

VORLESUNG 11

Vorlesung
Humboldt-Universität zu Berlin
Institut für Physik

Biologische Physik

Die Dynamik biologischer Prozesse im menschlichen Körper

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Max Planck Institute
of Colloids and Interfaces



5.9 bone at the material level

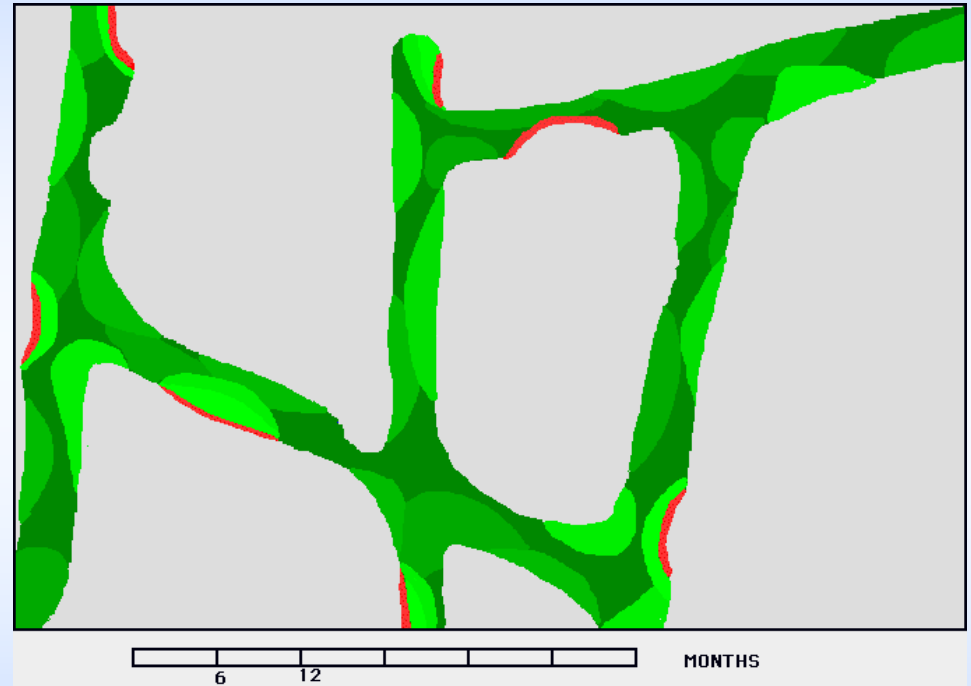
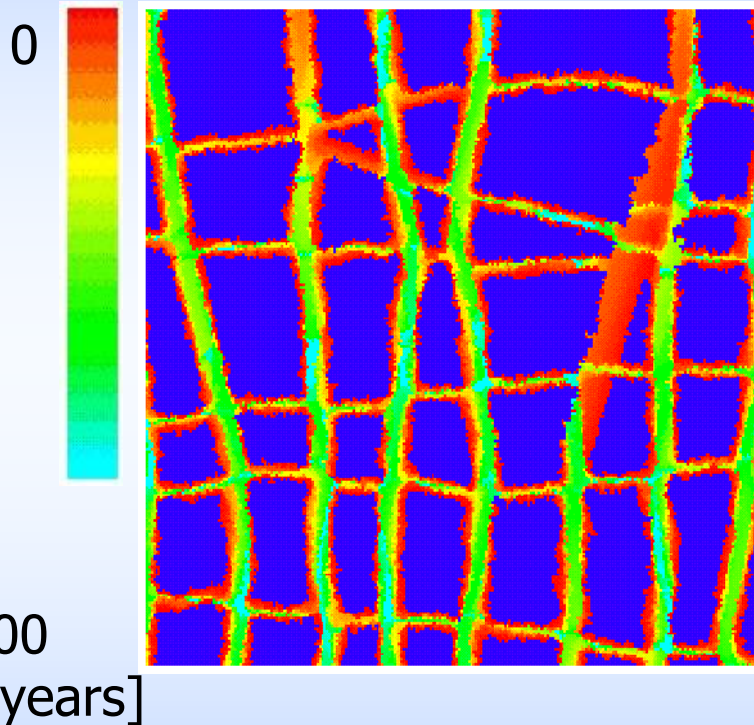
dynamics of the architecture



dynamics of the material

AGE DISTRIBUTION

BONE REMODELING



heterogeneous mineralization due to:

- remodeling process
- mineralization process

<http://courses.washington.edu/bonephys/opmovies.html>



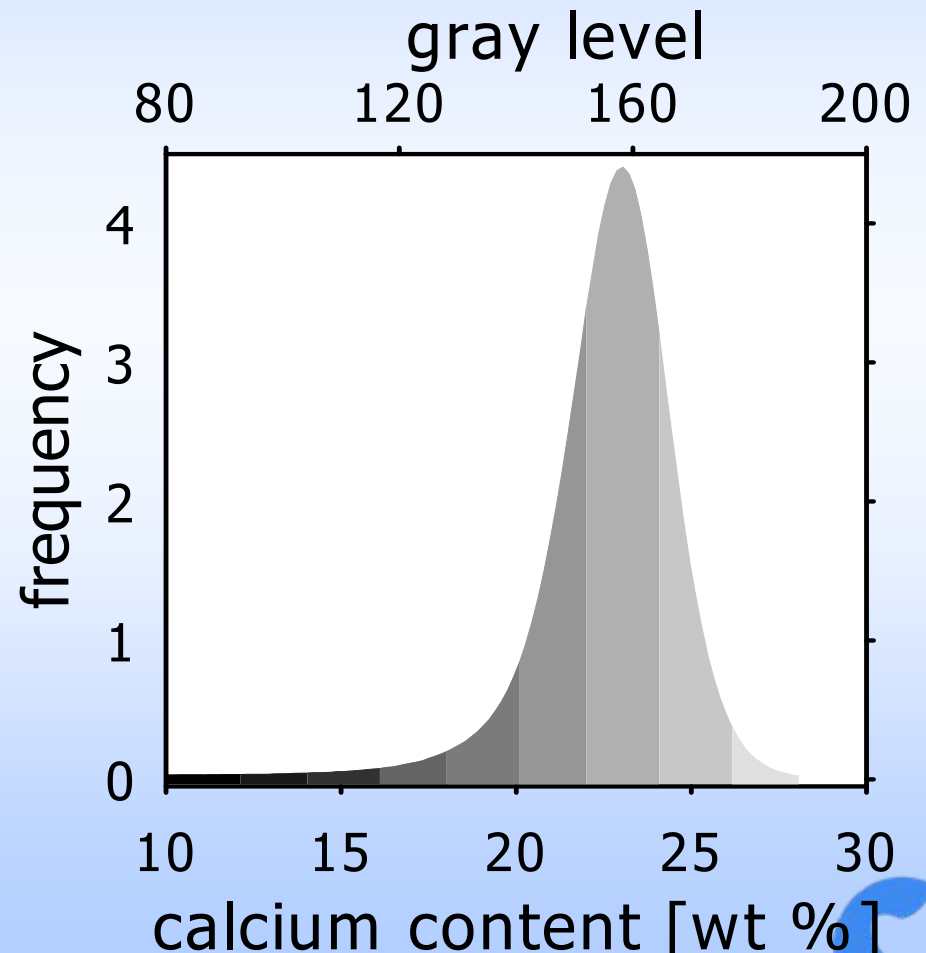
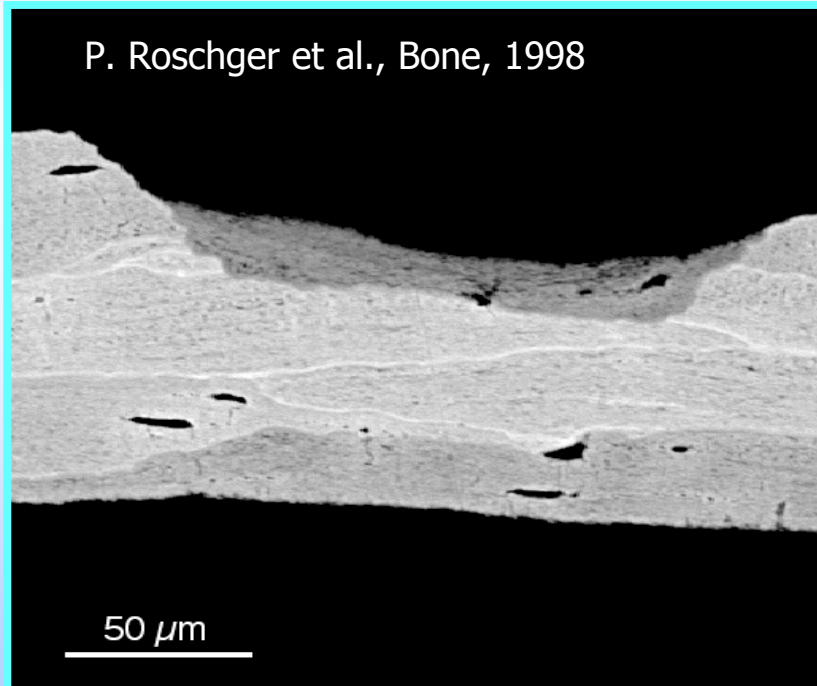


