Melt Extraction at Mid-Ocean Ridges
A play in three acts

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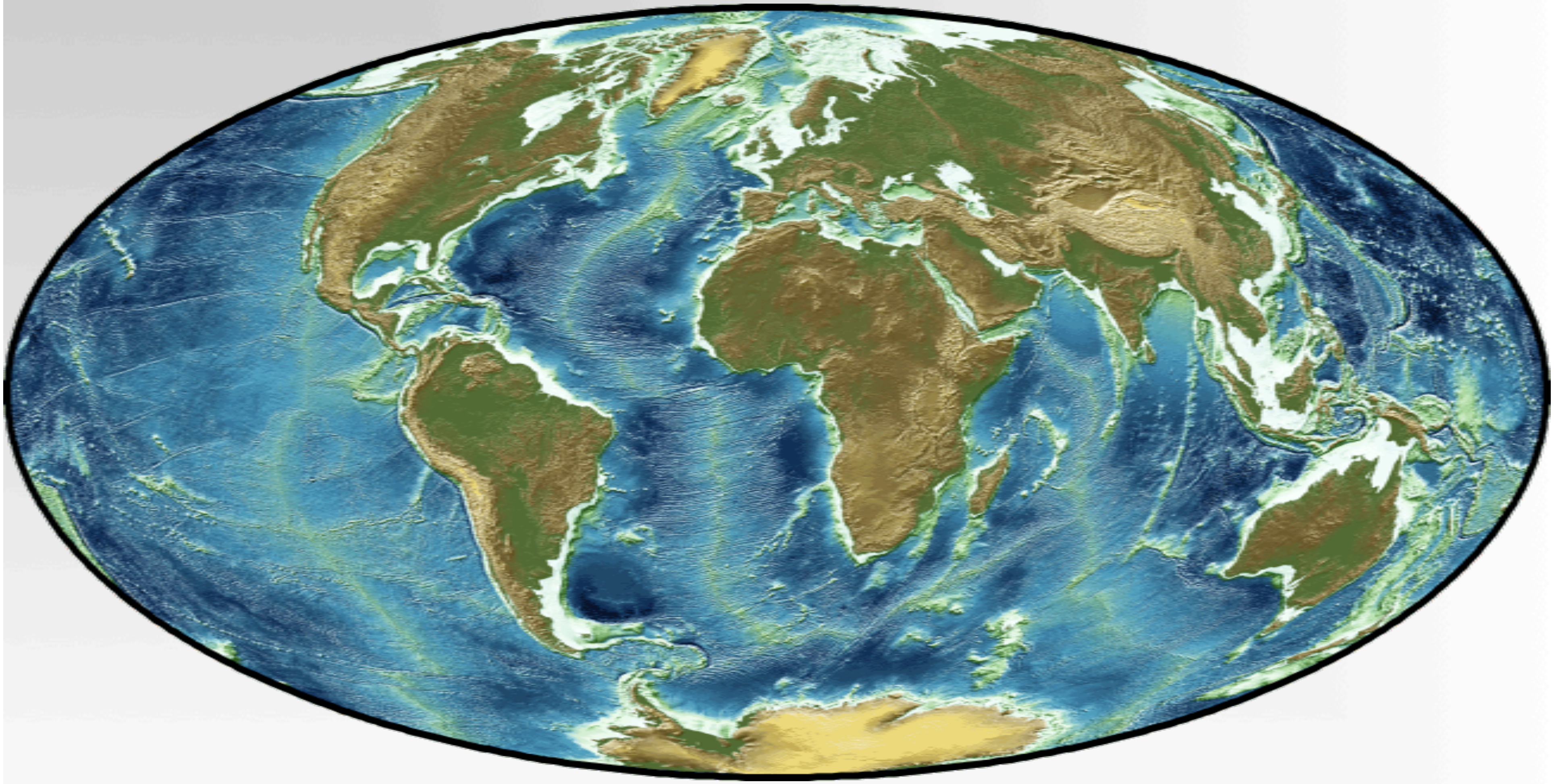
The Earth



Outline

- Motivation: focusing at Mid-ocean ridges
- Ridge morphology from fast to ultraslow spreading
  - Scaling relation of thermal structure
- A three-step melt migration scenario
  - Rapid extraction
  - Permeability barrier
- Application to Southwest Indian Ridge
- Application to East Pacific Rise (EPR)

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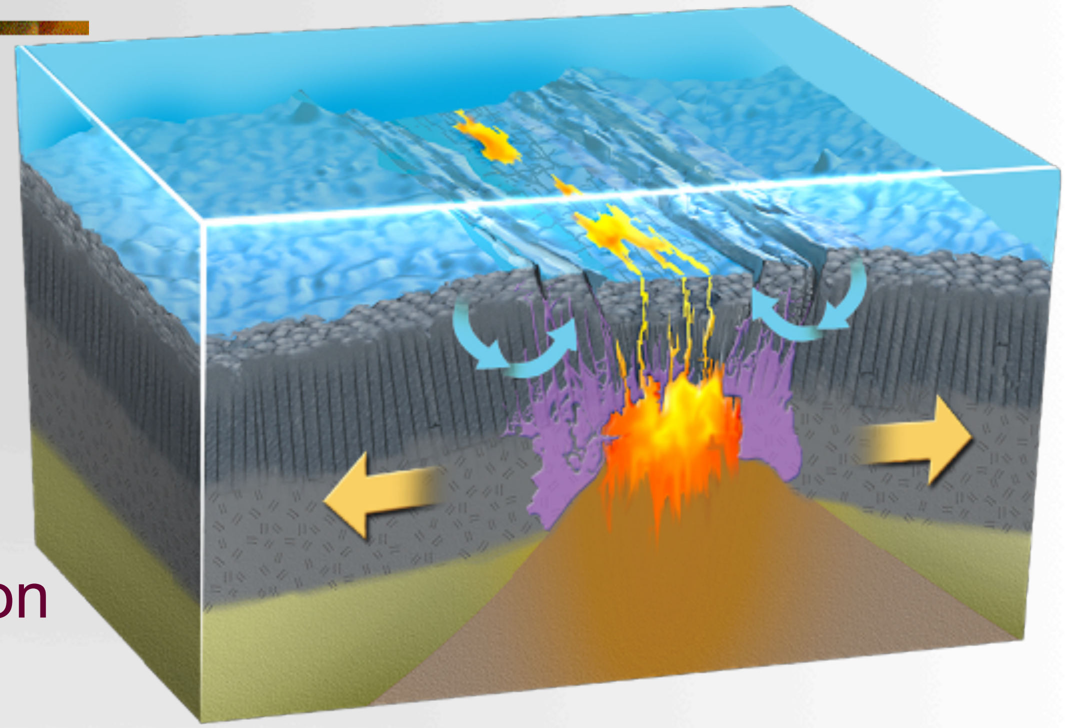
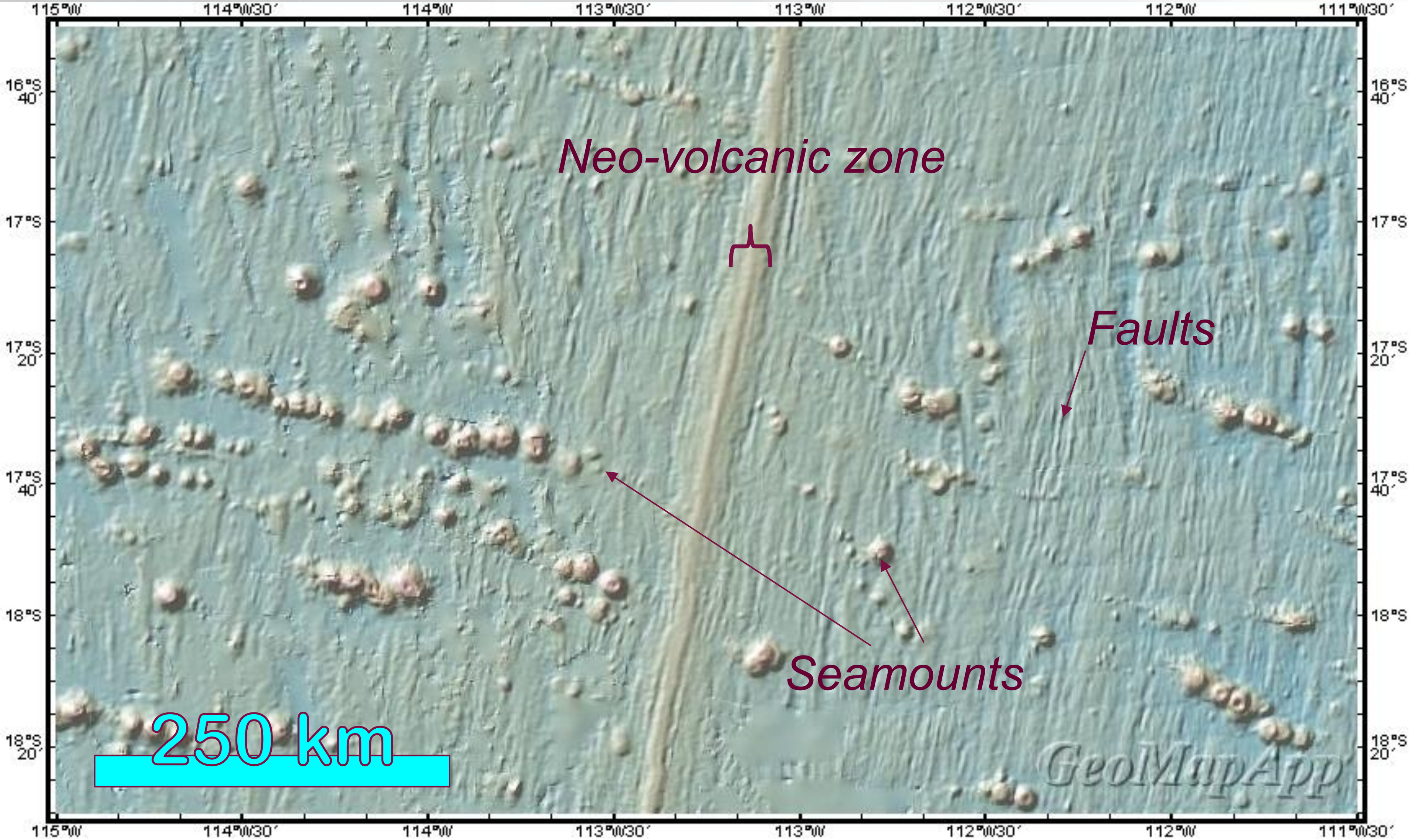
Mid-ocean ridge systems



- Multiple physics
  - Solid flow
  - Faulting
  - Porous melt migration
  - Magmatic intrusions
  - Hydrothermal circulation
- Multiple time scales
  - Seconds to day: earthquakes, intrusion
  - Day to year: eruptions
  - Year to millennium: hydrothermal circulation
  - Millennium to million years: mantle flow, melt migration

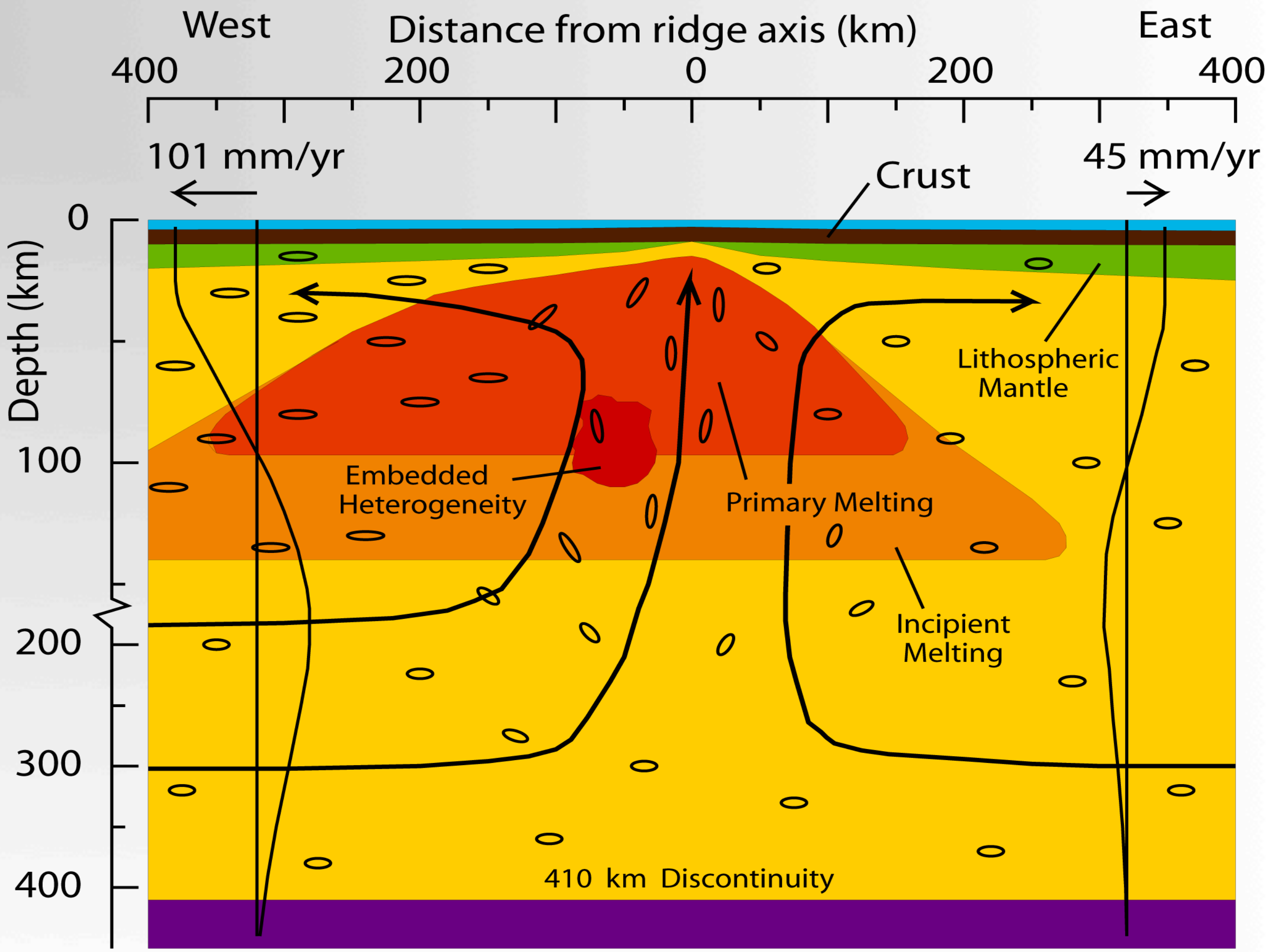
Ridge Morphology



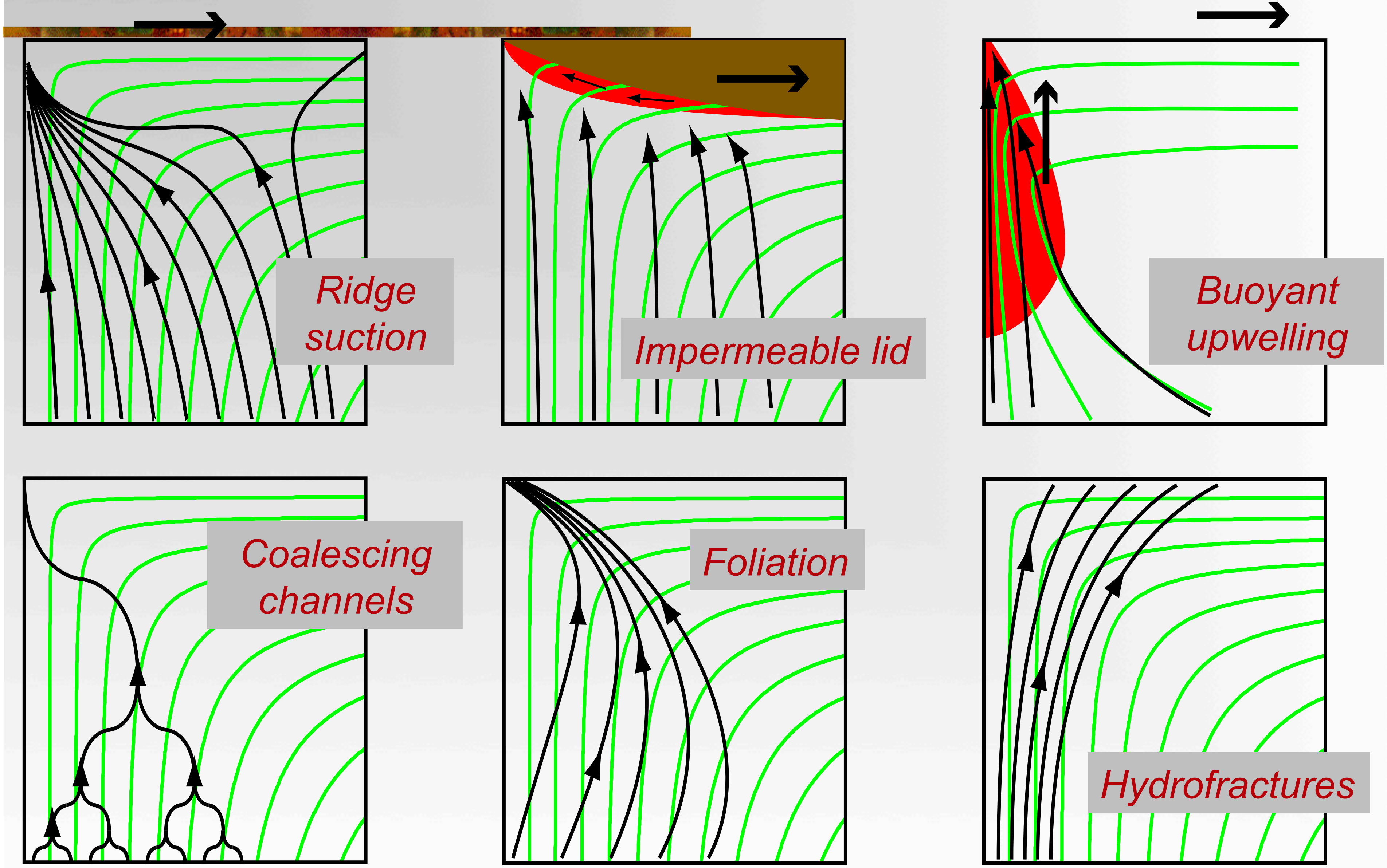
Melting at Depth

- Wide region where 1 to 2% partial melt is present

MELT Seismic Team, 1998



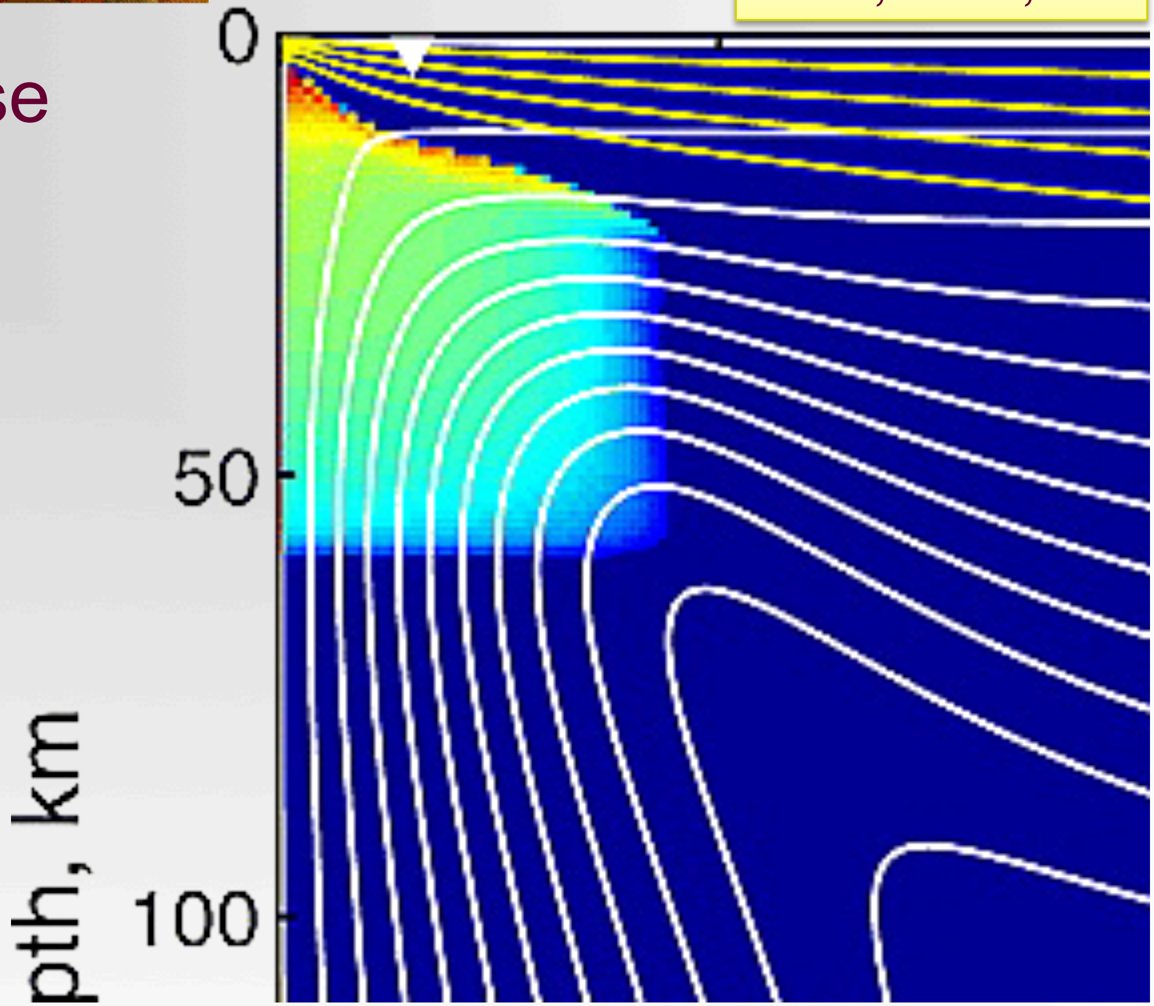
Proposed Focusing Mechanisms



Coupled model (Finite Volume)

- McKenzie two-phase flow equations + “Enthalpy” method (Katz 2008)
- Three-step melt migration
  - 1) Vertical melt migration
  - 2) Along a permeability barrier
  - 3) Extraction at the axis

Katz, 2010, G^3



Colors: $\log_{10}(\phi)$; white: mantle flow; yellow: isotherms
U_0=4cm/yr, $\eta=5x10^{17}$Pa.s

