Experimental investigation of the emergence of strain localization in geomaterials

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Outline

Textbook of the ALERT school

Experimental investigation of the emergence of strain localization in geomaterials

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Failures of geomaterials, including soils, rocks and concretes, are generally associated with a localized deformation. For about 40 years, strain localization phenomena have been investigated experimentaly in different materials. Most of these studies have been motivated by the theoretical background of shear band analysis using bifurcation theory. Strain field measurements have been developed to characterize strain localization, especially for sand specimens. Full field methods, imaging tools and experimental loading apparatus have evolved considerably over past 15 years. This chapter looks at on the contributions of recent developments on the characterization of the strain localization process. The emergence of strain localization involves the progressive evolution from diffuse to localized deformation. The text introduces the methods used and then shows some selected experimental results obtained from some sands and porous rocks.

1 Introduction

Localized deformation is a ubiquitous phenomenon in geomaterials (soils, rocks, concrete). It occurs over a vast range of size scales, from the microscale level of grains to faults extending over hundreds of kilometers. It occurs in a variety of forms, as a concentration or coalescence of cracks; a distinct, planar frictional surface; a gouge zone of finely comminuted material; or simply a region of higher shear strain or relative grain movements. In geomaterials, the severe shearing in regions of localized deformation may be accompanied by dilatancy (inelastic volume increase) and/or compaction (inelastic volume decrease) as well as by chemical alteration. If the material is fluid-saturated, as is frequently the case, inelastic volume changes can induce the flow of fluid or changes in pore pressure which will affect the response. Localization occurs under a variety of conditions that depend on the material and the loading process (*e.g.*, mean stress and loading rate). Although most frequently associated with the formation of faults under nominally brittle conditions or shear bands –semi-brittle

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Outline

- Introduction
  - *in situ* observations
  - impacts of strain localisation
- Experimental investigations: methods
  - *post-mortem* observations
  - multiple (internal) measurements
  - full field measurements
- Experimental results (a few)
  - strain localisation in sands
  - strain localisation in rocks
  - the emergence of strain localisation in geomaterials
- Conclusions

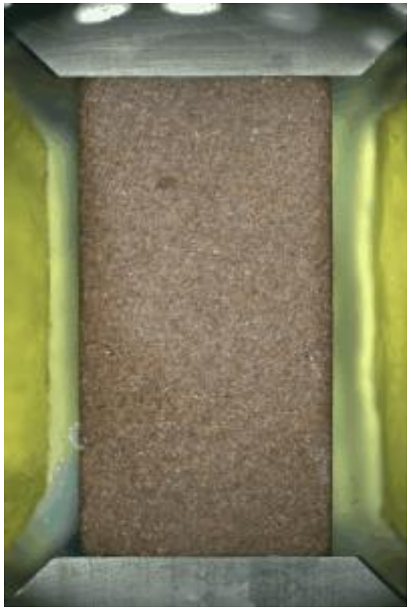
Introduction

What is strain localisation ?

- Strain localization is an important phenomenon for geomaterials that appears almost always when a structure is close to rupture.

Strain localisation during a plane strain compression in a ***clay specimen***
(Viggiani et al, 2001)

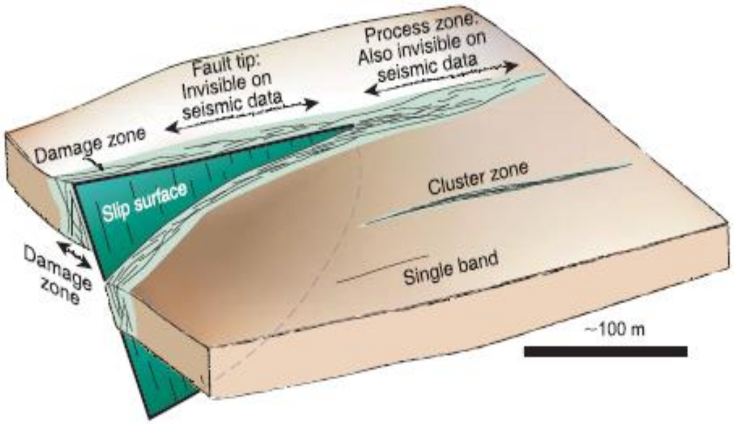
Accelerated movies

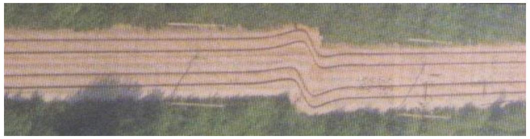


Strain localisation during a plane strain compression in a ***sandstone specimen***
(Bésuelle et al, 2011)

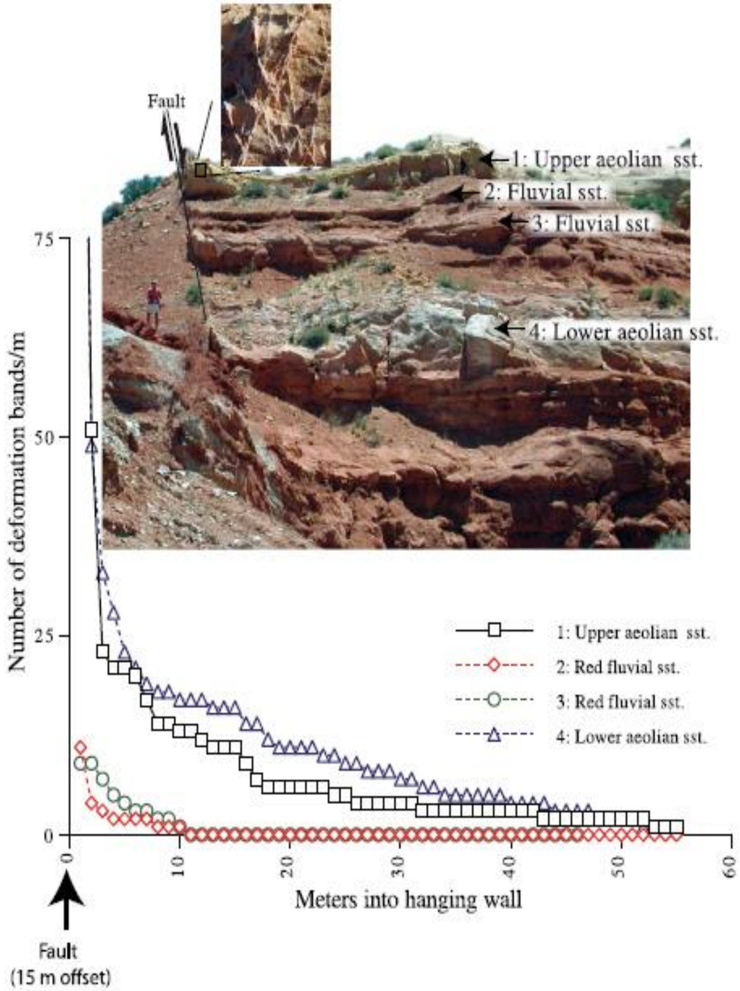
Introduction

- *in situ* observations



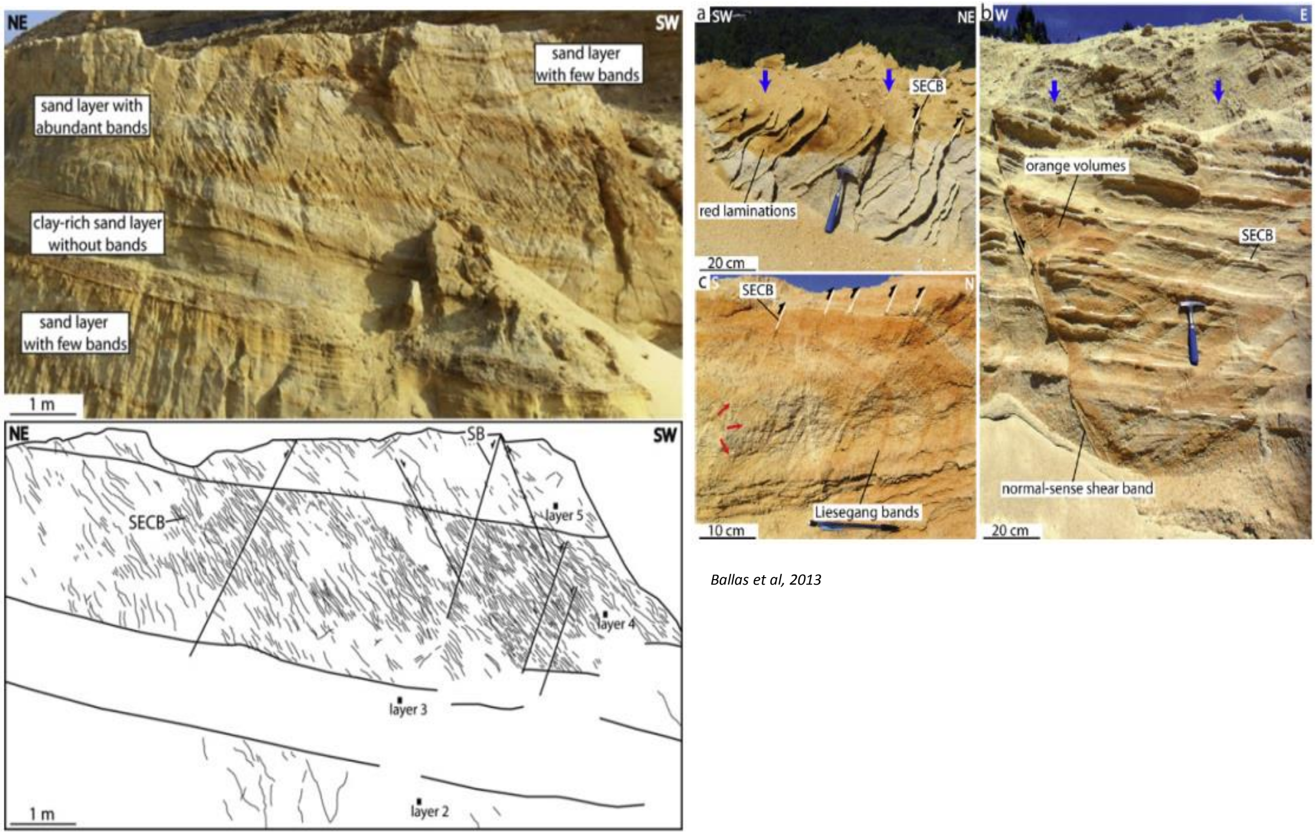


Fossen et al, 2007



Introduction

➢ *in situ* observations



Ballas et al, 2013

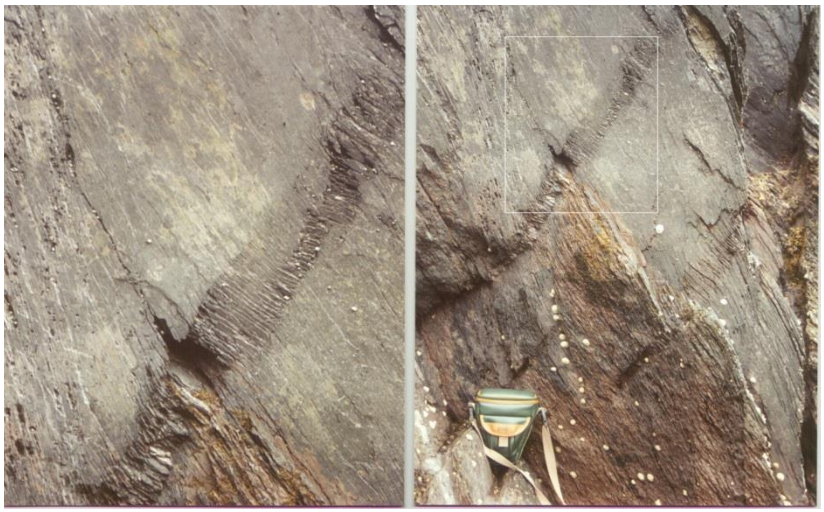
Introduction

➢ *in situ* observations

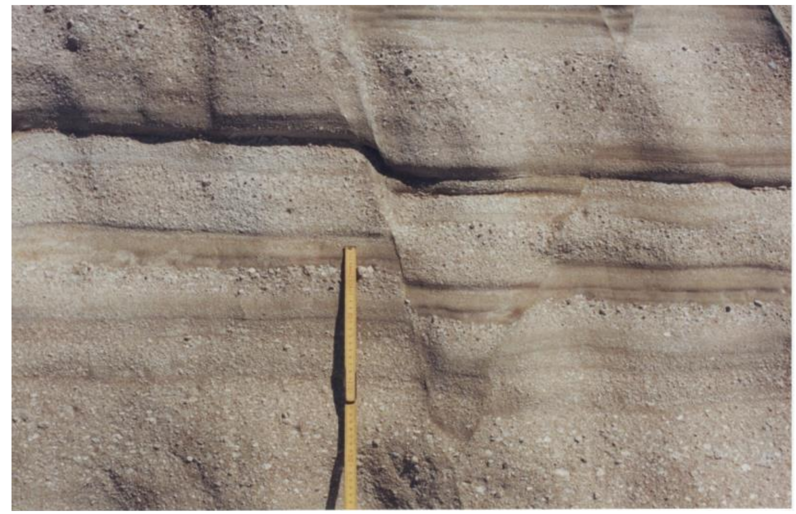
Courtesy of P. Bésuelle

Introduction

- *in situ* observations



Courtesy of J. Desrues



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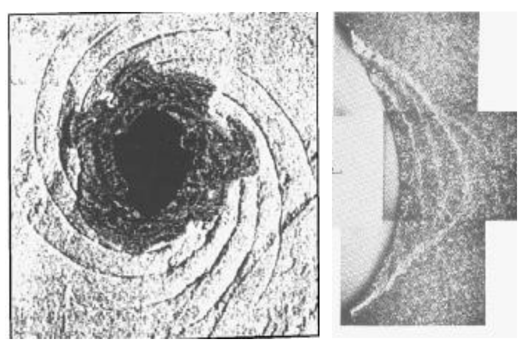
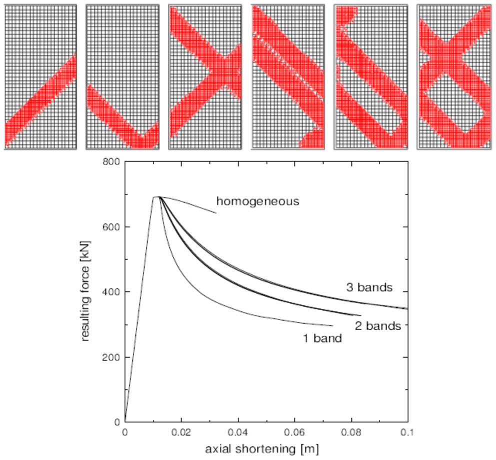


Shear localisation around a gallerie

Introduction

- Some impacts of strain localisation
  - mechanical
    - strain softening
    - damage (elastic properties)
    - mean stress dependency
    - dilatancy/compaction
    - global dispersion of the behaviour
    - hydro mechanical coupling
  - transfer properties
    - permeability change: high permeability channels or impermeable barriers
    - pore geometry change, capillary forces, etc.



Evidence of post peak dispersion (Bésuelle et al, 2006a)

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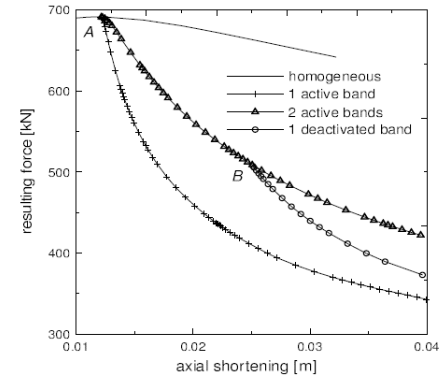

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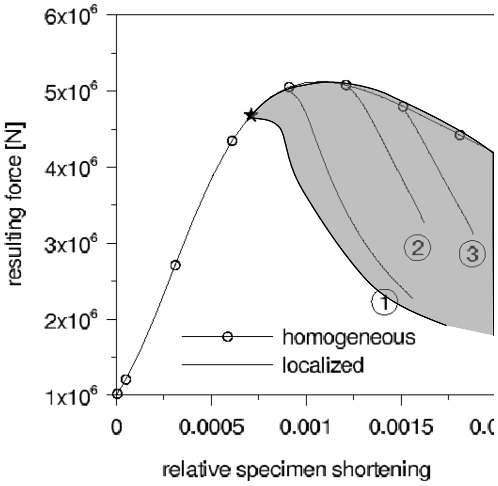

Evidence of post peak dispersion (Bésuelle et al, 2006b)

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Evidence of fluid flow channels

Introduction

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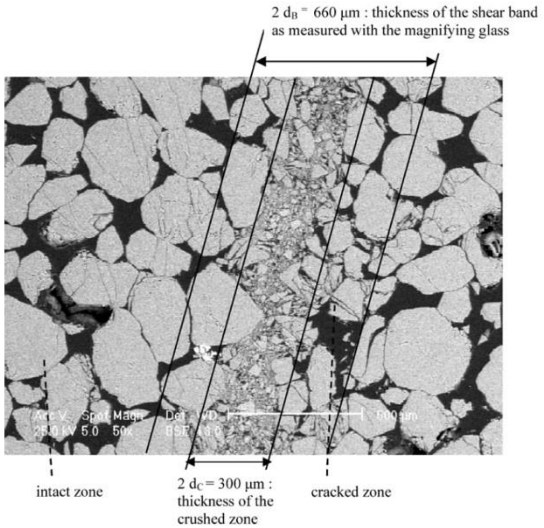

Evidence of grain comminution (El Bied et al, 2002)

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  - full field measurements
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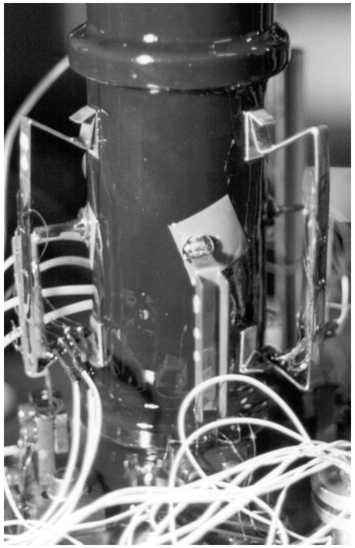
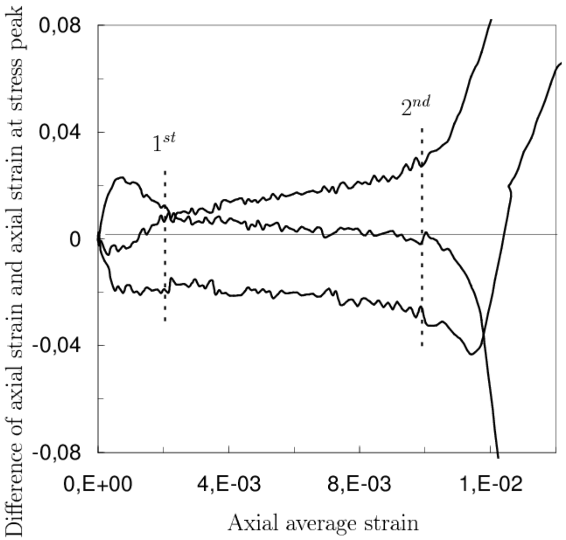
  - strain localisation in sands
  - strain localisation in rocks
  - the emergence of strain localisation in geomaterials
- Conclusions

Experimental investigations: methods

- *post-mortem* observations
  - strain localisation pattern, etc.
  - microstructural observations
- detection of strain localisation by multiple internal measurements
- full field measurements (field quantification + time evolution)
  - non-destructive image tools (tomography)
  - measurement of the kinematic fields (2D + t) or (3D + t)
  - location of acoustic events

*Detection of the loss of homogeneous deformation with several internal **displacement** transducers*
(Bésuelle and Desrues, 2001)





