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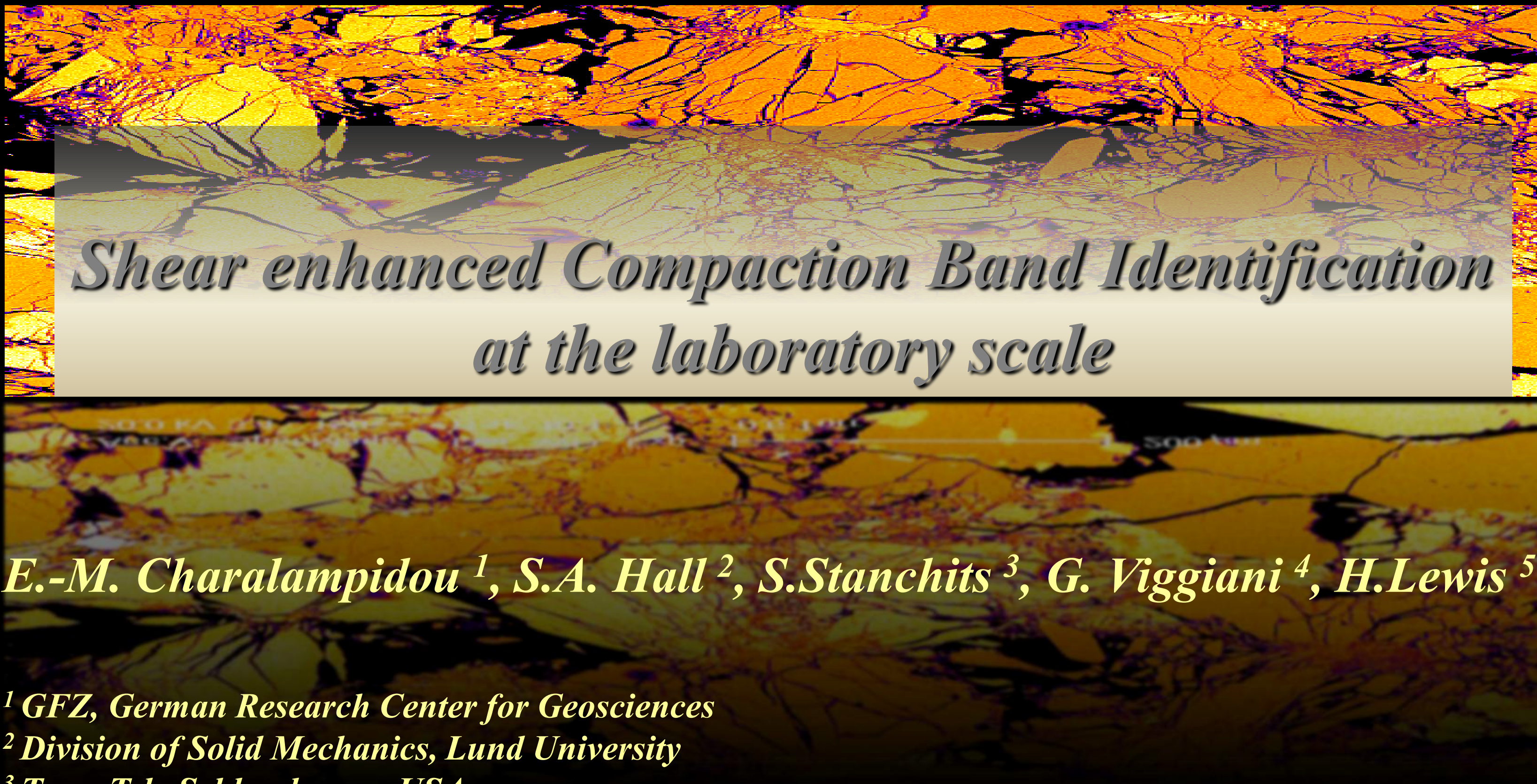

Shear enhanced Compaction Band Identification at the laboratory scale

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Compaction Bands in porous sandstones:

heterogeneity of the rock
(re-arrangement of grains, grain breakage, pore collapse, grain crushing)

- ✓ narrow, roughly planar zones of localised porosity loss
- ✓ reduced permeability
- ✓ barriers to fluid flow – sealing potential

presence in subsurface formations would affect

- ✓ applications involving fluid injection or withdrawal
- ✓ CO_2 storage
- ✓ hydrocarbon production

important to understand the ***conditions*** for their ***formation*** & ***propagation***

***Challenge*:**

Use ***advanced experimental non-destructive*** techniques to investigate how sandstones deform under triaxial compression