Modeling melt migration: the good guys

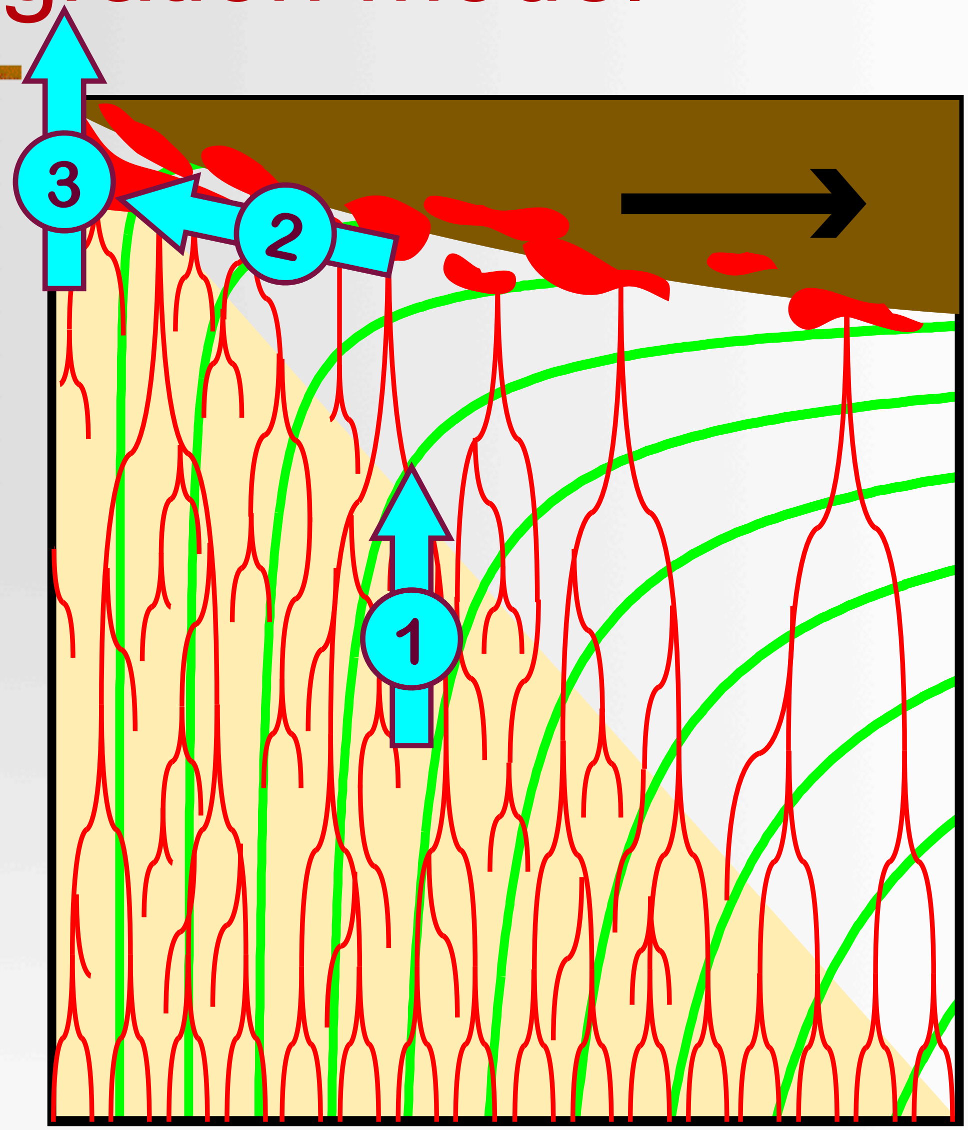
- Two phase flow
- Dynamic equilibrium
- Thermodynamics
- Interface interactions

Modeling melt migration: the slacker

- Parameterized
- Static
- No coupling
- Evaluate against observations
- Includes 3D effects

Simplified melt migration model

- 1) Rapid, subvertical melt extraction below the plate
- 2) Sub-horizontal migration along a permeability barrier at the base of the lithosphere
- 3) Subvertical extraction at tectonized plate boundary



Inspired by Sparks and Parmentier, 1991

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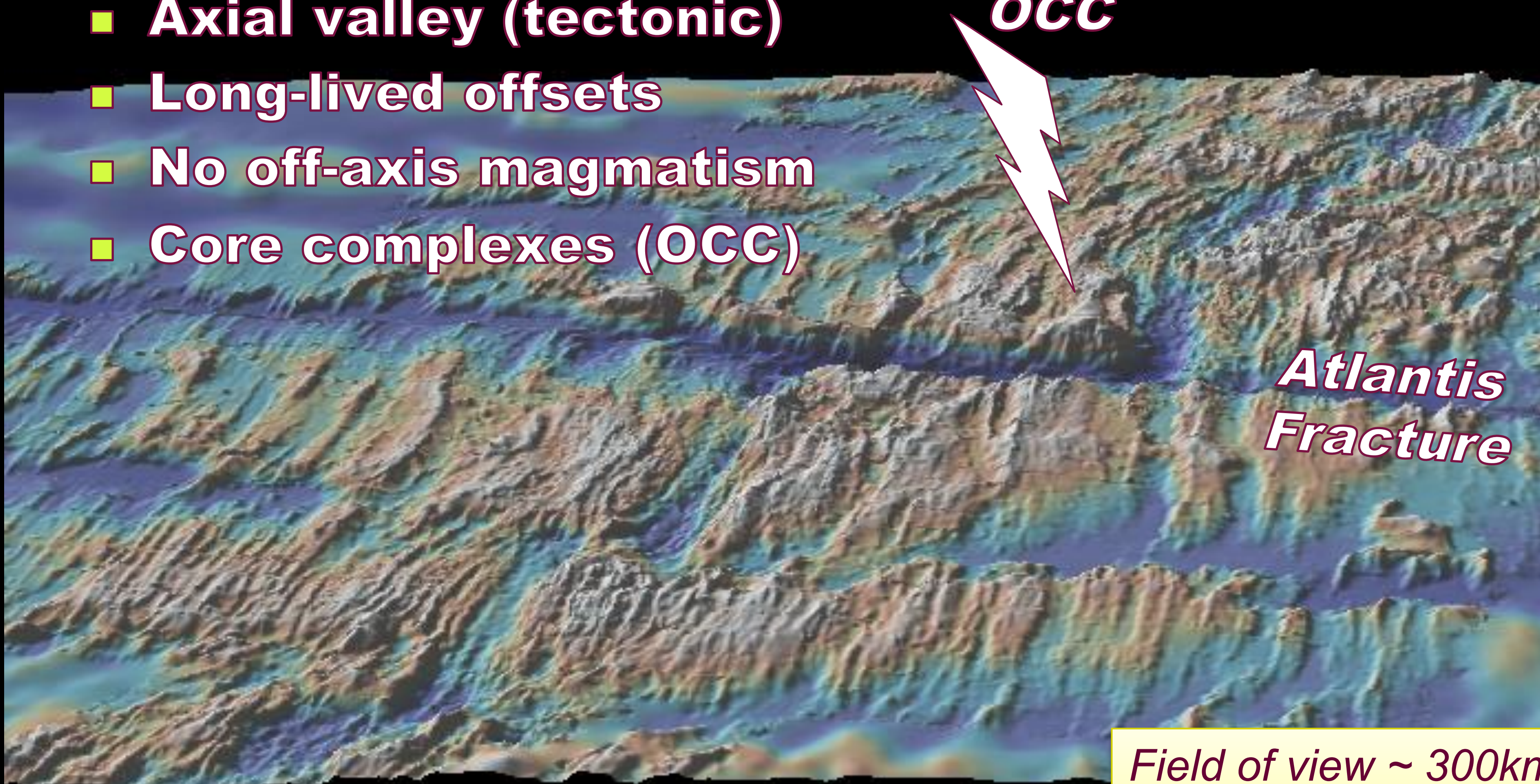
Slow Spreading: Mid-Atlantic Ridge

- **Axial valley (tectonic)**
- **Long-lived offsets**
- **No off-axis magmatism**
- **Core complexes (OCC)**

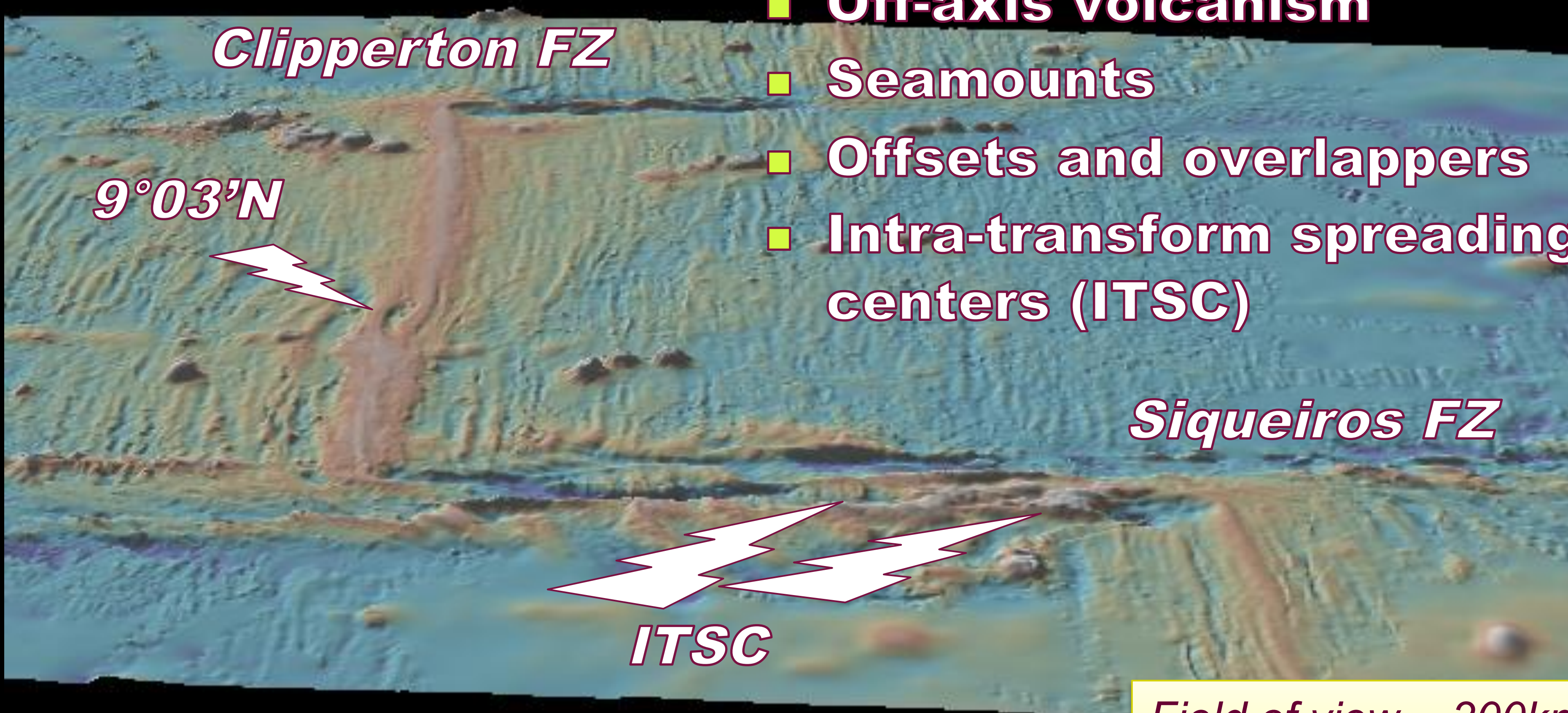


Field of view ~ 300km
2x VE

Multi-resolution gridded digital elevation model accessed using GeoMapApp

Fast Spreading: East Pacific Rise

- **Axial high**
- **Off-axis volcanism**
- **Seamounts**
- **Offsets and overlappers**
- **Intra-transform spreading centers (ITSC)**



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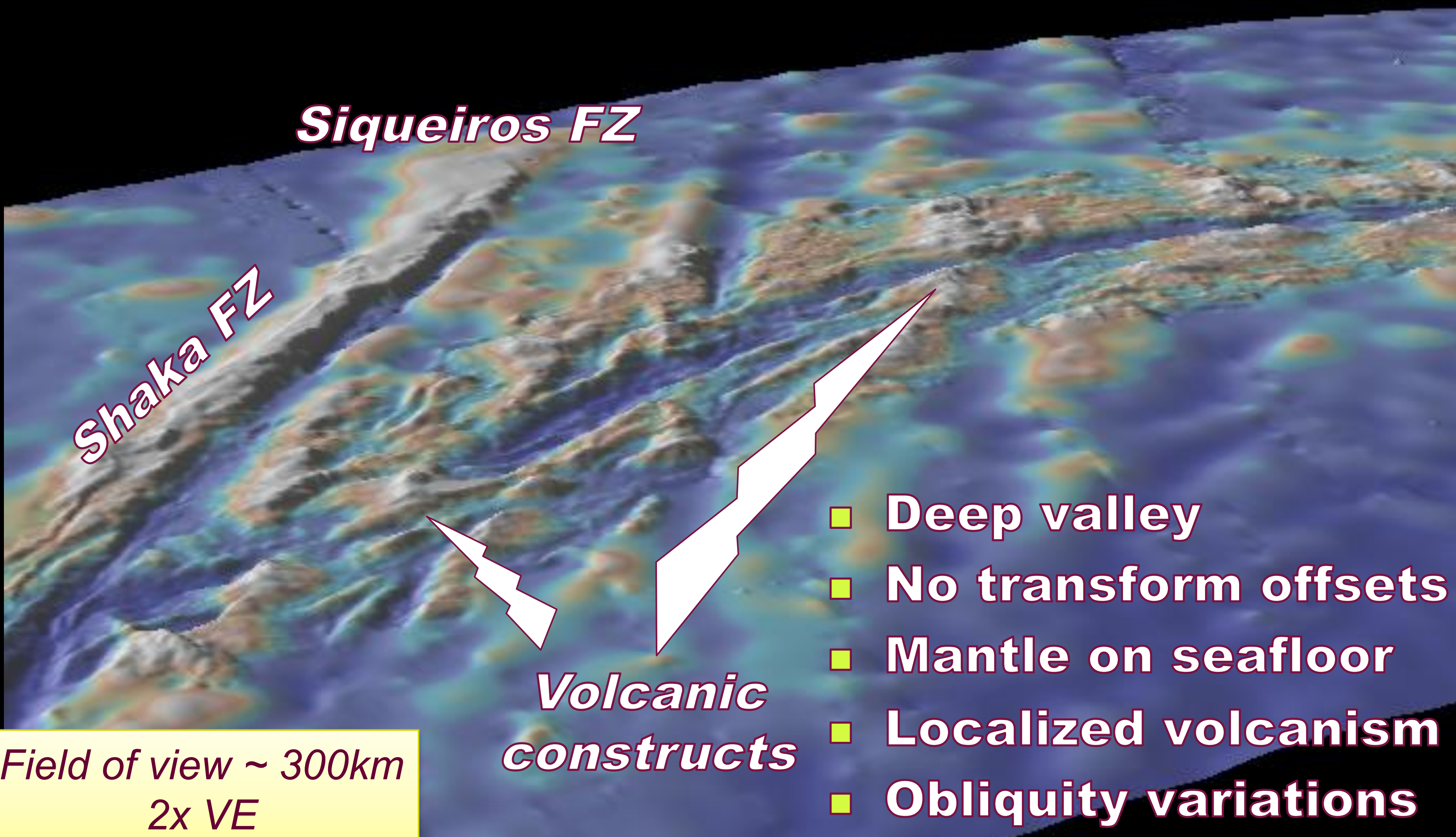
Multi-resolution gridded digital elevation model accessed using GeoMapApp

Ultraslow spreading: SW Indian Ridge

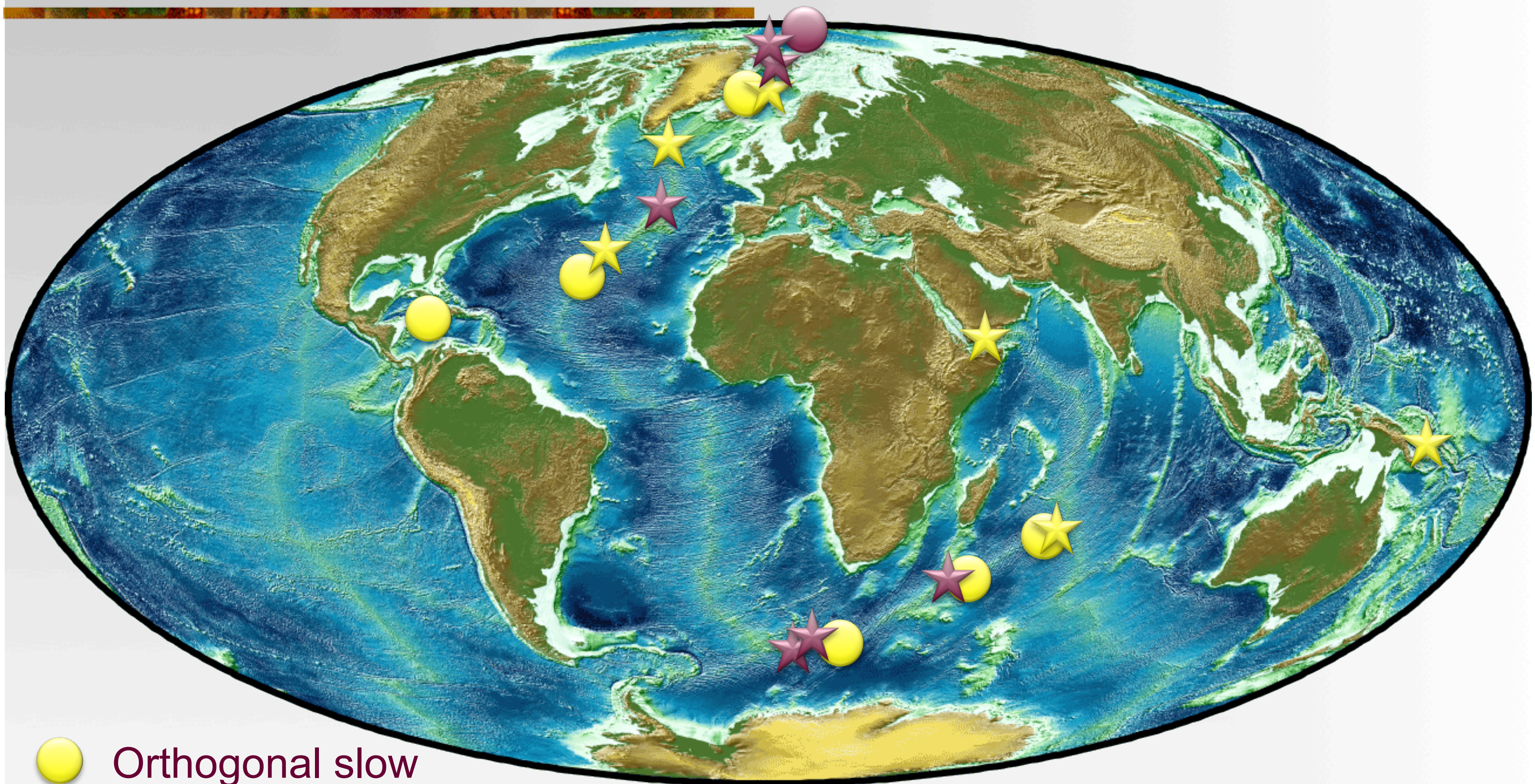


- Deep valley
- No transform offsets
- Mantle on seafloor
- Localized volcanism
- Obliquity variations

Field of view ~ 300km
2x VE

Multi-resolution gridded digital elevation model accessed using GeoMapApp

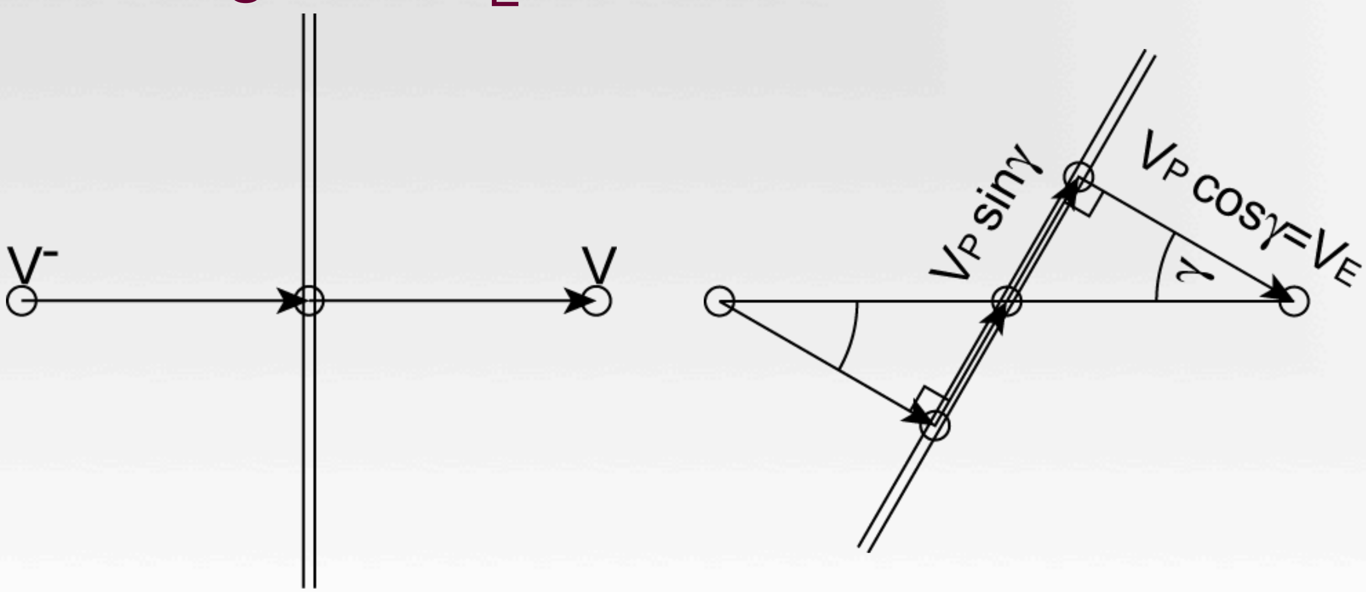
Mid-ocean Ridges



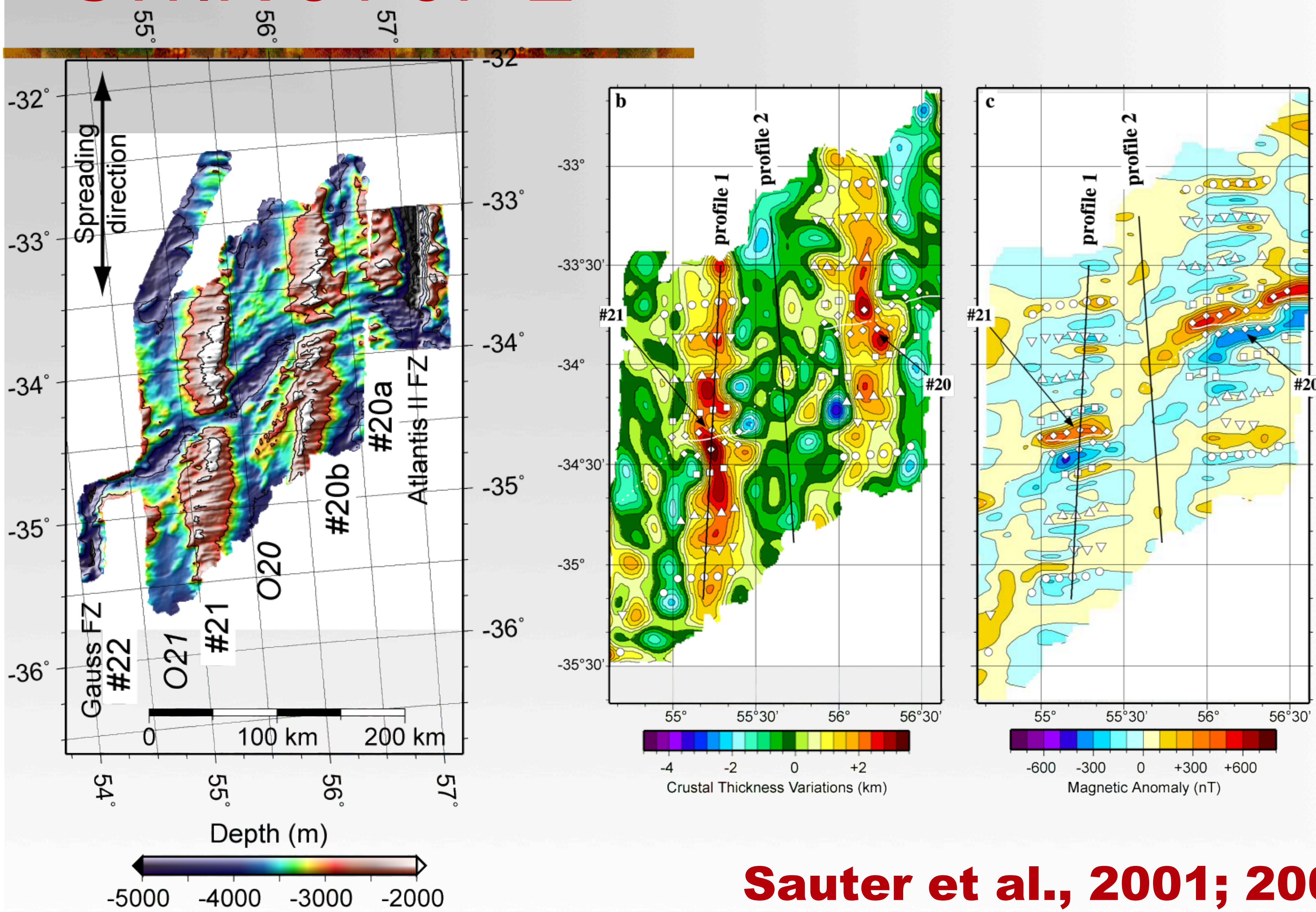
Orthogonal slow
Orthogonal ultraslow
Oblique slow
Oblique ultraslow

