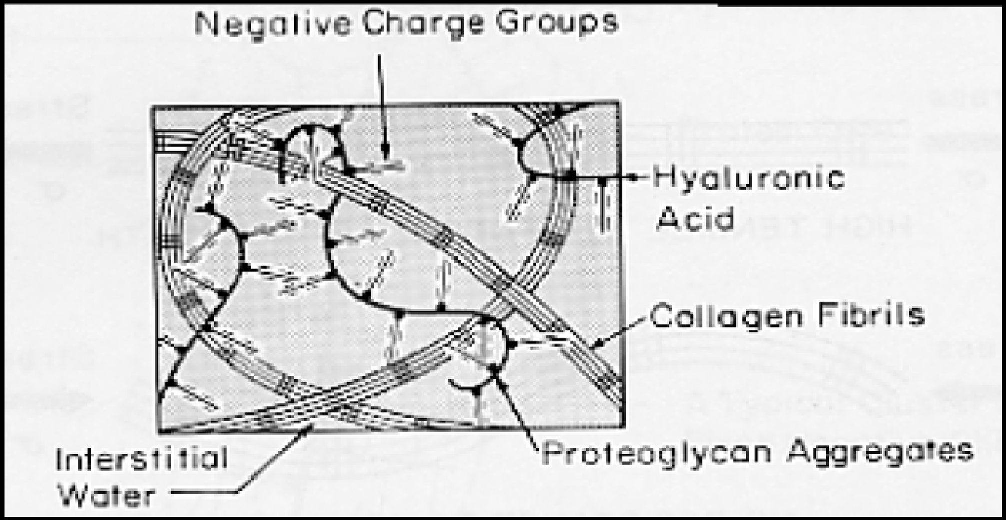
Section 24: Articular Cartilage Mechanical Properties

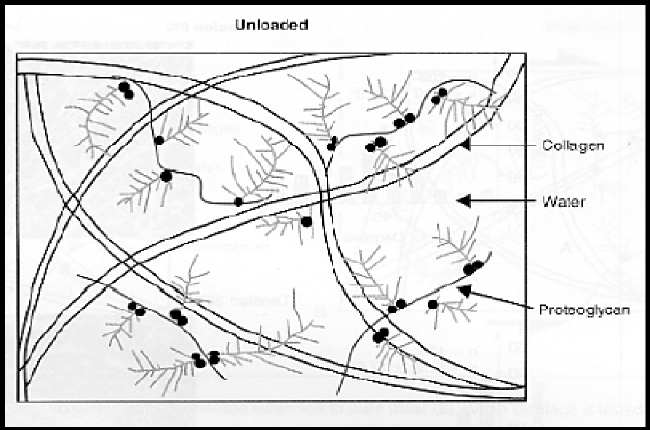
Mechanical Behavior

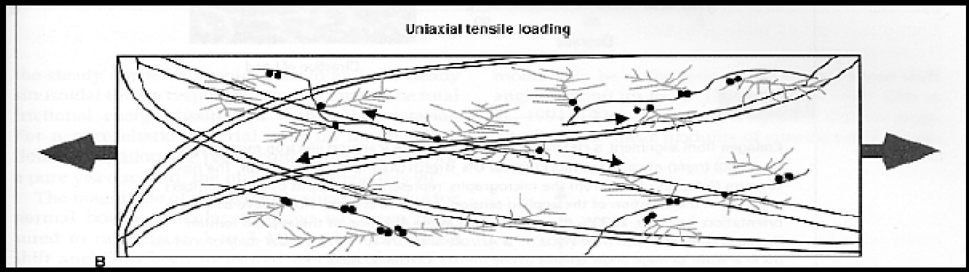


	Lateral Condyle	Patellar Groove
COMPRESSIVE AGGREGATE MODULUS (MPa)	0.70	0.53
POISSON'S RATIO	0.10	0.00
PERMEABILITY COEFFICIENT (10−15m4/N·s)	1.18	2.17

