Rheology

- What is ***rheology*** ?

From the root work "**rheo-**" Current: flow

Greek: ***rhein,*** to flow (river)

Like ***rheostat*** – flow of current

Rheology

- What physical properties control deformation ?
  - Rock type
  - Temperature
  - Pressure
  - Deviatoric (differential) Stress
  - Others ?

- What are the different types of strain ?
  - Brittle
  - Elastic

  $>$ Low T,P, Shallow

  - Plastic
  - Viscous

  $>$ High T,P, Deep

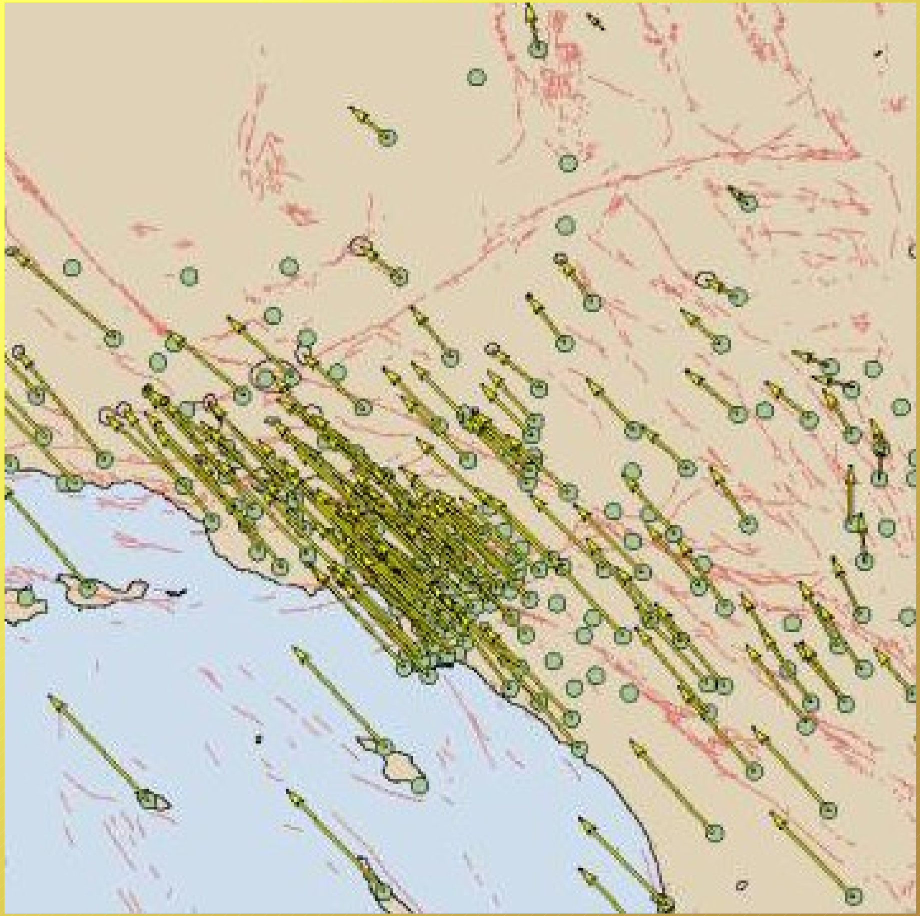
Rheology

- Strain rate measured by GPS in Southern California

- What do the GPS measurements indicate ?

- At what depth do these movements occur ?

- How can we test this ?



Rheology

Guest Lecture from Dr. Miranda!

- Brittle Deformation
- Plastic Deformation
- Brittle/Plastic Transition

Chapter 16: Macroscopic Aspects of Rock Deformation

PART I: RHEOLOGY AND MACROSCOPIC DEFORMATION

Earth materials respond to stresses, causing strain. Stress and strain are related through rheology. We describe the strain processes and categorize them into different behavior; these relationships are also described mathematically.

Chapter 16: Macroscopic Aspects of Rock Deformation

The name rheology derives from the Greek word “rheo”, which means “flow”.

Rheological studies handle the flow component of deformation, with emphasis on the interplay between stress, strain, and the rate of flow. In geosciences, rheology represents a branch of the science of rock mechanics.

Remember…
everything flows, even solids, under the right conditions of time and stress!

Chapter 16: Macroscopic Aspects of Rock Deformation

Rheological behaviors range from perfectly elastic solids at one Extreme to viscous Newtonian fluids at the other.

However, the rheology of natural materials such as rocks, falls *between* these extremes.

Question: the response of materials to stress depends on what properties?

Chapter 16: Macroscopic Aspects of Rock Deformation

We will now engage in a more quantitative study of how materials behave in response to stress.

A material can exhibit:

- Brittle behavior
- Elastic behavior
- Plastic behavior
- Viscous behavior
- Power-law behavior

There are other types of behavior, but we will focus on these main types in this course.

Chapter 16: Macroscopic Aspects of Rock Deformation

1. BRITTLE MATERIALS

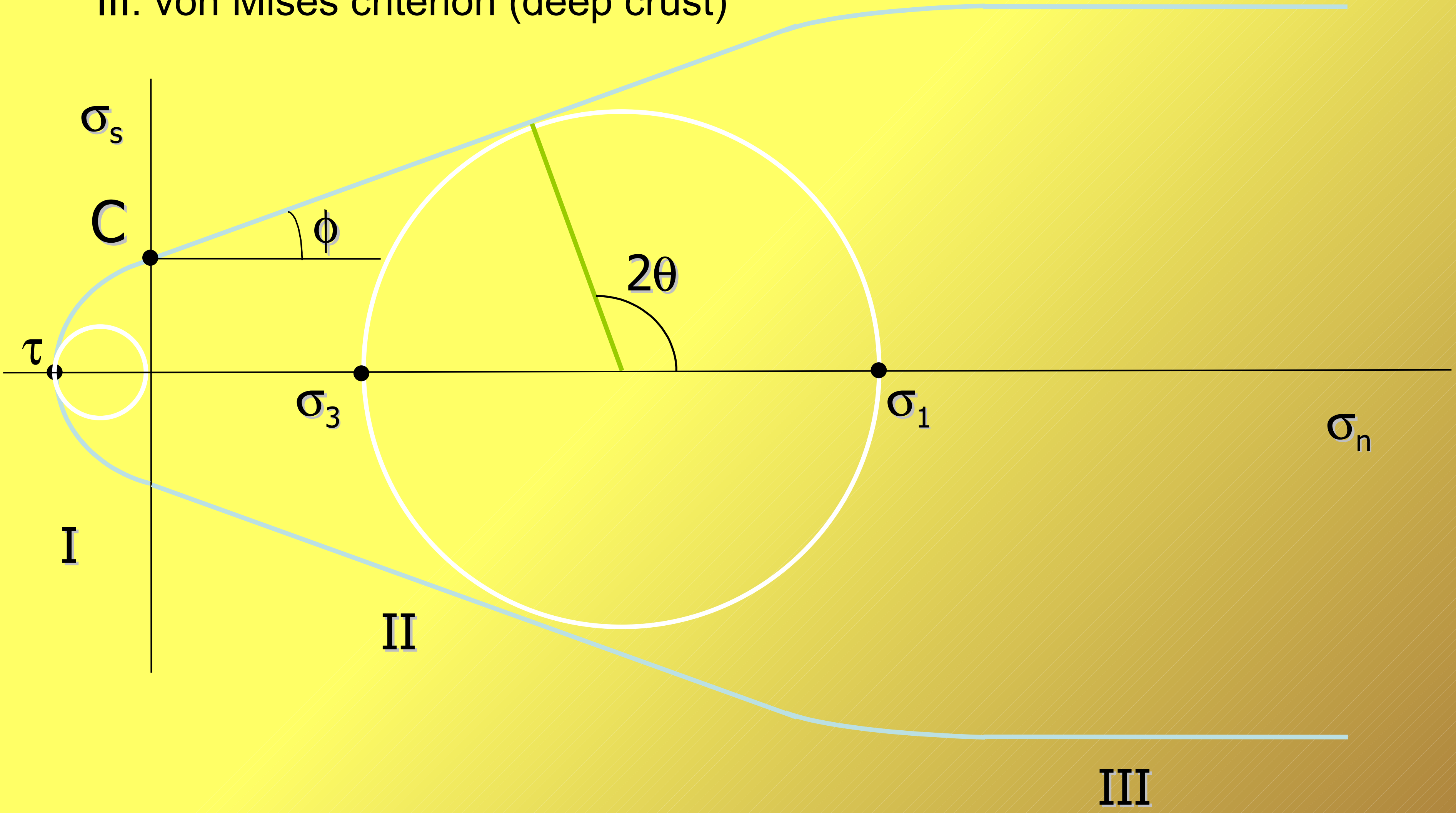
Brittle behavior can be generalized by Mohr Coulomb failure:

$$\sigma_s = \mu * \sigma_n + C$$

where σ_s is the shear stress, μ is the coefficient of friction, σ_n is the linear strain, and C is cohesion.

The Composite Failure Envelope: 3 parts

I: Tensile failure
II: Coulomb failure
III: von Mises criterion (deep crust)



2. ELASTIC MATERIALS

Elastic materials deform by an amount proportional to the applied stress, but when the stress is released, the material returns to its original undeformed state. The deformation is said to be recoverable. This relationship defines elastic behavior:

$$\sigma = Y \varepsilon$$

where σ is the applied stress, ε is the linear strain, and Y is Young's modulus (material specific).

Chapter 16: Macroscopic Aspects of Rock Deformation

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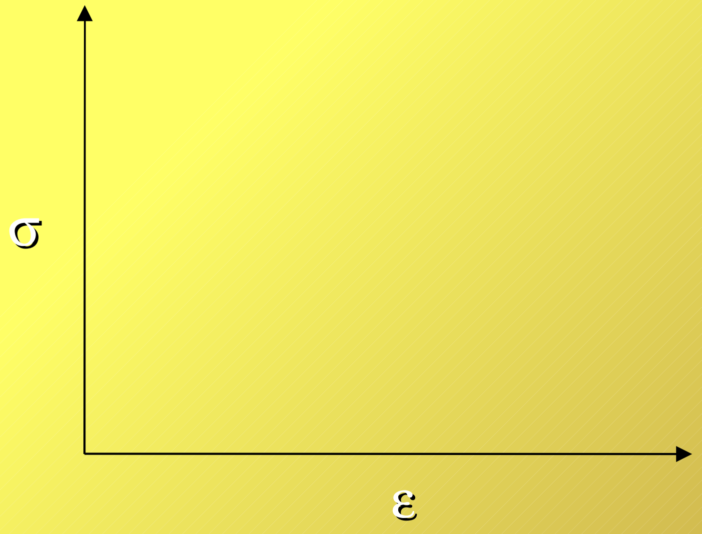
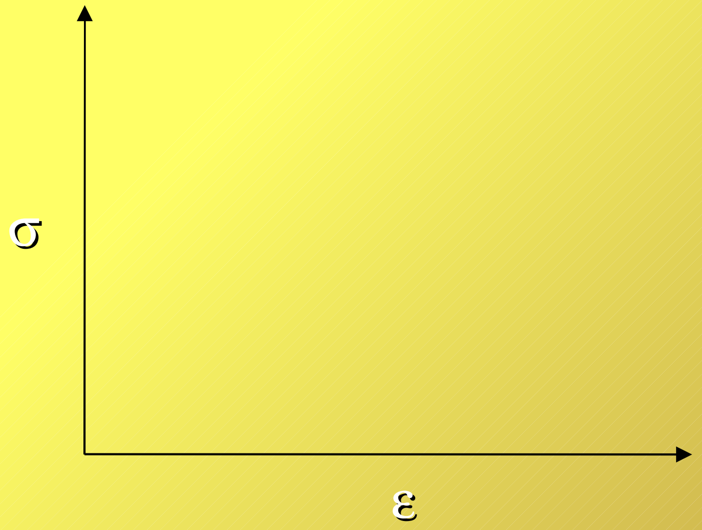


Chapter 16: Macroscopic Aspects of Rock Deformation

2. ELASTIC MATERIALS

$$\sigma = Y \varepsilon$$

Elastic behavior is modeled very well by a spring that is compressed and then released. The spring recovers the deformation. This equation is essentially the same as Hooke's Law.



