Lectures 10-11, T-bone Notes/Slides, 3.054

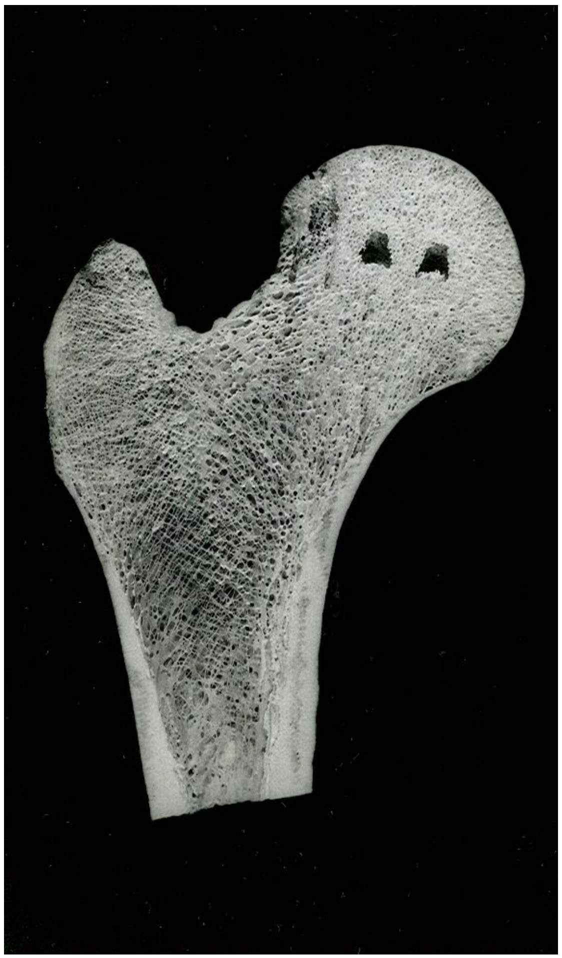
Trabecular bone

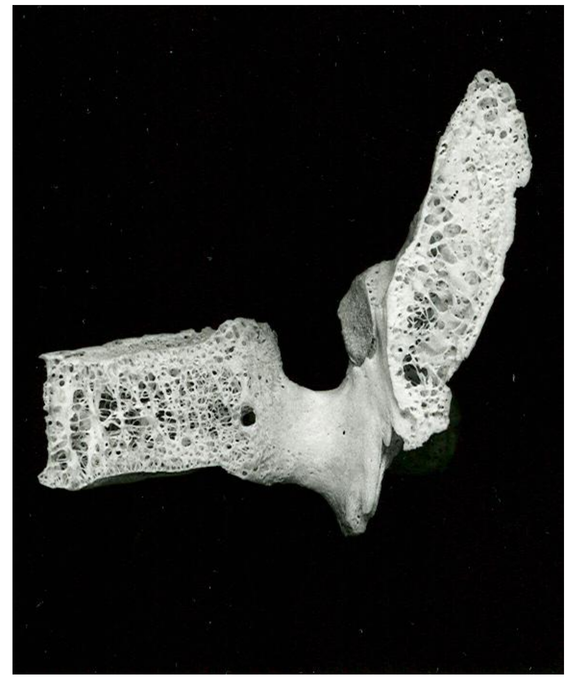
- Foam-like structure
- Exists at ends of long bones — ends have longer surface area than shafts to reduce stress on cartilage at joints; trabecular bone reduces weight
- Also exists in skull, iliac crest (pelvis) — forms sandwich structure — reduces weight
- Also makes up core of vertebrae
- Trabecular bone of interest: (1) osteoporosis (2) osteoarthritis (3) joint replacement

Osteoporosis

- Bone mass decreases with age; osteoporosis — extreme bone loss
- Most common fractures: hip (proximal femur)
  vertebrae
- At both sites, most of load carried by trabecular bone
- Hip fractures especially serious: 40% of elderly patients (>65 years old) die within a year (often due to loss of mobility — pneumonia)
- 300,000 hip fractures/year in US
- Costs $17 billion in 2005

Trabecular bone





Osteo arthritis

- Degradation of cartilage at joints
- Stress on cartilage affected by moduli of underlying bone
- Cortical bone shell can be thin (e.g. < 1mm)
- Mechanical properties of trabecular bone can affect stress distribution on cartilage

Joint replacement

- If osteoarthritis bad and significant damage to cartilage, may require joint replacement
- Cut end of bone off and insert stem of metal replacement into hollow of long section of bone
- Metals used: titanium, cobalt-chromium, stainless steel
- Bone grows in response to loads on it

