Hot Continental Tectonics:

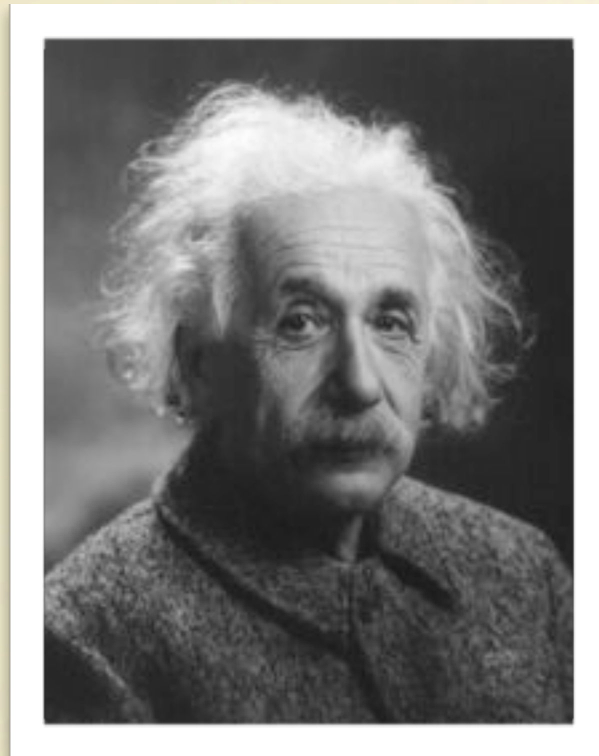
Deformation, flow, stress and strain

Insights from numerical experiments

Patrice F. Rey,
Nicolas Thébaud, Guillaume Duclaux, Nicolas Flament
Christian Teyssier, Donna L. Whitney
Greg Houseman, Nicolas Coltice
Louis Moresi, Julian Giordani, John Mansour

EarthBYTE
Linking observations to kinematic and dynamic models

SIDERE MENS EADEM MUTATO
The University of Sydney



“If at first the idea is not absurd, then there is no hope for it.”

- Deformation of hot continents consequences for early Earth
- Early continents and plate tectonics
- Strain regimes in hot crusts