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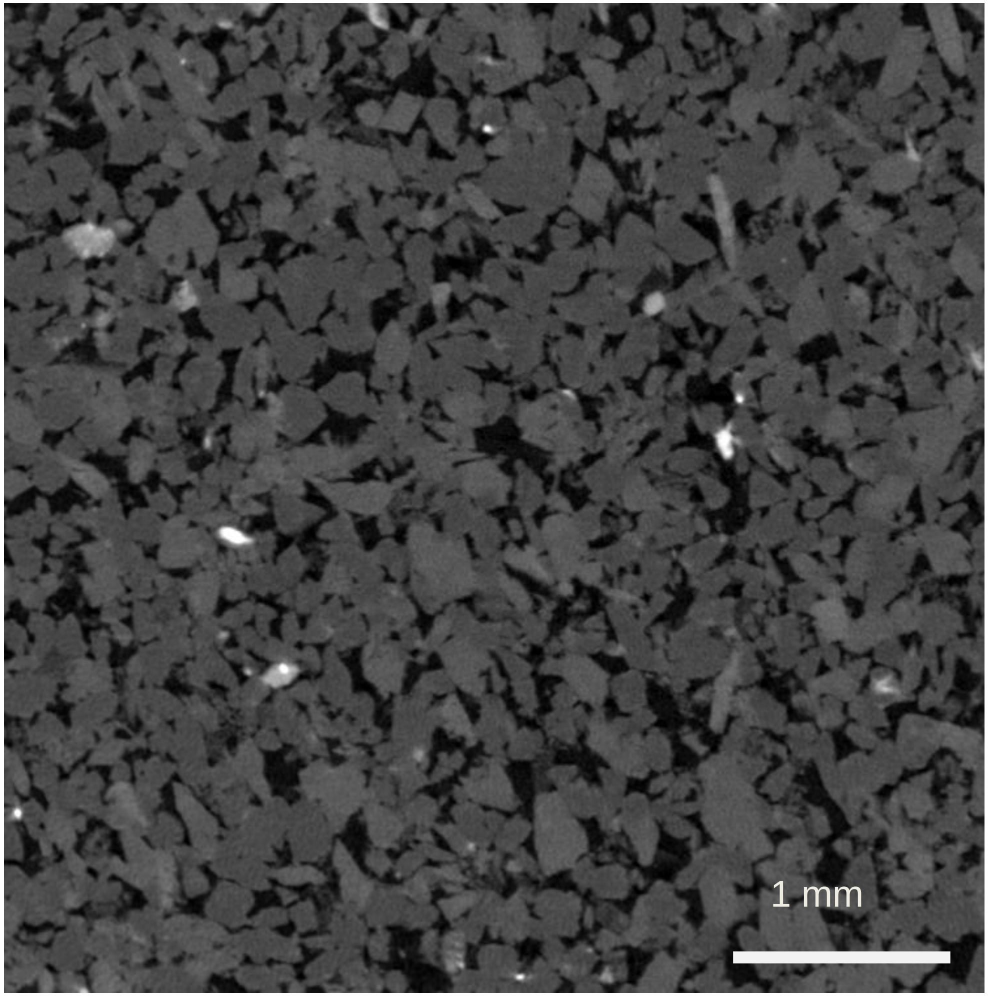
Vosges Sandstone

- mineralogy: 93% quartz,
  5% microcline,
  1% kaolinite
  1% micas
  + oxides
- mean grain ~ 300 µm
- average porosity of 22%

[Bésuelle, 1999; 2000; 2001]

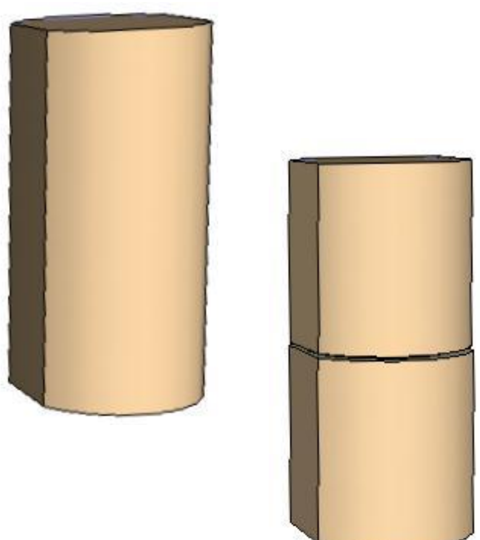
- sub-angular to sub-rounded grains
- moderately sorted



Very high resolution x-ray image of the laboratory undeformed sandstone (~6µm voxel size)

Triaxial compression

cylindrical specimens with two flatten surfaces **with & without** a **circumferential notch**



Dry specimens

Confining pressure range: 130 MPa -190 MPa

Full-field **measurements**

being used in the study of localised deformation in sandstones

point-wise measurements at the boundary do not illuminate precisely the mechanics of the system

full-field → *field record quantities*

Advantages

✓ usually, **non-destructive** (see thin sections …)

✓ different **sensitivities** to **different physical properties**

→characterise different aspects of the mechanical processes

- **Acoustic Emissions** (*syn-deformation*)
- **Ultrasonic Travel-time Tomography** (*pre- & post-deformation*)
- **X-ray tomography** (*pre- & post-deformation// different voxel size resolutions// porosity calculations of small deformed cores*)
- **3D Digital Image Correlation** (*pre- & post-deformation correlation)*
- **Thin sections micro-structural analysis**

