THE LIFE TECTONIC

devl

IGPP

Rheology of the Mantle and Plates (part 1):

Deformation mechanisms and flow rules of mantle minerals

Topics covered in this class

- **Rheology of Earth (viscous limit)**
- **Fluid Dynamics for geological phenomena**
- **Composition of the Earth**
- **Thermodynamics and high-pressure mineral physics**
- **Seismological structure of the mantle**
- **Geochemical structure of the mantle**
- **Dynamic processes of the Earth (plumes, slabs, thermochemical piles)**
- **Heat and mass transport in the deep Earth (convection, thermal history)**
- **Energetics of the core (magnetic field generation)**

Where to turn to for more help..

- *Mantle Convection in Earth + Planets*
  Schubert, Turcotte, and Olson (2001)
- *Numerical Geodynamic Modelling*
  Gerya (2009)
- Hirth and Kohlstedt (2003)
- Regenaur-Lieb and Yuen (2003)
- *Treatise on Geophysics* V. 7, Ch. 2

- Papers by those lucky people in the Rheology fan club (partial list only):
  - numerical modelers:
    Podladchikov, Solomatov, Burov, Gerya, Bercovici, Tackley, Yuen
  - experimentalists:
    Karato, Kolhstedt, Hirth, Jackson

What is rheology?

- Rheology is the physical property that characterizes deformation behavior of a material (solid, fluid, etc)

- Rheology of Earth materials includes elasticity, viscosity, plasticity, etc

- For the deep Earth: mantle is fluid on geological timescales so we focus on its viscosity

- For tectonic plates: still viscous on geological timescales, but the effective viscosity is a subject of debate

$$\sigma = E\varepsilon$$ solid mechanics

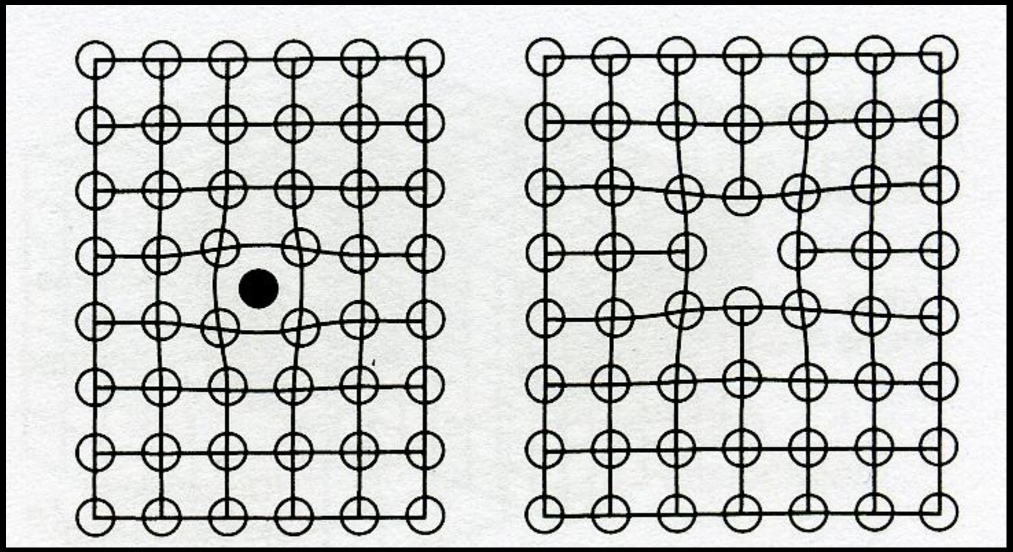
$$\sigma = 2\eta\dot{\varepsilon}$$ fluid mechanics

What is viscosity?

- constitutive relation between stress and strain-rate (deformation rate)
- in the continuum description, it is the analog of the elastic moduli which relate stress and strain
- measure of a fluid's ability to flow
- diffusivity of momentum

Definition of creep

- **movement of crystal defects**
  - **point defects - extra atoms or vacancies**



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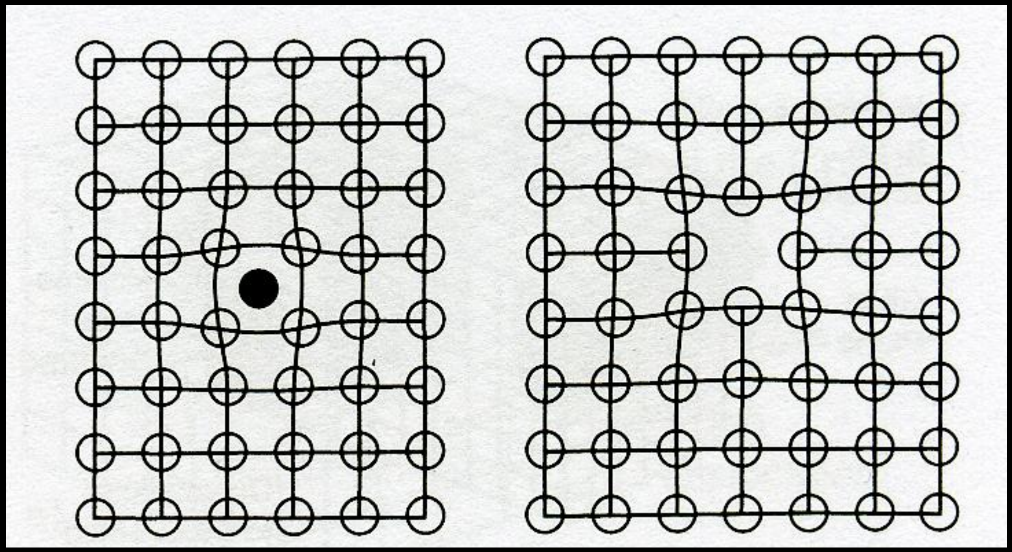

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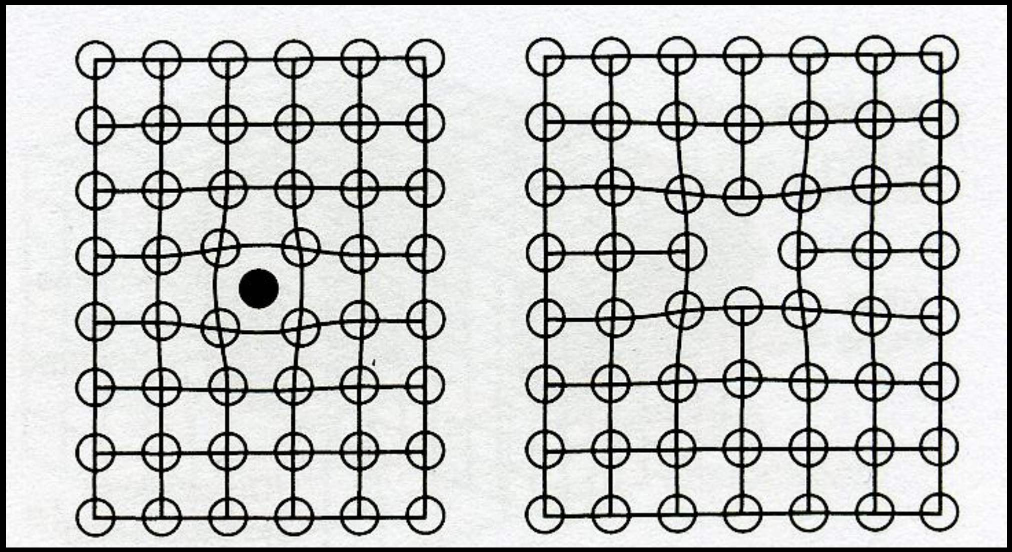
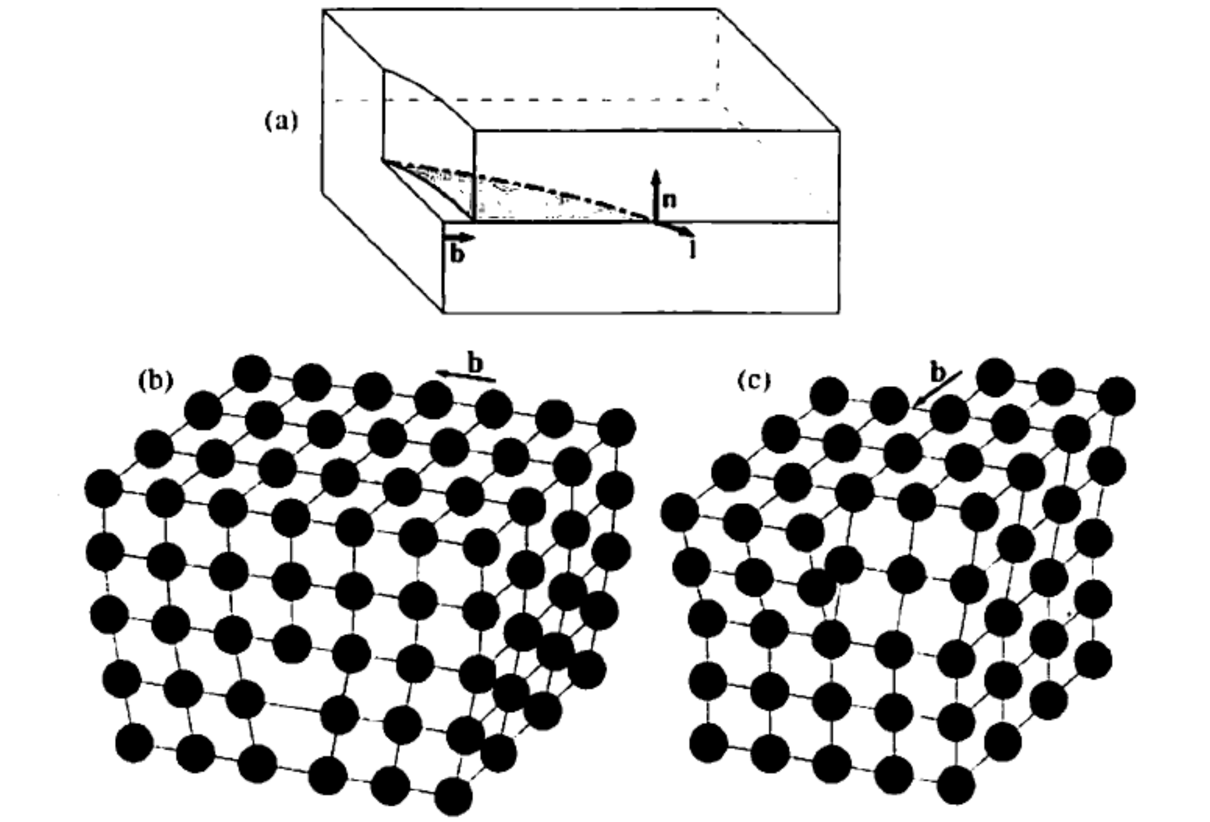
    - each described by parallel or normal Burgers vector (b*)





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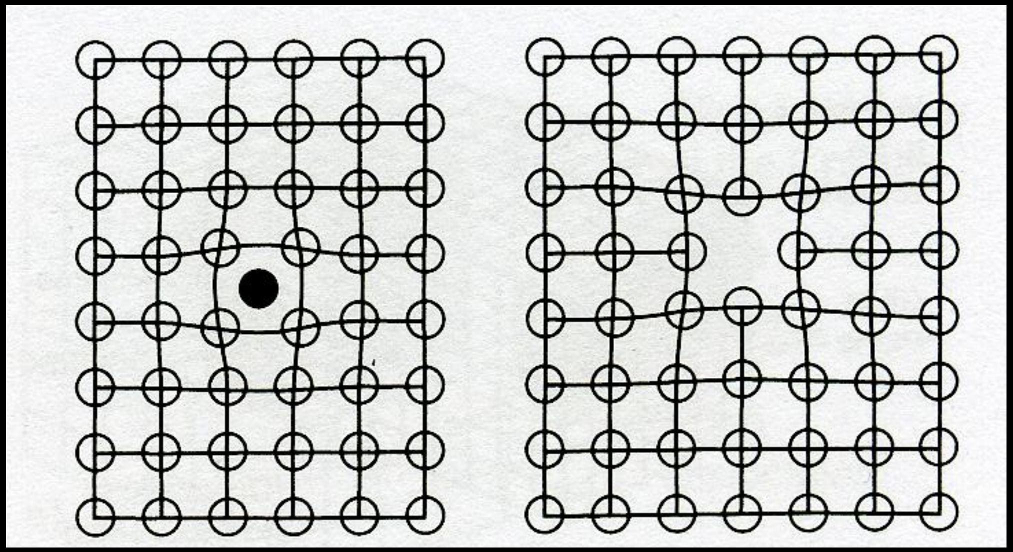
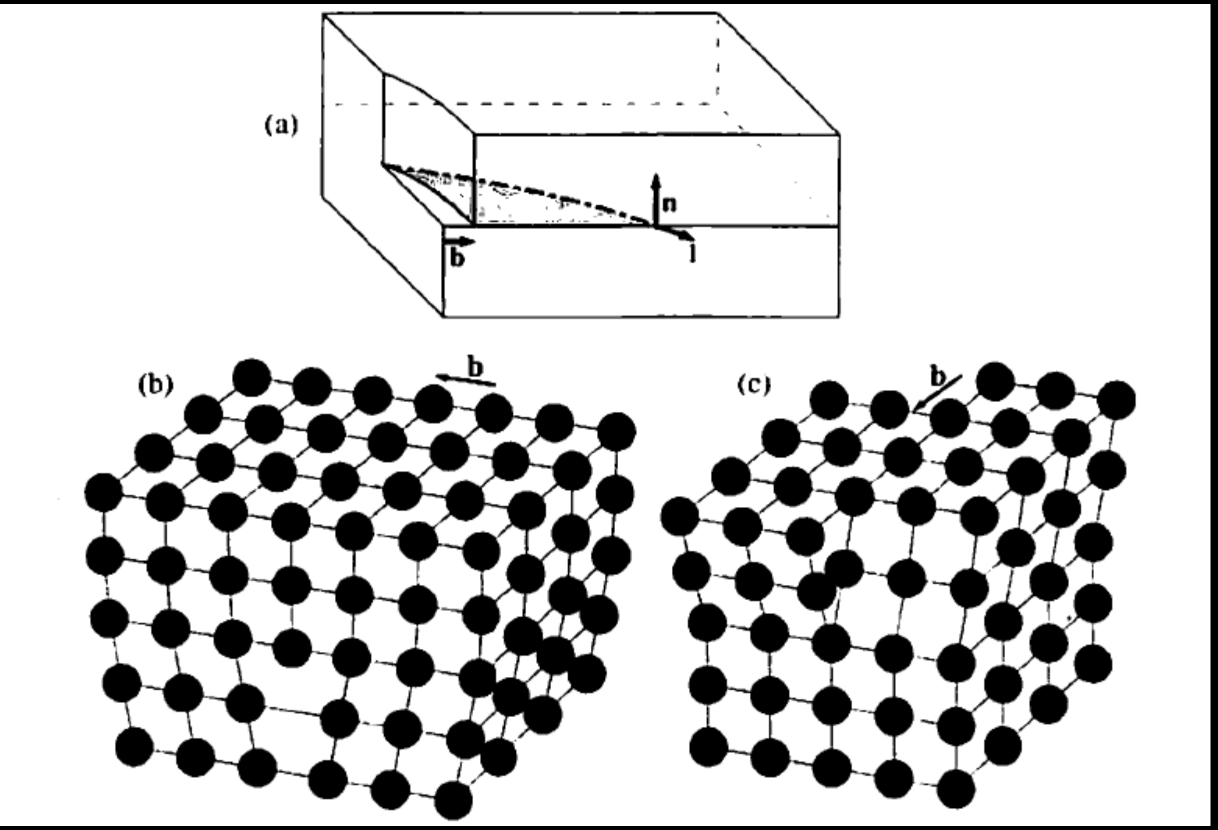
  - point defects - extra atoms or vacancies
  - line defects - dislocations which represent a rearrangement of atomic bonds
    - two types of dislocations: “edge” and “screw”
    - each described by parallel or normal Burgers vector (b*)
  - creep will occur through whichever mechanism requires least amount of energy

