MINERAL CONTENT AND MECHANICAL PROPERTIES OF CEMENT LINES IN HUMAN OSTEONAL BONE

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[4] Center of Forensics Medicine, Vienna, Austria.

Hard Tissue Biomechanics III: Bone Microstructure

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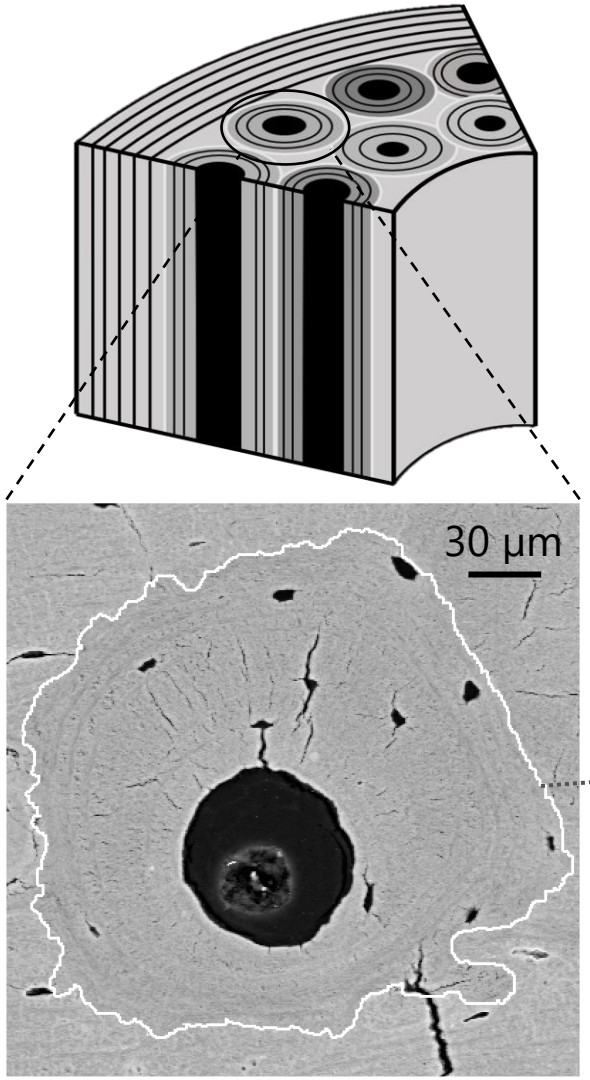
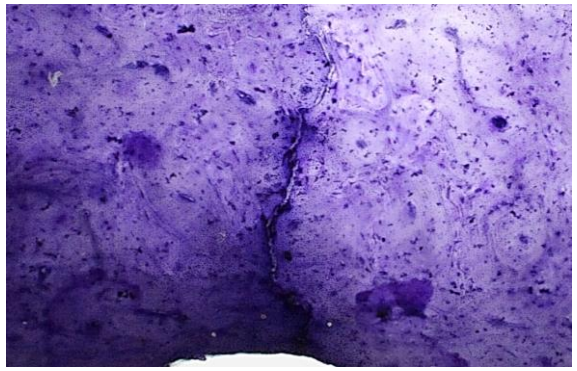
MBBM

What are cement lines (CLs)?

