The effect of brittle-ductile weakening on the formation of tectonic patterns at mid-ocean ridges

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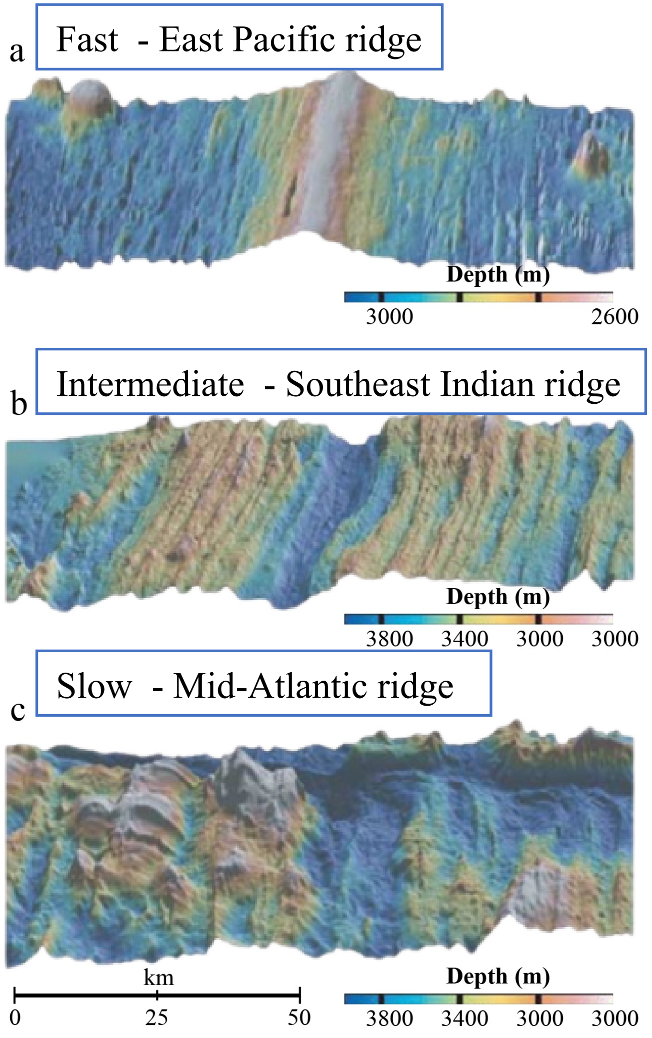
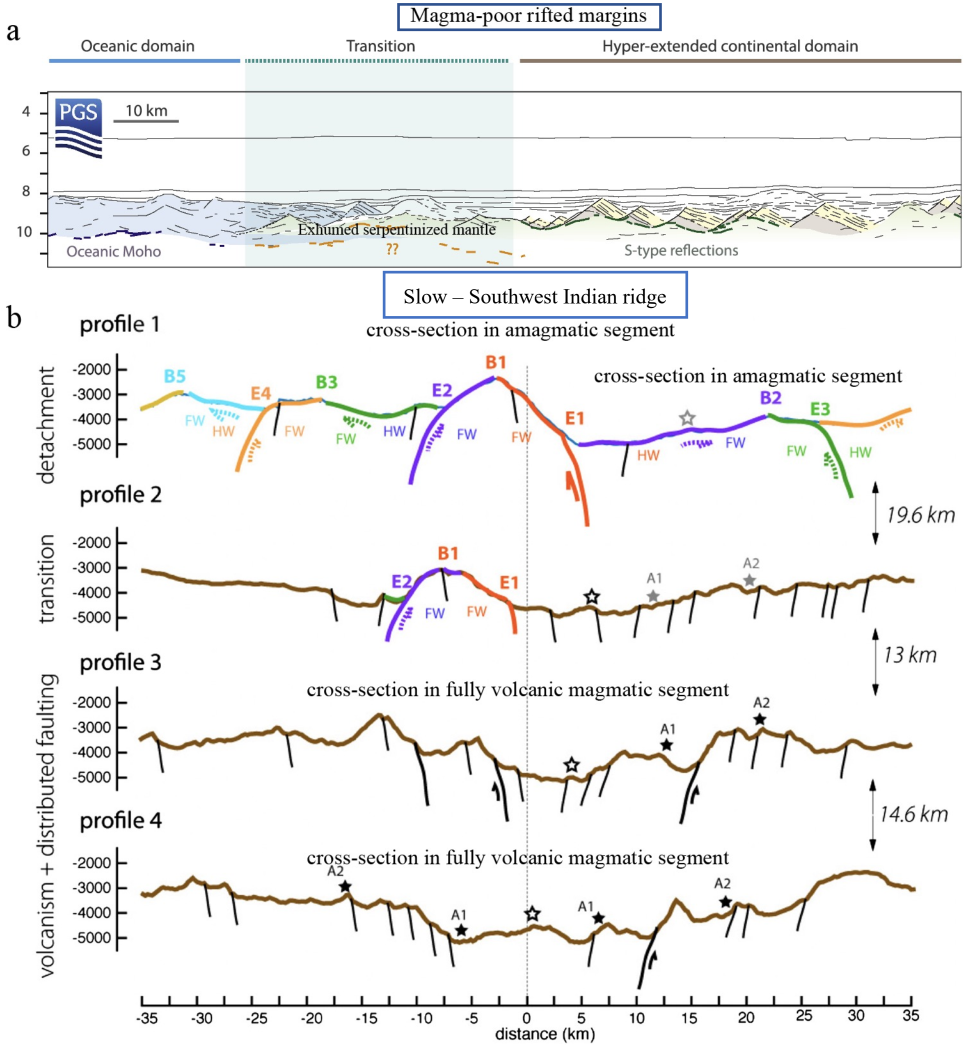


