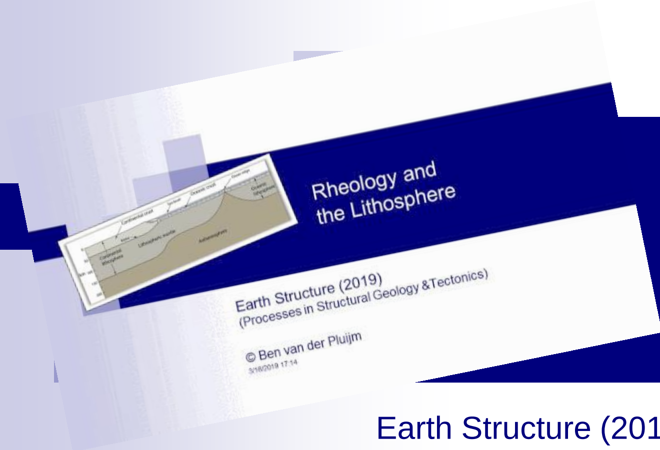


Rheology and the Lithosphere

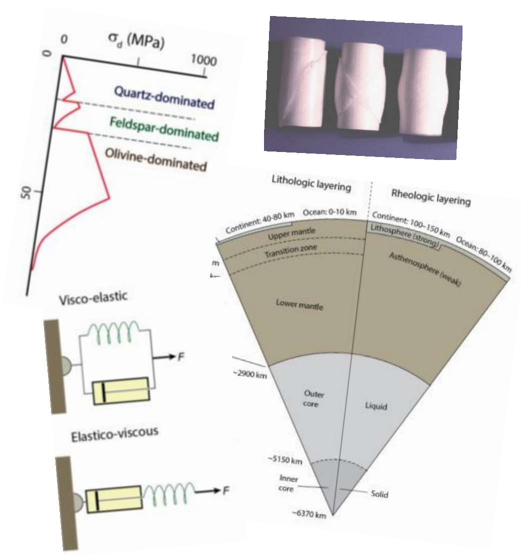
Earth Structure (2019)
(Processes in Structural Geology &Tectonics)

3/29/2019 13:28

We Discuss …

Rheology and the Lithosphere

- What is rheology?
- (Insights from rock deformation experiments
  - P_l, T, P_f, $\dot{e}$)
- Rock experiments: rock creep curve
- Composite elastic and viscous (=linear) rheologies
- Characteristic stress-strain behaviors
  - Strength and Competency
- Time-dependent rock behavior
  - Maxwell relaxation time
- Non-linear rheologies
- Plastic flow stresses
- Crust and mantle strength
- Defining lithosphere: lithologic vs rheologic layering

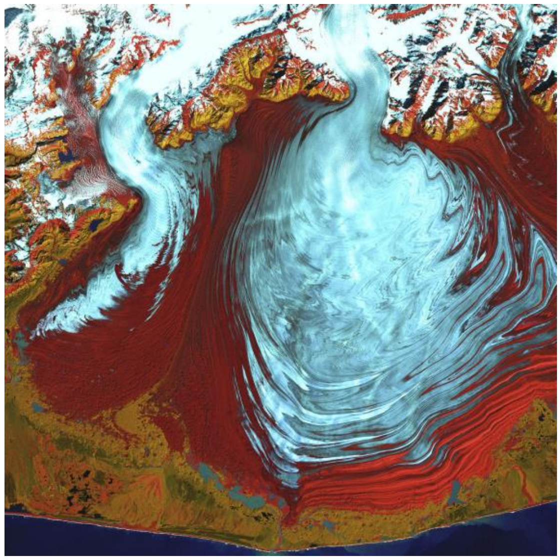


Rheology is ....

… the study of deformation (flow) of materials.