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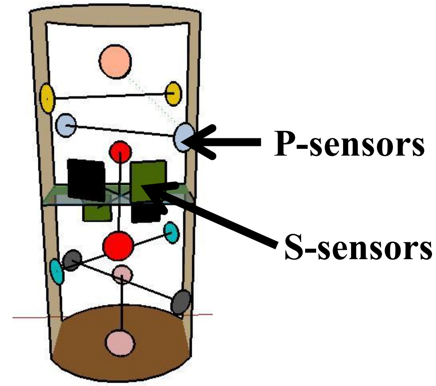
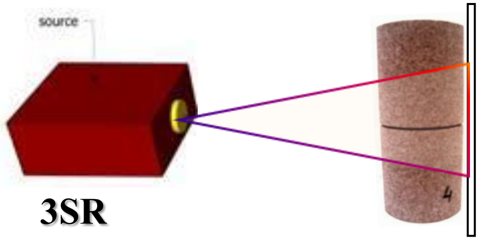
14 P- and
4S- sensors
(glued)

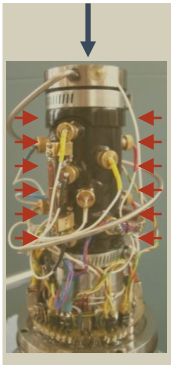


Syn-deformation AEs

Pre-mortem x-ray scans

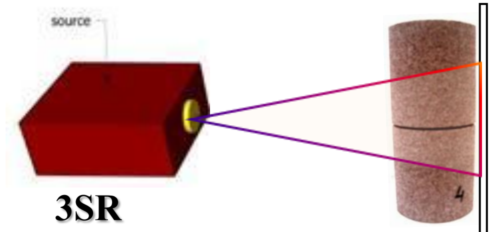


3SR



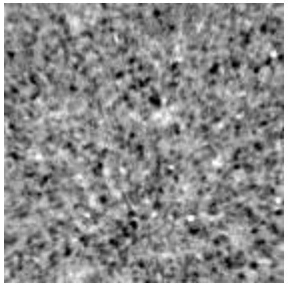
GFZ

Post-mortem x-ray scans

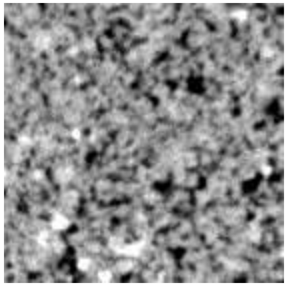


3SR

Low resolution
(~90 µm)
140 x 140 pixels



High resolution
(~30 µm)
140 x 140 pixels



3D-DIC
3SR

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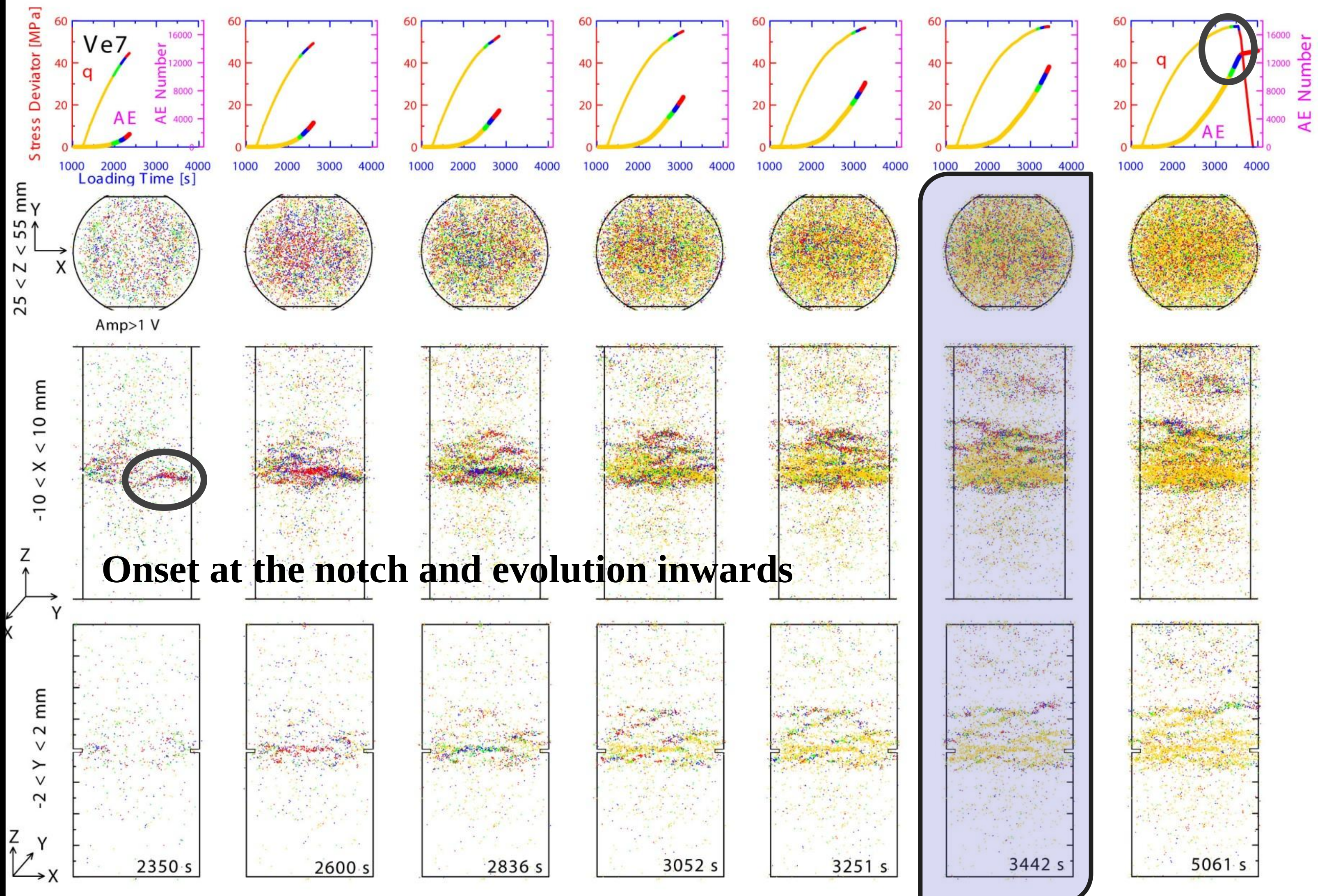
Ve7 specimen [190 MPa confining pressure]