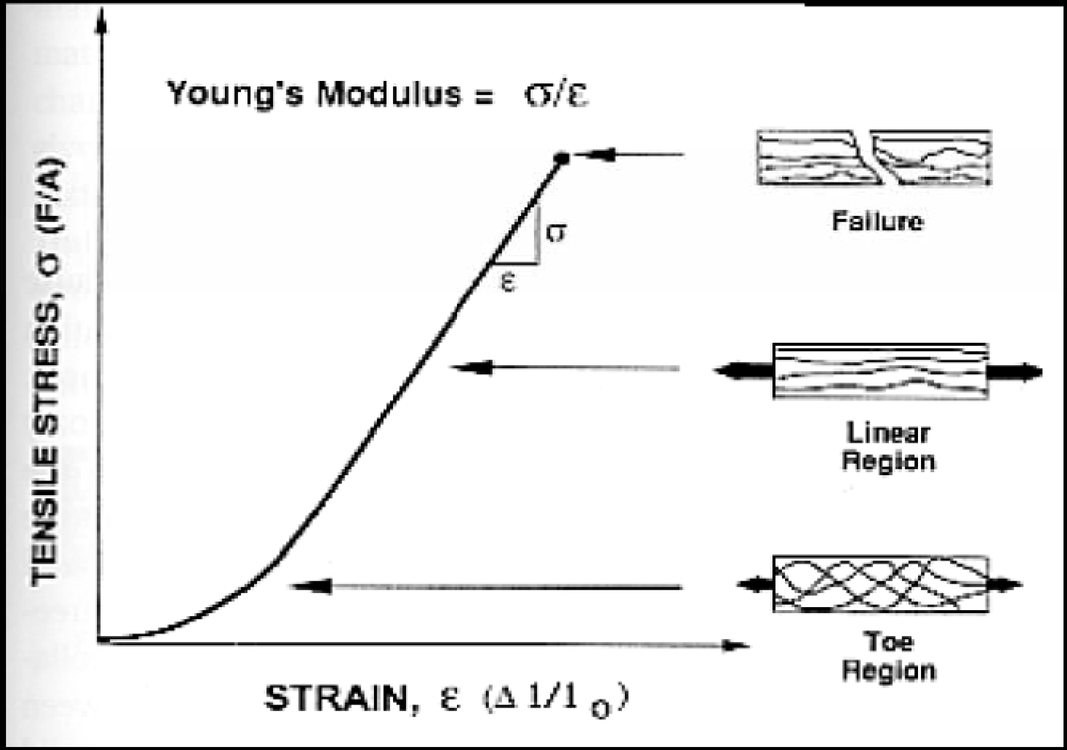
From: Ziv

Tensile Force



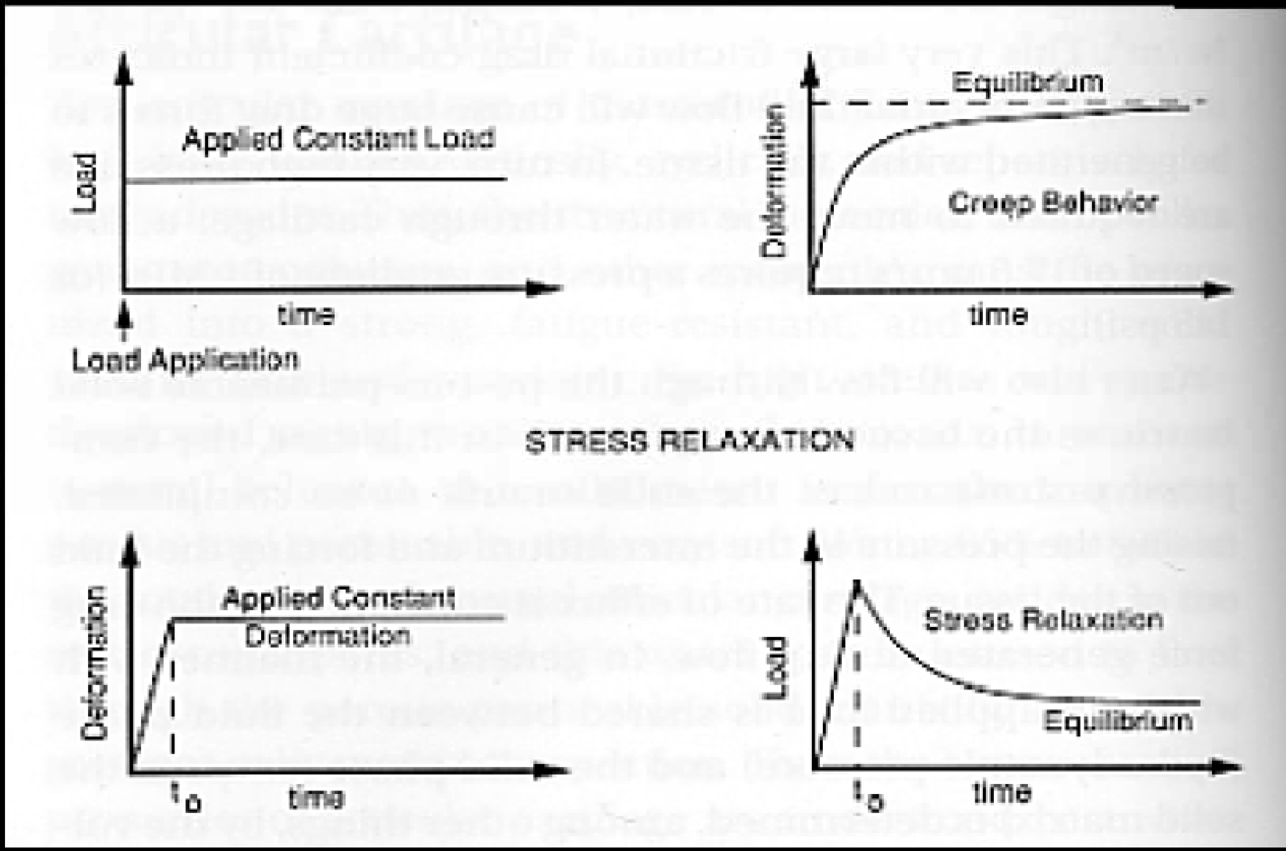


- Toe region: collagen fibrils straighten out and un- "crimp"
- Linear region that parallels the tensile strength of collagen fibrils: collagen aligns with axis of tension
- Failure region