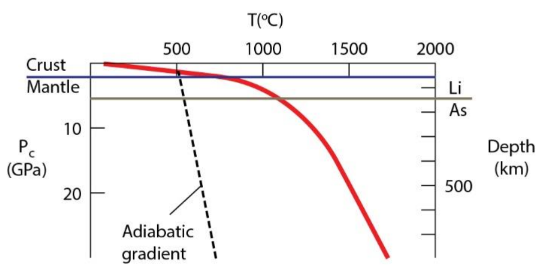
Associated concepts:

- Stress, σ
- Strain, Strain rate; e, ė
- Elasticity, E
- Viscosity, η
- Failure and Friction
- Plasticity



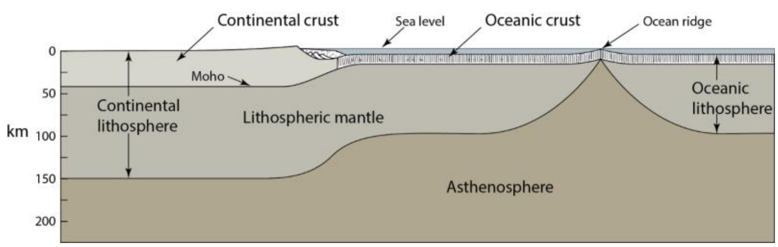
Malaspina Glacier, AK (NASA)

Earth's Conditions and Layers



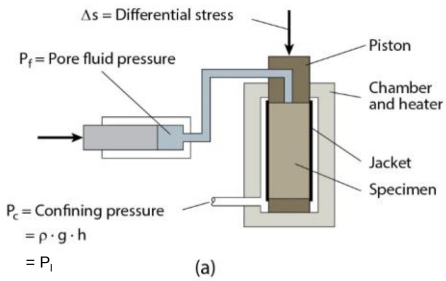
Variables:

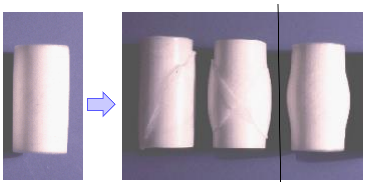
- Temperature, T
- Confining (Lithostatic) Pressure, P_l
- Fluid Pressure, P_f
- Strain Rate, ė



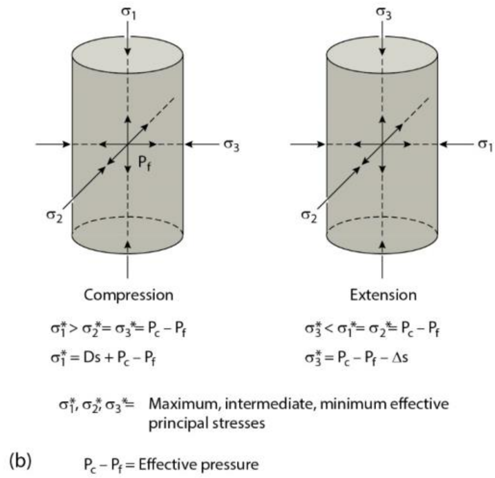
Insights from Rock Experiments

Triaxial deformation apparatus



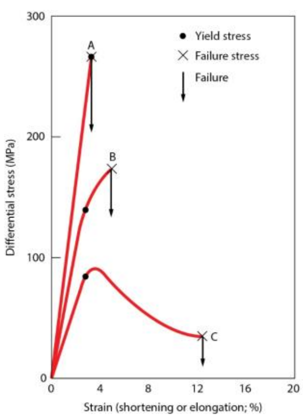


Frictional | Plastic



Compression and extension experiments

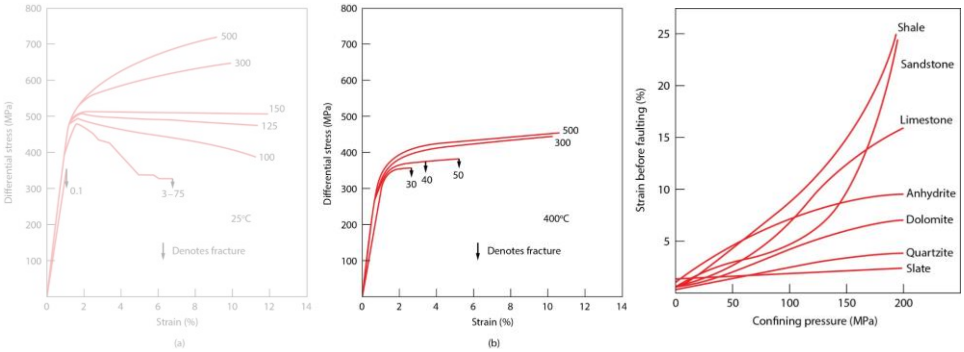
Characteristic Stress-Strain Behaviors



Representative stress-strain curves.
(A) *E*lastic behavior followed by failure.
(B) Small viscous (permanent) strain before failure.
(*C)* Significant viscous (permanent) strain before failure.