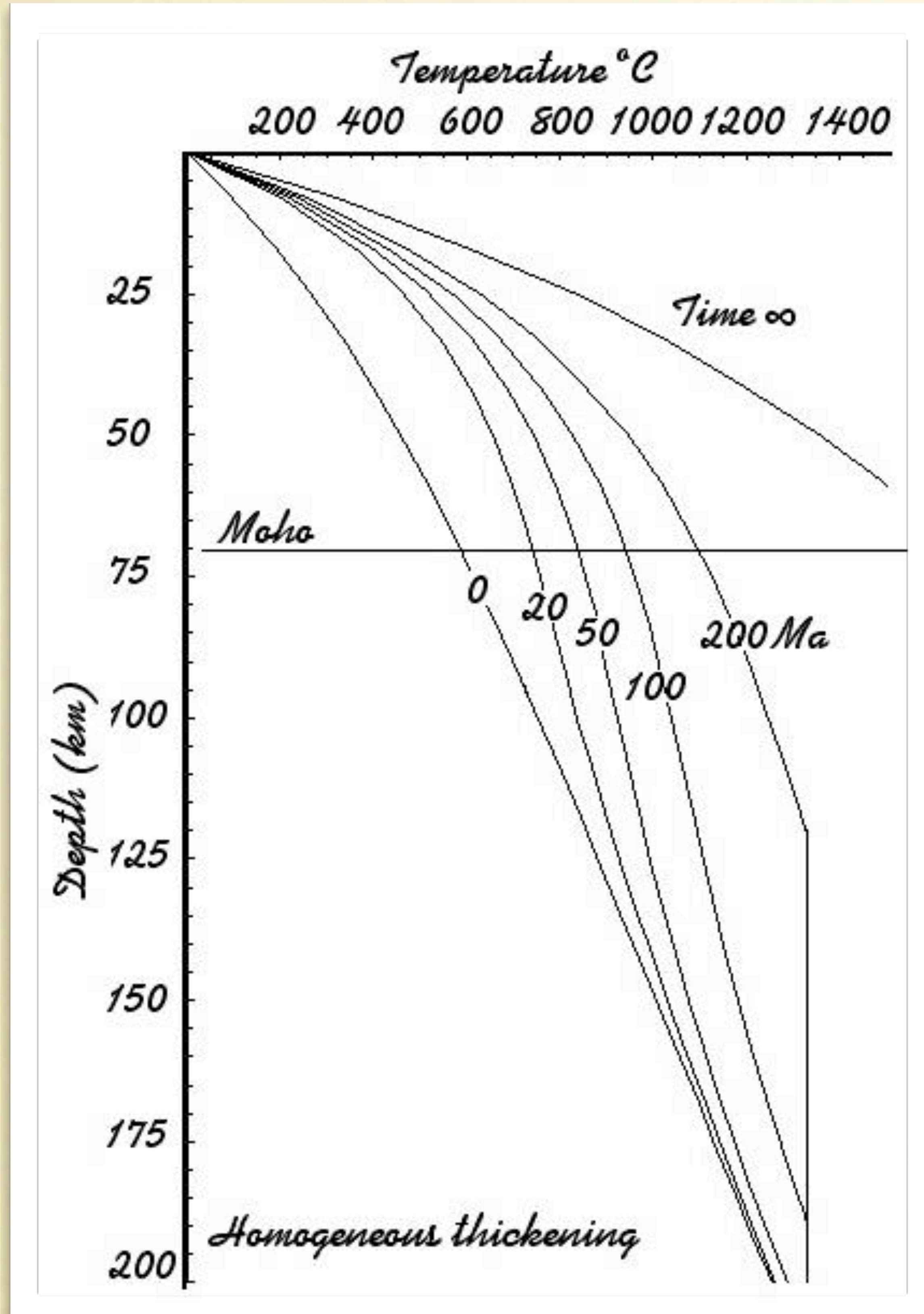
DEFORMATION OF HOT CONTINENTS

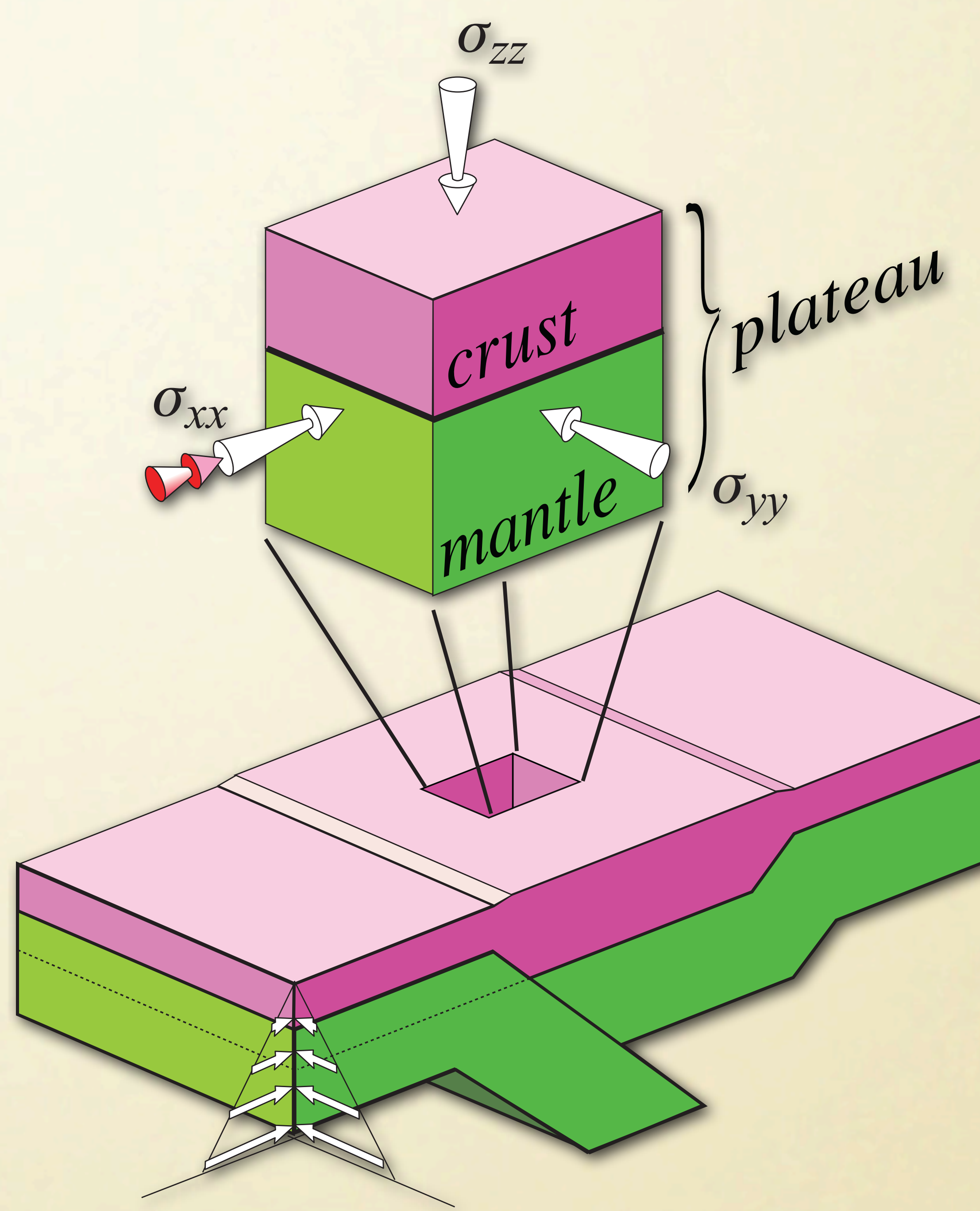
Hot?