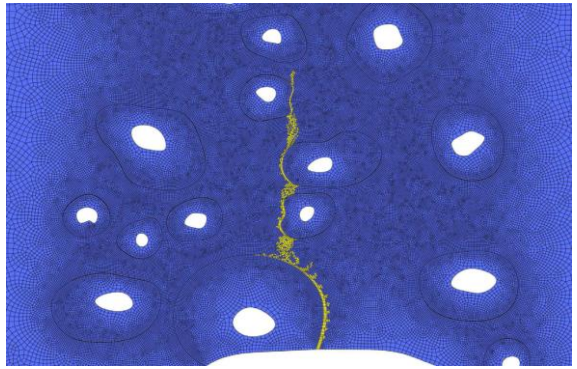


CL: thickness = 1–3 µm

Experimental studies



Computational studies

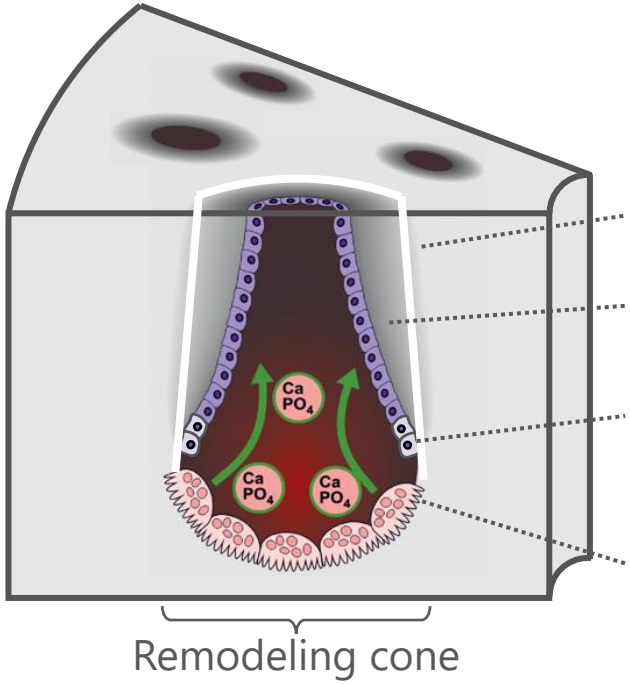


→ CLs are believed to interact with cracks = **Protective** role

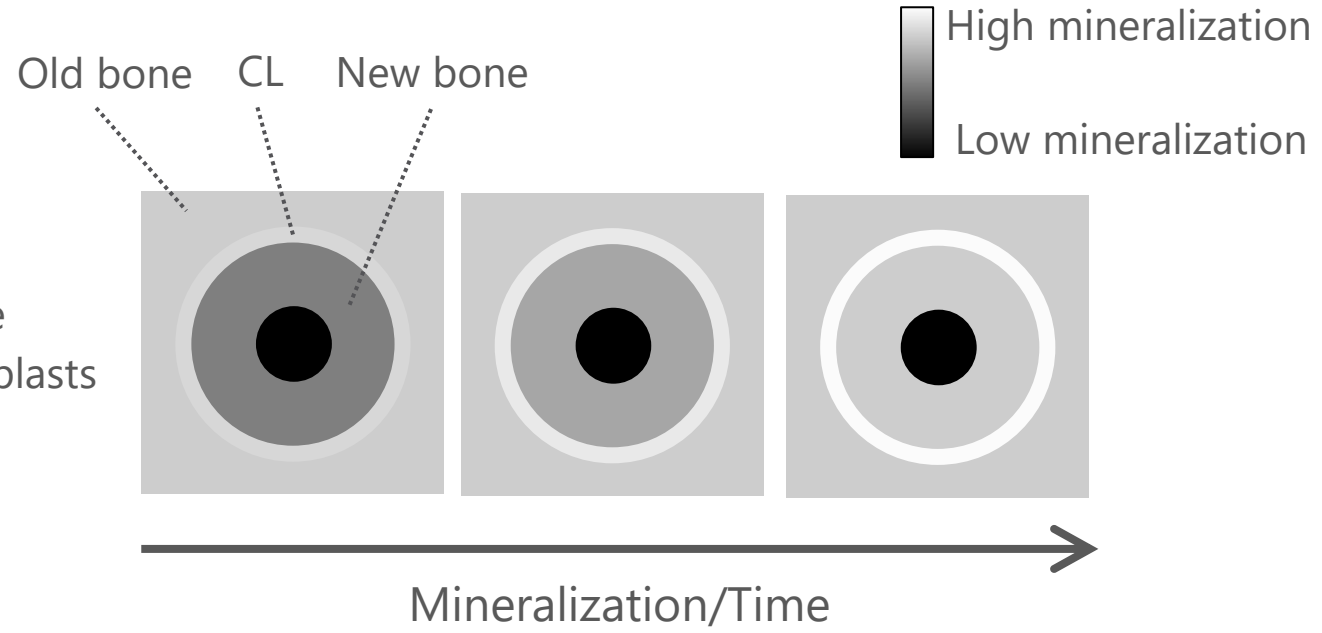
Giner et al., Engineering Fracture Mechanics, 2017

What are the unknowns about cement lines (CLs)?

Formation of secondary osteons



Mineralization kinetics



Research questions:
- Composition
- Structure
- Mechanical properties

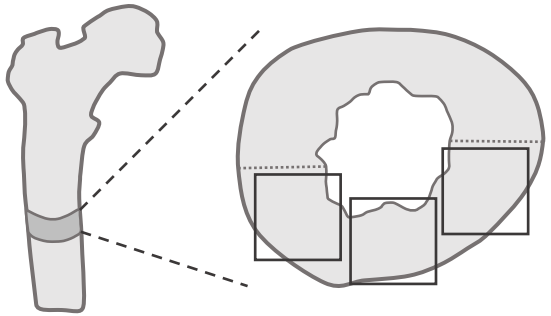
?

Outcomes:
- Bone fracture models
- Bone remodeling models
- New bioinspired composites

Adapted from Roschger et al., Acta Biomater., 2020

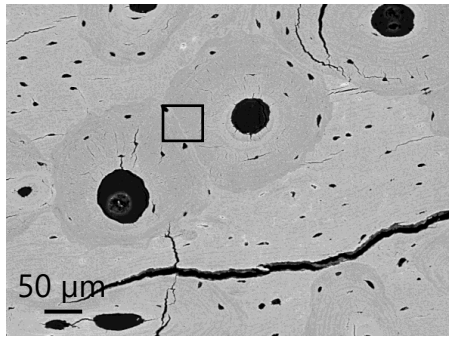
Aims & techniques

→ Characterization of mineral content and mechanical properties of CL and its surroundings



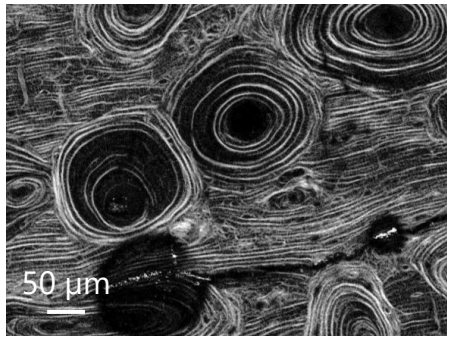
- Human femoral bone
- 2 samples (males, 40 & 81 y.o.)
- 35 uninterrupted osteons

Mineral content: Is there a relationship between the mineral content of CL and of surrounding bone?



qBEI (1)
Pixel size: 570 nm

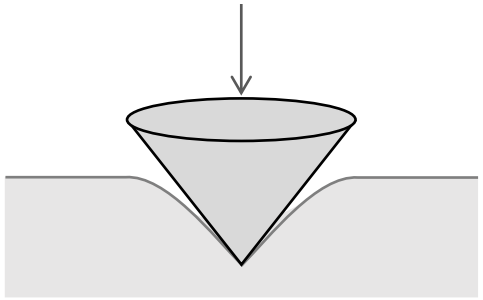
(1) Quantitative backscattered electron imaging



SHG (2)
Pixel size: 380 nm

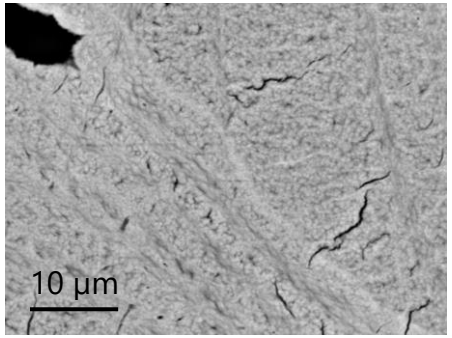
(2) Second harmonic generation

Mechanical properties: Is CL stiffer or more compliant than corresponding osteonal bone?



▼ nIND (4)
Lateral spacing: 1 µm

(4) Nanoindentation

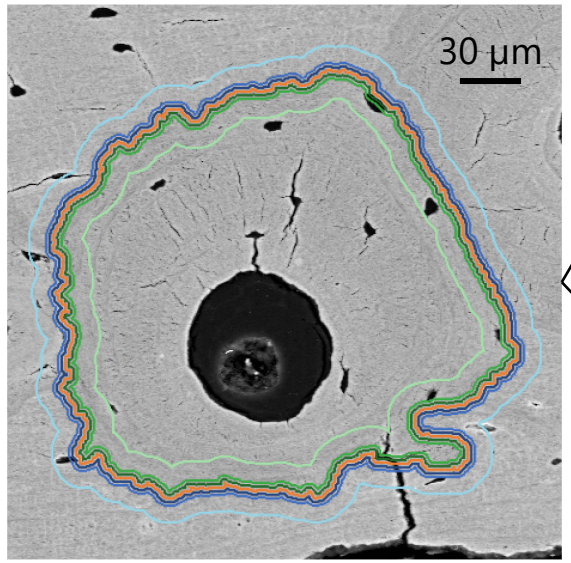


hrBEI (3)
Pixel size: 75 nm

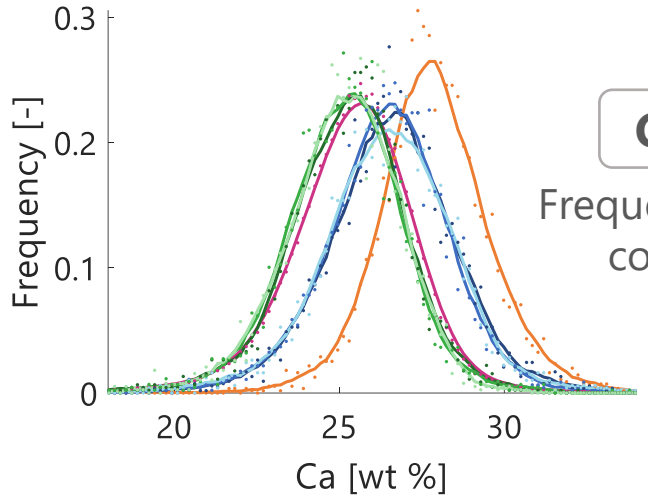
(3) High resolution backscattered electron imaging