[Modified from Buck et al., 2005]



[Modified from Gillard et al., 2017; Cannat et al., 2019]

Faulting patterns:

Transition from **symmetric normal faults at fast spreading ridges** to **very asymmetric detachment faults at slow-ultraslow spreading centers.**

Spreading modes:

Rolling-hinge mode (Asymmetric)

Flip-flop mode (Symmetric)

Why?

Methods

- Mass conservation:

$$\nabla \cdot v = 0$$

- Momentum conservation:

$$\nabla \cdot \tau - \nabla P + \rho g = 0$$

- Energy conservation:

$$\rho C_p \frac{DT}{Dt} = -\nabla \cdot \left(k\left(\nabla T\right)\right) + H_r + H_a + H_s$$

$$H_a = \alpha T \frac{DP}{Dt}$$

$$H_s = 2\sigma'_{ij}\dot{\varepsilon}'_{ij}$$

[Gerya and Yuen, 2003, 2007]

- Integrated rheology:

$$\eta_{eff} = \min(\eta_{plastic}, \eta_{ductile})$$

- Plastic deformation

$$\eta_{plastic} = \frac{\sigma_{yiled}}{2\dot{\varepsilon}_{II}}$$

$$\sigma_{yiled} = C_0 + P\sin(\varphi_{eff})$$

- Ductile rheology with **grain size evolution**

$$\eta_{df} = \frac{1}{2A_{df}}\exp\left(\frac{E_{df} + PV_{df}}{RT}\right)\left(\frac{\pi r}{2}\right)^m$$

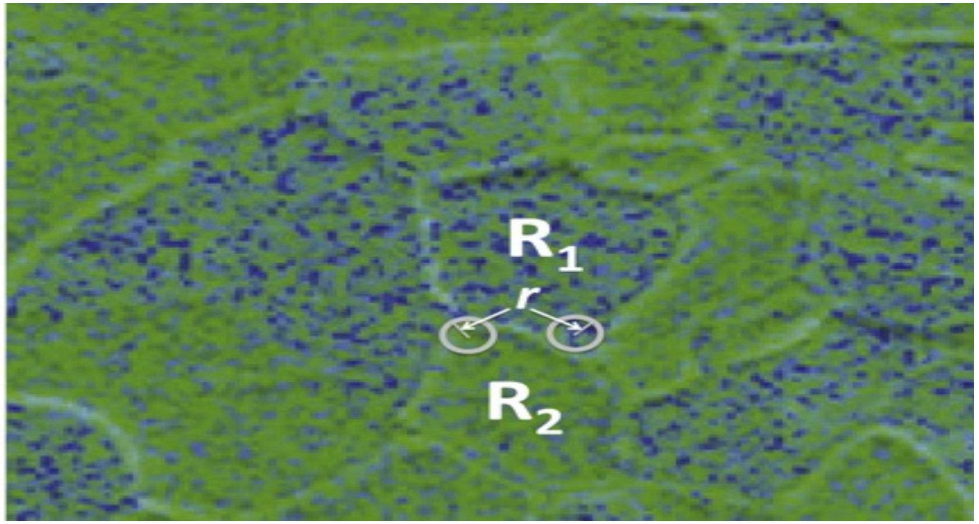
$$\eta_{ds} = \frac{1}{2A_{ds}}\exp\left(\frac{E_{ds} + PV_{ds}}{RT}\right)\sigma^{1-n}$$