AE hypocenter locations → **Damage *[in situ]***

Brittle activity : grain contacts breakage & possibly grain fragmentation



Onset at the notch and evolution inwards

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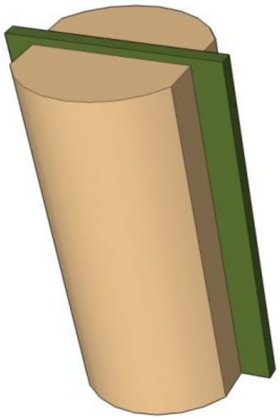
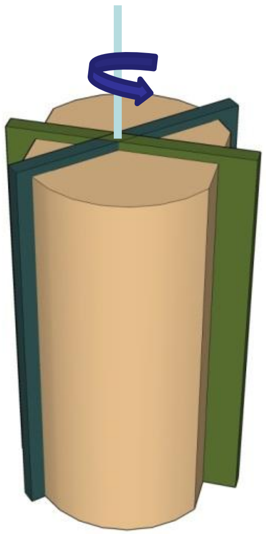
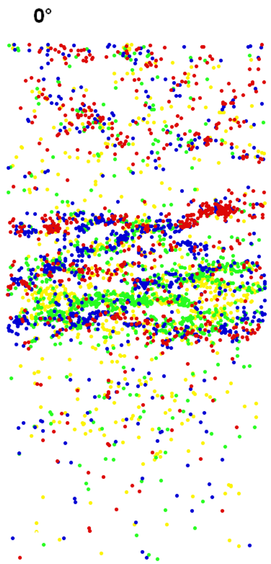
Ve7 specimen [190 MPa confining pressure]

2mm accuracy of the method

AE hypocenter locations







Info on:

- ✓ number & 3D \`network\` of the CBs
- ✓ width of the CBs
- ✓ orientation of the CBs

Ve7 specimen [190 MPa confining pressure]

2mm accuracy of the method

AE hypocenter locations

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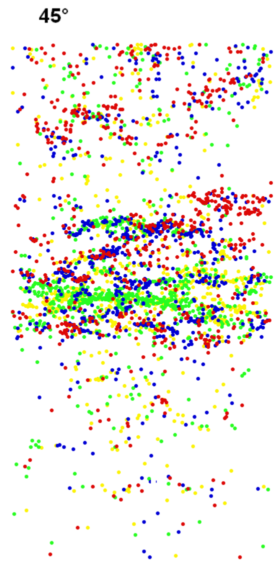

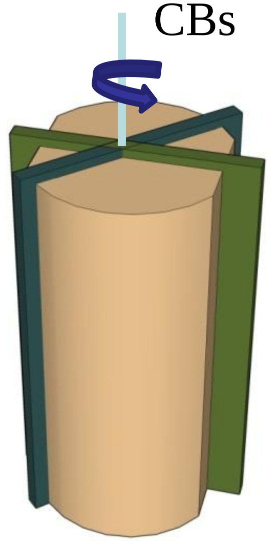

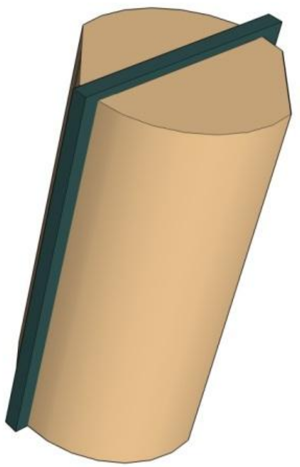

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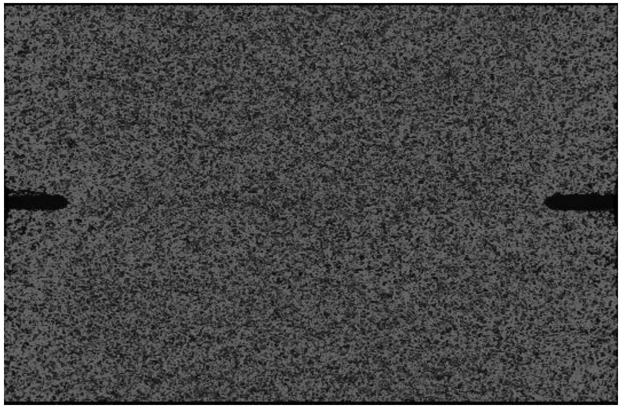
Ve7 specimen [190 MPa confining pressure]