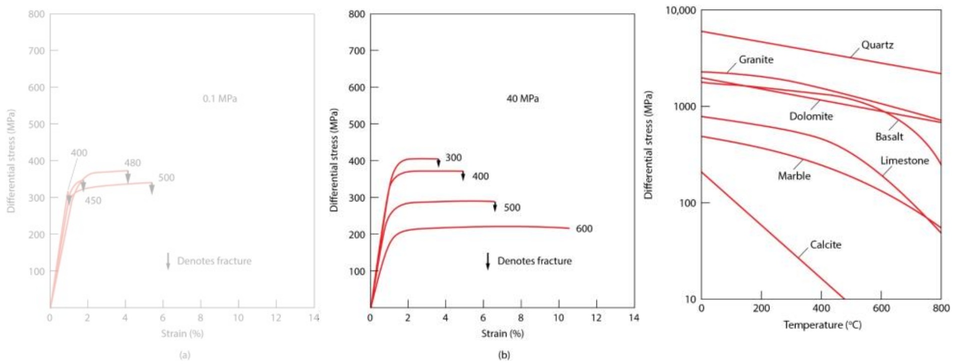
Yield stress marks stress at change from elastic (recoverable) to viscous (permanent) strain;
Failure stress is stress at fracturing.

Confining (= Lithostatic) Pressure



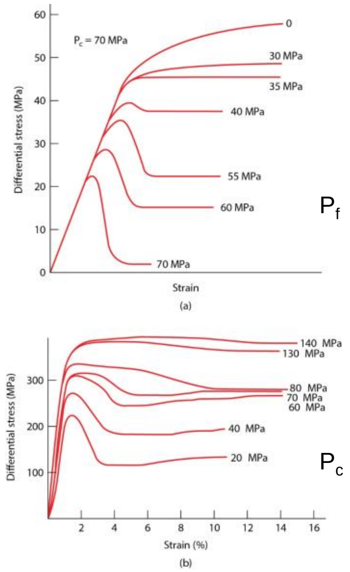
Suppresses fracturing
Promotes ductility (distributed strain)
Increases strength (maximum stress)

Temperature



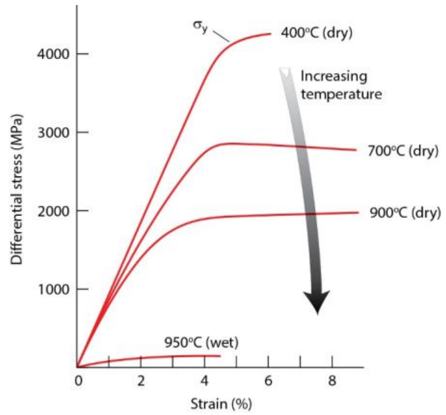
Suppresses fracturing
Promotes ductility
Reduces strength

