Subduction Dynamics: From Initiation to Maturity

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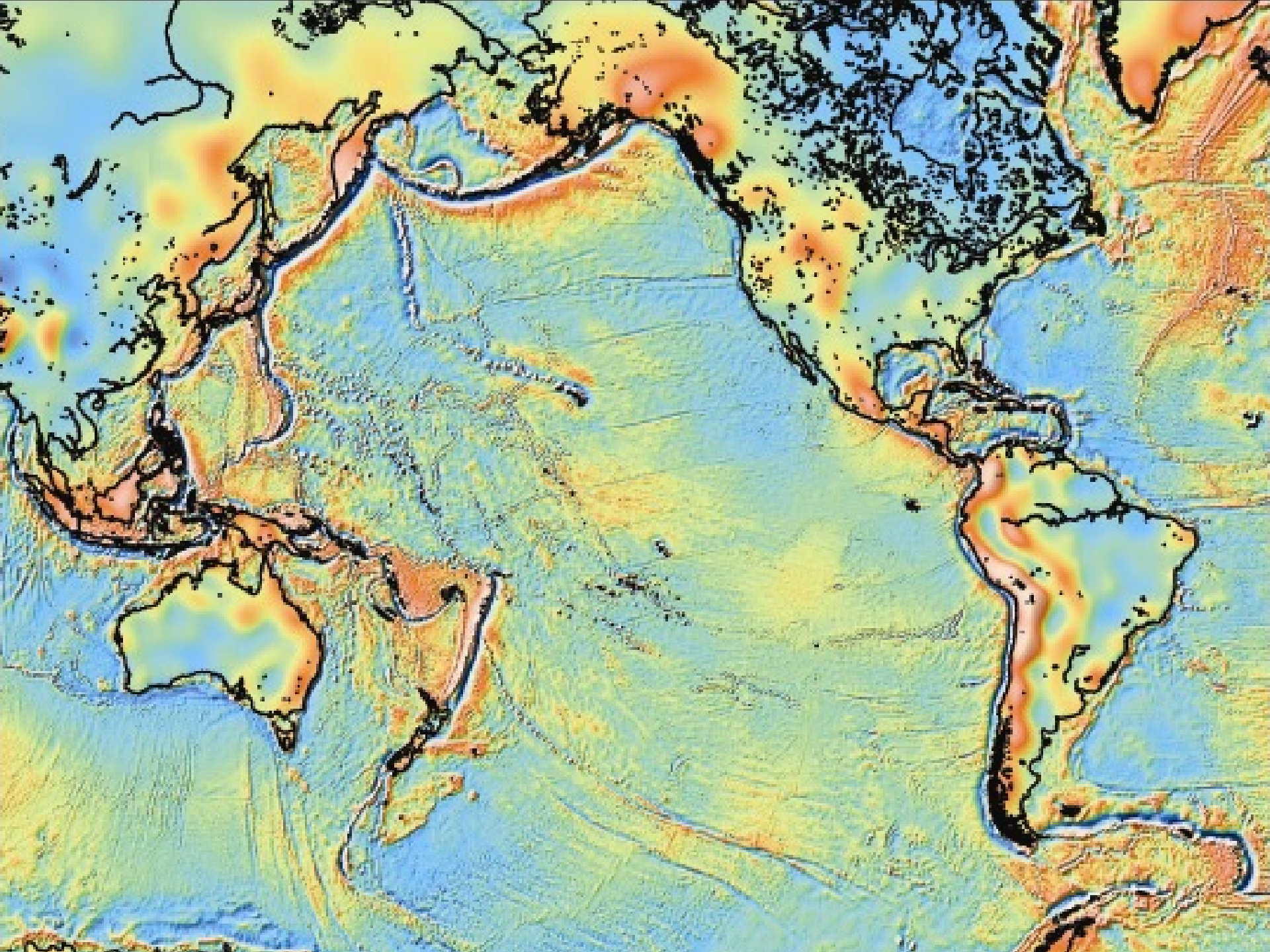
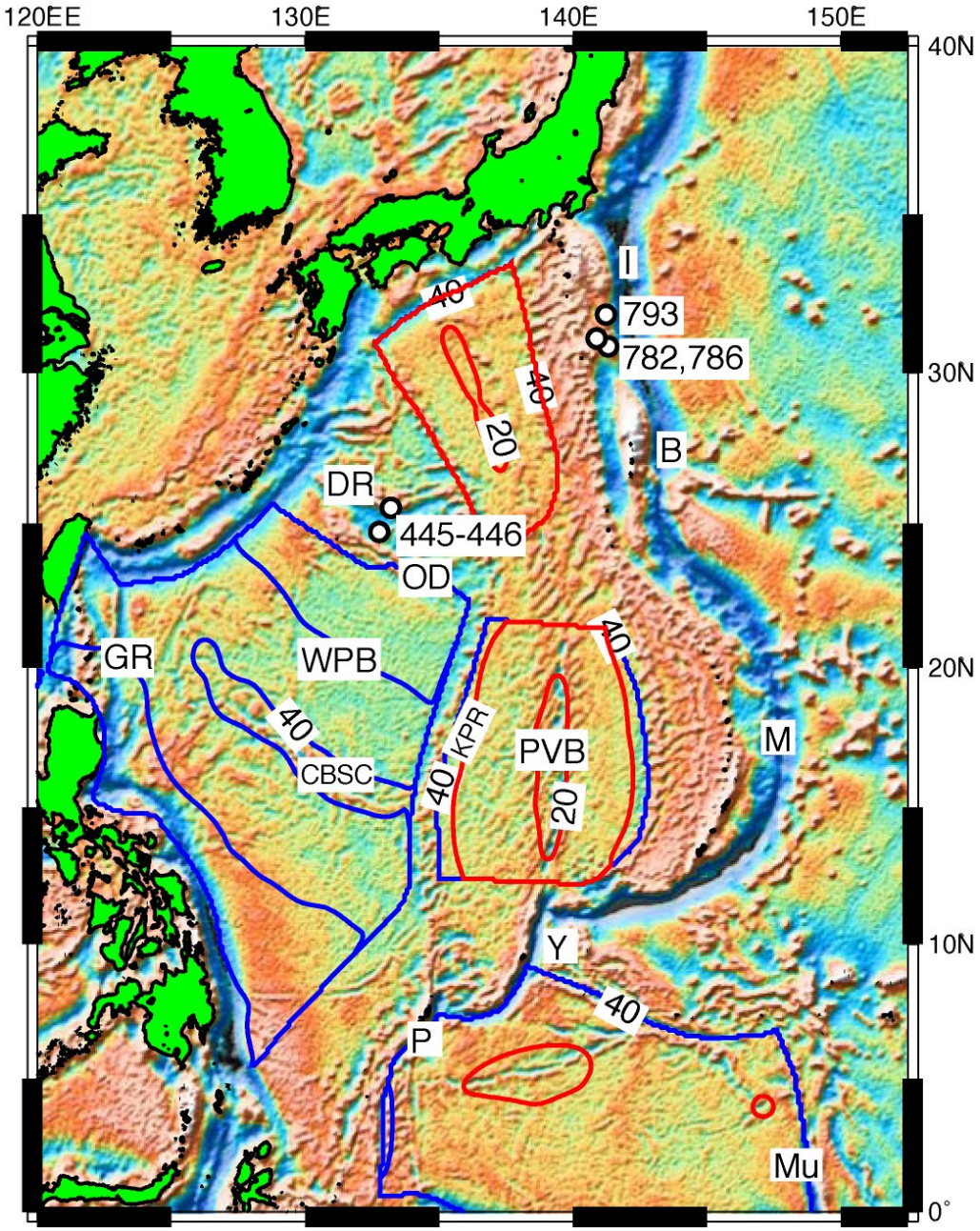
Caltech

Mantle Convection Workshop, June, 2005

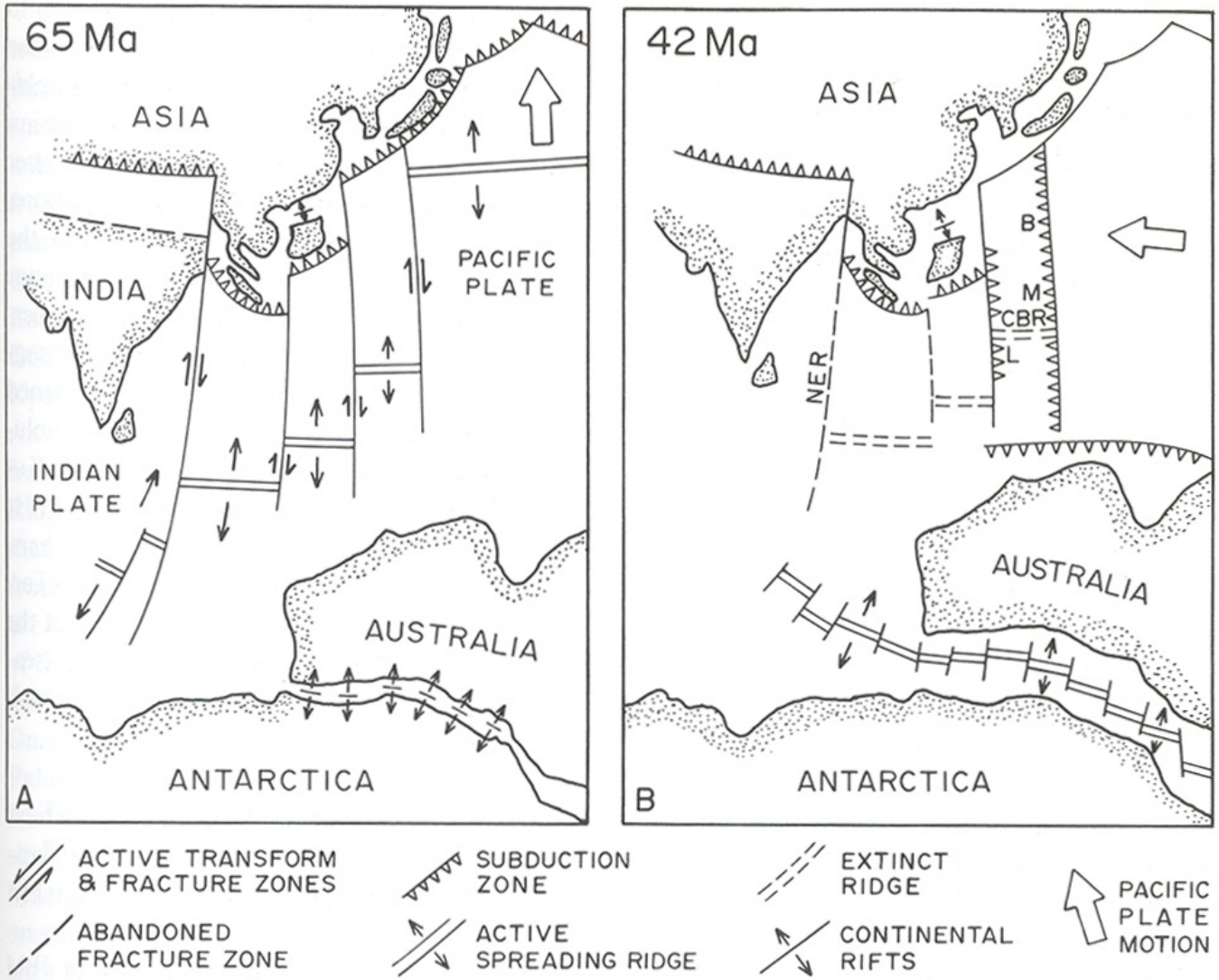
Outline

- Empirically: What's important for this problem
- Visco-elastoplastic models of transform faults & subduction initiation
  - Chad Hall, Luc Lavier
- Some thoughts on software needed for the future
  - Frameworks: Eh Tan
  - Coupling scales: Eun-seo Choi
  - Micro physics coupling to large-scale: Laura Baker, Paula Smith, Chad Hall, Paul Asimow

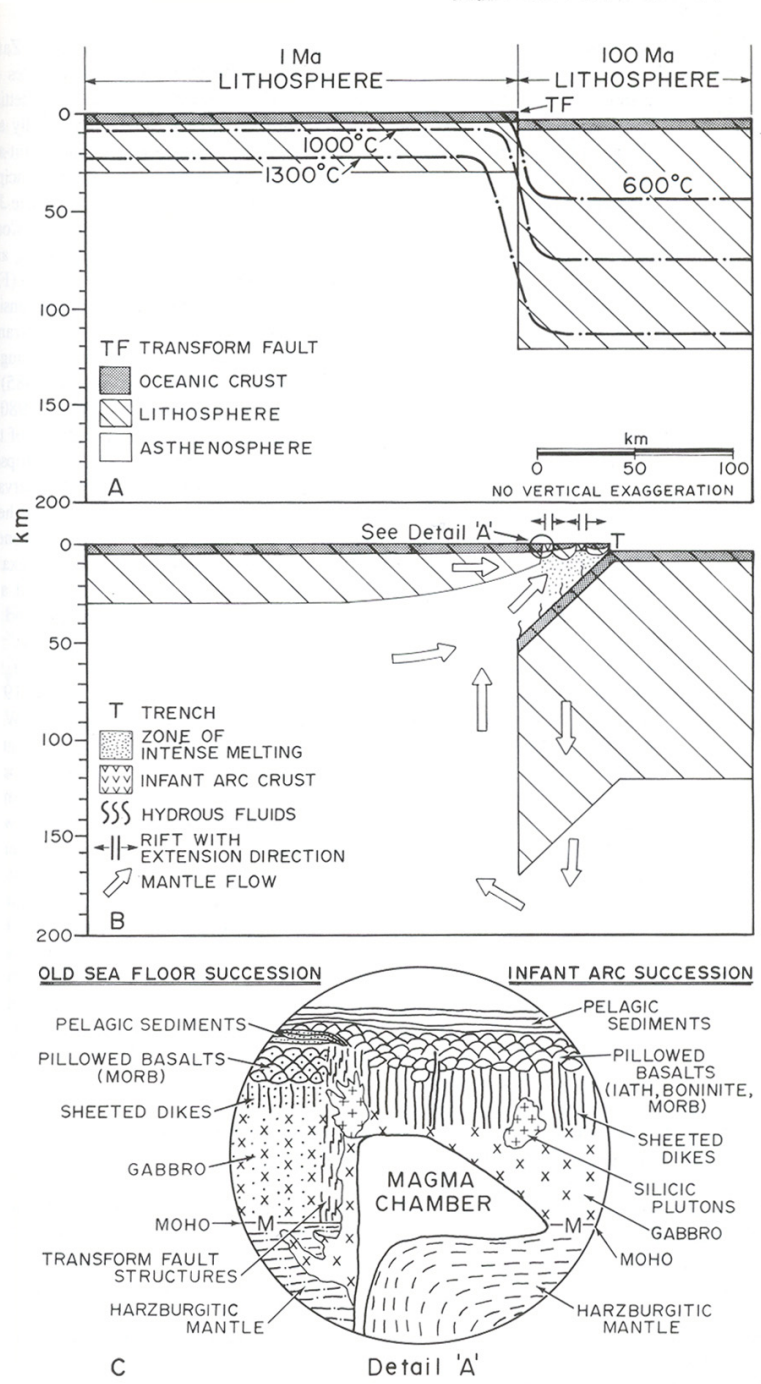



120EE
130E
140E
150E
40N
30N
20N
10N
0˚
I
793
782,786
B
DR
445-446
OD
GR
WPB
CBSC
KPR
PVB
M
Y
P
Mu
40
20

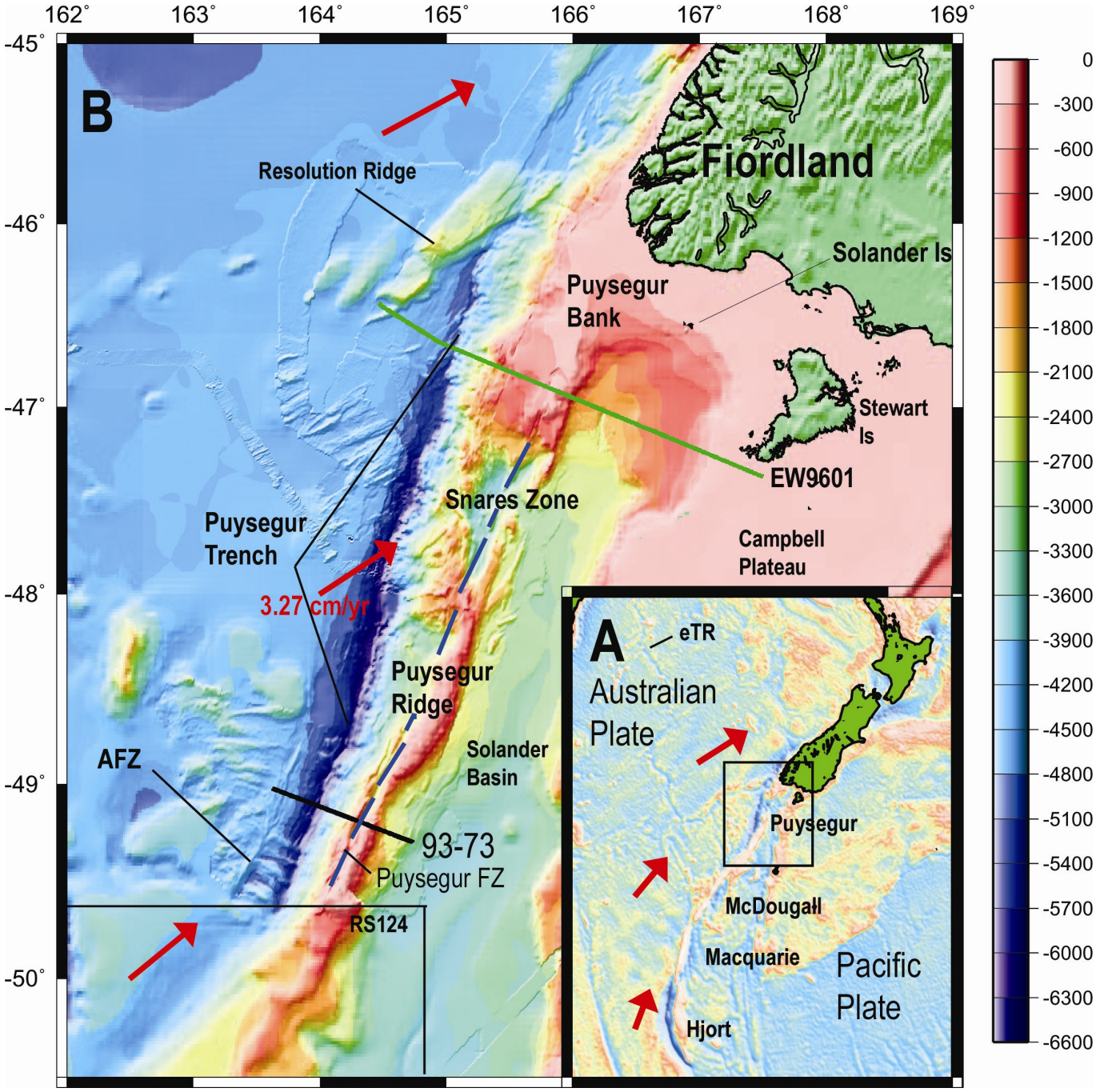
Evolutionary Model for the formation of the IBM



Originally
from
Hilde et al. [1977]
as modified by
Stern & Bloomer [1992].