Methods | Layers segmentation & data post-processing

qBEI
Pixel size: 570 nm

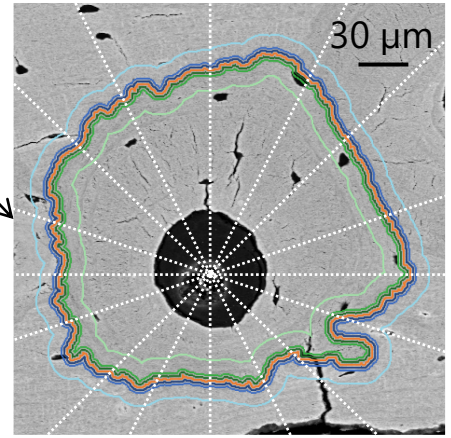


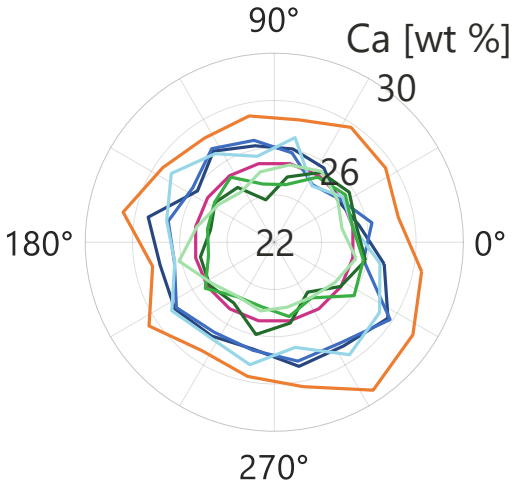
→ Layer analysis [2 pix ≃1 µm]



Global analysis

Frequency distribution of Ca content in each layer





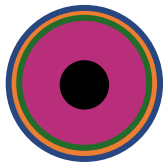
Local analysis

From layers to sectors

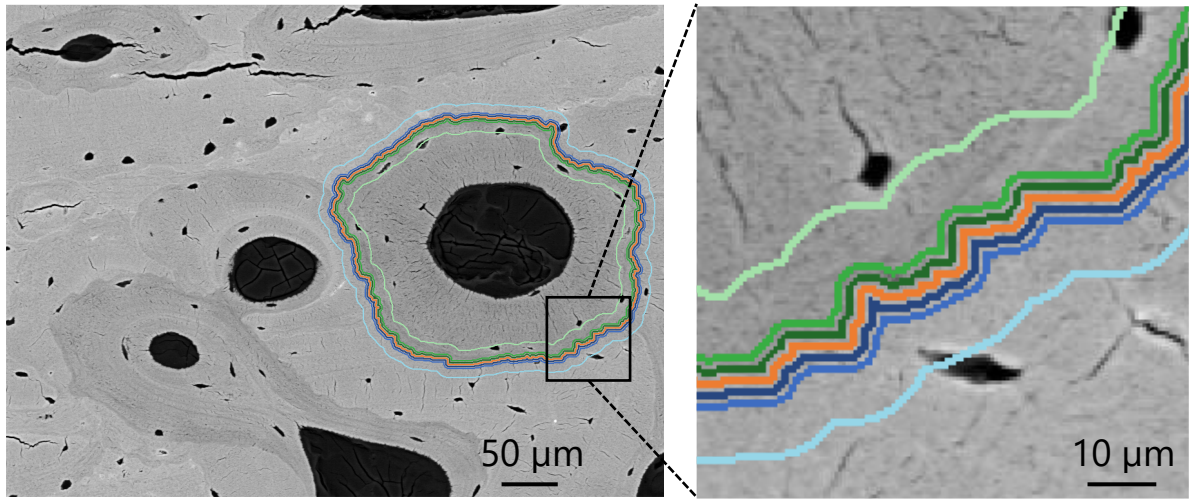
- Cement Line (CL)
- Average Osteon (Os)
- Layer inside 1 (I1)
- Layer inside 2 (I2)
- Layer inside 3 (I3)
- Layer outside 1 (O1)
- Layer outside 2 (O2)
- Layer outside 3 (O3)

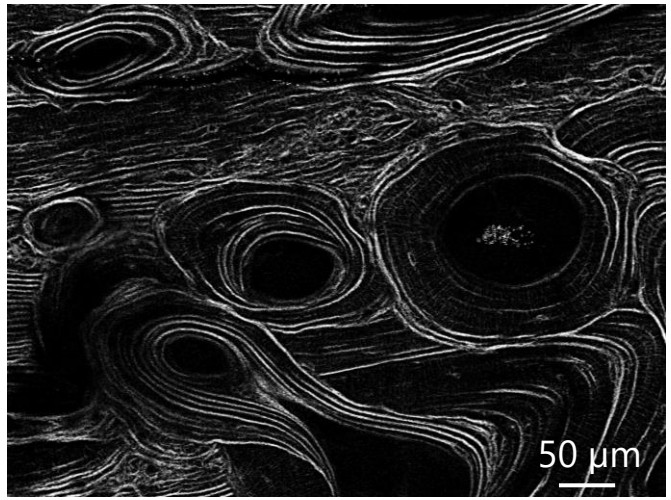
Results | Analysis of a low mineralized 'young' osteon

'Younger'