X-ray CT → Low standard deviation → (**reduction in grain size via grain crushing** to below the voxel size → homogenisation of the image) → ***grain breakage, compaction***

Raw data
Density variation



Standard deviator of the x-ray grey-scale

Threshold: 0 - 2.6%

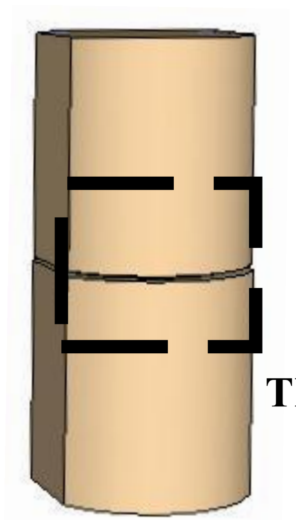
Calculations through the image volume, over sub-volumes of 300x300x300 μm^3 @ a spacing of 150 μm in each direction

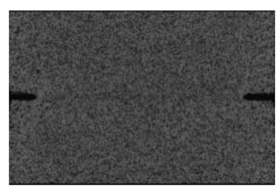
Ve7 specimen [190 MPa confining pressure]

X-ray CT → ***density variations***

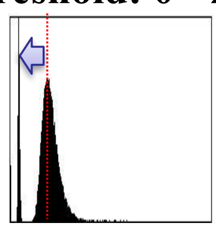
standard deviator

Low standard deviation →
grain breakage, compaction

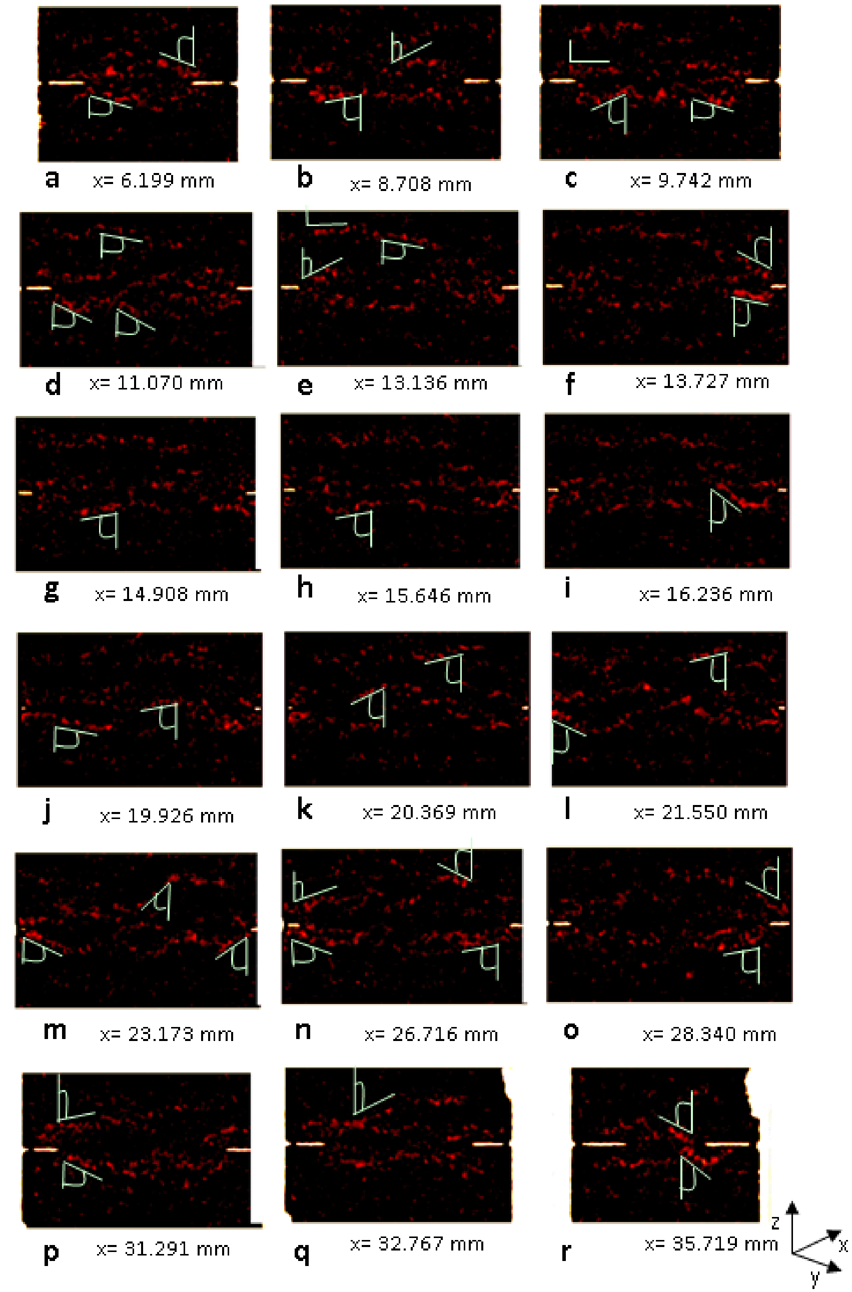




Threshold: 0 - 2.6%



Calculations through the image volume, over sub-volumes of 300x300x300 μm^3 @ a spacing of 150 μm in each direction



