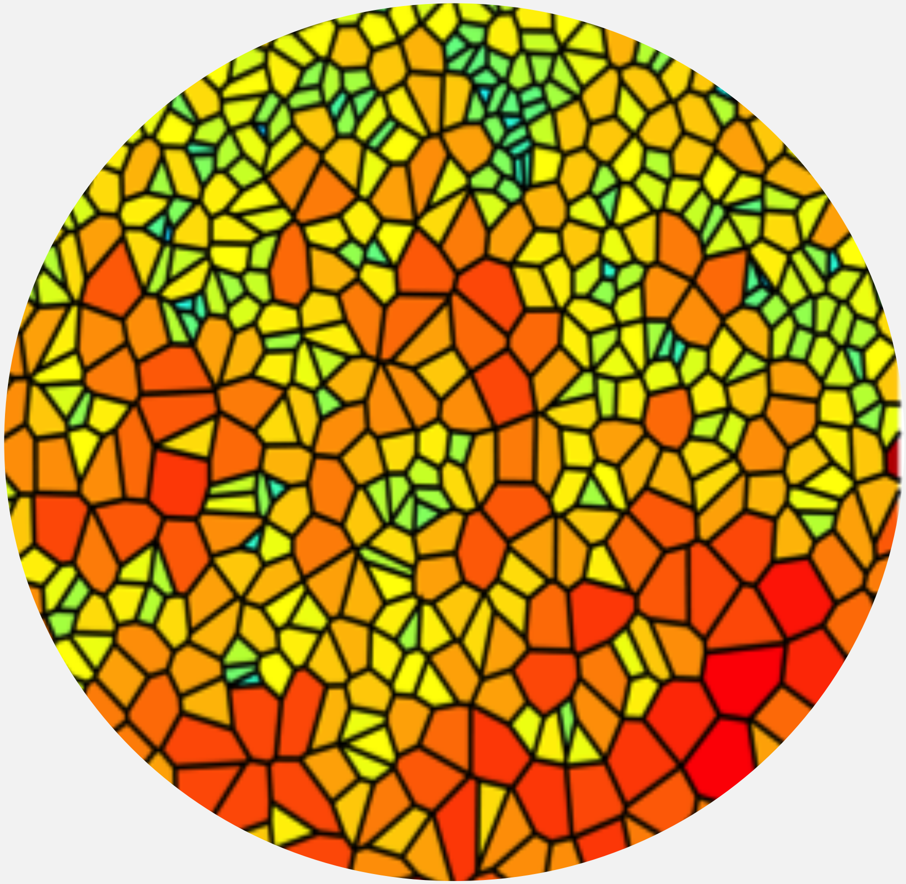
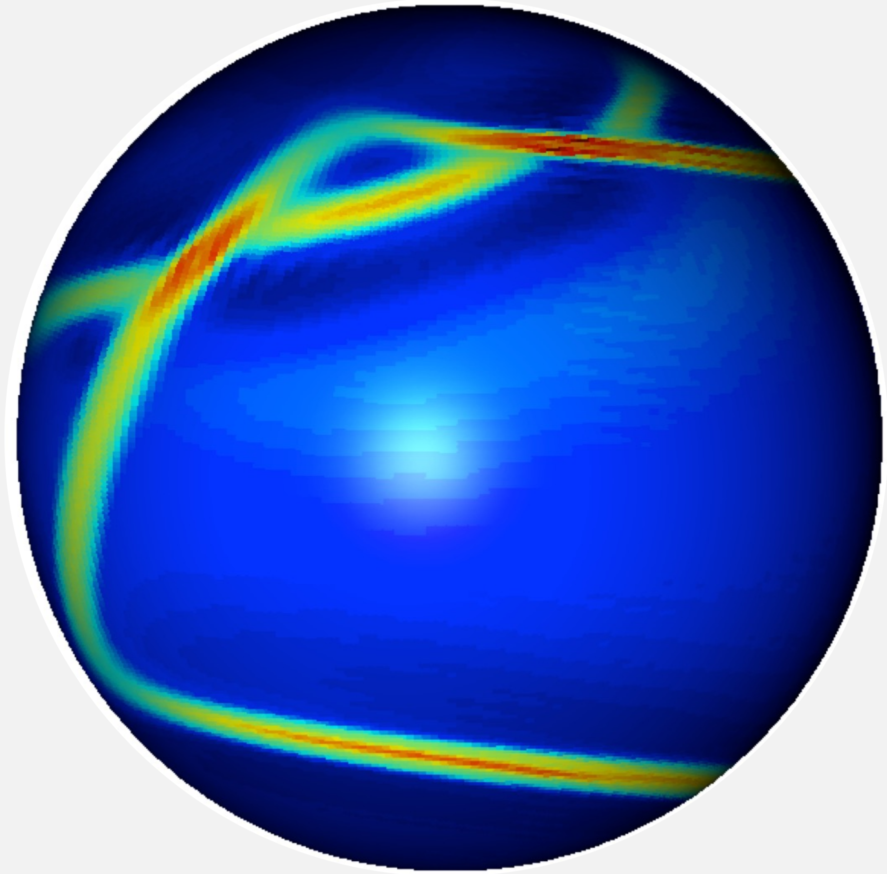
Searching for the origin of plate tectonics, leaving no grain unturned





David Bercovici
Yale University

Augustus Love Lecture

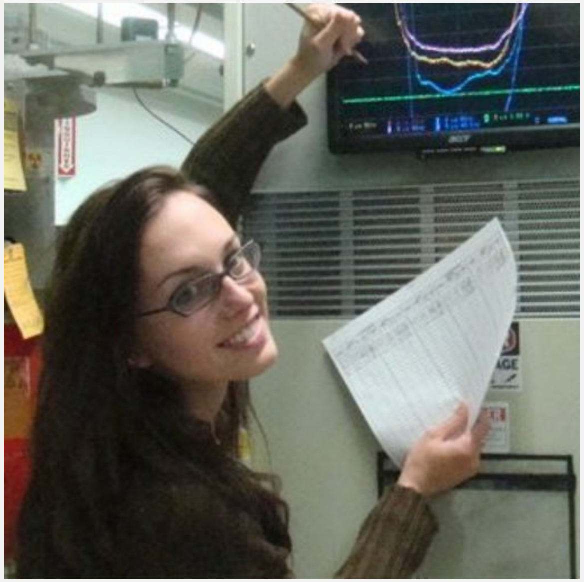
European Geosciences Union

May 24, 2022

Collaborators

Yanick Ricard
ENS Lyon

Elvira Mulyukova
Northwestern University



Jennifer Girard
Yale University

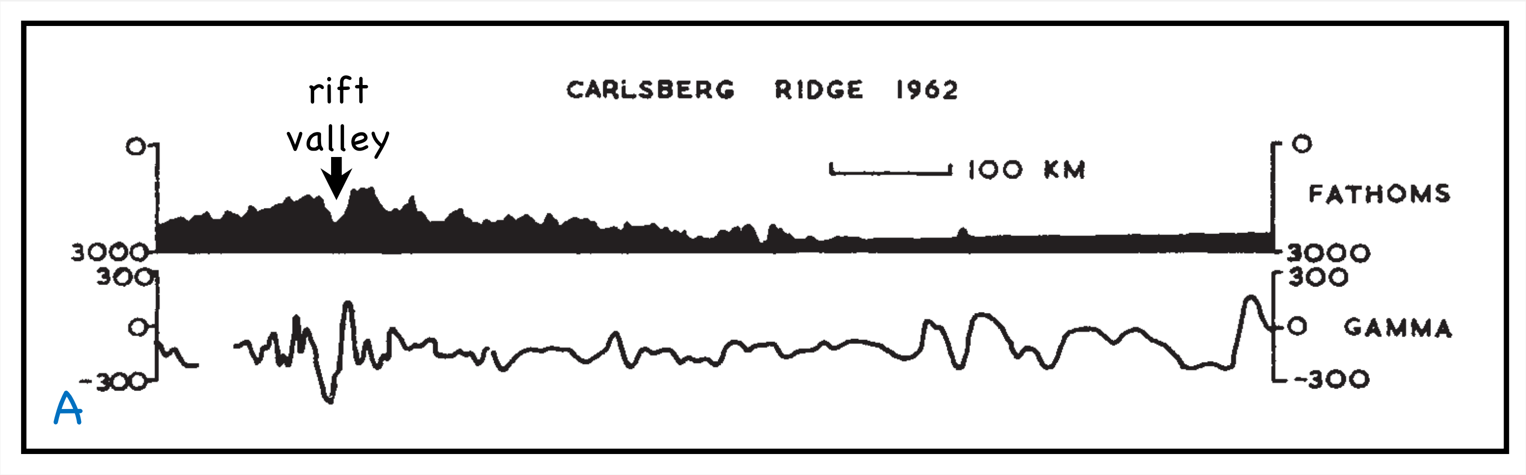
Brad Foley
Penn State Univ.

Billy Landuyt
ExxonMobil

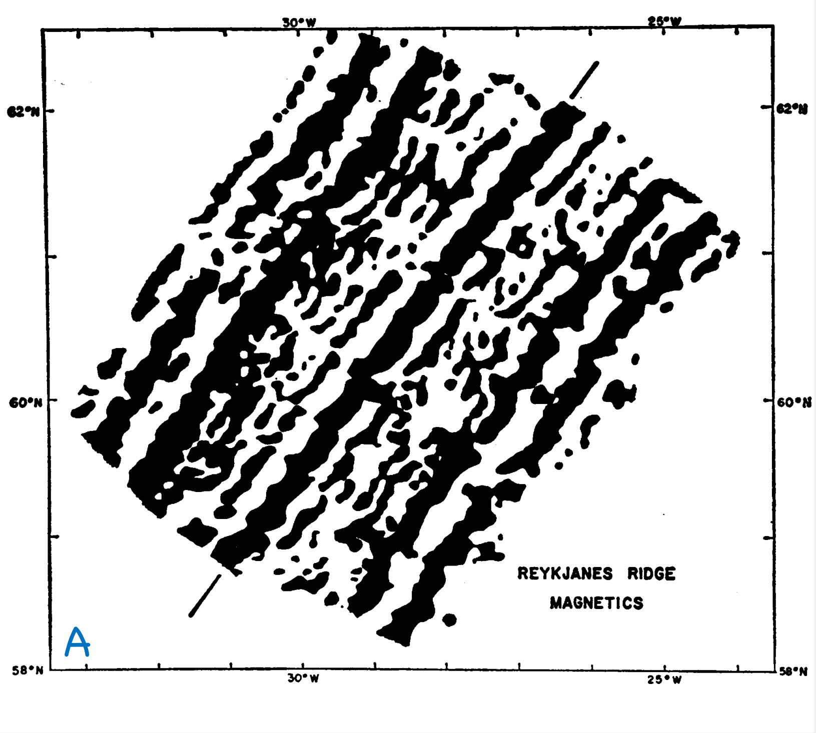
Phil Skemer
Wash. Univ. St. Louis

Taras Gerya
ETH Zurich

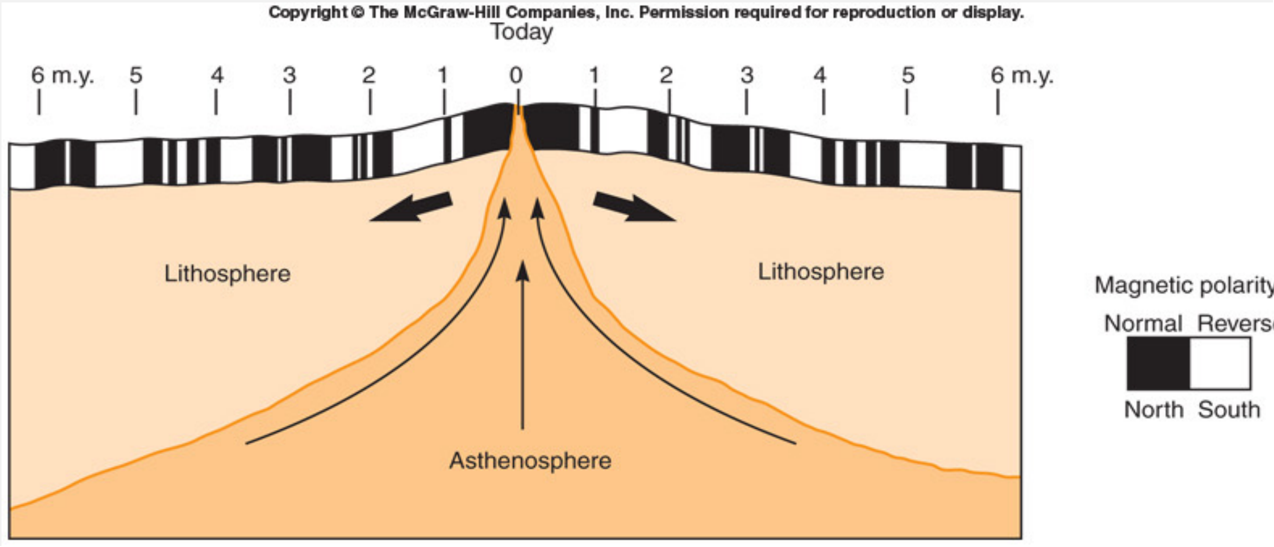
NSF

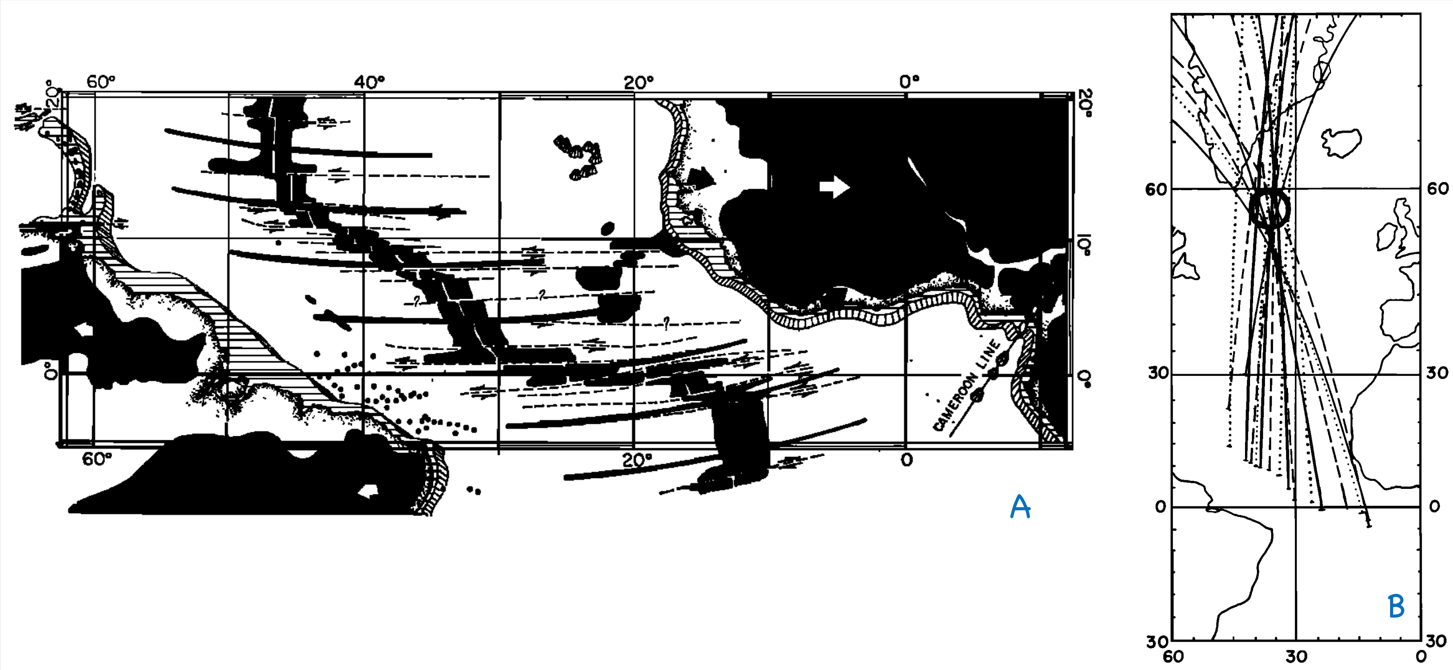


Vine & Matthews 1963

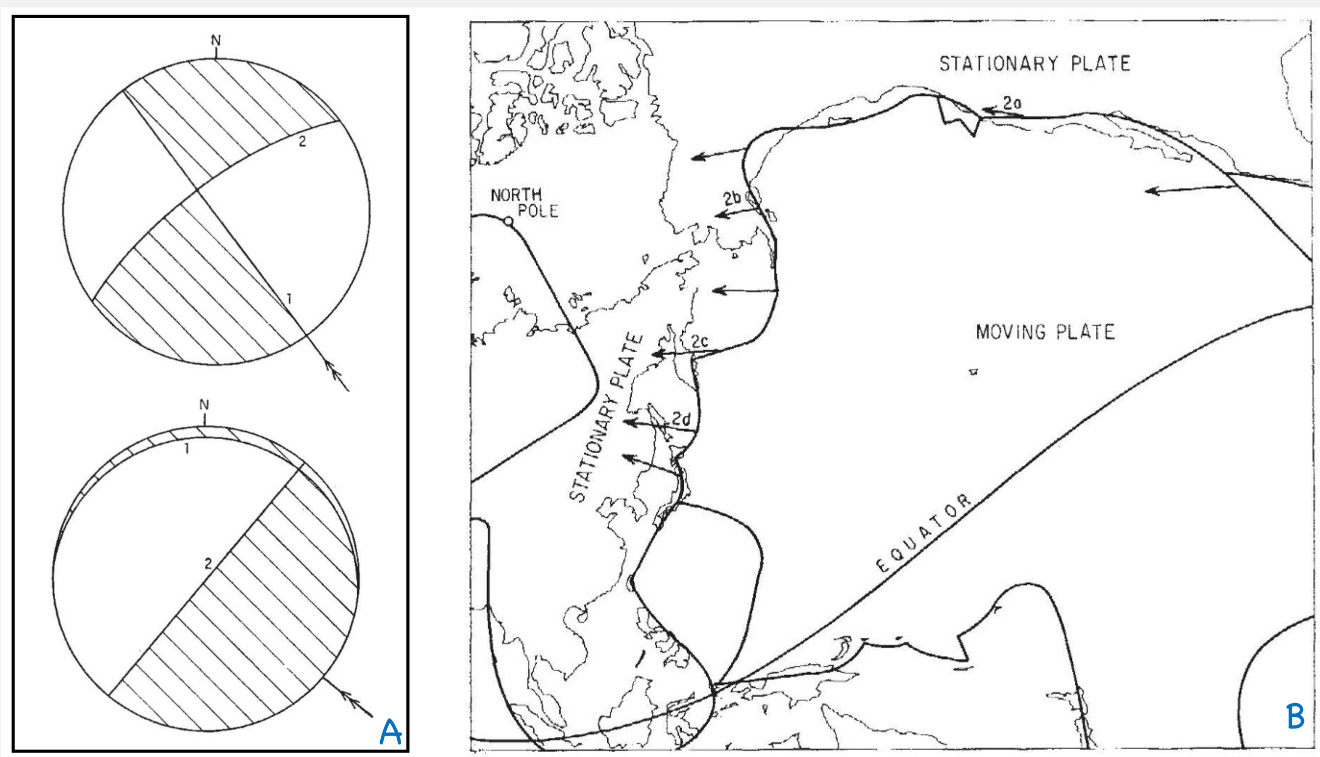


Vine & Wison 1966

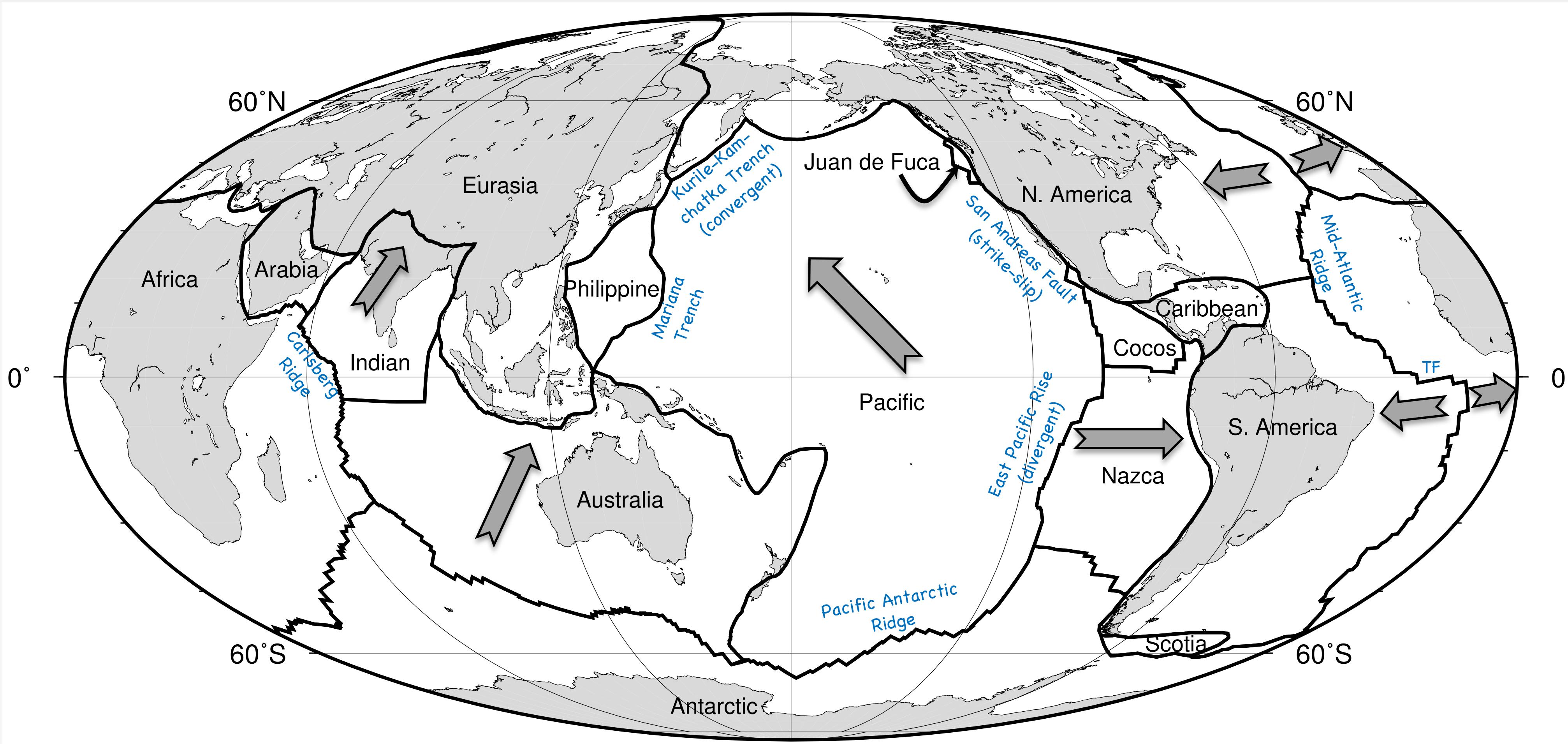




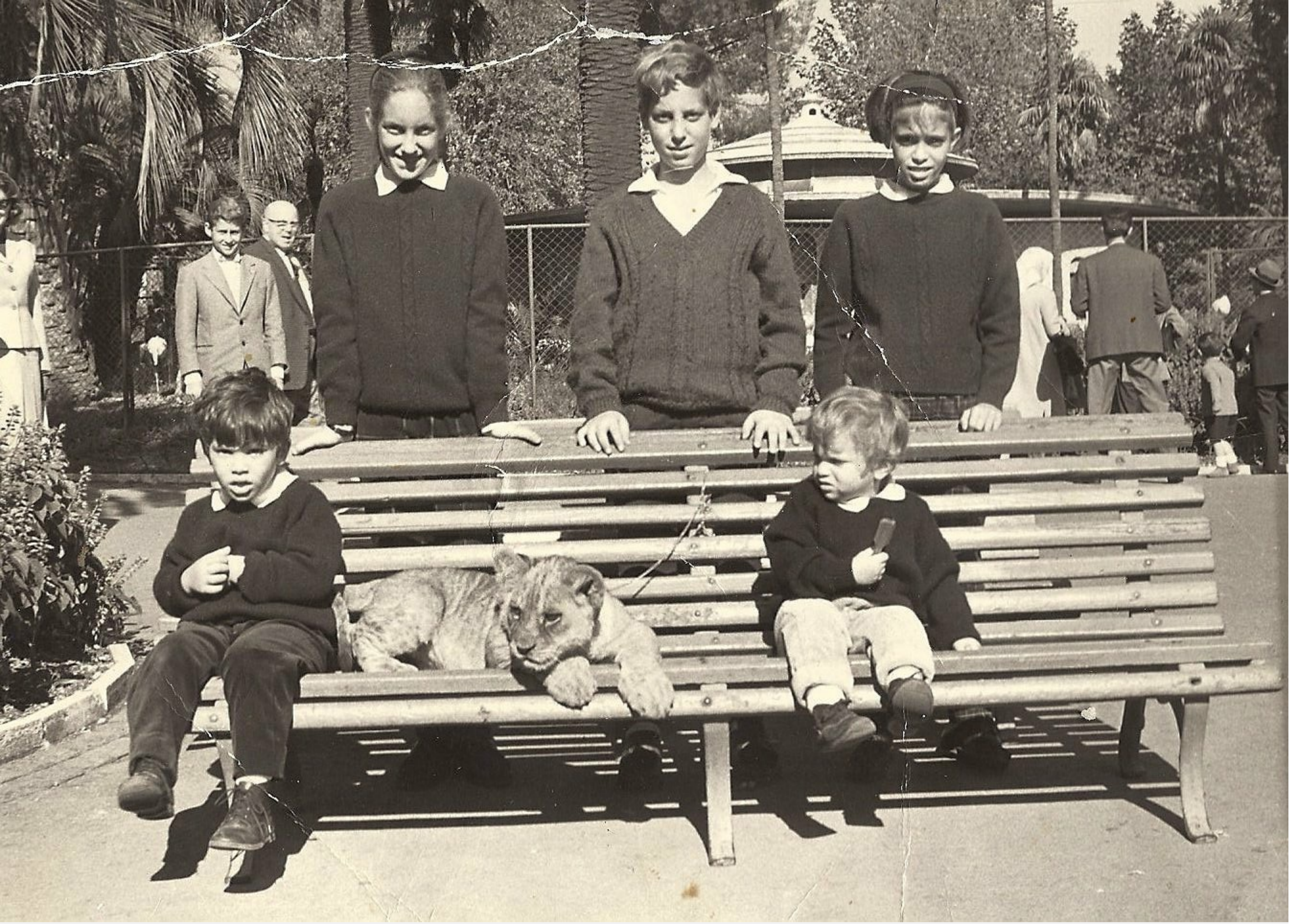
Morgan 1968



McKenzie & Parker 1967



60˚N
60˚N
0˚
0˚
60˚S
60˚S
Eurasia
Africa
Arabia
Indian
Philippine
Juan de Fuca
N. America
Caribbean
Cocos
Pacific
Australia
Nazca
S. America
Scotia
Antarctic
Kurile-Kam-
chatka Trench
(convergent)
Mariana
Trench
Carlsberg
Ridge
San Andreas Fault
(strike-slip)
East Pacific Rise
(divergent)
Mid-Atlantic
Ridge
TF
Pacific Antarctic
Ridge



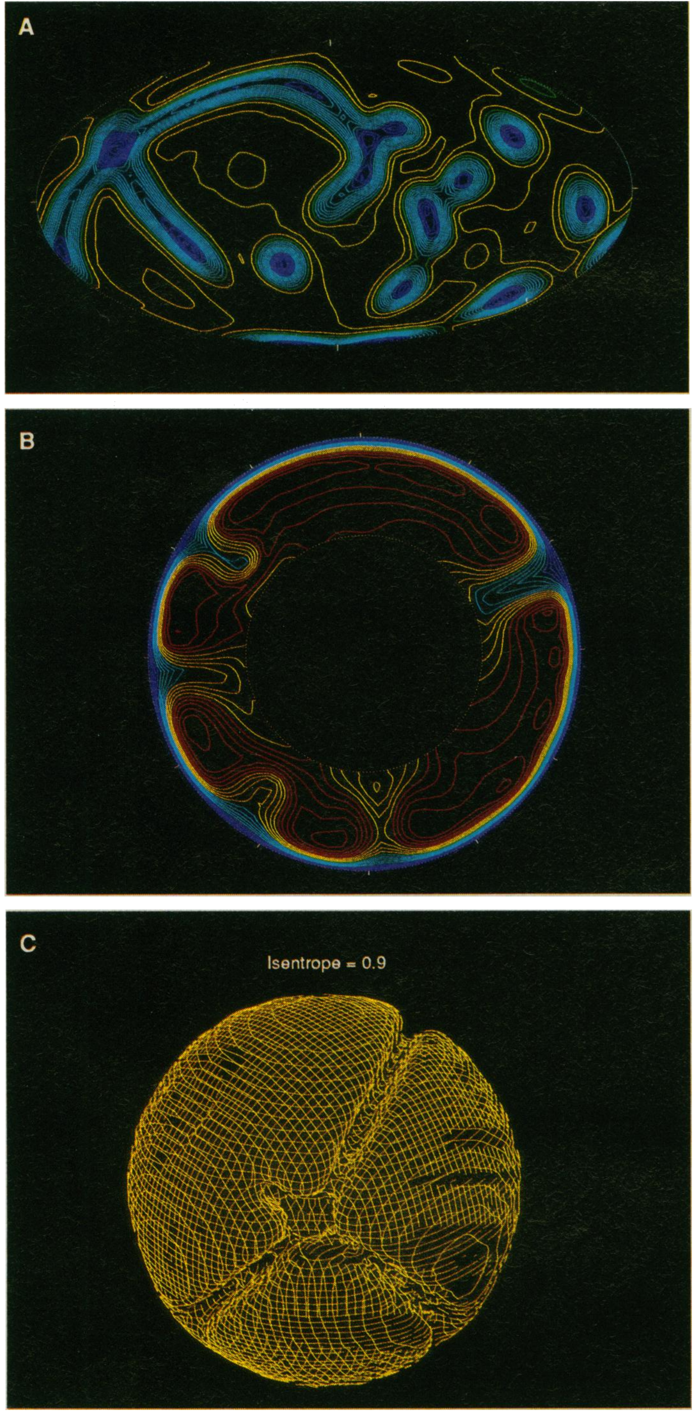
1963 (maybe)

1968

1980

1986, maybe?

