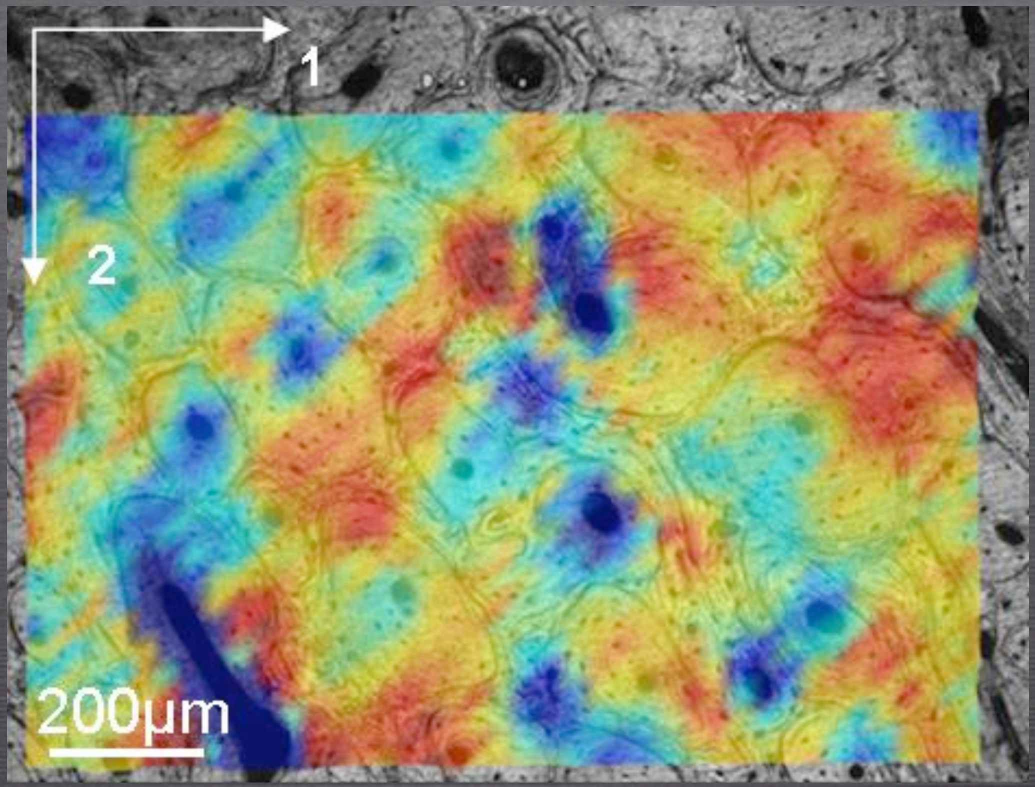
Microextensometry measurements and identification of mechanical properties on cortical bone



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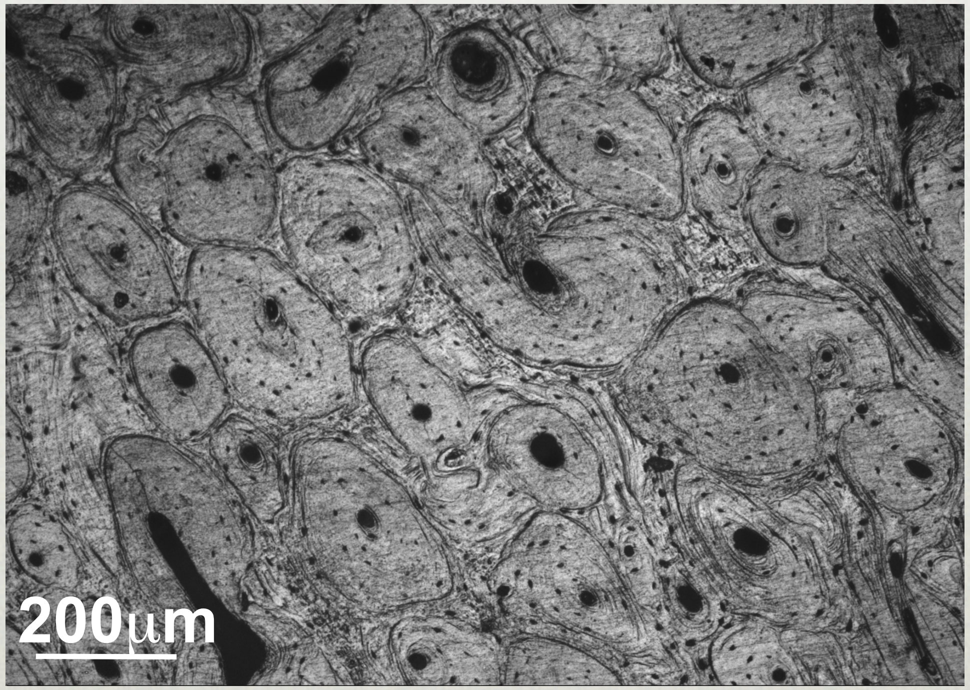
Context

- Current health issue: Osteoporosis
- Factors to be taken into account at the microstructure scale



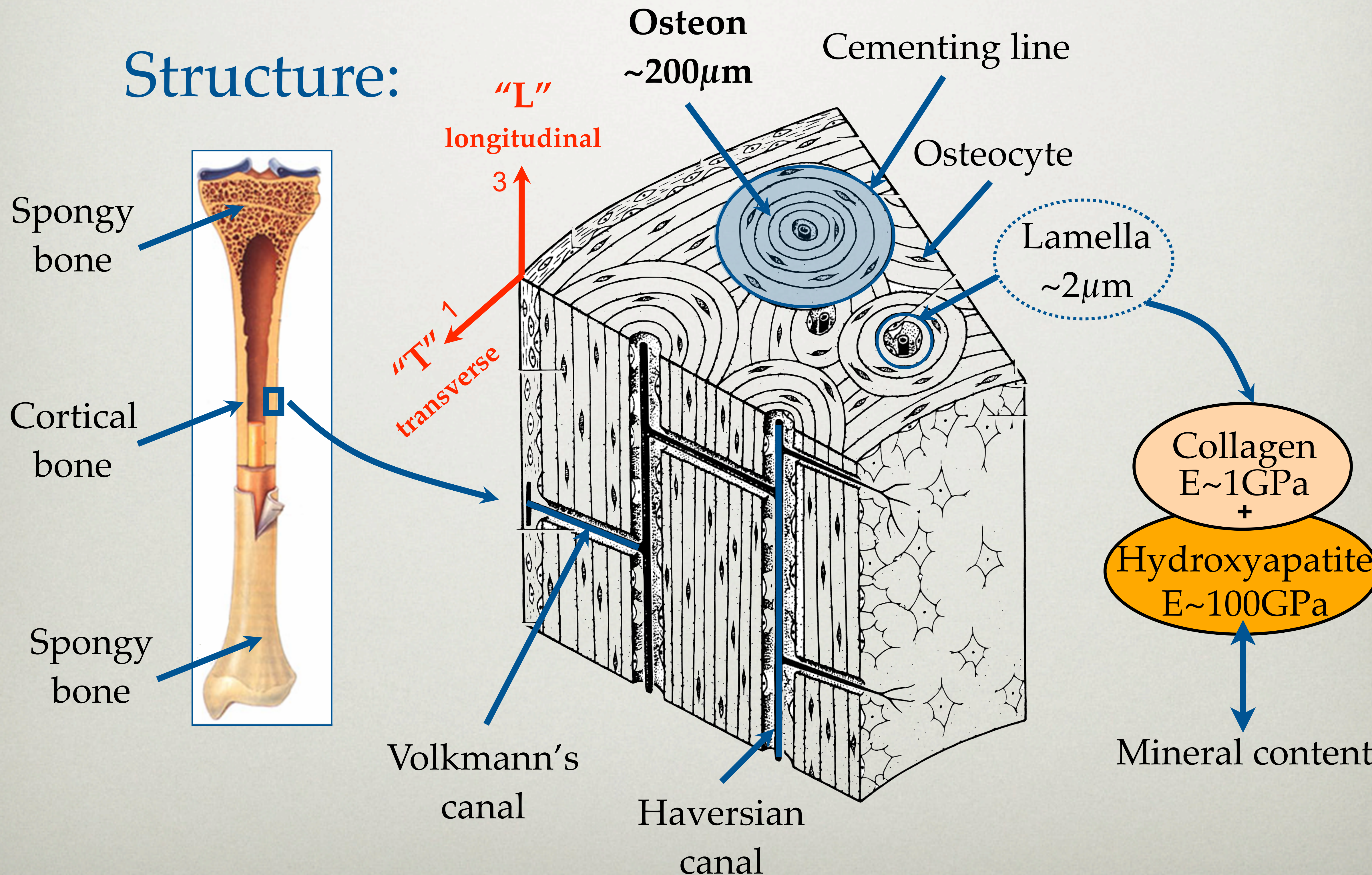
Digital Image Correlation (DIC)

Outline

- Part I: Experiments on cortical tissue:
  - description of the microstructure
  - DIC: principles and features
- Part II: Strain measurements
- Part III: Identification of mechanical properties

Cortical tissue

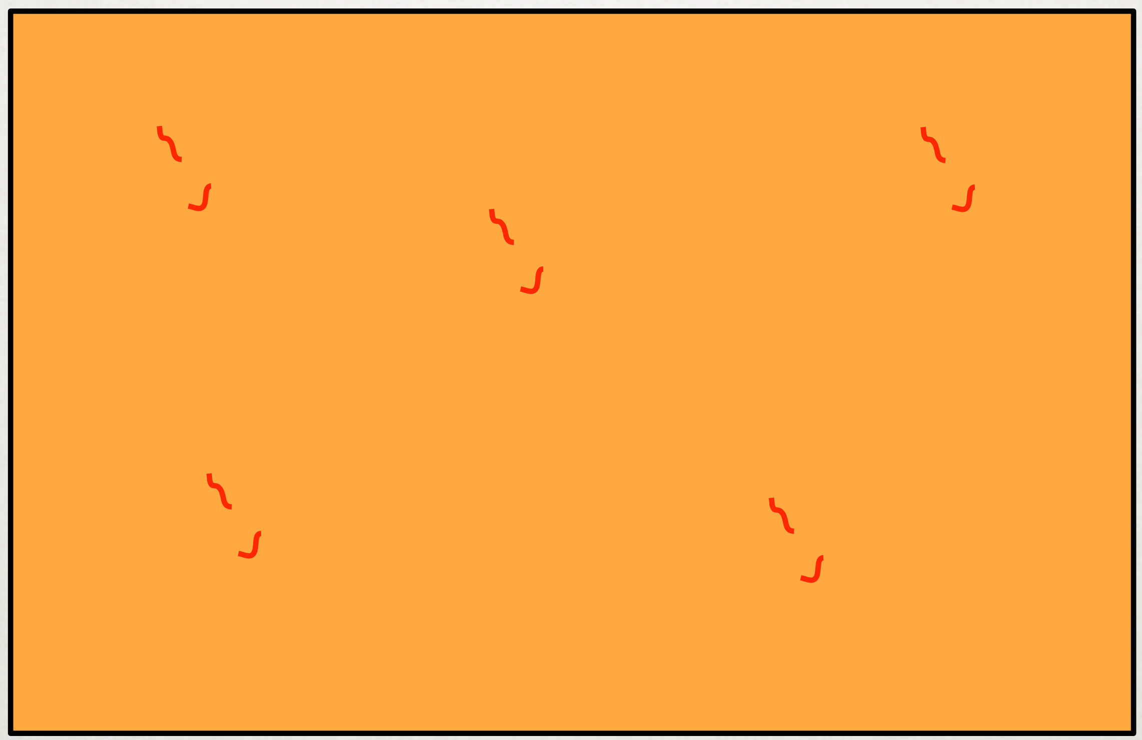
Structure:



Cortical tissue

Formation: Primary bone

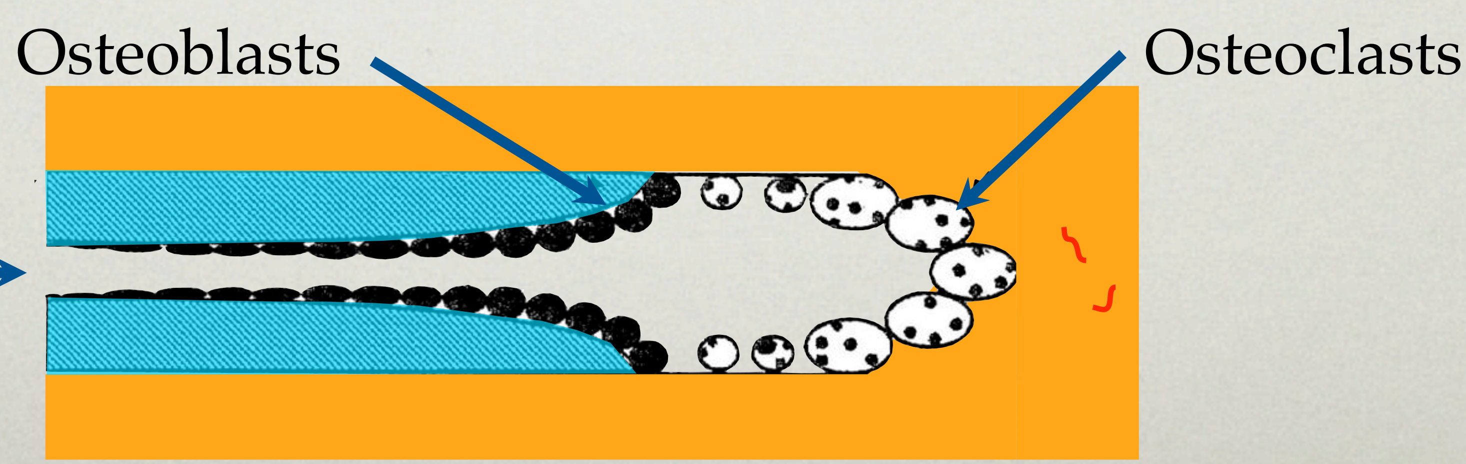
Transverse cut



Damage

initiating remodelling

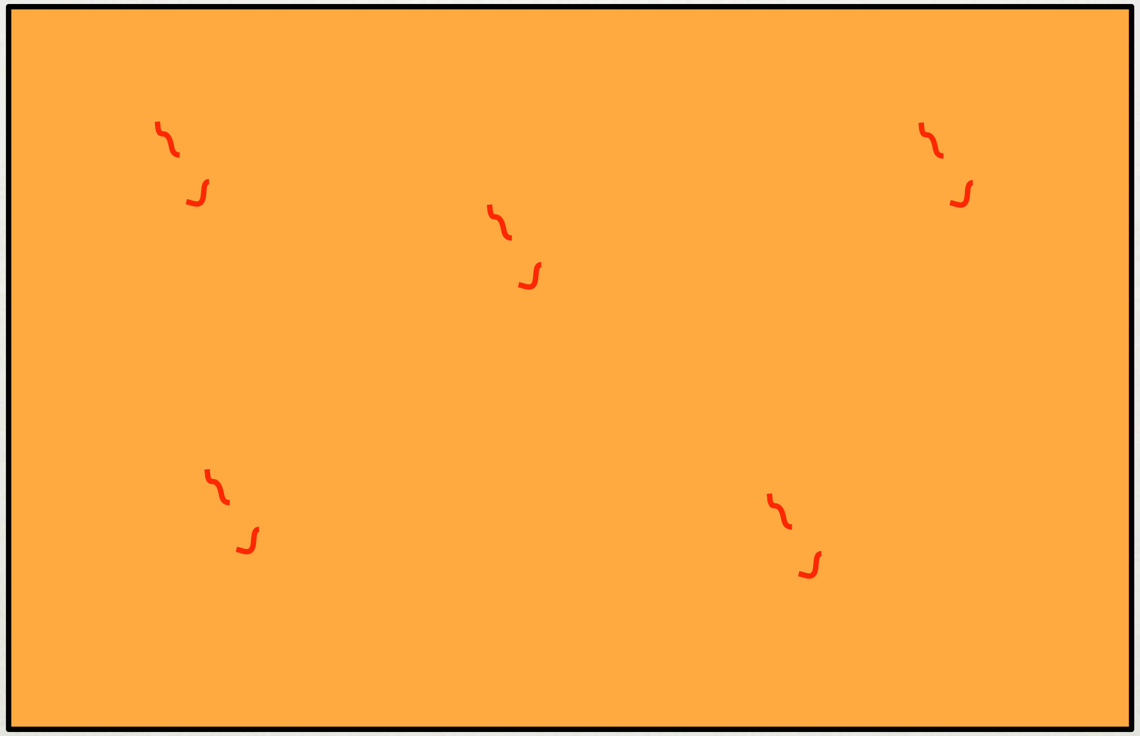
Longitudinal direction



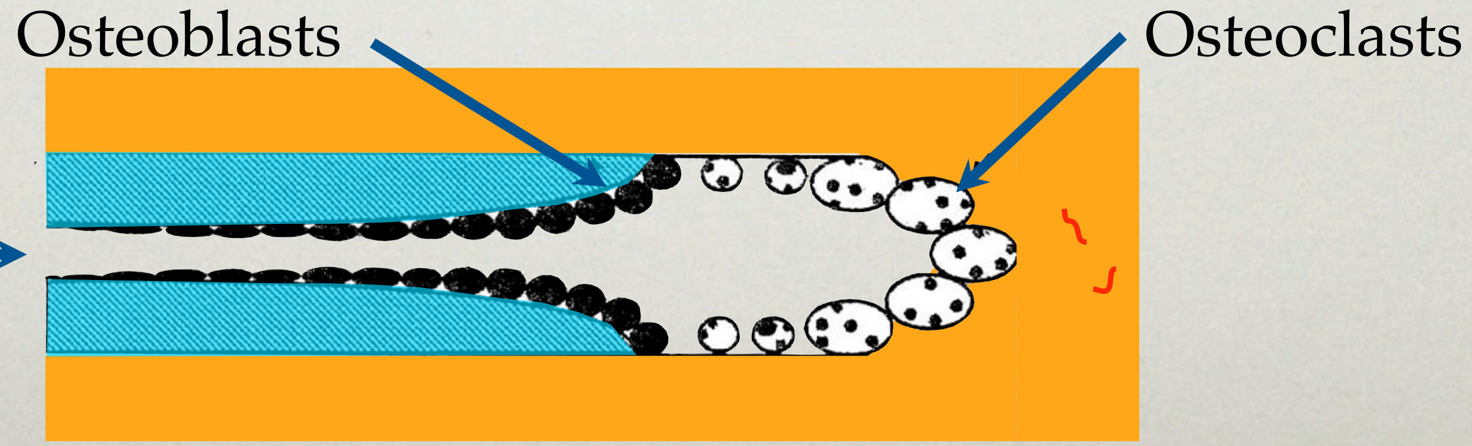
Cortical tissue

Formation: **Primary bone**

Transverse cut



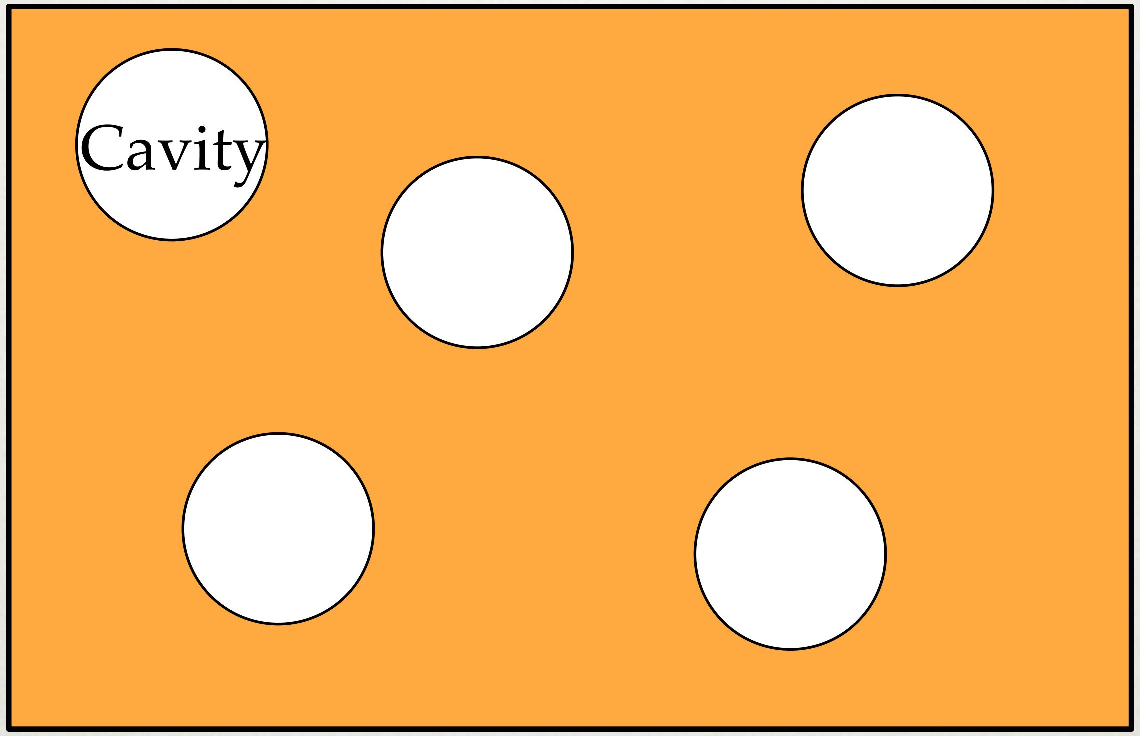
Longitudinal direction



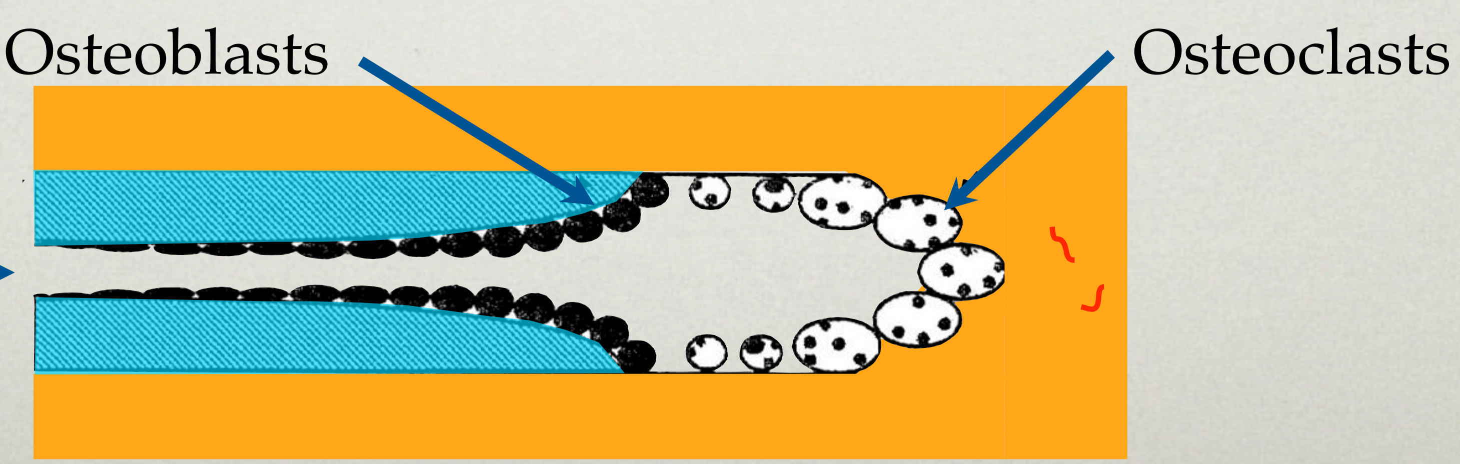
Cortical tissue

Formation: **Primary bone** **+ resorption cavities**

Transverse cut



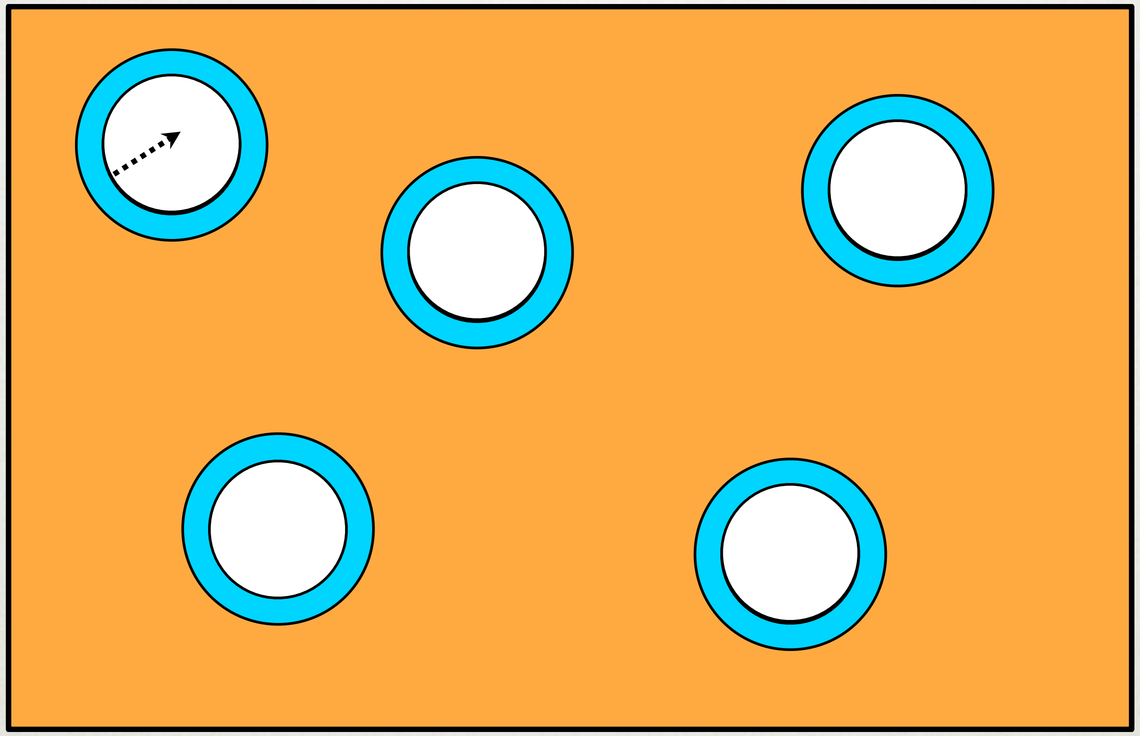
Longitudinal direction



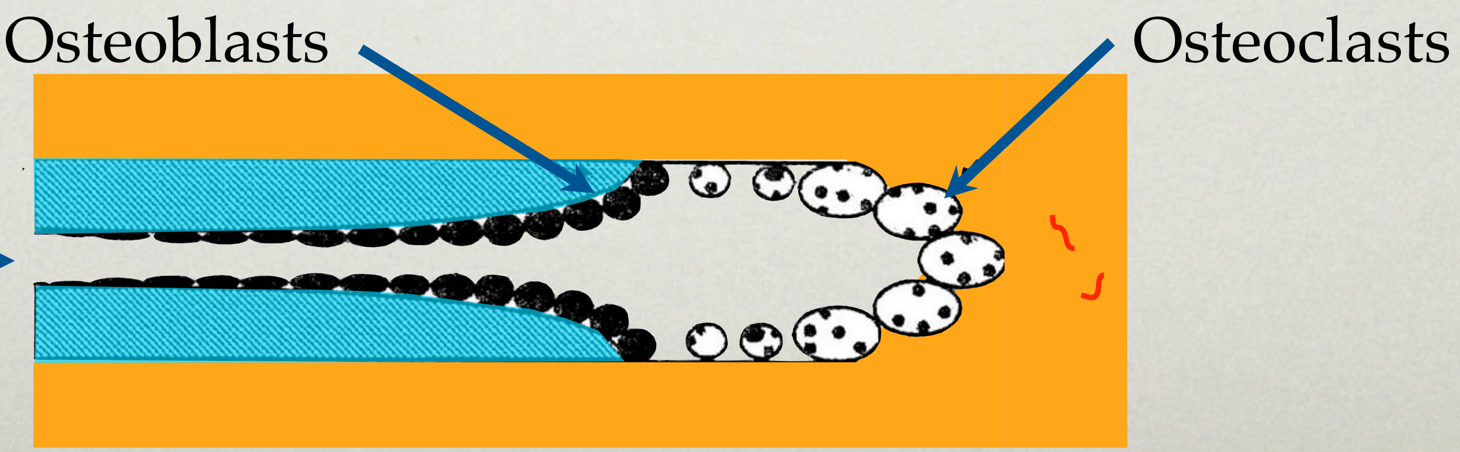
Cortical tissue

Formation: Primary bone + progressive apposition

Transverse cut



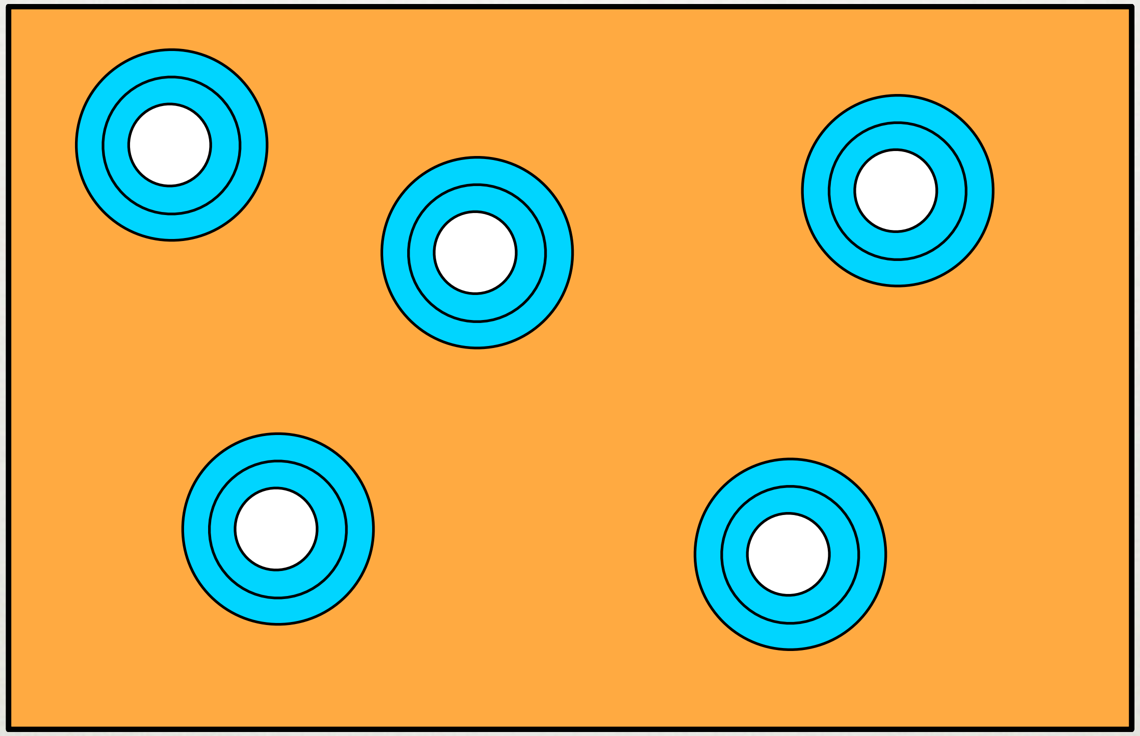
Longitudinal direction



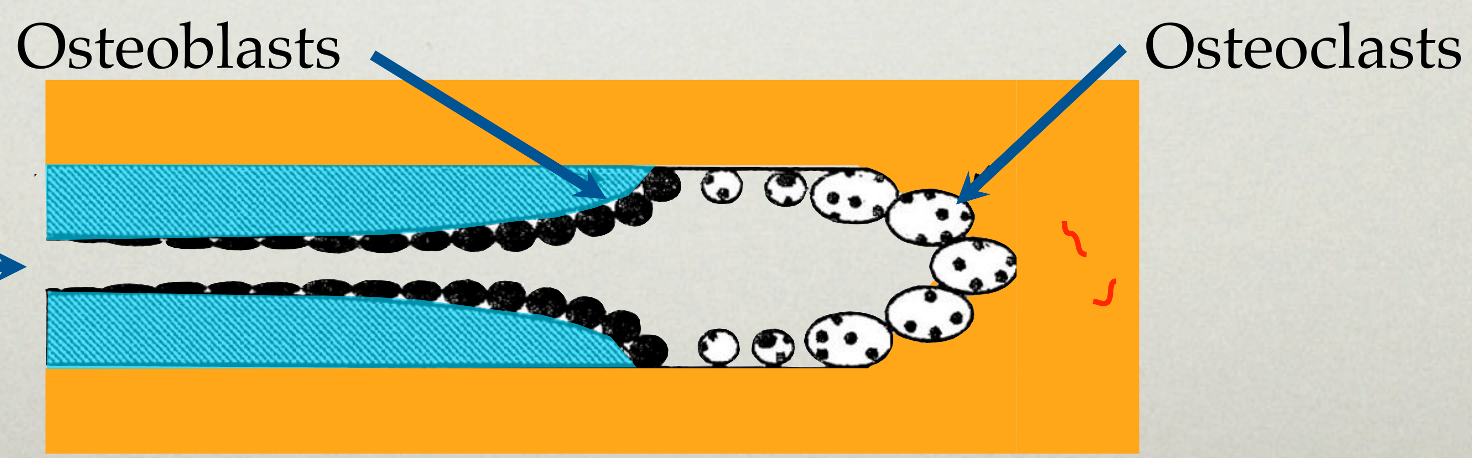
Cortical tissue

Formation: Primary bone + progressive apposition

Transverse cut



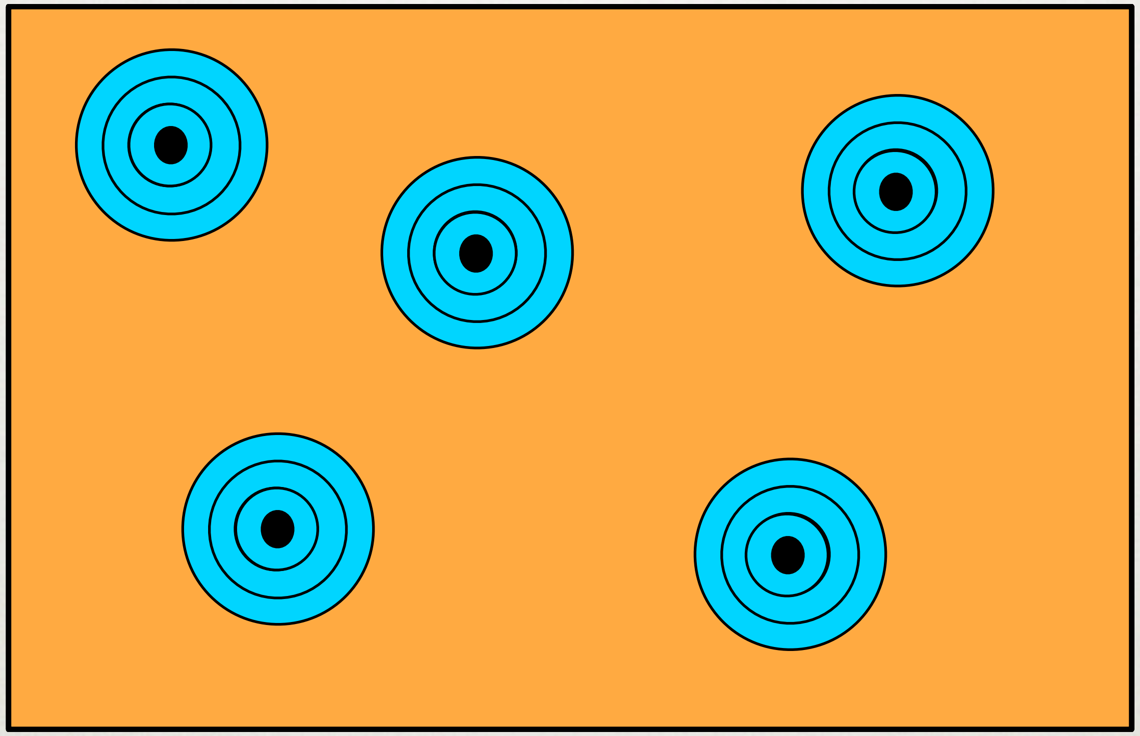
Longitudinal direction



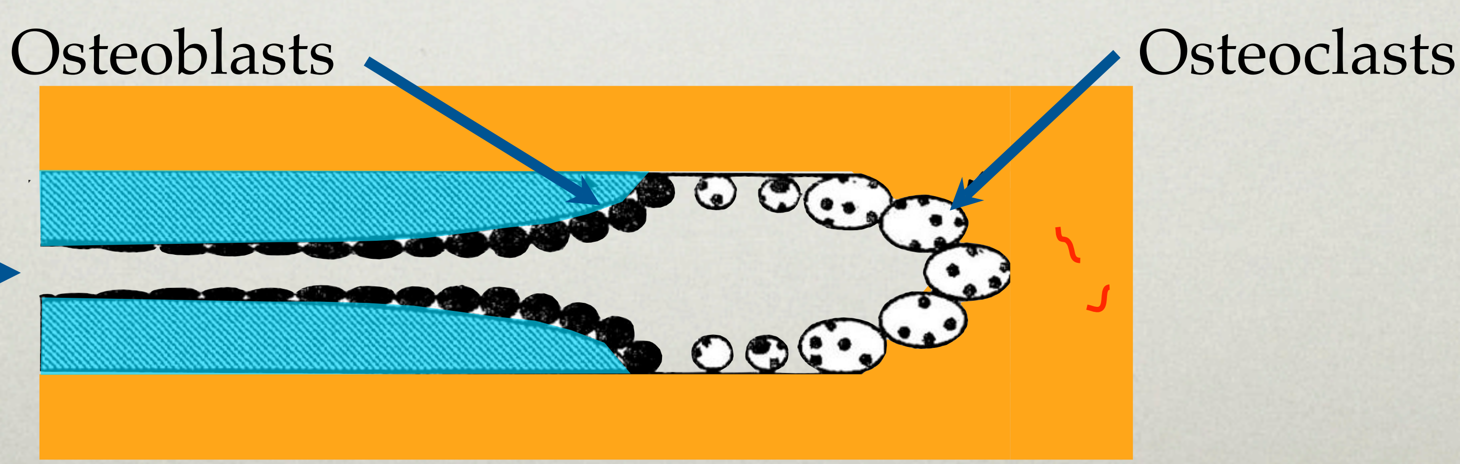
Cortical tissue

Formation: Primary bone + entire osteons

Transverse cut



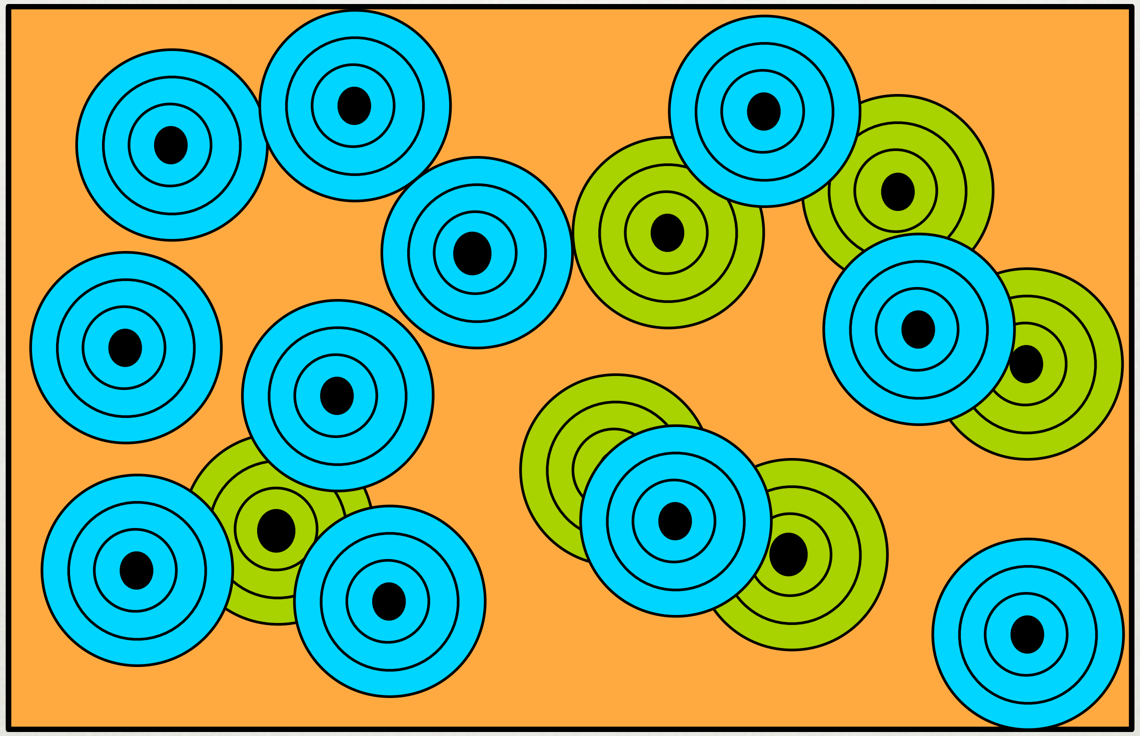
Longitudinal direction



Cortical tissue

Formation: Primary bone + entire osteons
+ partially remodelled osteons

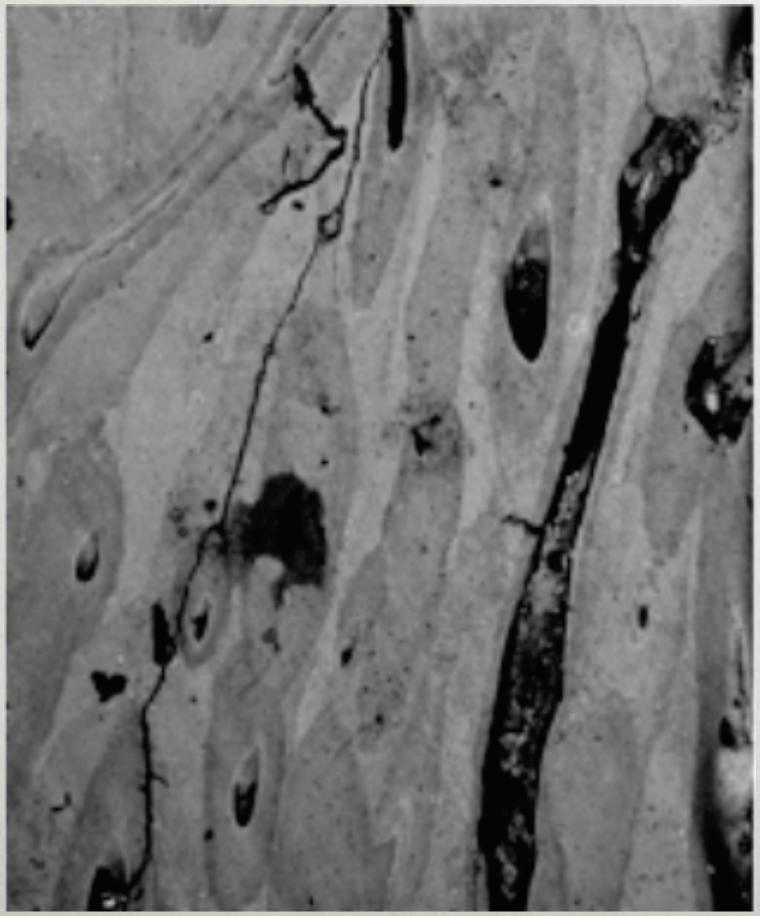
Transverse cut



Longitudinal direction

Studied bone samples

