Microstructure Mechanics

Biological (Natural) Materials

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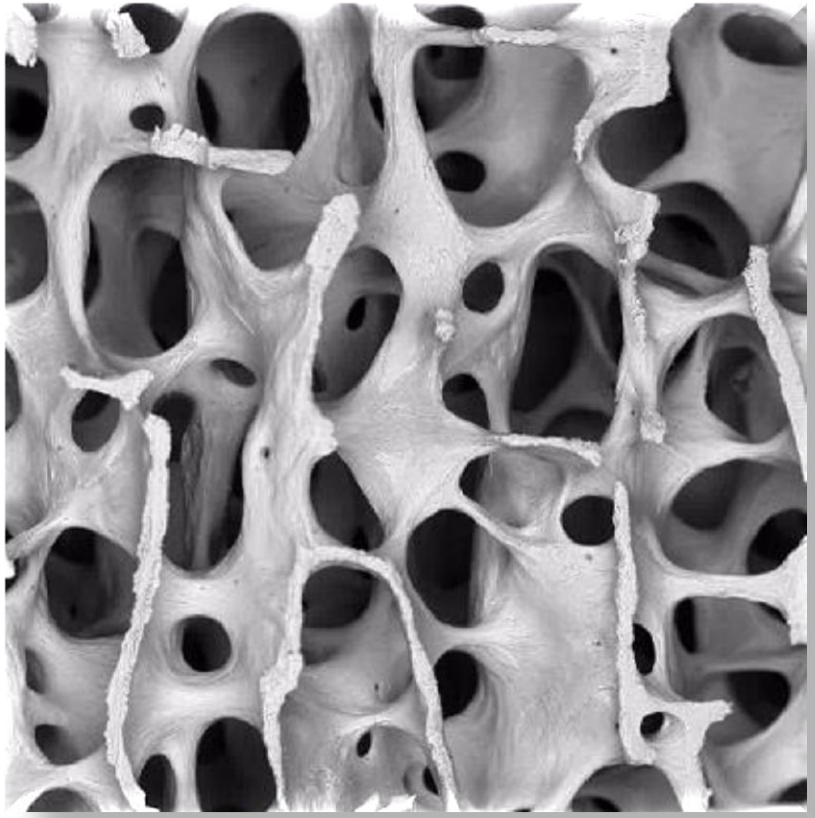
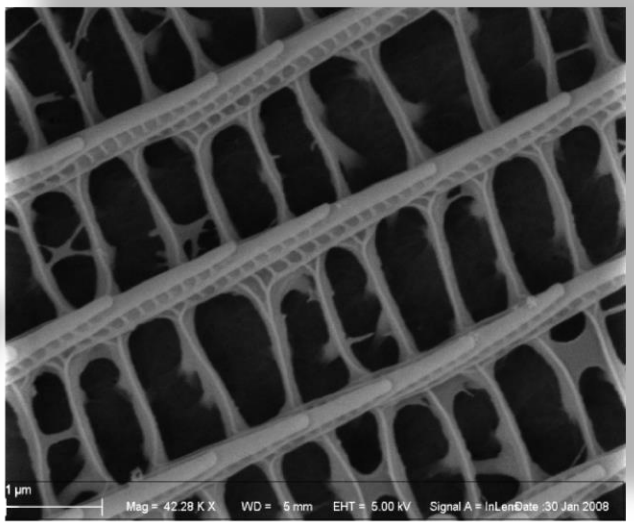
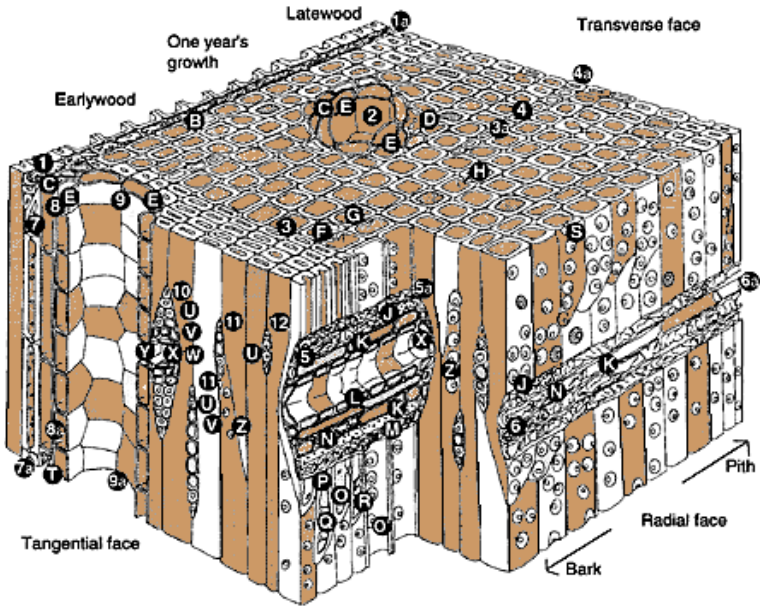
Class 2015 RWTH Aachen

Natural materials





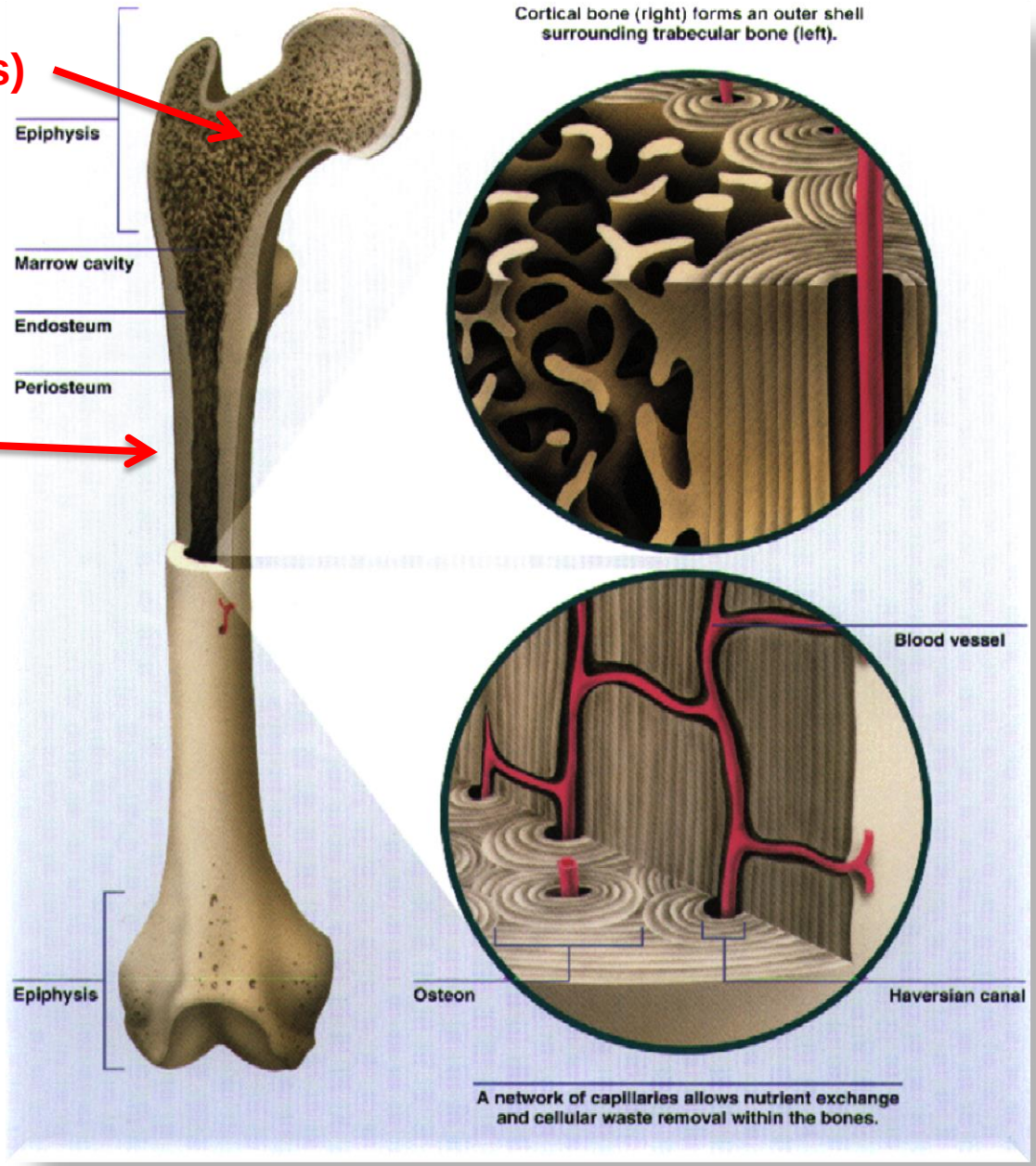


- complex structure
- hierarchical structure
- soft matter plus ceramics

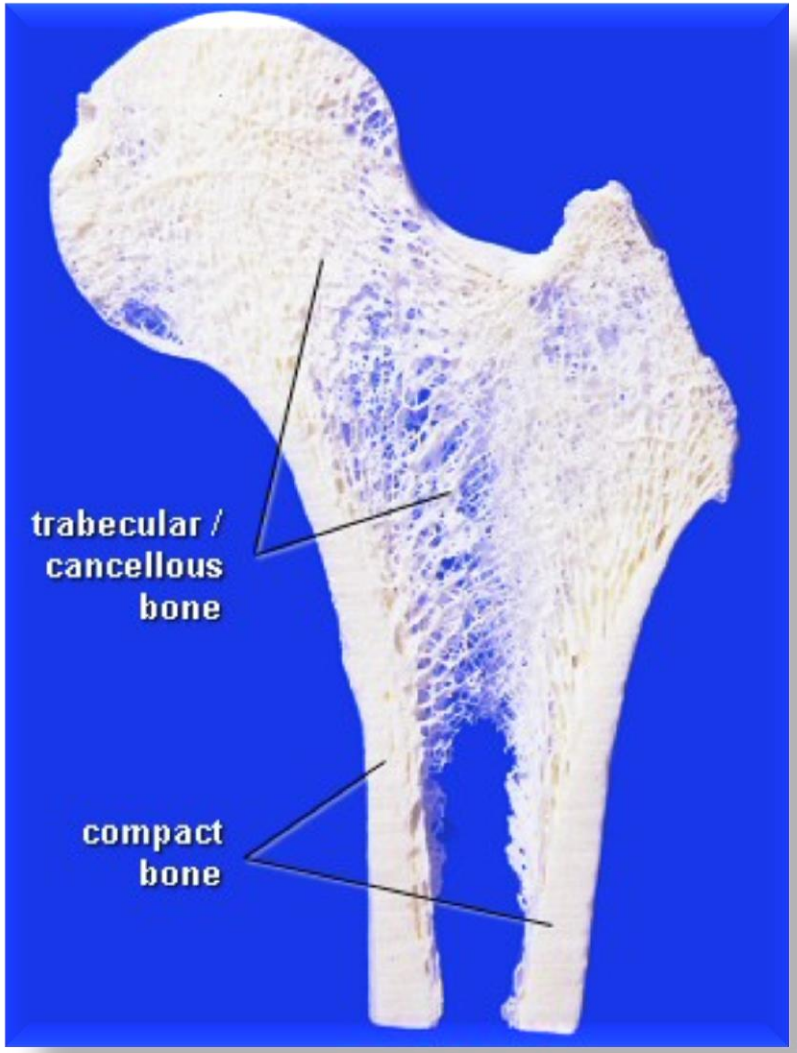
Bone

trabecular (cancellous) bone

cortical (compact) bone



Bone



Compact bone: mesoscopic structure

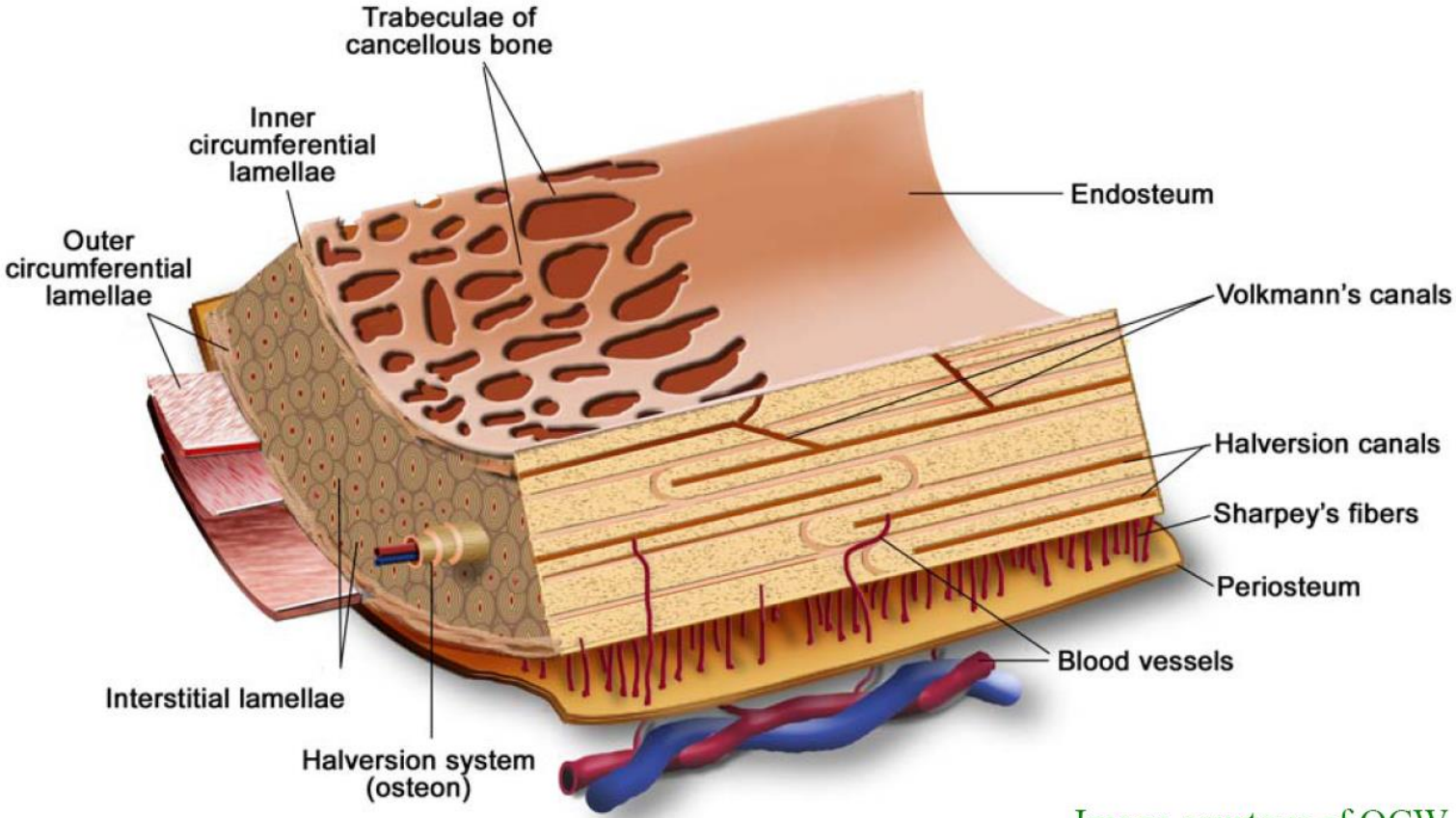
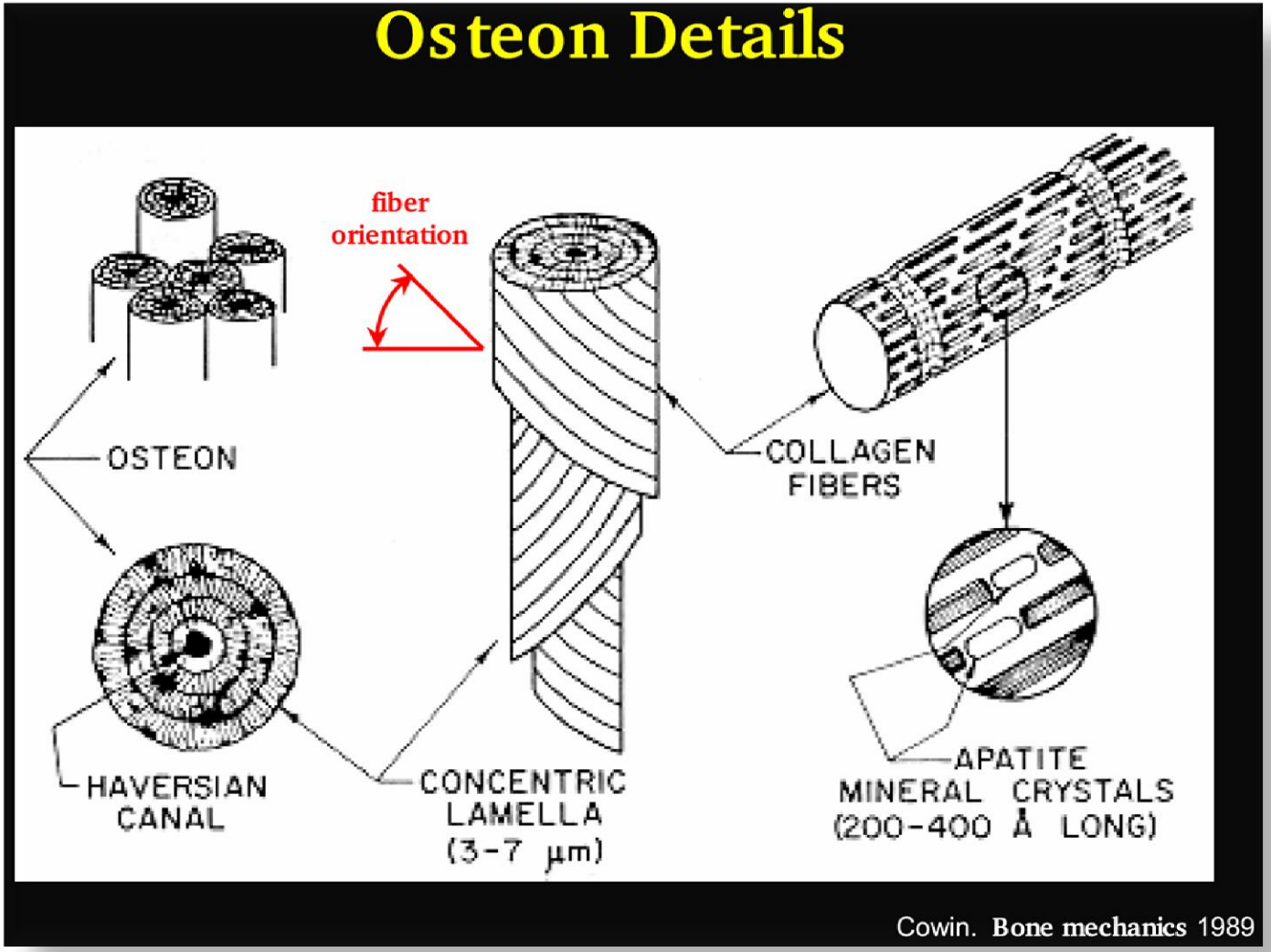