Stern & Bloomer, 1992


B
Resolution Ridge
Fiordland
Solander Is
Puysegur
Bank
Stewart
Is
EW9601
Snares Zone
Puysegur
Trench
3.27 cm/yr
Campbell
Plateau
Puysegur
Ridge
Solander
Basin
AFZ
93-73
Puysegur FZ
RS124
A
eTR
Australian
Plate
Puysegur
McDougall
Macquarie
Pacific
Plate
Hjort
162°
163°
164°
165°
166°
167°
168°
169°
-45°
-46°
-47°
-48°
-49°
-50°
0
-300
-600
-900
-1200
-1500
-1800
-2100
-2400
-2700
-3000
-3300
-3600
-3900
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-4500
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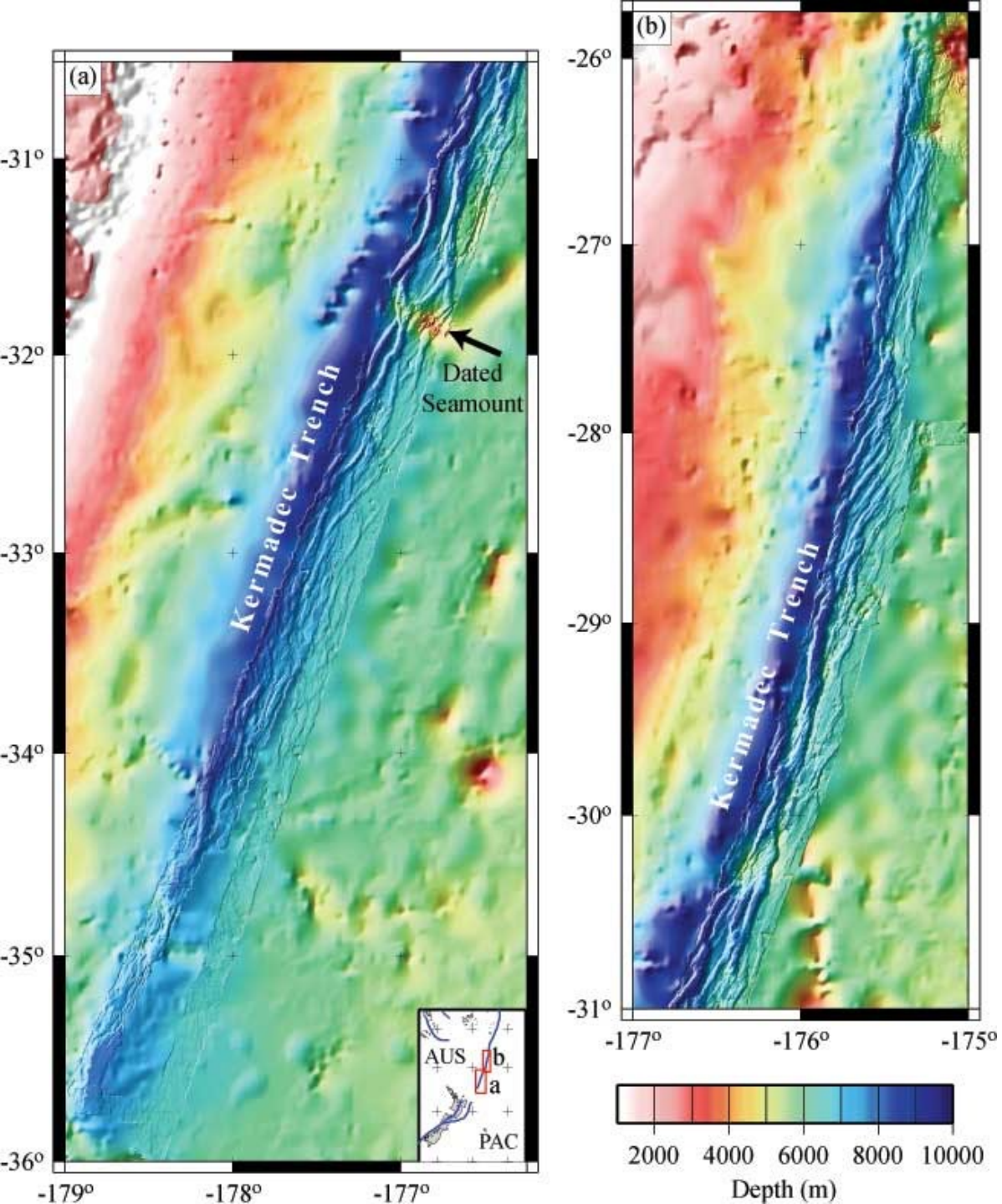
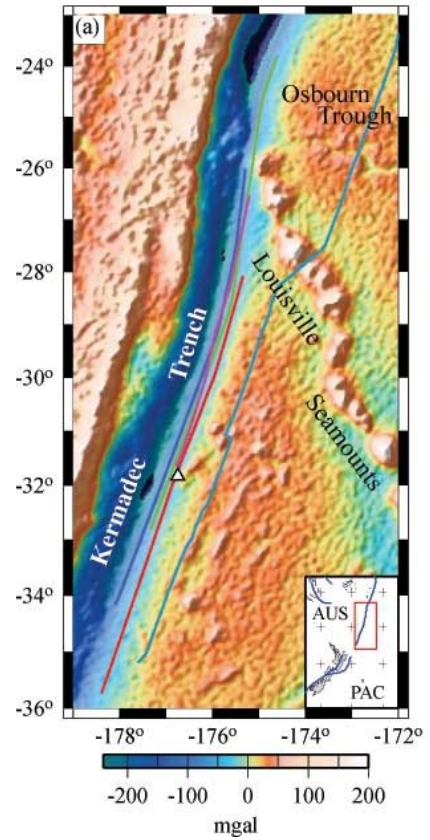
-6000
-6300
-6600



Billen & Gurnis, 2005



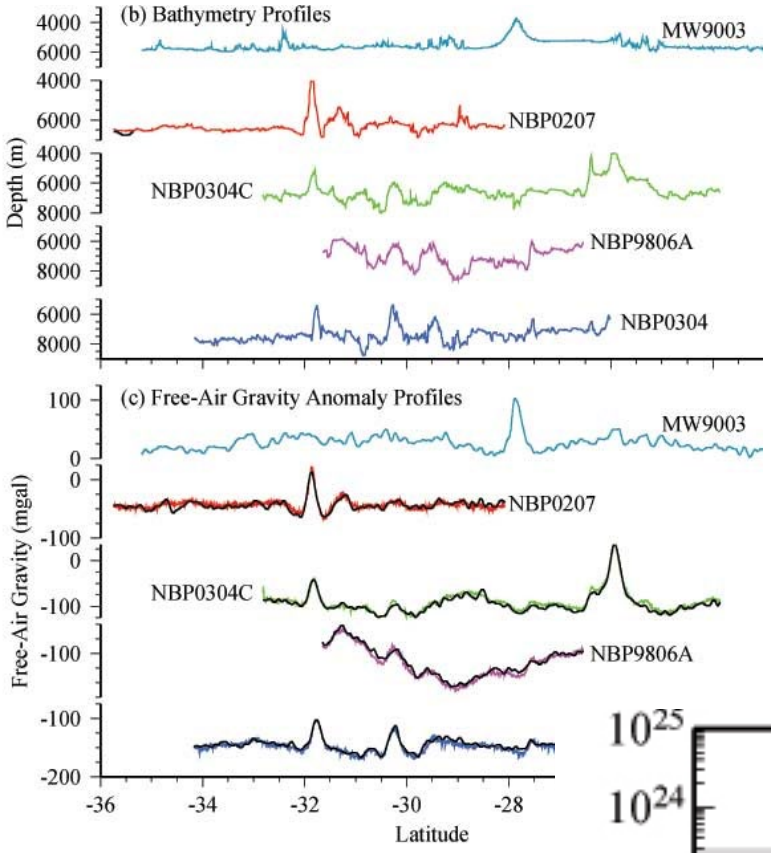
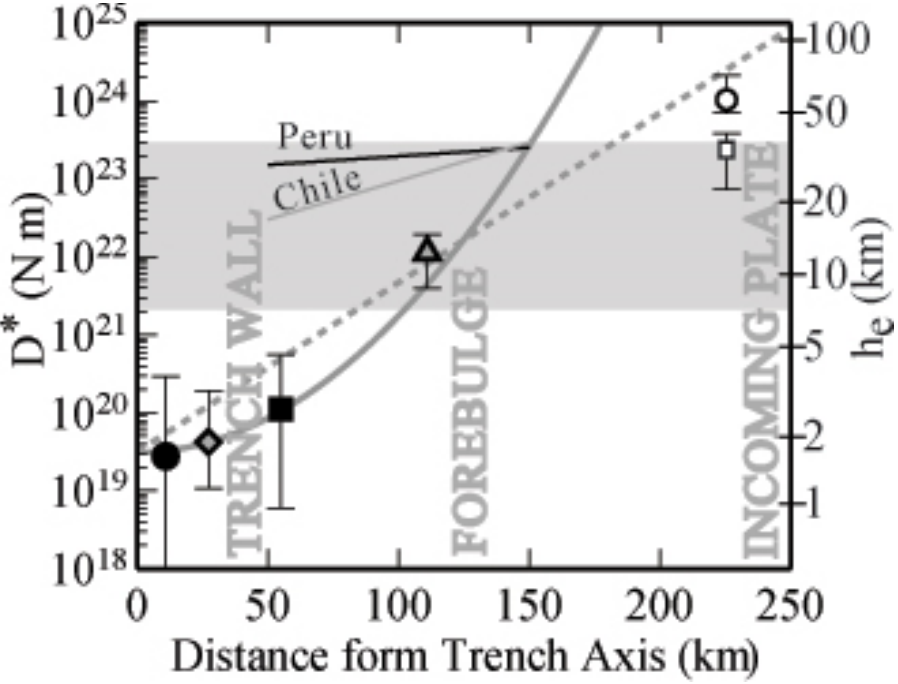
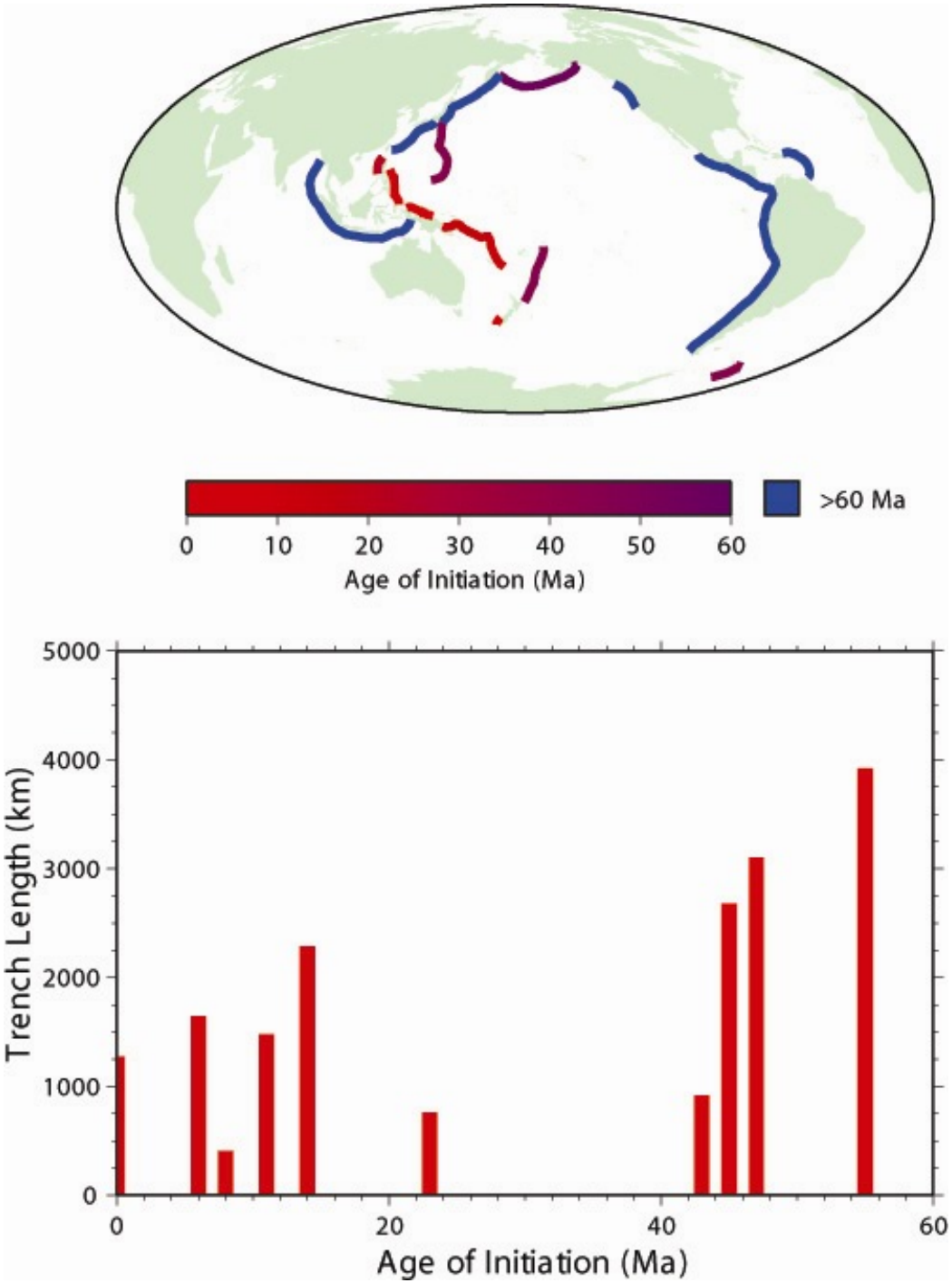


Plate has nearly lost all strength in the trench



Billen & Gurnis, 2005



Gurnis et al. 2004

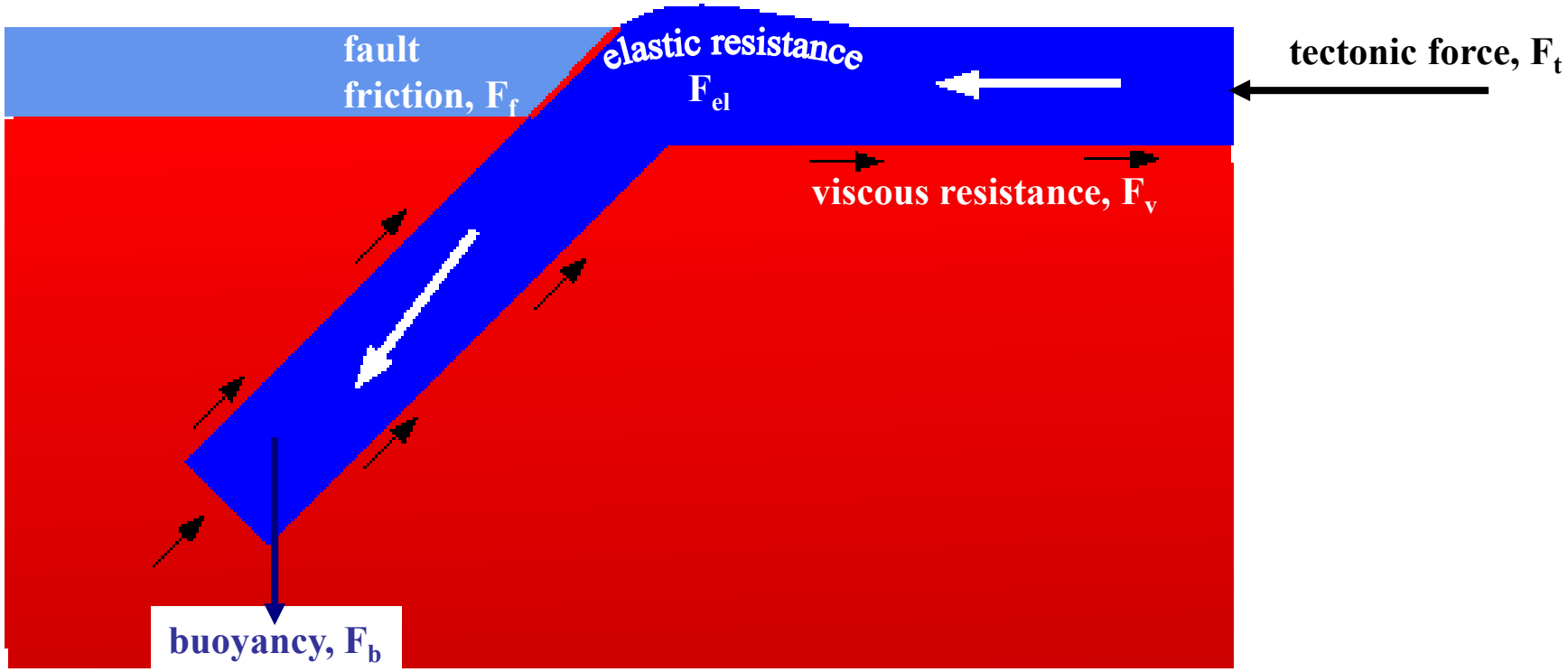
Time-scale of subduction initiation

- ~50% of known subduction zones initiated since early Cenozoic
- Time-scale for creating new subduction zones 10-100 Myr (τ_{SI})
- Age of oldest sea floor in Atlantic ~ 180Ma (τ_{atl})
- Time-scale for continental rearrangements 250-500 Myr (τ_{mc})
- $\tau_{SI} < \tau_{atl}$; $\tau_{SI} << \tau_{mc}$

Take home messages for subduction initiation

- 50% of SZ initiatiated since early Cenozoic
- Elasticity is important during SI, but may not be so after transition to self-sustaining state
- Some subduction zones initiate at fracture zones and near old spreading centers
- Rapid extension could be important during self-nucleation (Stern model)