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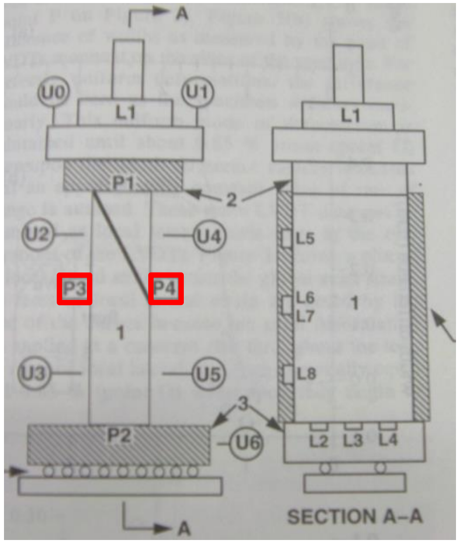
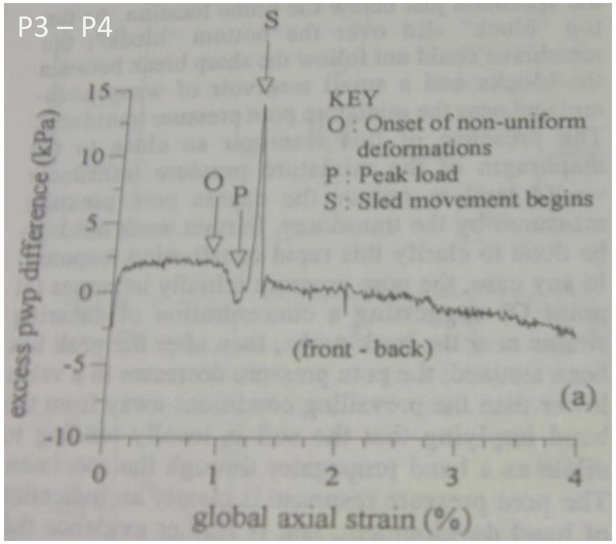
Evidence of pore pressure gradient induced by strain localisation, observed by several internal ***pressure*** *probes (Viggiani et al, 1994)*





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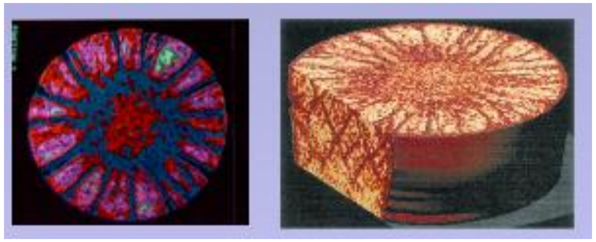
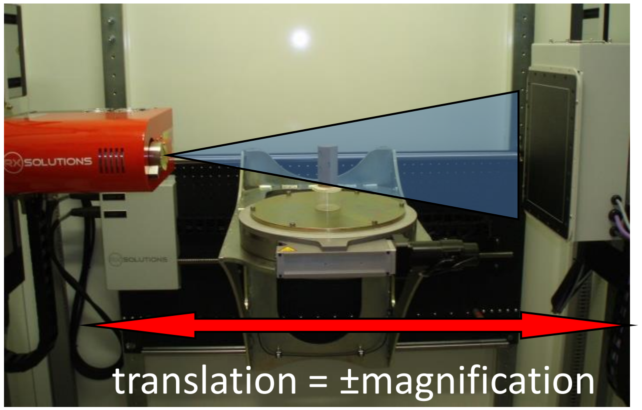
3D picture of a sand specimen by ***high resolution*** *X-ray CT (3SR Lab)*

Low resolution *X-ray CT of sand specimens: dilatant bands without grain-scale detail (e.g., Desrues et al. [1996]; Alshibli et al. [2000])*

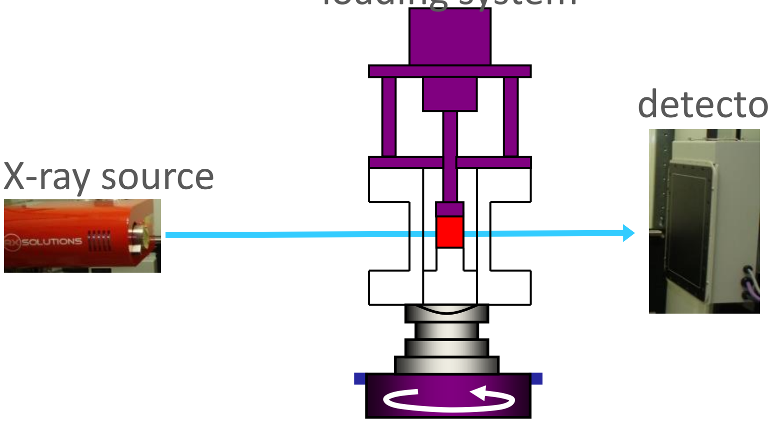


Experimental investigations: X-ray tomography (CT)

- *Industrial/research scanner (conical beam)*
- *Synchrotron beamline + tomography*

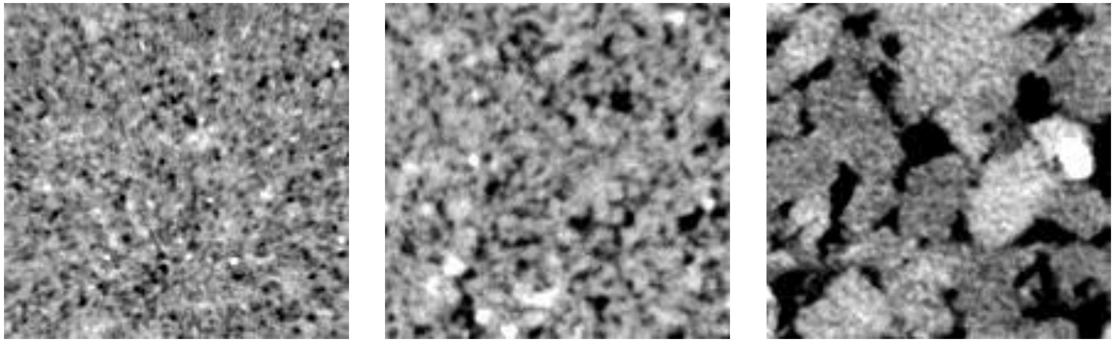


ESRF, Grenoble (France)



Vosges sandstone (grains size ~ 300 µm)

voxel width: 90 µm | *30 µm* | *7 µm*



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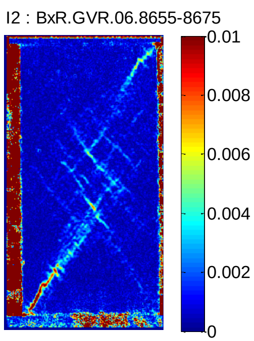
2D

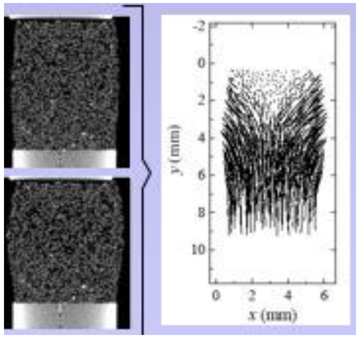
continuous DIC — *discrete DIC*

3D (volume)

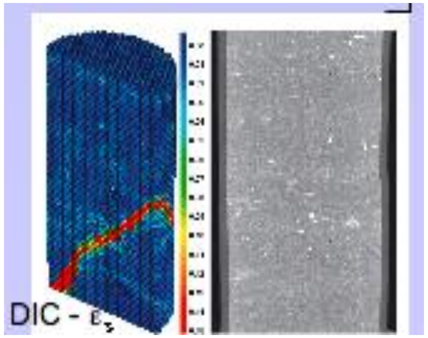
continuous DIC — *discrete DIC*



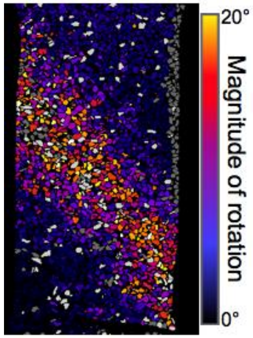
Photographs + 2D DIC



X-ray CT + 2D DIC



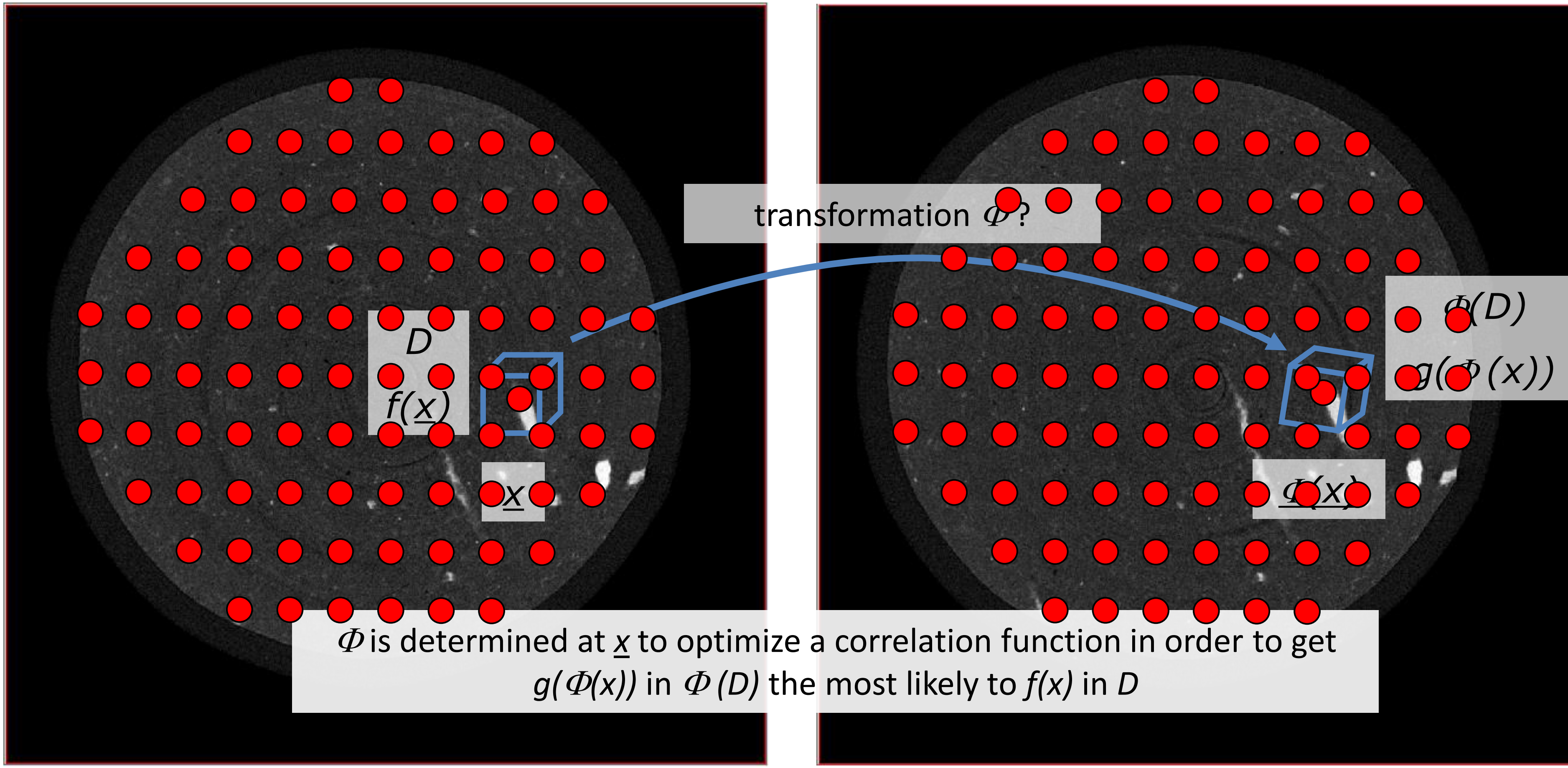
X-ray CT + V-DIC



X-ray CT + discrete V-DIC

Experimental investigations: Digital Image Correlation (DIC)

Two 3D-images of the same specimen at two steps of loading (strain increment)



D : subset around the material point

f(x): gray level distribution inside *D - characterizes the material point*

g(Φ(x)): gray level distribution inside *Φ (D)* in the 'deformed' image

Experimental investigations: Digital Image Correlation

1. The set of nodes distributed on the reference image is defined. Generally the nodes are regularly spaced, with a given number of pixels for the distance between nodes.

2. The subset around the node is determined, which is generally a square (2D) or a cube (3D) with a size of a few pixels (voxels).

3. The zone of research (zone of interest) is determined and the most similar subset in the deformed image is searched.

4. For all possible positions in the research area, a correlation coefficient is measured corresponding to a displacement of an integer number of pixels, assuming a rigid displacement (no deformation of the subset). The position that maximizes the similarity coefficient is guessed as the best approximation.

5. The previous approximation is refined by a sub-pixel algorithm, because the true displacement rarely corresponds to an integer numbers of pixels. Generally, the subset size in this step is smaller than in step 2. Moreover, the zone of research (step 3) is reduced to very few pixels (voxels).

Experimental investigations: methods

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  - strain localisation pattern, etc.
  - microstructural observations
- detection of strain localisation by multiple internal measurements
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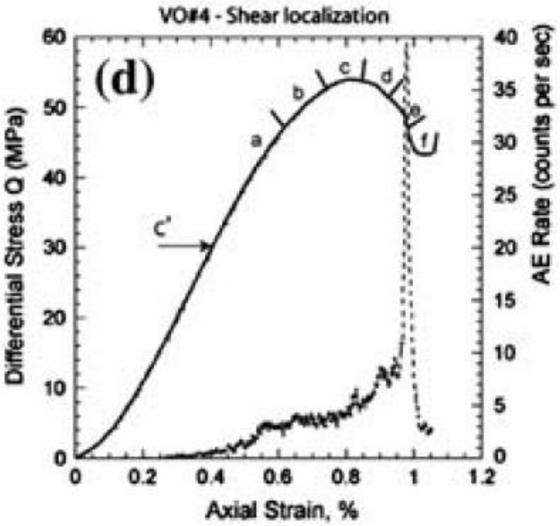
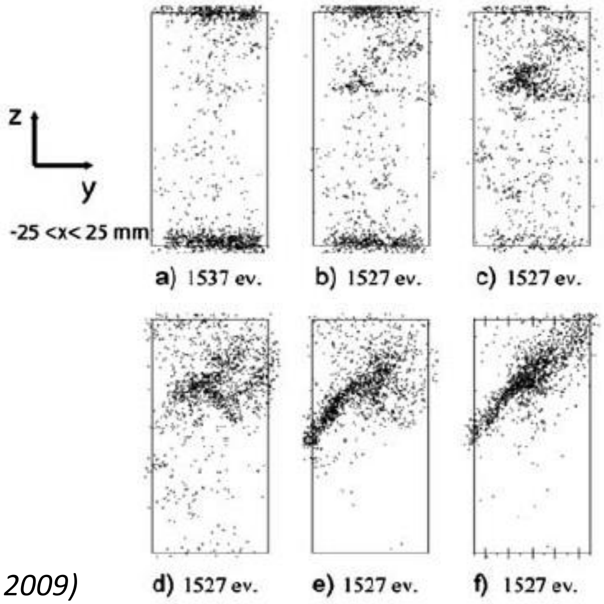
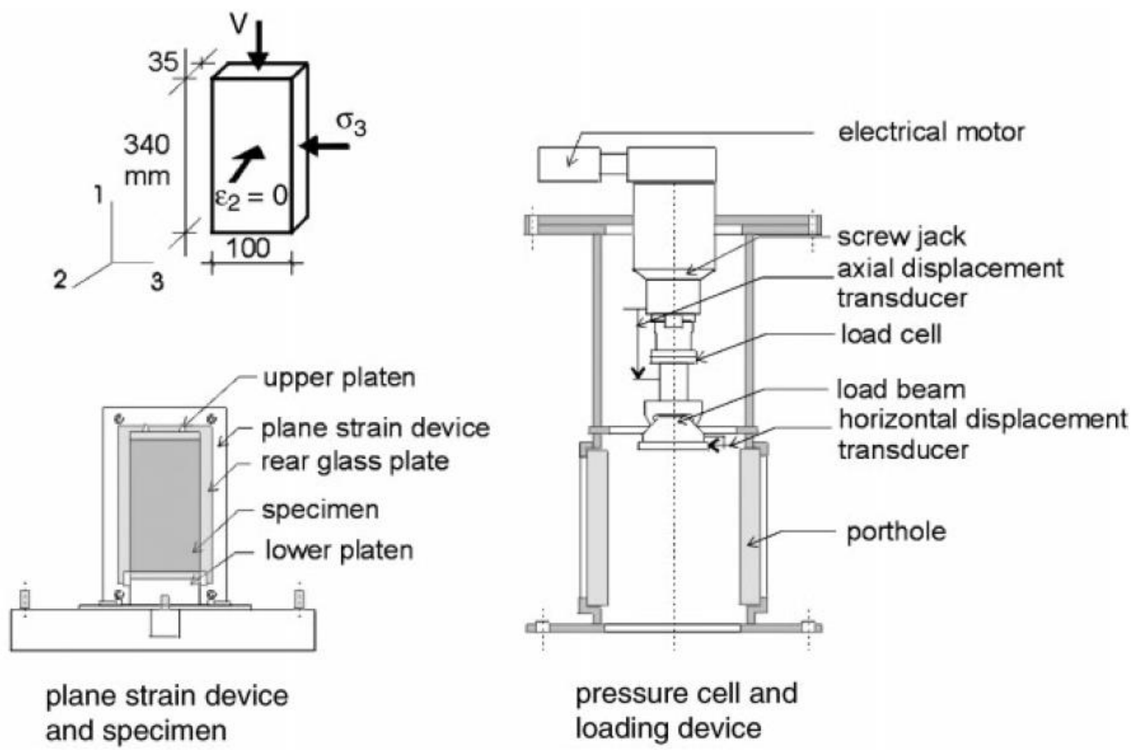




Location of acoustic events during triaxial compression tests (Fortin et al, 2009)

Experimental investigations: methods

- *Cells for full field measurement (need to see the specimen during loading)*
  - Plane strain apparatus for soils

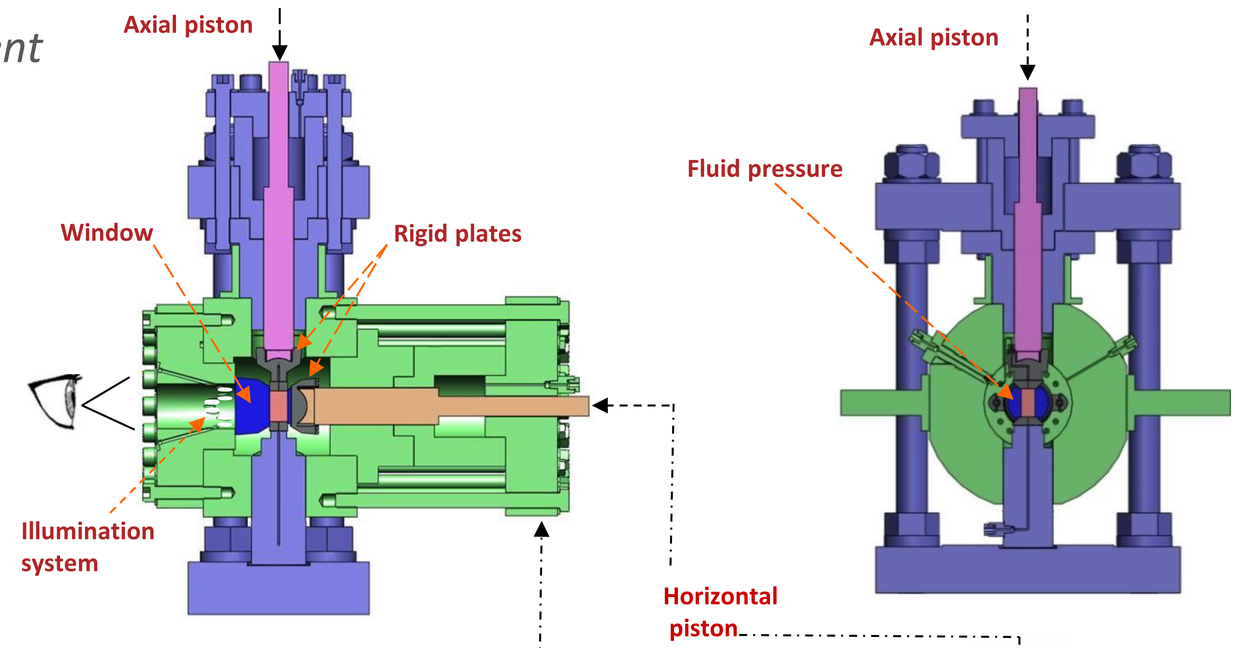


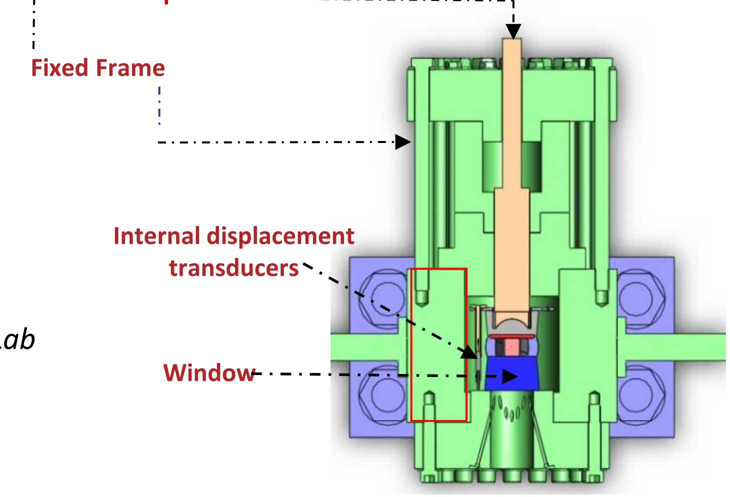
Plane strain cell at 3SR Lab (Desrues et al)