Image courtesy of OCW.
Adapted from figure in Martin, R.B. et al. *Skeletal Tissue Mechanics*. New York: Springer-Verlag, 1998

Bone: details of osteon structure

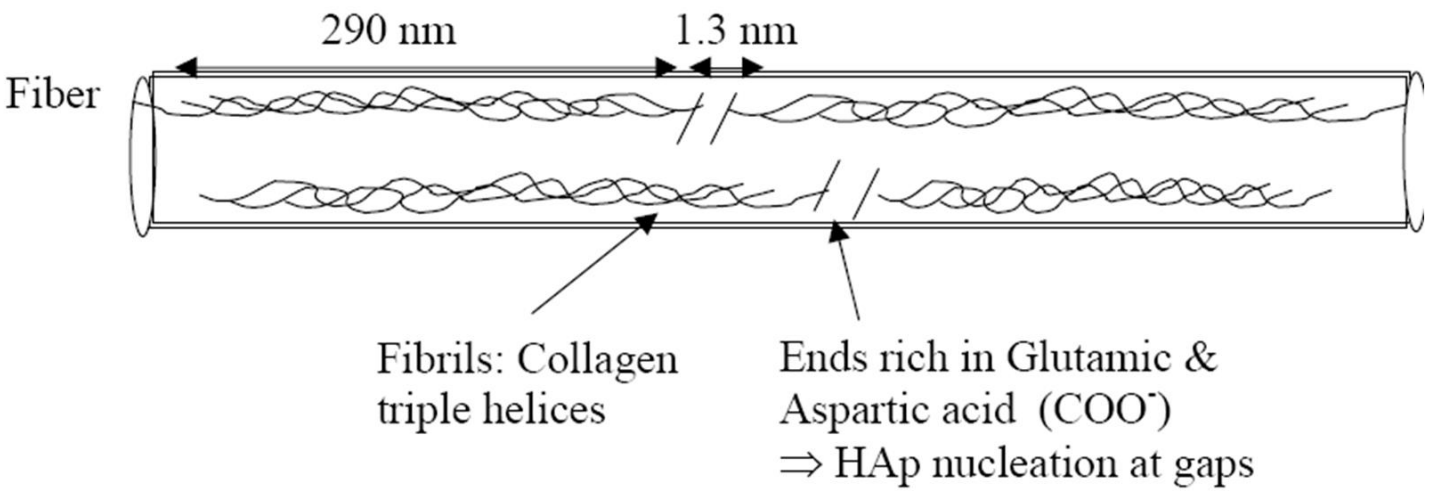


Bone: details of osteon structure

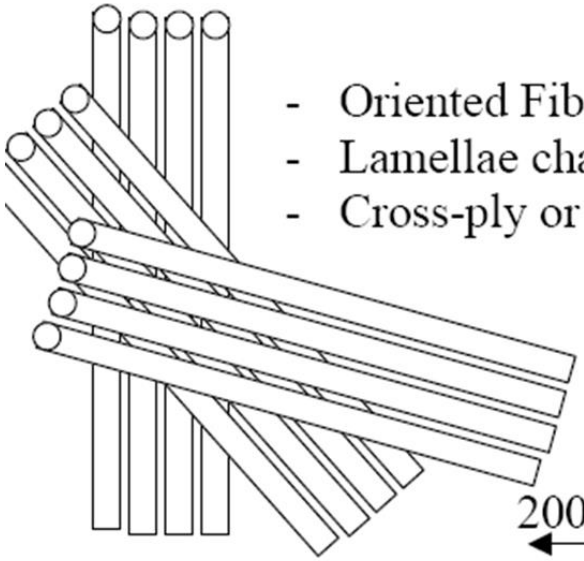
Cortical (compact) bone:

- Low porosity (<10%: Haversian canals in osteon centers)
- Found in long-bone shafts & cortex (shell) of trabecular bone
- Multi-ply *lamellar* structure

each lamellae: oriented collagen fibers (20wt%) &
HAp [$Ca_{10}(PO_4)_6(OH)_2$] 2x20x40 nm crystallites (70wt%)



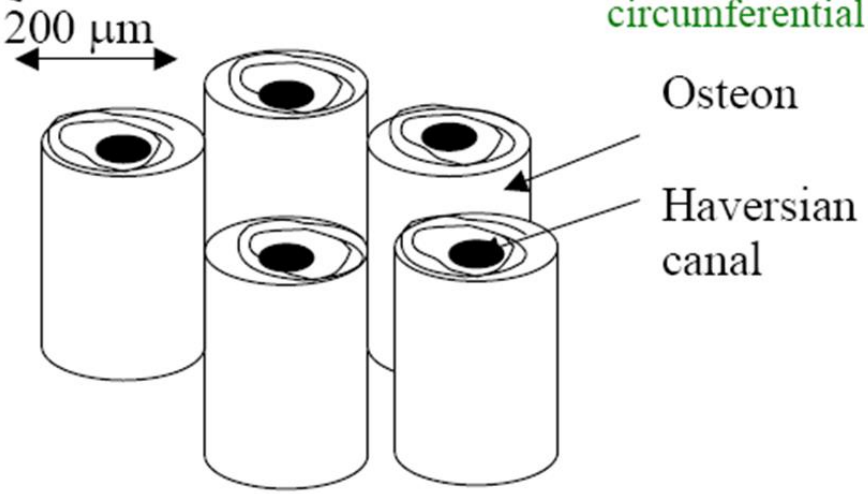
Bone: details of osteon structure



- Oriented Fibers form Lamellae
- Lamellae change orientation concentrically
- Cross-ply or Helicoid structures

In children:
- circumferential lamellae
-osteons around vessels

In adults:
-secondary osteons replace circumferential bone

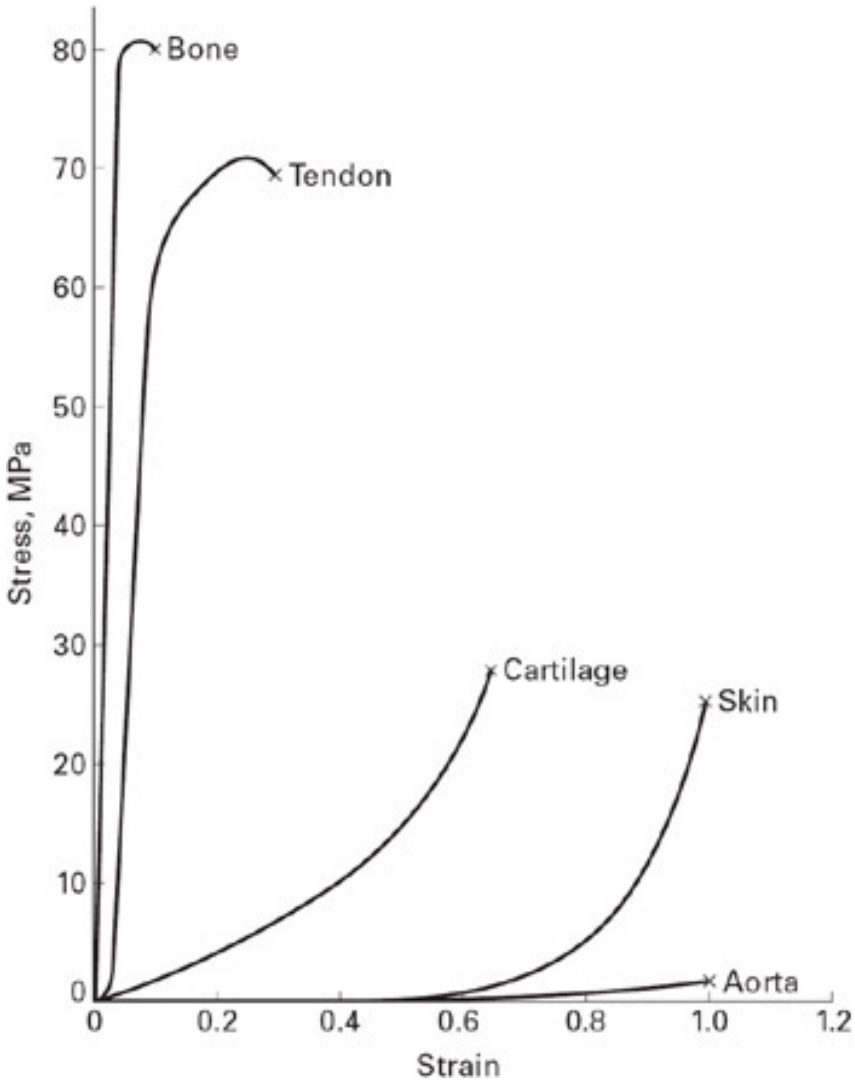


Bone: macroscopic mechanical properties: human materials

Very high variety by structure modifcation, particularly mineral content modifcation

Self-repair

Stiffness scaling by mineral content



Bone: macroscopic mechanical properties: human materials

	Ultimate Comp. Str. (MPa)	Modulus of Elasticity (GPa)
Cortical Bone	140 - 200	14 - 20
Cancellous Bone	5 - 60	0.7 - 1.5
Synthetic HA	200 - 900	34 - 100
Bone Mineral	25 (anorganic bone)	6

chitin: 3 examples

- Homarus americanus

- Carabus auronitens

- Chrysophanes virgaurea

Introduction - Arthropod cuticle

Main exoskeleton component of more than 90% of all animal species …













adaptive material → candidate for bio-inspired material

Crustacean cuticle (subgroup of arthropods)

- cuticle surrounds the whole animal
- forms different skeletal elements
- cover a vast variety of physical properties
- adapted to:
  - the specific function of the skeletal element
  - ecophysiological strains of the animal

Birgus latro

Porcellio scaber

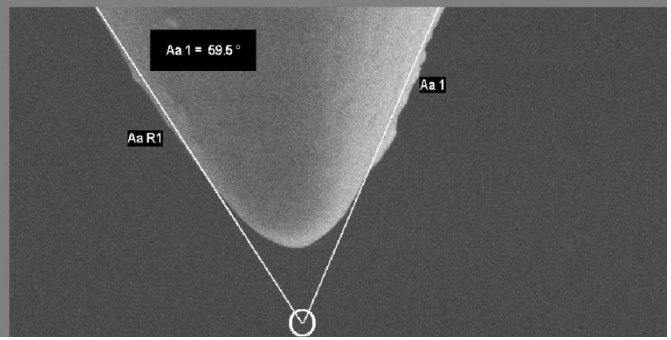
Armadillidium vulgare

Horseshoe crab

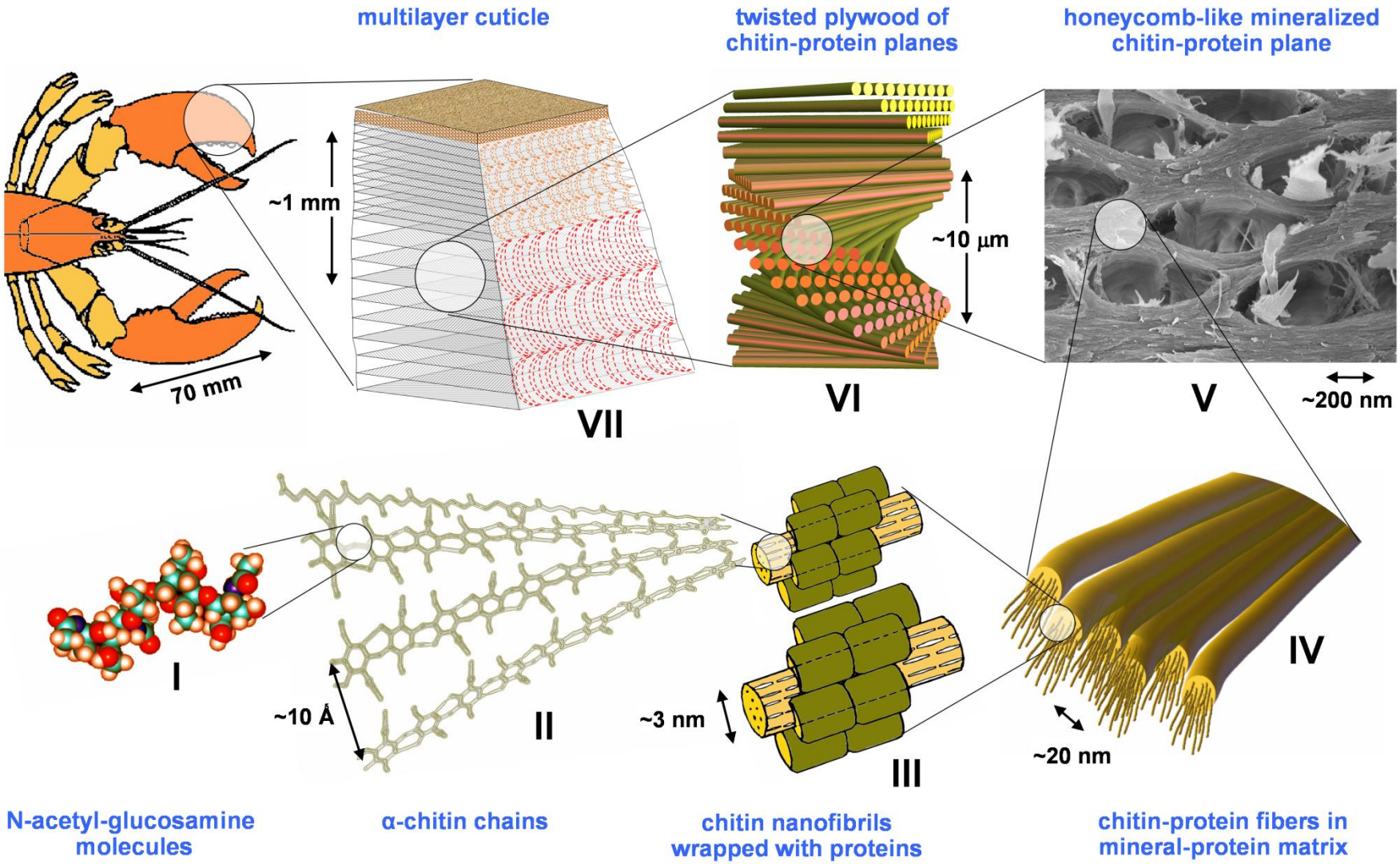
Homarus americanus

- hierarchical structure follows the same principle regardless of the specific properties of the cuticle