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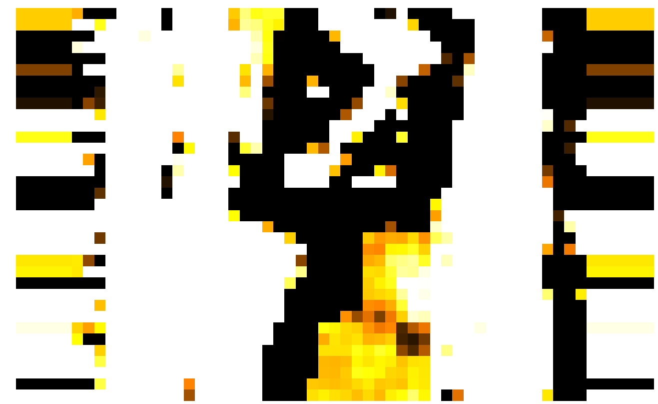
Ve7 specimen [190 MPa confining pressure]

DIC

Calculations through the image volume, over sub-volumes of 600x600x600 μm³ @ a spacing of 600 μm in each direction

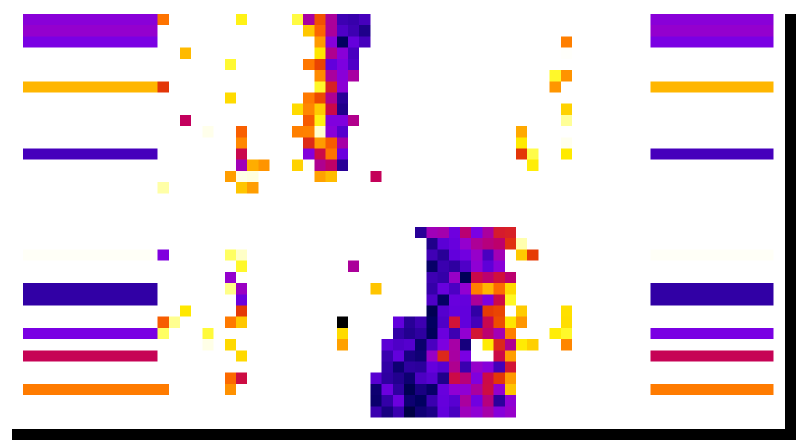
Volumetric strain

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$



Shear strains

$$\varepsilon_s = \sqrt{\left(\frac{\varepsilon_1 - \varepsilon_2}{2}\right)^2 + \left(\frac{\varepsilon_1 - \varepsilon_3}{2}\right)^2 + \left(\frac{\varepsilon_2 - \varepsilon_3}{2}\right)^2}$$