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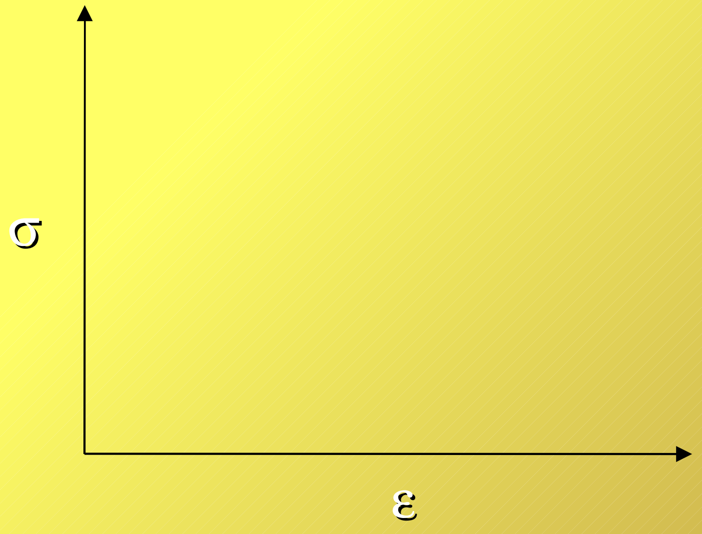
3. PLASTIC MATERIALS

Plastic materials deform by an amount proportional to the applied stress (elastic) at first, but when a critical yield stress is reached, they flow readily and undergo permanent deformation:

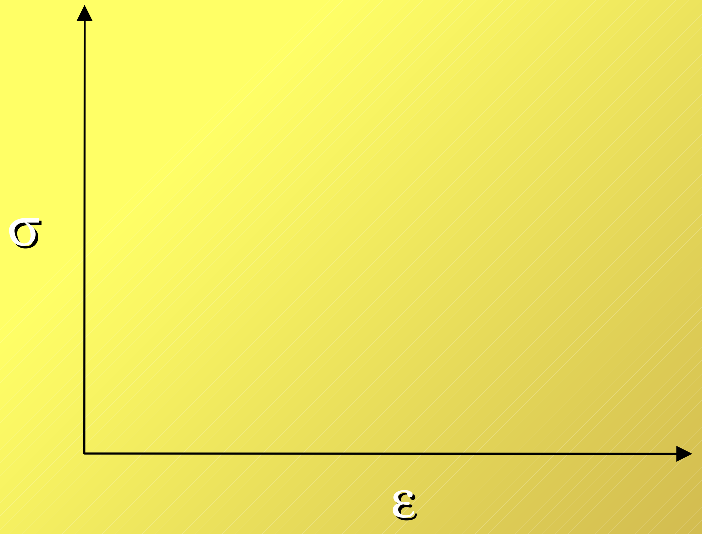


3. PLASTIC MATERIALS

Perfectly plastic materials exhibit no deformation at all below the the yield stress:

$$\sigma_s = K$$

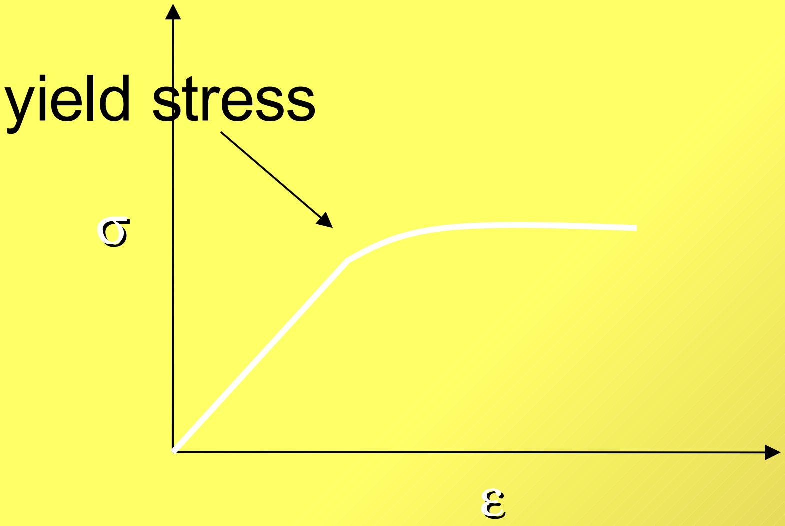
Where σ_s is the shear stress and K is the yield stress.



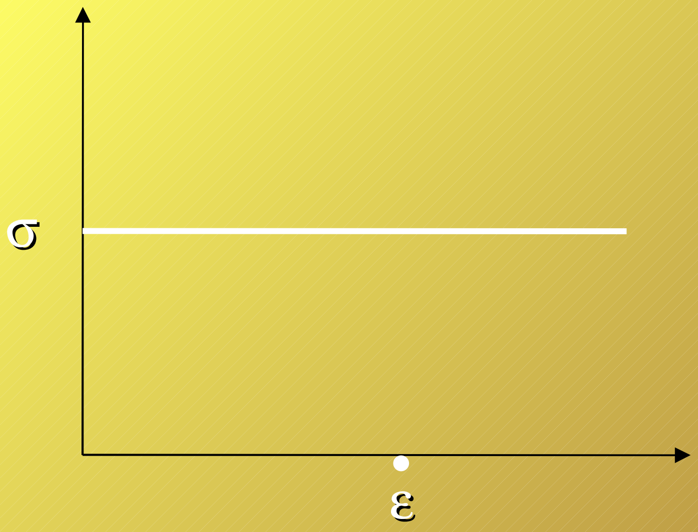
Chapter 16: Macroscopic Aspects of Rock Deformation

3. PLASTIC MATERIALS

A mechanical analog for plastic deformation is the idealized frictional resistance to the sliding of a block on a surface.



Just the plastic deformation:



Chapter 16: Macroscopic Aspects of Rock Deformation

4. VISCOUS MATERIALS

Viscous materials deform by flowing in response to a stress, but when the stress is removed, the material does not return to the undeformed configuration. It can be said that stress is proportional to *strain rate* during viscous deformation. Viscous behavior is described by:

$$\sigma = 2\ \eta\ \varepsilon$$

Where σ is stress, η is viscosity, and ε is shear strain rate.

Viscous behavior is common in Newtonian fluids.

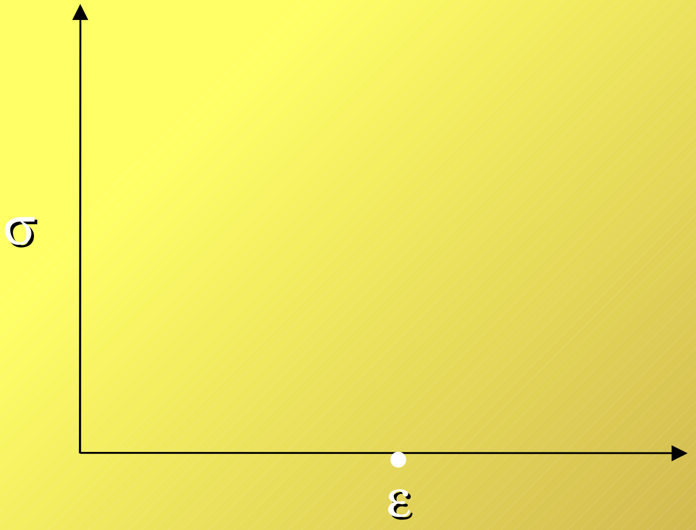
Chapter 16: Macroscopic Aspects of Rock Deformation

4. VISCOUS MATERIALS

It can be said that stress is proportional to *strain rate* during viscous deformation. Viscous behavior is described by:

$$\sigma = 2 \eta \dot{\varepsilon}$$

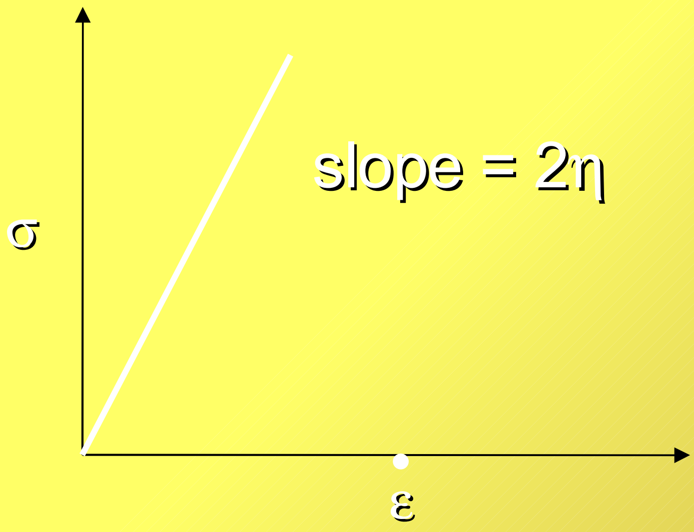
Where σ is stress, η is viscosity, and $\dot{\varepsilon}$ is shear strain rate.

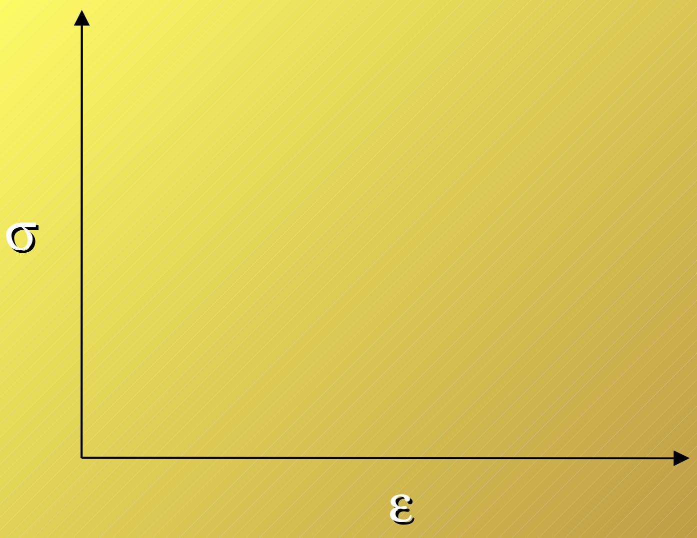


Chapter 16: Macroscopic Aspects of Rock Deformation

4. VISCOUS MATERIALS

A good mechanical analog for viscous deformation is a dashpot. When a force is applied across the system, the motion of the piston is governed by the rate at which the fluid flows through the pores in the piston.

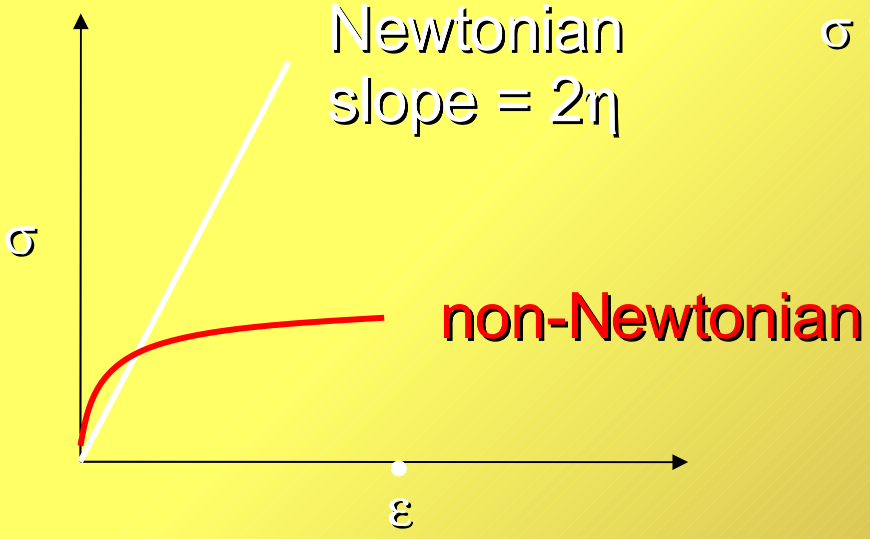




Chapter 16: Macroscopic Aspects of Rock Deformation

5. POWER-LAW MATERIALS

Non-Newtonian fluids do not have a constant slope on the stress-strain rate graph. Instead of viscous behavior, they exhibit power-law rheology.



$$\sigma = 2\,\eta\,\dot{\varepsilon}$$

$$\dot{\varepsilon} = A(\sigma_{diff})^n$$

Chapter 16: Macroscopic Aspects of Rock Deformation

5. POWER-LAW MATERIALS

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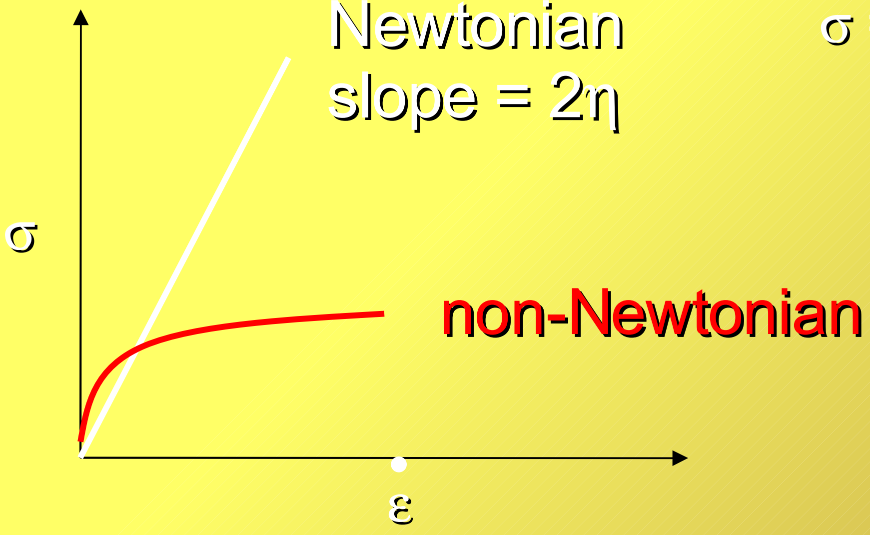


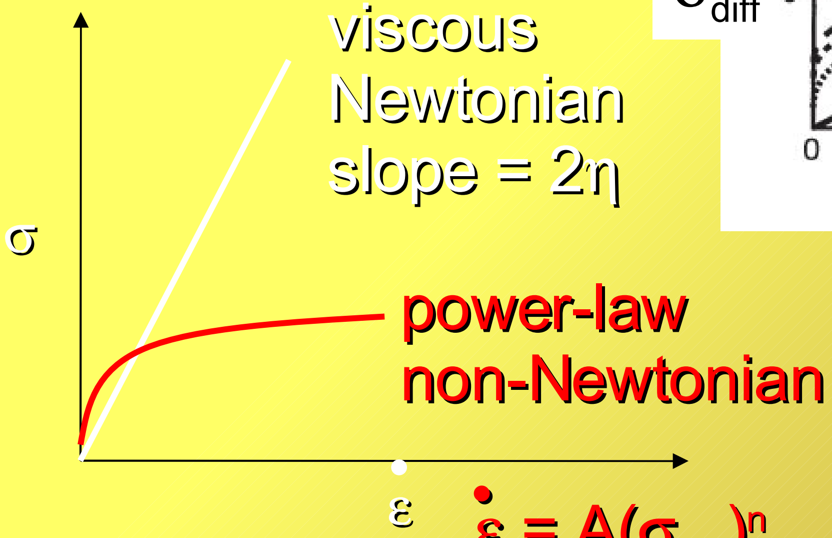
$$\sigma = 2\,\eta\,\dot{\varepsilon} \longrightarrow \dot{\varepsilon} = \frac{\sigma}{2\,\eta}$$

$$\dot{\varepsilon} = A(\sigma_{diff})^n$$

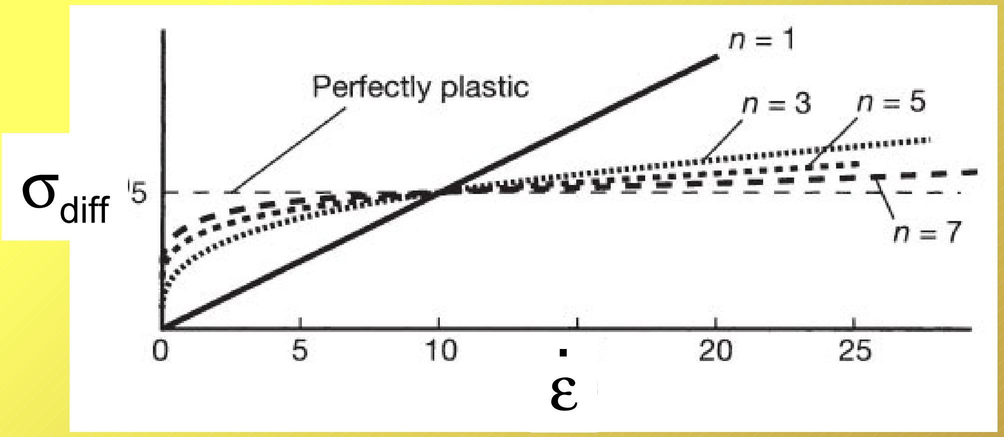
Chapter 16: Macroscopic Aspects of Rock Deformation

5. POWER-LAW MATERIALS

Rocks often deform as power-law materials in ductile shear zones. Common stress exponents are n = 3, 5, and 7.