Definition of Obliquity

- Angle between ridge-normal direction and plate spreading direction
  - Orthogonal ridges have 0 obliquity
- Decompose plate velocity into effective spreading rate V_E and effective shear rate V_S



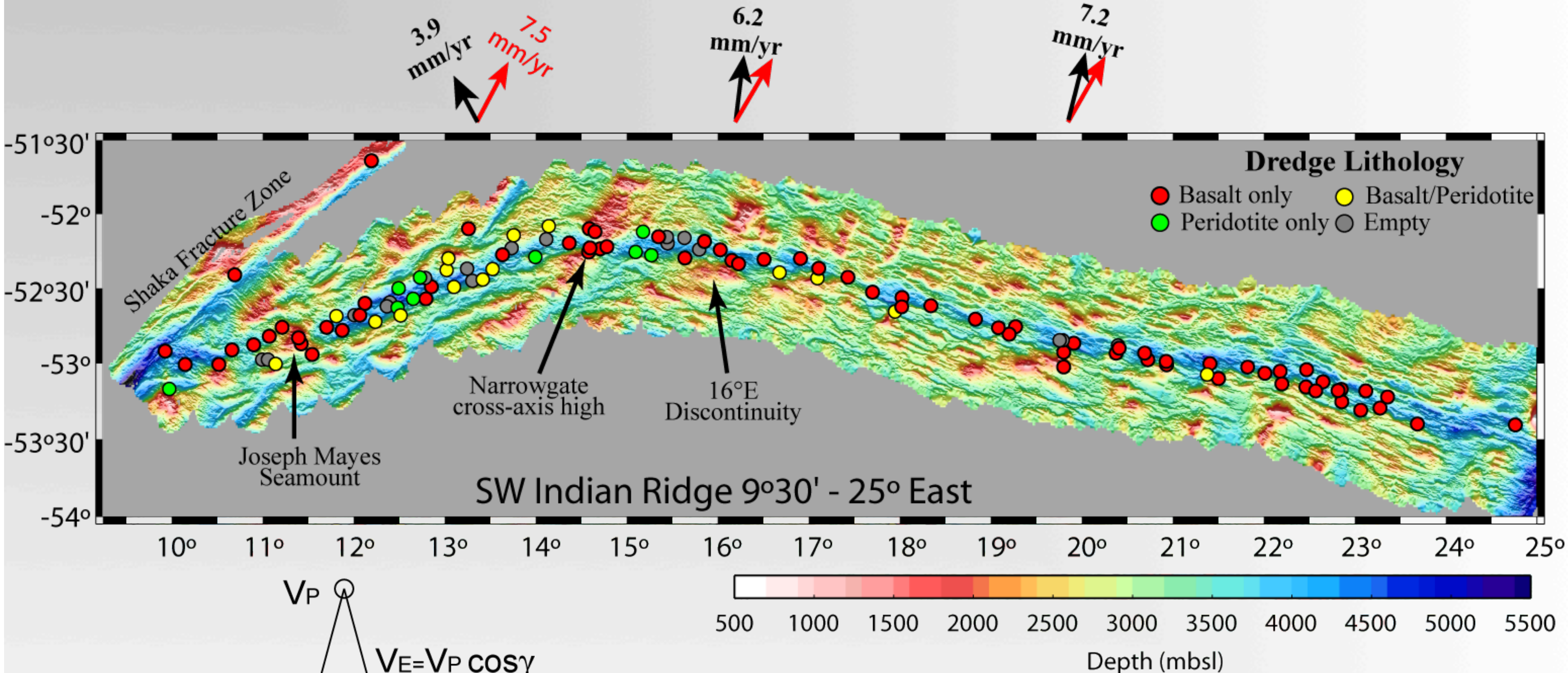
SWIR 54-57°E

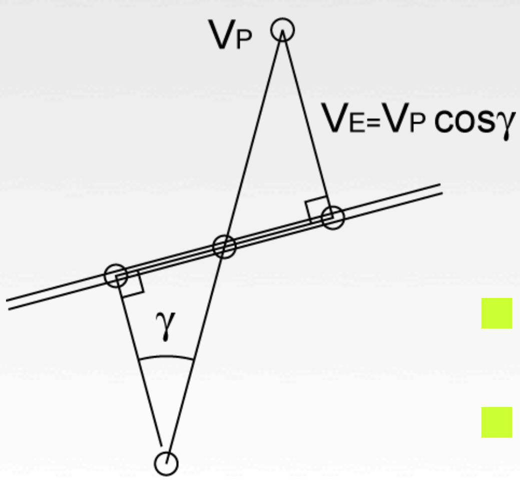


Sauter et al., 2001; 2004

Dick et al., 2003

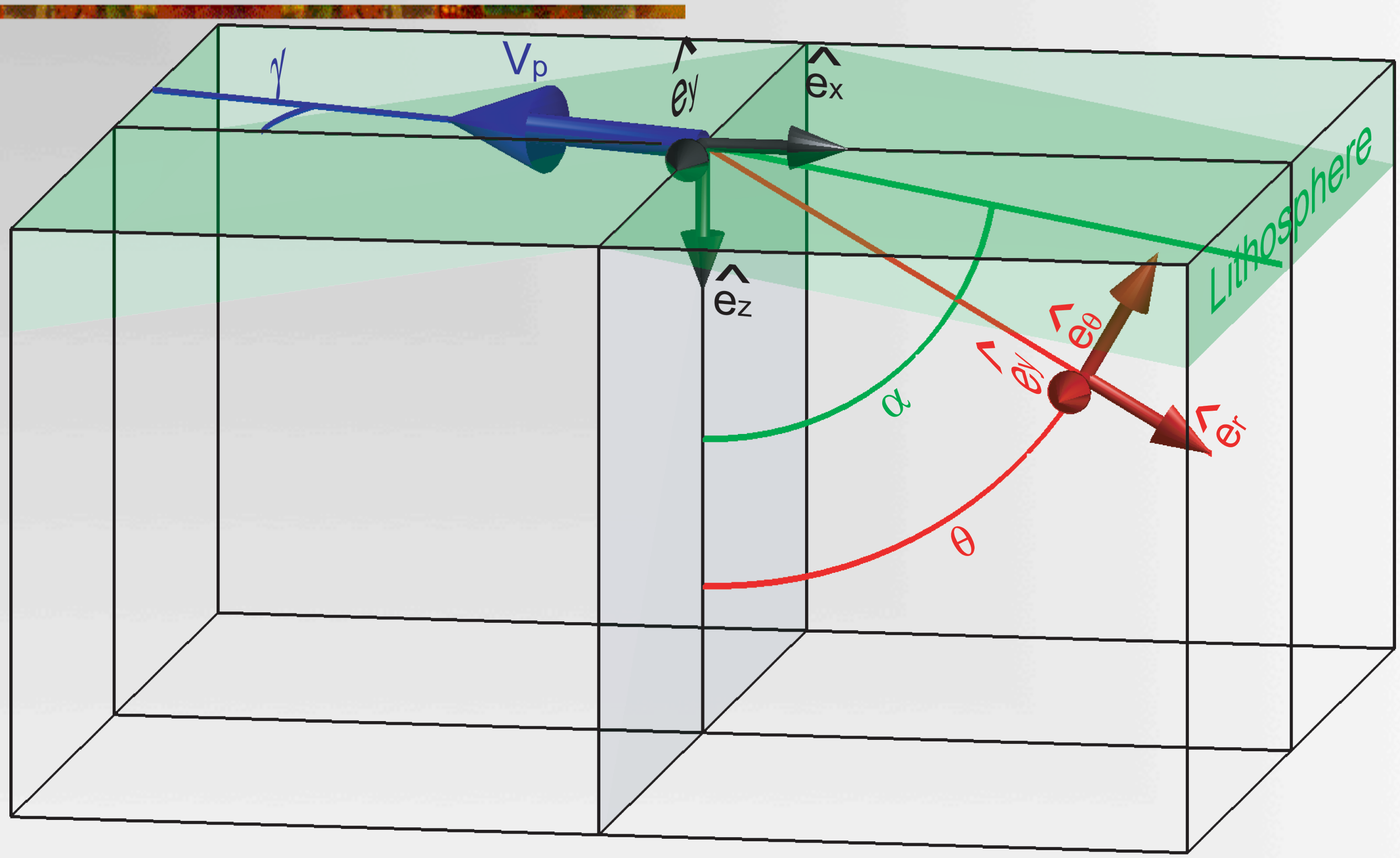
Ultraslow ridge





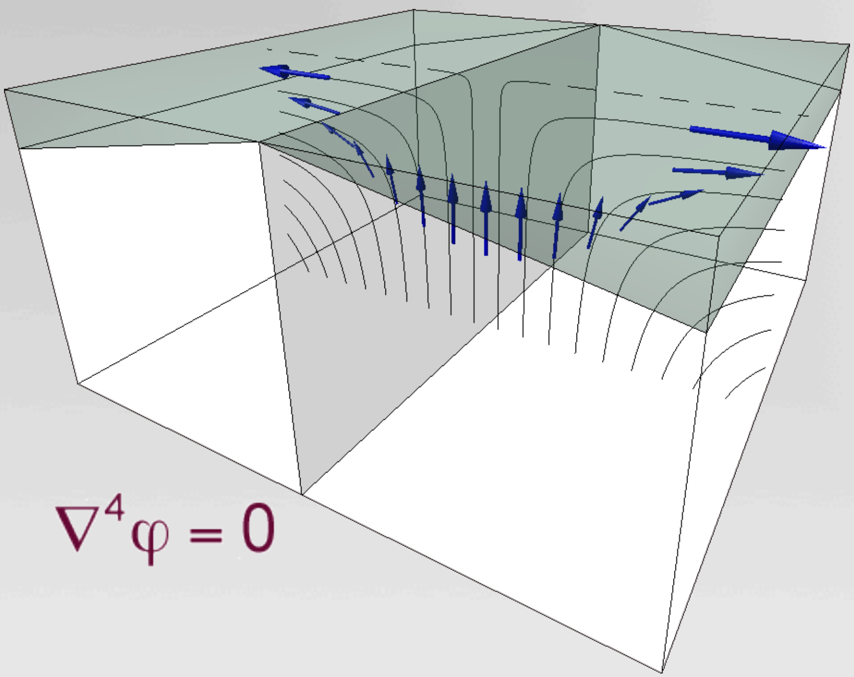
- Amagmatic, oblique segment
- Large, localized volcanic centers

Model Configuration



- Model invariant along ridge axis, steady-state
- Obliquity γ, lithosphere slope $\pi/2-\alpha$
- Obtain similarity solution

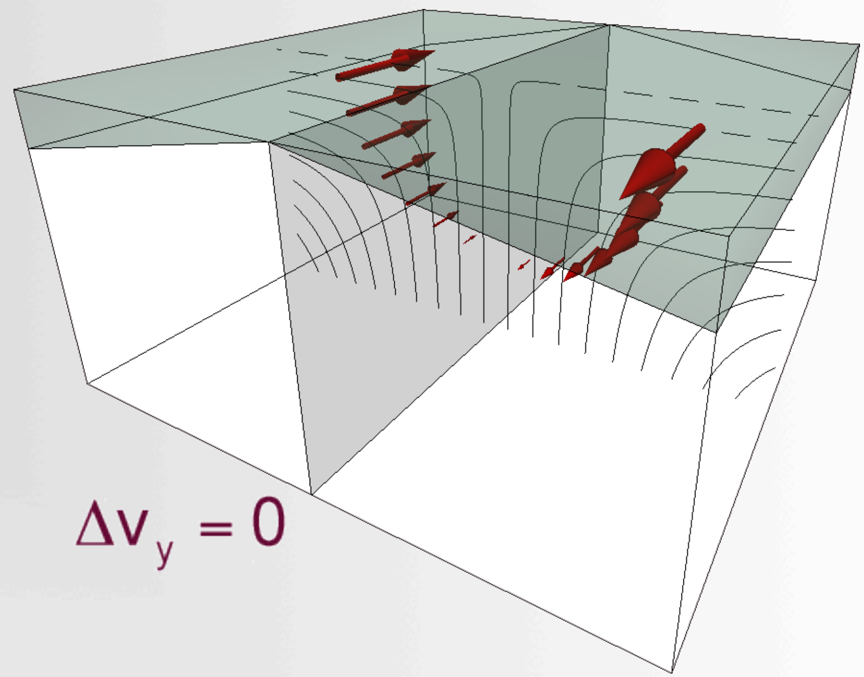
Mantle Flow Field Decomposition



$\nabla^4 \varphi = 0$

Ridge-perpendicular corner flow
Driven by effective opening velocity

$V_E = V_P \cos\gamma$



$\Delta v_y = 0$

Ridge-parallel shear flow
Driven by ridge-parallel velocity

$V_S = V_P \sin\gamma$

Thermal Structure

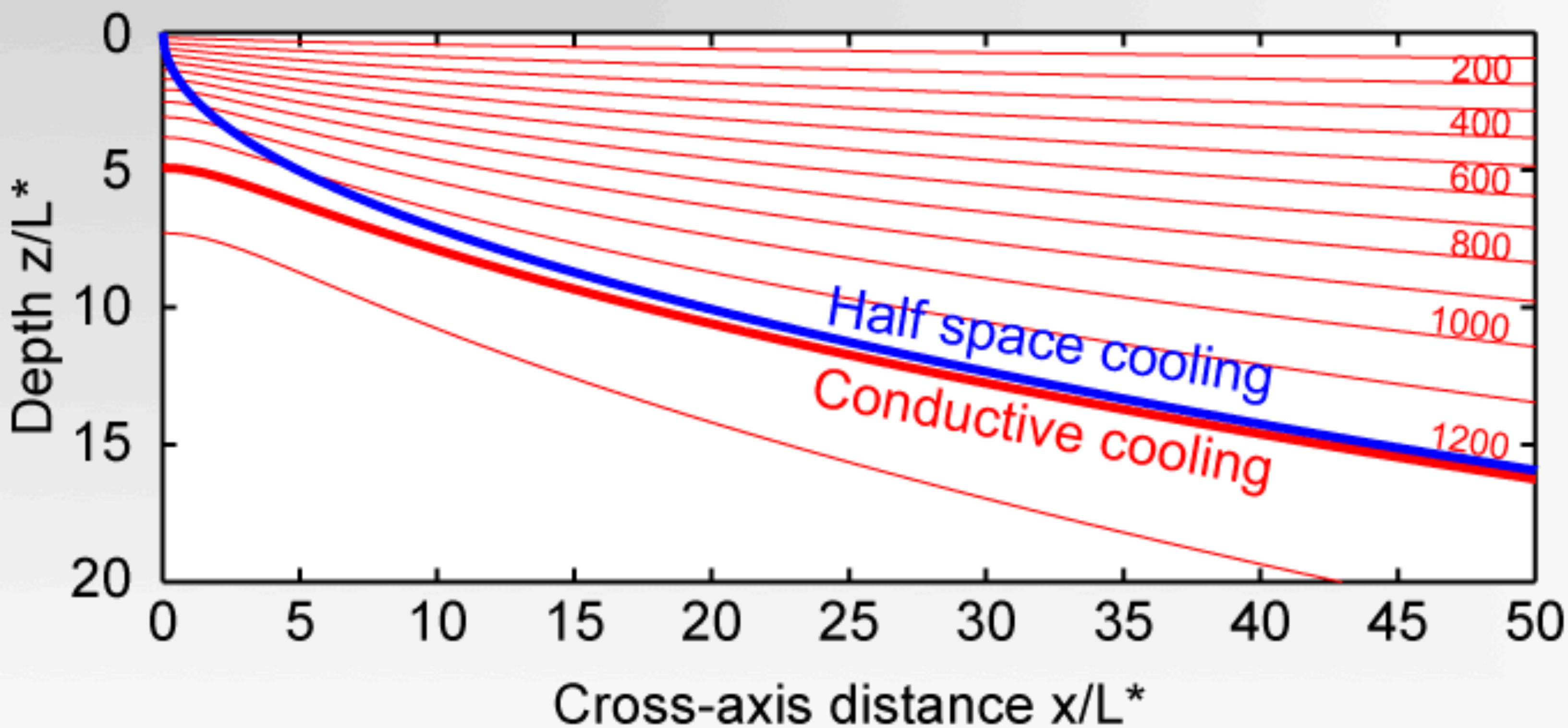
- Heat equation
  - Only corner flow components appear

$$v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

- Conduction balanced by corner flow component only
  - Single thermal length scale
  - $L^* = \kappa / V_E = \kappa / (V_P \cos\gamma)$

Thermal Boundary Layer

- Universal thermal solution scales with $L^*=\kappa/V_e$
- On axis: z_{TBL}~$5\kappa/V_e$

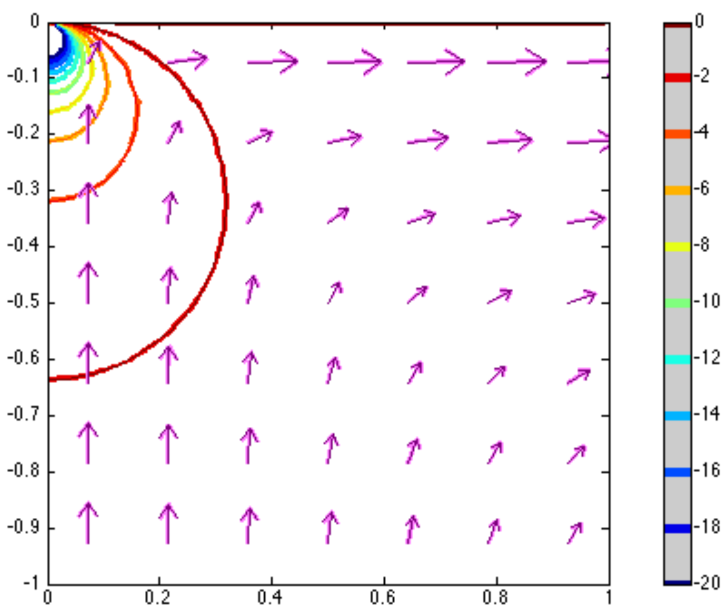


Montési and Behn, 2007

Why neglect buoyancy?