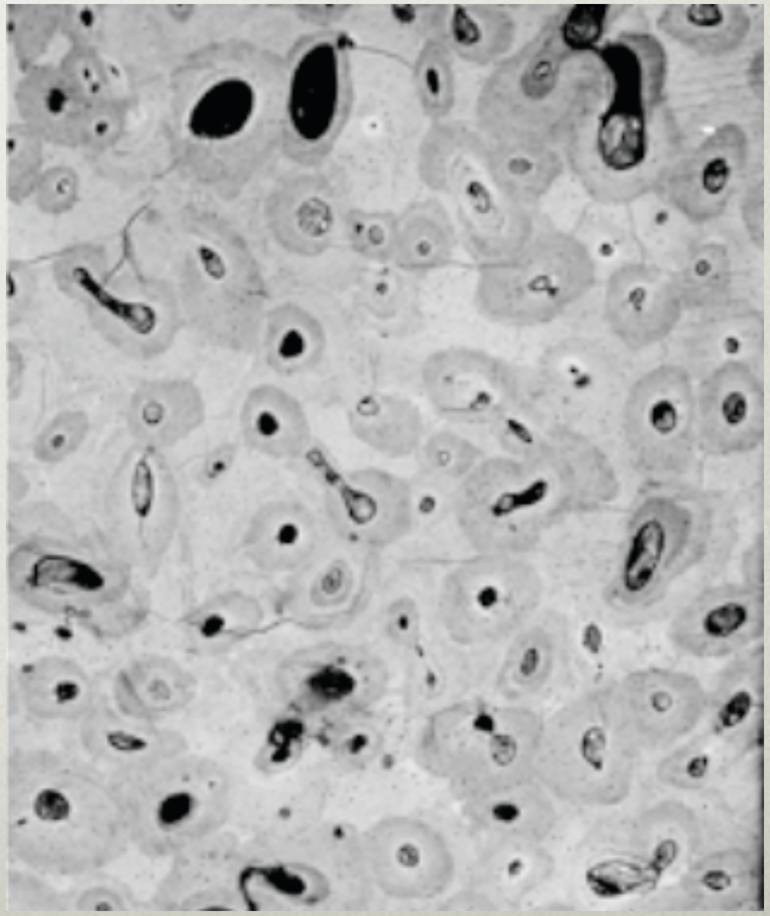
- Samples from 8 human subjects [Devulder 2009]
  - elderly women from 74 to 101 years old
  - dimensions of roughly 5mm x 3mm x 3mm



SEM images

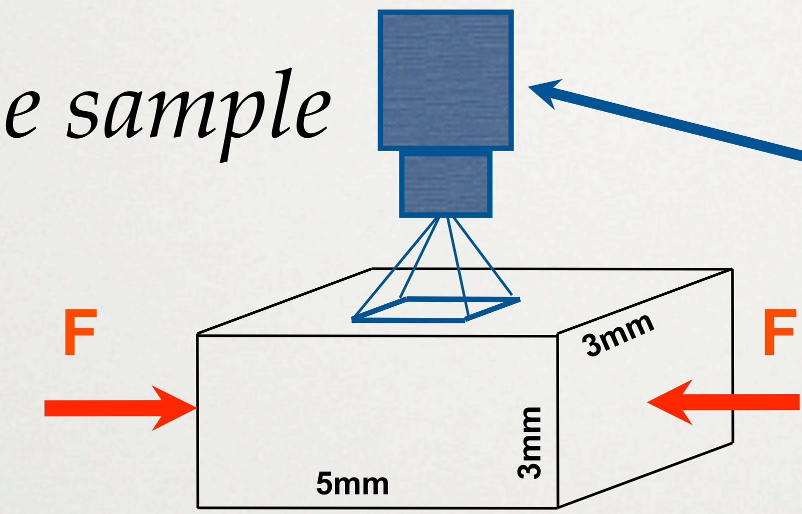
L and T samples
86 years old

200 μm

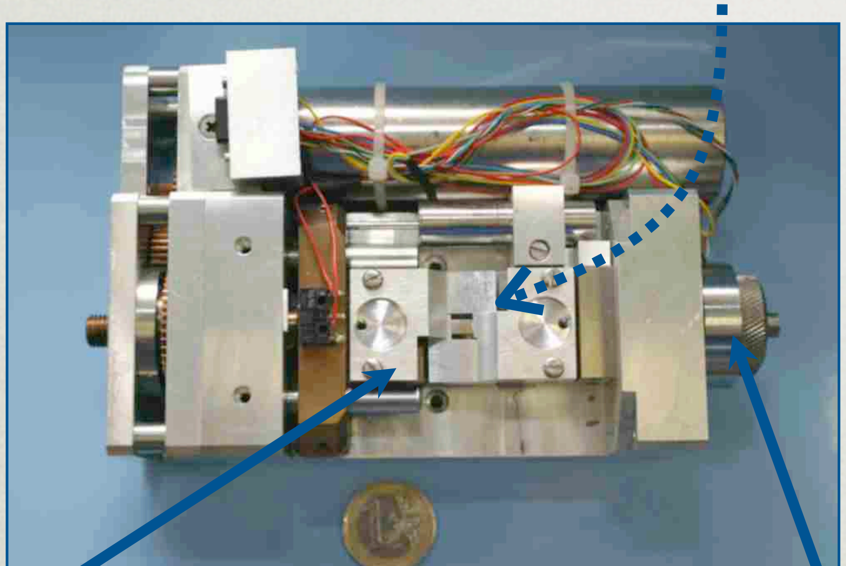


In situ microtensile tests

Studied bone sample



Leica DCC Camera
(2088 x 1552 pixels, 8 bits)



Mobile platen
($\dot{\varepsilon} \sim 2.10^{-4}\ s^{-1}$)

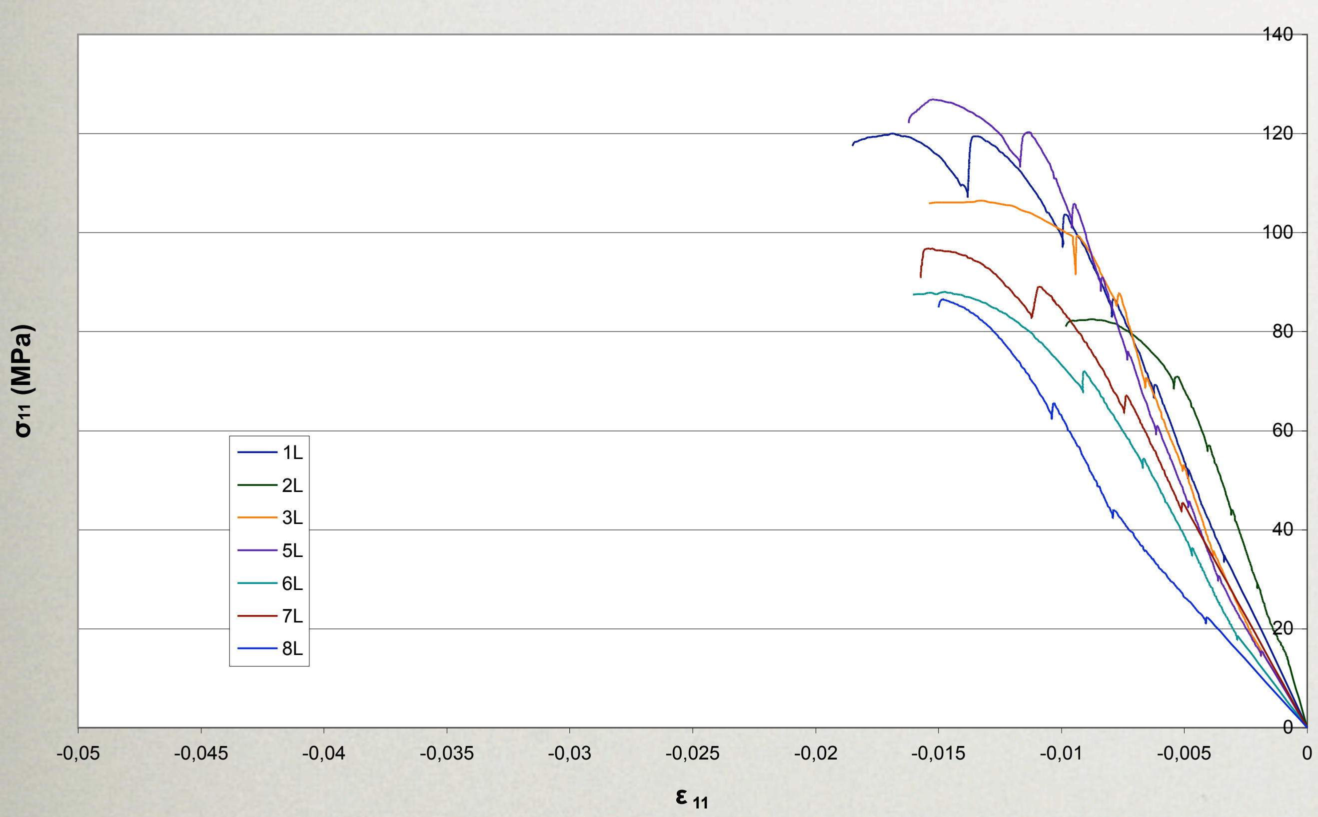
Load cell
(Entran 5kN)

Compression device

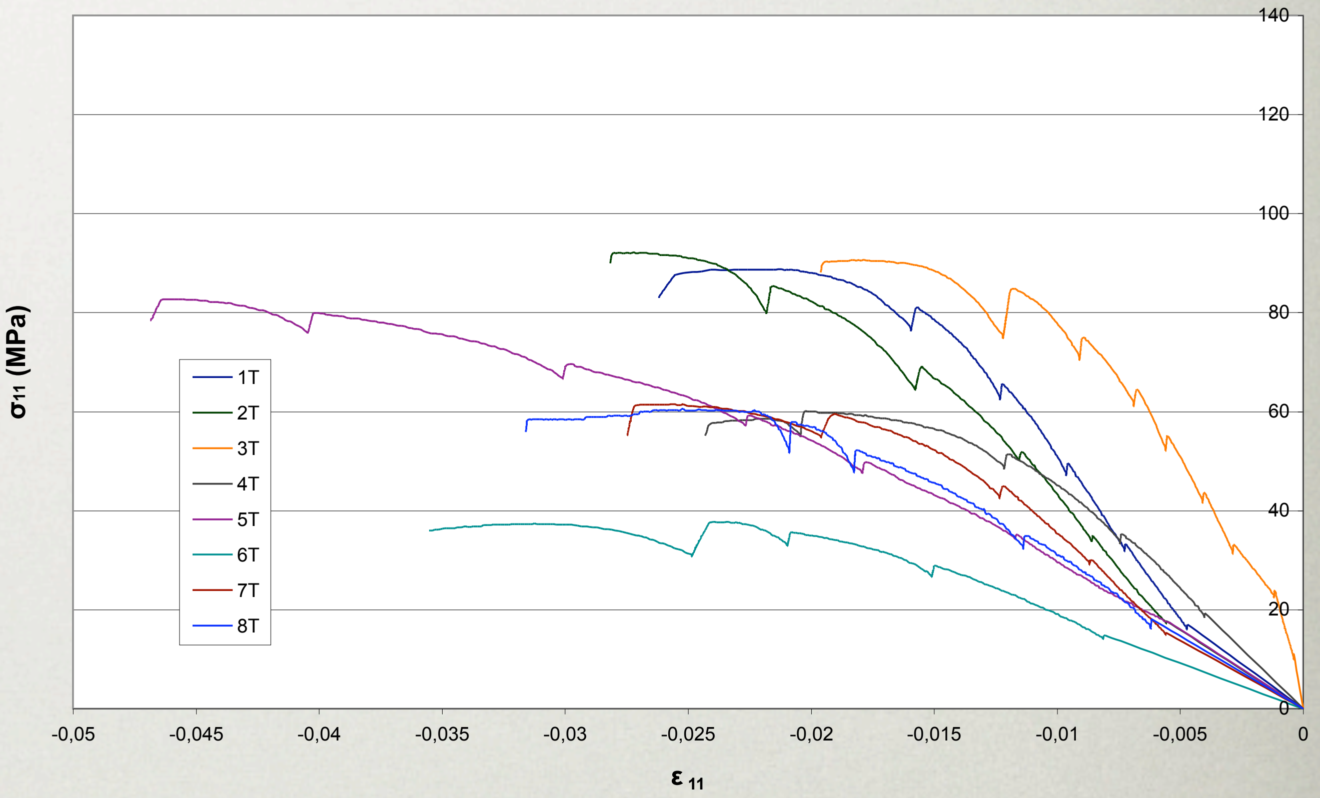
Optical microscope

Compression curves

- Compression curves along L and T axes



Longitudinal

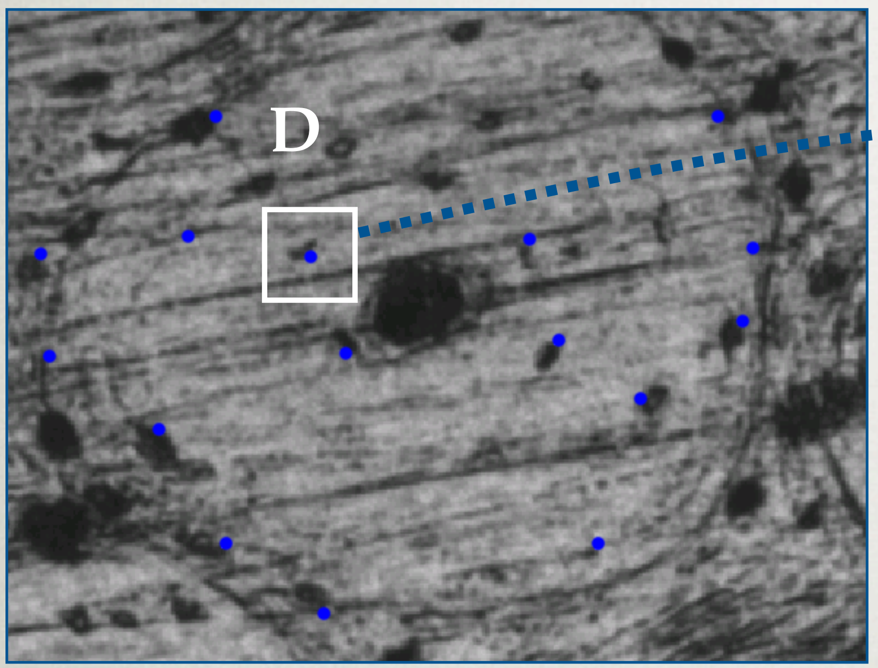


Transverse

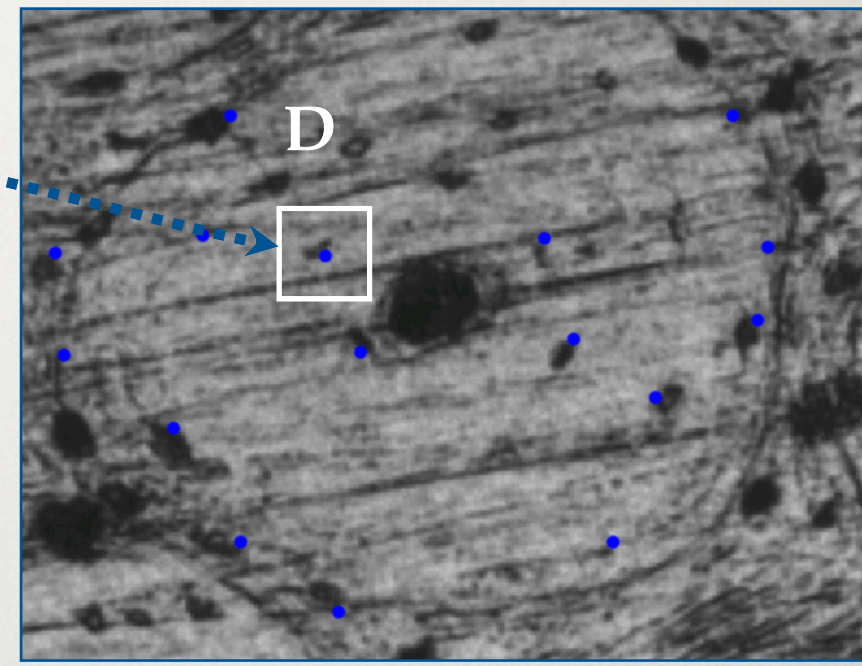
- DIC-corrected macroscopic strains

Digital Image Correlation (DIC)

Initial state



Current state



Minimization
of a correlation factor

Correlmanuv

- Measurement point associated with a correlation domain D (60 x 60 pixels)

Determining the location
of the measurement point
in the current state

➡ Displacements, then macro / micro strains

Outline

- Part I: Experiments on cortical tissue
- Part II: Strain measurements [Devulder 2009]
  - mean microscopic strain
  - crack step threshold strain
- Part III: Identification of mechanical properties