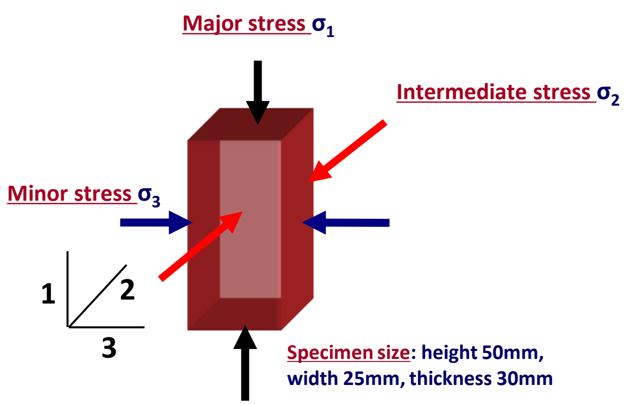
Experimental investigations: methods

- *Cells for full field measurement*
  - True triaxial cell for rocks

- Minor stress : fluid confinement, maxi 100 MPa
- Intermediate stress : piston, force or displacement control, maxi 650 MPa
- Major stress : piston, force or displacement control, maxi 750 MPa
- Window (sapphire) to see the specimen under loading.



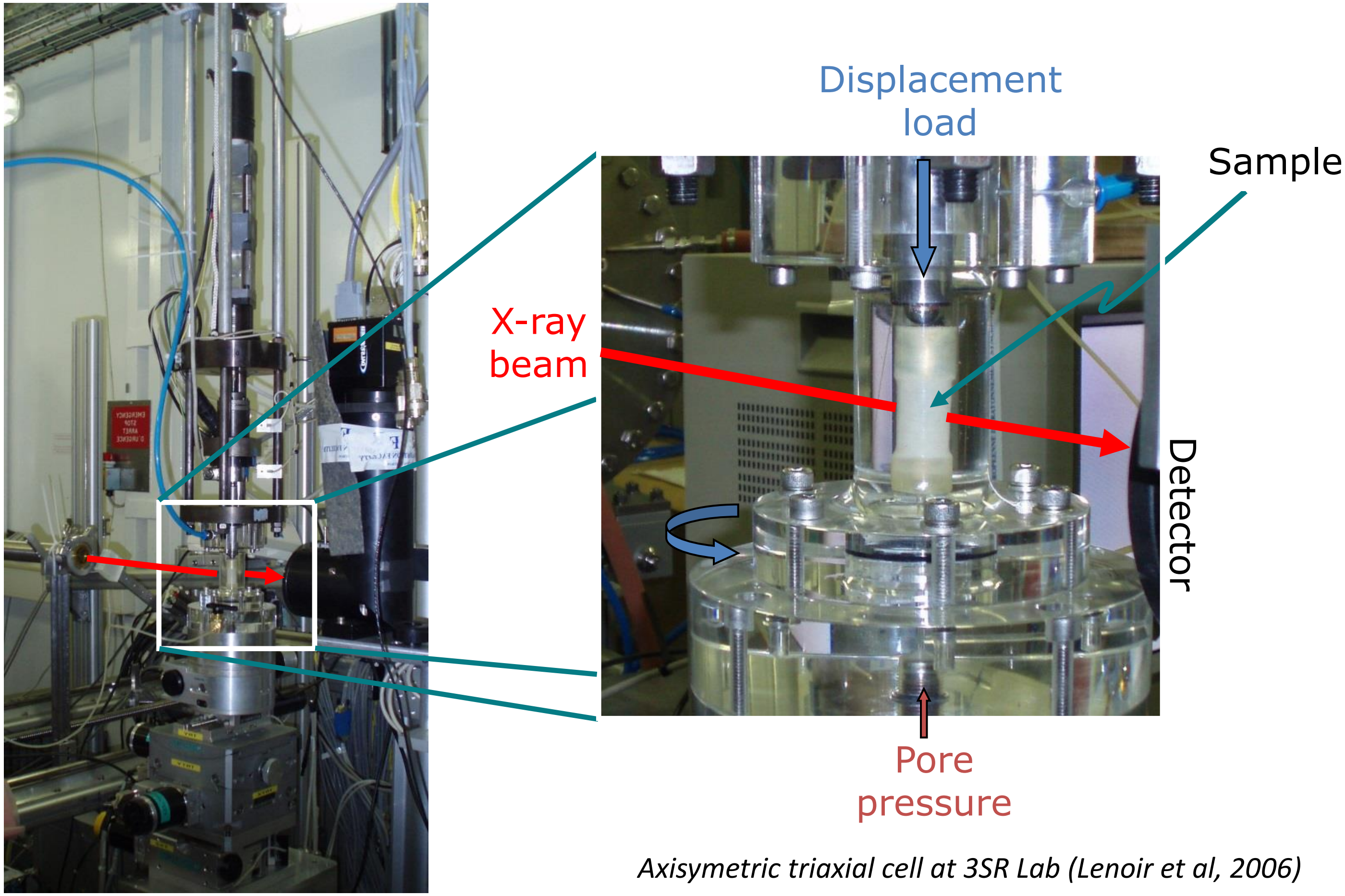




True triaxial cell at 3SR Lab (Bésuelle et al, 2016)

Experimental investigations: methods

- *Cells for full field measurement (need to see the specimen during loading)*
  - X-ray transparent triaxial cell



Axisymetric triaxial cell at 3SR Lab (Lenoir et al, 2006)

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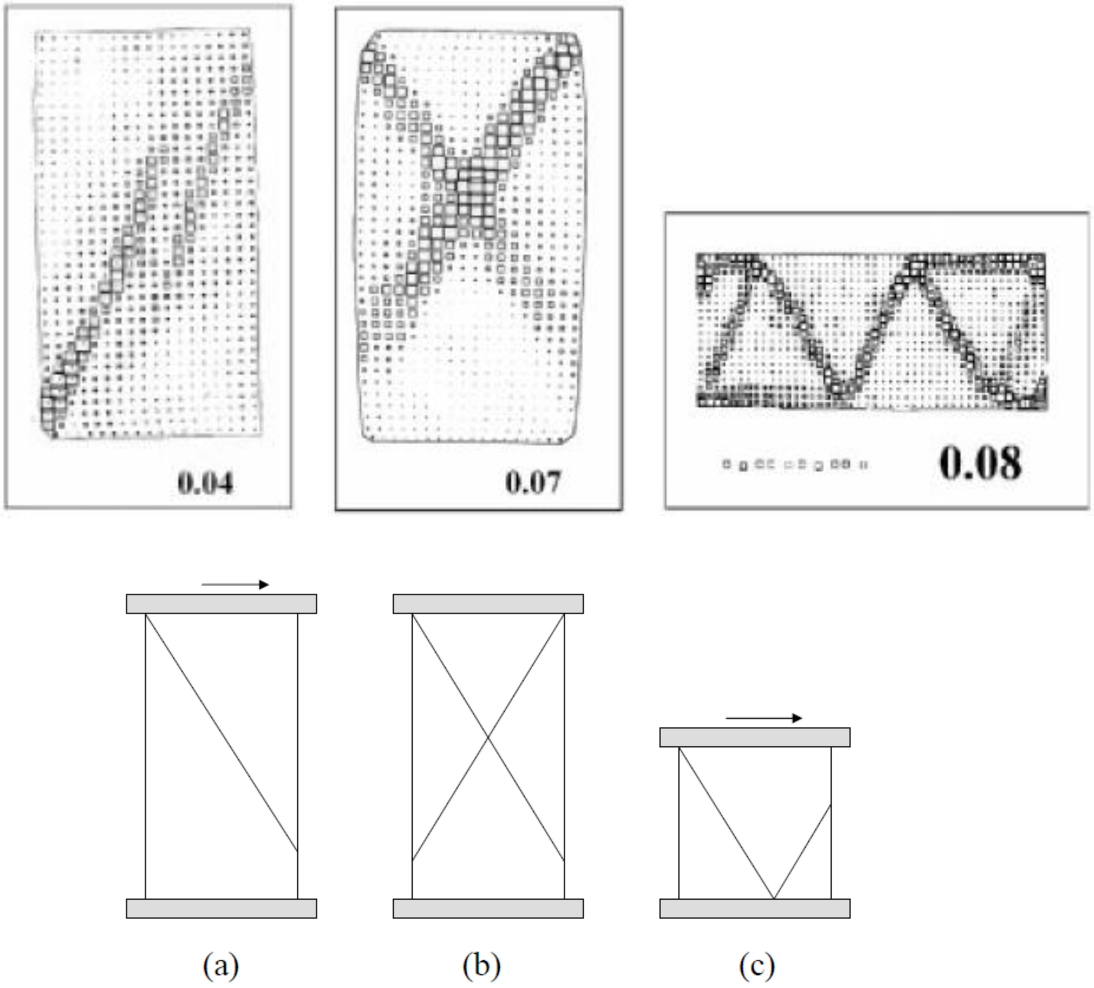
Experimental investigation in sands

- *Pattern of localisation*

Plane strain compression tests (Desrues et al, 1991-2004)

Effects of the boundaries conditions

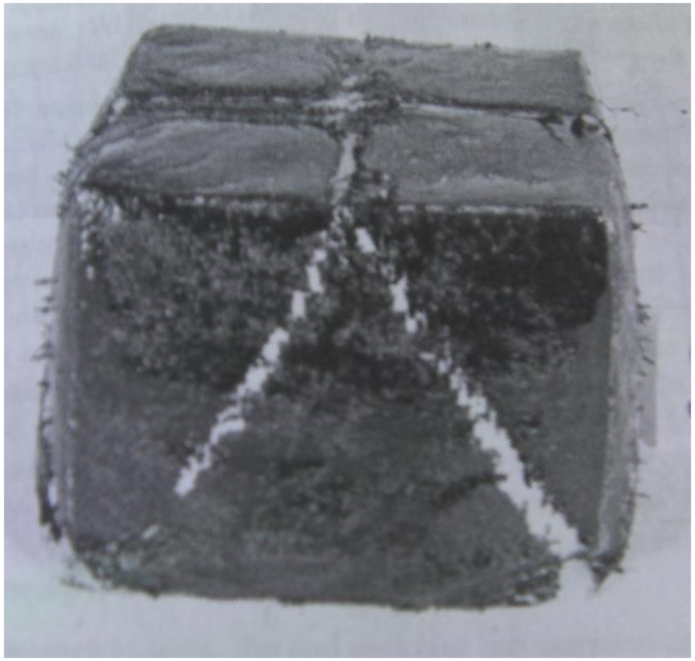


Experimental investigation in sands

- *Pattern of localisation*

True triaxial compression tests on a cubical specimen (Desrues et al, 1985)

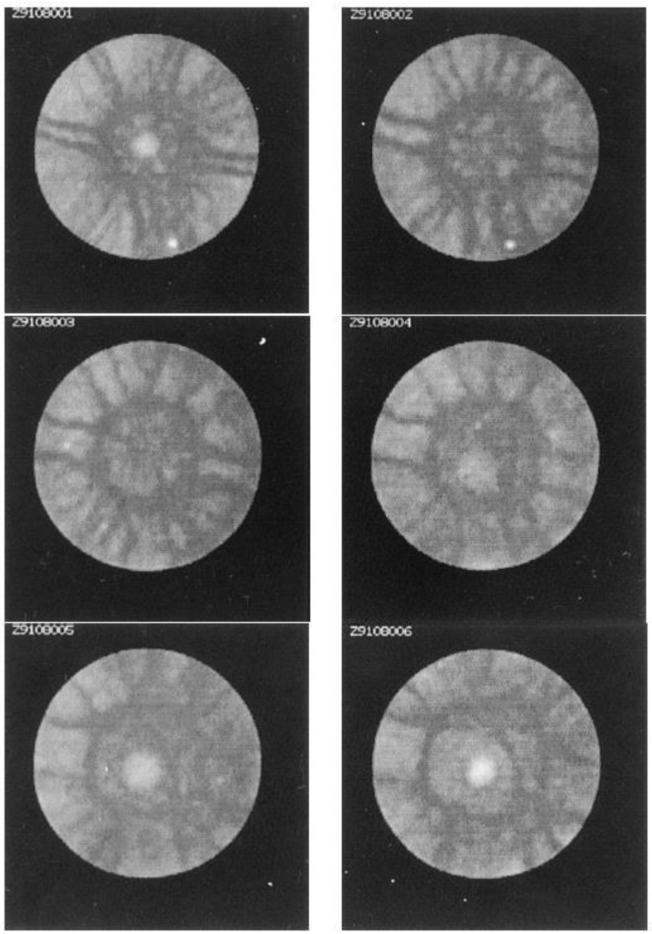
Effects of the boundaries conditions: Rigid platens on the six specimen's surfaces ---> reflexion of shear bands in the three spatial directions

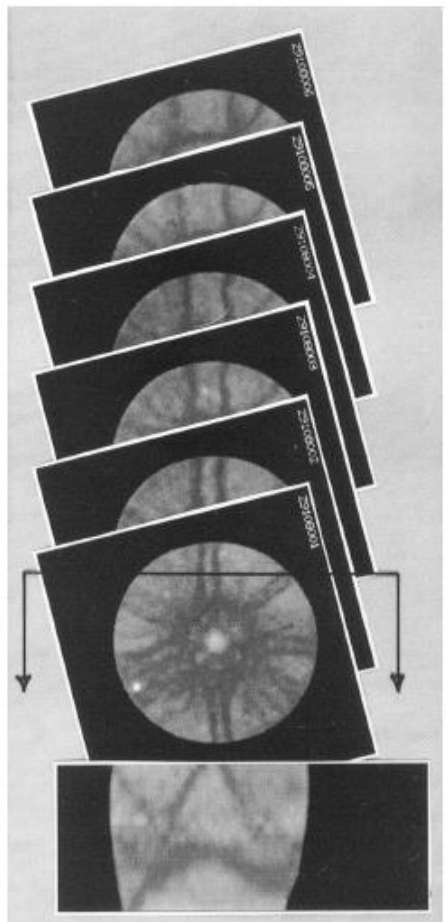


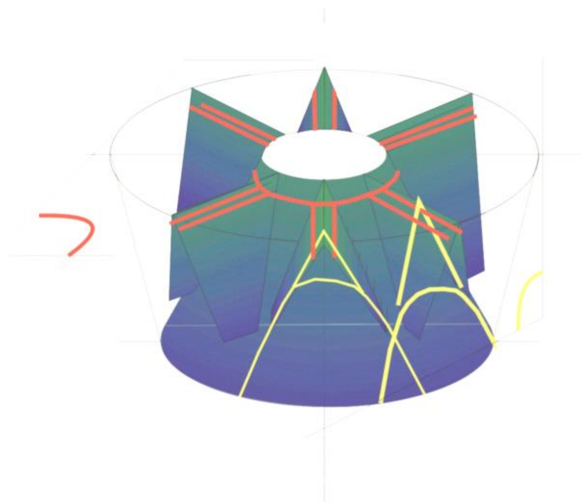
Experimental investigation in sands

- *Pattern of localisation*

axisymetric triaxial compression tests (Desrues et al, 1996)





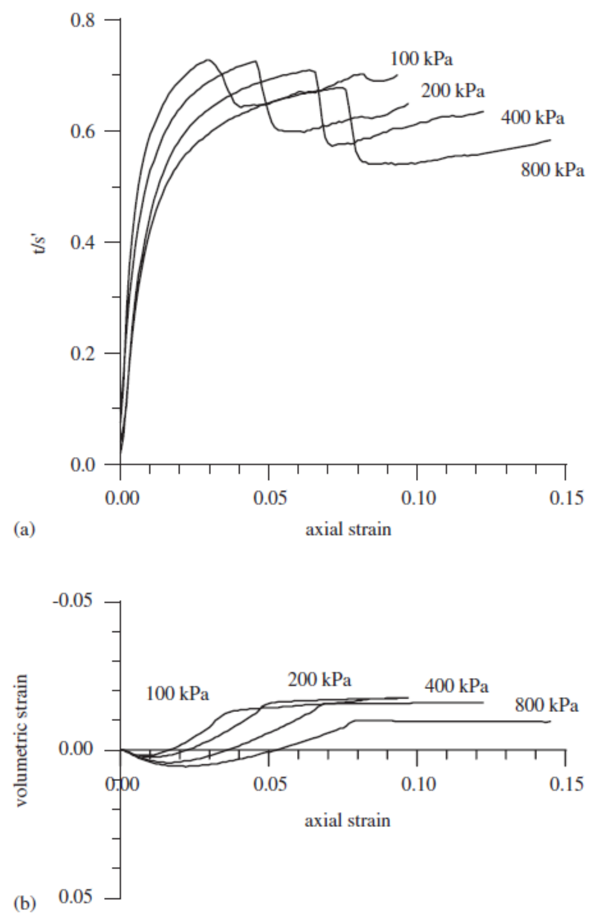


Experimental investigation in sands

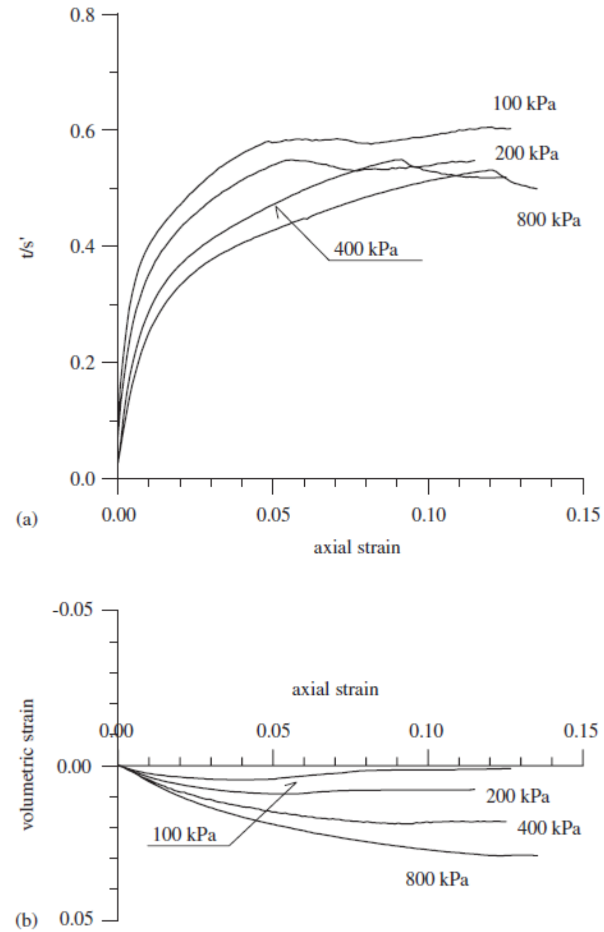
➢ *Onset of localisation*

- *Dense and loose specimen*
- *Effect of mean stress: Localisation occurs later when mean stress increases*