Fluid Pressure



P_f

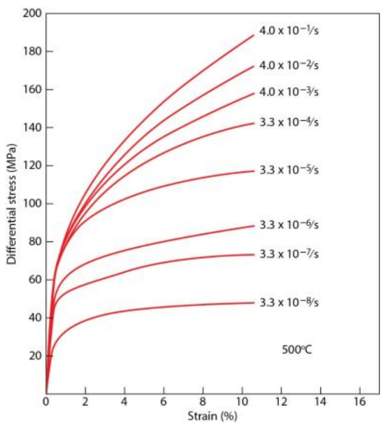
P_c

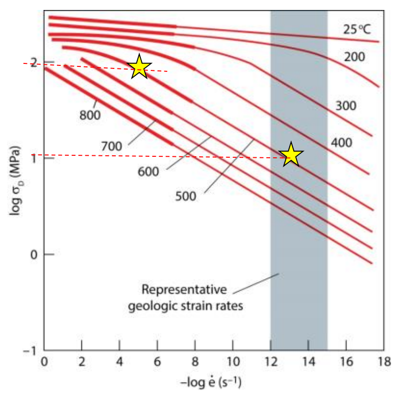


Inverse form P_c: $P_f \sim 1/P_c$

$P_{eff} = P_c - P_f$

Strain rate





$\dot{e} = 10^{-6}$/sec is 30% change in 4 days

$\dot{e} = 10^{-14}$/sec is 30% change in 1 million years

☆ "Fast" ~100 MPa

"Slow" ~10 MPa

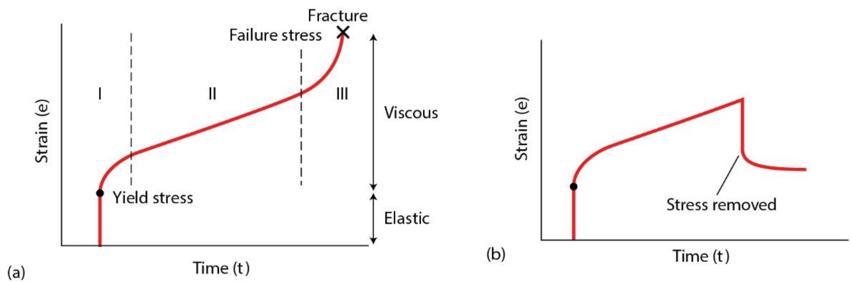
Small $\dot{e}$ (significantly) reduces rock strength

Summary of Rock Responses to $P_{c/l}$, P_f, T, $\dot{e}$

	Effect	Explanation
High $P_{c/l}$	Suppresses fracturing; increases plasticity; increases strength; increases work hardening	Prohibits fracturing and frictional sliding; higher stress necessary for fracturing exceeds that for viscous flow
High T	Decreases elastic component; suppresses fracturing; increases plasticity; reduces strength; decreases work hardening	Promotes crystal plastic processes
High P_f	Decreases elastic component; promotes fracturing; reduces strength or promotes flow	Decreases P_c ($P_e = P_c - P_f$) and weakens Si-O atomic bonds
Low $\dot{e}$	Decreases elastic component; increases flow; reduces strength; decreases work hardening	Promotes crystal plastic processes

Low Pc, high Pf, low T, (high $\dot{e}$): promotes fracturing **= upper crust**
High Pc, low Pf, high T, (low $\dot{e}$): promotes viscous flow **= lower crust, mantle**

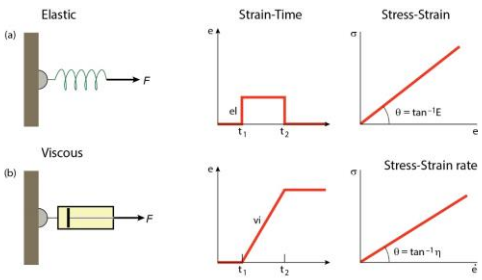
Rock Experiments: the Rock Creep Curve



Creep: I. Elastic; II. Viscous; III. Accelerated viscous.

a) Under continued stress a material will fail.
b) If we remove stress before failure, material relaxes (elastic component) while permanent (viscous) strain remains.

Rheologic Models: Elastic and Viscous Behavior



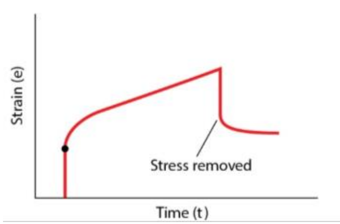
Elastic behavior
rubber band
$\sigma = E . e$ ($\sigma_s = G. \gamma$); Pa

Viscous behavior
water, syringe
$\sigma = \eta . \dot{e}$; t-dependent; Pa.s

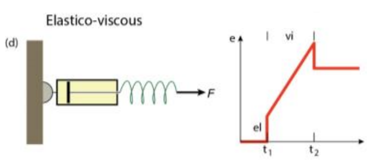
$\int \sigma \, dt = \sigma.t$

Matching the general creep curve with elastic and viscous rheologies …

Elastic+Viscous Rheologies: Elastico-viscous

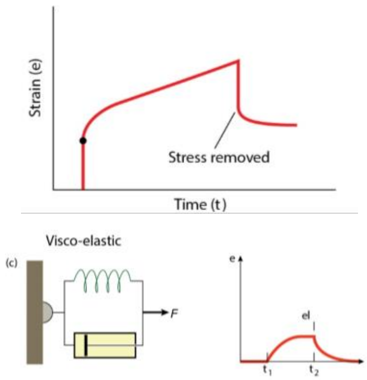


General creep curve (strain –time)



