Joint ICTP-EAIFR-IUGG Workshop on Computational Geodynamics: Towards Building a New Expertise Across Africa

ICTP

tectonic forces.

richard katz
university of oxford

AMBASSADE DE FRANCE AU RWANDA
Liberté Égalité Fraternité

UNIVERSITY of RWANDA

IUGG

United Nations Educational, Scientific and Cultural Organization

EAIFR
ICTP - East African Institute for Fundamental Research under the auspices of UNESCO

UNIVERSITY OF OXFORD

RIFT-O-MAT

erc

FOALAB


84° 126° 168° 210° 252° 294° 336° 18° 60°
88° 66° 44° 22° 0° −22° −44° −66° −88°
Eurasian
North American
JDF
Pacific
Philippine Sea
Indian
Arabian
Carrib.
Cocos
African
Nazca
South American
Australian
Antarctic
10 cm/yr

Plate tectonic theory in 1965

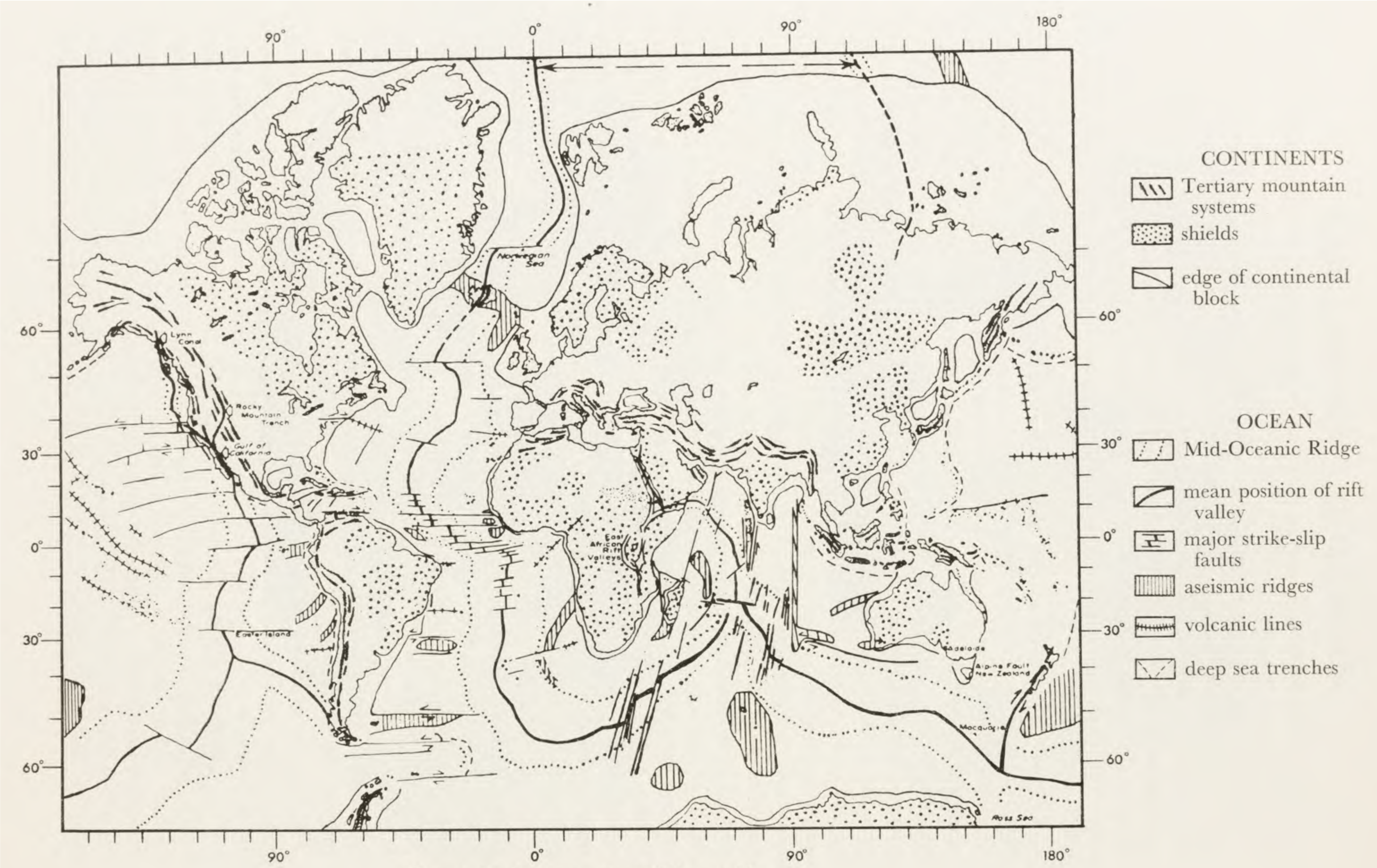
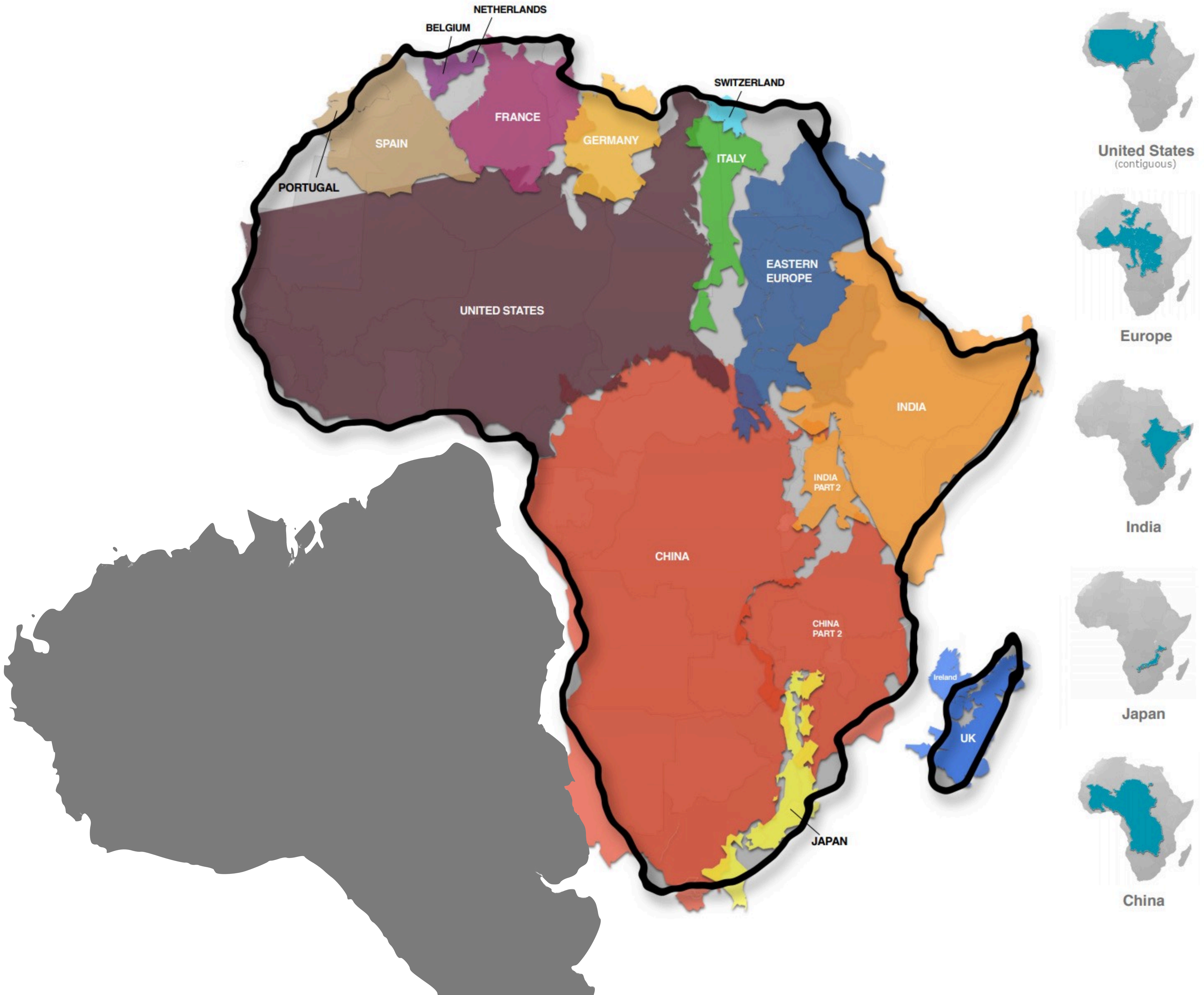


FIGURE 14. Tectonic chart of the world.

Heezen & Tharp, *PTRSA* 1965

How big is Africa, really?



Fake Tectonics, 2023

Plate tectonics as a *kinematic* theory

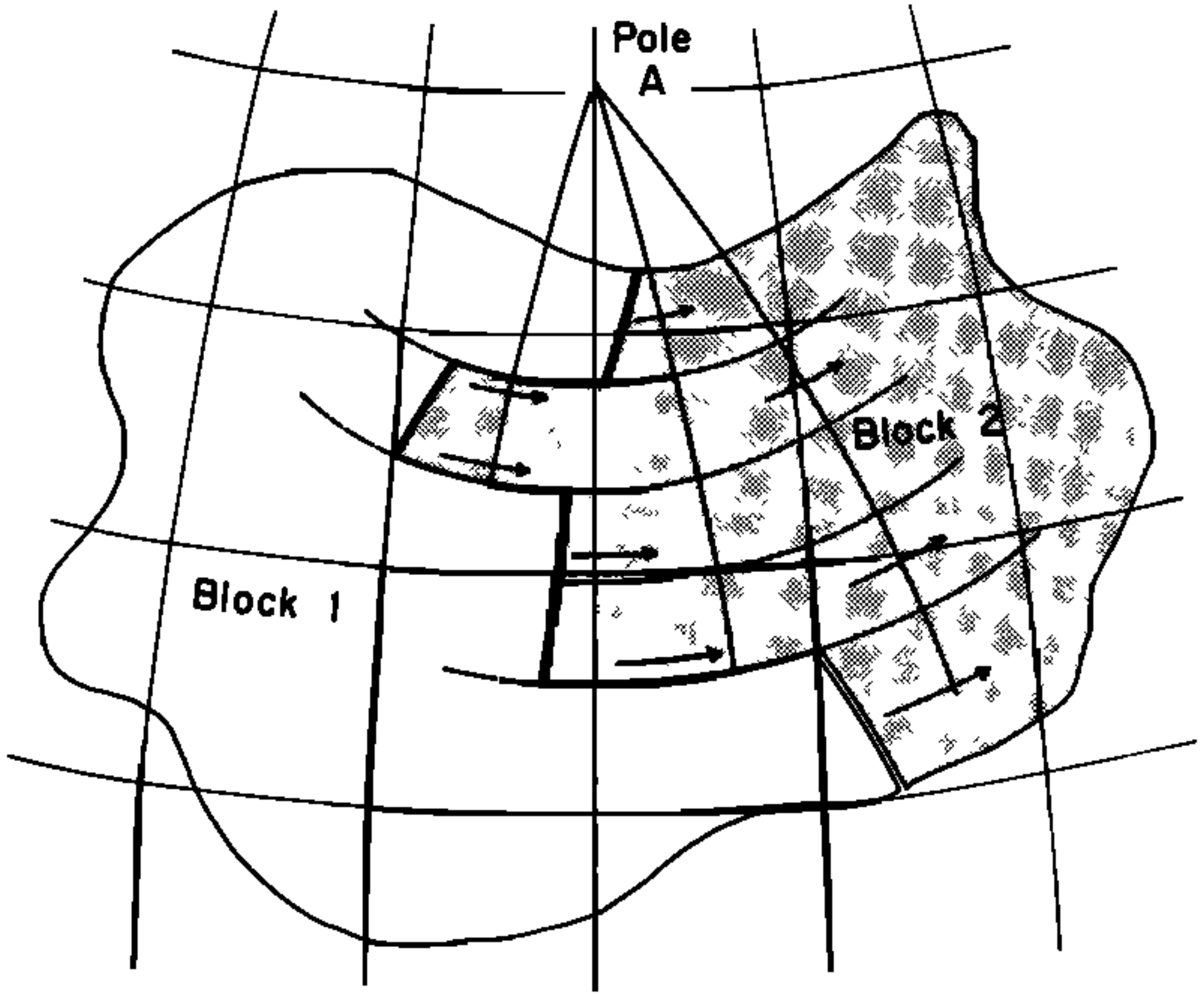


Fig. 4. On a sphere, the motion of block 2 relative to block 1 must be a rotation about some pole. All faults on the boundary between 1 and 2 must be small circles concentric about the pole A.

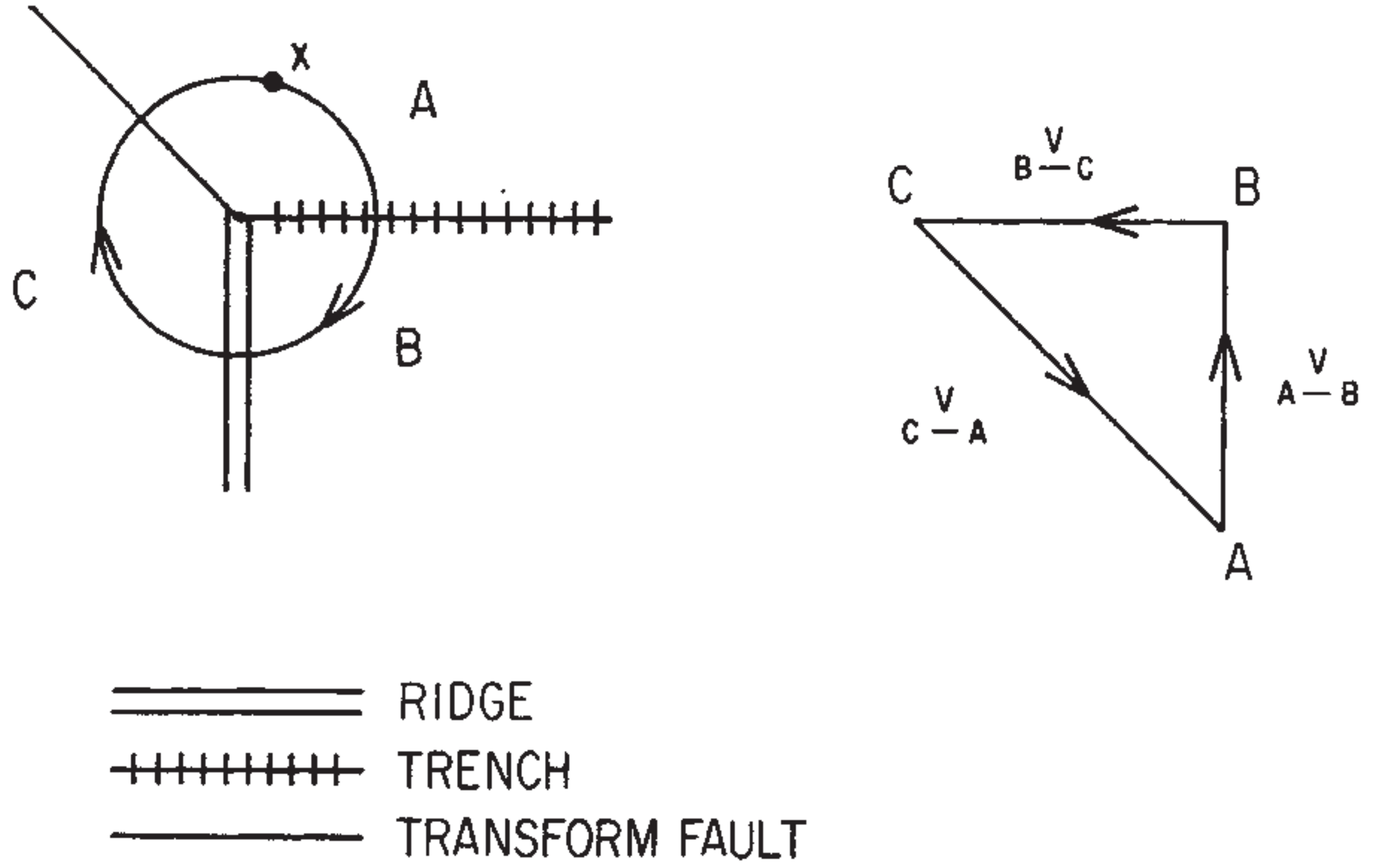
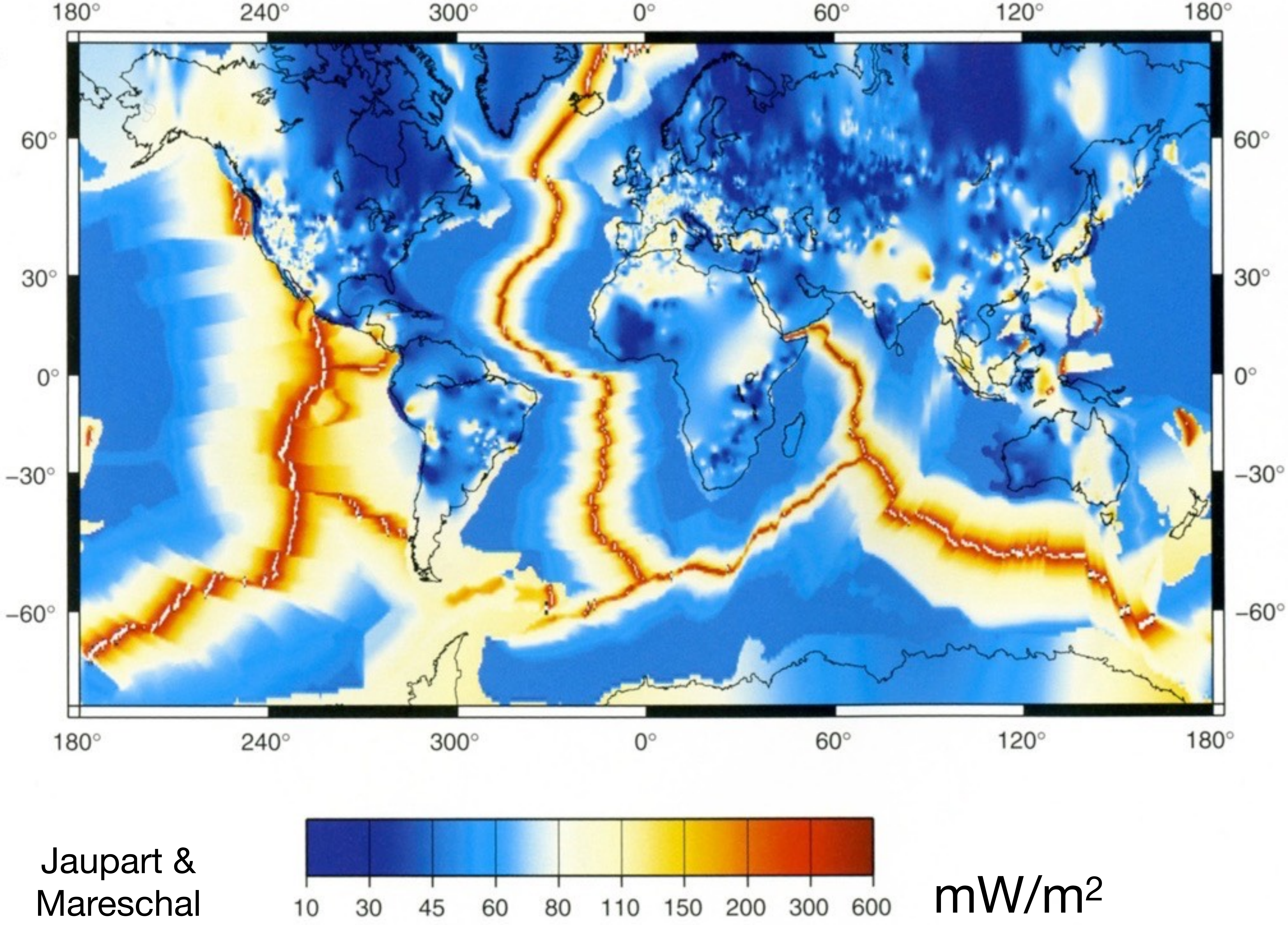


Fig. 1. The circuit and its vector diagram show how a ridge and a trench can meet to form a transform fault.

Morgan, *JGR* 1968

McKenzie, *Nature* 1967

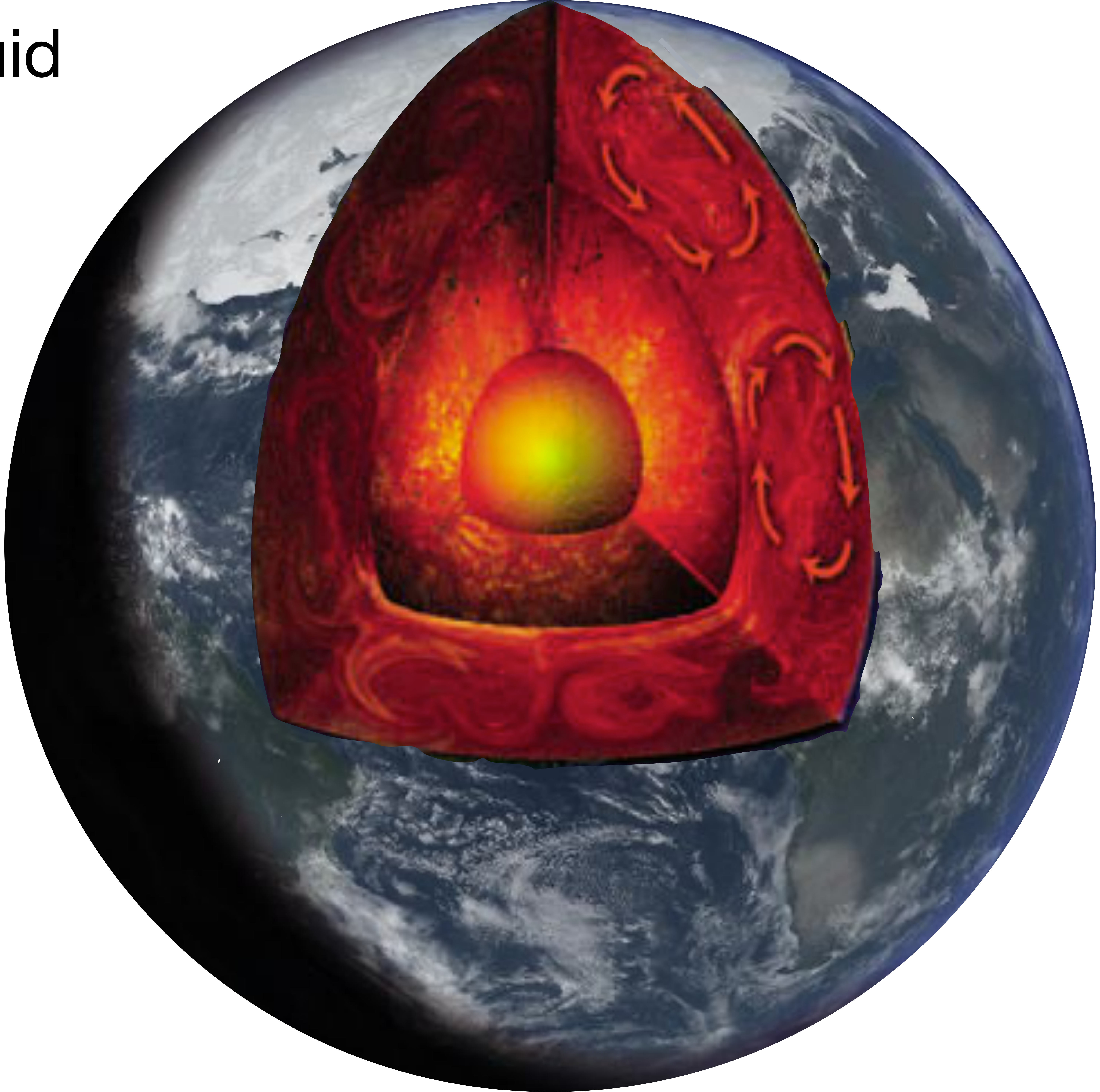
Plate tectonics controls heat flow



Jaupart & Mareschal

The solid mantle is a fluid (on long timescales)