Dense sand (Desrues et al, 1991-2004)



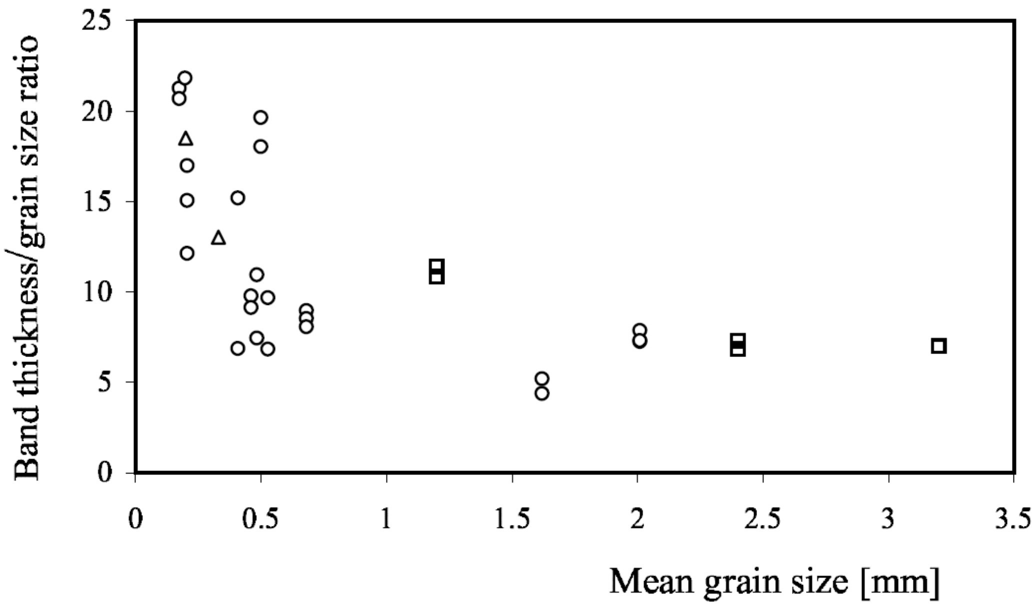
Loose sand (Desrues et al, 1991-2004)



Experimental investigation in sands

- *Shear band thickness*

The band thickness is about 5-20 x the mean grain size

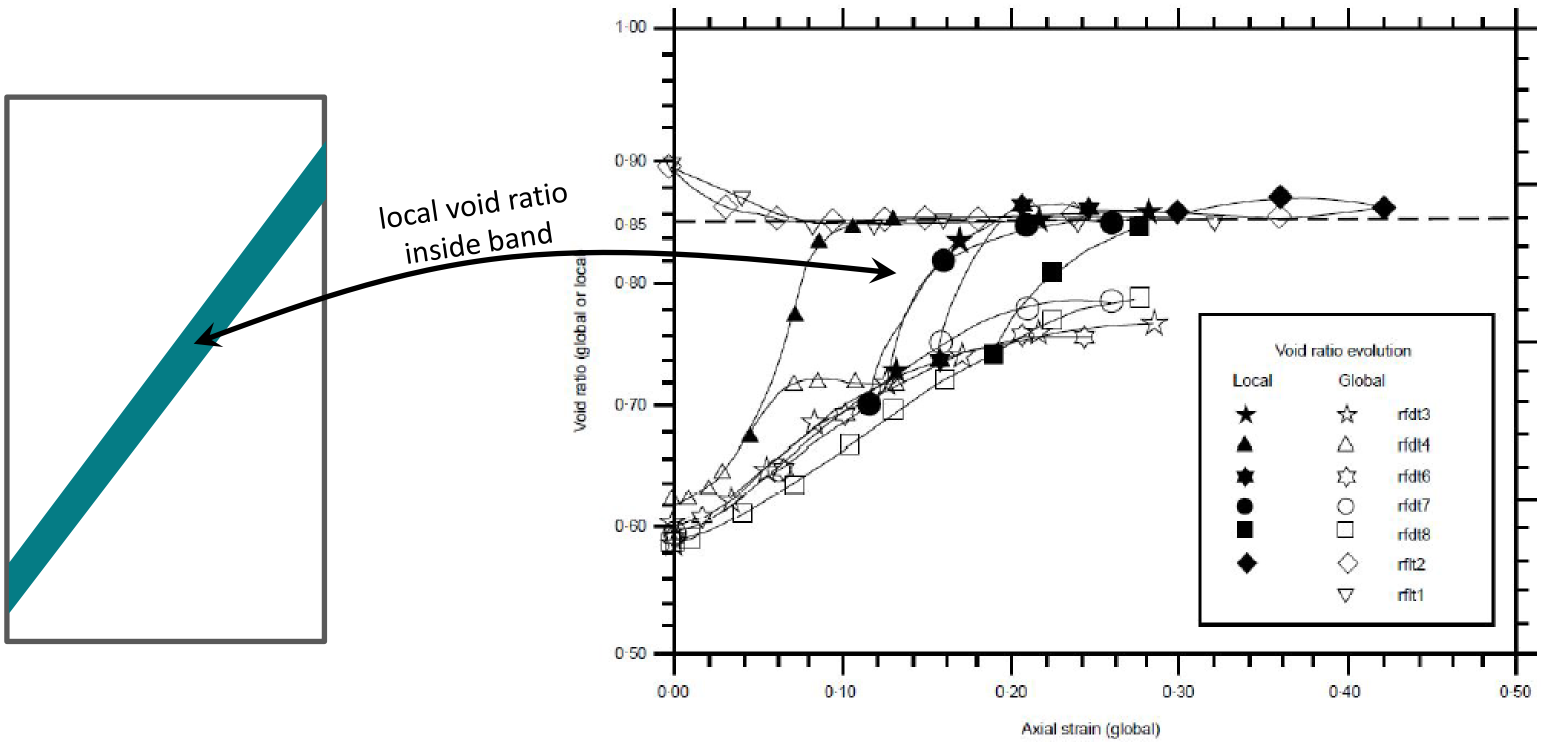


from Bésuelle and Rudnicki (2006), data from Yoshida and Tatsuoka (1997), Mokni (1992), Mühlhaus and Vardoulakis (1987)

Experimental investigation in sands

- *Critical porosity in shear band*

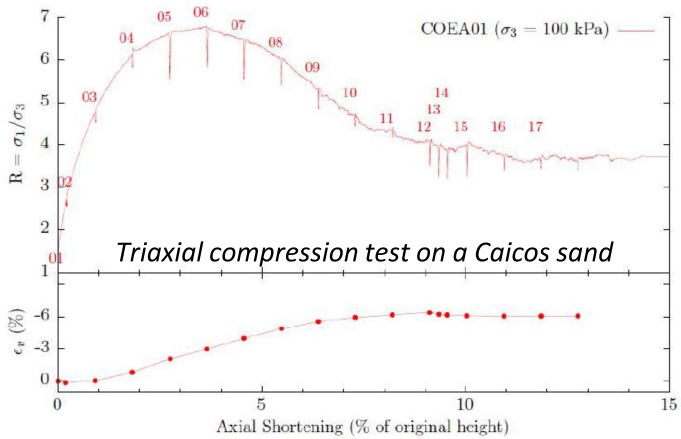
From loose and dense state, the porosity inside shear bands converges toward a critical porosity (which is mean stress dependant)

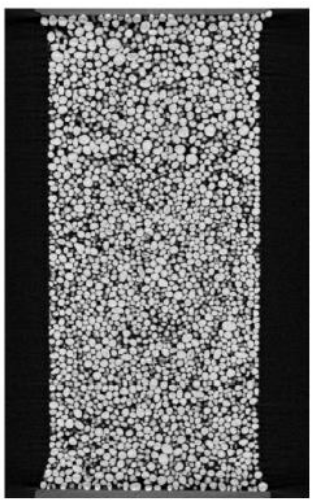


from Desrues et al (1996)

Experimental investigation in sands

- *Grain rearrangement in shear bands: grains rotation concentration*

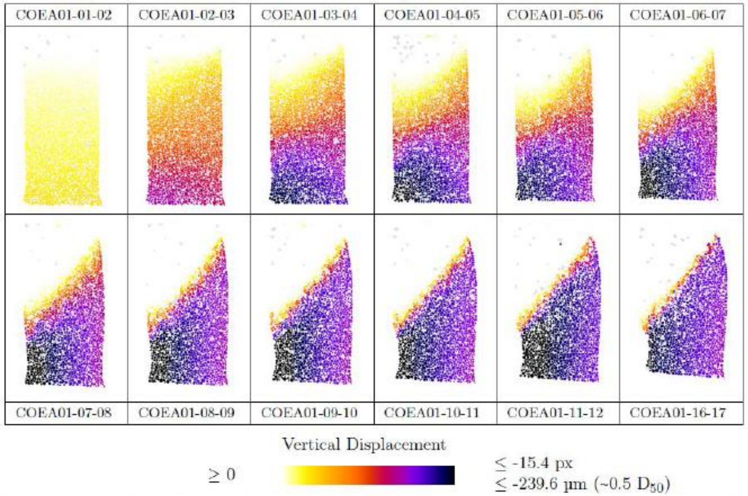




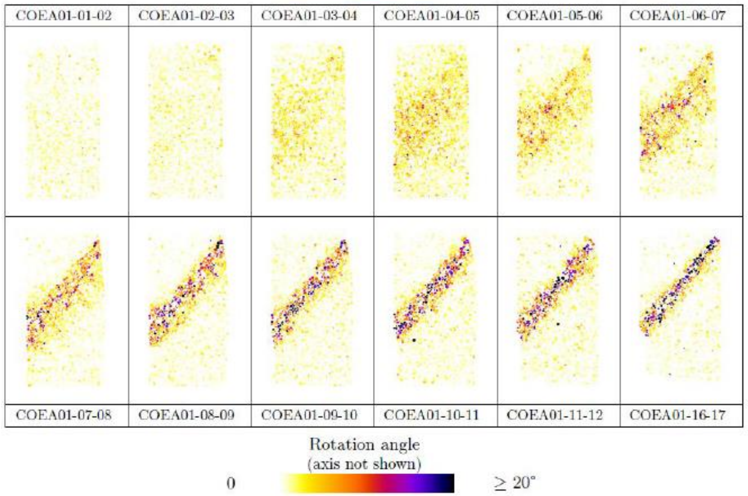
X-ray CT scan
from Andò (2015)

grains tracking

Vertical displacement of sand grains



Rotation angle of sand grains

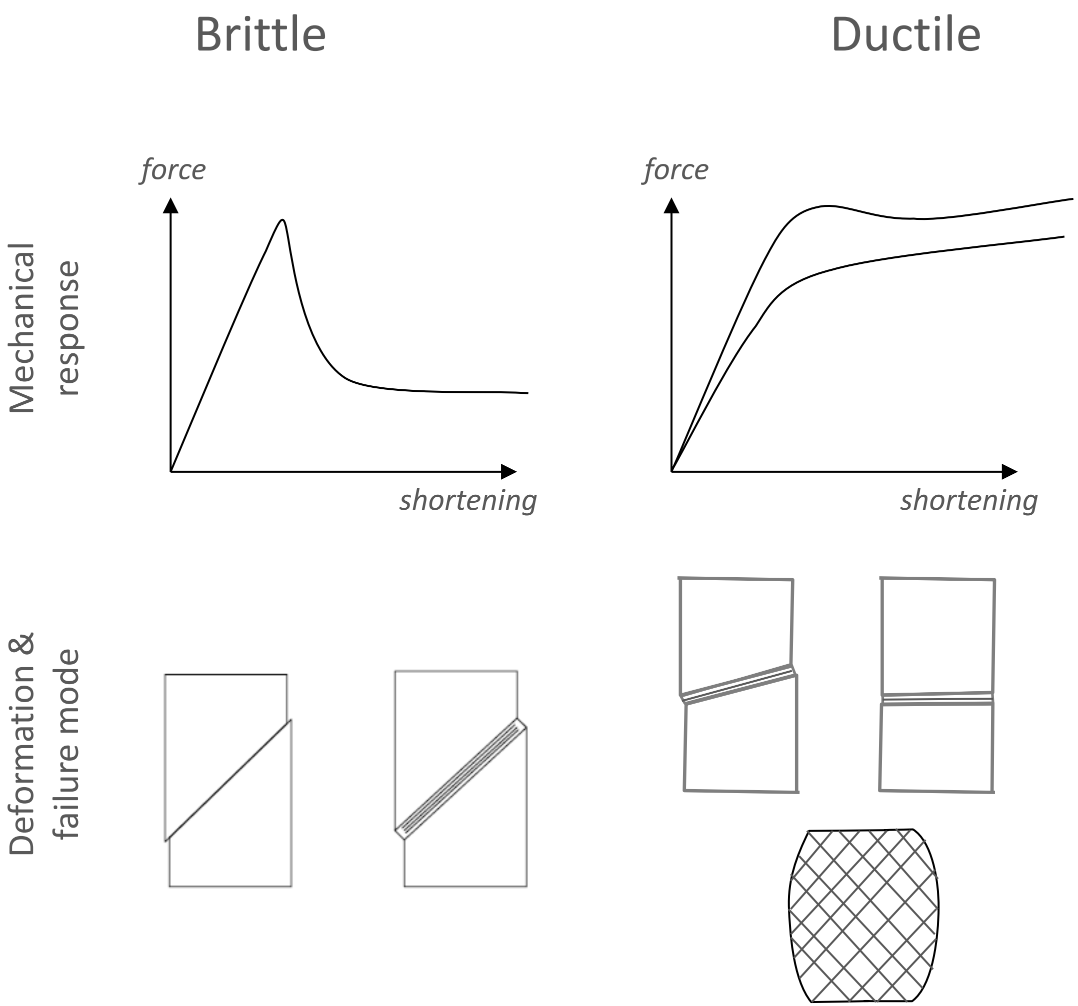


from Andò (2015)

Outline

- Introduction
  - *in situ* observations
  - impacts of strain localisation
- Experimental investigations: methods
  - *post-mortem* observations
  - multiple (internal) measurements
  - full field measurements
- Experimental results (a few)
  - strain localisation in sands
  - strain localisation in rocks
  - the emergence of strain localisation in geomaterials
- Conclusions

➢ *Mechanical responses and failure modes: brittle vs. ductile regimes*

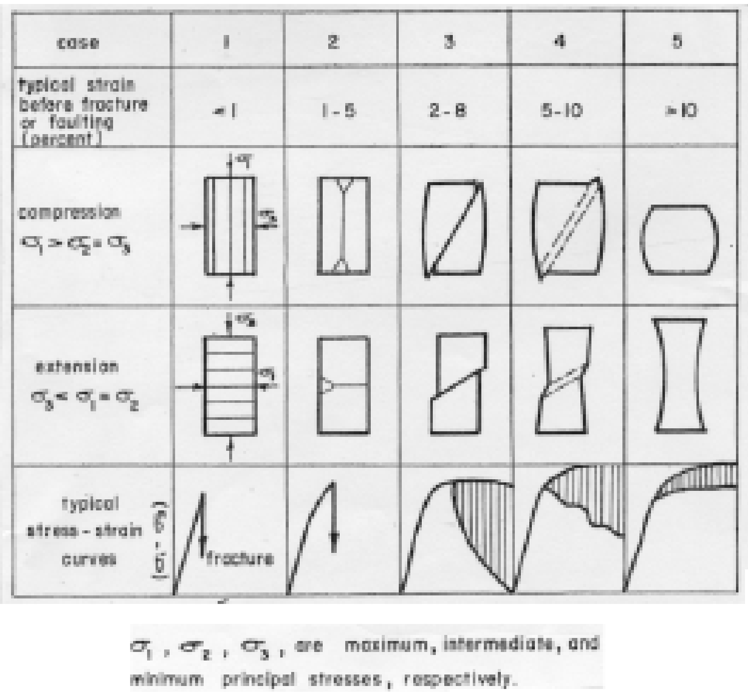


- Brittle:
  - a sudden failure, without substantial precursors
  - a strongly localised deformation (fault, shear band)
  - a strong strain softening after the peak
- Ductile:
  - able to sustain a substantial deformation
  - a diffuse strain field or highly inclined band
  - no significant stress softening
- Semi-brittle: intermediate (localisation without significant stress softening)

The brittle/ductile failure is not intrinsic to the rock. A rock can be brittle with a low confining pressure and then ductile with a high confining pressure.

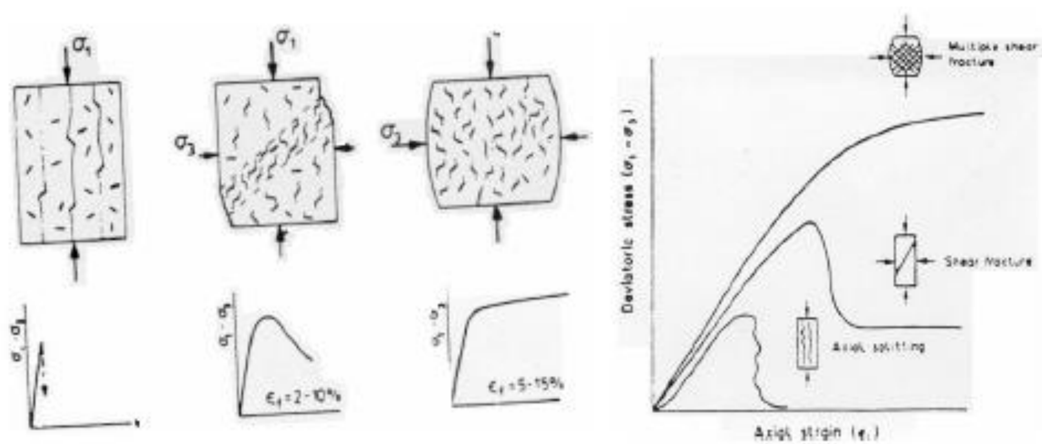
Experimental investigation in rocks

➢ *Effect of mean stress: failure modes*



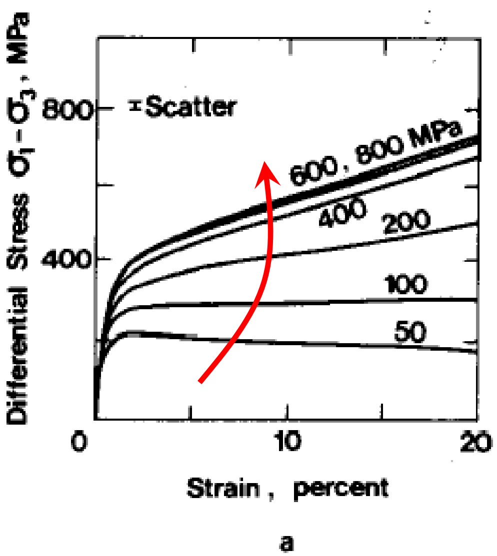
from Paterson (1977)