Mean microscopic strain

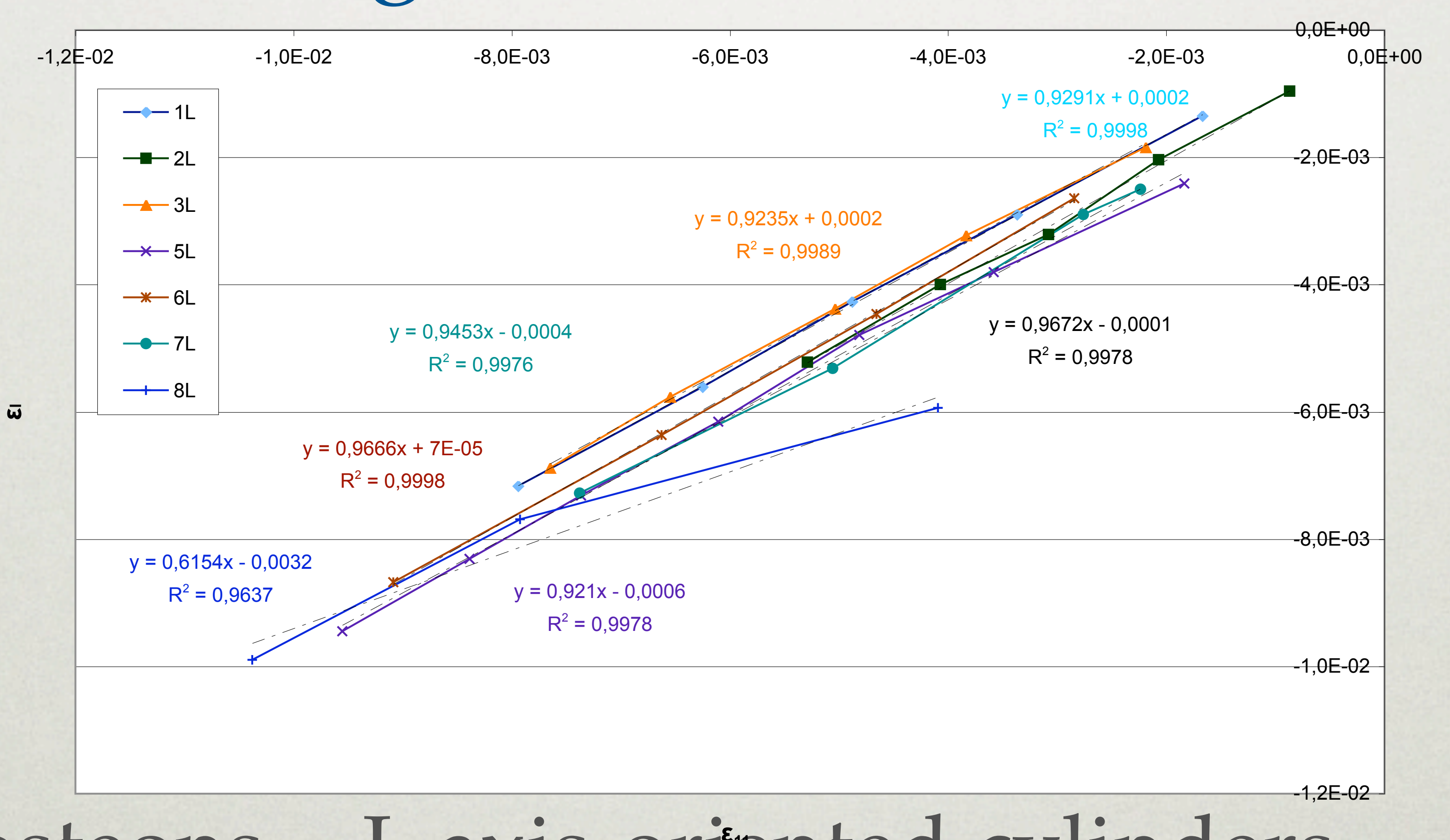
- Local uniaxial microscopic strains ➔ ε_l^i
  - computed on each correlation domain $\boxed{\mathrm{D}}$
- Mean uniaxial microscopic strain ➔ ε_l

$$\varepsilon_l = \frac{1}{N}\sum_{i=1}^{N}\varepsilon_l^i$$

- Macroscopic uniaxial strain ➔ ε_{11}
  - computed based on the displacements of the 4 corners of the observation area

Mean microscopic strain

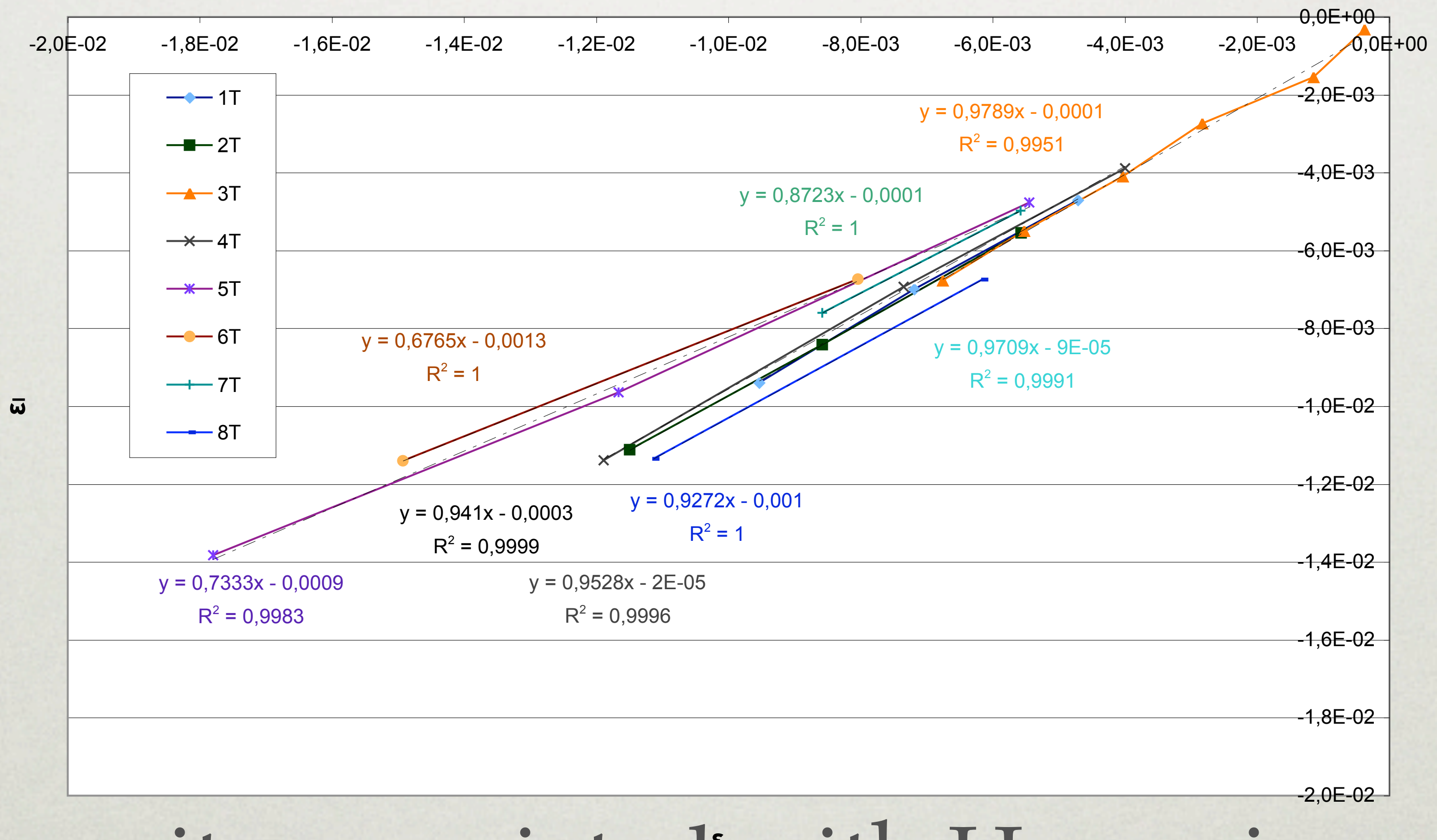
- Good agreement with the macroscopic strain along the L axis



- osteons = L axis-oriented cylinders

Mean microscopic strain

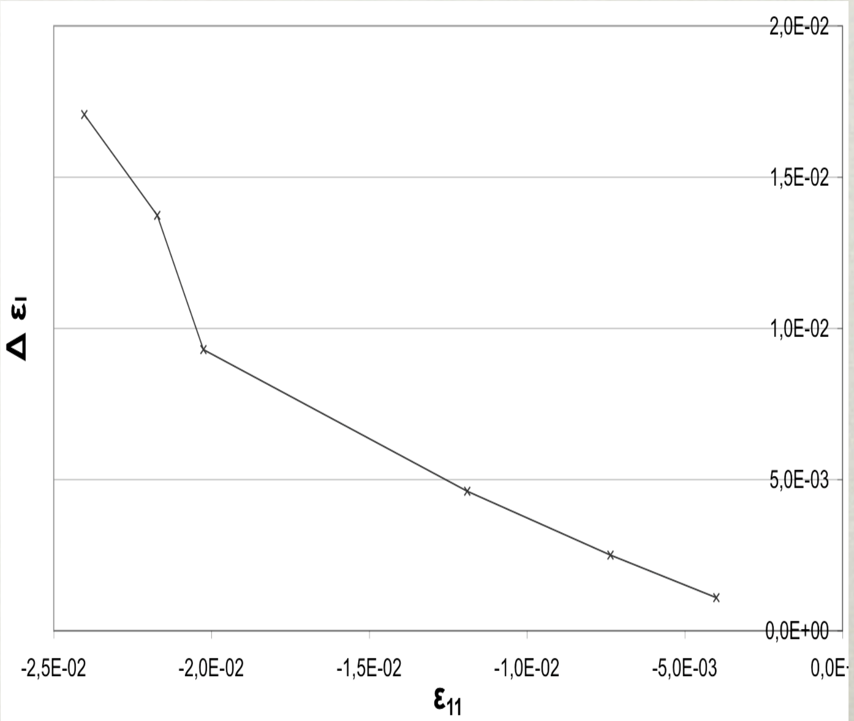
- Weaker agreement with macroscopic strain along the T axis



- porosity associated with Haversian canals
- microstructure heterogeneity

Crack step detection

- Determining the standard deviation $\Delta\varepsilon_l$ of the local microscopic strains
- $\Delta\varepsilon_l$ vs macroscopic strain ε_{11} curve



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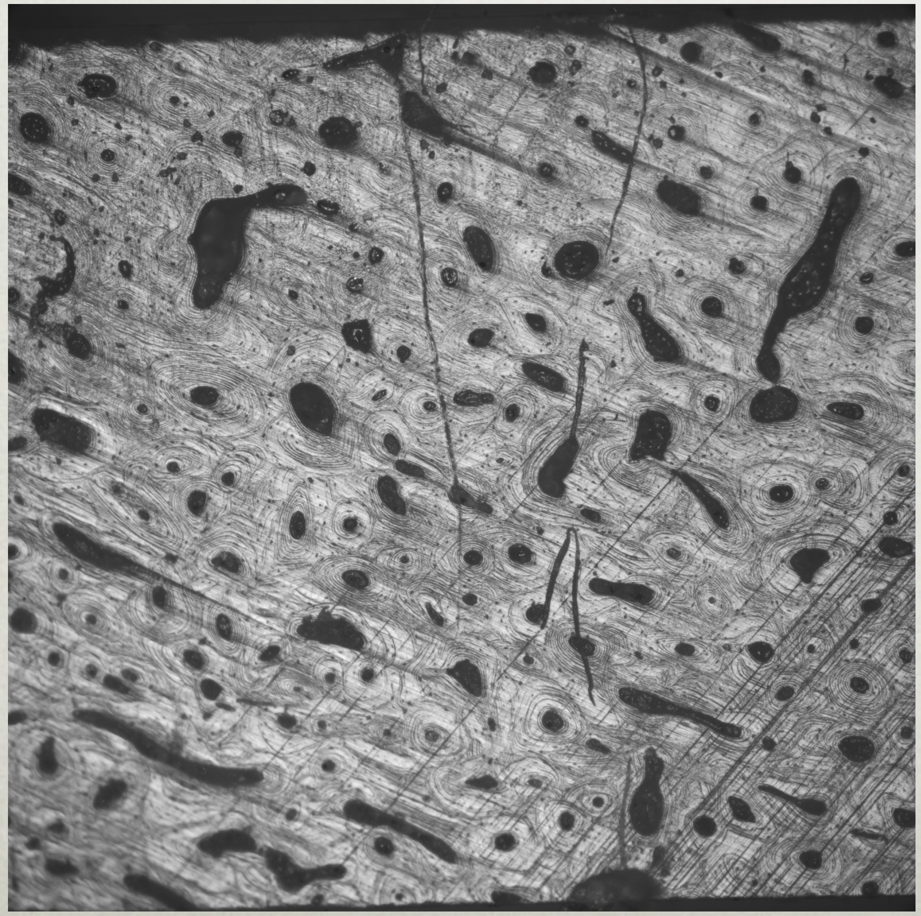

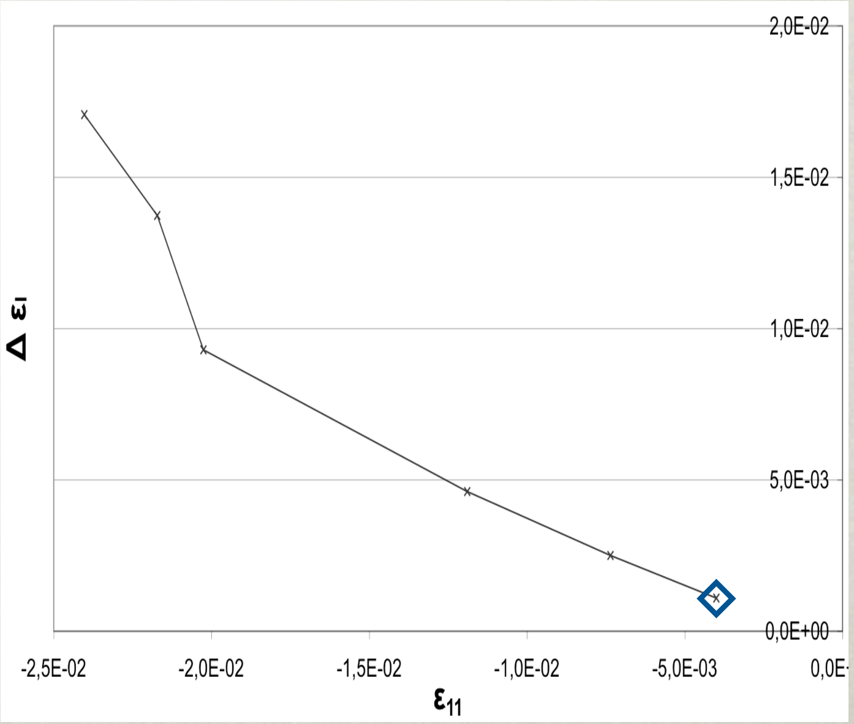

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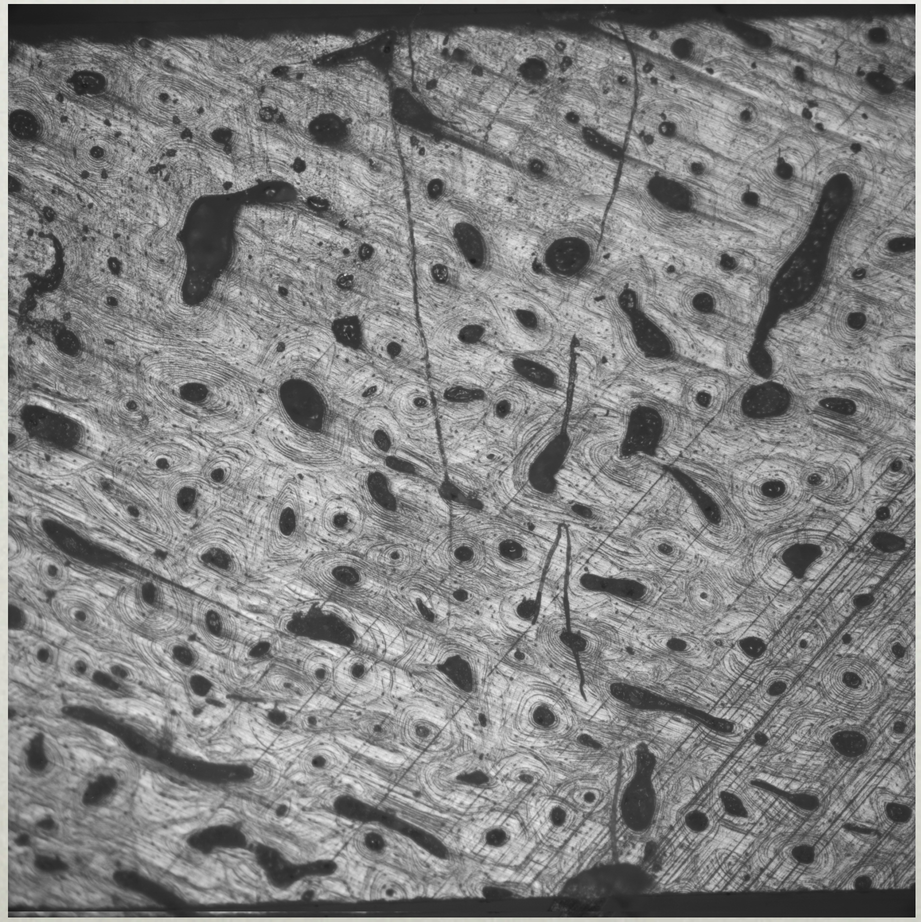

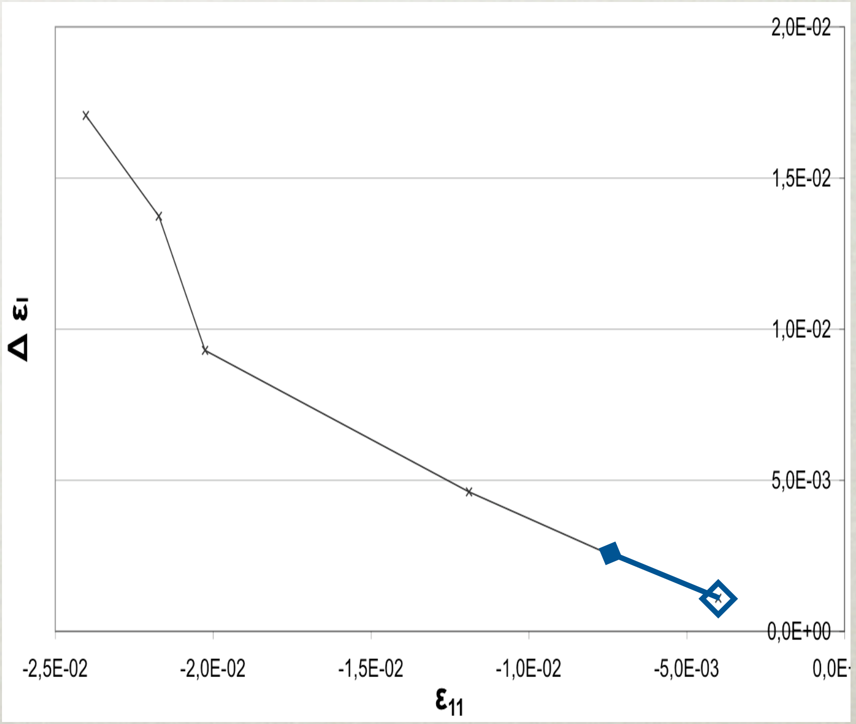

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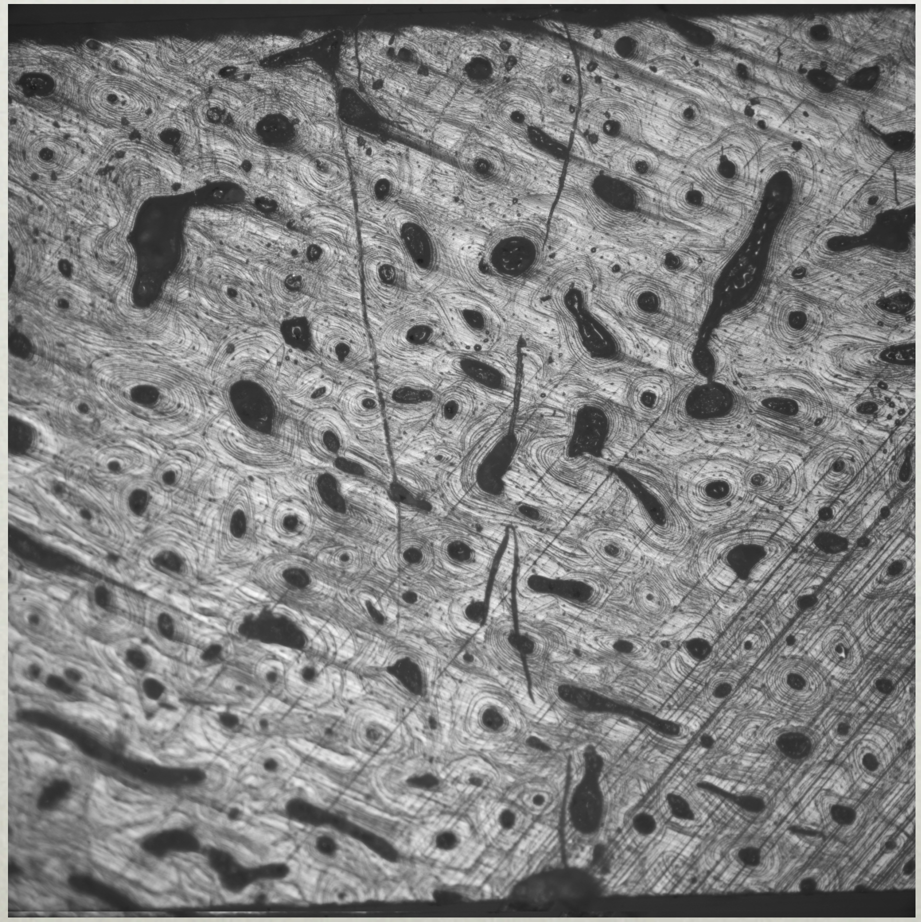