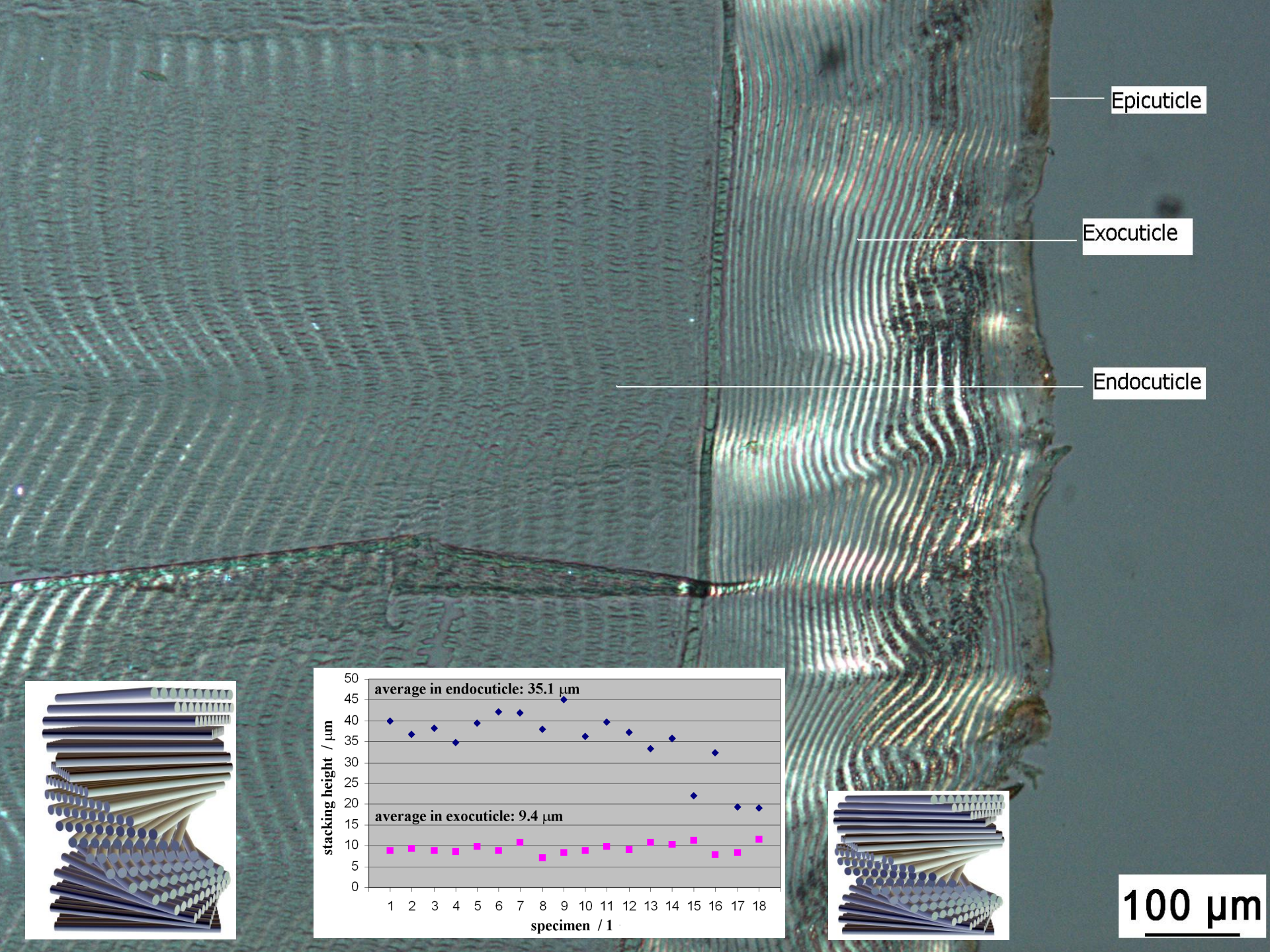
The materials science of the arthropods

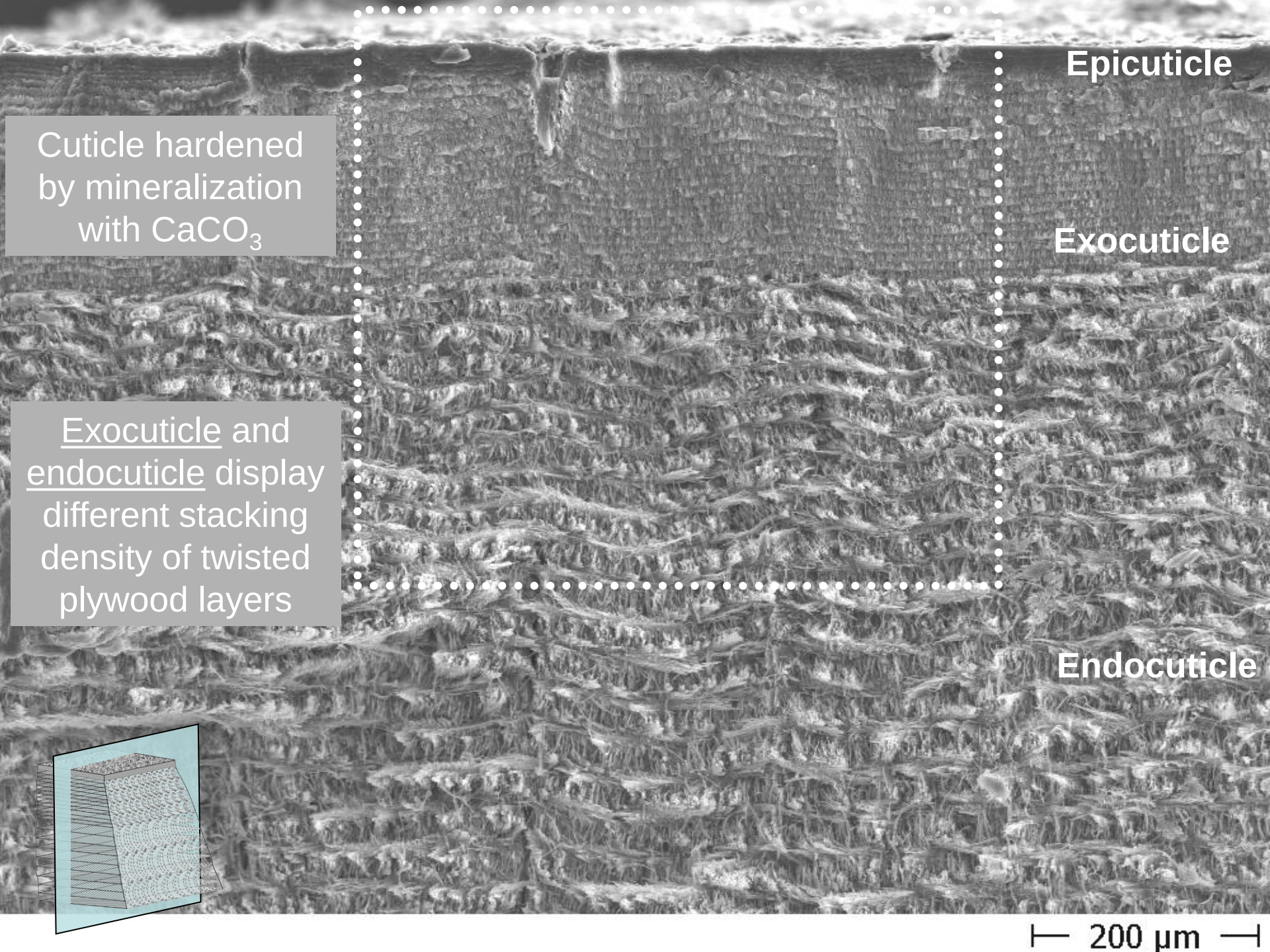


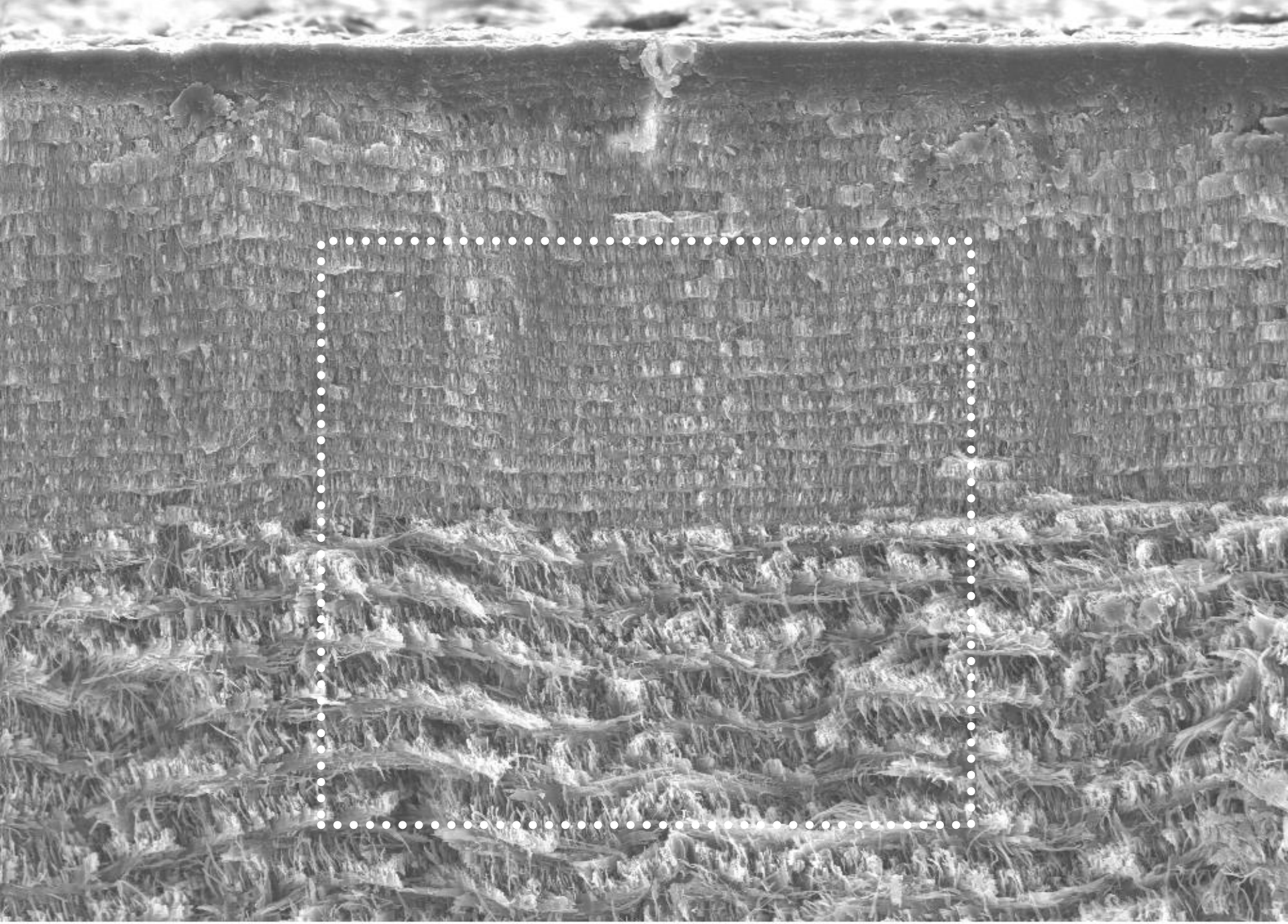
Structure hierarchy of arthropods

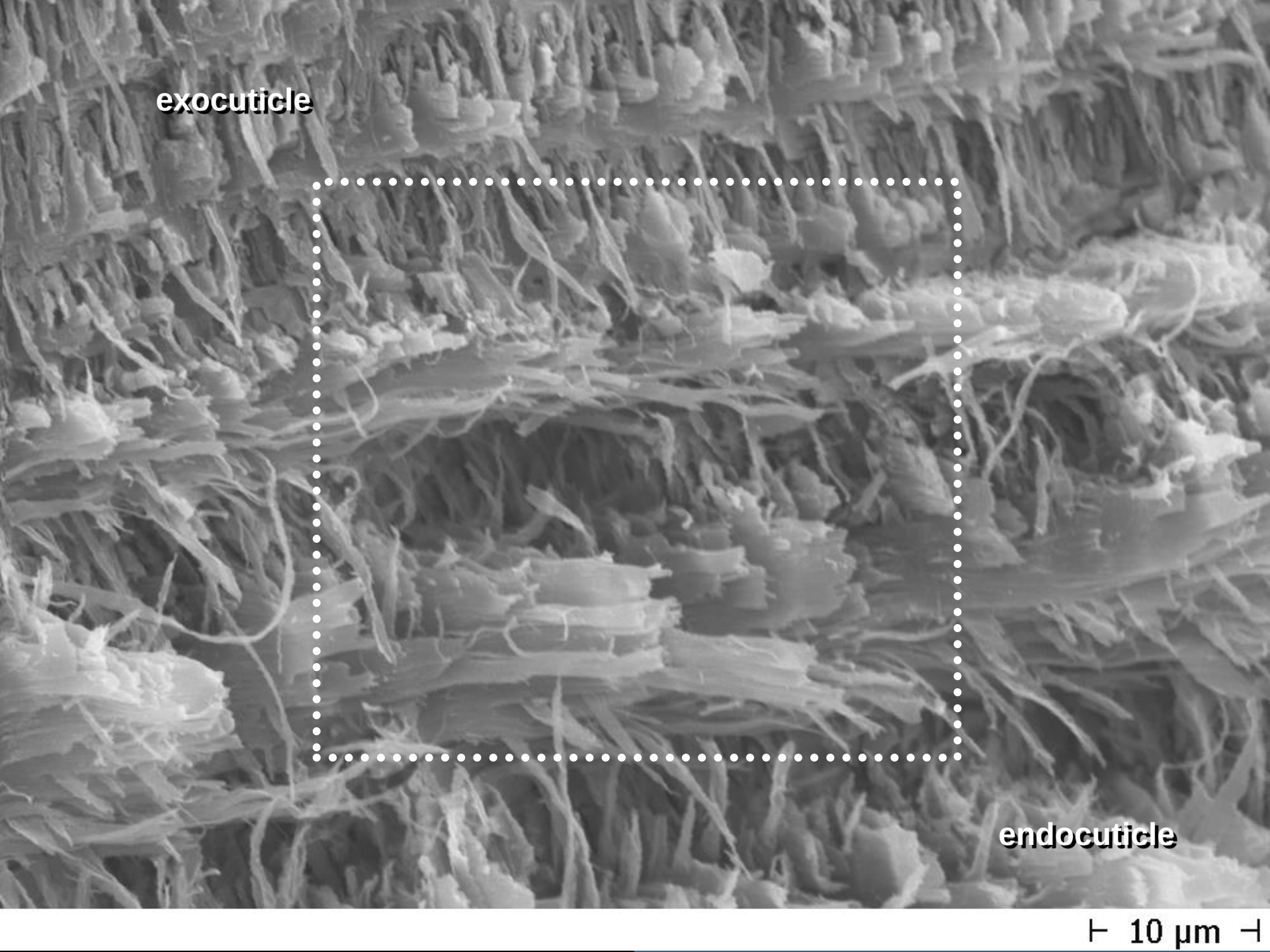


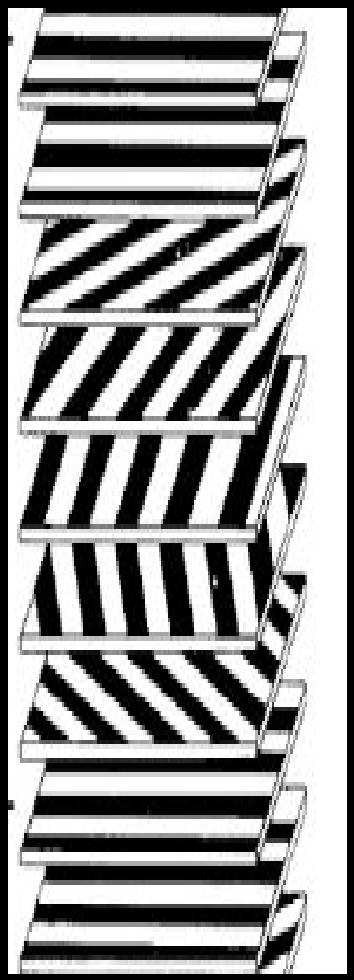
Al-Sawalmih, C. Li, S. Siegel, H. Fabritius, S.B. Yi, D. Raabe, P. Fratzl, O. Paris: Advanced functional materials 18 (2008) 3307
H. Fabritius, C. Sachs, S. Nikolov, and D. Raabe, Advanced materials , in press

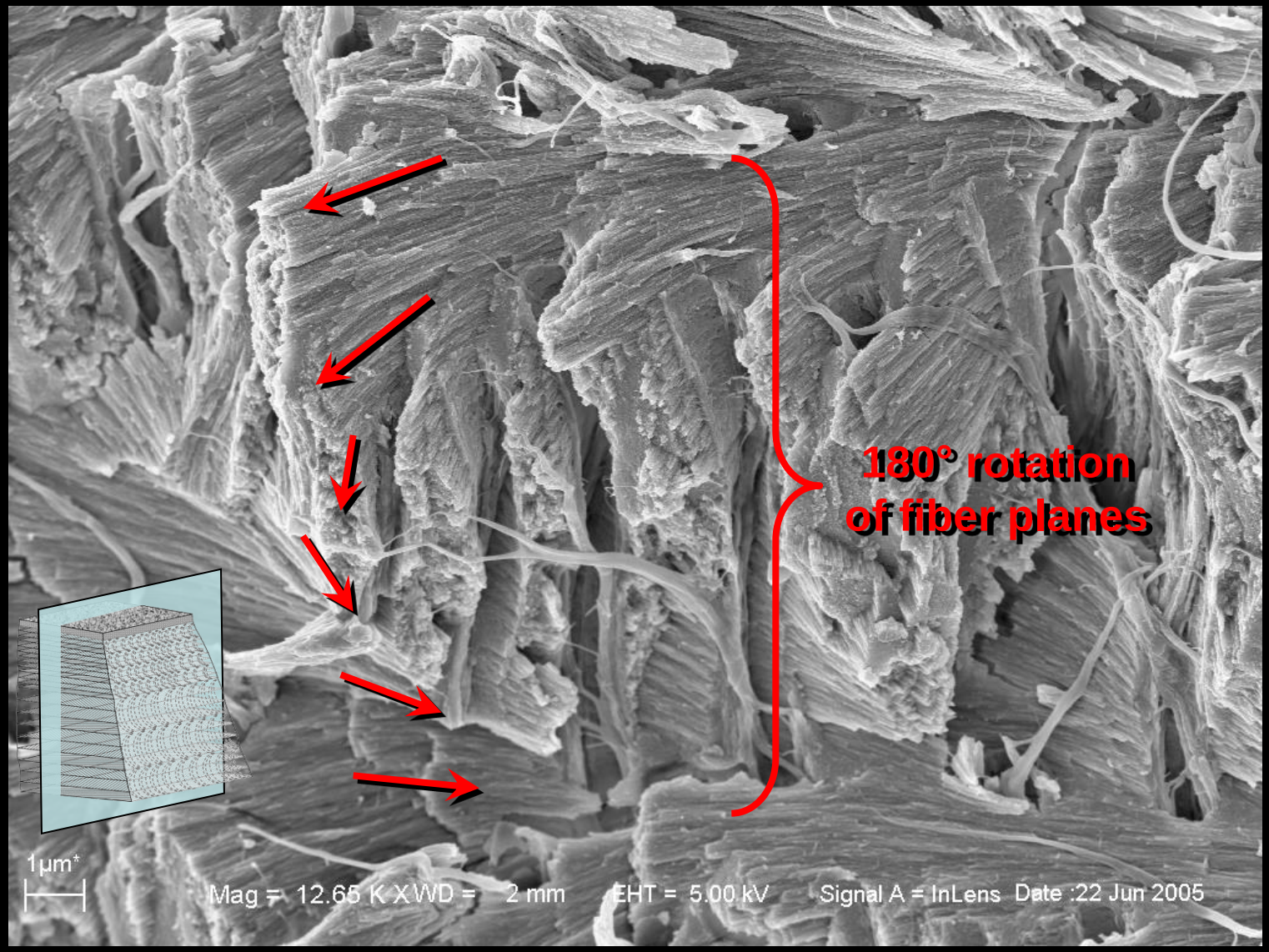

Epicuticle
Exocuticle
Endocuticle
average in endocuticle: 35.1 µm
average in exocuticle: 9.4 µm
stacking height / µm
specimen / 1
0
5
10
15
20
25
30
35
40
45
50
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
100 µm

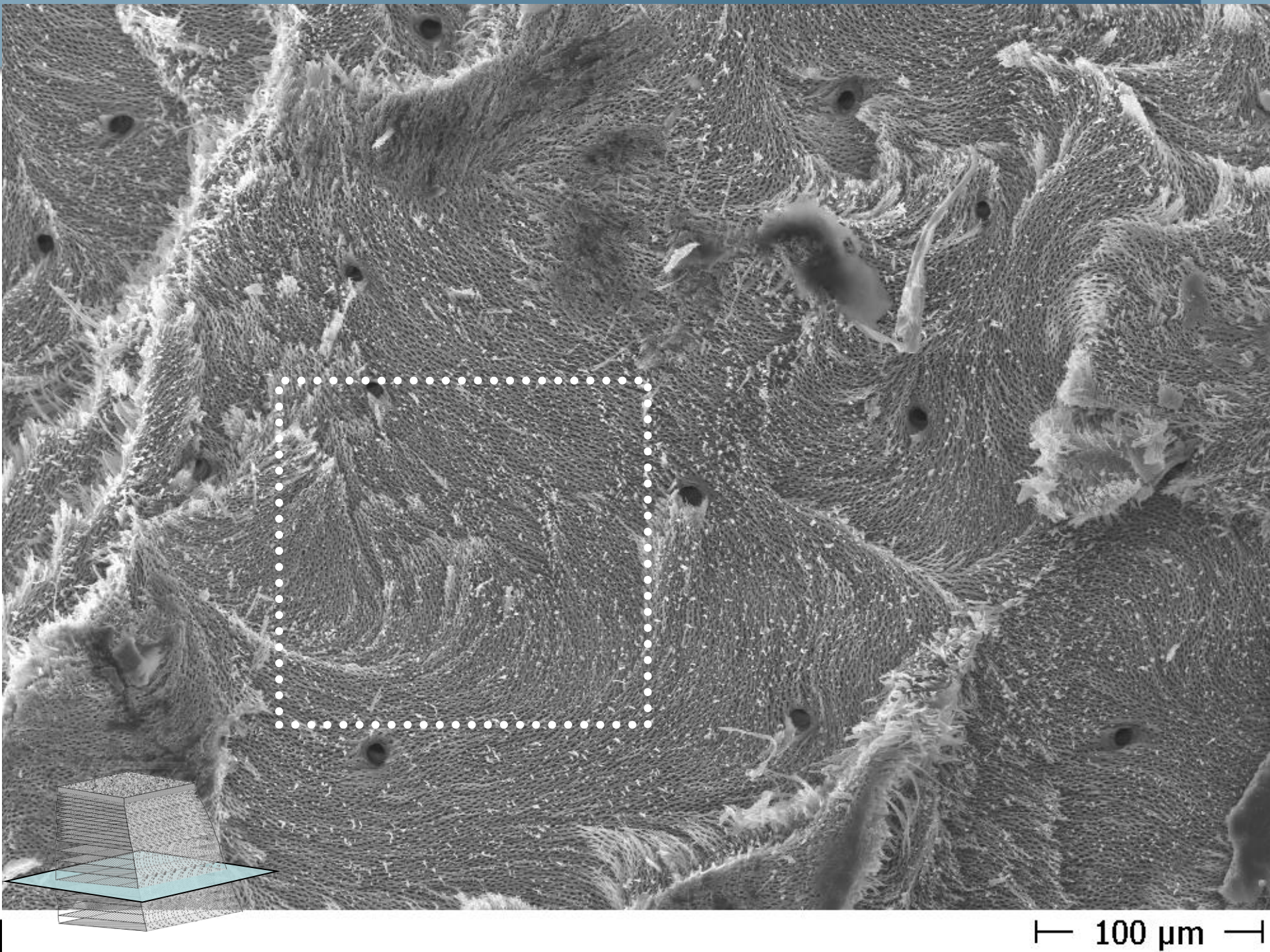

Epicuticle
Exocuticle
Endocuticle
Cuticle hardened by mineralization with $CaCO_3$
Exocuticle and endocuticle display different stacking density of twisted plywood layers
200 µm