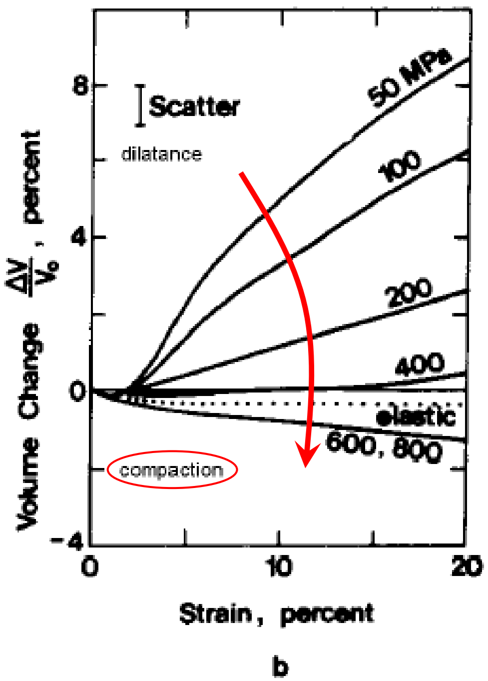
- No confining pressure: axial splitting, brittle response
- 'Medium' confining pressure: shear band, inclined fracture, strain softening
- 'Very high' confining pressure: cataclastic deformation (more or less diffuse) or compaction bands, strain hardening



Experimental investigation in rocks

➢ *Effect of mean stress: mechanical behaviour and failure modes*





A marble

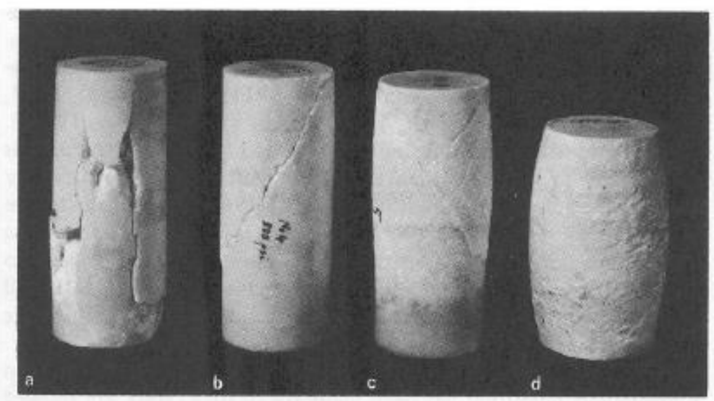


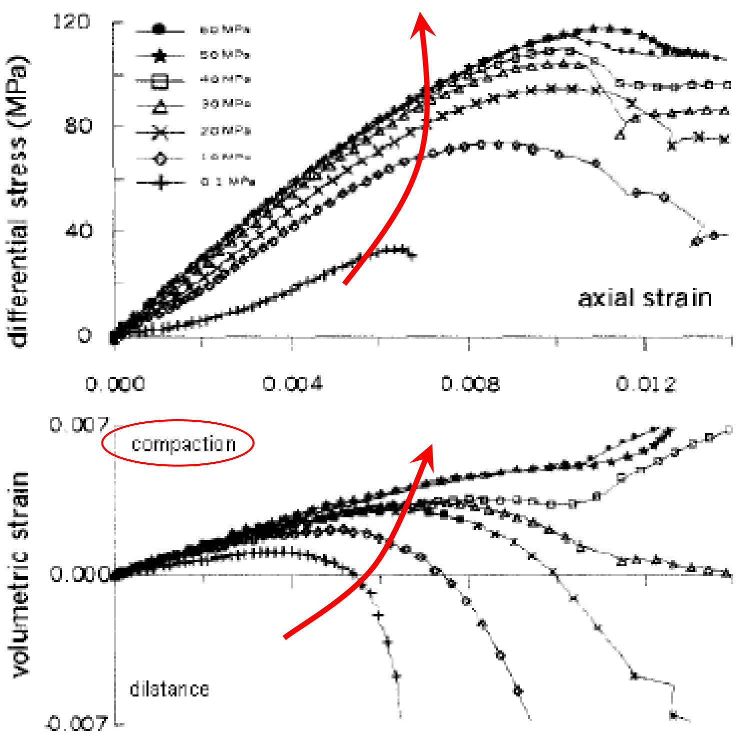
Fig. 48a–d. Types of fractures or flow in Wombeyan marble at various confining pressures: a axial splitting failure at atmospheric pressure; b single shear failure at 3.5 MPa (35 bars); c conjugate shears at 35 MPa (350 bars); d ductile behaviour at 100 MPa (1 kbar). (From experiments of the author; cf. Paterson, 1958)

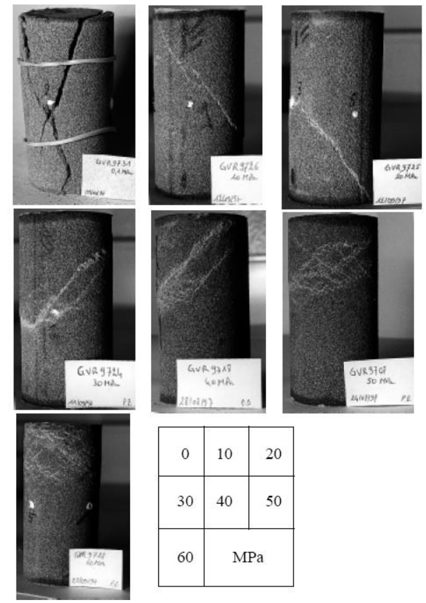
from Paterson and Wong (2005)

Experimental investigation in rocks

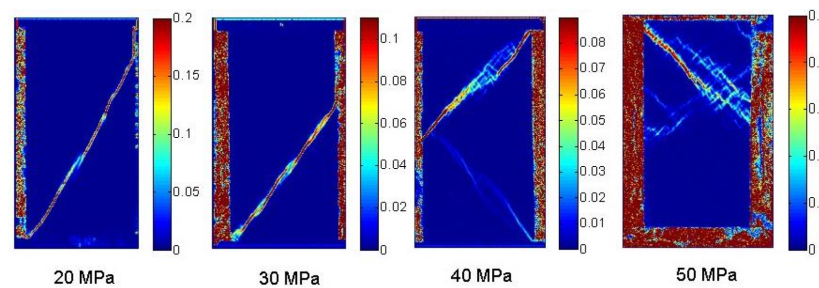
➢ *Effect of mean stress: mechanical behaviour and failure modes*

A sandstone





from Bésuelle et al (2000)



Plane strain compression tests, increments of the 2nd strain invariant, from Lanatà (2015)

Experimental investigation in rocks

- *Effect of mean stress: mechanical behaviour and failure modes*

A sandstone

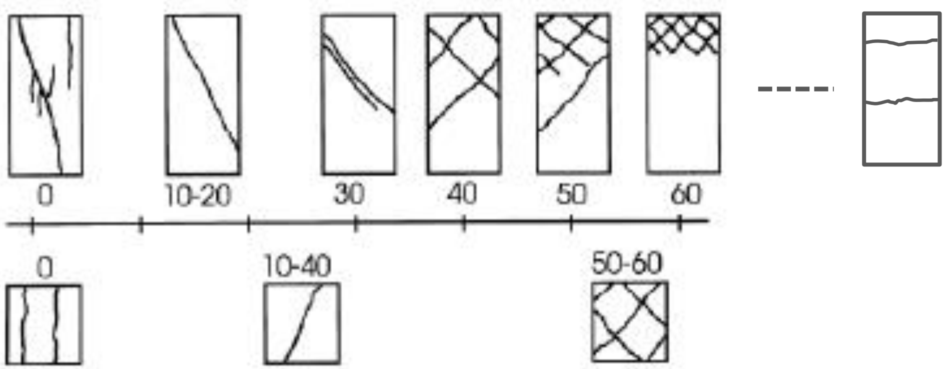


Fig. 6. Observed shear band patterns versus confining pressure for compression test with $H/D = 2$ and 1. The angle of the bands with respect to the major principal stress increases with the confining pressure, and bands become more and more numerous and close.

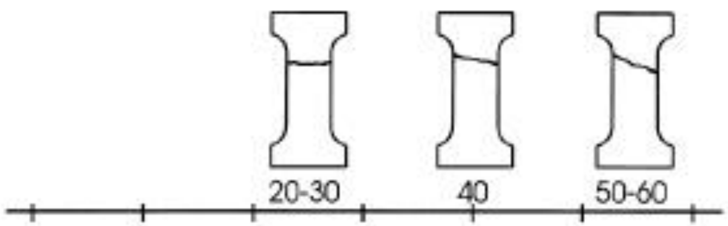
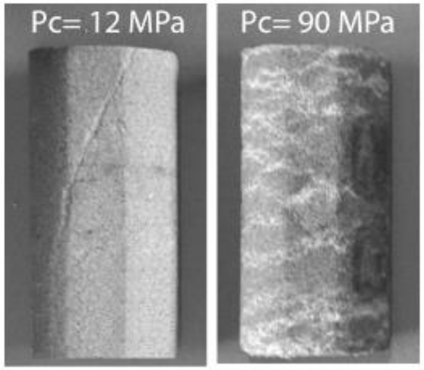


Fig. 9. Observed shear band patterns versus confining pressure for extension test.

from Bésuelle et al (2000)

Shear band & compaction band

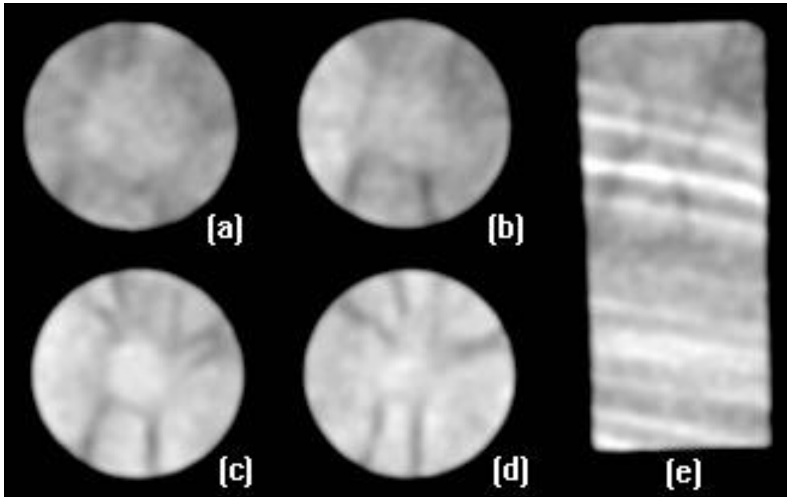


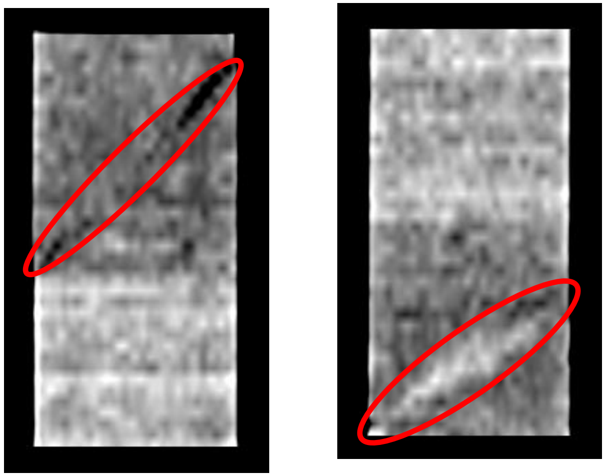
from Fortin et al (2006)

Experimental investigation in rocks

➢ *Effect of mean stress: volume strain inside shear bands in porous rocks*

A sandstone

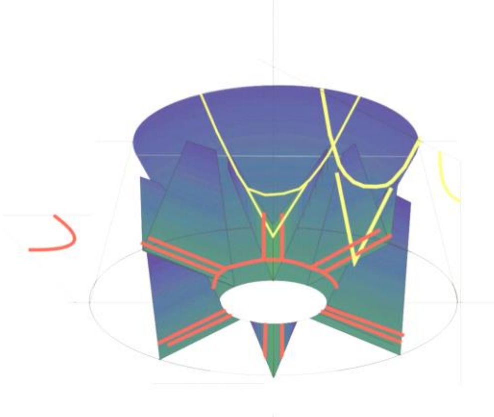




30 MPa
SB with dilation

50 MPa
SB with compaction

from Bésuelle et al (2000)



For porous rocks, the volume strain inside shear band is dilative at low mean stress and can be compactive at high mean stress

Experimental investigation in rocks

➤ *Effect of mean stress: shear band orientation*

Granite

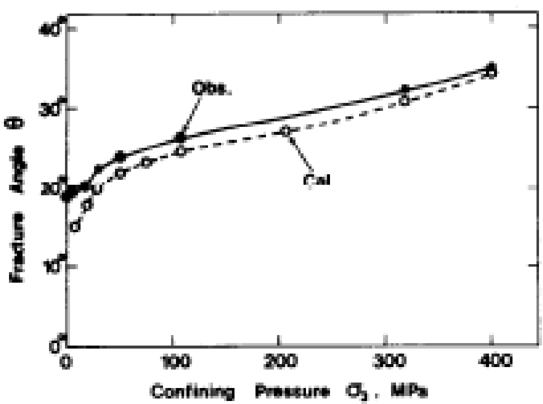


Fig. 10. Relation between confining pressure and inclination θ of shear fracture to compression direction in Westerly granite; *closed circle:* observed angle; *open circle:* angle calculated from coefficient of internal friction ϕ according to $\theta = 1/4\,\pi - 1/2\,\varphi$. (After Mogi, 1966a)

from Mogi et al (1966)

Sandstone

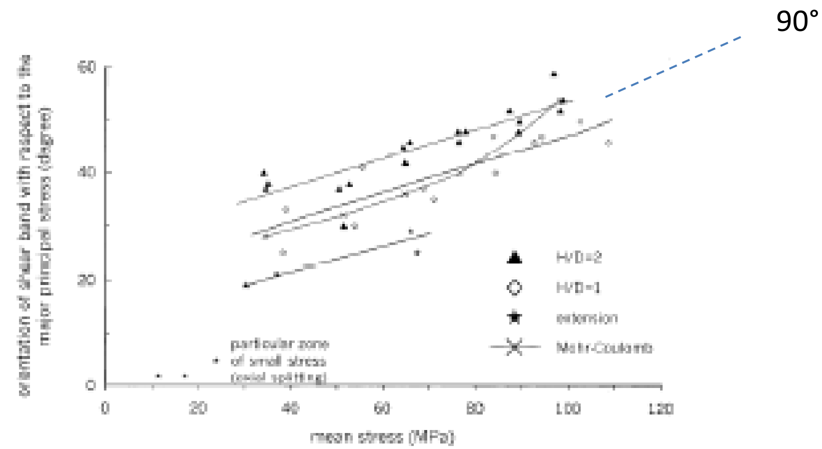


Fig. 8. Orientation of the shear bands with respect to the major principal stress axis versus the mean stress at failure, for compression ($H/D = 1$ and 2) and extension test. Solid line shows the prediction with the Mohr–Coulomb criterion: $\theta = 45° - \phi/2$, for the $H/D = 2$ compression tests.

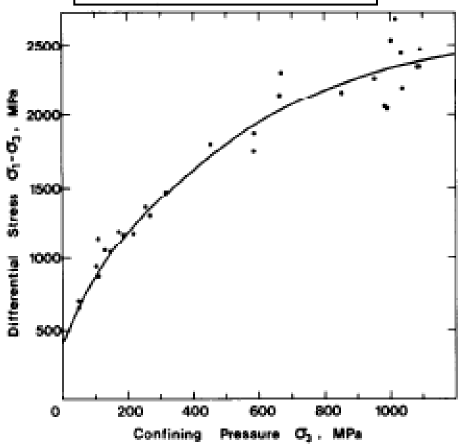
from Bésuelle et al (2000)

The angle between the maximum stress direction and the shear band tends to increase with the mean stress

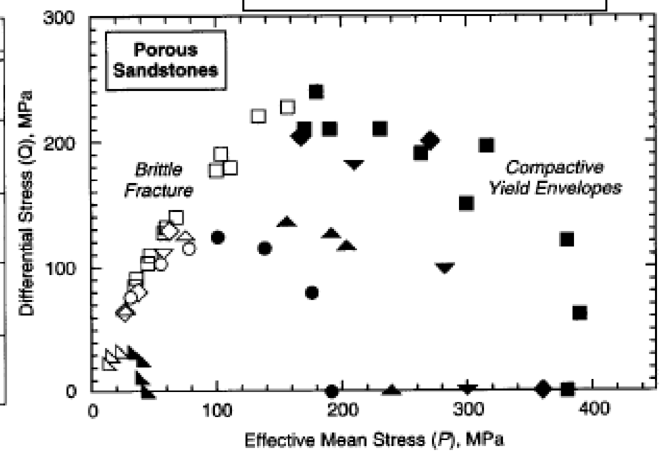
Experimental investigation in rocks

➢ *Effect of mean stress: failure envelope*

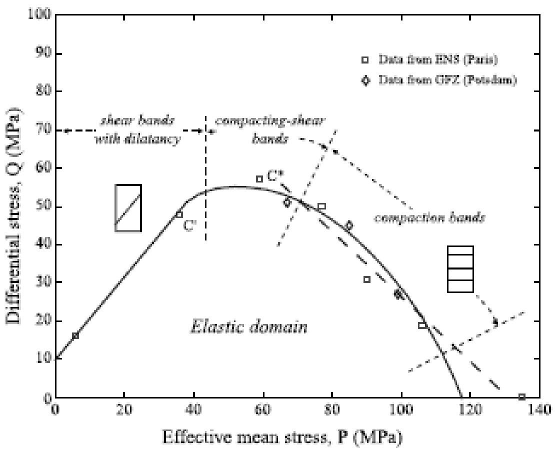
Marble



Sandstone



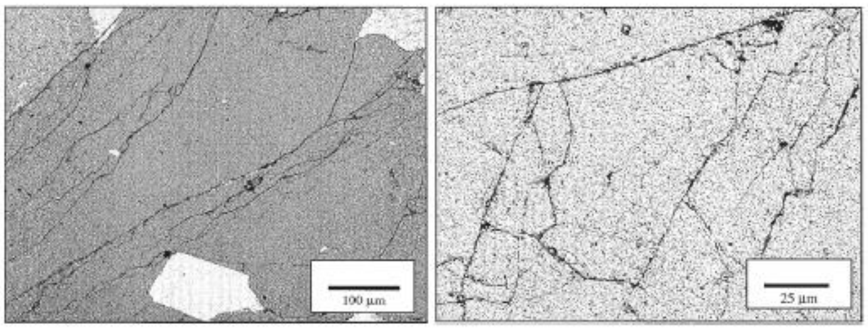
- Frictional behaviour at low mean stress
- Cap surface in porous rocks at high mean stress
- Evolution of the micro-mechanisms of deformation with mean stress