From: Ziv

Creep behavior

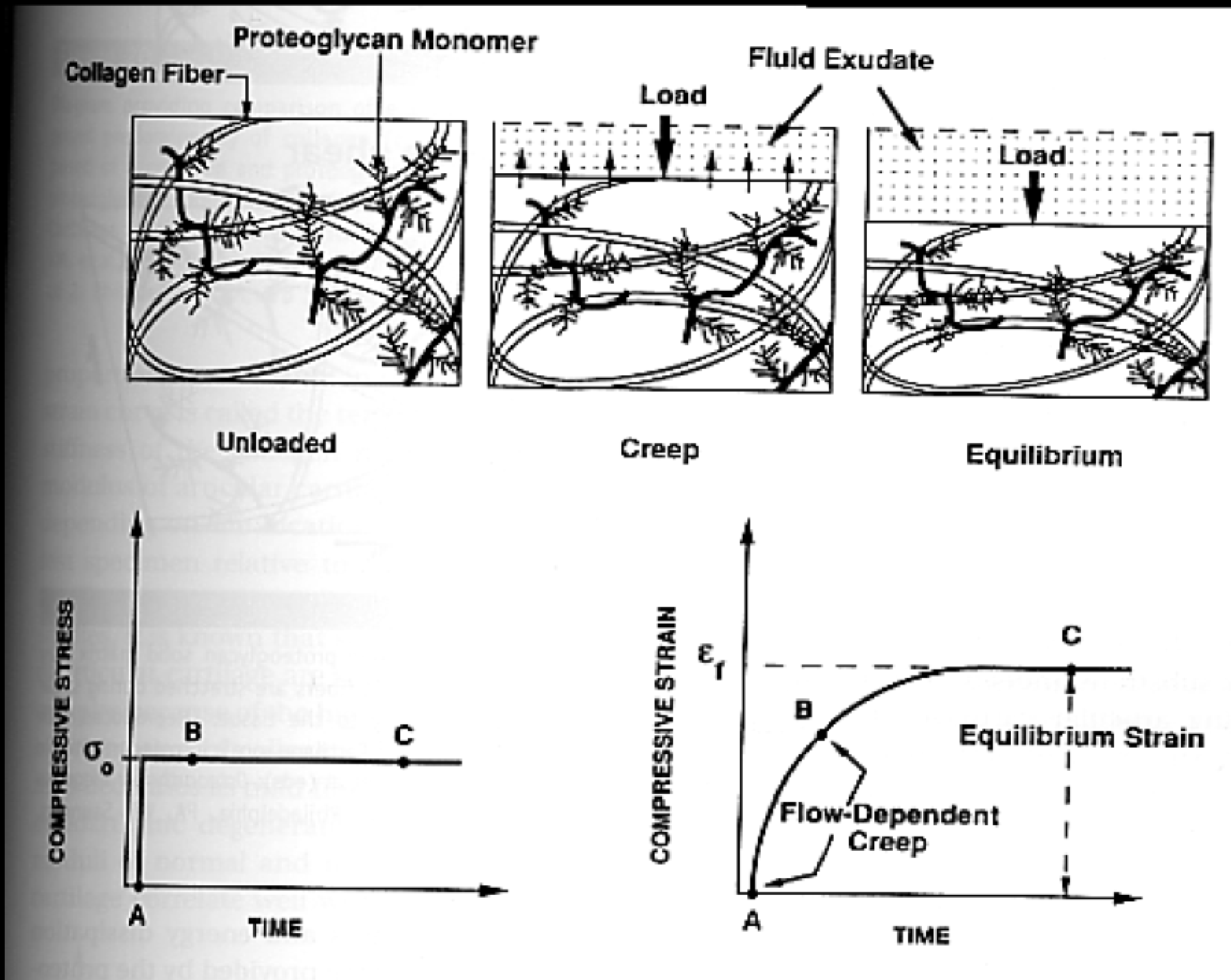


Creep of a visco-elastic material under constant loading

Stress rise during a ramp displacement compression of a visco-elastic material and stress relaxation under constant compression