- Compare pressure gradients from corner flow with melt-induced buoyancy

$$\frac{4\eta_s V_e}{\pi r^2} \geq \phi\ \Delta\rho\ g$$



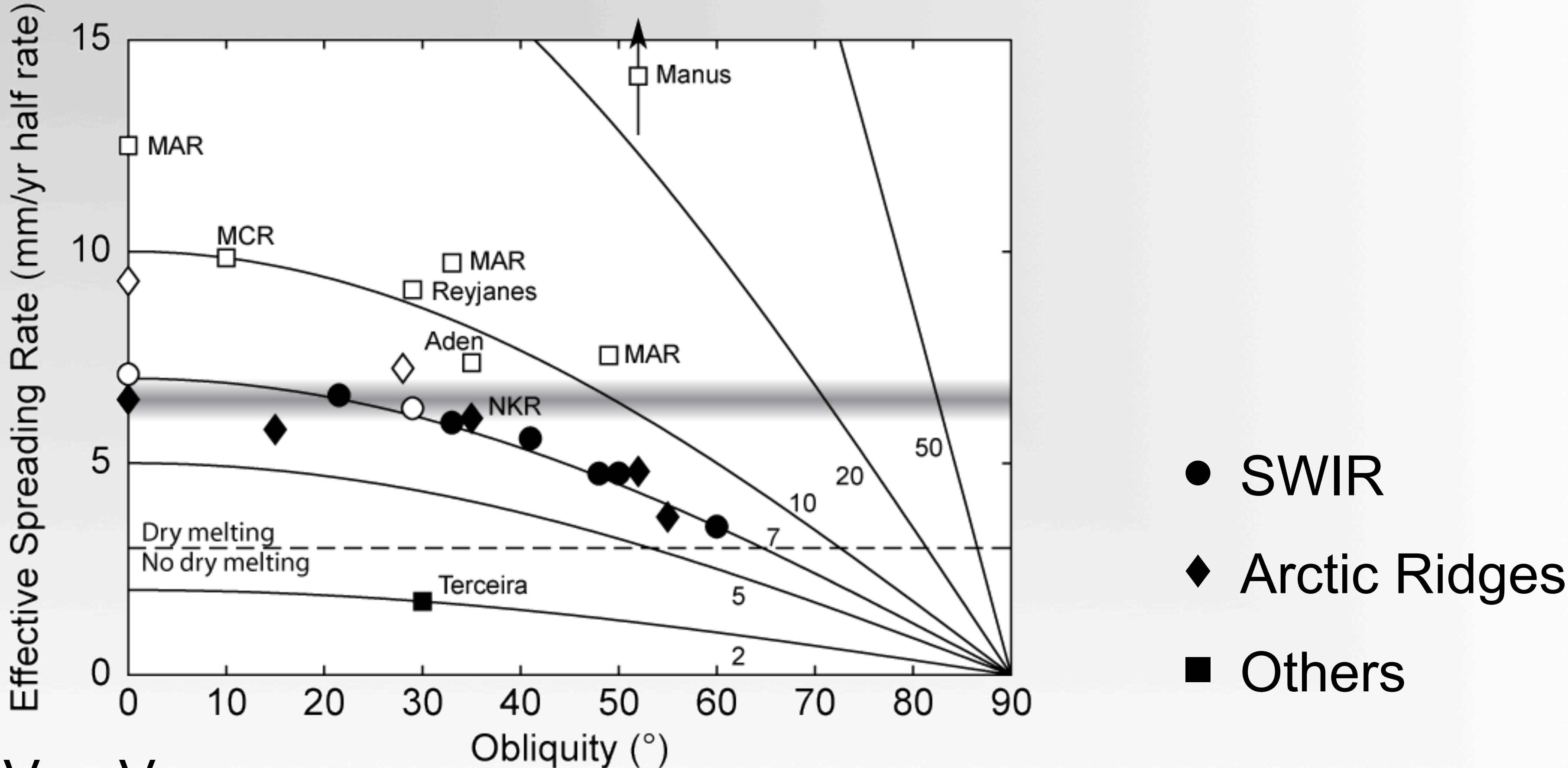
$$p^c = -\eta_s V_e \frac{4}{\pi}\frac{1}{r}\cos\theta$$

- Assume
  - Depth of TBL with Thermal diffusivity 10^{-6} mm^2/s
  - 1% melt with $\Delta\rho$=300 kg/m^3
  - Viscosity 10^{19}Pa.s
- Corner flow dominates if V_e>1cm/yr

$$V_e \geq \left(\frac{25\pi\kappa^2\phi\ \Delta\rho\ g}{4\eta_s}\right)^{1/3}$$

Effective Velocity at Ultraslow Ridges

- Critical effective velocity: 6.5 mm/yr



$V_E = V_P \cos\gamma$

Montési and Behn, 2007

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Melt migration; 1st simplification

- Darcy flow $$\phi(\mathbf{v_f} - \mathbf{v}_s) = -\frac{k}{\eta_f}\left[\nabla P_f - \rho_f \mathbf{g}\right]$$ (with ∇P_f crossed out)
- Melt buoyancy ($\Delta\rho g$~3 MPa/km) dominates over pressure gradients from corner flow if velocity is larger than

$$V_e \geq \left(\frac{25\pi\kappa^2\Delta\rho\, g}{4\eta_s}\right)^{1/3} \sim 24\text{cm/yr}$$

- For all ridges on Earths, melt propagation is buoyancy-dominated

Melt migration; 2nd simplification

- Darcy flow

$$\mathbf{v}_f = \cancel{\mathbf{v}_s} + \frac{k}{\phi \eta_f} \rho_f \mathbf{g}$$

- Permeability of 10^{-11} m^2 for grain size of 1cm and 2% melt induces melt velocities of 1m/yr
- Melt velocity far exceeds that of the mantle
- Melt moves upward, and fast!

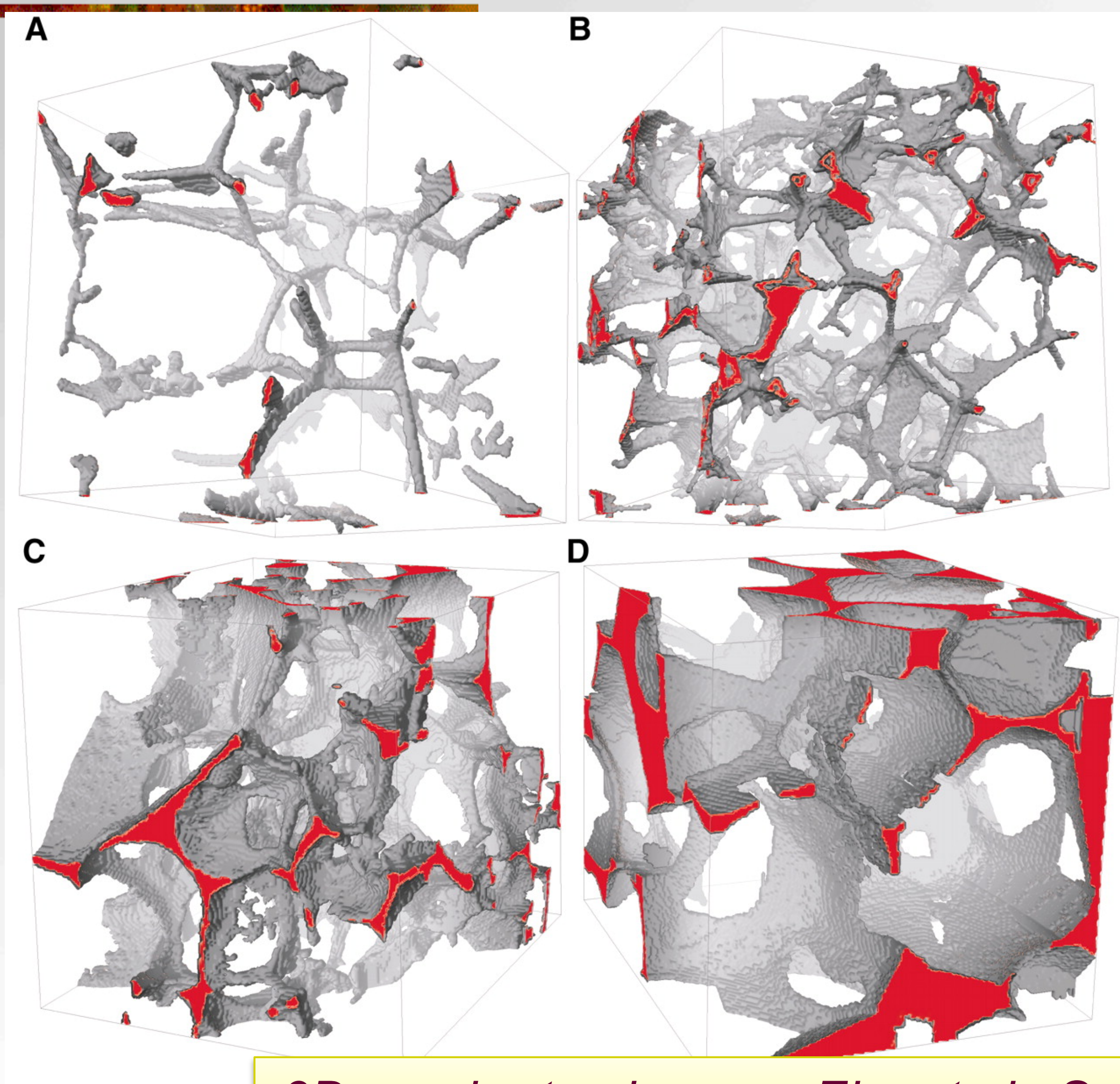
5% melt

Olivine + basalt system, 3D synchrotron images (0.7μm resolution) Zhu et al., 2011

Melt distribution: microscale

2% melt

Interconnected network along grain edges



5% melt

10% melt

20% melt

$$k \propto d^2\phi^3$$

$k \sim 10^{-11}$ m^2 if $d \sim 1cm$ $\phi \sim 2\%$

3D synchroton images, Zhu et al., Science, 2011'

Melt channels

- Feedback between
  - Porosity/viscosity
    - Stevenson, Holtzman, Katz, Butler
  - Porosity/melting
    - Hewitt and Fowler
  - Reactive flow
    - Kelemen, Aharonov, Spiegelman

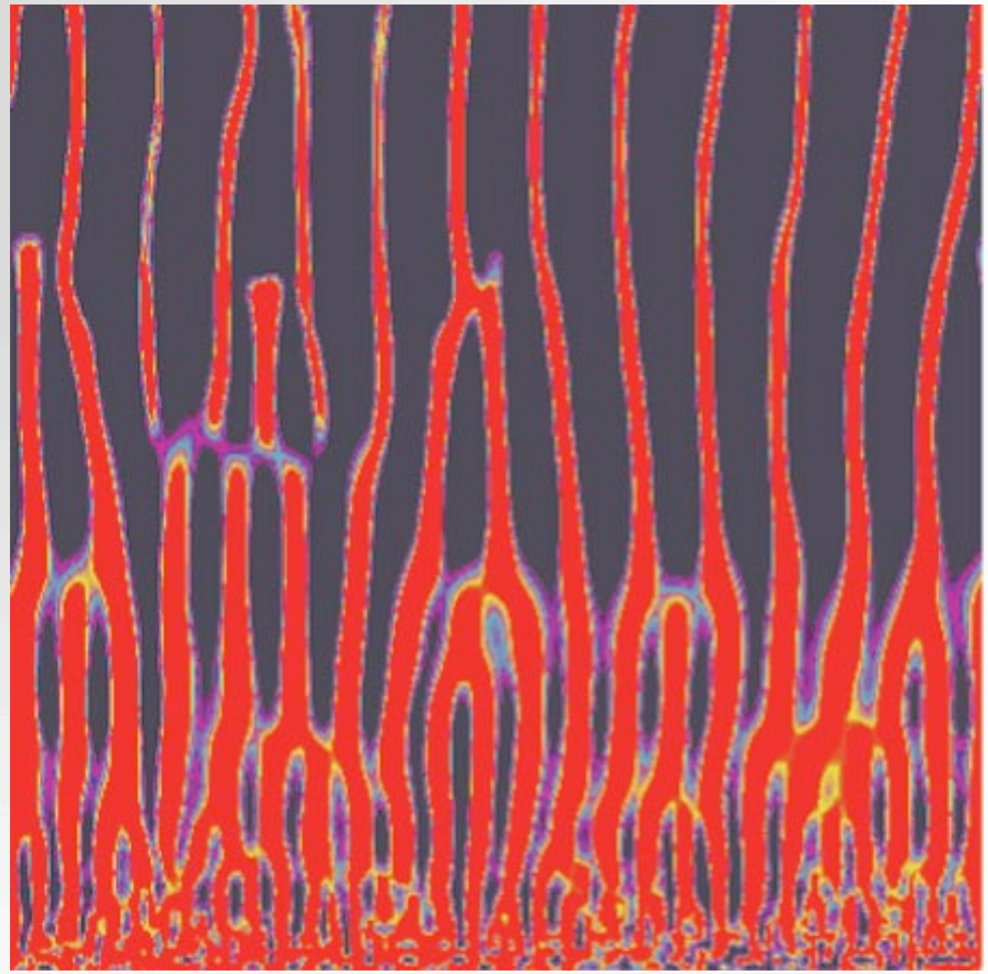


Image by Marc Spiegelman

Simplified melt migration model

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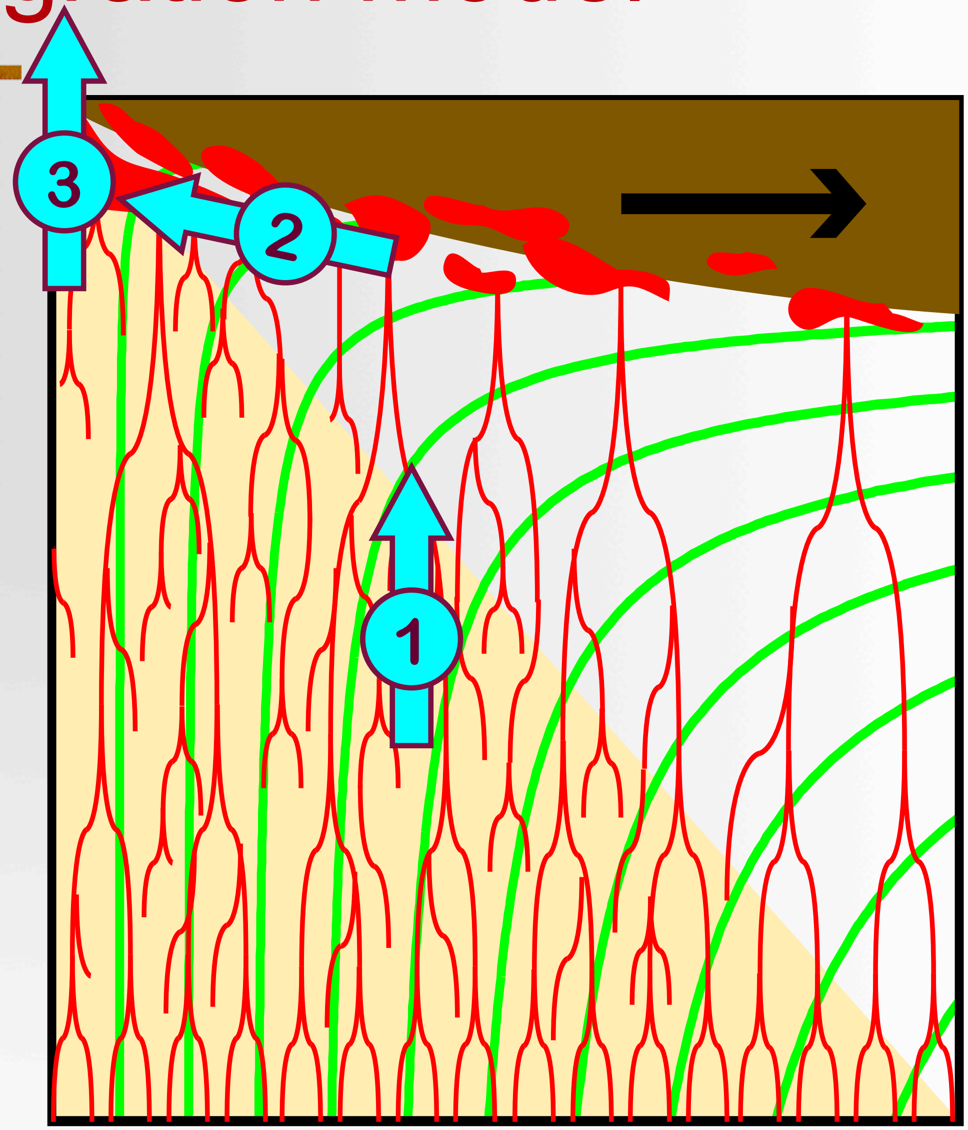
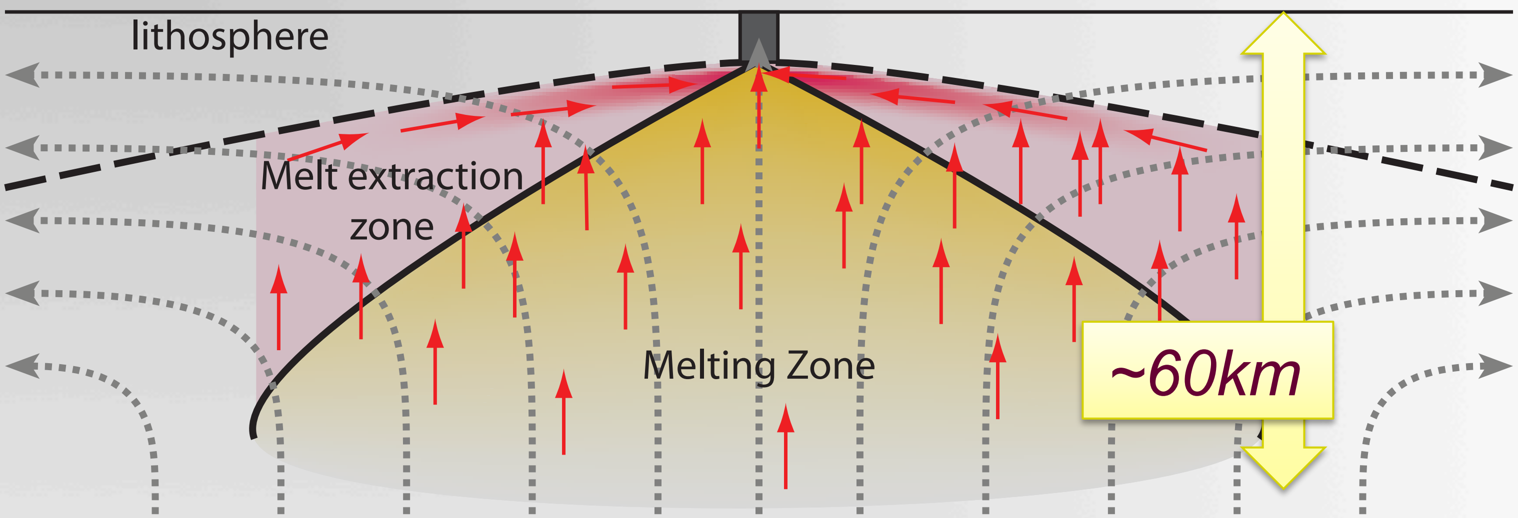


Inspired by Sparks and Parmentier, 1991

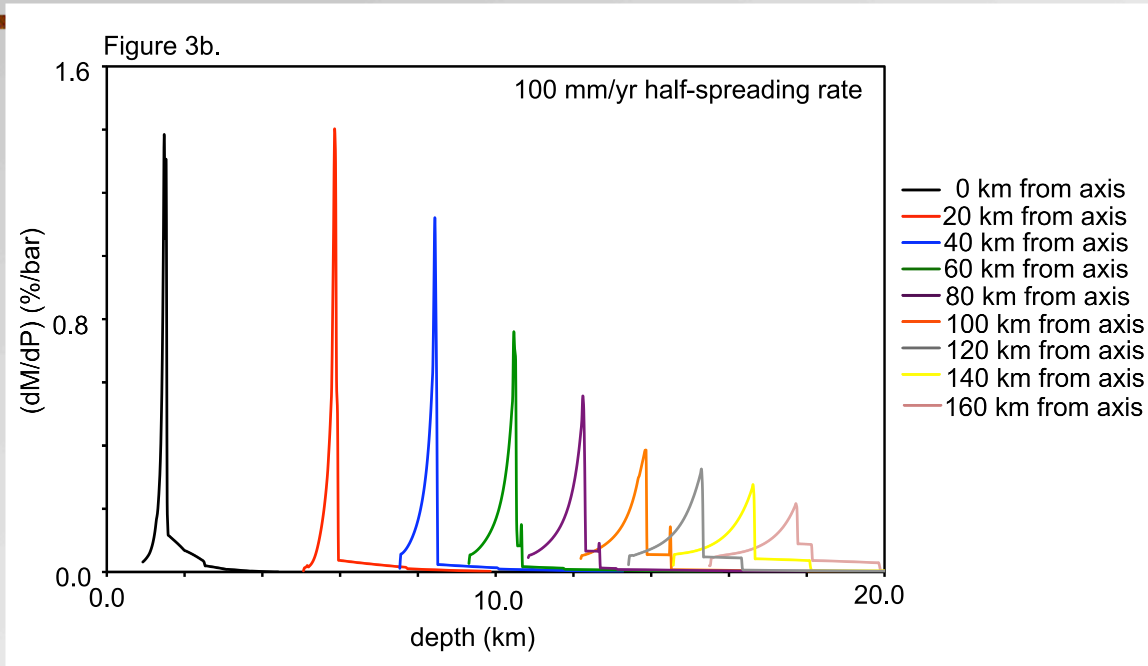
Definition of the permeability barrier



- Accumulate fractional melt produced in melting zone
- Cooling at the base of the lithosphere
- Ignores wet melying

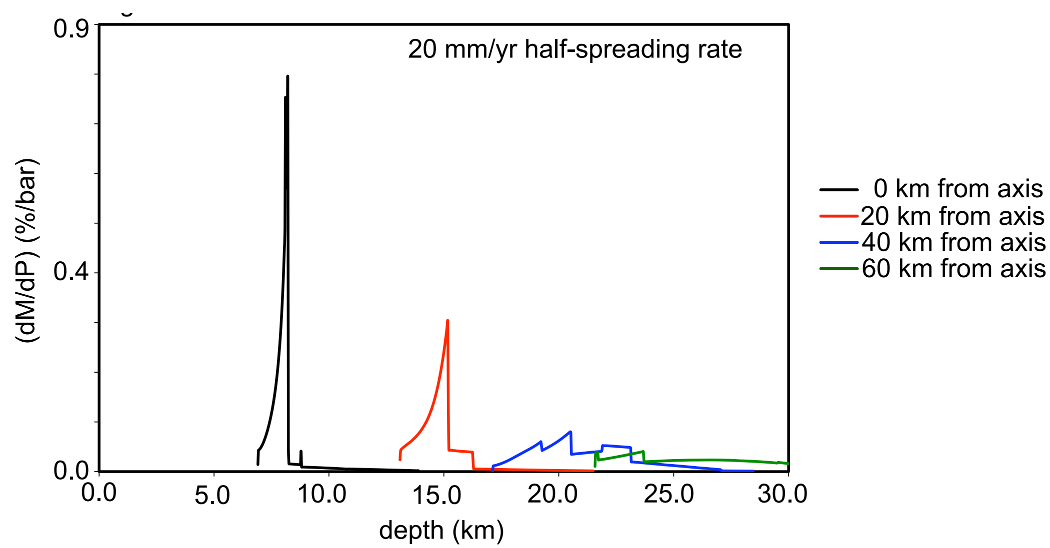
Hebert and Montési, 2010, following Sparks and Parmentier, 1991