  Trabecular bone: density depends on magnitude of σ
orientation depends on direction of principal stresses

- Mismatch in moduli between metal and bone leads to stress shielding

	E(GPa)		E(GPa)
Co - 28Cr - Mo	210	Cortical bone	18
Ti alloys	110	Trab. bone	0.01-2
316 Stainless Steel	210		

- After joint replacement, remodeling of remaining bone affected
  - Stiffer metal carries more of load, remaining bone carries less
  - Bone may resorb — can lead to loosening of prosthesis
  - Can cause problems after $\sim$ 15 years
  - Reasons surgeons don't like to do joint replacement on younger patients

Sturcture of trabecular bone

- Resembles foam: "trabecula" = little beam (Latin)
- Relative density typically 0.05-0.50
- Low density trabecular bone — like open cell foam
- Higher density — becomes like perforated plates
- Can be highly anisotropic, depending on stress field

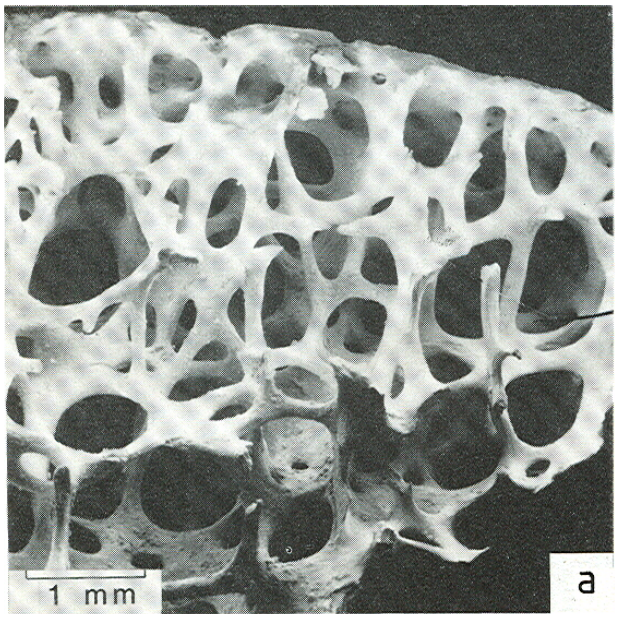
Trabecular Bone Structure

Images removed due to copyright restrictions.

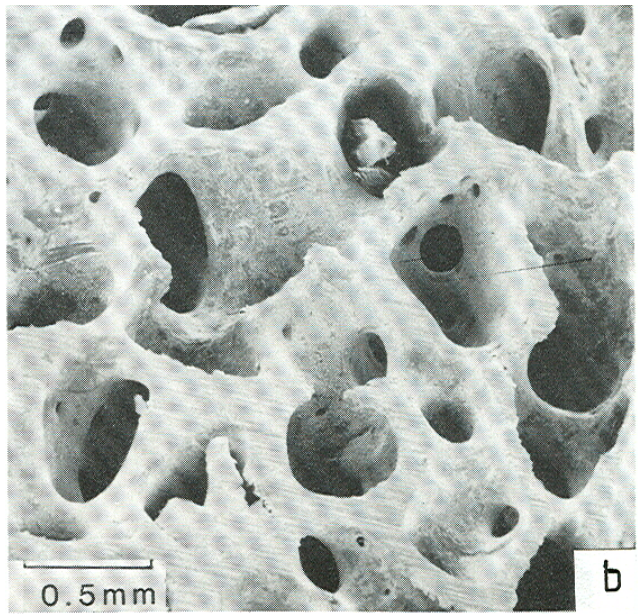
Lumbar spine 11% dense 42 year old male	Femoral head 26% dense 37 year old male	Lumbar spine 6% dense 59 year old male