5.9 bone at the material level

how to describe the heterogeneous mineralization?

Bone Mineralization Density Distribution (BMDD)

measurable quantity
(quantitative Backscattered
Electron Imaging (qBEI))

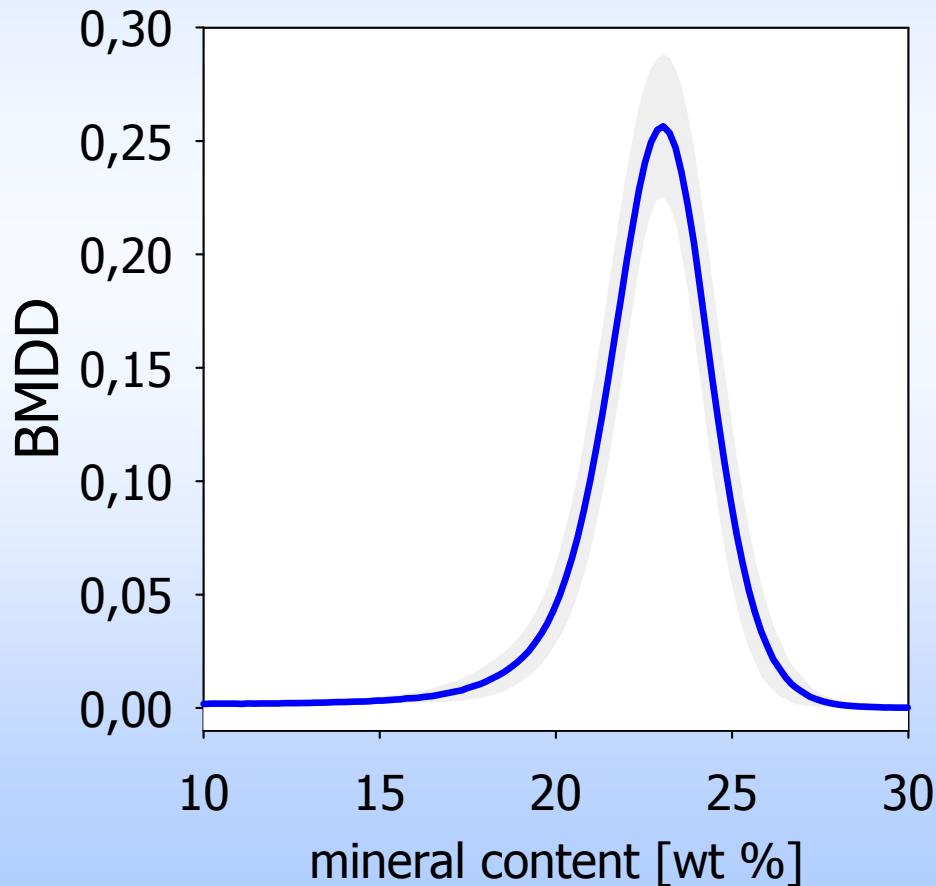




5.9 bone at the material level

experimental result:

the BMDD of trabecular bone in healthy humans is independent of gender, ethnicity, skeletal site and age



P. Roschger et al., Bone 32 (2003)

steady-state
reference BMDD

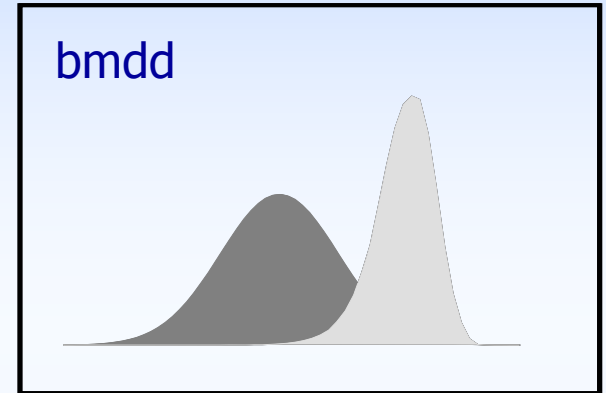
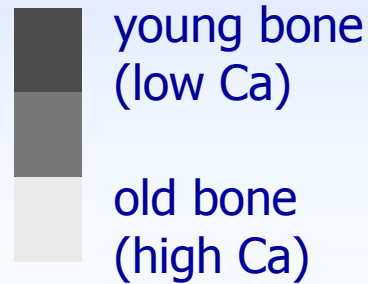
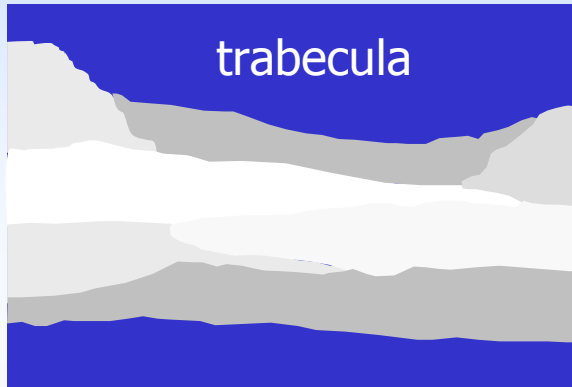