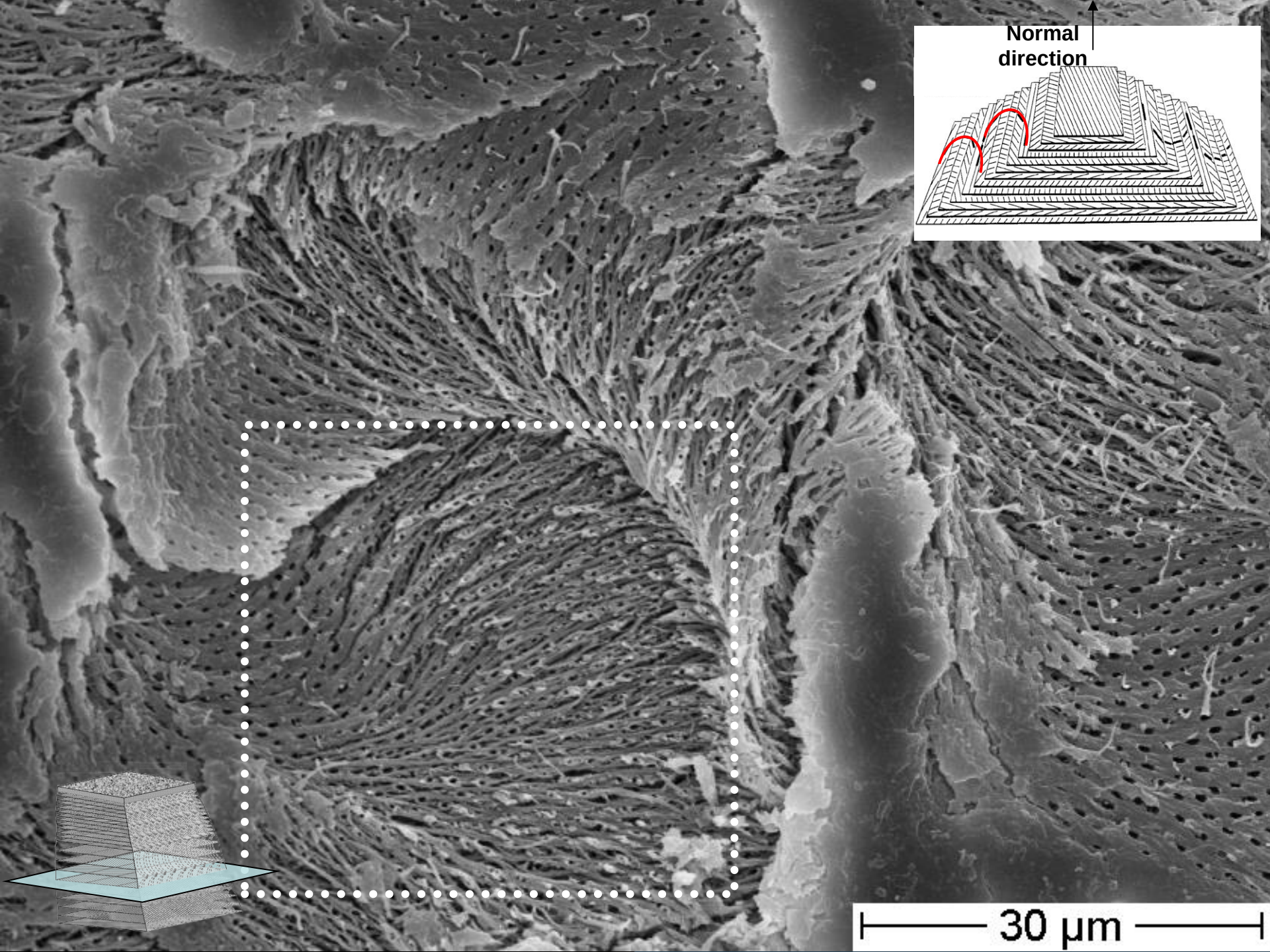

100 µm

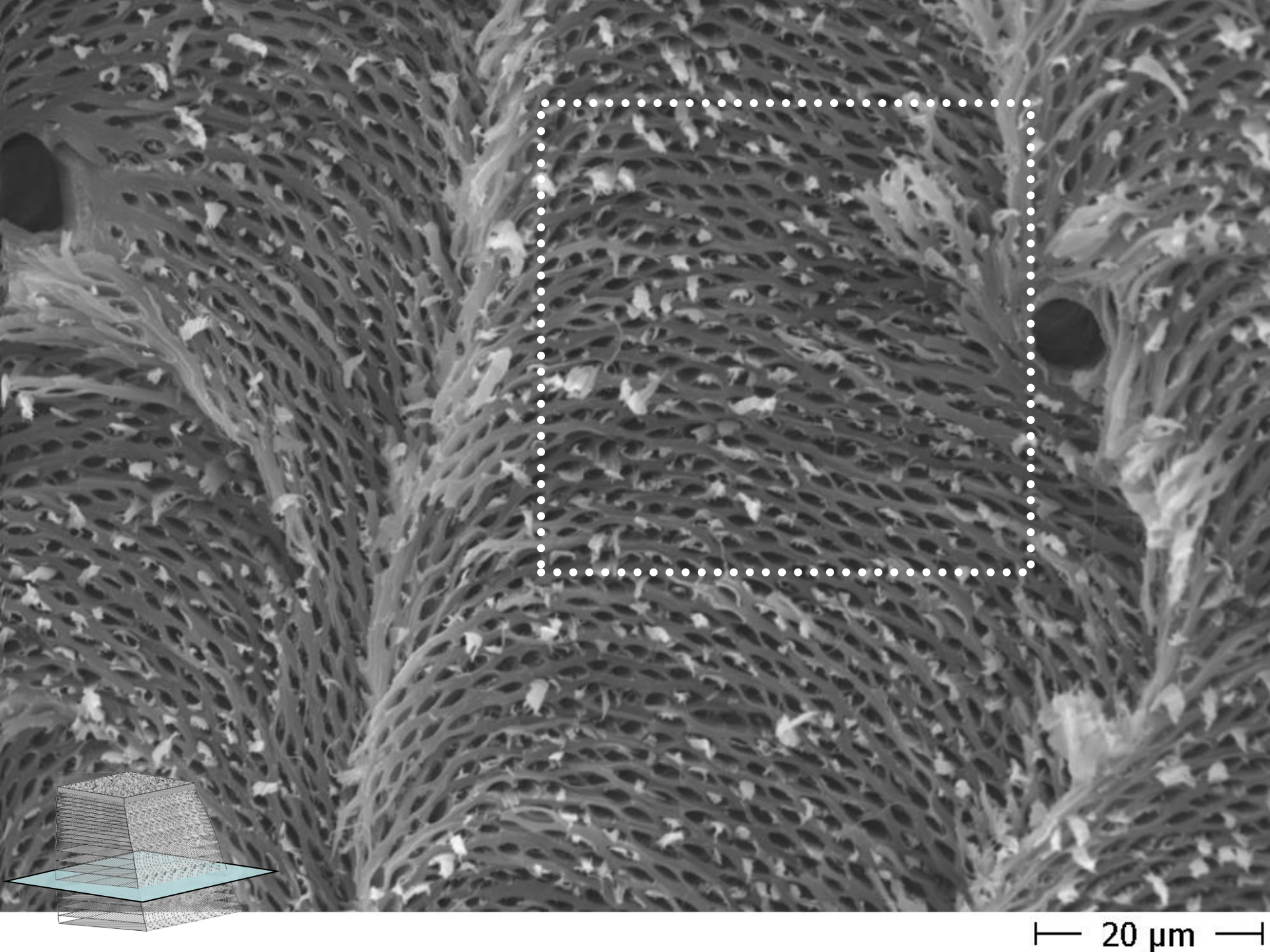

exocuticle
endocuticle
10 µm

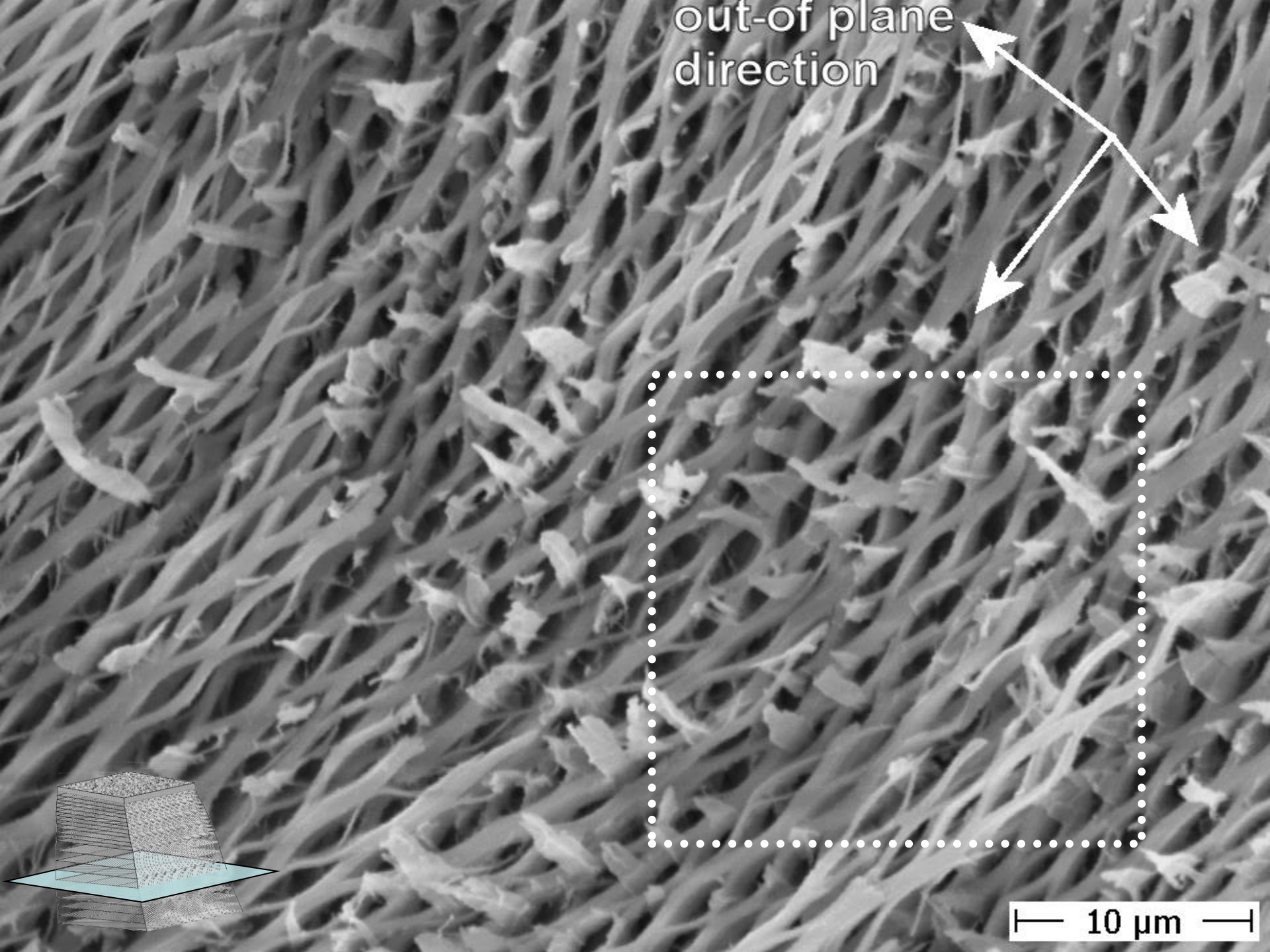


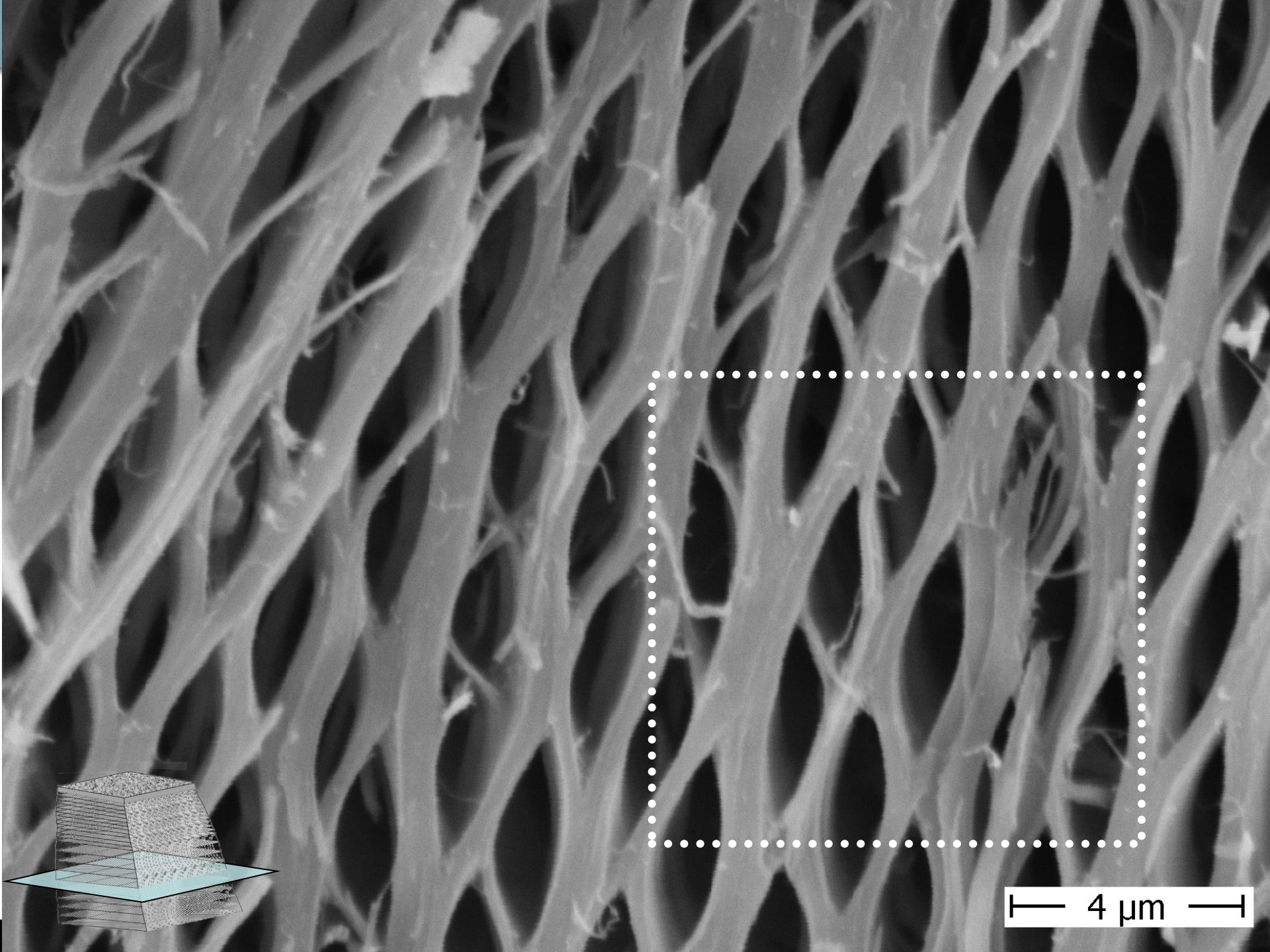

180° rotation
of fiber planes
1µm*
Mag = 12.66 K X WD = 2 mm
EHT = 5.00 kV
Signal A = InLens Date :22 Jun 2005