Ralph Muller, ETH Zurich
Micro-CT images

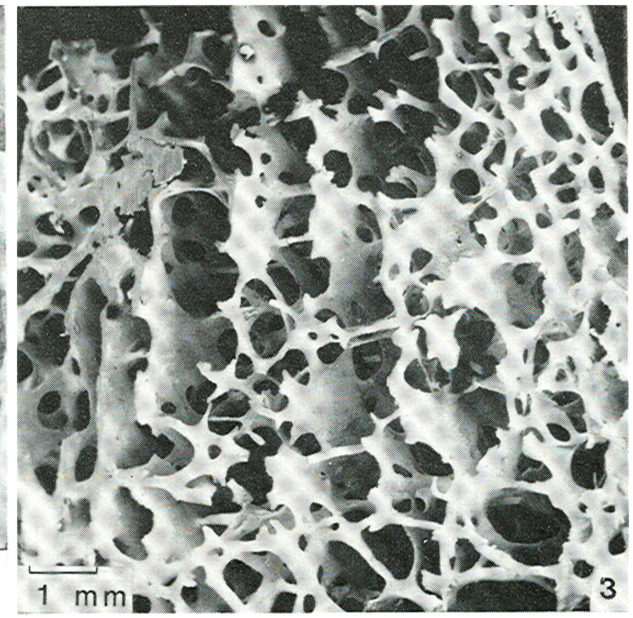
Trabecular Bone Structure



Femoral head



Femoral head



Femoral condyle (knee)

Source: Gibson. L. J. "The Mecahnical Behaviour of Cancellous Bone." *Journal of Biomechanics* 18 (1985): 317-28. Courtesy of Elsevier. Used with permission.

Bone grows with response to loads

- Studies on juvenile guinea fowl (Ponzer et al 2006)
  (a) running on level treadmill
  (b) running on inclined treadmill (20°)
  (c) control — no running
- Measured knee flexian angle at max force on treadmill
- After $\sim$6 weeks, sacrificed birds and measured orientation of peak trabecular density (OPTD)
- Knee flexian angle changed by 13.7° with incline vs level treadmill running
- OPTD changed by 13.6° with incline vs level treadmill running
- Orientation of trabecula changed to match orientation of loading
- Video: Concord Field Station (Science Friday)

Trabecular architecture and mechanical loading

Figure removed due to copyright restrictions. See Figure 1: Pontzer, H., et al. "Trabecular Bone in the Bird Knee Responds with High Sensitivity to Changes in Load Orientation." *The Journal of Experimental Biology* 209 (2006): 57-65.

Trabecular architecture and mechanical loading

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Video: "Studying Locomotion With Rat Treadmills, Wind Tunnels." March 9, 2012. Science Friday. Accessed November 12, 2014.

Properties of solid in trabeculae

- Foam models: require ρ_s, E_s, σ_{ys} for the solid
- Ultrasonic wave propagation $E_s = 15 - 18$ GPa
- Finite element models of exact trabecular architecture from micro-CT scans
  If do uniaxial compression test — can measure E^* and back-calculate E_s
  $E_s = 18$ GPa
- Find properties of trabeculae (solid) similar to cortical bone:

  $\rho_s = 1800$ kg/m^3

  $E_s = 18$ GPa

  $\sigma_{\mathbf{ys}} = 182$ MPa (compression)

  $\sigma_{\mathbf{ys}} = 115$ MPa (tension)

Mechanical Properties of Trabecular Bone

- Compressive stress-strain curve - characteristic shape
- Mechanisms of deformation and failure
  - Usually bending followed by inelastic buckling
  - Sometimes, if trabeculae are aligned or very dense: axial deformation
  - Observations by deformation stage in μCT; also FEA modeling
- Tensile $\sigma - \epsilon$ curve: failure at smaller strains; trabecular micro cracking
- Data for E^*, σ_c^*, σ_T^* (normalized by values for cortical bone)
  - Spread is large — anisotropy, alignment of trabecular orientation and loading direction; variations in solid properties, $\dot{\epsilon}$, species
- Models — based on open-cell foams

Compression	$E^*/E_s \propto (\rho^*/\rho_s)^2$	bending
	$\sigma_{\text{el}}^*/E_s \propto (\rho^*/\rho_s)^2$	buckling
Tension	$\sigma_T^*/\sigma_{\text{ys}} \propto (\rho^*/\rho_s)^{3/2}$	plastic hinges