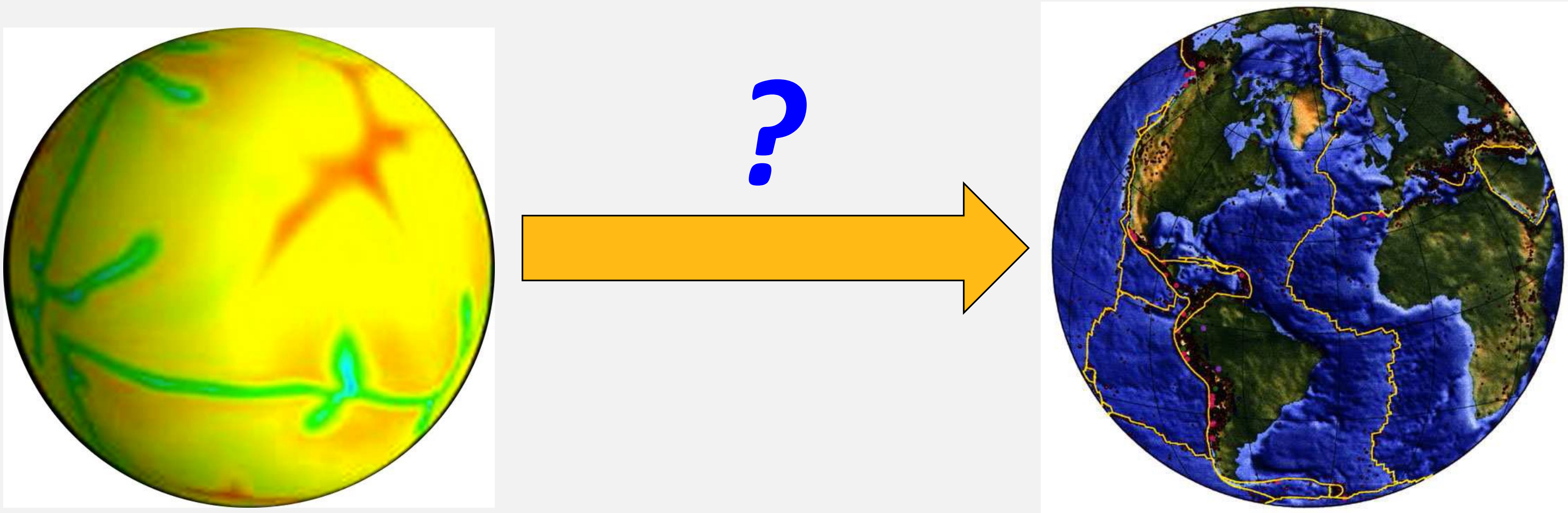
2018



Three-Dimensional Spherical Models of Convection in the Earth's Mantle

DAVE BERCOVICI, GERALD SCHUBERT, GARY A. GLATZMAIER 1989

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?

GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 9, PAGES 1751-1754, SEPTEMBER 1991

ON THE EQUIPARTITION OF KINETIC ENERGY IN PLATE TECTONICS

Peter Olson

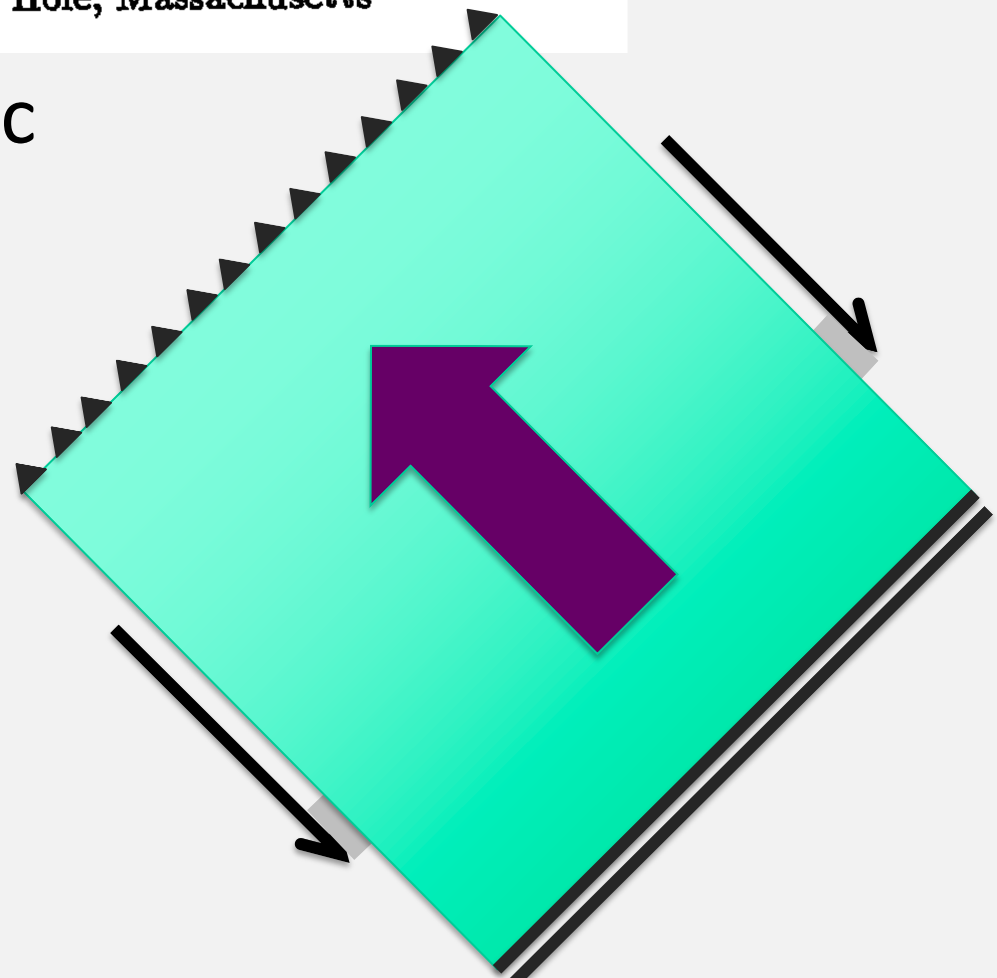
Department of Earth & Planetary Sciences
The Johns Hopkins University, Baltimore,Maryland

David Bercovici[1]

Department of Geology & Geophysics
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Remarkable finding that tectonic plates are square

Verified repeatedly thereafter

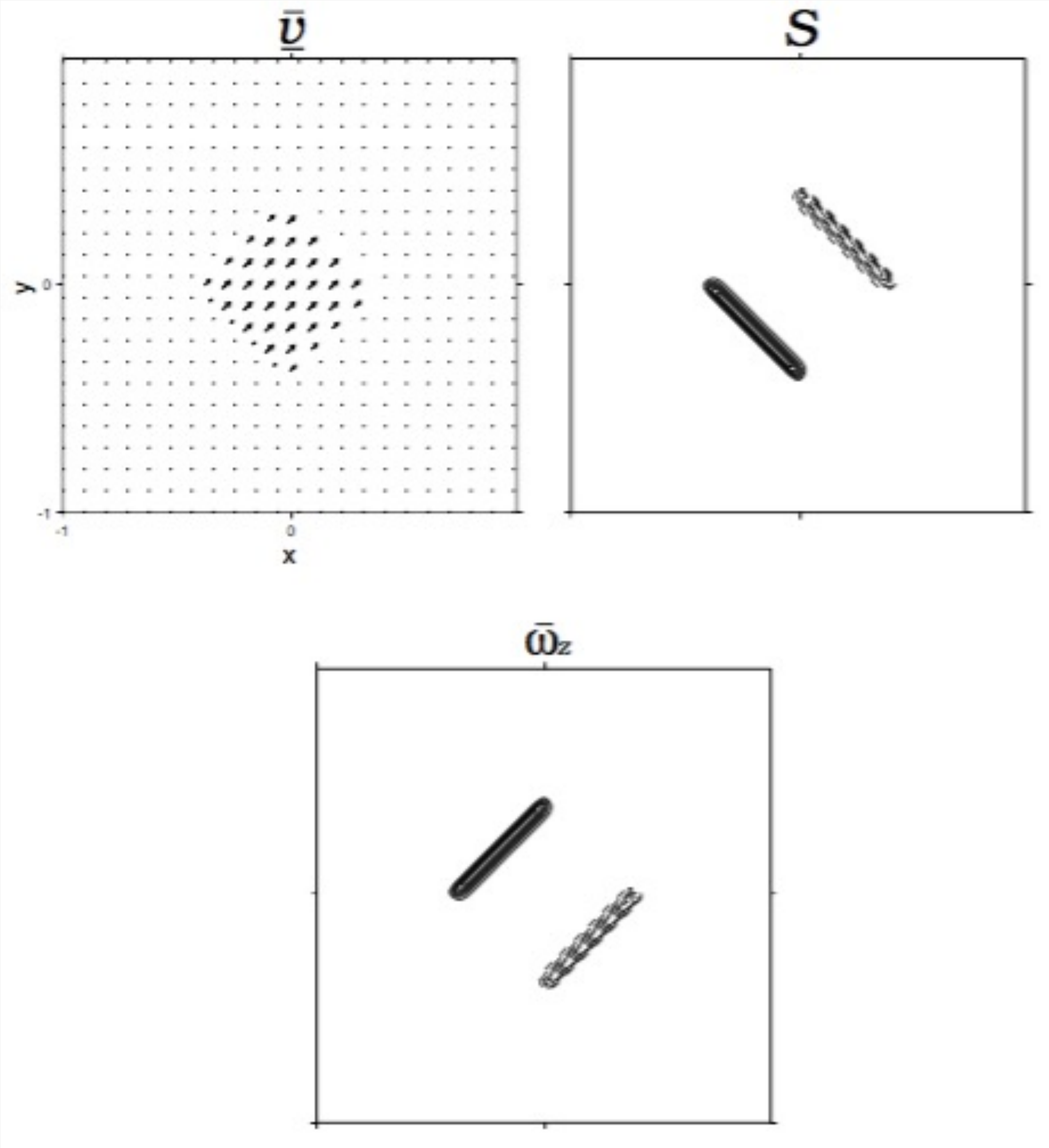


Geophys. J. Int. (1993) **114,** 635–650

1993

A Simple Model of Plate Generation from Mantle Flow

David Bercovici*
Department of Geology & Geophysics
School of Ocean & Earth Science & Technology
University of Hawaii, Honolulu

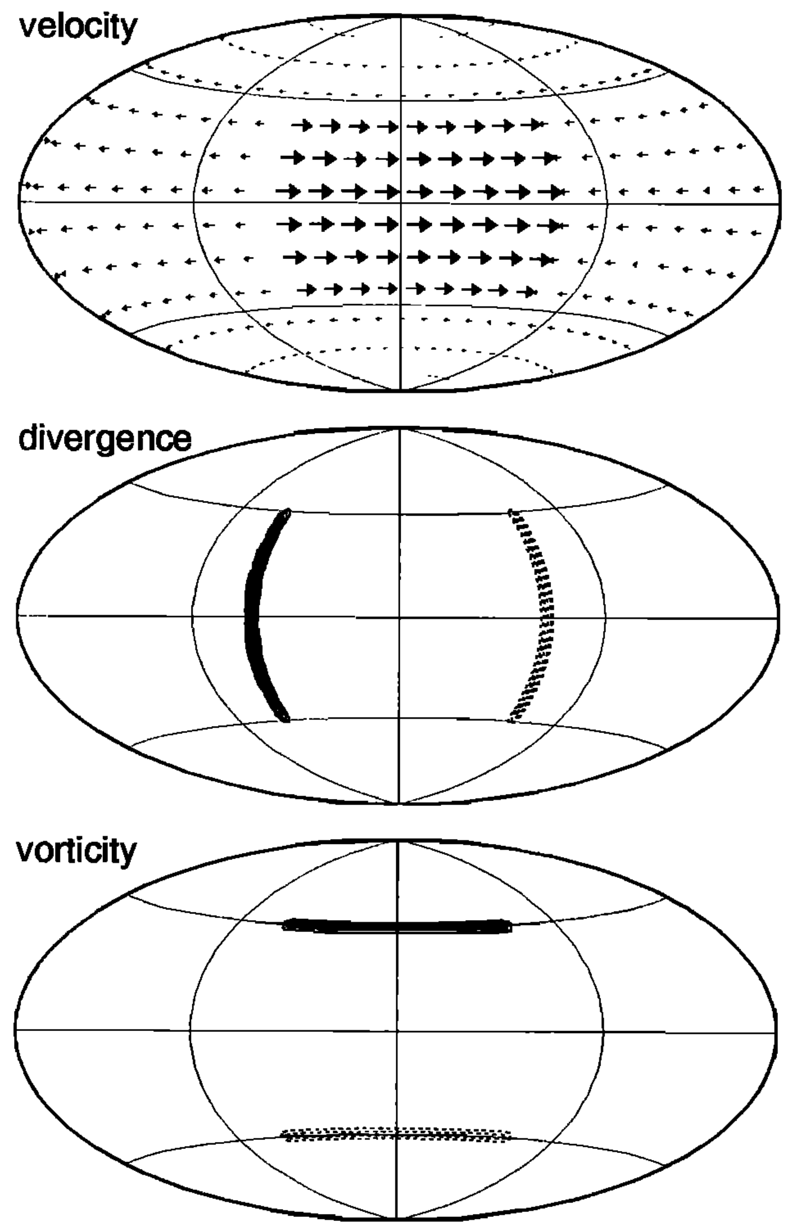


JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. B2, PAGES 2013–2030, FEBRUARY 10, 1995

1995

A source-sink model of the generation of plate tectonics from non-Newtonian mantle flow

David Bercovici
Department of Geology and Geophysics, School of Ocean and Earth Science and Technology
University of Hawaii, Honolulu



ELSEVIER

Earth and Planetary Science Letters 144 (1996) 41–51

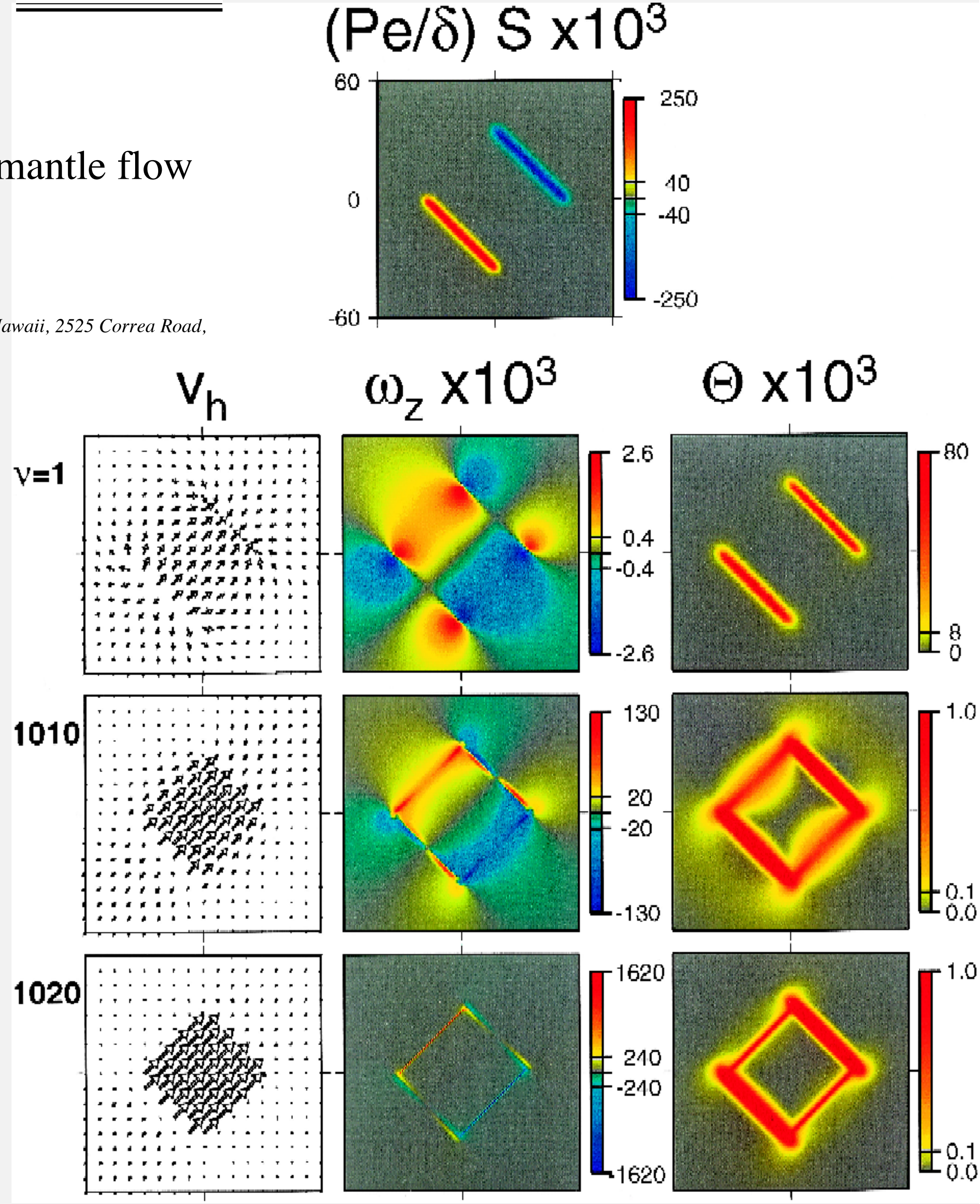
EPSL

1996

Plate generation in a simple model of lithosphere–mantle flow with dynamic self-lubrication

David Bercovici *

Department of Geology and Geophysics, School of Ocean and Earth Science and Technology, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822, USA



ELSEVIER

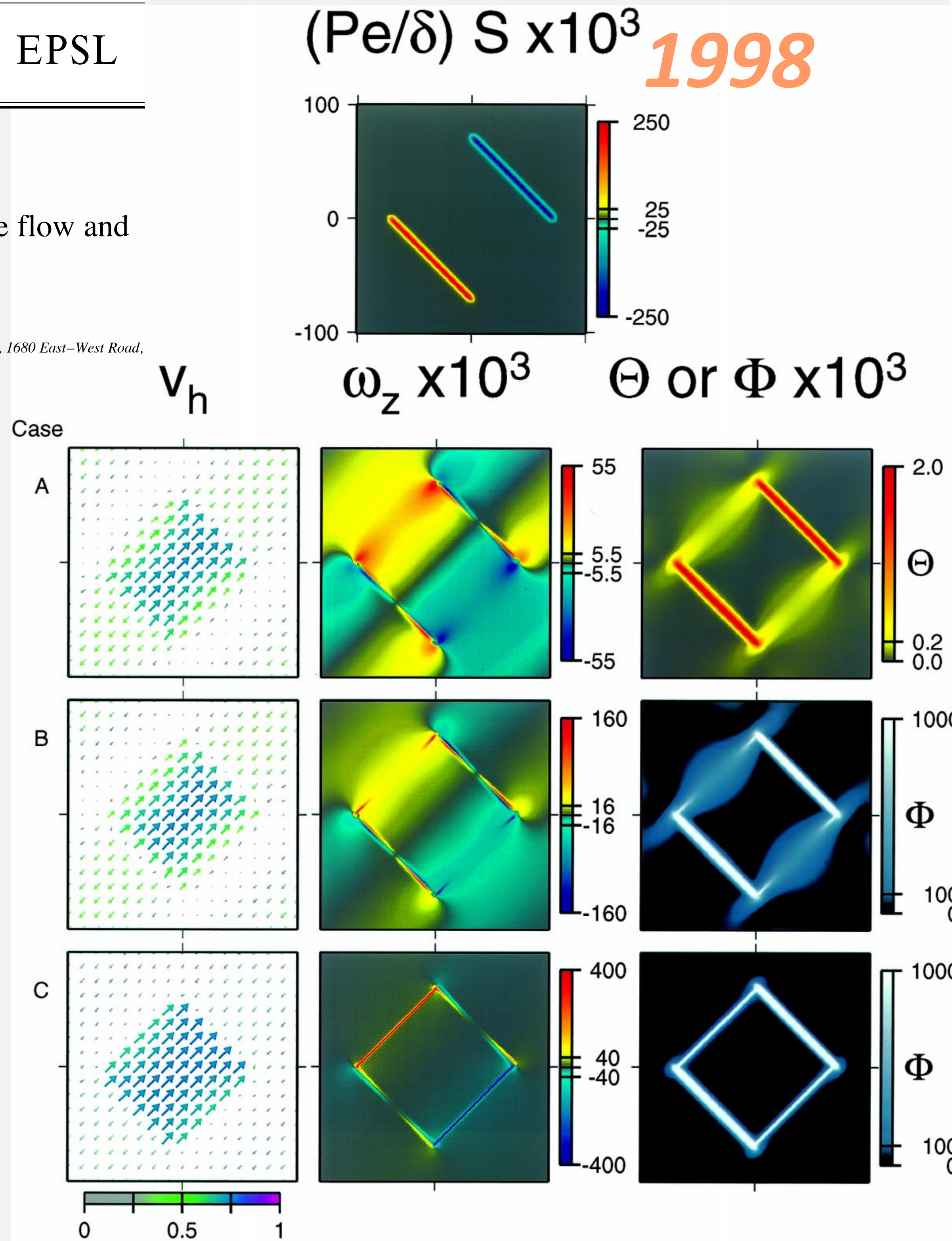
Earth and Planetary Science Letters 154 (1998) 139–151

EPSL

Generation of plate tectonics from lithosphere–mantle flow and void–volatile self-lubrication

David Bercovici *

Department of Geology and Geophysics, School of Ocean and Earth Science and Technology, University of Hawaii, 1680 East–West Road, Honolulu, HI 96822, USA



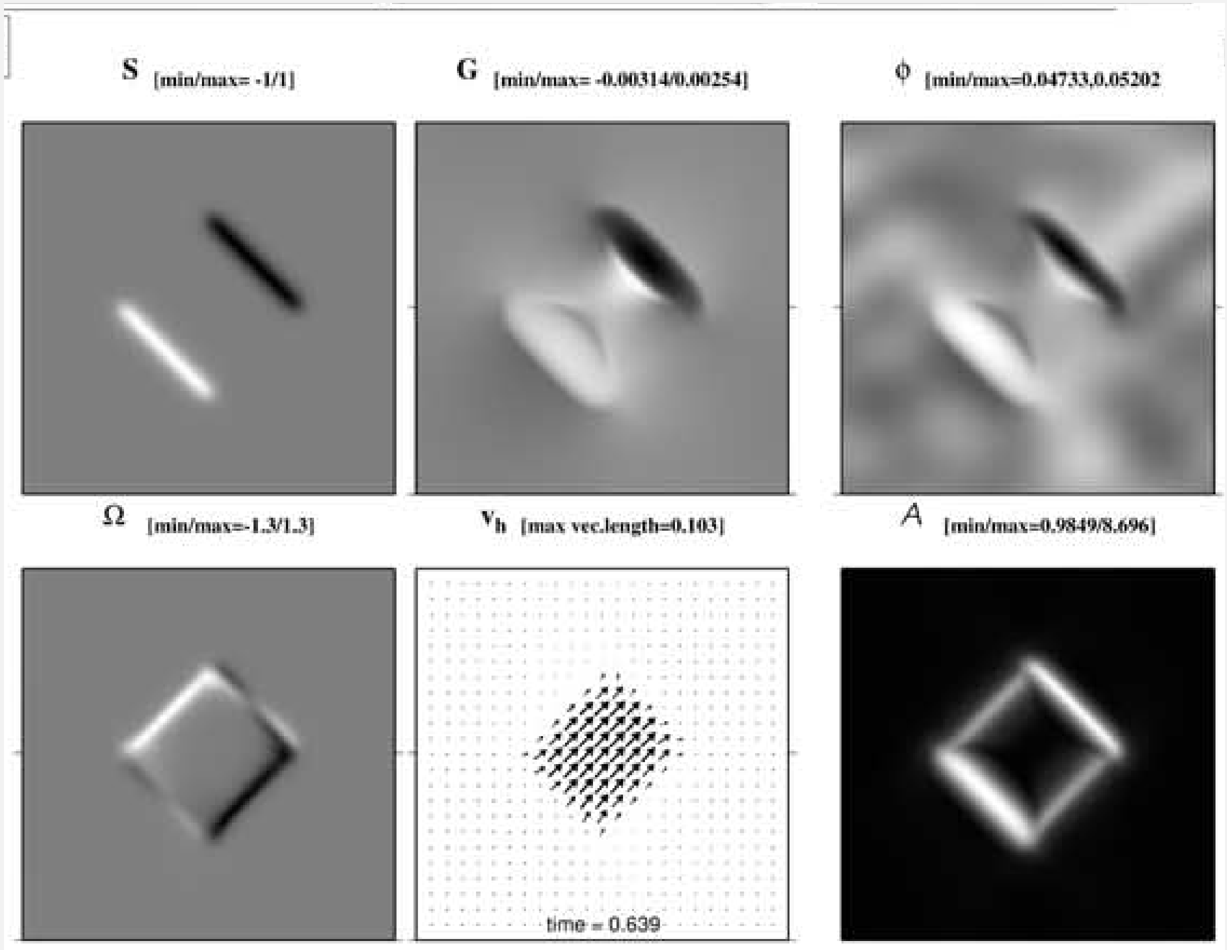
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, B03401, doi:10.1029/2004JB003181, 2005