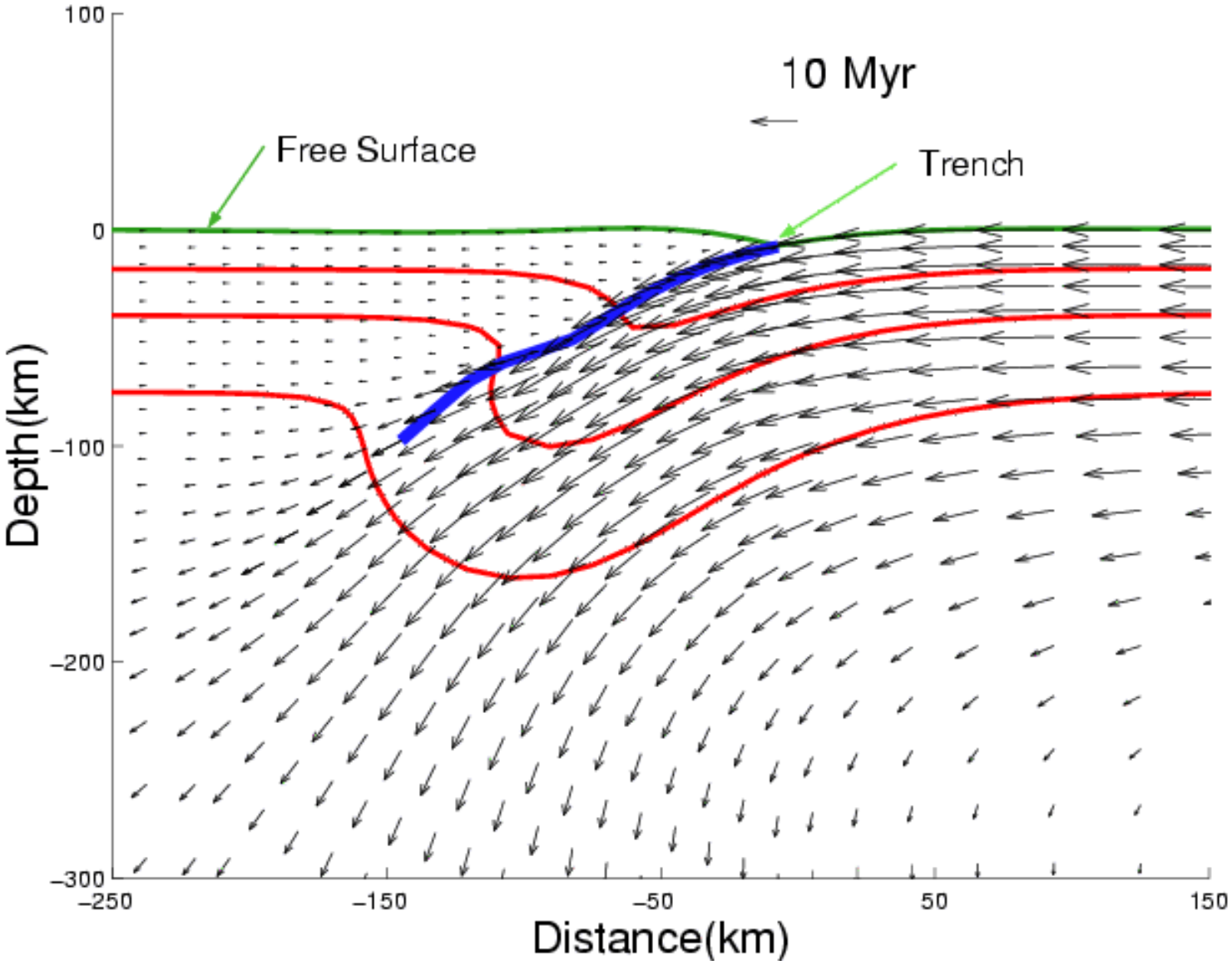
Subduction Dynamics: Driving & Resisting Forces



subduction occurs if

$$F_b + F_t > F_{el} + F_f + F_v$$

(modified from *McKenzie*, 1977)

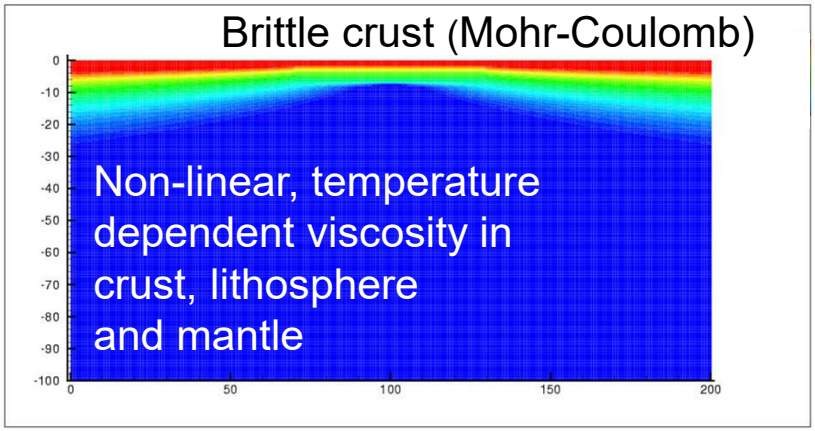


Toth & Gurnis, 1998

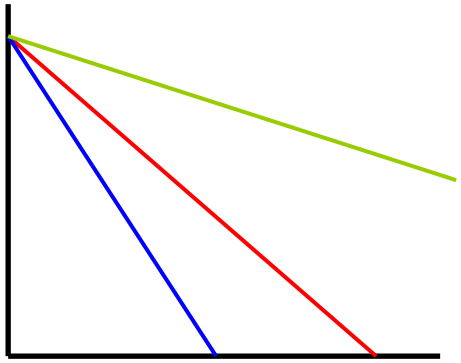
Visco-elastoplastic models of transform faults & subduction initiation

With Chad Hall & Luc Lavier

Use an explicit finite difference method to solve the force balance equation



C, ϕ



Plastic strain

A. Poliakov, Y. Podladchikov & Talbot [1993] Benchmarked method against Rayleigh-Taylor problem

Method akin to Fast Lagrangian Analysis of Continua (FLAC) [Poliakov and Buck, 1998; Lavier et al., 2000].

- Explict method
- Visco elasto-plastic material
- Track plastic strain
- Frequent regridding

Conceptual Basis

- FLAC (Cundall 1989)
  - Solve a force balance equation for each node

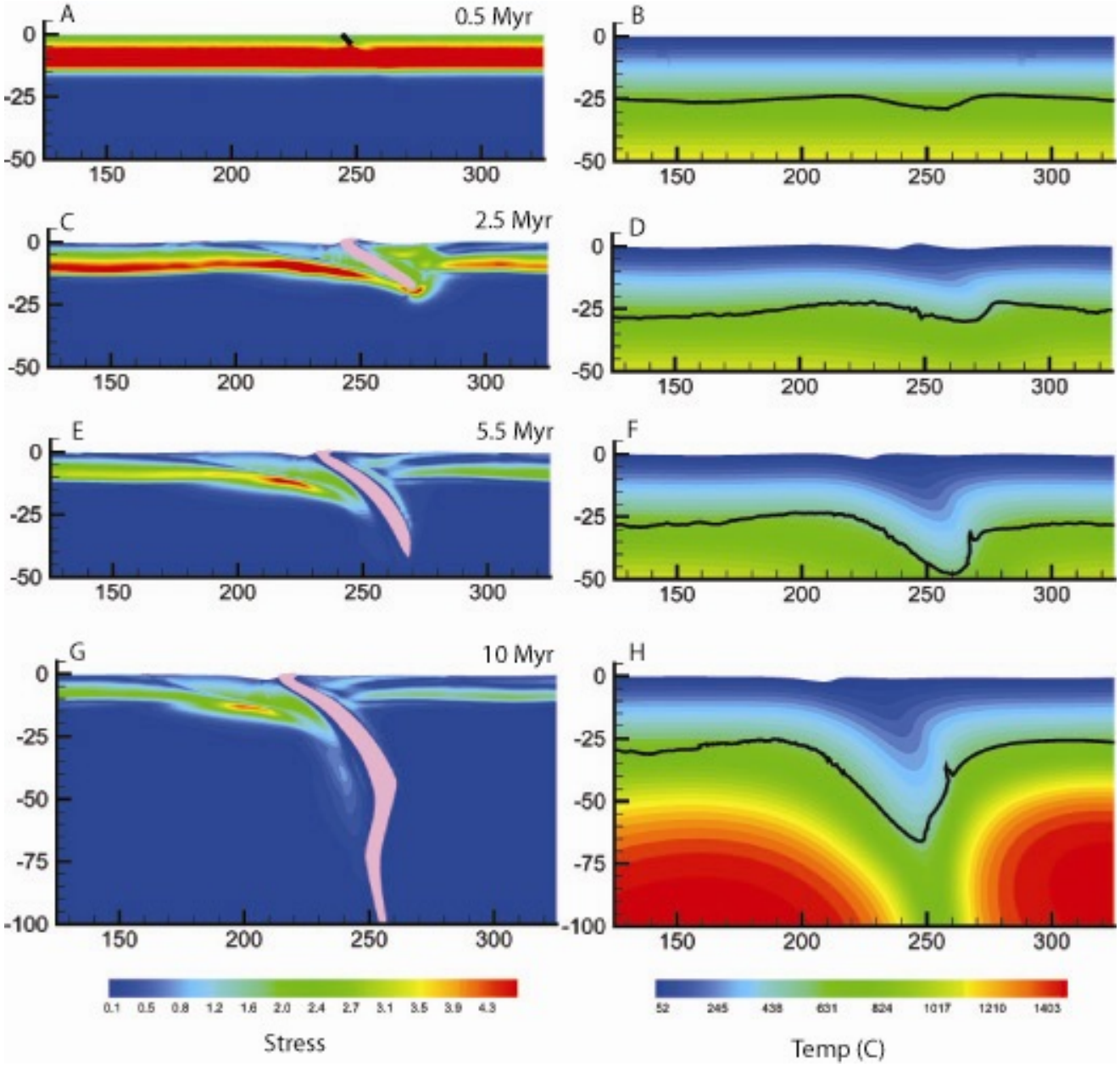
$$\frac{\partial v_i}{\partial t} = \frac{F_i}{M}, \; or \;\; \rho \frac{\partial v_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i$$

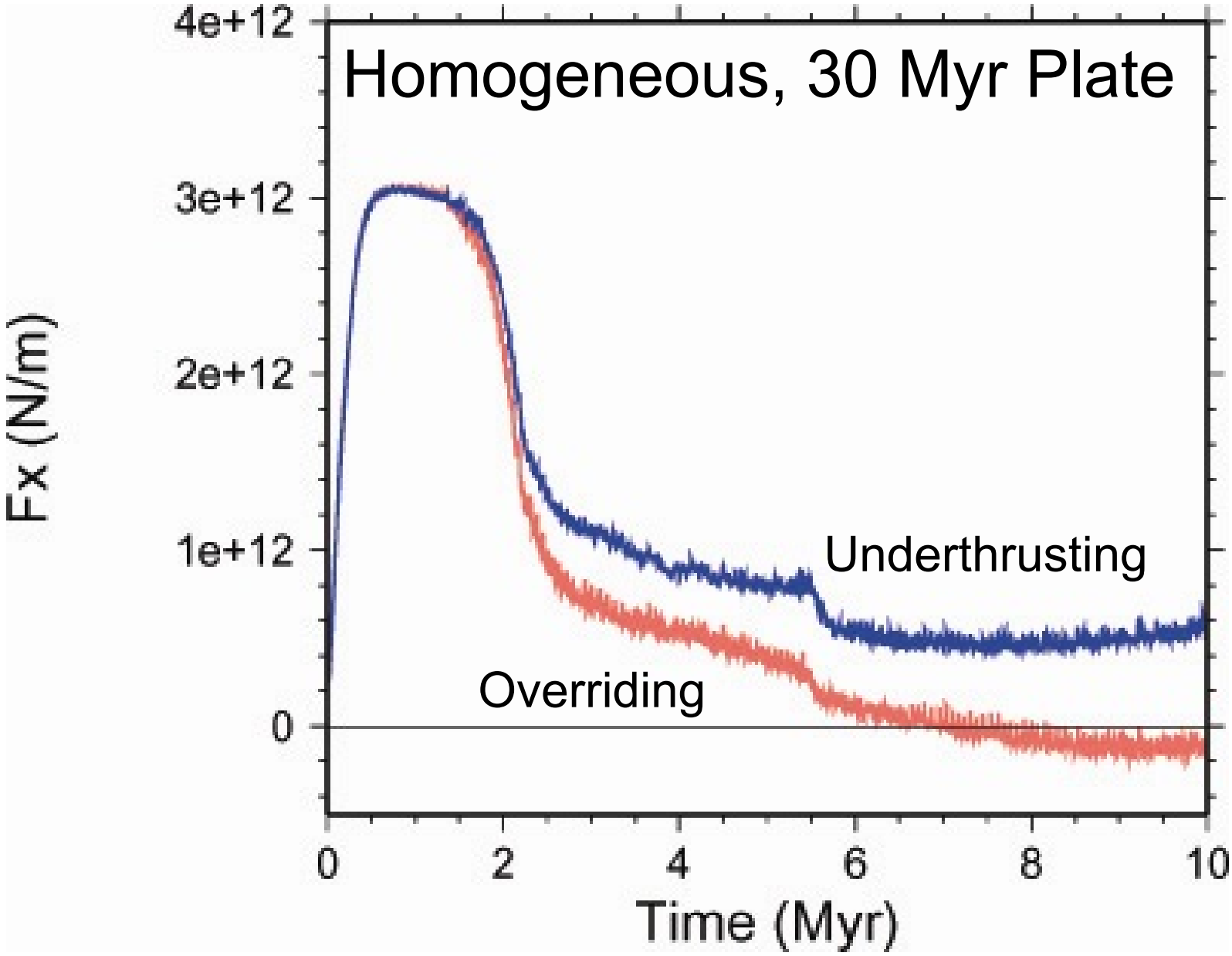
  - Explicit finite difference formulation in time

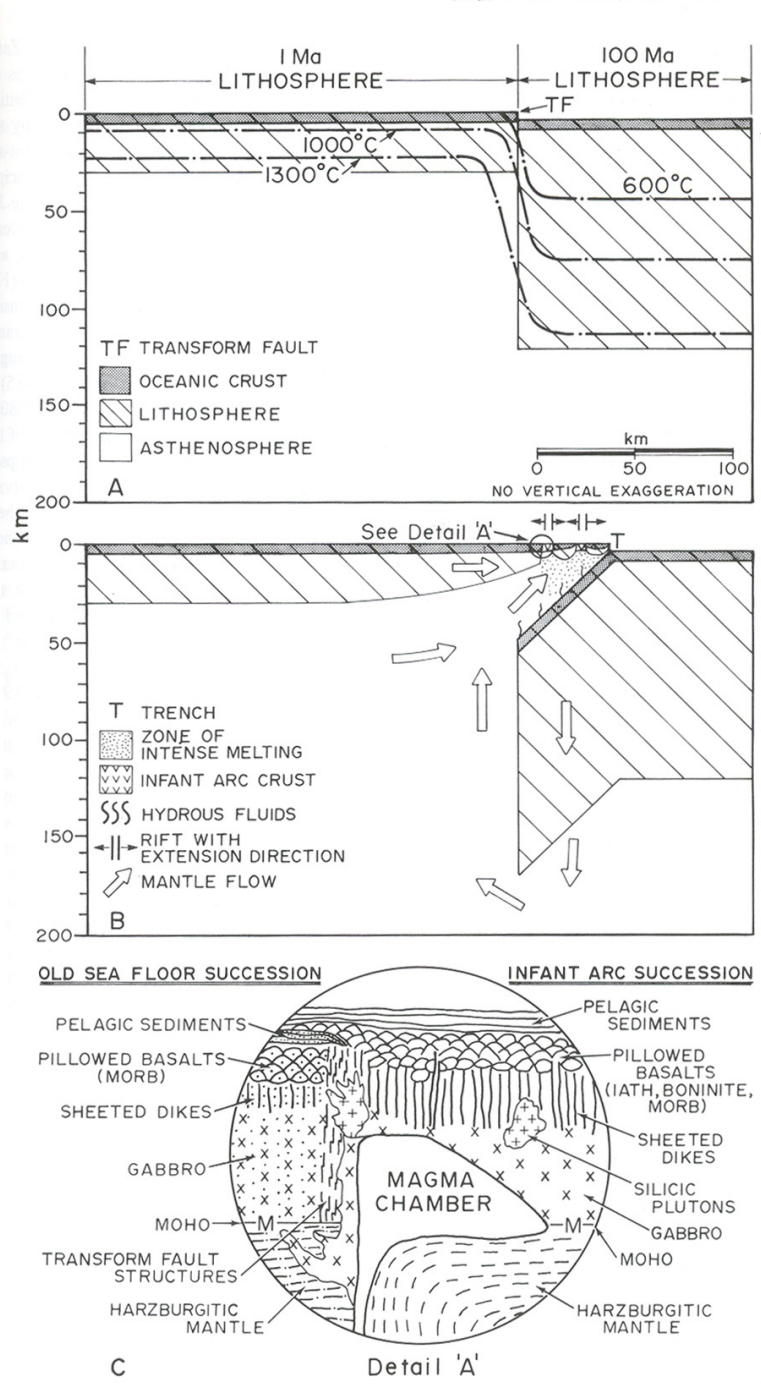
$$v_i(t + \Delta t) = v_i(t + \Delta t) + \Delta t \frac{F_i}{M}$$

$$x_i(t + \Delta t) = x_i(t + \Delta t) + \Delta t v_i(t)$$

Homogeneous 30 Myr Plate



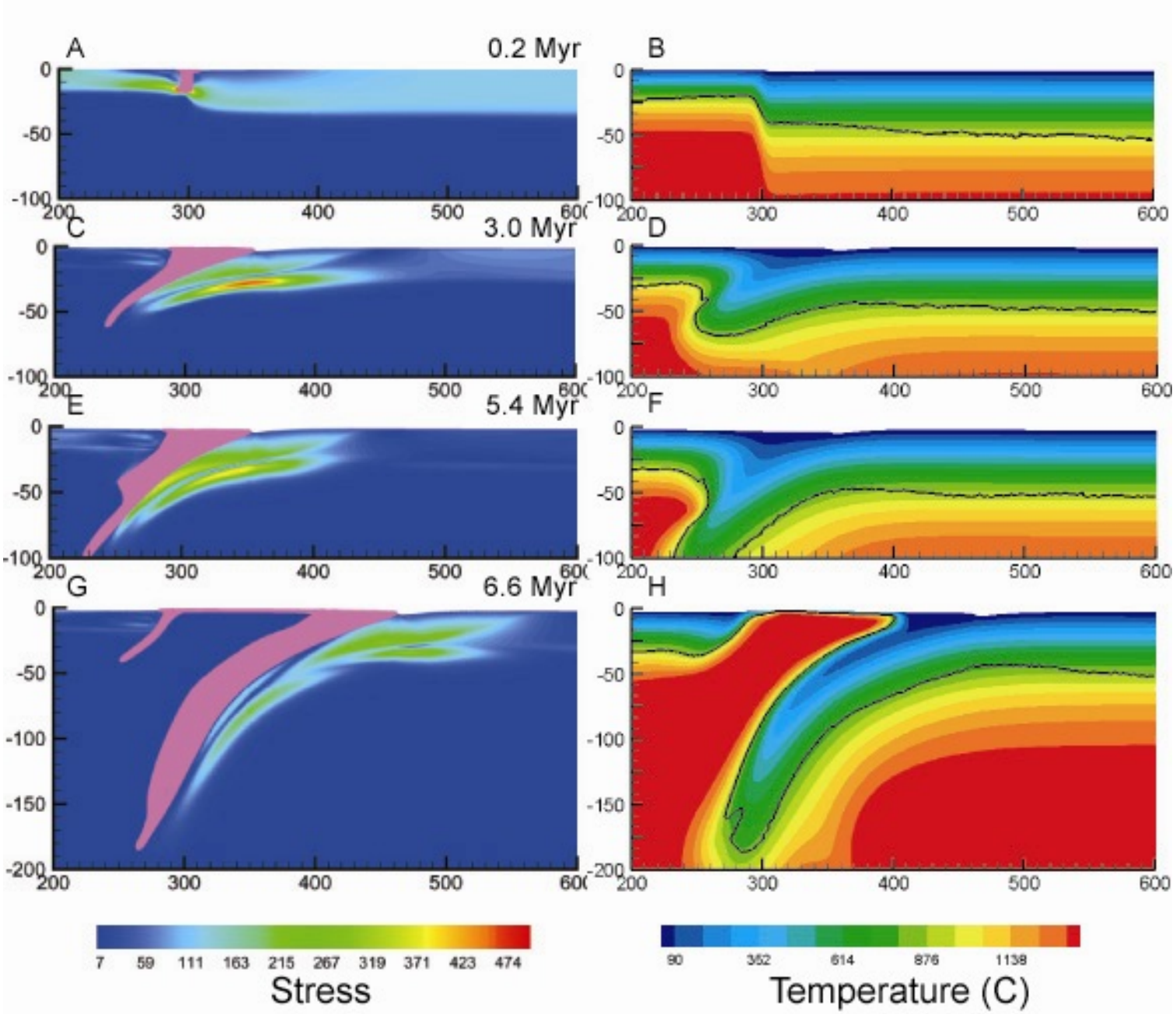

Homogeneous, 30 Myr Plate
4e+12
3e+12
2e+12
1e+12
0
Fx (N/m)
Underthrusting
Overriding
0
2
4
6
8
10
Time (Myr)