Crystallization rate



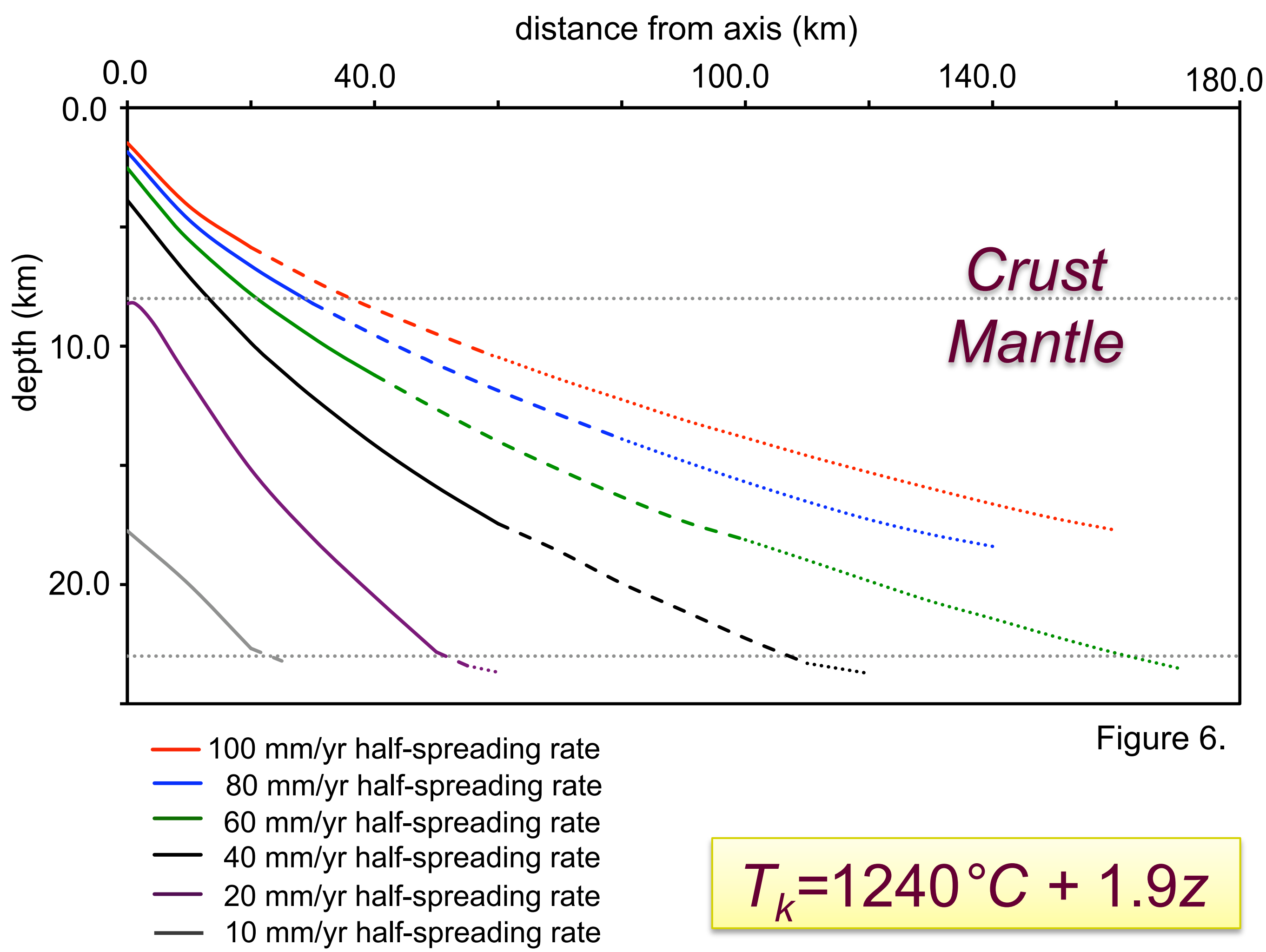
- Calculate with MELTS software
- Magma batches ascending in the thermal boundary layer

- Initially slow crystallization
- Peaks at pg±cpx



Hebert and Montési, 2010
Kelemen and Aharonov, 1998

Permeability barrier geometry



$T_k = 1240°C + 1.9z$

Hebert and Montési, 2010, Montési and Behn,, 2007

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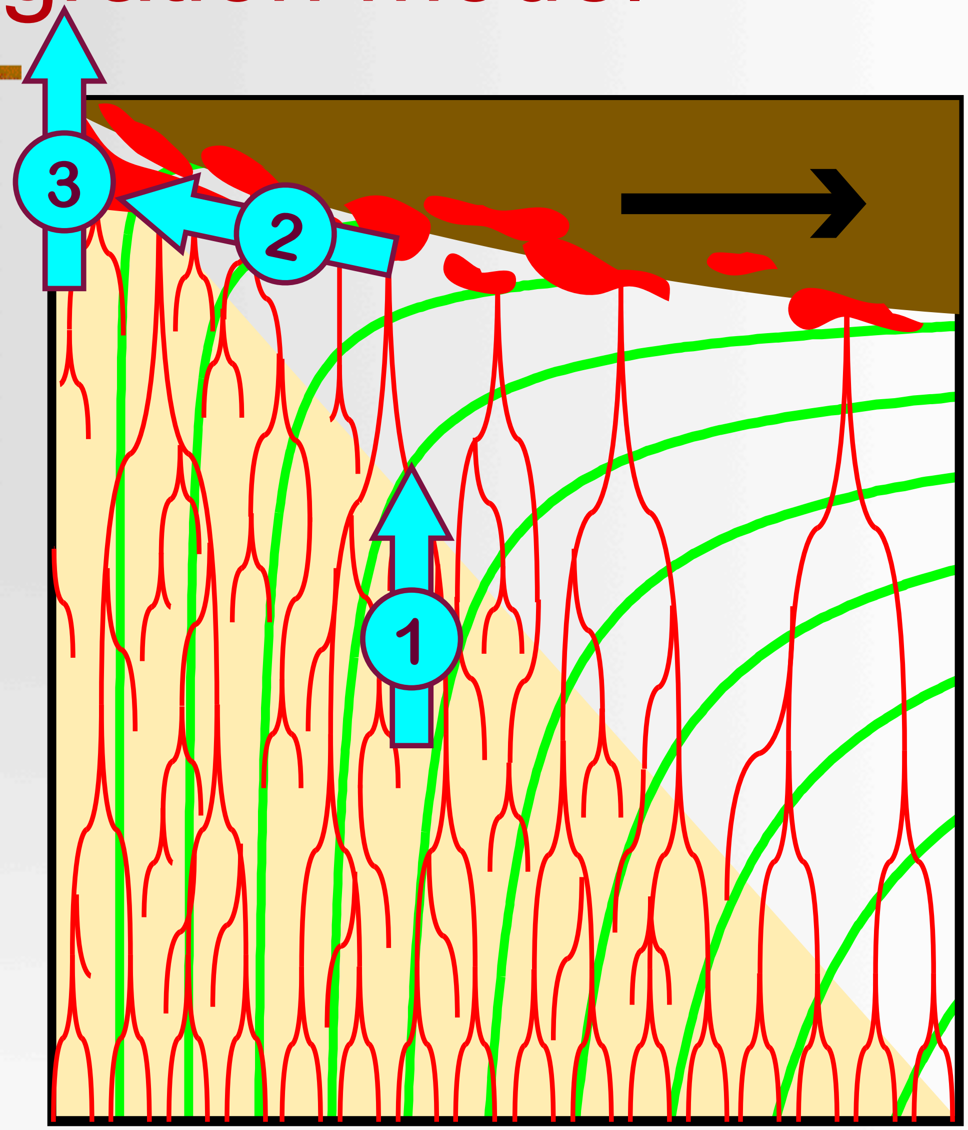

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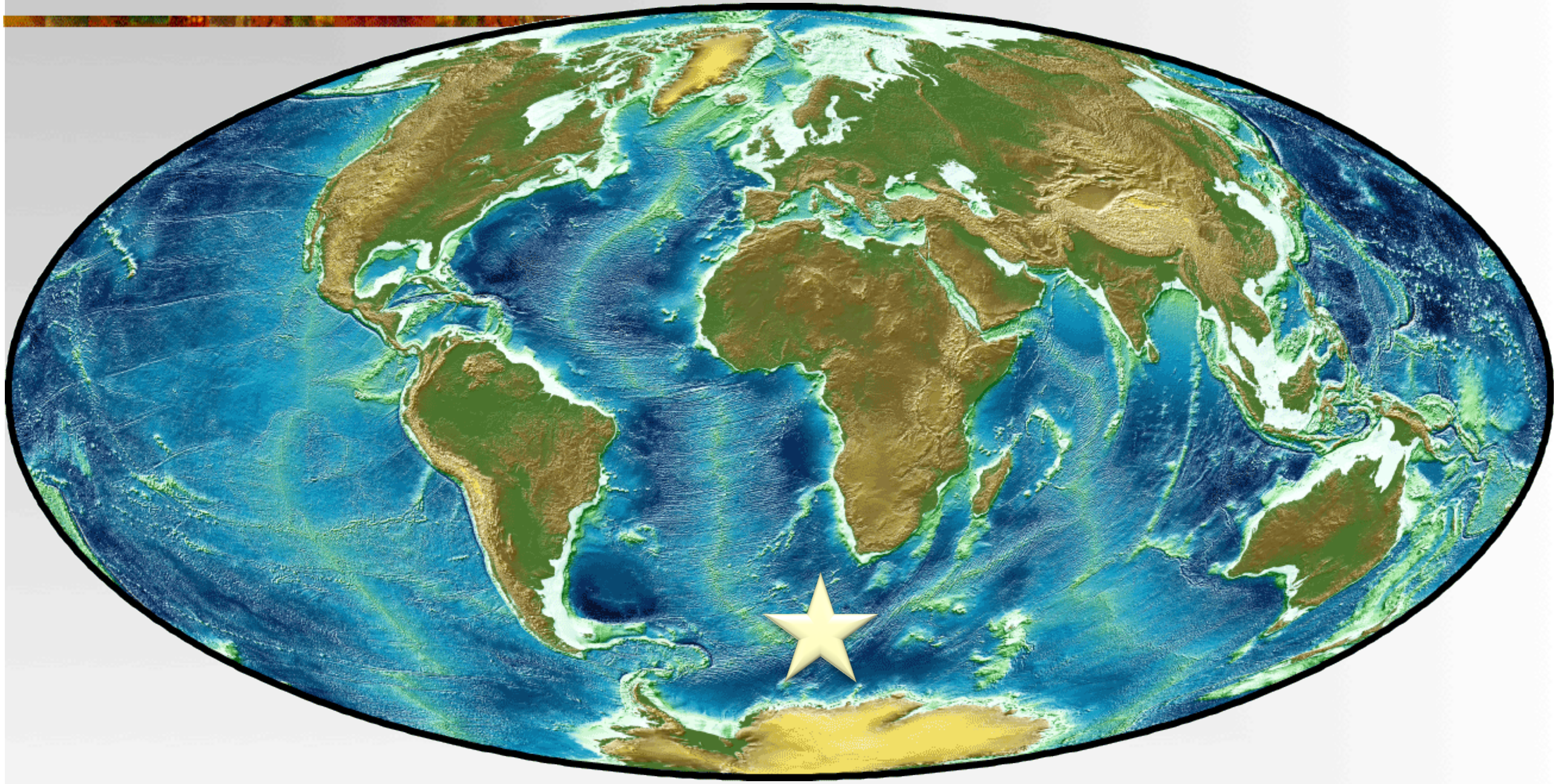
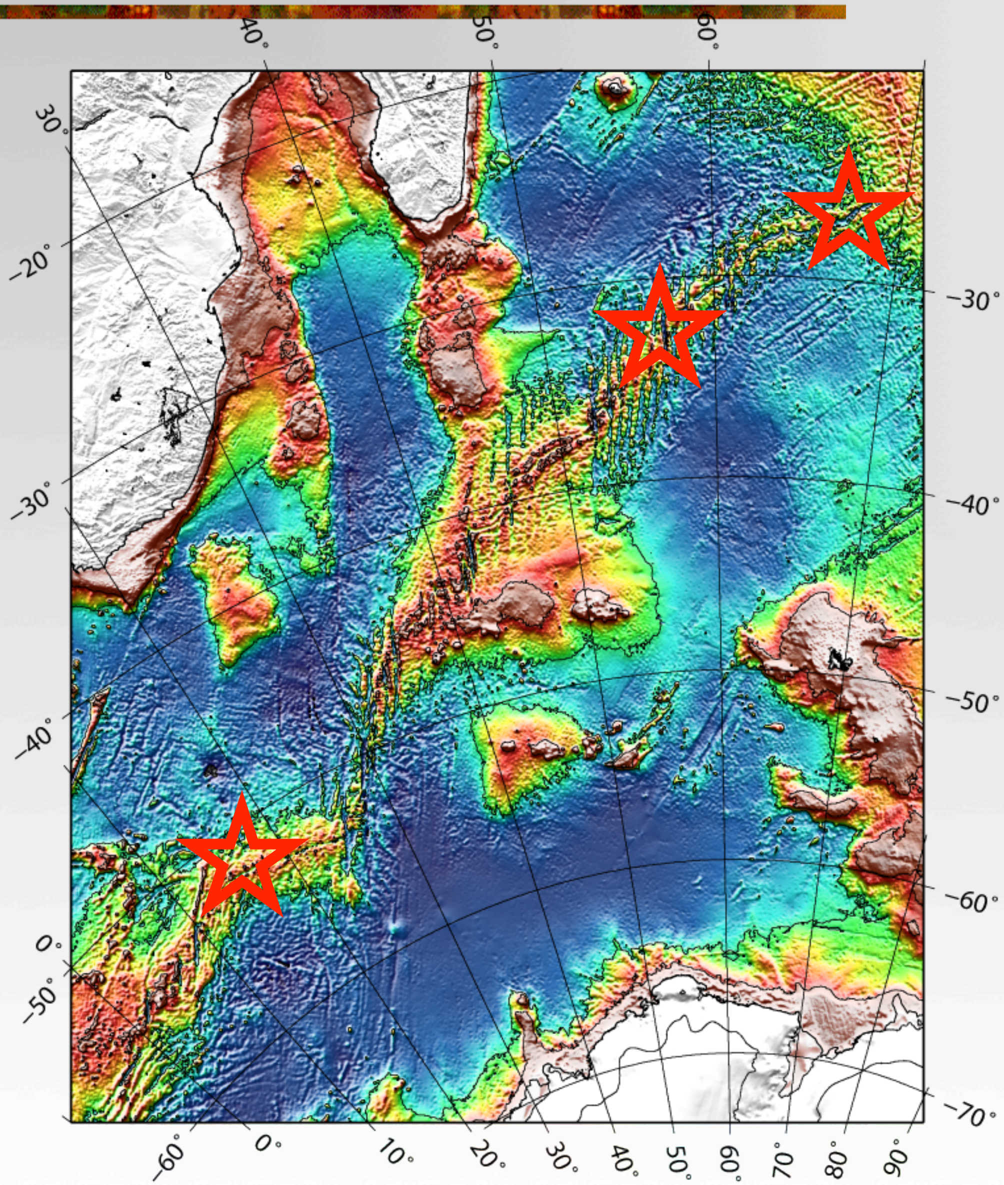
SWIR 10-16°E



- Slow to ultraslow morphology
- Spreading half rate: 7.5 mm/yr

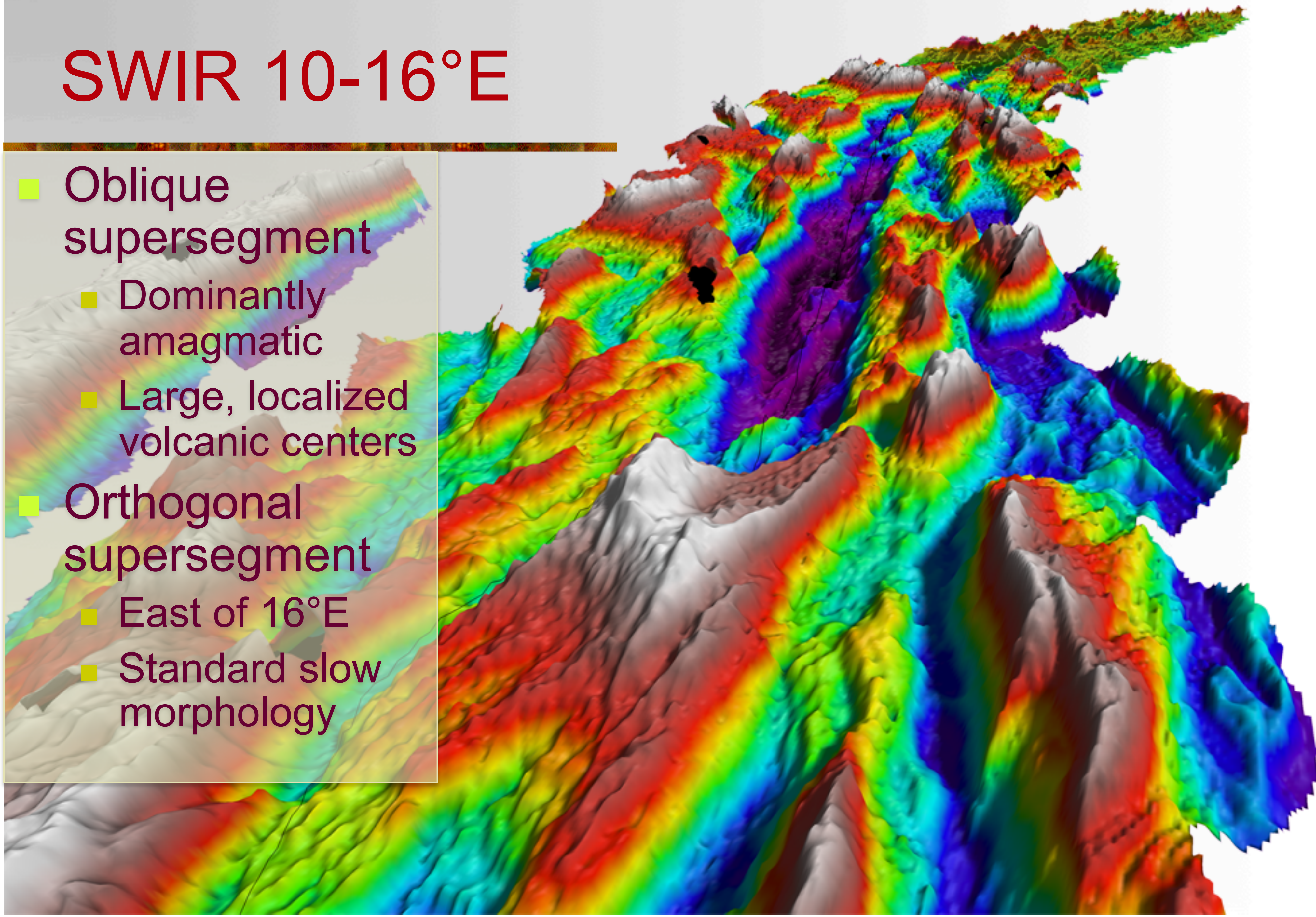
Southwest Indian Ridge



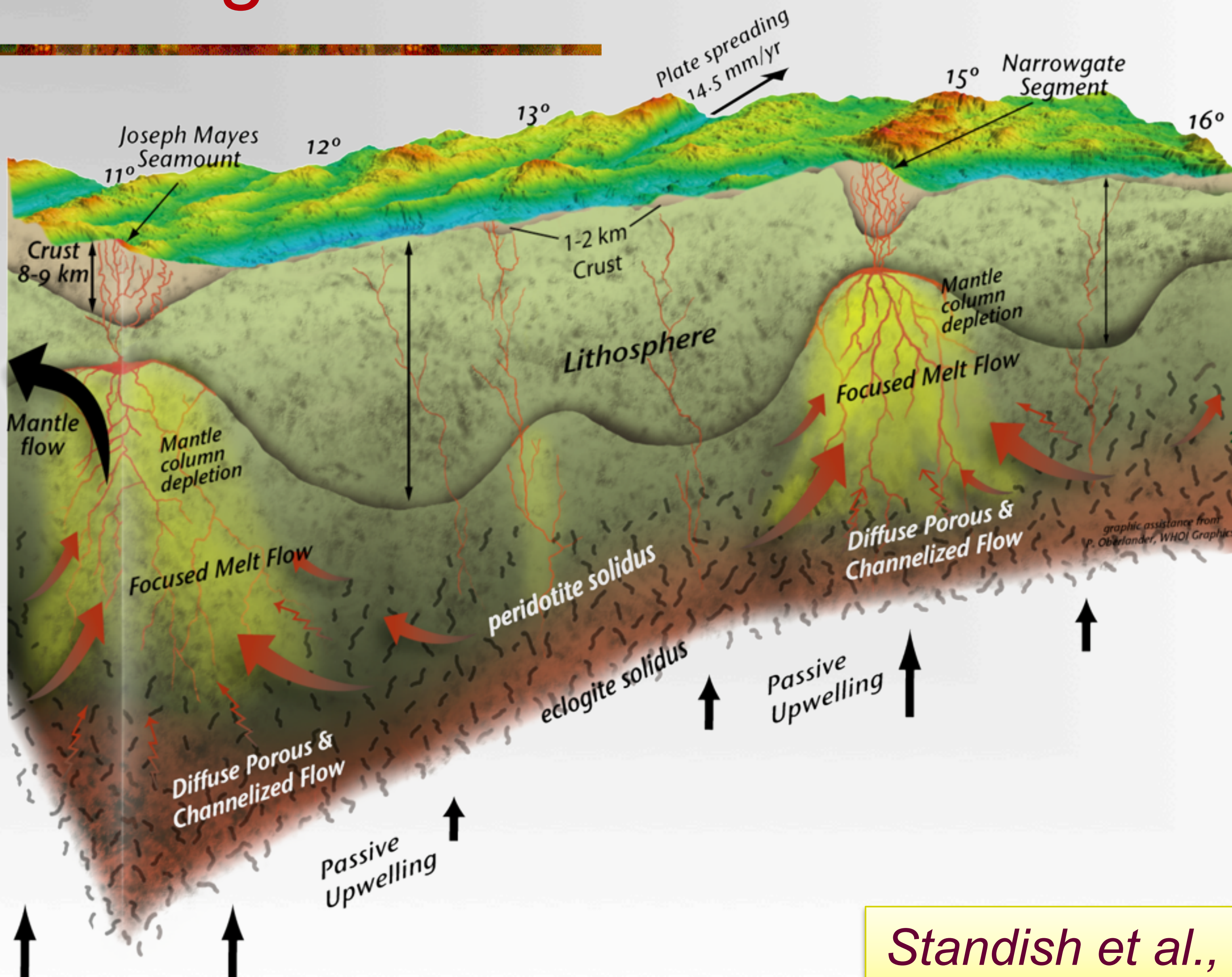
- 7700 km long ridge separating Africa and Antarctica
- 7 to 7.5 mm/yr (half rate)
- Several oblique segments

SWIR 10-16°E

- Oblique supersegment
  - Dominantly amagmatic
  - Large, localized volcanic centers
- Orthogonal supersegment
  - East of 16°E
  - Standard slow morphology