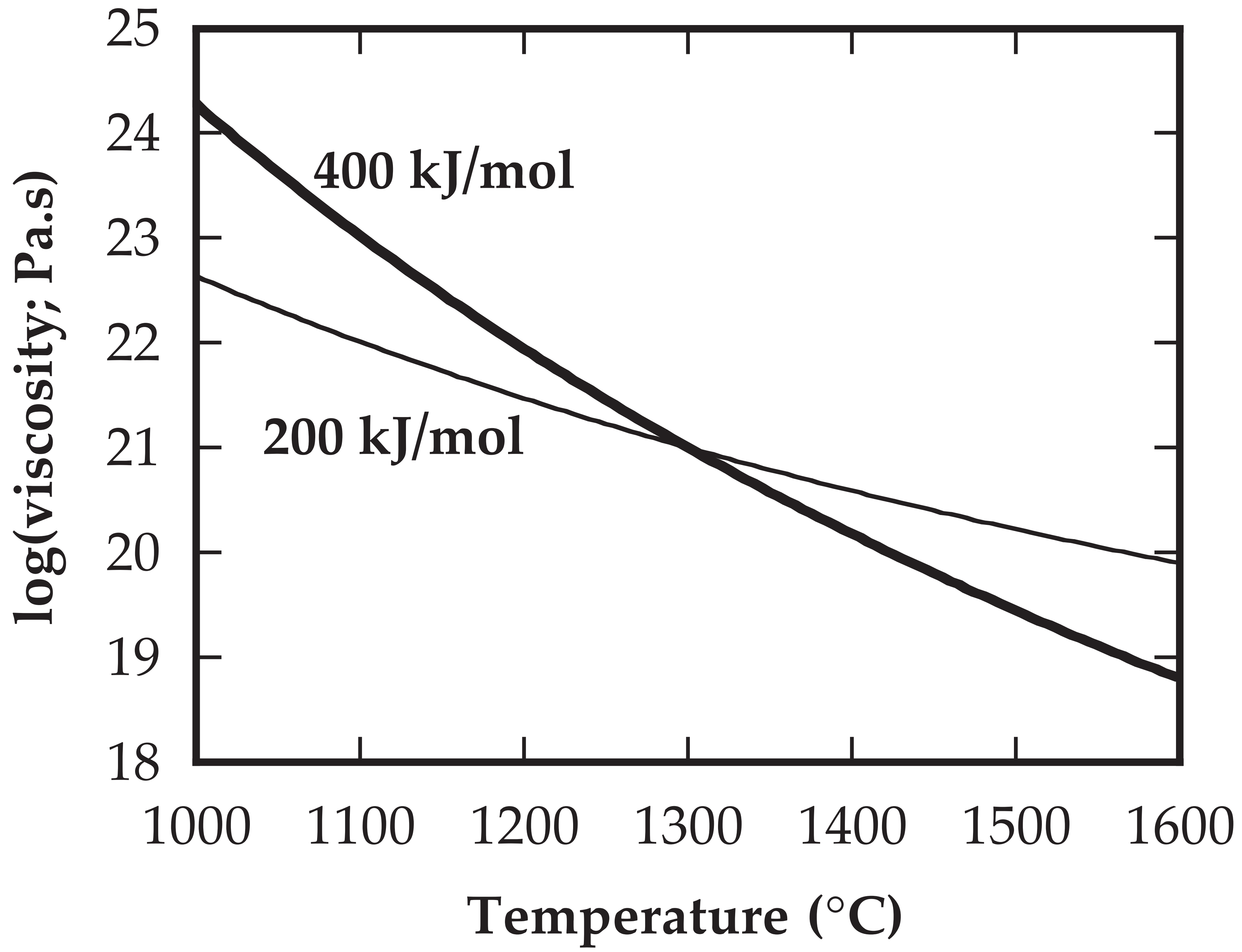
(Solid ice is a fluid too)



Isoviscous thermal convection far above critical Ra

courtesy of S. Labrosse, ENS Lyon

Mantle viscosity, plates and convection



$$\eta(T) = \eta_0 \exp\left[\frac{E^*}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

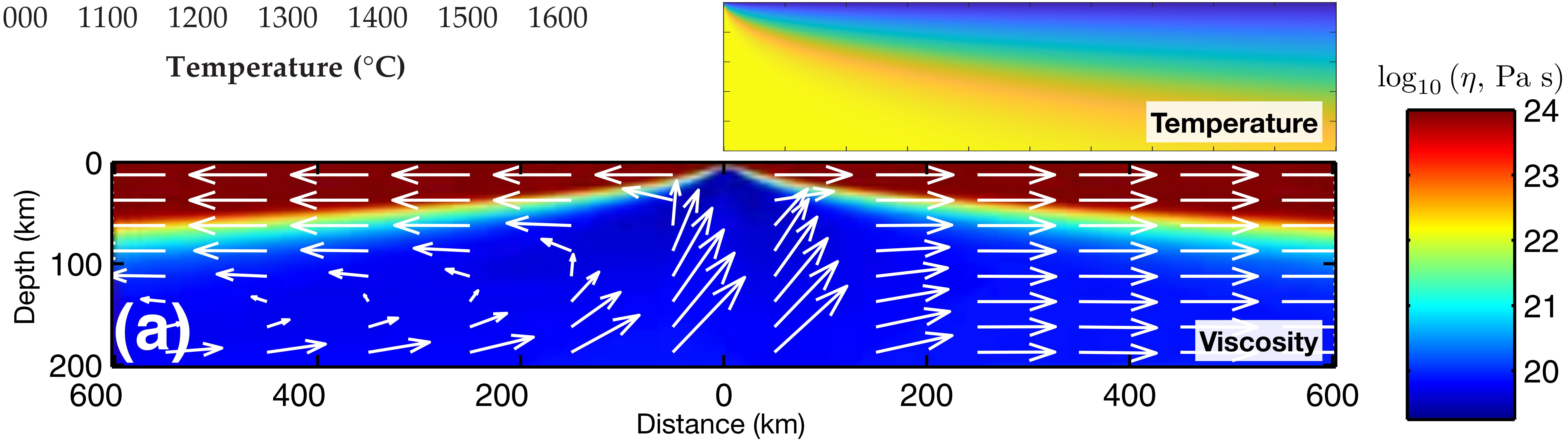
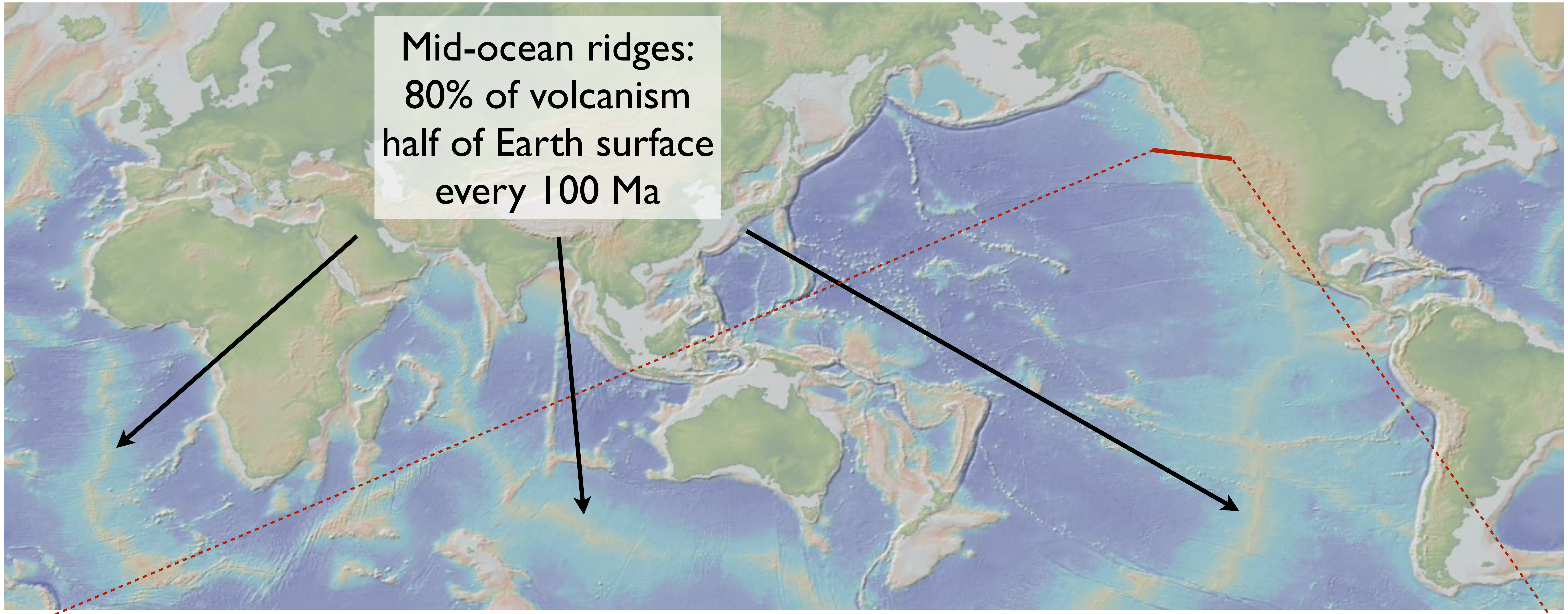
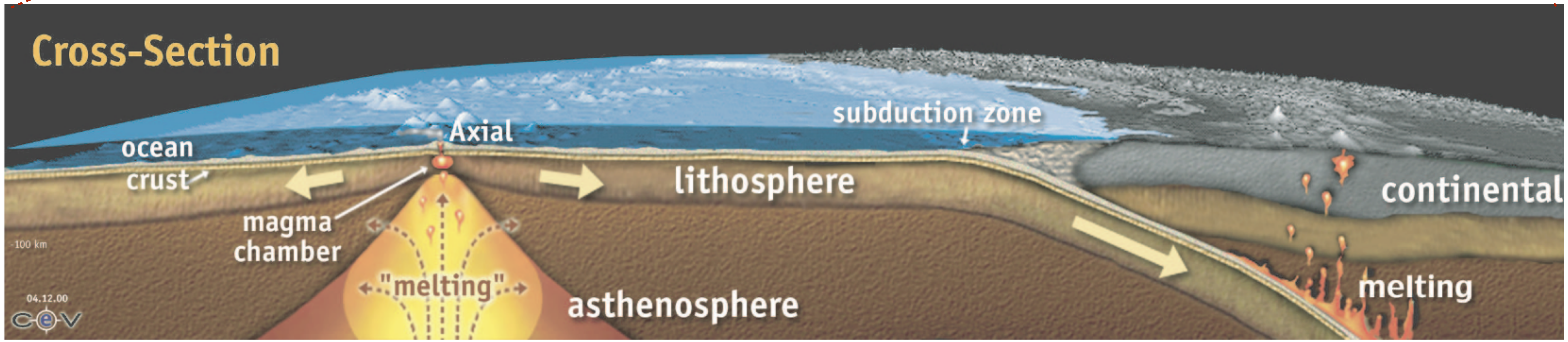
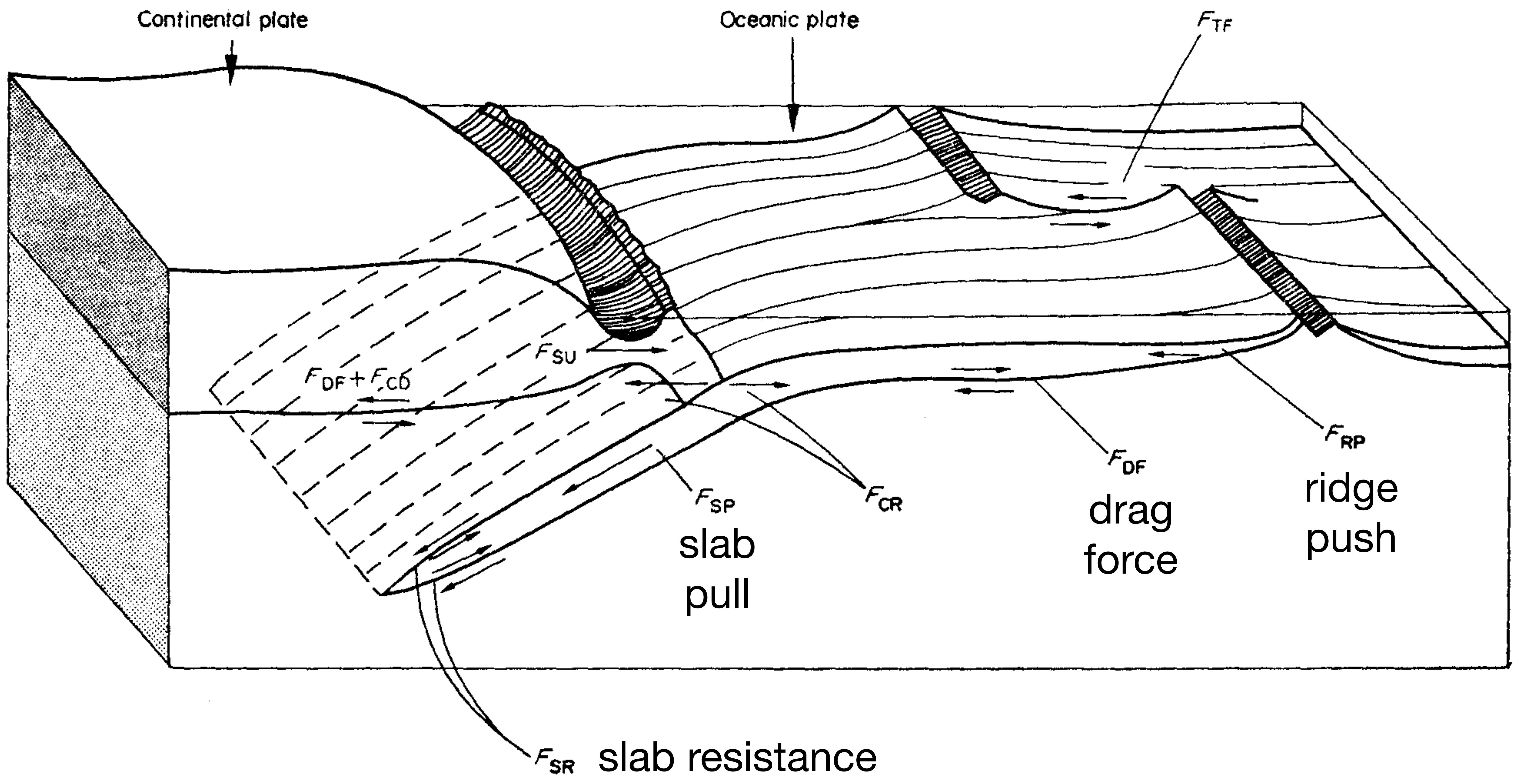


Plate tectonics controls sea-floor volcanism





Forces driving and resisting plate motion



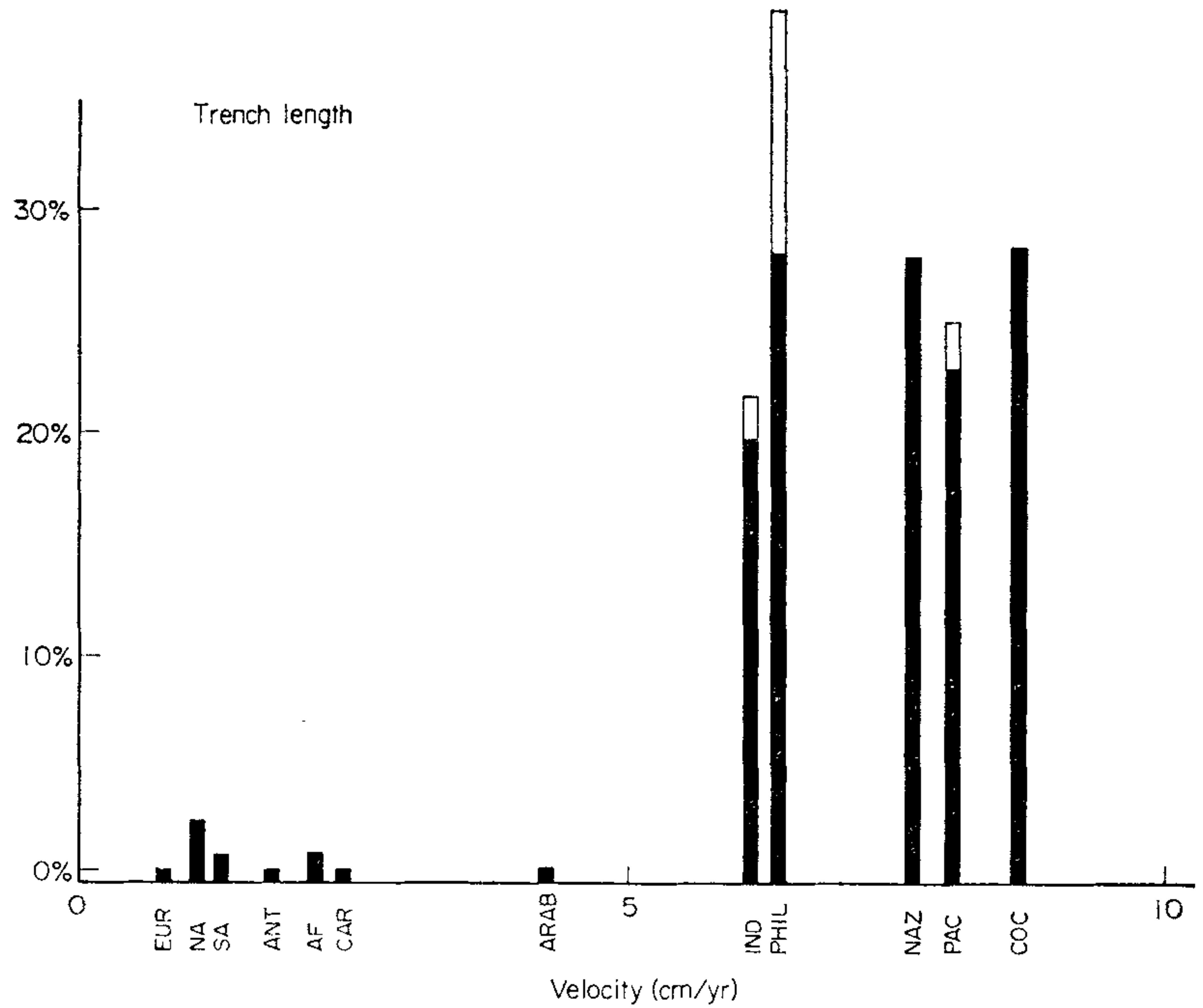


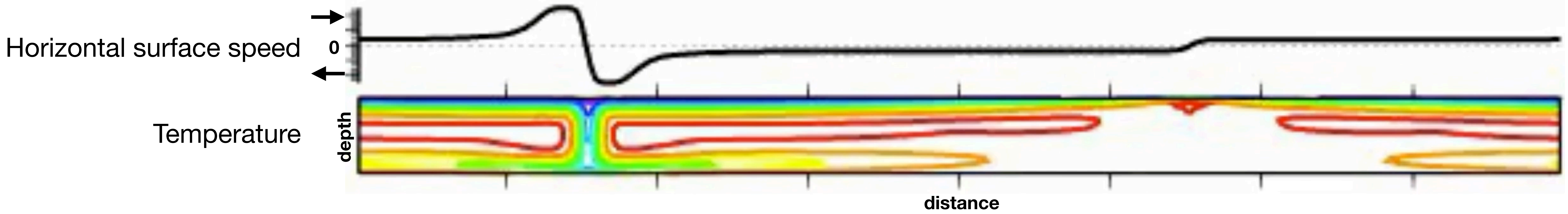
FIG. 8. Percentage of circumference of plate connected to downgoing slab. Open bar is total length, filled bar is effective length.

Summary of the forces

Force	Form	Direction	Importance, X_s	Relative strength		Uncertainty	Units
F_{RP}	$\propto dl$	⊥ strike	0·075	0·36	±	0·10	km^{-1}
F_{CR}	$\propto dl$	opp. rel. motion	0·040	0·16	±	0·09	km^{-1}
F_{TF}	$\propto dl$	opp. rel. motion	0·063	0·36	±	0·13	km^{-1}
F_{SP}	$\propto dl$	⊥ strike	0·745	6·43	±	0·19	km^{-1}
F_{SU}	$\propto dl$	⊥ strike	0·044	0·50	±	0·25	km^{-1}
F_{SR}	$\propto V_{M\perp}\, dl$	⊥ strike	0·652	0·89	±	0·03	$km^{-1} cm^{-1}$ yr
F_{CD}	$\propto V_M\, dA$	opp. abs. motion	0·056	5·65	±	2·22	10^{-5} km^{-2} cm^{-1} yr
F_{DF}	$\propto V_M\, dA$	opp. abs. motion	0·061	0·82	±	0·30	10^{-5} km^{-2} cm^{-1} yr

Forsyth & Uyeda, *JGRAS* 1975

Internal heating + T-dependent viscosity + Plastic yield stress = Plate Tectonics



Grigne, Labrosse & Tackley 2005

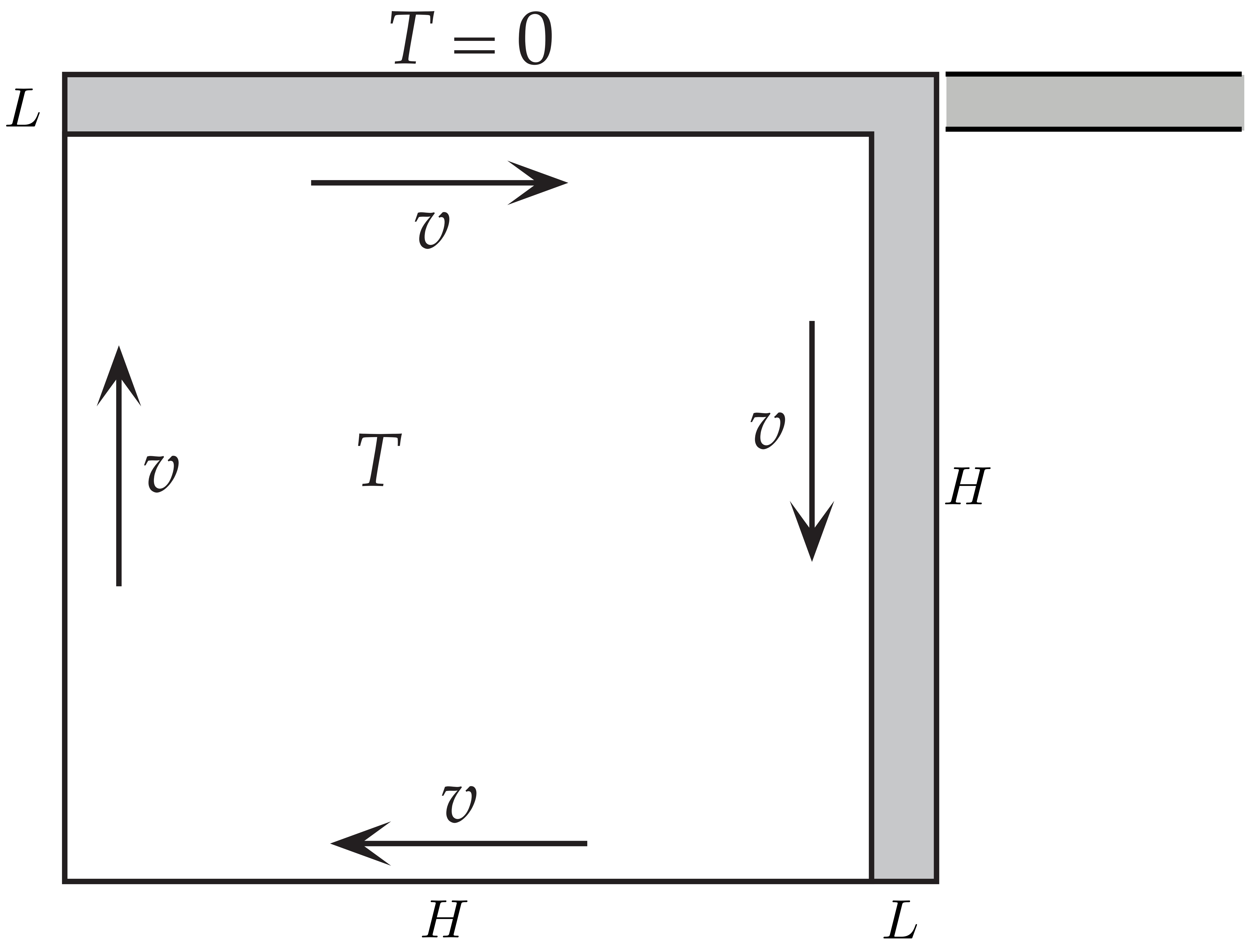
- broad plates with narrow boundaries
- passive divergent boundaries (MORs)
- active convergent boundaries (SZs)

- physical basis(es) for yield stress
- chemical heterogeneity
- continents and continental rifting
- one-sided subduction
- strike-slip (poloidal) motion
- role of magma in mechanics

Force of slab pull — simple estimate

$$F \sim (\Delta\rho) g L H$$
$$\sim \rho_0 \alpha (\Delta T) g L H$$
$$\sim \rho_0 \alpha (T_m/2) g L H$$
$$\approx 3 \times 10^{13}\ \mathrm{N/m} = 30\ \mathrm{TN/m}$$

