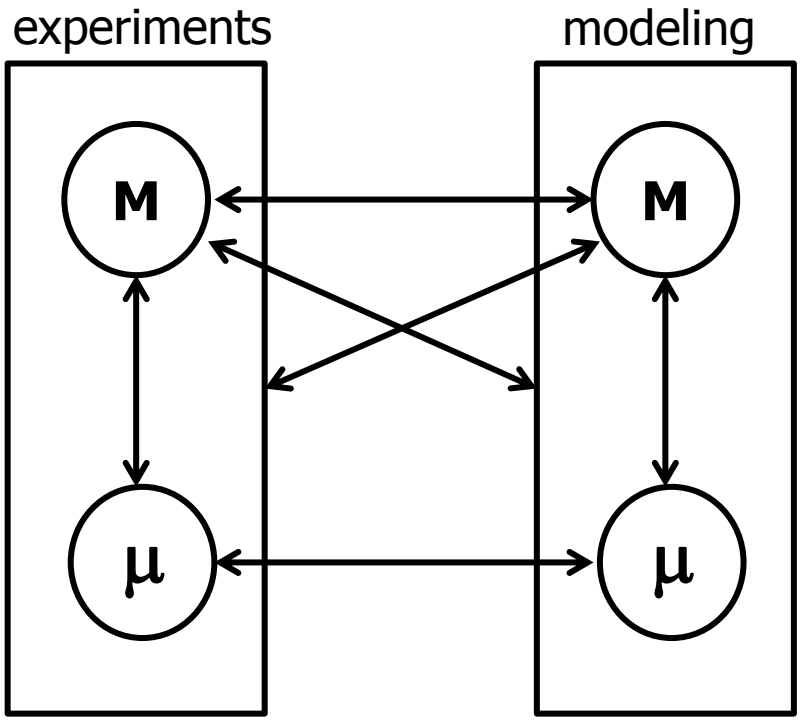
Shear strain field 02-03



Shear strain field 03-04



the Jose Andrade's question



micro AND macro → multi scale

take-home message

1. observing, measuring (w/statistics), understanding the relevant physics at some appropriately small scale

2. injecting this physics into double-scale models or micro-inspired models (micro → macro)

the success of multi-scale approaches crucially depends on the quality of the physics one injects: ideally, this comes directly from experiments

there is still plenty of work (and fun) ahead of us!