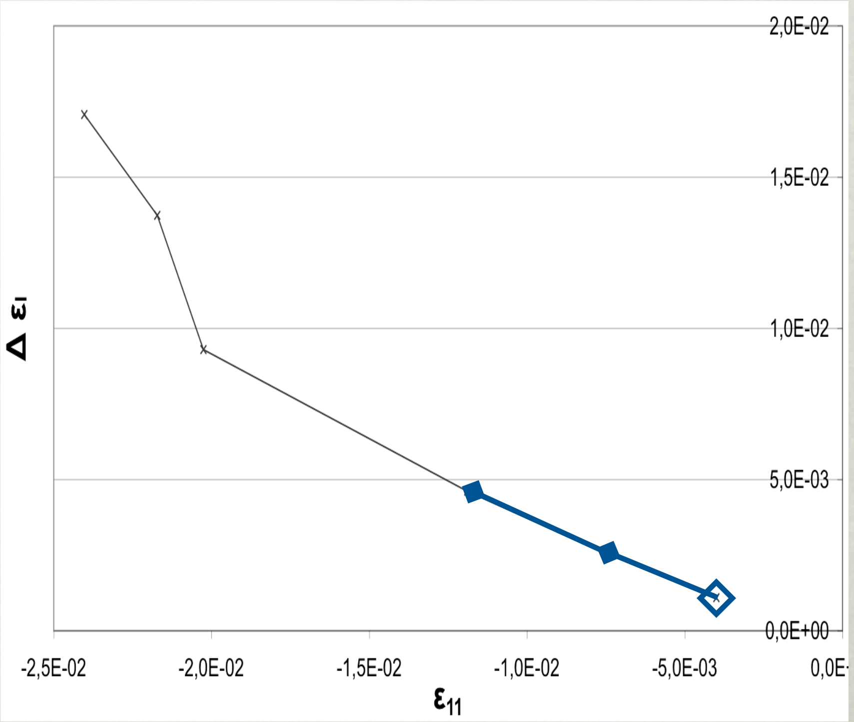

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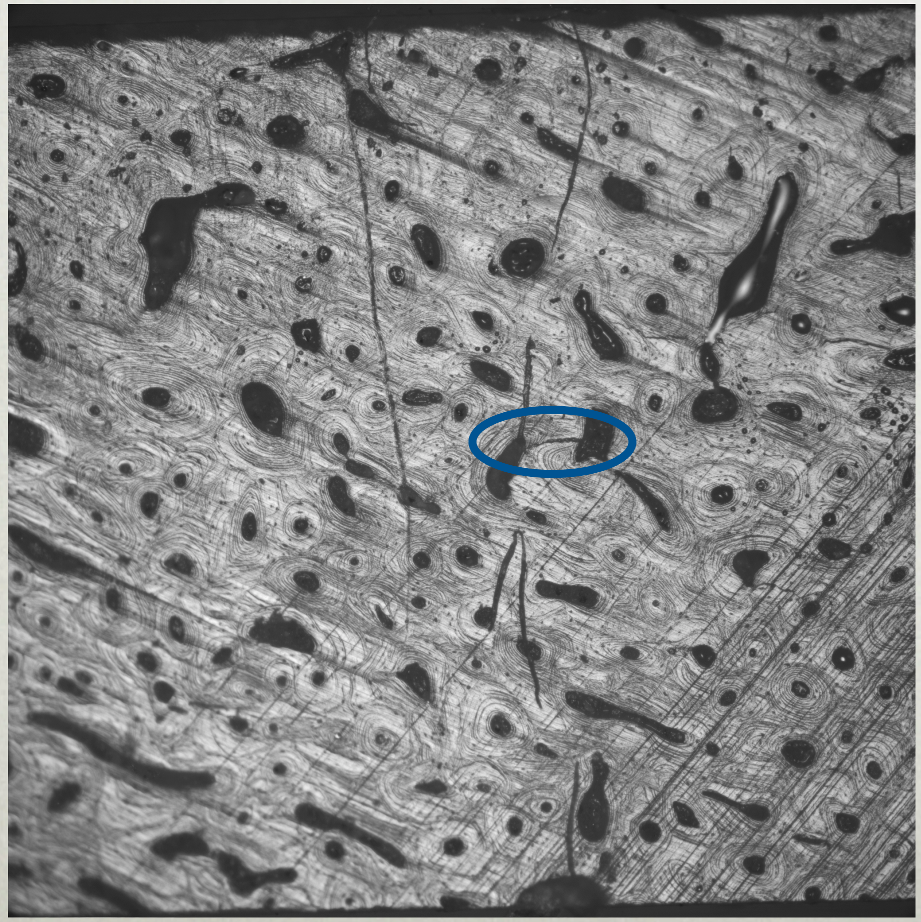

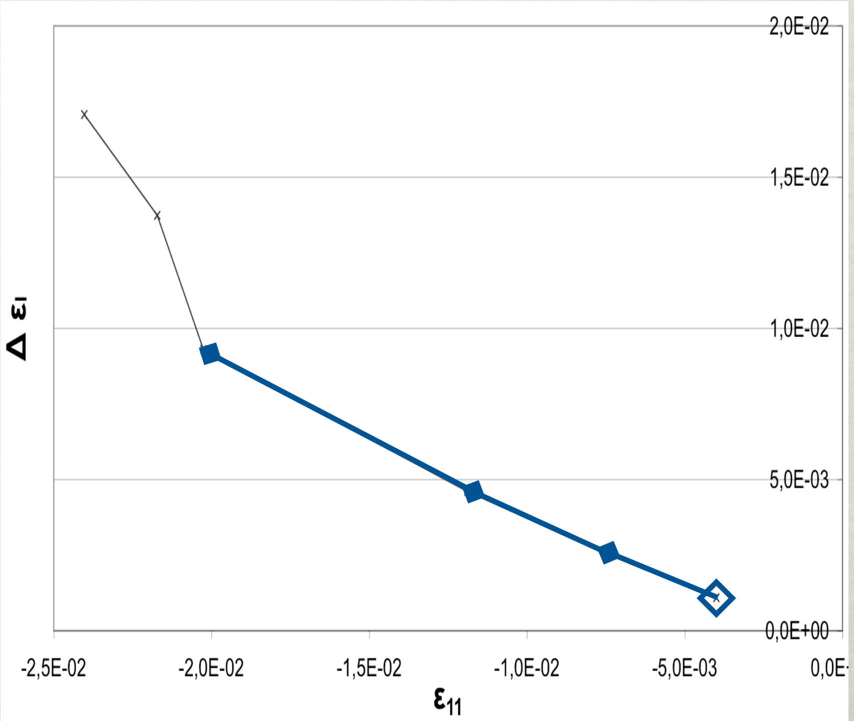

Crack step detection

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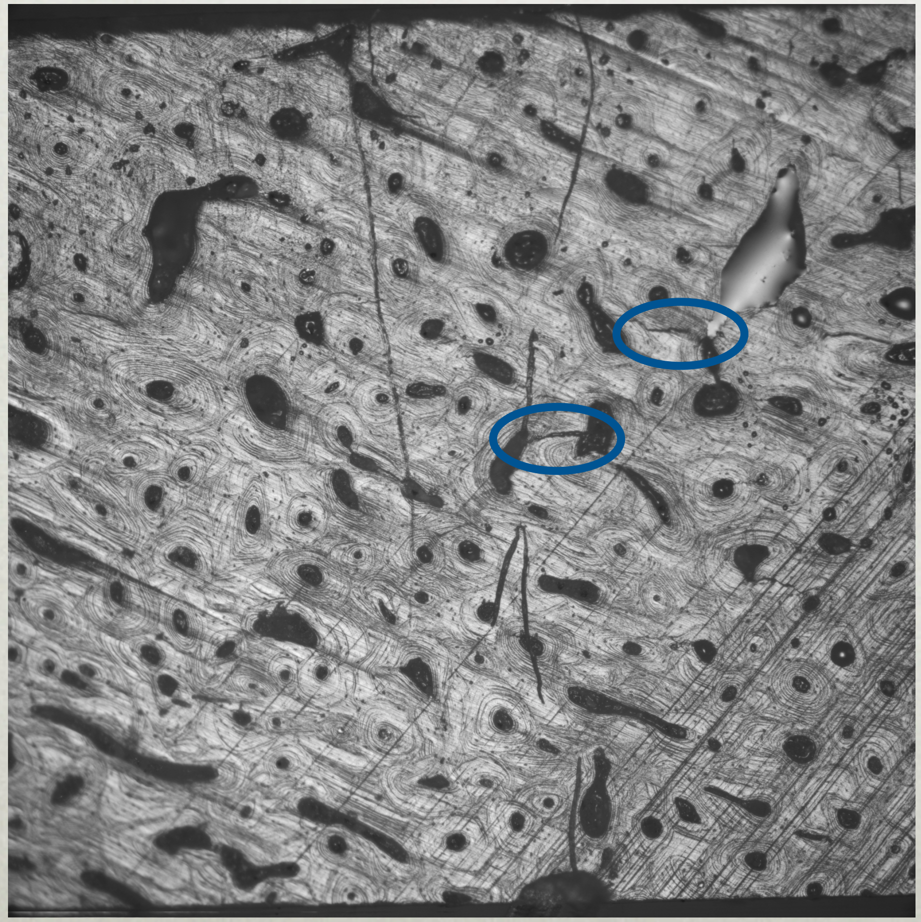

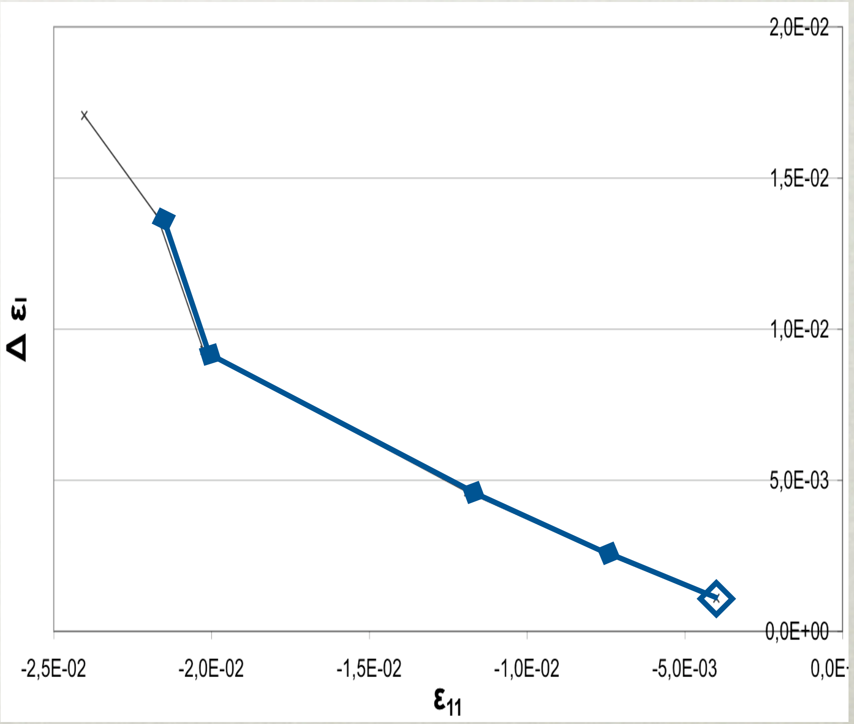

Crack step detection

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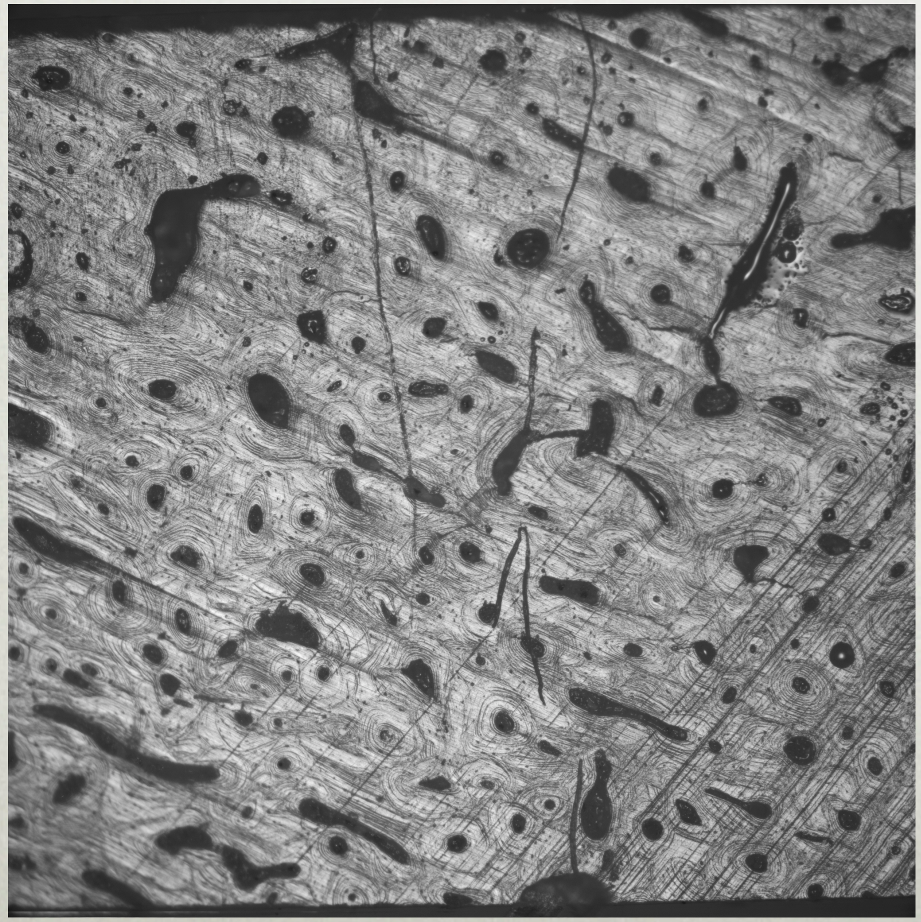
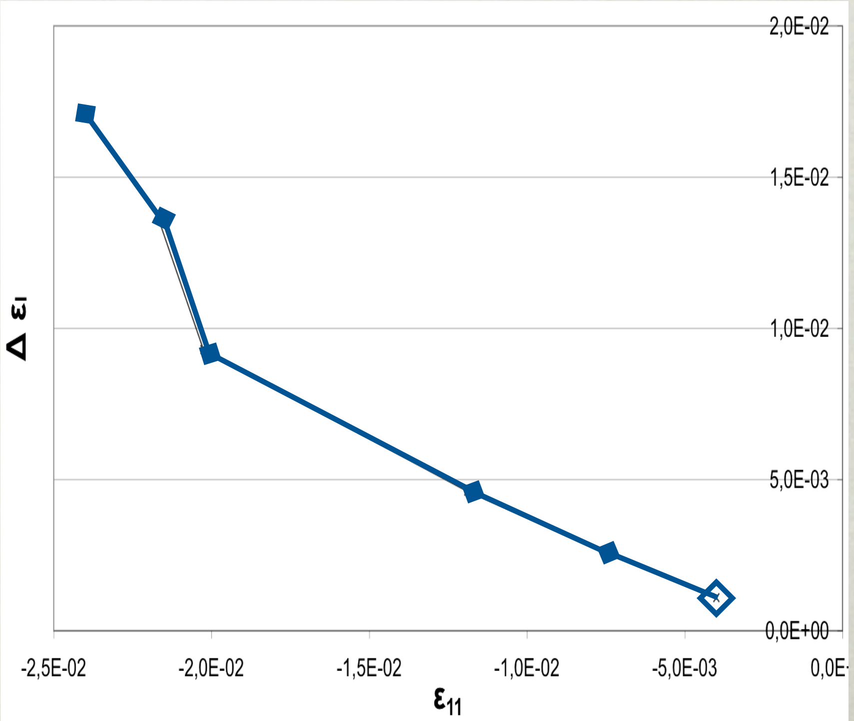




Crack step threshold strain

- Definition of a threshold strain → ε_s

$$\varepsilon_s = \varepsilon_l + 2\Delta\varepsilon_l$$

  - 95% of the local strain values in $[\varepsilon_l - 2\Delta\varepsilon_l ; \varepsilon_s]$ (Gaussian distribution)

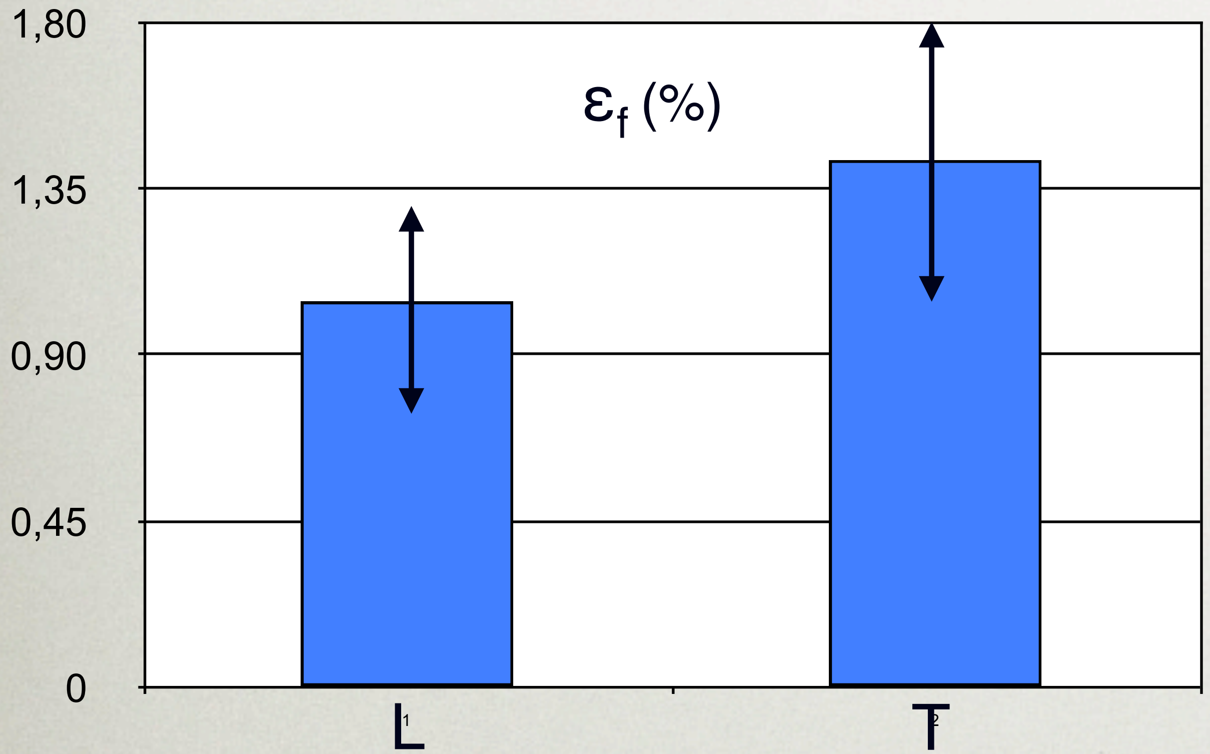
- Crack step threshold strain → ε_{sf}

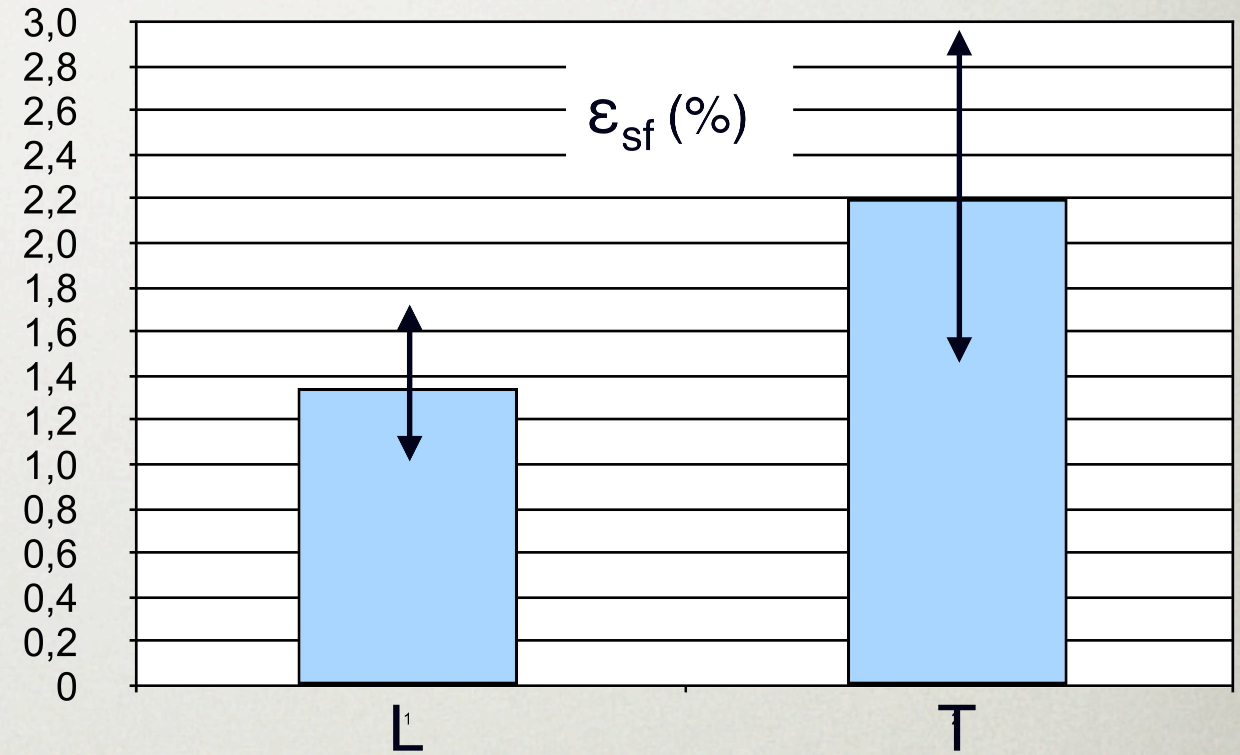
$$\varepsilon_{sf} = \varepsilon_f + 2\Delta\varepsilon_f$$