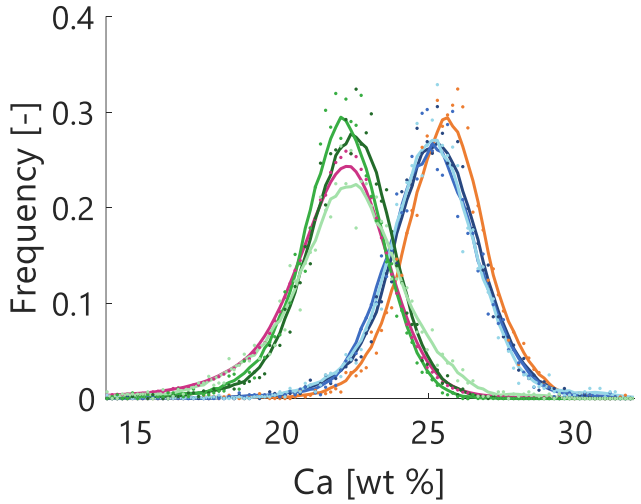
Ca mean = 21.79 wt %

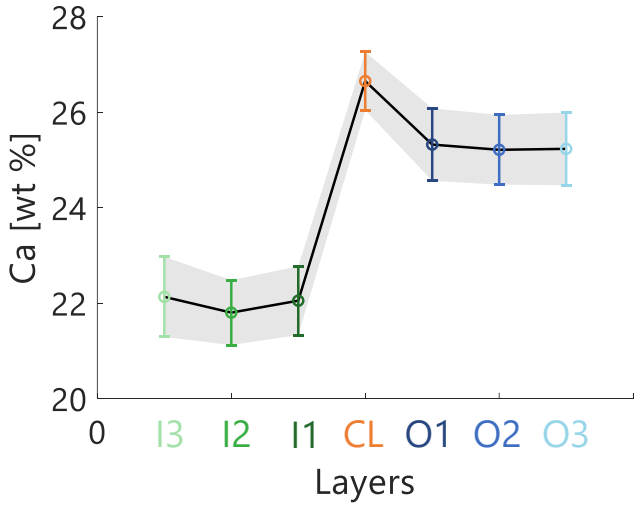




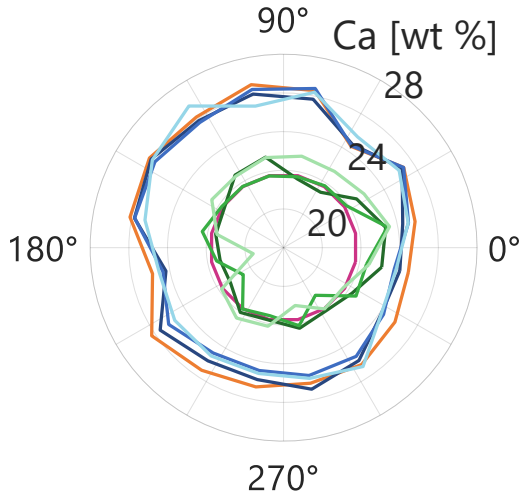
CL Os
I1 O1
I2 O2
I3 O3

Global analysis





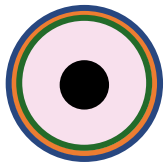
Local analysis



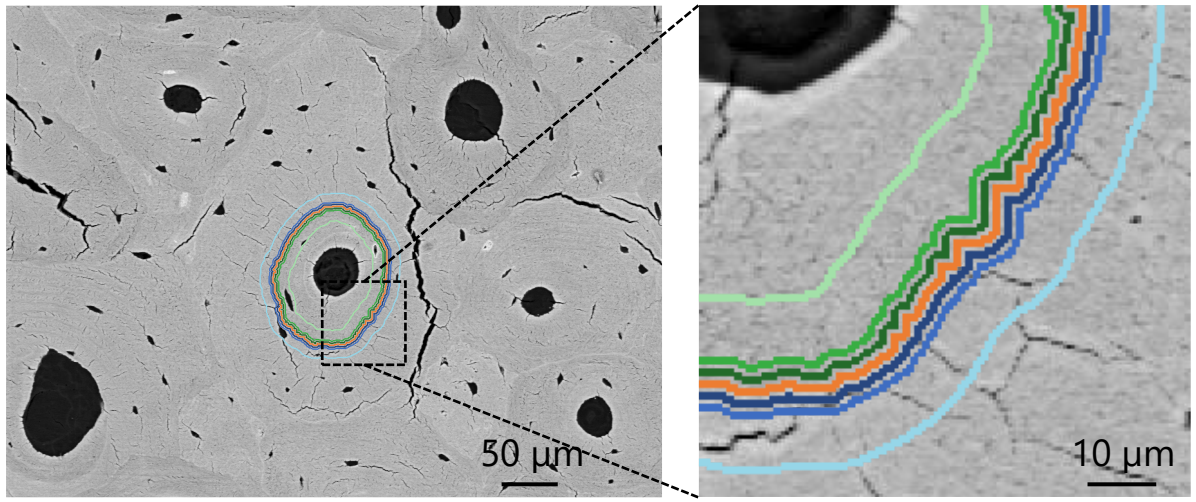
- CL higher mineral content
- Mineral content of CL follows outer layers polar profile

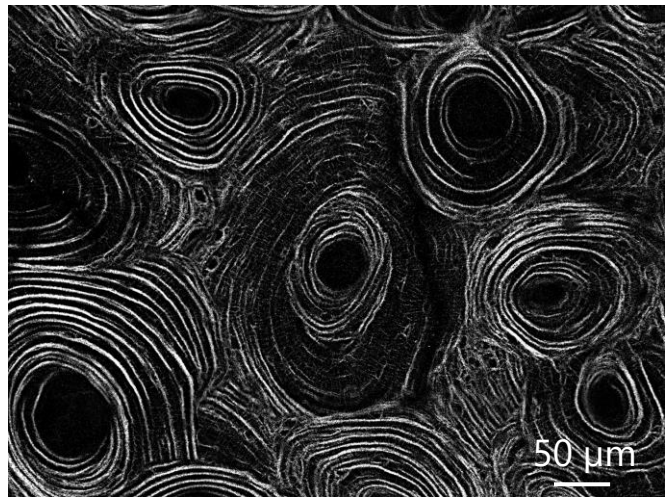
Results | Analysis of a high mineralized ‘old’ osteon

‘Older’