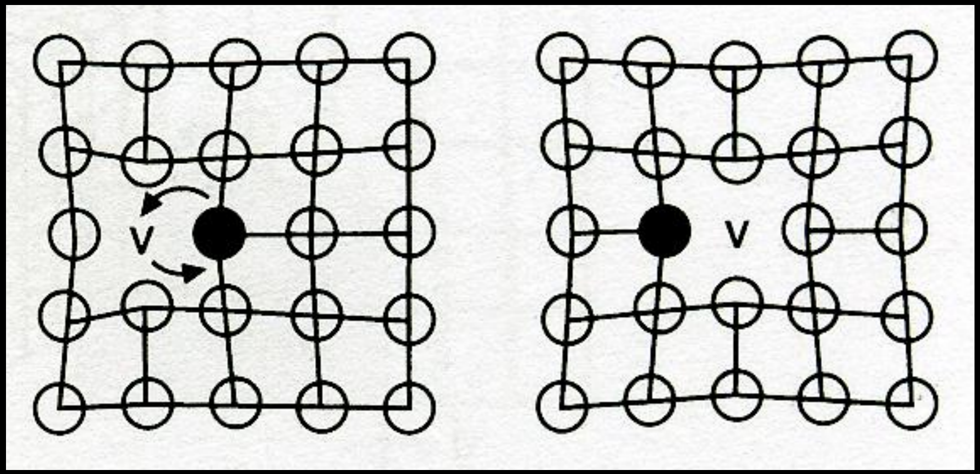




Diffusion creep

point defects move by *diffusion*

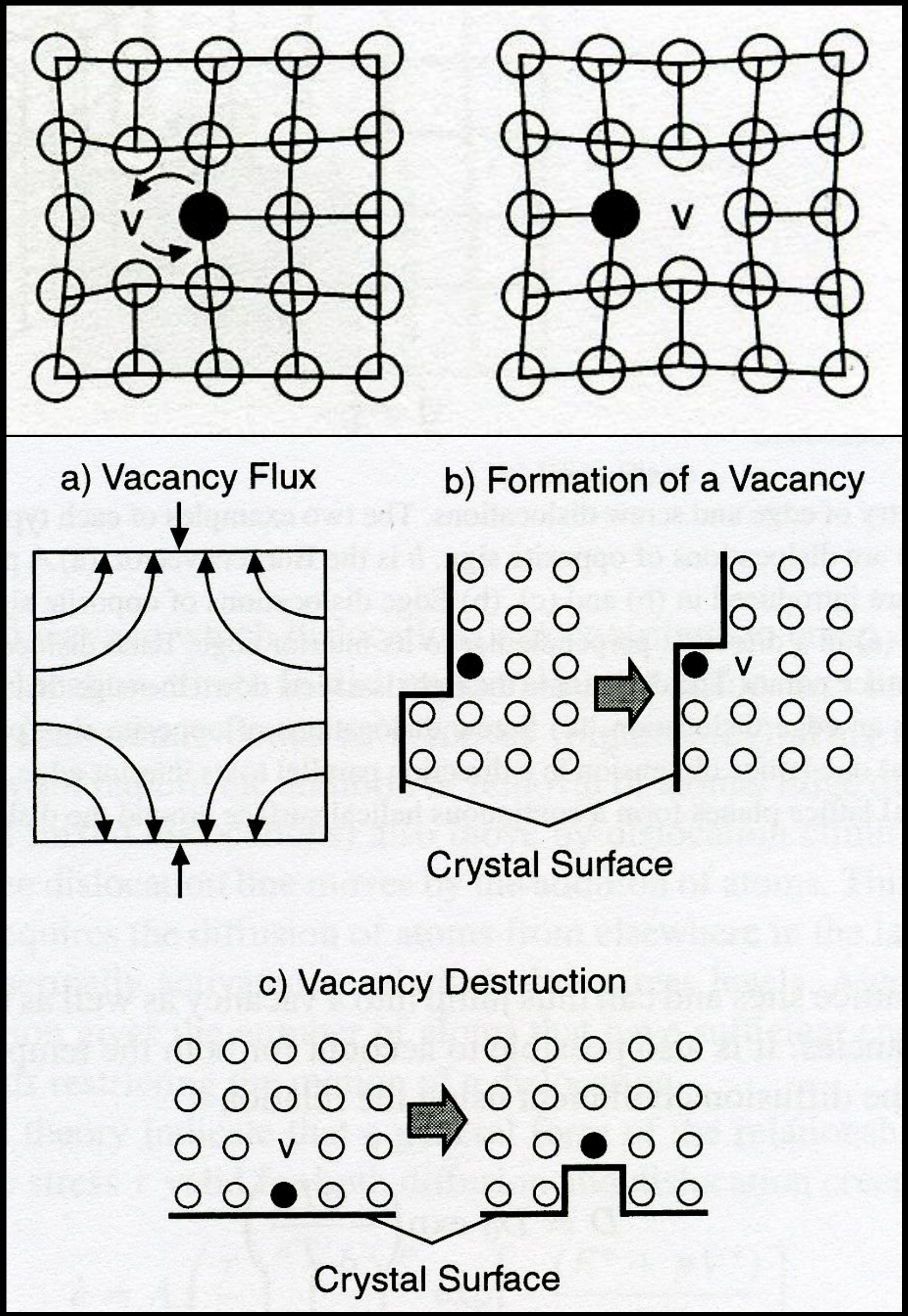
- **through the crystal matrix (Nabarro-Herring)**



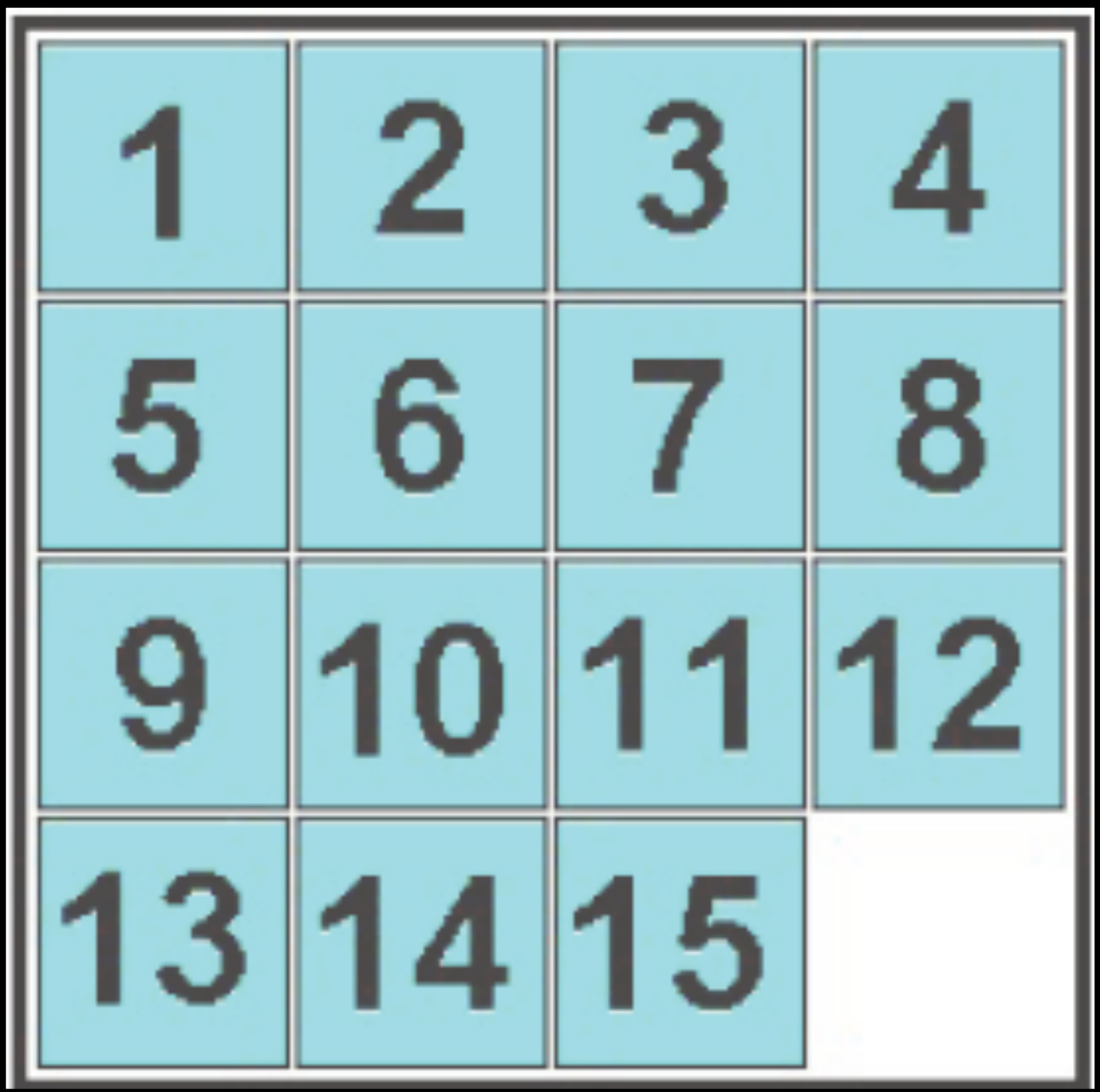
Diffusion creep

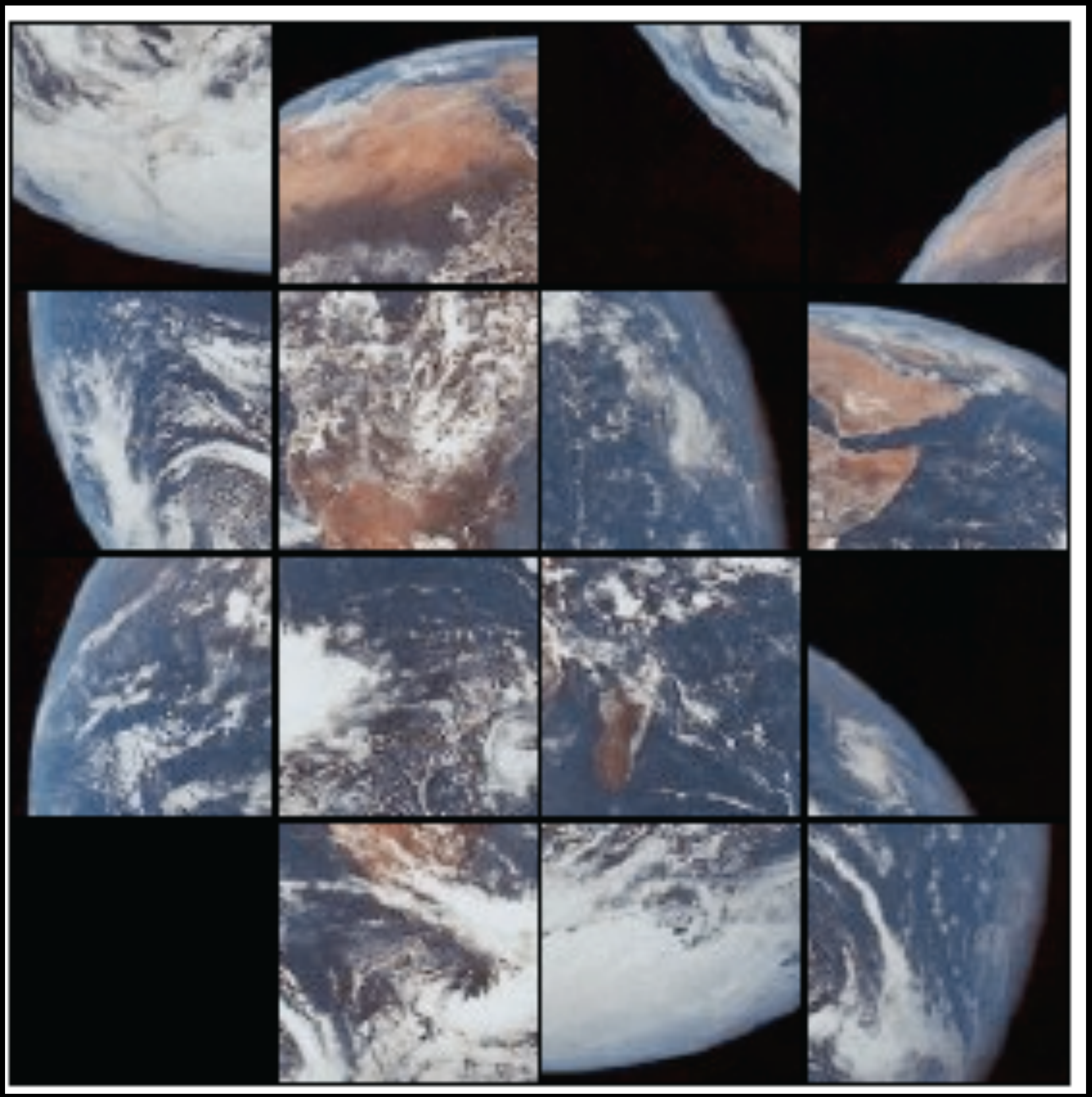
point defects move by *diffusion*

- **through the crystal matrix (Nabarro-Herring)**
- **along the grain boundaries (Coble)**