$$\frac{1}{\eta_{ductile}} = \frac{1}{\eta_{df}} + \frac{1}{\eta_{ds}}$$

Methods

Compared with single-phase material:

- Damage and rheological weakening can coexist
- Pinning inhibits grain growth and shear-zone healing
    - Shear-localization is rapid (< 1 Myr)
    - Healing time is slow (> 100 Myr)



[Hiraga et al., 2012]

- Zener pinning factor between two-phase medium at pinned state:

$$Z_i = 1 - C(1-\phi_i)\frac{R_g^2}{r^2} \approx 0$$

r : the interface curvature

R_g : the grain size

- Convert **grain size** to **interface curvature**:

$$R_g = \frac{r}{\sqrt{C}}\left[\frac{\phi_1}{\sqrt{\phi_2}} + \frac{\phi_2}{\sqrt{\phi_1}}\right] \Rightarrow R_g = \frac{\pi}{2} r$$

[Bercovici et al., 2015]

Methods

$$\frac{Dr}{Dt} = \frac{\theta G_I}{q r^{p-1}} - \frac{f_I r^2}{\gamma_I \theta} \psi_{DRX}$$

Only used in mantle rocks

$\frac{Dr}{Dt}$:the change of interface curvature with time

$\theta = 2\phi_1\phi_2$ how the interface area density depends on the two mineral volume fractions ϕ_1 and ϕ_2

G_I: the interface coarsening factor

p: the grain-size coarsening exponent

q: the roughness coarsening exponent

f_I: interface damage fraction (create new interface)

γ_I: the interface surface tension

[Gerya et al., 2021; Liu et al., 2022]

- Mechanical work:

$$\psi_{DRX} = \psi_{ds} = \sigma \dot{\varepsilon}_{ds}$$

- Strain rate:

$$\dot{\varepsilon}_{df} = A_{df} \exp\left(-\frac{E_{df} + PV_{df}}{RT}\right)\sigma\left(\frac{\pi r}{2}\right)^{-m}$$

$$\dot{\varepsilon}_{ds} = A_{ds} \exp\left(-\frac{E_{ds} + PV_{ds}}{RT}\right)\sigma^{n-1}\sigma$$

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{df} + \dot{\varepsilon}_{ds}$$

[Bercovici and Richard, 2012]