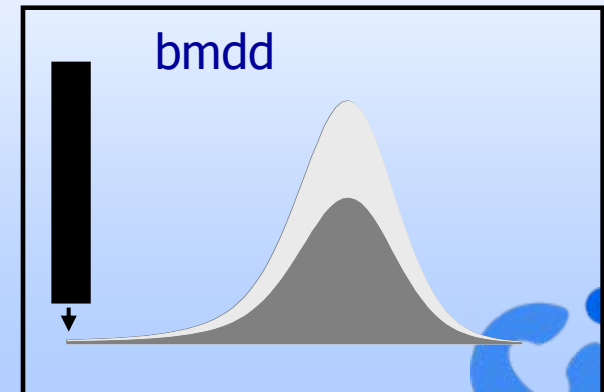
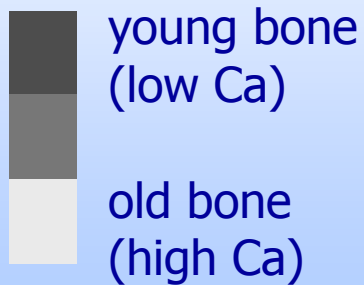
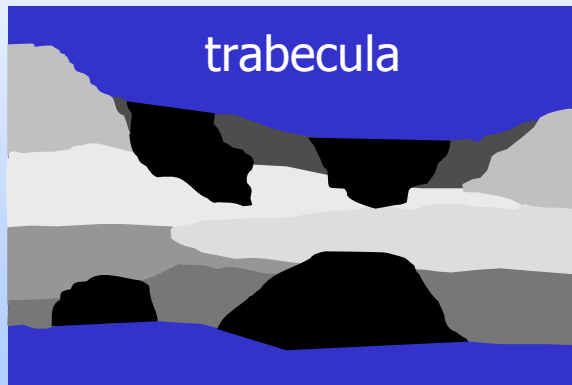
5.9 bone at the material level

BMDD changes due to mineralization and remodeling:

mineralization



remodeling





5.9 bone at the material level

modeling:

AIM

mineralization law
turnover rate

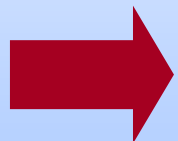
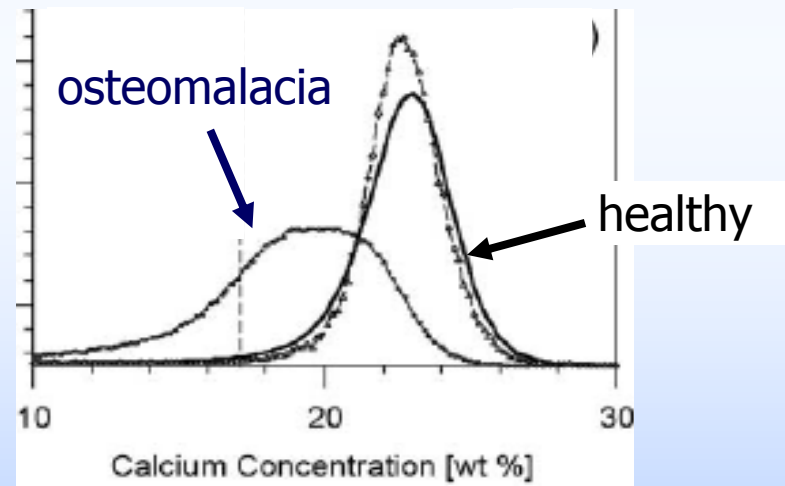


BMDD

MOTIVATION

implications for
bone quality

P. Roschger et al., Bone, 2003



mechanical properties:

**SOFT
DUCTILE**

**STIFF
BRITTLE**





5.10 modeling the material heterogeneity

THE MODEL

$$\frac{\partial \rho}{\partial t}(c, t) = \frac{\partial}{\partial c} [\rho(c, t) v(c)]$$

rate of change
of bone

continuity
equation

ρ ... BMDD
 c ... mineral content
 t ... time

MINERALIZATION

mineralization
process

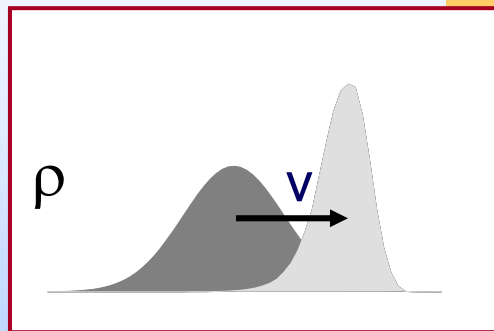
REMODELING

$$- \omega_{oc}(c, t) \rho(c, t)$$

bone removal
due to osteoclasts

$$\rho(0, t) v(0) = j_{OB}(t)$$

bone addition
due to osteoblasts



c

Ruffoni et al., Bone 40 (2007)





5.10 modeling the material heterogeneity

$$\frac{\partial \rho}{\partial t}(c, t) = \frac{\partial}{\partial c} [\rho(c, t) v(c)] - \omega_{oc}(c, t) \rho(c, t)$$

steady state solution: $\frac{\partial \rho}{\partial t} = 0$

$$\omega_{oc}(c) = \omega_{oc} = \text{const}$$

$$\tau = t / t_{TO}$$

bone removal is independent
of the mineral content

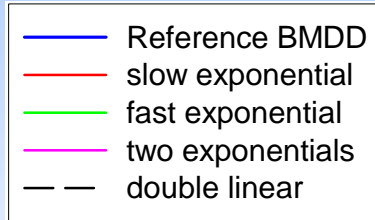
dimensionless time –
time rescaled in units of turnover time

$$\frac{\rho(c)}{BV} = -\frac{d}{dc} [\exp(-\tau(c))] \quad \longleftrightarrow \quad \tau(c) = -\ln \int_c^{c_{\max}} \frac{\rho(c')}{BV} dc'$$