Elastico-**viscous** behavior
mayonnaise, toothpaste

Elastic+Viscous Rheologies: Visco-elastic

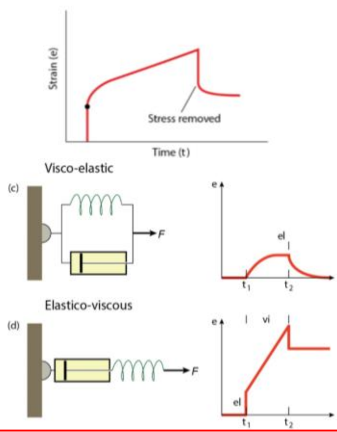


General creep curve (strain –time)

Visco-**elastic** behavior
water-soaked sponge, memory foam

$$\sigma = E \cdot \mathbf{e} + \eta \cdot \dot{e}$$

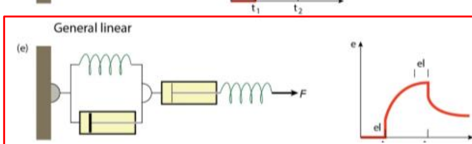
Elastic+Viscous Rheologies: General Linear Behavior



General creep curve (strain –time)

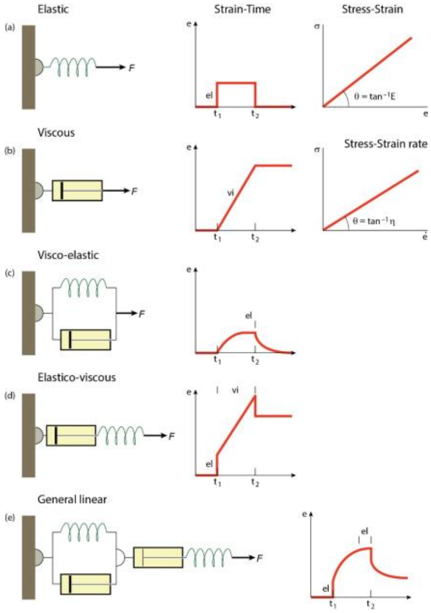
Visco-elastic behavior
water-soaked sponge, memory foam

Elastico-viscous behavior
mayonnaise, silly putty



General Linear behavior
~natural rock

Summary: Linear Rheologic Models



Elastic behavior
rubber band
σ = E . e (σ_s = G. γ)

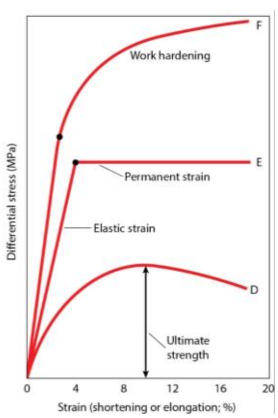
Viscous behavior
water
σ = η . ė ; ∫σ dt = σ.t

Visco-elastic behavior
water-soaked sponge, memory foam

Elastico-viscous behavior
mayonnaise, silly putty

General Linear behavior
~rock

Strength and Competency



Rock strength is maximum stress value a material can support before deformation.

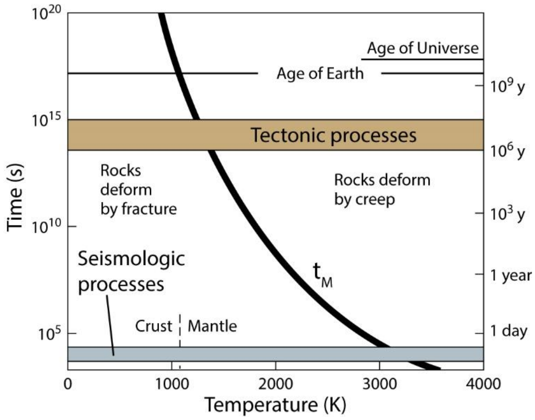
Competency is *relative* strength term that compares resistance of rocks to deformation.