From: Ziv

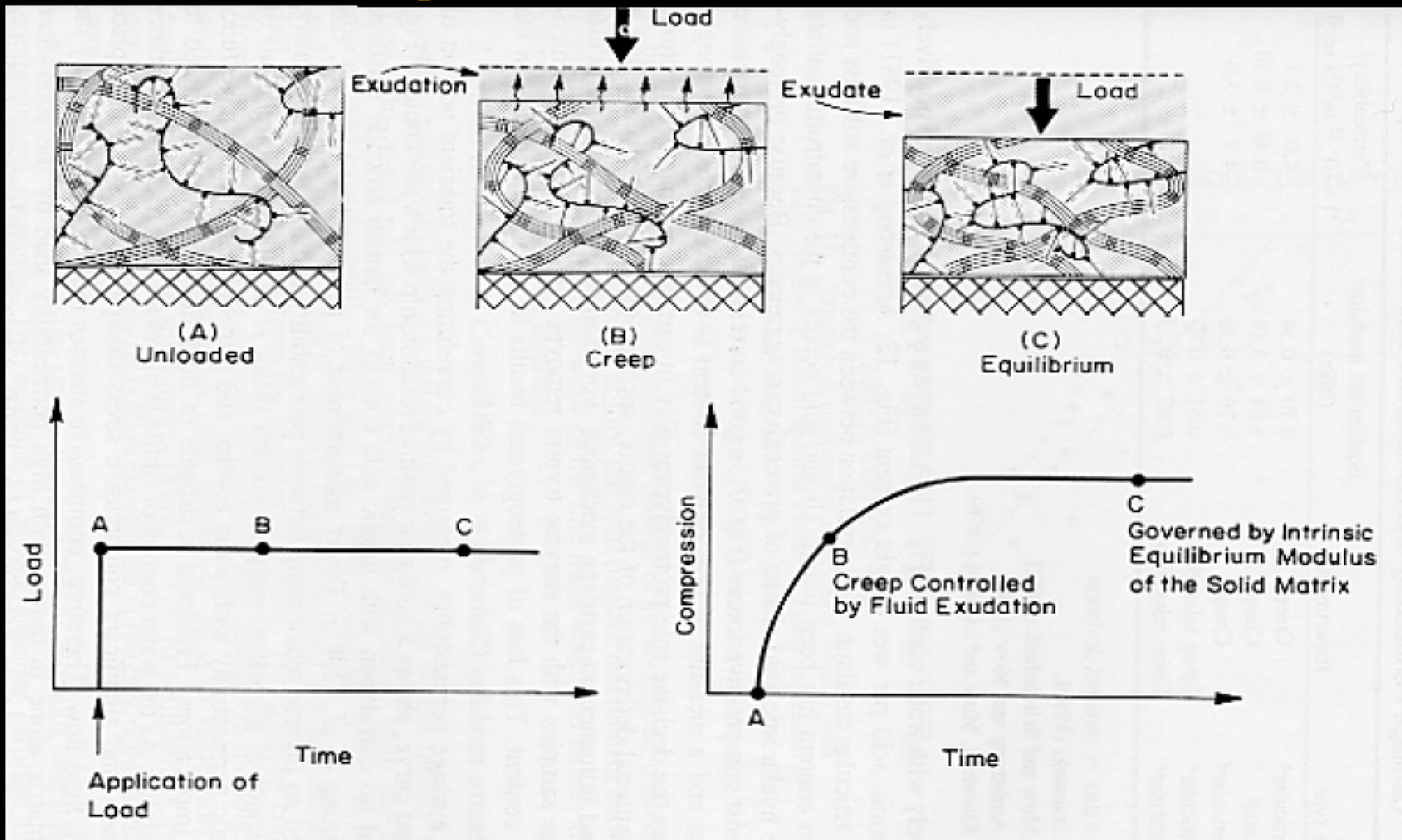
Compressive force



- Rate of creep is determined by the rate at which fluid may be forced out of the tissue
- This, in turn, is governed by the permeability and stiffness of the porous-permeable collagen-proteoglycan solid matrix

From: Ziv

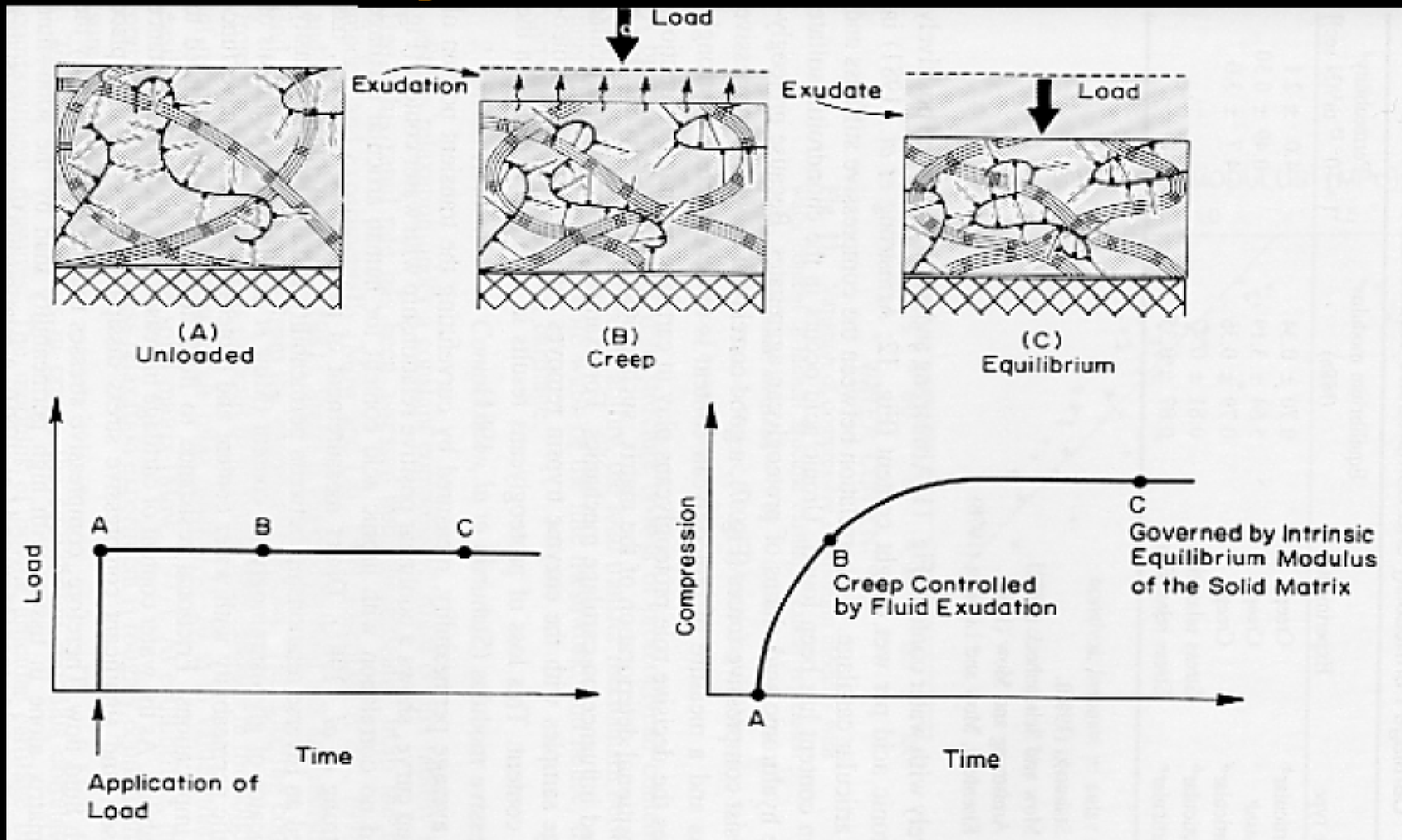
Compressive force



Copious exudation of fluid at start but the rate of exudation decreases over time from points A to B to C