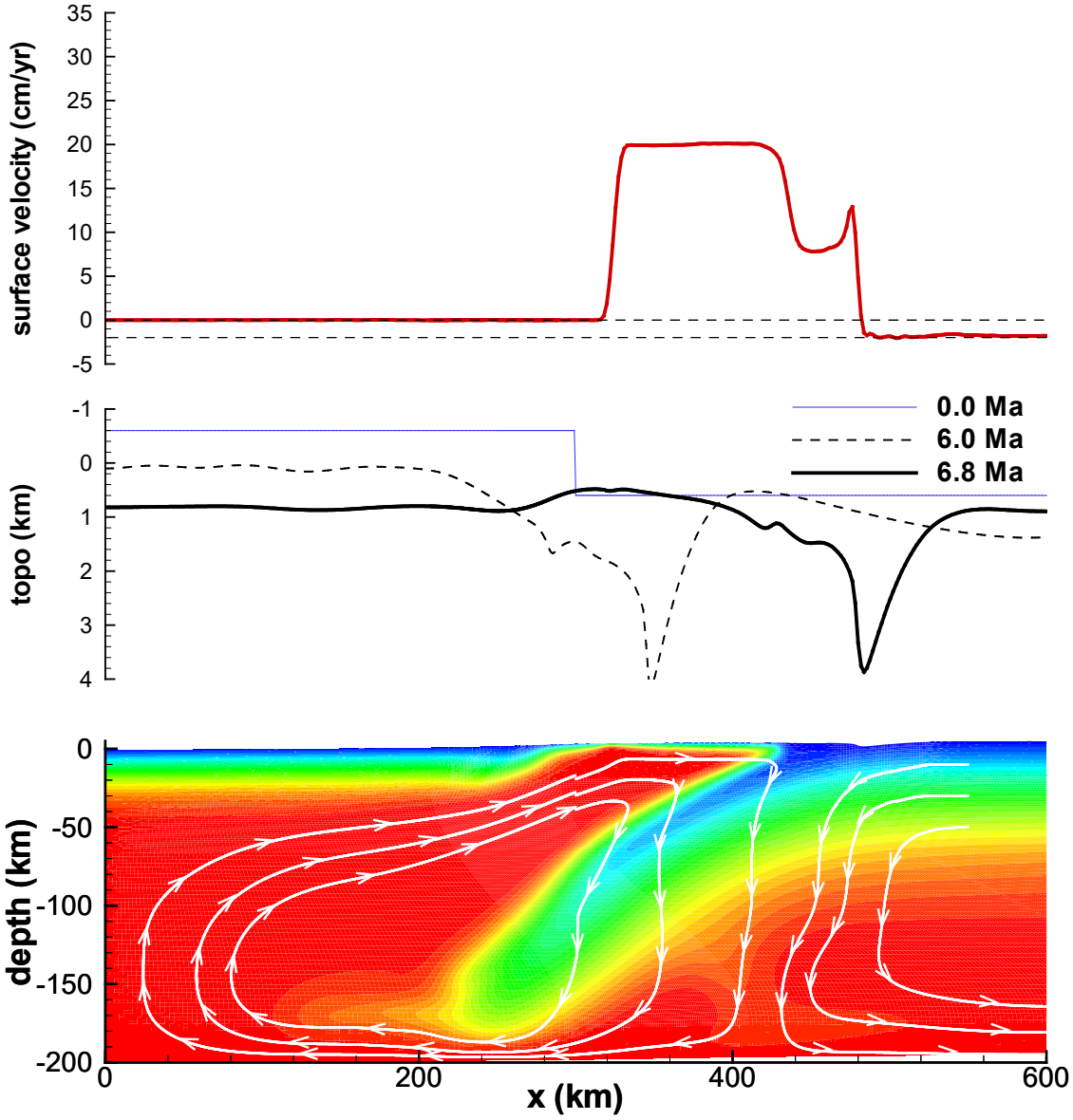


Stern & Bloomer, 1992

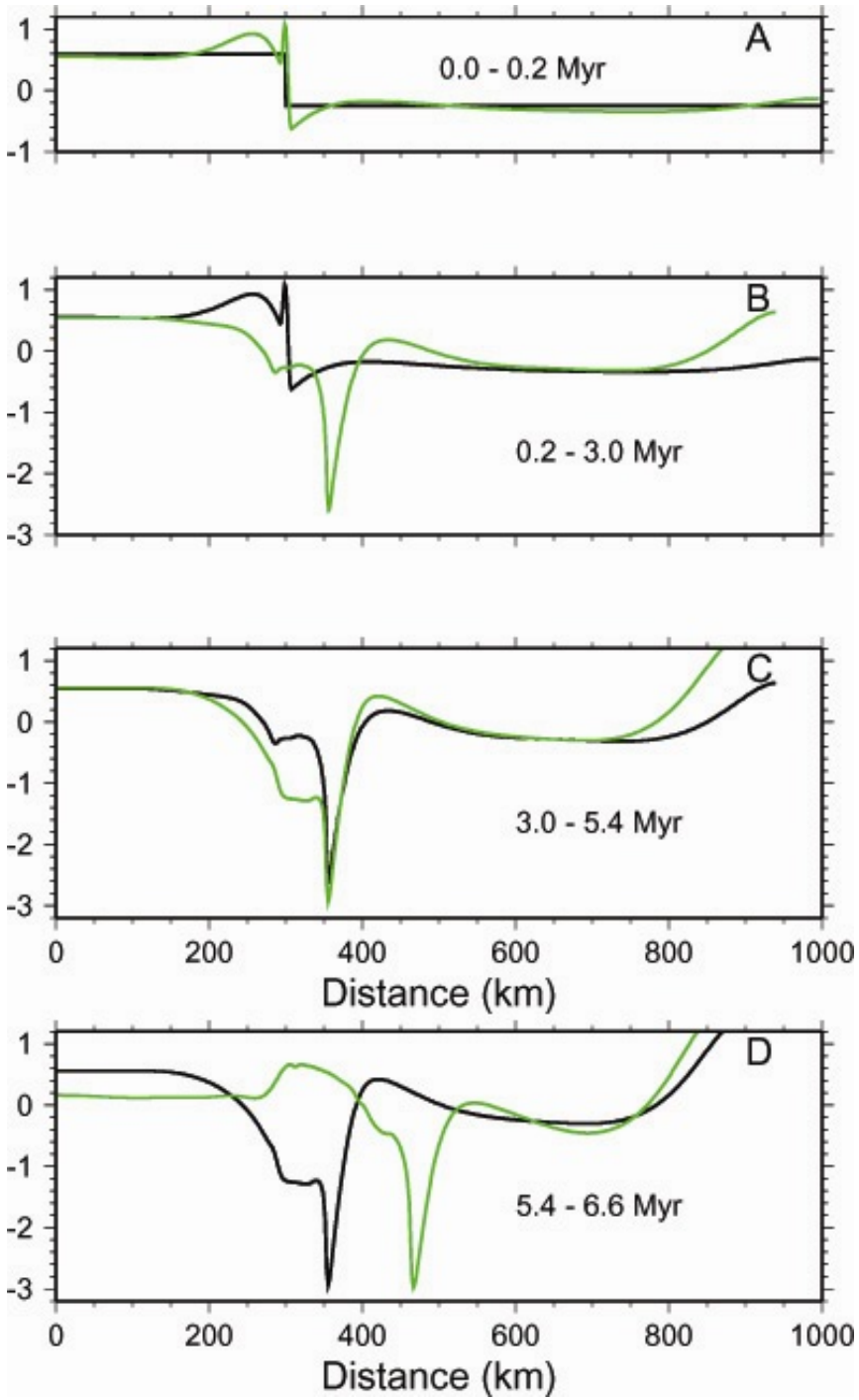
The primer can't be displayed.

10 Ma – 40 Ma Fracture Zone



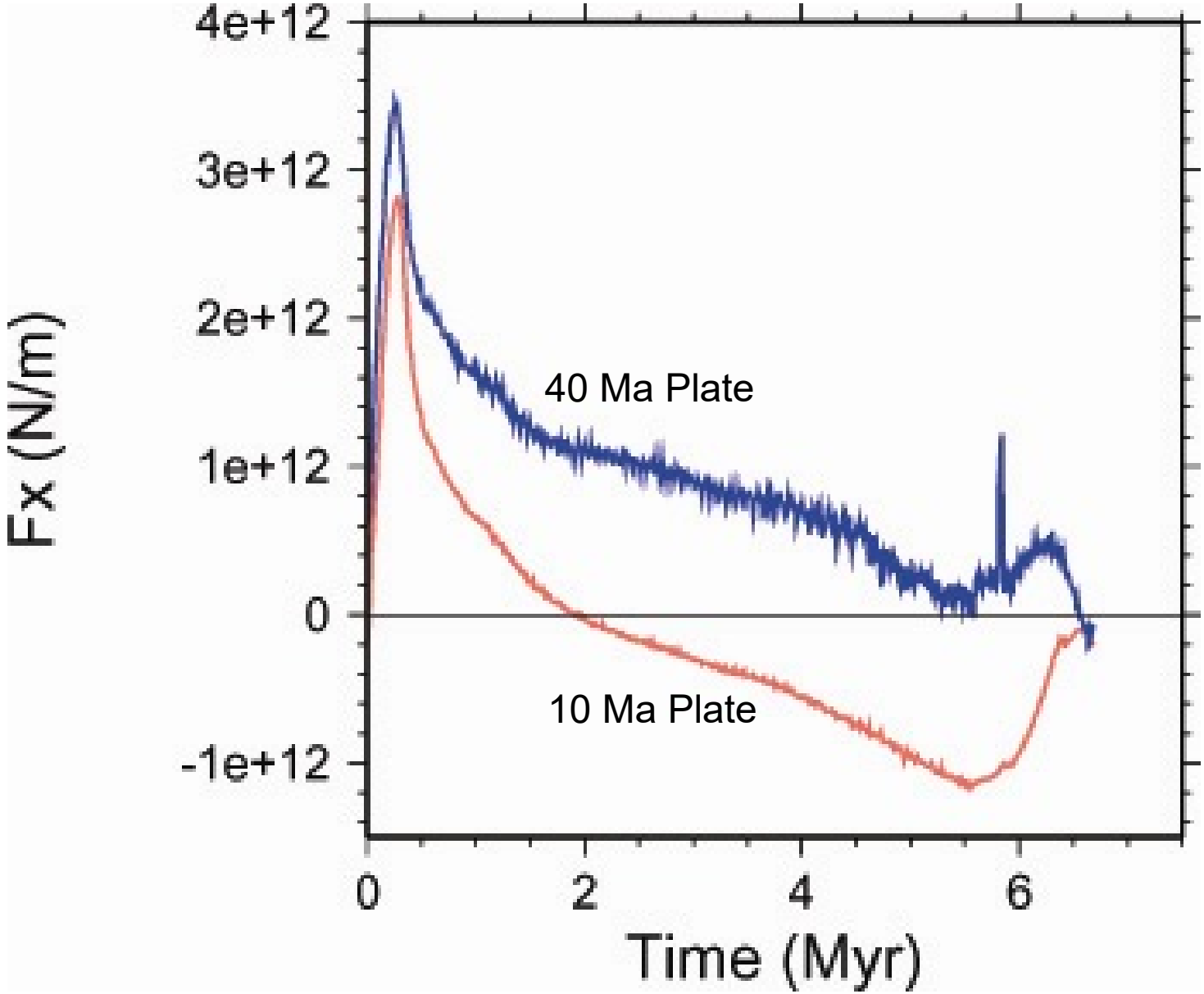


Hall et al., 2003

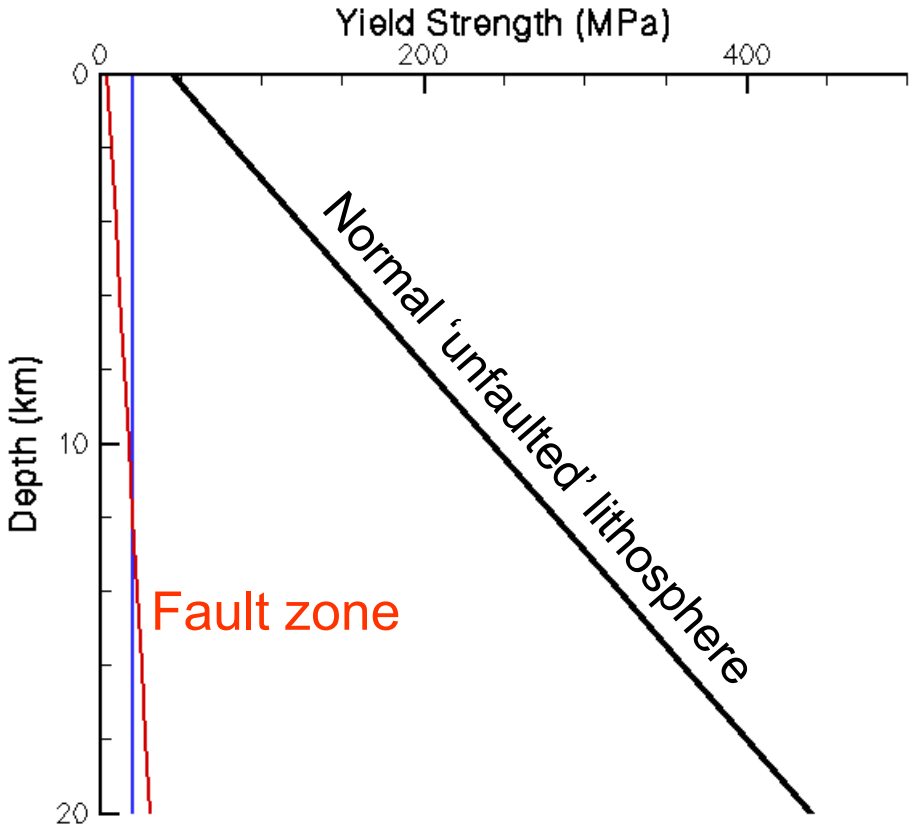


Evolution of topography for 10 Ma – 40 Ma Fracture Zone Model

Evolution of Forces



Plastic Yielding Envelopes



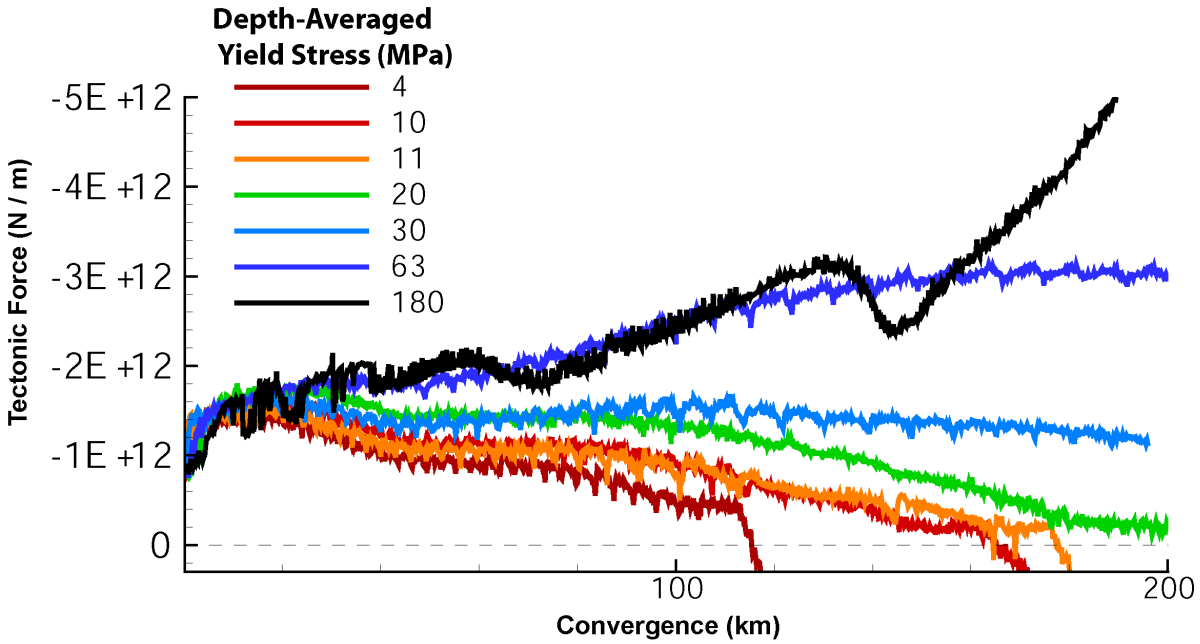
$$\sigma_y = C + \mu\sigma_n$$

σ_y	yield strength
C	cohesion
μ	coeff. of friction

$$\overline{\sigma}_y = \frac{1}{z_f}\int_0^{z_f} \sigma_y(z)\,dz$$

$$\approx C + \frac{1}{2}\mu\rho g z_f$$

Fault Strength and Evolution of Convergence Zones



< 25 MPa: Localized (Arc in Extensional)