$\dot{\varepsilon} = A(\sigma_{diff})^n$



Power-law curves

Chapter 16: Macroscopic Aspects of Rock Deformation

Now that we’ve covered 5 common types of rheologies, we can use them to understand *experimental ductile flow*.

Who cares?

The experiments are important to geologists because they produce textures that are similar to those observed in naturally deformed rocks. The lab experiments are done at a specified temperature, pressure, strain rate, water content, etc.. The experiments are then used to “calibrate” the conditions that produced the textures observed in naturally-deformed rocks.

Chapter 16: Macroscopic Aspects of Rock Deformation

The experiments involve the slow continuous deformation, or creep, of the specimen. They are done at much faster strain rates than natural geologic strain rates. Lab rates $\sim10^{-7}$.

Are the results still applicable?

Experiments are either done at 1) constant stress, or 2) constant strain rate.

If we want to compare two sets of experimental data, then we compare them in terms of a homologous temperature, which is the ratio of the temperature of a substance to its melting point.

Chapter 16: Macroscopic Aspects of Rock Deformation

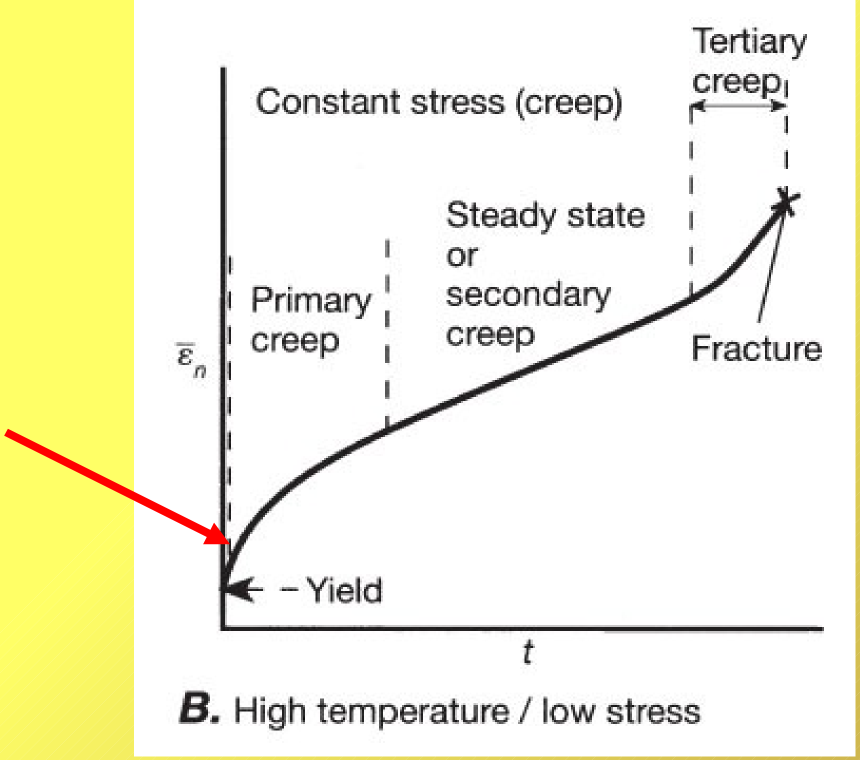
We can examine the results of an experiment by graphing strain versus time, or differential stress versus time.

We differentiate between cold working experiments where The homologous temperature is < 0.5, and hot working experiments where the homologous temperature is > 0.5.

Chapter 16: Macroscopic Aspects of Rock Deformation

#1: This is a hot-worked, constant stress experiment result.

1) It has a very short duration of some initial elastic behavior when the stress is applied. It quickly exceeds yield stress.



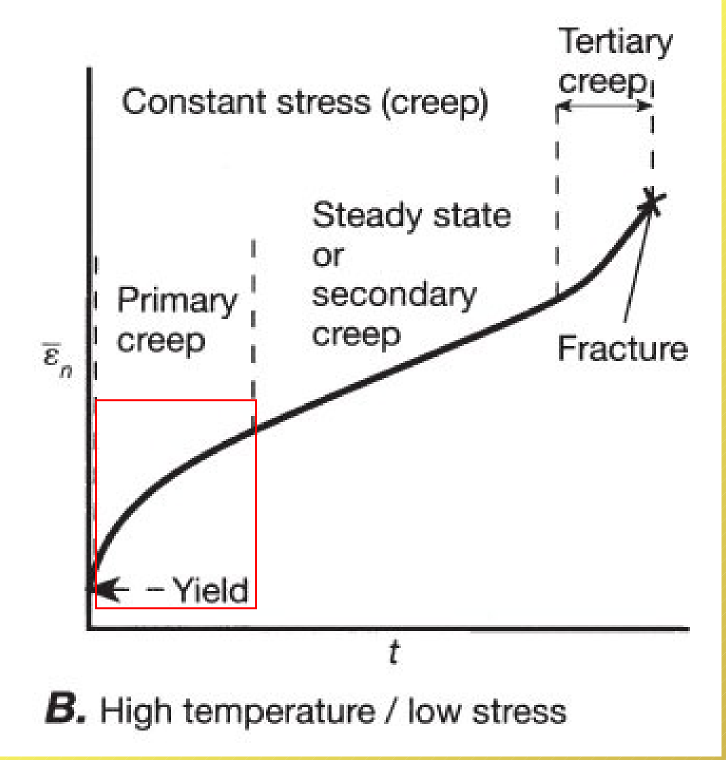
B. High temperature / low stress

Chapter 16: Macroscopic Aspects of Rock Deformation

#1: This is a hot-worked, constant stress experiment result.

2) The creep rate is initially high, but steadily declines as the experiment proceeds--this is primary creep.

The phenomenon of decreasing creep rate with constant stress is called "work hardening"

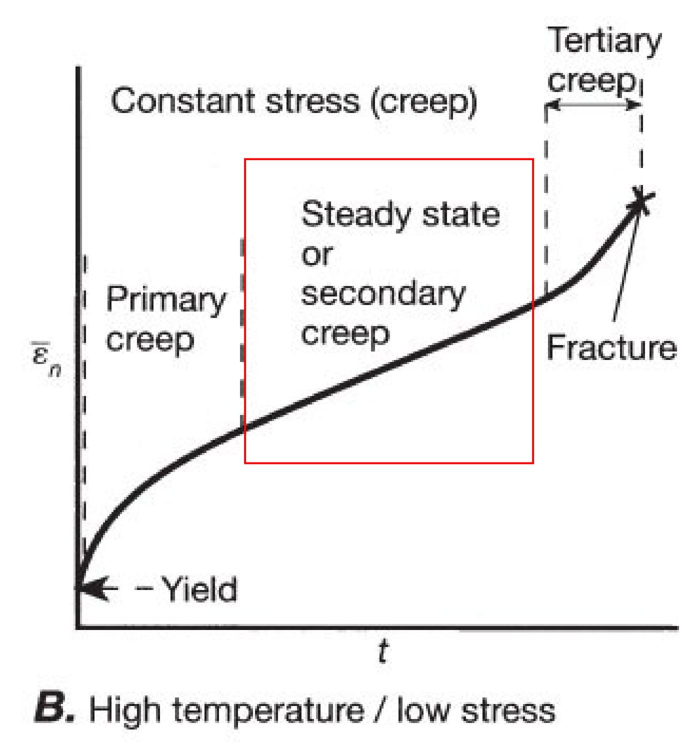


B. High temperature / low stress

Chapter 16: Macroscopic Aspects of Rock Deformation

#1: This is a hot-worked, constant stress experiment result.

3) The creep rate eventually stabilizes at some constant level, and this is called steady state, or secondary creep.

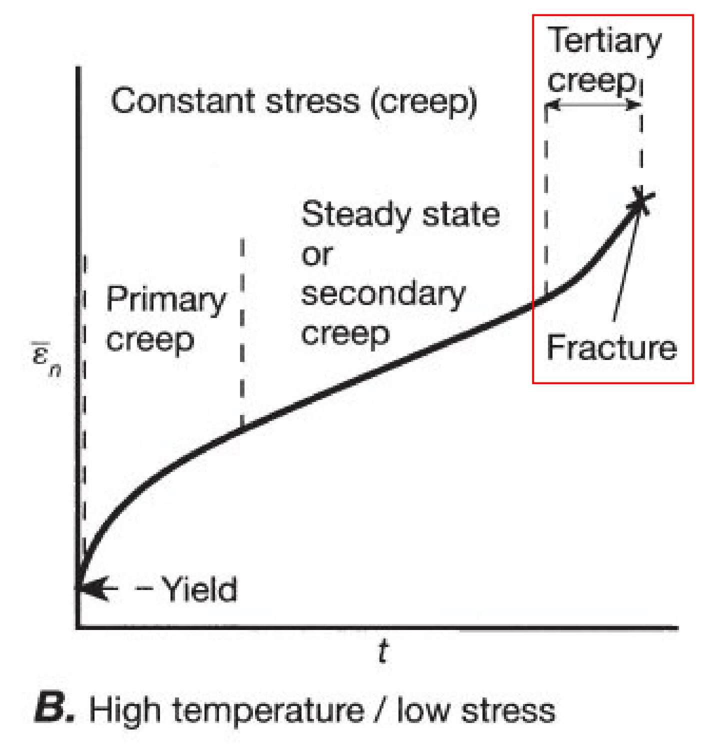


B. High temperature / low stress

Chapter 16: Macroscopic Aspects of Rock Deformation

#1: This is a **hot-worked**, constant stress experiment result.

3) Sometimes the steady-state regime gives way to tertiary creep, where the strain rate accelerates and the sample fractures.

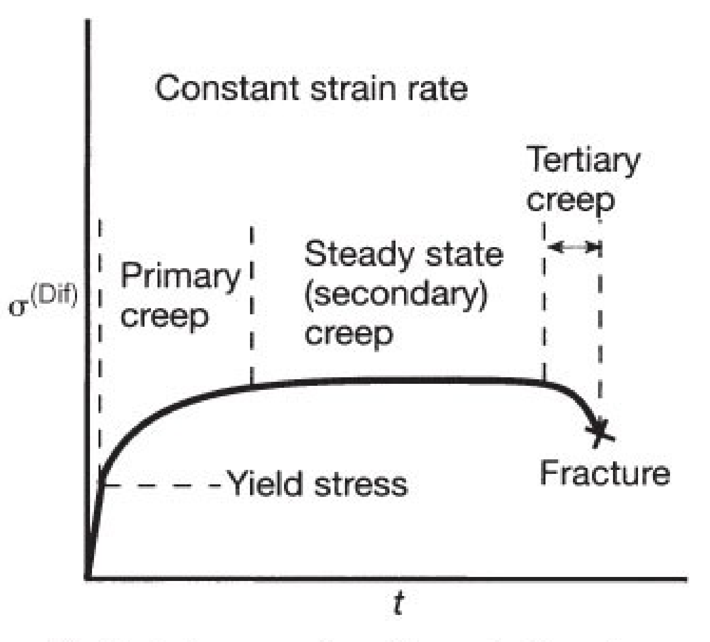


B. High temperature / low stress

Chapter 16: Macroscopic Aspects of Rock Deformation

#2: This is a hot-worked, constant strain rate experiment result.