2005

Tectonic plate generation and two-phase damage: Void growth versus grain size reduction

David Bercovici
Department of Geology and Geophysics, Yale University, New Haven, Connecticut, USA

Yanick Ricard
Laboratoire des Sciences de la Terre, CNRS, Ecole Normale Supérieure de Lyon, Lyon, France



Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

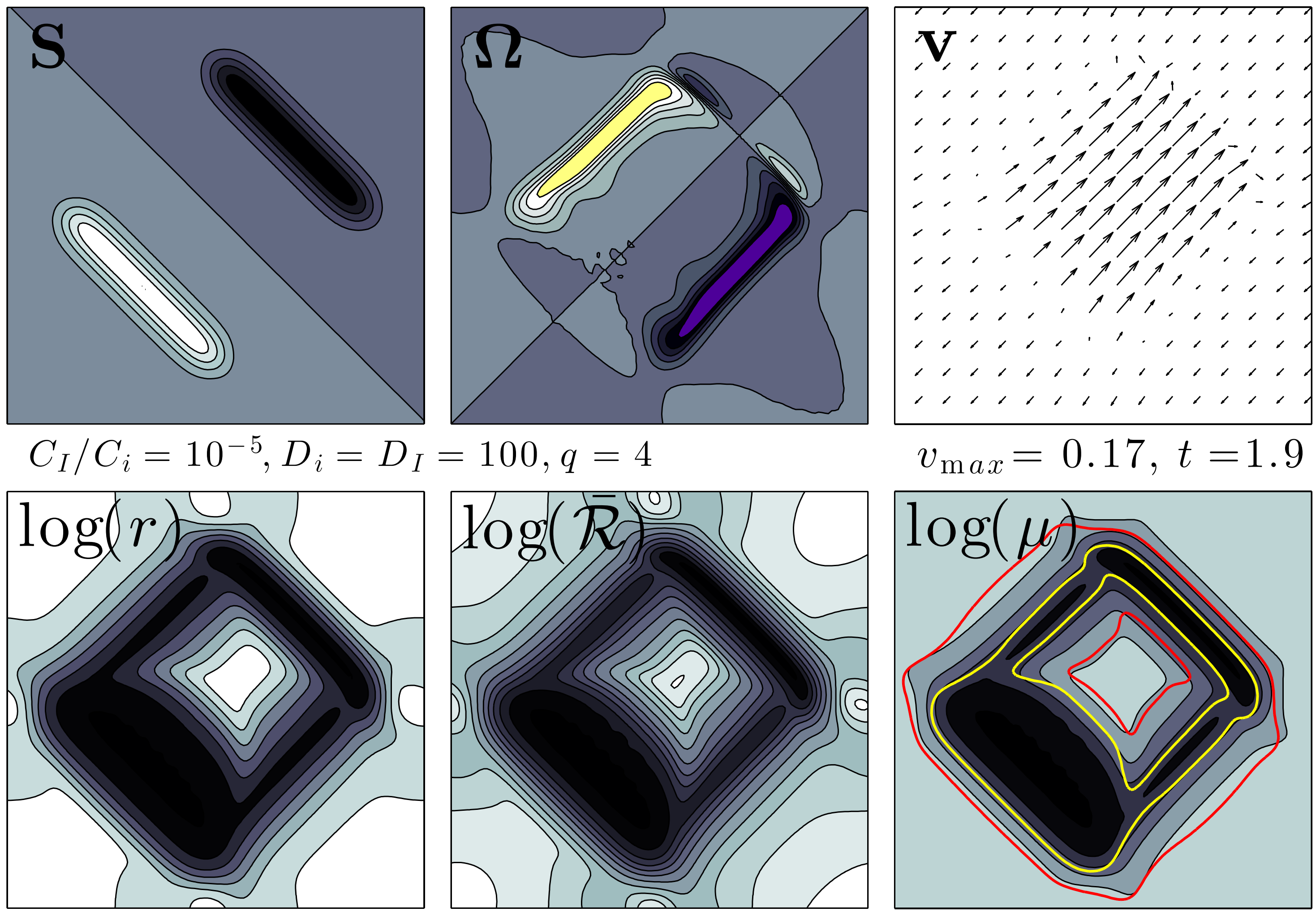
journal homepage: www.elsevier.com/locate/epsl

2013

Generation of plate tectonics with two-phase grain-damage and pinning: Source–sink model and toroidal flow

David Bercovici [a,*], Yanick Ricard [b]

[a] Yale University, Department of Geology & Geophysics, New Haven, CT, USA
[b] Laboratoire des Sciences de la Terre, CNRS, ENS, Université de Lyon, Lyon, France



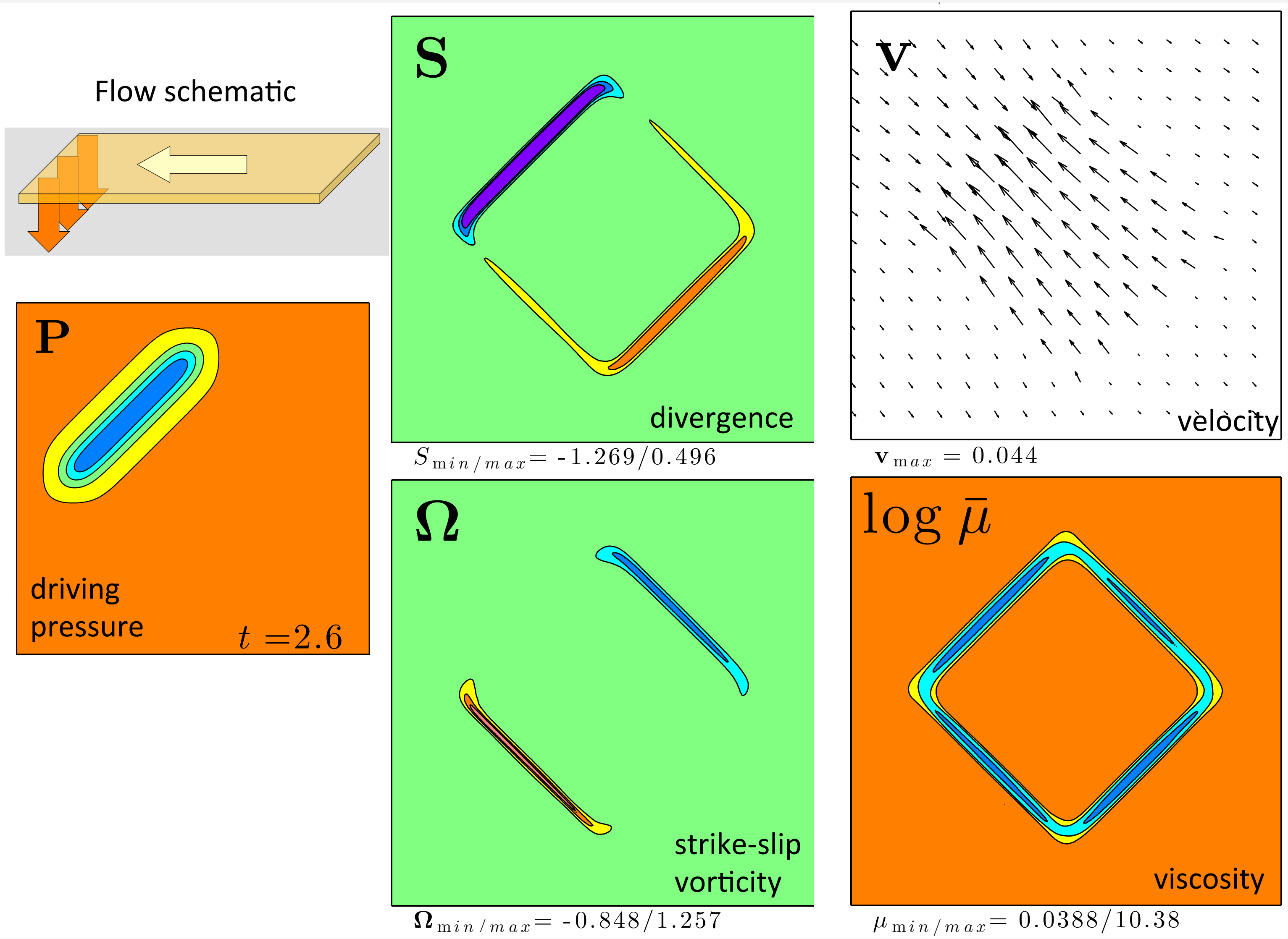
LETTER

2014

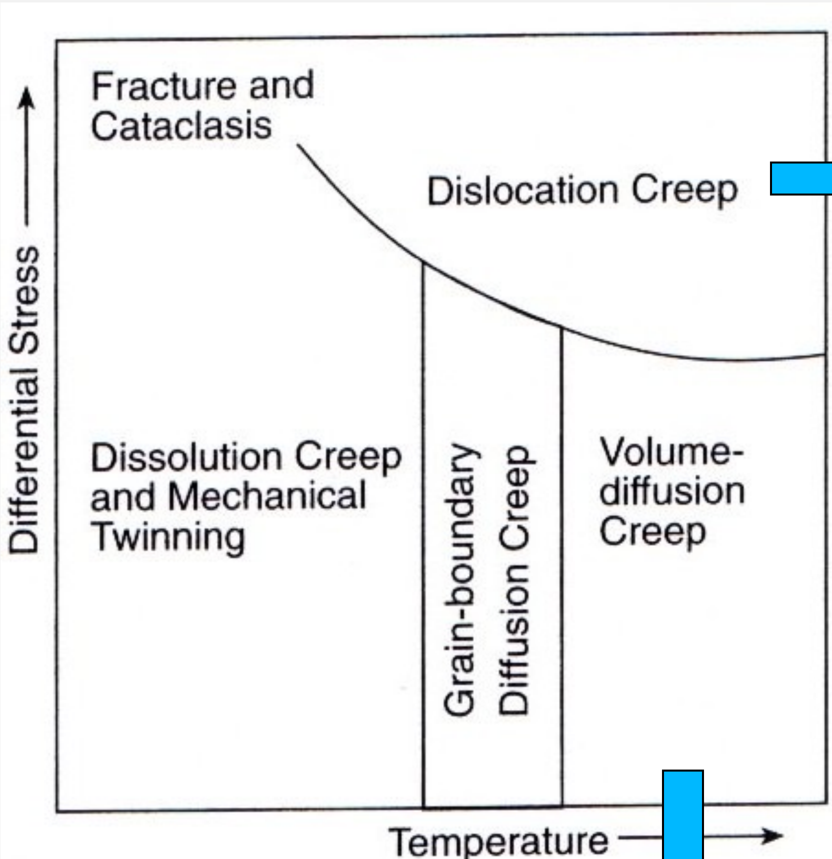
doi:10.1038/nature13072

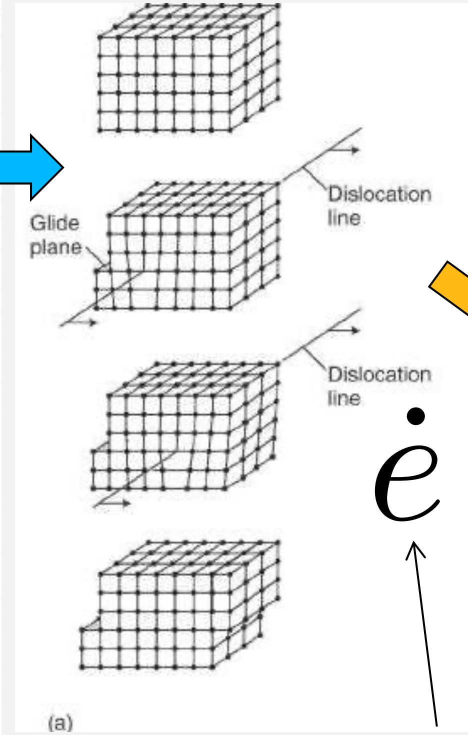
Plate tectonics, damage and inheritance

David Bercovici[1] & Yanick Ricard[2]



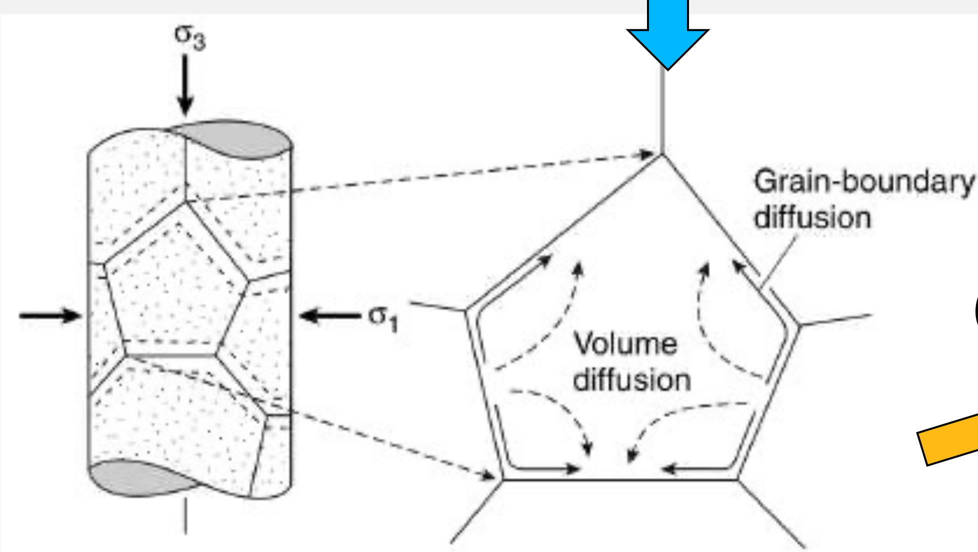
Mantle rock "creep" rheology





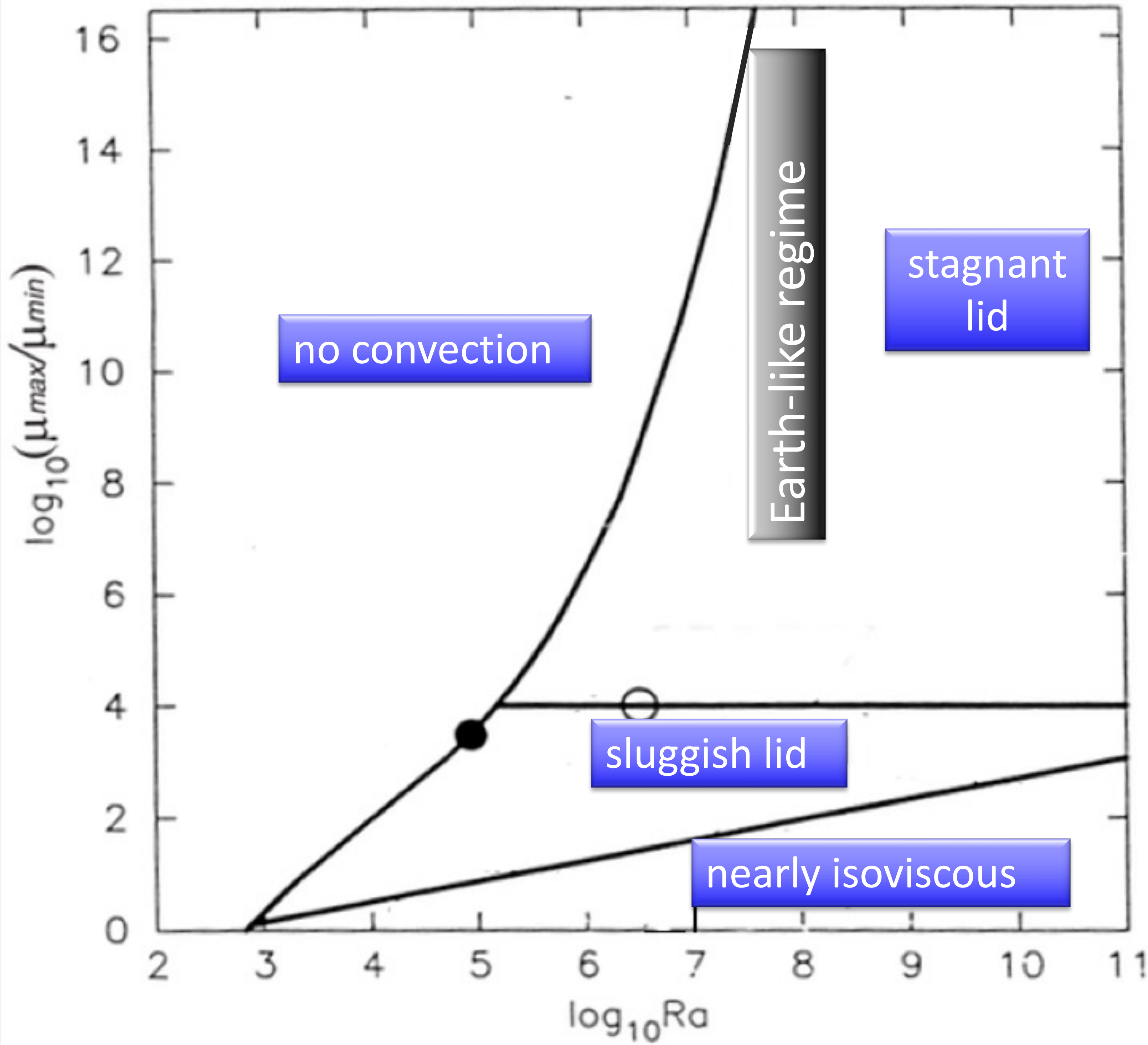
$$\dot{e} = A(T)\sigma^n$$

strain-rate, temperature, stress



$$\dot{e} = B(T)\sigma/\mathcal{R}^m$$

strain-rate, temperature, stress, grain-size



V. Solomatov (1995)

Plate Generation Mechanisms

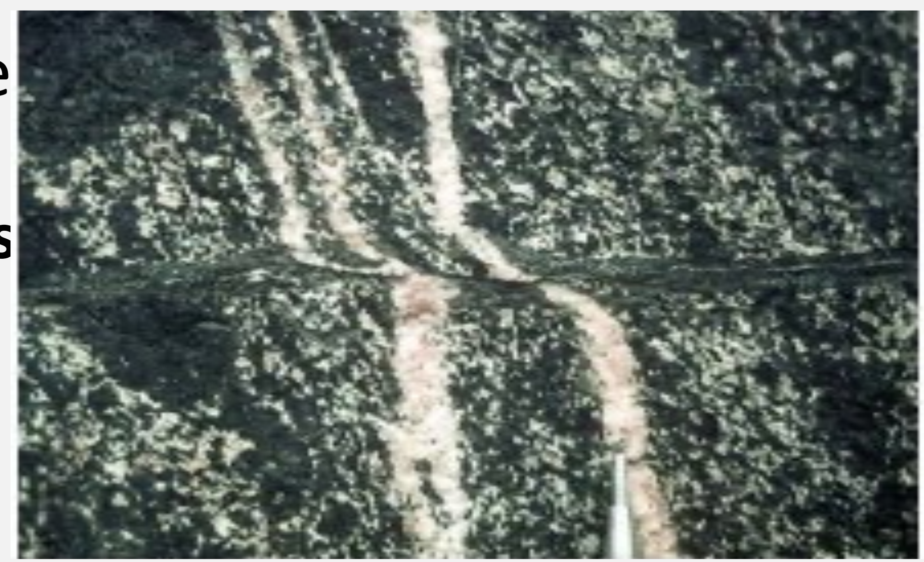
Most terrestrial mantles undergo *stagnant lid* convection

Earth has self-softening feedbacks

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

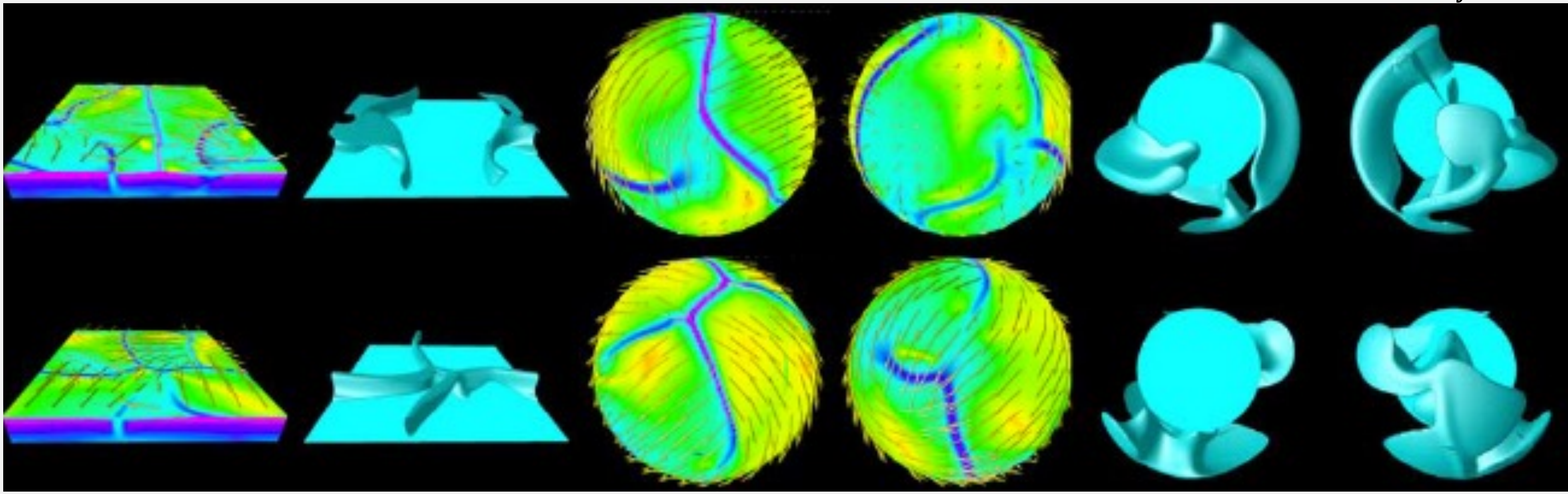
Allows convecting mantle to generate

- strong broad plates,
- narrow, weak **long-lasting boundaries**
- **localized strike-slip shear**

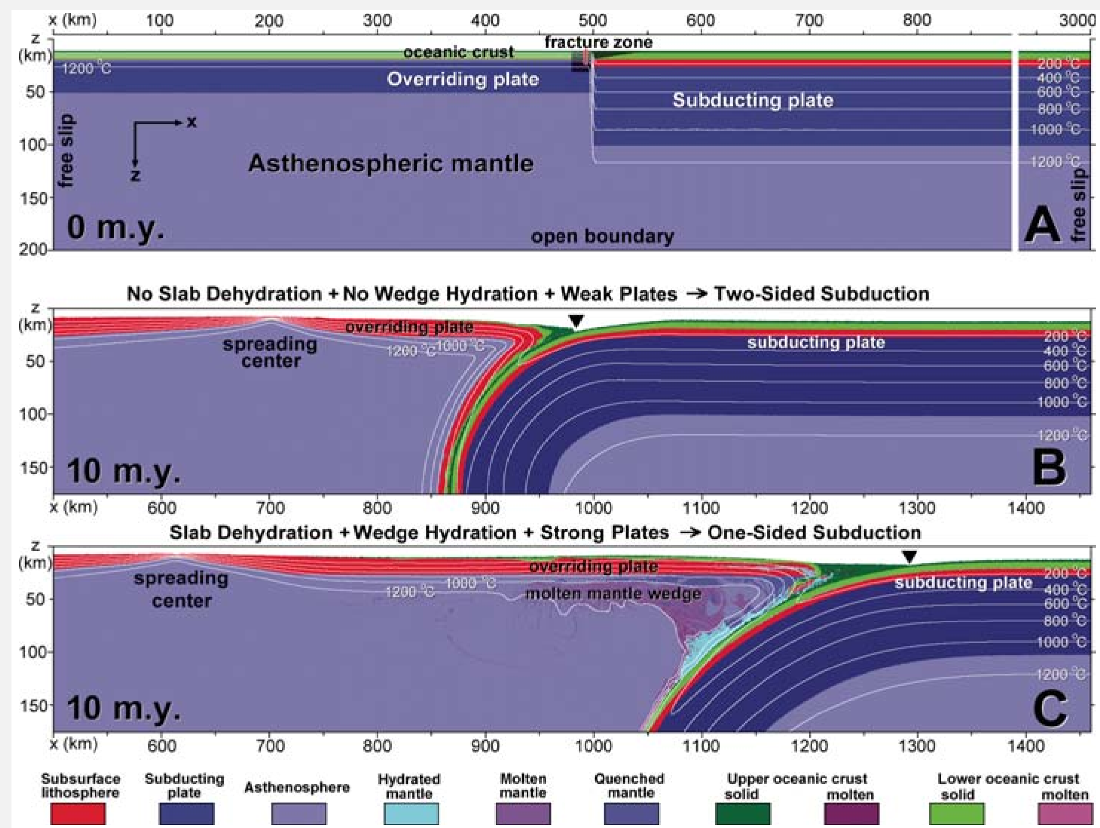


Self-weakening mechanisms

Van Heck & Tackley 2008



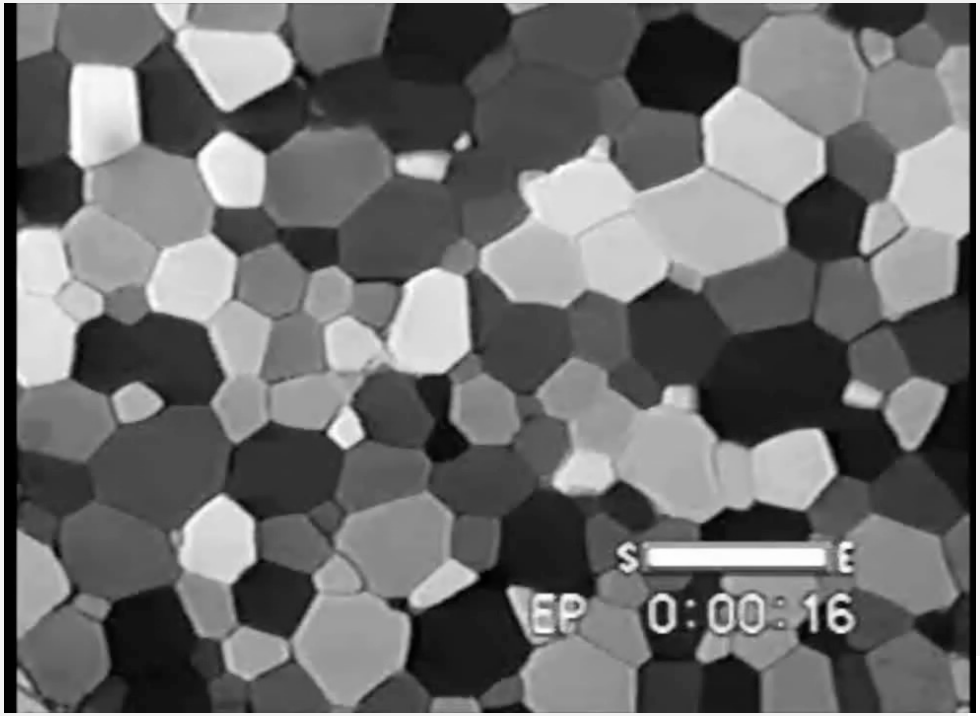
- Plastic yielding
- Velocity weakening
- Water ingestion