Hall, Gurnis & Lavier

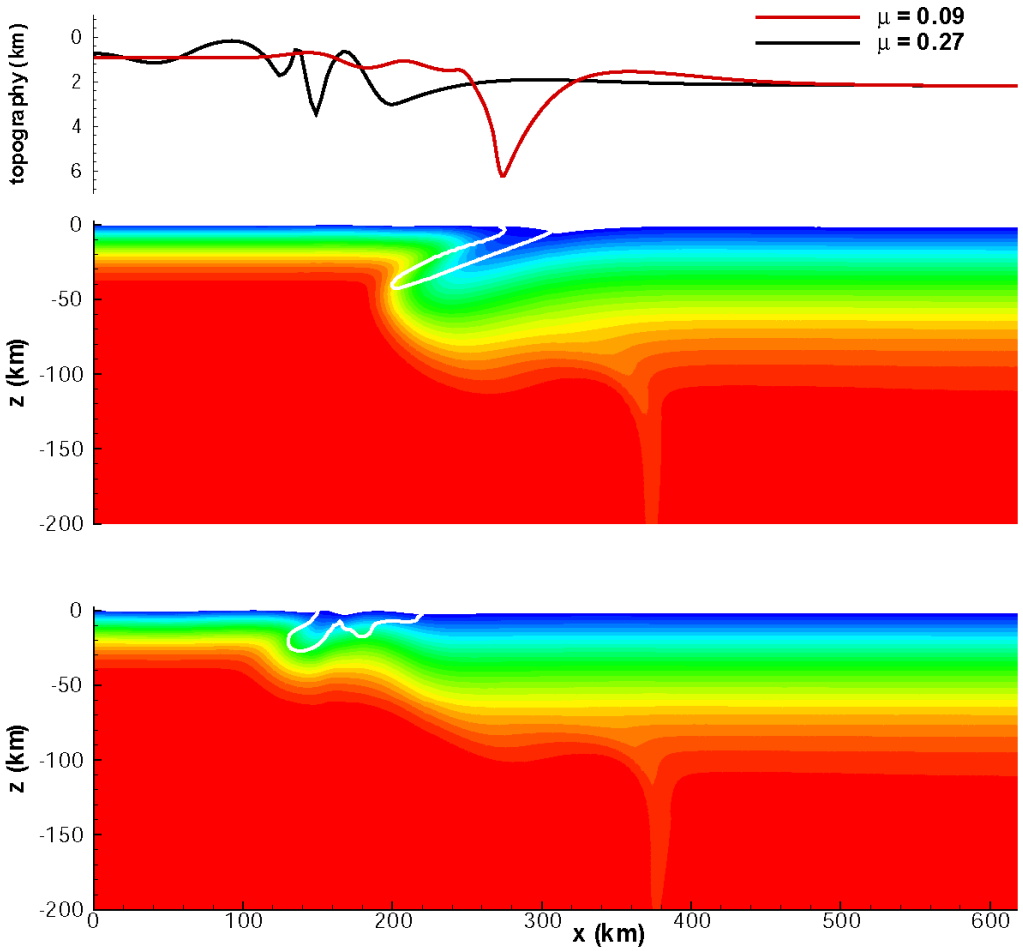
> 25 MPa: Localized (Arc in Compression)

60 – 180 MPa: Transition to distributed deformation (buckling)

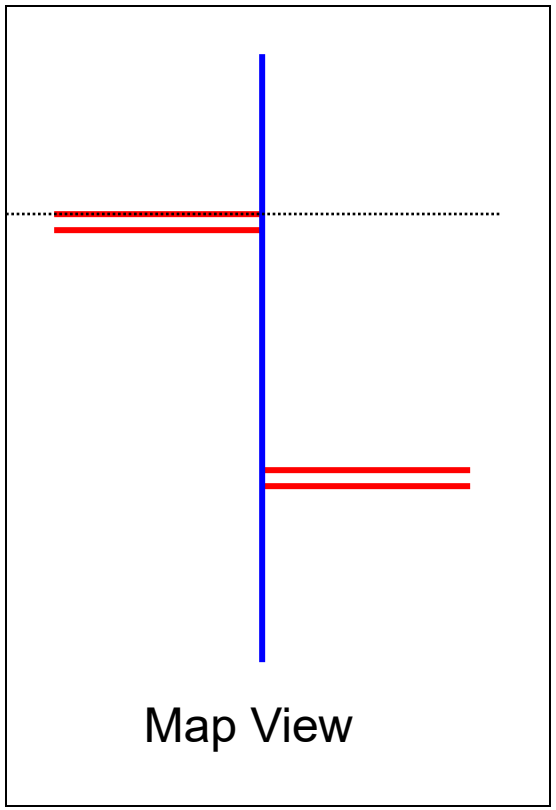
Fault Strength and Evolution of Convergence Zones

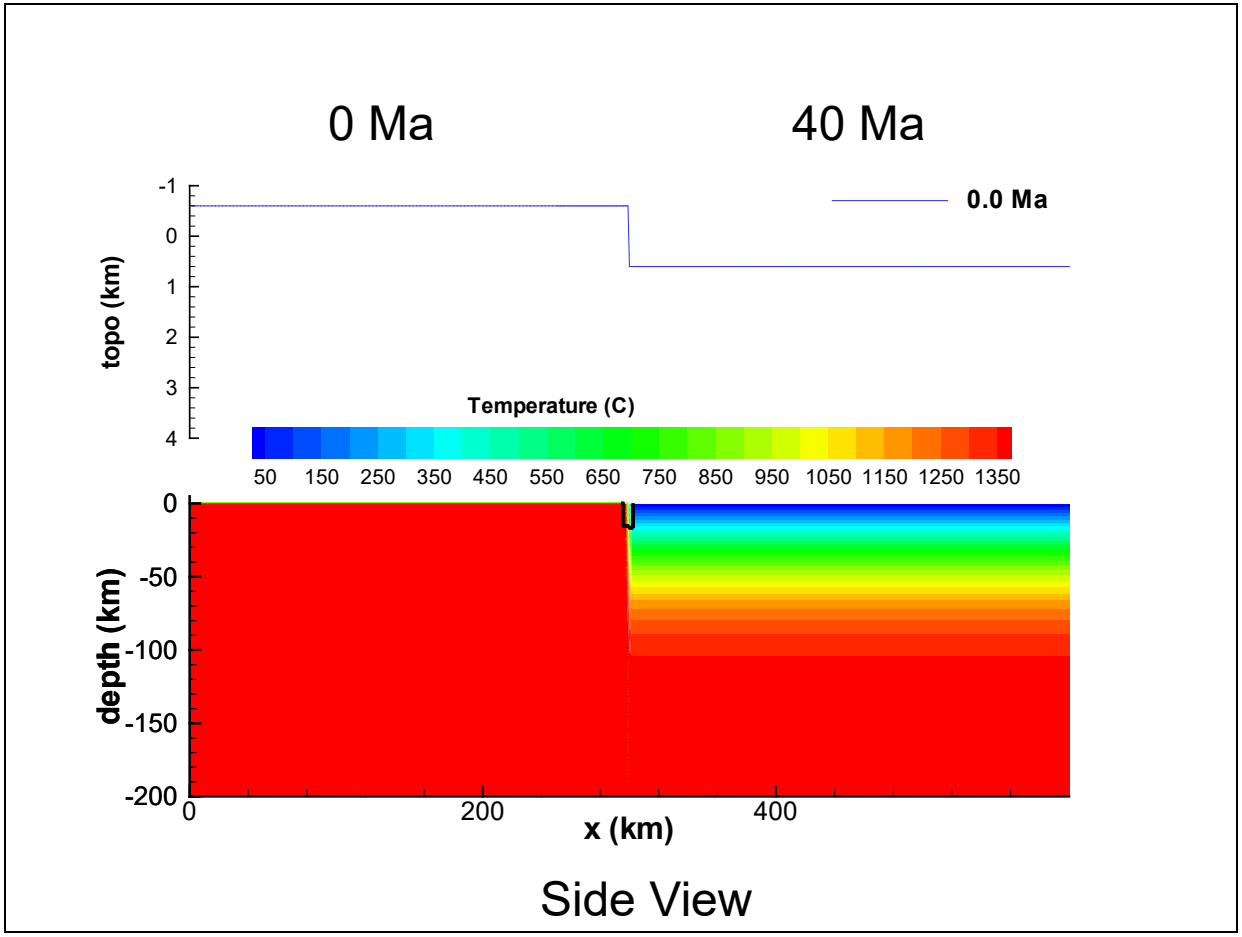
Lower Friction
(63 MPa)

Higher Friction
(180 MPa)

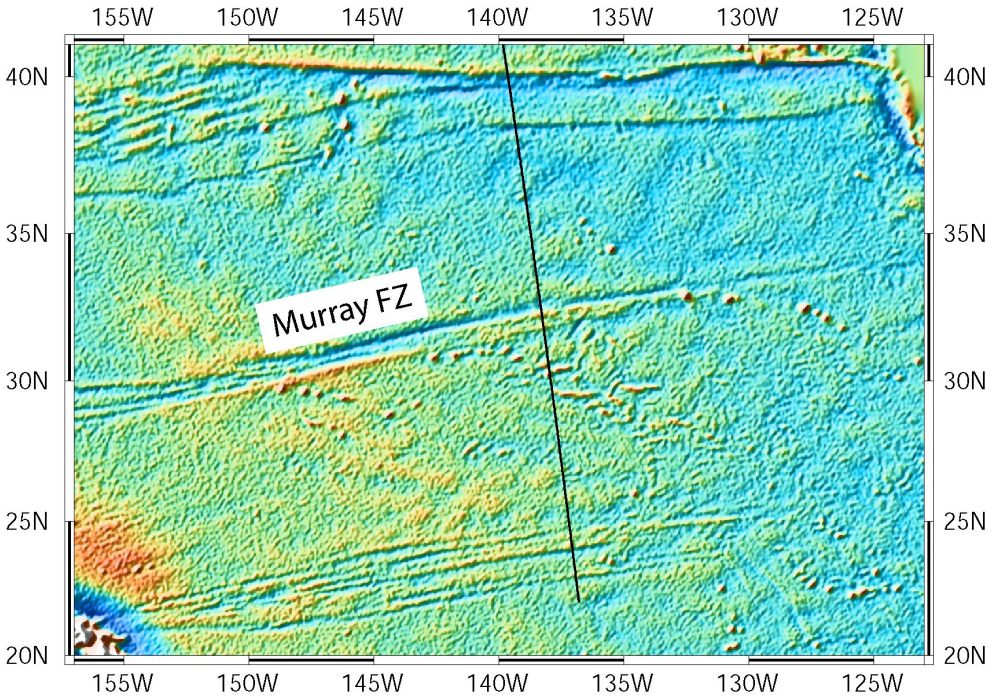


Hall, Gurnis & Lavier

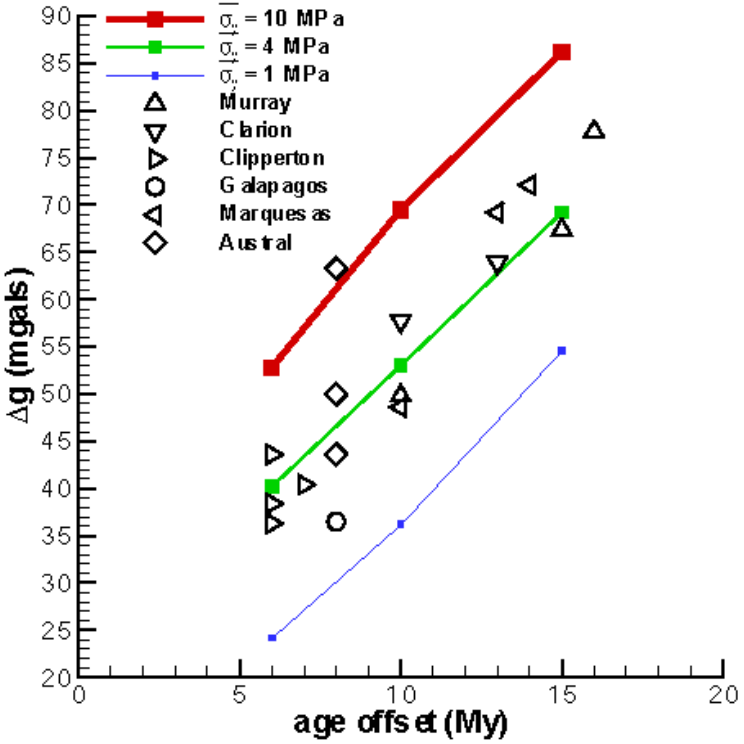

Map View


0 Ma
40 Ma
0.0 Ma
topo (km)
-1
0
1
2
3
4
Temperature (C)
50 150 250 350 450 550 650 750 850 950 1050 1150 1250 1350
depth (km)
0
-50
-100
-150
-200
0
200
400
x (km)
Side View