  - estimation of the strength in terms of strain
  - relevant quantity for a remodelling model

Crack step threshold strain

- Summary of the studied samples



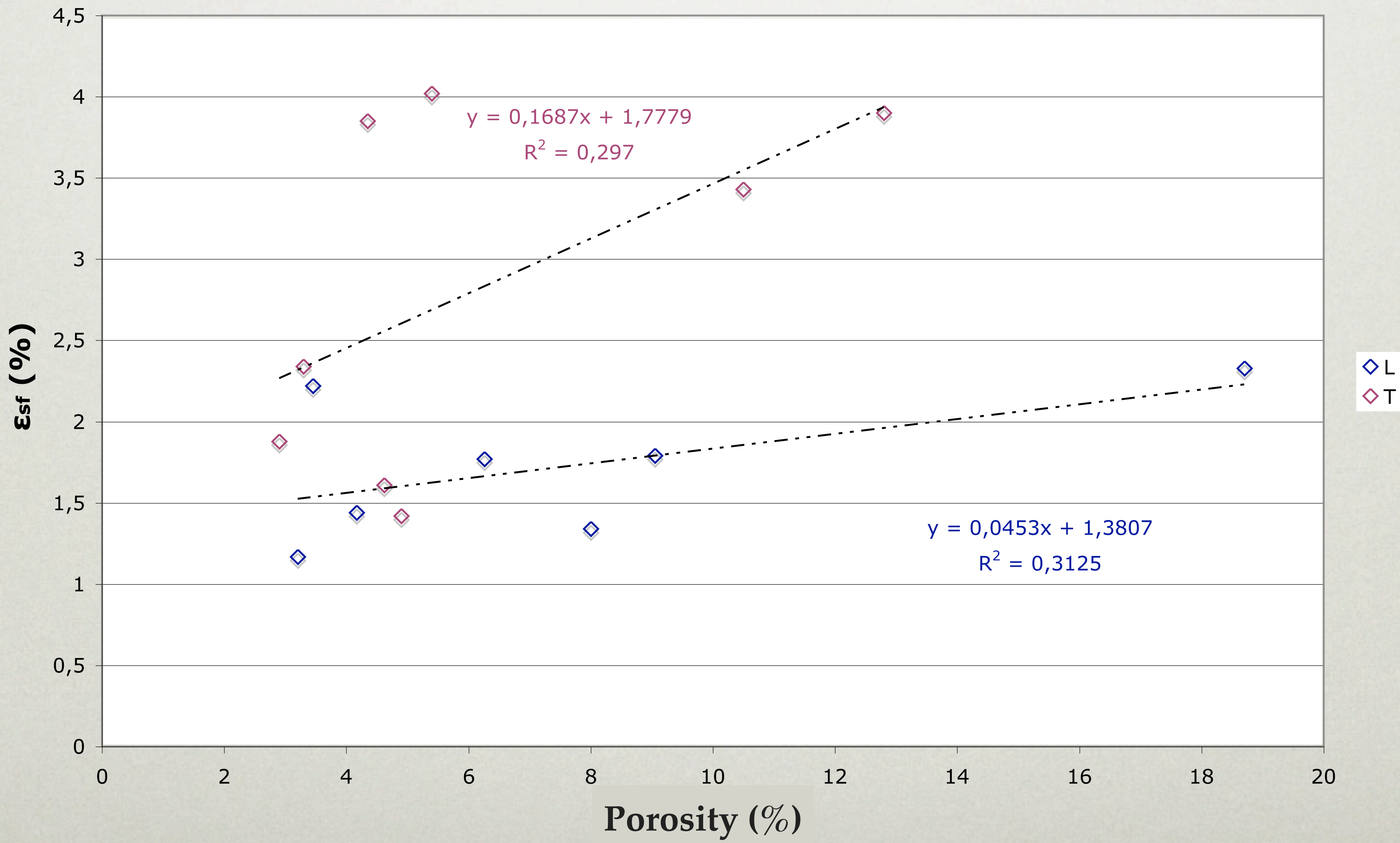


1.05 ± 0.26 | 1.43 ± 0.36 | 1.35 ± 0.36 | 2.2 ± 0.75

Crack step mean strain | Crack step threshold strain

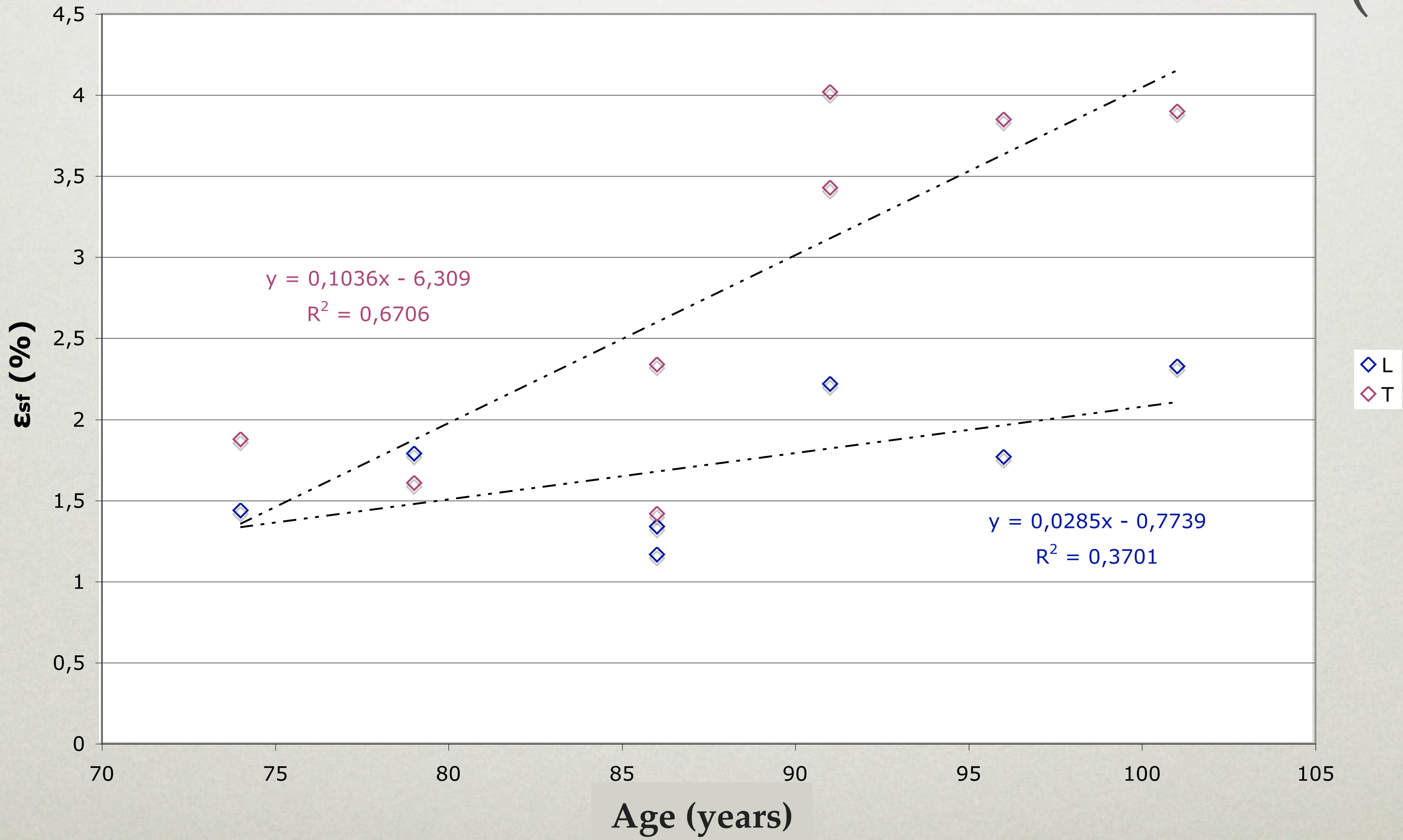
Crack step threshold strain

- Slight correlation with porosity (~30%)



Crack step threshold strain

- Stronger correlation with the patients' age (~50%)

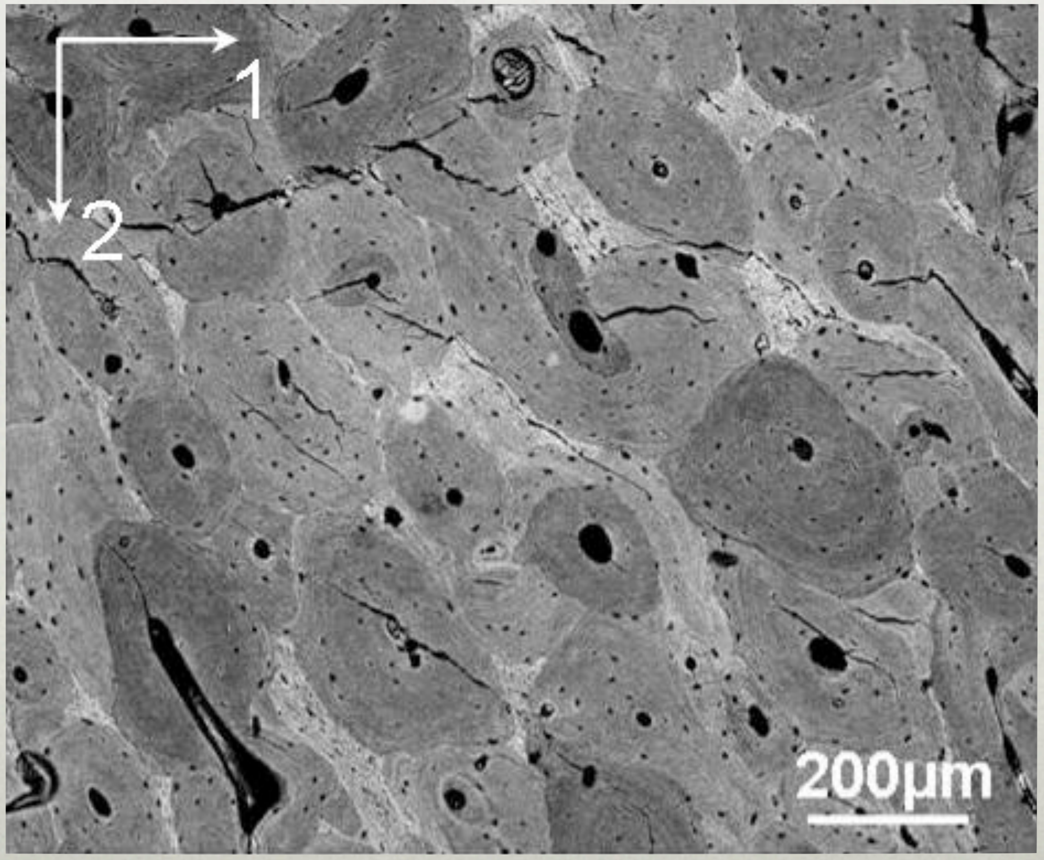


Outline

- Part I: Experiments on cortical tissue
- Part II: Strain measurements
- Part III: Identification of mechanical properties
  - Young's modulus and Poisson's ratio on bovine cortical bone [Henry 2006]
  - Young's modulus and Poisson's ratio on human cortical bone [Devulder 2009]

Specimen geometry

- Studied bone sample
  - bovine cortical bone
  - cavities and primary bone are removed



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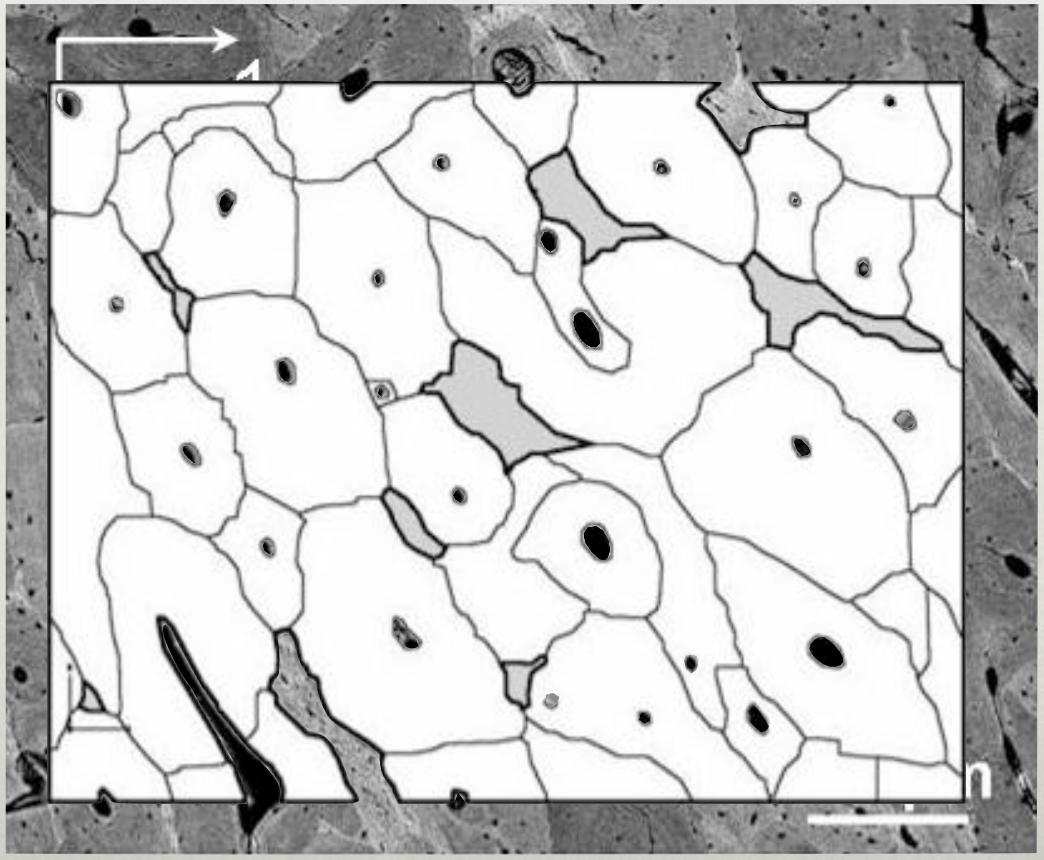

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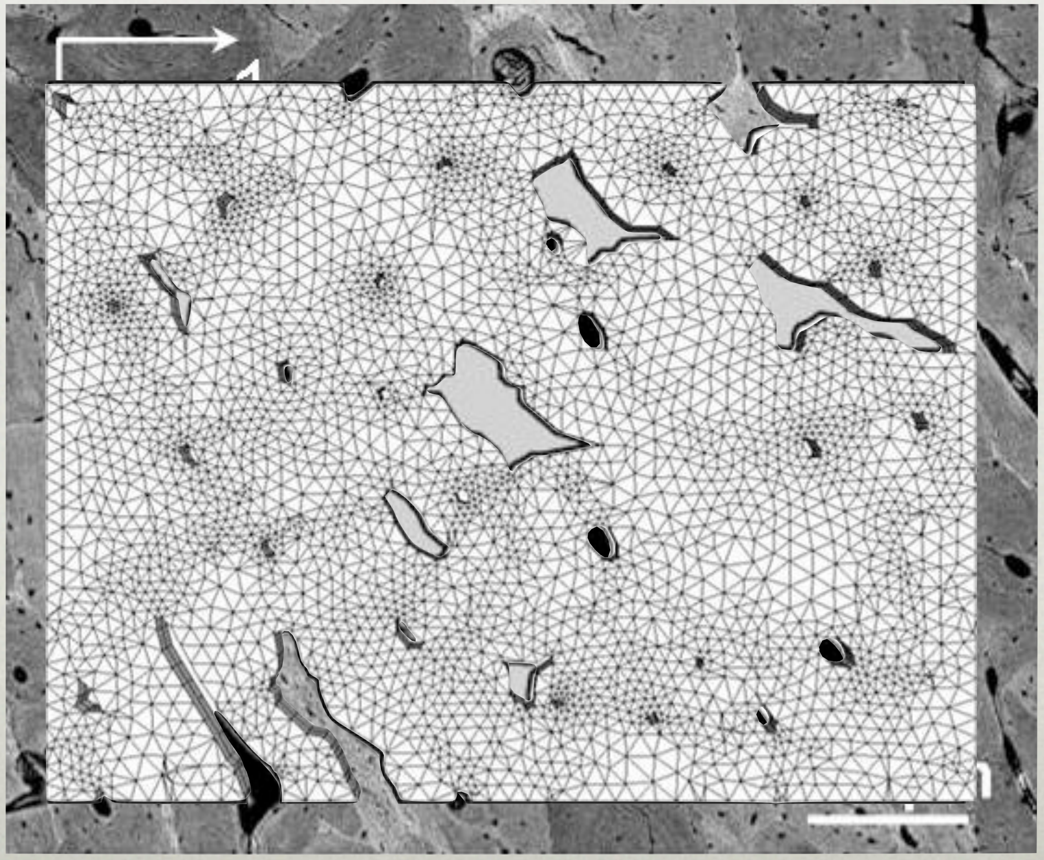
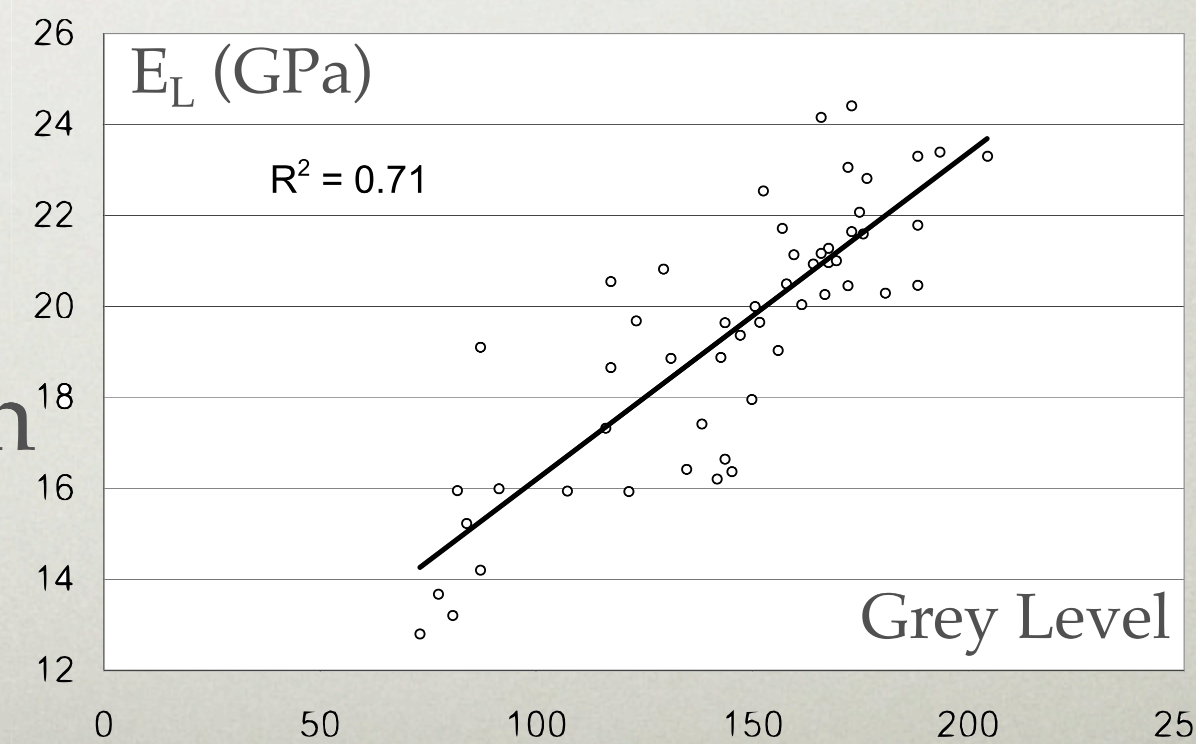
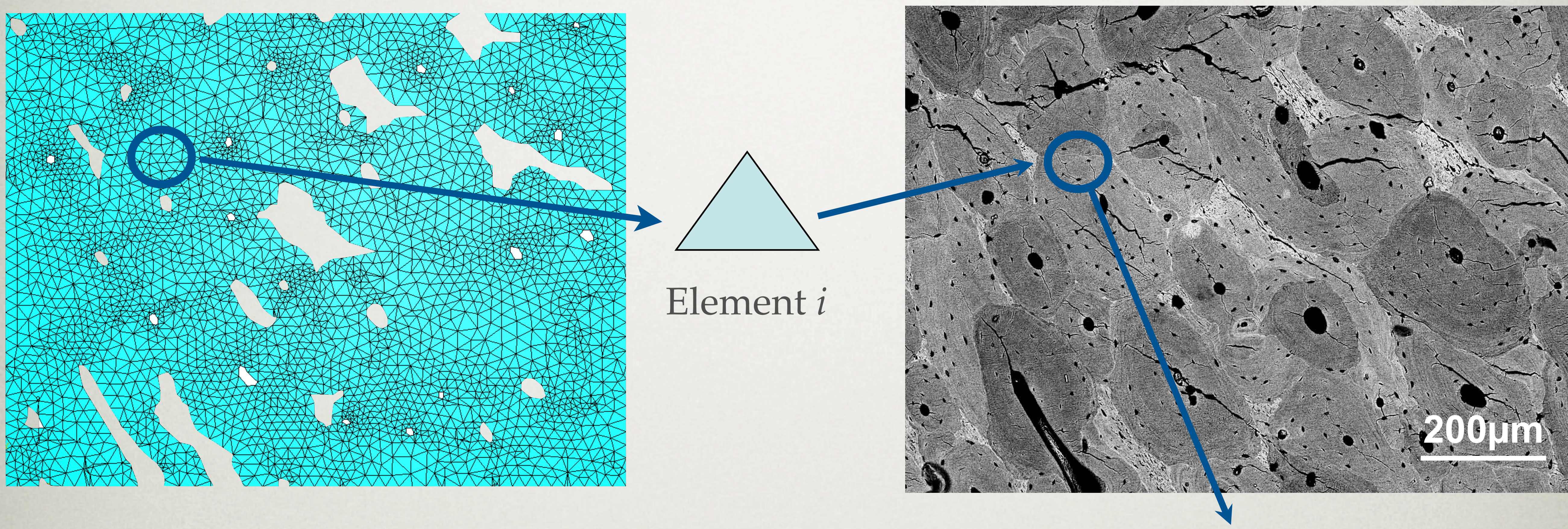