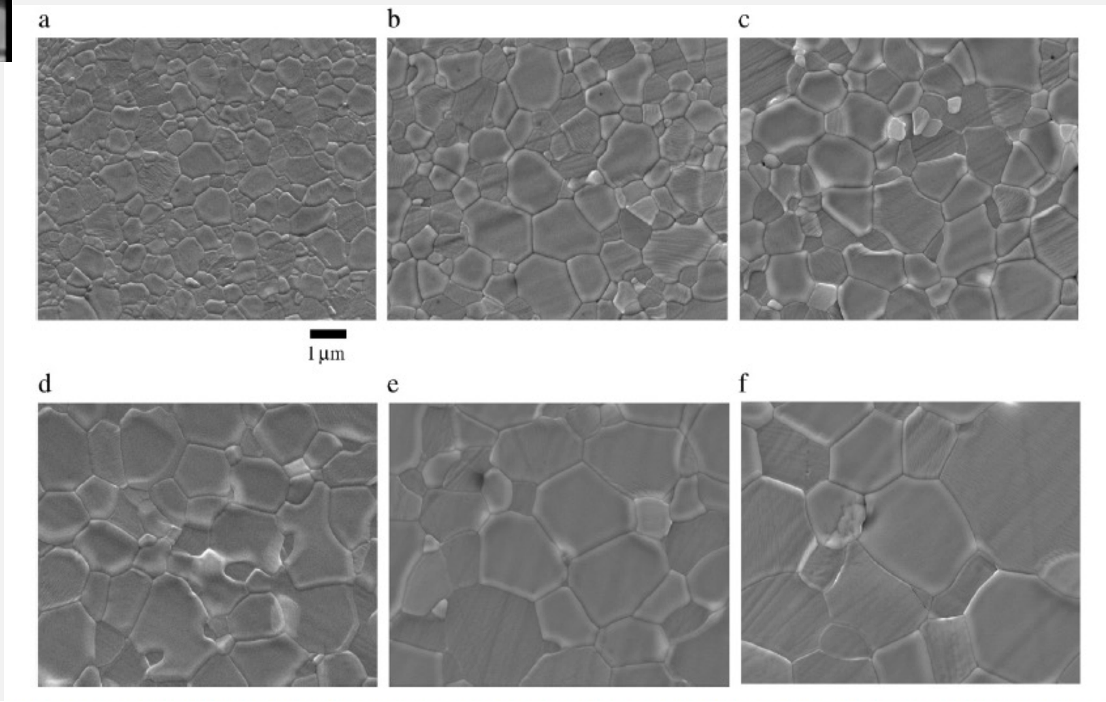
Gerya, et al 2008

Grain-scale Processes

- Mineral grains grow if “static”



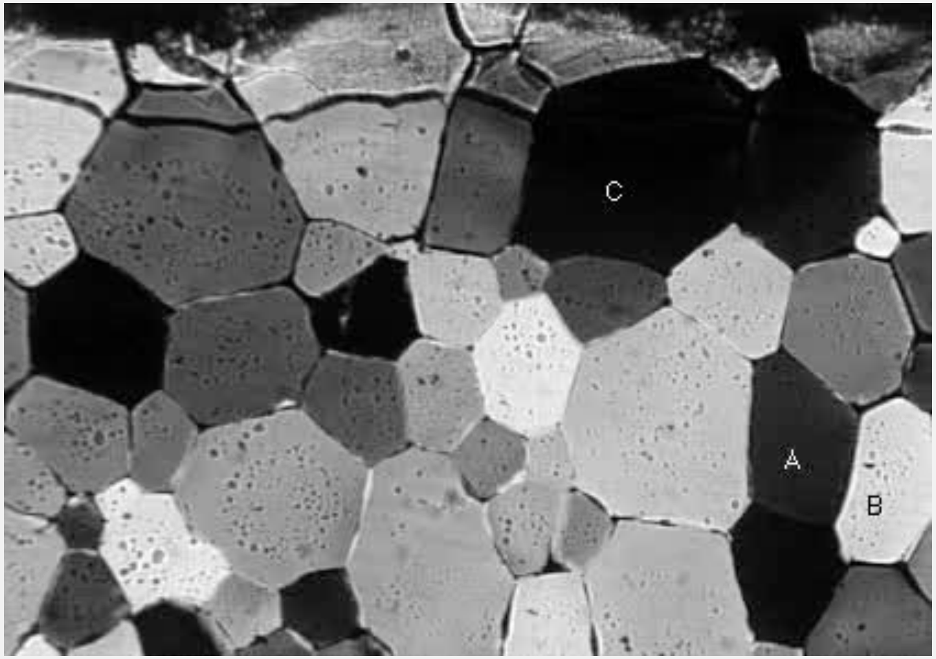
Octochlorpropane (Park et al 1997)



Hiraga et al 2010

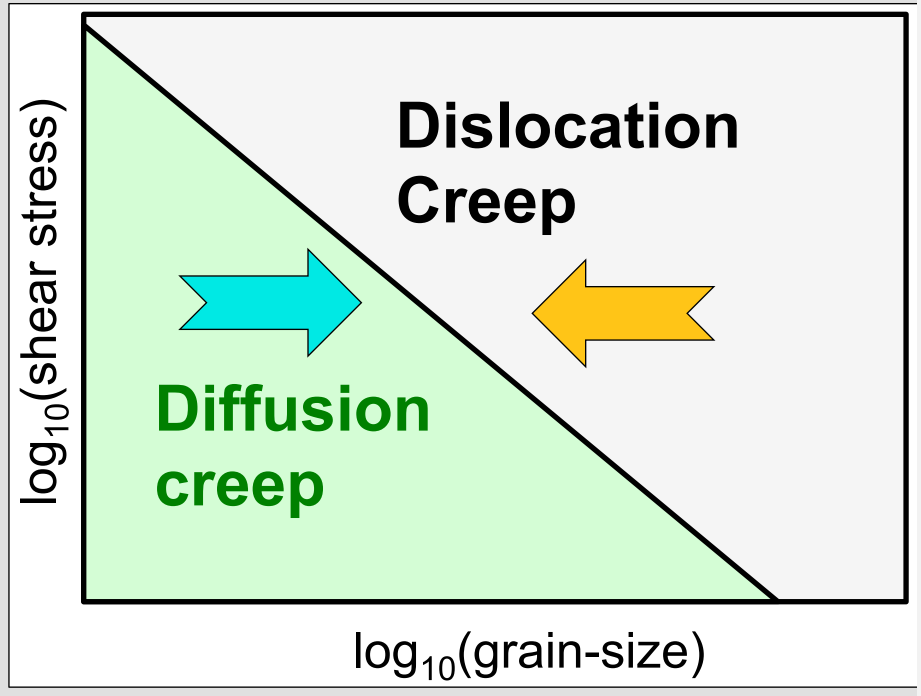
Grain-scale Processes

- 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**

www.atmos.albany.edu/geology/webpages/wdmovies/wdmoviep.html



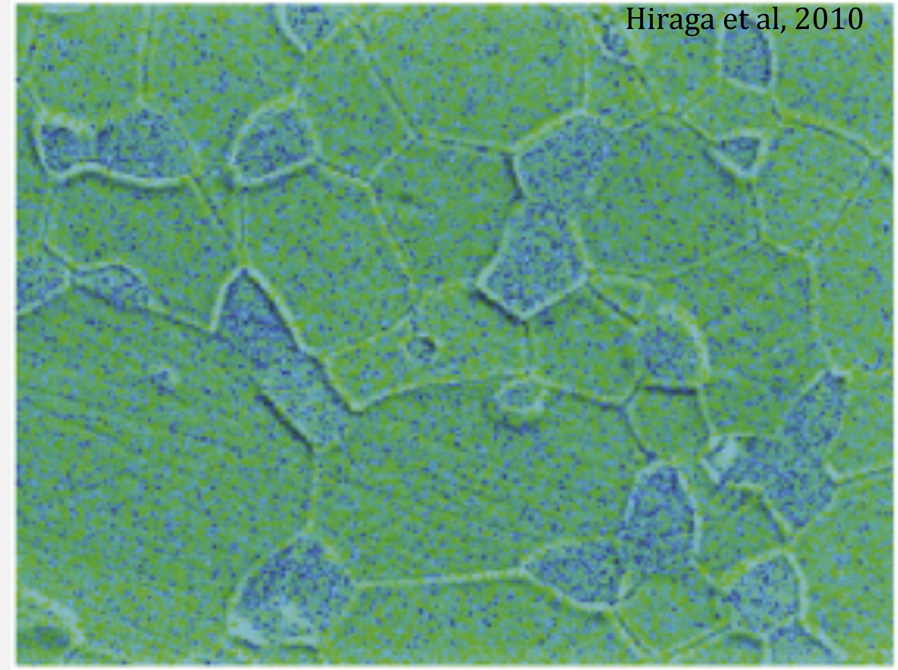
But in single-phase rocks…

- Grain reduction only in dislocation creep (*dynamic recrystallization):* independent of grain-size
- Grain-size weakening only in diffusion creep when grains only grow
- **Shoudn't be any self-softening feedback**
  - de Bresser et al (2001)

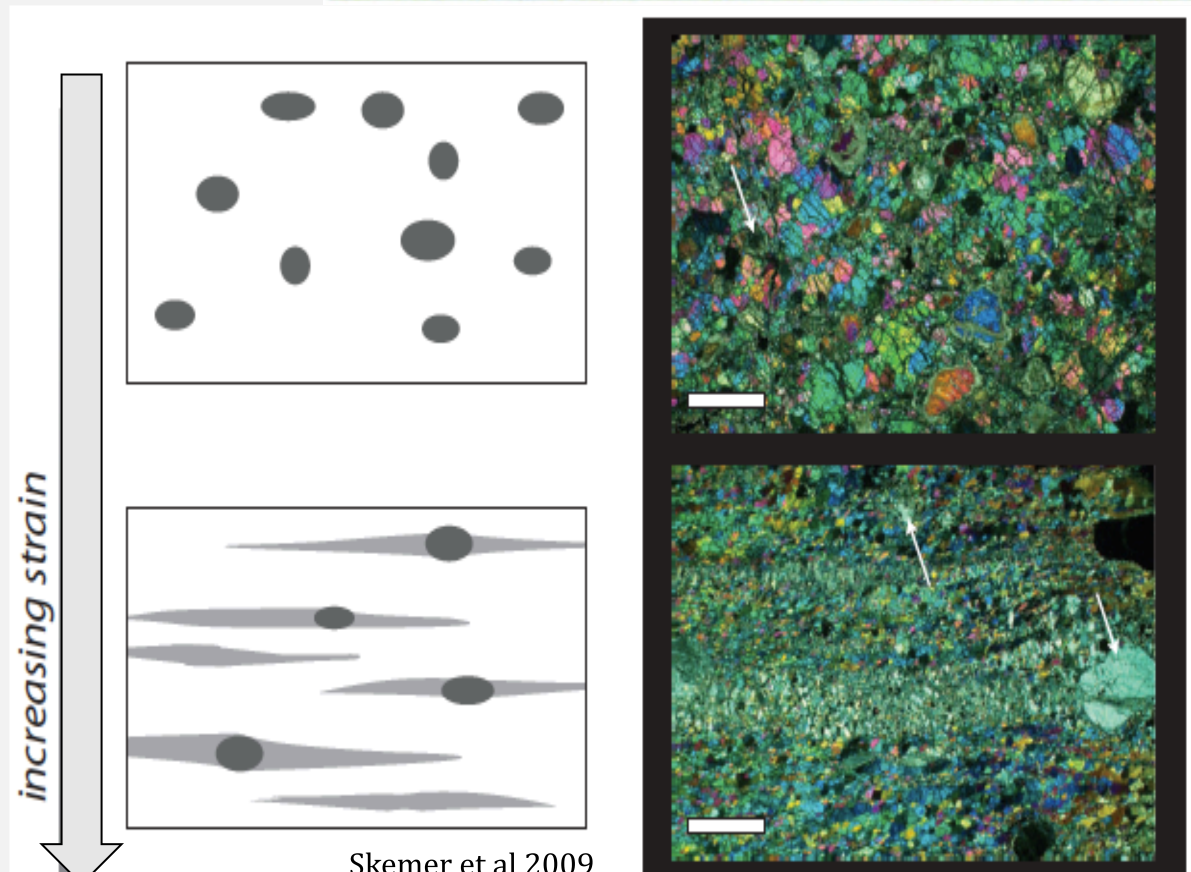
*Grain-damage & pinning in rock mixtures**

- 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 *pinning* drives grains to smaller sizes and material softens
- **Damage and softening coexist**
- **Pinning retards healing**

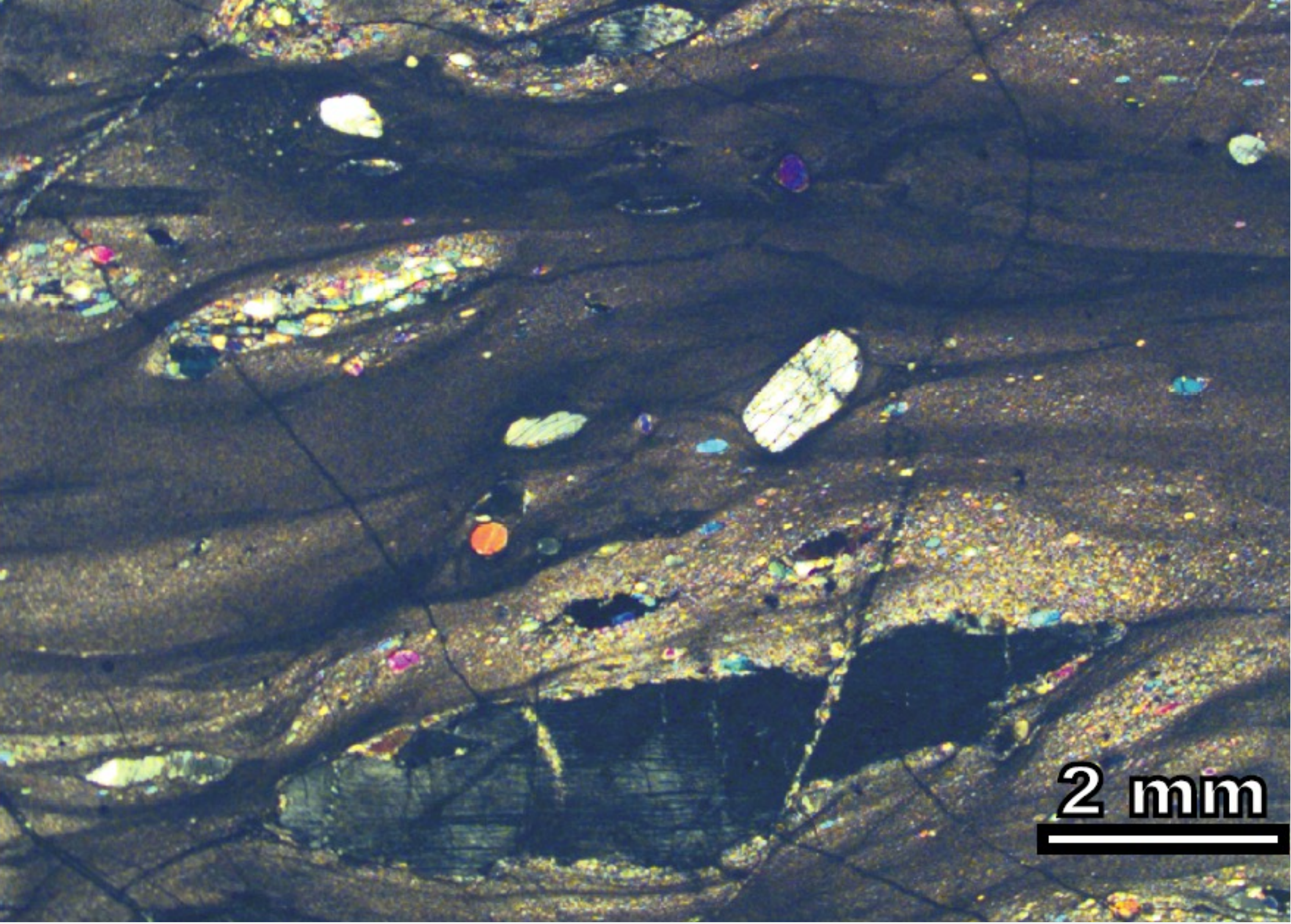
*Bercovici & Ricard 2012, 2013



Hiraga et al, 2010

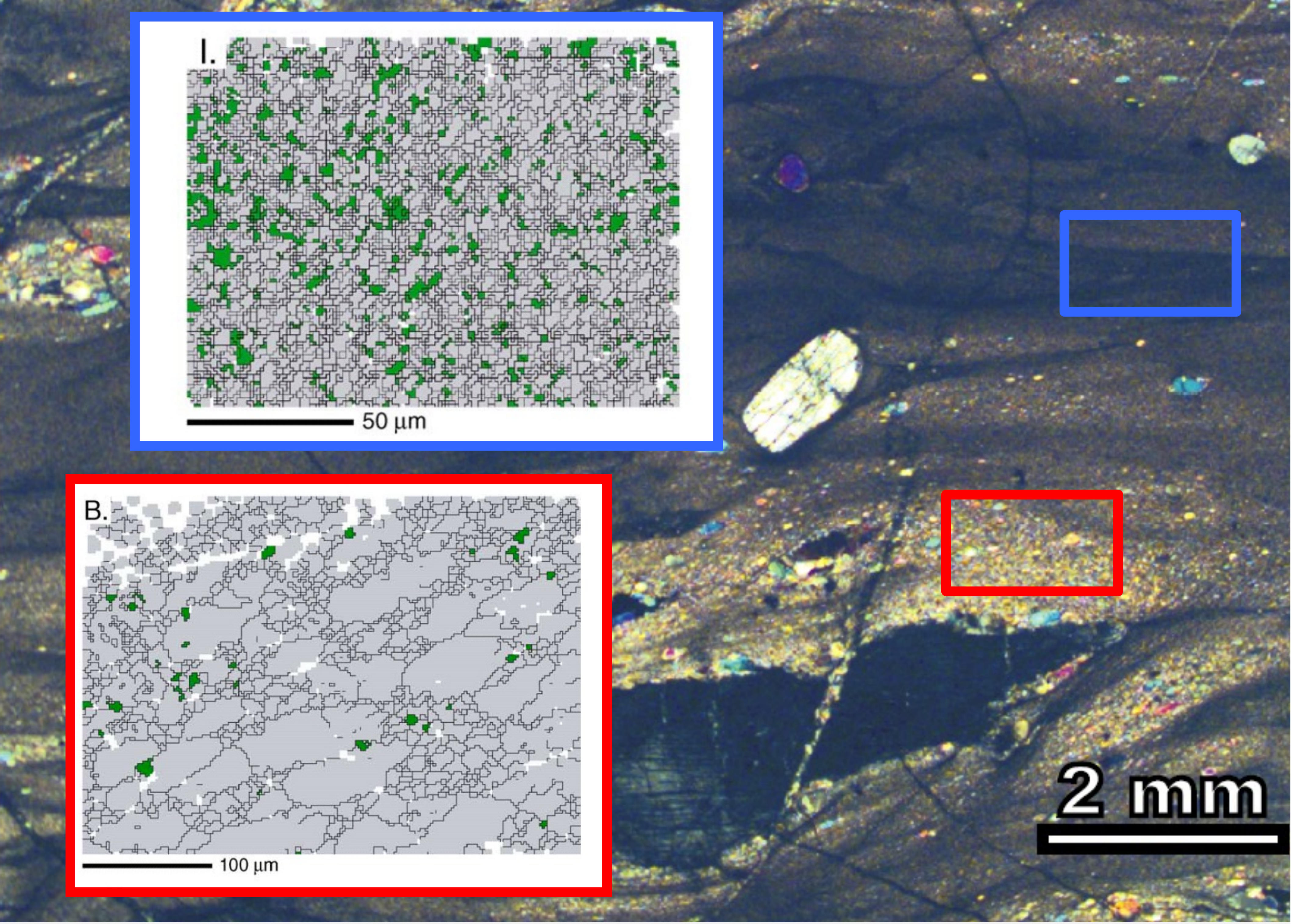


Skemer et al 2009



Peridotite Mylonite from MAR Fracture Zone

Jaroslow et al., 1996



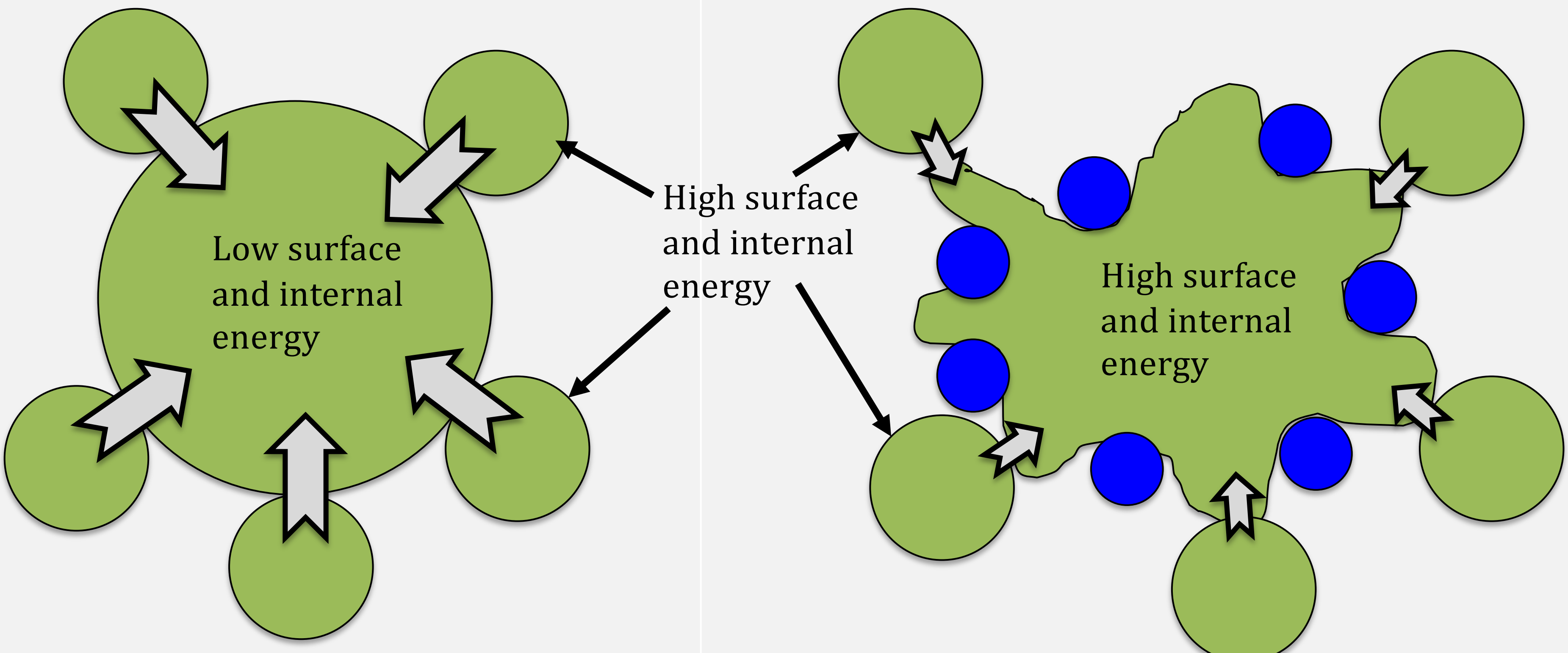
Peridotite Mylonite from MAR Fracture Zone

Jaroslow et al., 1996

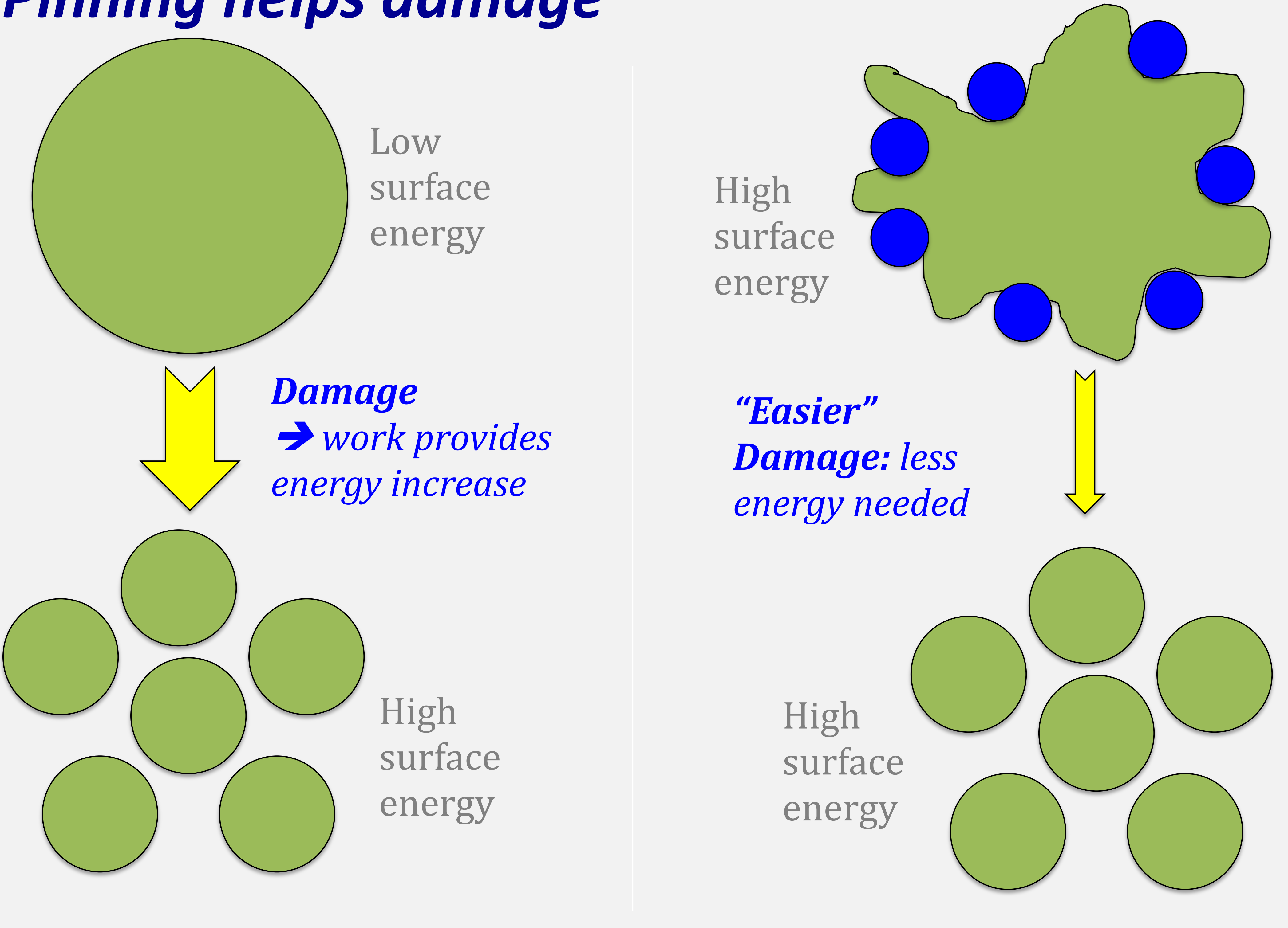
Pinning slows grain-growth

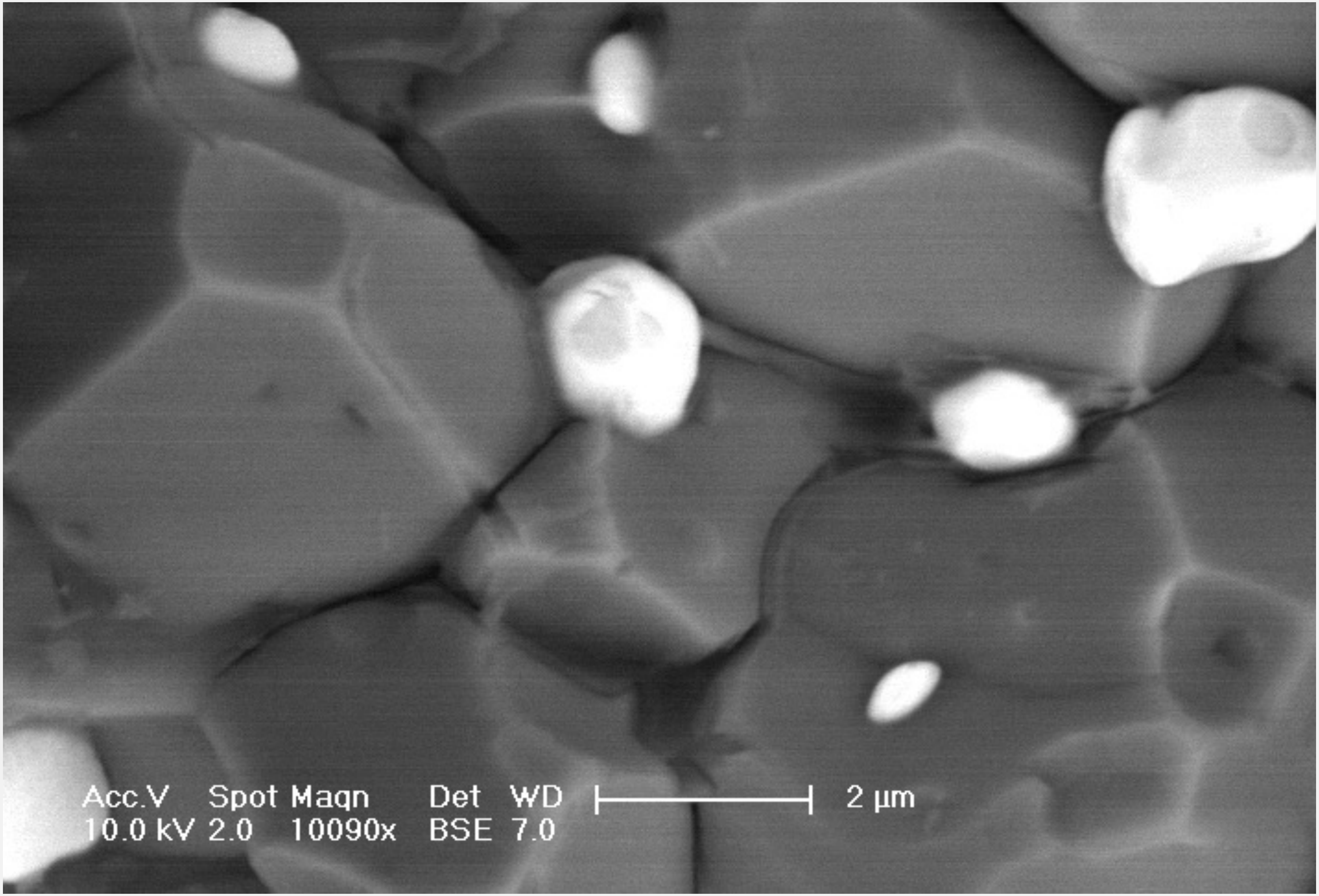
Single-phase coarsening

In two-phases with pinning, coarsening is impeded



Pinning helps damage





Grain growth experiments in MgO +ZrO_2 composite (1000K, 5GPa, 1hour)
Shows divots in MgO grains from distortion by ZrO_2 grains
Compliments of Jennifer Girard, Yale