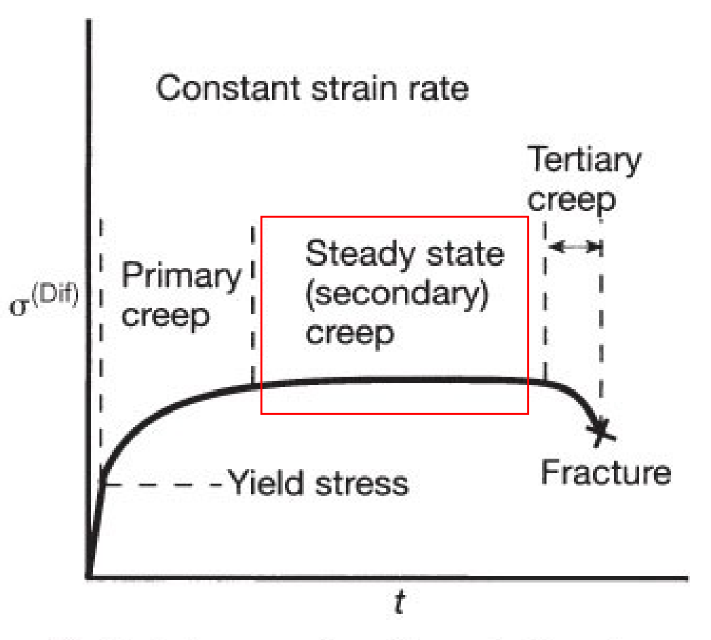
Similarly, the sample displays primary, steady-state, and tertiary creep regimes. However, elastic strain is not built up quickly because the *strain rate* is constant, so the stress builds slowly.



D. High temperature / low strain rate

Chapter 16: Macroscopic Aspects of Rock Deformation

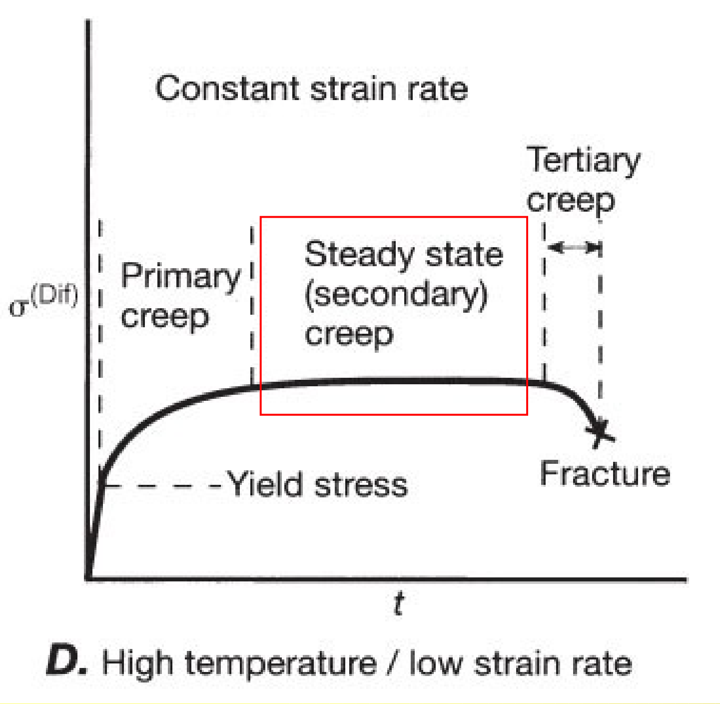
We care about these experiments because ductile flow deep In the Earth is largely characterized by steady state creep. Large amounts of deformation can accumulate in these rocks, producing complex folds, etc. The flow laws used to describe this behavior are useful for modeling real shear zones and the strain rates under which they deform.



D. High temperature / low strain rate

Chapter 16: Macroscopic Aspects of Rock Deformation

We will just focus on moderate-stress flow laws for this course because 1) this regime is the most investigated, and 2) is thought to be most applicable for deformation in the Earth.



D. High temperature / low strain rate

flow laws take the form:

$$\dot{\varepsilon} = A\,(\sigma_{diff})^n\,(f_{O2})\,\exp[-E+PV/RT]$$

Geologic materials have
n = 3 and can be up to n = 5

Chapter 16: Macroscopic Aspects of Rock Deformation

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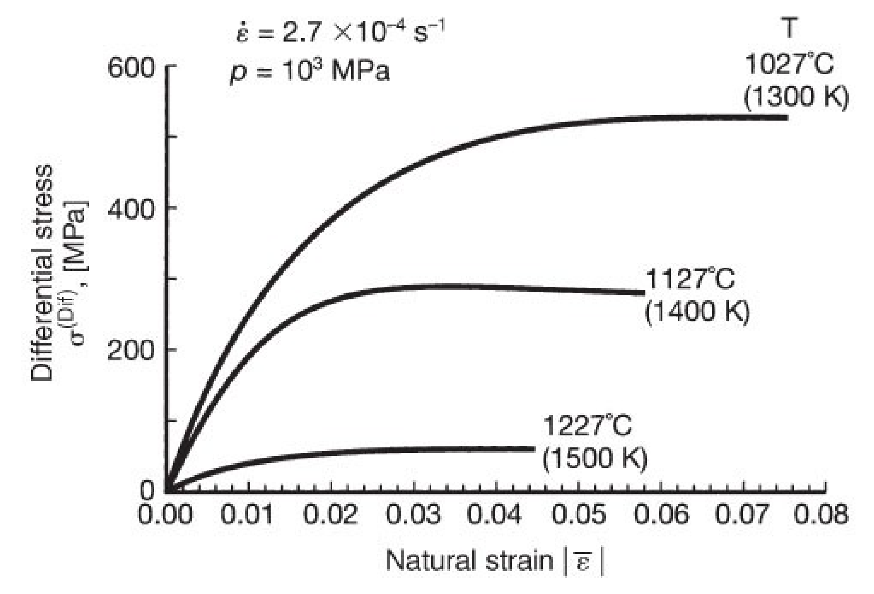


olivine experiment

flow laws take the form:

$$\dot{\varepsilon} = A\,(\sigma_{diff})^n\,(f_{O2})\,\exp[-E+PV/RT]$$

Flow laws are determined for:

e Single mineral phases

e Multiple mineral phases

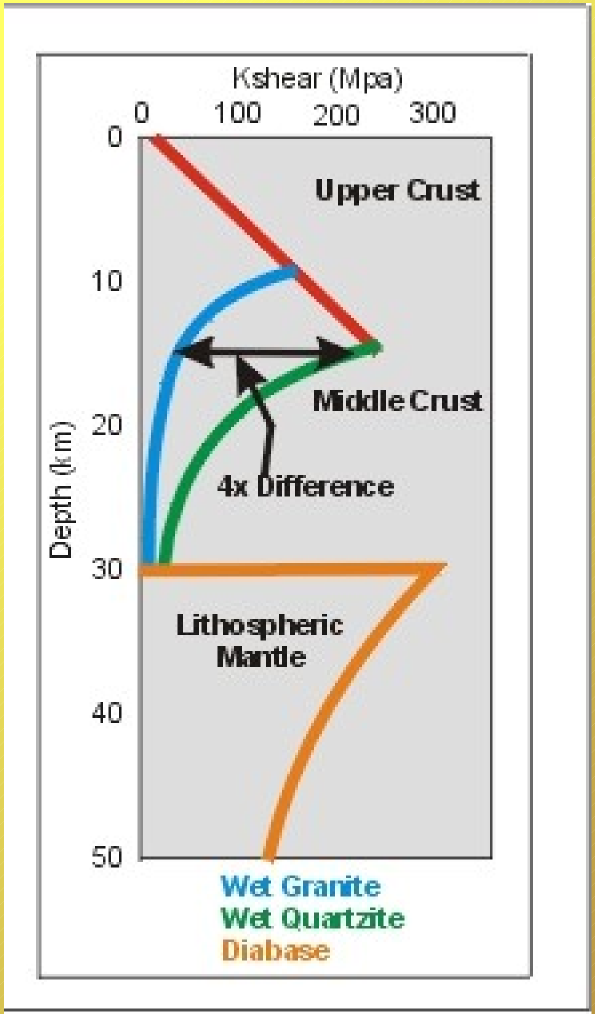
Chapter 16: Macroscopic Aspects of Rock Deformation

The flow laws can also be used to construct strength envelopes that describe the strength of the crust and mantle with depth.

$$\dot{\varepsilon} = A\,(\sigma_{diff})^{n}\,(f_{O2})\,\exp\,[-E+PV/RT]$$

Flow laws are determined for:

- Single mineral phases
- Multiple mineral phases



PART 2: DEFORMATION MECHANISMS

Deformation mechanisms are grain scale processes that occur in response to deformation of a rock. These are processes that are occurring at the microscopic scale.

Chapter 17: Microscopic Aspects of Rock Deformation

Up until now, we considered rock deformation from the continuum point of view, which assumes that the rock is homogeneous and has no discontinuities…

But…this is a question of scale!

Rocks are made of *crystal grains* which are imperfect in the microscopic scale. These crystal imperfections give the rock average mechanical properties and contribute to the overall macroscopic behavior of the rock under stress.

So…if we want to study the macroscopically ductile behavior of rocks, we must zoom in to the micro- and submicroscopic scale.

Chapter 17: Microscopic Aspects of Rock Deformation

By examining rocks on the micro- and submicroscopic scales, we will be able to answer:

- What deformation mechanisms permit solid rocks to flow?
- Under what conditions do these deformation mechanisms operate?
- What rheology is associated with each of these mechanisms?
- What micro- and submicroscopic structures can we identify in the rock that reflect the deformation mechanisms that produced them?
- What can we infer from these structures about the conditions of deformation?

Chapter 17: Microscopic Aspects of Rock Deformation

It would be most helpful to understand which deformation mechanisms dominate for a given set of stress and temperature conditions for a particular mineral. We use a deformation mechanism map to accomplish this task.

Defm. Mech.	Stress	Rheology
Cataclastic flow	high	
Dislocation creep	high to med.	Power-law Exponential-law
Diffusion creep	med.	Linear viscous

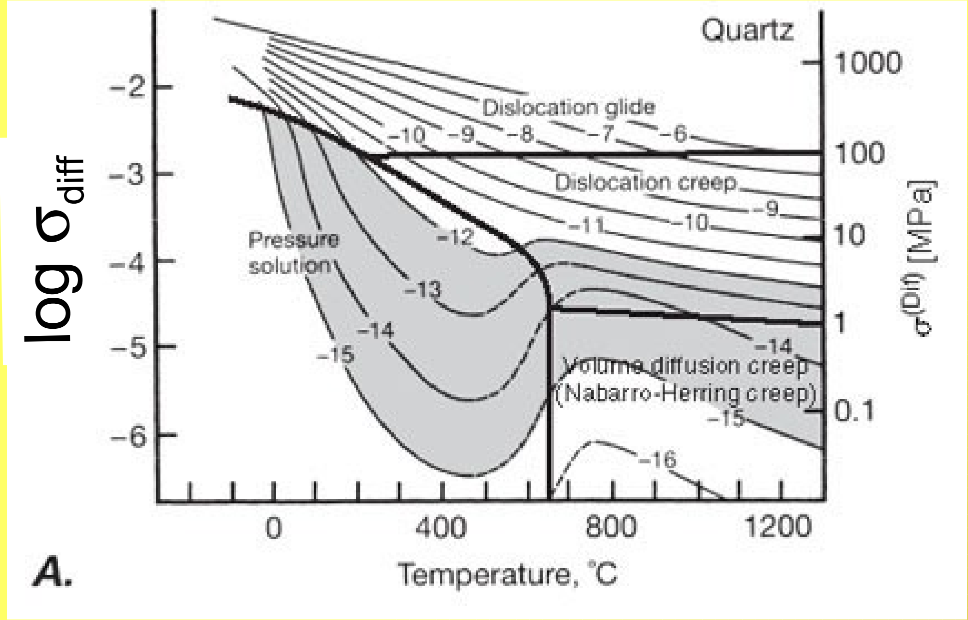
Chapter 17: Microscopic Aspects of Rock Deformation

Let’s reorganize these deformation mechanisms and the stress conditions with which they are typically associated:

Defm. Mech.	Stress	Rheology
• Cataclastic flow	high	
• Dislocation creep	high to med.	Power-law Exponential-law
• Diffusion creep	med.	Linear viscous

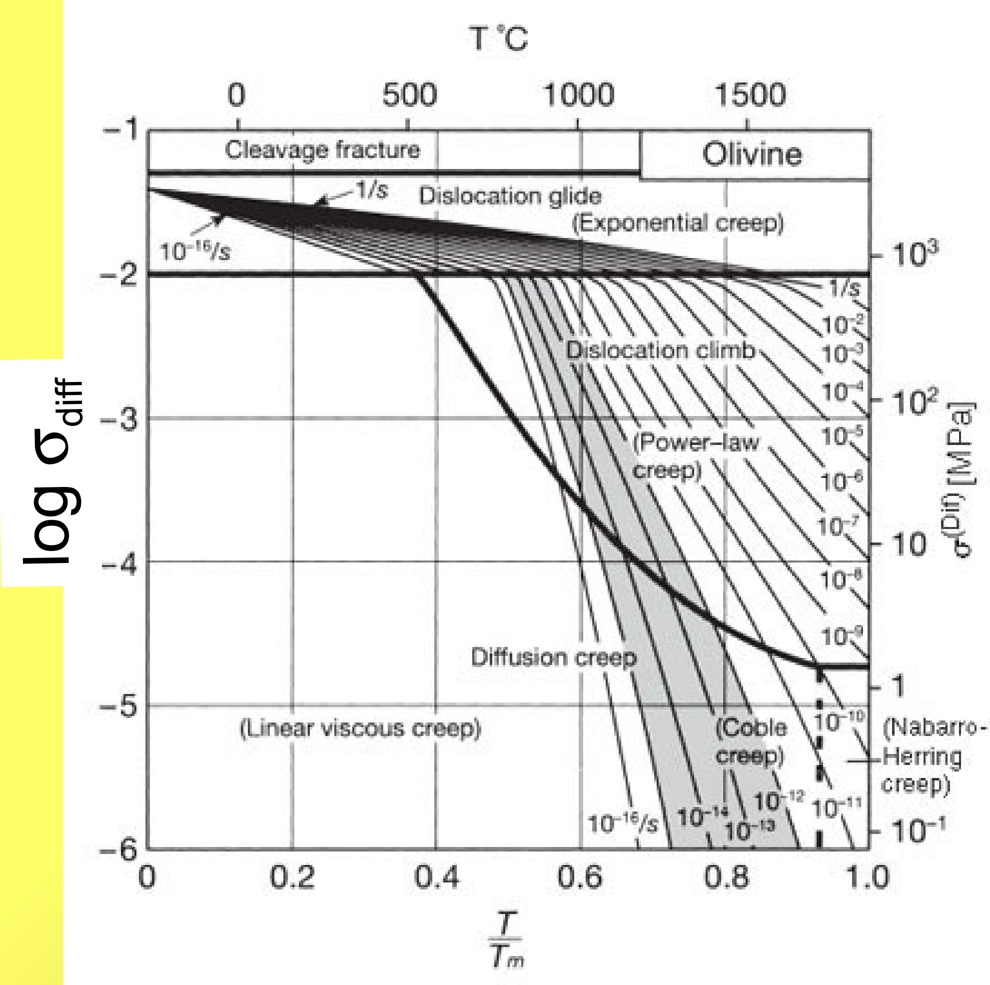
Chapter 17: Microscopic Aspects of Rock Deformation

It would be most helpful to understand which deformation mechanisms dominate for a given set of stress and temperature conditions for a particular mineral. We use a deformation mechanism map to accomplish this task. The maps are based on *experimental data*.