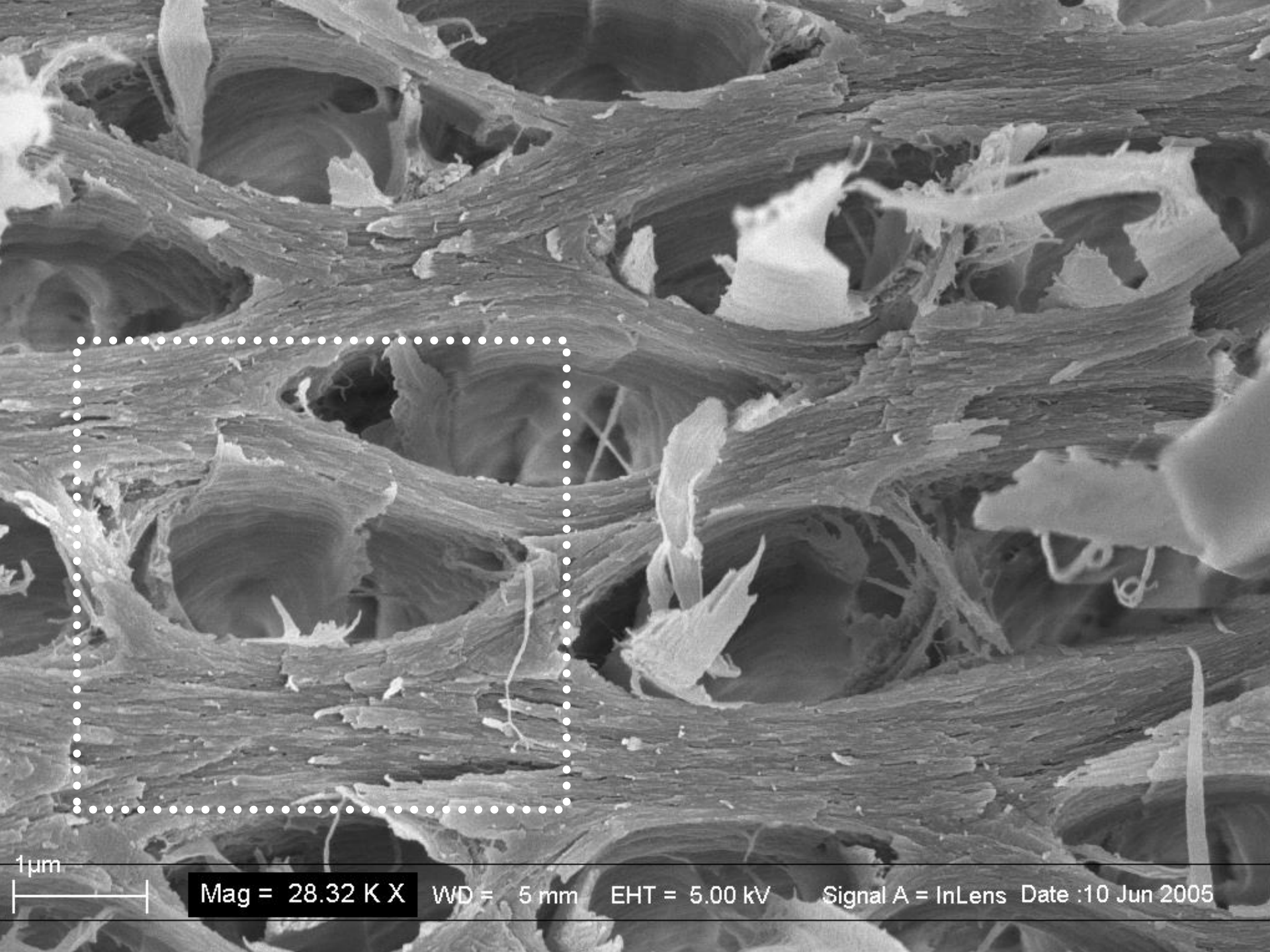

100 µm

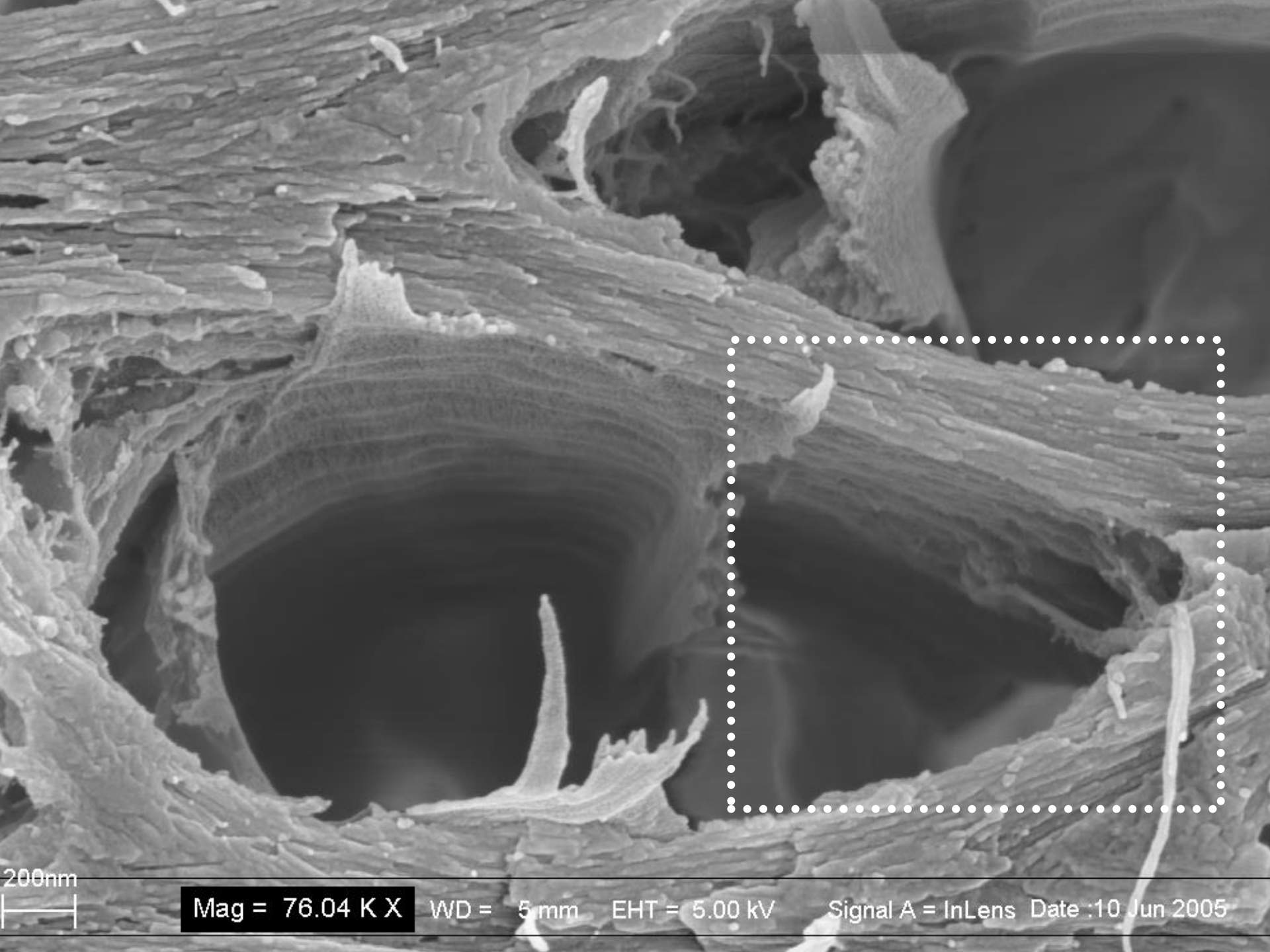

Normal
direction
30 µm


20 µm

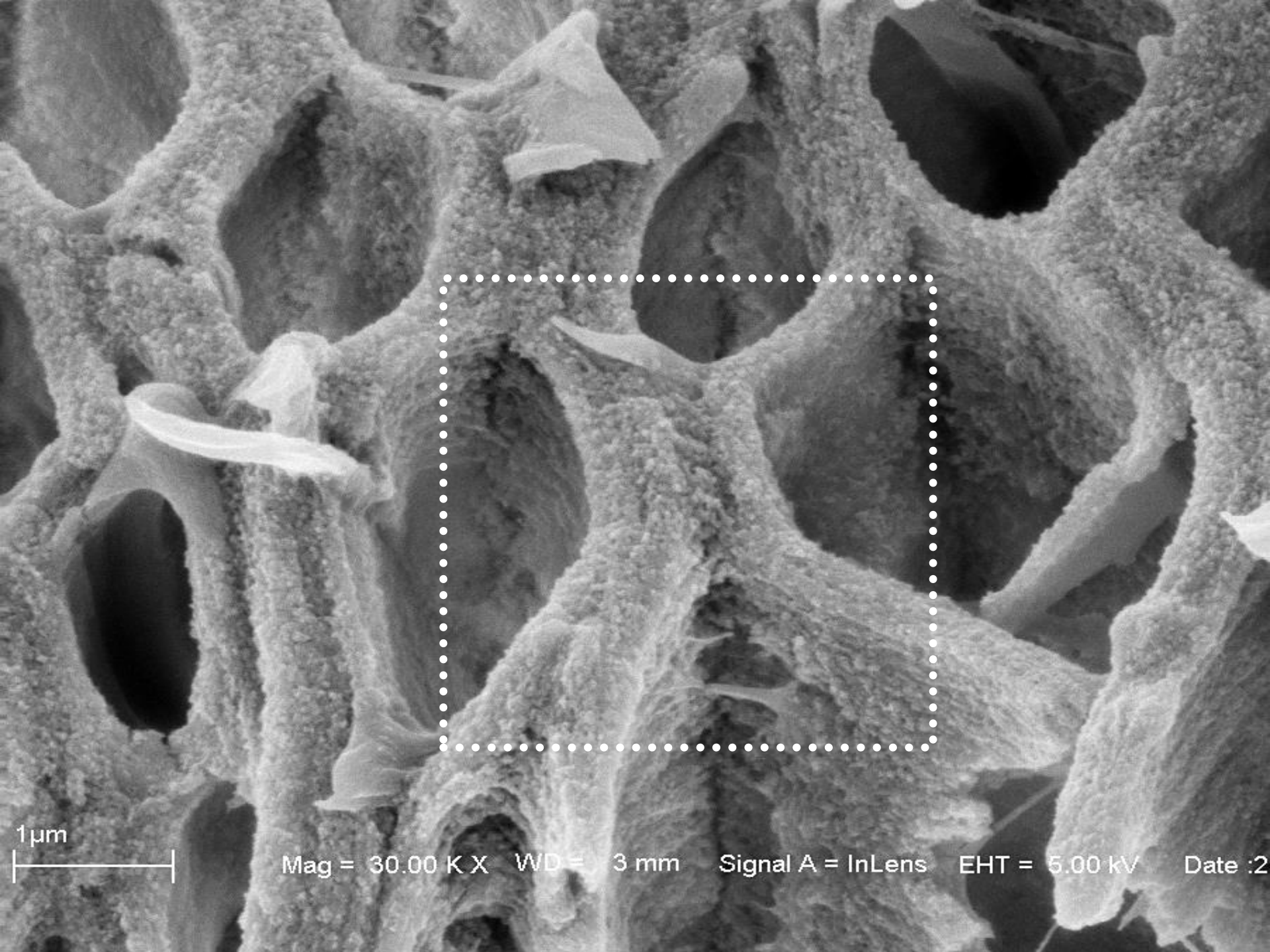

out-of plane
direction
10 µm

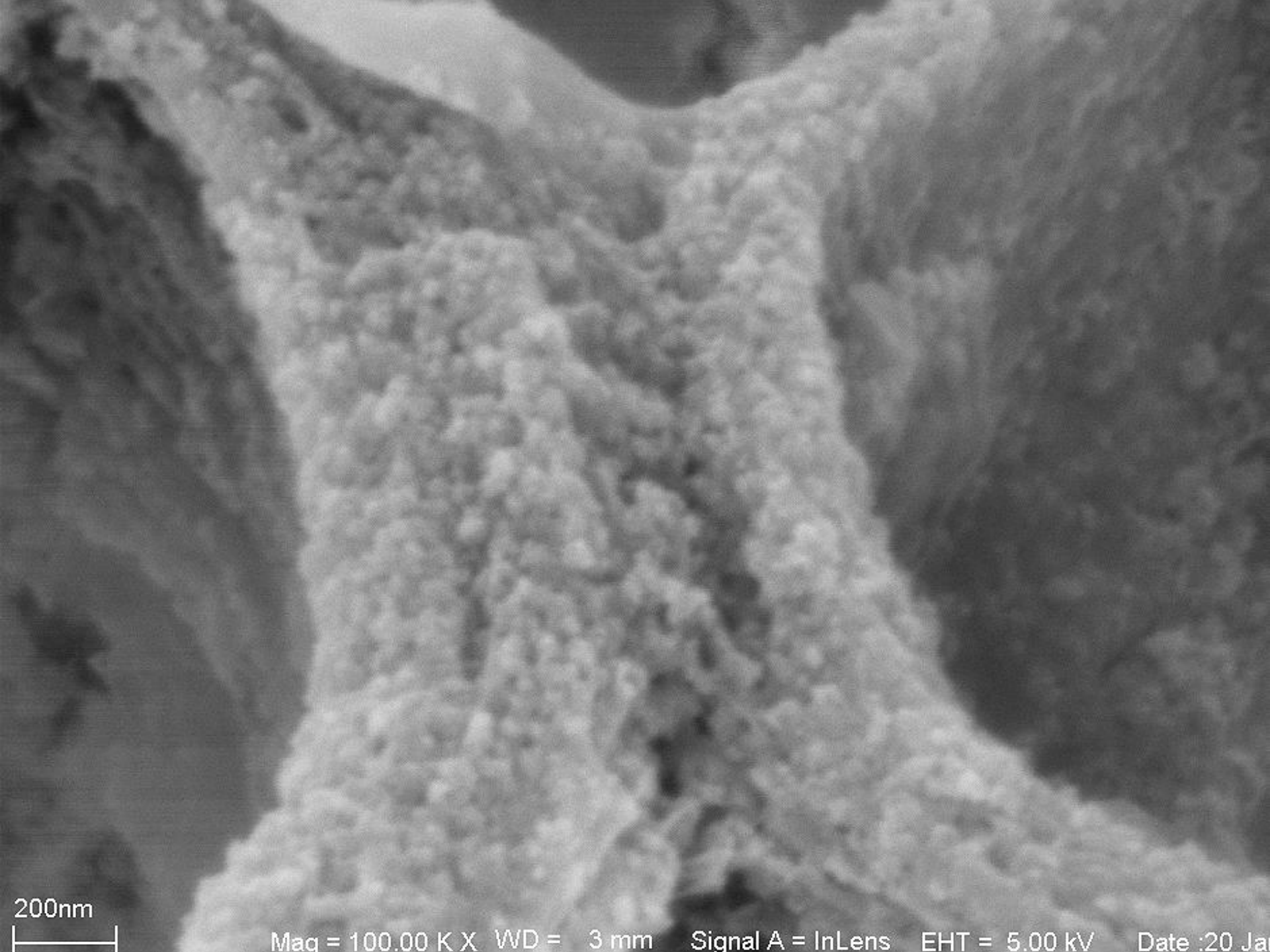

4 µm


1µm
Mag = 28.32 K X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date :10 Jun 2005

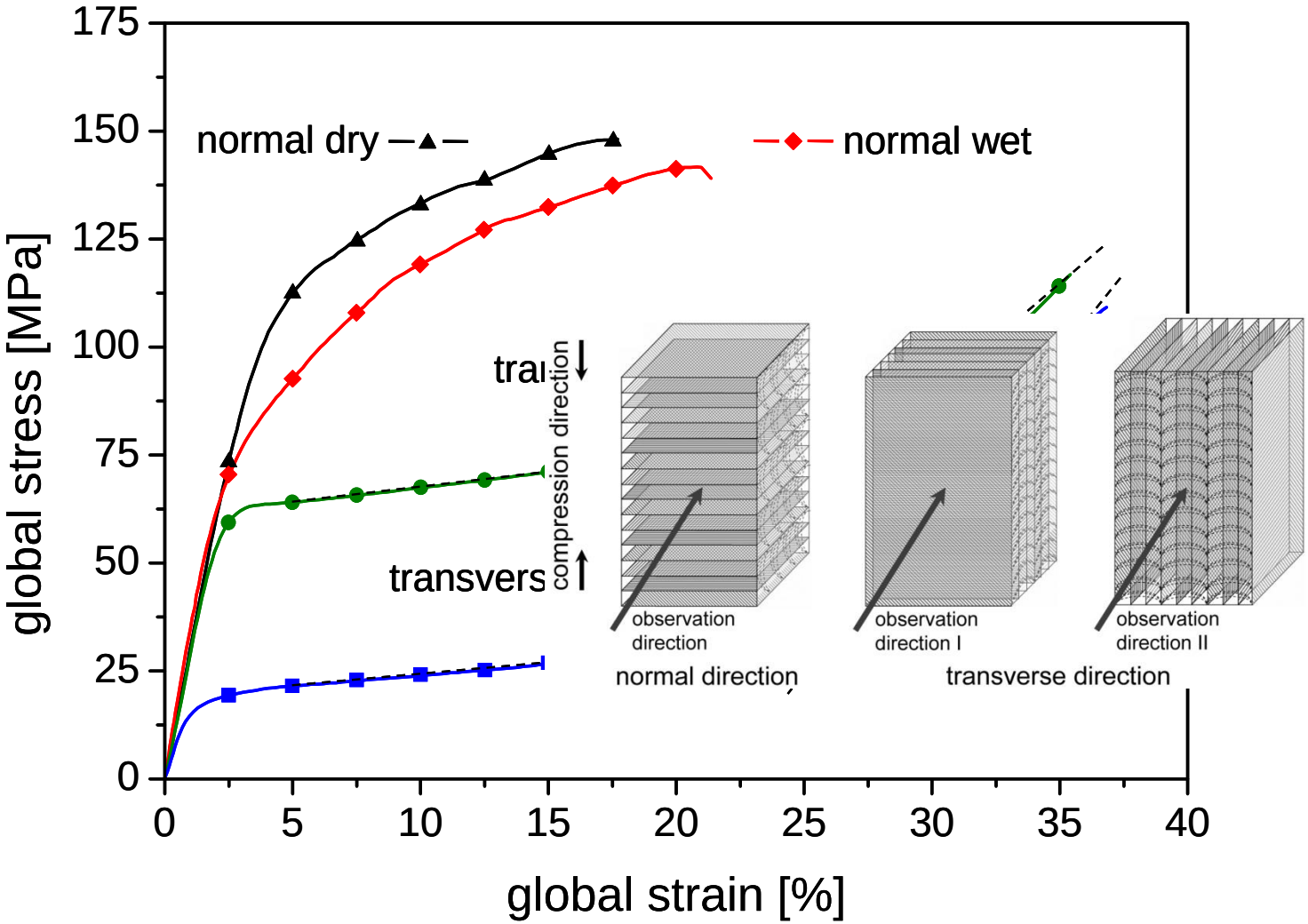

200nm
Mag = 76.04 K X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date :10 Jun 2005


100nm
Mag = 133.31 K X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date :9 Jun 2005

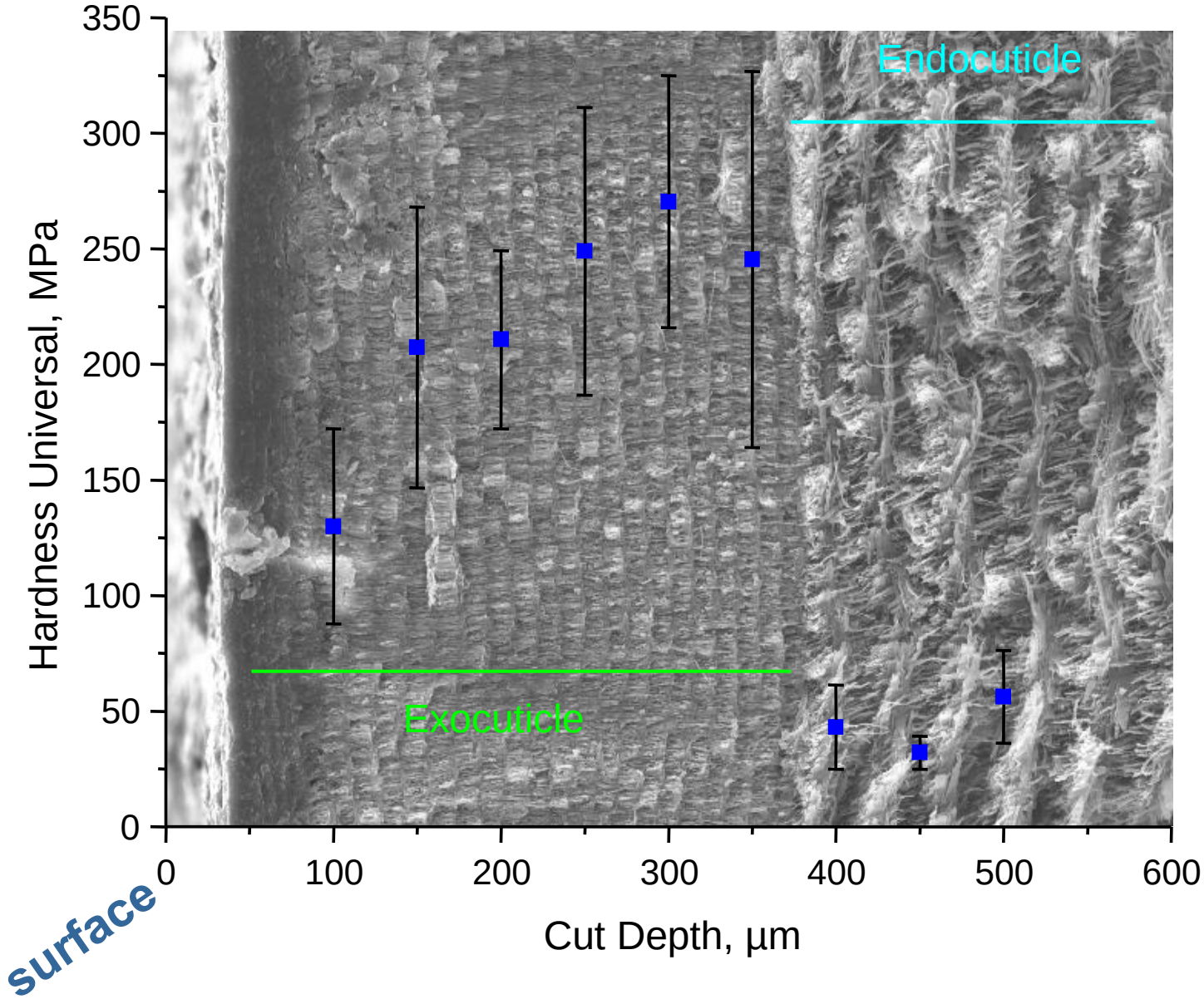

1µm
Mag = 30.00 K X
WD = 3 mm
Signal A = InLens
EHT = 5.00 kV
Date :2


200nm
Mag = 100.00 K X WD = 3 mm Signal A = InLens EHT = 5.00 kV Date :20 Ja

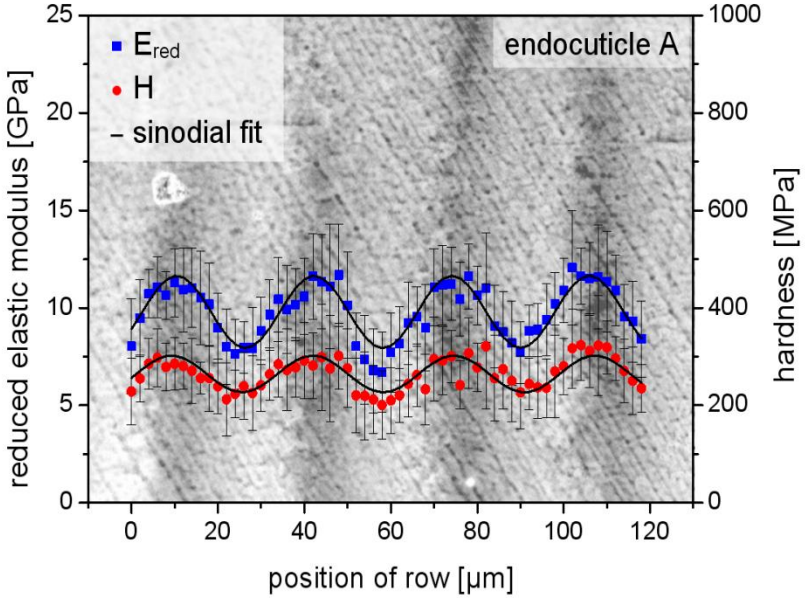
Compression tests (macroscopic), lobster