Coupled "interface" and "grain-size" evolution laws

coarsening healing

damage

Interface "roughness" or radius of curvature *r*

$$\frac{Dr^q}{Dt} = \mathcal{C}_I - q\mathcal{D}r^{q+1}\bar{\Psi}$$

Grain-size $\mathcal{R}_i$ in each phase

$$\frac{D\mathcal{R}_i^p}{Dt} = \mathcal{C}_i\mathcal{Z}_i - p\mathcal{D}\mathcal{R}_i^{p+1}\frac{a_i\tau_i^{n+1}}{\mathcal{Z}_i}$$

Zener pinning factor

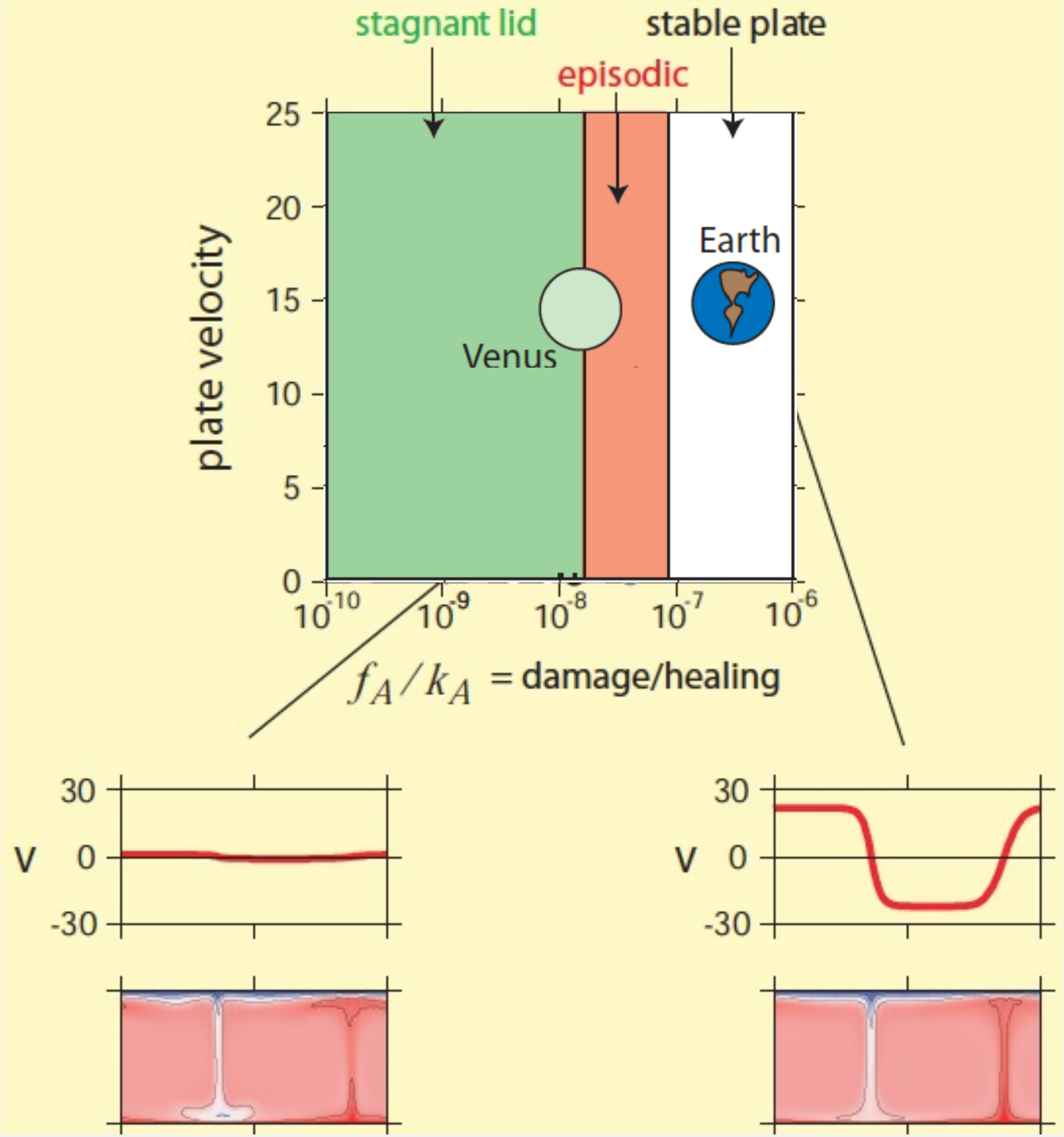
$$\mathcal{Z}_i = 1 - \mathfrak{c}(1-\phi_i)\frac{\mathcal{R}_i^2}{r^2}$$

Composite dislocation + diffusion creep rheology

$$\underline{\dot{\mathrm{e}}} = \left(a_i\tau_i^{n-1} + b_i\mathcal{R}_i^{-m}\right)\underline{\tau}_i$$

Coefficients based on comparison to lab experiments

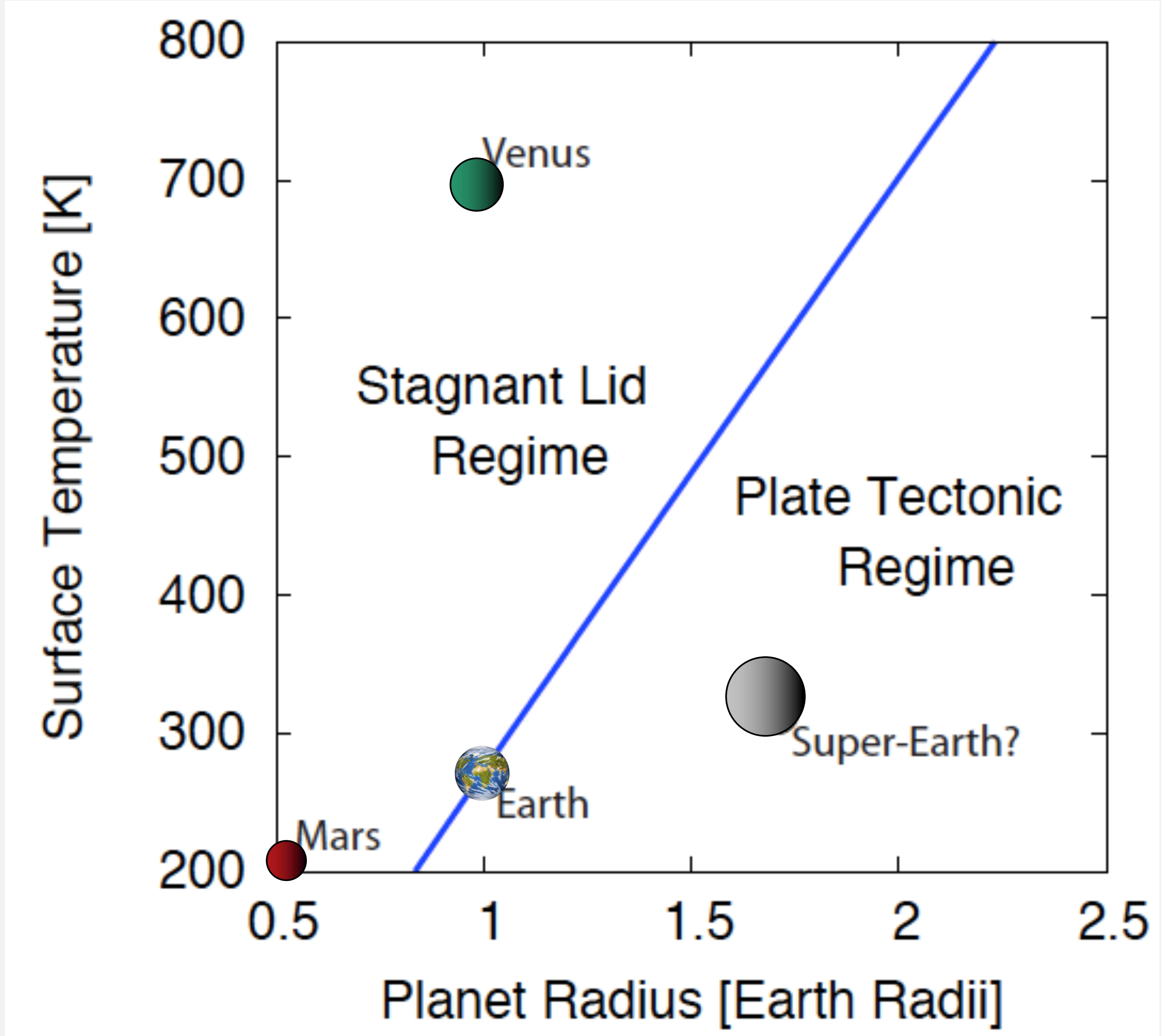
Bercovici & Ricard 2012-2016



Landuyt & Bercovici EPSL 2009

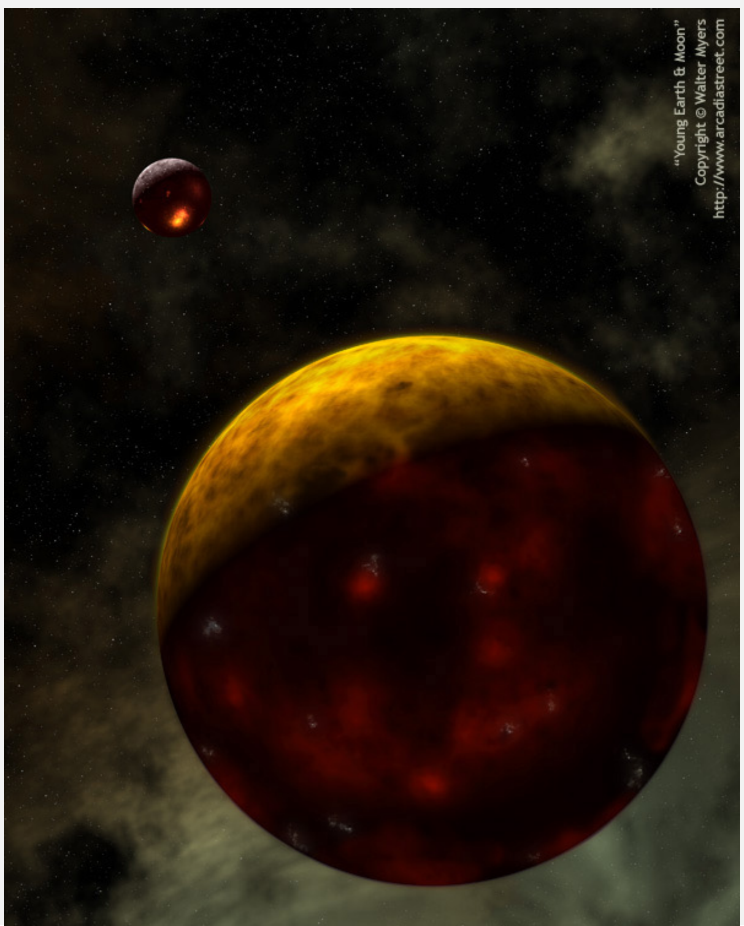
Planetary plate generation phase diagram

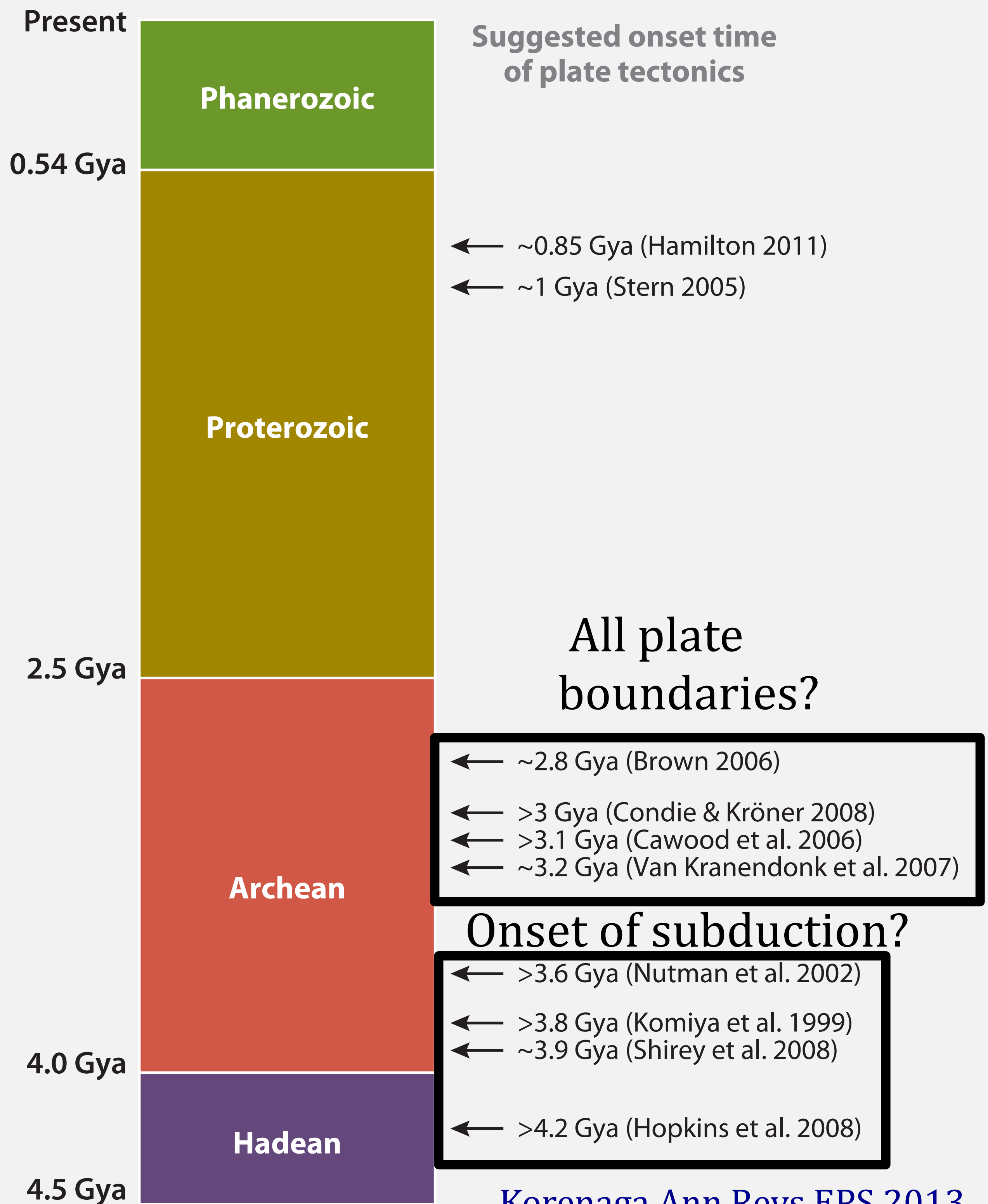
- Convection models with grain damage: "plate" state depends on ratio of damage to healing
- Healing is surface T dependent
- Convection, damage depend on size (Ra number)
- Yields a "*phase boundary*" defining when planet's surface is plate-like or stagnant



Foley et al (EPSL2012)

Emergence of plate tectonics: When and how did plate tectonics begin?

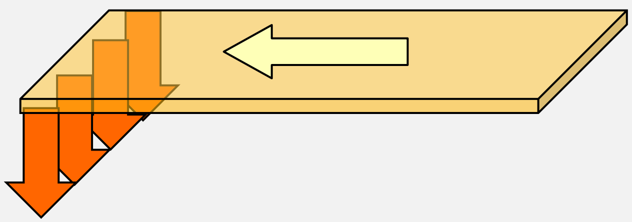


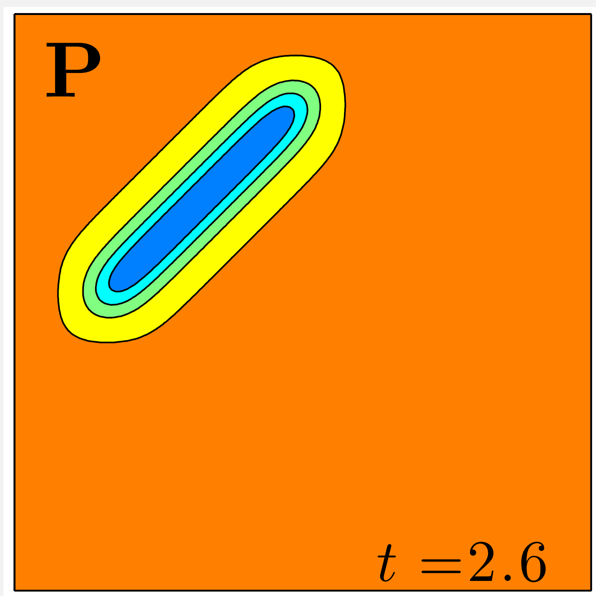


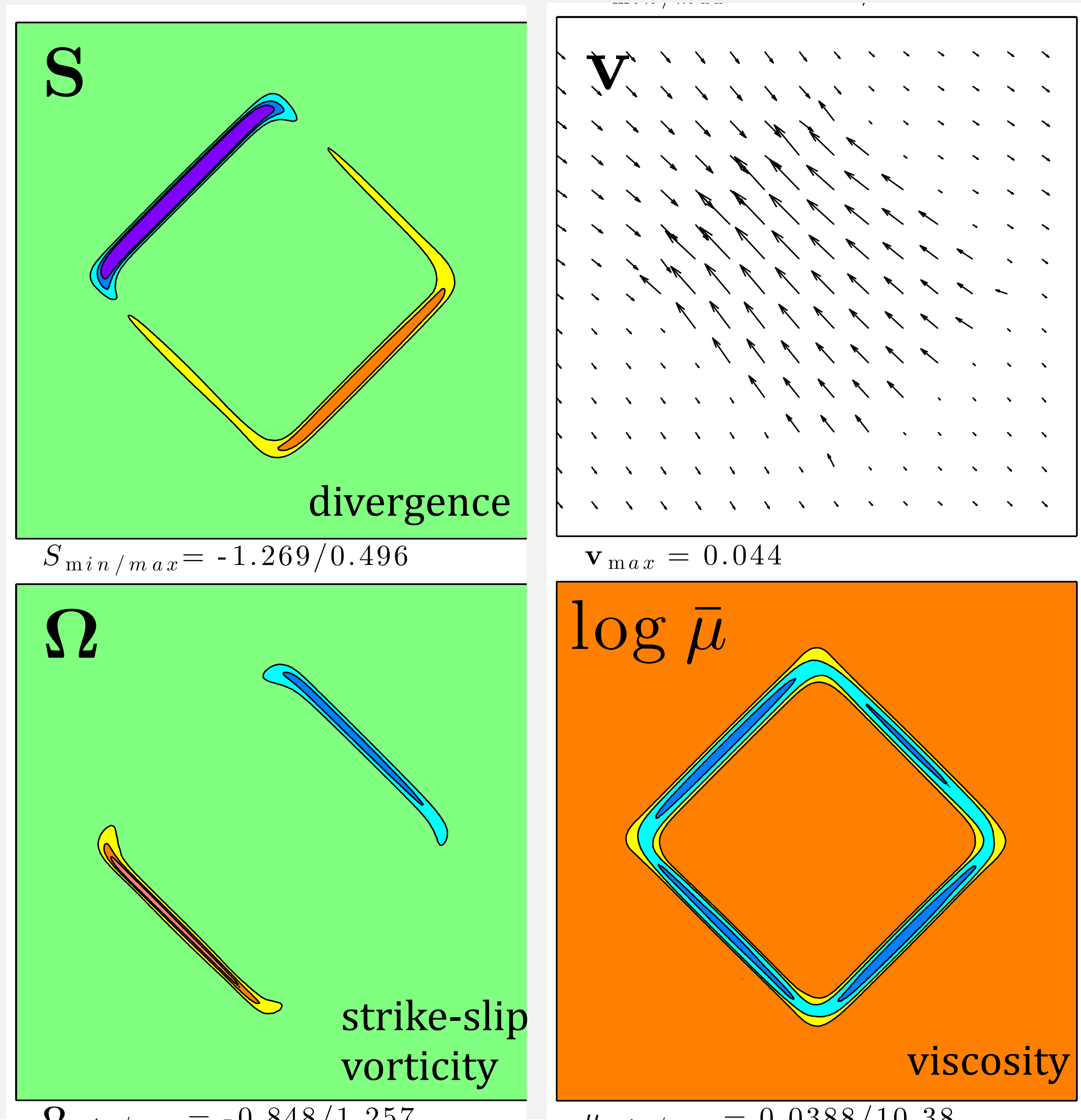
Korenaga Ann.Revs EPS 2013

Intermittent subduction and inherited damage

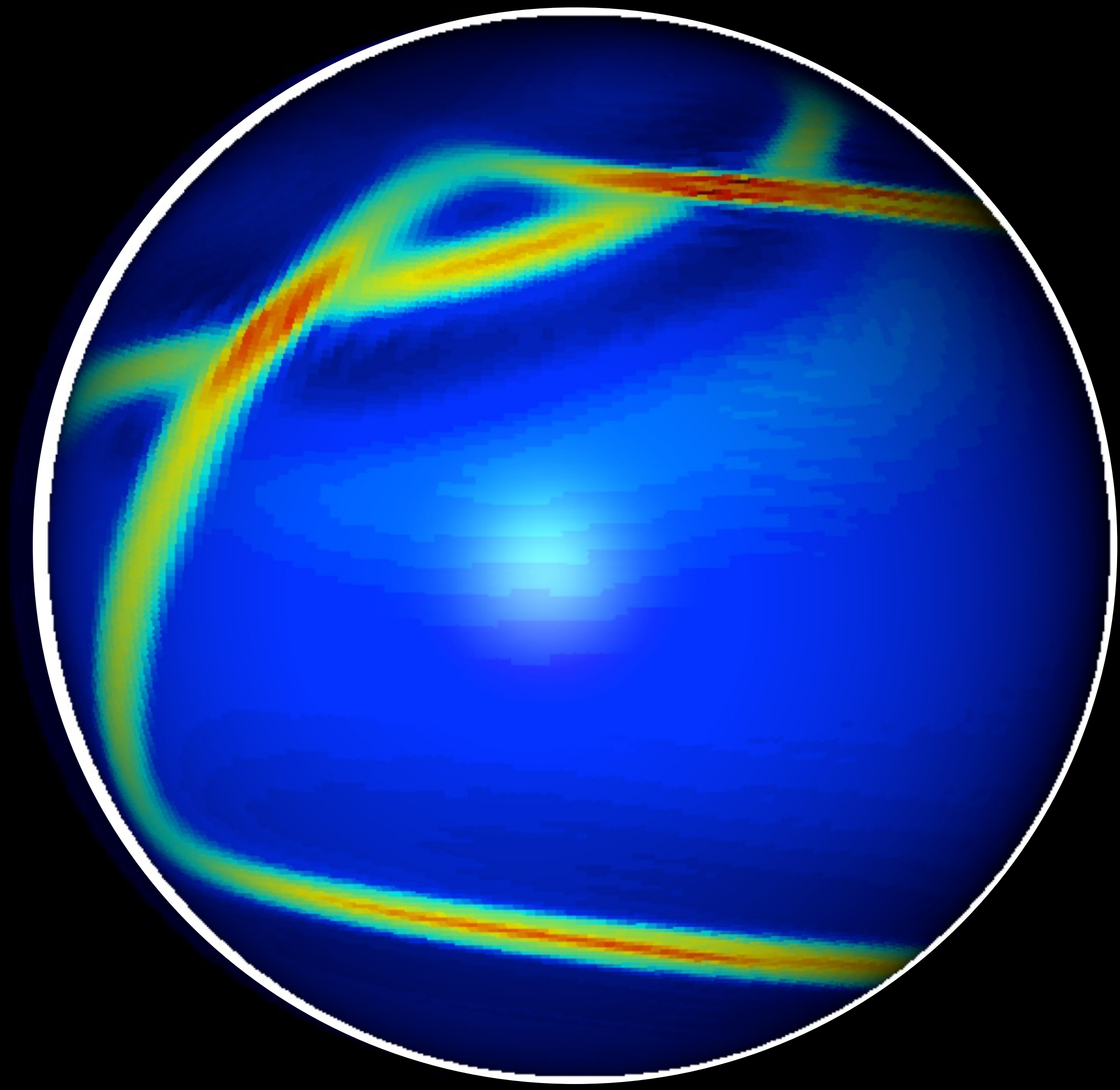
Bercovici & Ricard (2014)