Murray Fracture Zone

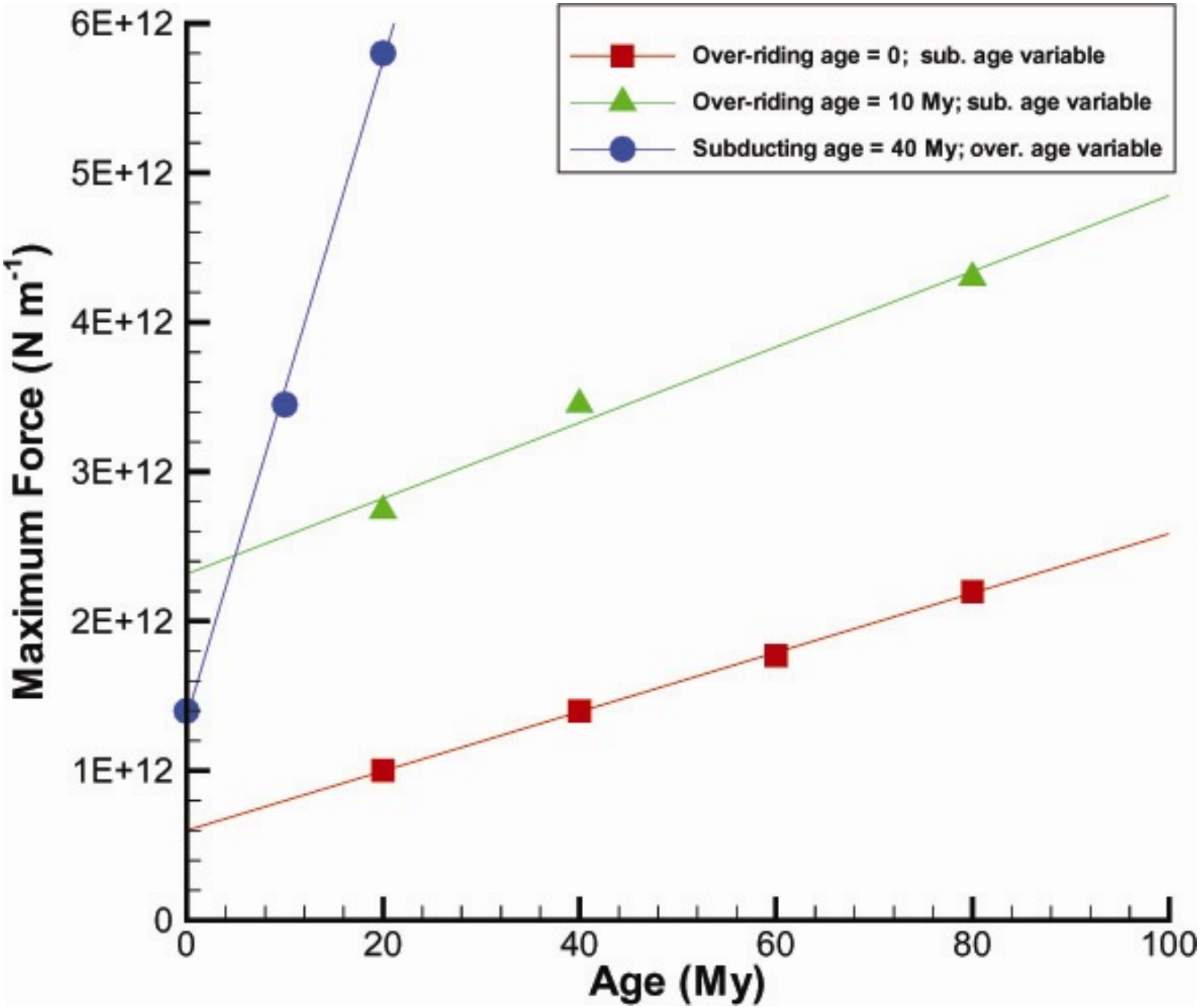


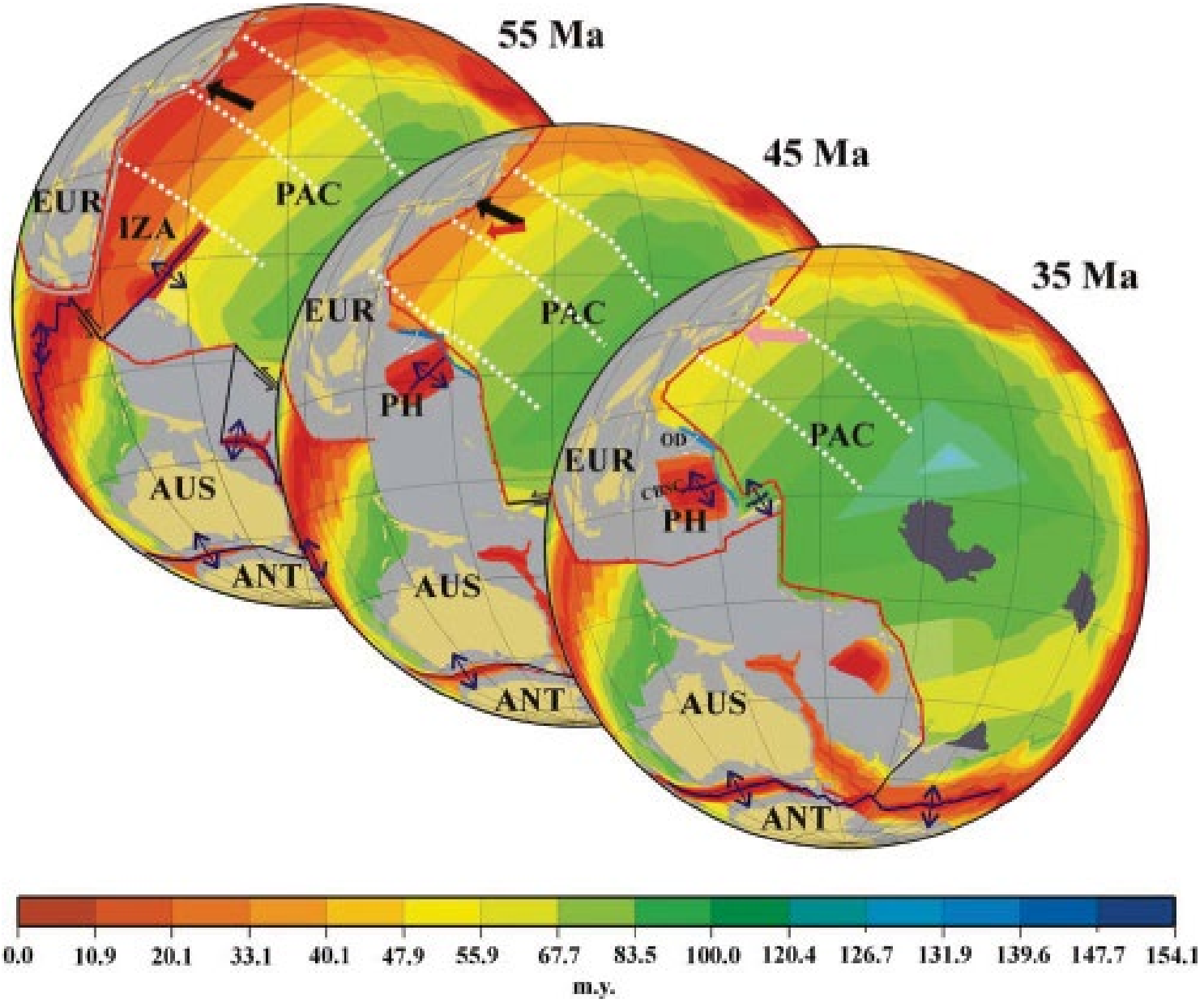
Forward Gravity Models



10 MPa models typically too strong

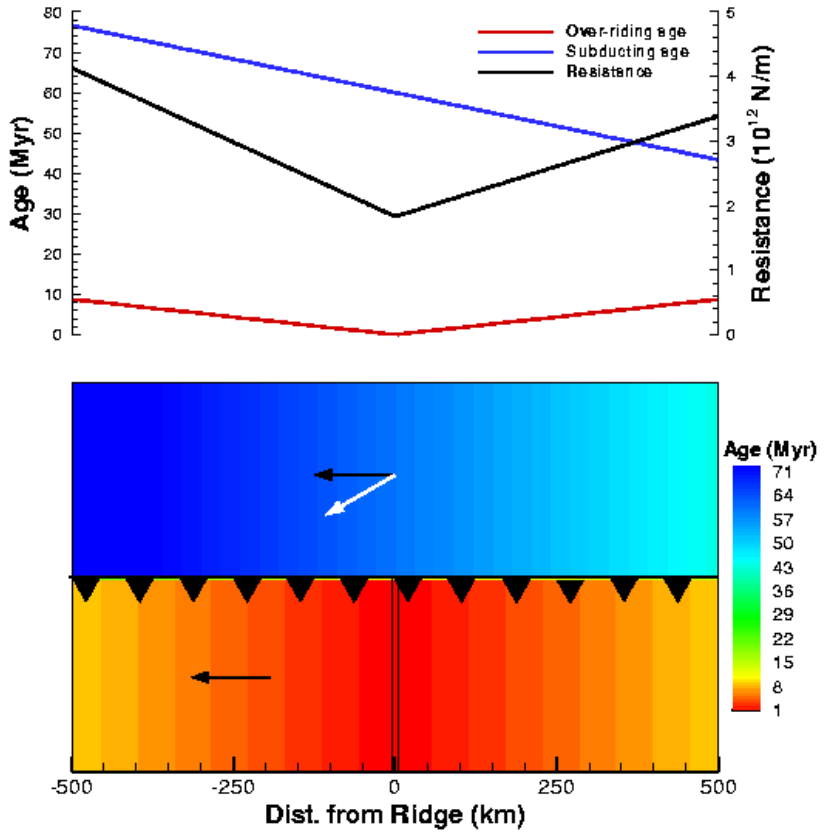
Hall & Gurnis, 2005


Over-riding age = 0; sub. age variable
Over-riding age = 10 My; sub. age variable
Subducting age = 40 My; over. age variable
Maximum Force (N m-1)
6E+12
5E+12
4E+12
3E+12
2E+12
1E+12
0
0
20
40
60
80
100
Age (My)



Paleo age grids from Mueller and Sdrolias in Hall et al. [2003]

Estimate Resistance at ~55 Ma



- Total resistance over 2500 km of plate boundary is 2×10^{19} N (Hall et al., 2003).
- Small compared to current driving forces (2×10^{21} N globally, value from Conrad & Lithgow-Bertelloni, 2002)

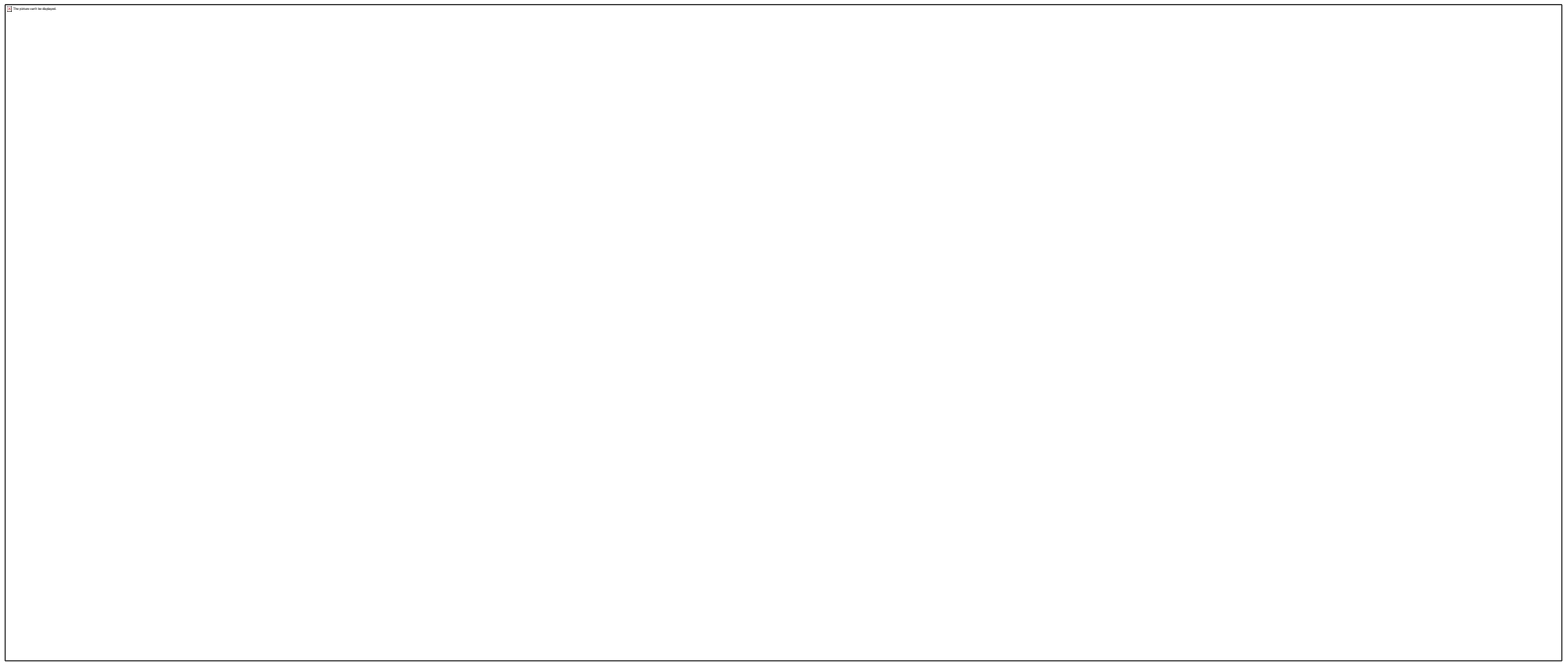
Outcomes of computational models

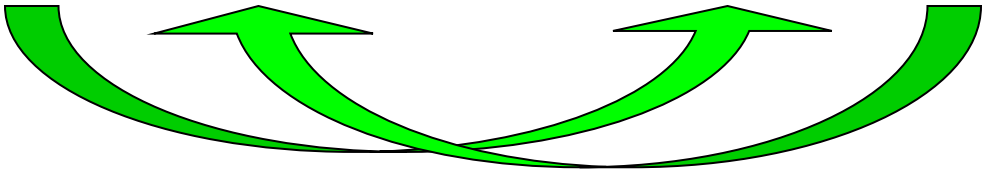
- Reinterpreted Eocene history of IBM. Earlier compressive stage preceded rapid extension
- Most intense periods of back-arc extension all followed subduction initiation
- Developing explicit test (through IODP) for initiation of Tonga-Kermadec SI

Some thoughts on software needed for the future

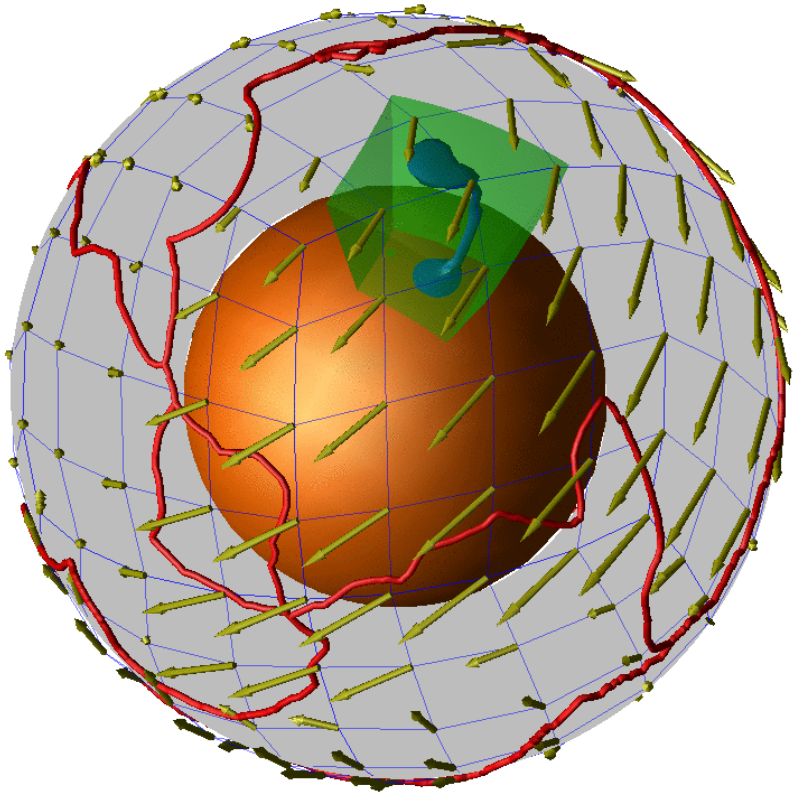
- Frameworks: Eh Tan
- Coupling scales: Eun-seo Choi
- Micro physics coupling to large-scale: Laura Baker, Paula Smith, Chad Hall, Paul Asimow

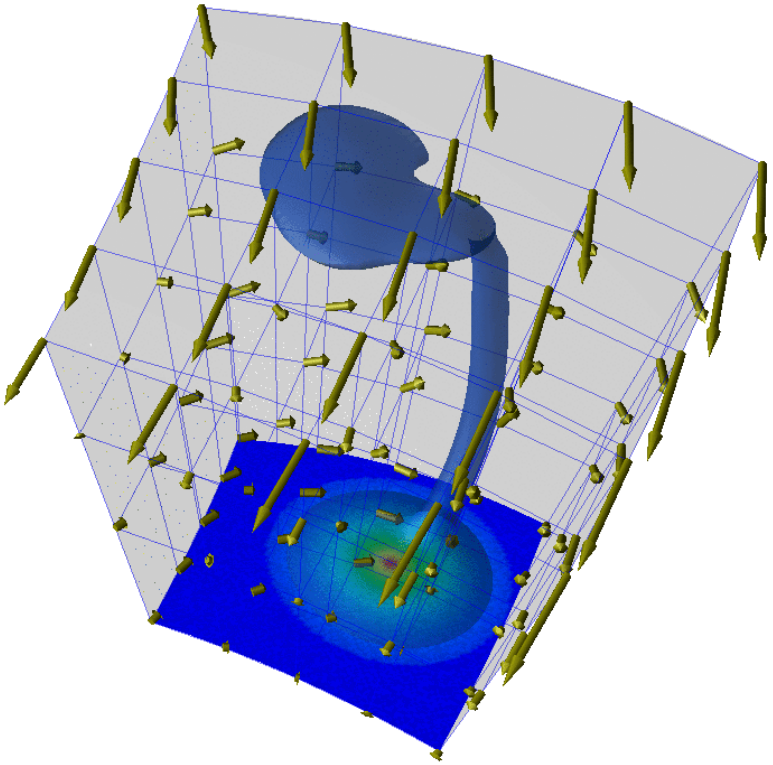
Coupling With Pyre





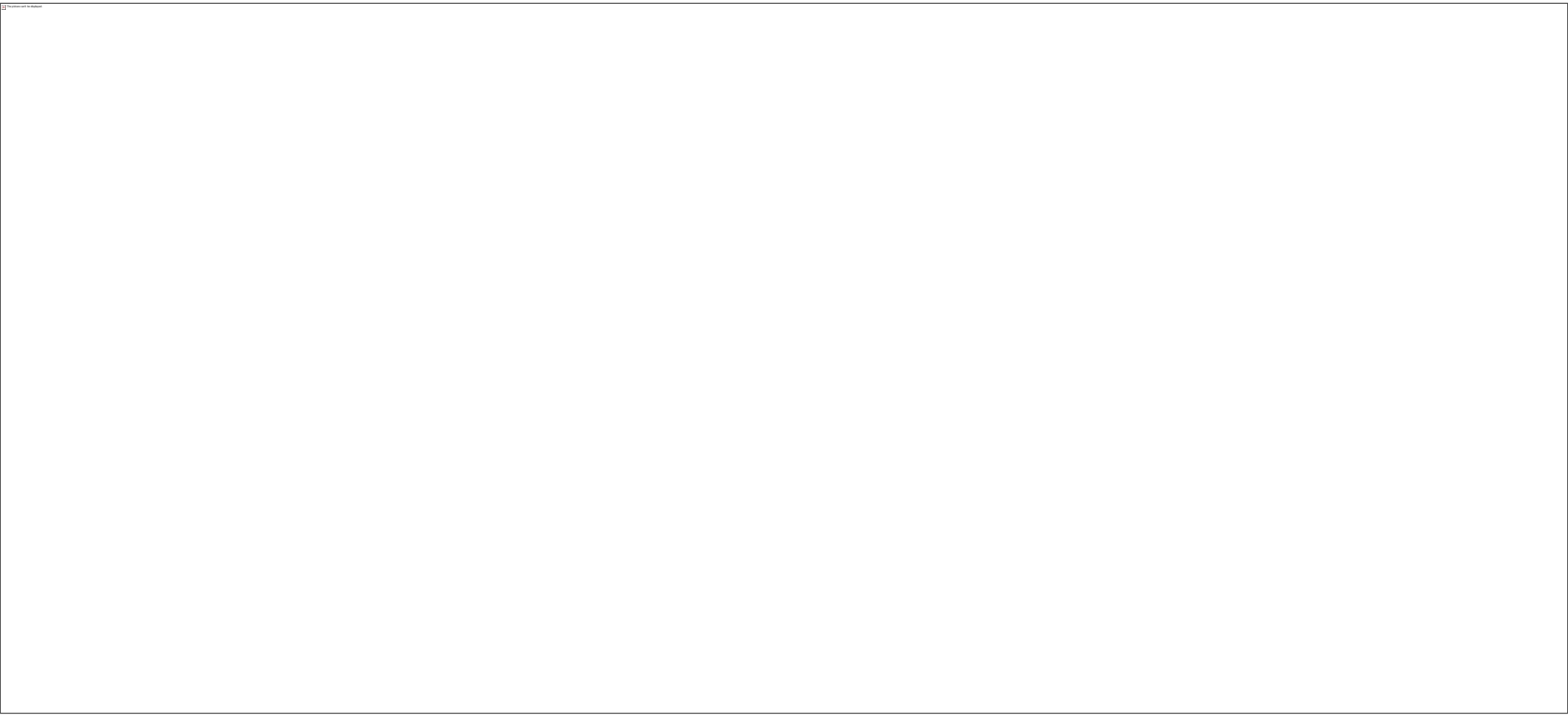
Regional and Global Mantle Flow Coupled with Pyre