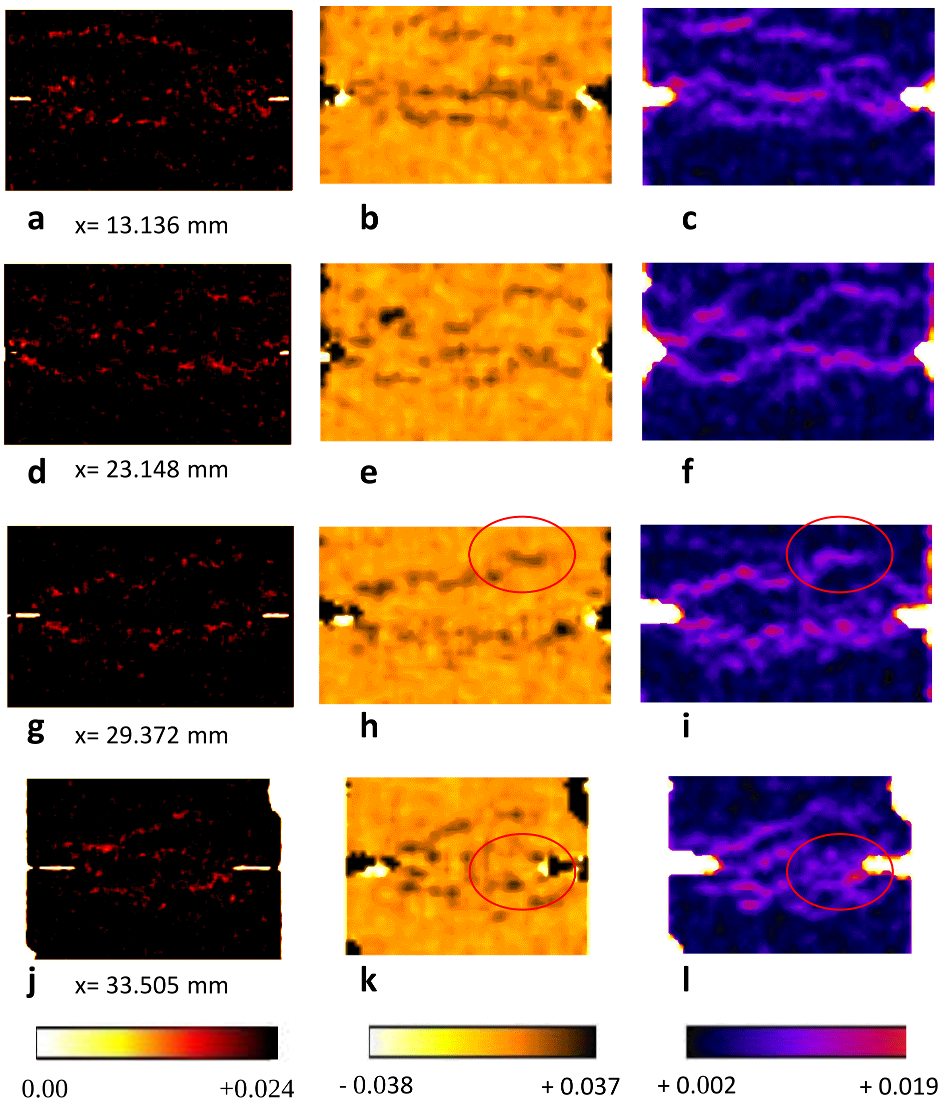


Ve7 specimen [190 MPa confining pressure]

Standard deviation (x-ray CT) & DIC

single slices →
for further details

strains close and far from the notch



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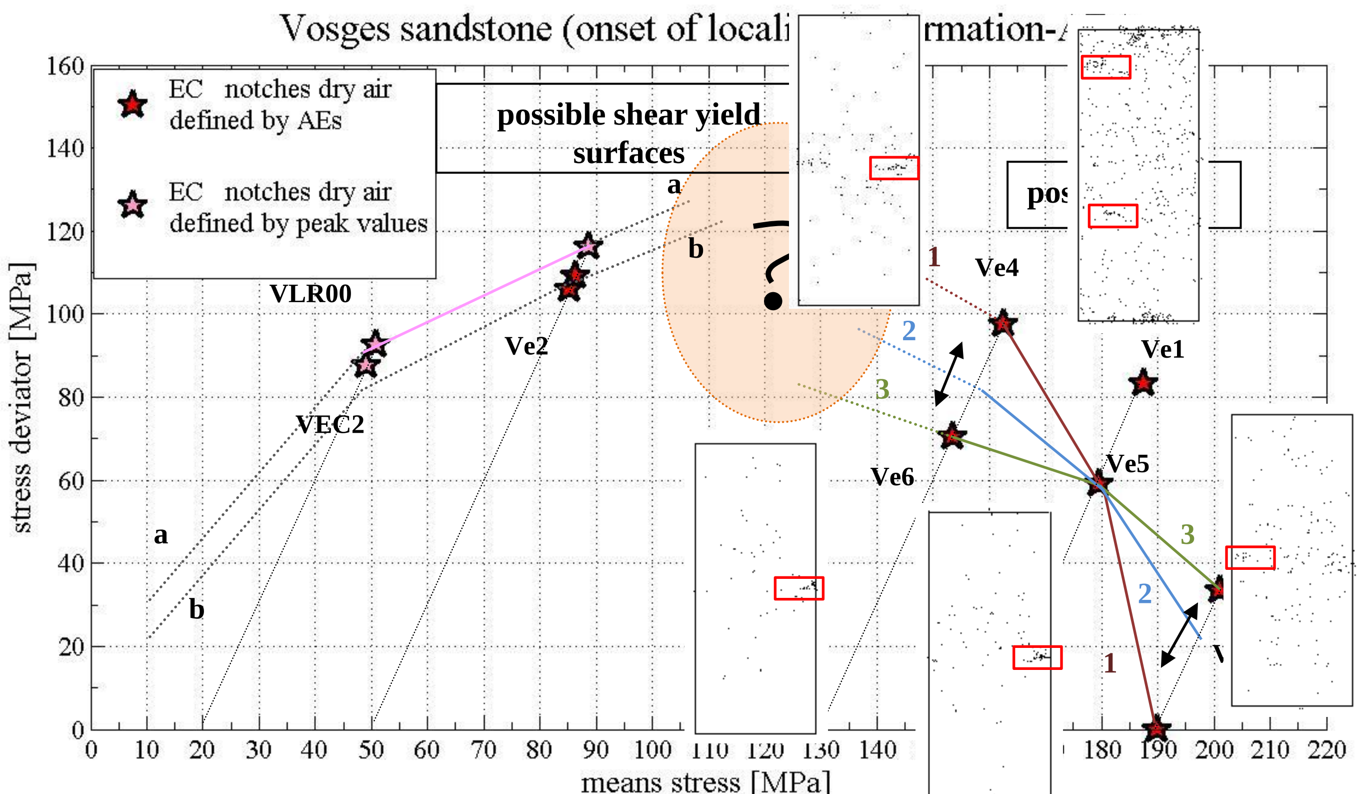
Summary of the mechanical results

name of specimen	notches	confining pressure	deformation bands	measurements										
				UT		AEs	x-ray CT					3D DIC		thin sections
				pre-	post-	syn-	pre-		post-			pre-, post-		post-
							LR	HR	LR	HR	VHR	LR	HR	
Ve4	✓	130 MPa	CB	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ve6	✓	130 MPa	CB	✓	✗	✓	✗	✓	✗	✓	✓	✗	✓	✓
Ve1	✗	160 MPa	CB	✗	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓
Ve5	✓	160 MPa	CB	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗
Ve7	✓	190 MPa	CB	✓	✓	✓	✗	✓	✗	✓	✗	✗	✓	✗