Young's modulus heterogeneity

- SEM images (backscattered electron mode)
  - grey level proportional to mineral content
- Existence of a correlation
  between the local Young's modulus and mineral content
  - ~70%
  - nanoindentation tests



FE Mesh properties



- Finding local elastic properties

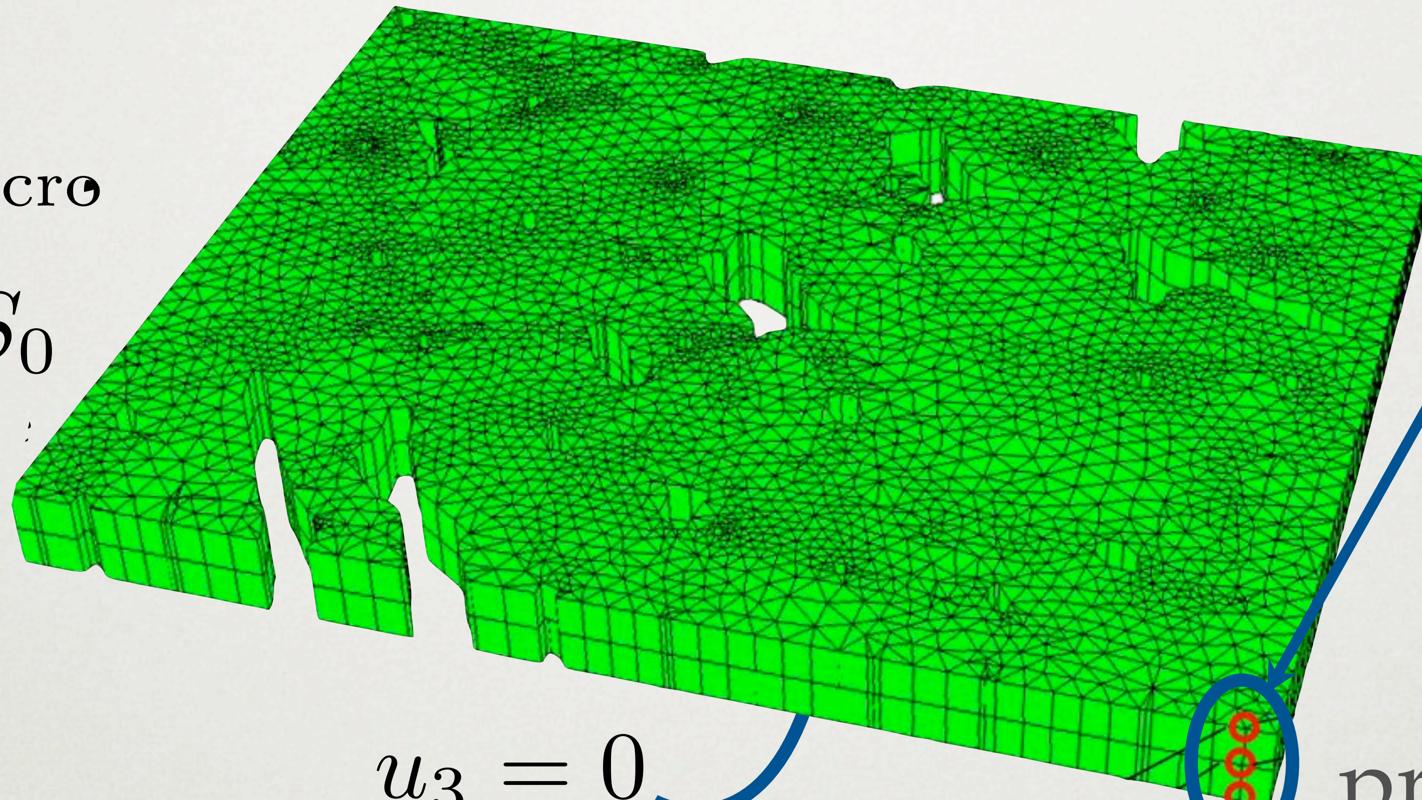
  $E = a\,GL + b$ (experimental correlation)

  $\nu = c\,GL + d$ (assumption)

- GL distribution leads to a Gaussian law

  $(a, b, c, d) \longleftrightarrow \boxed{(\bar{E}, sd_E, \bar{\nu}, sd_\nu)\ \text{to be identified}}$

Boundary conditions



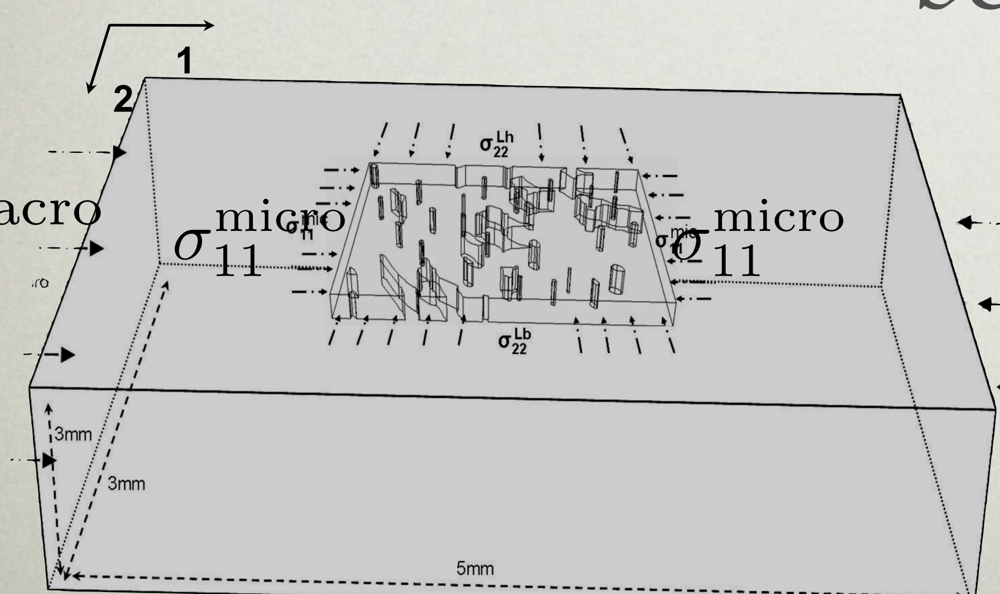
$$\sigma_{11}^{\text{micro}} = \sigma_{11}^{\text{macro}} = F/S_0$$

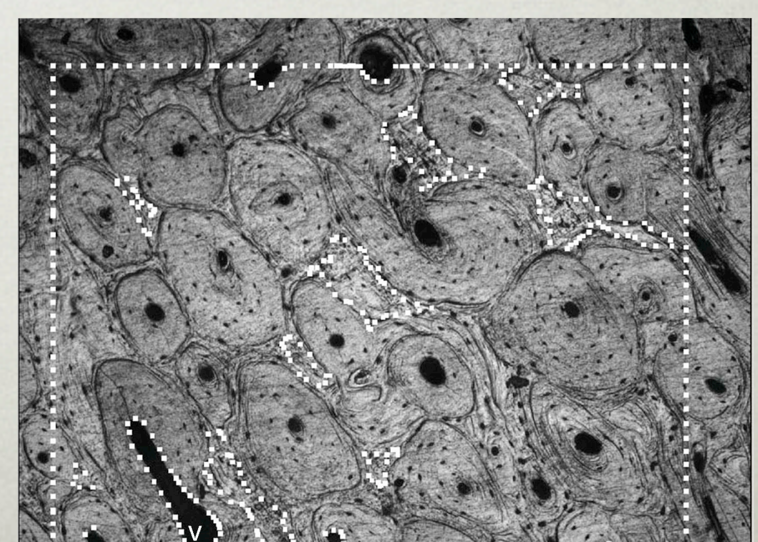
Assumption on the local stress values

$u_3 = 0$ below

$$u_1 = u_1^{\exp}$$
$$u_2 = u_2^{\exp}$$

Experimental displacements prescribed on ……



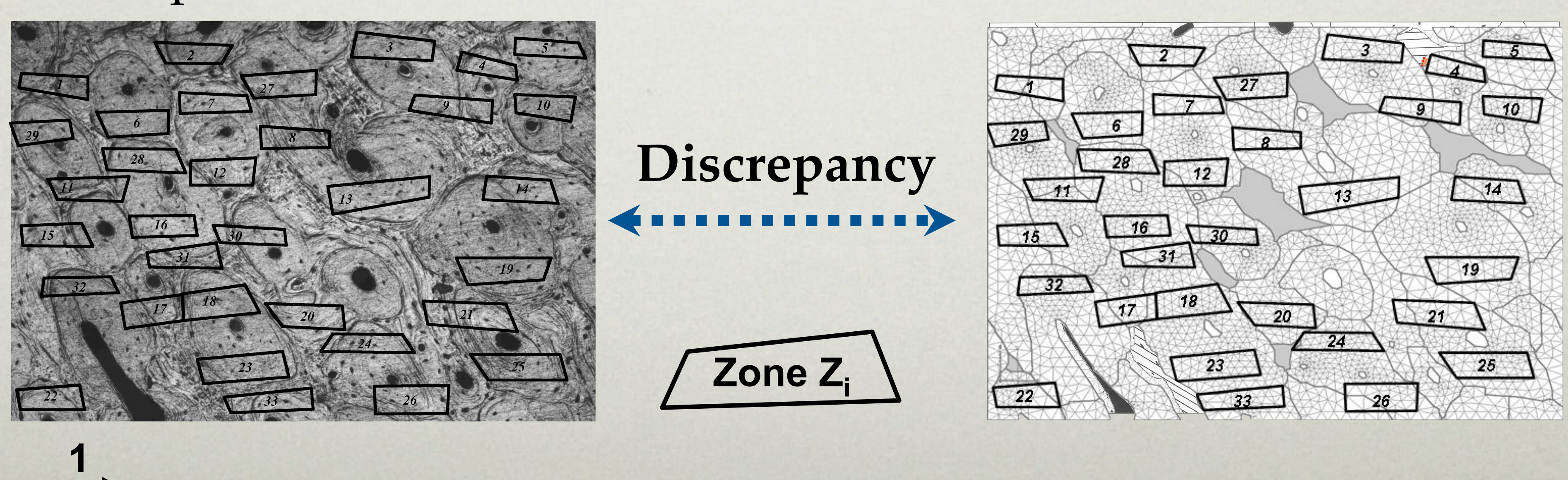


Identifying the mechanical properties

- Mean properties
  - identified from the macro stress assumption
  - $\overline{E} = 5.4\ \text{GPa}$ and $\overline{\nu} = 0.22$
- Heterogeneous properties

DIC experimental strains

FE numerical strains



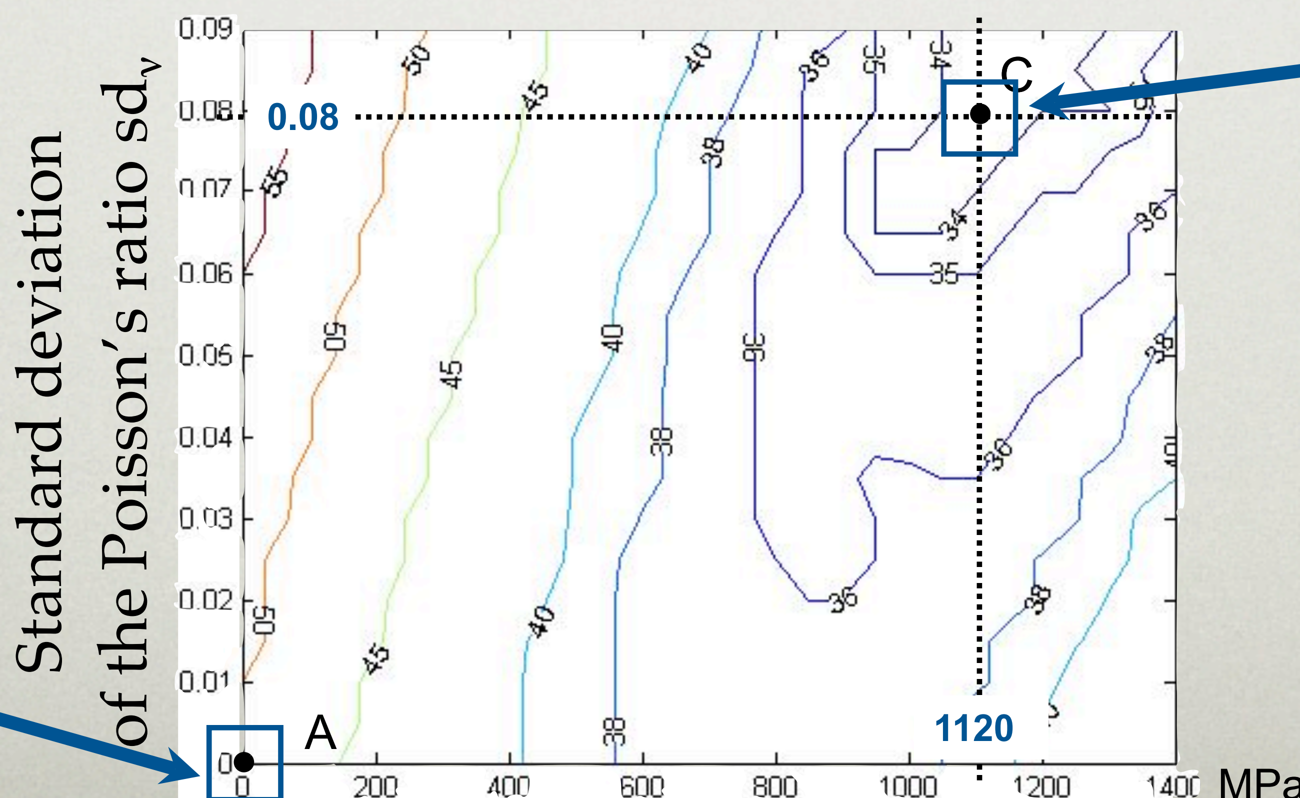
Misfit function

- Definition of a misfit function

$$\Delta'_{\varepsilon} = \sum_{i=1}^{N} \max\left(\frac{\left|\varepsilon_{Z_i}^{\mathrm{EF}} - \varepsilon_{Z_i}^{\exp}\right|}{e_{\mathrm{noise}}} - 1, 0 \right)$$

- Minimum of the misfit function

Standard deviation of the Young's modulus sd_E

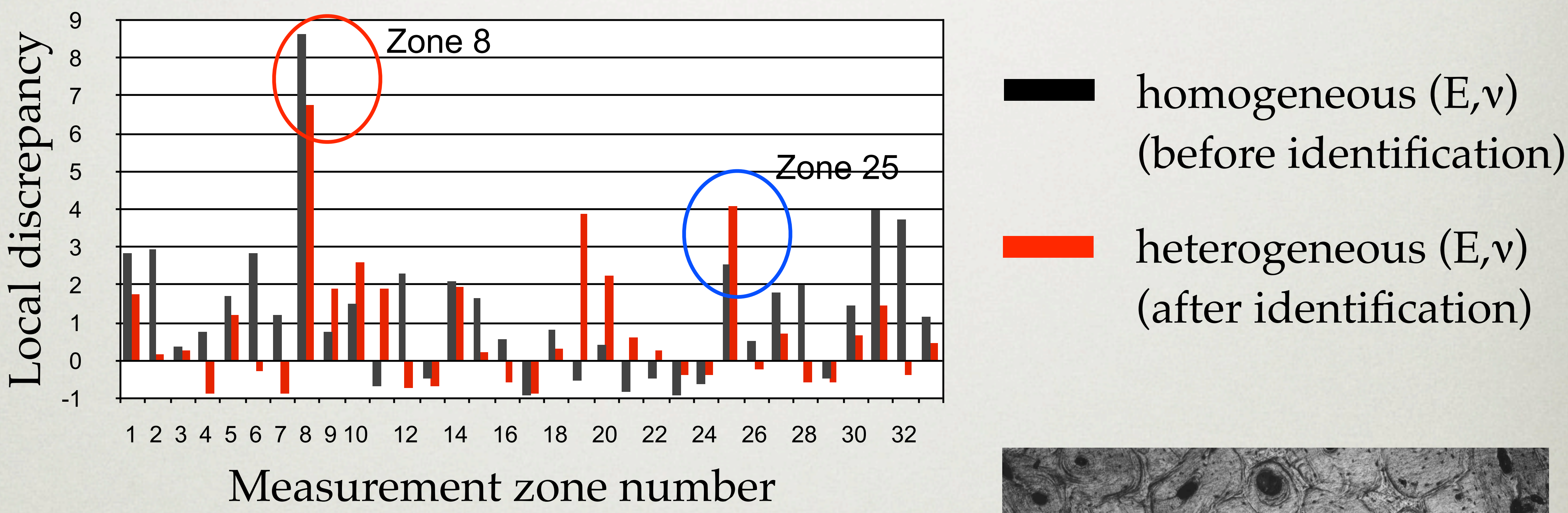


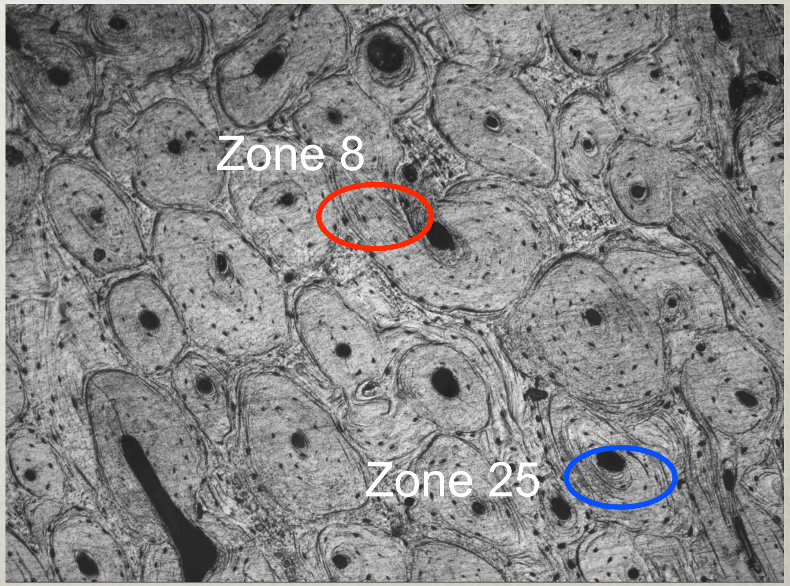
Optimal heterogeneous solution $\Delta'_{\varepsilon} = 34$