Slab pull and plate speed — simple estimate



Newton's 2nd law: $F_D + F_R \approx 0$

$$F_D \sim \rho_0 \alpha (T_m/2) g L H$$

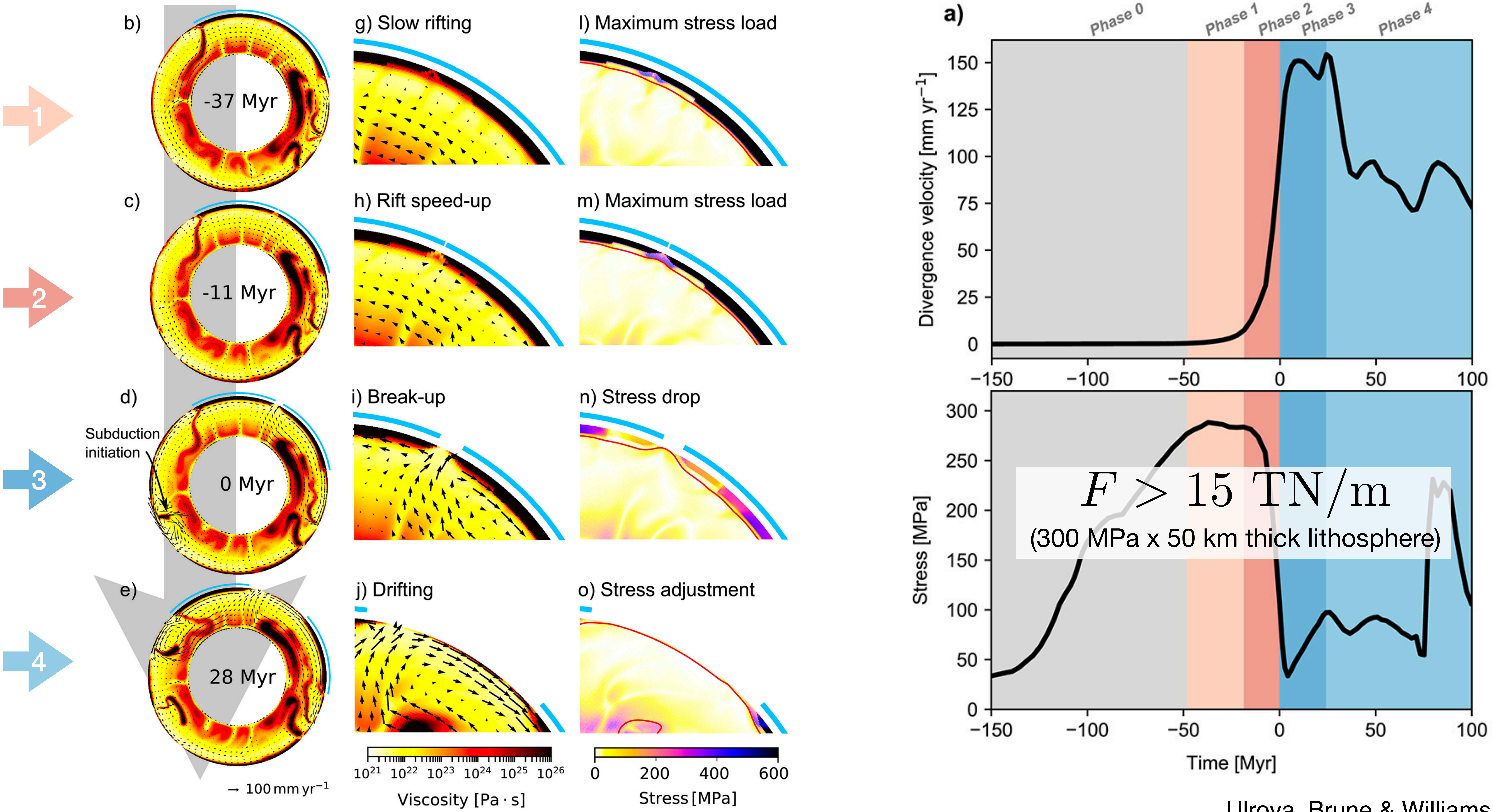
$$F_R \sim 3H(\eta \times 2v/H)$$

$$\Rightarrow \quad v = \rho_0 \alpha T g L H / 12\eta$$

$$\approx 10 \text{ cm/yr}$$

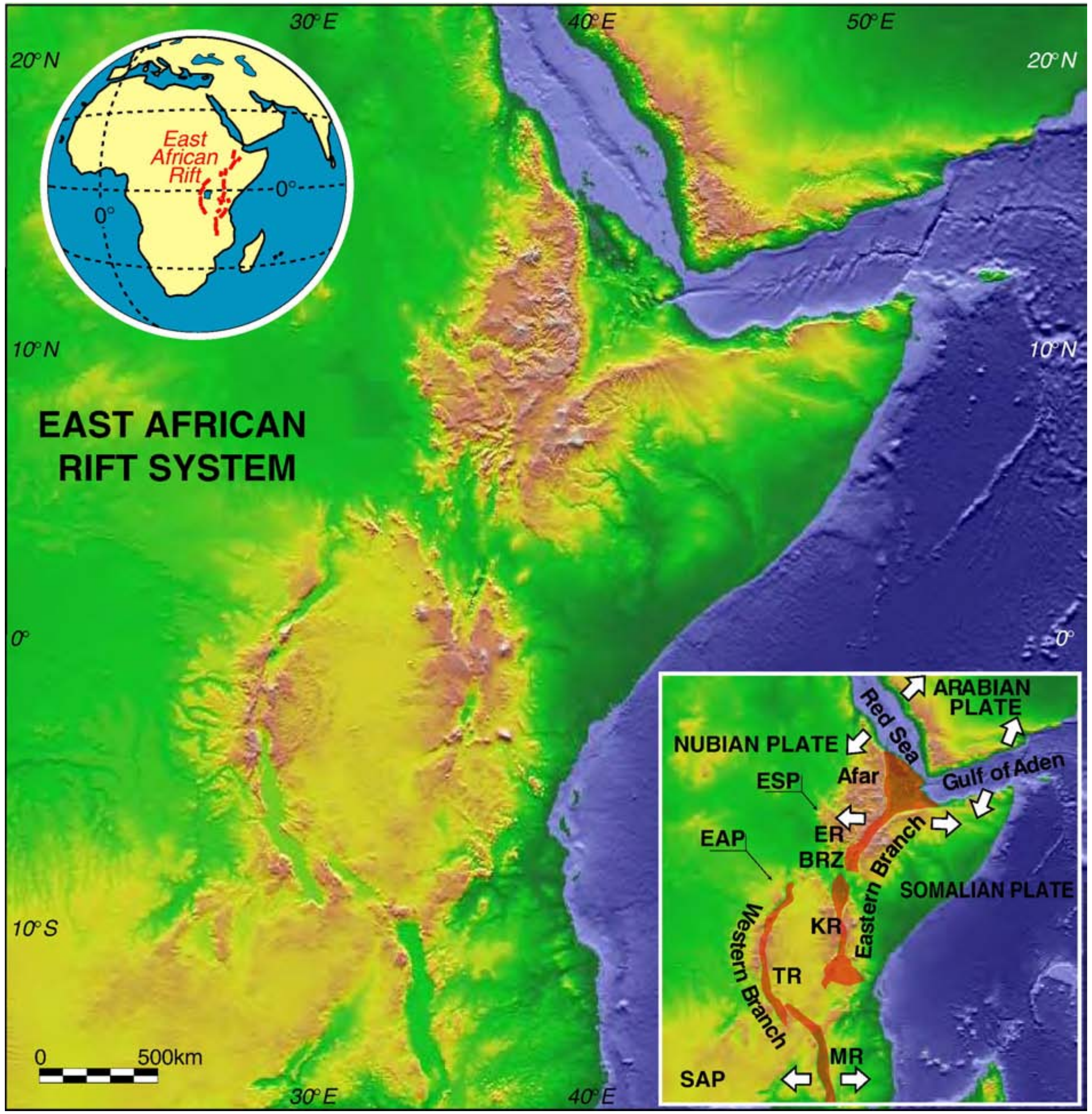

84° 126° 168° 210° 252° 294° 336° 18° 60°
88°
66°
44°
22°
0°
−22°
−44°
−66°
−88°
Eurasian
North
American
JDF
Philippine
Sea
Pacific
Indian
Arabian
Carrib.
Cocos
African
Nazca
South
American
Australian
10 cm/yr
Antarctic

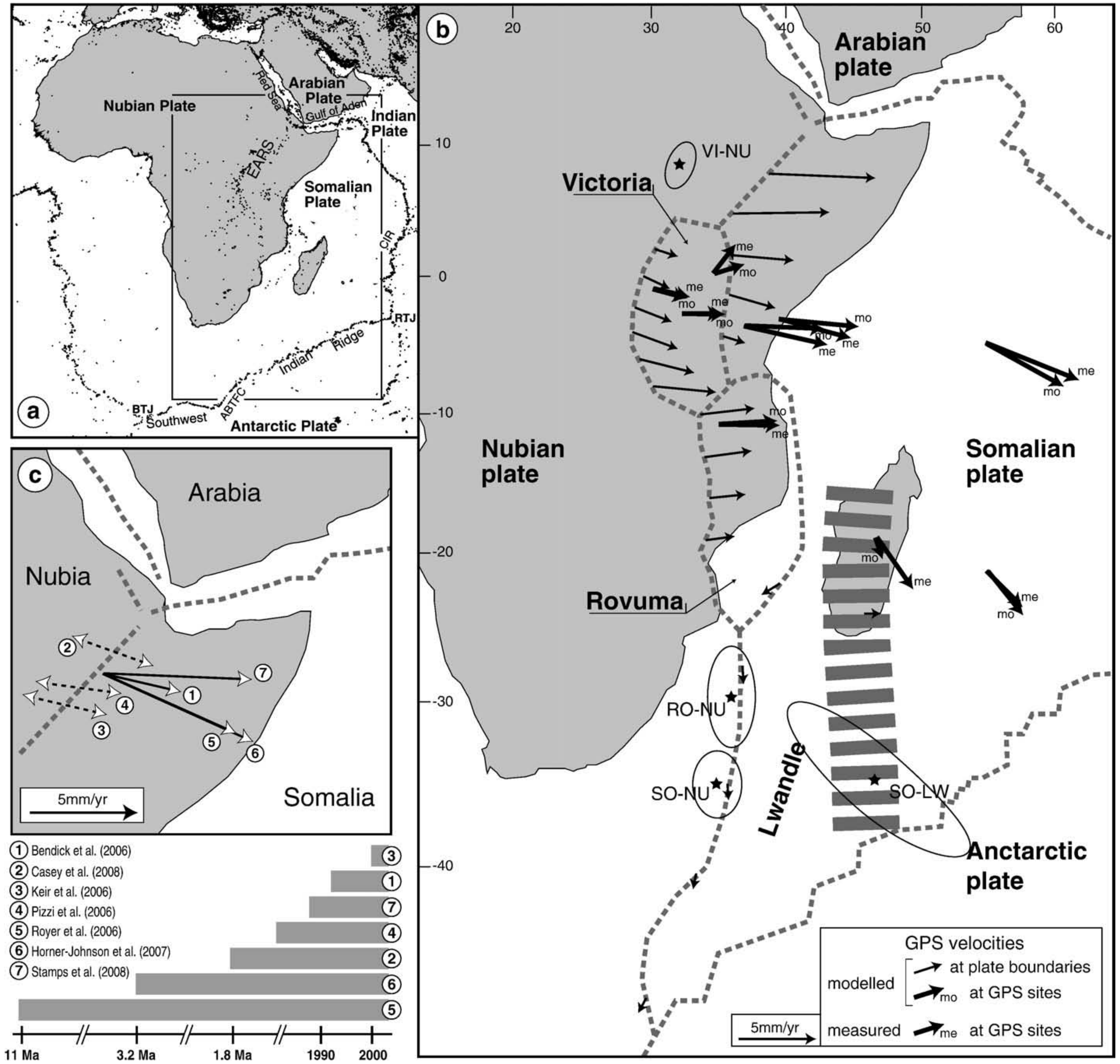
Force within lithosphere causing rifting



Ulrova, Brune & Williams *GRL* 2018

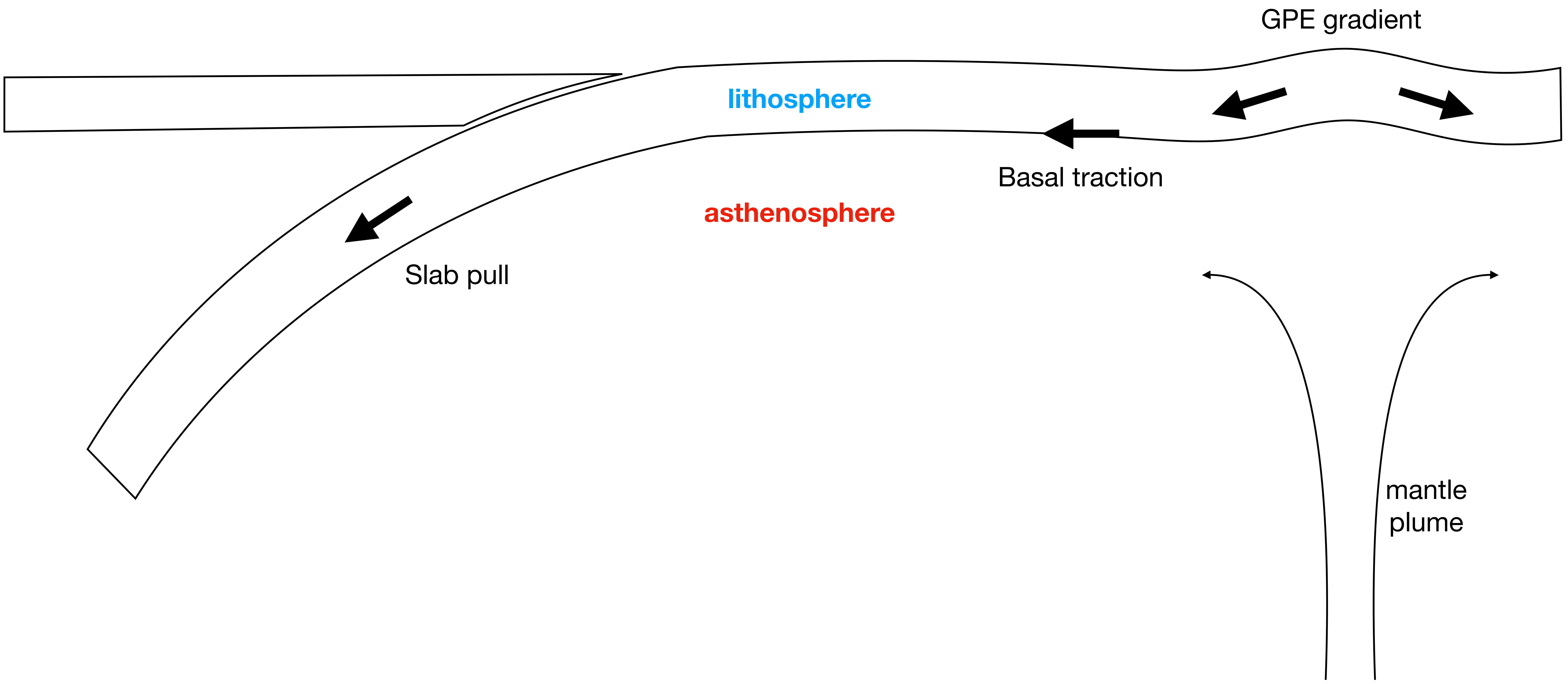
What is happening here in Africa?



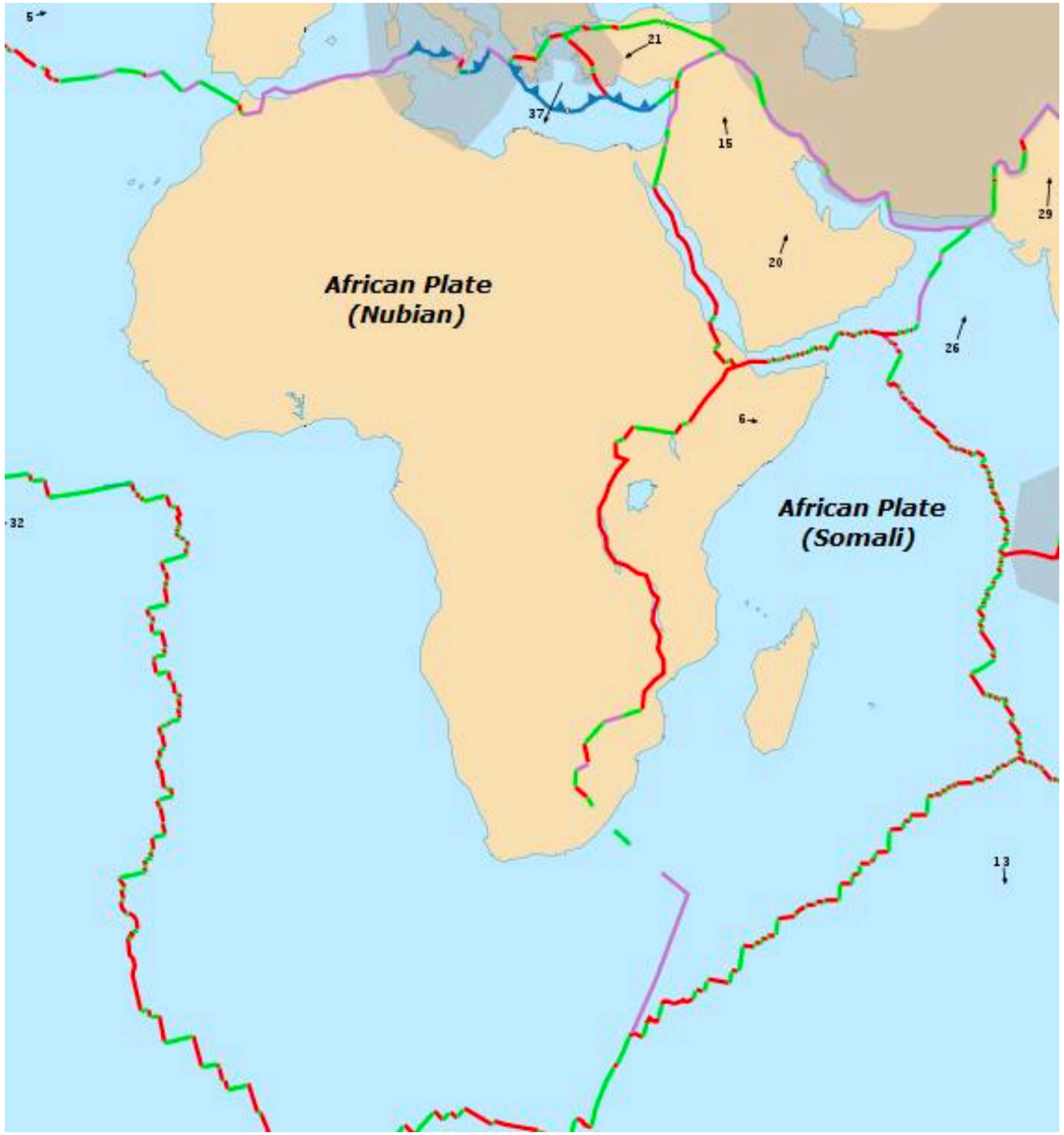


Corti, *Tectonophys* 2012

Candidate forces for rifting continents

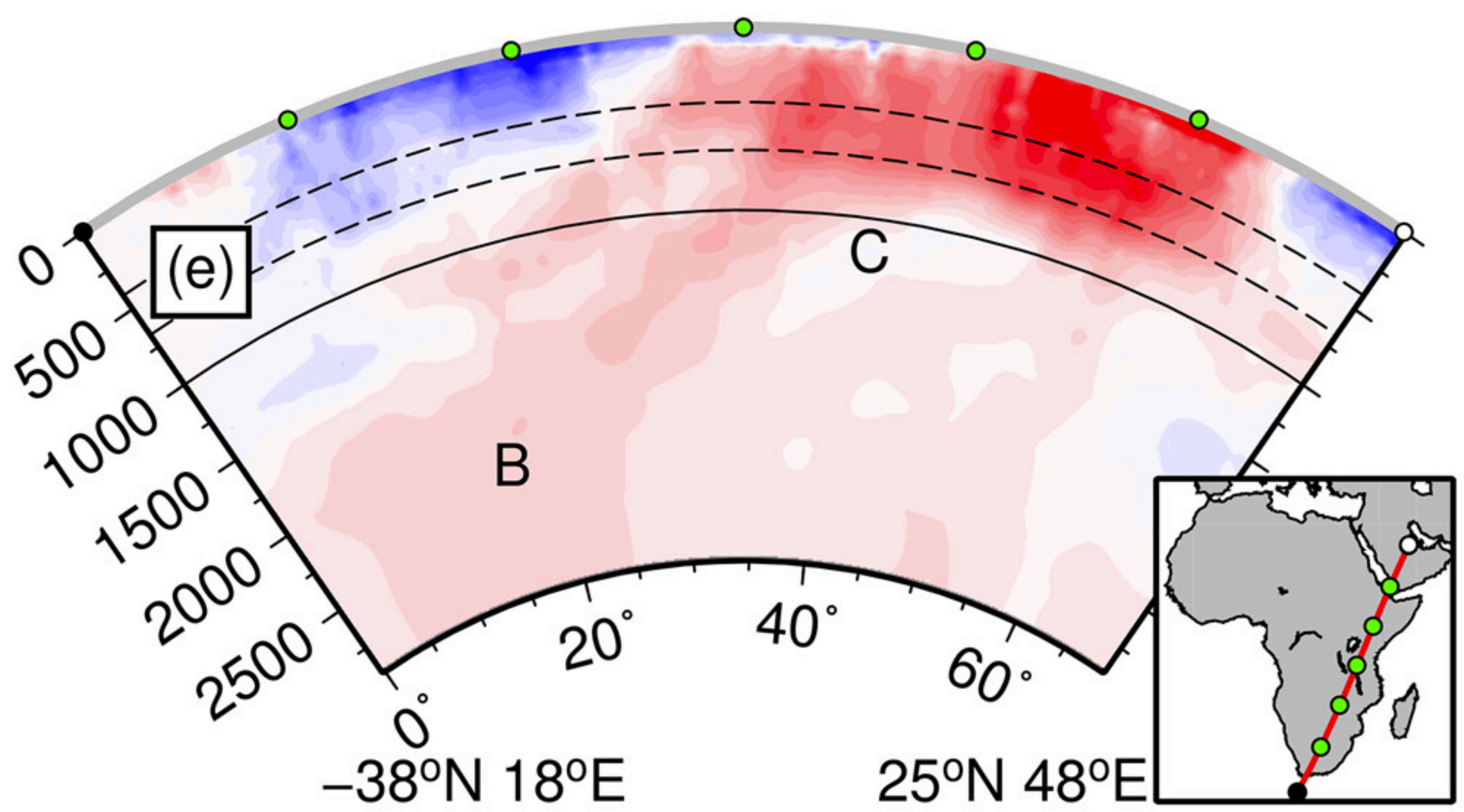


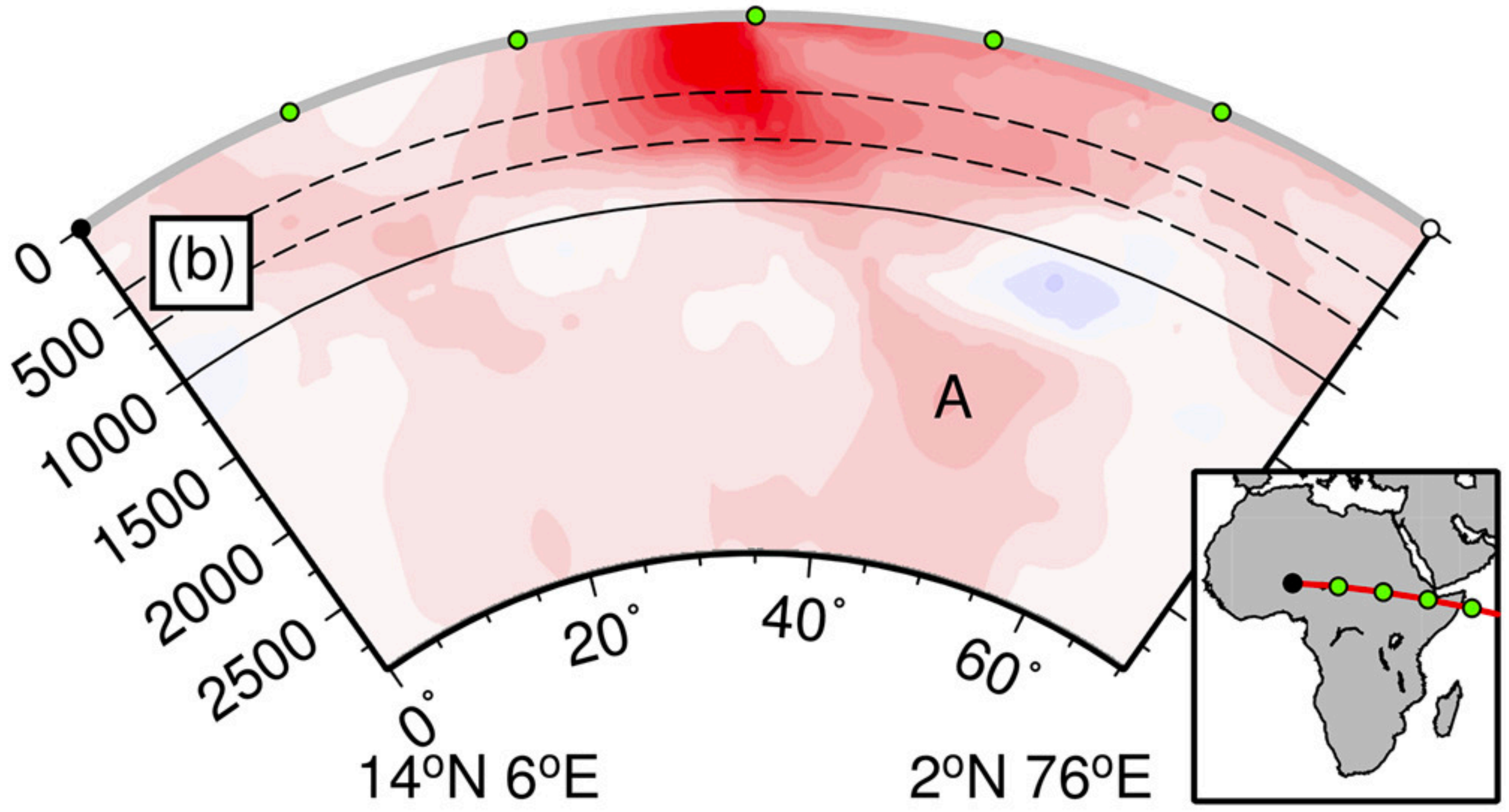
What is happening here in Africa?