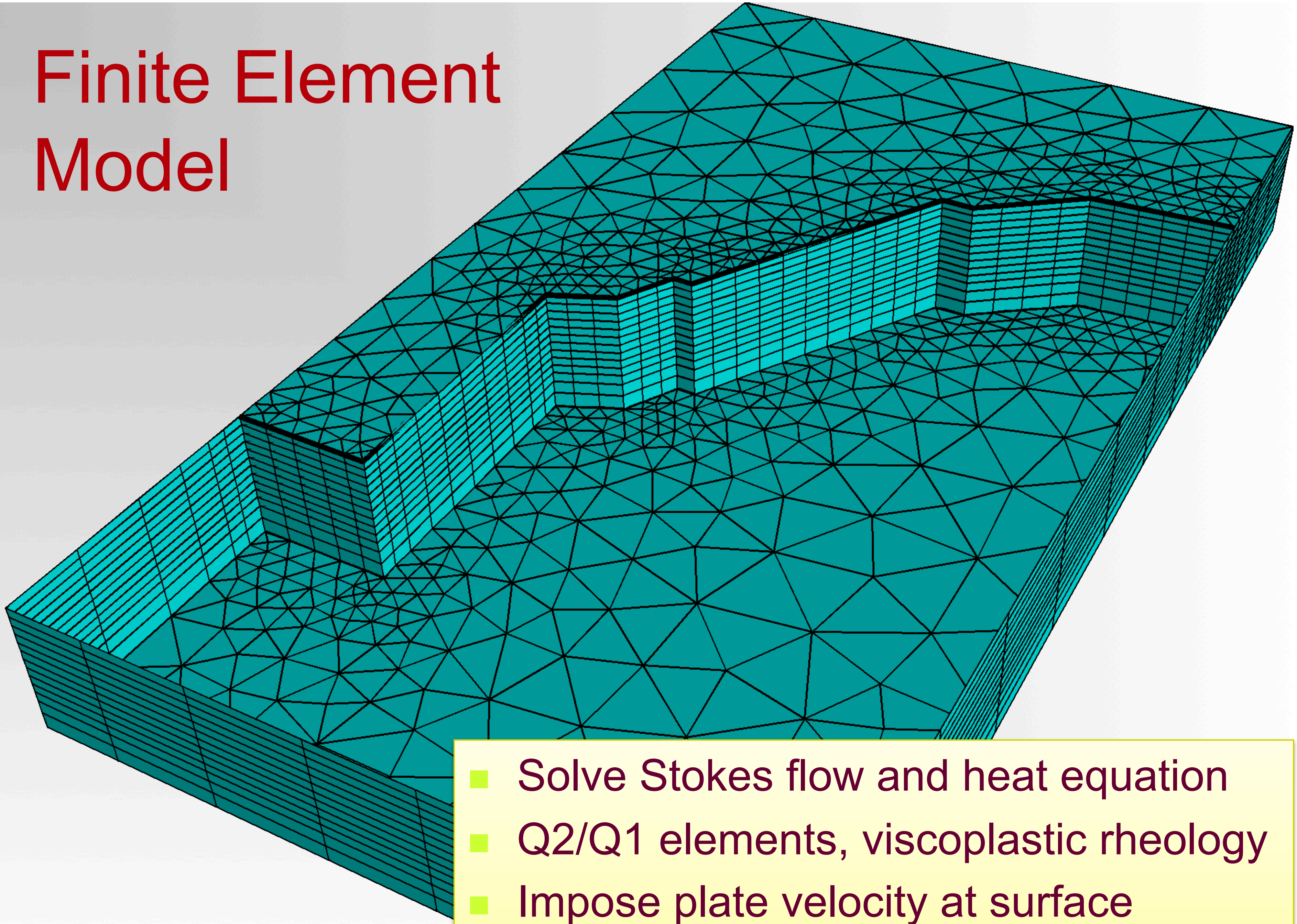


Focusing of Enriched Melts



Standish et al., 2008

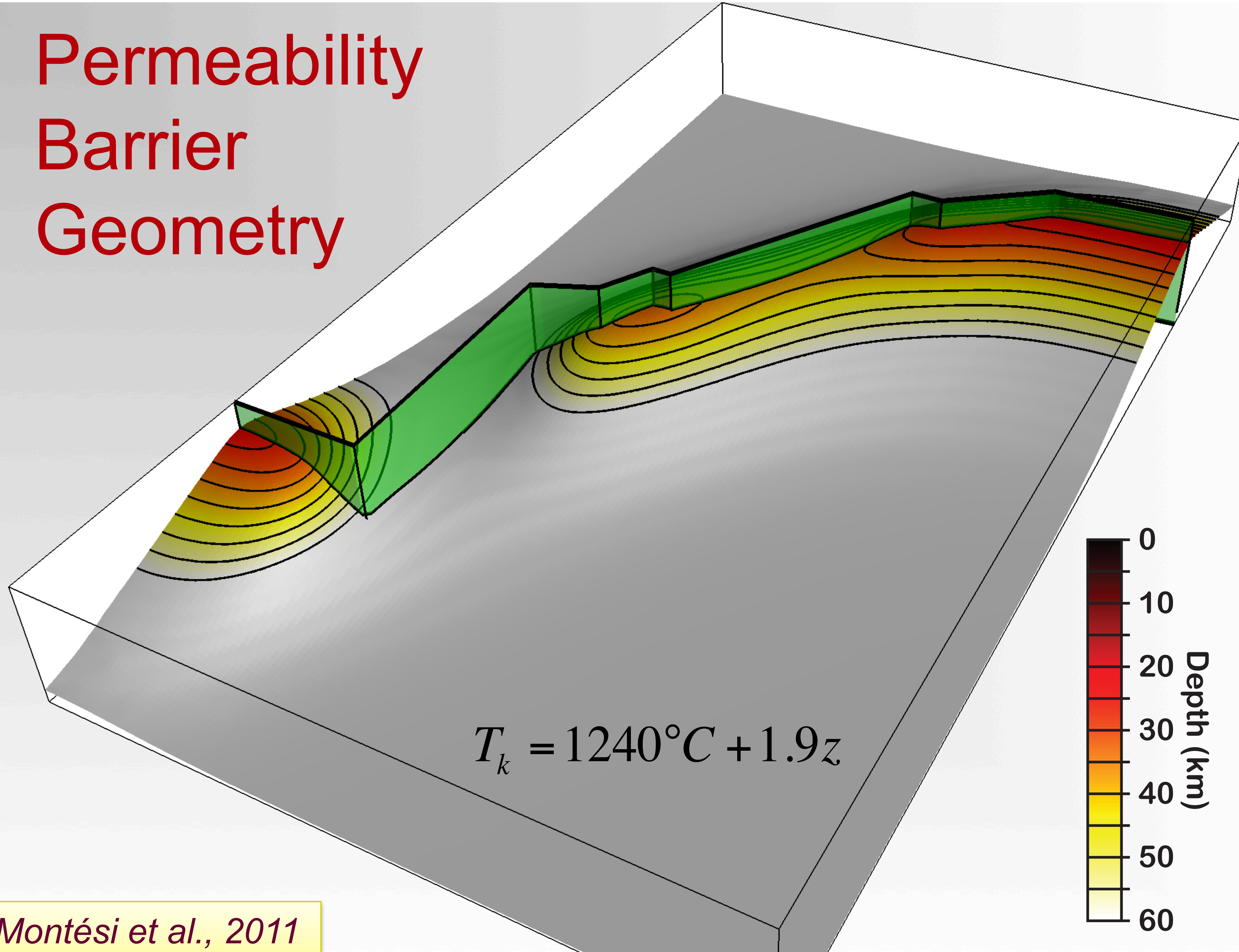
Finite Element Model



- Solve Stokes flow and heat equation
- Q2/Q1 elements, viscoplastic rheology
- Impose plate velocity at surface
- Fixed surface and bottom temperature

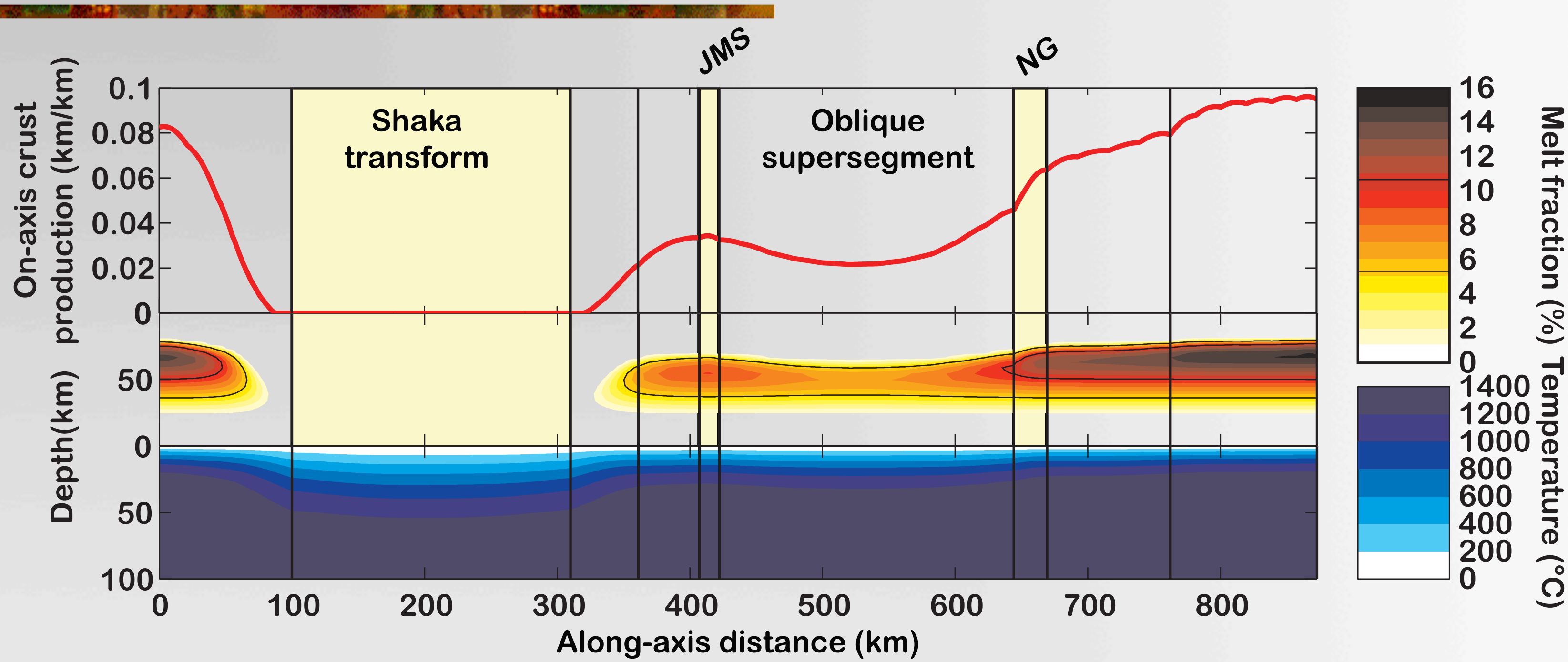
Montési et al., 2011

Permeability Barrier Geometry



Montési et al., 2011

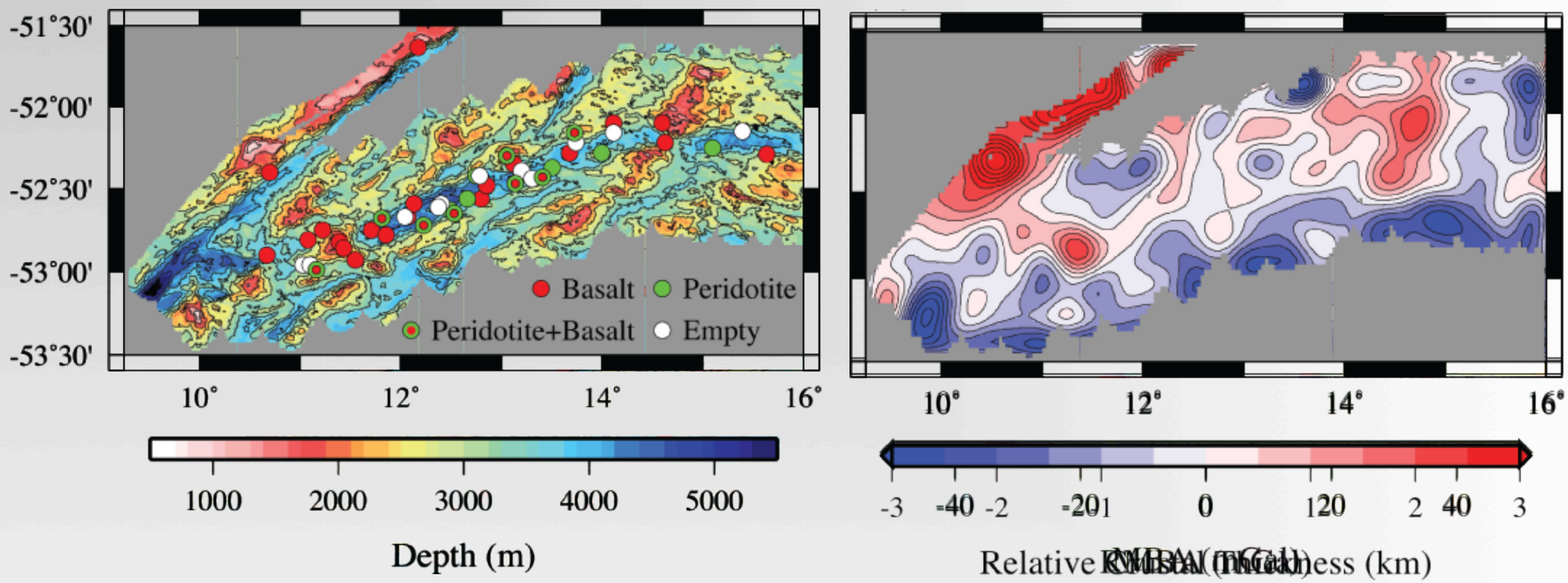
SWIR Along-axis variations



- Thermal maximum at JMS, no Narrowgate
- JMS anomaly not of sufficient amplitude

Montési et al., 2011

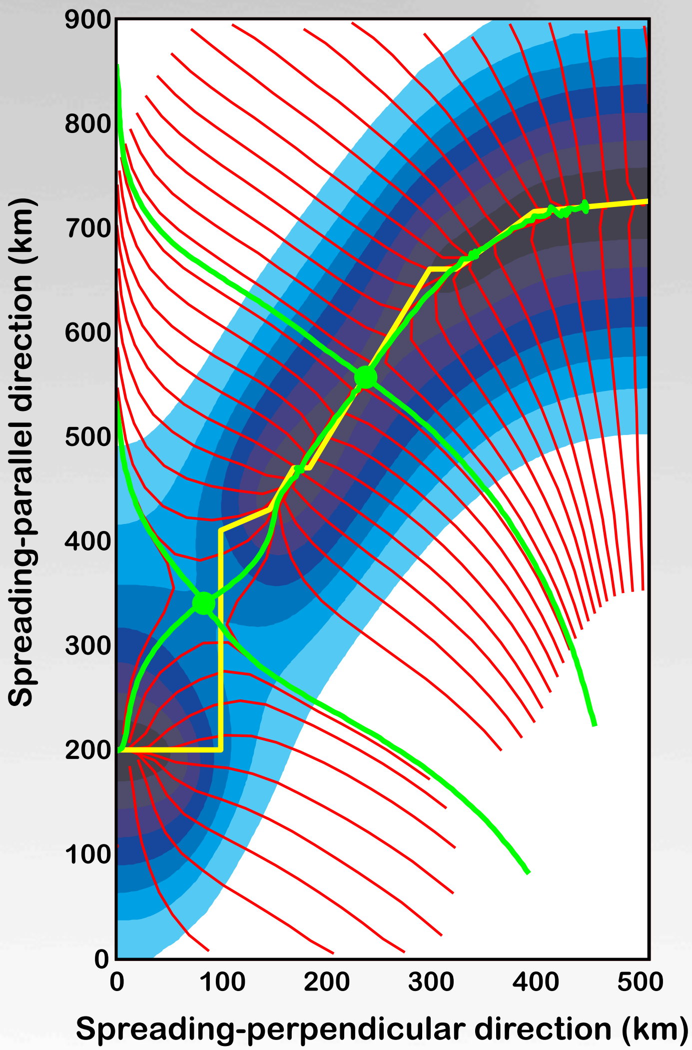
SWIR: Geophysical Constraints

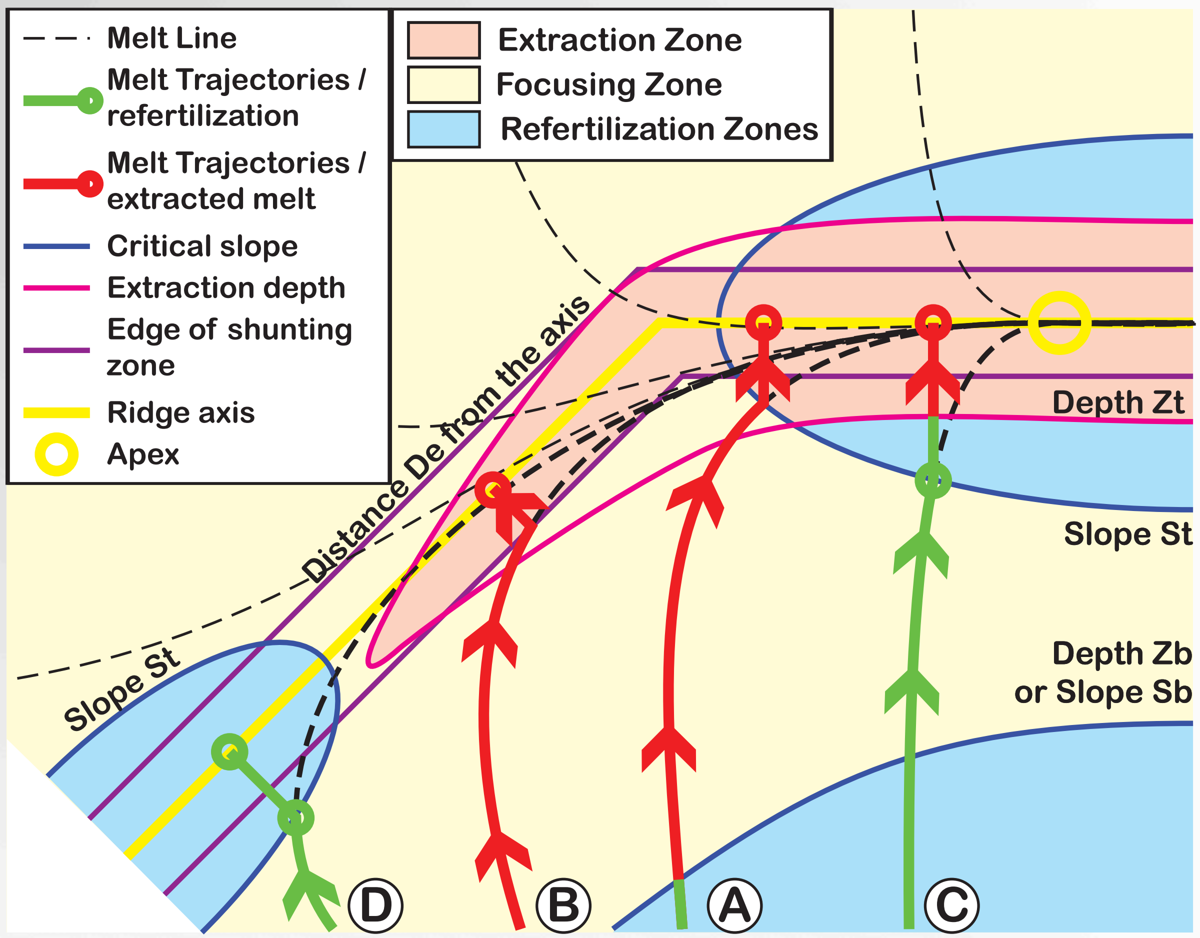


- "No" crust at oblique supersegment
- Thick crust at Joseph Mayes Seamount and Narrowgate