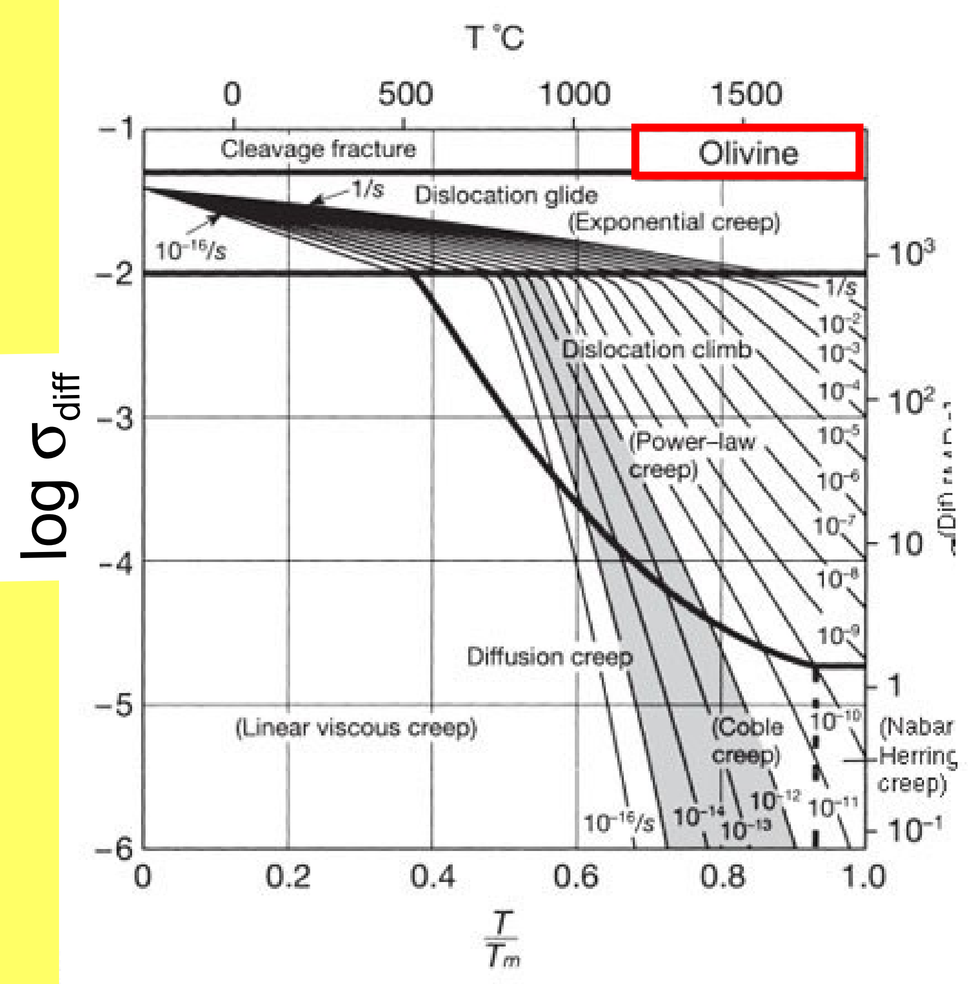
Chapter 17: Microscopic Aspects of Rock Deformation

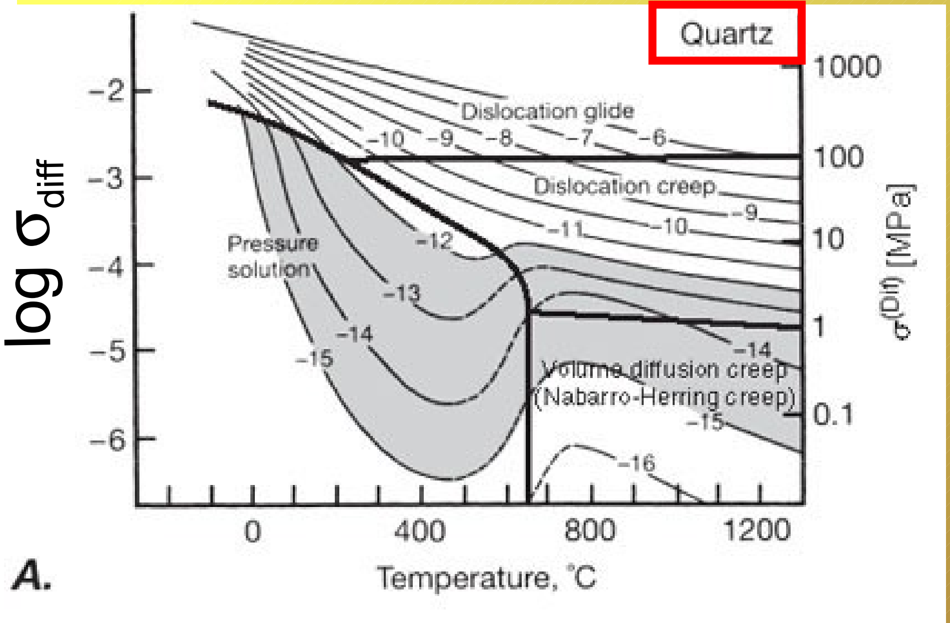
Some deformation mechanism maps are shown in terms of the homologous temperature, so that the behavior of different minerals is normalized for temperature.



Chapter 17: Microscopic Aspects of Rock Deformation

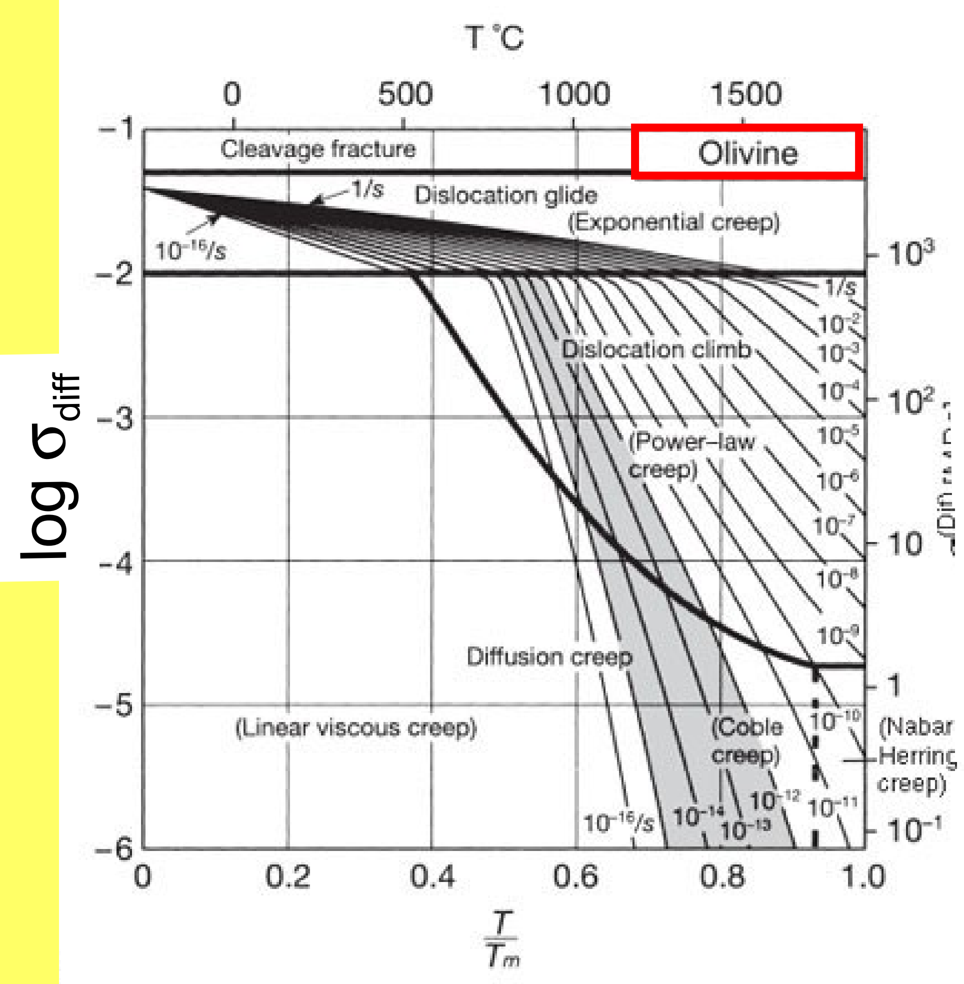
Notice that the deformation mechanism maps are constructed for common minerals in the crust and mantle; this is how we try to understand material flow in the Earth.

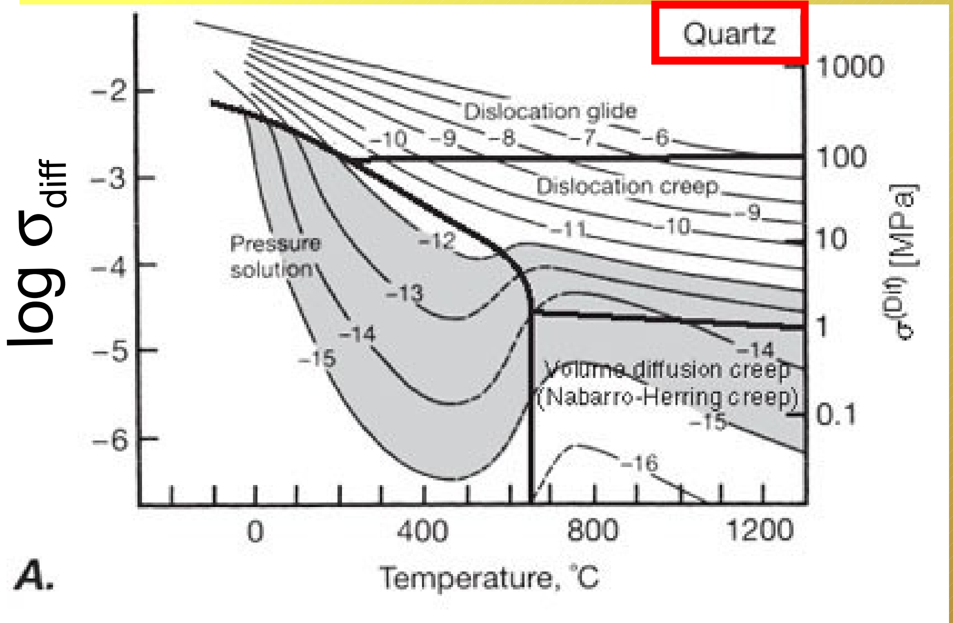




Chapter 17: Microscopic Aspects of Rock Deformation

It is important to understand the microscopic evidence for a particular deformation mechanism in a naturally-deformed rock because it allows us to use these maps to see where our natural data plot. We can therefore calibrate our natural data in terms of temperature or strain rate!





Chapter 17: Microscopic Aspects of Rock Deformation

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Chapter 17: Microscopic Aspects of Rock Deformation

We will now discuss these deformation mechanisms and the structural effects that these mechanisms leave in the rocks.

We begin with **low-temperature** deformation mechanisms that are highly sensitive to the magnitude of *confining pressure* (brittle deformation).

We will then continue with **high-temperature** deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (ductile deformation).

Chapter 17: Microscopic Aspects of Rock Deformation

We begin with **low-temperature** deformation mechanisms that are highly sensitive to the magnitude of *confining pressure* (brittle deformation).