From: Ziv

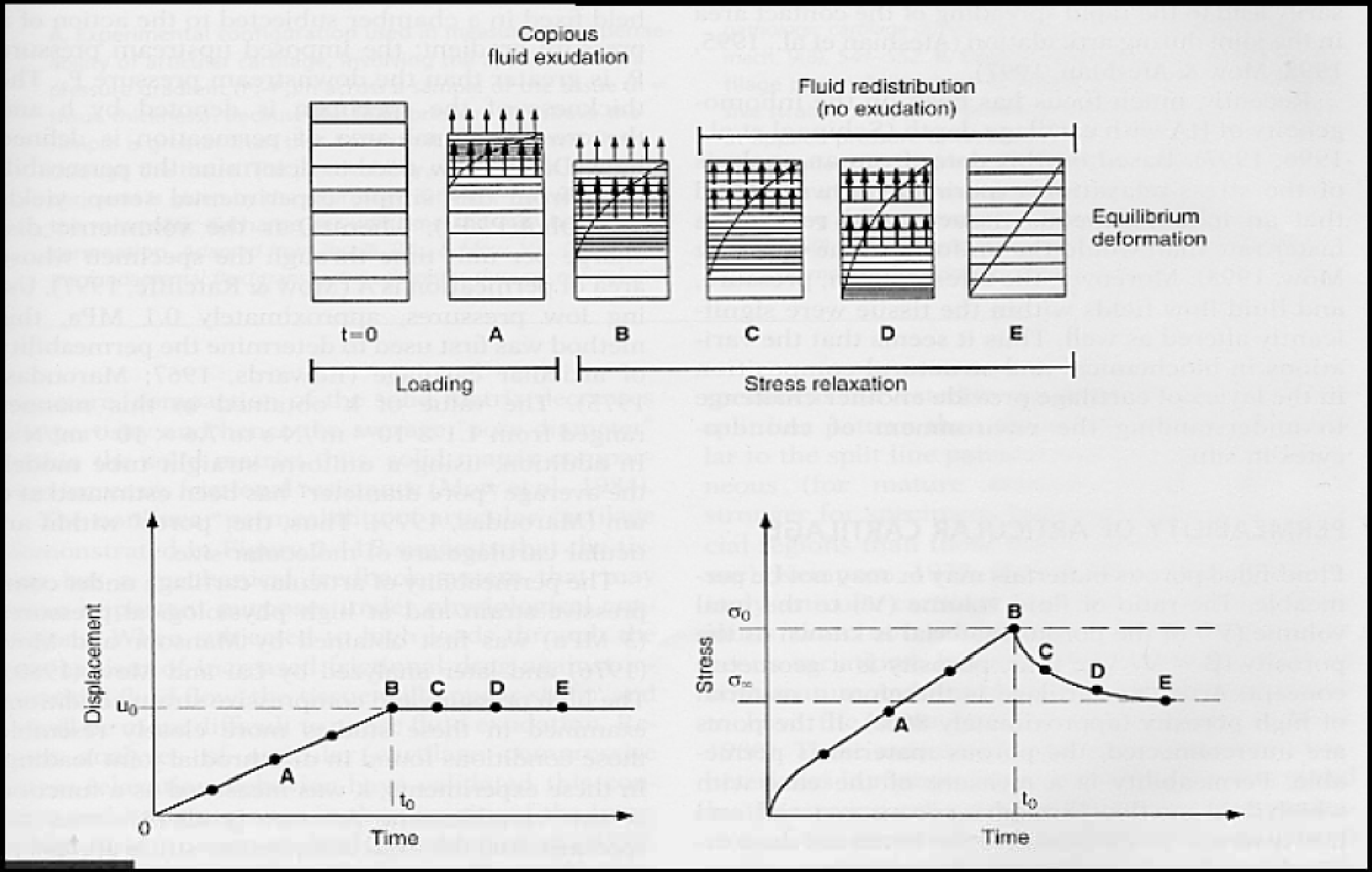
Compressive force



At equilibrium, fluid flow ceases and the load is borne entirely by the solid matrix (point C)