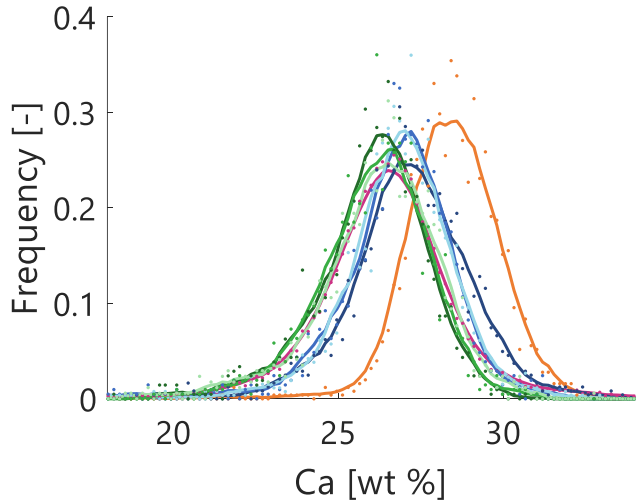
Ca mean = 26.4 wt %

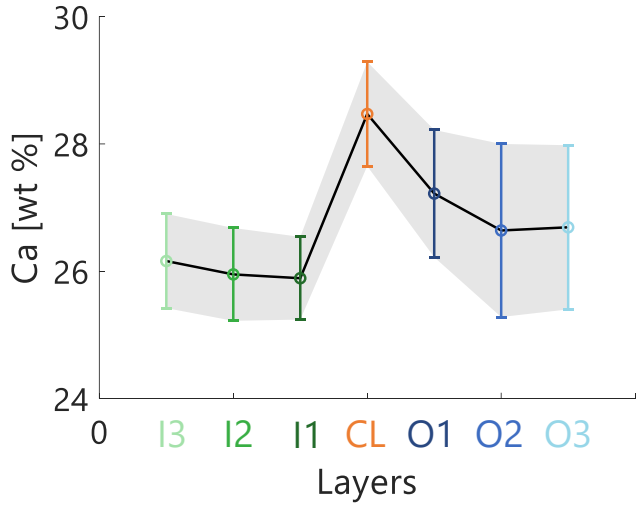




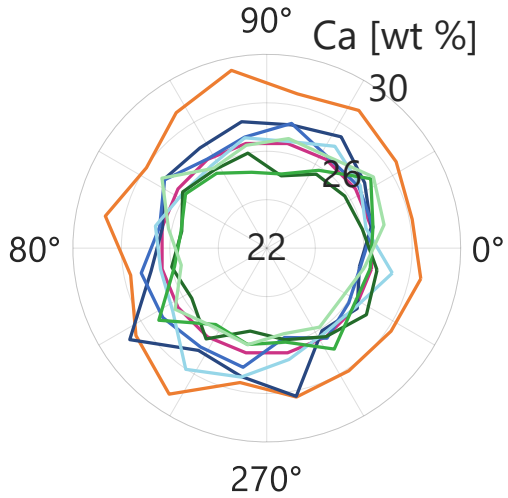
CL	Os
I1	O1
I2	O2
I3	O3

Global analysis



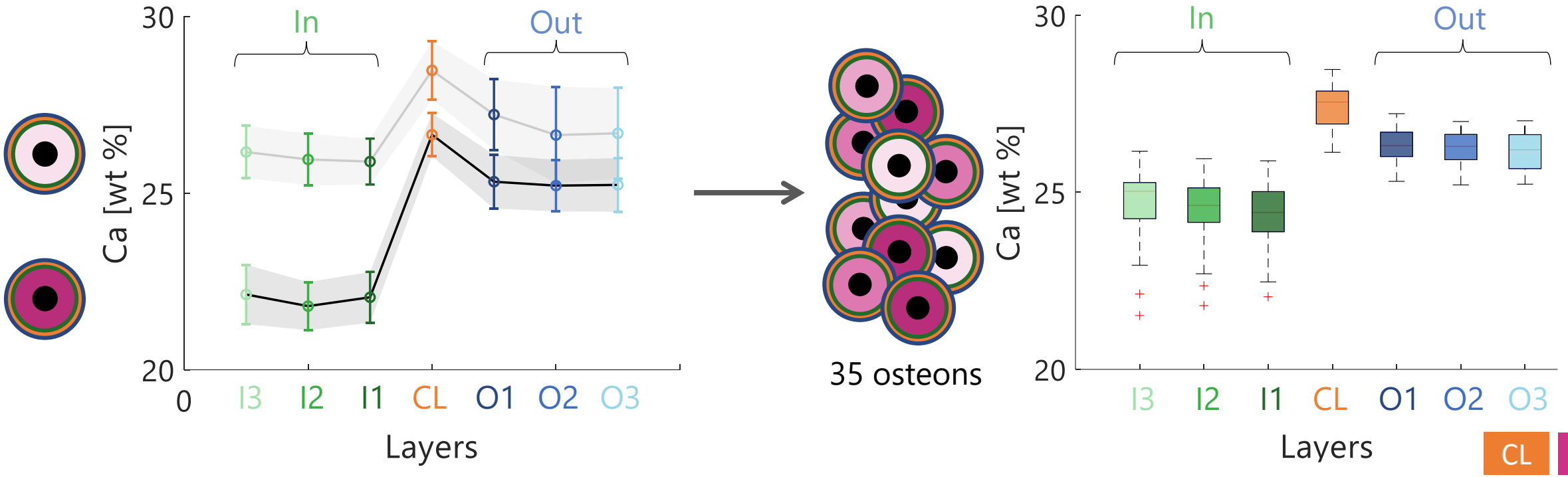


Local analysis



- CL higher mineral content
- Mineral content of CL follows much less outer layers polar profile

Results | Analysis of the whole set of osteons

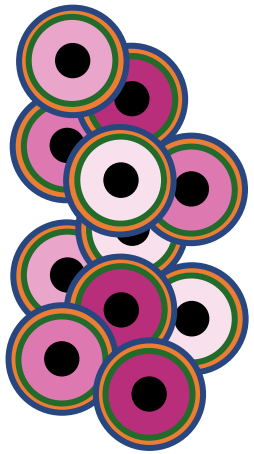


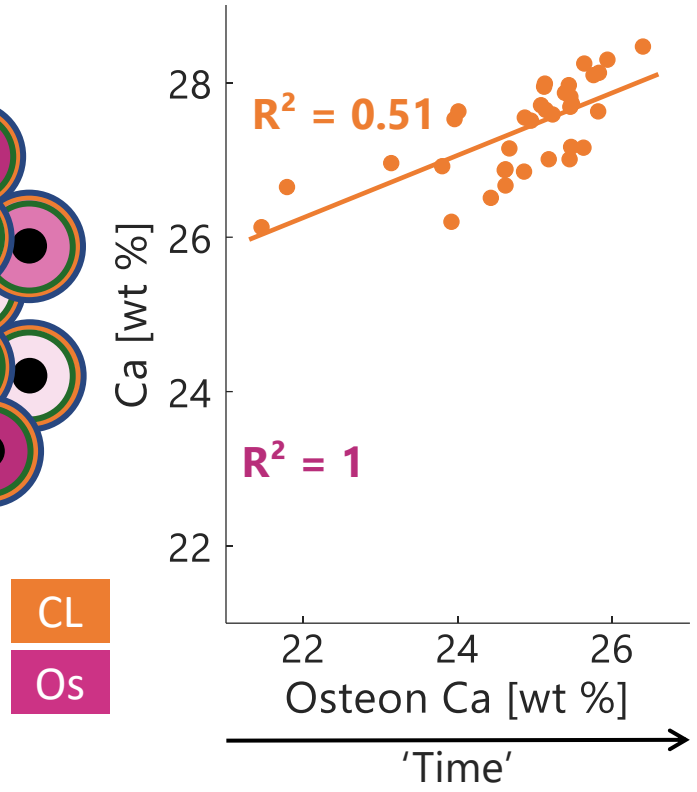
→ CL ~10% **more mineralized** than corresponding osteon