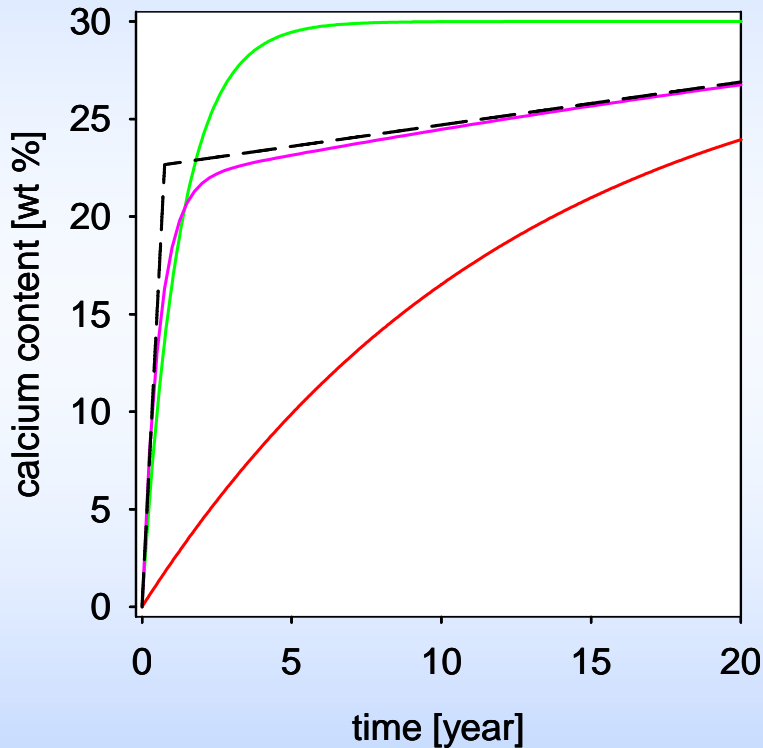


5.10 modeling the material heterogeneity

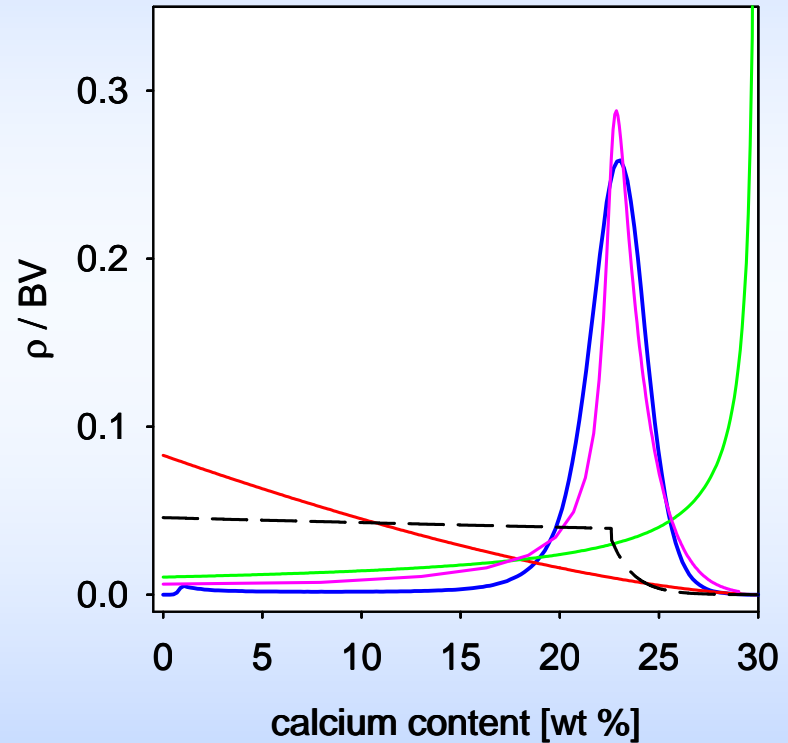
mineralization law → BMDD



mineralization law



BMDD



peaked BMDD → biphasic mineralization law



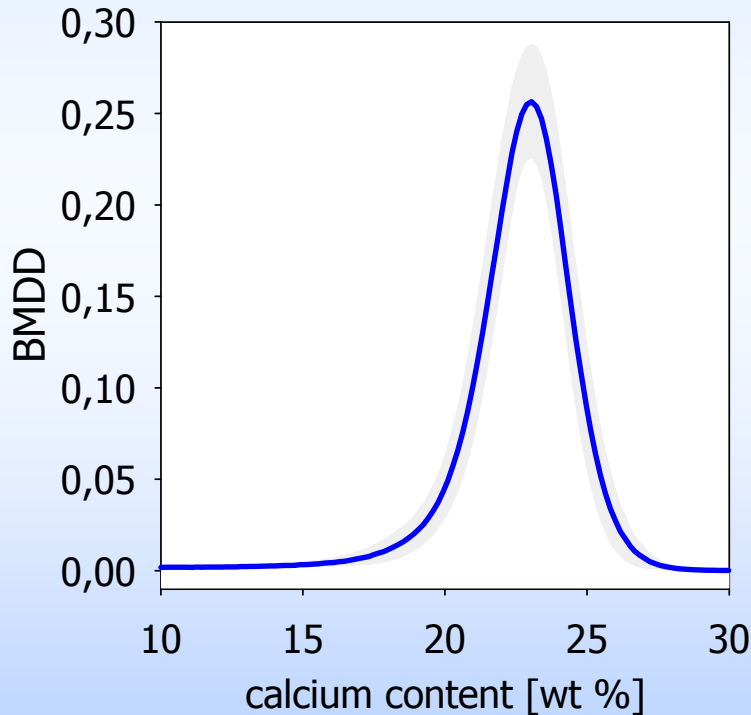


5.10 modeling the material heterogeneity

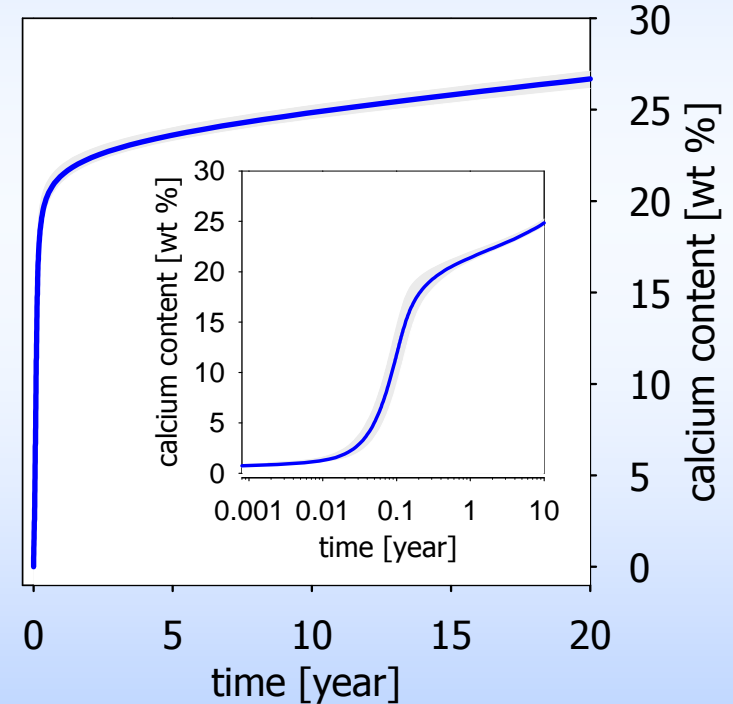
BMDD → mineralization law

starting point

experimental reference
BMDD for healthy humans



mineralization law



Ruffoni et al., Bone 40 (2007)