From: Ziv

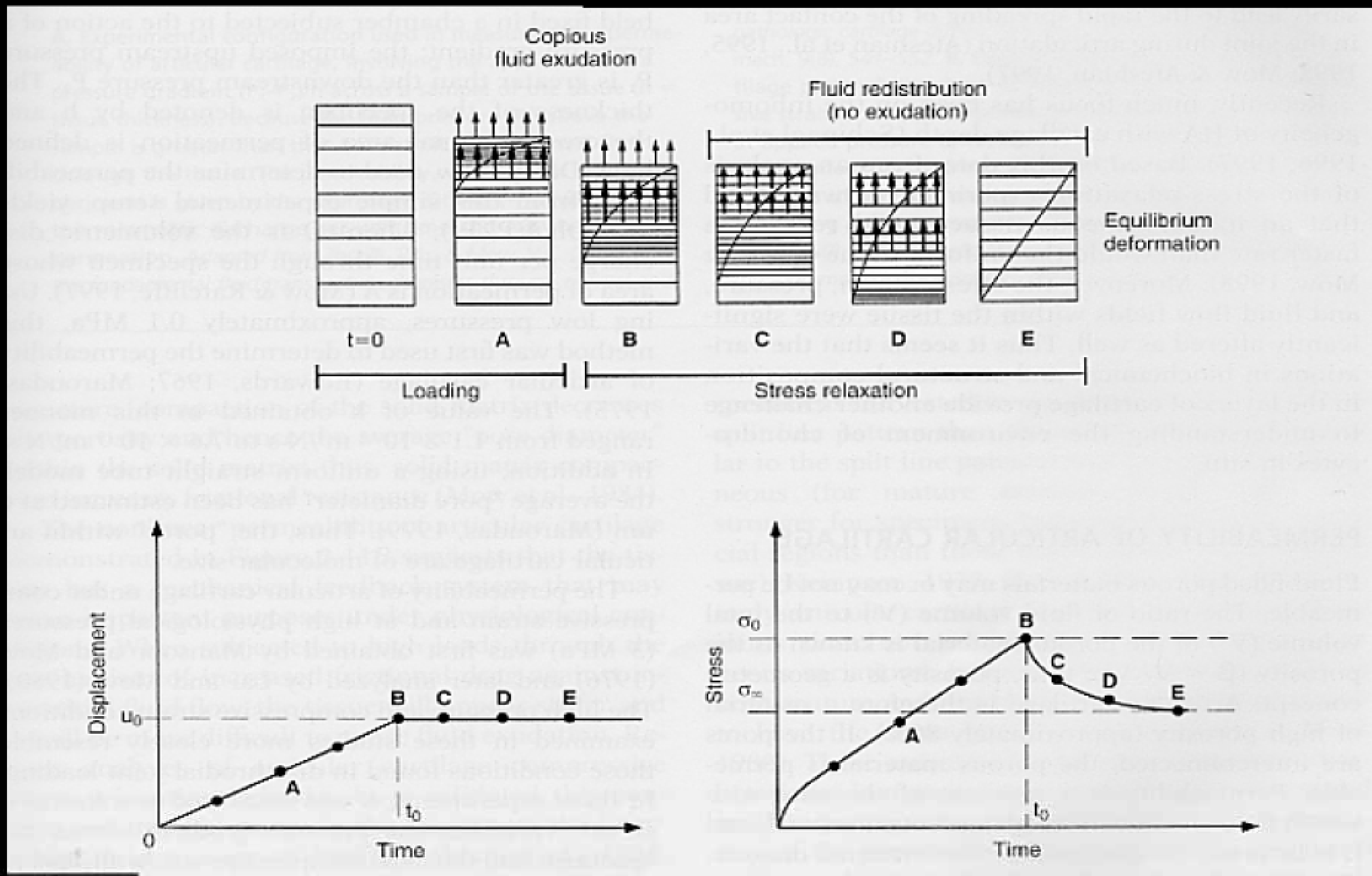
Stress Relaxation



The sample is compressed to point B and then maintained over time (points B to E)