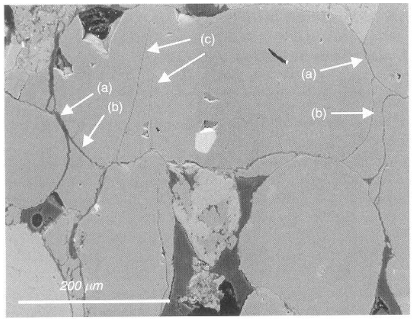
Experimental investigation in rocks

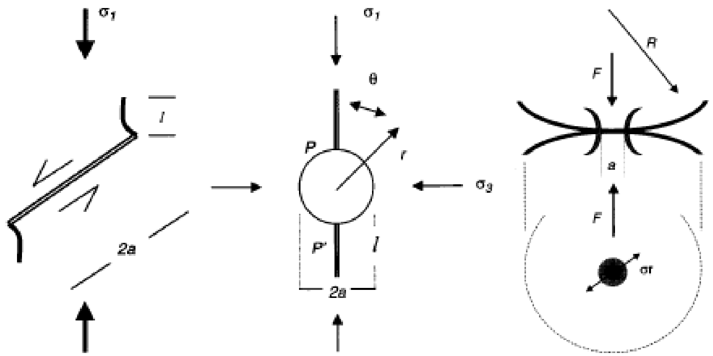
- *Effect of mean stress: micro-mechanisms of deformation*

granite



sandstone





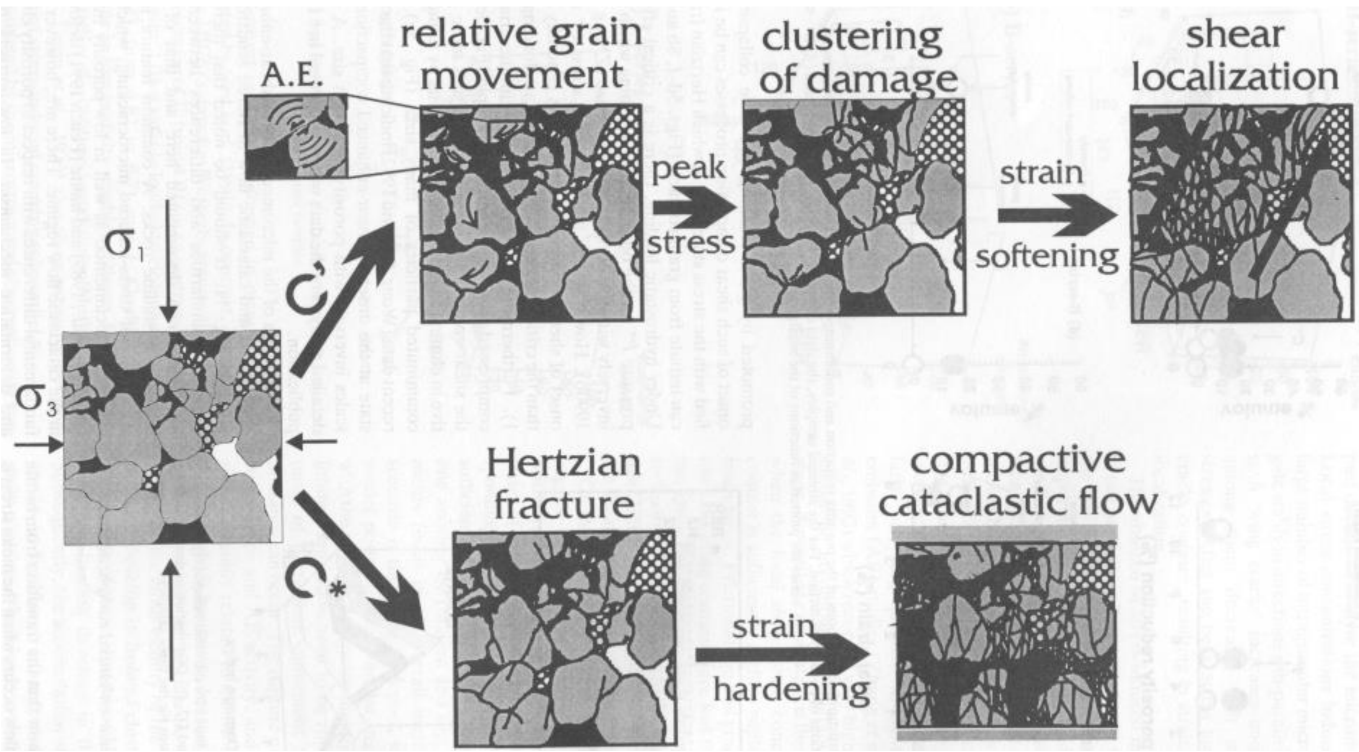
from Guéguen et al (2004)

Conceptual crack initiation reasons:

- propagation of a crack from initial fissure (in mode I),
- crack initiation from an (equant) pore (concentration of tensile stress)
- crack initiation at a grain contact (Hertzian fracturation - concentration of tensile stress)

Experimental investigation in rocks

➤ *Effect of mean stress: micro-mechanisms of deformation*



from Ménendez et al (1996)

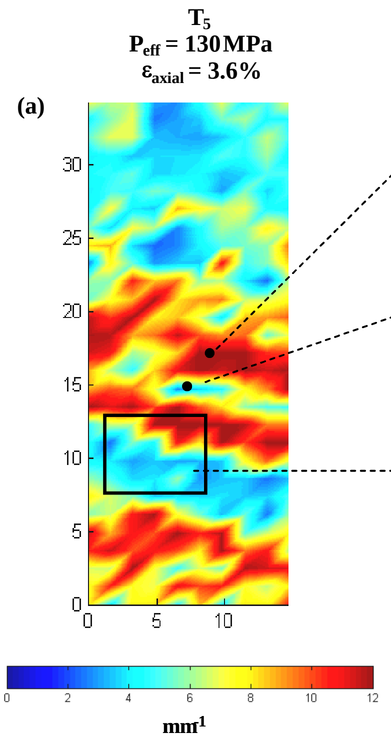
Confining pressure

- Grain breakage
- Inter and intra granular cracks
- dilatancy

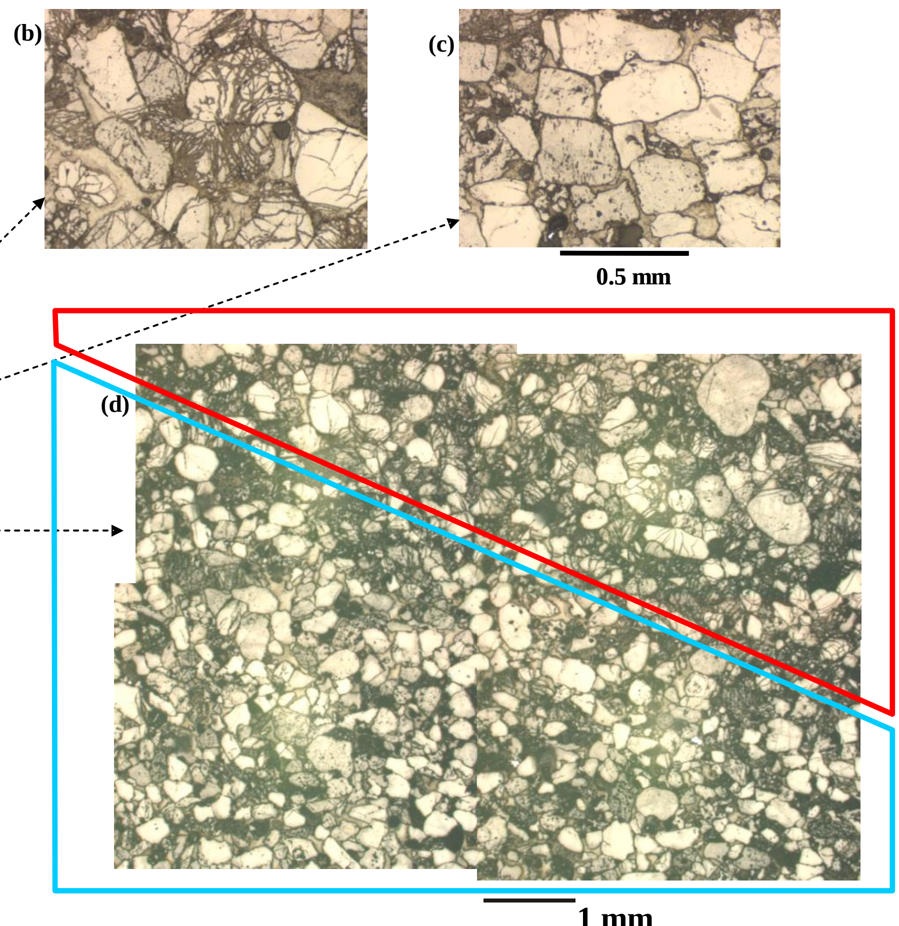
- Grain crushing
- Pore collapse
- compaction

Experimental investigation in rocks

- *Effect of mean stress: micro-mechanisms of deformation (sandstone)*



cracks density scale



from Bésuelle et al (2003)

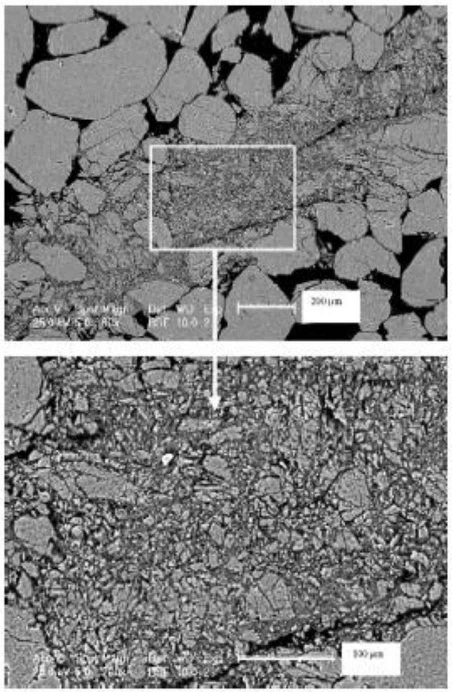
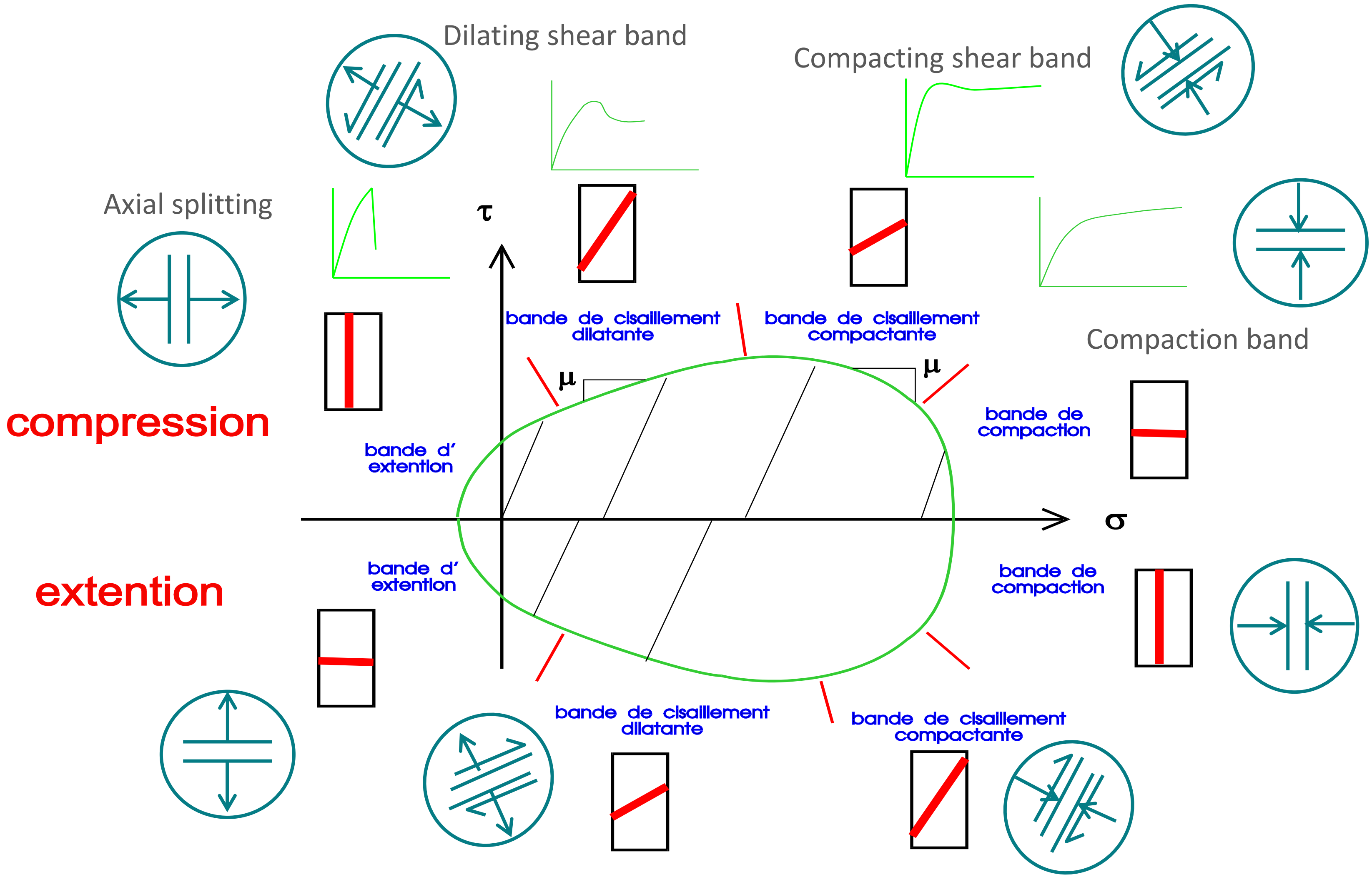


Fig. 14. Microphotographs of a shear band formed in a drained test under 50 MPa of confinement: general view and detail.

from Sulem et al (2006)

Experimental investigation in rocks

- *Effect of mean stress: synthesis (for porous rocks)*



Outline

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  - *in situ* observations
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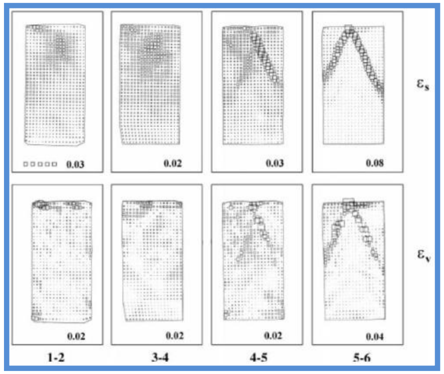
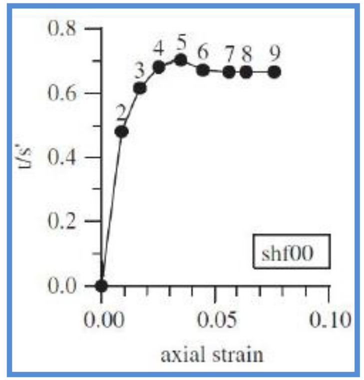
  - strain localisation in rocks
  - the emergence of strain localisation in geomaterials
- Conclusions

The emergence of strain localisation: sands

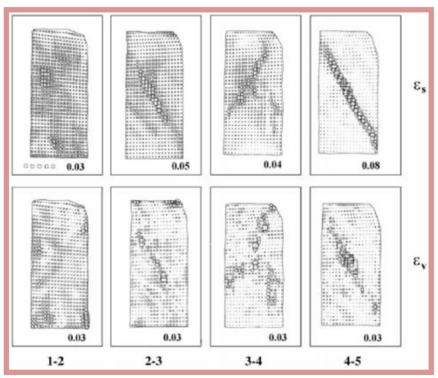


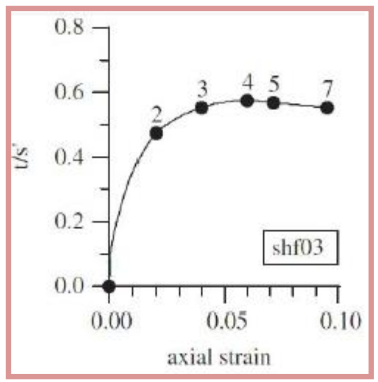


Plane strain compression tests on Hostun sand

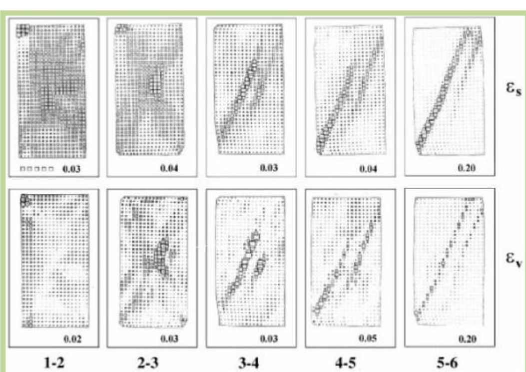
Incremental fields of shear strain measured by *false relief stereo-photogrammetry* (Desrues et al.):

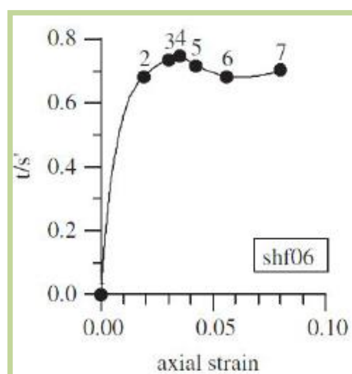
- intermediate state (density)
- mostly dilative inside the shear band





- loose state
- both contractive and dilative incremental behaviors were exhibited inside the band

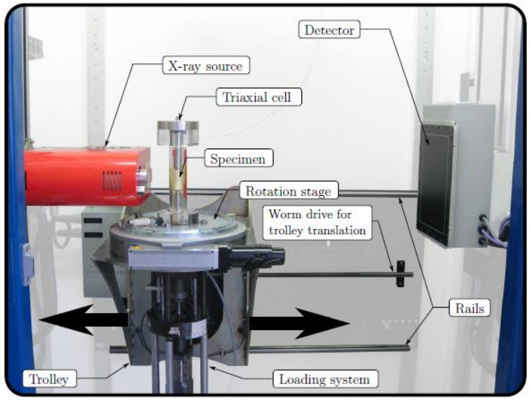


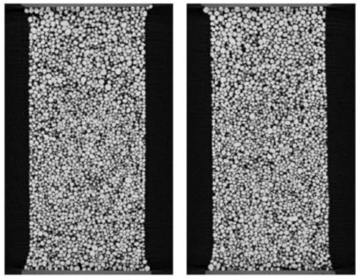


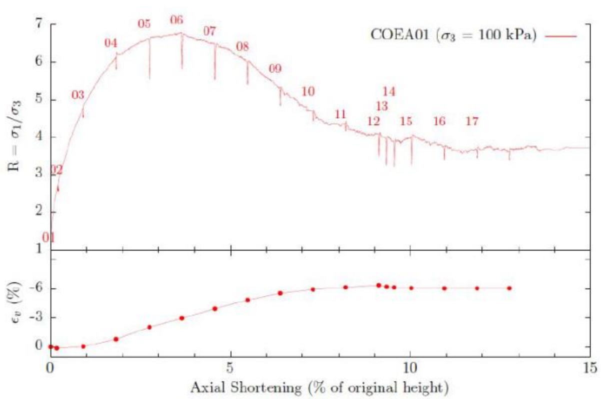
- dense state
- dilative inside shear band

Is strain localisation an abrupt phenomena ?
The relative 'low' spatial and strain resolution of FRS doesn't allow to respond. Probably not…

The emergence of strain localisation: sands

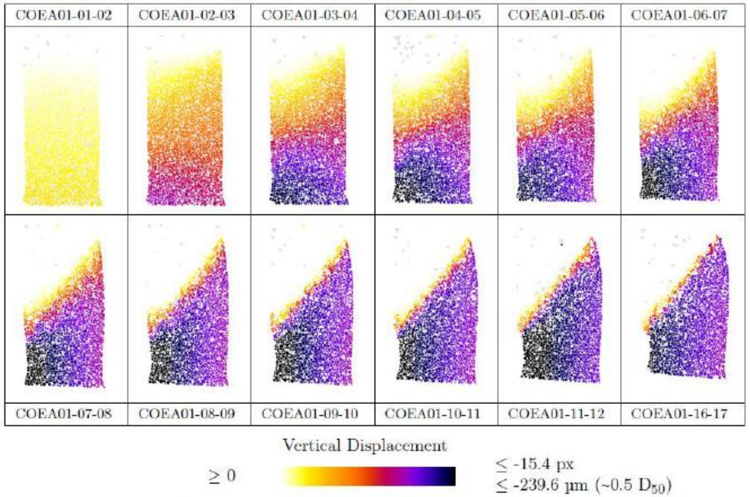




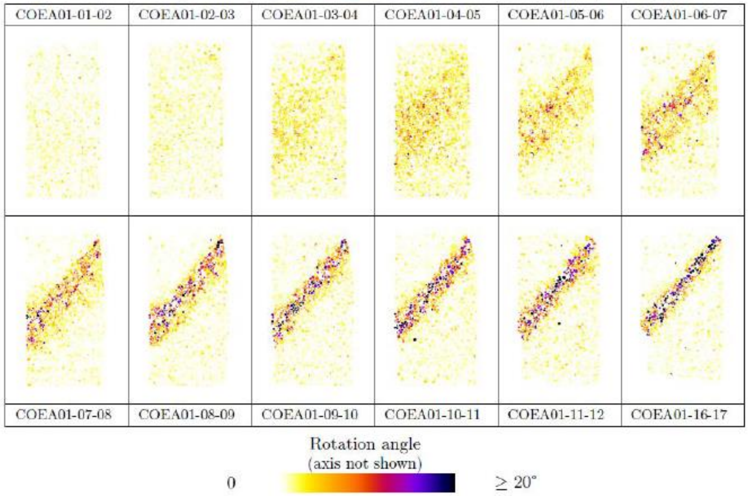


in situ triaxial compression tests on Caicos sand

Incremental fields of grain kinematic measured by *X-ray CT* and *discrete V-DIC* (Andò et al.):