Montési et al., 2011

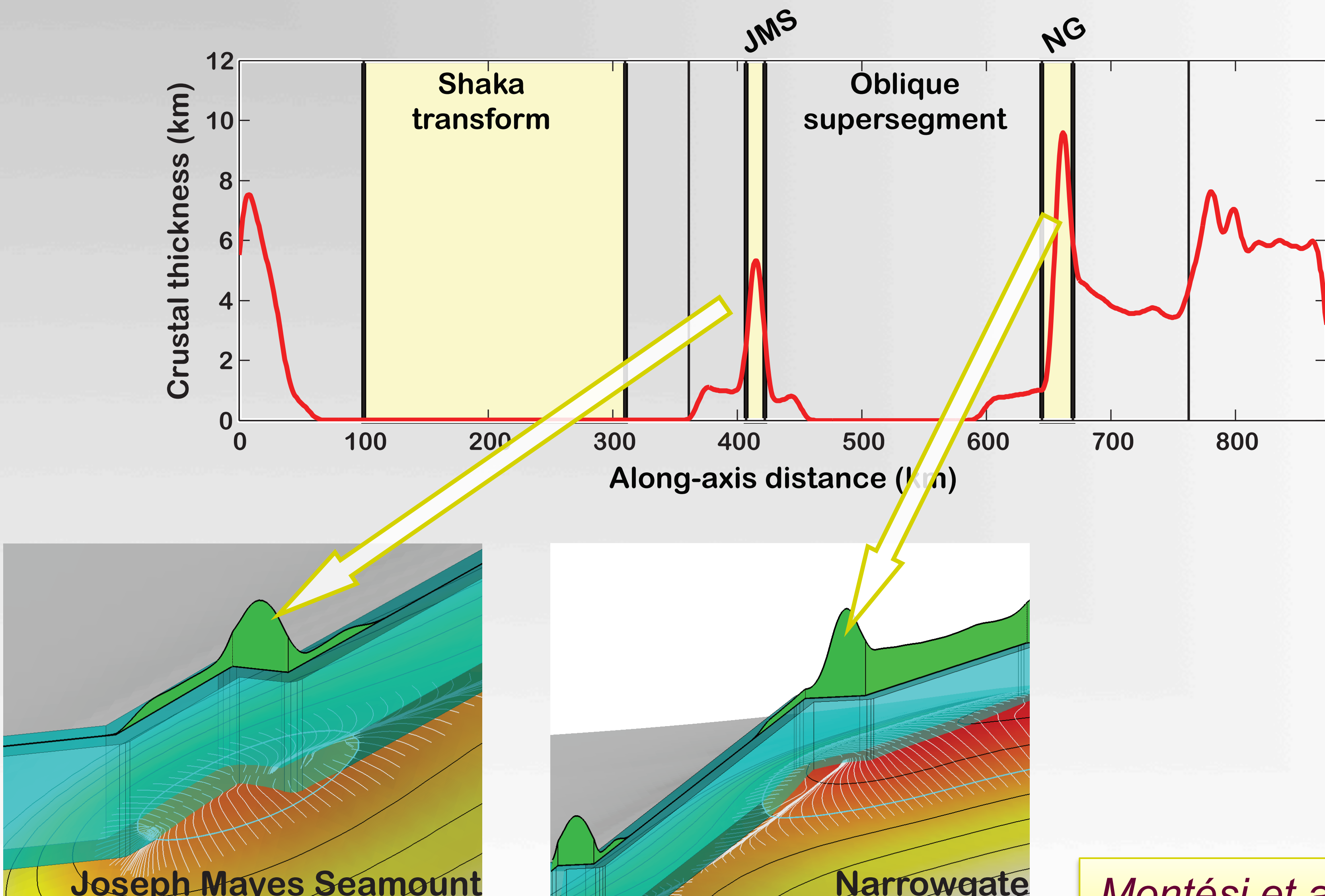
Melt extraction strategy





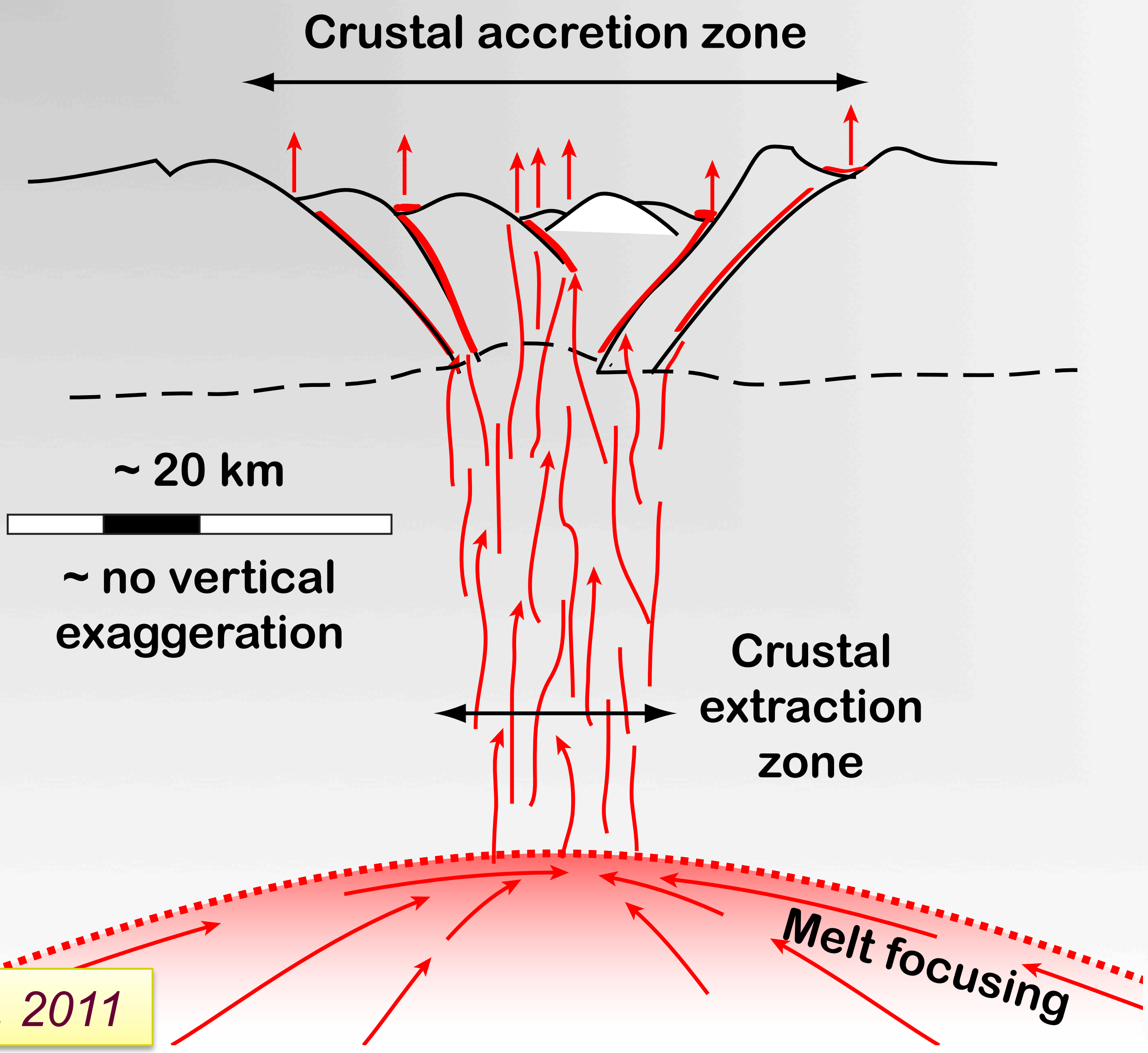
Montési et al., 2011

Melt focusing a SWIR 10°-16°E



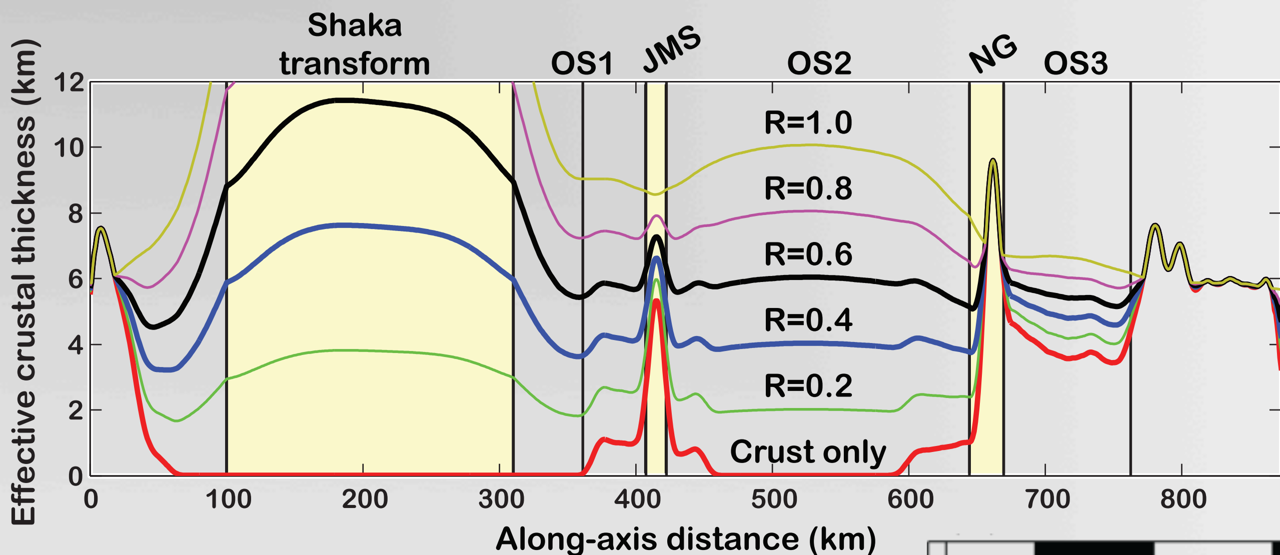
Montési et al., 2011

Melt extraction at Narrowgate



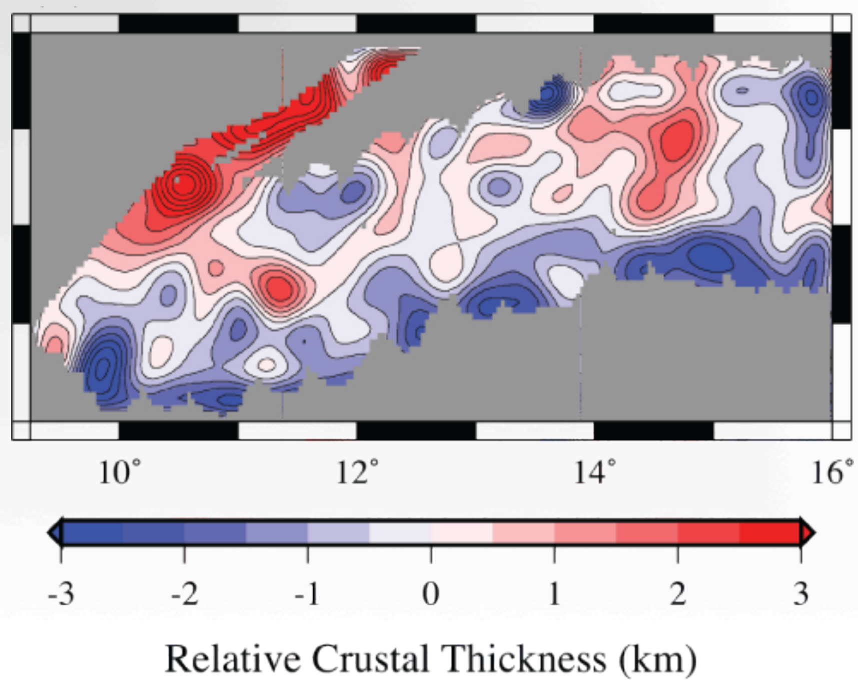
Montési et al., 2011

Importance of serpentine?



- No anomaly underneath OS2 implies low density material
- Serpentinize 60% of material cooler than 450°C

Relative crustal thickness



Montési et al., 2011

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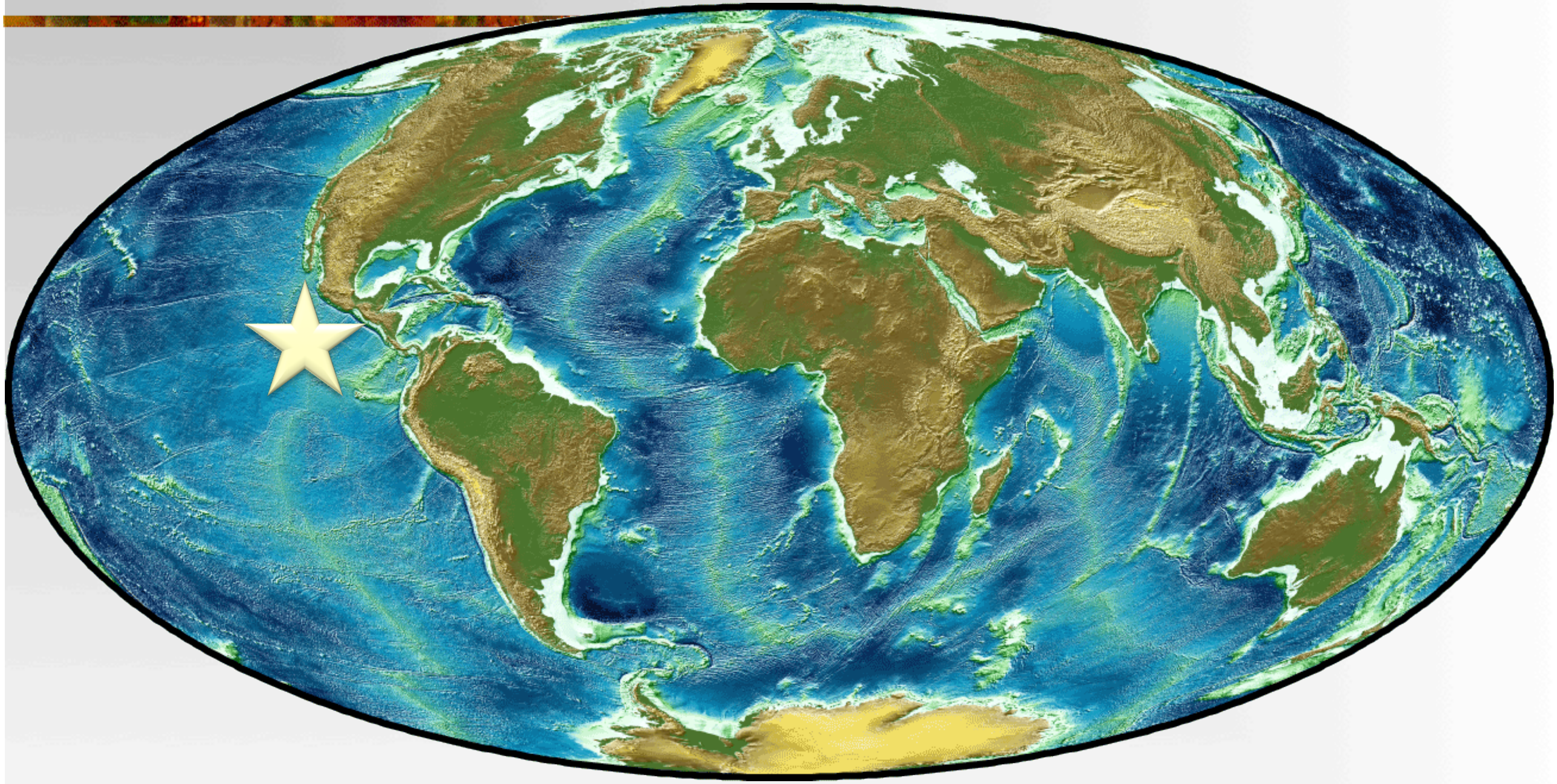
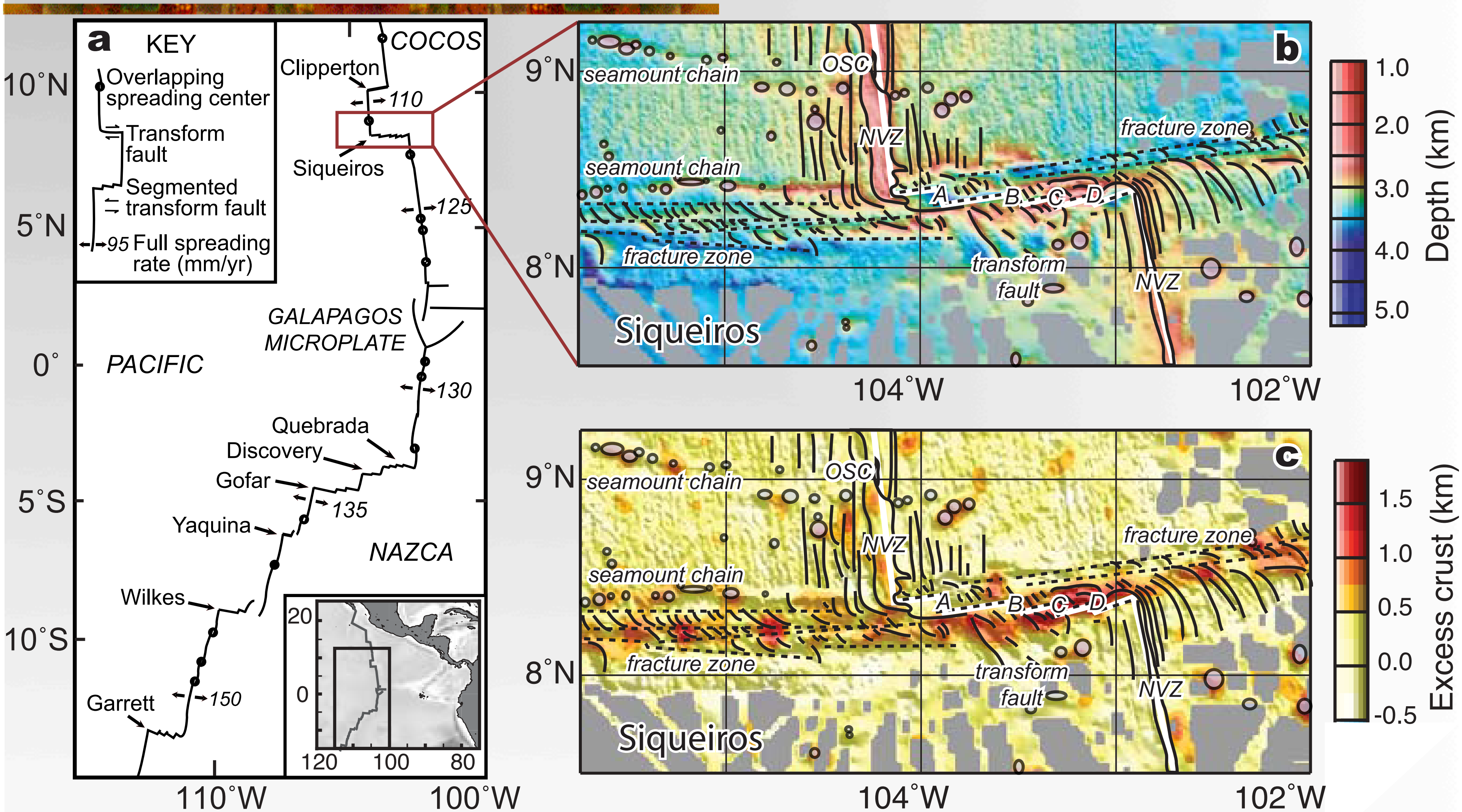
EPR 9°N



- Very fast spreading (105 mm/yr)
- ~100km long transform faults

EPR 9°N geology

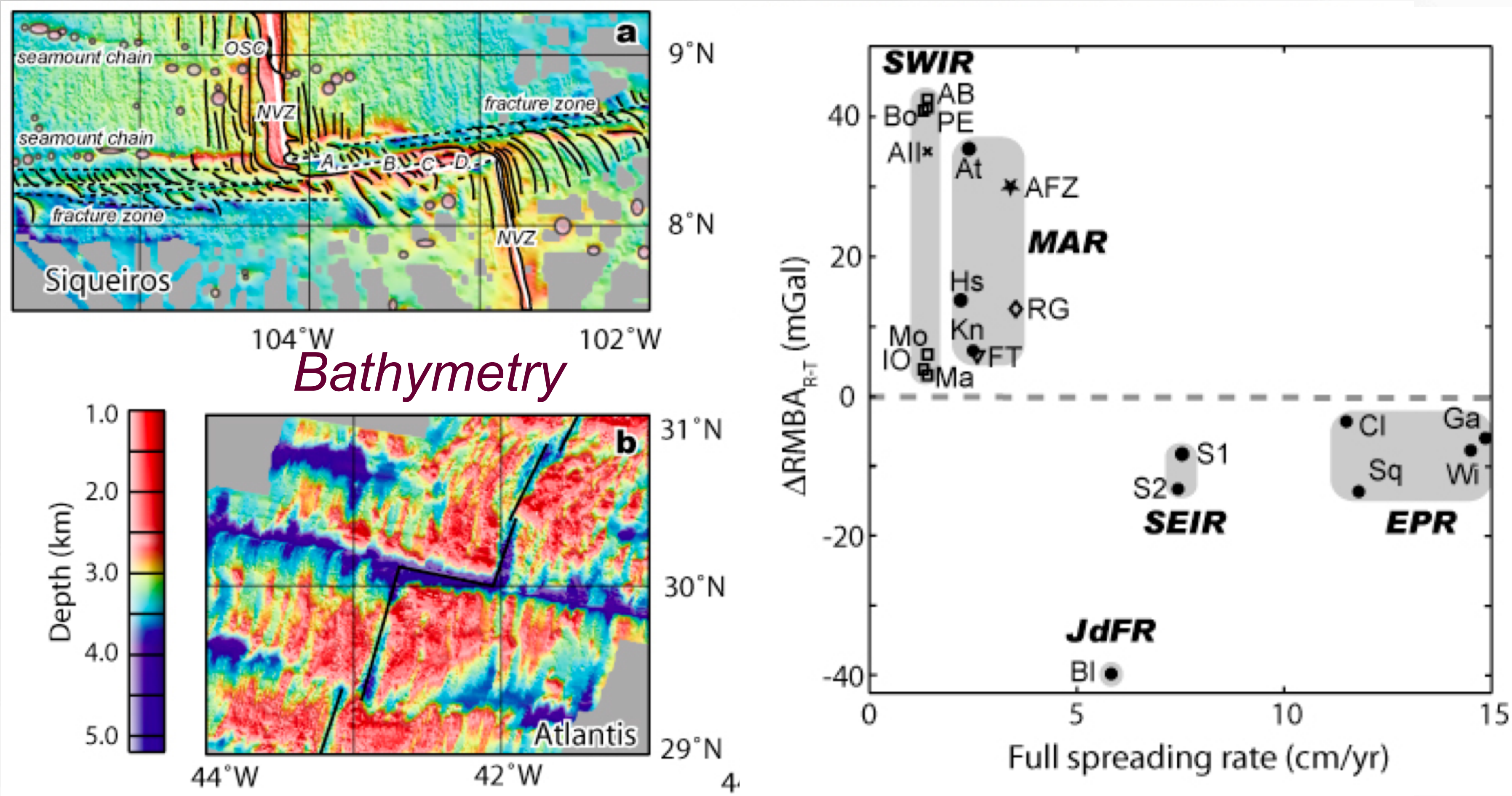


Gregg et al., 2009

Gravity anomalies at transforms

Fast (EPR)

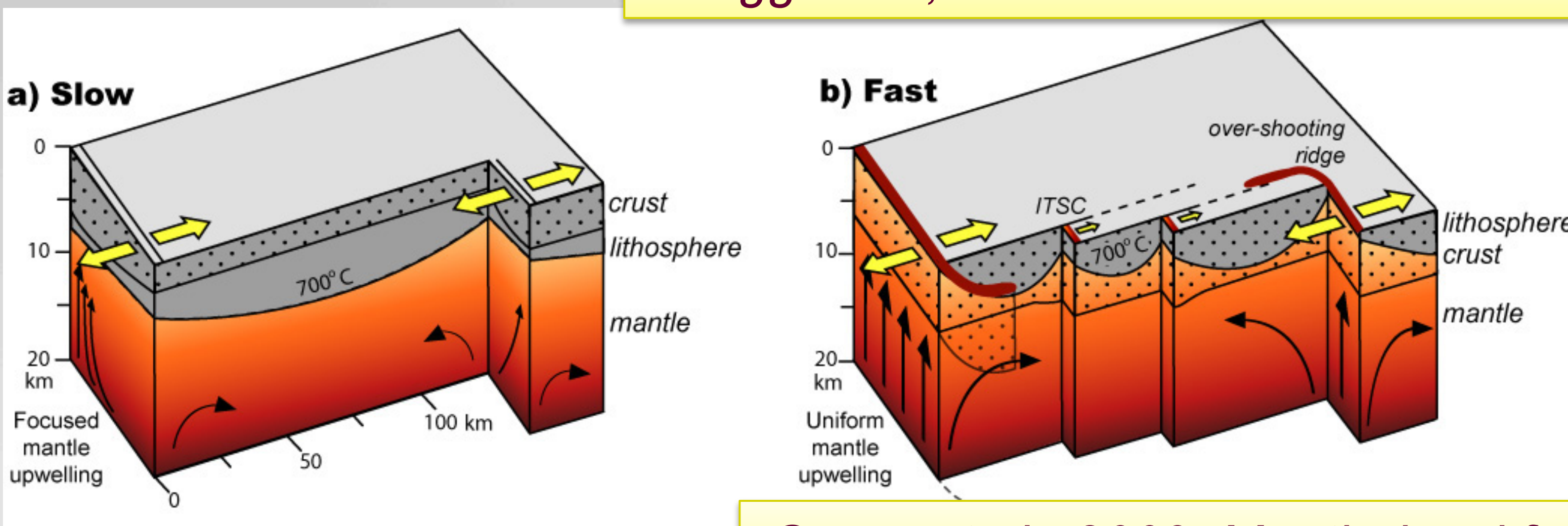
Slow (MAR)