- Elastic behavior

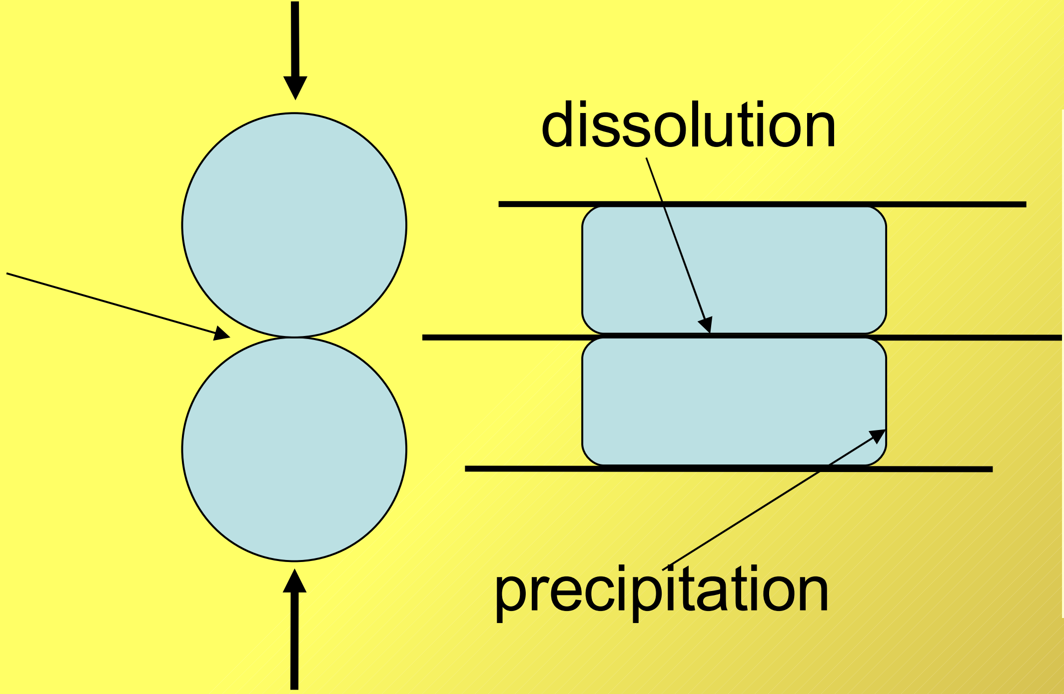
When stress is added, ions are forced out of their lattice positions and begin to exchange positions with other ions in the lattice. The crystal lattice will relax when the stress is removed.

Chapter 17: Microscopic Aspects of Rock Deformation

This deformation mechanism can occur at low-temperature or mid-grade temperatures.

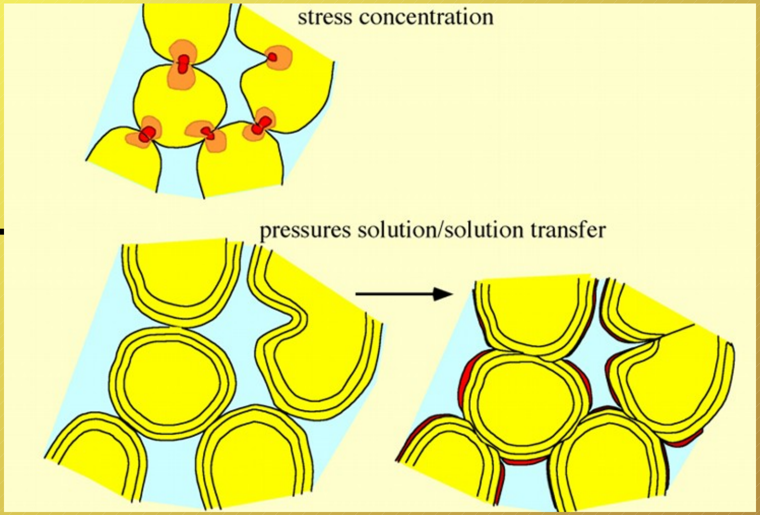
2. Solution Creep, or pressure solution

During solution creep, mineral grains dissolve more readily at faces under high compressive stress. The dissolved components then diffusion through the fluid phase on the grain boundaries and precipitate on surfaces of low compressive stress.



dissolution

precipitation

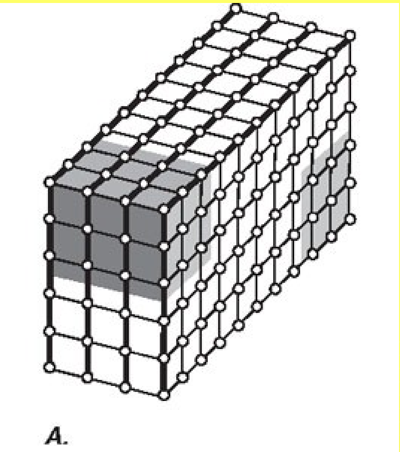


Chapter 17: Microscopic Aspects of Rock Deformation

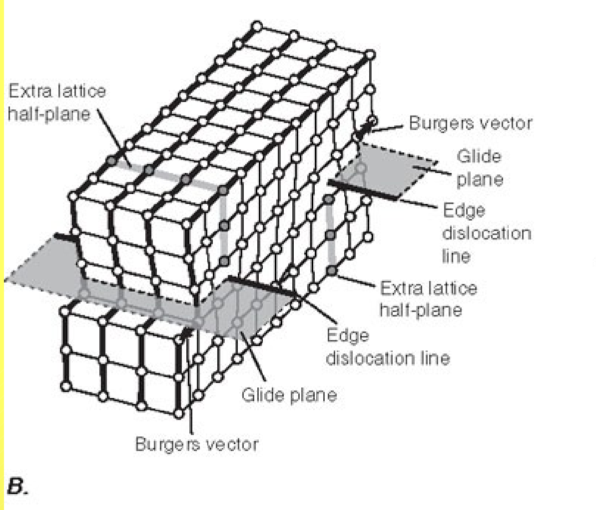
We will then continue with **high-temperature** deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

3. Dislocation Creep

This process occurs from the movement of dislocations through the crystal lattice along a glide plane. The crystal is literally sheared along the glide plane. The bonds between atoms are broken for this to occur; this takes a LOT of energy, which is why it is thermally activated.



initial



finite

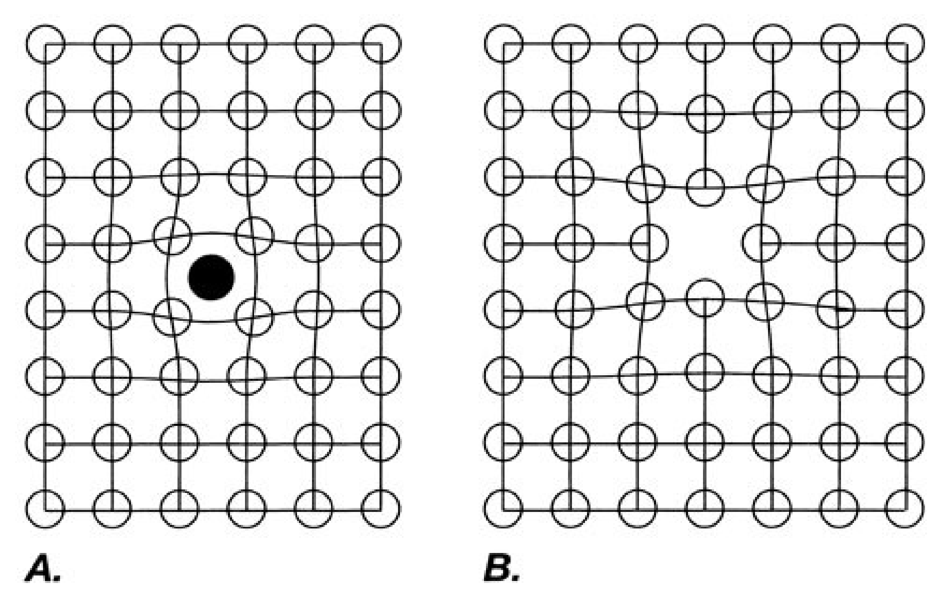
QuickTime and a
Animation decompressor
are needed to see this picture.

motion of dislocations

Chapter 17: Microscopic Aspects of Rock Deformation

Macroscopic flow of rocks can result from a number of different mechanisms, most of which involve either the motion of point defects or the motion of linear crystal defects called dislocations.

Point defects



interstitial

vacancy

QuickTime and a
Animation decompressor
are needed to see this picture.

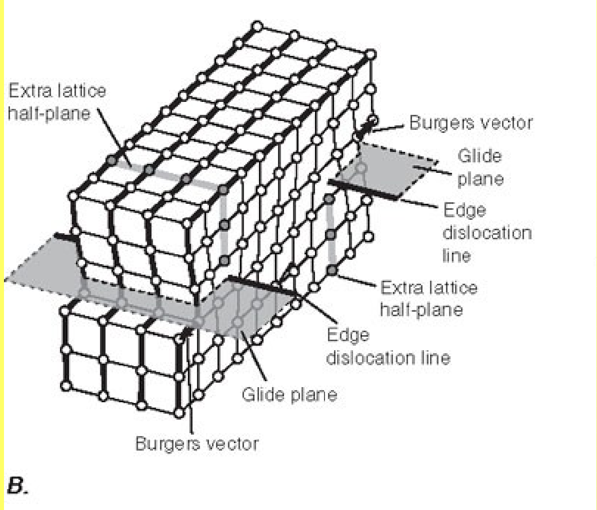
motion of point defects

Chapter 17: Microscopic Aspects of Rock Deformation

We will then continue with **high-temperature** deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

3. Dislocation Creep

With increasing stress and temperature during further deformation, more dislocations are randomly generated. Because the crystal lattice is such a regularly spaced and ordered structure, those dislocations can only move along certain planes in limited directions within the lattice.

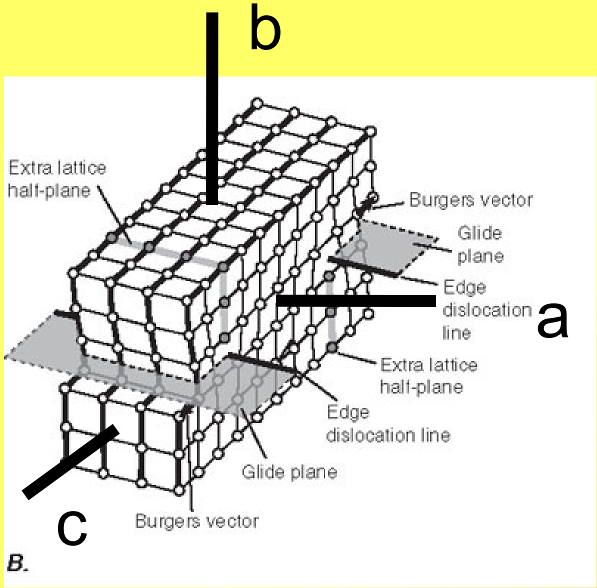


Chapter 17: Microscopic Aspects of Rock Deformation

We will then continue with high-temperature deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

3. Dislocation Creep

These specific glide planes and slip directions together define a slip system for a given mineral. Each mineral has a unique crystal lattice, therefore different minerals have different sets of slip systems.



We write the slip system for a mineral in the following manner using Miller indices notation:

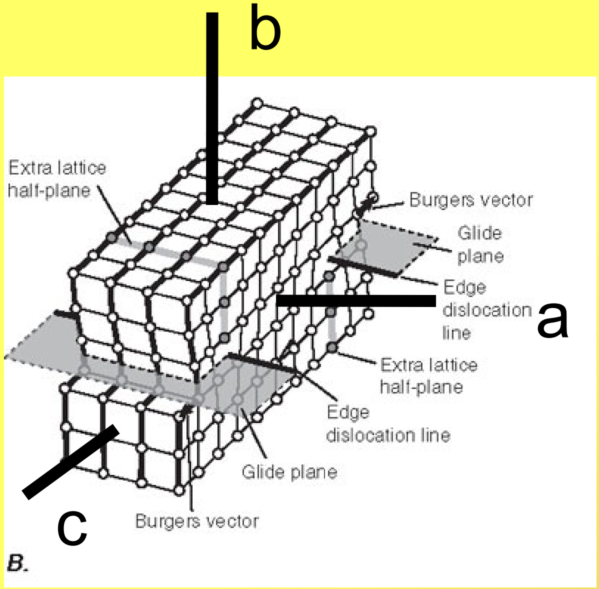
{crystal glide plane}<slip direction>
{010} <001>

Chapter 17: Microscopic Aspects of Rock Deformation

We will then continue with **high-temperature** deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

3. Dislocation Creep

There are several mechanisms of dislocation creep; we will examine many of these in the next lecture.



Chapter 17: Microscopic Aspects of Rock Deformation

We will then continue with **high-temperature** deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

4. Diffusion Creep

During diffusion creep, rock deformation takes place by the migration of atoms Of the material through the solid material itself from areas of high compressive Stress to areas of low compressive stress.

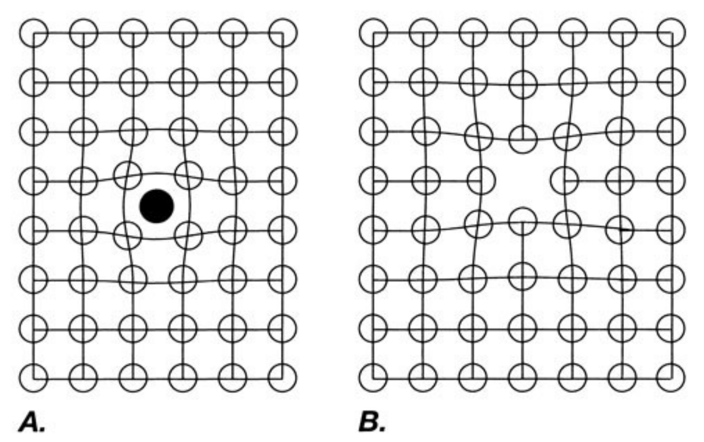
Diffusion may result from the diffusion of 1) point defects through the lattice (called volume diffusion), and 2) atoms or ions along grain boundaries (called grain boundary diffusion). Diffusion may greatly enhance the rate of strain by aiding the motion of linear crystal defects, and by accommodating the shape changes of minerals required for grain boundary sliding.

Chapter 17: Microscopic Aspects of Rock Deformation

We will then continue with **high-temperature** deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

4. Diffusion Creep (Volume Diffusion)

Volume diffusion is a thermally-activated mechanism that is very sensitive to grain size. It operates at very high temperatures and low stresses, and is characterized by the migration of vacancies.



interstitial

vacancy
(more common)

QuickTime and a
Animation decompressor
are needed to see this picture.