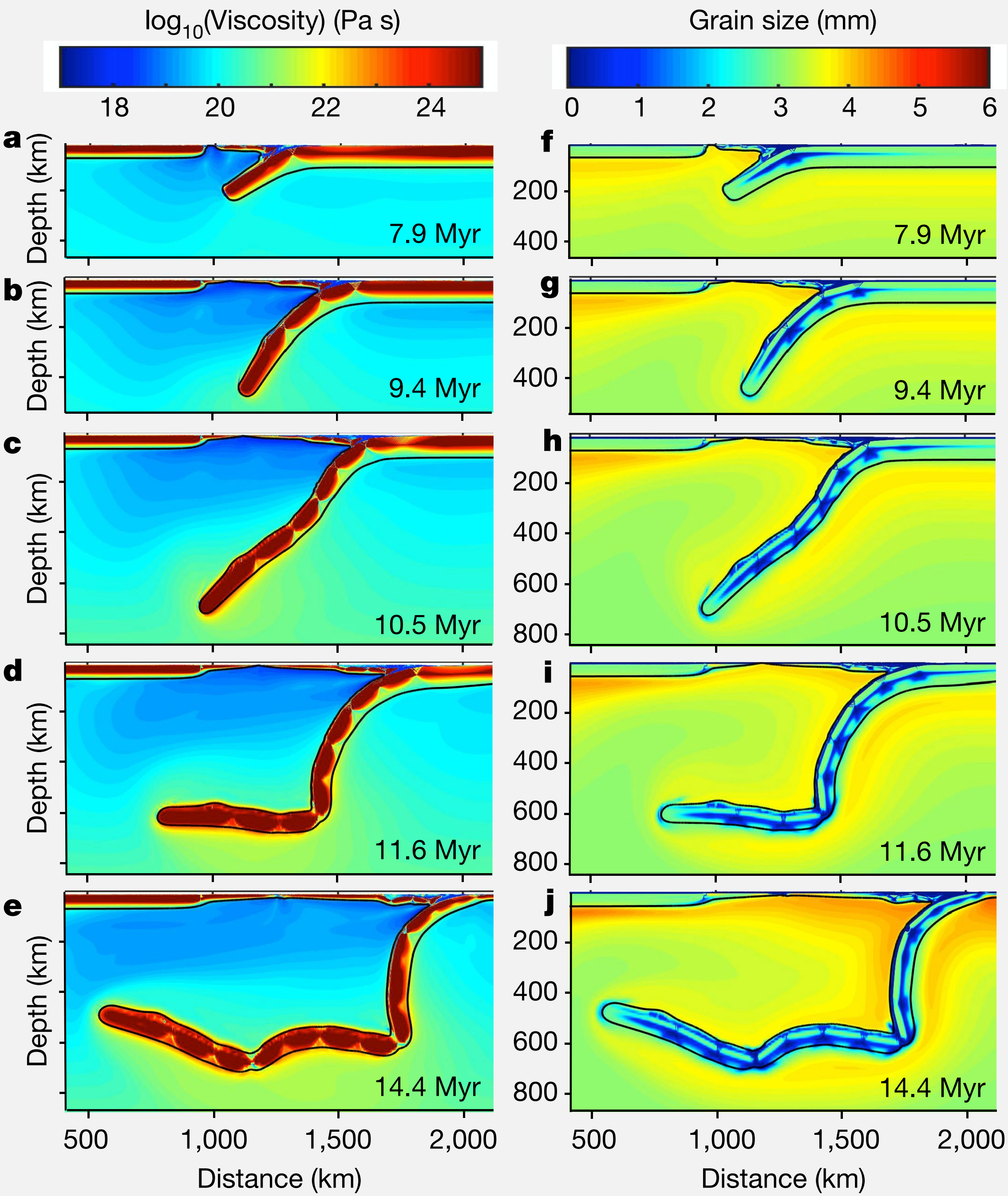




- **Migrating subduction low P zone**
- **Inherited weak zones**
- **Accumulate plate boundaries in ~ 1Gyr**



Viscosity



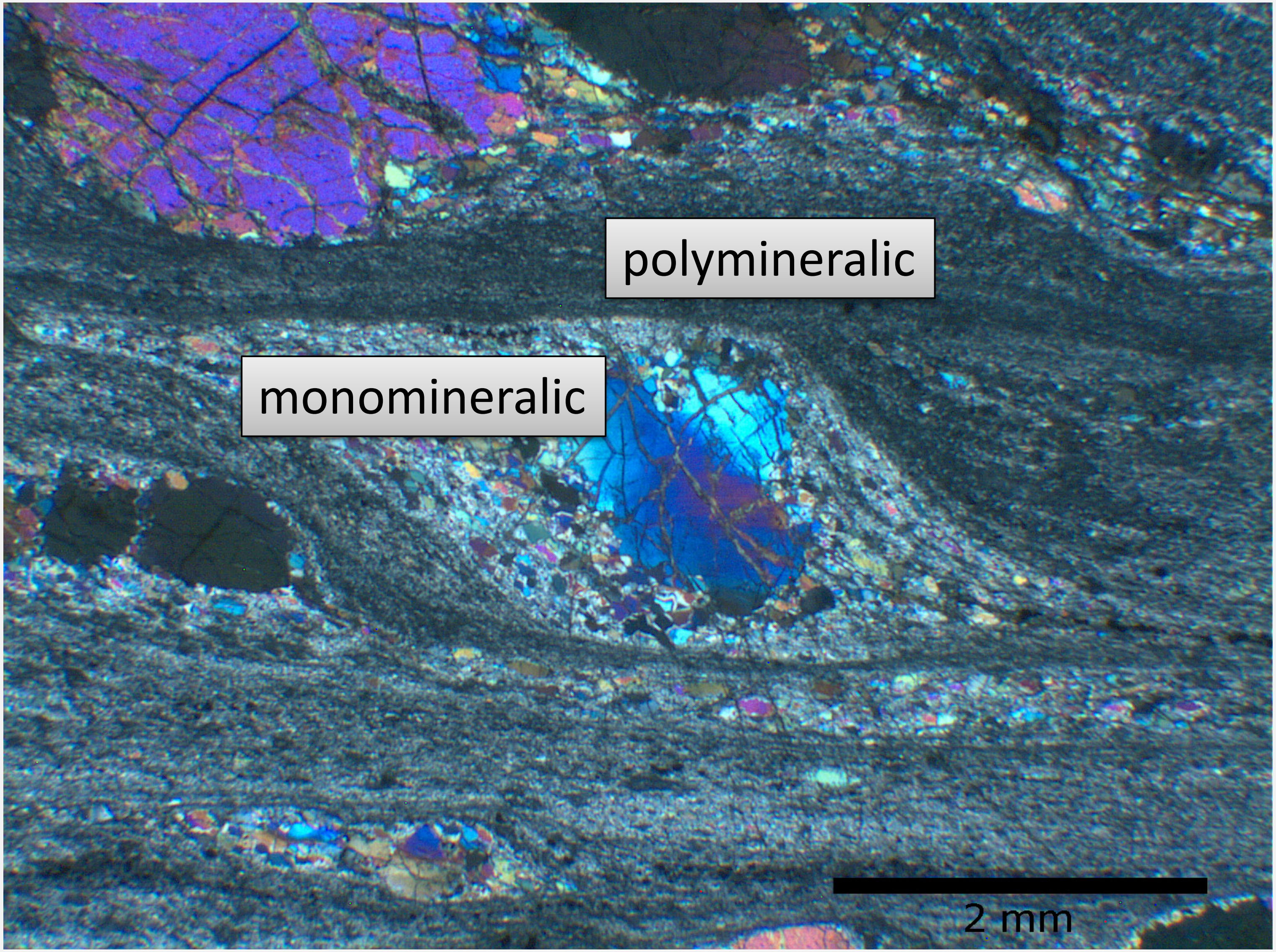
Coupling of shallow brittle failure and deeper ductile grain-damage predicts slab segmentation

Transition from strong plates to weak slabs

Large offset normal faults in outer rise

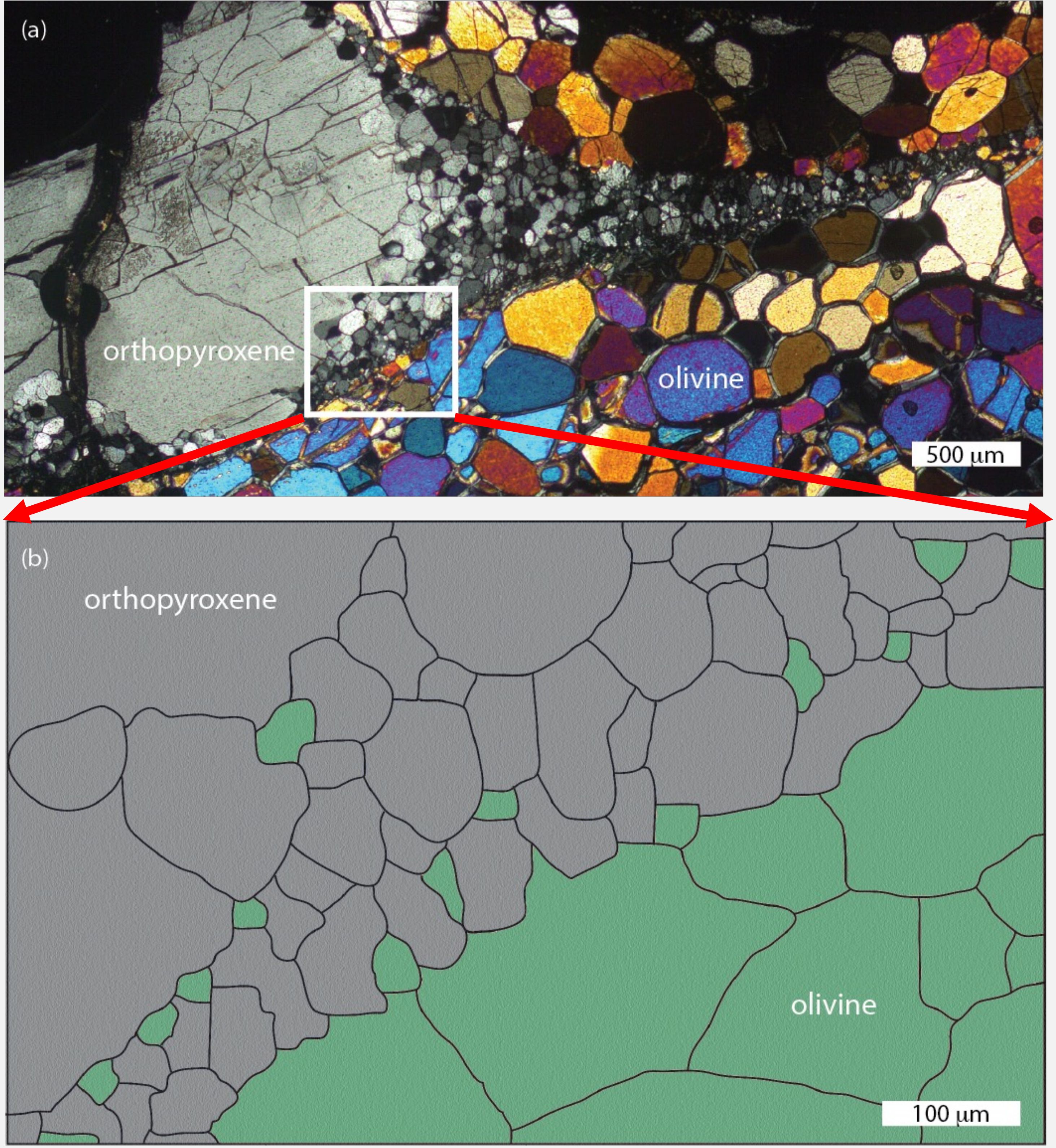
Gerya et al, Nature 2021

Grain damage and mixing



- Mylonites and ultramylonites often form bands of mixed grains (esp. in peridotites)
- Polymunerallic damage+pinning enhanced by inter-grain mixing

Grain mixing in deformation

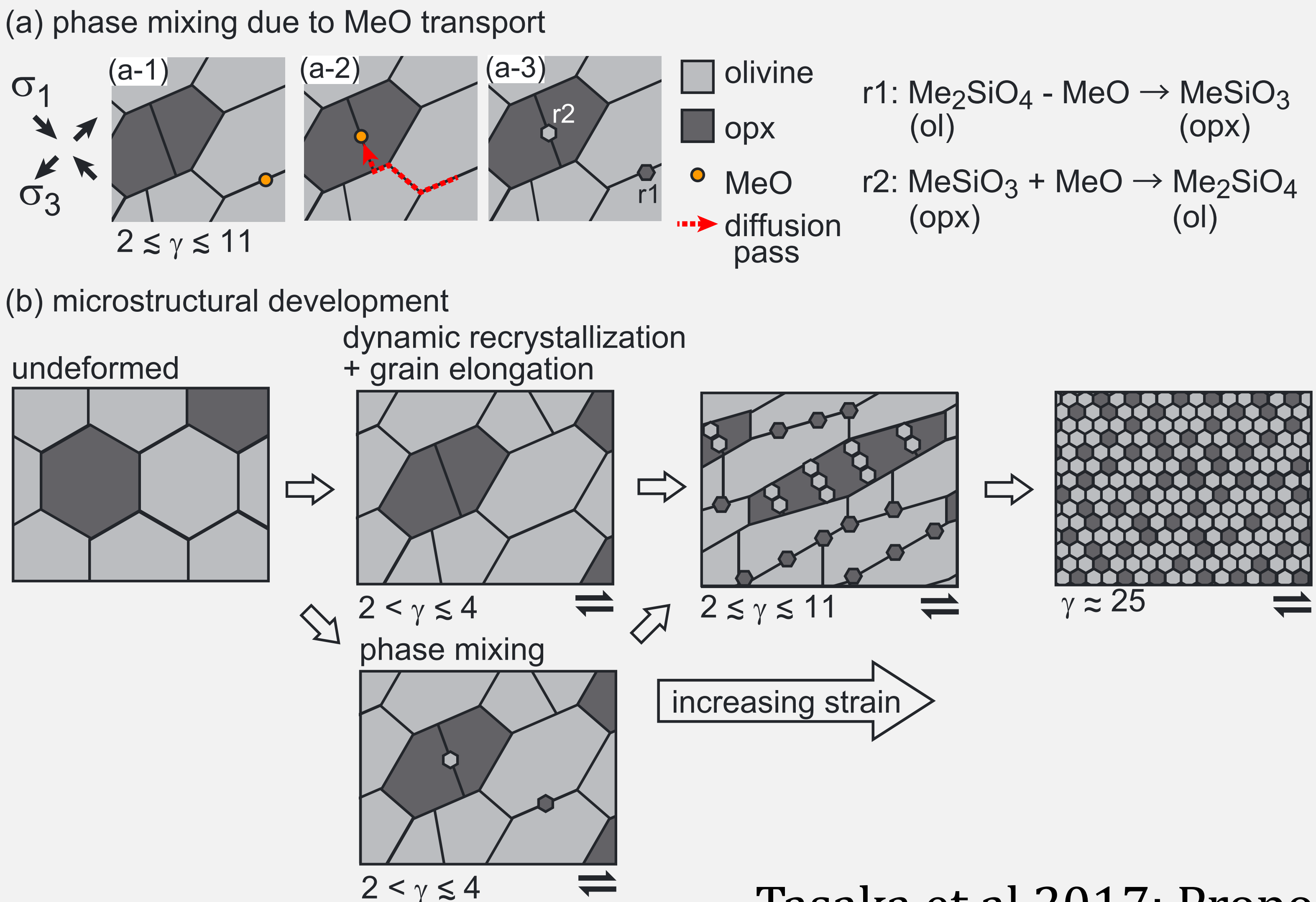


Sheared (lherzolite) peridotite (Skemer & Karato 2008)

Drawing after EBSD image (Bruijn & Skemer 2014)

Inspired "tooth" model of Bercovici & Skemer 2017

Grain mixing in deformation

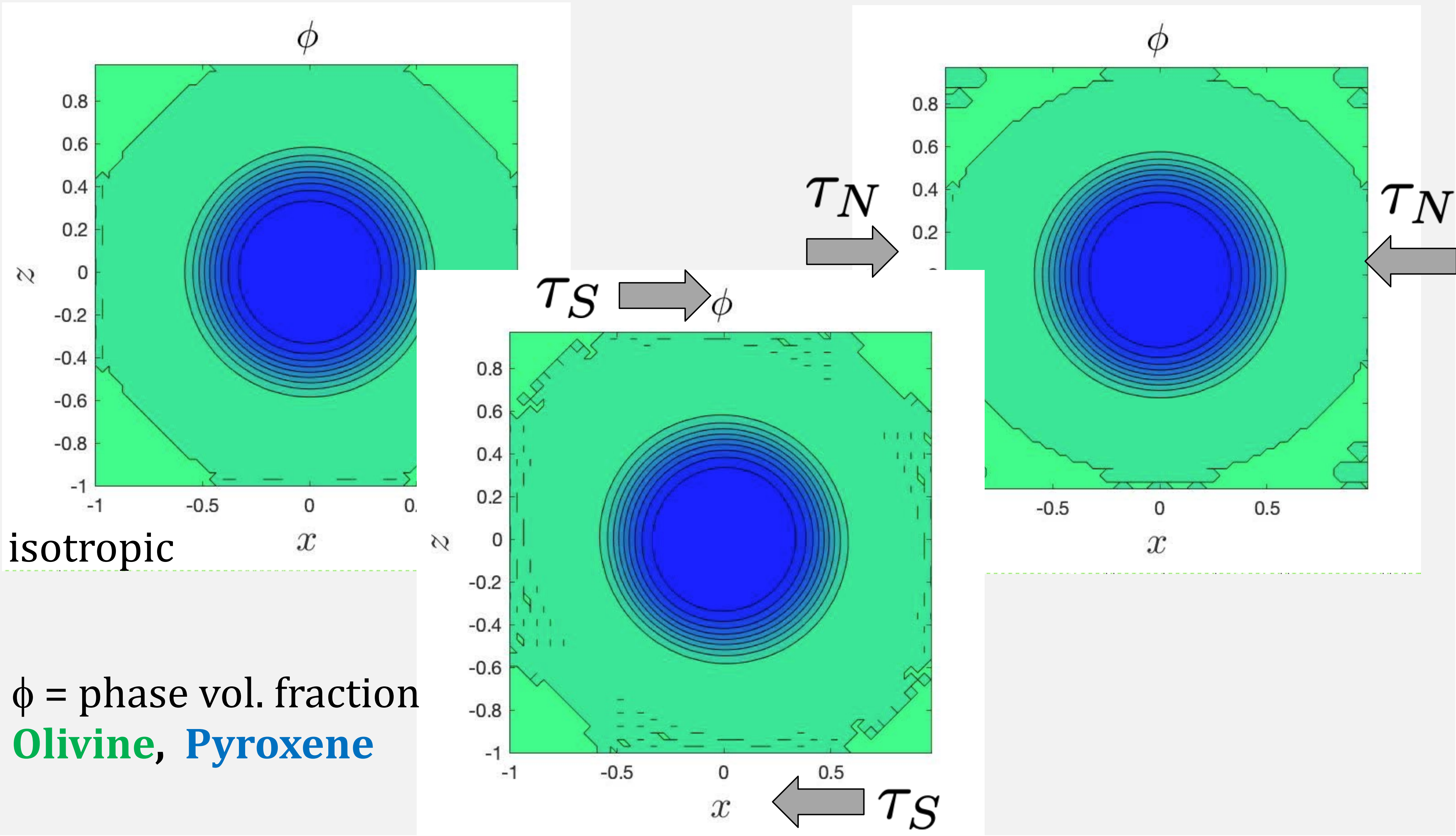


Tasaka et al 2017: Proposed mixing by heterogenous nucleation:
Ion diffusion from compression to tension

Grain mixing and stress in 2D

Simple diffusive grain mixing under applied normal or shear stress

$$\frac{D\phi_i}{Dt} = \boldsymbol{\nabla} \cdot \left(\phi(1-\phi_i)\chi \boldsymbol{\tau}_c \cdot \boldsymbol{\nabla}\phi_i\right)$$

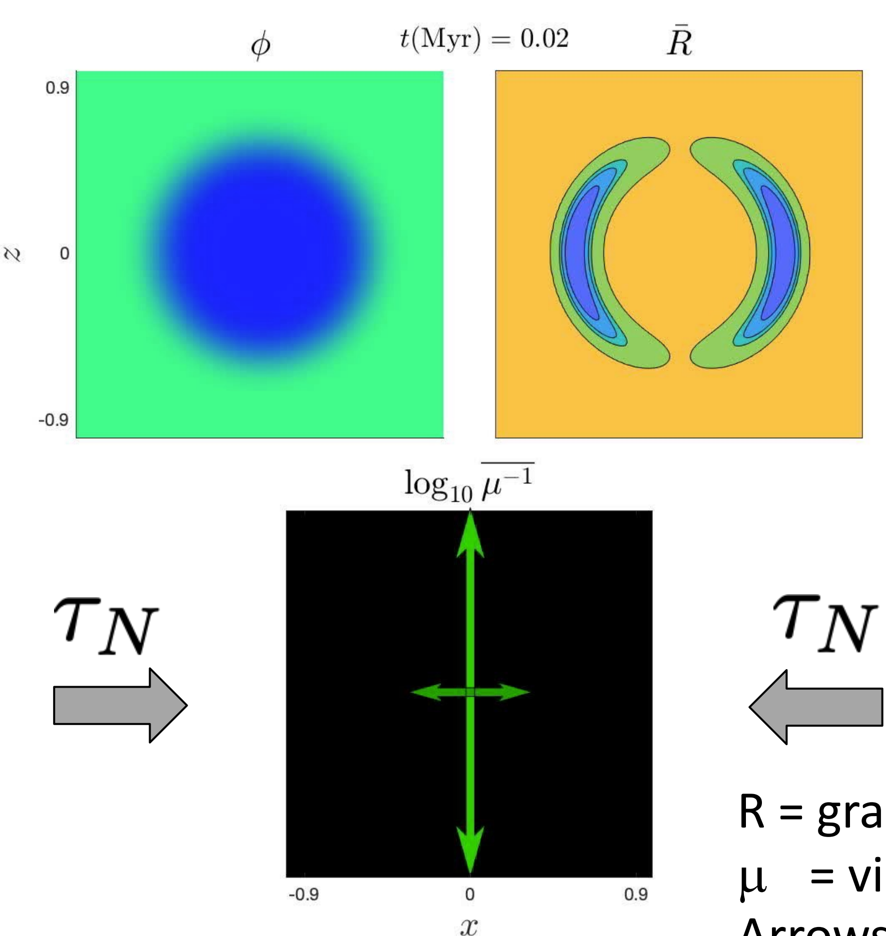


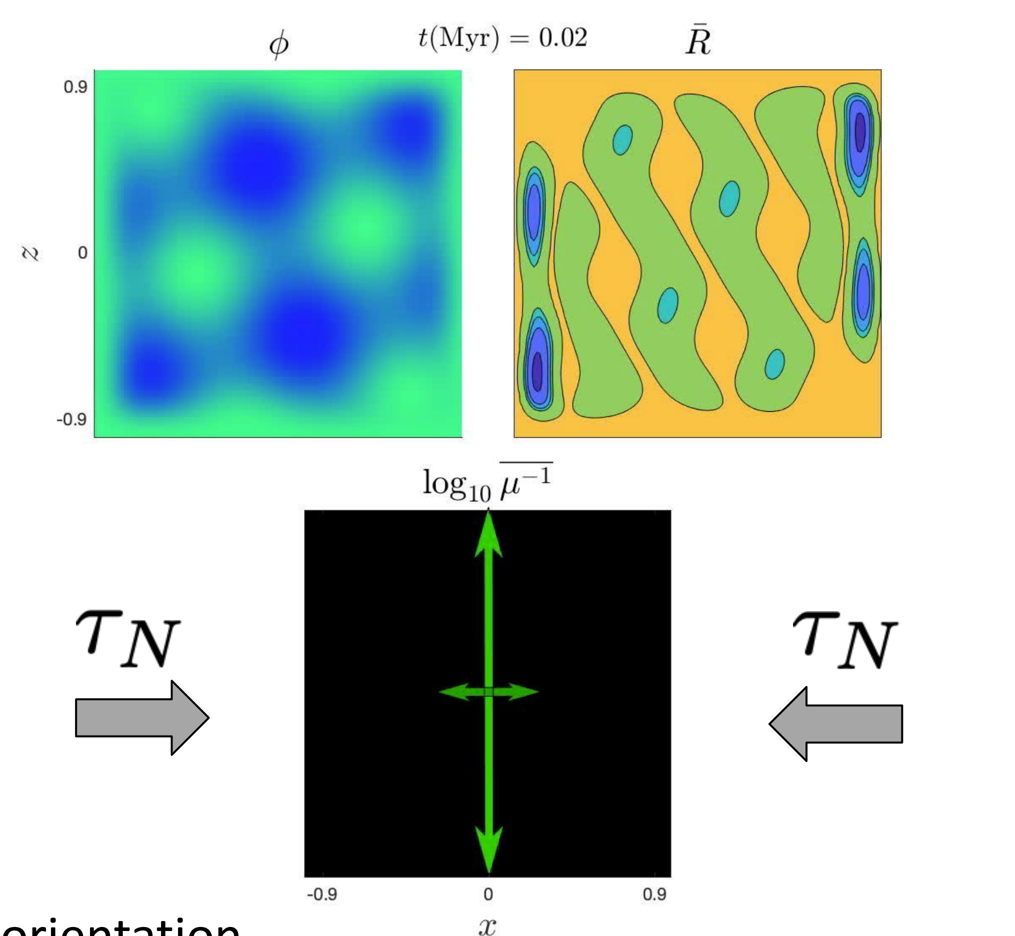
ϕ = phase vol. fraction

Olivine, **Pyroxene**

Grain mixing and damage in 2D

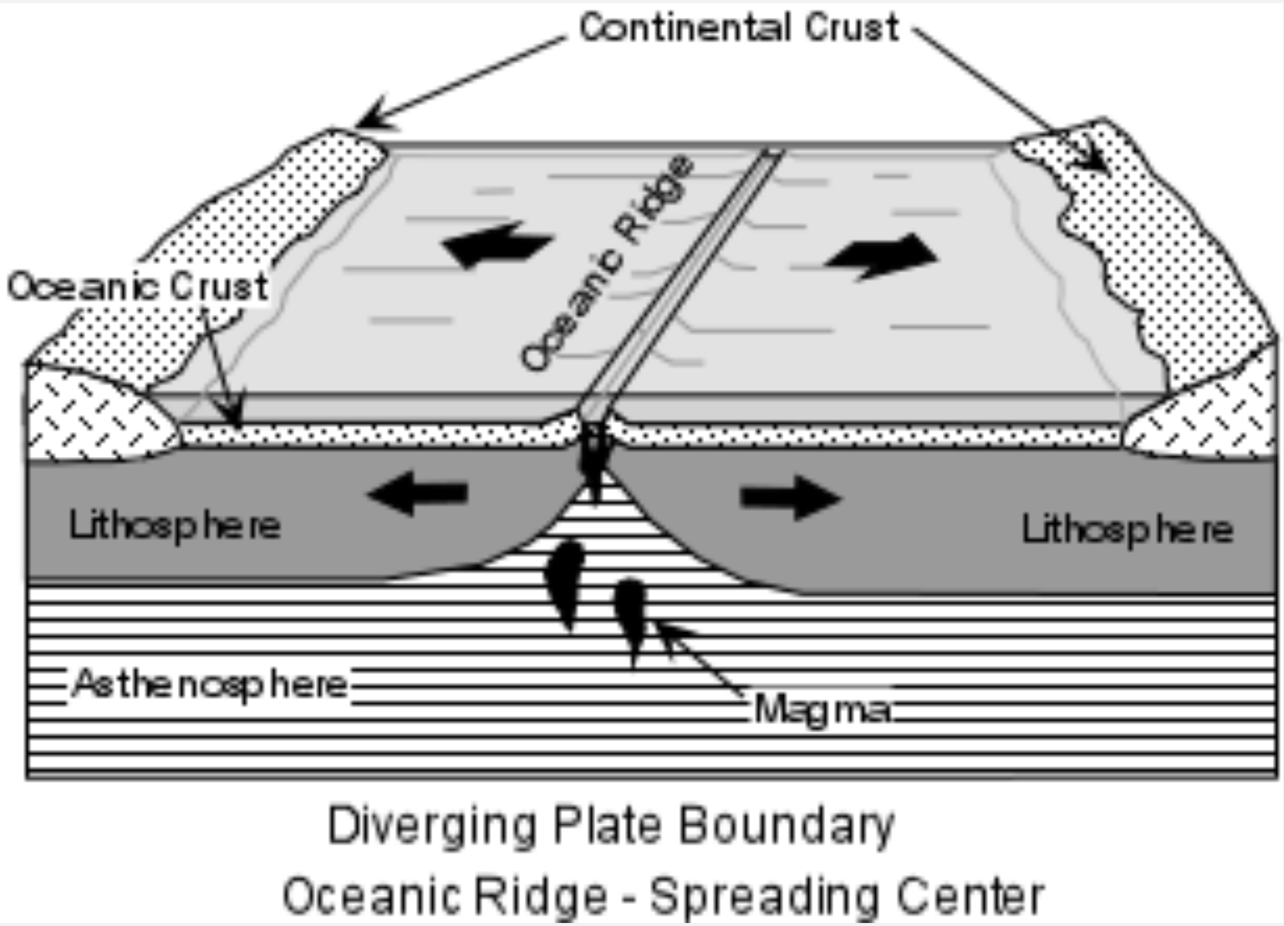
- Focussed Damage + Zener pinning where mono-phase units mix (diffusion fronts)
- “Mylonite” formation in mixed regions