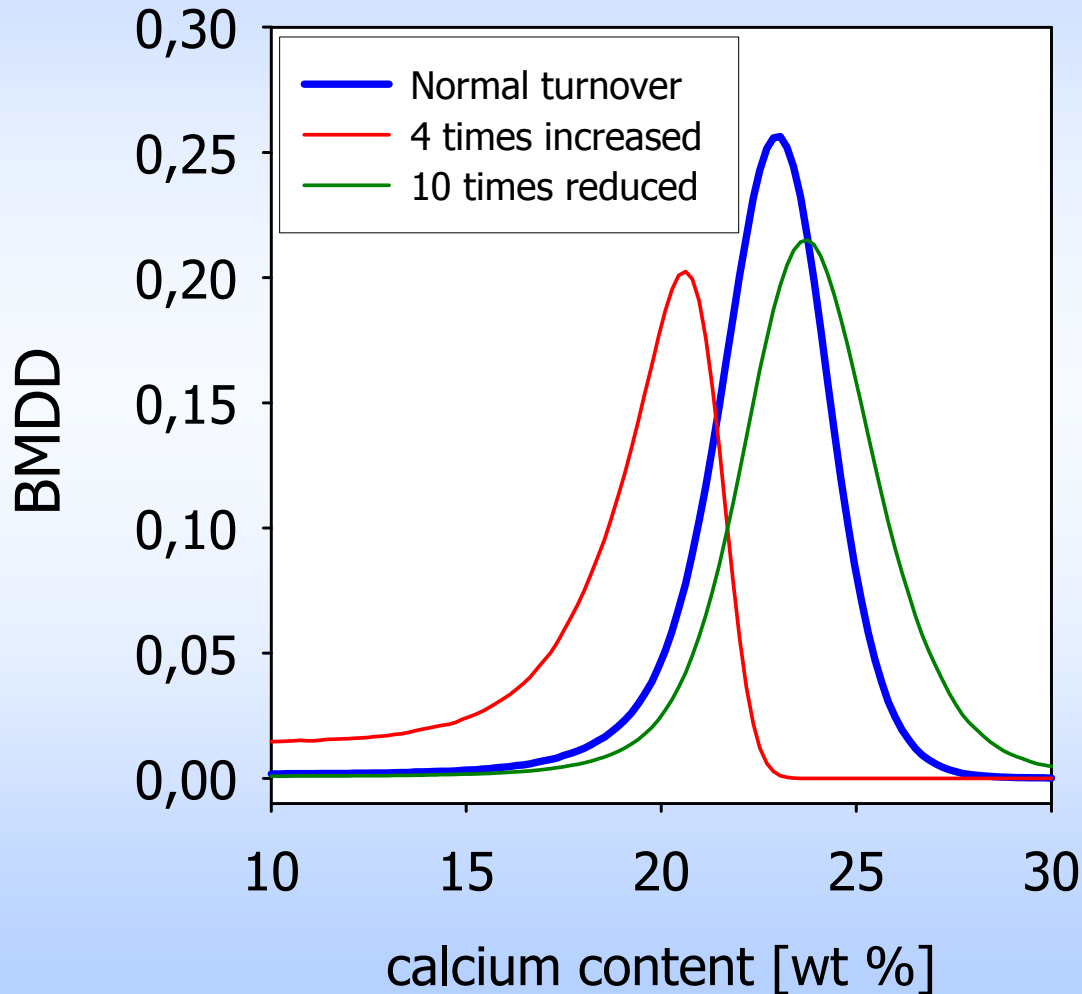
Department of Biomaterials





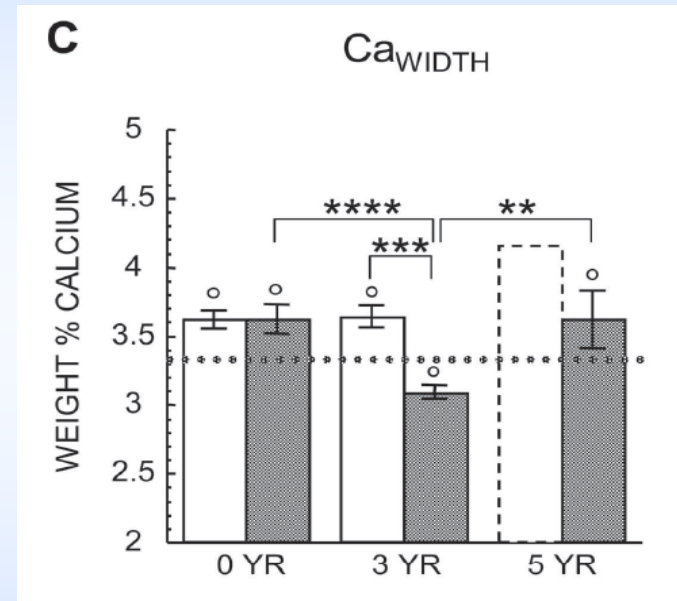
5.10 modeling the material heterogeneity

effect of turnover rate:



assuming a fixed mineralization law

bisphosphonate treatment:



□ PLACEBO (0 AND 3 YR / N=8, 5 YR / N=2)
■ RISEDRONATE (0 AND 3 YR / N=10, 5 YR / N=8)
***** NORMAL REFERENCE (N=52)

Zoehrer et al., J Bone Min Res 21 (2006)





5.10 modeling the material heterogeneity

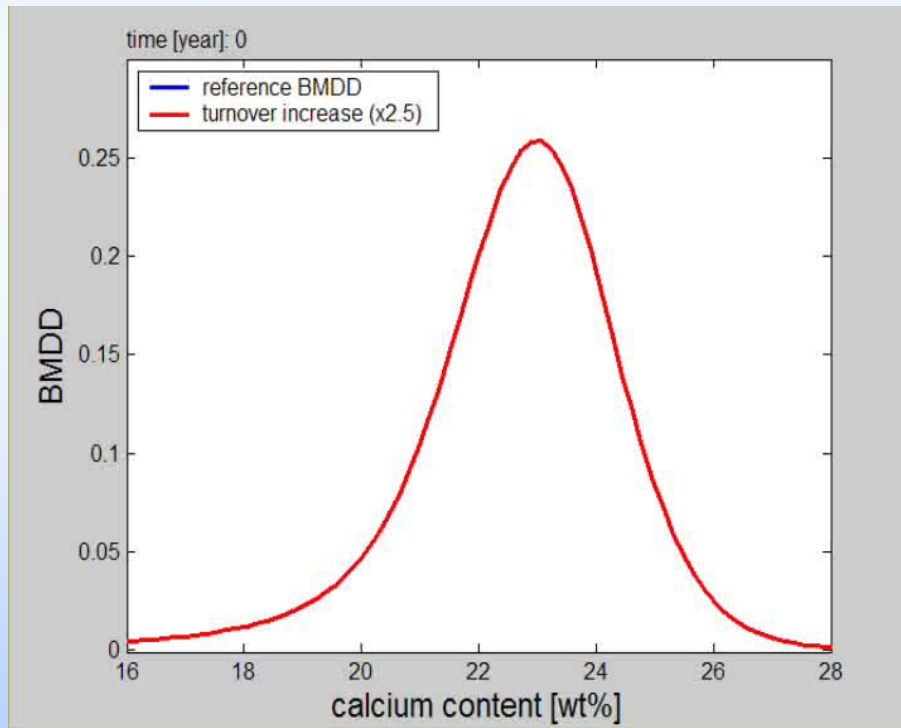
QUESTION:

how does the BMDD change when the rate of bone remodeling changes?

example: menopause

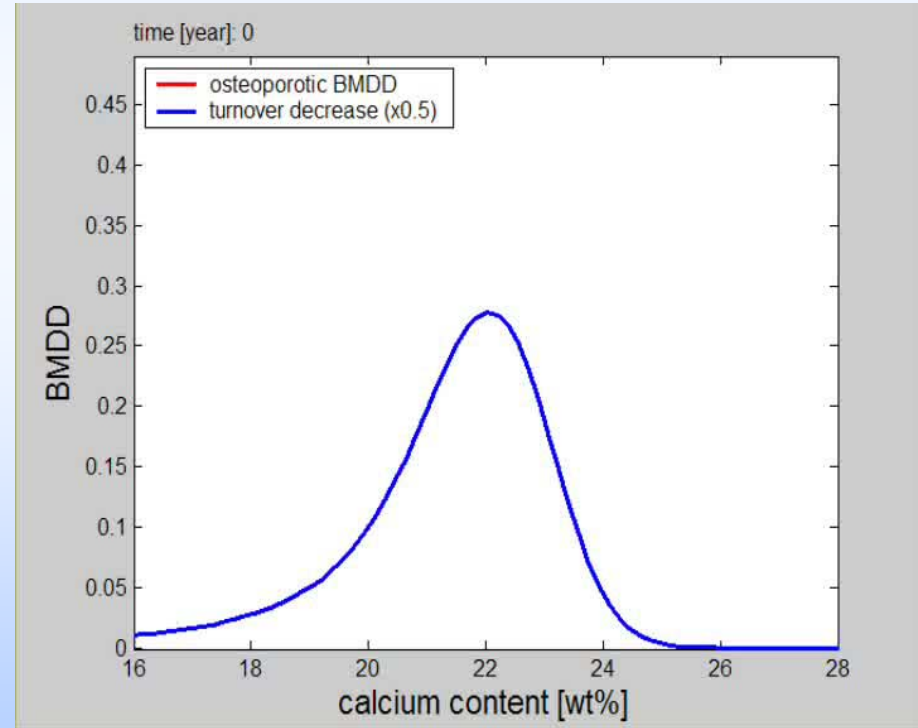
increase of the rate of bone remodeling

example: osteoporosis treatment with bisphosphonates (risedronate)
reduction of the rate of bone remodeling