Data generally consistent
with models
Also: statistical analysis of data

$$E^*,\ \sigma_c^* \propto \rho^2$$

Note: compression: $\epsilon_{\text{el}}^* = \text{constant} = 0.7\%$

Compressive stress-strain curves

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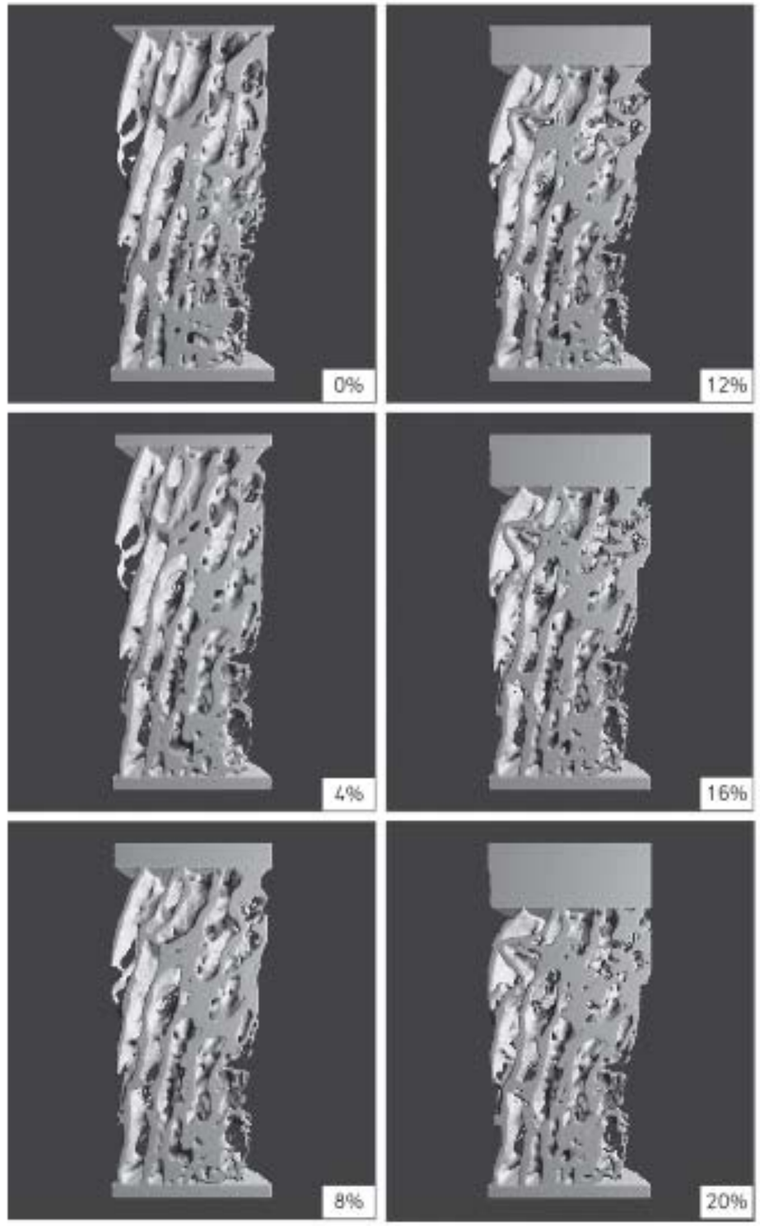
Hayes and Carter, 1976

Compression
Whale Vertebra

Muller et al, 1998



Nazarian and Muller 2004

Images removed due to copyright restrictions.