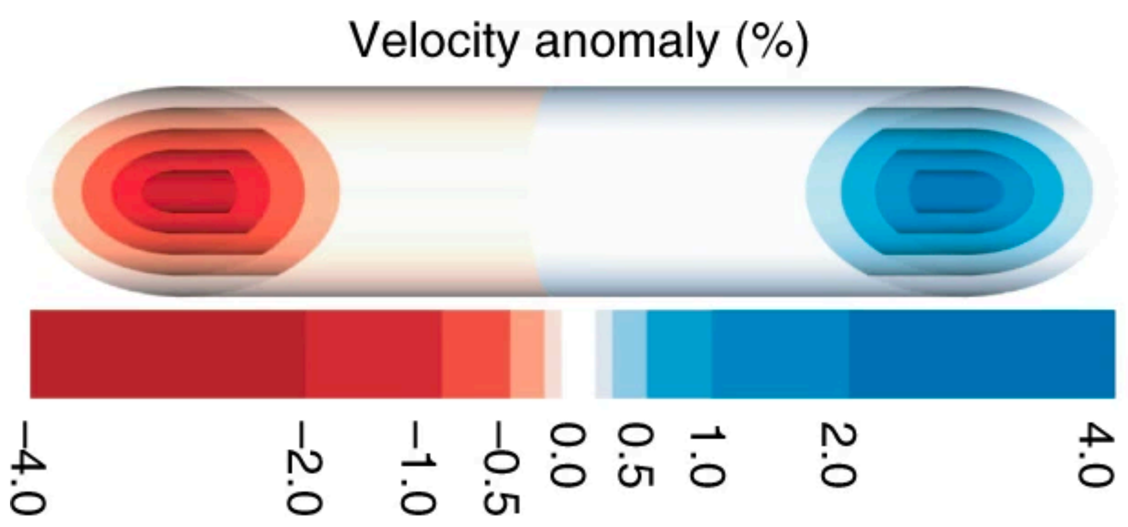


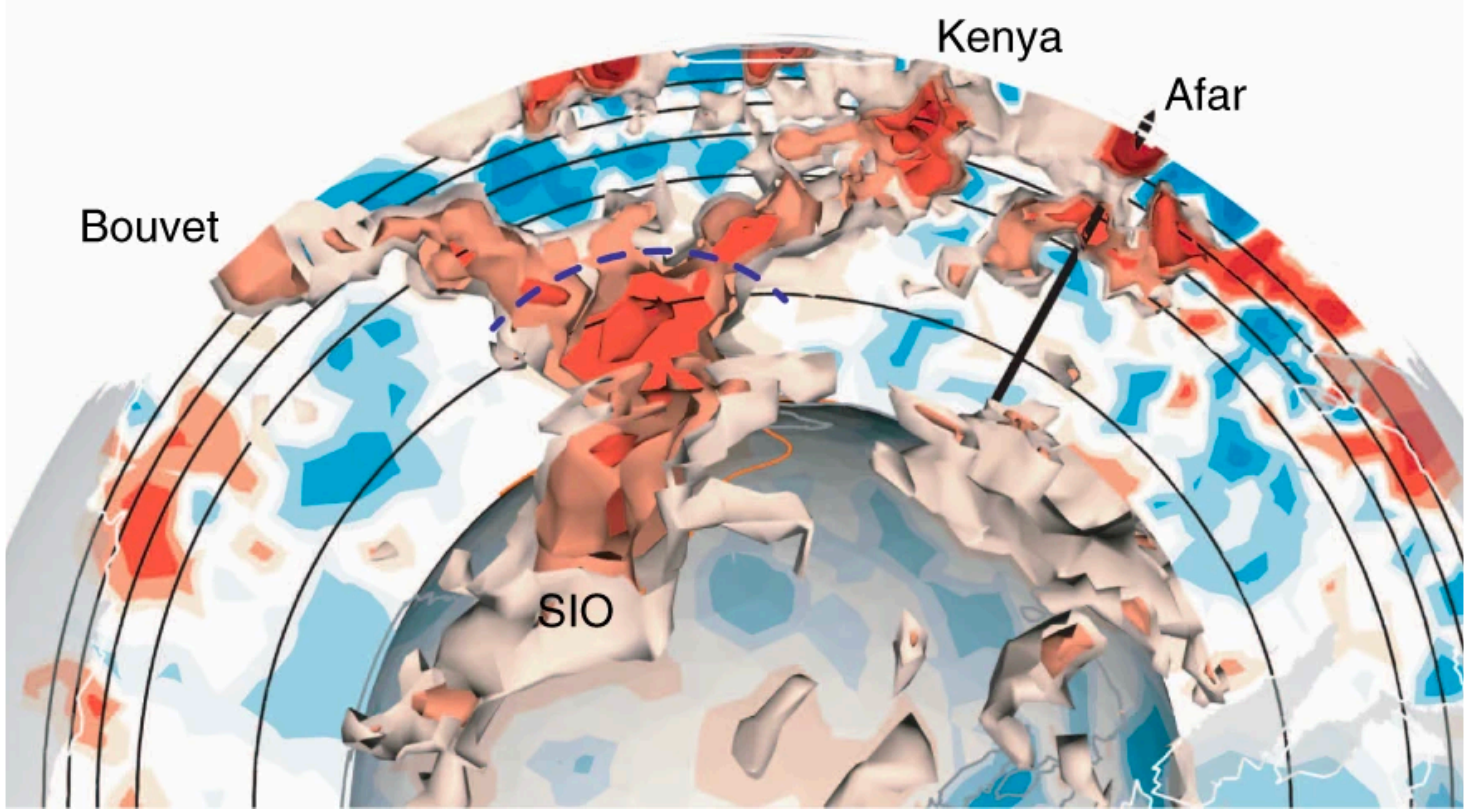
Heezen & Tharp, *PTRSA* 1965

What is happening here in Africa?





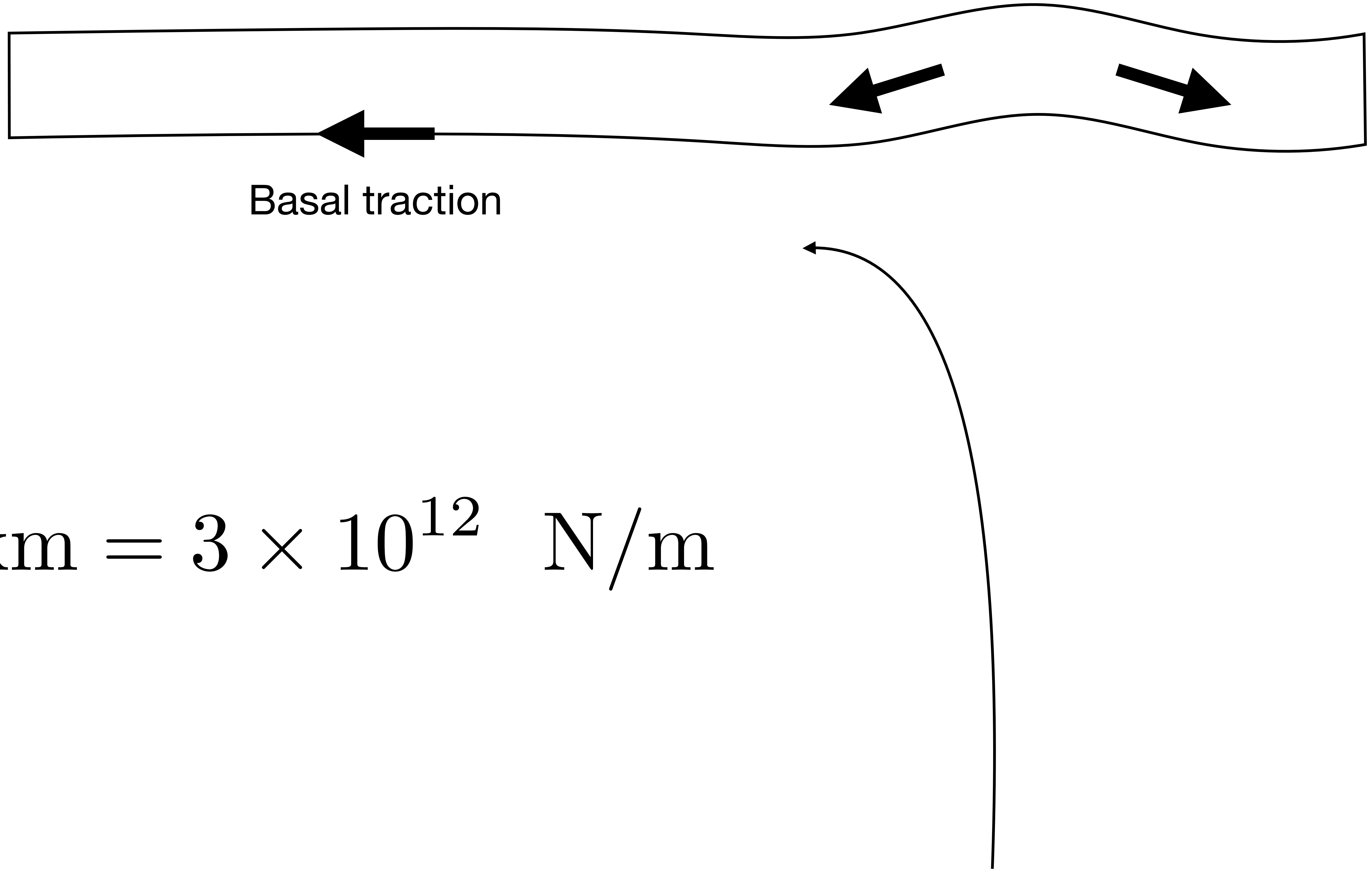




Boyce et al, *G3* 2021

Tsekhmistrenko et al, *Nature Geoscience* 2021

Basal traction force (from mantle convection)



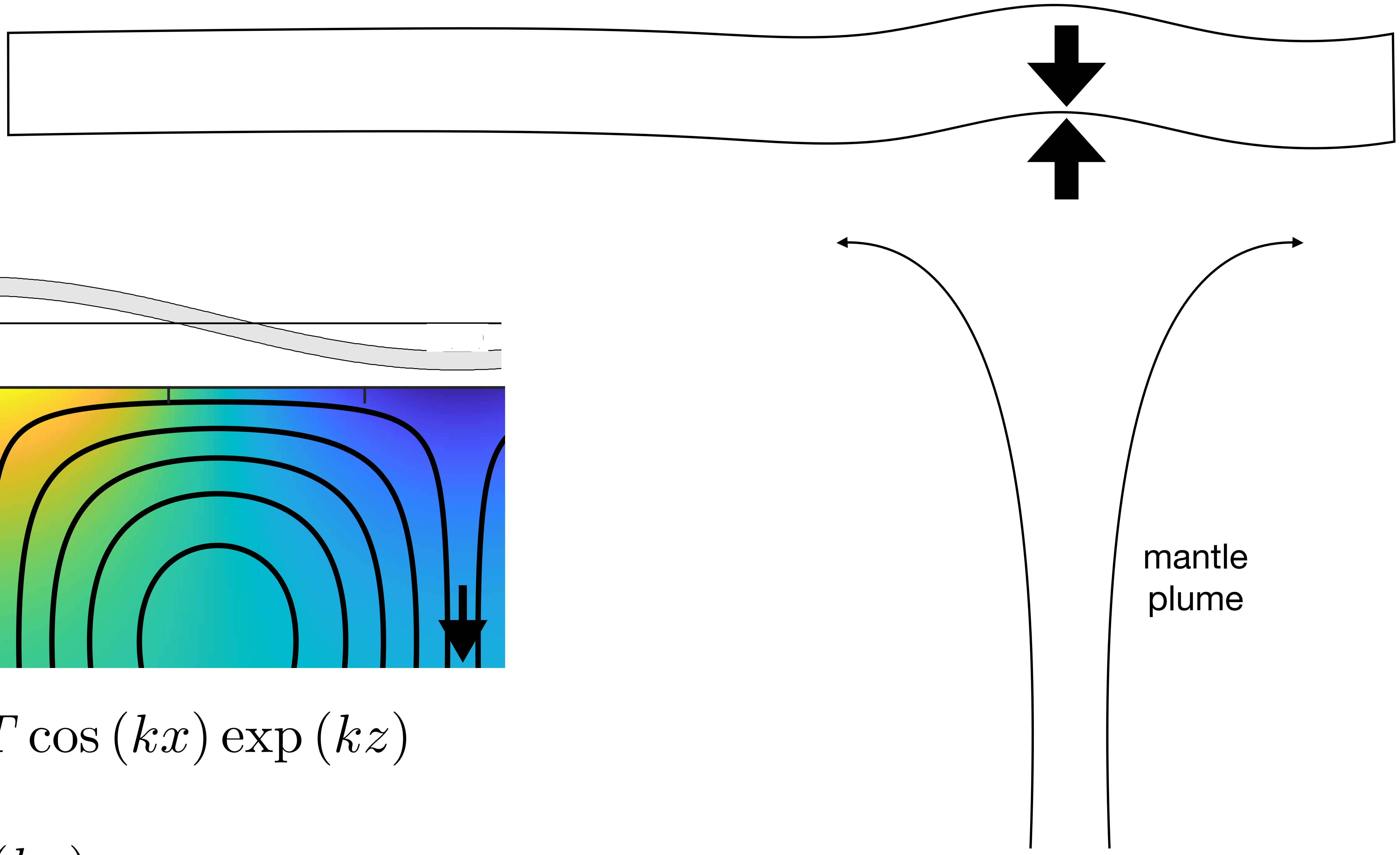
$$F \leq 3\ \mathrm{MPa} \times 1000\ \mathrm{km} = 3 \times 10^{12}\ \ \mathrm{N/m}$$

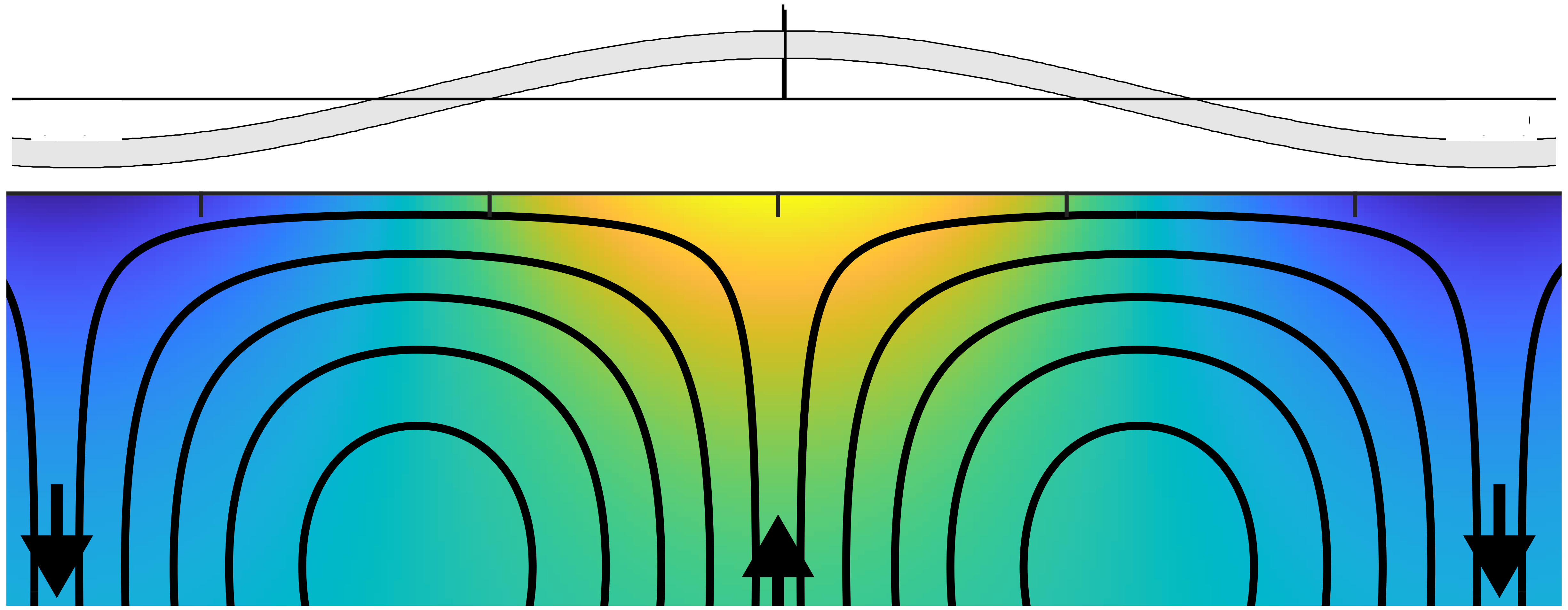
typical convective stress

plate application length

Dynamic topography

$$F_{\text{buoyancy}} + F_{\text{viscous}} - F_{\text{weight}} = 0$$

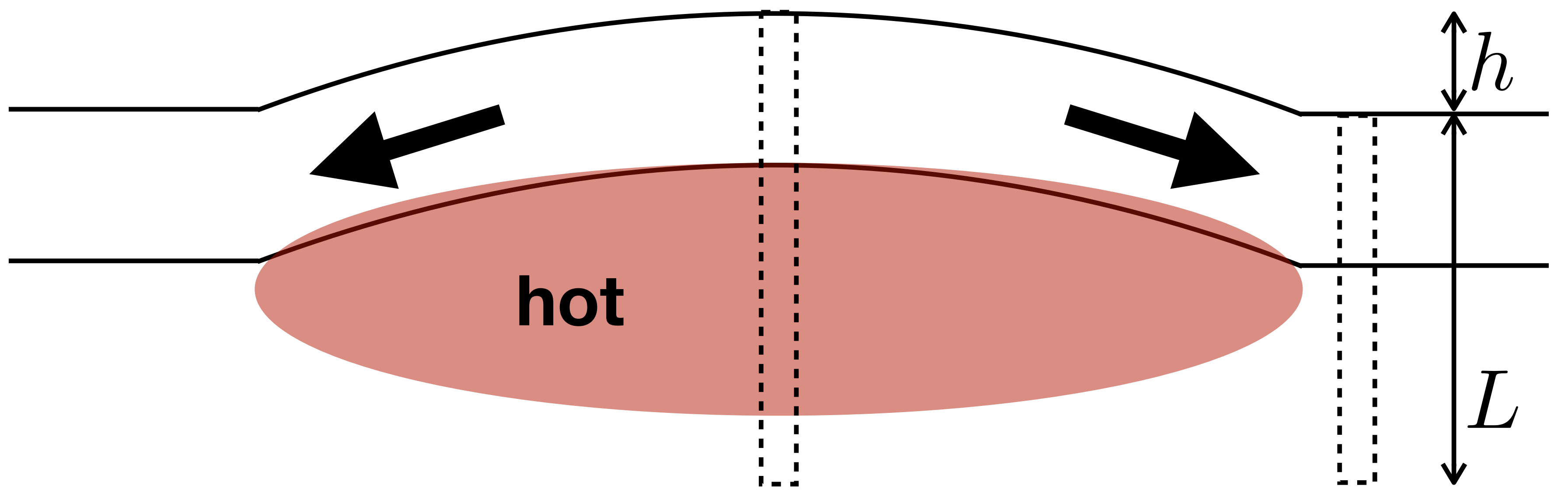




$$T(x,z) = T_m + \Delta T \cos(kx) \exp(kz)$$

$$\Delta h = \frac{3\rho_0 \alpha \Delta T}{4 \Delta \rho k} \cos(kx)$$

GPE gradient force (~same as ridge push force)



vertical avg. density: $\rho_1 < \rho_0$

Pratt isostasy: $\rho_1(L+h) = \rho_0 L$

Potential energy: $\mathrm{GPE}(x) = \int_{-L}^{h(x)} \rho(z) g z \, \mathrm{d}z$

Force per length: $F = \Delta\mathrm{GPE} = \dfrac{\rho_1 g (L+h)^2}{2} - \dfrac{\rho_0 g L^2}{2}$

$$= \frac{\rho_0 g L h}{2}$$

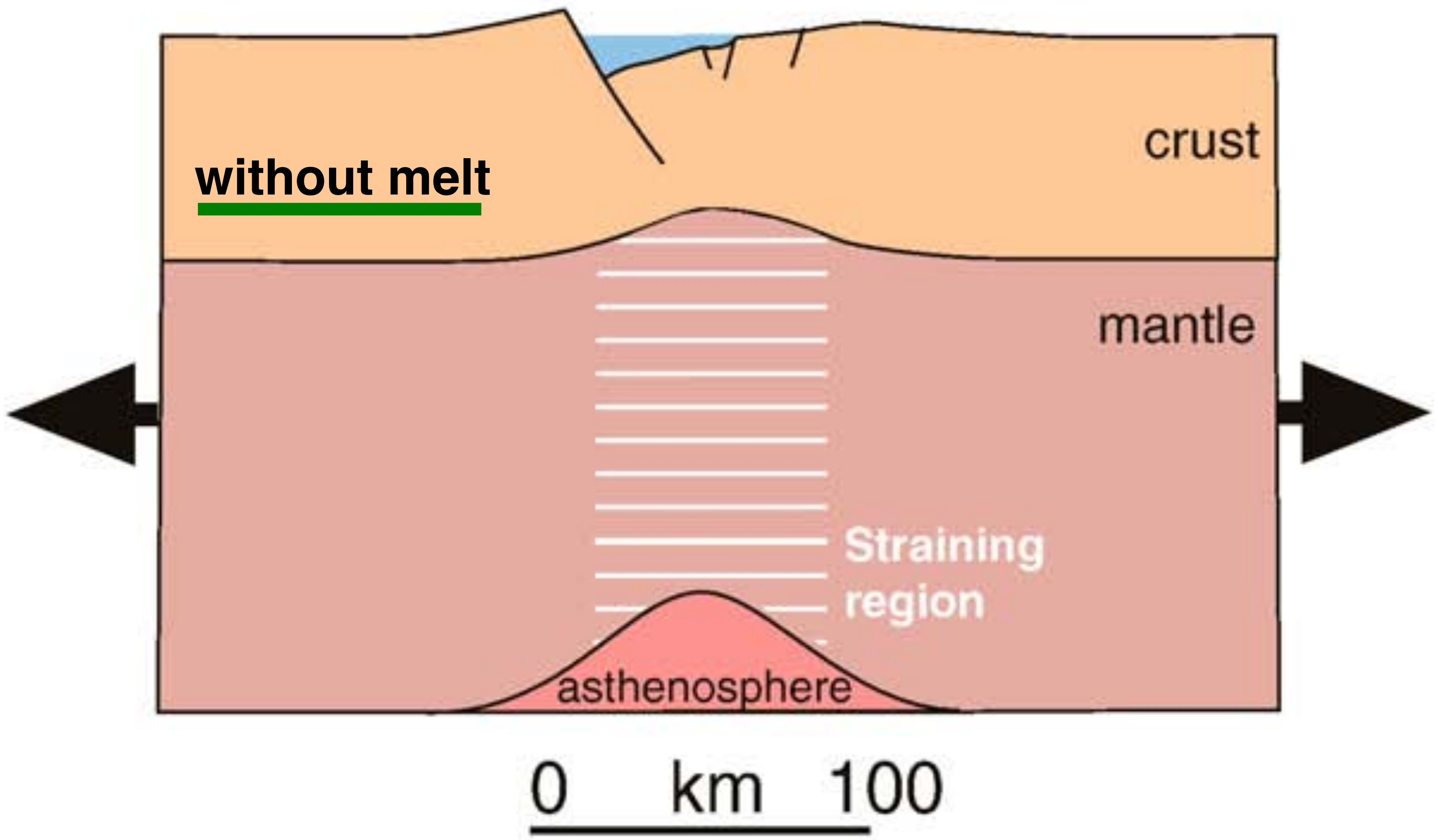
For an upper bound:

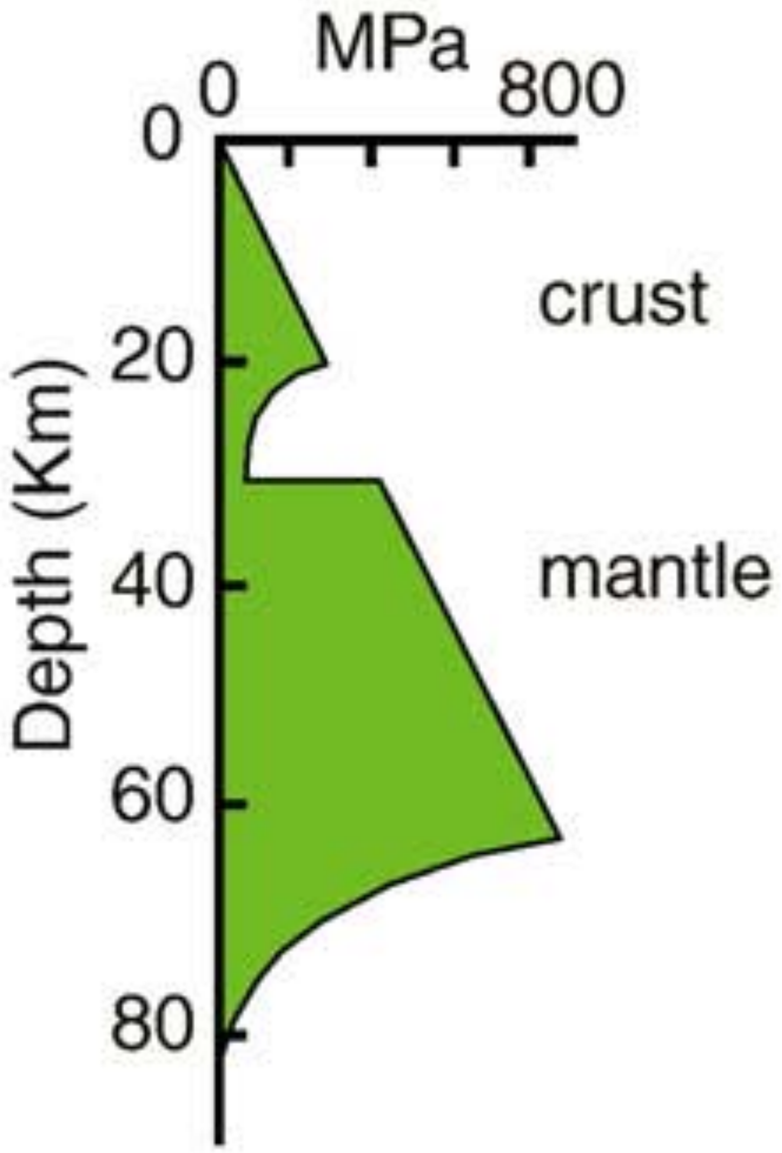
$$h = 1 \text{ km}, \; L = 150 \text{ km}, \; \rho = 3000 \text{ kg/m}^3$$

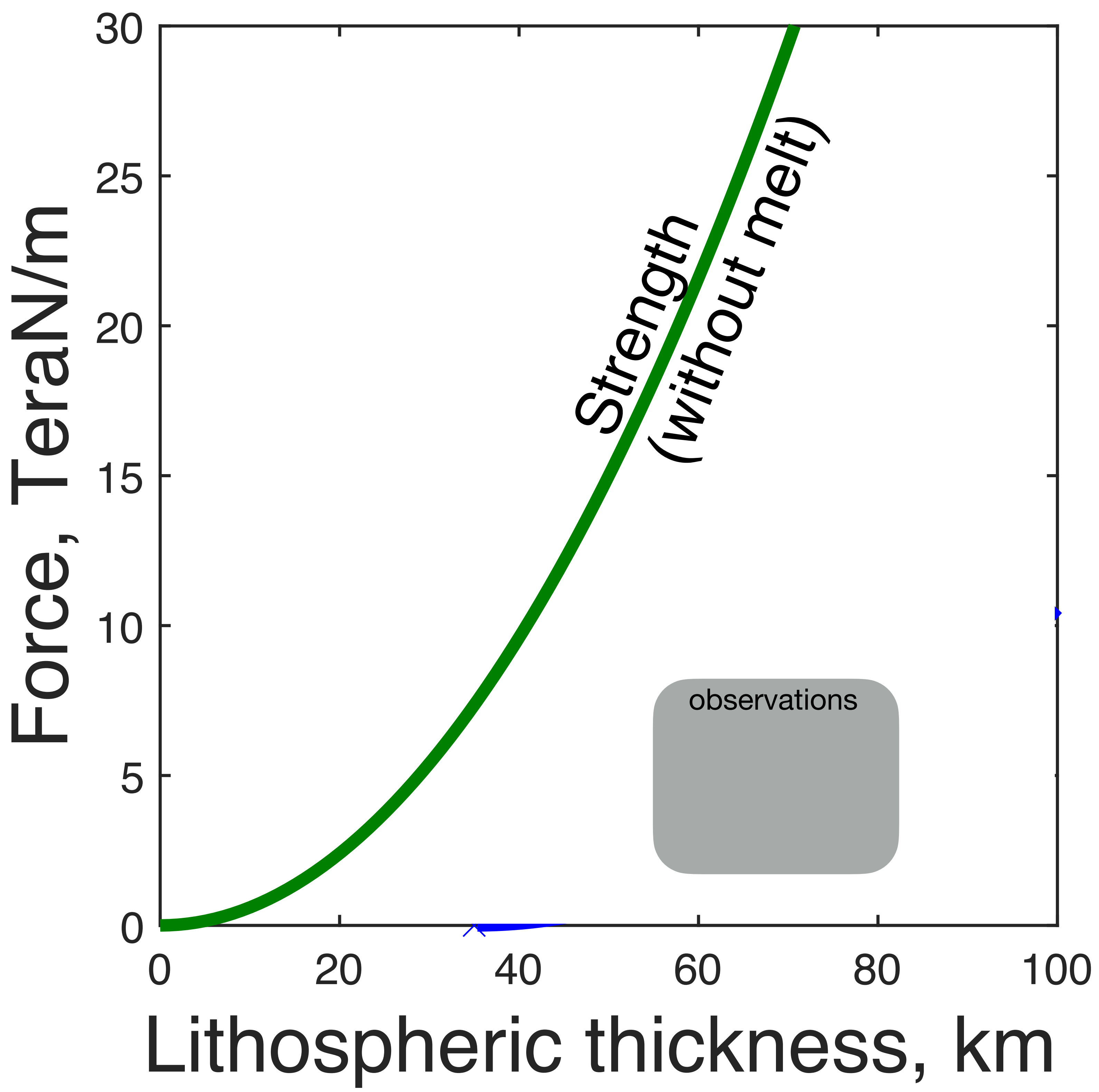
$$F \leq 5 \times 10^{12} \text{ N/m}$$

Observation: rifting can occur at driving force less than ~5 TN/m

Rifting by frictional slip on faults







$$F \sim A(\rho_{\text{lith}} - \rho_w)gL^2$$

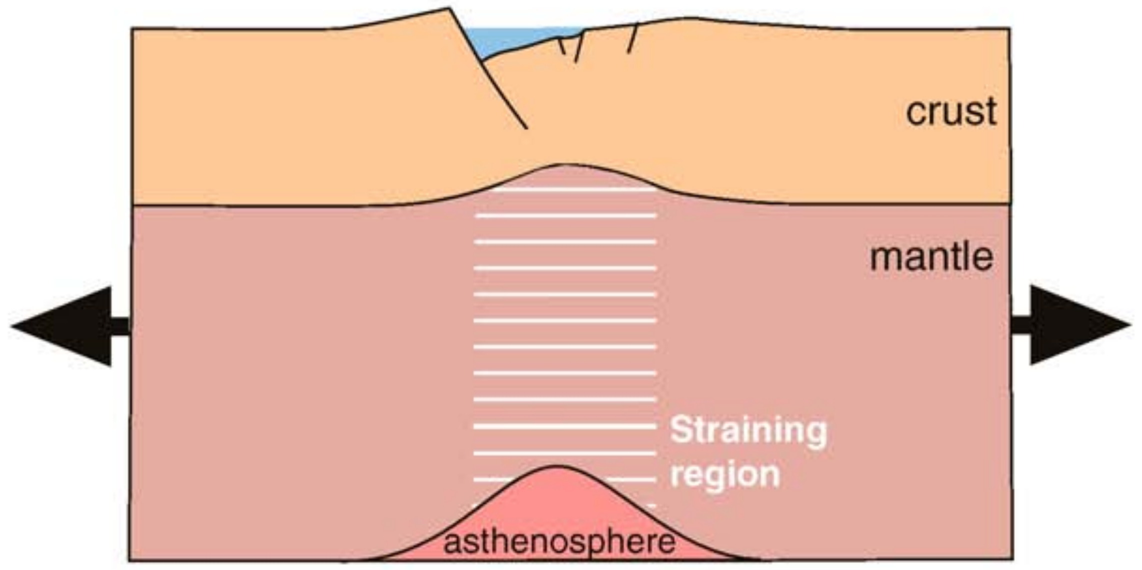
Andersonian faulting strength

Hydrostatic pressure

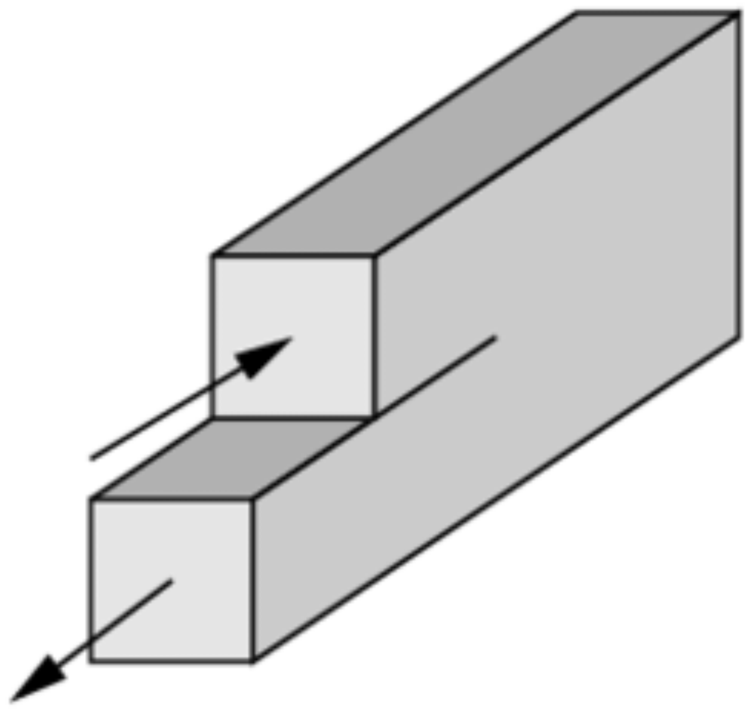
(N.B., $F = \sigma L$)

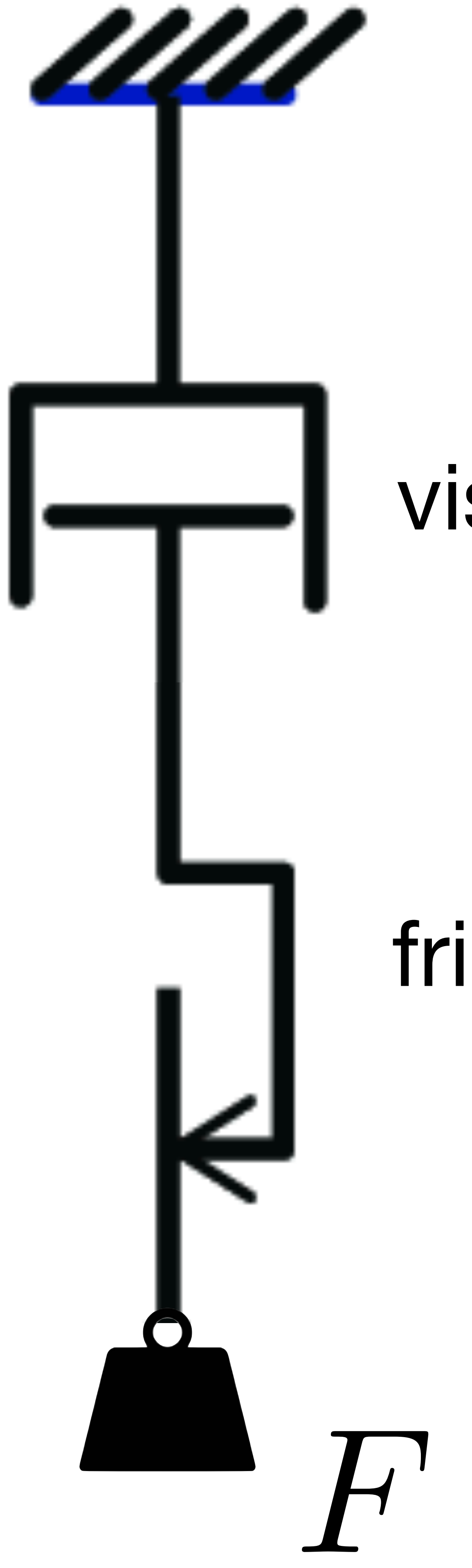
Corti 2009, Buck 2006

Using plasticity to represent faults



Mode II





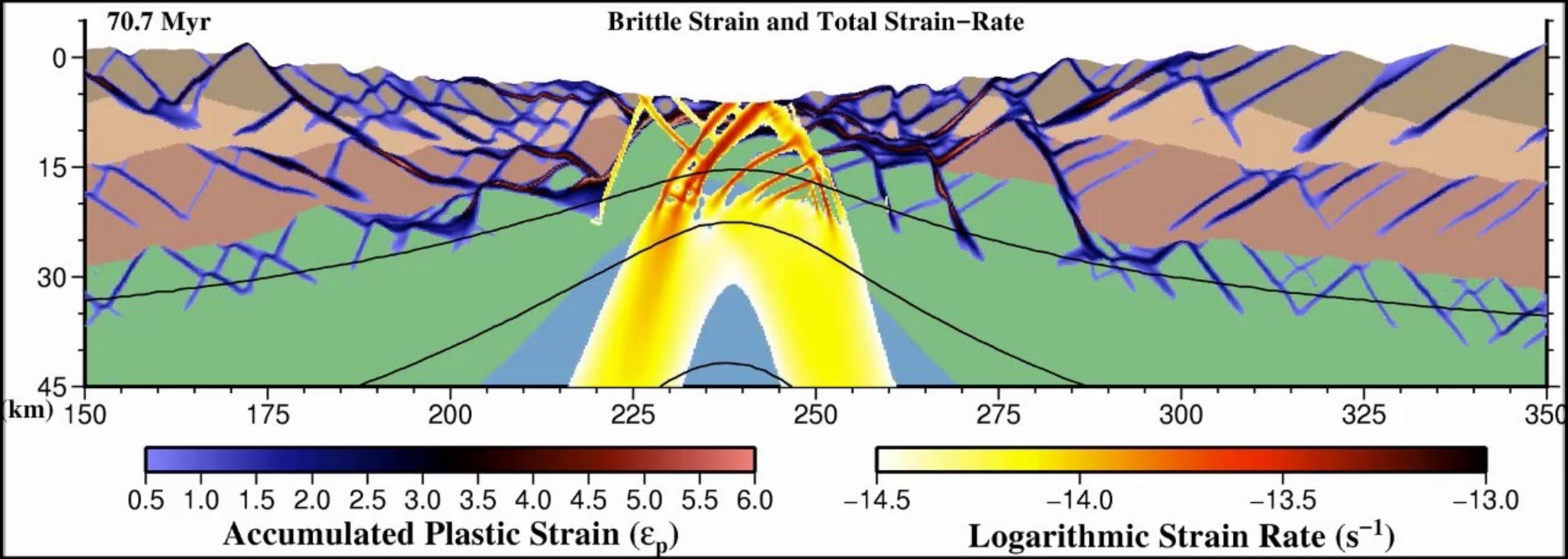
viscous dashpot representing *creep deformation*

extends at a rate $\propto F$

frictional slider representing *fracture and fault slip*

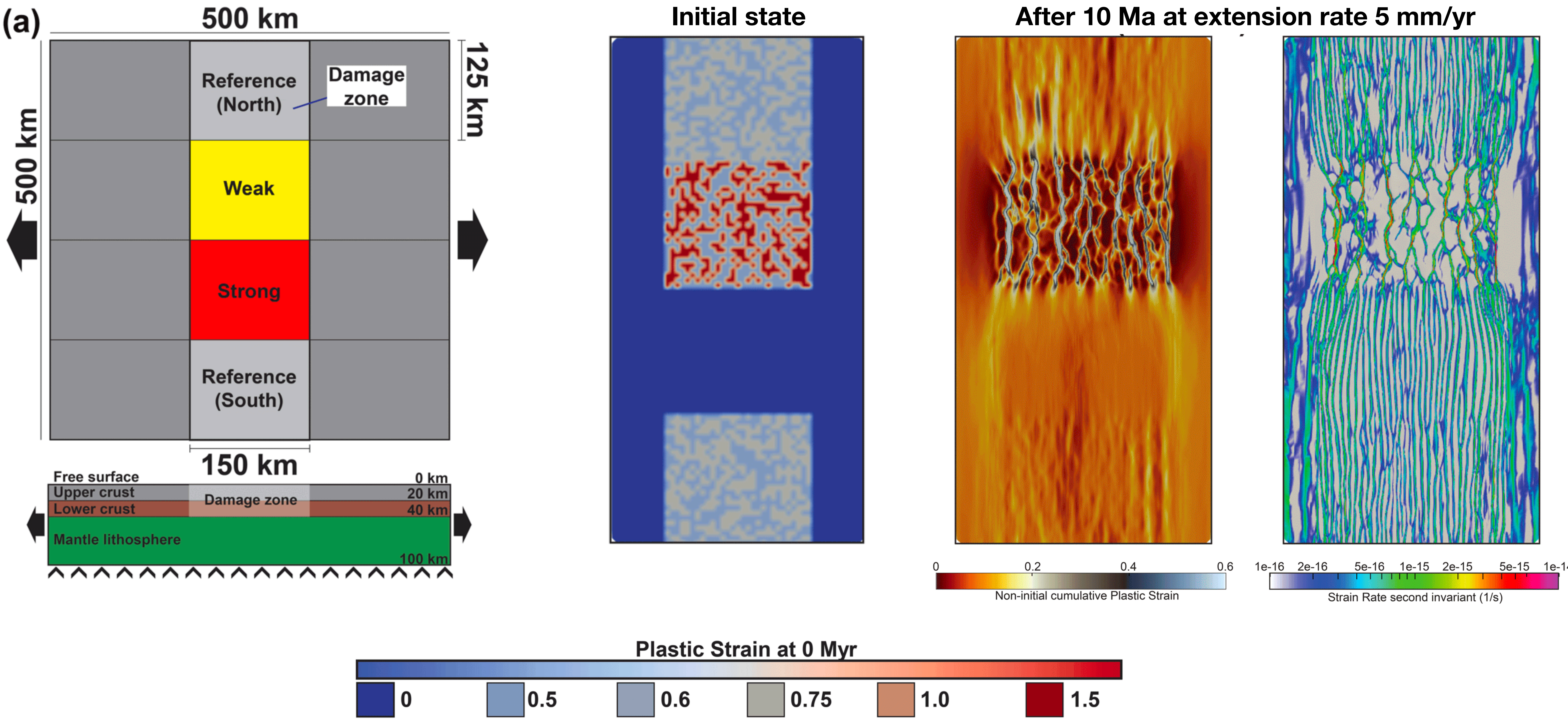
extends if $F > F_{\mathrm{crit}}$

Faulting & frictional slip modelled as plastic deformation



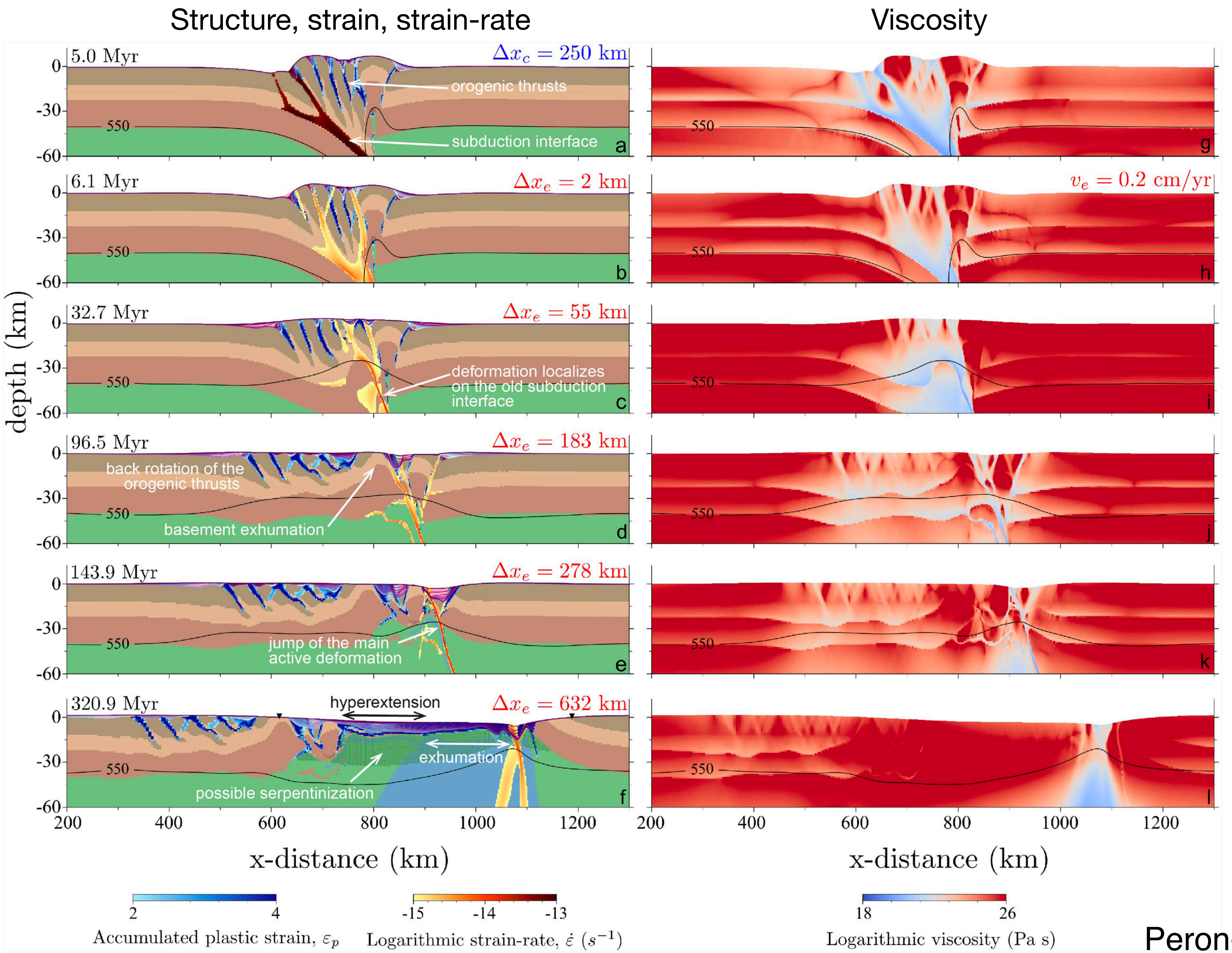
Naliboff et al *Nature Comms* 2017

Consequences of preexisting plastic damage variations (“inheritance”)



Philliips et al *Solid Earth* 2023

Influence of orogenic collision inheritance (Mid-Norwegian margin)