CL | Os
I1 | O1
I2 | O2
I3 | O3

Results | Kinetics analysis & impact of surrounding bone

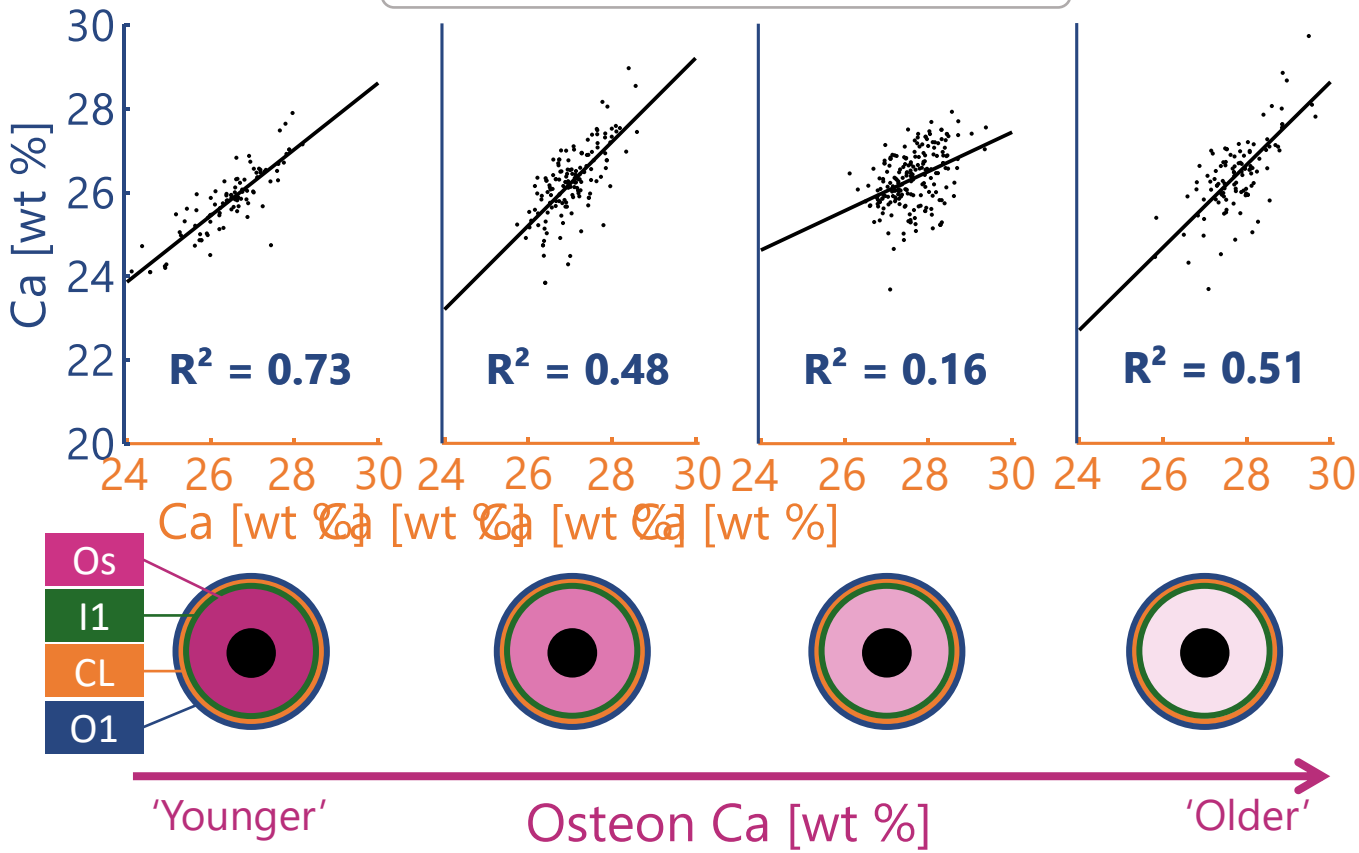
Mineralization kinetics





- **Correlation** between Ca content of CL and osteon
- Different mineralization kinetics

Impact of surrounding bone

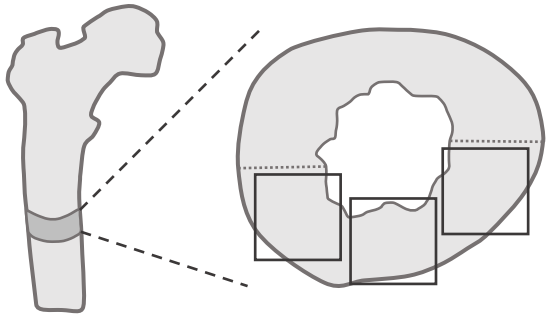


Strong **correlation** between Ca content of CL and outside environment

Milovanovic et al., Bone, 2018

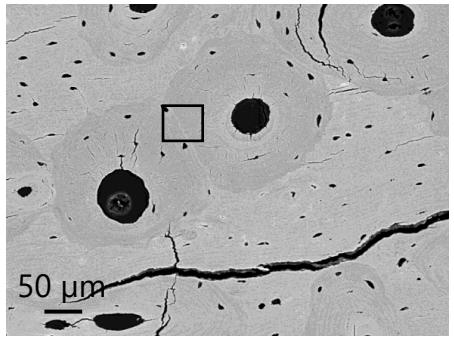
Aims & techniques

→ Characterization of mineral content and mechanical properties of CL and its surroundings



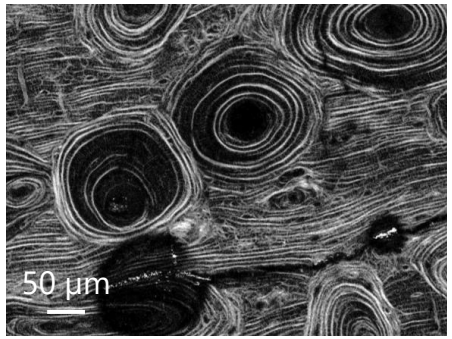
- Human femoral bone
- 2 samples (40 & 81 y.o.)
- 35 uninterrupted osteons

Mineral content: Is there a relationship between the mineral content of CL and of surrounding bone?



qBEI (1)
Pixel size: 570 nm

(1) Quantitative backscattered electron imaging



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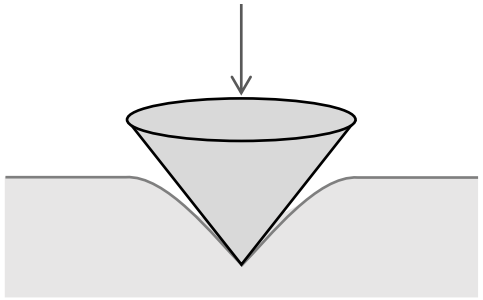
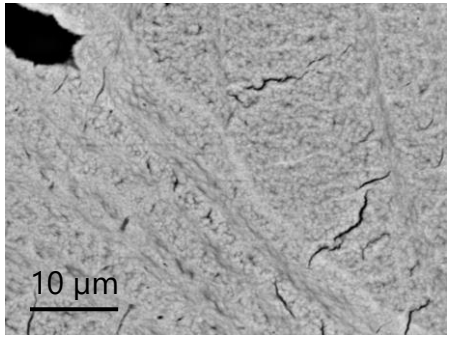
(2) Second harmonic generation