Methods

- Ductile deformation

$$\frac{1}{\eta_{ductile}} = \frac{1}{\eta_{df}} + \frac{1}{\eta_{ds}}$$

$\eta_{df}:1$
$\eta_{ds}:10$
0.1 → $\eta_{ductile} = 0.91 \approx \eta_{df}$

$\eta_{df}:10$
$\eta_{ds}:1$
10 → $\eta_{ductile} = 0.91 \approx \eta_{ds}$

Rheological mechanism calculation

$$\eta_{eff} = \min(\eta_{plastic}, \eta_{ductile})$$

$\eta_{ductile} \geq \eta_{plastic}$

$\eta_{eff} = \eta_{plastic}$

$\eta_{plastic} \geq \eta_{ductile}$

$\eta_{diffusion} / \eta_{dislocation}$

<0.1 Diffusion

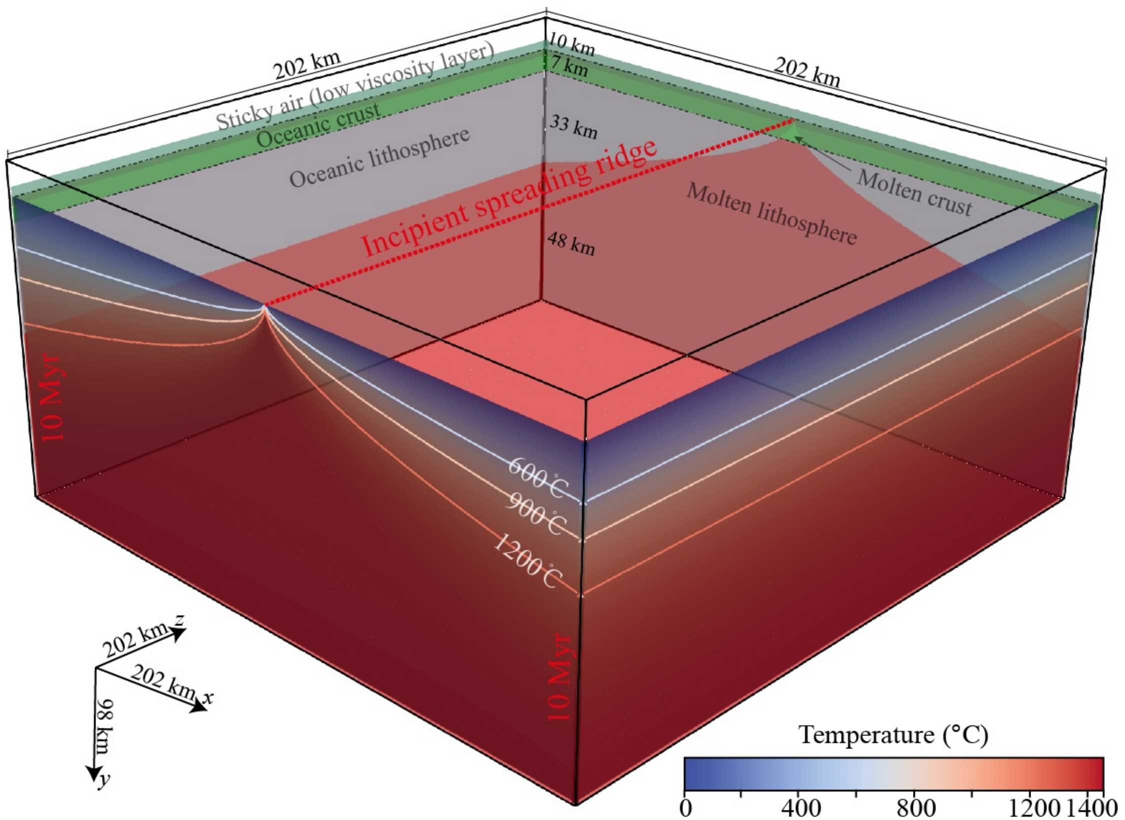
0.1-1 Transition

1-10 Transition

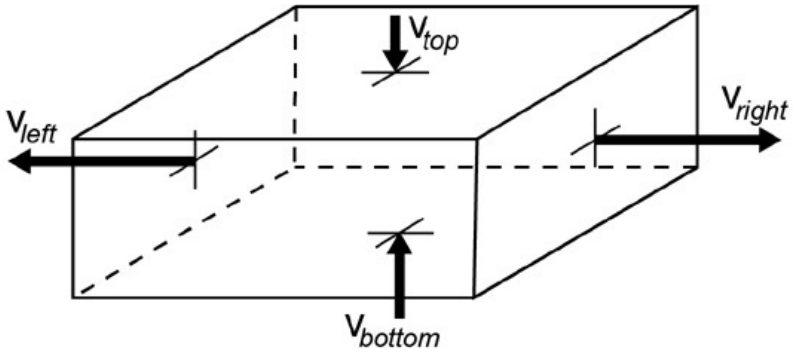
>10 Dislocation

Model setup

- Initial model setup:



- Velocity boundaries:



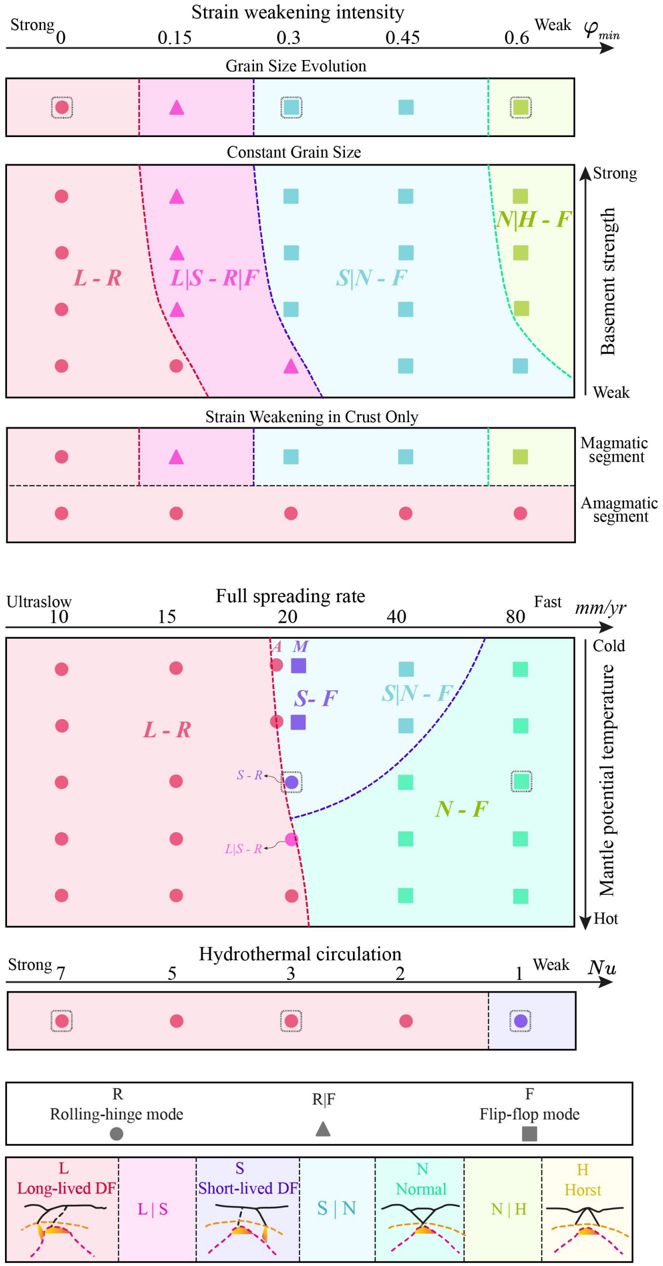
$$v_{top} = y_{water} \cdot \frac{v_{right} - v_{left}}{x_{size}}$$

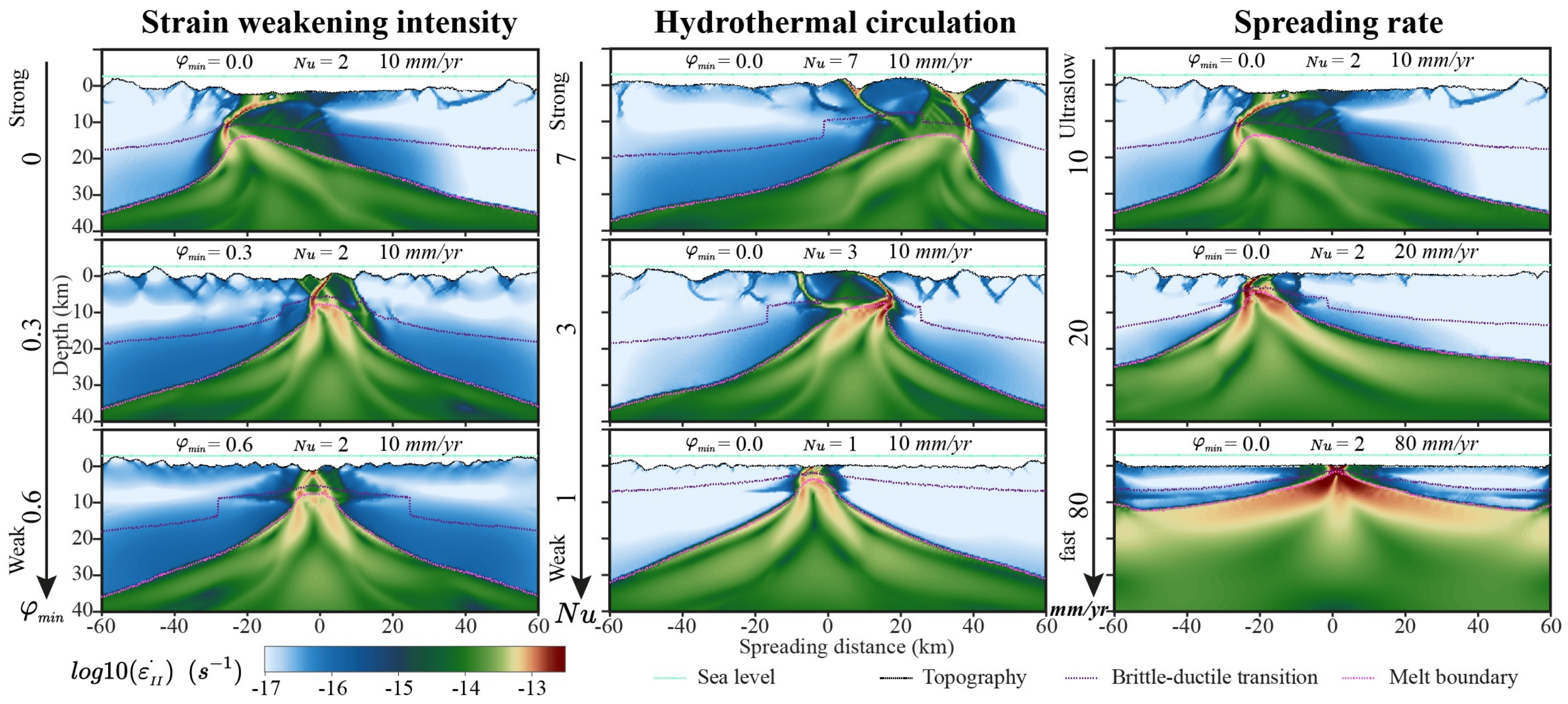
$$v_{bottom} = \left(y_{size} - y_{water}\right) \cdot \frac{v_{right} - v_{left}}{x_{size}}$$