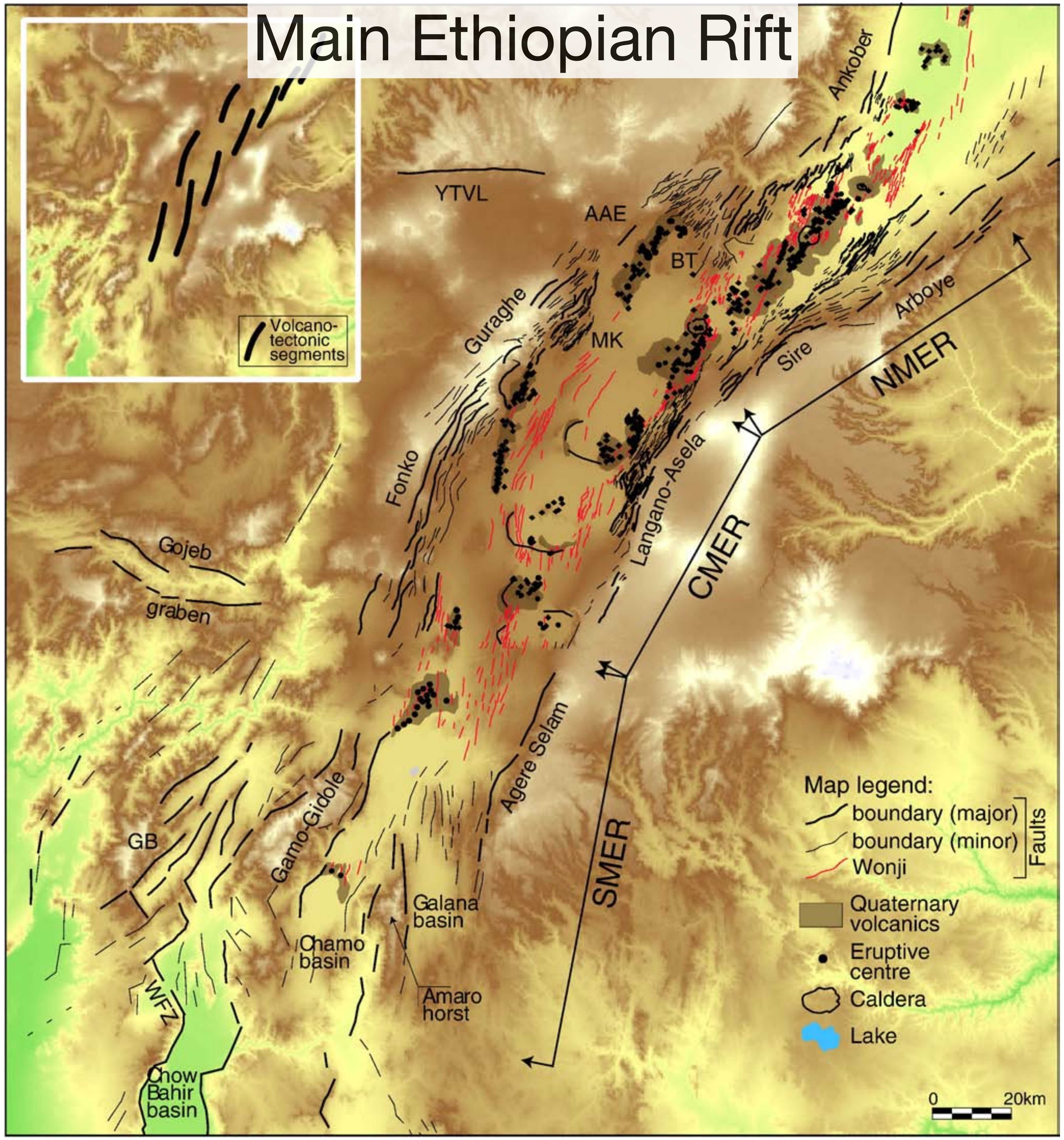


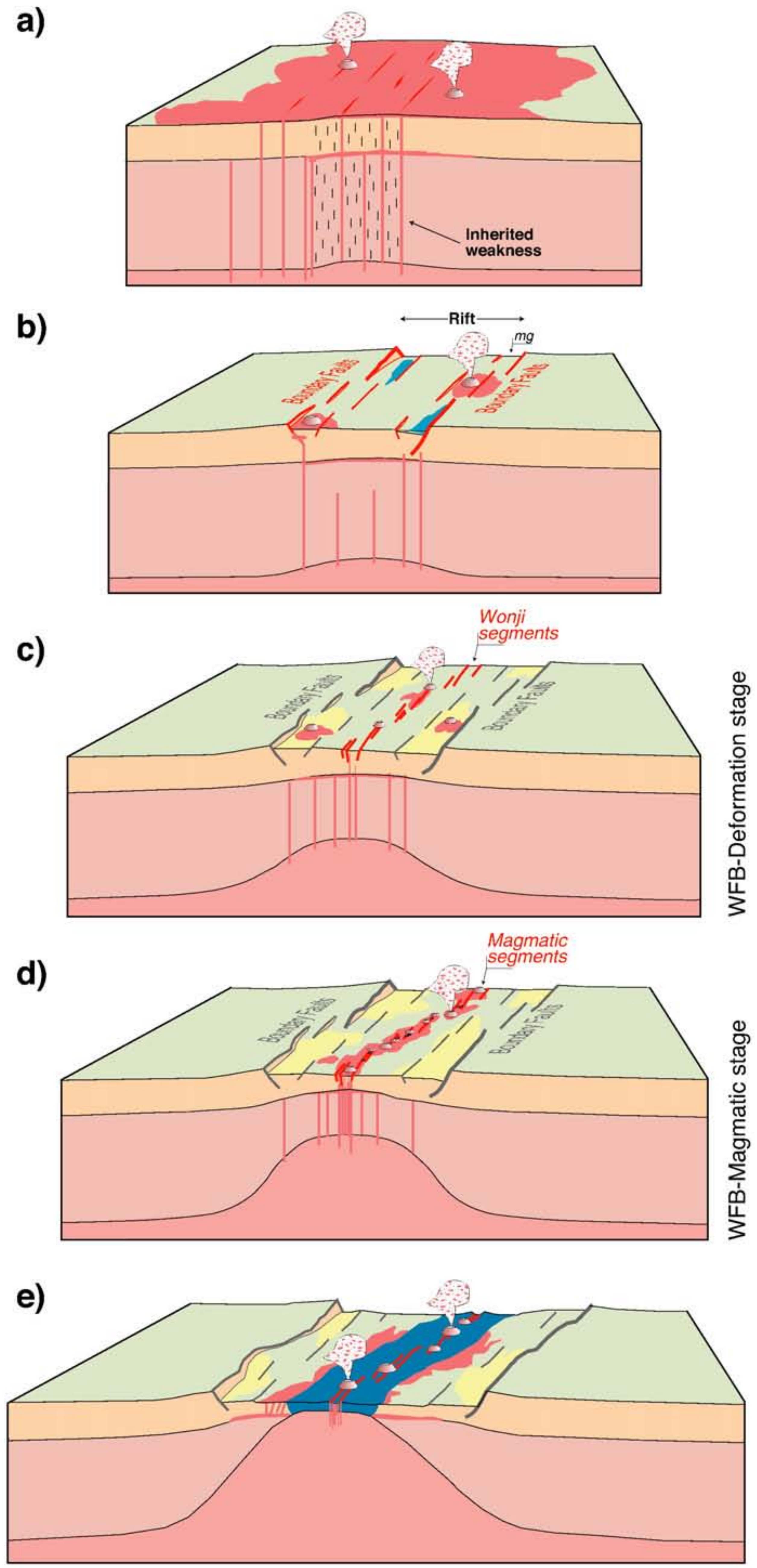
Collision & subduction phase

Extension phase

Peron-Pinvidic et al *Tectonophysics* 2022

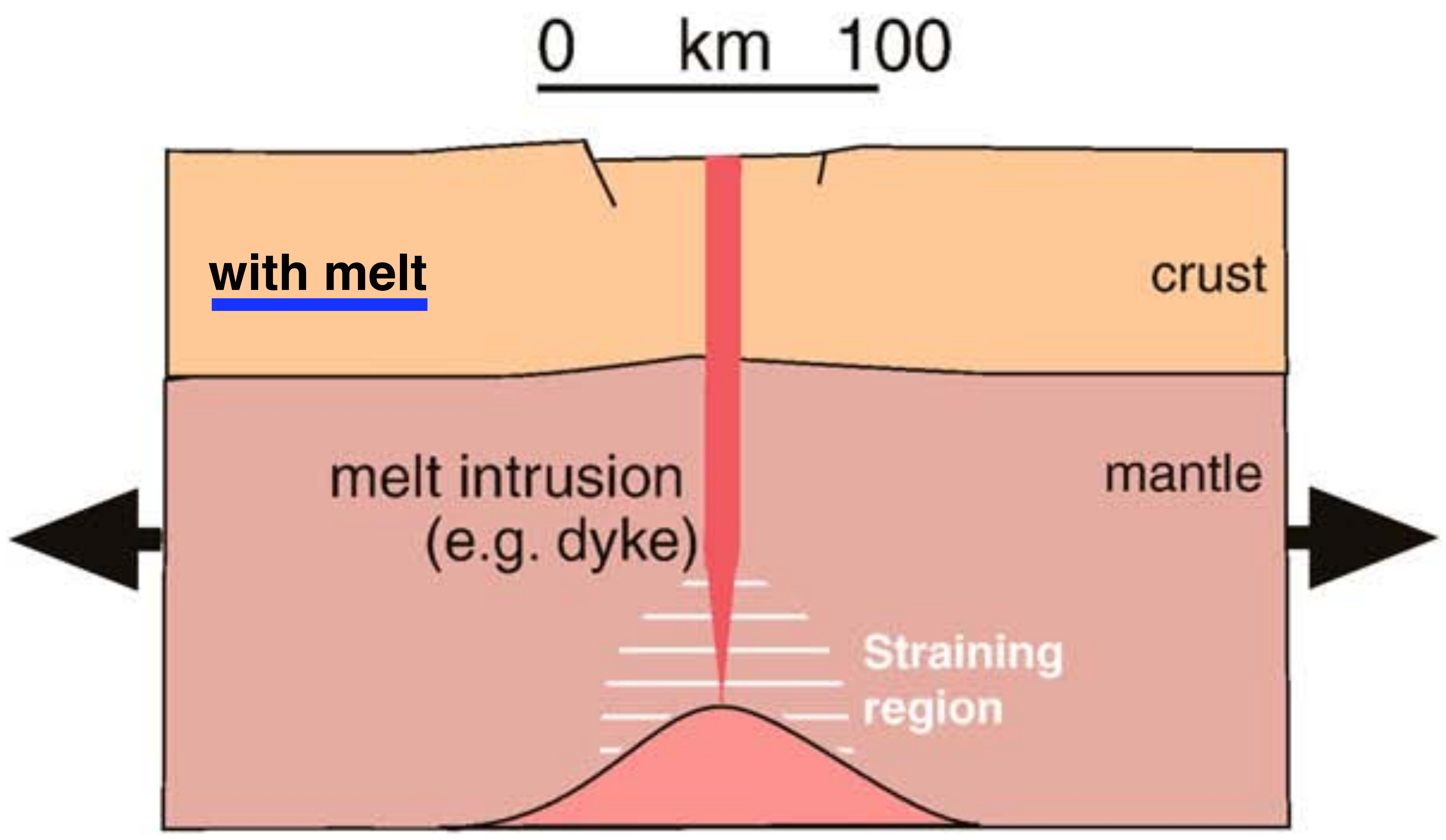
Main Ethiopian Rift

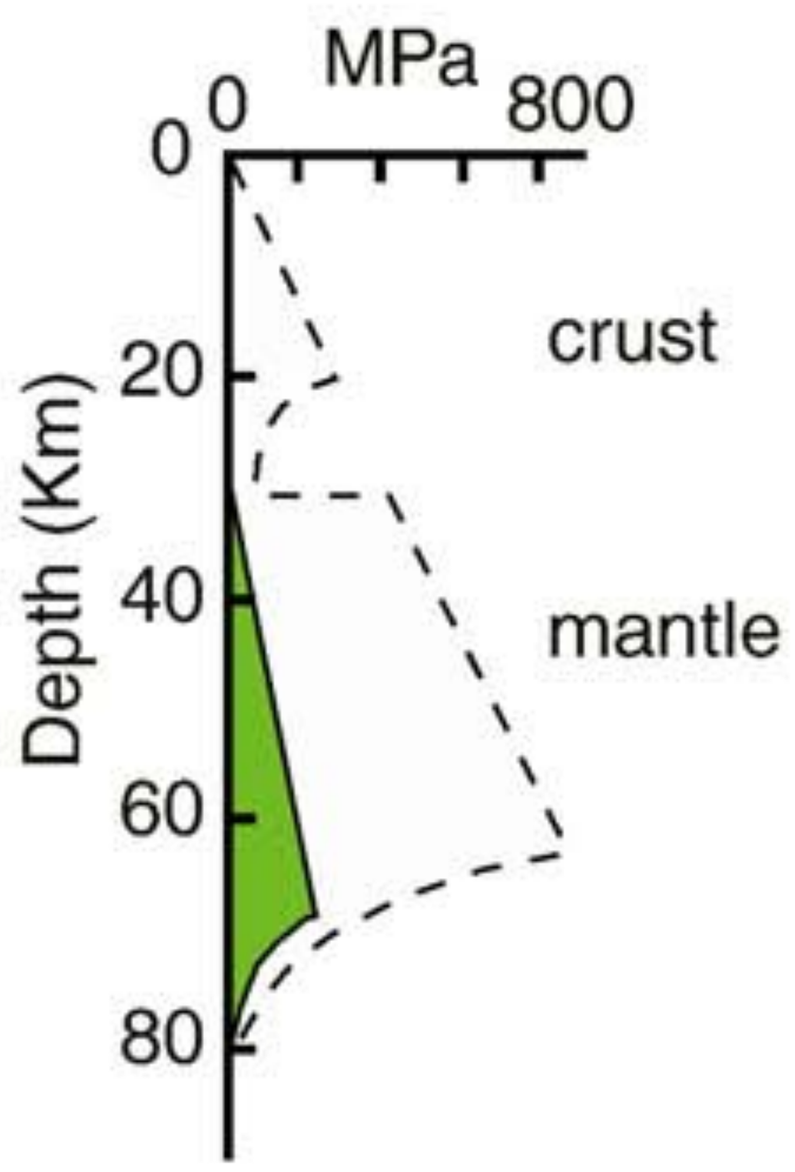




Ebinger 2005, Corti 2009, Boccaletti et al 1998, Casey *et al* 2006

Magma reduces the stress required for rifting





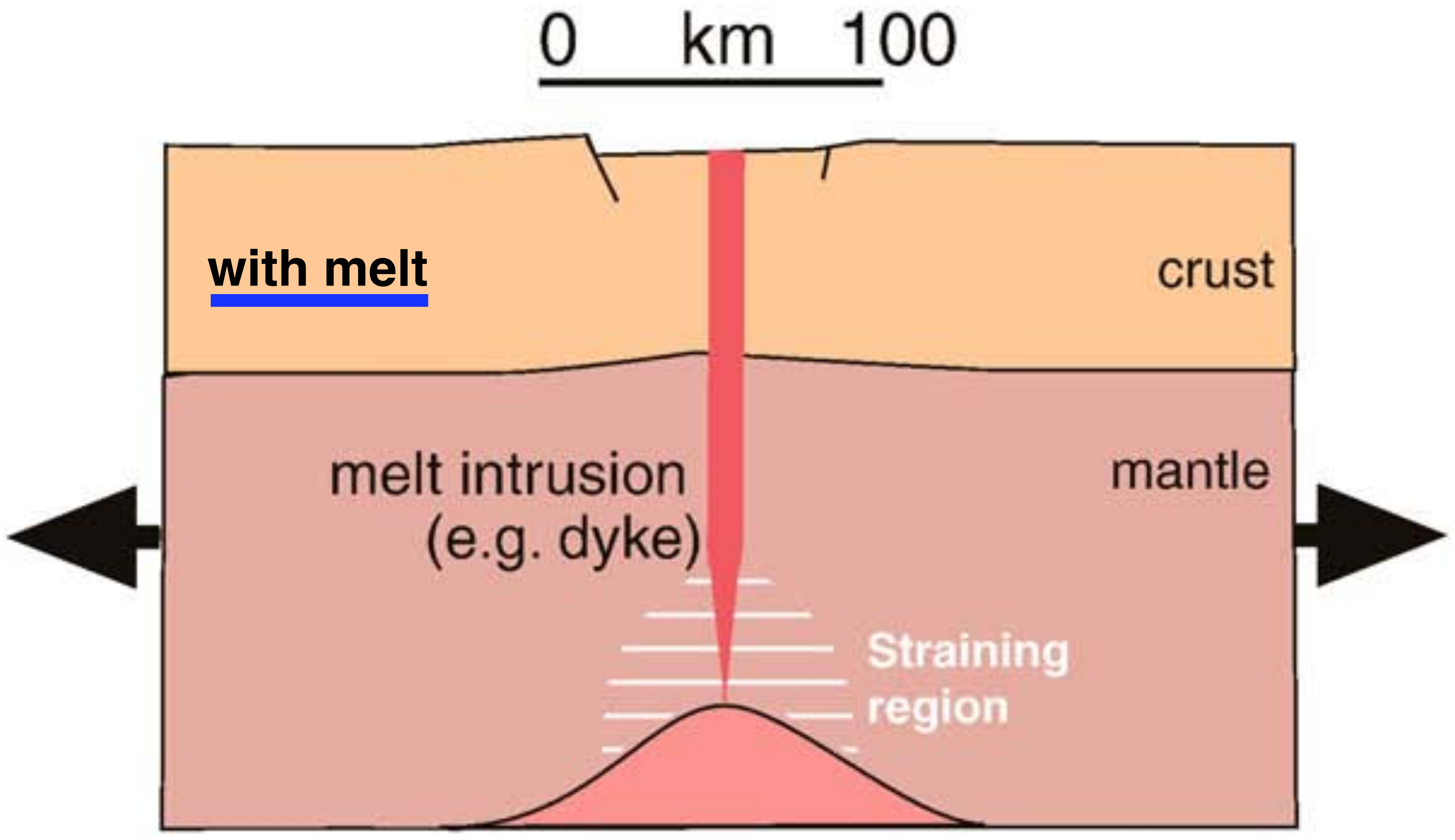
Assume zero cohesion (fracture toughness)

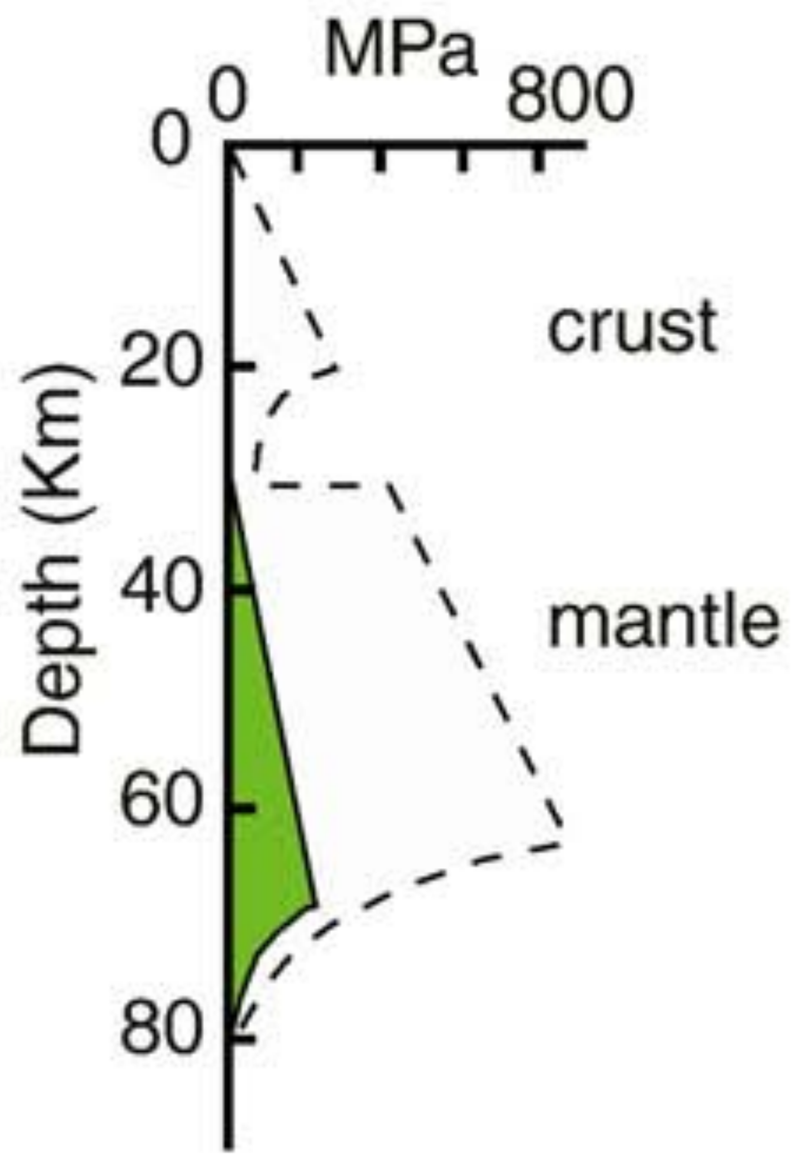
$$F = \Delta \mathrm{GPE} = \int_{-L}^{0} [\rho_f - \rho_{\mathrm{lith}}(z)] g z \, \mathrm{d}z$$

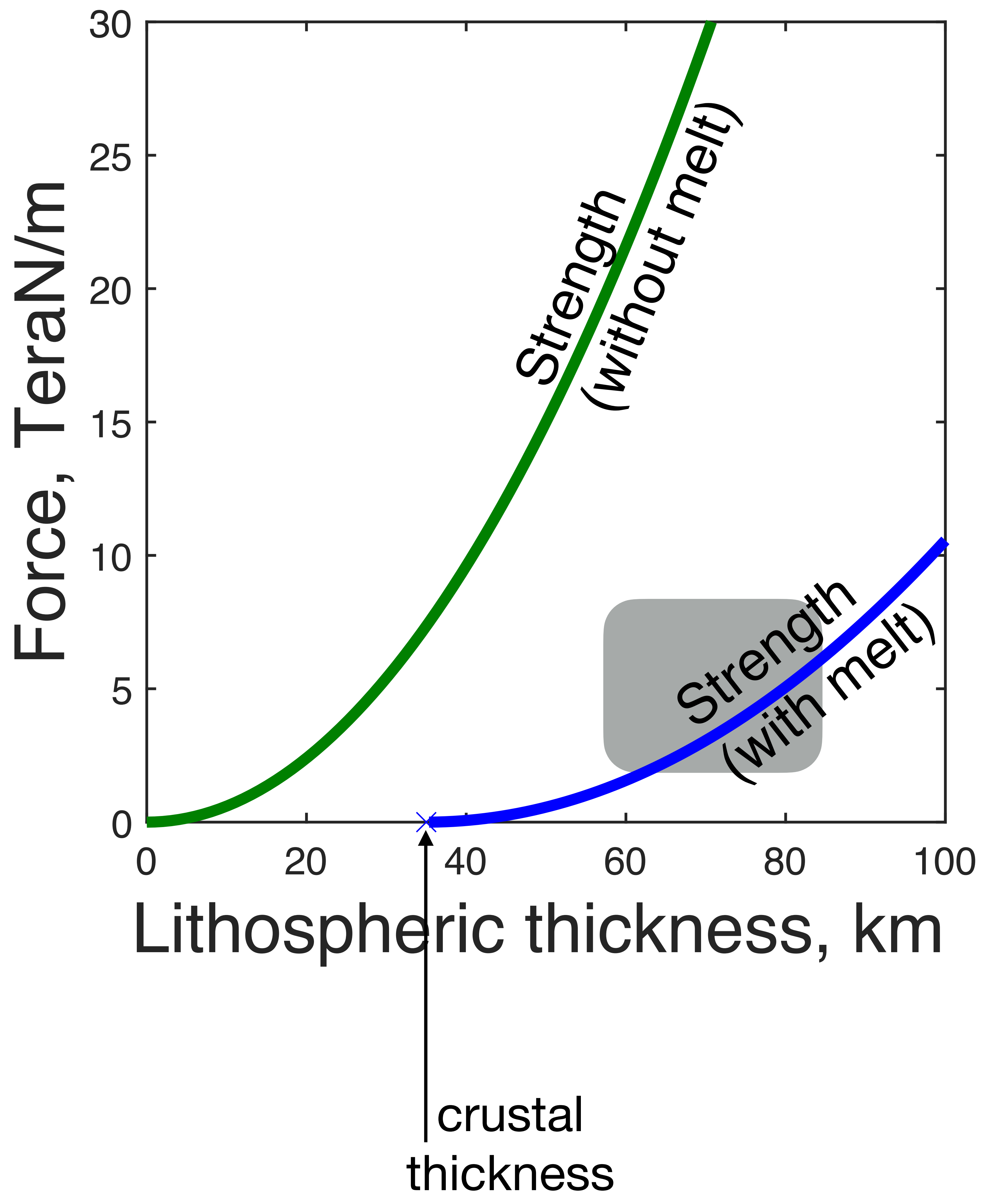
$\rho_f \approx \rho_c < \rho_m$ Buoyant magma