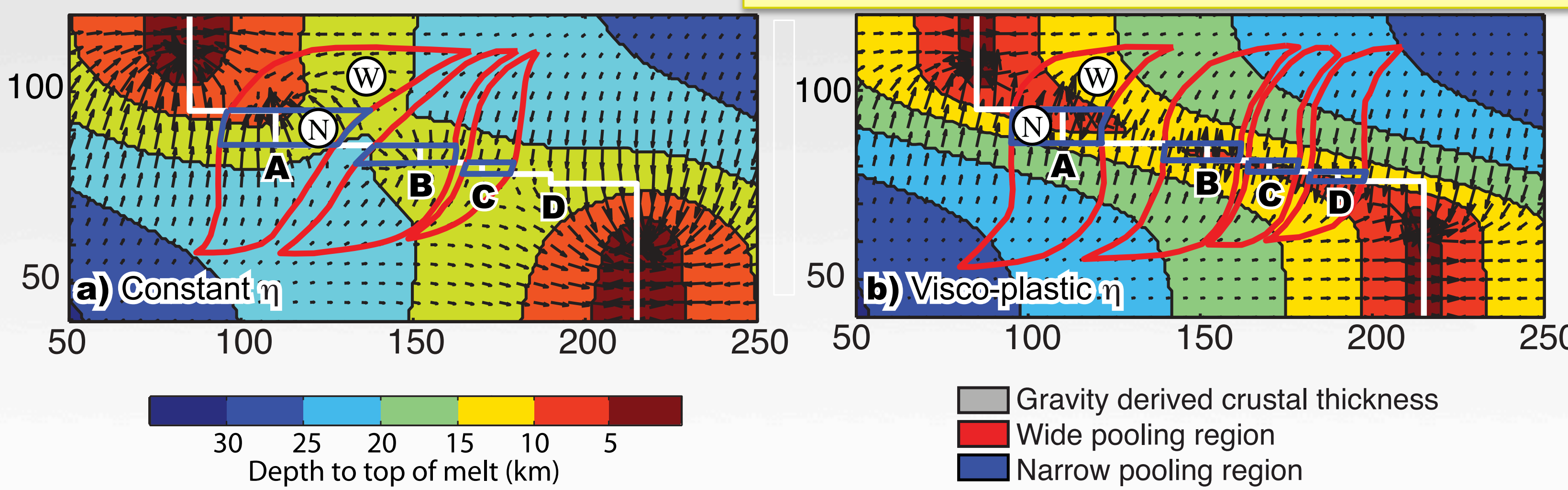
Gregg et al., 2007

Two explanations

Gregg et al., 2007: Crustal-level redistribution

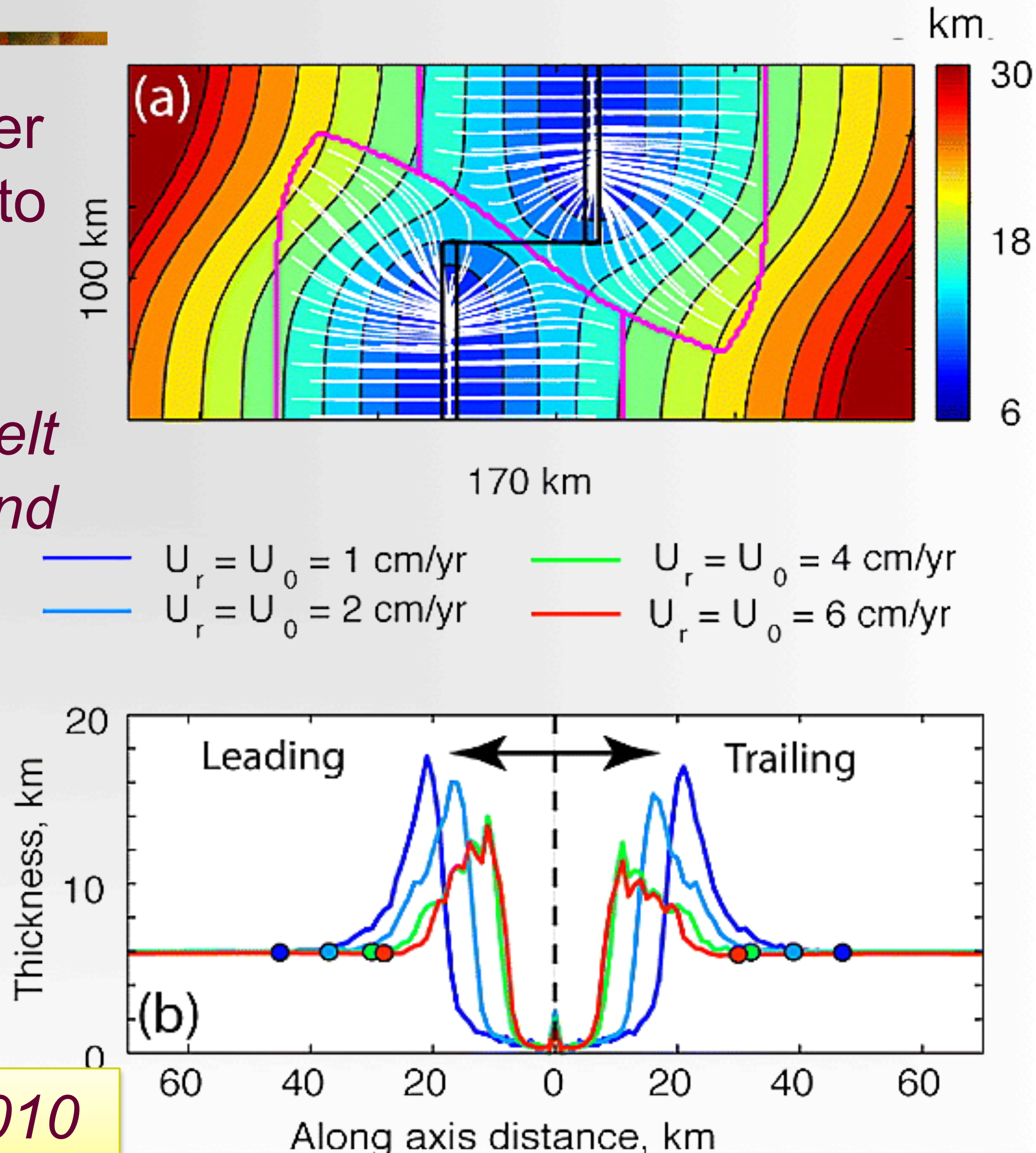


Gregg et al., 2009: Mantle-level focusing



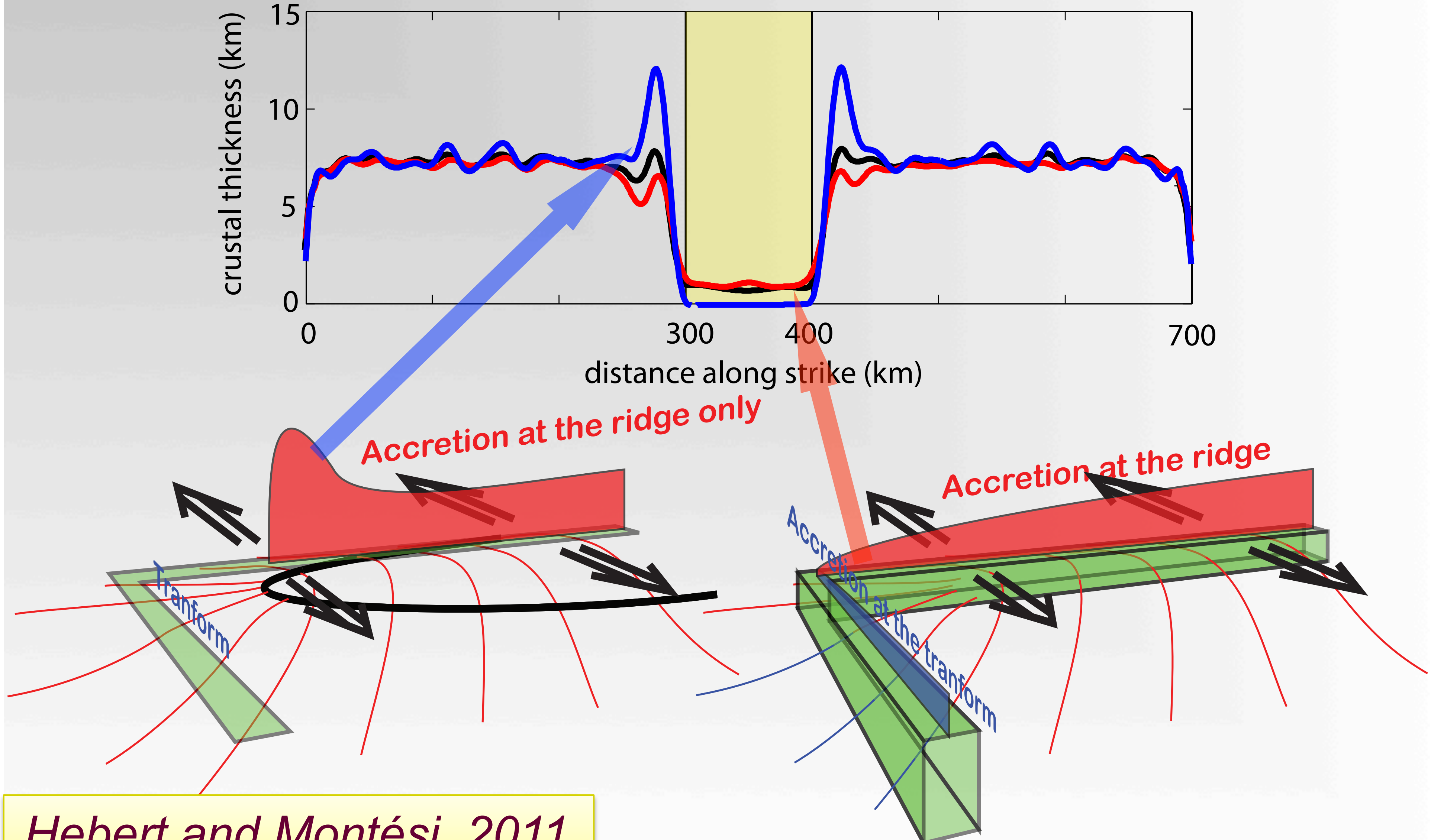
Focusing away from transforms

- Trajectory along a barrier (here solidus) focus 10 to 25 km away from transform
- "*We assume that the melt between these points and the transform fault is redistributed evenly by along-axis melt transport.*"



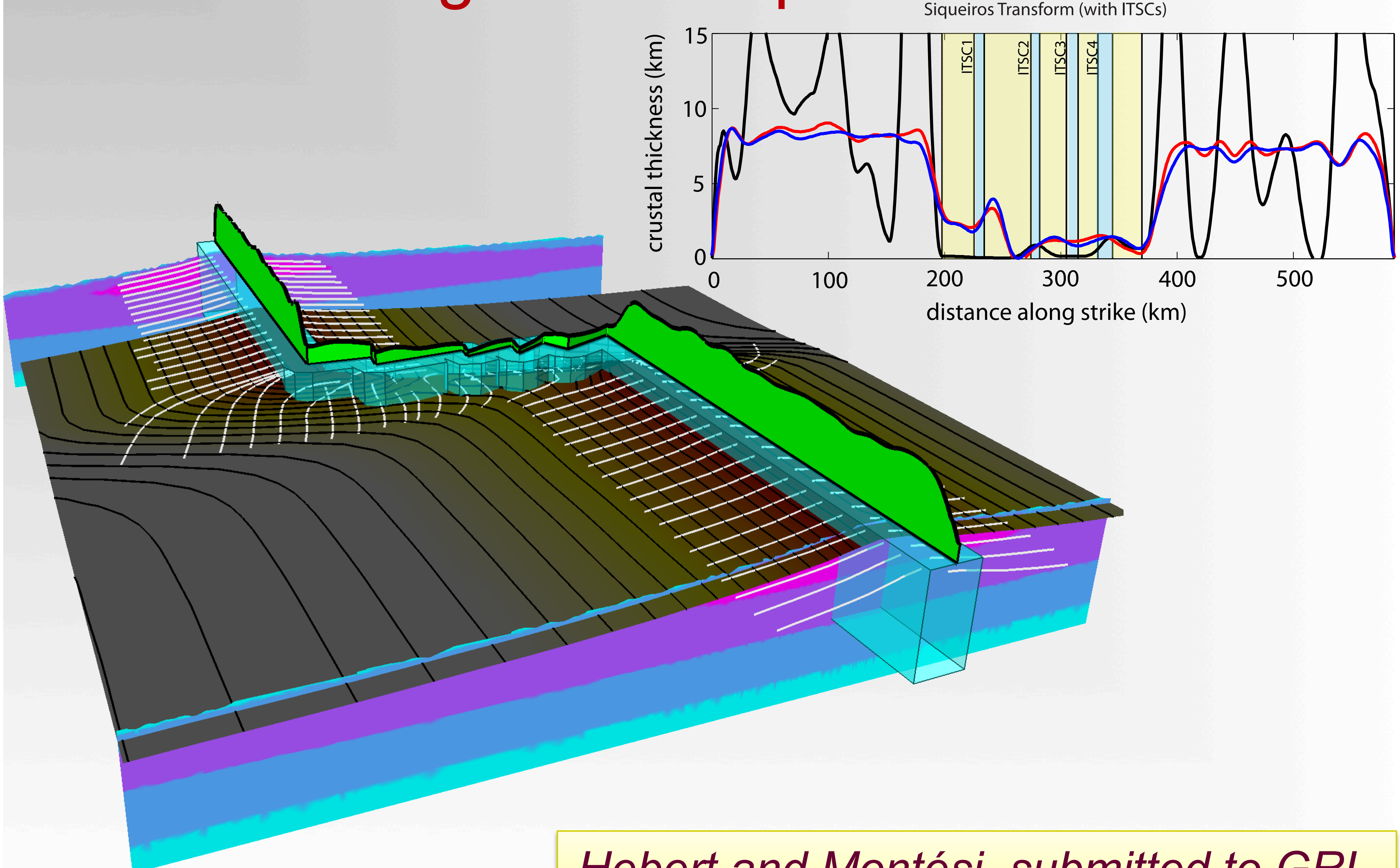
Weatherley and Katz, G[3], 2010

Melt focusing at transforms



Hebert and Montési, 2011

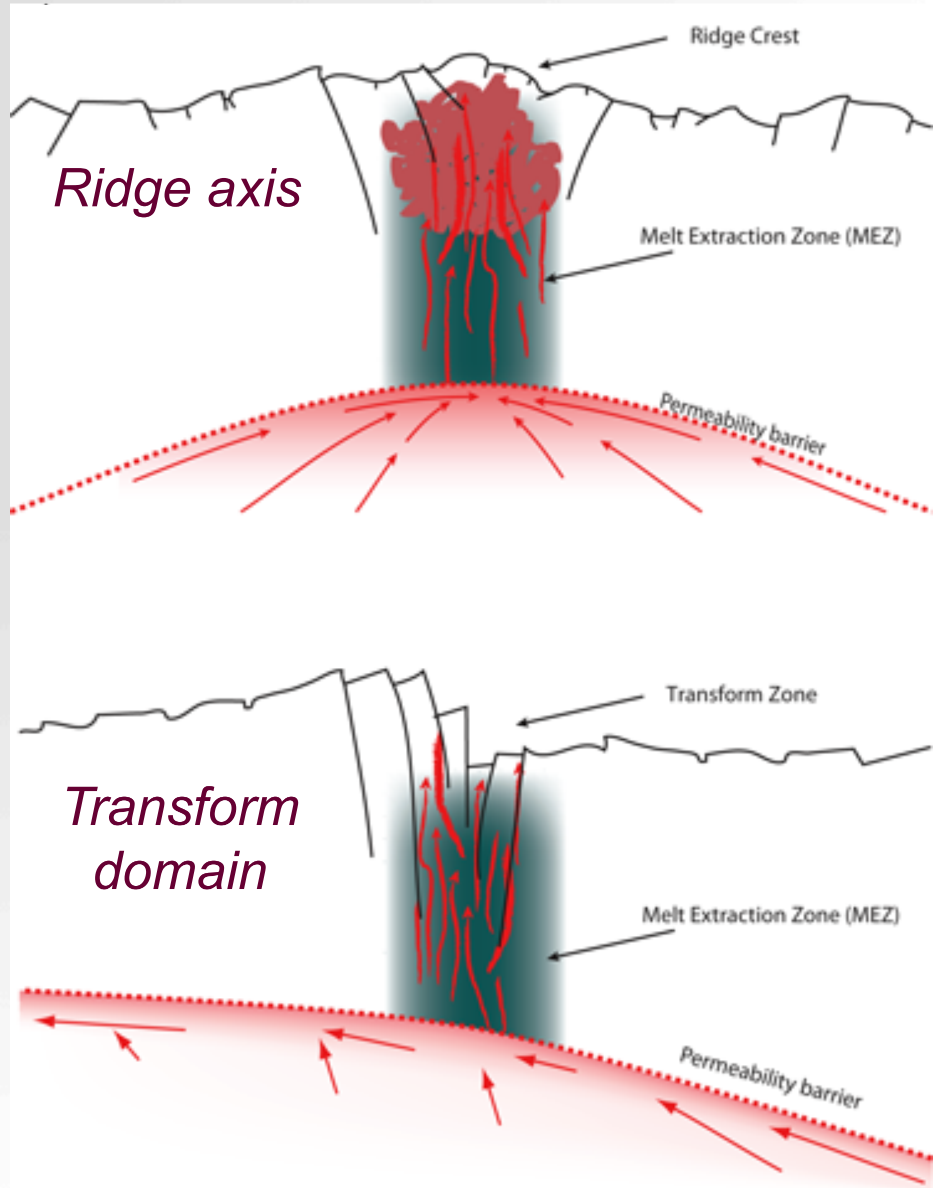
Melt focusing at the Siqueiros transform



Hebert and Montési, submitted to GRL

Melt Extraction Zones

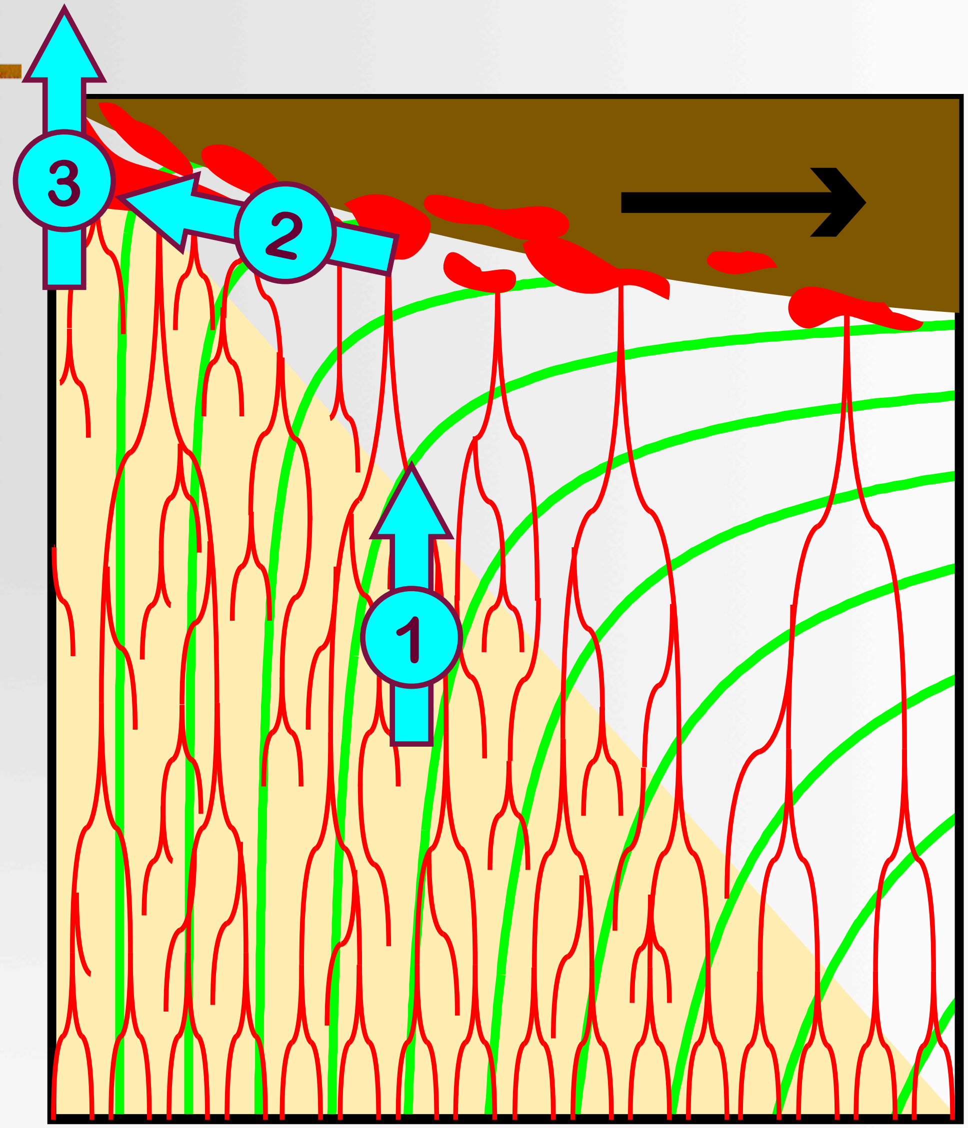
- Extraction facilitated by tectonic damage
  - Faults
  - Dikes
- Extraction at transform shunts melt focused toward axis



Hebert and Montési, 2011

Summary

- Modeling melt migration
  - 3-step melt migration model works great!
  - Permeability barrier at 1240°C+1.9z
  - Melt extraction zone <10km from plate boundary and 30km depth
- Ultraslow ridges
  - Melt production but inefficient extraction
- Intermediate/fast transforms
  - Additional melt extraction if TBL is thin enough



Inspired by Sparks and Parmentier, 1991

Outstanding issues

- Transition from continuous to discrete physics
  - Porous flow to intrusion
    - Multiple porosity model?
  - Mantle flow to faulting
- Interaction across time scales
  - Repeated events
- Accretion / evolving plate boundary