Diffusion creep

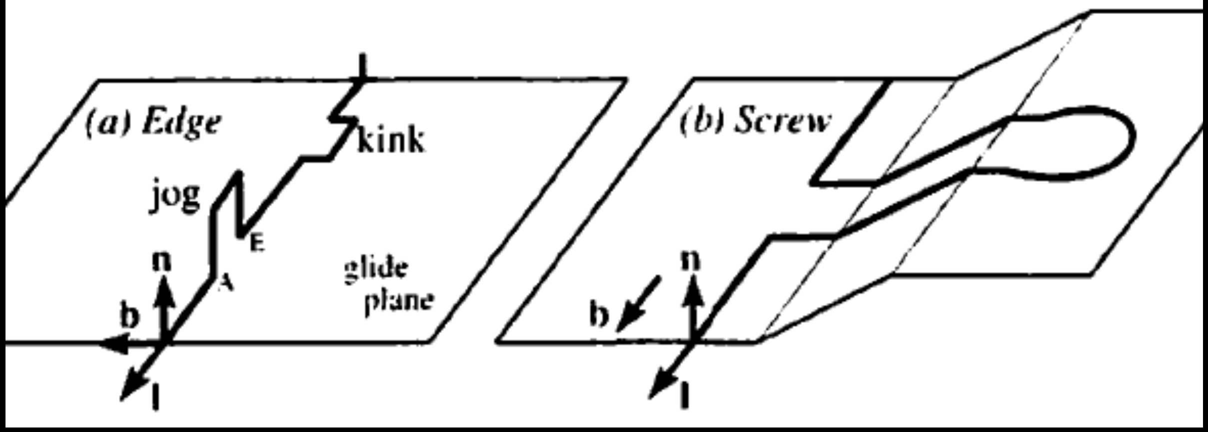




Dislocation creep

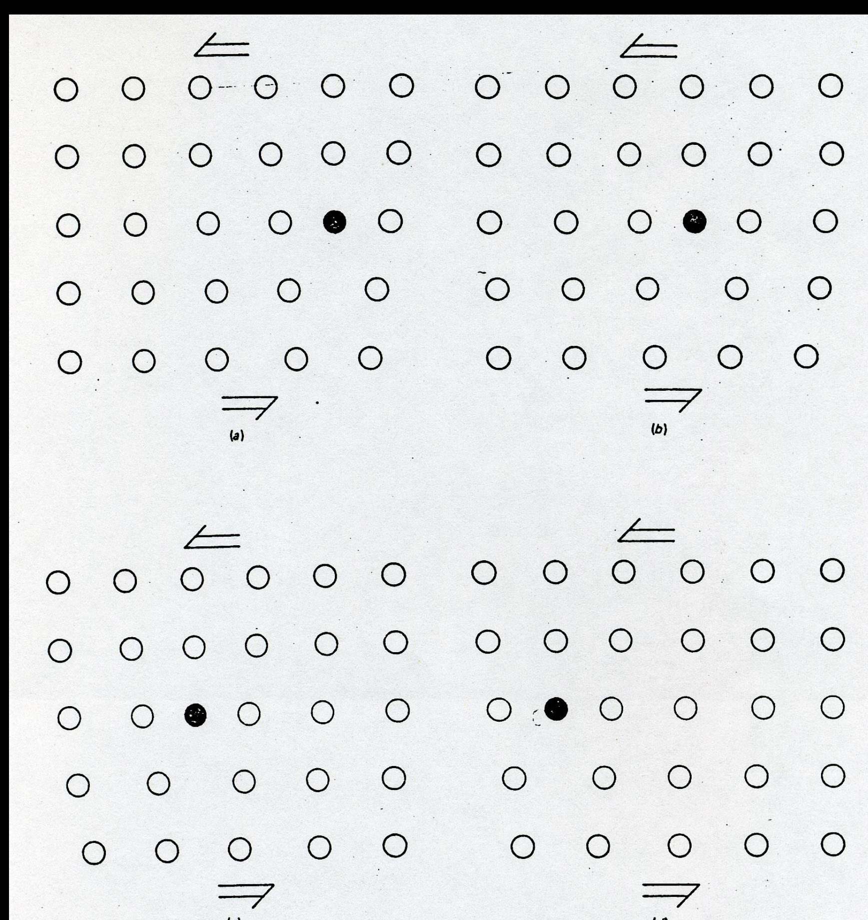
line defects move by *dislocation*

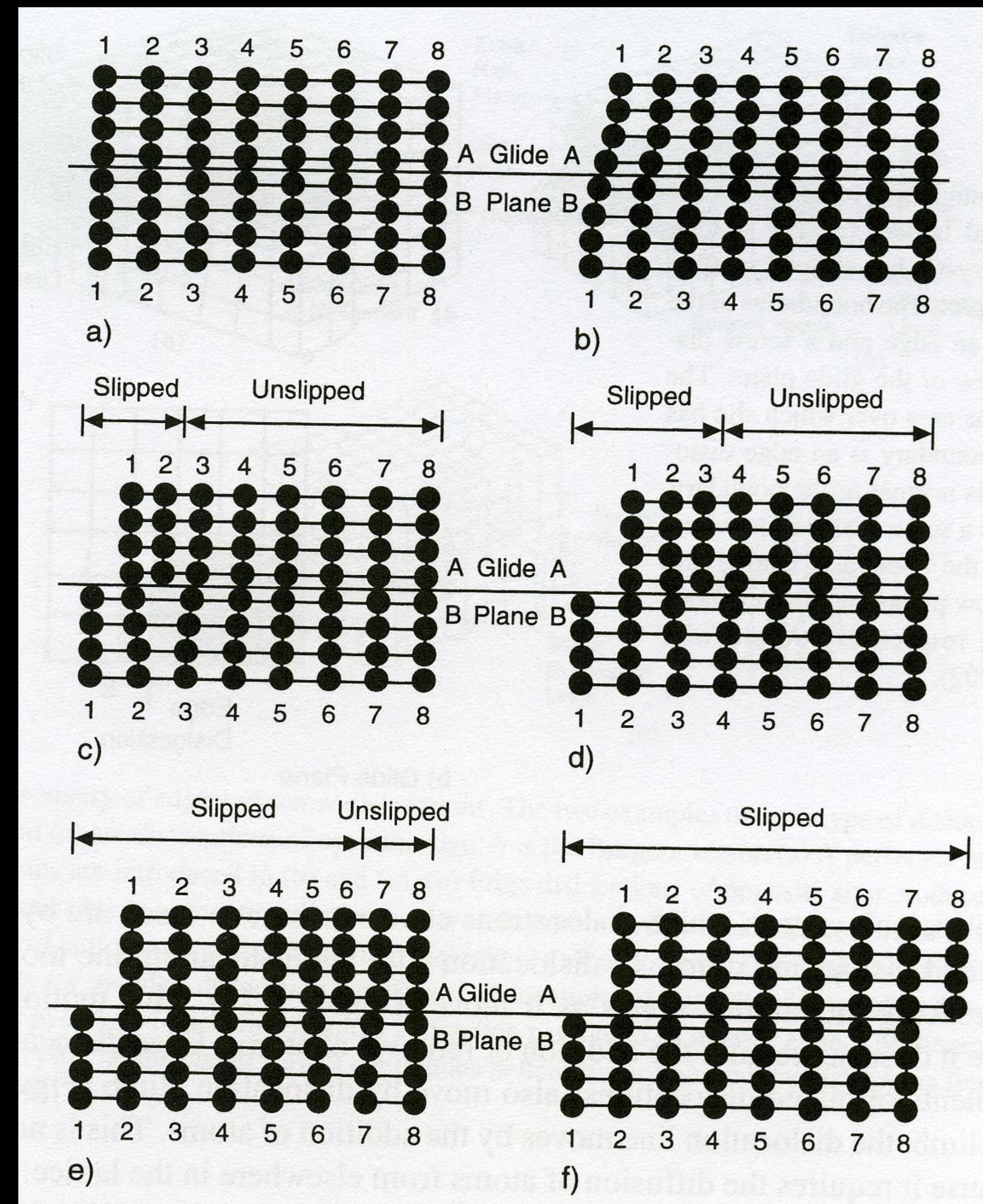
- **two types of dislocations: “edge” and “screw”**
- **any line defect can be represented by linear combination of the two (simply add Burgers vectors)**
- **line dislocations have two types of motion: glide and climb**
- **independent of grain-size (point of difference with diffusion creep)**



Glide process of dislocation creep

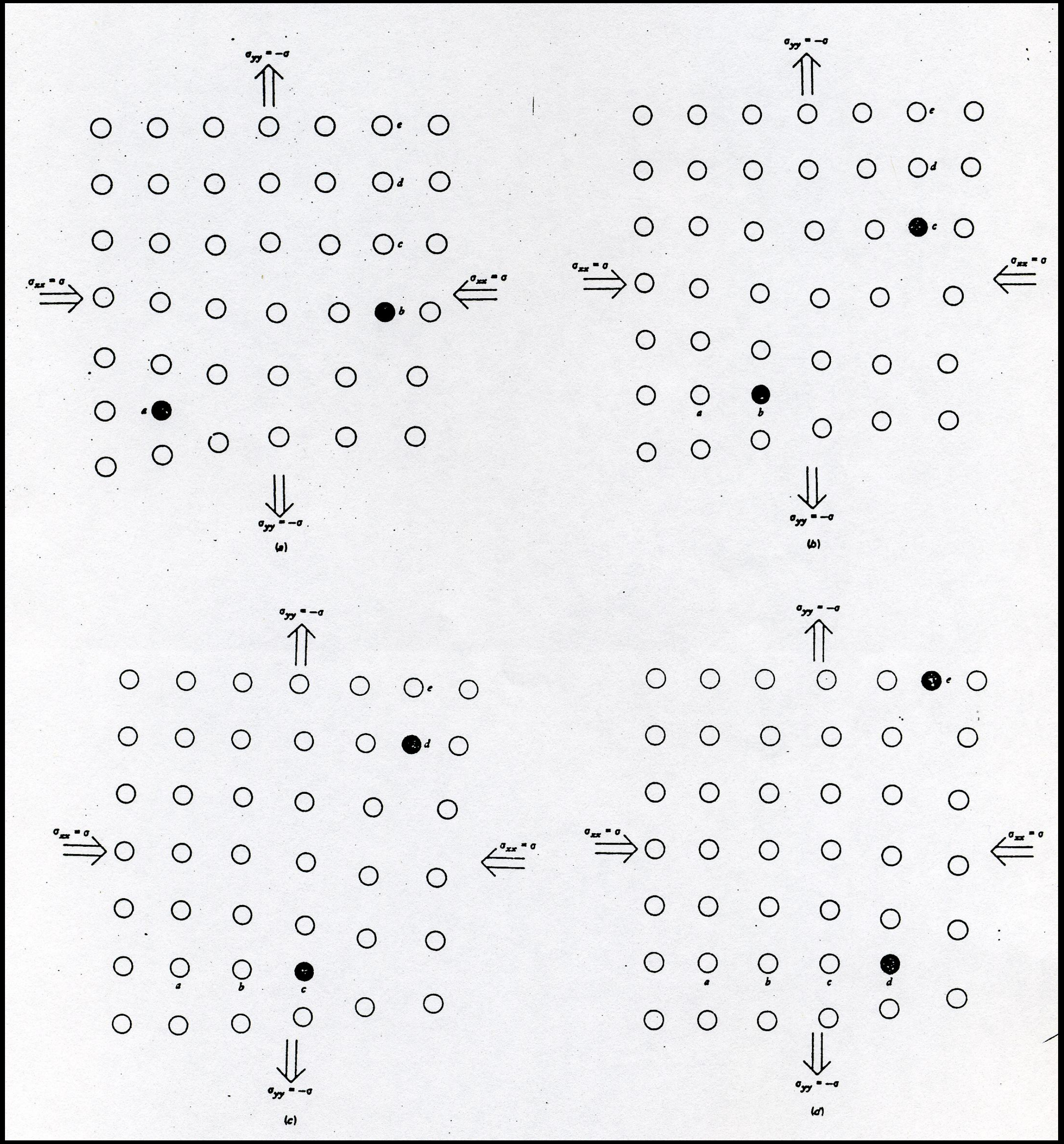
- **glide motion stays within glide plane**

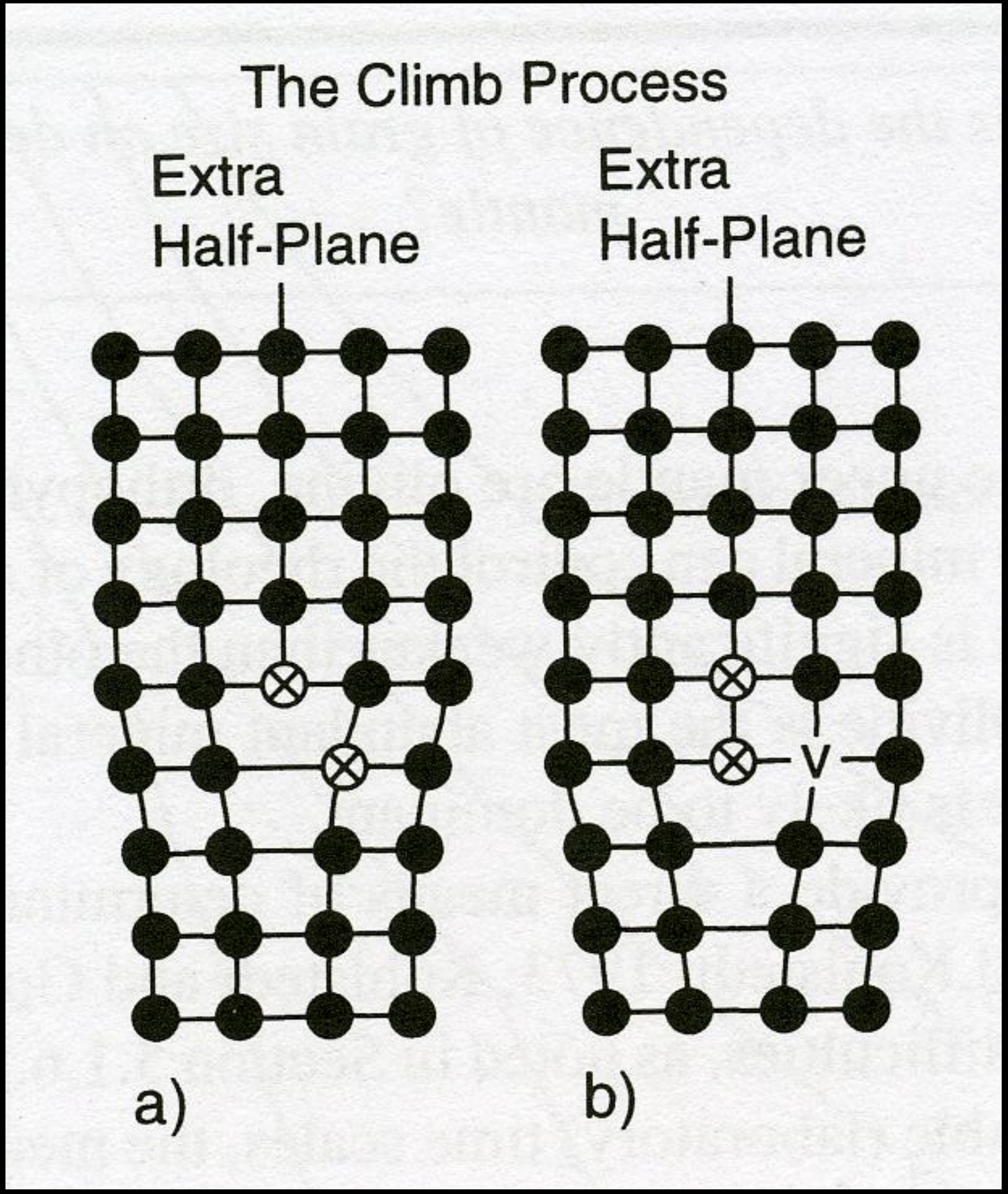




Climb process of dislocation creep

- **climb dislocation occurs outside the glide surface**



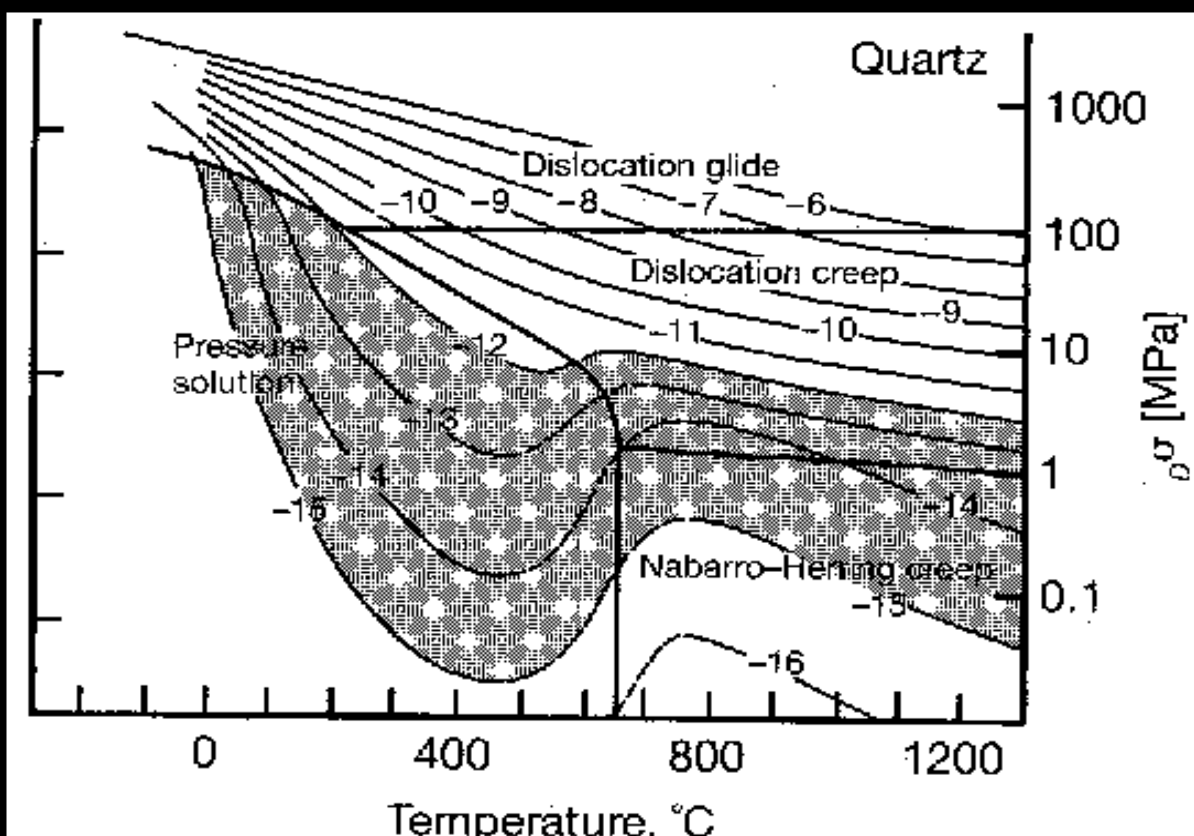


Deformation maps

- **for any given stress + temperature, one mechanism will be weaker (and preferred) over all others**

$$\dot{\varepsilon} = \dot{\varepsilon}_{disl} + \dot{\varepsilon}_{diff}$$

- **map assumes constant grain size**



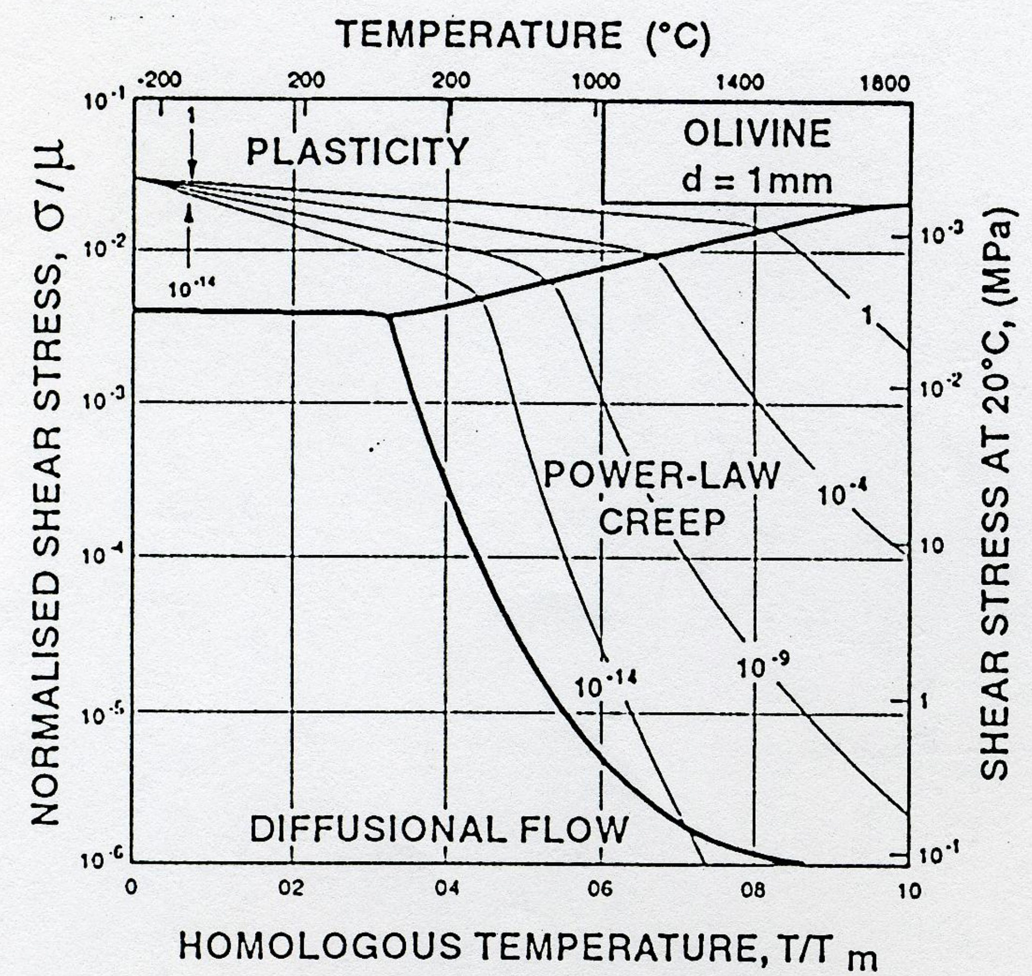
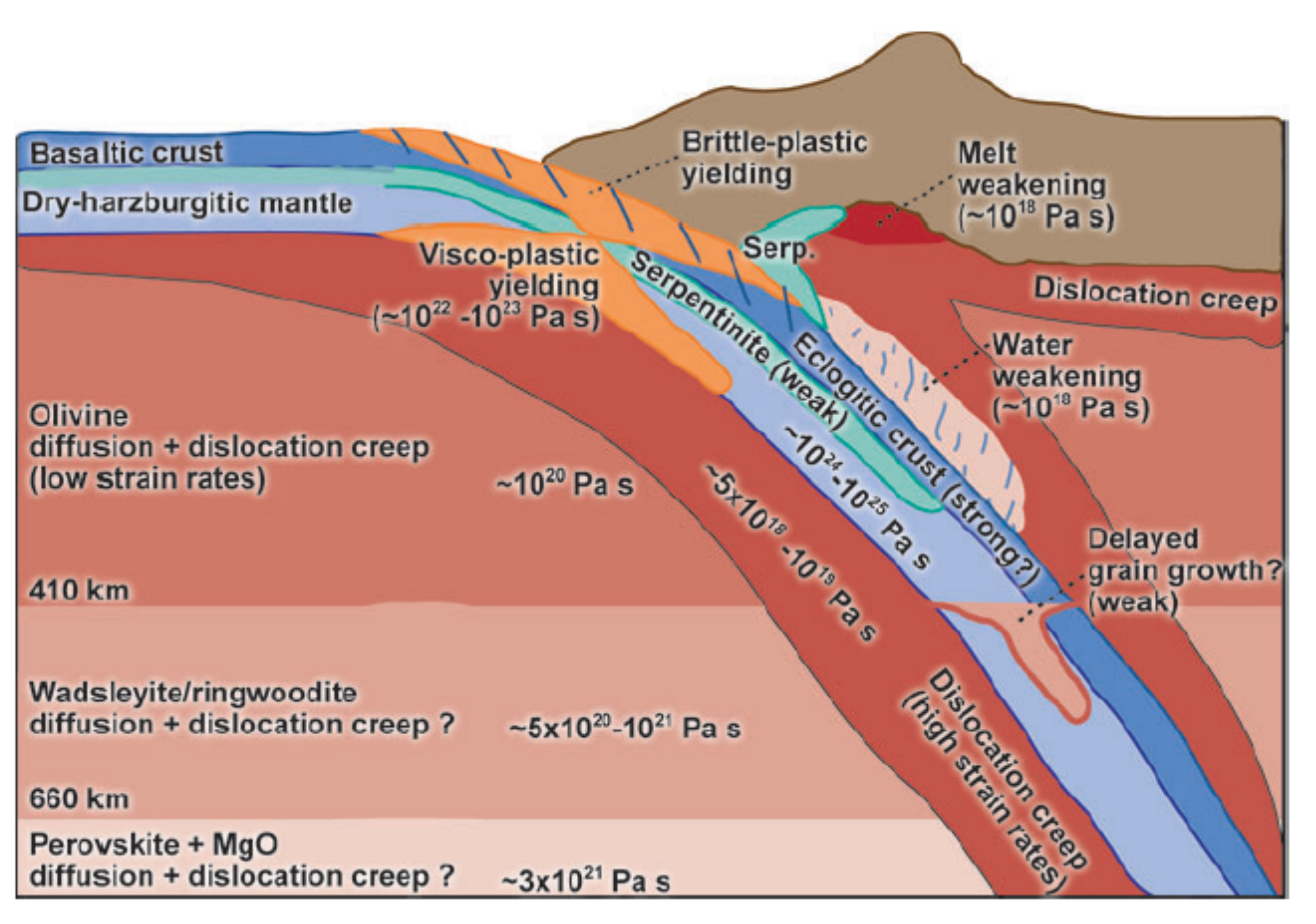


Fig. 3 Deformation mechanism map for olivine, with grain size 1 mm, showing iso-strain rate contours (after Frost and Ashby, 1982).

Creep mechanisms in the mantle



Billen, Annual Rev. Geophys., 2008

Flow rule

- **relates the deformation (strain rate) to the applied deviatoric stress through a viscosity**
- **deformations add in series (viscosities add in parallel)**

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

$$\dot{\varepsilon} = \frac{1}{\eta}\sigma$$

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_1 + \dot{\varepsilon}_2 + \ldots$$

$$\frac{1}{\eta_{eff}} = \frac{1}{\eta_1} + \frac{1}{\eta_2} + \ldots$$

Flow rule

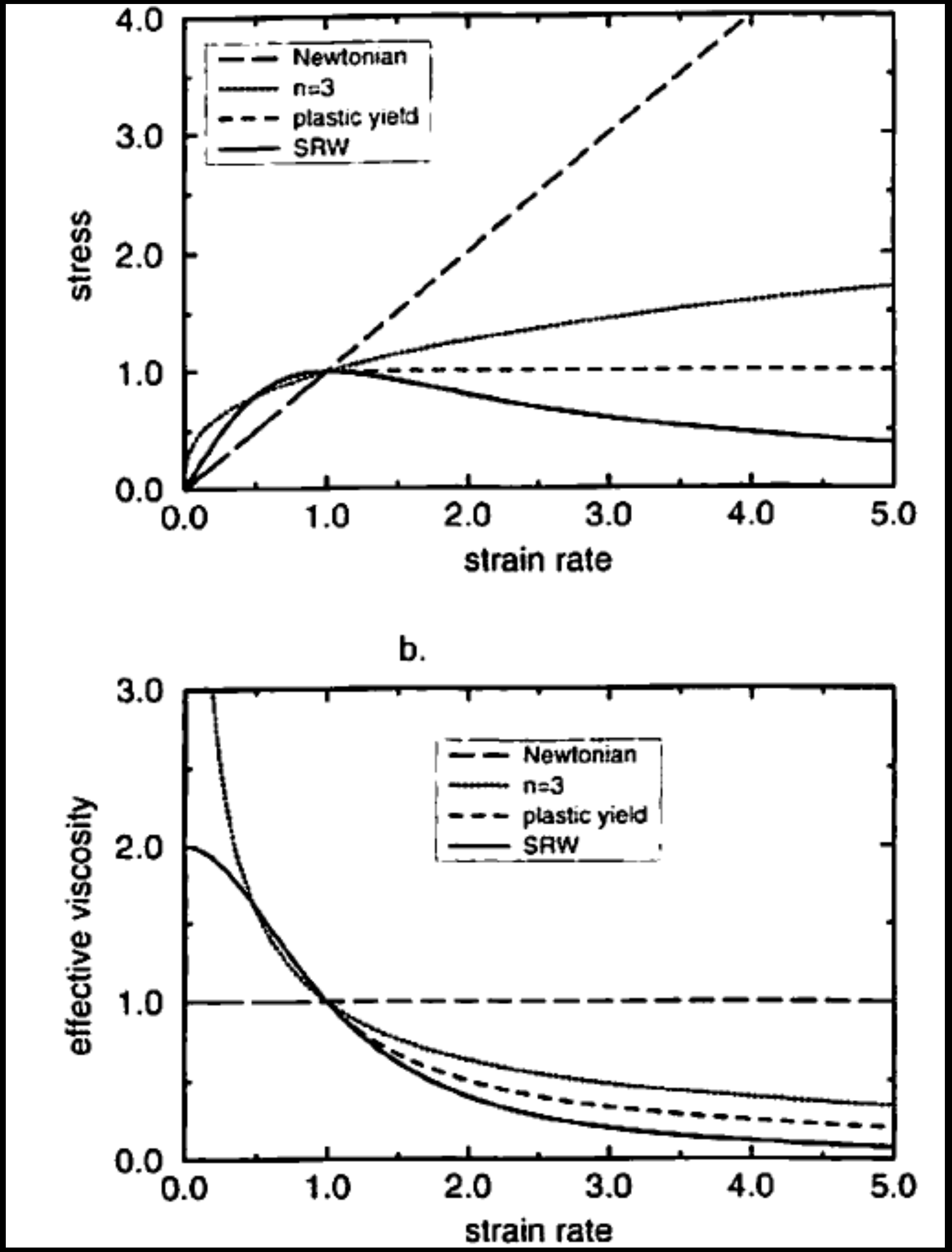
- for isotropic fluids, we can describe the flow rules with an effective strain rate, an effective stress, and an effective viscosity
- 2nd invariants of deviatoric stress and strain rates are scalars
- in practice, we know the strain-rates from the velocity field rather than stress, so viscosity is normally rewritten in terms of strain-rate

$$\sigma_{II} = \sqrt{\sigma : \sigma}$$
$$\dot{\varepsilon}_{II} = \sqrt{\dot{\varepsilon} : \dot{\varepsilon}}$$
$$\sigma_{II} = \eta_{eff}\dot{\varepsilon}_{II}$$

NOTE: contractions of these tensors usually have a 1/2 term times the sum of the squares of the components (when assuming co-axial compression / pure shear)

Rheology: land of jargon and confusion

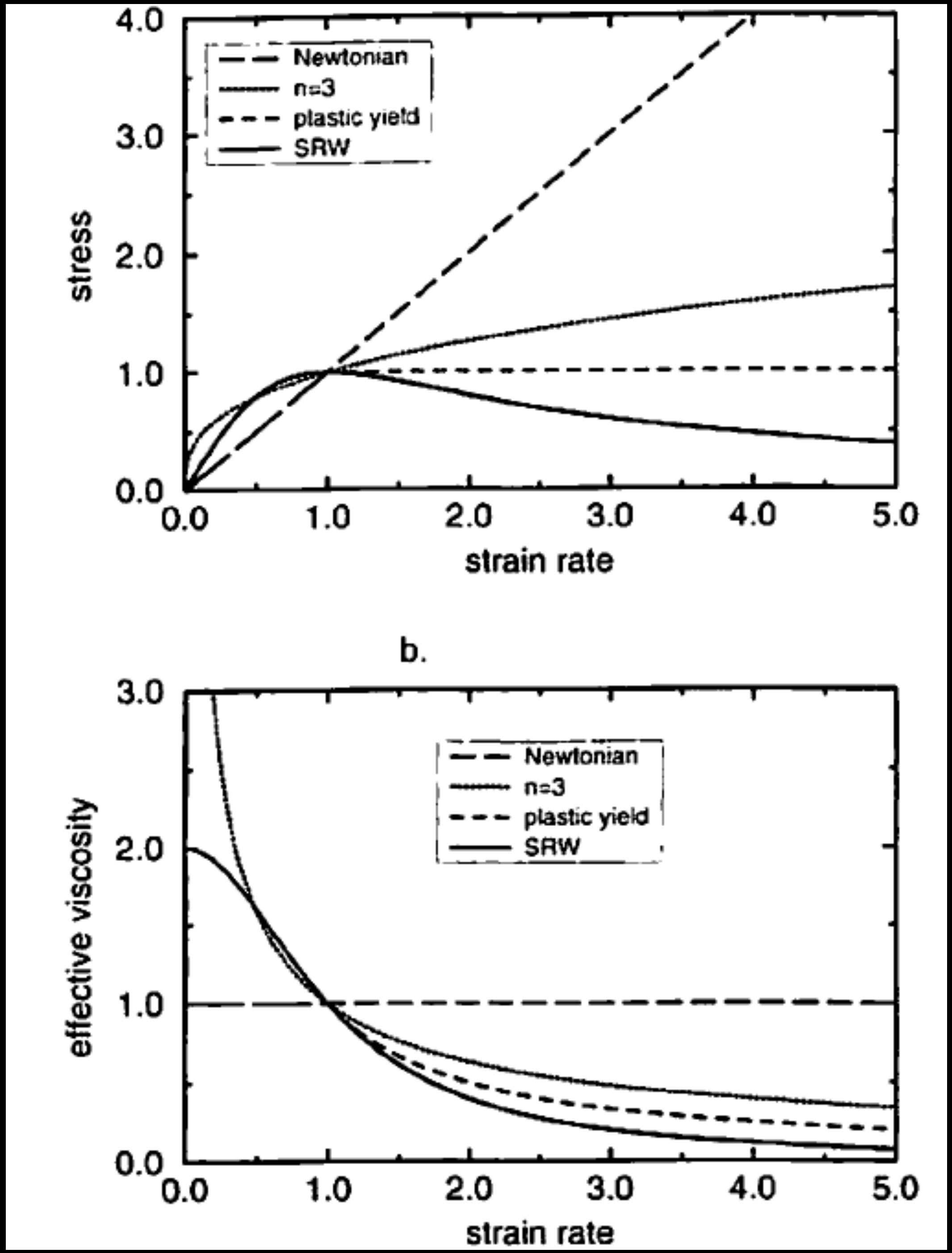
- *Newtonian* strictly means *linear* viscosity, but is commonly used to refer to *diffusion* creep with stress exponent (n=1)
- *Non-Newtonian* usually refers to *non-linear* rheology resulting from *dislocation* creep that is *stress dependent* through *power law* on stress with an exponent (n=3.5, or historically n=3)
- Example: diffusion creep is thermally activated and pressure dependent, and thus has exponential sensitivity to T,P but is sometimes referred to as "Newtonian" even though it is a non-linear f(T,P)



Tackley, 2000

Comparison of deformation processes

- any non-linear rheology can be represented by an effective linear rheology
- the effective viscosity is simply the slope of the line drawn from the origin to the stress-strainrate curve
- example of effective viscosity for several different rheologies that may be important for the mantle + plates
- think a little more about these curves stress vs. effort, efficiency vs. effort, and total productivity vs. effort



Tackley, 2000

Arrhenius dependence

- one can use thermodynamics to describe the sensitivity of diffusion when it is thermally activated

$$D = D_0 exp\left[-\frac{(E_A + P\,V_A)}{R\,T}\right]$$

- the diffusion of vacancies, etc has an exponential dependence on T,P
- this can also be understood in terms of the homologous temperature

$$D = D_0 exp\left[-g\frac{T_m\,(P)}{T}\right]$$

- the deformation resulting from the diffusion creep is the strain rate and is inversely proportional to viscosity

$$\dot{\varepsilon} = \frac{1}{\eta}\sigma$$

- the Arrhenius term describes the exponential behavior of viscosity

$$\eta(T,P) = \eta_0 exp\left[\frac{(E_A + P\,V_A)}{R\,T}\right]$$

- also valid for dislocation creep

General flow rule for mantle material

$$\dot{\varepsilon} = A\left(\frac{b^*}{d}\right)^m \left(\frac{\sigma}{\mu}\right)^n exp\left[-\frac{(E_A + PV_A)}{RT}\right]$$

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$$\dot{\varepsilon} = \frac{A}{\mu}\left(\frac{b^*}{d}\right)^m \sigma \left(\frac{\sigma}{\mu}\right)^{n-1} exp\left[-\frac{(E_A + P V_A)}{R T}\right]$$

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$$\frac{1}{\eta} = \frac{A}{\mu}\left(\frac{b^*}{d}\right)^m \left(\frac{\sigma}{\mu}\right)^{n-1} exp\left[-\frac{(E_A + P\,V_A)}{R\,T}\right]$$

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General flow rule for mantle material

$$\eta = \frac{\mu}{A}\left(\frac{d}{b^*}\right)^m \left(\frac{\mu}{\sigma}\right)^{n-1} exp\left[\frac{(E_A + PV_A)}{RT}\right]$$

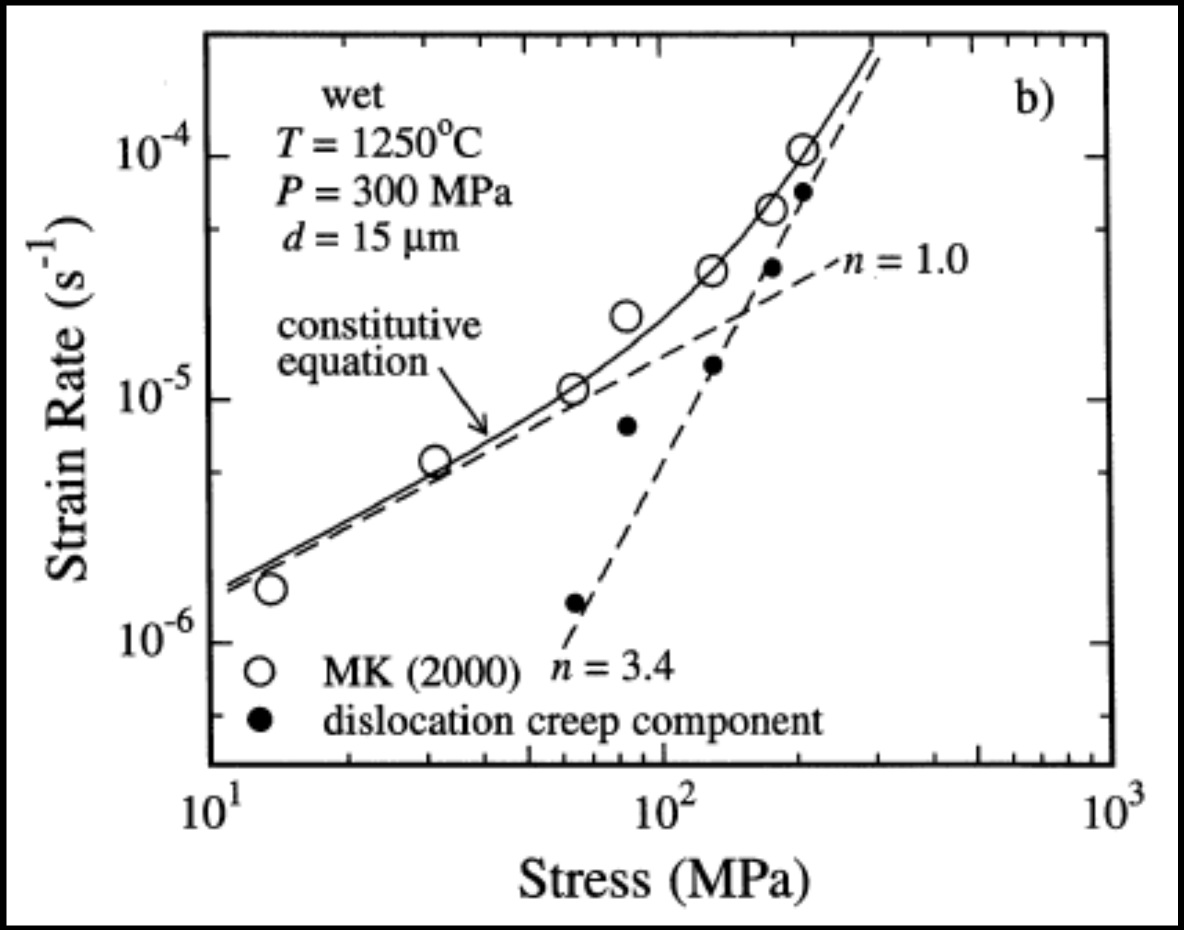
$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{diff} + \dot{\varepsilon}_{disl}$$

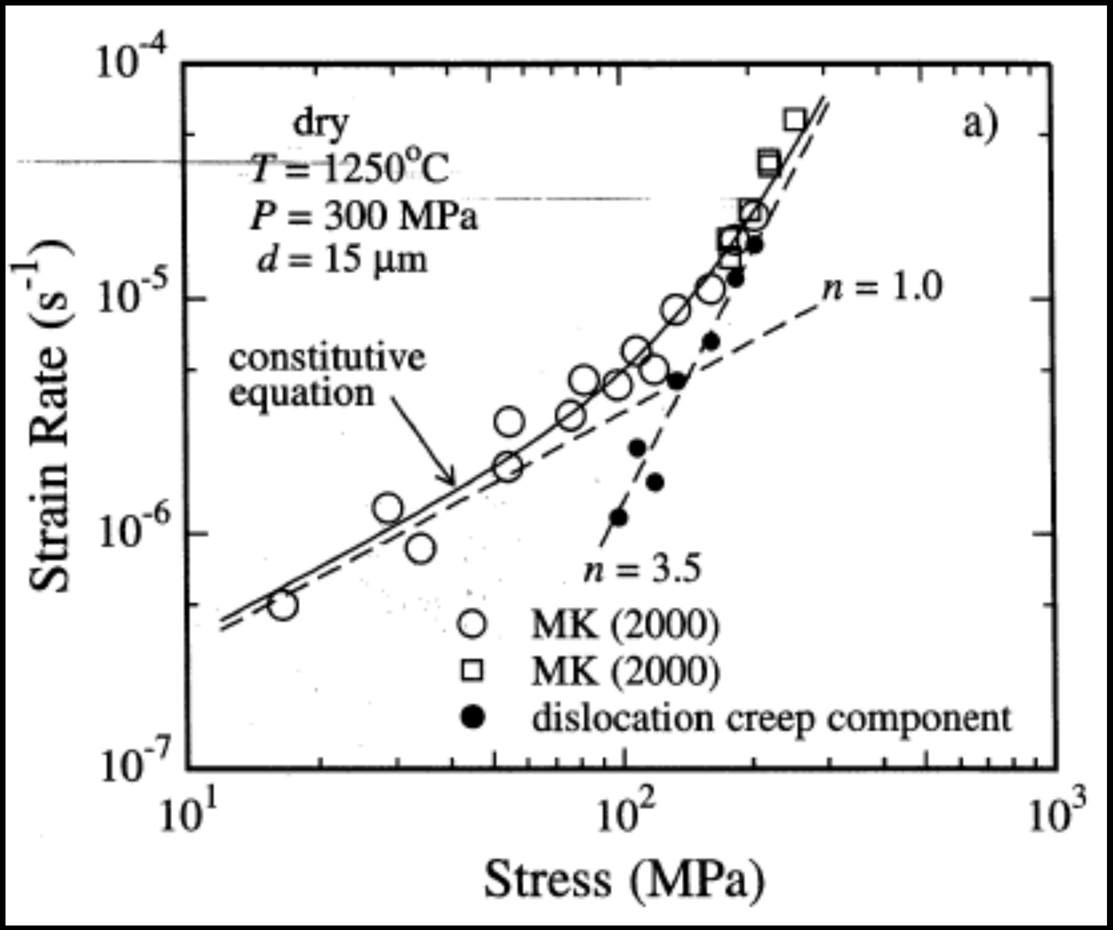
$$\frac{1}{\eta_{eff}} = \frac{1}{\eta_{diff}} + \frac{1}{\eta_{disl}}$$

- **note: diffusion and dislocation creep have different activation enthalpies**

What is “n” for dislocation creep?

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{diff} + \dot{\varepsilon}_{disl}$$

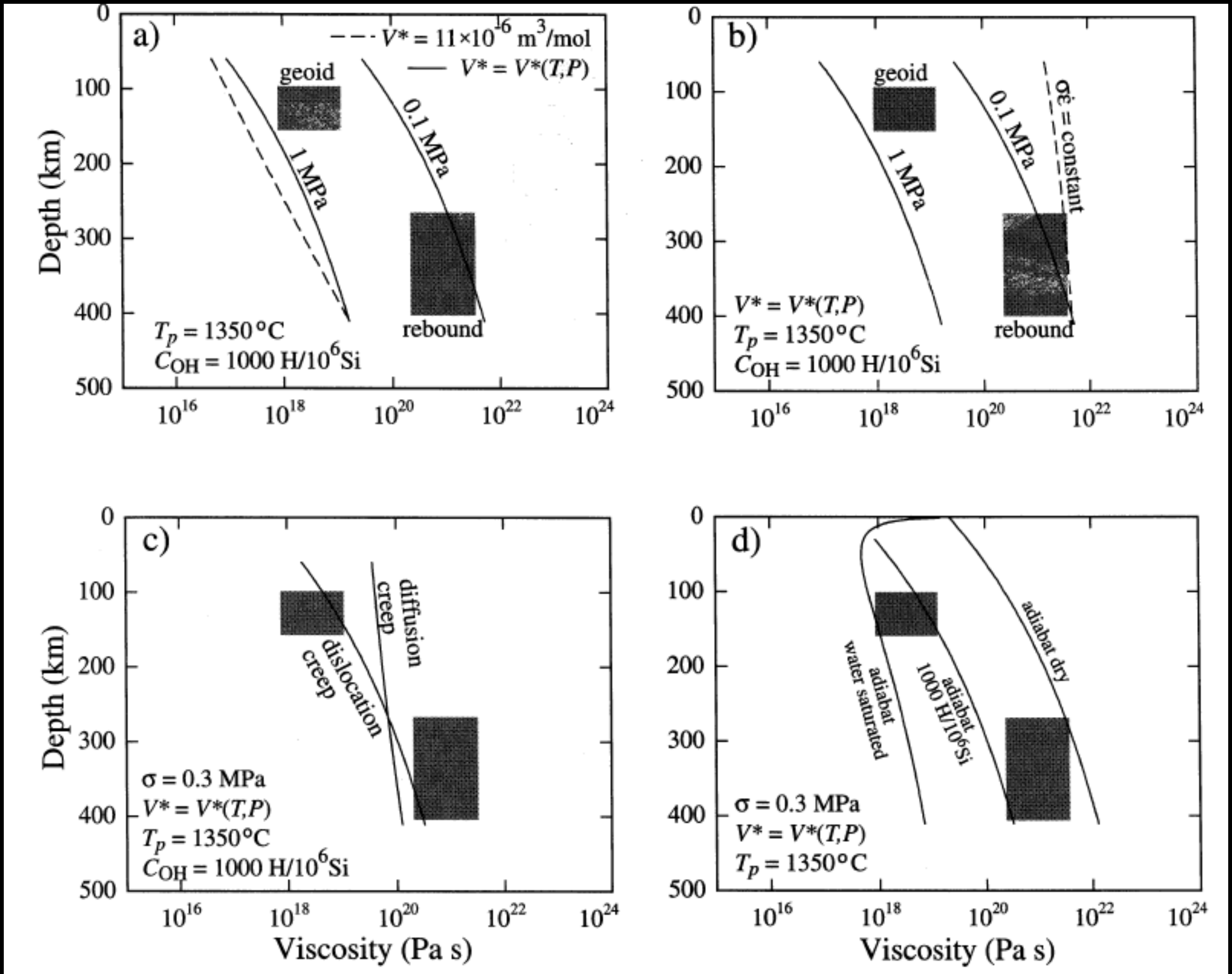




Hirth and Kohlstedt, 2003

- **note: different y-intercept corresponds to different activation enthalpies which is due to the influence of water**

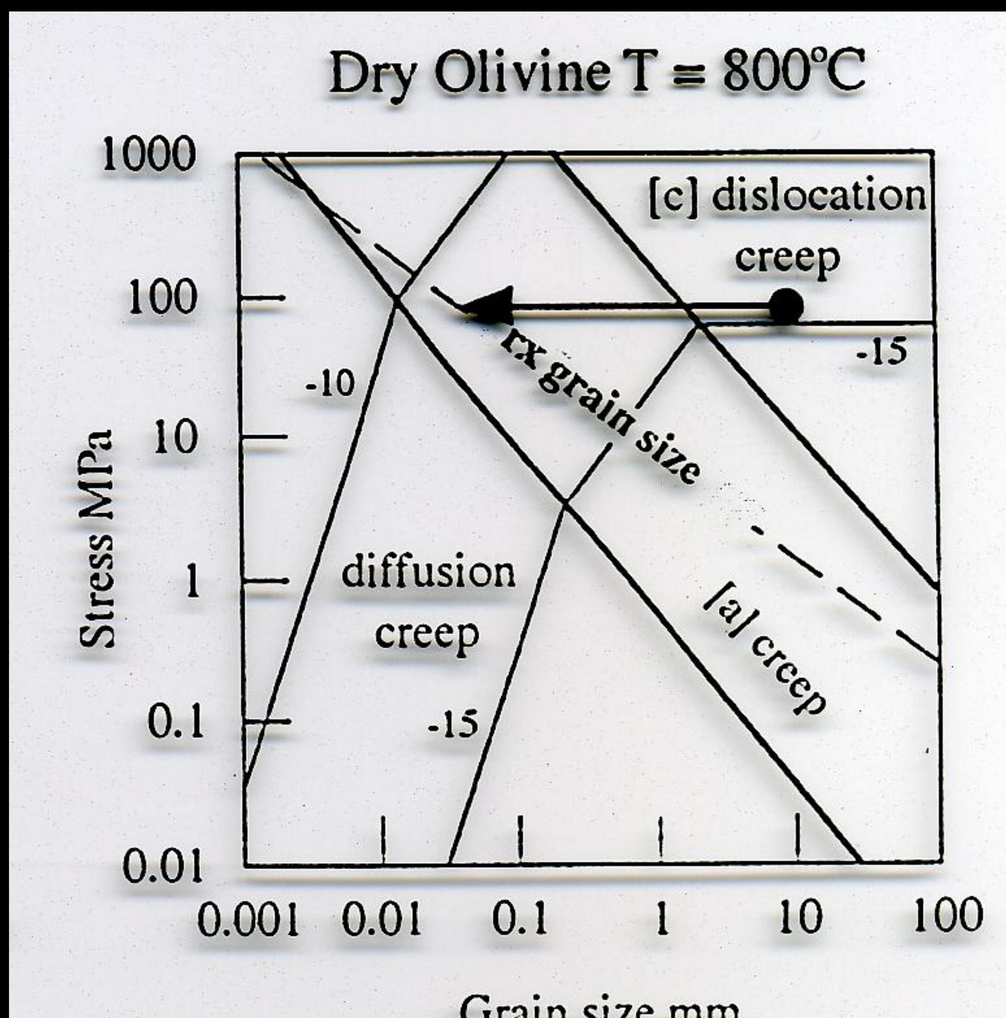
Extrapolating to mantle conditions

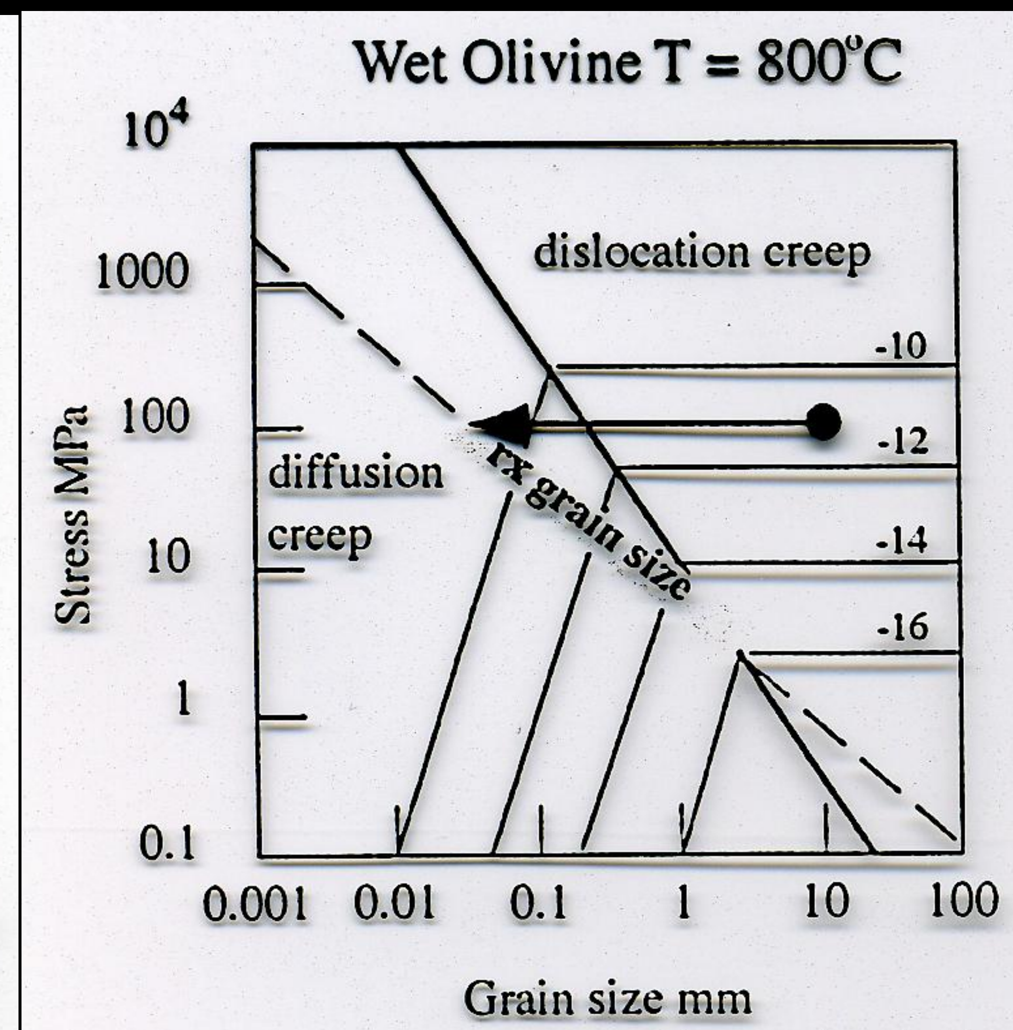


Hirth and Kohlstedt, 2003

Just add water...

- contour lines are strain rates in (1/s) - dislocation is horizontal because it is independent on grain size but diffusion creep shows grain size dependence
- much lower stresses required to achieve same strain rate when water is present (note different y-axis) which translates into lower activation enthalpy





Just add water...

- contour lines are strain rates in (1/s) - dislocation is horizontal because it is independent on grain size but diffusion creep shows grain size dependence
- much lower stresses required to achieve same strain rate when water is present (note different y-axis)
- translates into lower activation energy and volume (E* and V*)

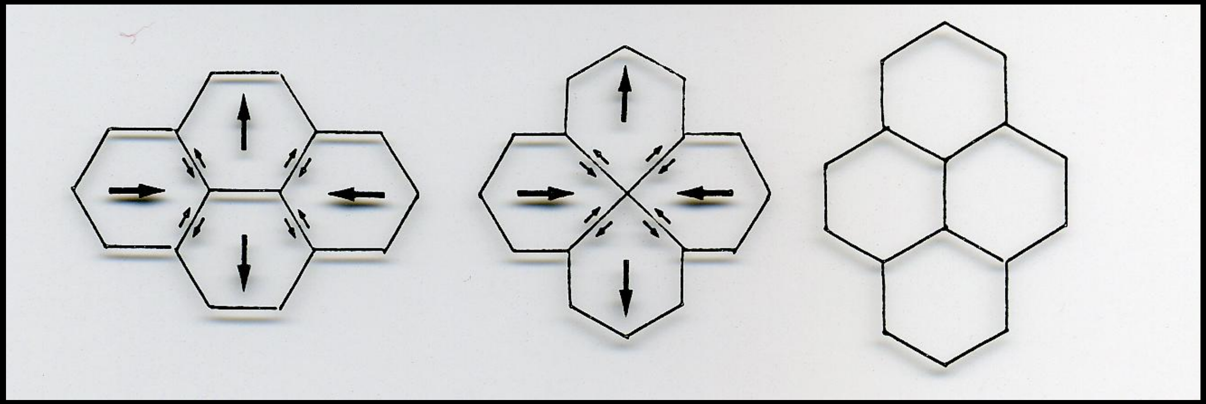
$$\dot{\varepsilon}(C_{OH}) = A\left(\frac{b^*}{d}\right)^m \left(\frac{\sigma}{\mu}\right)^n exp\left[-\frac{(E_A^* + P\,V_A^*)}{R\,T}\right]$$

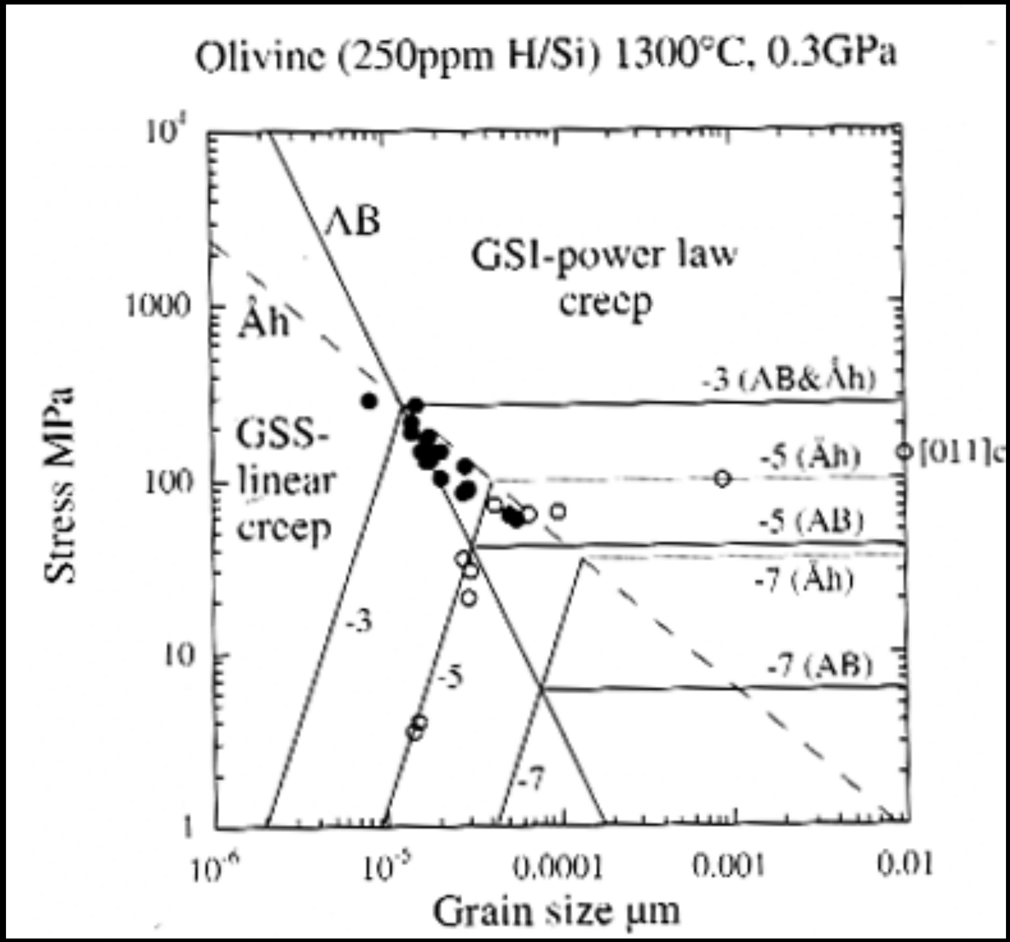
Grain size sensitive creep

- **GSS creep relies on combination of mechanisms: grain boundary sliding (GBS) and basal slip along the easiest slip system (easy)**

$$\dot{\varepsilon} = \dot{\varepsilon}_{disl} + \dot{\varepsilon}_{diff} + [1/\dot{\varepsilon}_{gbs} + 1/\dot{\varepsilon}_{easy}]^{-1}$$

- **GSS operates at small grain size only relevant to diffusion creep**
- **accommodates large amounts of strain without deforming crystals (referred to as superplasticity)**
- **GSS important process in lower mantle with small grain size (Karato et al., Science, 1995) through extrapolation to high P, low strainrate**

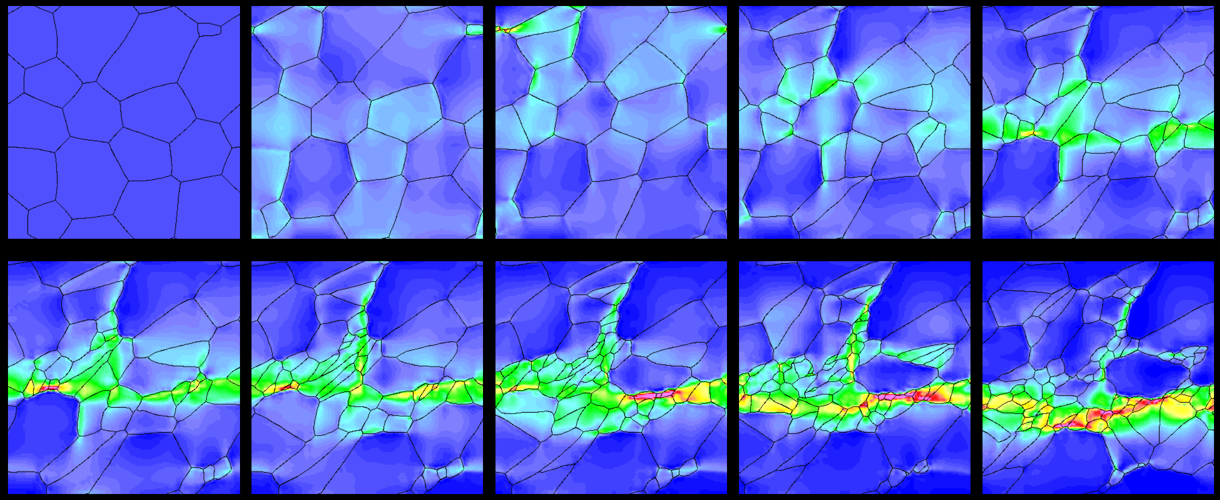


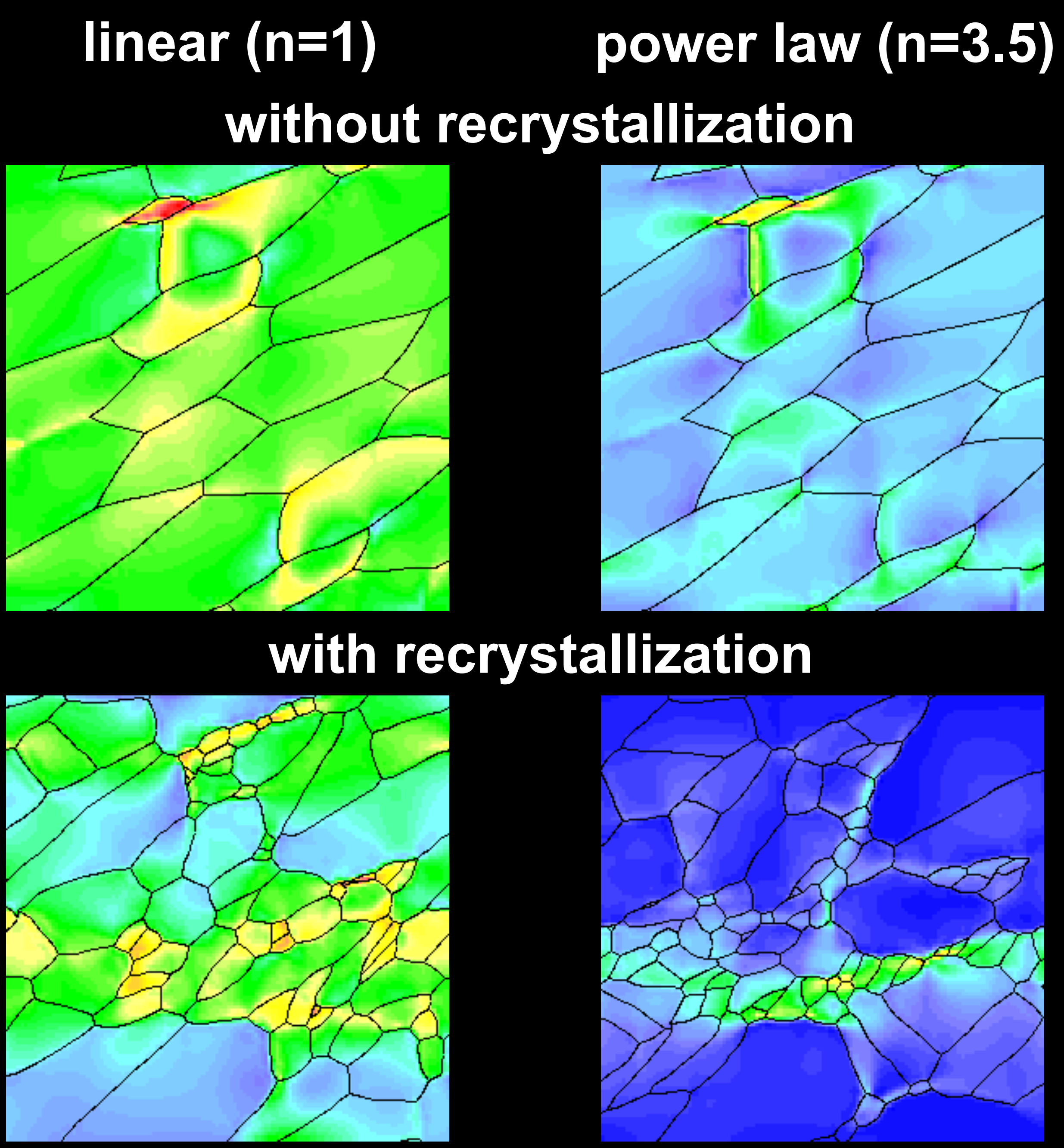


Drury, 2005

Recrystallization

- dynamic process changing the distribution of grain sizes
- grain size reduction (large grains fracture) and growth (small grains fuse together)
- microstructure important feedback with dislocation creep
- time-dependent process

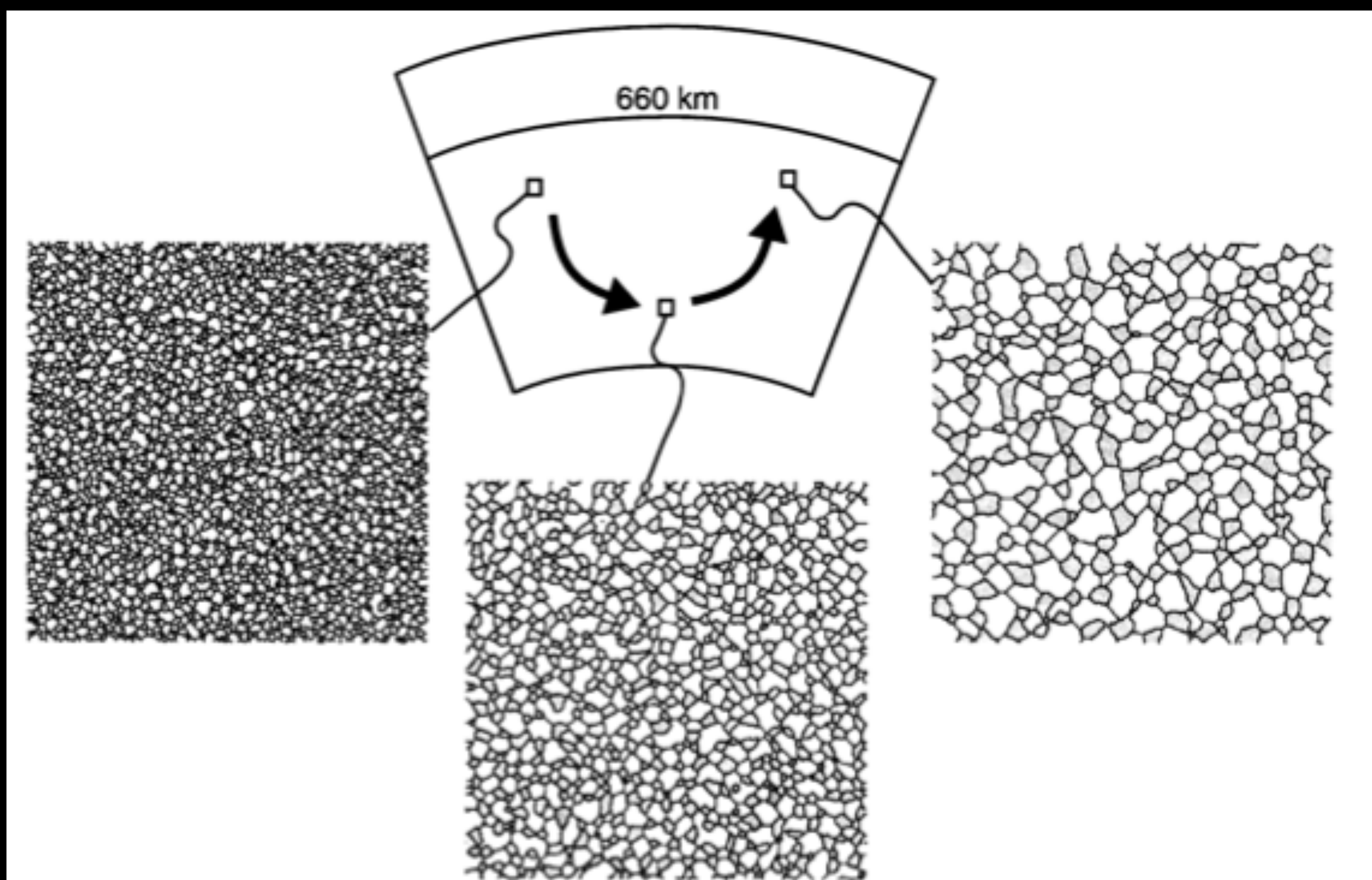


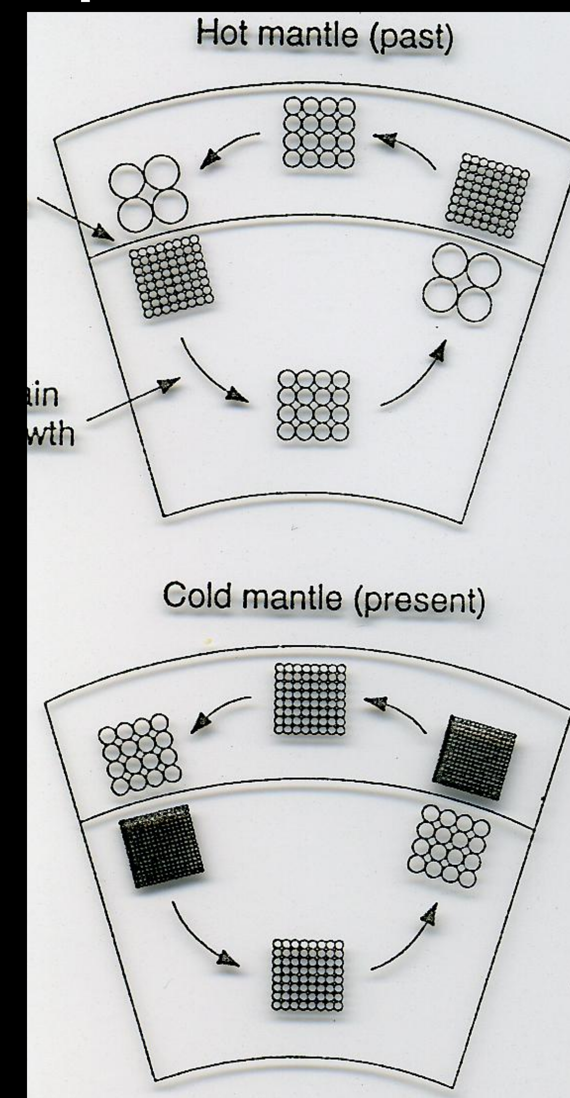


Jessell et al, EPSL, 2005

Grain growth in the lower mantle

- recrystallization for material going down through 660 phase change
- diffusion creep likely dominant mechanism for lower mantle but if the grain size is sufficiently small, then superplasticity could be important mechanism





Solomatov, EPSL, 2001

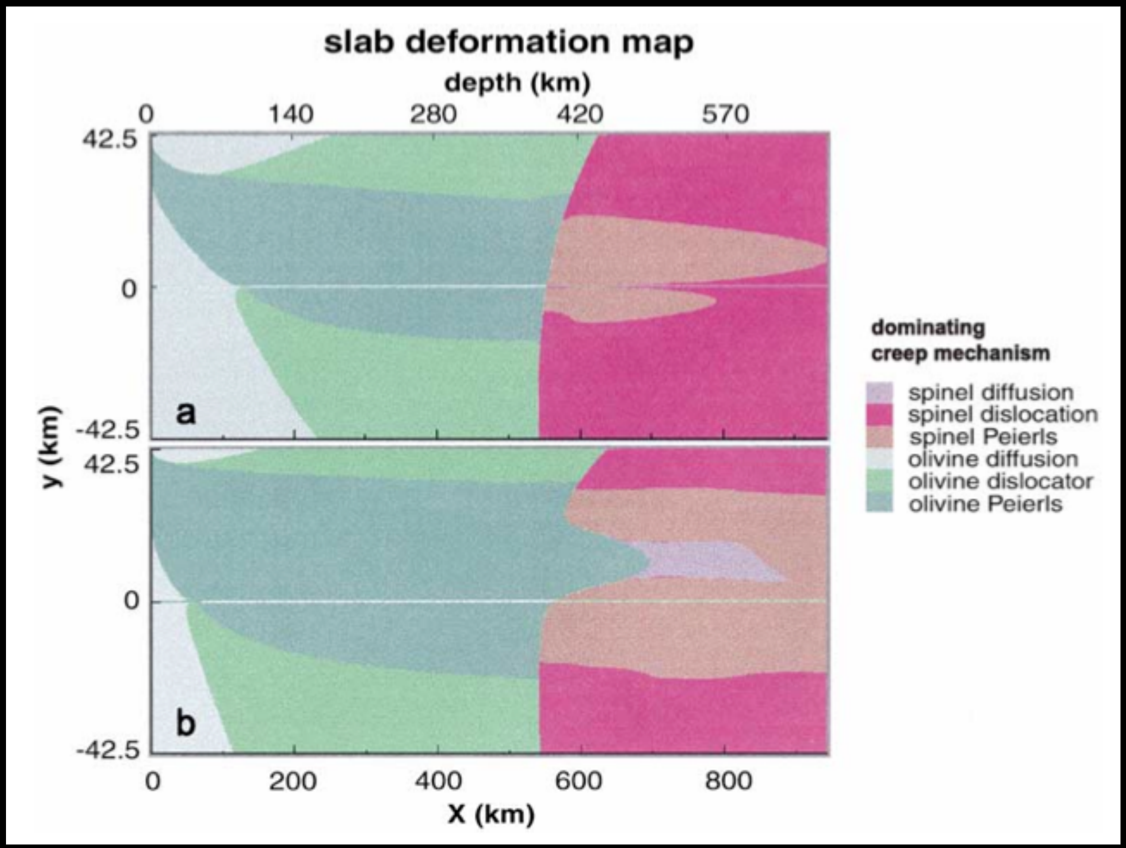
Harper-Dorn creep

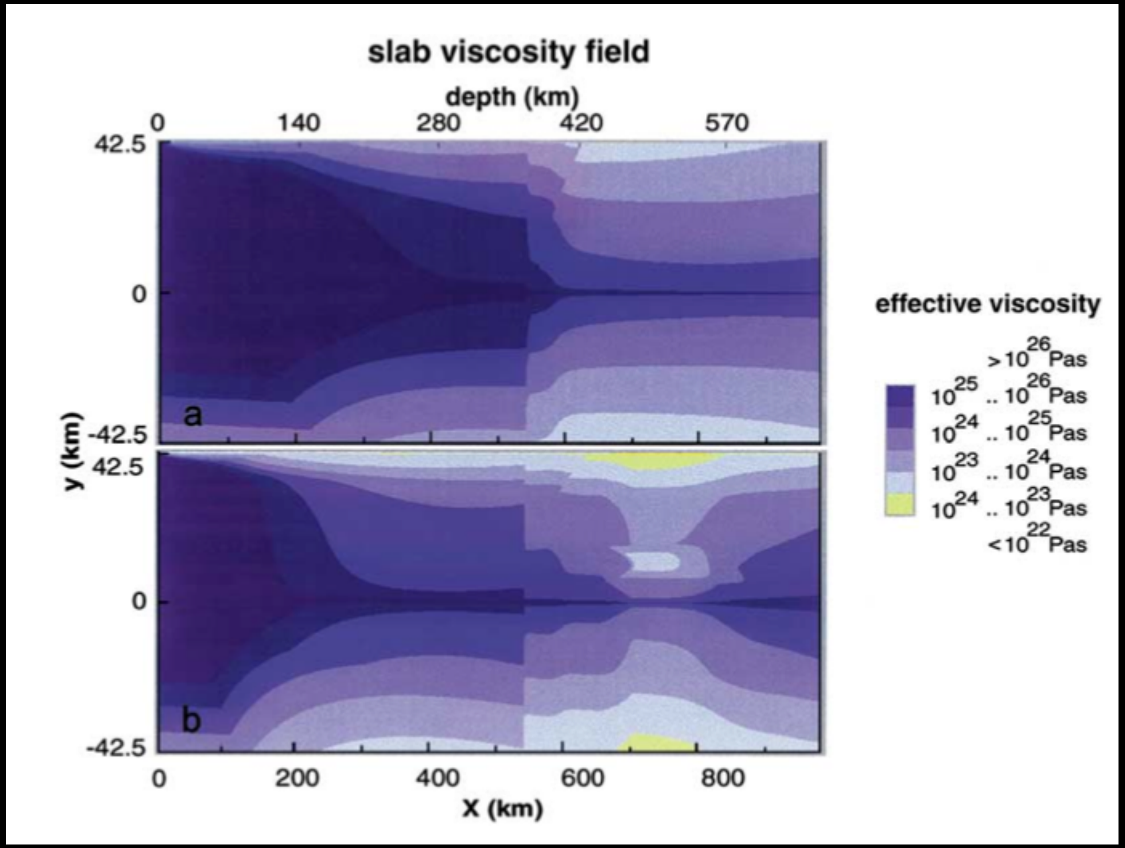
- **low-temperature plasticity OR Peierls stress mechanism***

$$\dot{\varepsilon} = A\left(\frac{b^*}{d}\right)^m \left(\frac{\sigma}{\mu}\right)^n exp\left[-\frac{(E_A + P\,V_A)}{R\,T}\left(1 - \frac{\sigma}{\sigma_p}\right)^q\right]$$

***read about Peierls other contributions to science here: https://en.wikipedia.org/wiki/Rudolf_Peierls**

- **applicable to the interior of a subducted slab (below: 4 cm/yr and 10 cm/yr)**





Karato et al, PEPI, 2001

Generalized flow rule for a slab

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{diff} + \dot{\varepsilon}_{disl} + \dot{\varepsilon}_{H-D}$$

$$\frac{1}{\eta_{eff}} = \frac{1}{\eta_{diff}} + \frac{1}{\eta_{disl}} + \frac{1}{\eta_{H-D}}$$

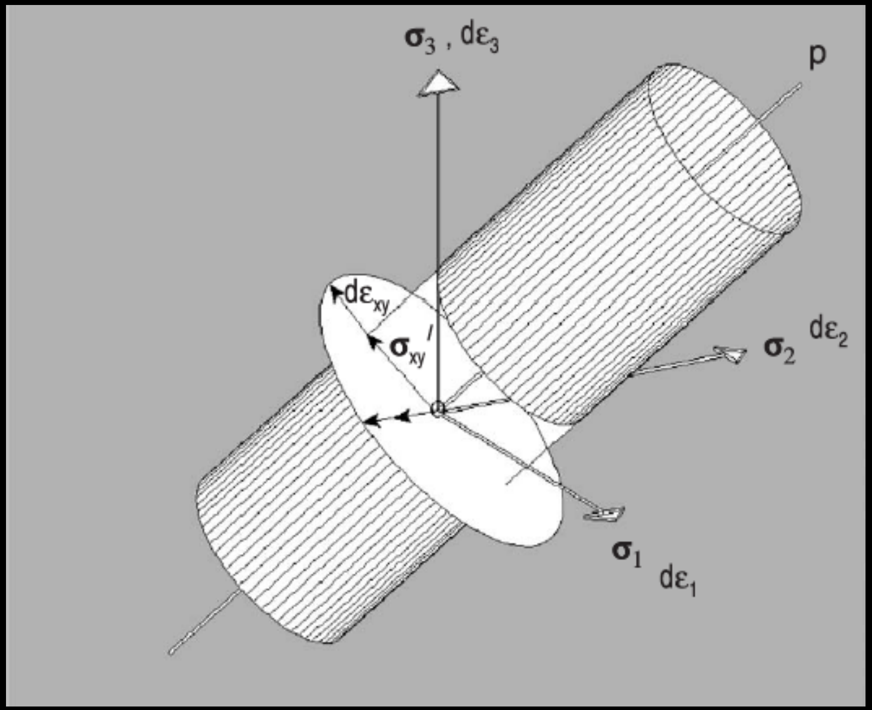
- **diffusion, dislocation, Harper-Dorn creep mechanisms work independently, so in general, only a single power-law (m,n,q) is in effect at any given time**
- **usual values for exponents (m,n,q) are (2.5,1,0) + (0,3.5,0) + (0,2,2)**
- **each mechanism has a different value for A; E and V depend on water content**

$$\dot{\varepsilon} = A\left(\frac{b^*}{d}\right)^m \left(\frac{\sigma}{\mu}\right)^n exp\left[-\frac{(E_A + P\,V_A)}{R\,T}\left(1 - \frac{\sigma}{\sigma_p}\right)^q\right]$$

Viscoplasticity

- **most materials have finite strength described by limiting stress and materials cannot support stresses in excess of their yield stress**