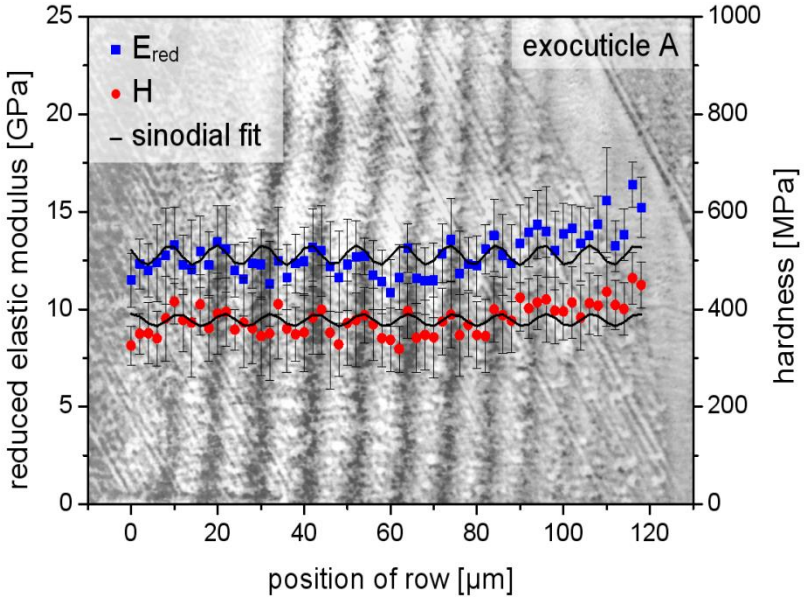


Hardness (mesoscopic)