Buck 2006

Magma reduces the stress required for rifting







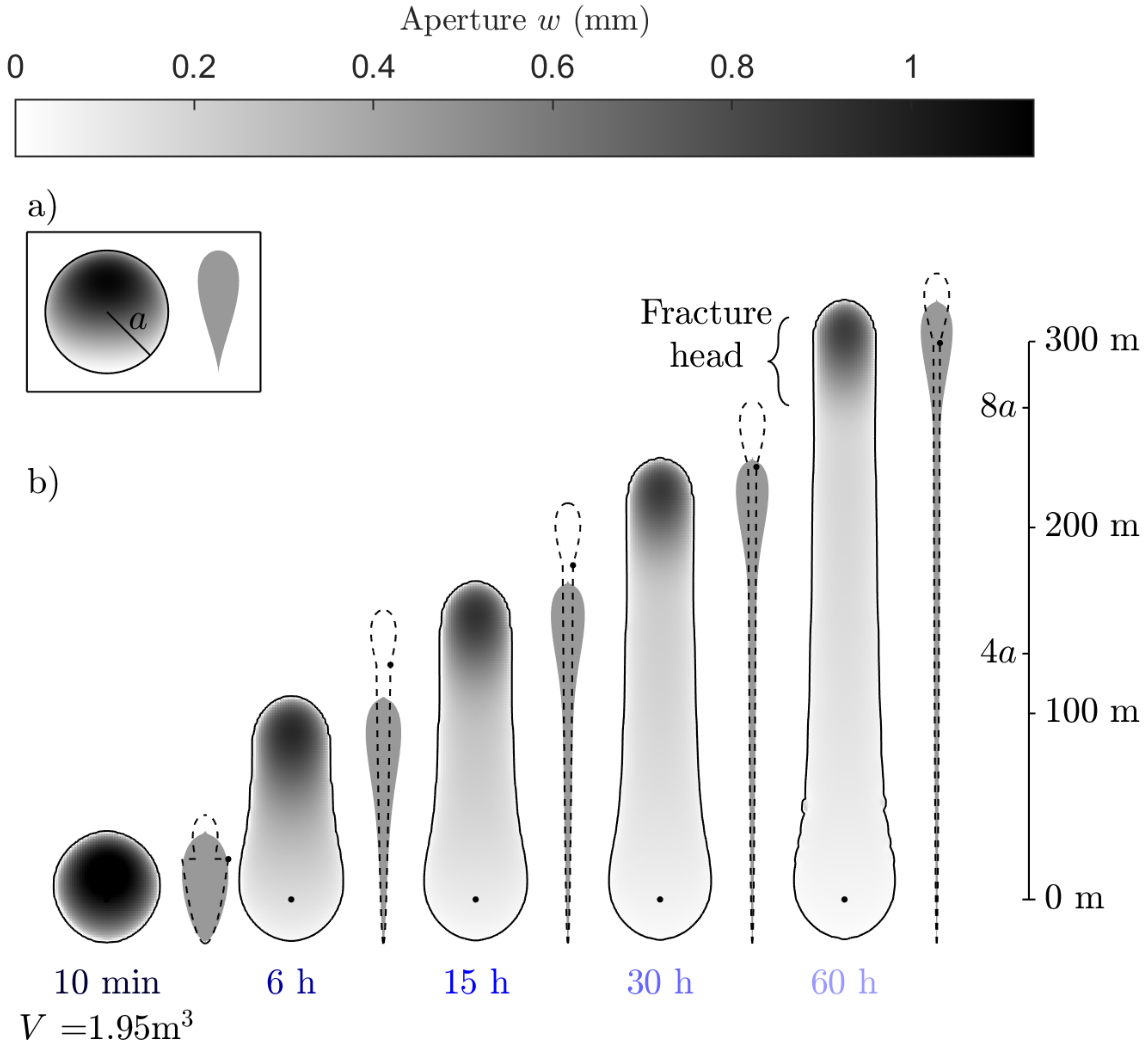
Assume zero cohesion (fracture toughness)

$$F = \Delta\mathrm{GPE} = \int_{-L}^{0} [\rho_f - \rho_{\mathrm{lith}}(z)] g z \, \mathrm{d}z$$

$\rho_f \approx \rho_c < \rho_m$ Buoyant magma

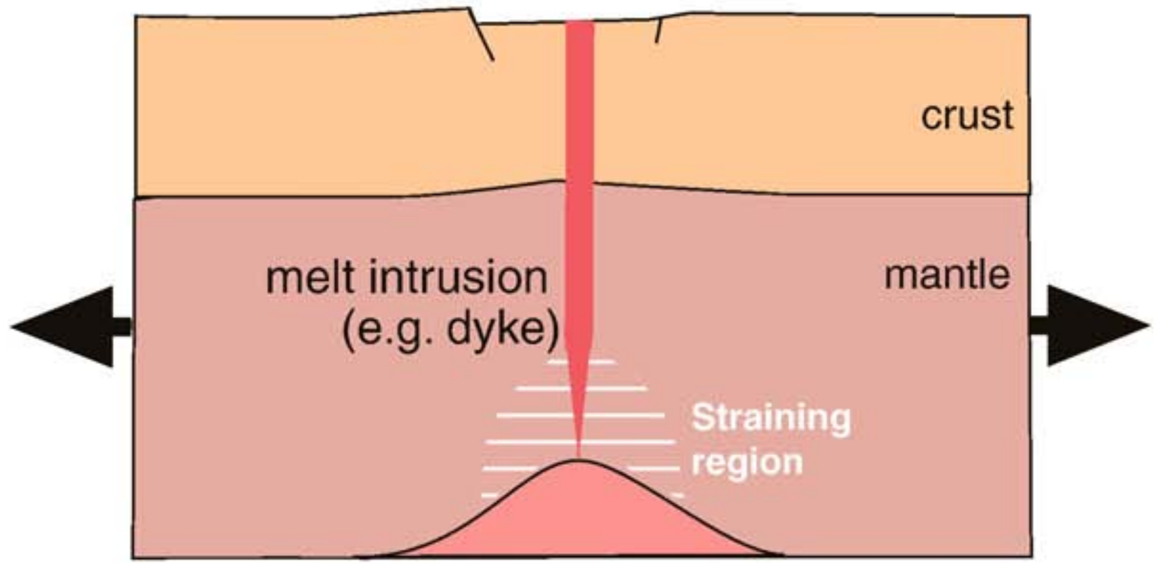
Buck 2006

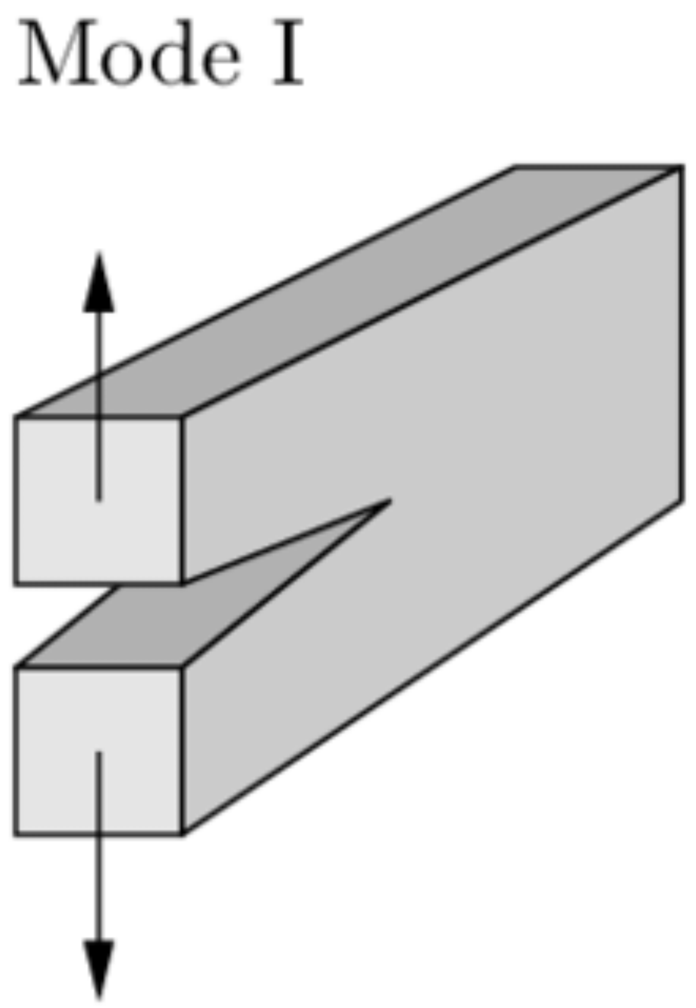
Fluid-driven fracture (e.g., hydrofracture)

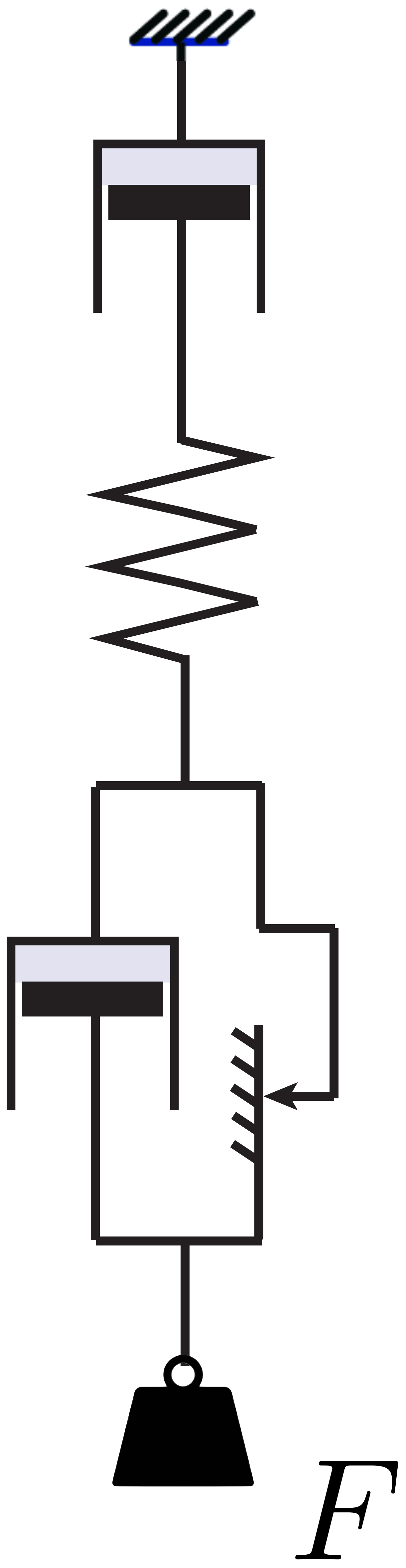


Davis et al *JFM* 2023

Using plasticity to represent dikes?







dashpot representing *creep deformation*

extends at a rate $\propto F$

spring representing *elastic deformation*

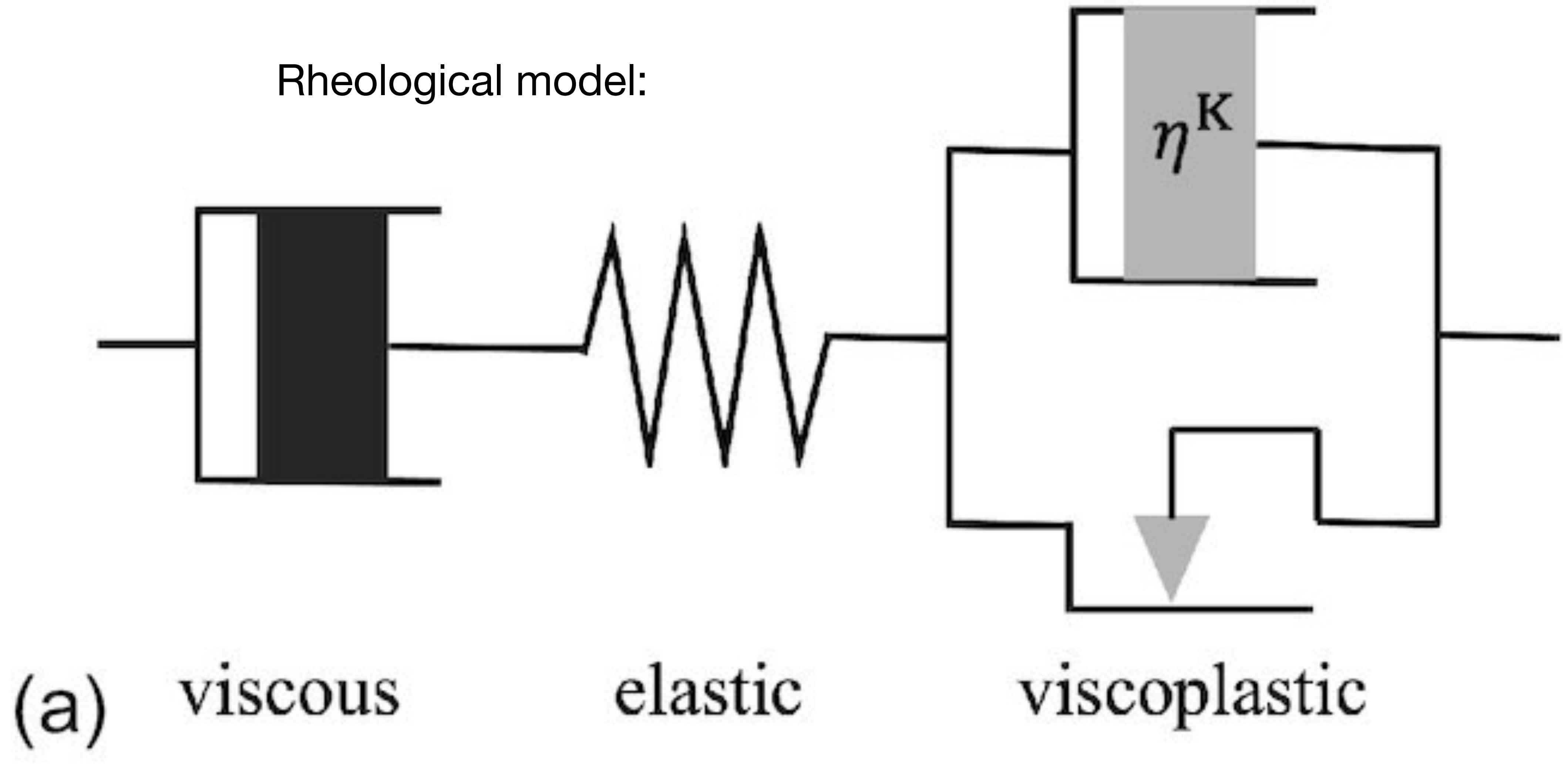
extends by an amount $\propto F$

slider representing *fracture and frictional slip*

extends if $F > F_{\text{crit}}$
(at a rate determined by dashpot)

A poro-viscoelastic—viscoplastic model of diking, faulting & rifting

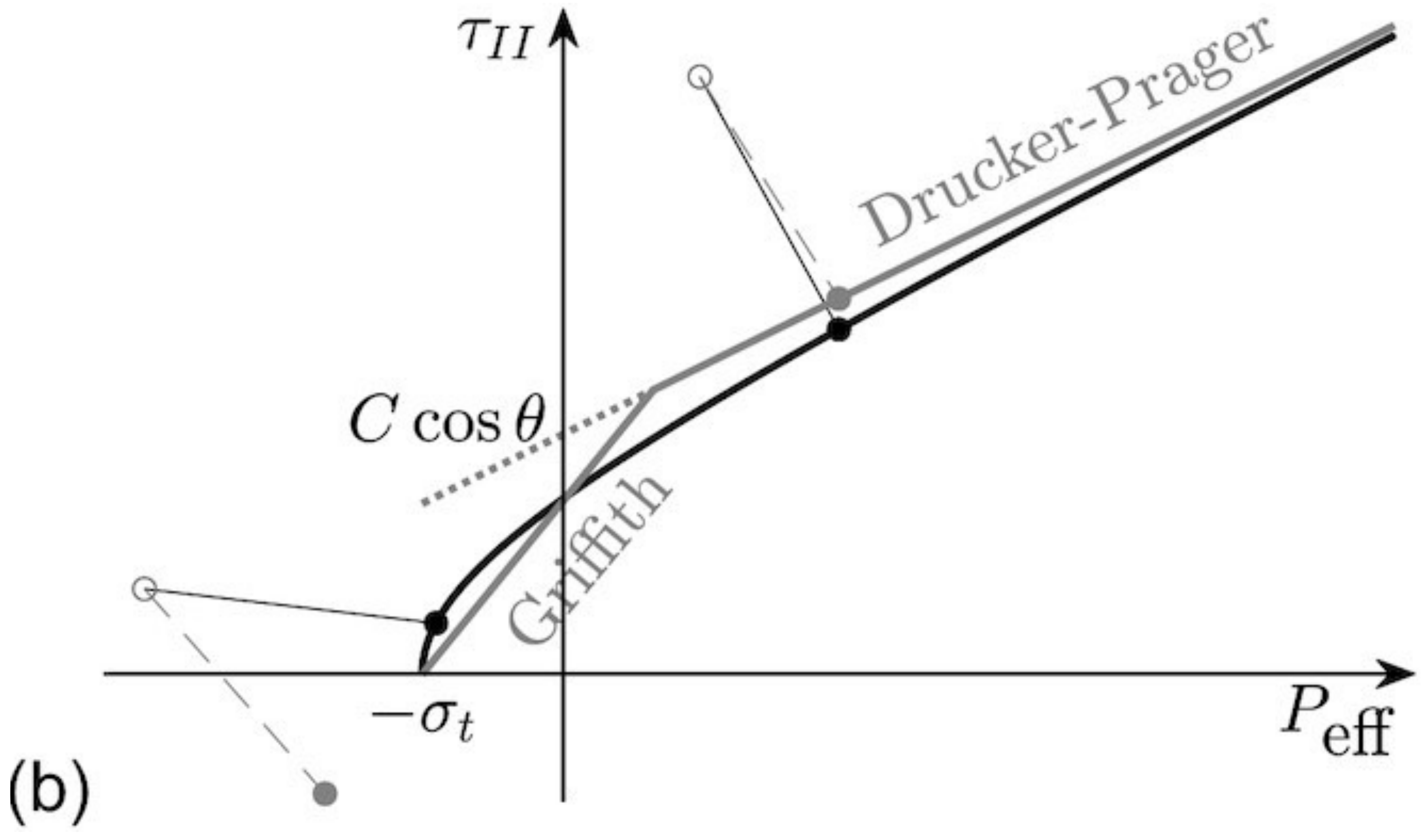
Rheological model:



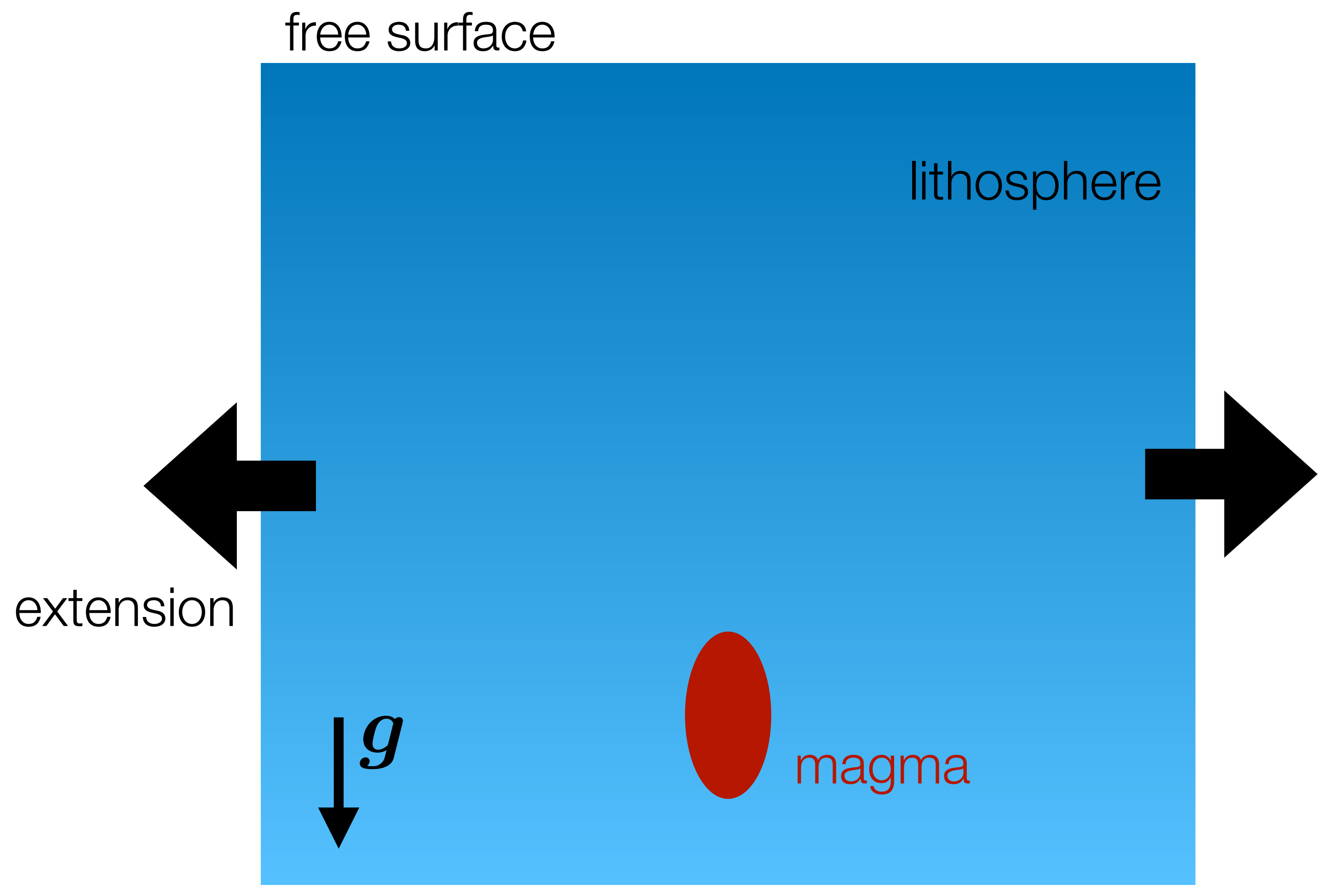
3 cases:

$$\eta_K = \begin{cases} 10^{21} \text{ Pa s} \\ 10^{20} \text{ Pa s} \\ 10^{19} \text{ Pa s} \end{cases}$$

Plastic failure envelope:

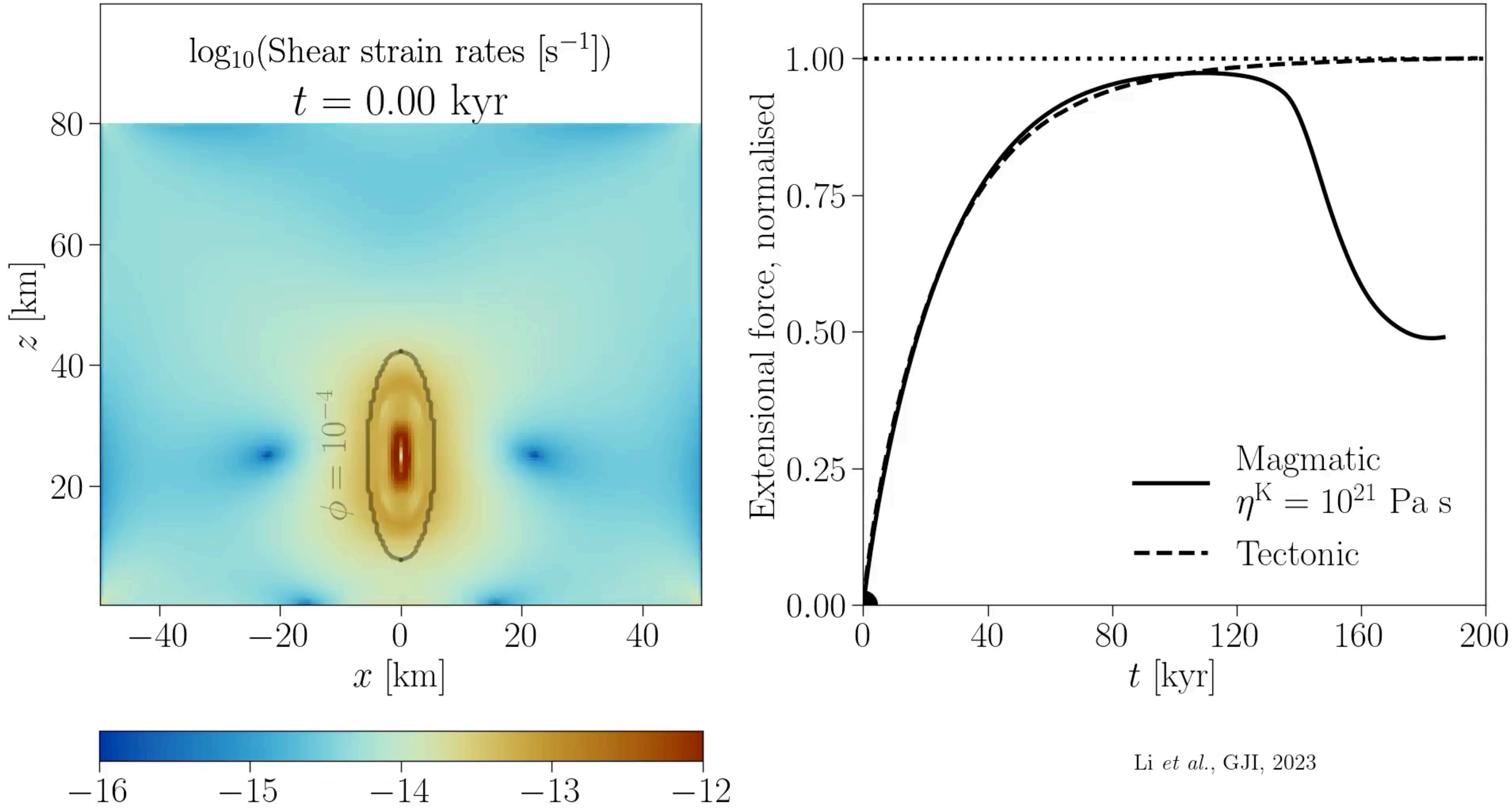


Model set-up:



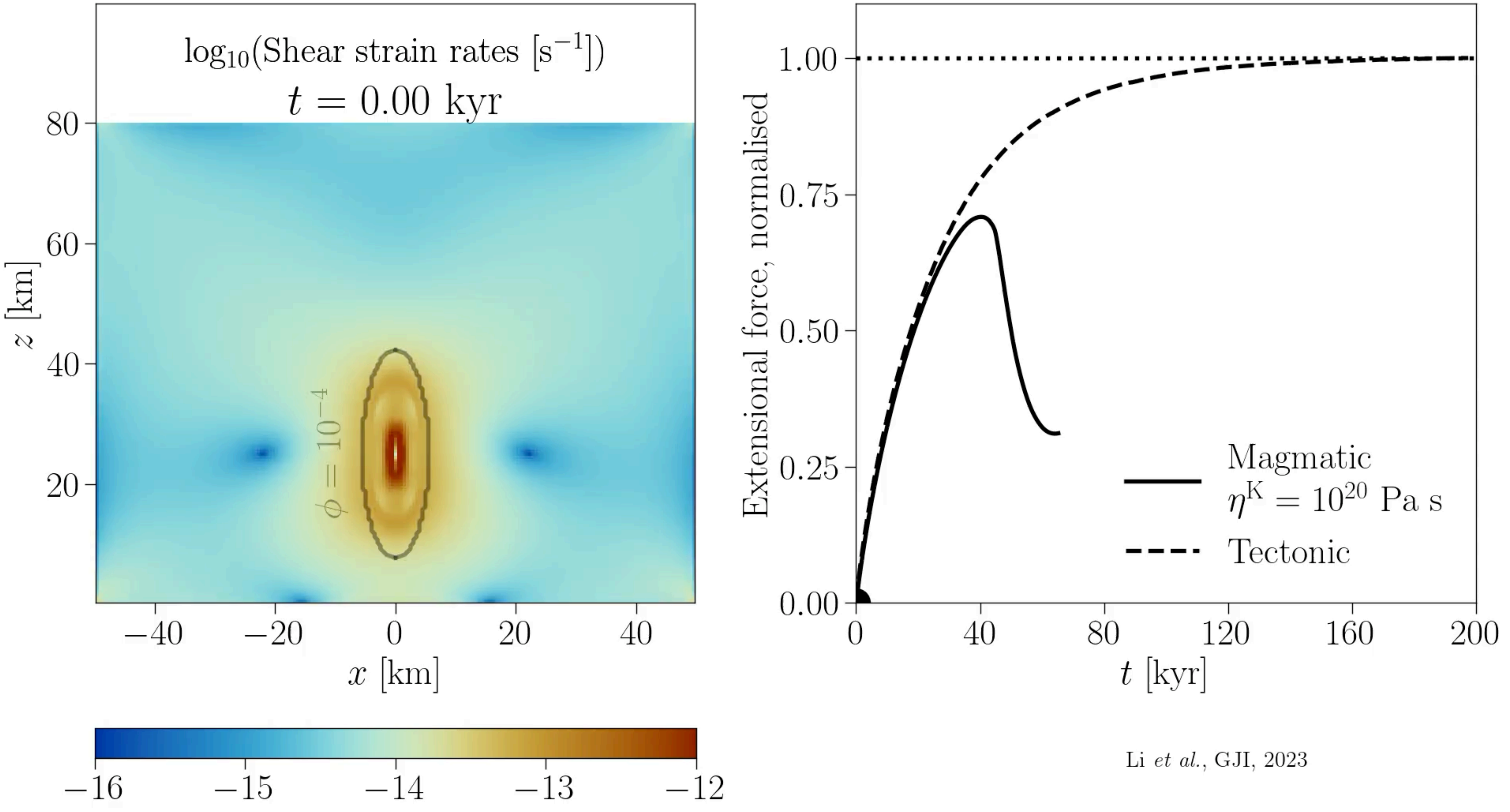
Li et al *GJI* 2023

A poro-viscoelastic—viscoplastic model of diking, faulting & rifting



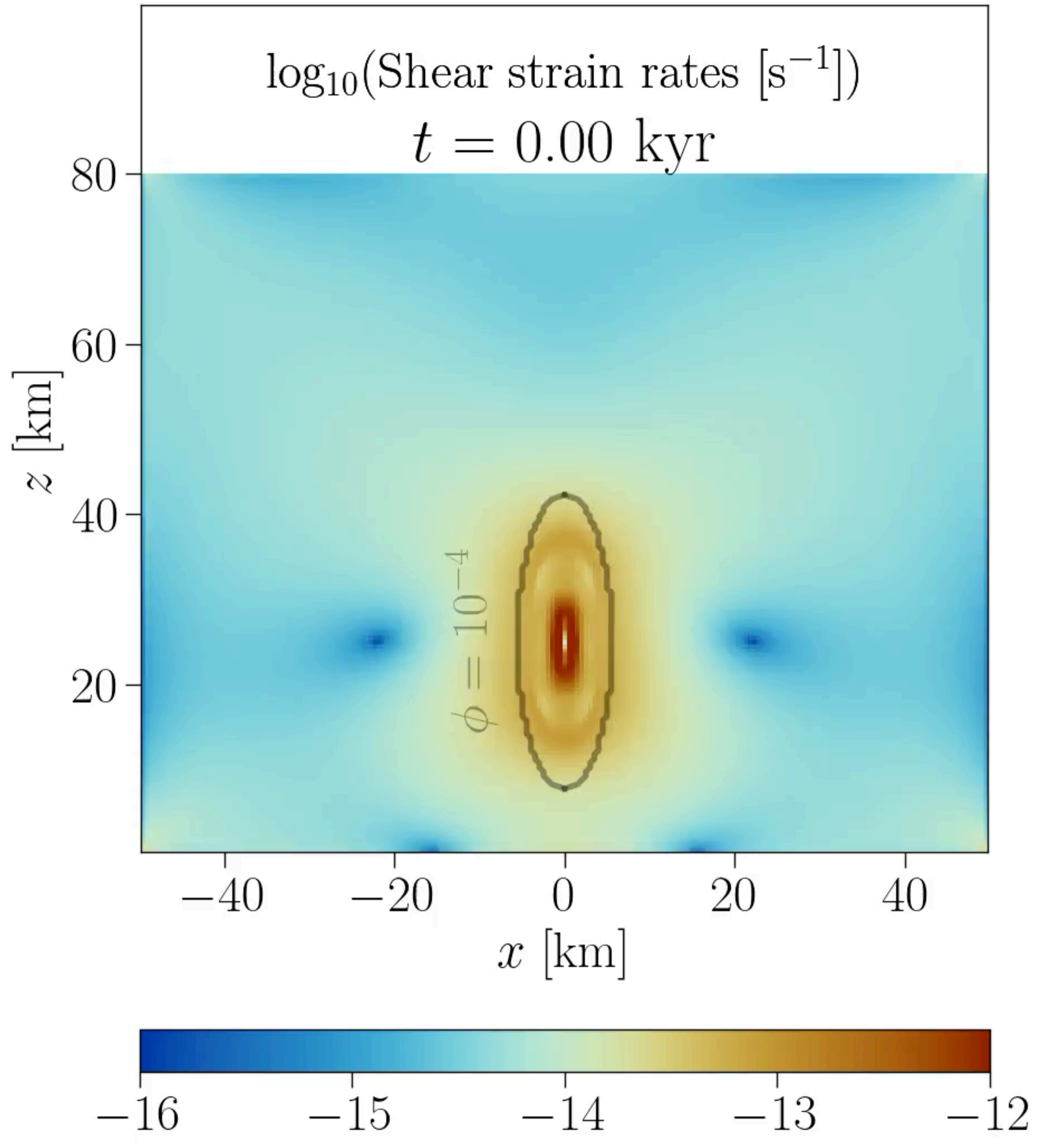
Li *et al.*, GJI, 2023

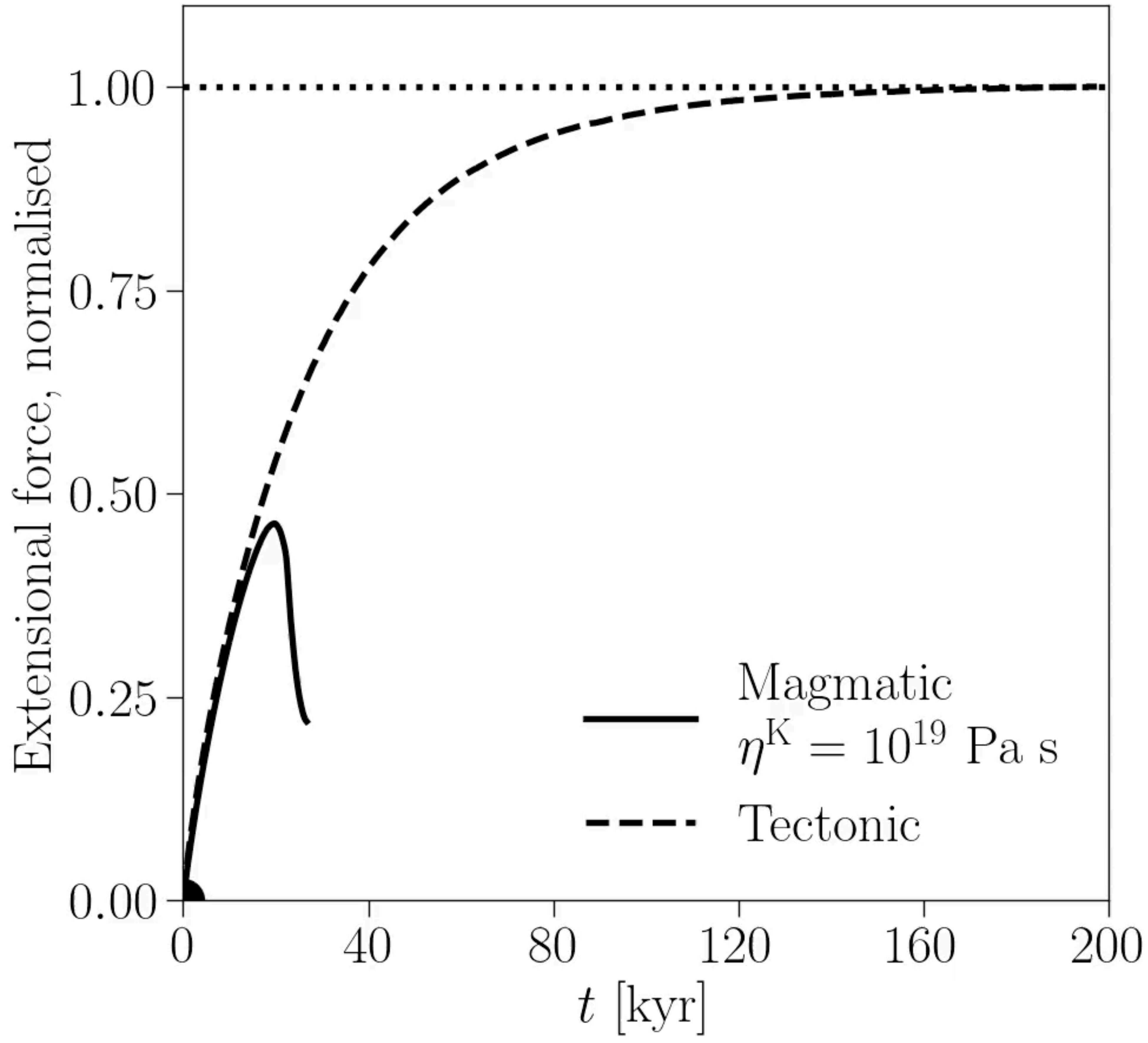
A poro-viscoelastic—viscoplastic model of diking, faulting & rifting



Li *et al.*, GJI, 2023

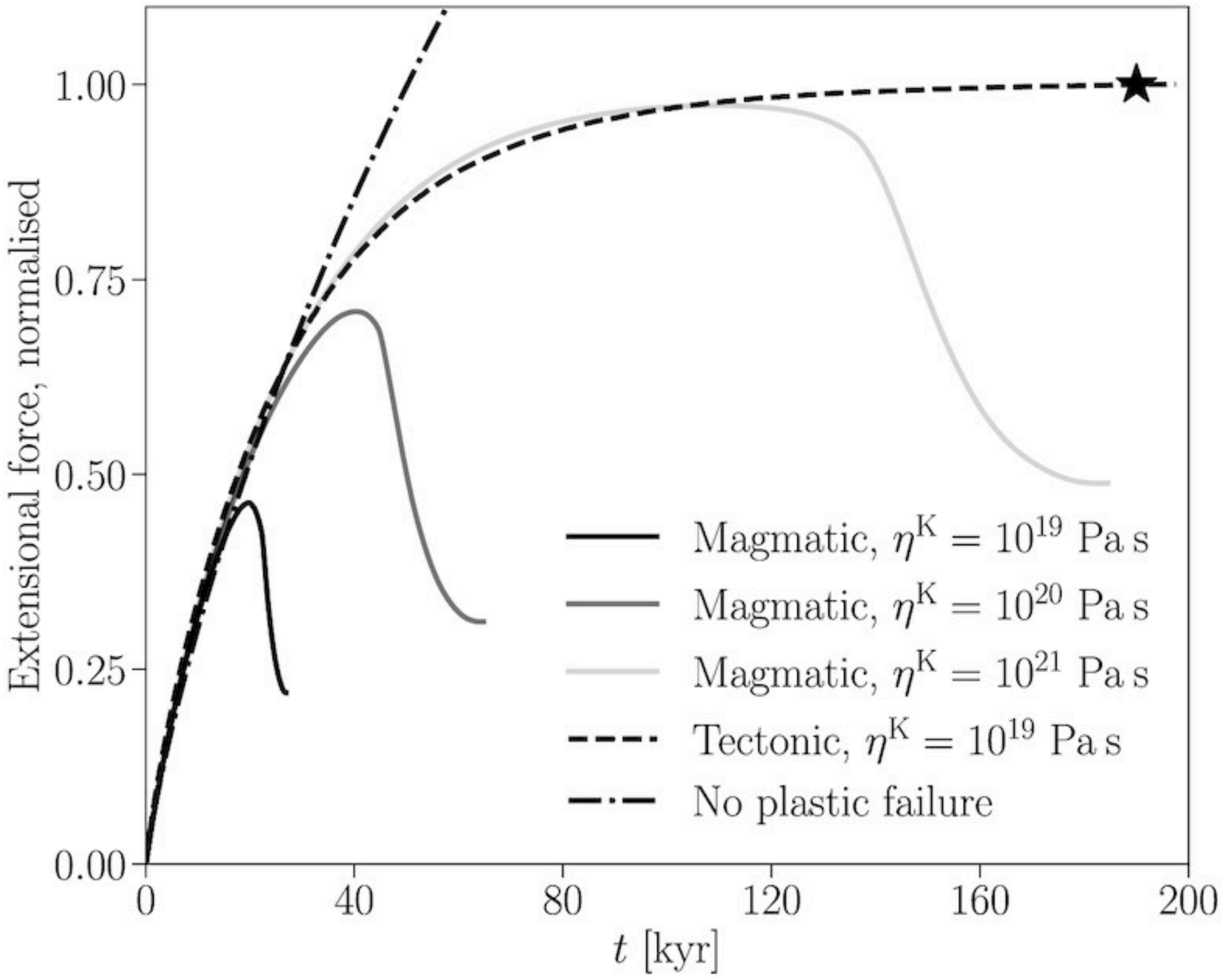
A poro-viscoelastic—viscoplastic model of diking, faulting & rifting



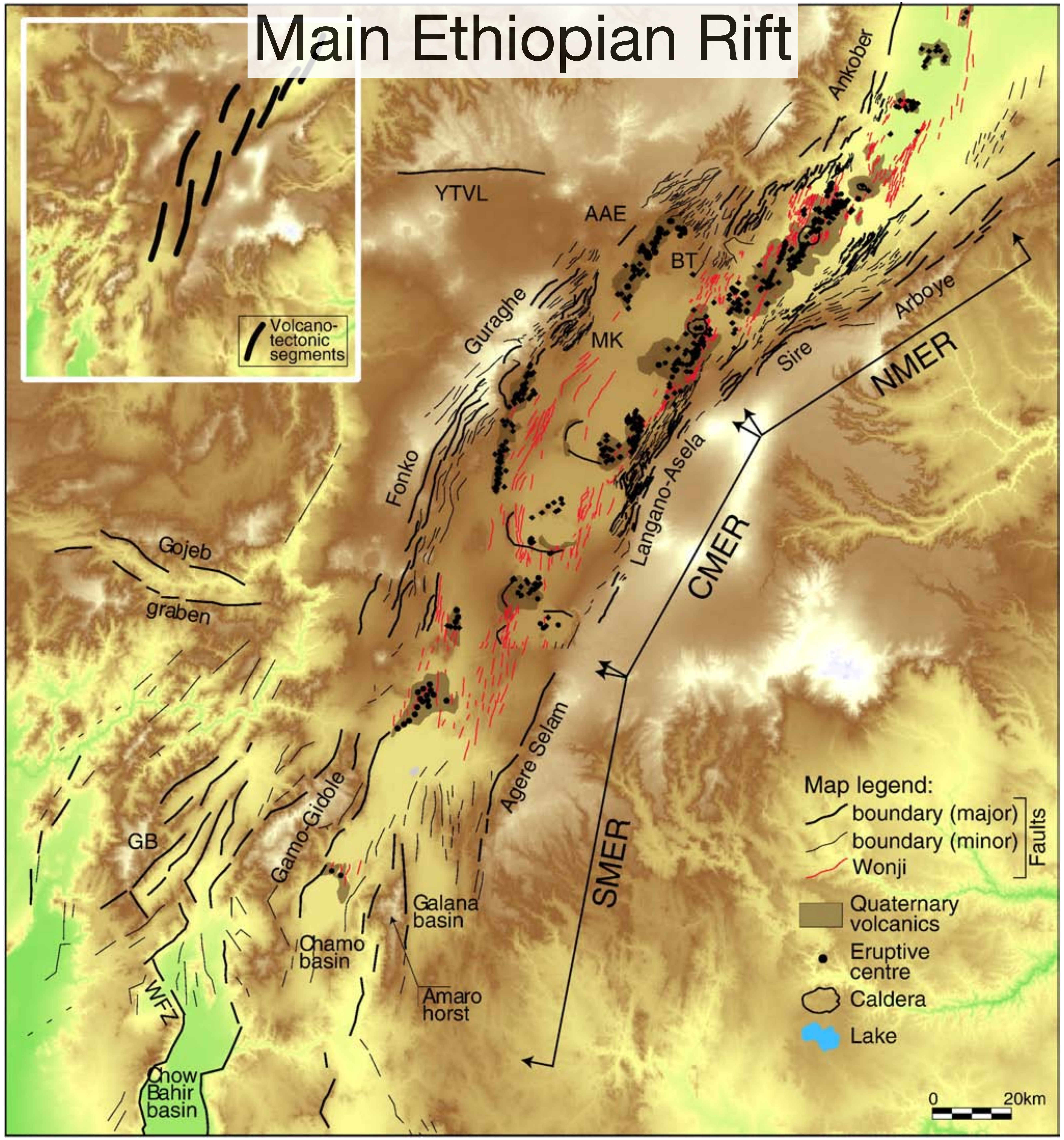


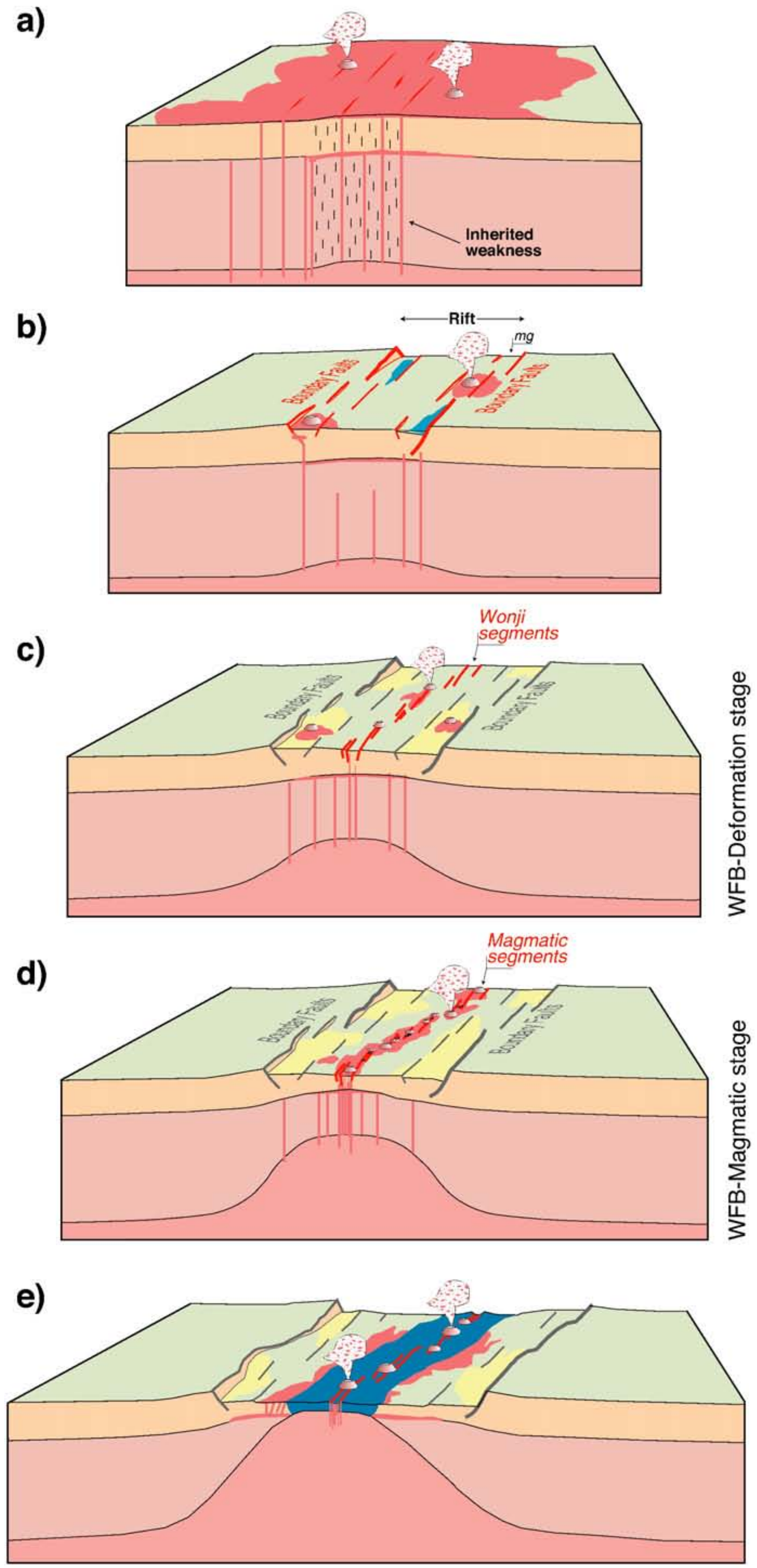
Li *et al.*, GJI, 2023

The force for magmatic rifting



Li et al *GJI* 2023





Ebinger 2005, Corti 2009, Boccaletti et al 1998, Casey *et al* 2006

Summary and questions

- Earth is a *thermal engine* that converts heat (radiogenic, primordial) into work by *convection*.
- Plate tectonics is the surface expression of mantle convection.
- Continents rift under the convective forces of slab pull, topographic/GPE gradients, and basal drag.
- Tectonic forces are of order 10 TN/m.
- Why do rocks yield and what do they remember of past yielding? What is mechanical role of magma at rifts and mid-ocean ridges? How do faults and dikes interact mechanically?