Numerical results

Parameter study

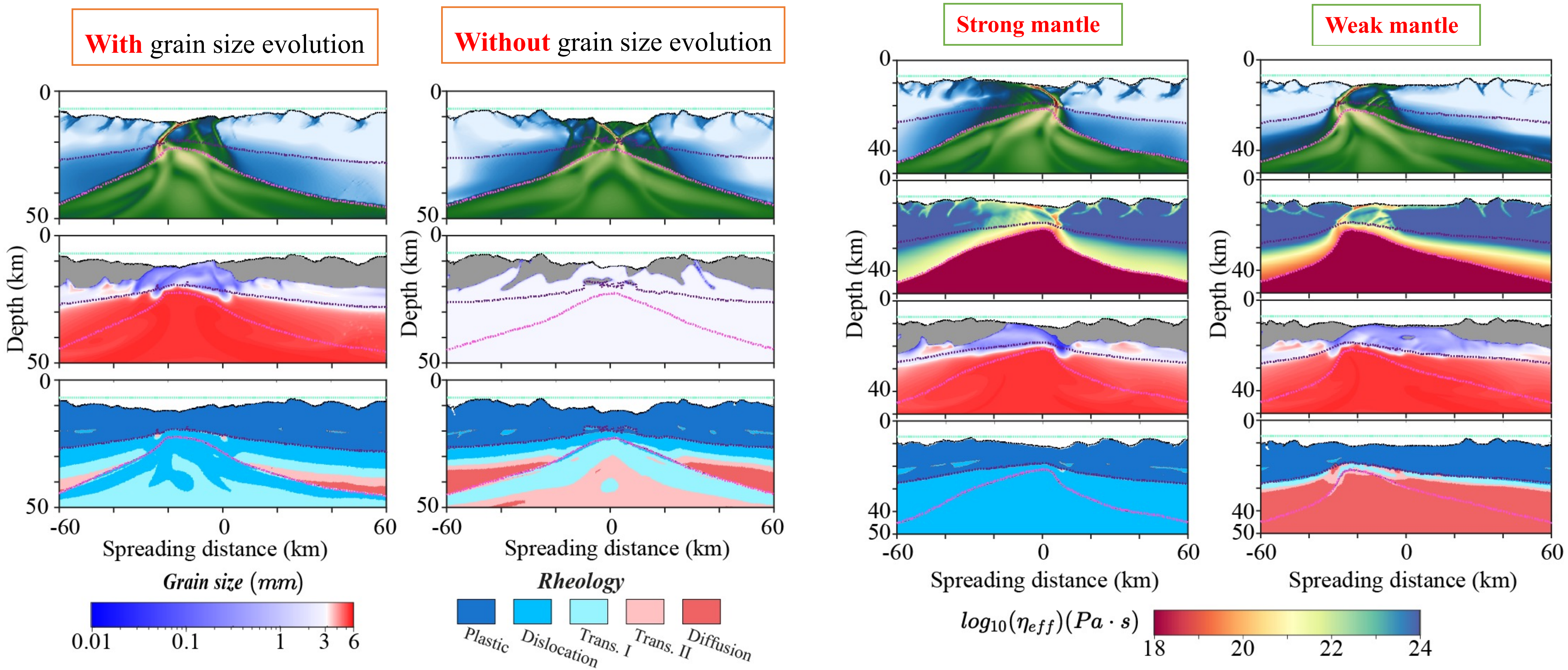
A wide span of faulting patterns and spreading modes, from asymmetric long-lived detachment faults to symmetric conjugate faults and from rolling-hinge mode to flip-flop mode, are documented in our models.