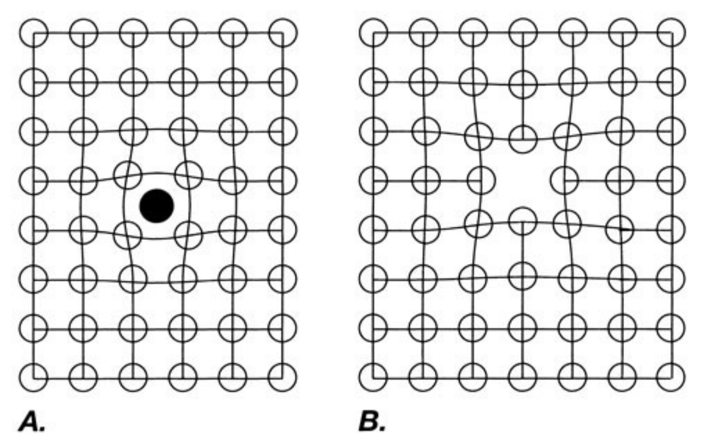
motion of point defects

Chapter 17: Microscopic Aspects of Rock Deformation

We will then continue with high-temperature deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

4. Diffusion Creep (Grain Boundary Diffusion)

Grain boundary diffusion is a thermally-activated mechanism that is also very sensitive to grain size. It is characterized by the movement of atoms along grain boundaries, and operates at slightly lower temperatures than volume diffusion.



interstitial vacancy

Chapter 17: Microscopic Aspects of Rock Deformation

We will then continue with **high-temperature** deformation mechanisms that are sensitive to *temperature*, rather than confining pressure (plastic deformation).

4. Diffusion Creep

Both volume and grain boundary diffusion are very sensitive to grain size because the diffusion paths must be short. When the grain size remains small (<< 100 µm) during deformation, then grain boundary sliding may be a significant mechanism that accommodates strain. Superplastic creep results from coherent grain boundary sliding in which deformation occurs without the opening of gaps or pores between adjacent crystal grains.

Chapter 16: Macroscopic Aspects of Rock Deformation

In a nutshell, here's how to relate natural and experimental deformation:

- Examine *naturally* deformed samples, such as mylonites
- Identify rheology-controlling mineral phase(s)
- Determine T, P, σ_{diff}, grain size in *naturally* deformed samples
- Select *experimental* flow law for same mineral phase
- Use *experimental* flow law equation to find strain rate

$$\dot{\varepsilon} = A\,(\sigma_{diff})^{n} \exp\,[-E/RT]$$

Rheology: Review

- What physical properties control deformation ?

  - Rock type
  - Temperature
  - Pressure
  - Applied Stress
  - Deviatoric (differential) Stress
  - Grain size
  - Others ?

- How are each of these processes related to "*strain rate*" (**$\dot{\varepsilon}$**) ?

$$\boxed{\dot{\varepsilon} = A\,\sigma^{n}/d^{m}\ e^{-(E+PV/RT)}}$$

Rheology: Review

- What are the different types of strain ?

- Brittle
- Elastic

> Low T,P, Shallow

- Plastic
- Viscous

> High T,P, Deep

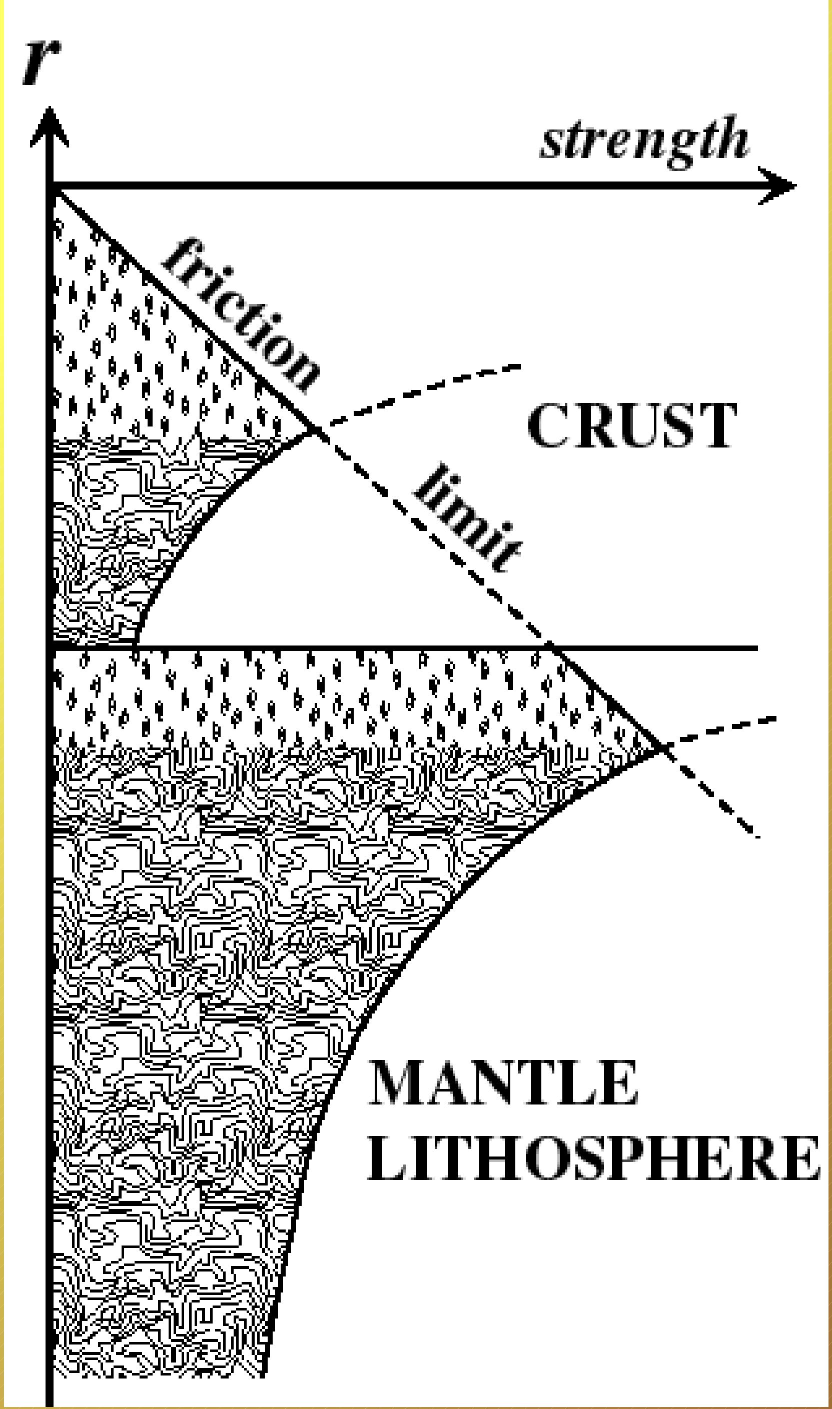
Brittle/Plastic Transition

- Where do these transitions occur in the Earth ?

  - Upper/Lower crust
  - Lithosphere/Asthenosphere

- **Brittle** deformation occurs above The friction limit (linear differential stress)

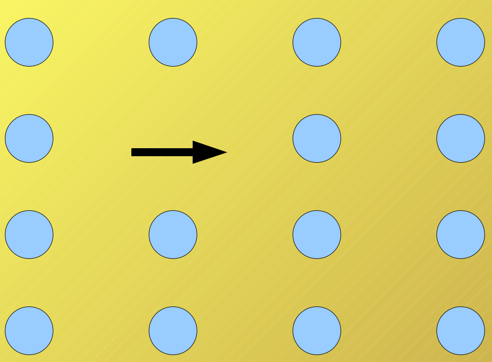
- **Plastic** deformation occurs where differential stress is non-linear (*exp*$^{-z}$)



Plastic Deformation

- In the ***plastic*** regime rocks deform by creep ?
- What is creep ?
- ***Diffusion creep*:** diffusion of atoms or vacancies through grains

  - stress dependence for σ^{n} is linear (n=1)
  - strong dependence on grain size d^{m} (m = 2-3)



Plastic Deformation

- ***Dislocation creep*:** the motion of dislocations through grains

  - stress dependence for σ^n is nonlinear (n=3-5)
  - no dependence on grain size d^m ($m = 0$)

  - strongly dependent on temperature

- What is a ***dislocation*** ?

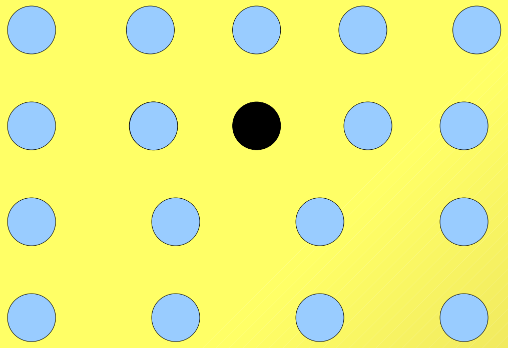
  - imperfections in the crystalline lattice structure

  - All imperfections can be described with the superposition of 2 basic types: ***edge*** and ***screw*** dislocation

Plastic Deformation

- ***Dislocation creep*:** the motion of dislocations through grains

- **Edge Dislocation**: the lattice structure is not uniform across the face of the atomic structure causing stress



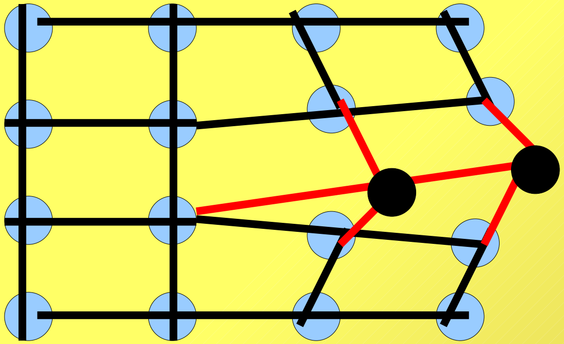
- Atoms are in compression above the plane of discontinuity

- Atoms are in tension below

Plastic Deformation

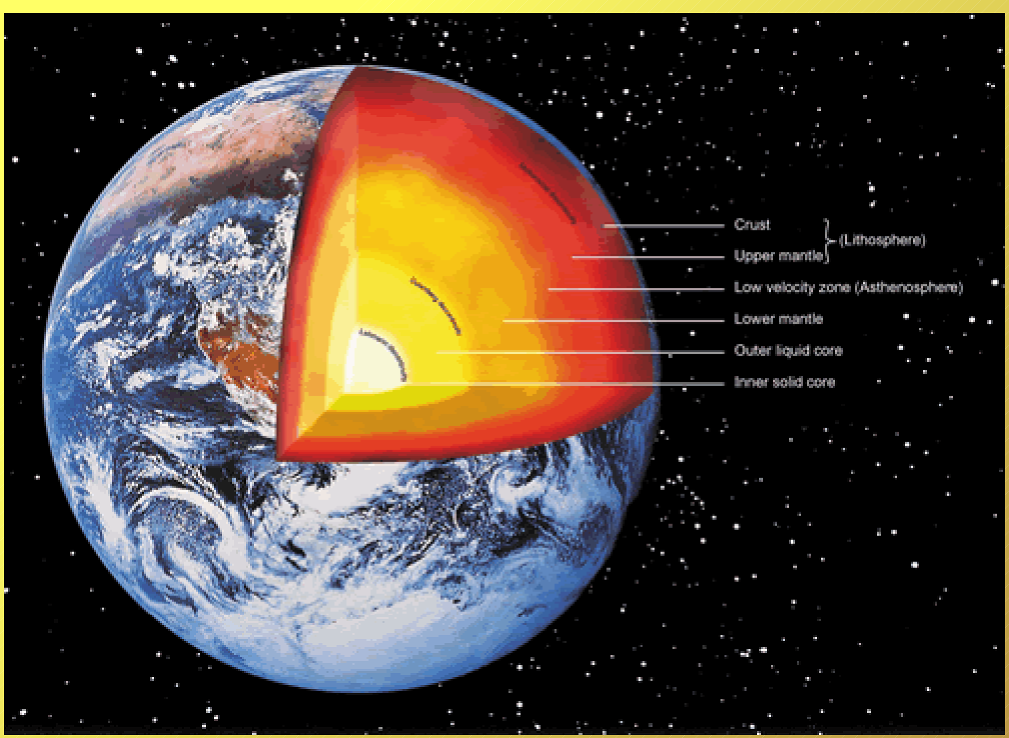
- ***Dislocation creep*:** the motion of dislocations through grains

- **Screw Dislocation**: the lattice structure is not uniform creating an "out of the plane" discontinuity in the atomic structure