Human Vertebral Bone

Mueller, ETH

Tension

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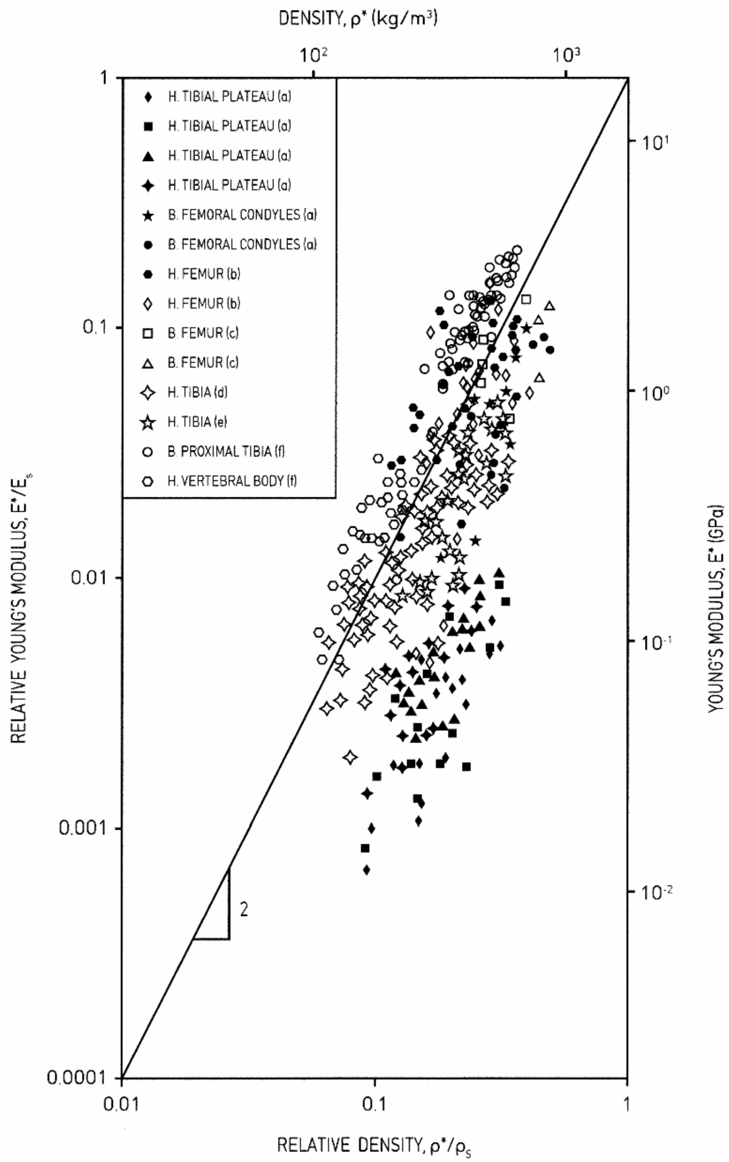
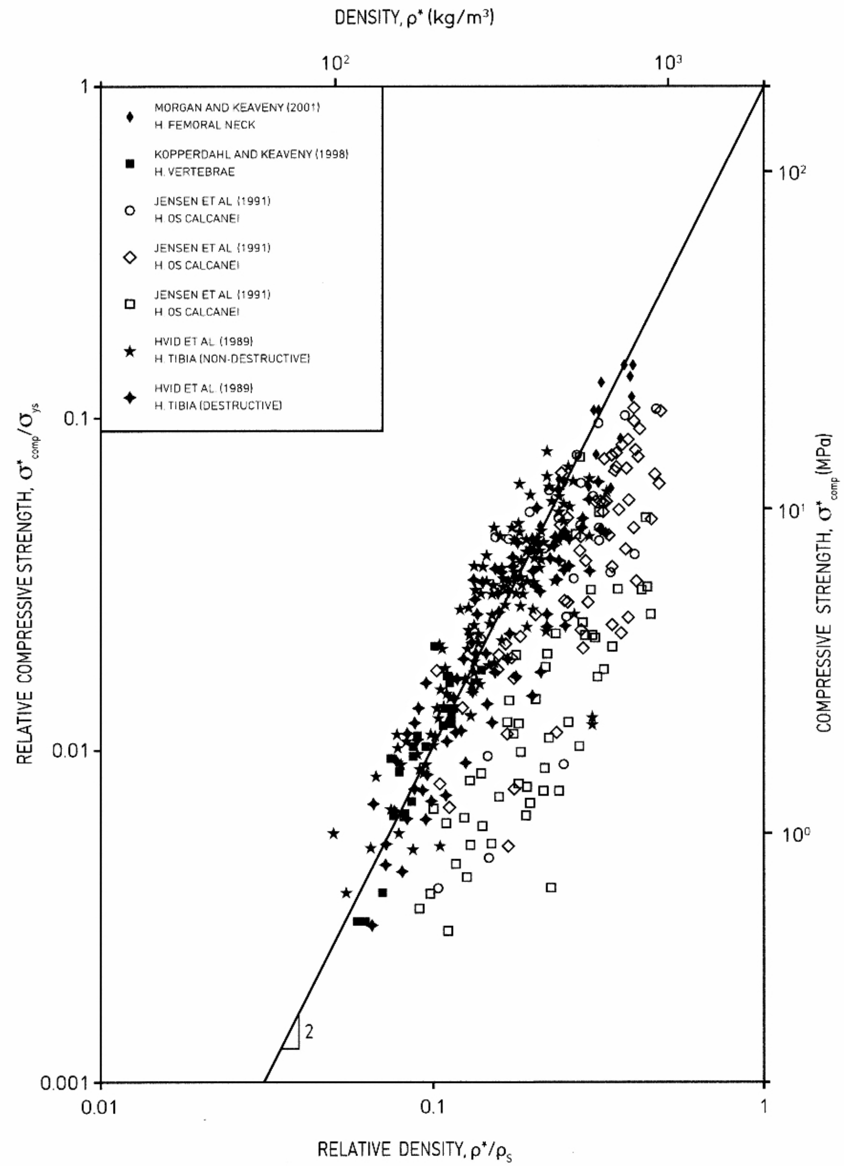
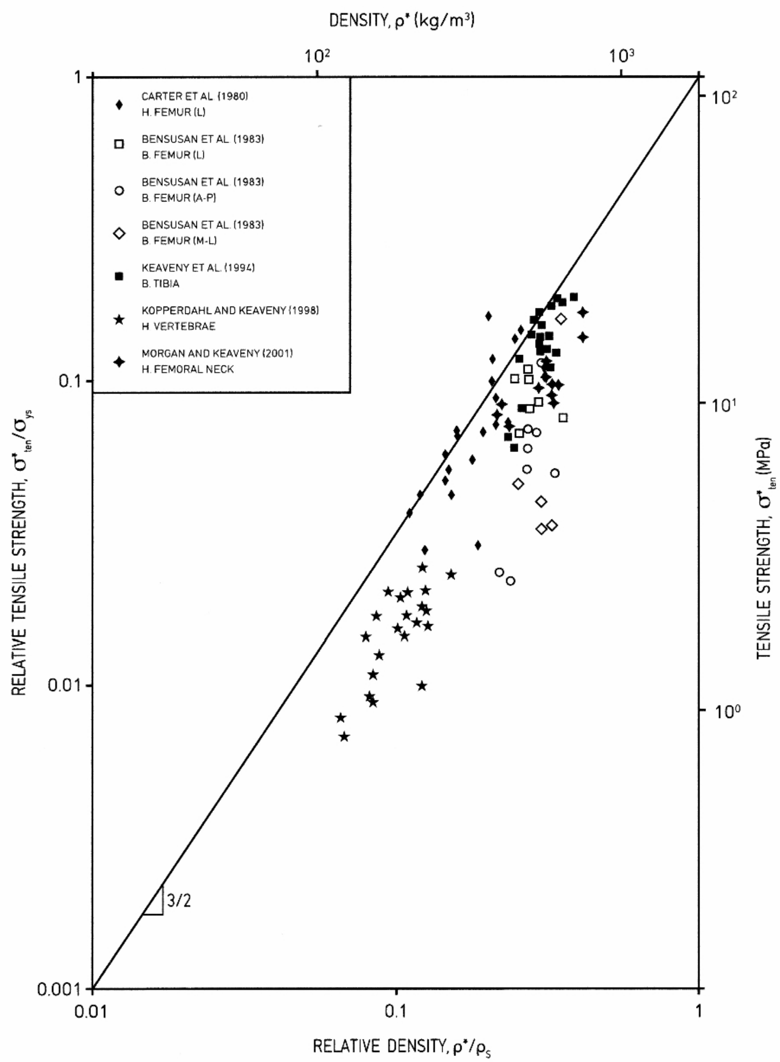
Carter et al., 1980