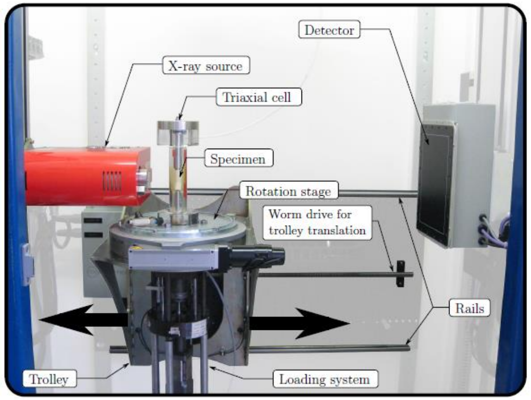


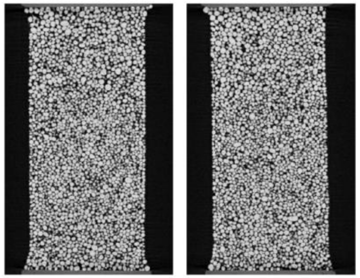
vertical displacement

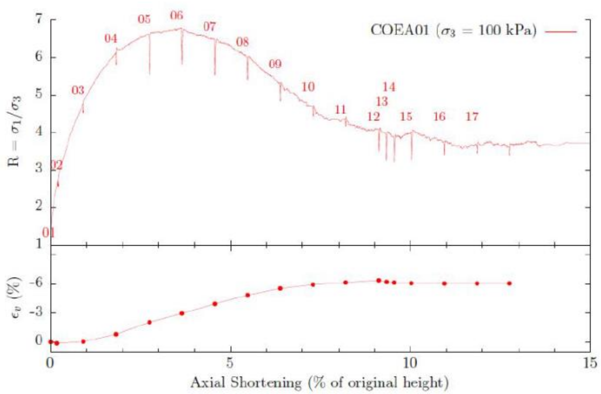


rotation angle

The emergence of strain localisation: sands

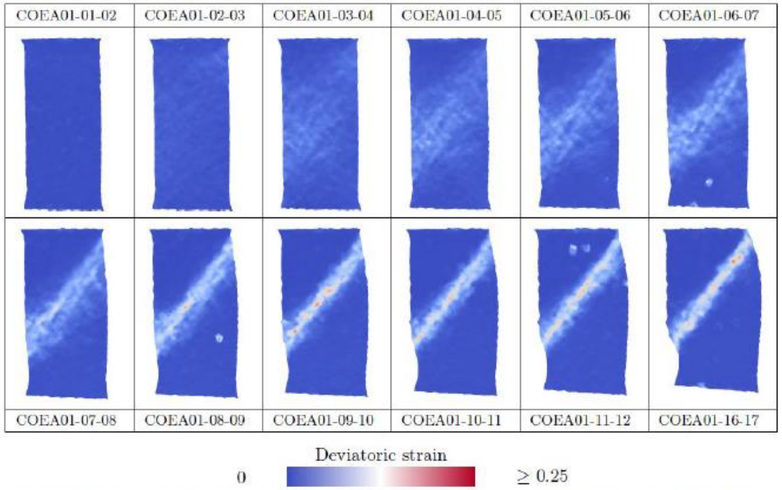




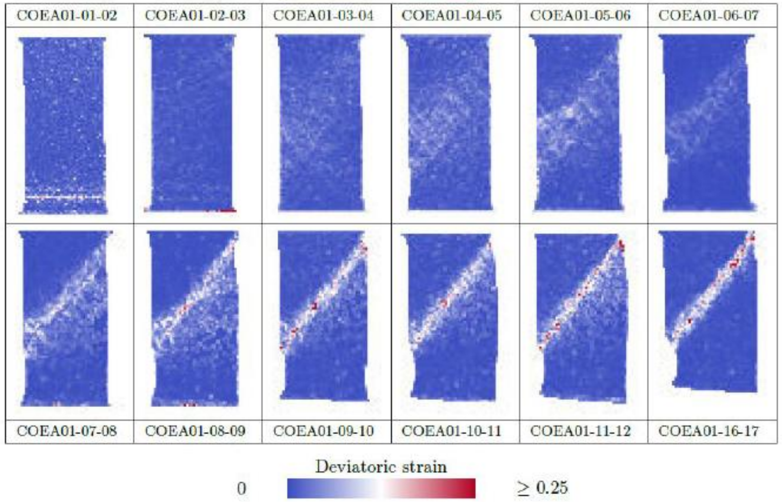


in situ triaxial compression tests on Caicos sand

Incremental fields of shear strain measured by *X-ray CT* , *grain tracking* and *discrete V-DIC* (Andò et al.):

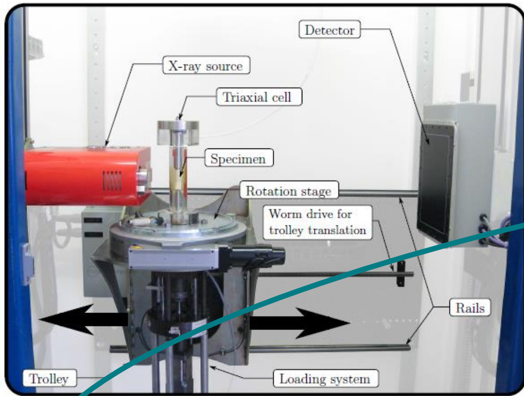


Shear strain (from grain tracking – without DIC)



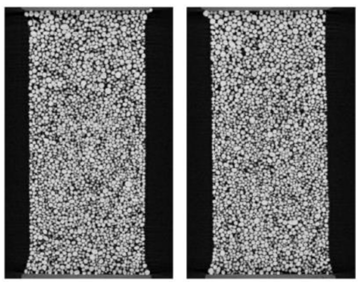
Shear strain (continuous V-DIC)

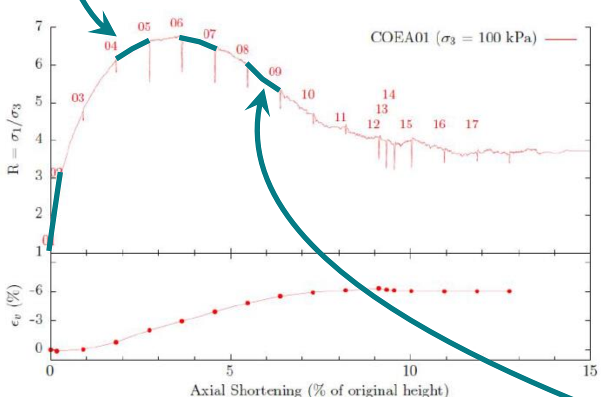
The emergence of strain localisation: sands

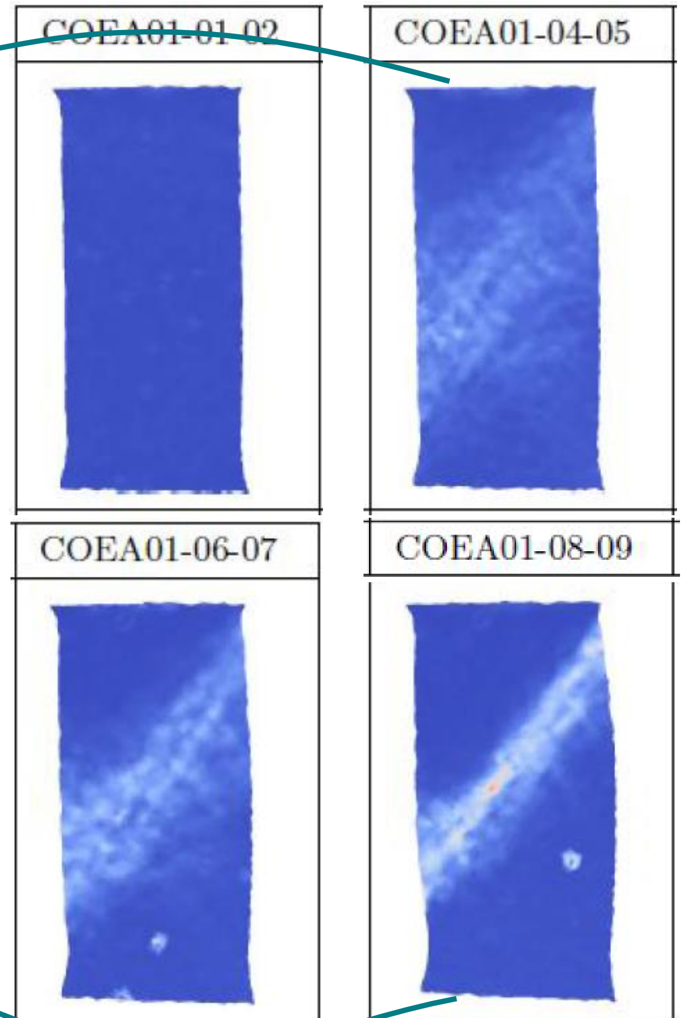


in situ triaxial compression tests on Caicos sand

Incremental fields of grain kinematic measured by *X-ray CT* and *discrete V-DIC* (Andò et al.):





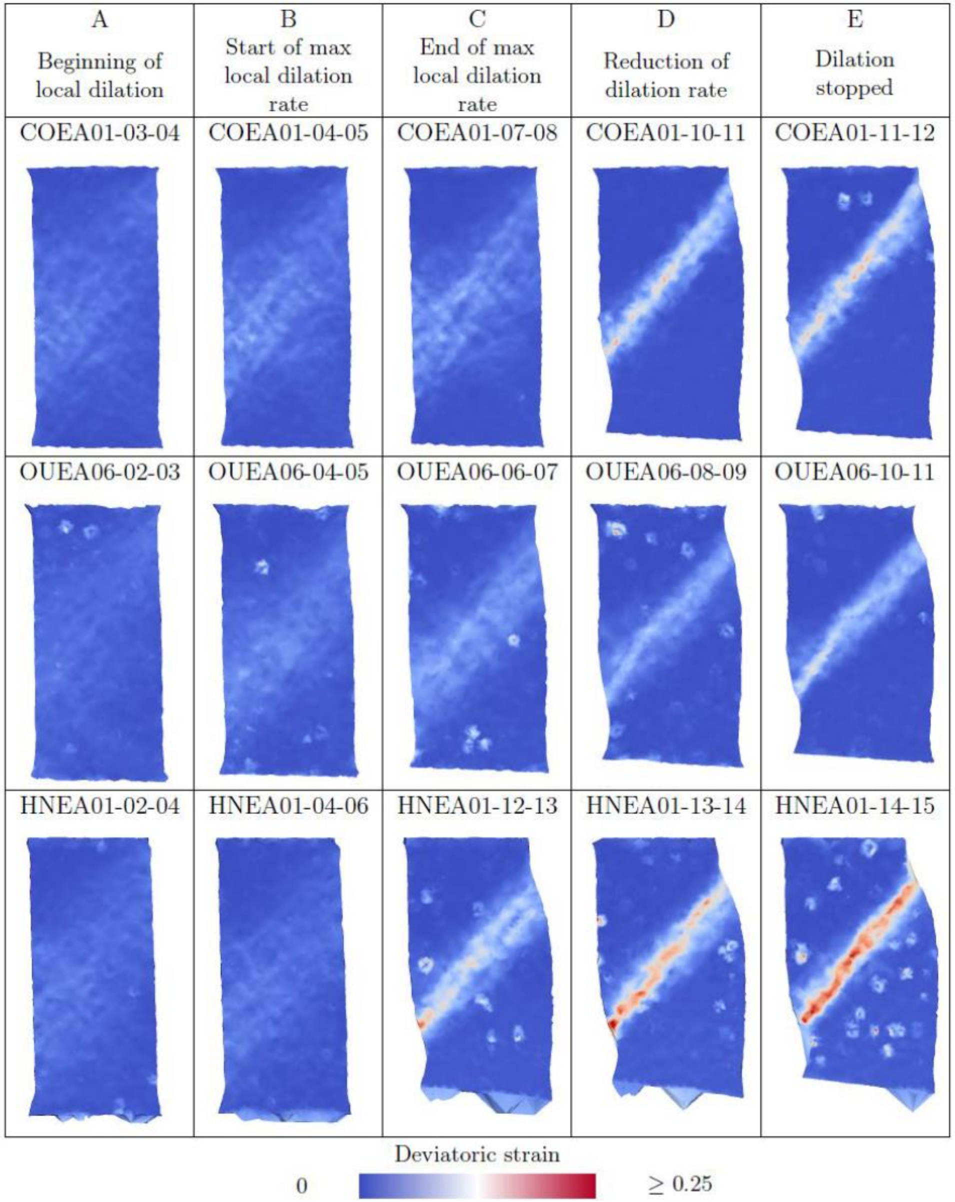


Shear strain (from grain tracking – without DIC)

- initial loading: perfectly homogeneous
- before peak: a large zone of strain concentration with a texture like multiple parallel and conjugate bands
- after peak: one main band through the previous zone of strain concentration

The strain localization appears as a progressive process

The emergence of strain localisation: sands



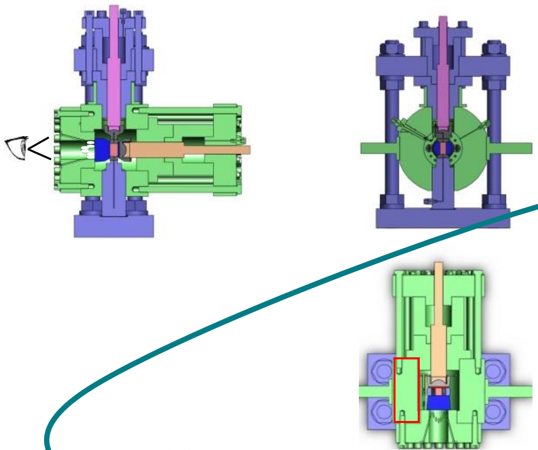
in situ triaxial compression tests on three sands

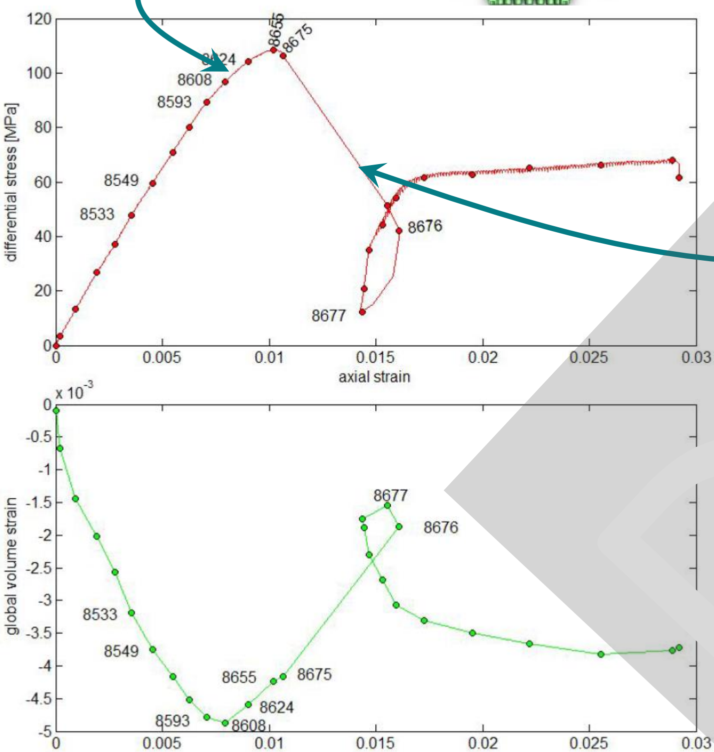
Incremental fields of grain kinematic measured by *X-ray CT* and *discrete V-DIC* (Andò et al.):

- a fine texture of multiple parallel and conjugate bands appears at the begining of dilation
- the fine texture is reinforced during the dilative regime
- progressively, the pattern become a main shear band. The volume changed is then stopped

The strain localization appears as a progressive process

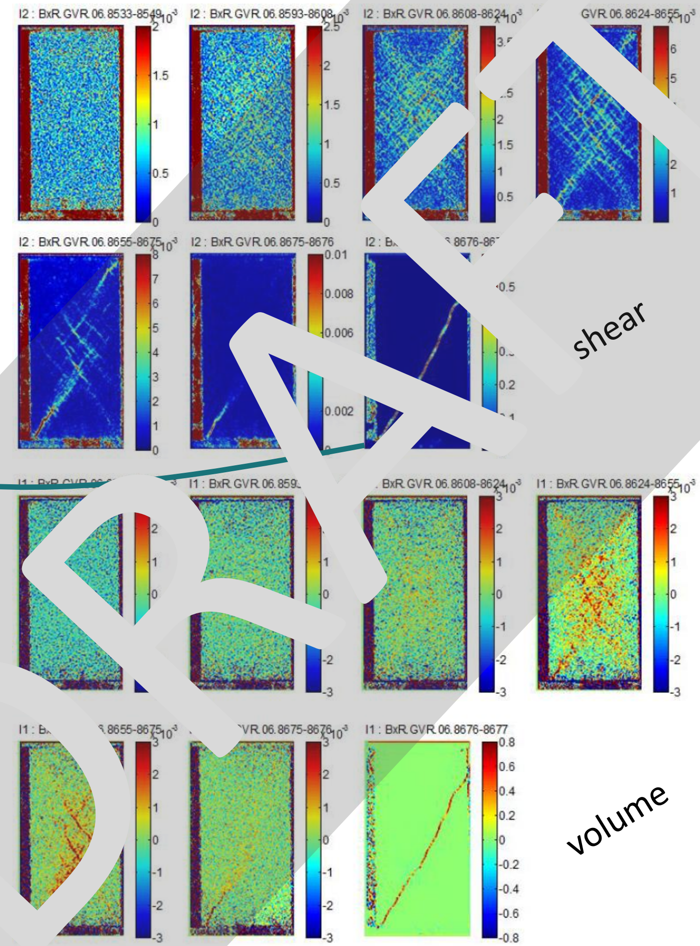
The emergence of strain localisation: rocks





in situ plane strain compression tests on a Vosges **sandstone**

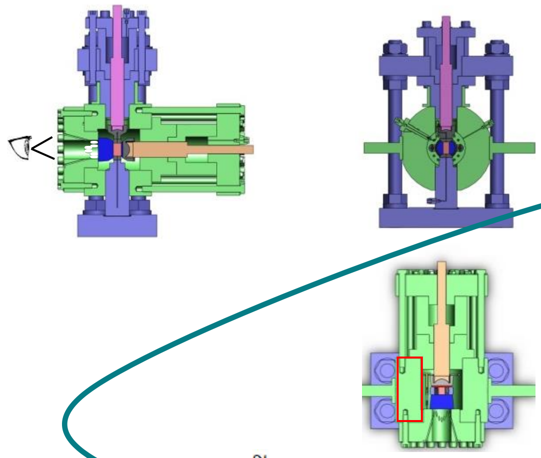
Incremental fields of shear and volume strain measured by *DIC* (Lanatà et al.):

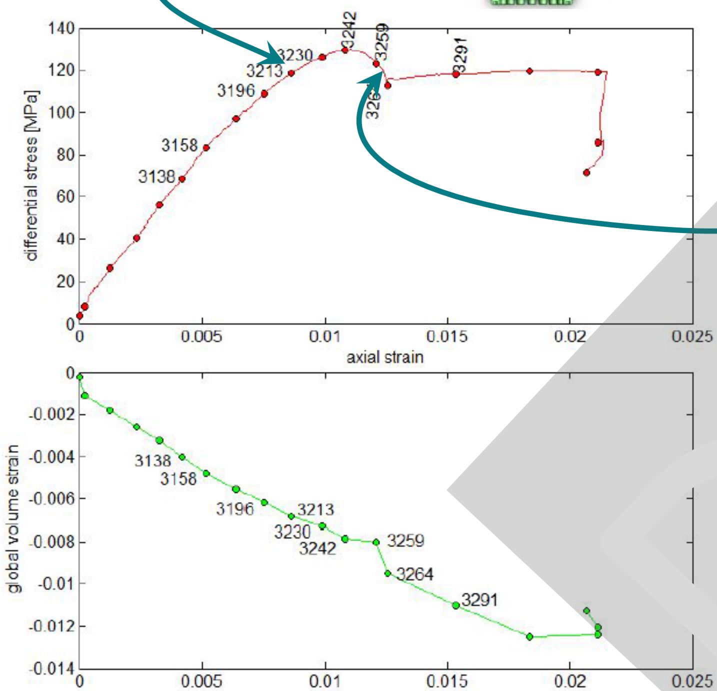


- a fine texture of multiple parallel and conjugate bands appears before the stress peak
- until the peak, some band are de-activated – *natural selection*
- progressively, the pattern become a main shear band after the peak
- deformation inside bands is dilative

The strain localization appears as a progressive process

The emergence of strain localisation: rocks

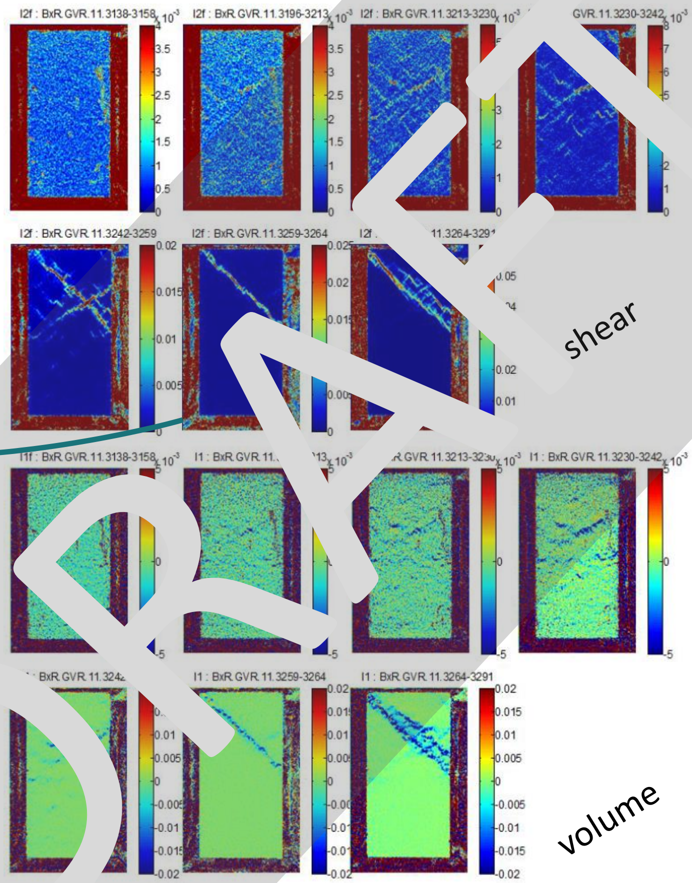




in situ plane strain compression tests on a Vosges **sandstone**

Incremental fields of shear and volume strain measured by *DIC* (Lanatà et al.):

Confining pressure … MPa



- a fine texture of multiple parallel and conjugate bands appears before the stress peak
- until the peak, some band are de-activated – *natural selection*
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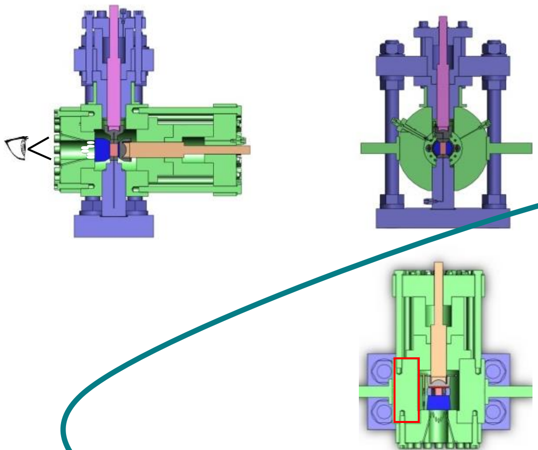
- deformation inside bands is compactive

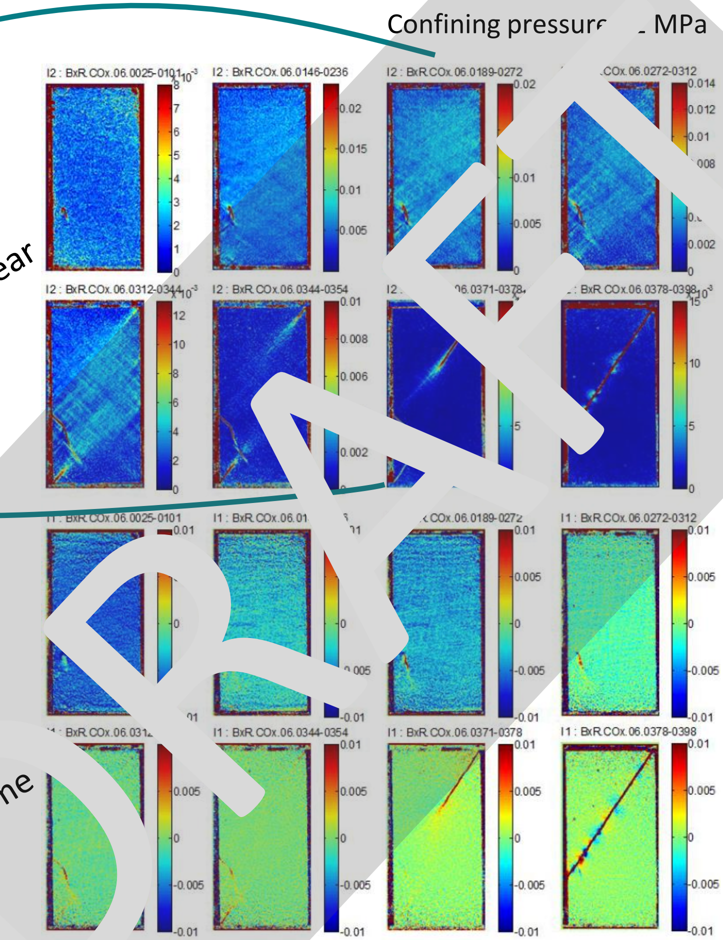
The strain localization appears as a progressive process

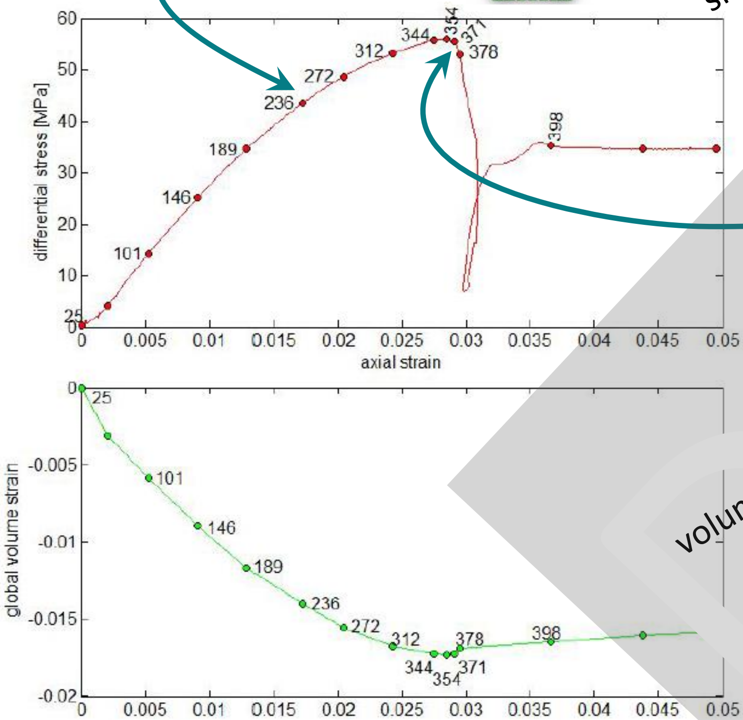
The emergence of strain localisation: rocks



in situ plane strain compression tests on a **clayey stone**

Incremental fields of shear and volume strain measured by *DIC* (Bésuelle et al.):





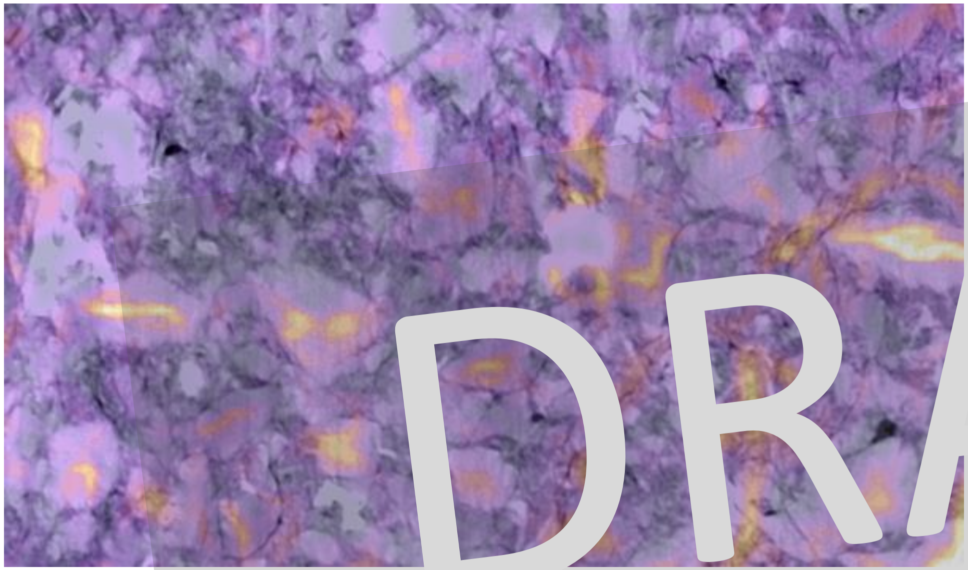
- a fine texture of multiple parallel and conjugate bands appears before the stress peak
- until the peak, some band are de-activated – *natural selection*
- progressively, the pattern become a main shear band after the peak

The strain localization appears as a progressive process

The emergence of strain localisation: rocks

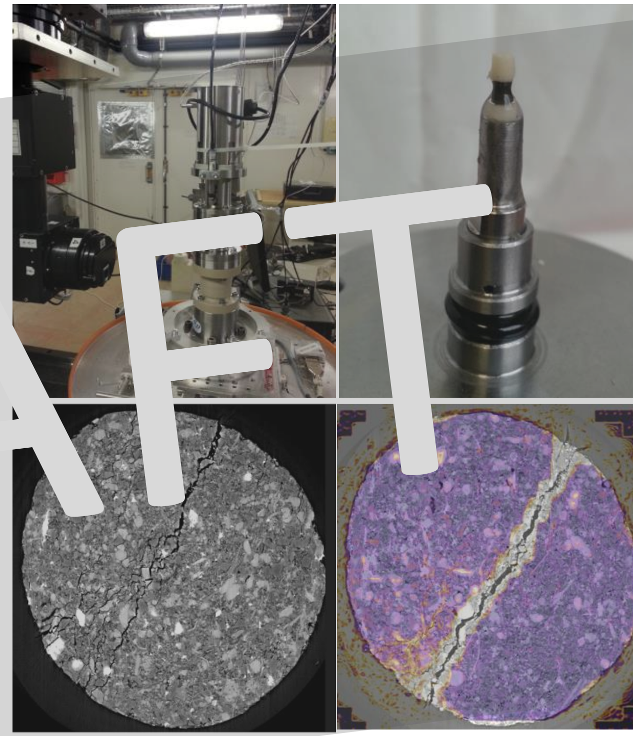
in situ triaxial compression tests on a **clayey stone**

Incremental fields of shear strain measured by *DIC* (Bésuelle et al.):



10µm

Overlapping between X-ray ηano-CT and incremental 2nd strain invariant field (DIC)



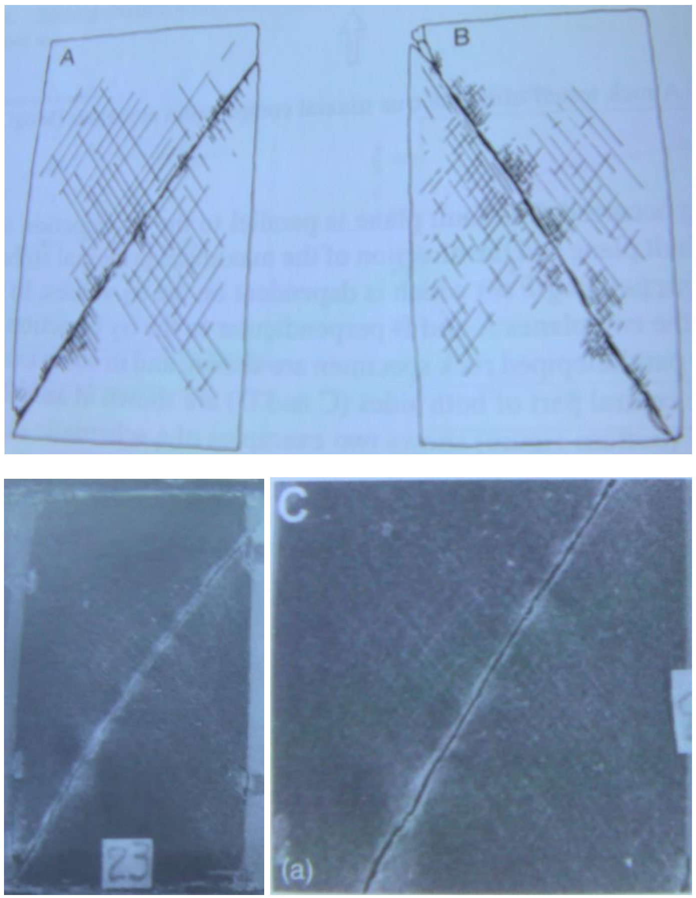
100µm

In situ triaxial loading test at ESRF (ID19)
X-ray nanotomography + volume DIC
Specimen Ø 1.3 mm, H 2.5 mm

The emergence of strain localisation: rocks

True triaxial compression tests on the Dunham **dolomite**

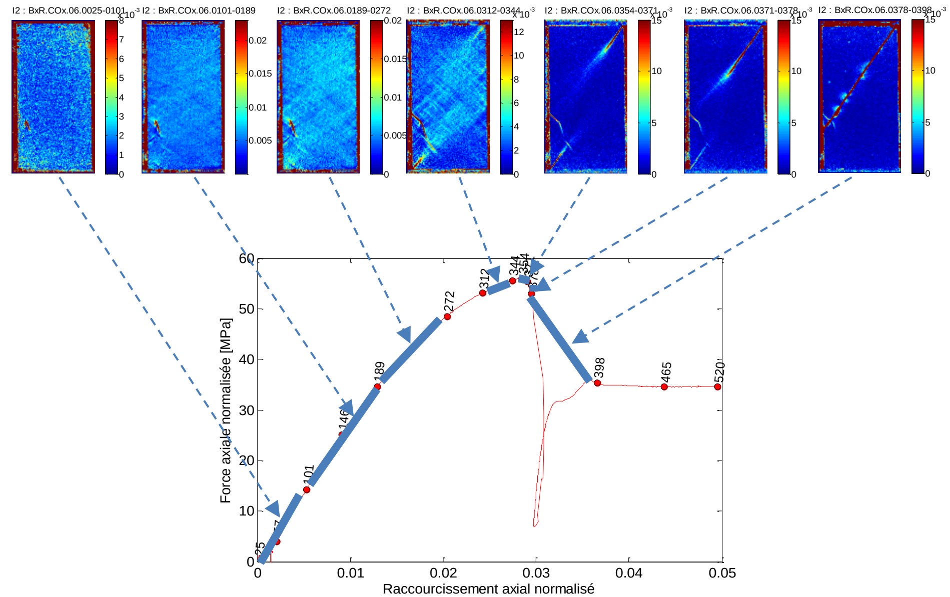
post mortem observations of the specimens (from Mogi):



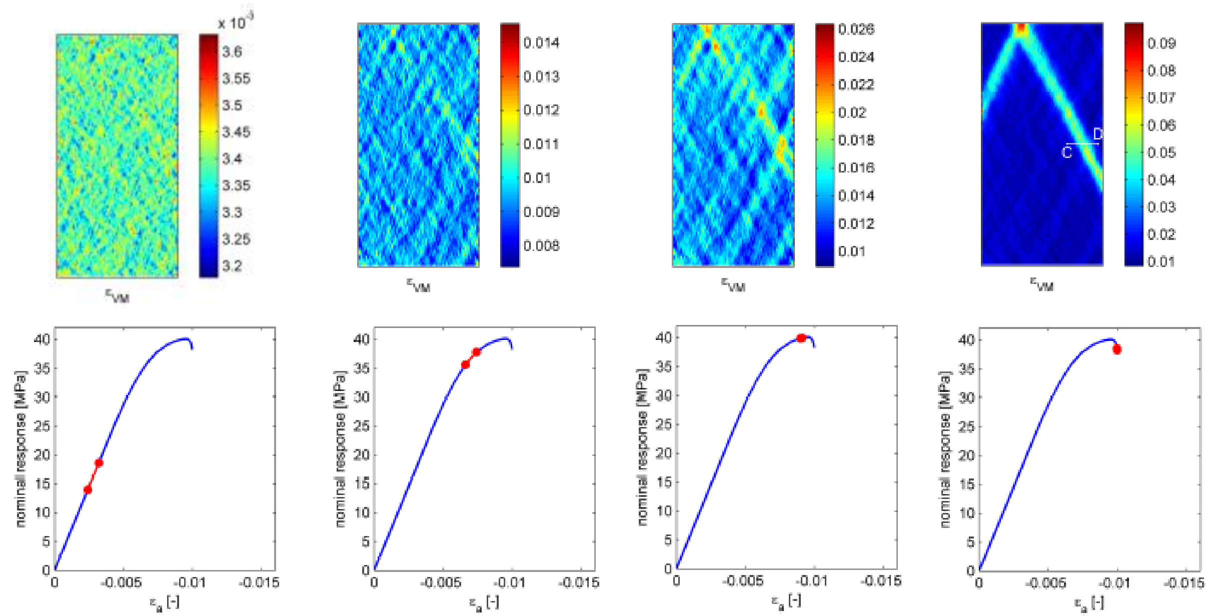
Evidence of an early strain localisation by multiple parallel and conjugated shear bands ?

The emergence of strain localisation: rocks

What about numerical modeling ?



- a double scale model FEM x FEM
- heterogeneity of the VER
- progressively process of strain localisation (PhD thesis, B. van den Eijnden, 2015)



Conclusions

- Methods
  - *Improvement of the methods during last decades: higher photograph resolution, finer resolution of X-ray CT, Volume-DIC, discrete volume-DIC, new experimental devices, etc…*
  - *The improvement of the spatial resolution and the grey-level resolution allows to detect finer and finer details of the regimes of deformation*
- Experimental investigations of the strain localisation
  - *Quasi-general mode of failure in geomaterials (without high temperature)*
  - *Reproducibility of some characteristics: shear band orientation, band thickness, kind of deformation inside shear band (compaction/dilation)*
  - *Non-reproducibility of some observations: shear band pattern, post-peak response*
- Experimental investigations of the emergence of localisation

  Recent investigations thanks to more advanced experimental devices

  - *strain localisation is a progressive process*
  - *localisation starts well before stress peak under the form of multiple parallel and conjugated shear bands. Some of these bands are de-activated in the next loading. A few bands keep active after stress peak. Today observed in several sands and rocks.*

Thank you for your attention

Field observation of multiple parallel and conjugated shear bands – disused quarry in Orange, France