Mechanical properties: Is CL stiffer or more compliant than corresponding osteonal bone?



nIND (4)
Lateral spacing: 1 µm

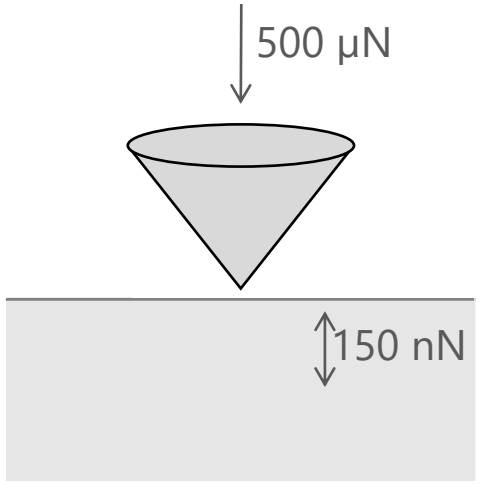
(4) Nanoindentation



hrBEI (3)
Pixel size: 75 nm

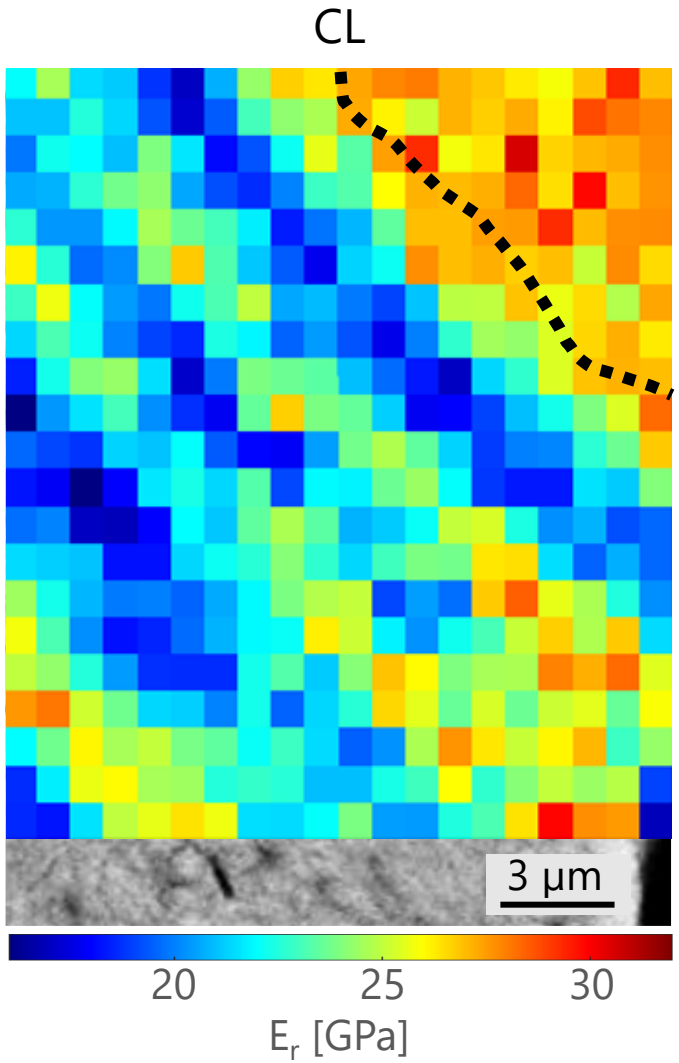
(3) High resolution backscattered electron imaging

Methods | Nanoindentation & data processing



▼ nIND

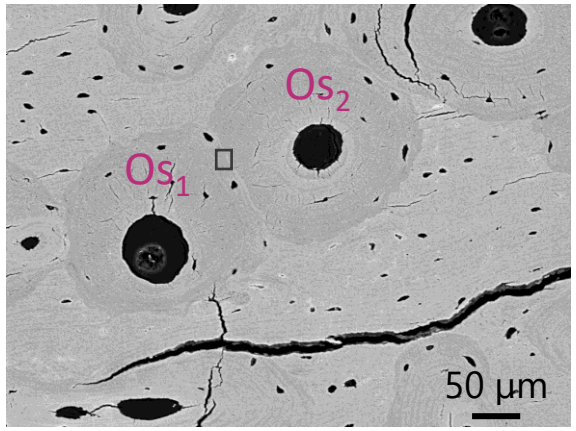
- Lateral spacing: 1 µm
- Applied force: 500 µN
- Penetration depth: ~150 nm