soft, tough

stiff, brittle



Ruffoni et al., J Bone Miner Res, 2008

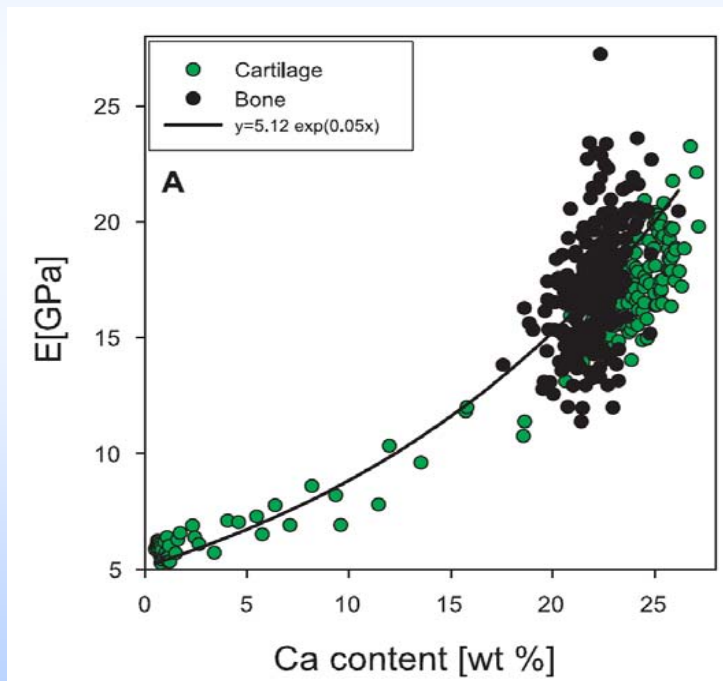




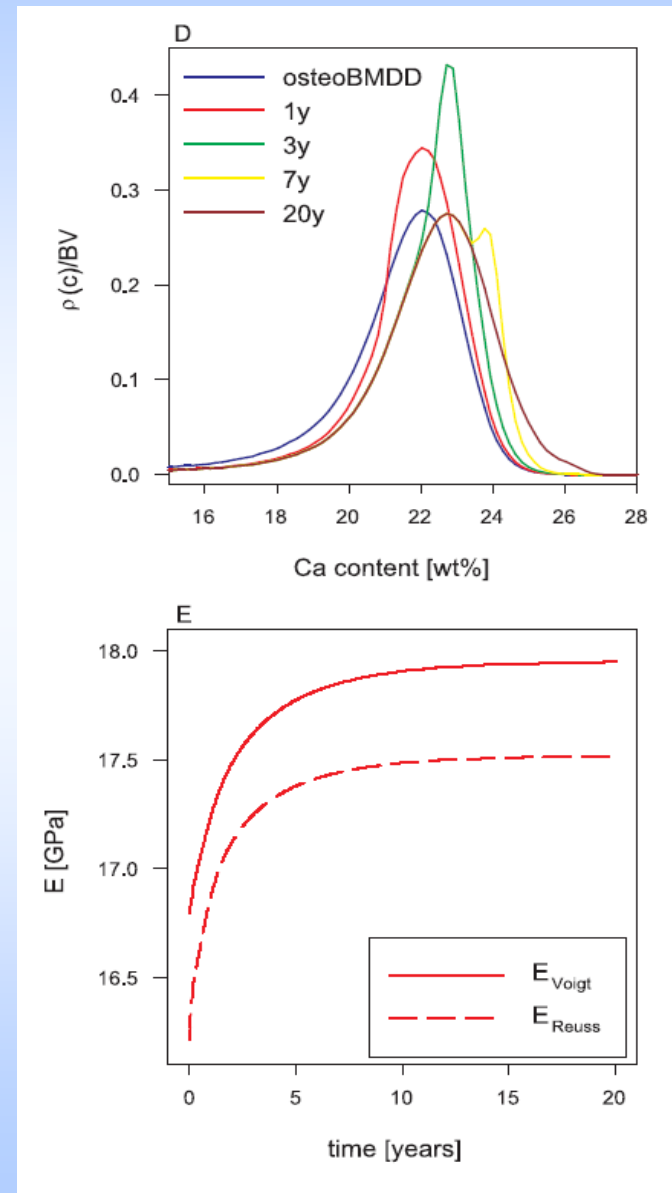
5.10 modeling the material heterogeneity

mechanical implications:

relation between
mineral content and Young's modulus:



Carolin Lukas, diploma thesis





5.11 bone fracture healing

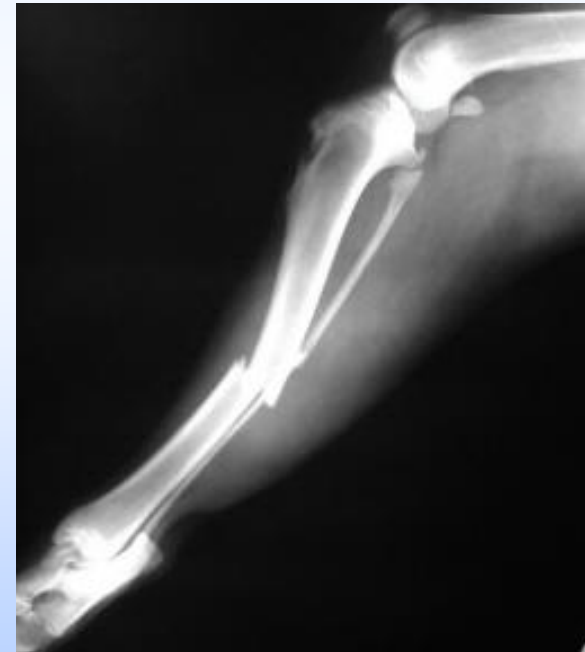
bone: a self-healing material

limb regeneration
in salamanders:



Max-Planck-Institut für
Molekulare Zellbiologie und Genetik

bone is capable of healing
without the formation
of scar tissue

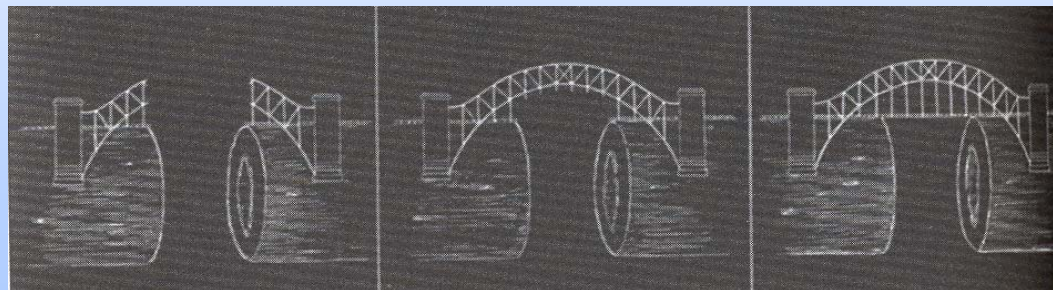
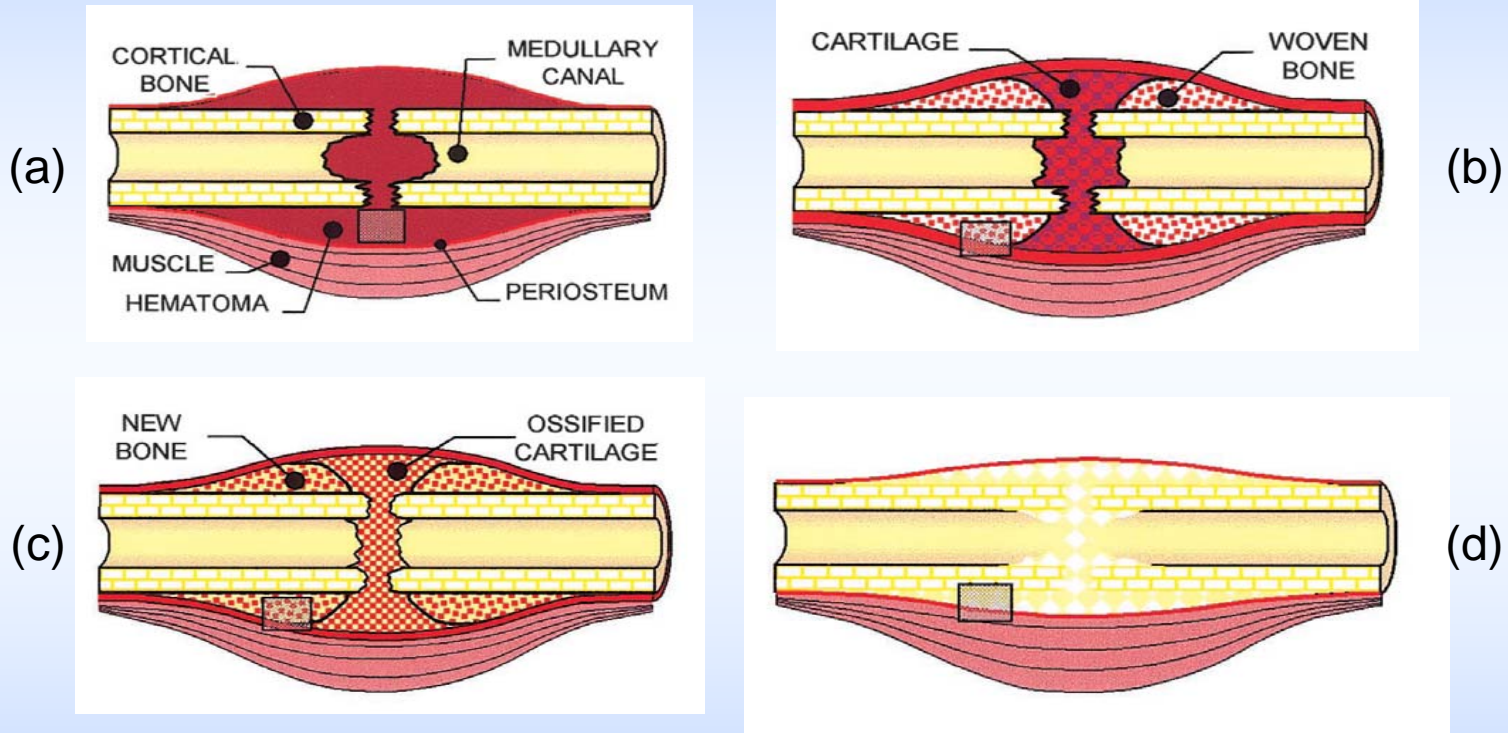




5.11 bone fracture healing

secondary fracture healing:

via a geometrical and material detour



Li et al., J Bone Min Res 16 (2001)

Urist and Johnson, (1943)

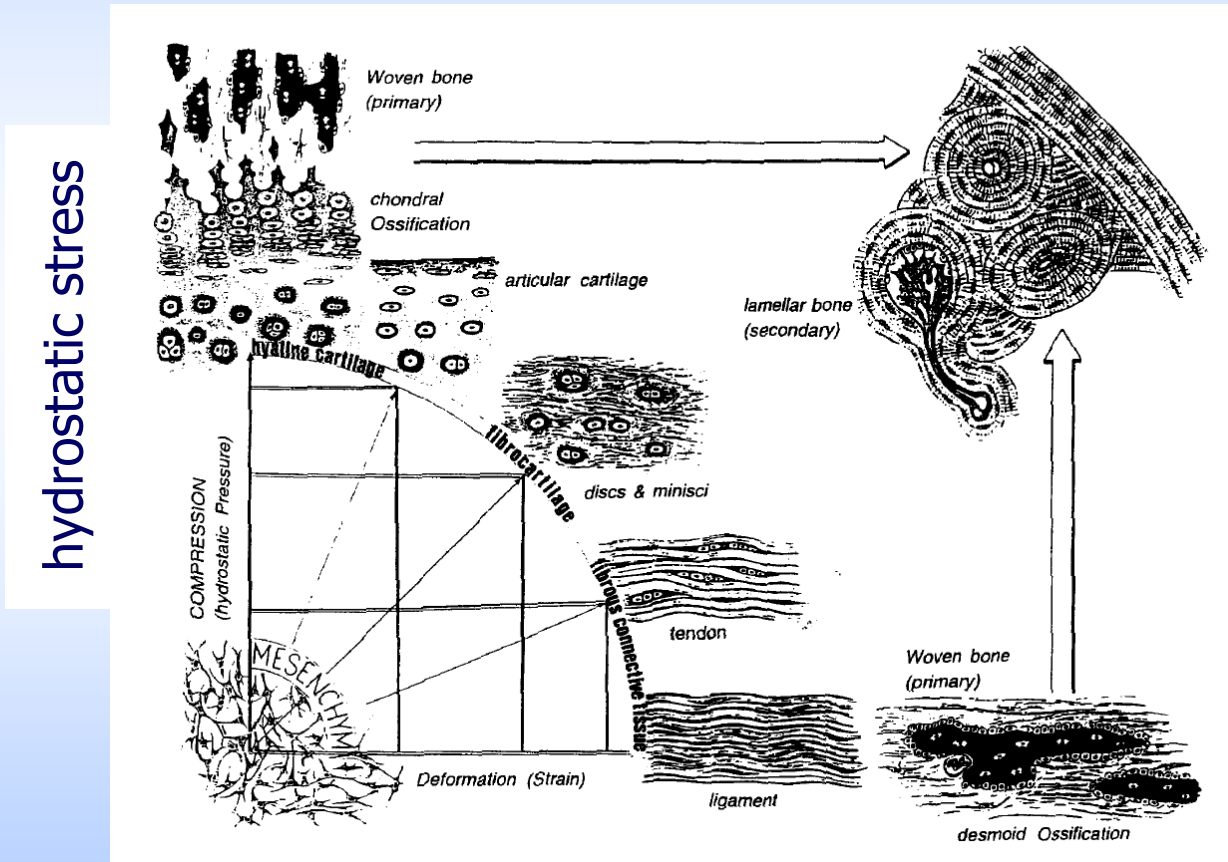




5.11 bone fracture healing

tissue differentiation is a mechano-regulated process:

phase diagram of tissue differentiation:



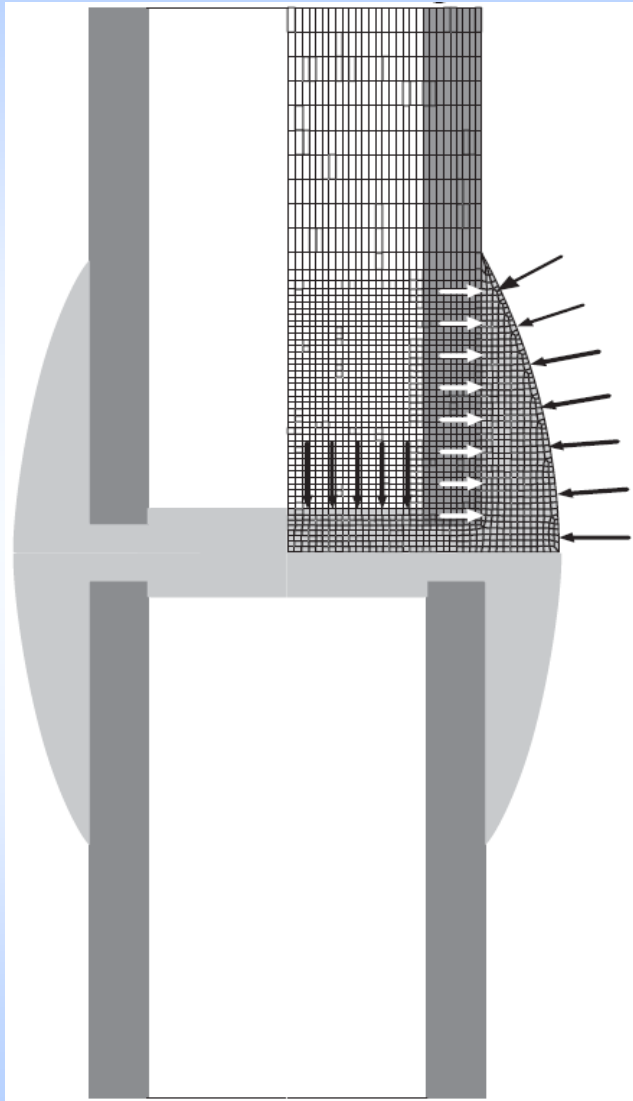
distortional stress

Weinans et al., Bone 19 (1996)





5.12 modeling bone fracture healing



mechanobiological model for bone fracture healing:

lattice model with voxels of
different tissue type (stiffness)

two different stimuli:

- **mechanical** (long-range)
- **biological** (short-range)

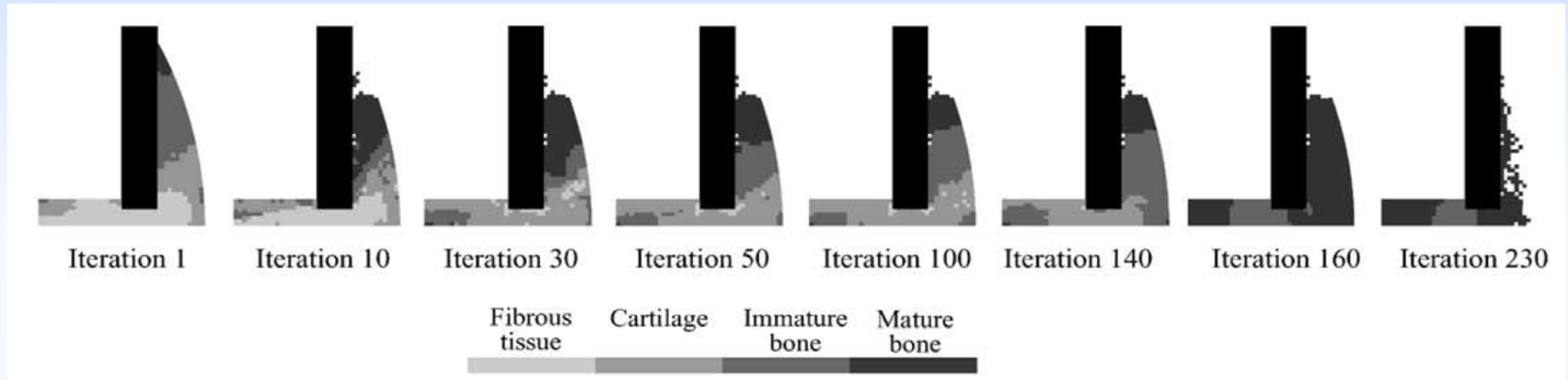
tissue differentiation regulation
rules as a function of the
mechanical and biological stimulus





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simulations:



Lacroix et al.,
J Biomech 35 (2002)

„simulations in agreement with experiments“

BUT

QUESTION:
how does the “normal” healing path look like?



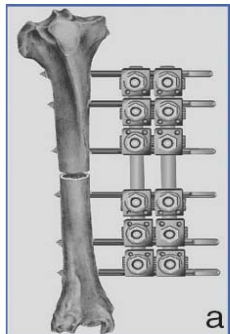


5.12 modeling bone fracture healing

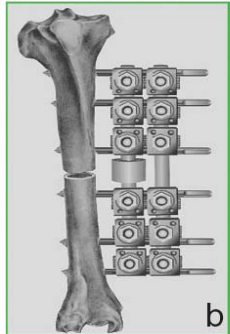
animal experiments (sheep):

- osteotomy of the tibia
- fixation of the bone fracture ends

longitudinal histological sections:



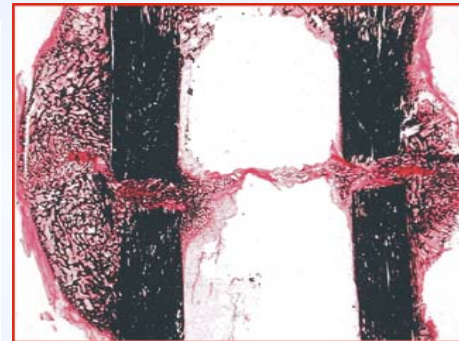
a



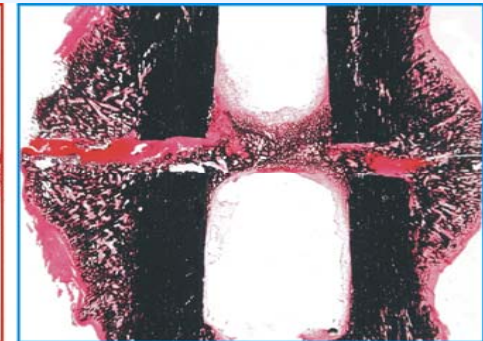
b



c



rigid fixation



semi-rigid fixation

Schell et al., J Orthop Res 23 (2005)

Charité, Berlin,
Gruppe Prof. Duda

Epari et al., Bone 38 (2006)





5.12 modeling bone fracture healing

problem of interindividual variability

normal healing path:

