Generation of plate tectonics from grain to global scale

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Unique Earth?

Why is Earth the only terrestrial planet in our solar system with plate tectonics, liquid water, temperate climate, and life

- **Plate tectonics likely governs planetary evolution from core to atmosphere**
  - Plate tectonics as a carbon scrubber (Walker et al 1981; Berner et al 1983)
- **Desire a predictive theory about conditions for plate tectonics to occur**
The “Plate Generation” questions

- How does plate tectonics arise from a convecting mantle?
- Why Earth, not Venus (or Mars)?
- What governs whether we expect to find plate tectonics in other solar systems?
- When and how did plate tectonics emerge?
- How do plates evolve and reorganize?
Mantle rock “creep” rheology

\[ \dot{e} = A(T) \sigma^n \]

\[ \dot{e} = B(T) \sigma / R^m \]

strain-rate
stress
temperature
grain-size

Fracture and Cataclasis
Dislocation Creep
Dissolution Creep and Mechanical Twinning
Grain-boundary Creep
Volume-diffusion Creep

Differential Stress
Temperature
V. Solomatov (1995)

- no convection
- stagnant lid
- Earth-like regime
- sluggish lid
- nearly isoviscous
Plate Generation Mechanisms

Most terrestrial mantles undergo *stagnant lid* convection

Earth has self-softening feedbacks

- deformation softens material
- weak zones focus deformation
- causes more softening, more focusing: shear-localization

Allows convecting mantle to generate

- strong broad plates,
- narrow, weak *long-lasting boundaries*
- localized strike-slip shear
Peridotite mylonite (Lars Hansen)
**Grain-scale Processes**

- Mineral grains grow if “static”

Octochlorpropane (Park et al 1997)

Hiraga et al 2010
**Grain-scale Processes**

- Mineral grain-size reduction?

- With deformation and *damage* (dislocations), grain-size reduces
- Rocks apparently soften as grains “shrink” ➔ positive feedback
- “Deep” lithospheric mechanism
  - cold ductile region
- Evident in mylonites

But in single-phase rocks...

- Grain reduction only in dislocation creep (*dynamic recrystallization*): independent of grain-size
- Grain-size weakening only in diffusion creep when grains only grow
- **Shouldn’t be any self-softening feedback**
  - de Bresser et al (2001)
Grain-damage & pinning in rock mixtures*

- Mantle rocks (peridotite) are mixture of olivine and pyroxene
- Grain growth blocked \((pinned)\) by interface between components
- Damage acts to “sharpen” interface
- Sharpening of interface and \textit{pinning} drives grains to smaller sizes and material softens
- Damage and softening coexist
- Pinning retards healing

* Bercovici & Ricard 2012, 2013
Pinning slows grain-growth

Single-phase coarsening

In two-phases with pinning, coarsening is impeded

Low surface and internal energy

High surface and internal energy

High surface and internal energy
**Pinning helps damage**

- **Low surface energy**
  - Damage: work provides energy increase
  - High surface energy

- **High surface energy**
  - "Easier" Damage: less energy needed
Coupled “interface” and “grain-size” evolution laws

Interface “roughness” or radius of curvature $r$

Grain-size $R_i$ in each phase

Zener pinning factor

Composite dislocation + diffusion creep rheology

Coefficients based on comparison to lab experiments
Emergence of plate tectonics: When and how did plate tectonics begin?

It is the larger conception which determines the expression of the details. — Joseph Barrell (Barrell 1919, p. 282)

Five decades after the advent of the plate tectonics theory (e.g., Hess 1962, Vine & Matthews 1963, Wilson 1965), our understanding of geology seems to have matured enough to discuss the initiation of plate tectonics in Earth's history, which might have been regarded in the past century as too speculative to be legitimate. In recent years, quite a few papers have been published to suggest when plate tectonics started, with proposed timings covering almost the entire history of Earth (Figure 1).

The diversity of opinions results from ambiguities in the interpretation of relevant geological observations as well as different weightings on different kinds of data. Stern (2005), for example, suggests that modern-style plate tectonics started around the beginning of the Neoproterozoic era (~1 billion years ago (1 Gya)) on the basis of the absence of ultrahigh-pressure...
Intermittent subduction and inherited damage

- Migrating subduction low P zone
- Inherited weak zones
- Accumulate plate boundaries in ~ 1Gyr

Bercovici & Ricard (2014)
Earth-like case
Cool surface:
Low healing
High damage
Venus-like case
Hot surface:
High healing
Low damage
Mylonites and ultramylonites often form bands of mixed grains (esp. in peridotites)
Polyminerallic damage+pinning enhanced by inter-grain mixing
Grain mixing

Sheared (lherzolite) peridotite (Skemer & Karato 2008)

Drawing after EBSD image (Bruijn & Skemer 2014)
Diffusive grain mixing model

\[
\frac{\partial \phi_i}{\partial t} + \nabla \cdot (\phi_i \mathbf{v}_i) = 0 \quad \text{mass conservation}
\]

\[
\mathbf{v}_i = \mathbf{v} + \mathbf{u}_i \quad \mathbf{v} = \sum_i \phi_i \mathbf{v}_i \quad \sum_i \phi_i \mathbf{u}_i = 0 \quad \text{mean and grain-diffusive velocity}
\]

\[
\mathbf{u}_i = -\phi_j \mathbf{K} \cdot \nabla \phi_i \quad \text{where} \quad j \neq i \quad \text{diffusive velocity} \sim \text{vol. fraction gradient}
\]

\[
\mathbf{K} = \chi(\phi, R_i, r) \mathbf{\tau} \quad \text{anisotropic diffusivity} \sim \text{stress tensor}
\]

\[
\frac{D\phi_i}{Dt} = \nabla \cdot (\phi_i \phi_j \chi \mathbf{\tau} \cdot \nabla \phi_i) \quad \text{Mass advection-diffusion eqn}
\]

Bercovici & Skemer (2017)
Bercovici & Mulyukova (2018)
Diffusive grain mixing + damage: 1D example

\[ \mathbf{\tau} = \begin{bmatrix} \tau_N & \tau_S \\ \tau_S & -\tau_N \end{bmatrix} \equiv \tau_N (\hat{x}\hat{x} - \hat{z}\hat{z}) + \tau_S (\hat{x}\hat{z} + \hat{z}\hat{x}) \]

\[ v_x = \dot{e}_N x + U(z), \quad v_z = \dot{e}_N z \]

\[ \tau_N = 2\mu\dot{e}_N \quad \tau_S = \mu \frac{\partial U}{\partial z} \]

Mass advection-diffusion eqn

\[ \frac{\partial \phi}{\partial t} - \dot{e}_N z \frac{\partial \phi}{\partial z} = \tau_N \frac{\partial}{\partial z} \left( K(\phi, r) \frac{\partial \phi}{\partial z} \right) \]

Grain damage (simplified)

\[ \frac{\partial r}{\partial t} - \dot{e}_N z \frac{\partial r}{\partial z} = \frac{C}{qr^{q-1}} - Dr^2 \left( A\tau^{n+1} + B(\phi)\tau^2 r^{-m} + \tau^2 K \left( \frac{\partial \phi}{\partial z} \right)^2 \right) \]
Zoomed out ("wide" domain)
Figure 10. Different olivine deformation mechanism maps, grain size (\(\text{m}\)) versus differential stress (MPa), at different temperatures: (a) 1100°C, (b and c) 800°C, and (d and e) 700°C. Different flow laws are used for diffusion creep; [HiKo, 2003] from Hirth and Kohlstedt [2003] (Figures 10a, 10b, and 10d), and [FaJa, 2007] from Faul and Jackson [2007] (Figures 10c and 10e). The parameters used for the other flow laws are summarized in Table 1. For the mylonite the differential stress is assumed to be the same in the polymineralic domains (small olivine grain sizes) as the differential stress in the monomineralic layers (large olivine grain sizes) calculated with the paleopiezometer. For the ultramylonite, the stippled box shows the range in average grain sizes in the polymineralic domains, with the corresponding differential stresses for the whole range.
Figure 10: Deformation mechanism maps for (a) calcite, constructed from the dislocation creep flow law of Renner et al. (2002) and the diffusion creep flow law of Herwegh et al. (2003), and (b) anhydrite, constructed from the dislocation and diffusion creep flow laws of Dell’Angelo & Olgaard (1995). The thick black line indicates the field boundary between dislocation and diffusion dominated creep. For calcite, the paleopiezometers of Barnhoorn et al (2004; red line) and Rutter (1995; green line) are given alongside the paleowattmeter of Austin & Evans (2007; blue line). Data points (colored by shear strain) are plotted using median grain sizes (Figure 8c; Table S1) and the shear strain rates given in Table 1, converted to effective strain rates using a factor of $1/\sqrt{3}$ (Paterson & Olgaard, 2000).
Two-phase grain damage with mixing transition

- Three equilibrium branches
  1. Unmixed, large grain, strong “creeping” branch
  2. Mixed, small grain, weak “mylonite” branch
  3. Intermediate grain unstable branch

Bercovici & Ricard (2016)
**Planetary states**

Grain-damage hysteresis

- implies a plate-tectonic state allows for coexistence of strong and very weak states
- representing plates and plate boundaries

- Co-existence largely depends on damage:healing $qD/C$
- Earth has large $qD/C$ and Venus much smaller
Summary

- Grain-damage mechanism, built from basic physics, consistent with lab and field observations, allows generation of plate tectonics with Earth conditions.
- Emergence of global plate tectonics takes 1Gyr as damage zones accumulate and are inherited to yield fully formed plates driven by subduction only.
  - On, Venus damaged weak zones heal and don’t accumulate.
- Grain-damage, mixing and (effective) hysteresis implies two deformation states: plates and plate boundaries.