Gibson, L. J., M. Ashby, et al. *Cellular Materials in Nature and Medicine*. Cambridge University Press, © 2010. Figures courtesy of Lorna Gibson and Cambridge University Press.



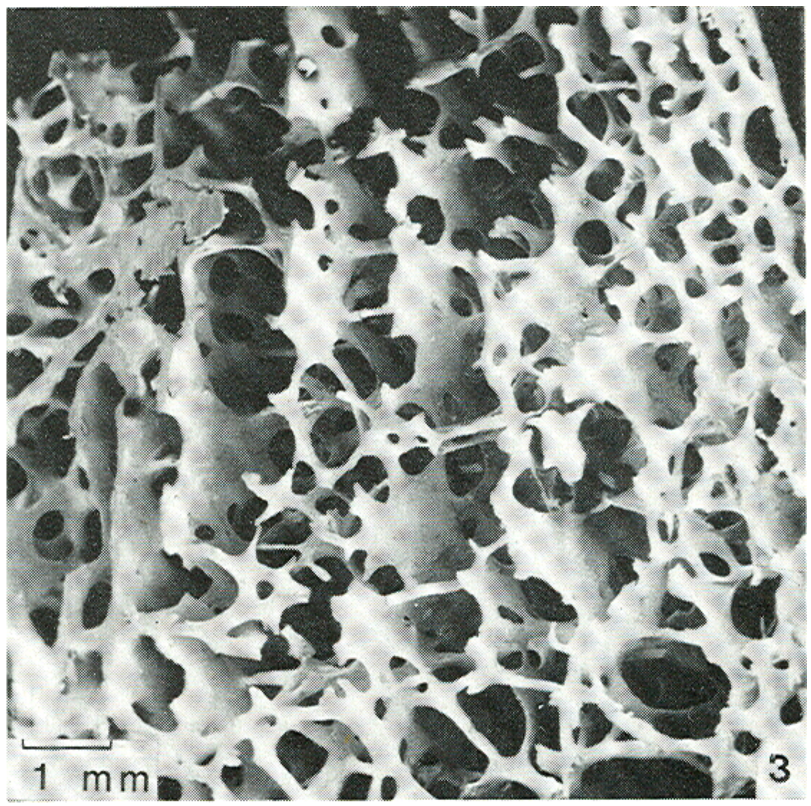
Gibson, L. J., M. Ashby, et al. *Cellular Materials in Nature and Medicine*. Cambridge University Press, © 2010. Figure courtesy of Lorna Gibson and Cambridge University Press.