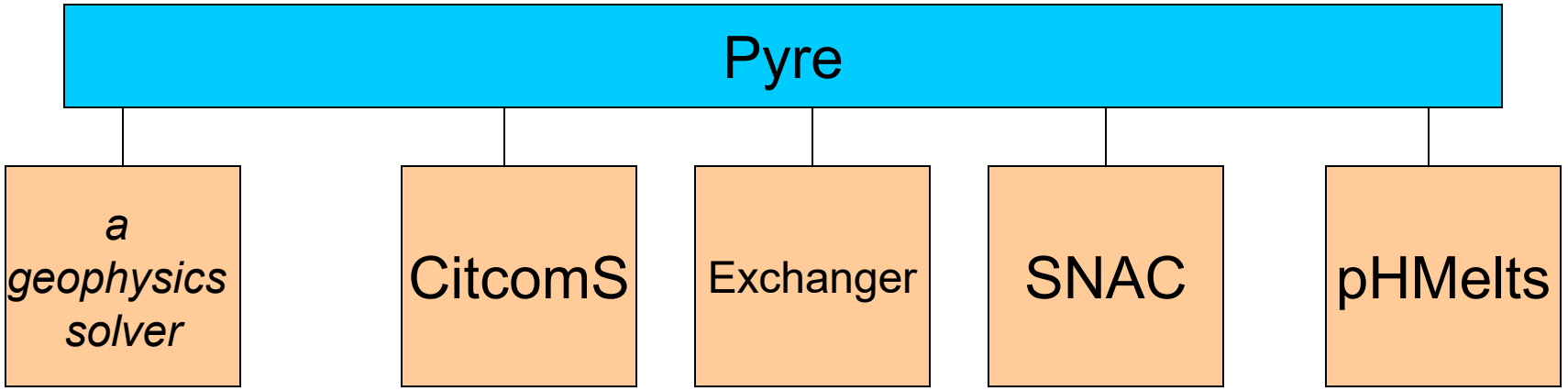
CitcomS.py, Eh Tan

Regional CitcomS coupled to full CitcomS

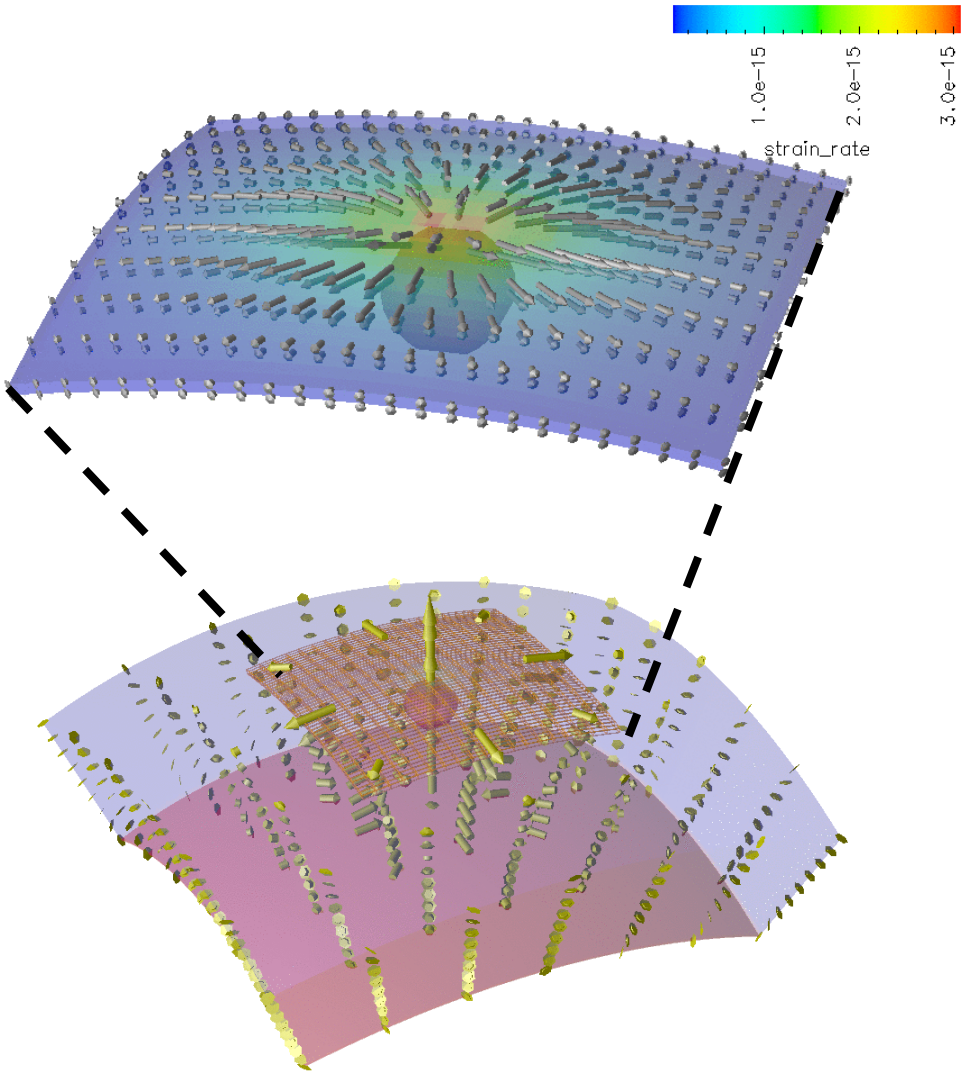


CitcomS.py, Eh Tan

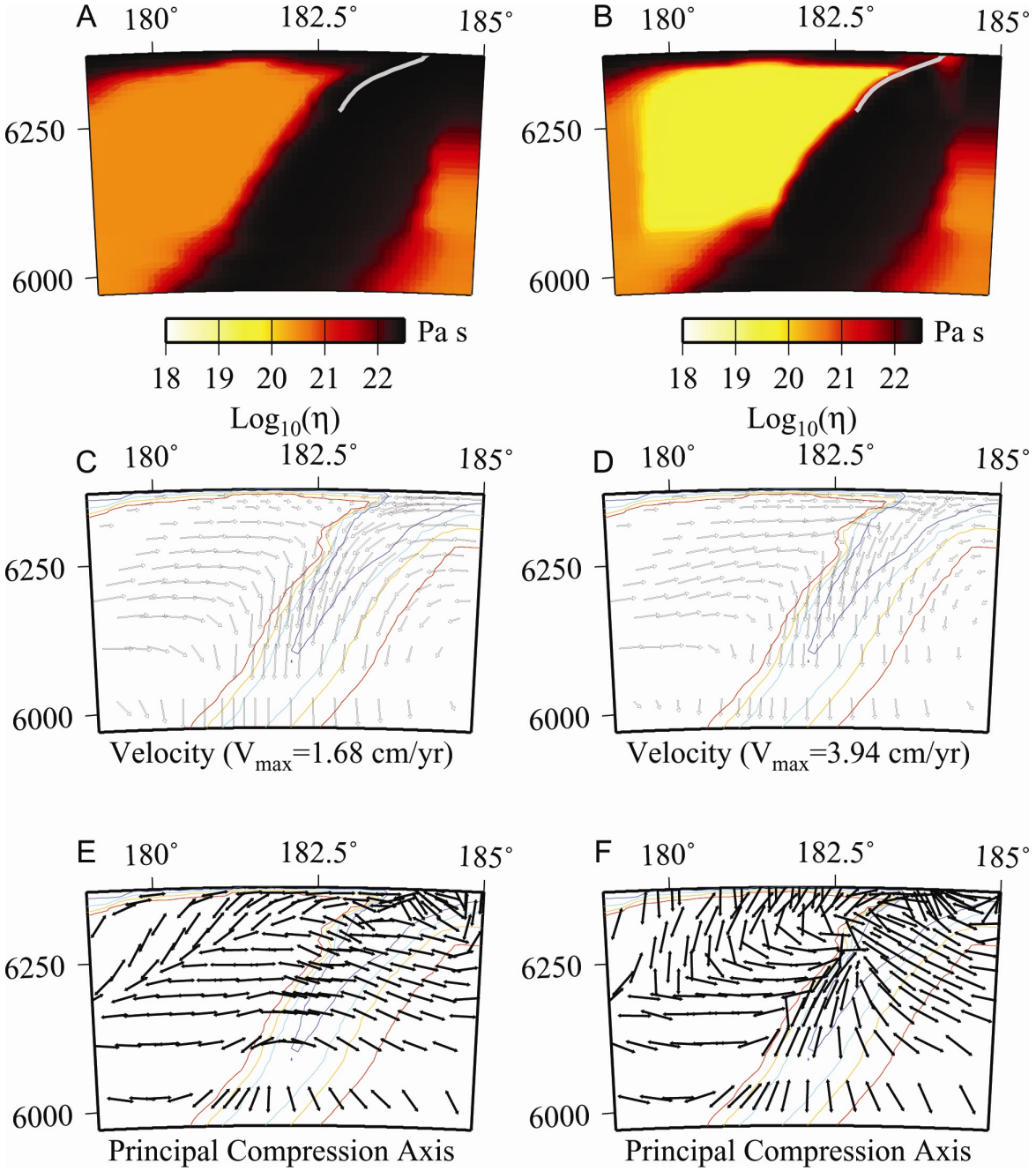
Examples of coupling codes with Pyre (“superstructure” framework): GeoFramework



SNAC CitcomS coupling (Crust-Mantle Interaction)



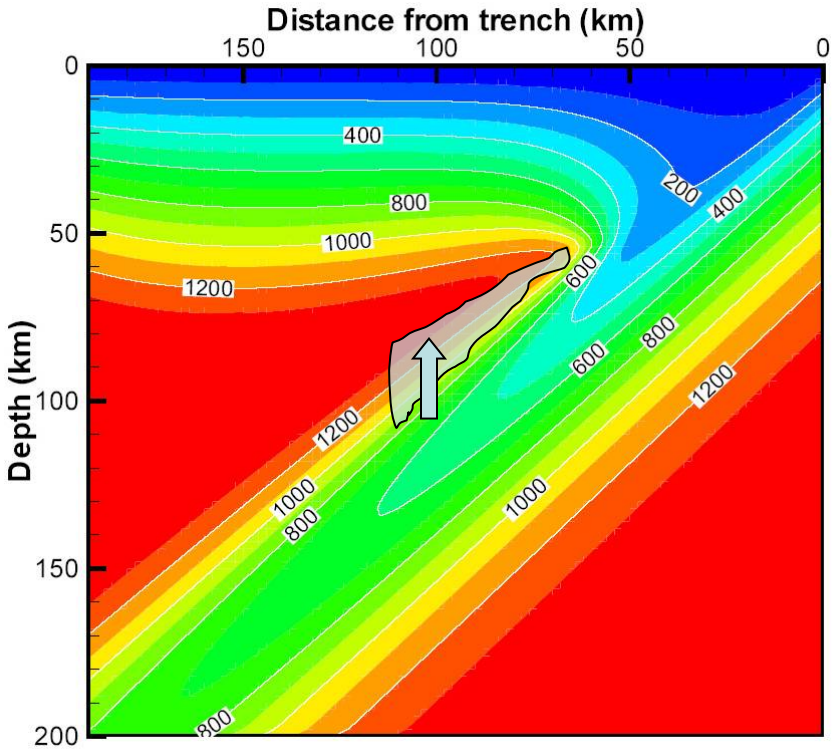
Eun-seo Choi et al.



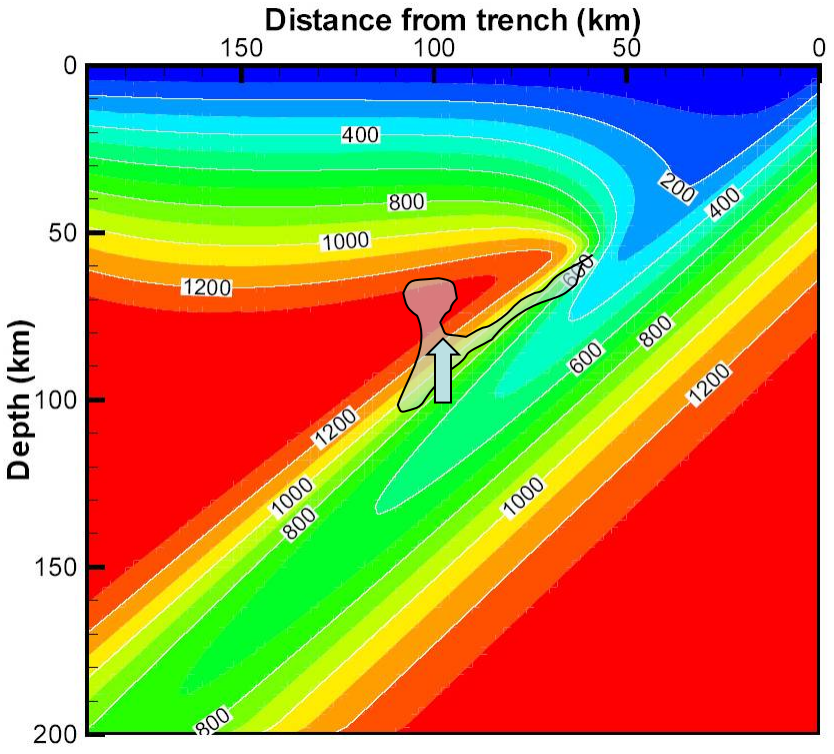
Billen et al. 2003

Cartoon Models of Wedge Melting

Formation of water-saturated zone

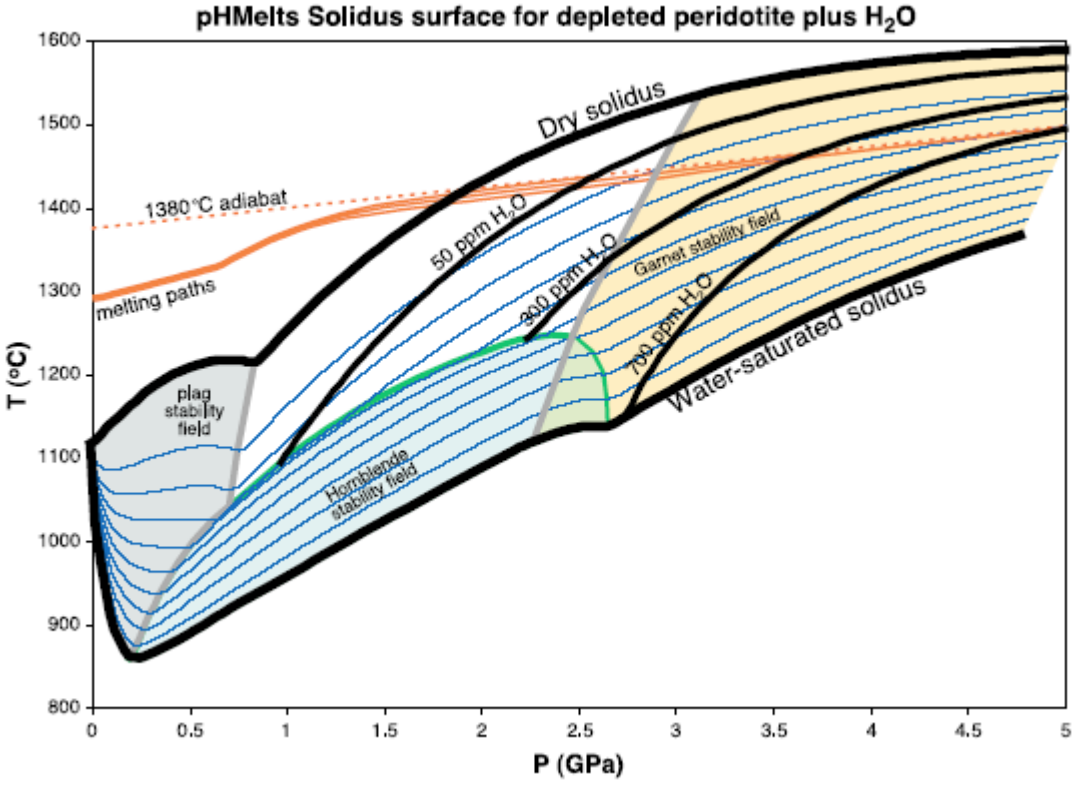


Diapirism of hydrated mantle



Baker, Smith, Hall, Gurnis, & Asimow

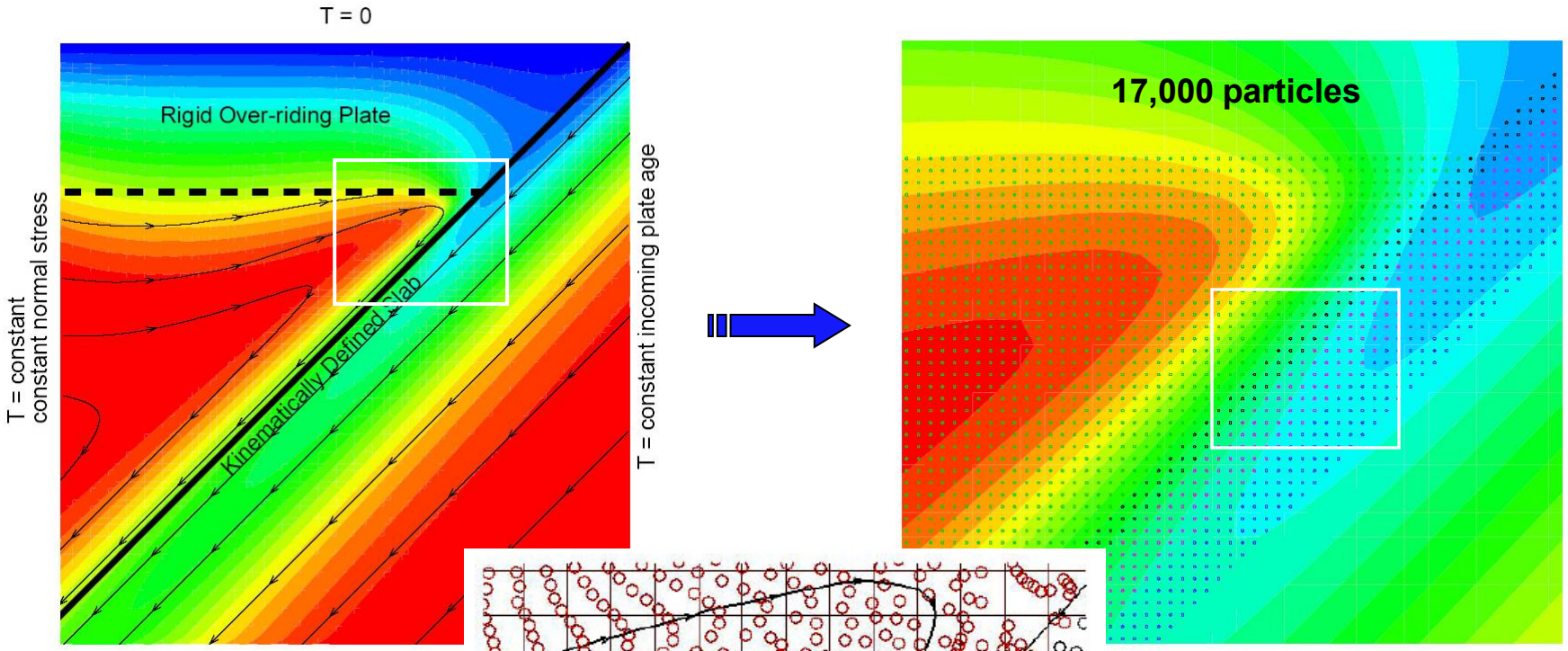
pHMelts Petrological Model



(*Asimow et al.*, 2004; *Ghiorso et al*., 2002)

Given composition and state variables, pHMelts will return the assemblage that minimizes free energy