Map yield surface caps with negative slopes in the p-q plane



Summary of strain measurements

Specimen	Min volumetric strains inside the band [%]	Max volumetric strains inside the band [%]
Ve4	0.26	0.87
Ve6	0.87	1.86
Ve5	0.91	1.89
Ve7	0.82	1.36

Specimen	Min shear strains inside the bands [%]	Max shear strains inside the bands	Indicative shear strains outside the bands
Ve4	0.6	0.9, 1.2 (notch)	~0.3
Ve6	0.8	1.9 (notch)	~0.5
Ve7	0.8	1.5, 2.1 (notch)	~0.4-0.6

Increasing axial strain → increase in strain field values (DIC)

Max shear strain @ the notch; lower shear strain inside the band

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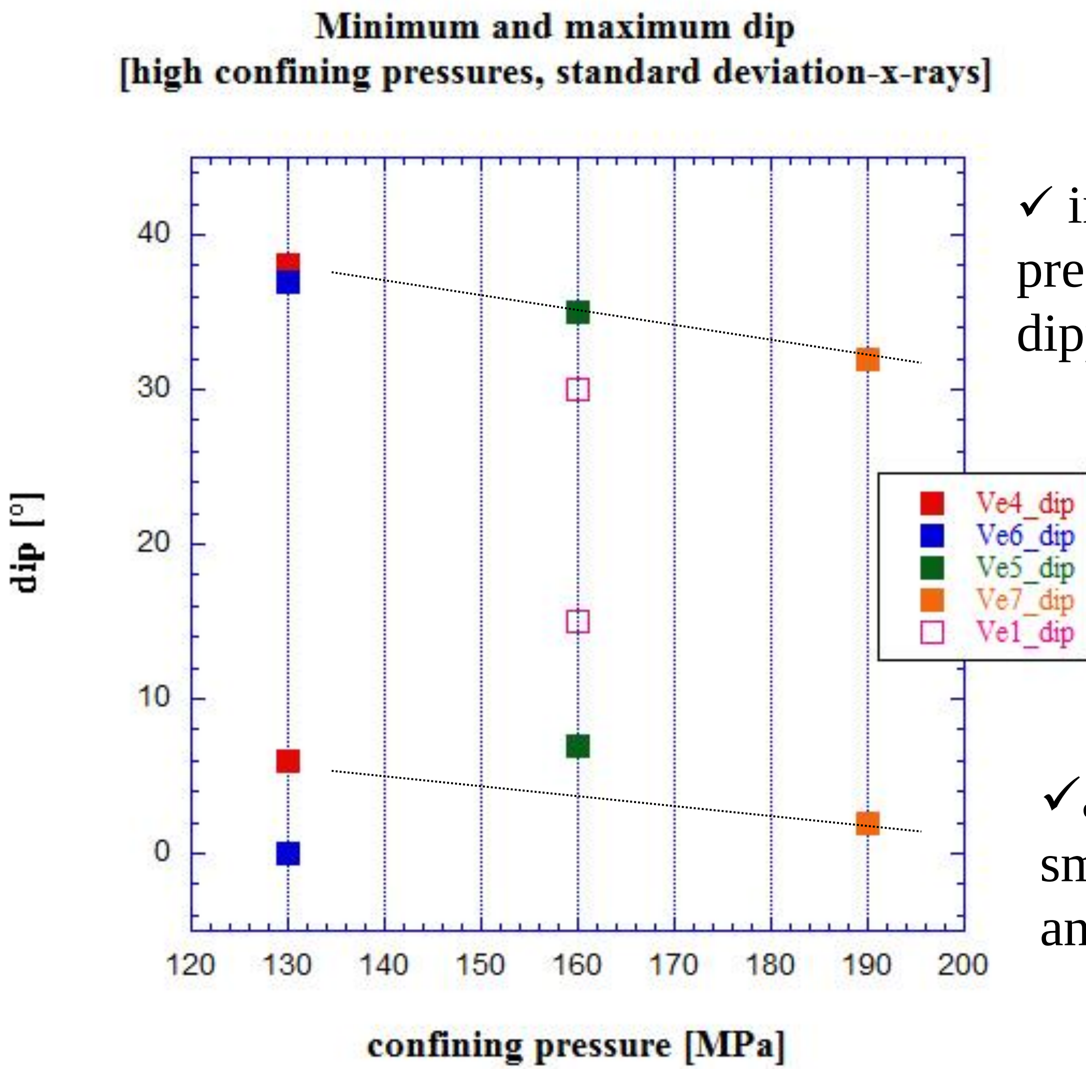
Summary of dipping angles



- ✓ increasing confining pressure → decrease in dipping angles
- ✓ higher strain → smaller dipping angles (e.g. Ve6)
- ✓absence of notch → smaller range of dipping angles (e.g. Ve5, Ve1)

- **Shear enhanced compaction bands** →high compactant volumetric strains together with shear strains
- Absence of pure compaction bands
- Onset at the notch (stress concentration) → propagation inwards
- AE concentration (***breakage of grain cements and grains***)
- Low standard deviation values (**reduction in grain size via grain crushing** to below the voxel size and thus homogenisation of the image)
- Compactant volumetric strain (**porosity reduction**)
- Shear strain (**grain rearrangement and sliding**)

Thank you for your attention!