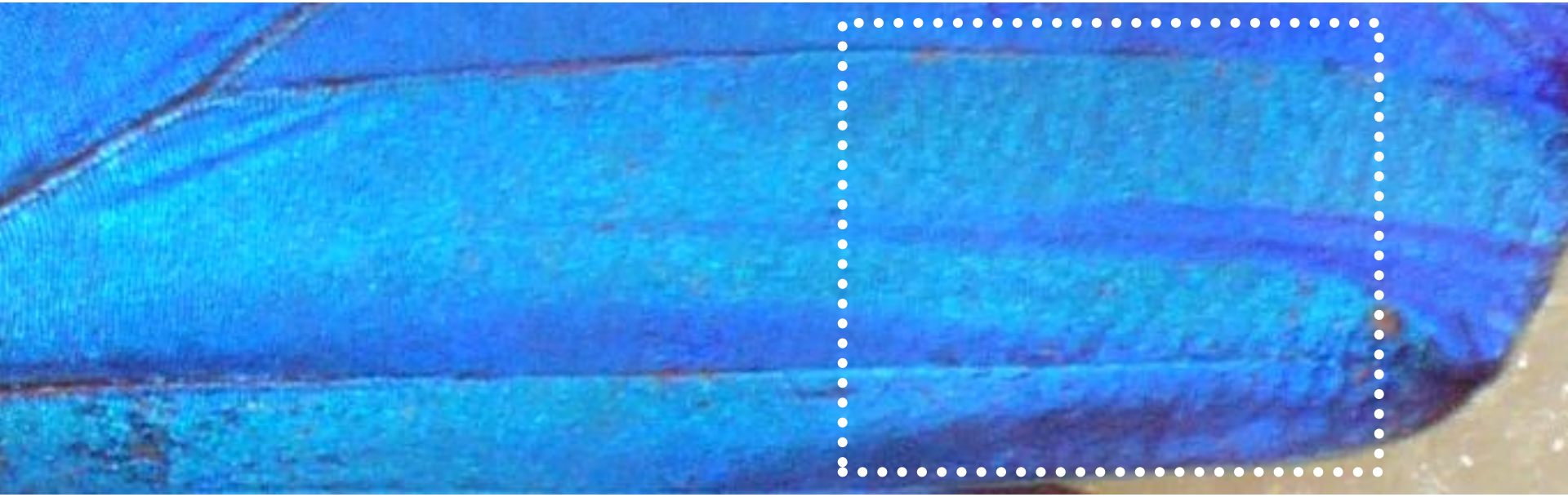


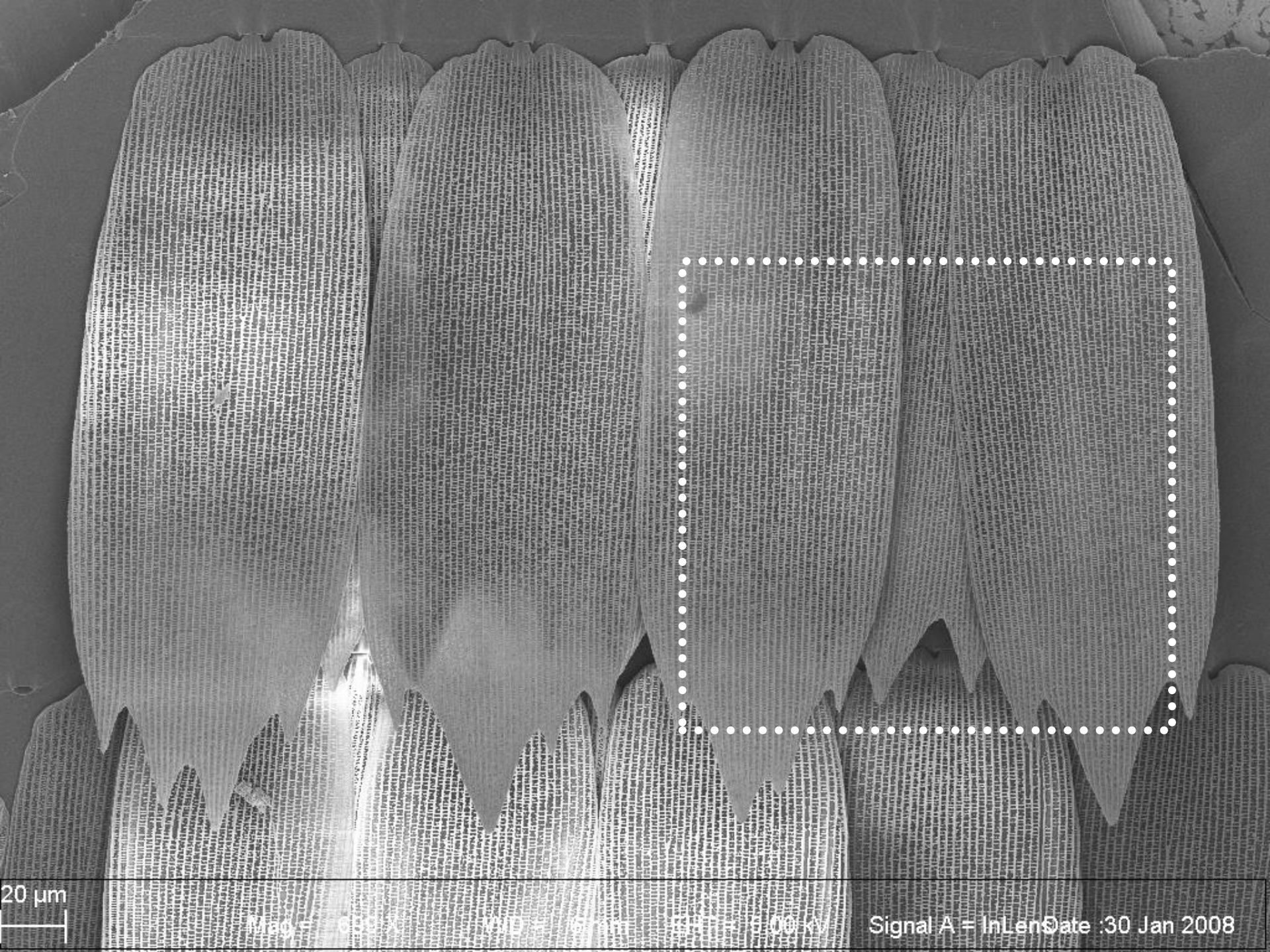
nanoindentation

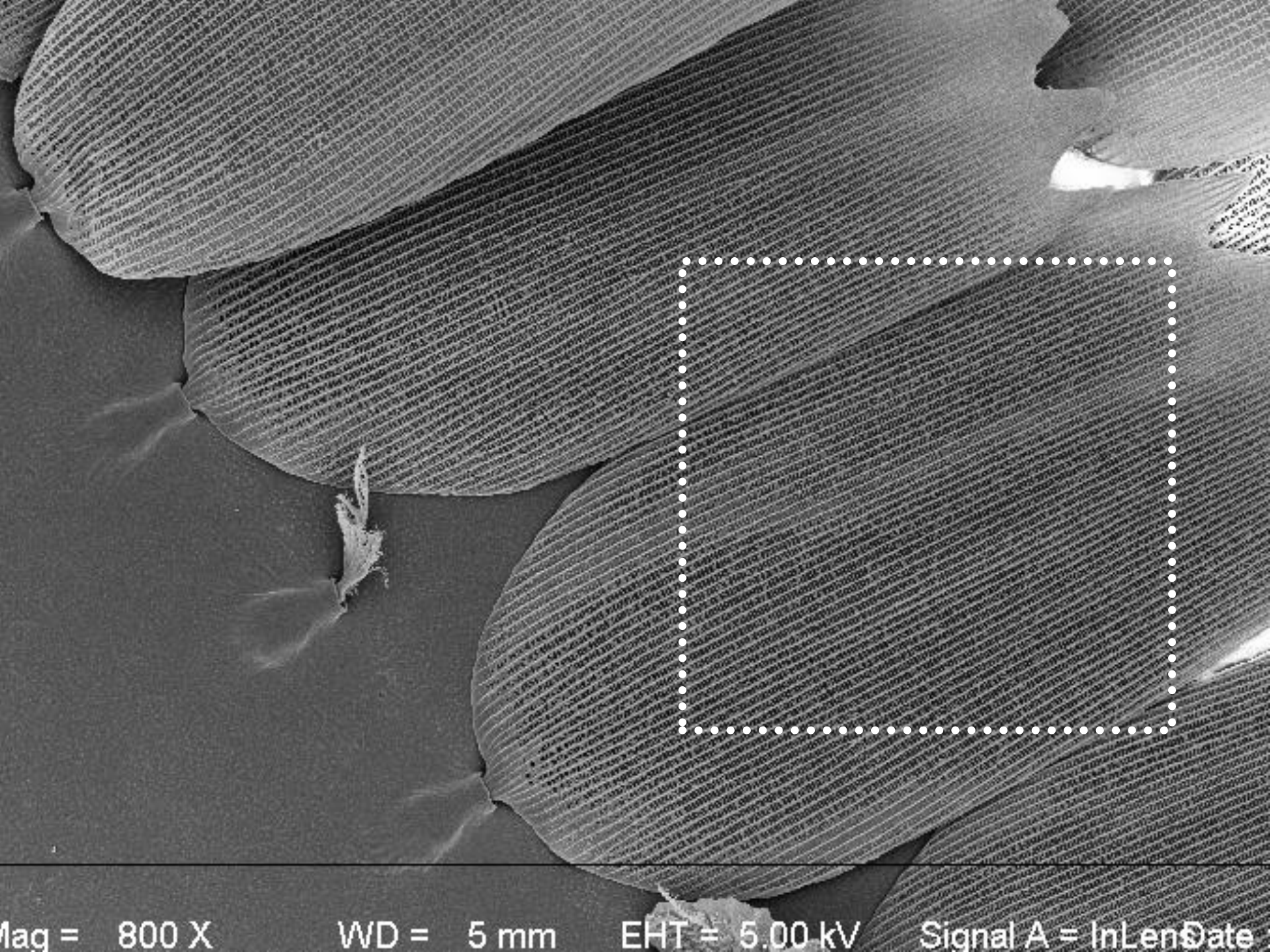


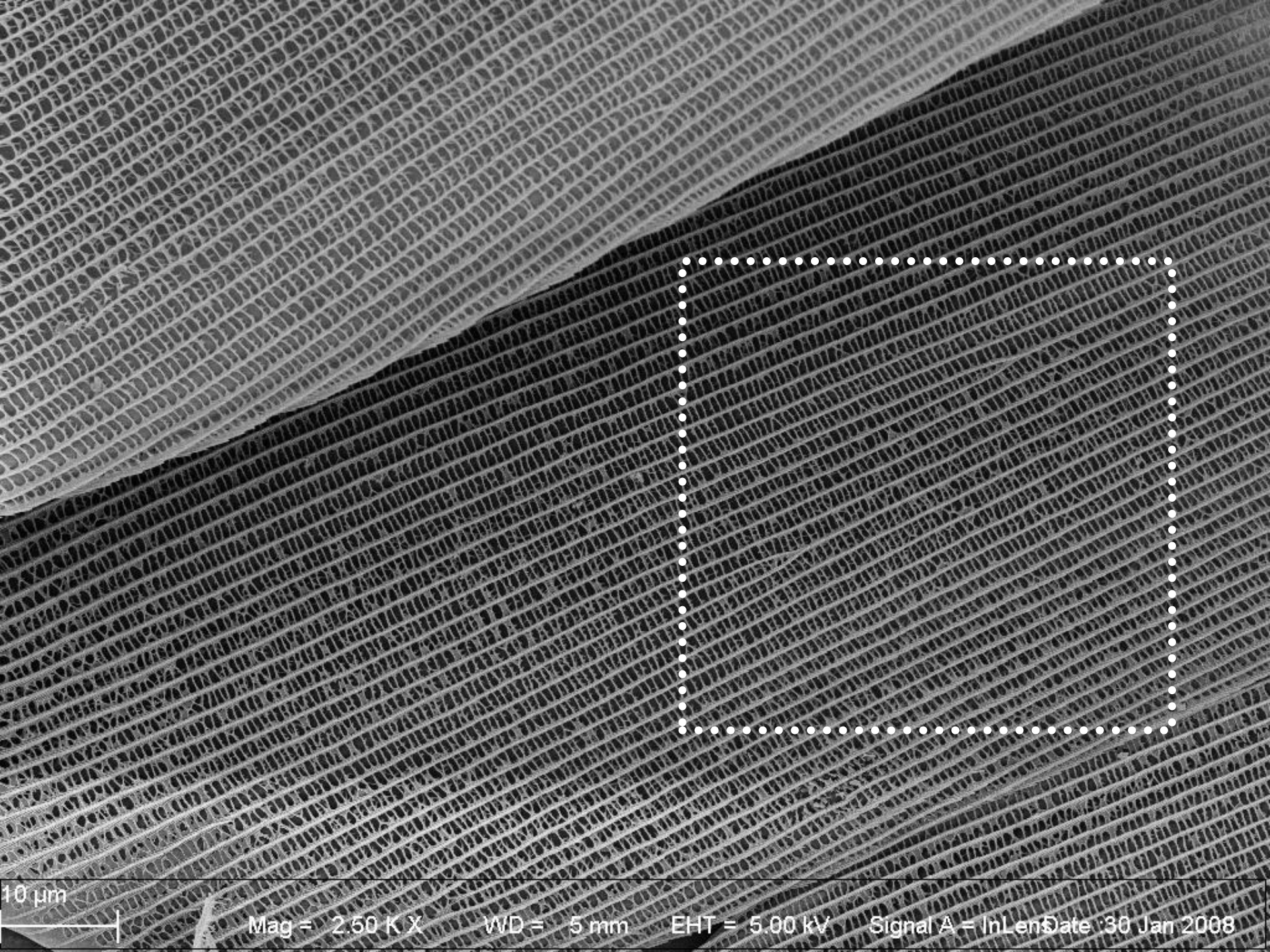


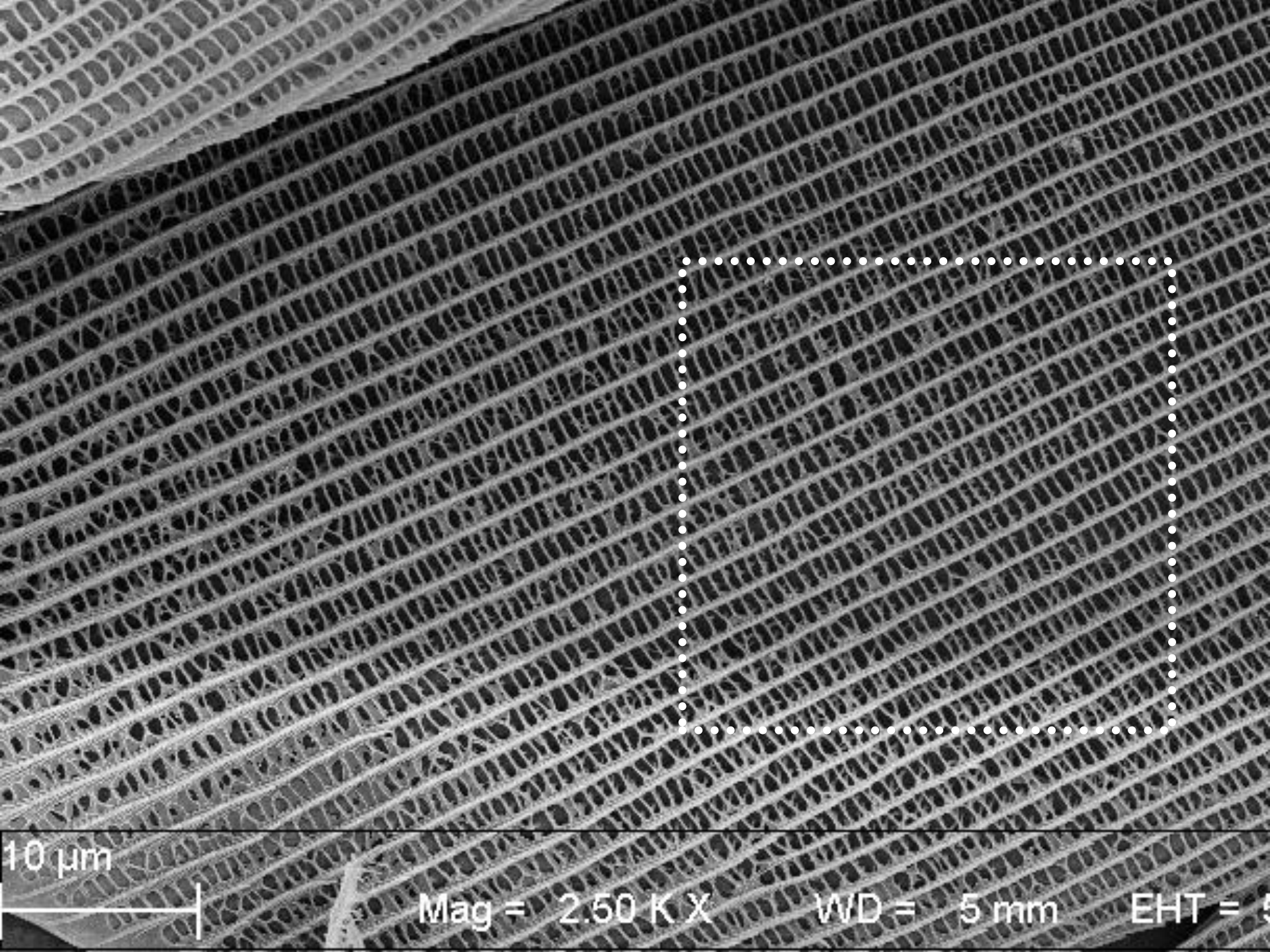
Variations in mechanical properties are the result of structural and chemical variations within the hierarchical level rather than by changes in the overal structural organisation

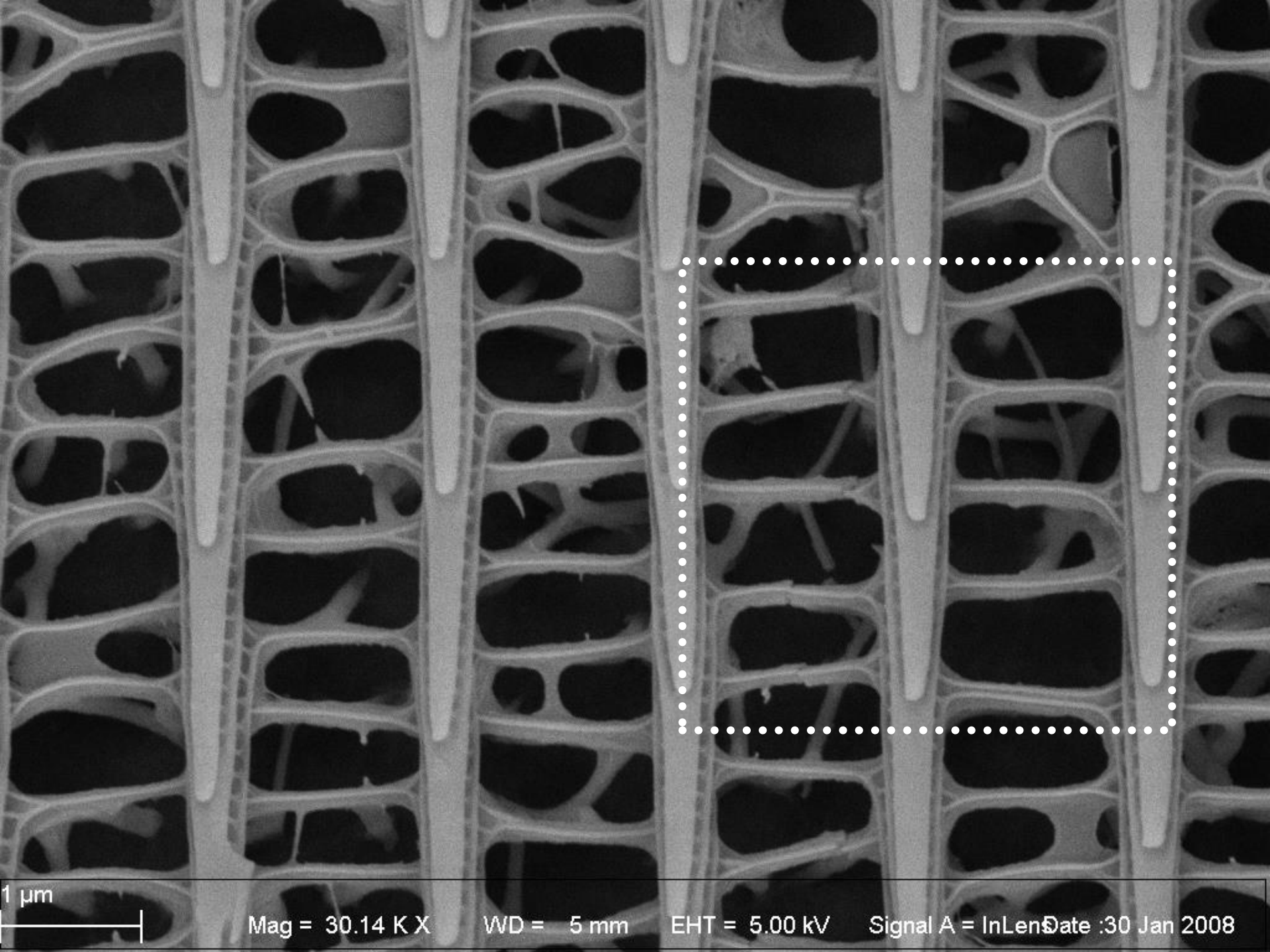


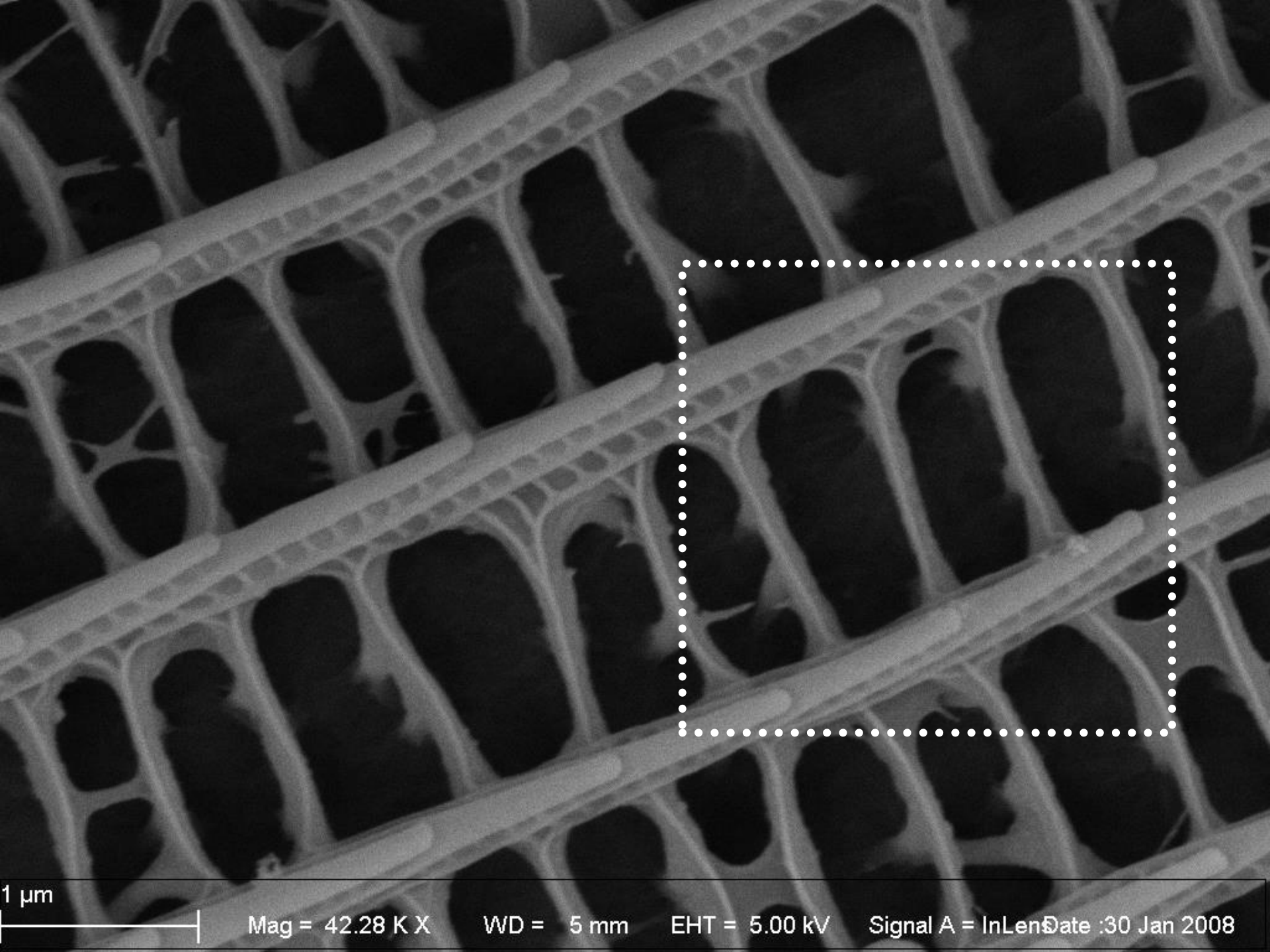

20 µm
Signal A = InLens
Date :30 Jan 2008

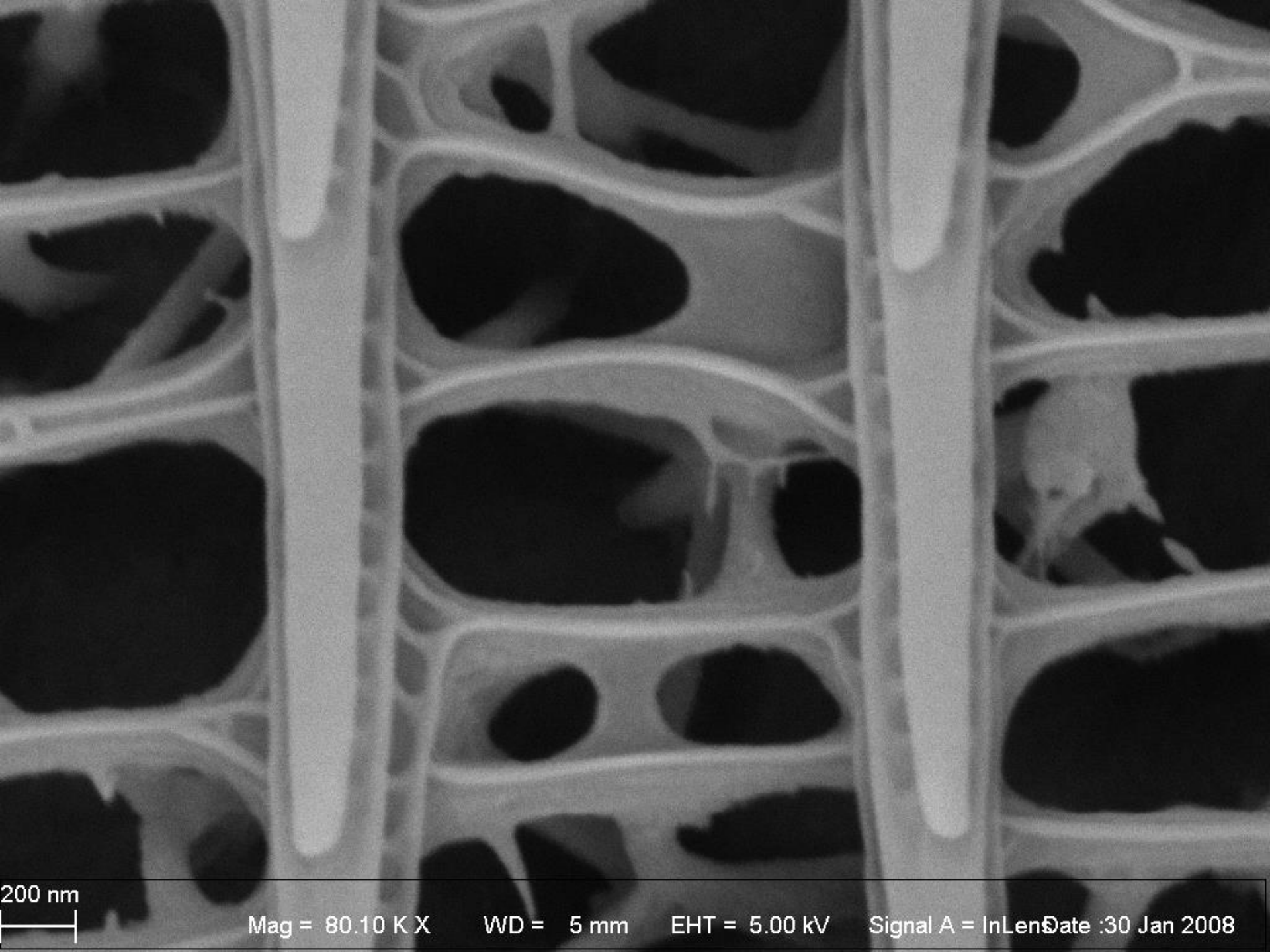

Mag = 800 X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date


10 µm
Mag = 2.50 K X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date :30 Jan 2008


10 µm
Mag = 2.50 K X
WD = 5 mm
EHT =

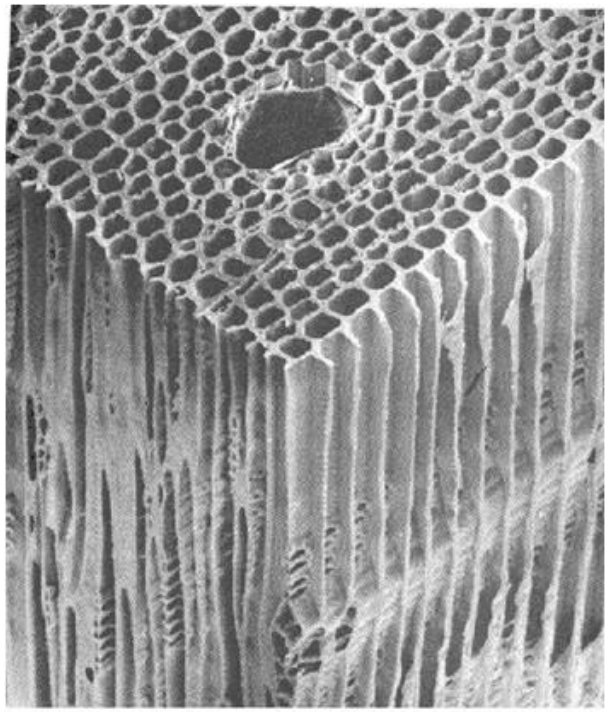

1 µm
Mag = 30.14 K X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date :30 Jan 2008


1 µm
Mag = 42.28 K X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date :30 Jan 2008


200 nm
Mag = 80.10 K X
WD = 5 mm
EHT = 5.00 kV
Signal A = InLens
Date :30 Jan 2008

Description of wood

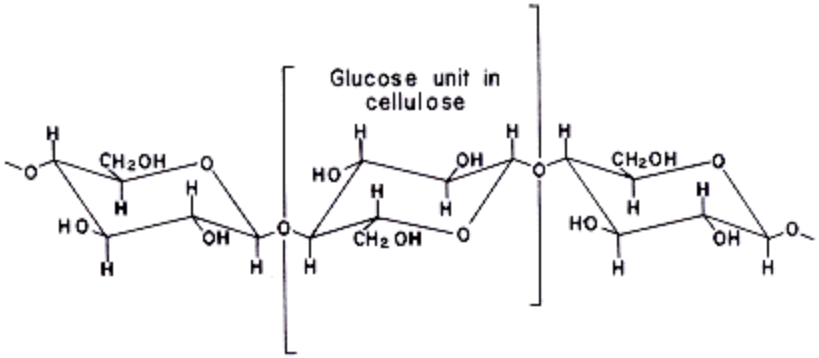
multicomponent hygroscopic anisotropic inhomogeneous discontinuous	inelastic fibrous porous biodegradable renewable

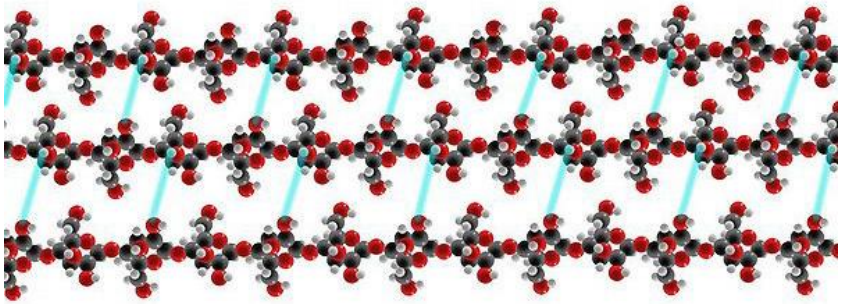


Eastern white pine in 3-D view, magnified 150x
(Source: 1980. Panshin, A.J. and C. de Zeeuw,
Textbook of Wood Technology, McGraw Hill, page 128).