- **upon reaching their yield stress they deform through plastic flow (a solid beam starts to act like toothpaste)**



von Mises yield envelope

Viscoplasticity

- **most materials have finite strength described by limiting stress and materials cannot support stresses in excess of their yield stress**
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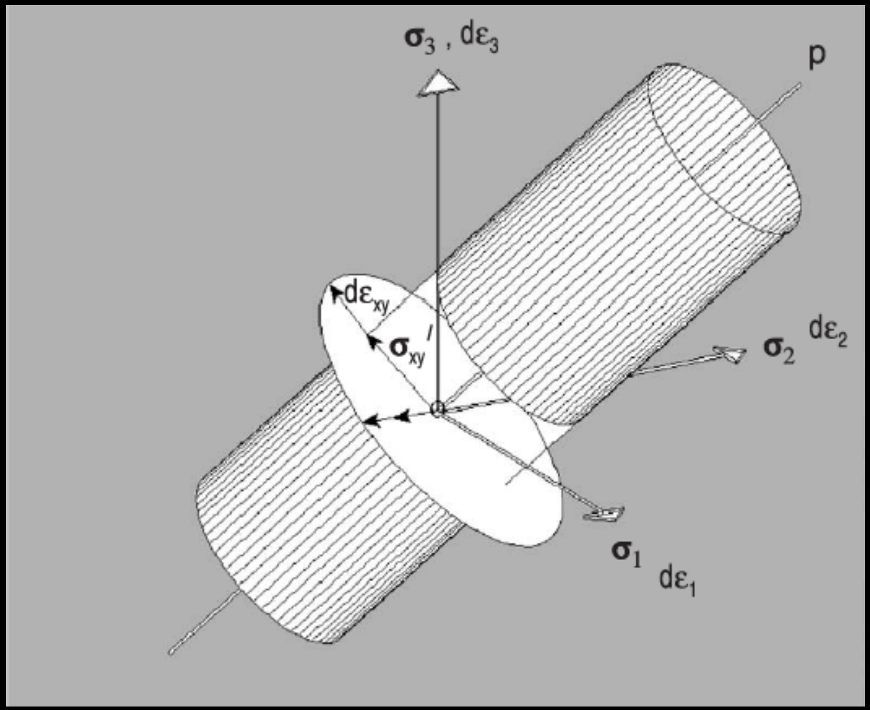
- **actually, care must be taken to guarantee one is actually on the yield surface and remains on it (i.e. use harmonic avg at your own risk)**

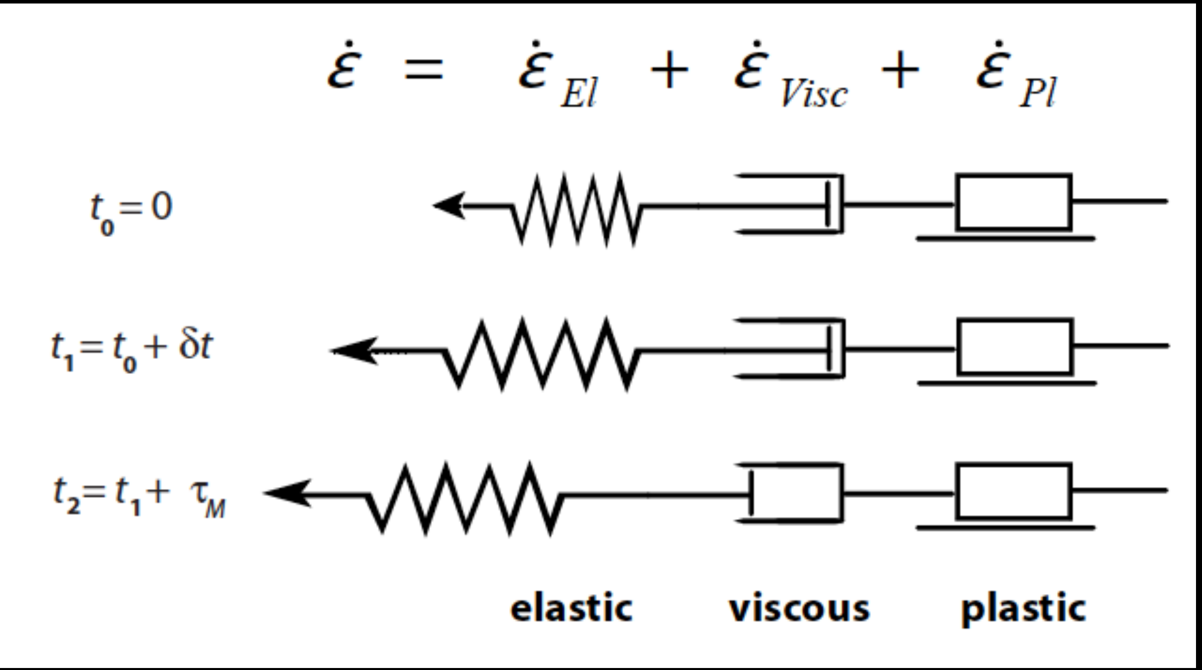


von Mises yield envelope

$$\eta = \begin{cases} \eta = \dfrac{\sigma_{II}}{\dot{\varepsilon}_{II}} & (\sigma < \sigma_{yield}) \\ \eta_{\text{eff}} = \dfrac{\sigma_{yield}}{\dot{\varepsilon}_{II}} & (\sigma \geq \sigma_{yield}) \end{cases}$$

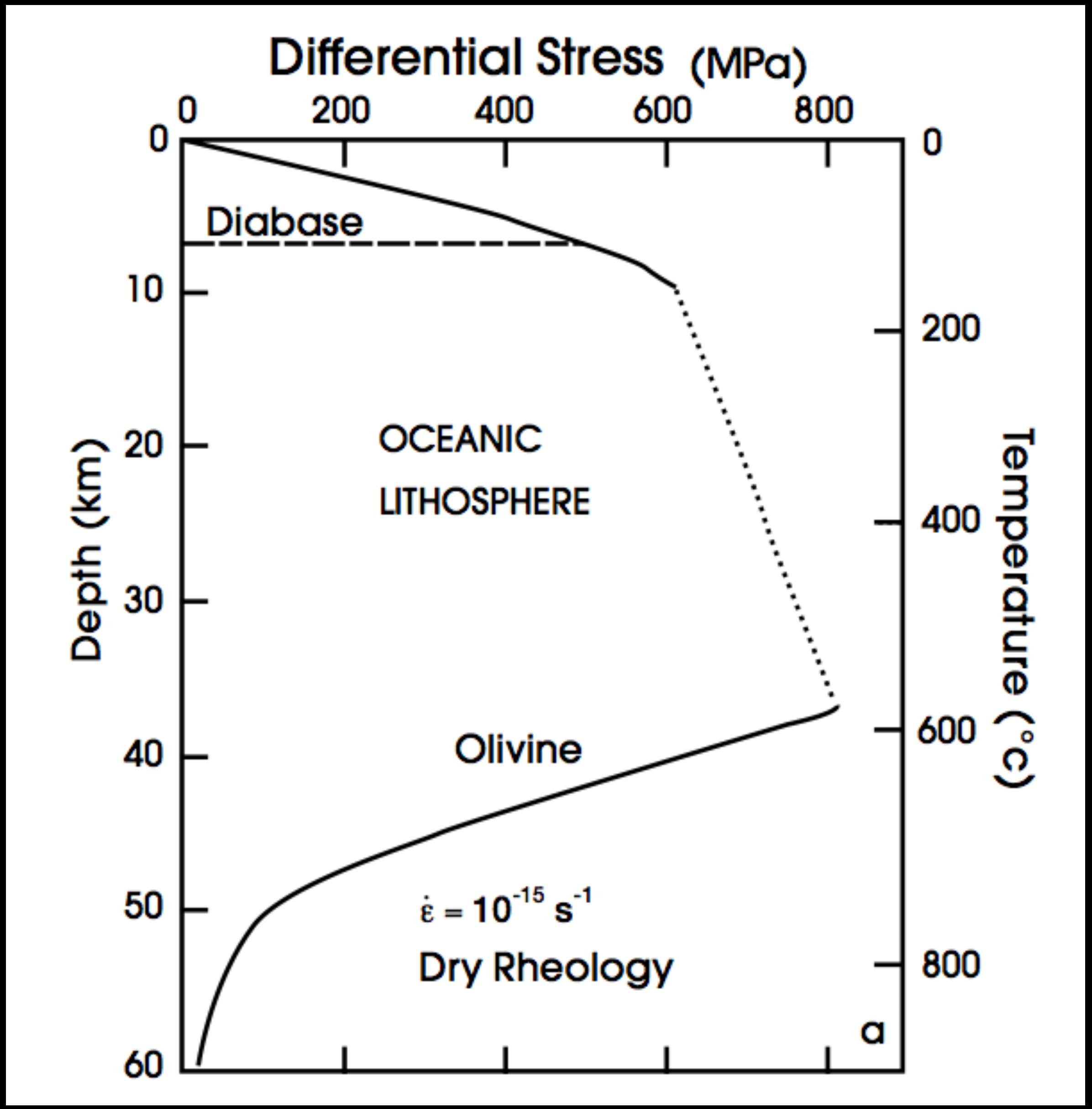
Viscoplasticity

- most materials have finite strength described by limiting stress and materials cannot support stresses in excess of their yield stress
- upon reaching their yield stress they deform through plastic flow (a solid beam starts to act like toothpaste)
- actually, care must be taken to guarantee one is actually on the yield surface and remains on it (i.e. use harmonic avg at your own risk)
- visco-elasto-plastic behavior can be written as generalized flow rule with an associated flow for each of the viscous, elastic, and plastic parts



Strength envelope for an oceanic plate

- **maximum stress that is supported is equivalent to a yield stress**
- **three layer lithosphere: brittle crust, strong core, ductile underside**
- **based on extrapolating the deformation behavior of crystals (microscale) to that of a rock scale (macroscale)**
- **role of large scale faults and tectonic fabric (mesoscale)**
- **likely mechanism in strong core is Peierls creep (low strainrate, high stress)**



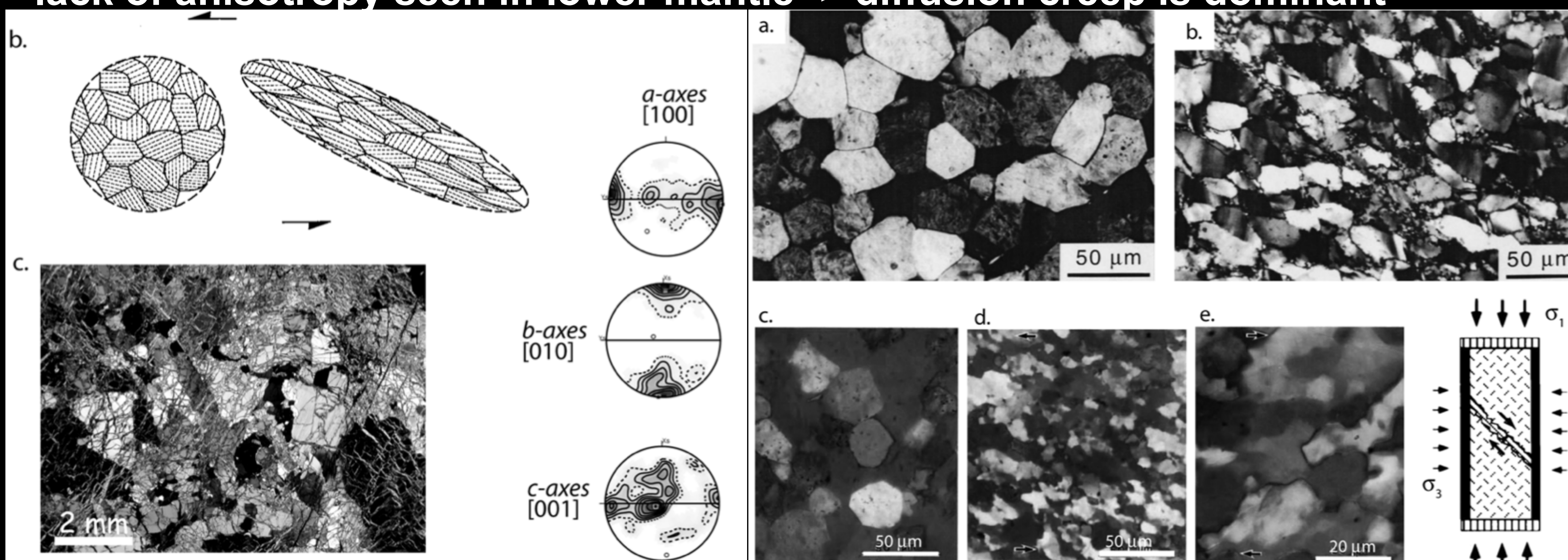
Kohlstedt et al, JGR, 1995

Anisotropy

- dislocation creep (n=3.5) and dynamic recrystallization during deformation generate crystal alignments and lattice preferred orientation (LPO) of crystals

- significant seismic anisotropy observed in the upper mantle -> implies dislocation creep is the dominant mechanism

- lack of anisotropy seen in lower mantle -> diffusion creep is dominant

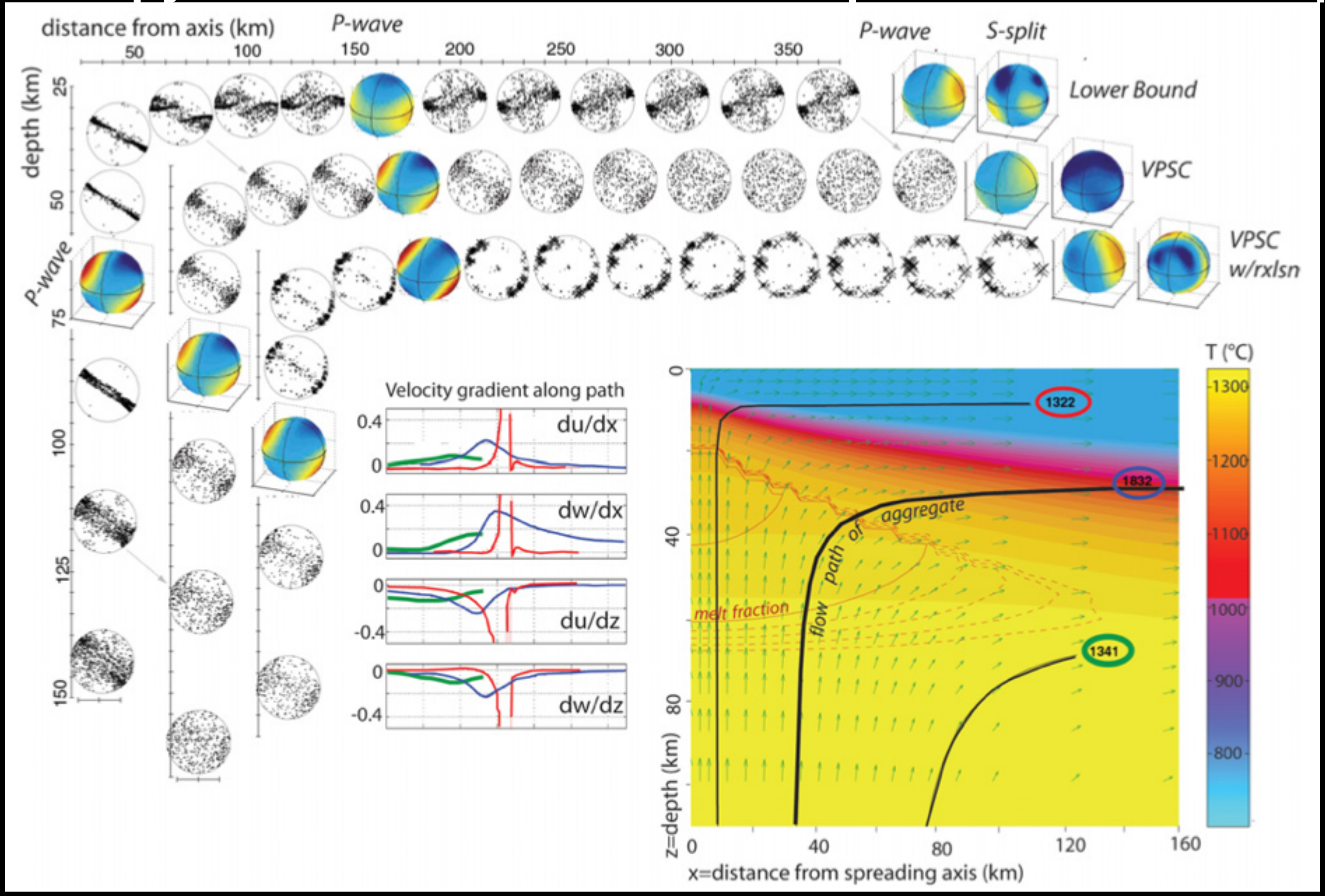


Blackman, Rep. Prog. Phys, 2007

Anisotropy

- **significant seismic anisotropy observed in upper mantle -> implies dislocation creep is the dominant mechanism**

- **lack of anisotropy seen in lower mantle -> implies diffusion creep is dominant**



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Thank you! Questions??