Rock competency scale:

Low-grade: rock salt < shale < limestone < greywacke < sandstone < dolomite

High-grade: schist < marble < quartzite < gneiss < granite < basalt

Time-dependent Rock Behavior



Maxwell Relaxation Time:

$t_M = \eta/E$

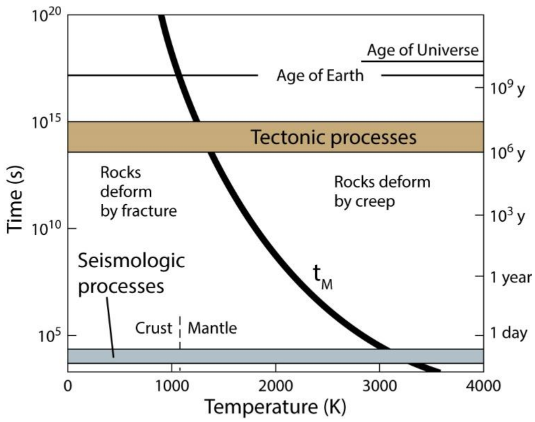
is ratio of viscosity (η) over elasticity (E)

Unit: $t_M = (\sigma/(\mathbf{e}/t)) / \sigma/\mathbf{e}$ = time

Viscosity (strain rate) is temperature-dependent, so t_M is T-dependent.

t_M range plotted in time-Temperature space.

Time-dependent Rock Behavior



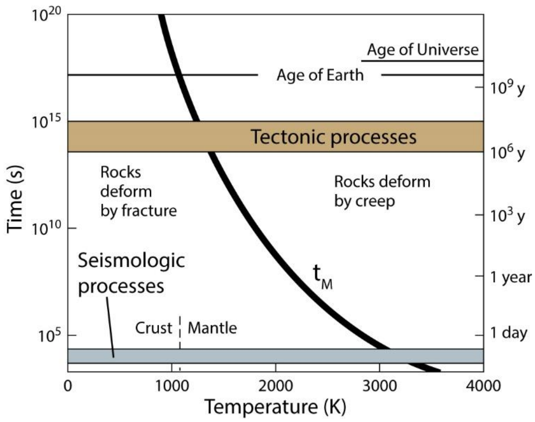
Elasticity dominates on seismic timescales (failure).

Viscosity dominates on tectonic timescales (flow).

Rock is like *silly putty*®: elastic/breaks (fast deformation) or viscous (slow deformation), so f^{ion} of time (strain rate).

Both elastic earthquake waves and viscous flow in Earth's mantle.

Elastic and Viscous Earth



Elastic Earth:
Mantle viscosity of 10^{21} Pa·s, elasticity of 10^{11} Pa (olivine-dominated mantle)

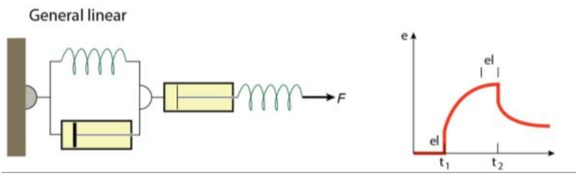
$t_M = 10^{10}$ s

that is, order of 1000 years (Earth's glacial rebound).

Viscous Earth:
Mantle viscous flow stress:
$\sigma = \eta \,.\, \dot{e}$
$= 10^{21} \,.\, 10^{-14} = 10^7$ Pa
$= 10$MPa

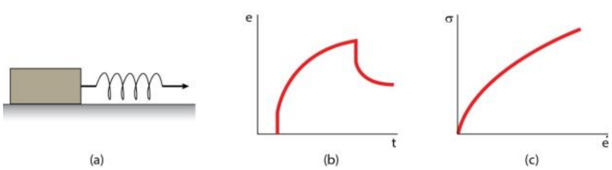
Linear vs. Non-linear Rheologies

General linear behavior (from analogues)



$\sigma \equiv \dot{e}$

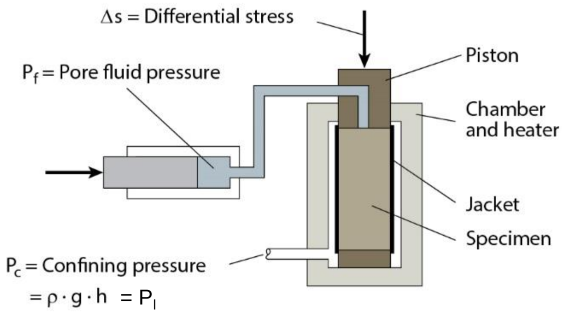
Non-linear (or elastic-**plastic**) behavior (from experiments)