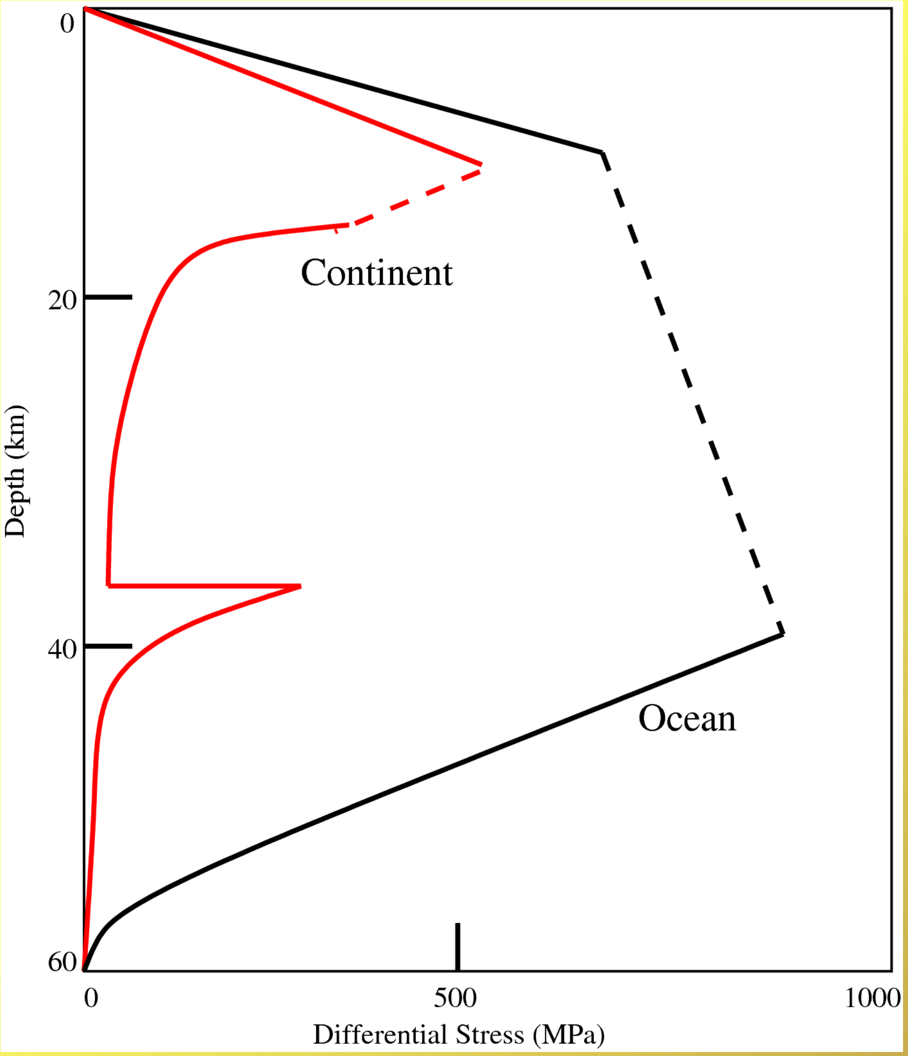
- The atoms (solid black) are in a "second plane"

How Creepy is the Earth's Mantle ?



- The ***upper mantle***:
  - both diffusion and dislocation creep are active
  - seismic anisotropy is ***only*** observed in dislocation creep regime
- The ***lower mantle***:
  - dominated mainly by the diffusion creep regime

Brittle/Plastic Transition

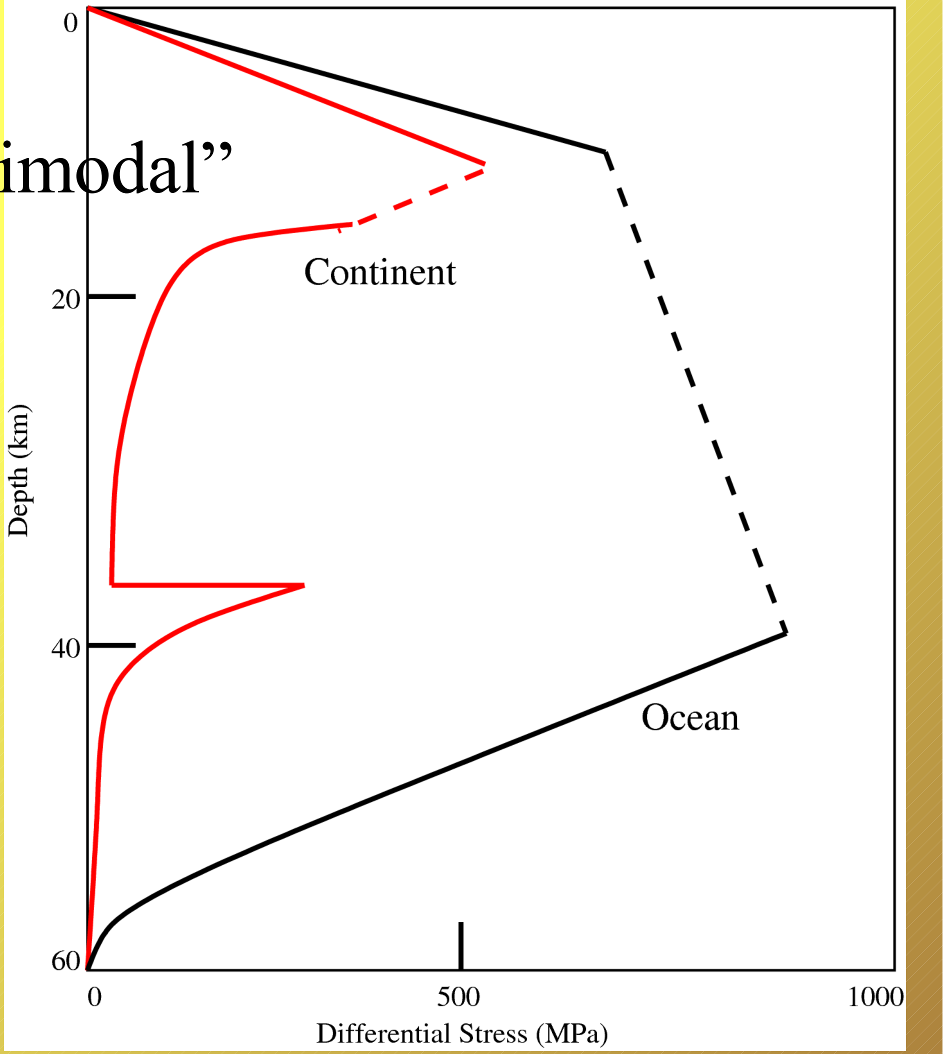


- Differential Stress in Continental and Oceanic plate

Brittle/Plastic Transition

- **Continental** stress envelopes are “bimodal”

  -crustal rocks deform faster than mantle rocks
  -the lower crust deforms rapidly avoiding brittle failure



- Continental lithosphere is “weaker” than **oceanic** lithosphere

  - notice what happens at plate boundaries
  - which plate deforms more during collisions ?

Brittle/Plastic Transition

$$\boxed{\dot{\varepsilon} = A\,\sigma^{n}/d^{m}\; e^{-(E+PV/RT)}}$$

- What other factors effect viscosity of mantle material ?

  - Depth (pressure)
  - Water content (addition or removal)
  - Temperature-dependence
  - Partial melt content

$$\dot{\varepsilon} = A\,\sigma^{n}/d^{m}\, f(\phi + C_{OH})\; e^{-(E+PV/RT)}$$

E = Activation Energy
V = Activation Volume
R = Gas constant
ϕ is melt fraction
OH describes water concentration

Temperature-Dependence of Viscosity

$$\mu = \mu_r \, e^{-(1/T - 1/Tr)}$$

- In "***plastic flow***" regime, viscosity can change with temperature

  - For a temperature change of 100°C
  - Viscosity can change by factor of 10

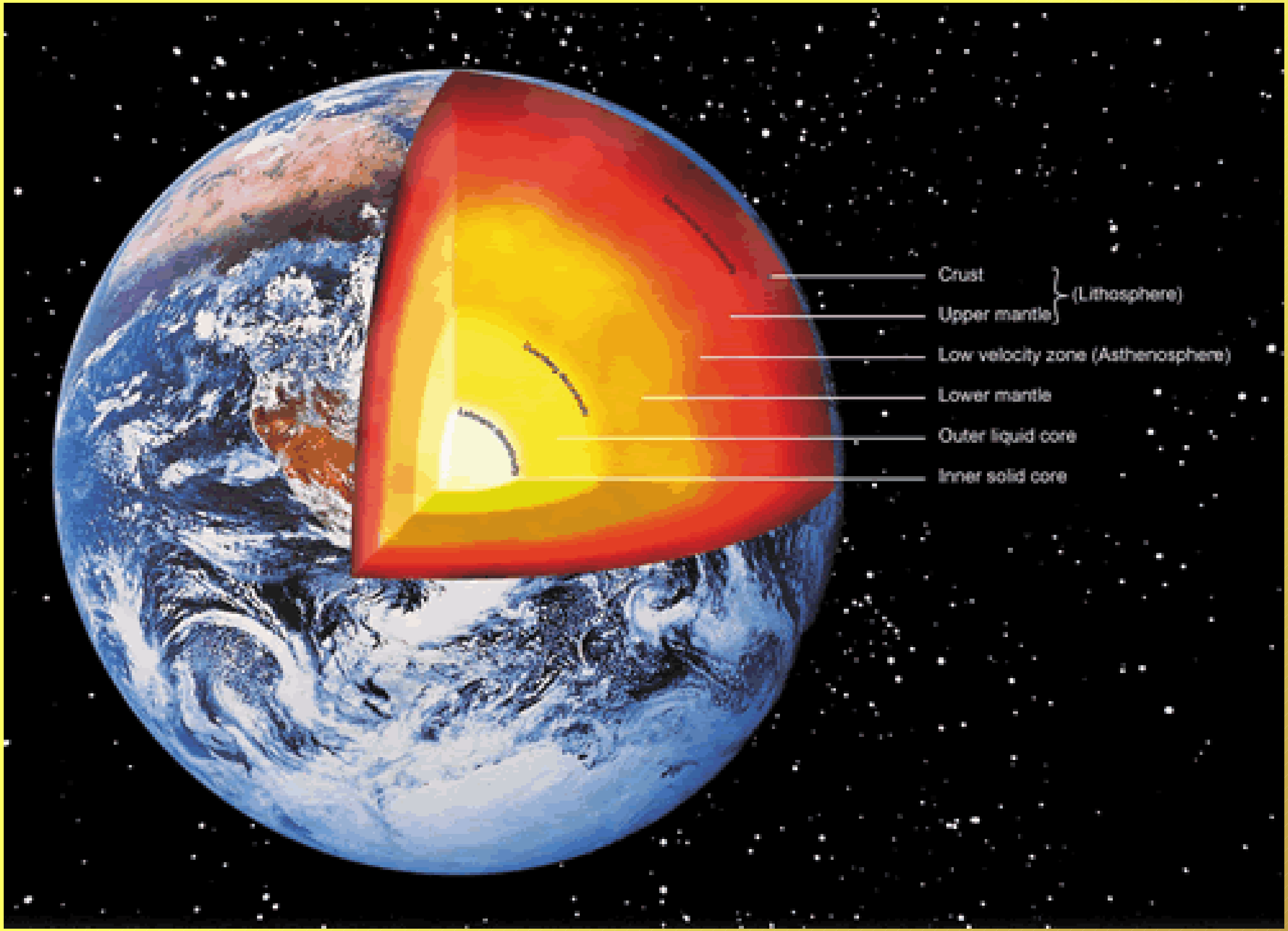
- Melting Temp (Tm increases with depth giving pressure effects)

- Viscosity is not easy to determine in the Earth's interior

- High pressure and temperatures are difficult to achieve in lab.

- Also time scales of flow are long!

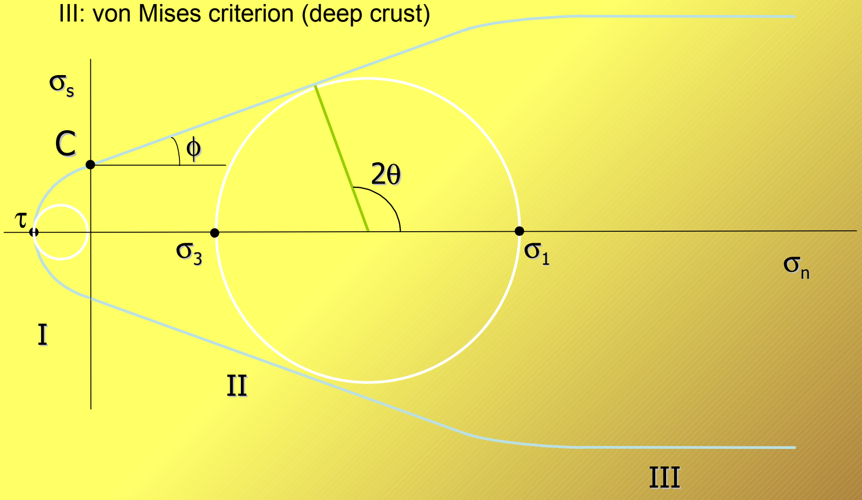
Deformation and Flow in the Earth's Interior



- The Earth's mantle behaves as brittle material at shallow depths
- But behaves as ***plastic*** or ***viscous material*** at deeper depths
- We can consider the deep interior as a viscous fluid over geologic time

The Composite Failure Envelope: 3 parts

I: Tensile failure
II: Coulomb failure
III: von Mises criterion (deep crust)



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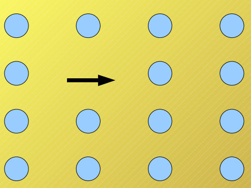

Plastic Deformation

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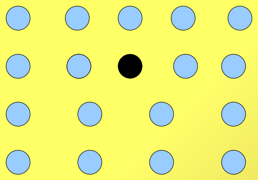

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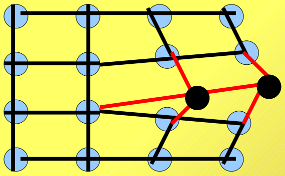

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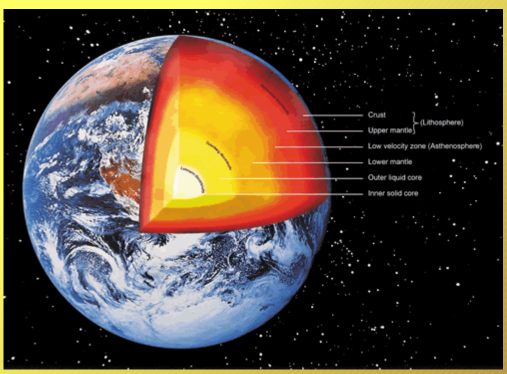

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