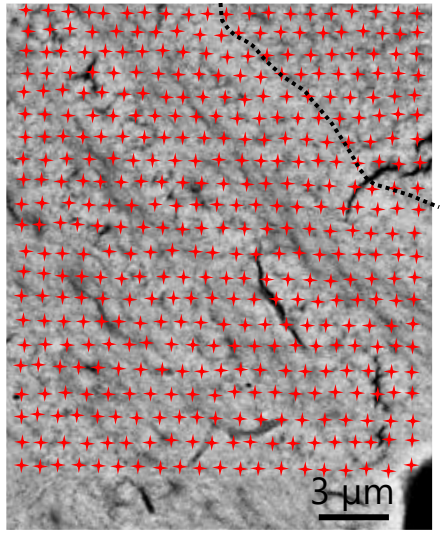


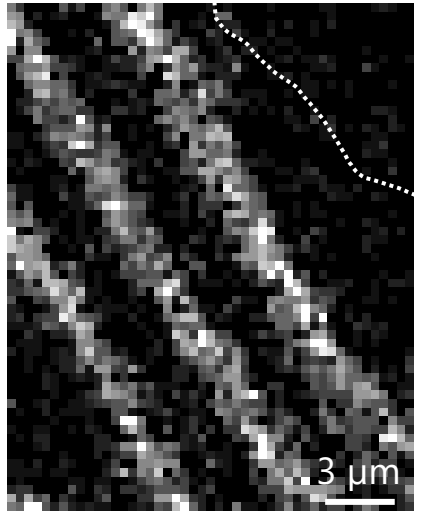
hrSEI
Pixel size: 75 nm

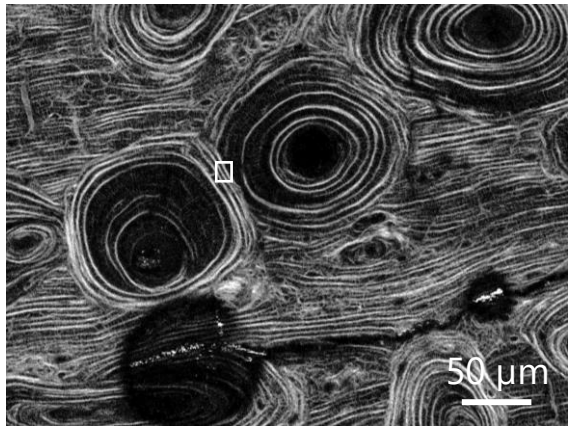
hrBEI
Pixel size: 75 nm

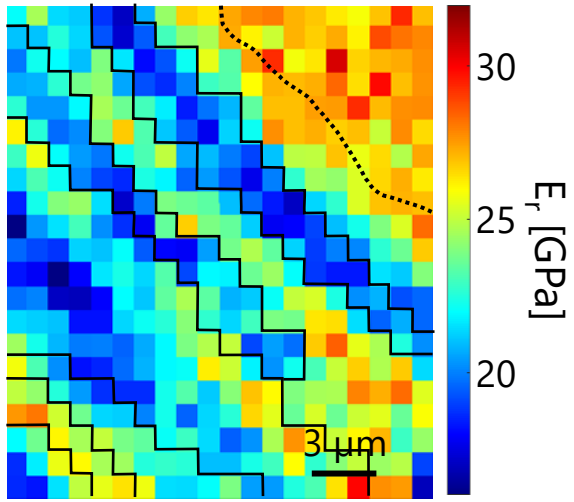
General analysis of the mechanical properties



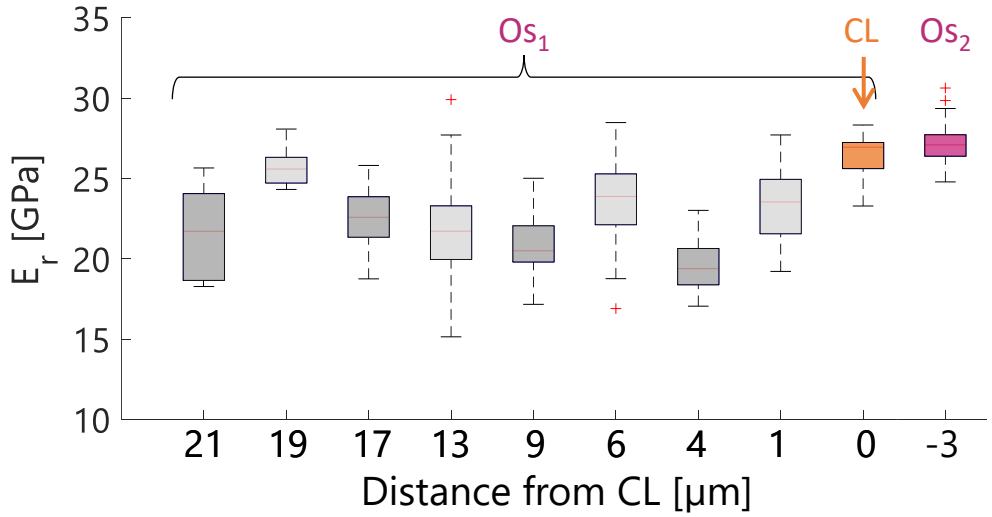








- Periodic alternation of:
  - Stiffer (22.98 ± 2.71 GPa) lamellae
  - Softer (20.69 ± 2.05 GPa) lamellae
- Distinct peak for CL (26.45 ± 1.31 GPa) compared to corresponding osteon (p <0.01)

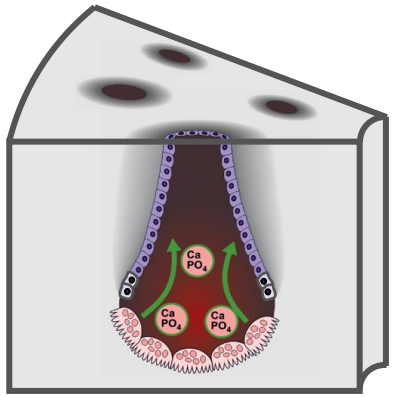


Conclusions & perspectives

Mineral Content:

- CL **hypermineralized**
- **Strong** correlation between mineral content of CL and outside environment within **young** osteon

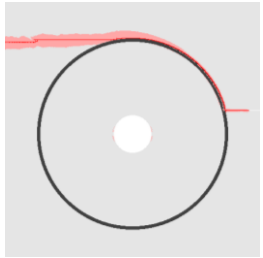
→ Local **recycling** of minerals already there to build new CL



→ Consistent with [1]

Mechanical Properties:

CL **stiffer** than its corresponding osteon

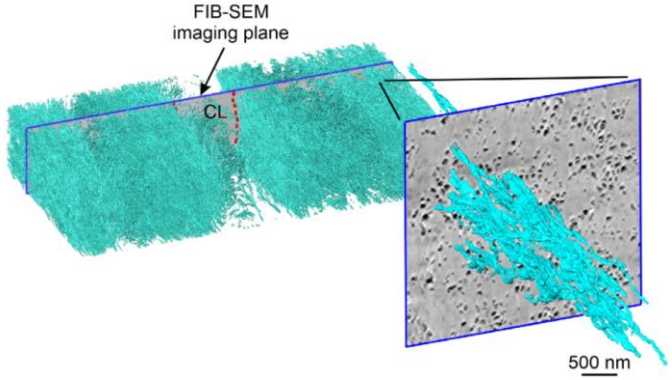


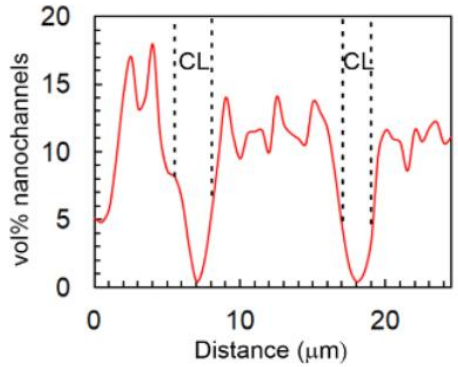
→ Hamper crack propagation

T. Volders – Poster session III @13:15
« Damage propagation in osteon-inspired structures: the role of the cement line »

→ In contradictions with softer CL [2,3]

→ Consistent with reduced nanoporosity of CL [4]

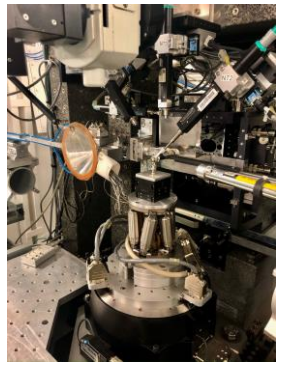




Perspectives:

- Mineral properties of CL measured with X-ray scattering @ESRF
- Interplay between CL and osteocyte lacuno-canalicular network

ESRF
The European Synchrotron



[1] Roschger et al., Acta Biomater., 2020
[2] Zhou et al., EMI, 2020
[3] Montalbano et al., J. Mater. Res., 2011
[4] Tang et al., JBMR, 2023

Thanks to all co-authors

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Shahrouz AMINI


Maximilian RUMMLER


Richard WEINKAMER


Stéphane BLOUIN


Markus HARTMANN


Andrea BERZLANOVICH

Thank you for your attention!

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Astrid Cantamessa