Numerical results

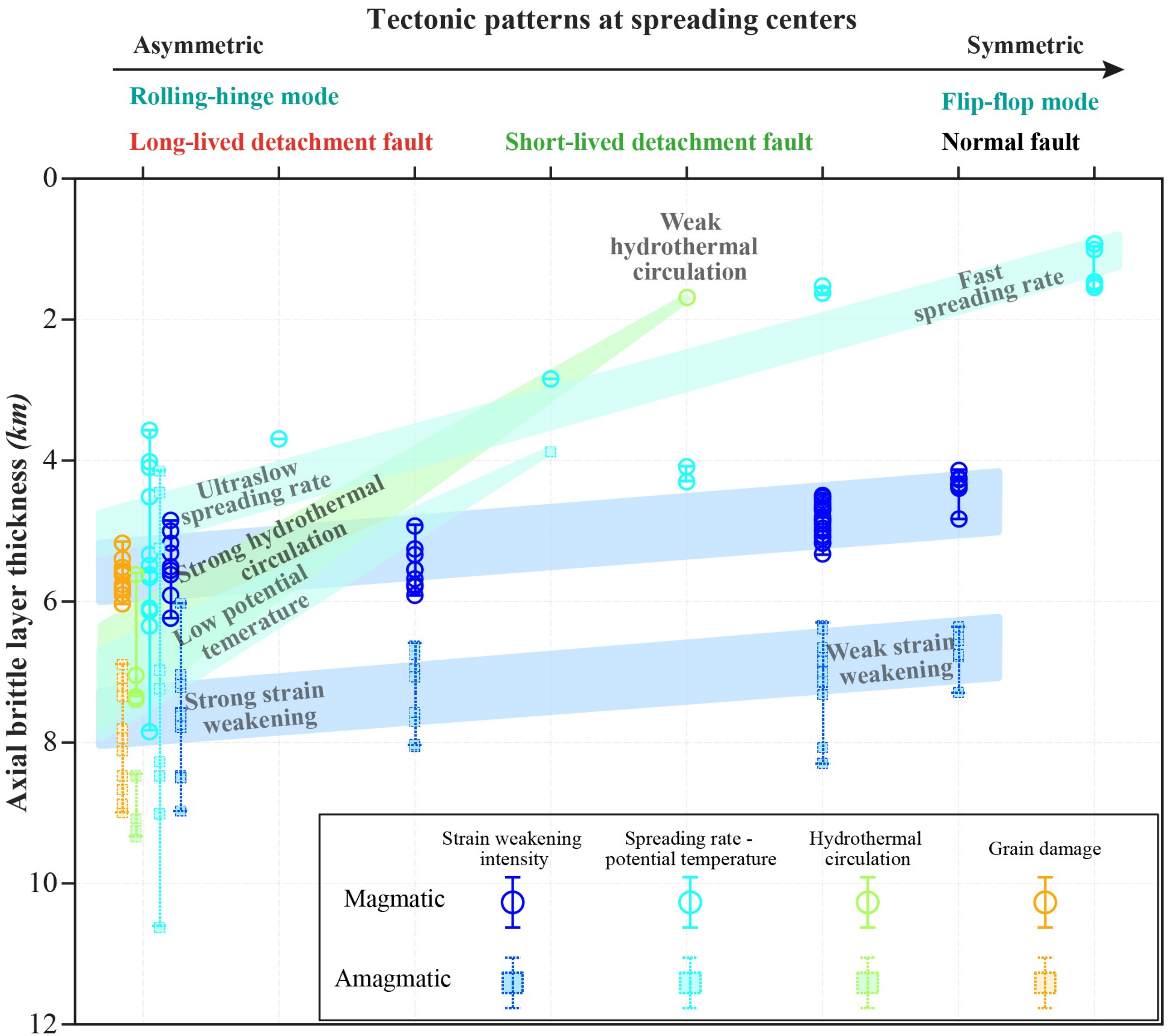
Effects of grain size evolution



Grain size reduction occurs at the root of detachment faults, facilitating the strength reduction and increasing the fault offset.

However, due to very weak decompression melting and small change of brittle layer thickness, its effect in faulting patterns is negligible.

Discussion



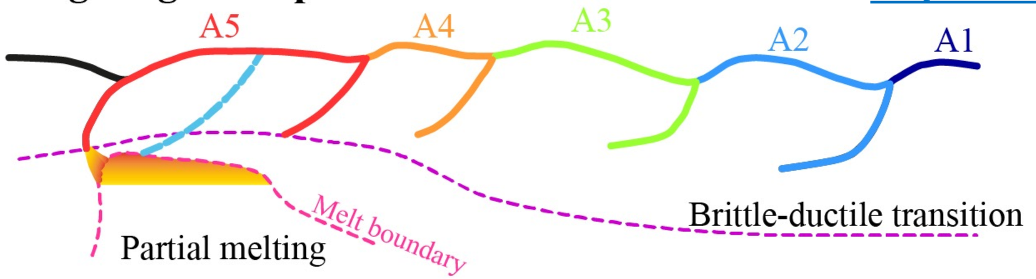
Main factors to control faulting patterns and spreading modes:

- **Strain weakening intensity**
- **Brittle layer thickness**