From: Ziv

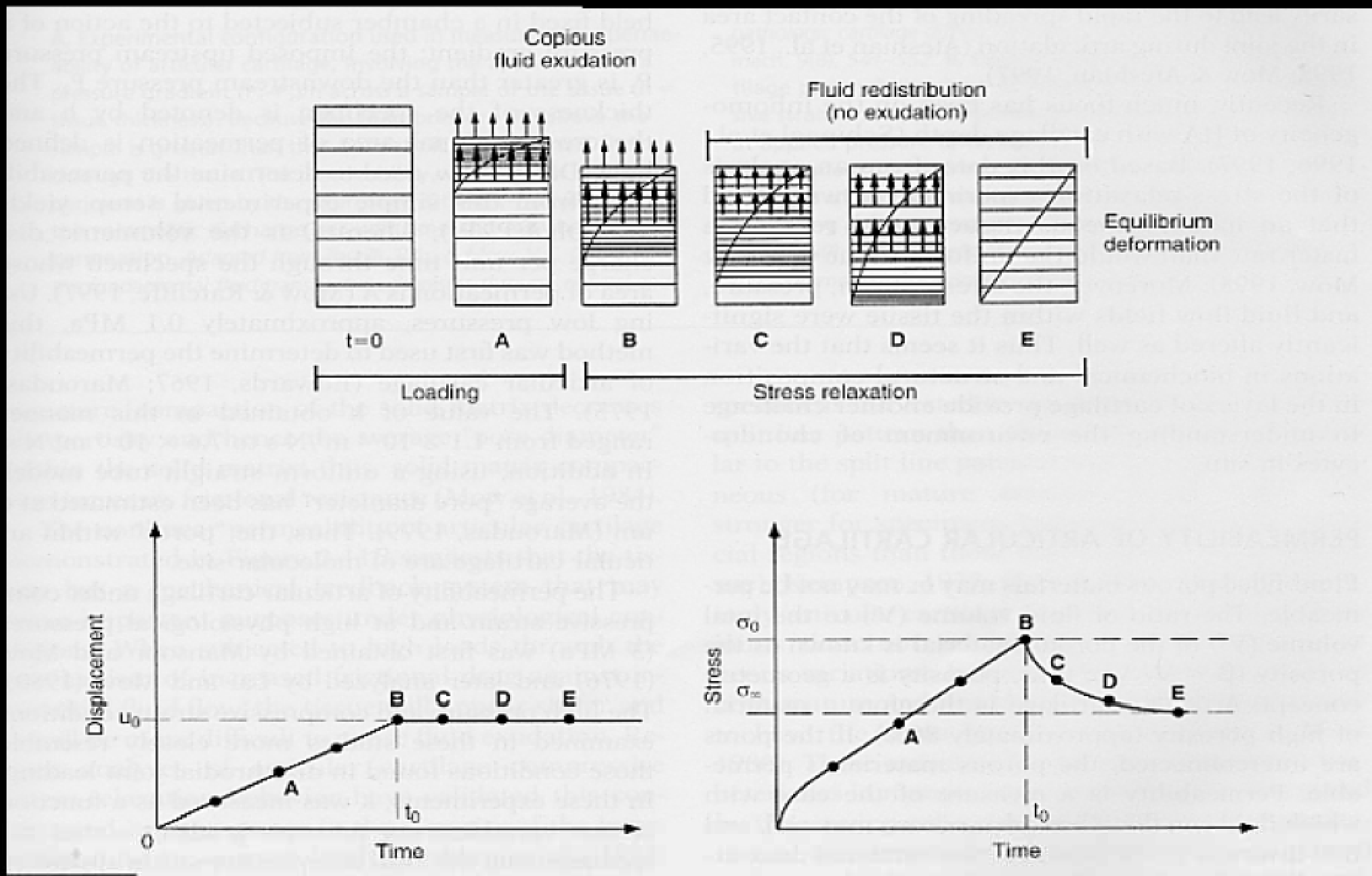
Stress Relaxation



Increase stress to reach end of compressive phase

From: Ziv

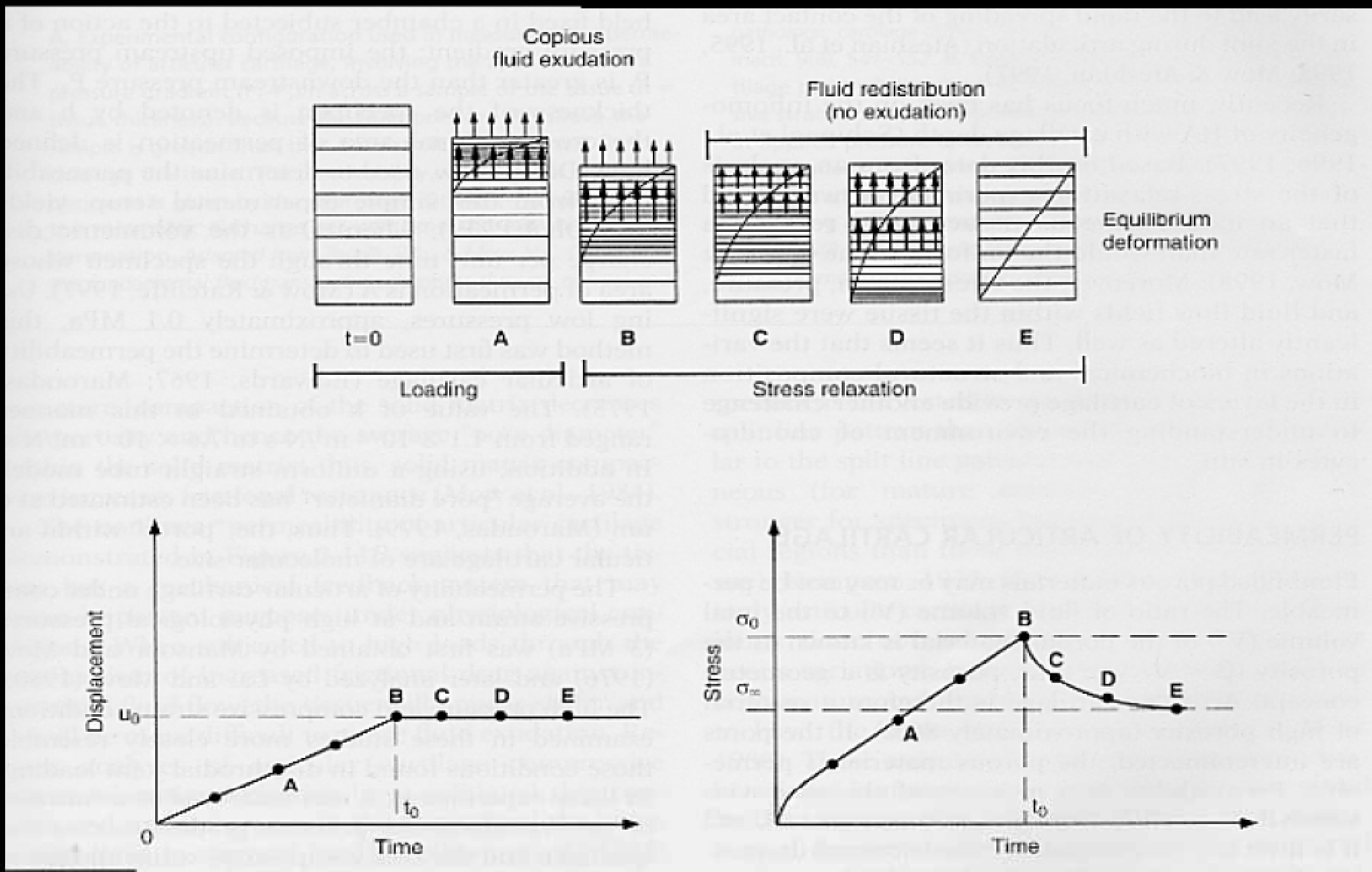
Stress Relaxation



Fluid redistribution allows for relaxation phase (points B to D) and matrix deformation

From: Ziv

Stress Relaxation

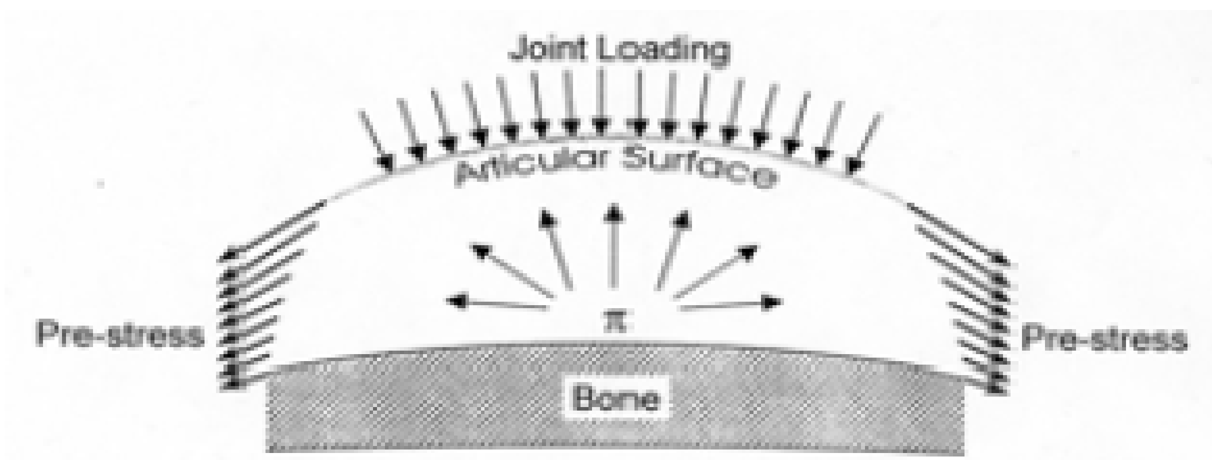


Equilibrium is reached at point E

From: Ziv

Prestress in cartilage

- GAG swelling pressure π is resisted by collagen tension to create prestress in the collagen network