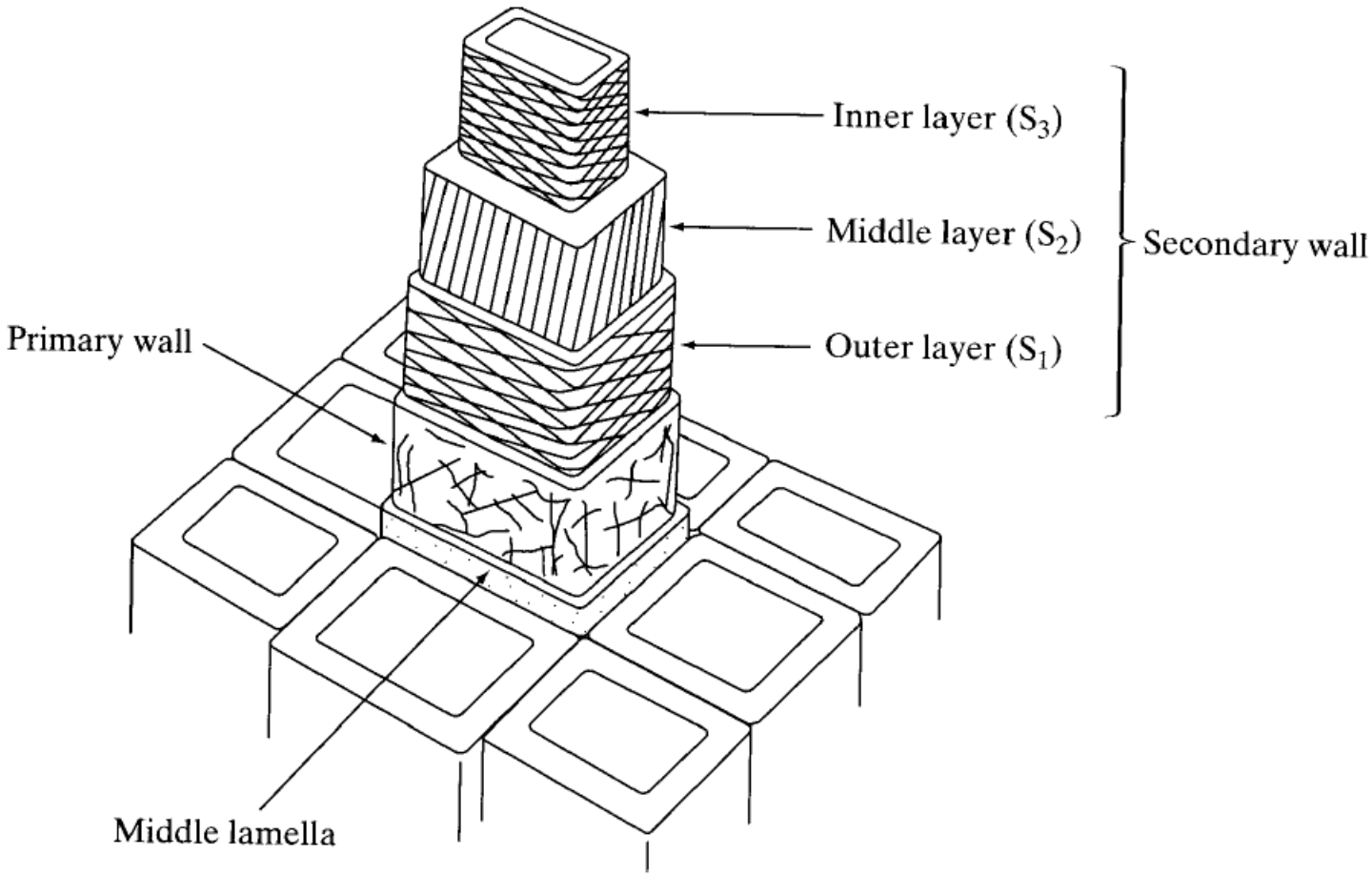
Composition of cell wall of wood

Material		Structure	Approx. wt %
Fibres	Cellulose $(C_6H_{10}O_5)_n$	Crystalline	45
Matrix	Lignin	Amorphous	20
	Hemicellulose	Semi-crystalline	20
	Water	Dissolved in the matrix	10
	Extractives	Dissolved in the matrix	5



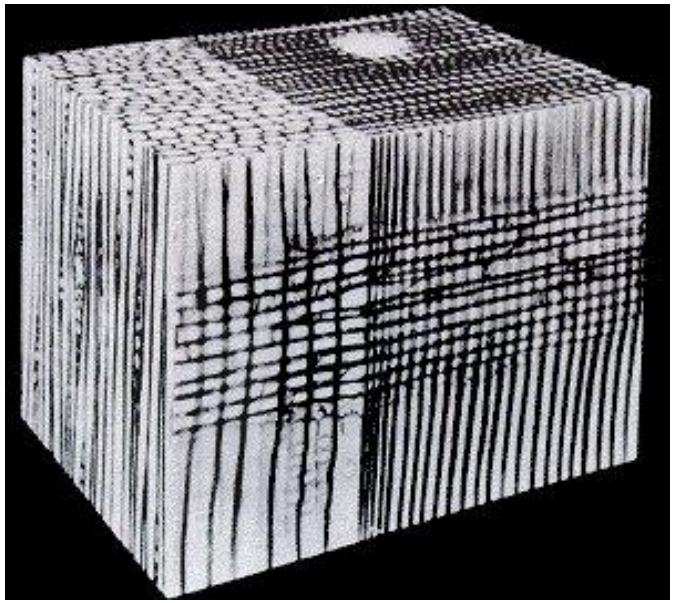


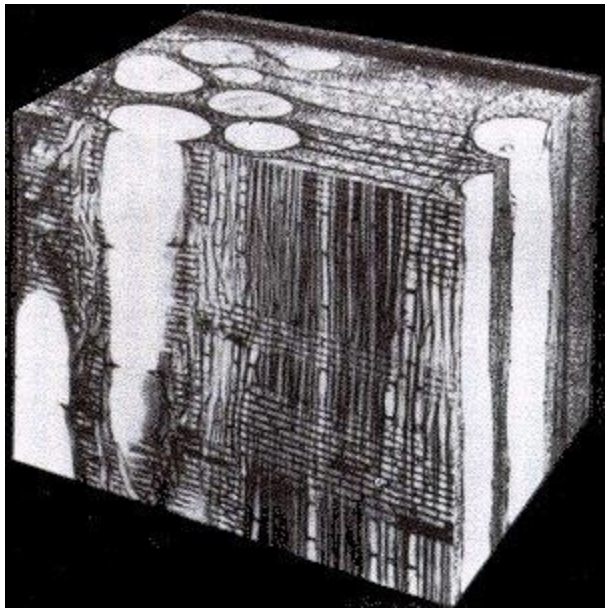
Wood


Inner layer (S_3)
Middle layer (S_2)
Outer layer (S_1)
Secondary wall
Primary wall
Middle lamella

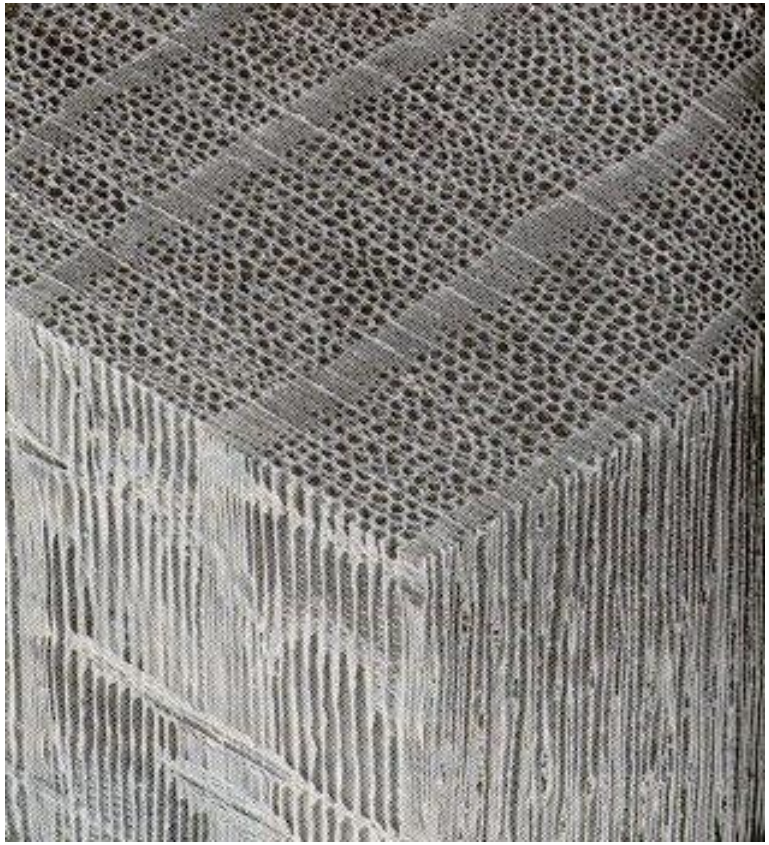
Wood

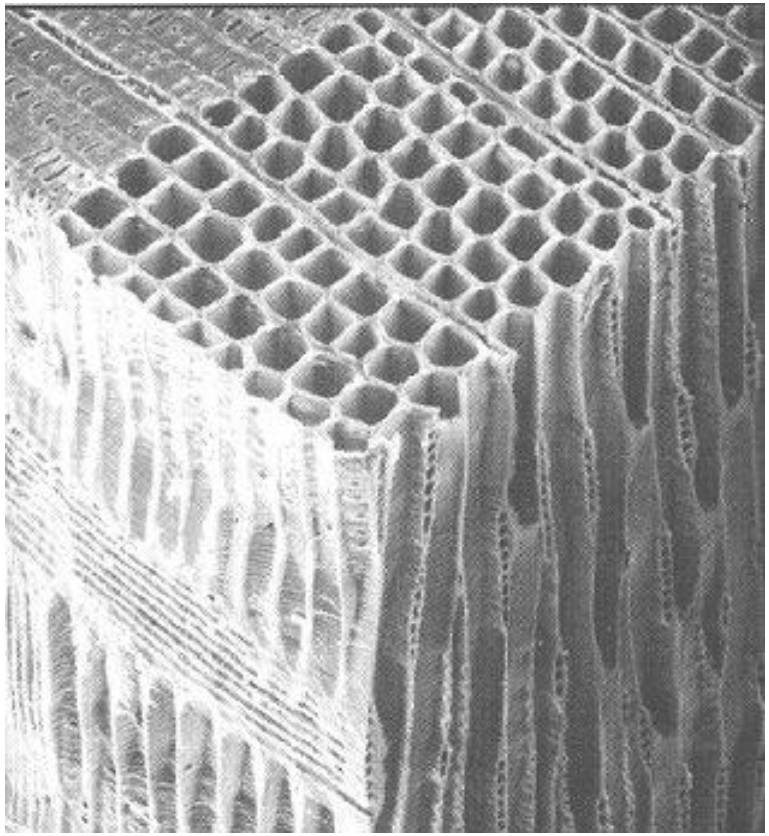
Softwood	Hardwood
Larger, longer cells Water transported by cells	Contains large-diameter vessels Water transported by these vessels





Yellow Pine

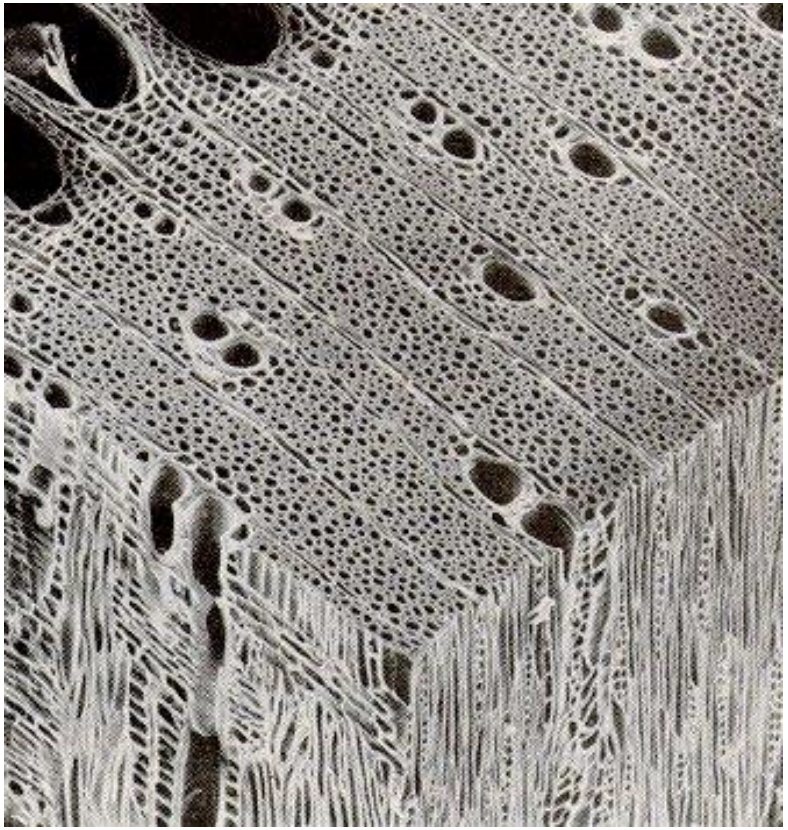




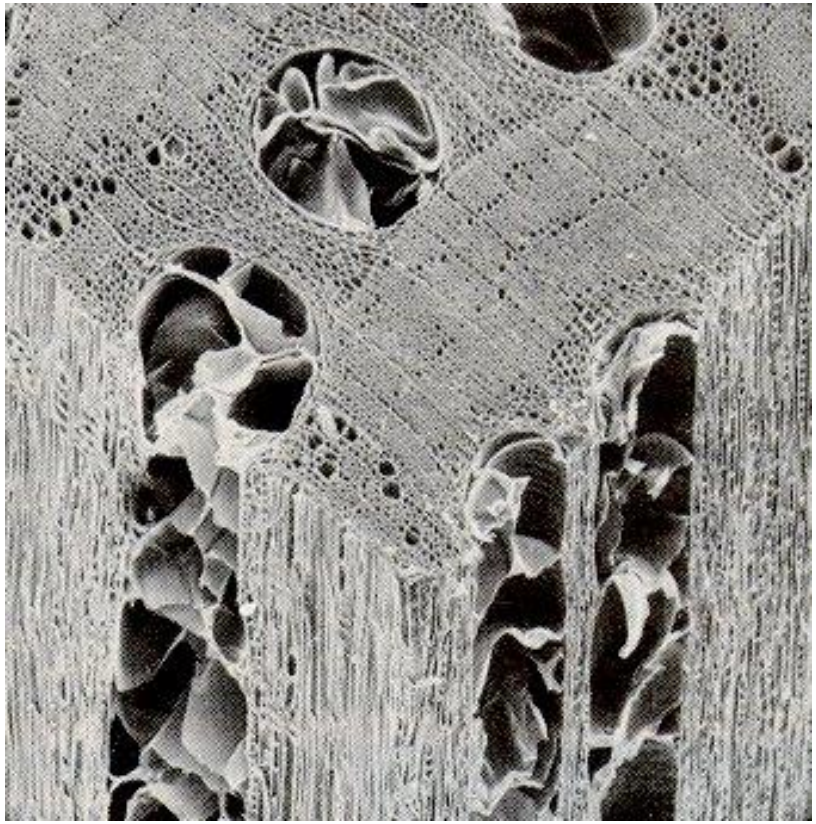
Koch, P. 1972a. Utilization of the southern pines. I. The raw material. *USDA Forest Service Agricultural Handbook* No. 420. 733 pp.
Koch, P. 1972b. Utilization of the southern pines. II. The raw material. *USDA Forest Service Agricultural Handbook* No. 420. 926 pp.

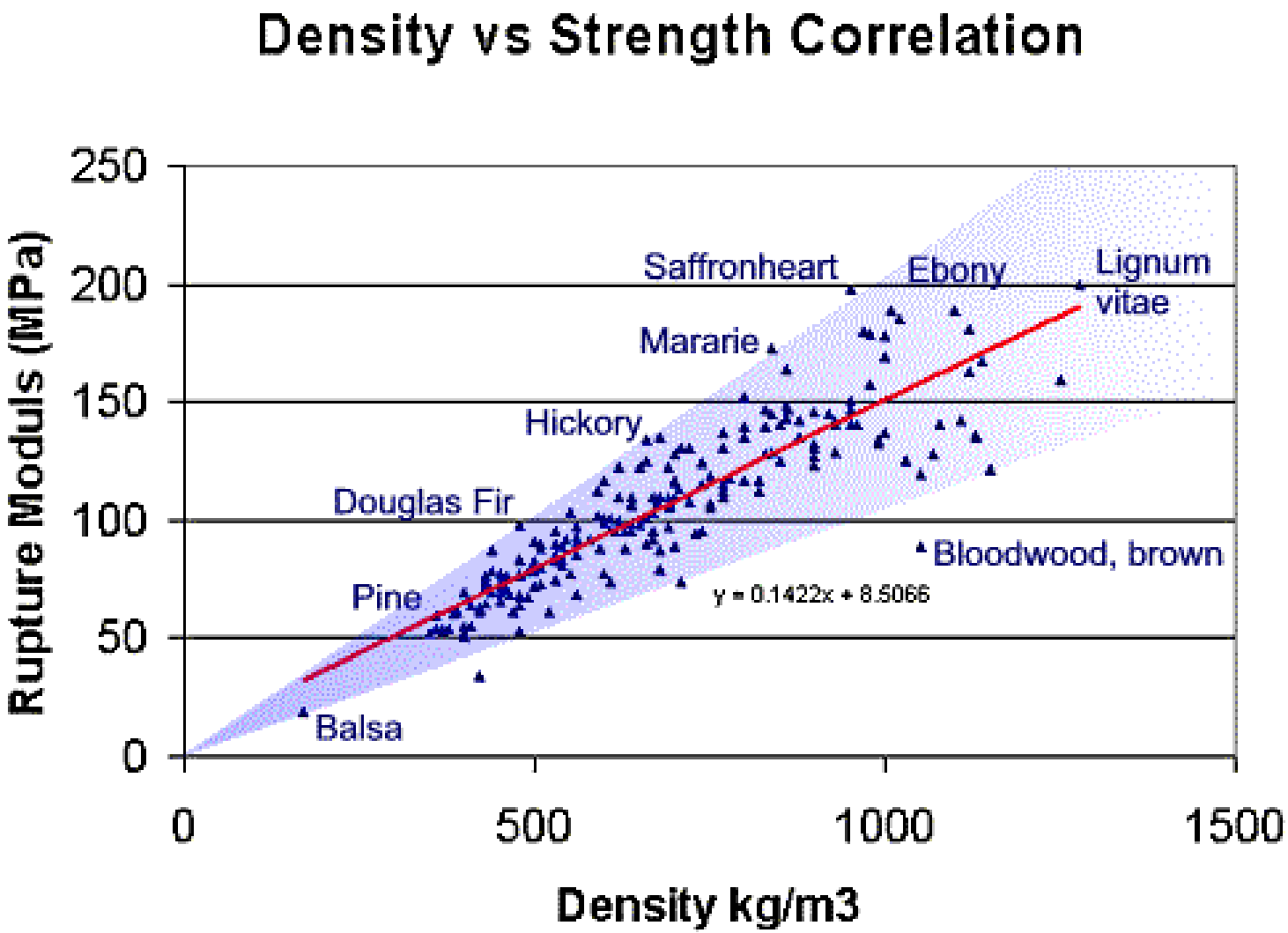
Wood

White Ash



Oak




Density vs Strength Correlation
Rupture Moduls (MPa)
250
200
150
100
50
0
0
500
1000
1500
Density kg/m3
Saffronheart
Ebony
Lignum vitae
Mararie
Hickory
Douglas Fir
Bloodwood, brown
Pine
y = 0.1422x + 8.5066
Balsa

Wood: mechanical properties