Homogeneous solution $\Delta'_{\varepsilon} = 49$

Final discrepancy

- Strains comparison

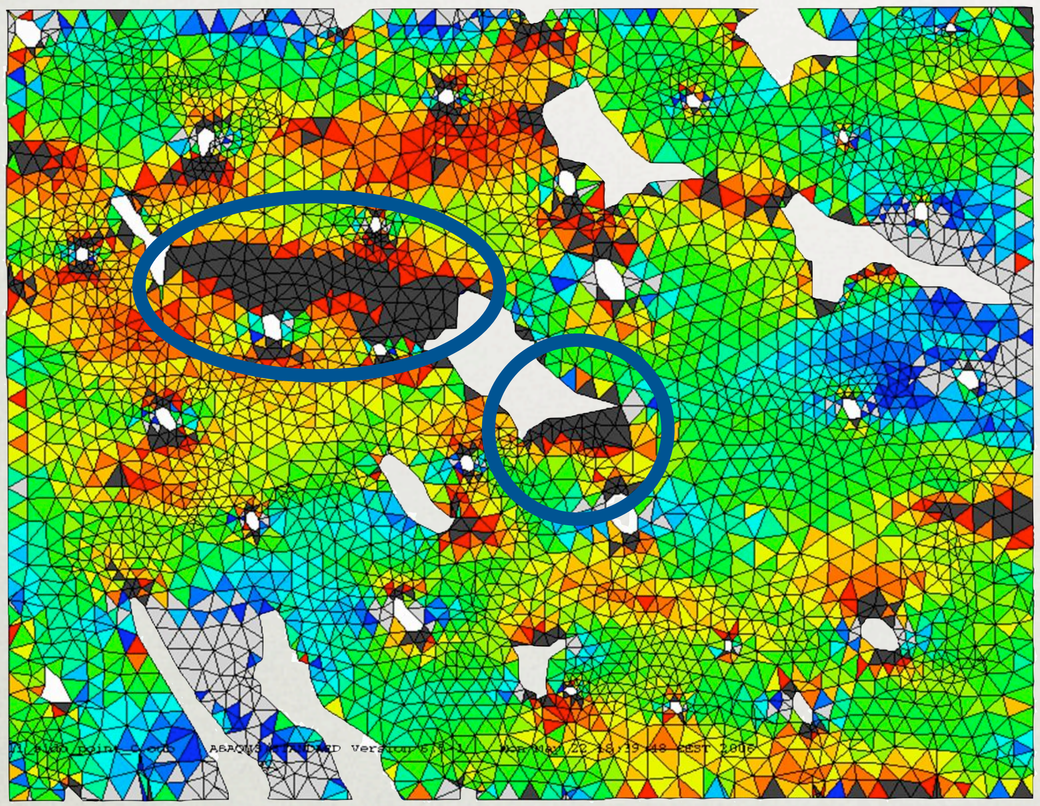




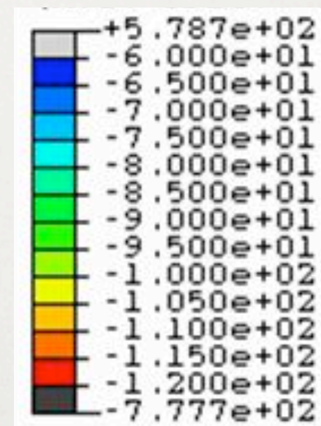
- global reduction
- still some erroneous zones

Influence of the heterogeneities

- Uniaxial stresses field



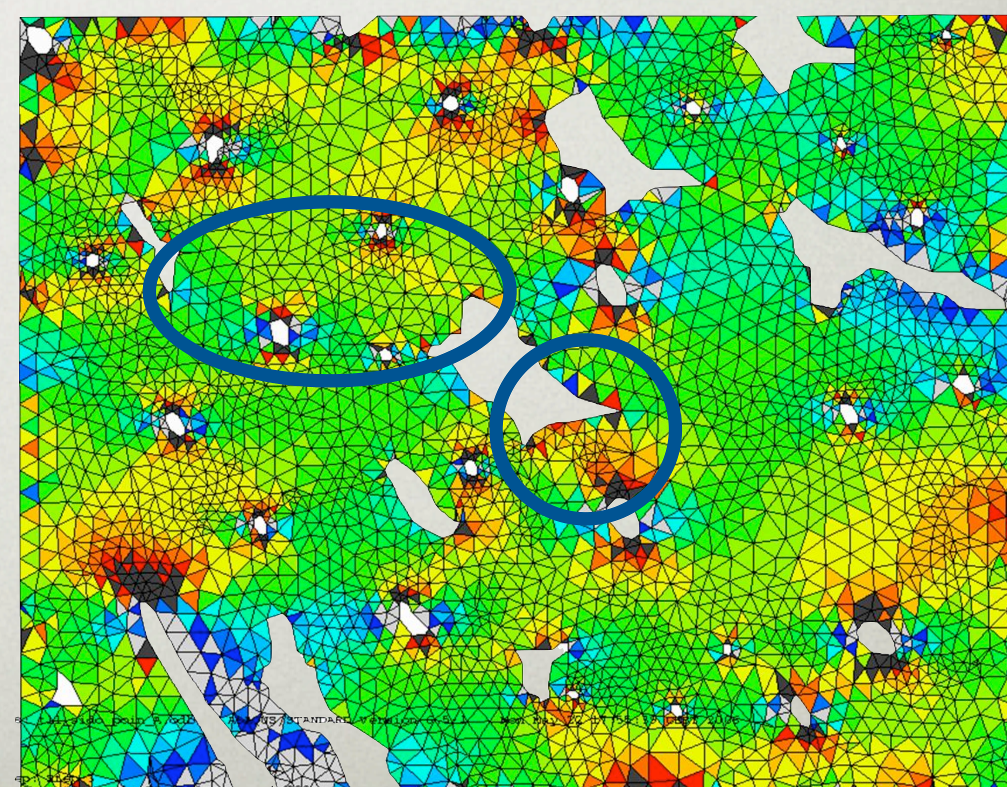
Heterogeneous (E,ν)



1

σ_{11} (Mpa)

Homogeneous (E,ν)



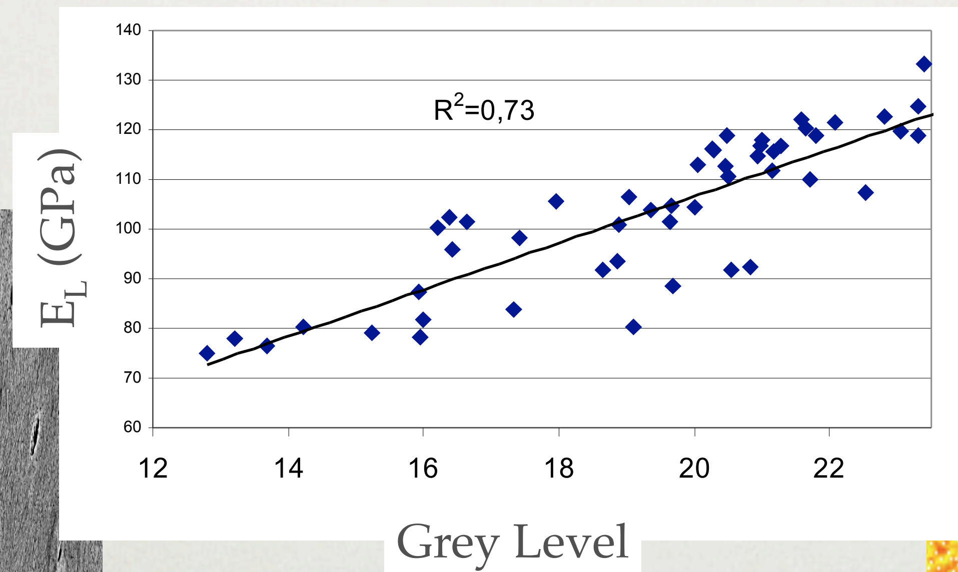
- stress concentrations

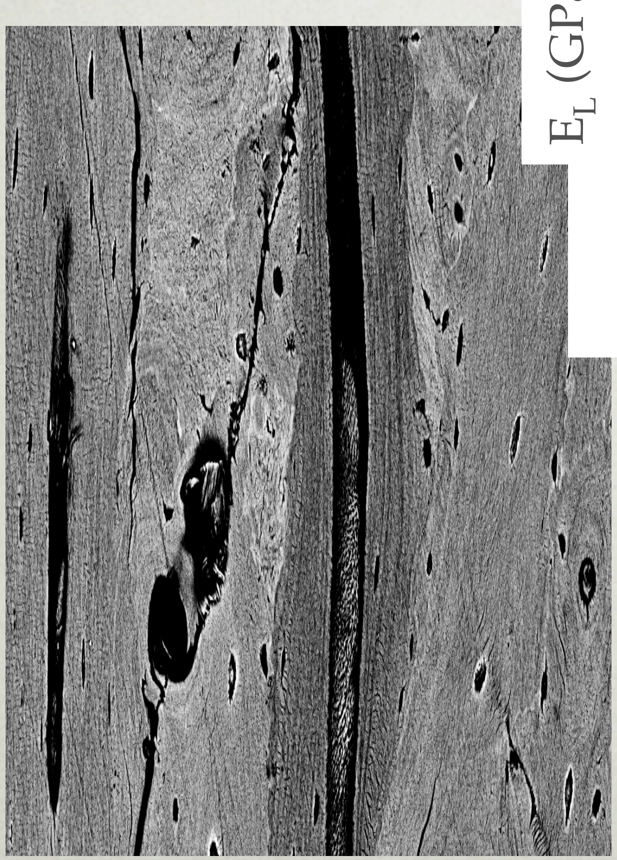
  ➡ bone remodelling

Human bone samples

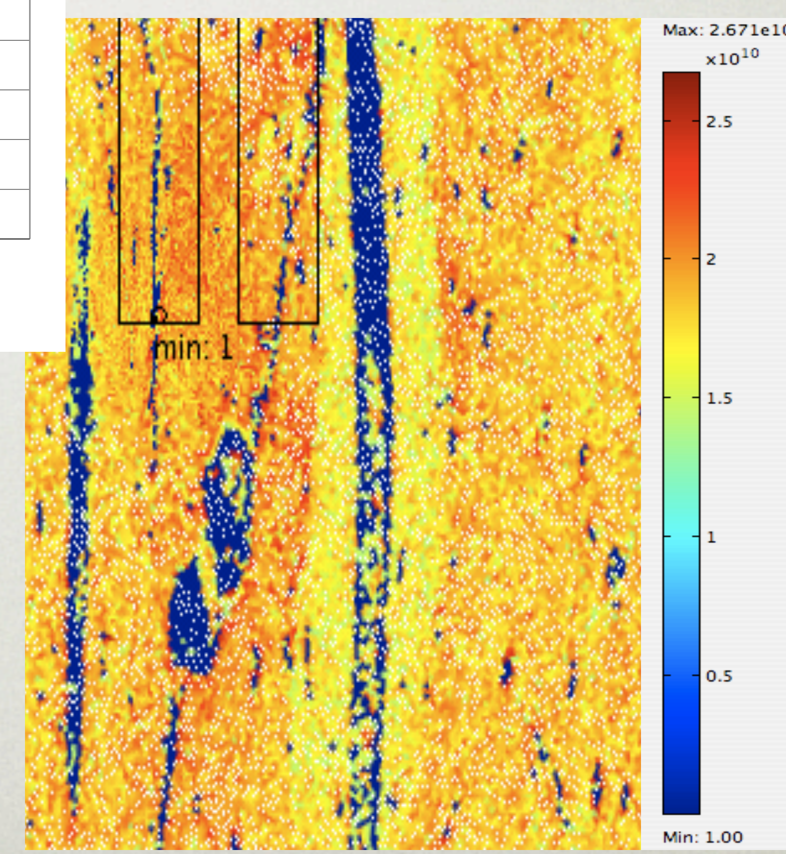
- Determining the local Young's modulus

Nanoindentation tests





73% correlation



Backscattered electron SEM image

Young's modulus in the FE mesh

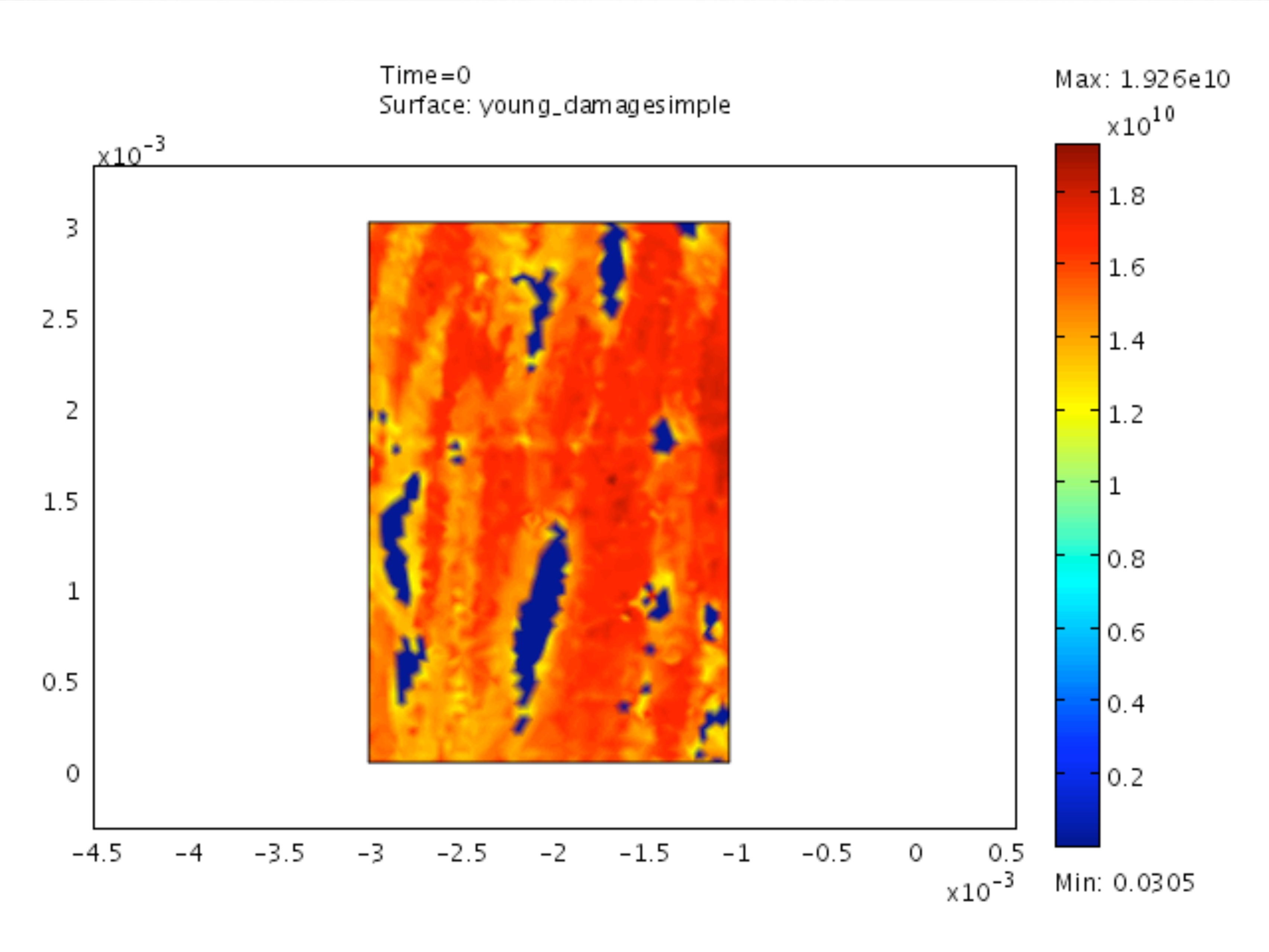
Summary

- DIC-based experiments
  - macro/micro strain values
- Highlighted correlations
  - effects of the microsctructure
- Identified mechanical parameters
  - Young's modulus and Poisson's ratio
  - crack step threshold strain

Remodelling simulation

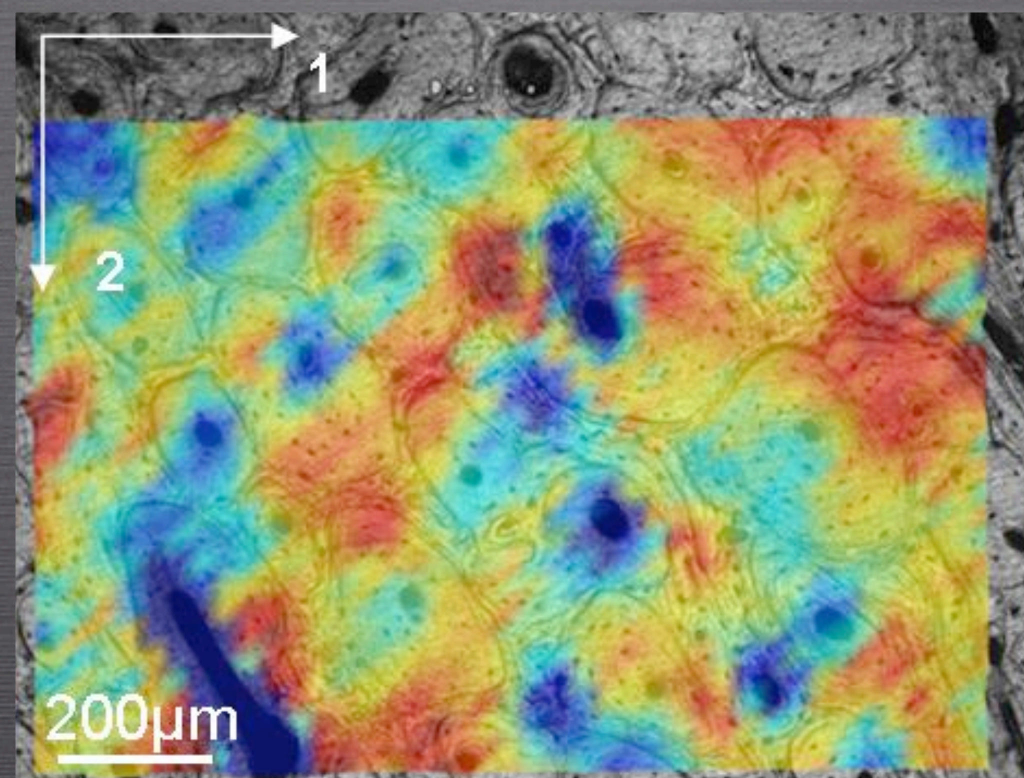
[Devulder 2009]

Remodelling simulation



[Devulder 2009]

Microextensometry measurements and identification of mechanical properties on cortical bone



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