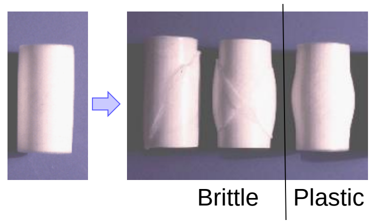
exponent

$\sigma^n \equiv \dot{e}$

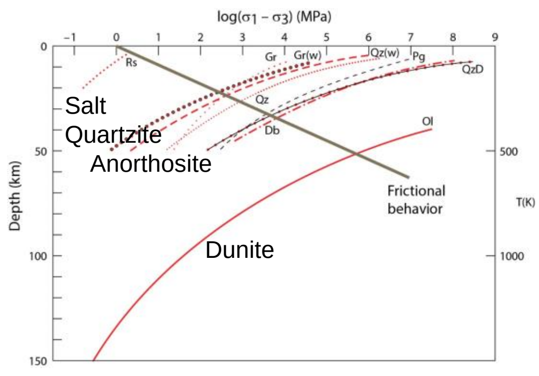
Quantification from Rock Experiments



Triaxial deformation apparatus



Plastic Flow Stresses



$$\dot{e} = A\,\sigma^n \exp(-E^*/RT)$$

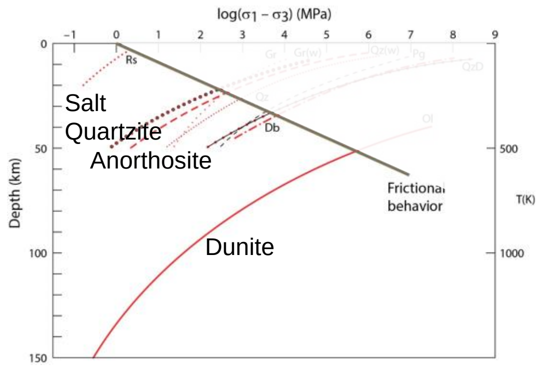
solve for σ

$$\sigma = (\dot{e}/A)^{1/n} \exp(E^*/RT)$$

Rock type	A ($MPa^{-n}s^{-1}$)	n	E* ($kJ\cdot mol^{-1}$)
Albite rock	2.6×10^{-6}	3.9	234
Anorthosite	3.2×10^{-4}	3.2	238
Clinopyroxene	15.7	2.6	335
Diabase	2.0×10^{-4}	3.4	260
Granite	1.8×10^{-9}	3.2	123
Granite (wet)	2.0×10^{-4}	1.9	137
Granulite (felsic)	8.0×10^{-3}	3.1	243
Granulite (mafic)	1.4×10^{-4}	4.2	445
Marble (< 20 MPa)	2.0×10^{-9}	4.2	427
Orthopyroxene	0.32	2.4	293
Peridotite (dry)	2.5×10^{4}	3.5	532
Peridotite (wet)	2.0×10^{3}	4.0	471
Plagioclase (An75)	3.3×10^{-4}	3.2	238
Quartz	1.0×10^{-3}	2.0	167
Quartz diorite	1.3×10^{-3}	2.4	219
Quartzite	6.7×10^{-6}	2.4	156
Quartzite (wet)	3.2×10^{-4}	2.3	154
Rock salt	6.29	5.3	102

Experimentally-derived creep parameters for common minerals and rock types. From Ranalli (1995) and other sources.

Friction vs. Plasticity (strength curves)



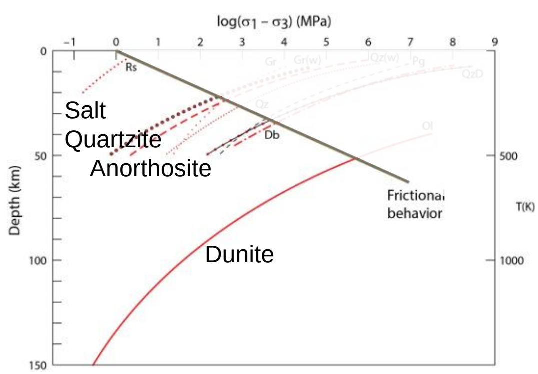
Frictional behavior (T-independent):