- In some regions, trab. may be aligned: e.g. parallel plates
  - deformation then axial (in longitudinal direction) $E^* \propto \rho$, $\sigma^* \propto \rho$
- Can also summarize data for solid trabeculae and trabecular bone (similar to wood)
  Solid-composite of hydroxyapatite and collagen

Osteoporosis (Latin: "porpus bones")

- As age, lose bone mass
- Bone mass peaks at 25 years, then decreases 1-2% per year
- Women, menopause — cessation of estrogen production, increases rate of bone loss
- Osteoporosis defined as bone mass 2.5 standard deviations (or more) below young normal mean
- Trabeculae thin and then resorb completely

Aligned Trabeculae



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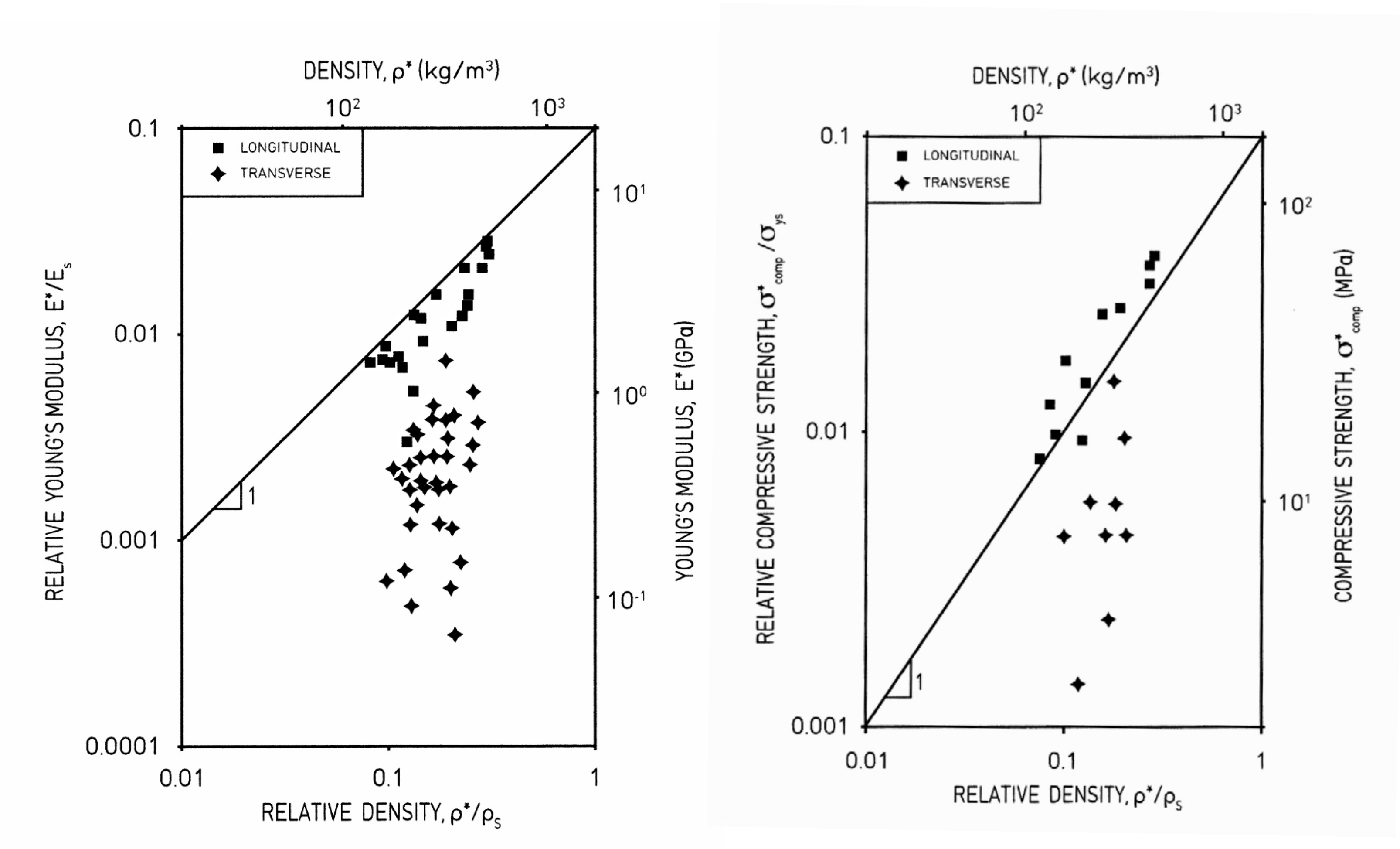