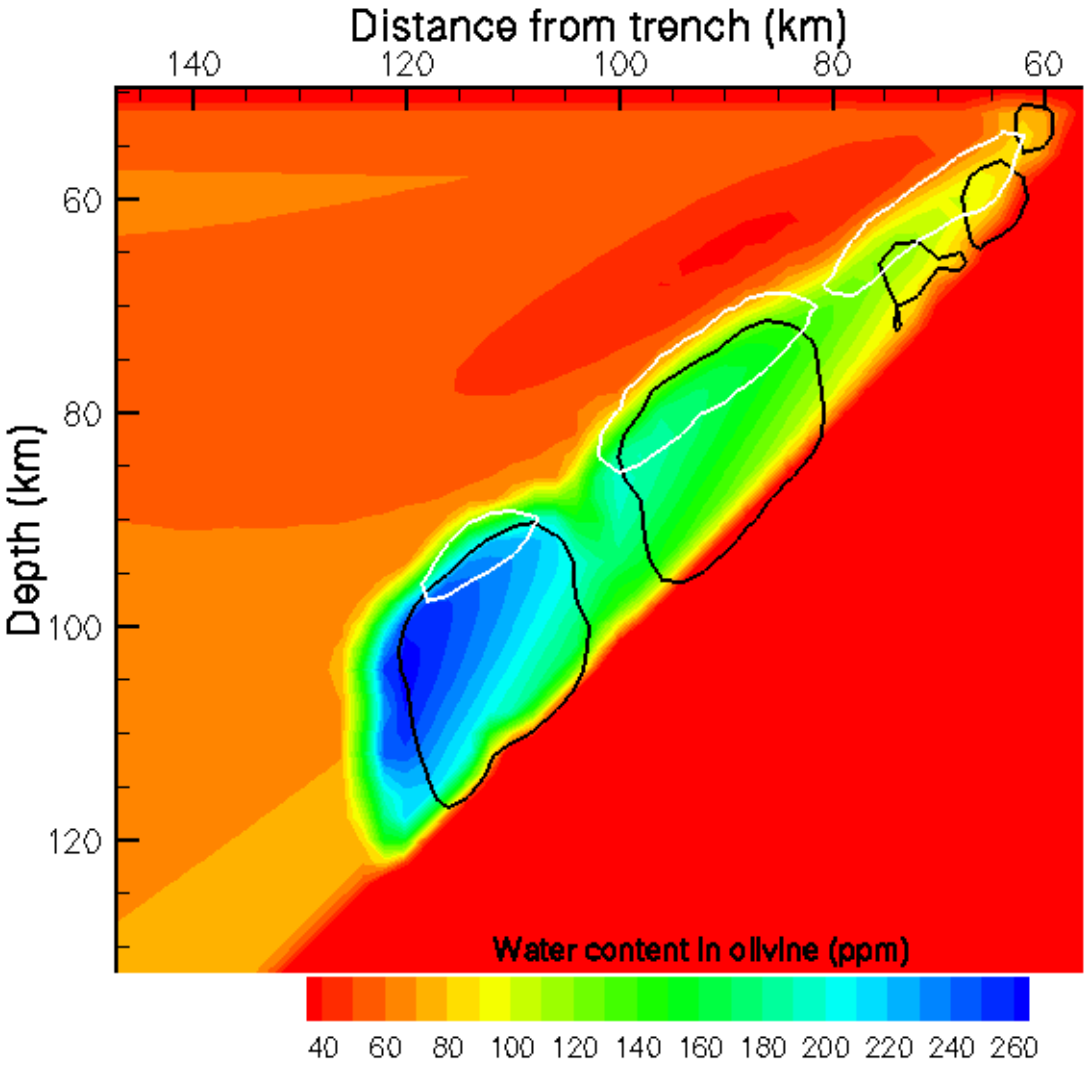
Gives partitioning of water to nominally anhydrous minerals



Thermodynamic data from pHMelts passed back to solid flow solver:
Water content, melt fraction, buoyancy, latent heat

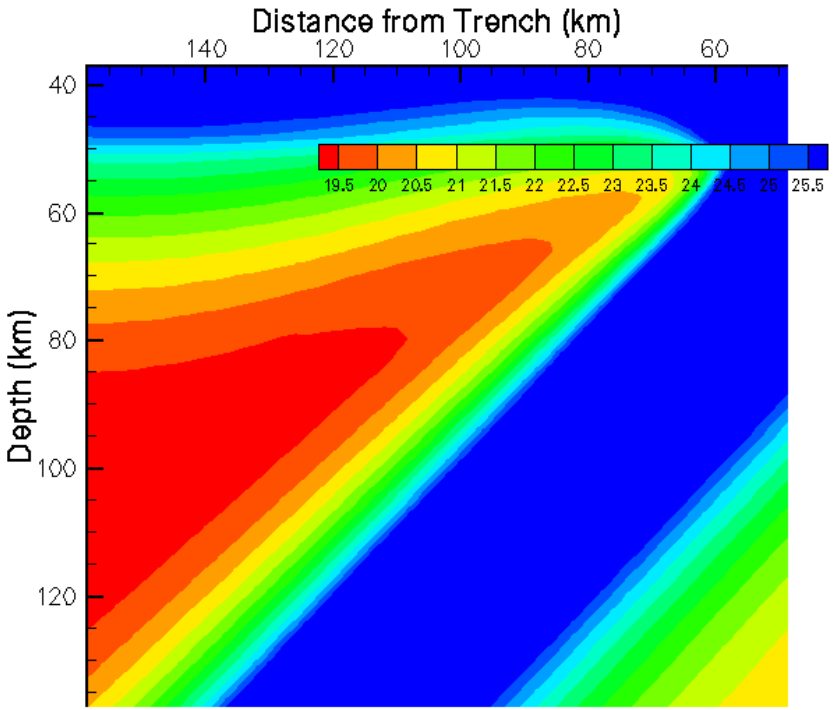
- Particles advected by solid flow solver

- (P, T, *X*) are passed to pHMelts

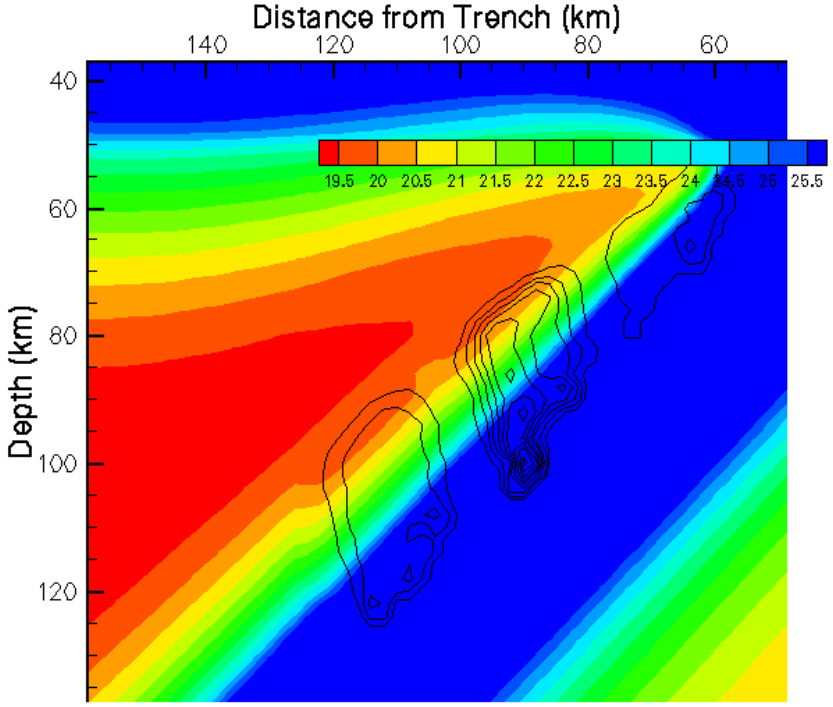


Free water (black contours) passes through saturated zone to generate partial melt (white contours)

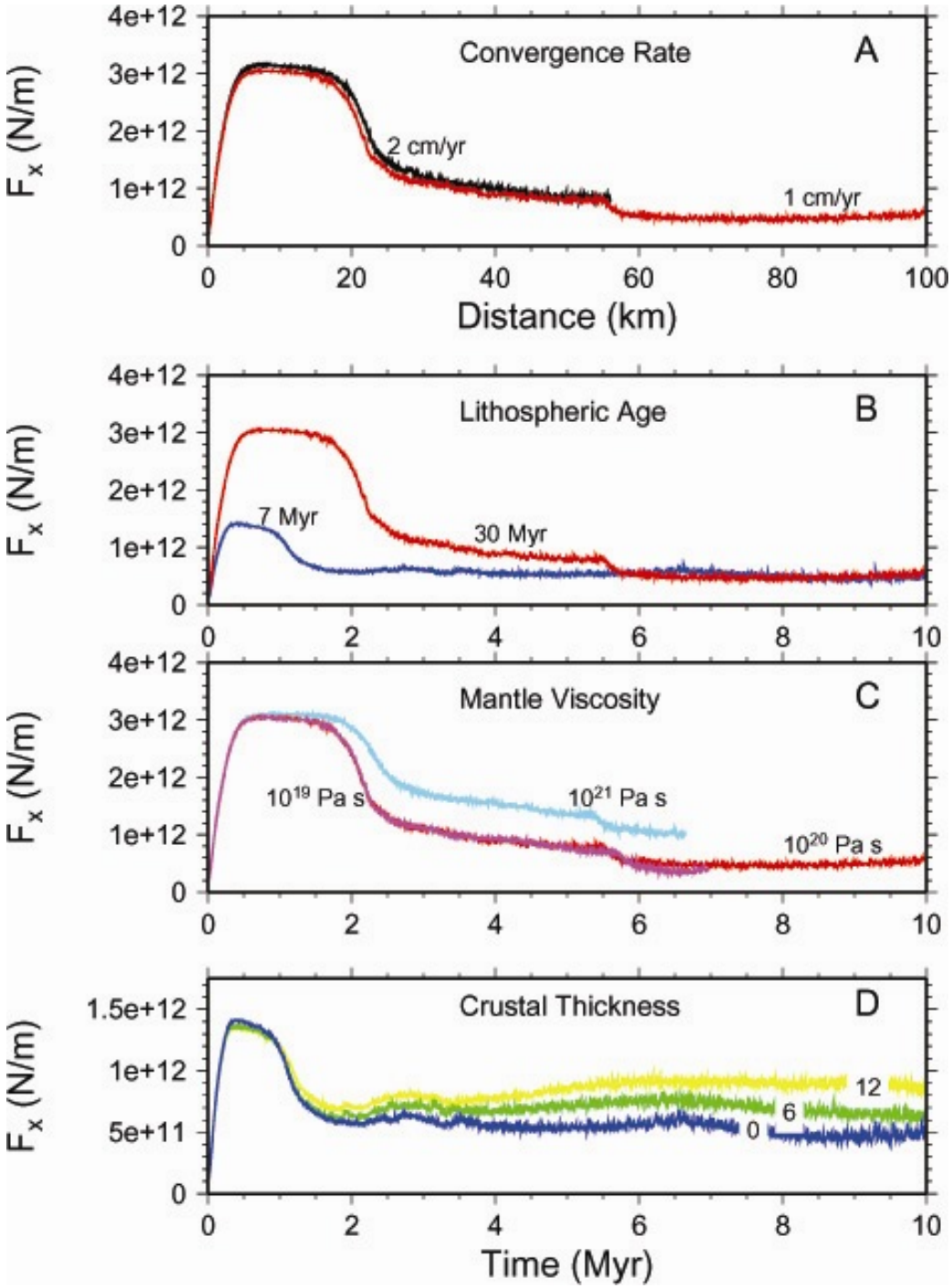
Feedback between Thermodynamics & Mechanics

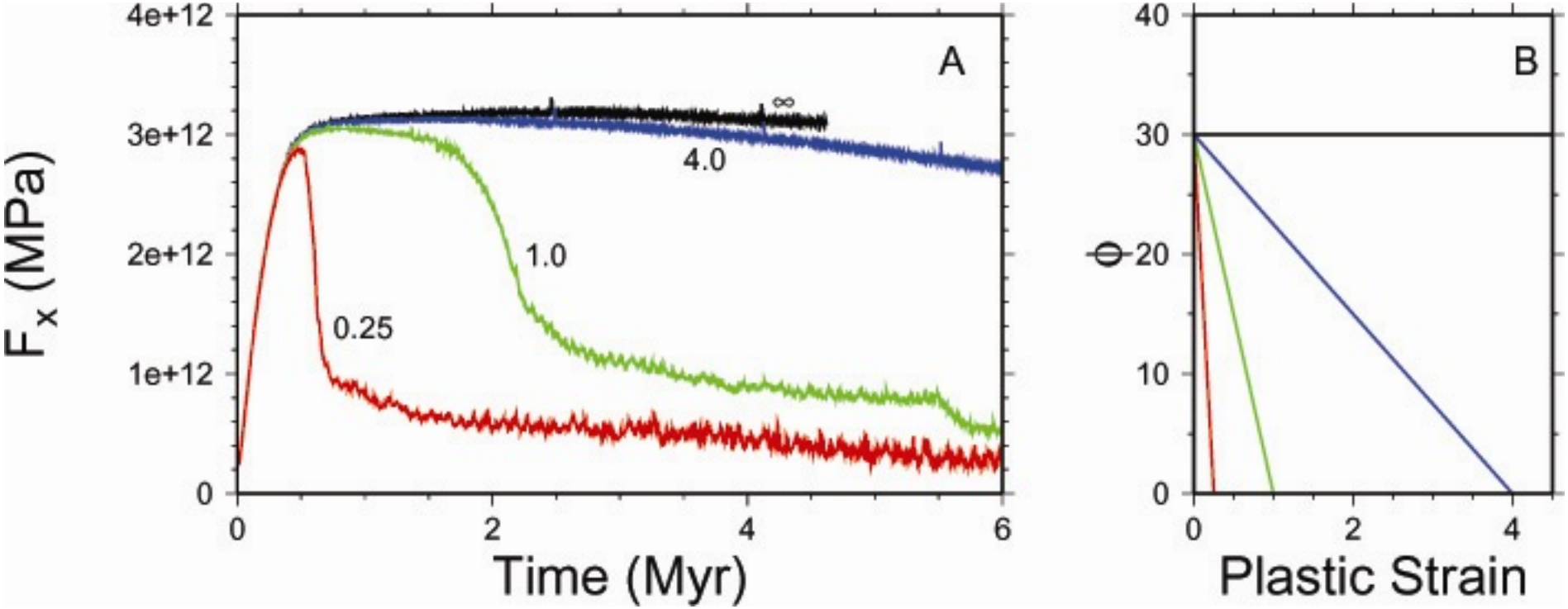


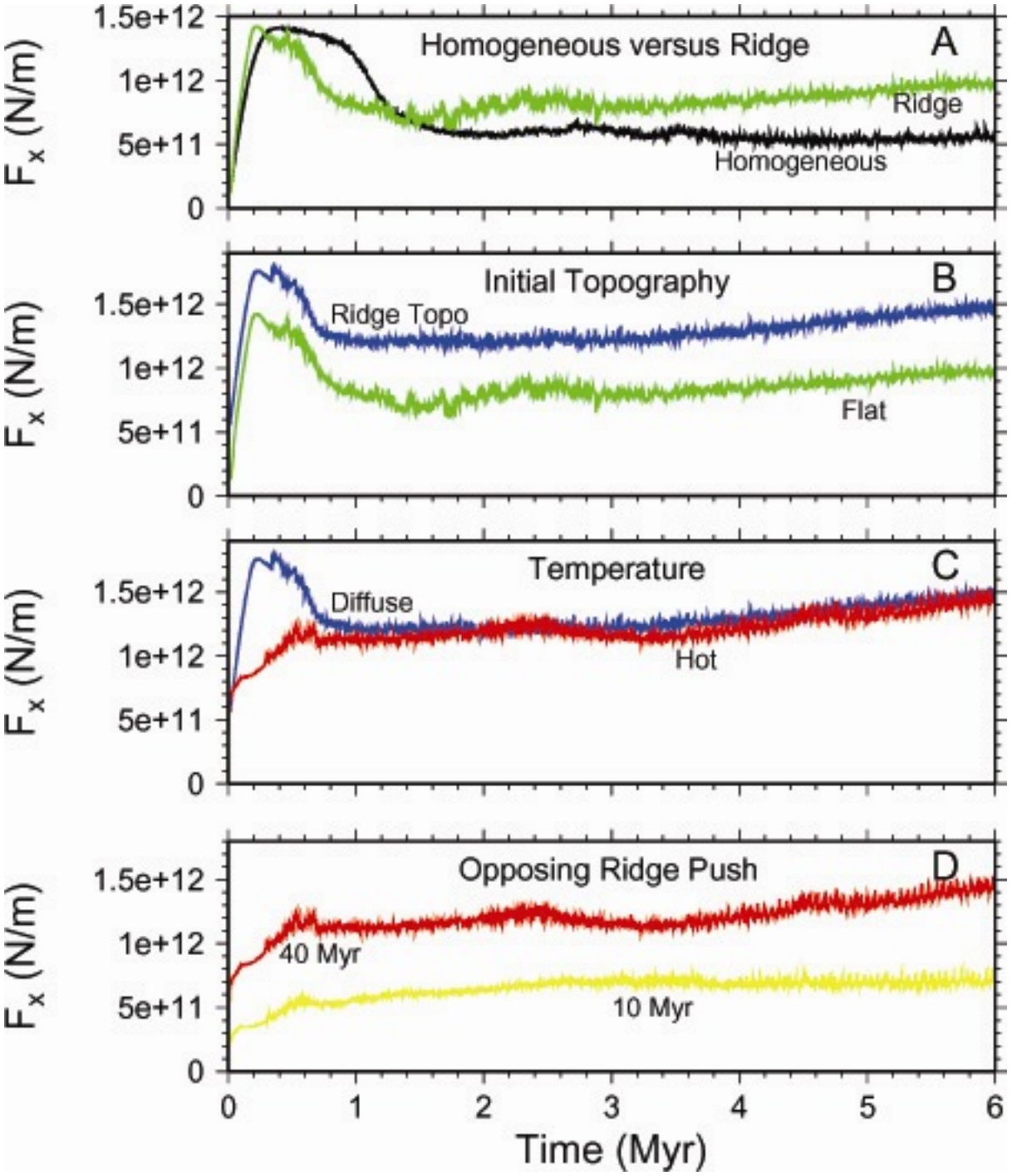
Initial (temperature-dependent) viscosity structure



Thinning of mechanical boundary layer as water lowers viscosity


Convergence Rate
A
2 cm/yr
1 cm/yr
Distance (km)
Lithospheric Age
B
7 Myr
30 Myr
Mantle Viscosity
C
10^19 Pa s
10^21 Pa s
10^20 Pa s
Crustal Thickness
D
12
6
0
Time (Myr)
F_x (N/m)


A
B
F_x (MPa)
4e+12
3e+12
2e+12
1e+12
0
0
2
4
6
Time (Myr)
∞
4.0
1.0
0.25
40
30
20
10
0
0
2
4
Plastic Strain
Θ


Homogeneous versus Ridge
A
Ridge
Homogeneous
Initial Topography
B
Ridge Topo
Flat
Temperature
C
Diffuse
Hot
Opposing Ridge Push
D
40 Myr
10 Myr
F_x (N/m)
1.5e+12
1e+12
5e+11
0
0
1
2
3
4
5
6
Time (Myr)