R = grain size
μ = viscosity
Arrows: fabric orientation

Grain-damage and collapse of passive margin (subduction initiation)



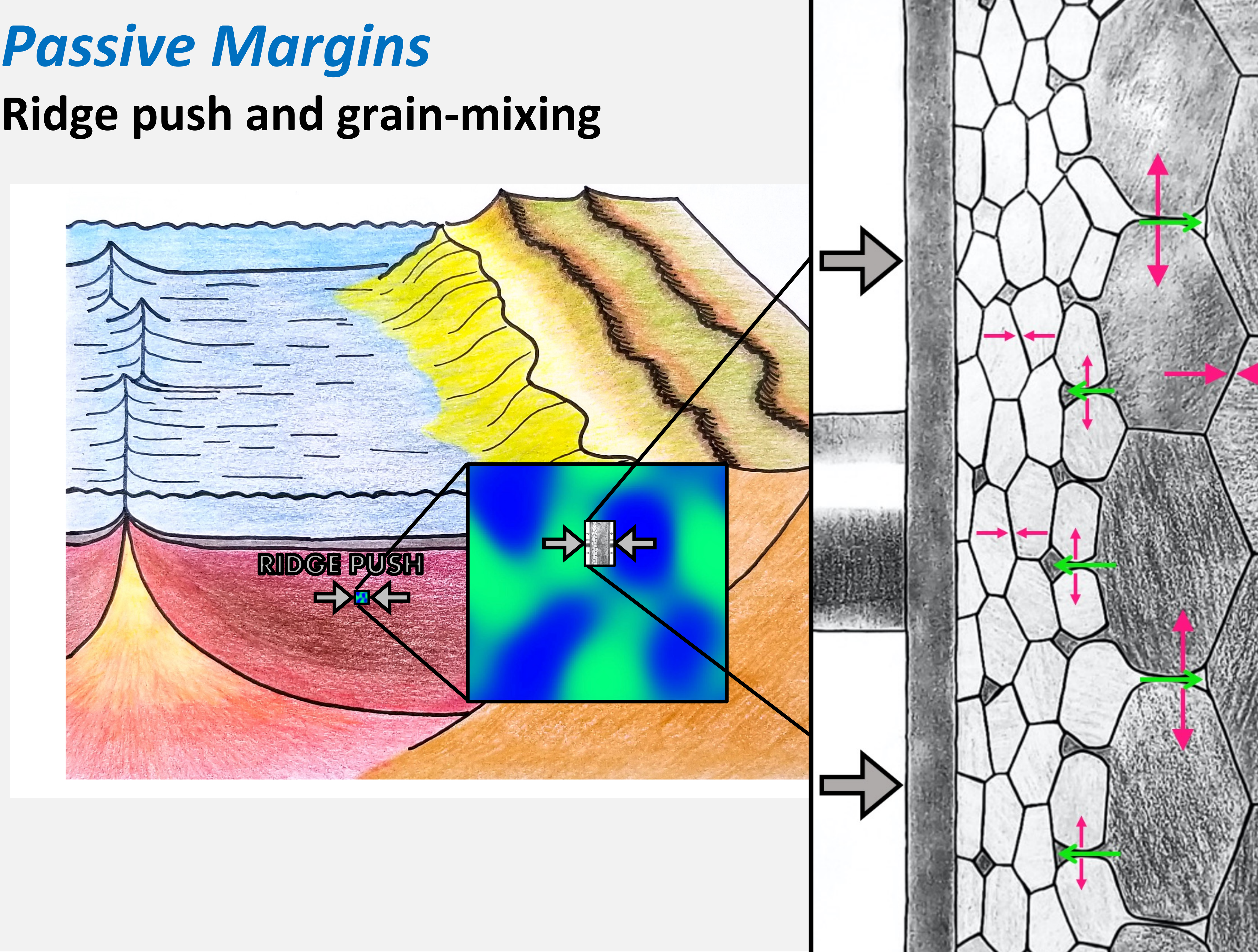
Diverging, aging lithosphere has increased stress on passive margin from
- Ridge push
- Sediment load
- Other (convection, sagging)

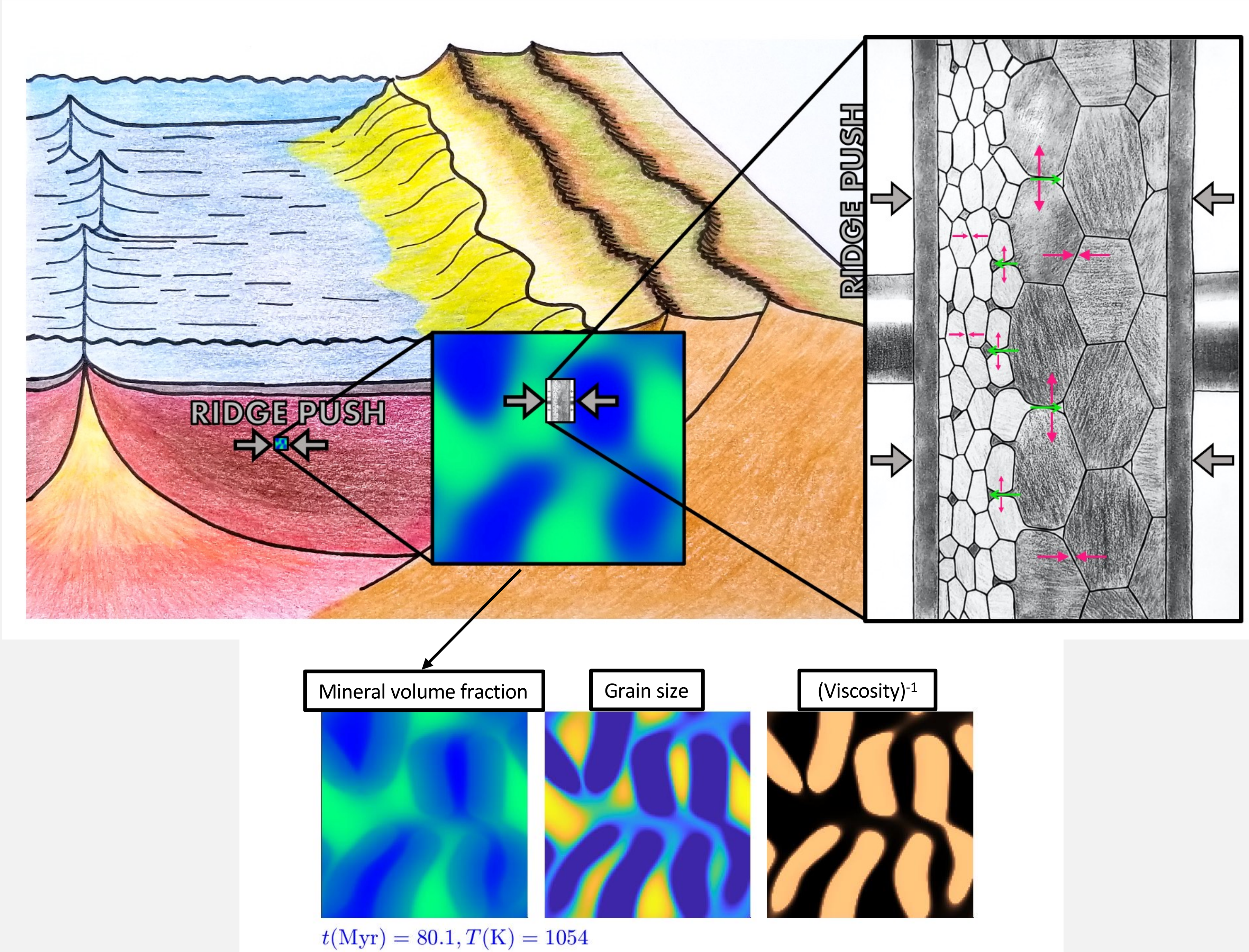
Grain-damage driven by stress can offset thermal stiffening with age

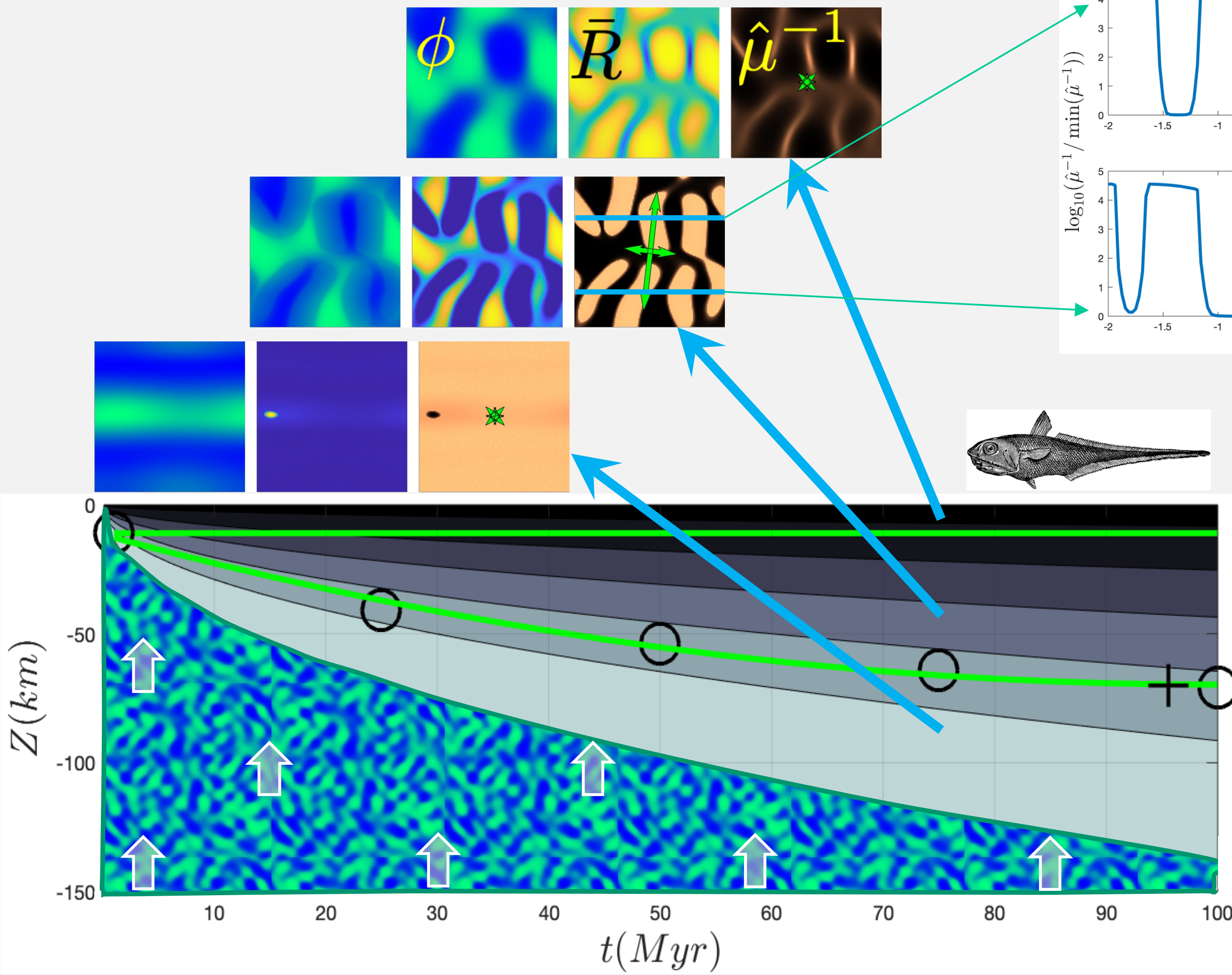
Mulyukova & Bercovici (2018); Bercovici & Mulyukova (2021)

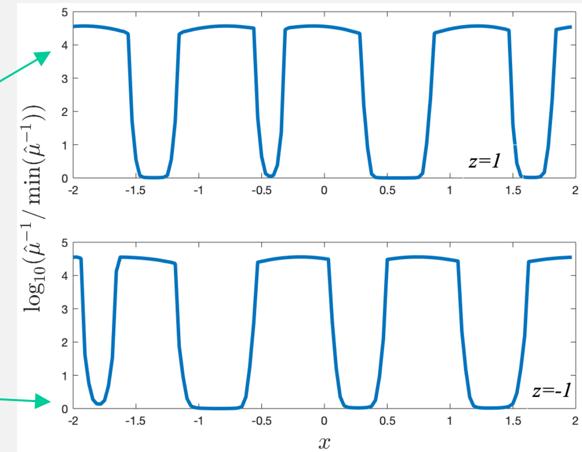
Passive Margins

Ridge push and grain-mixing




RIDGE PUSH
RIDGE PUSH
Mineral volume fraction
Grain size
(Viscosity)-1
$t(\mathrm{Myr}) = 80.1, T(\mathrm{K}) = 1054$





Cold, brittle

Weak vertical bands

Pervasively damaged/weak

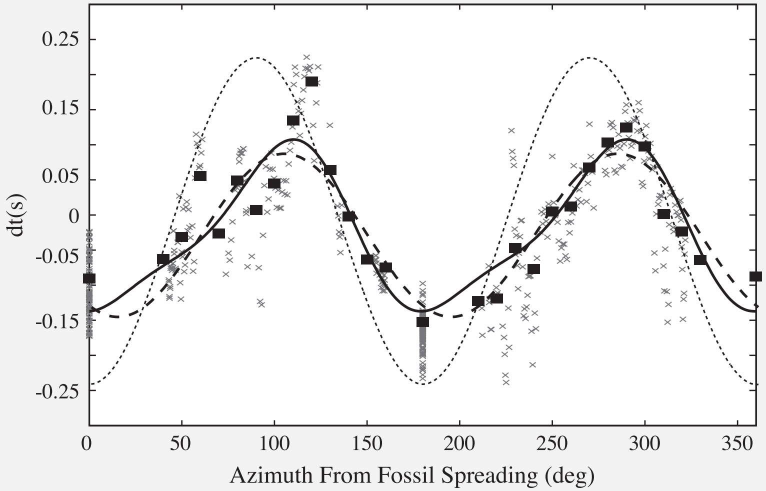
Facilitates vertical shearing, subduction, passive margin collapse

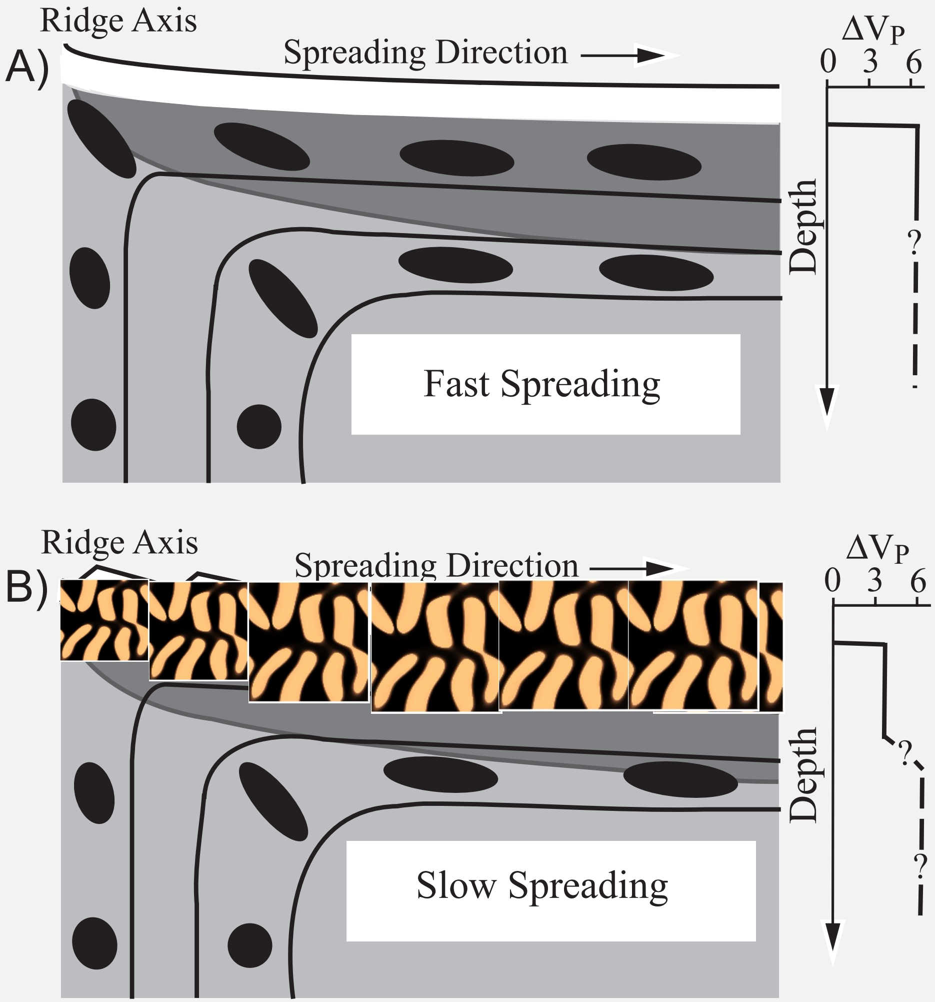
Seismic anisotropy in passive margins

Grain-mixing reduces spreading-parallel fabric?

Mantle deformation during slow seafloor spreading constrained by observations of seismic anisotropy in the western Atlantic

J.B. Gaherty et al. / Earth and Planetary Science Letters 228 (2004) 255–265





With a magnitude of 3–4%, the *P*-wave anisotropy in this portion of the Atlantic is small compared to estimates of *P*-wave anisotropy from modern refraction data in fast-spreading regions. The most comparable result is from the Ngendei experiment in old Pacific lithosphere east of the Tonga trench, which had a similar spatial scale (offsets to 100–150 km) [14,21]. They found upper-mantle *P*-wave anisotropy of 5.5%, approximately 50% larger than that observed here. *P*-wave anisotropy of 6–7% was also found in two short-offset (<50 km) experiments on the fast-spreading East Pacific Rise [22,23]

Polymineralic deformation & mixing experiments

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Research

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Cite this article: Wiesman HS, Zimmerman ME, Kohlstedt DL. 2018 Laboratory investigation of mechanisms for phase mixing in olivine + ferropericlase aggregates. *Phil. Trans. R. Soc. A* **376**: 20170417. http://dx.doi.org/10.1098/rsta.2017.0417

Laboratory investigation of mechanisms for phase mixing in olivine + ferropericlase aggregates

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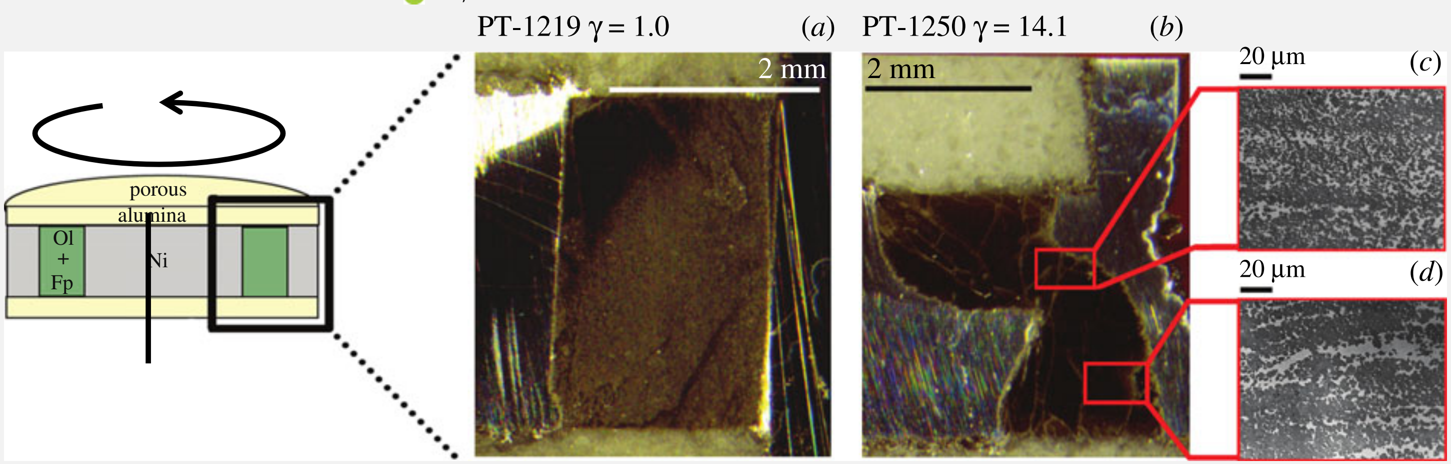
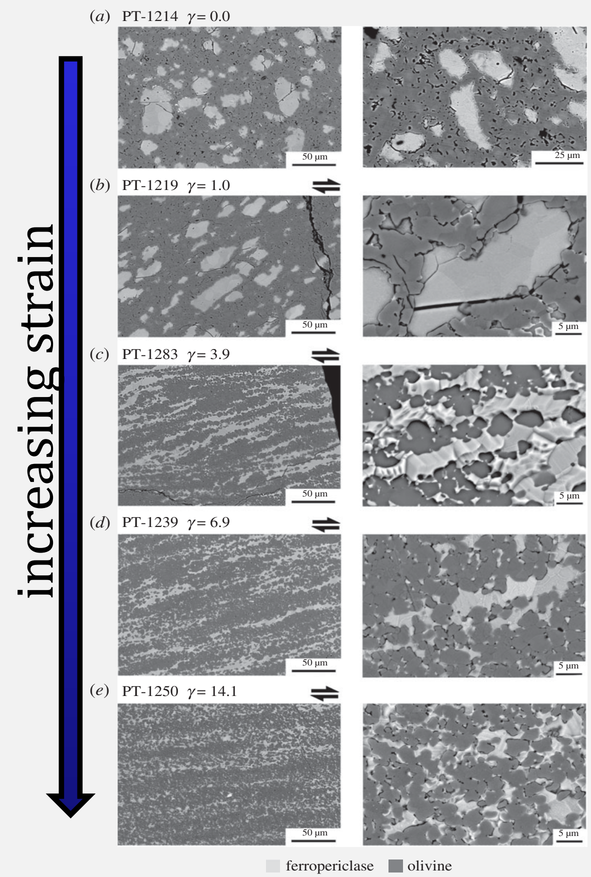
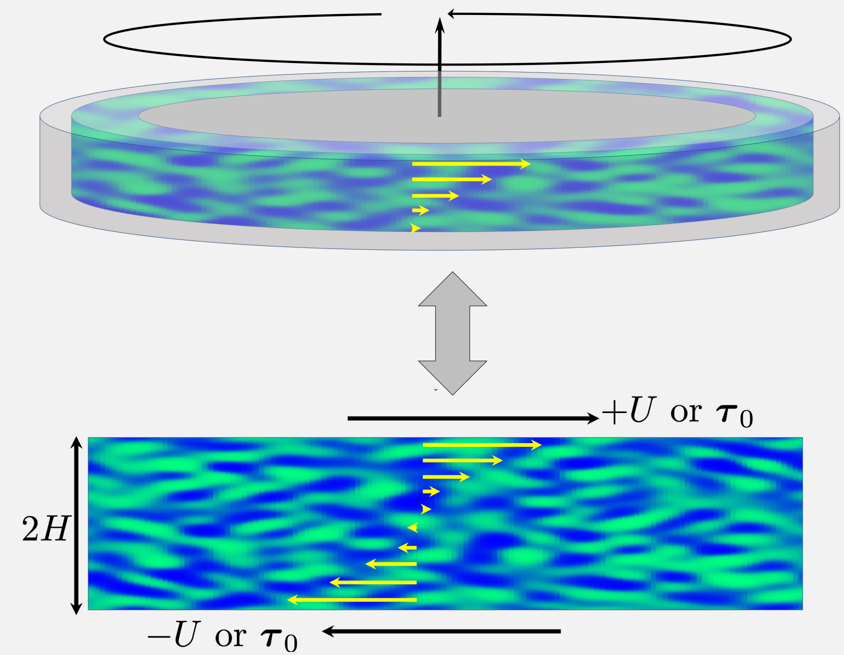




(See also Tasaka et al *JGR* 2017a,b, 2020; Cross & Skemer *JGR* 2017; Cross et al *JGR* 2020)

Diffusive Grain mixing and Damage



Stress driven grain mixing of mineral phases

$$\frac{D\phi}{Dt} = \alpha \boldsymbol{\nabla} \cdot \left(\chi(\bar{R}, \phi) \boldsymbol{\tau}_{\rm c} \cdot \boldsymbol{\nabla}\phi\right)$$

Interphase- and grain-boundary evolution: coarsening vs damage

- *r = roughness of inter-phase boundary (aka interface)x*
- *R_i = grain-size of phase i*

$$\frac{Dr}{Dt} = \frac{\eta \mathcal{C}_I}{q r^{q-1}} - \mathcal{D}_I \eta^\ell r^2 \left(2\tau\dot{e} + \alpha\chi \left[\underline{\boldsymbol{\tau}}_{\rm c} \cdot \boldsymbol{\nabla}\phi\right]^2\right)$$