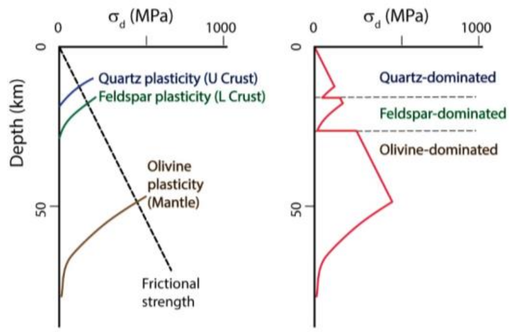
$\sigma_d = 2\sigma_n \cdot \mu$ $[\sigma_d = 2\sigma_s]$

Plastic behavior (T-dependent):

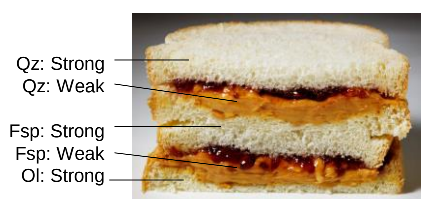
$\sigma_d = (\dot{e}/A)^{1/n} \exp(E^*/RT)$

Composite Strength Curves

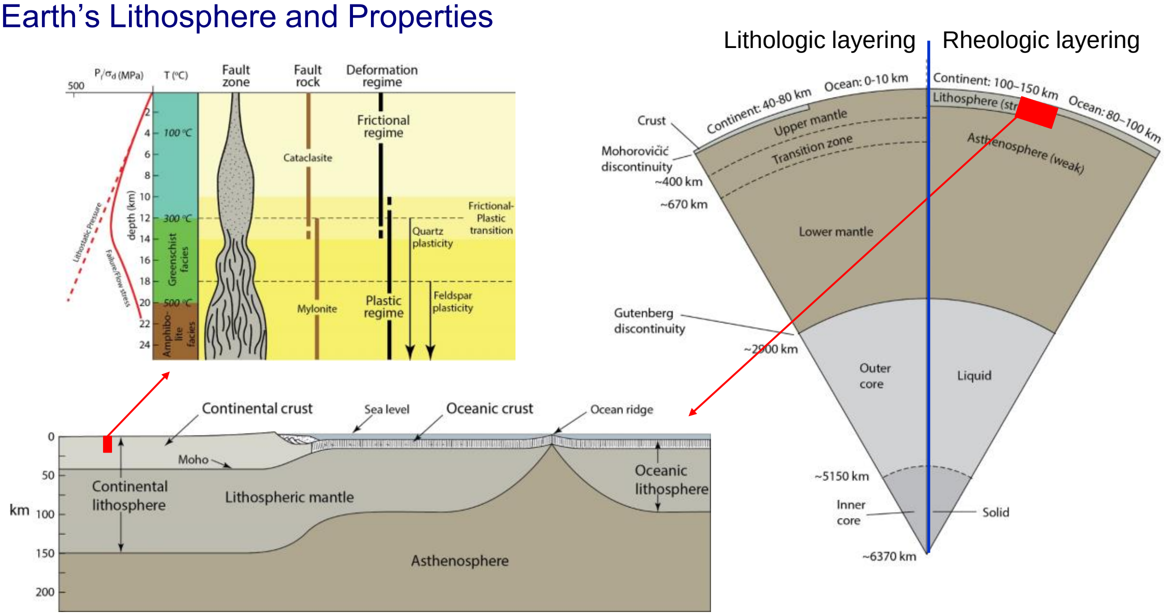




"Stacked sandwich" lithosphere model
(deluxe peanut butter-jelly sandwich)



Earth's Lithosphere and Properties



Lithospheric Deformation Regimes

Frictional Regime

- Pressure (P_l and P_f) dependent (frictional law)
- temperature and strain insensitive
- Shear/differential stress is primarily function of normal stress: $\sigma_s \approx f(\sigma_n)$

Plastic Regime

- Pressure (P_l and P_f) insensitive (crystal plasticity laws)
- temperature and strain rate dependent
- Shear/differential stress is primarily function of temperature and strain rate: $\sigma_s \approx f(T,\dot{e})$