Iatridis ME208

 From: Iatridis

Friction and wear

- Frictional force (F) dependent:
- Normal force (i.e., applied load, W)
  - We must know joint geometry and loading
- Frictional coefficient
  - Surfactant, i.e. surface lubricant
- $F = \mu W$

From: Iatridis

Frictional coefficients

TABLE 2. *Coefficients of friction for typical materials*

Material combination	Coefficient of friction
Gold on gold	2.8
Aluminum on aluminum	1.9
Silver on silver	1.5
Steel on steel	0.6–0.8
Brass on steel	0.35
Glass on glass	0.9
Wood on wood	0.25–0.5
Nylon on nylon	0.2
Graphite on steel	0.1
Ice on ice at 0°C	0.1
UHMWPE on cobalt chrome (artificial joints)	0.01–0.05

Adapted from Dowson (50), with permission.

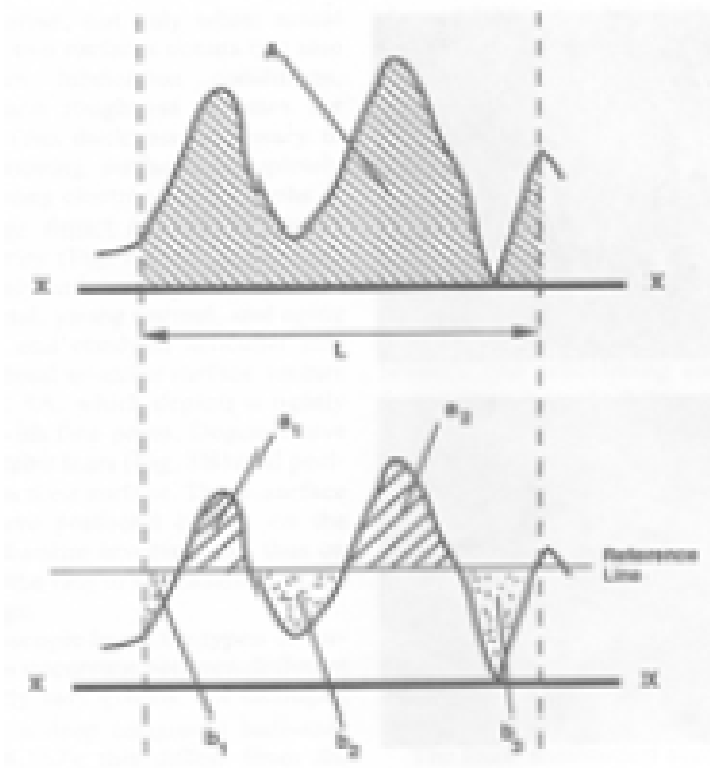
What is the frictional coefficient for cartilage?

TABLE 3. *Coefficients of friction for articular cartilage in synovial joints*

Investigator	Coefficient of friction	Joint tested
Charnley (36)	0.005–0.02	Human ankle
McCutchen (128)	0.02–0.35	Porcine shoulder
Linn (110,111)	0.005–0.01	Canine ankle
Unsworth et al. (190)	0.01–0.04	Human hip
Malcom (122)	0.002–0.03	Bovine shoulder

Surface roughness

Arithmetic mean deviation



$$R_a = \frac{\text{Sum of areas (a)} + \text{Sum of areas (b)}}{L}$$

TABLE 1. *Typical values of R_a for various surfaces*

Components	R_a (μm)
Plain bearings	
Bearing (bush or pad)	0.25–1.2
Journal or runner	0.12–0.5
Rolling bearings	
Tracks	0.2–0.3
Rolling element	0.05–0.12
Gears	0.25–1.0
Articular cartilage	1.0–6.0
Endoprostheses	
Metal (e.g., femoral head)	0.025
Plastic (e.g., acetabulum)	0.25–2.5

Data from Dowson (50).

Why is the frictional coefficient of cartilage so low?

- Tissue is mostly water
- Relatively large surface asperities provide
  - Are for surfactants to lay
  - Mechanism for water to be squeezed out of the cartilage…cartilage surfaces are ‘floating on water’

From: Iatridis

Tissue mechanics

- The composition and structure of cartilage determine the tissue mechanical behaviors
- Cartilage tissue mechanics is complex
  - Viscoelastic – part solid, part fluid – time dependent behavior
    - Fluid flow moving through the matrix
    - Polymeric interactions
  - Nonlinear stress-strain
  - Compression-tension nonlinearities
  - Anisotropic
- We will investigate how to model most of these phenomena this semester

From: Iatridis

Material models for articular cartilage

- Early: isotropic, linear elastic
  - Doesn't describe time variation of response
- Later: viscoelastic (springs and dampers)
  - Doesn't consider influence of fluid (loss in compression, swelling)
- Later still: poroelastic, biphasic
  - Doesn't consider viscous solid, ion effects
- Most recent: biphasic poro-viscoelastic, tri-phasic theories

From: Grimm and Atkinson