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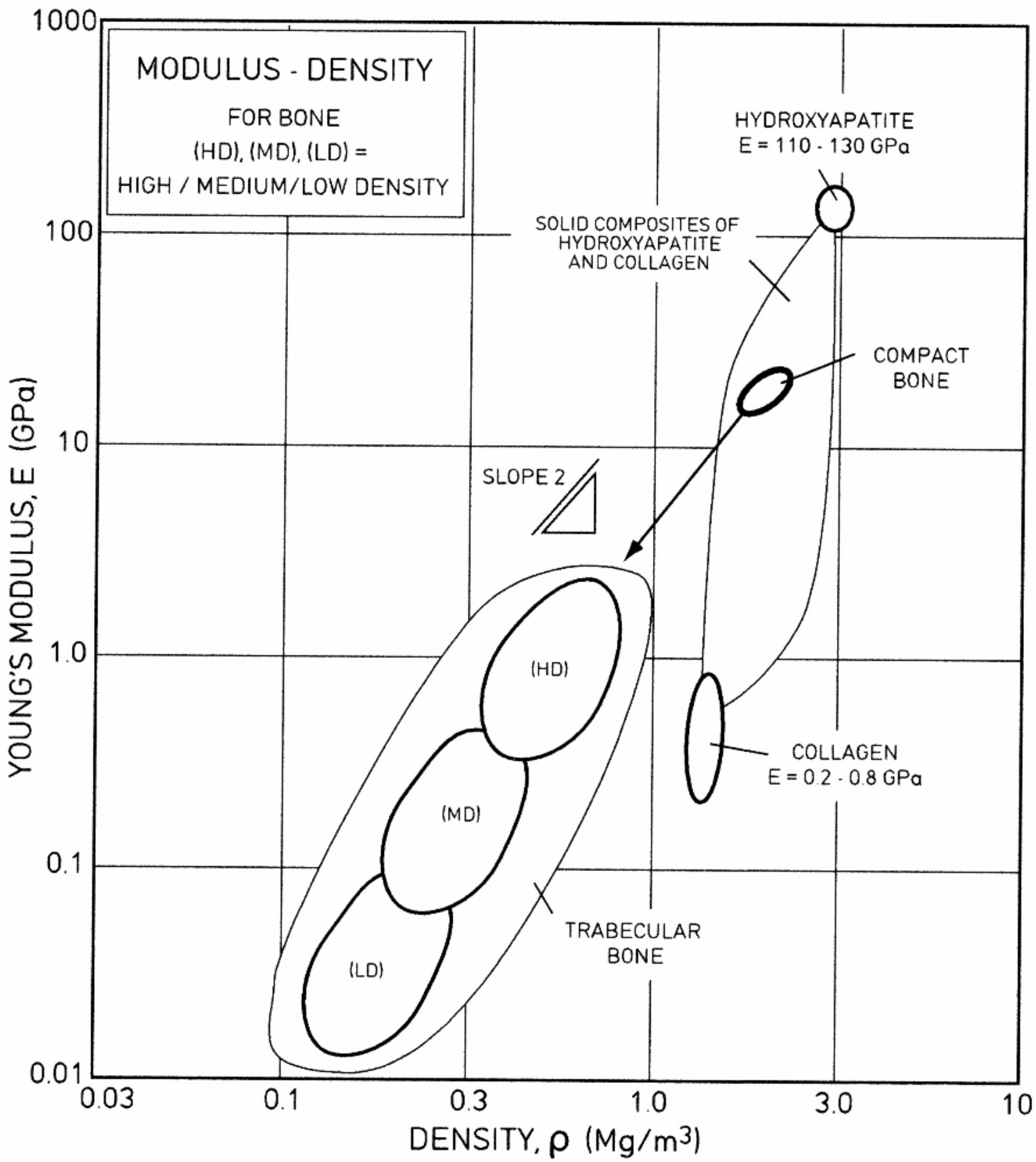

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3.054 / 3.36 Cellular Solids: Structure, Properties and Applications
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