  - **Spreading rates**
  - **Potential temperature**
  - **Hydrothermal circulation**

Three different spreading end-member models are proposed:

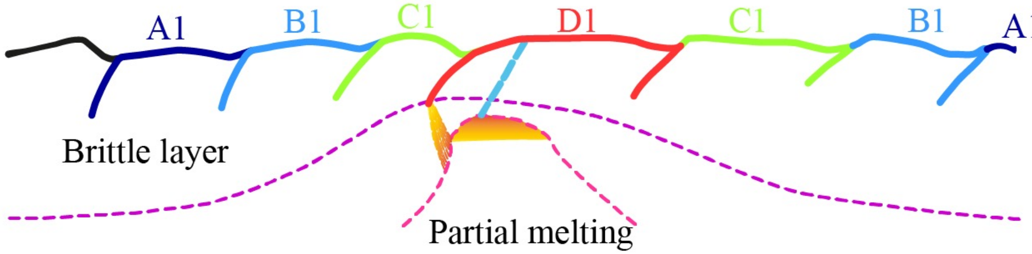
a Rolling hinge - coupled model

Asymmetric - Magma-poor rifted margins



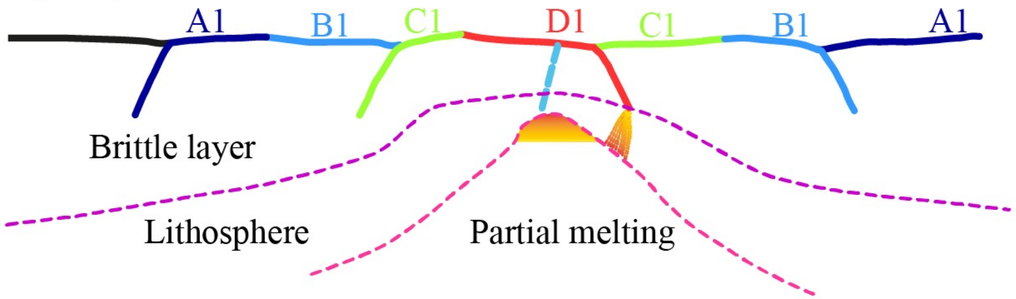
b Rolling hinge - decoupled model

Symmetric - Weak and slow spreading ridges



c Flip-flop model

Symmetric - Strong and slow spreading ridges



Thank you for your attention!

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