Interphase boundary damage where phases mix

$$\frac{DR_i}{Dt} = \frac{\mathcal{C}_i}{p R_i^{p-1}} \mathcal{Z}_i - \mathcal{D}_i R_i^2 \tau_i^{n+1} \mathcal{Z}_i^{-1}$$

Grain-boundary damage faster (healing slower) by Zener pinning, where phases are mixed

Flow equations (mass, momentum, rheology), sample in shear or torsion

Momentum (stream-function ψ, vorticity ω)

$$\nabla^2\psi = -\omega$$

$$\nabla^2\omega = -\mathcal{M}\nabla^2\omega - 2\boldsymbol{\nabla}\mathcal{M} \cdot \boldsymbol{\nabla}\omega + \Delta^*\mathcal{M}\left(\Omega_0 + \Delta^*\psi\right) + 4\frac{\partial^2\mathcal{M}}{\partial x \partial z}\frac{\partial^2\psi}{\partial x \partial z}$$

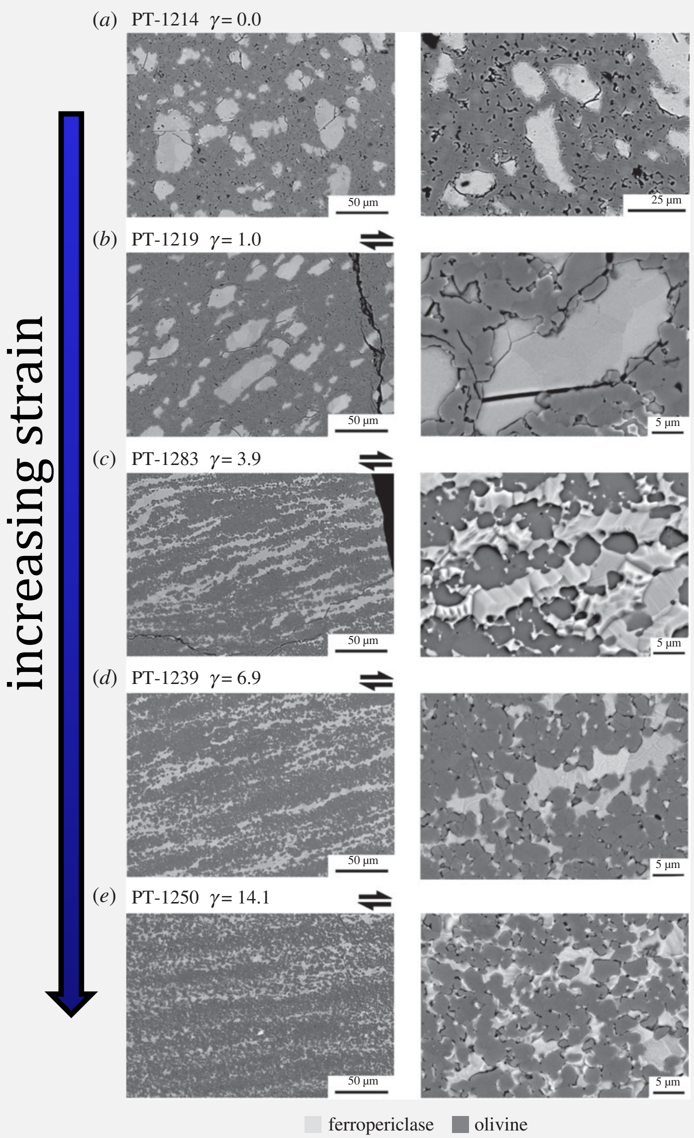
$$\mathcal{M} = \text{viscosity heterogeneity due to variations in } \phi, R_i$$

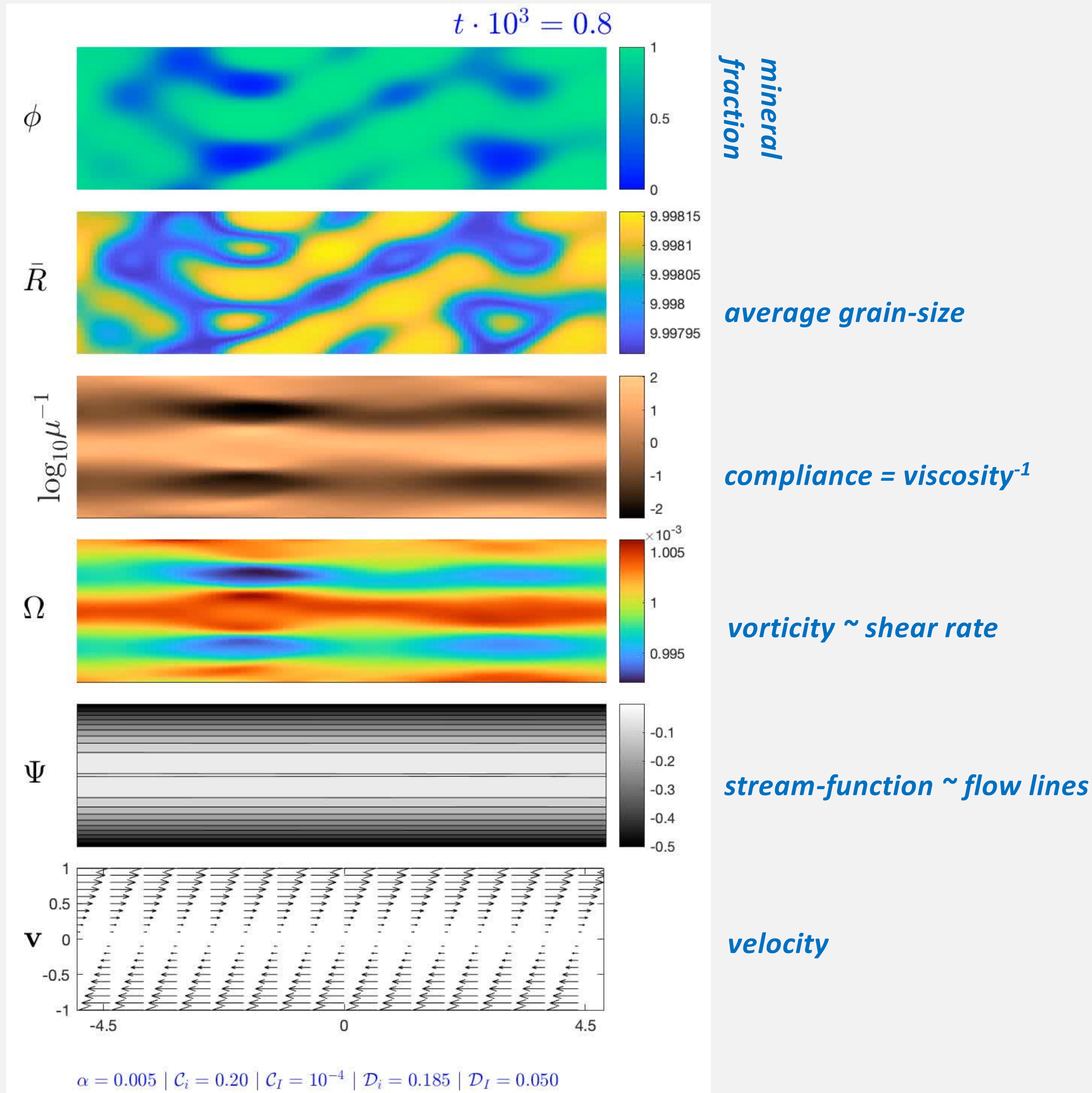
strain rate, rheology

$$\dot{e}^2 = \left(\frac{\partial^2\psi}{\partial x \partial z}\right)^2 + \frac{1}{4}\left(\Omega_0 + \Delta^*\psi\right)^2$$

$$2\dot{e} = \tau_i^n + \frac{\tau_i}{R_i^m}$$

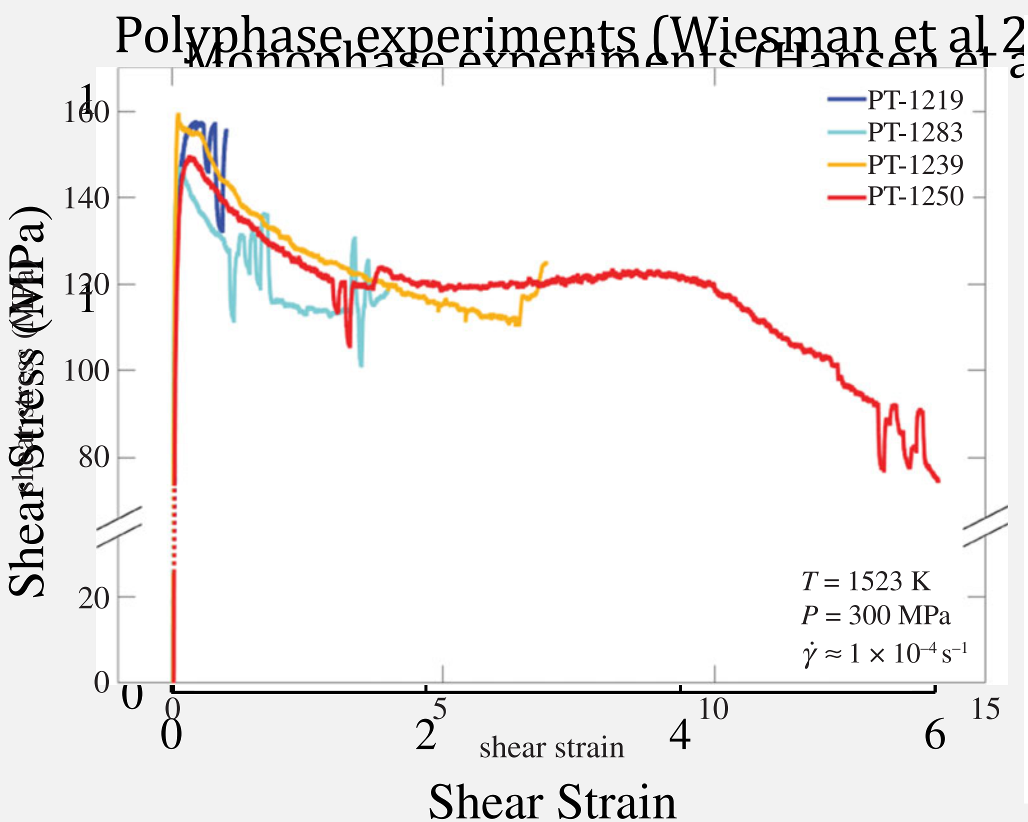
Bercovici, Mulyukova, Girard & Skemer (in prep 2022)

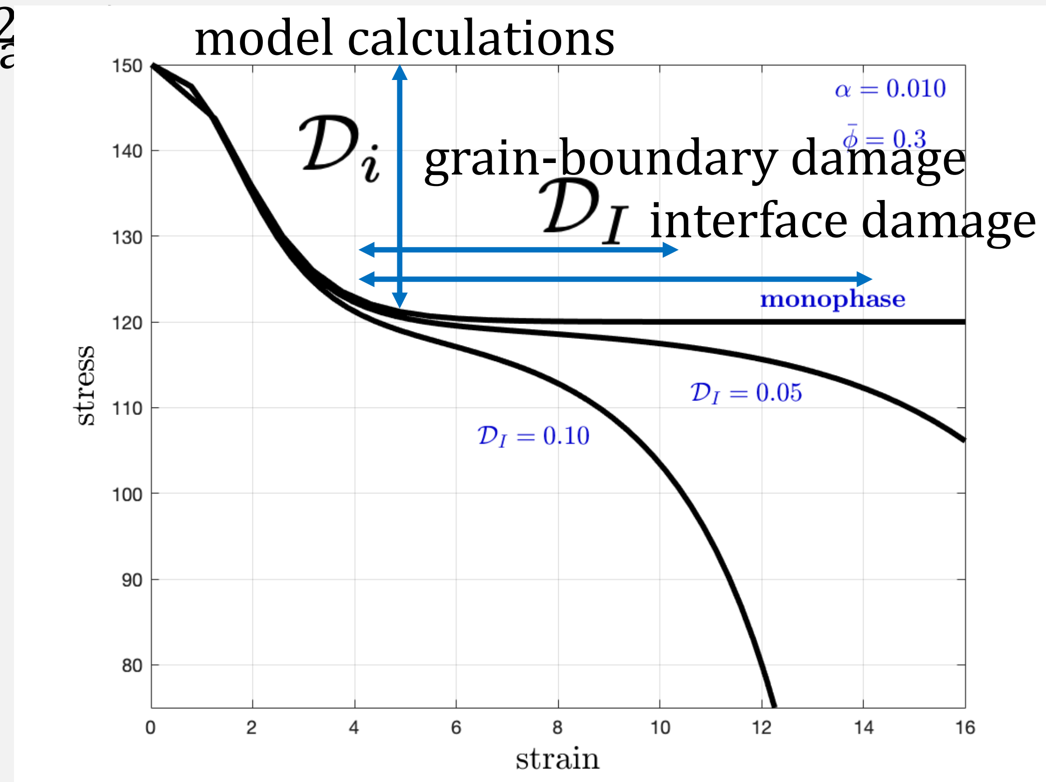

increasing strain
(a) PT-1214 γ = 0.0
(b) PT-1219 γ = 1.0
(c) PT-1283 γ = 3.9
(d) PT-1239 γ = 6.9
(e) PT-1250 γ = 14.1
ferropericlase
olivine

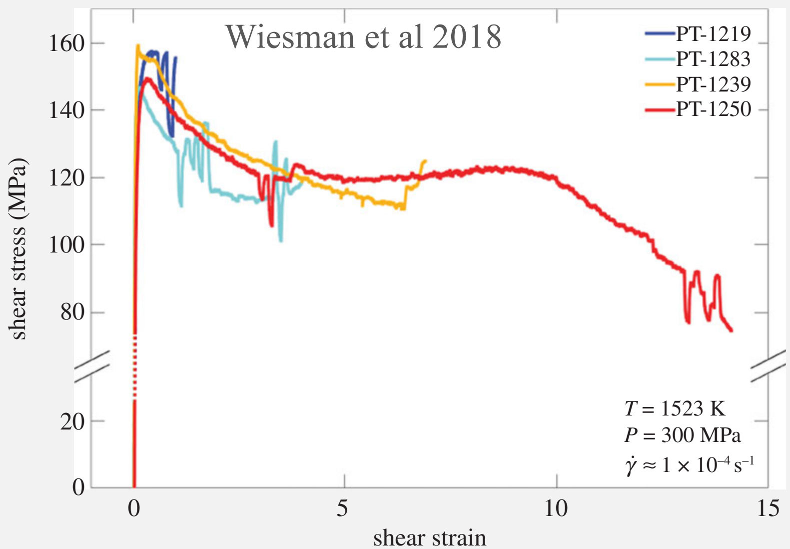

$t \cdot 10^3 = 0.8$
mineral fraction
average grain-size
compliance = viscosity^-1
vorticity ~ shear rate
stream-function ~ flow lines
velocity
$\alpha = 0.005 \mid \mathcal{C}_i = 0.20 \mid \mathcal{C}_I = 10^{-4} \mid \mathcal{D}_i = 0.185 \mid \mathcal{D}_I = 0.050$

Stress vs strain

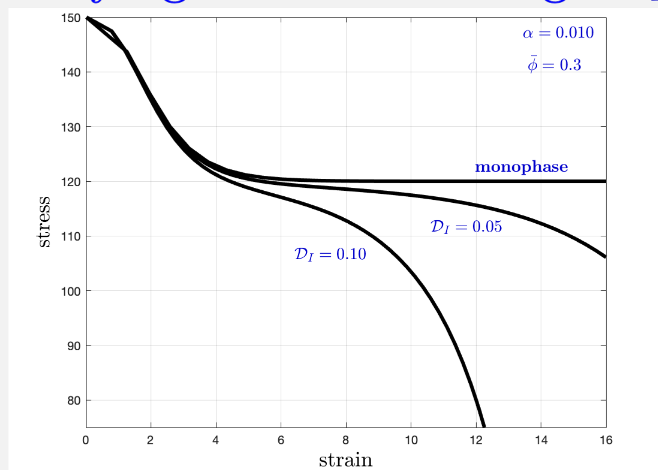
- Mono- and polyphase have 1st stress drop (to piezometric or “wattmeter” balance of grain-boundary damage and coarsening)
- Poly-phase has 2nd stress drop associated with mixing (interface ‘damage’)



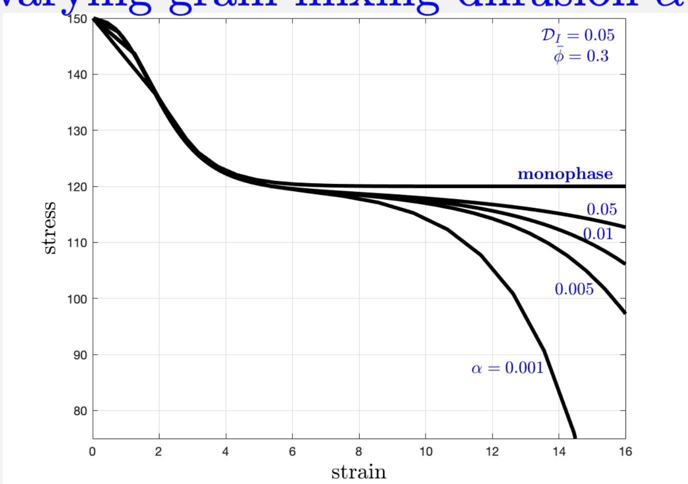




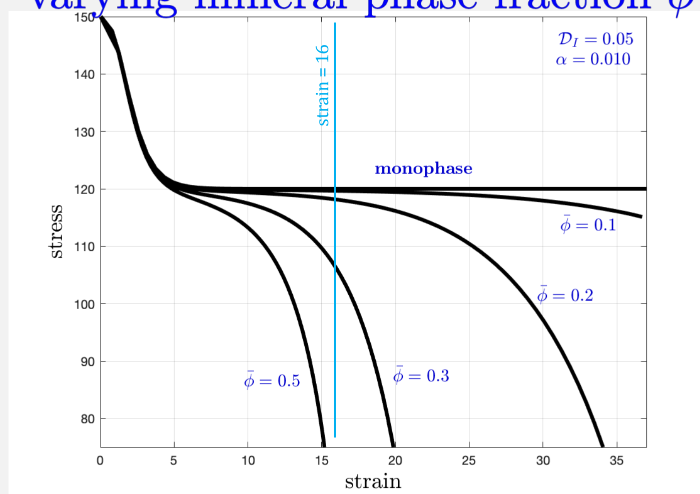
varying interface damage $\mathcal{D}_I$



varying grain-mixing diffusion α



varying mineral phase fraction $\bar{\phi}$



Interface damage represents energy going to inter-phase boundary surface energy

Grain-mixing diffusion also spreads out heterogeneity; *slower diffusion allows more localization and weakening*

Phase fraction controls heterogeneity: 50-50 mix allows most weakening, less than 20% minor phase causes negligible weakening within strains O(10), if phases are moderately dispersed

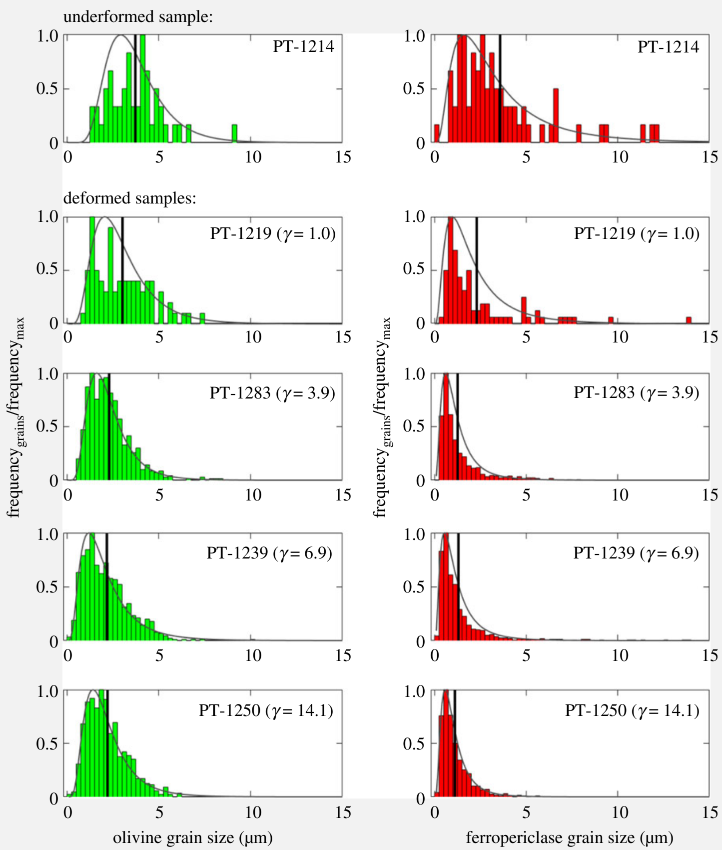
Fixed parameters: $\mathcal{C}_i = 0.2, \mathcal{C}_I = 10^{-4}, \mathcal{D}_i = 0.185$

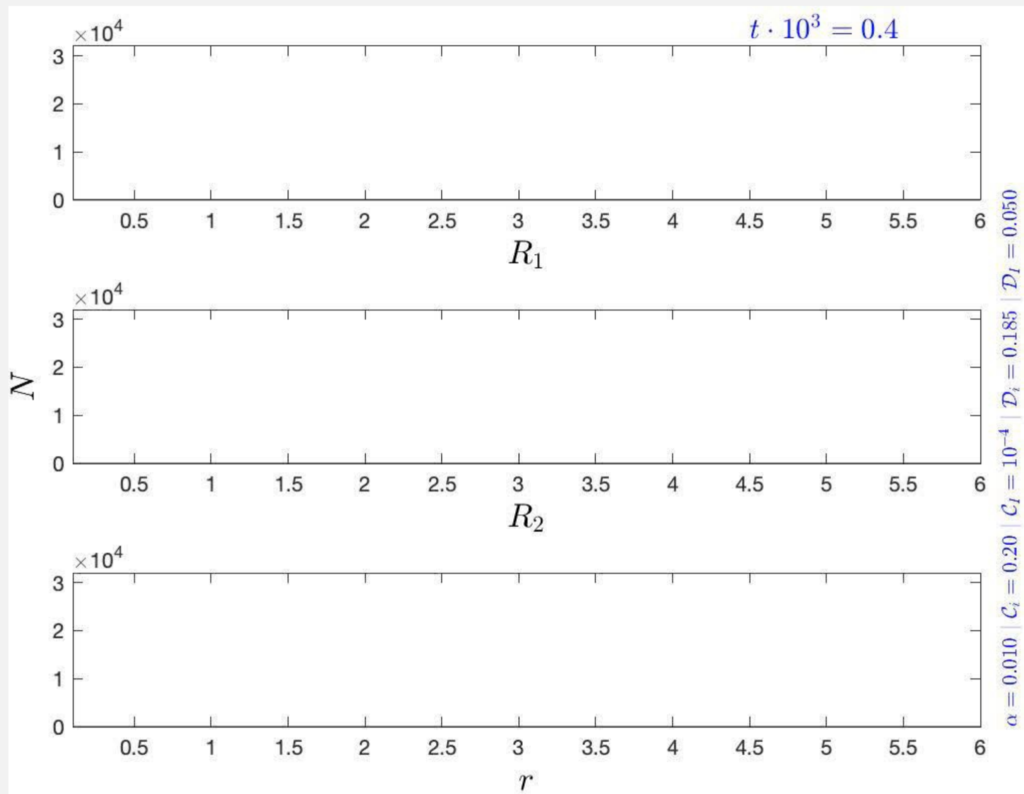
Grain-size distribution

Initial reduction in grain-sizes R_1 and R_2 in each phase associated with first stress drop

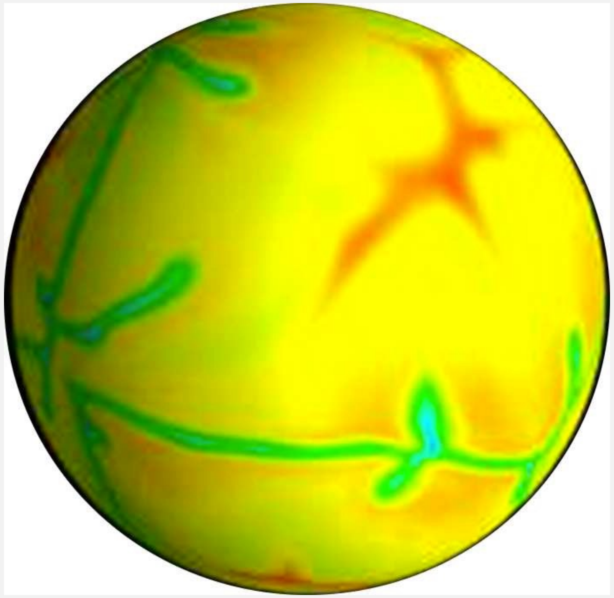
Interface roughness ’’ r reduces later with growth of mixed regions; catches up with R_1 and R_2 and drives them to smaller sizes with Zener pinning (which slows grain-growth and facilitates grain damage)

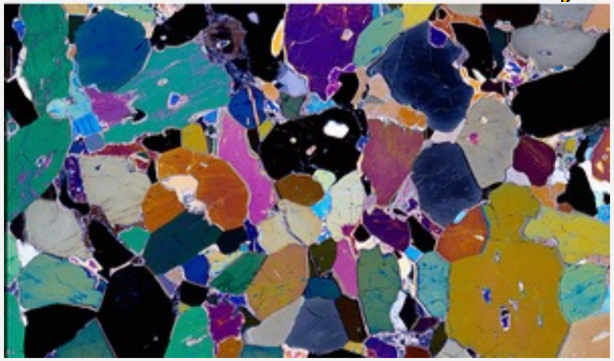
Wiesman et al 2018

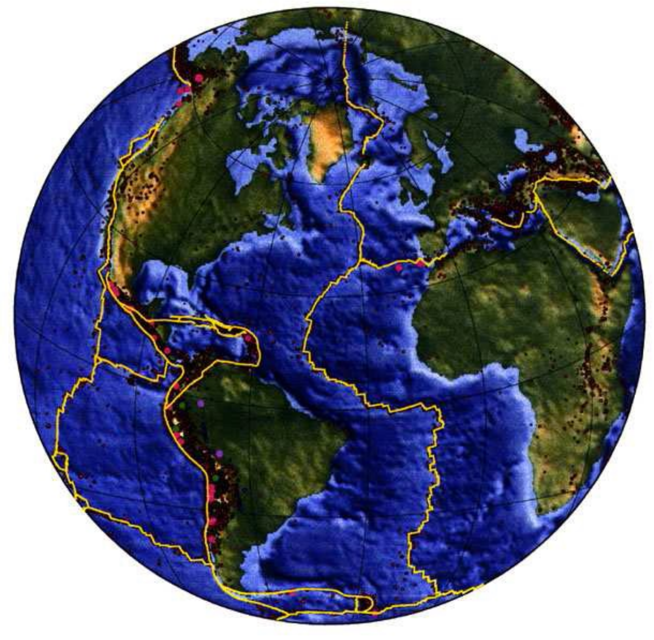




Summary







- The physics of plate generation has progressed over the last 20-30 years
- Grain-damage mechanism, built from basic physics, consistent with lab and field observations
- Allows predictions of conditions for plate tectonics on terrestrial planets, emergence on Earth 1Gya, and subduction dynamics
- Grain mixing and damage
  - predicts co-existing strong & weak deformation states (e.g., plates and plate boundaries)
  - Makes vertical weak bands in ocean lithosphere; facilitates passive margin collapse and subduction initiation
  - Comparison to lab experiments elucidates the co-evolution of stress and microstructure