$T_{MOHO} > 0.85\ T_{MELT}$

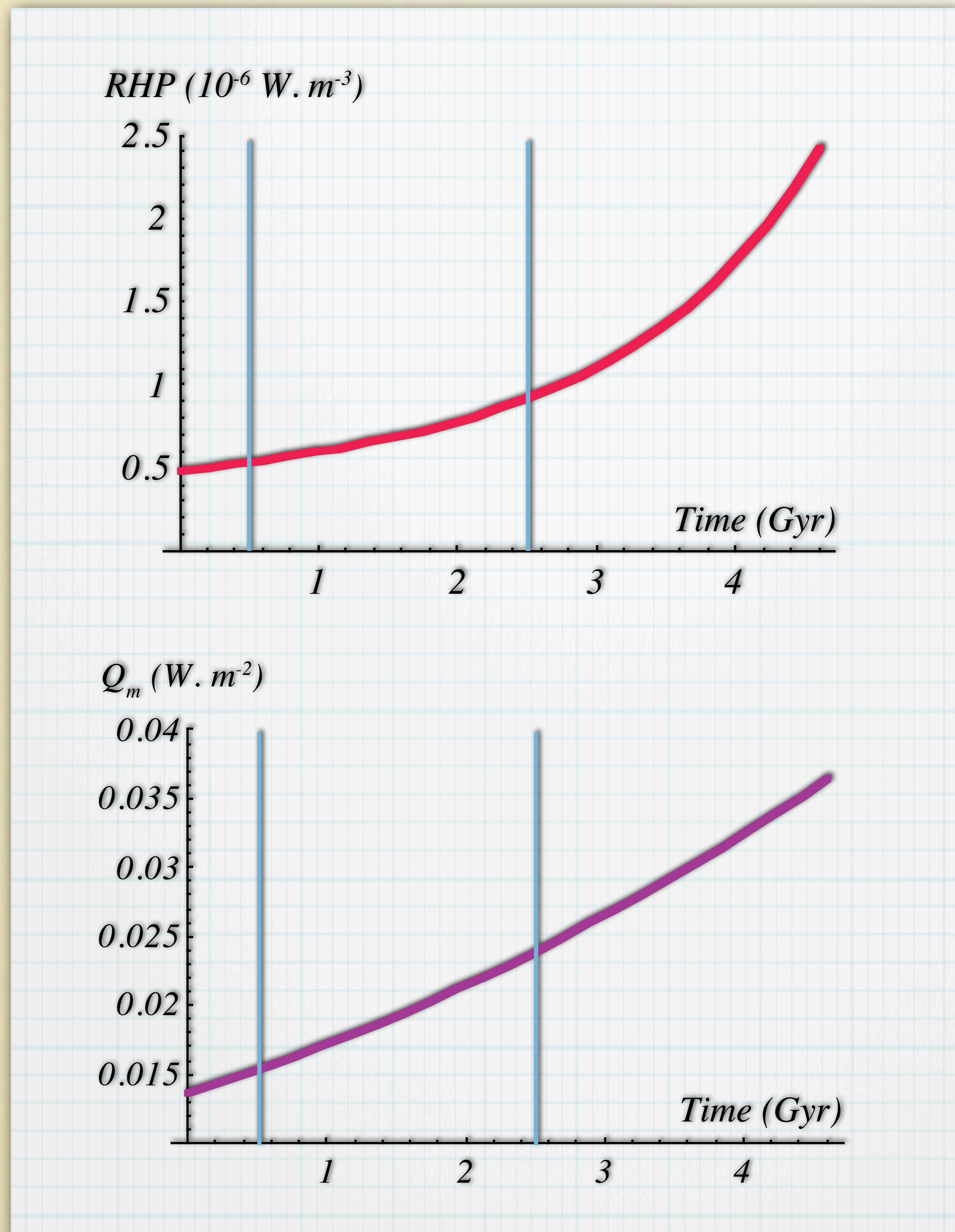
Where do hot continents come from?

- Crustal thickening

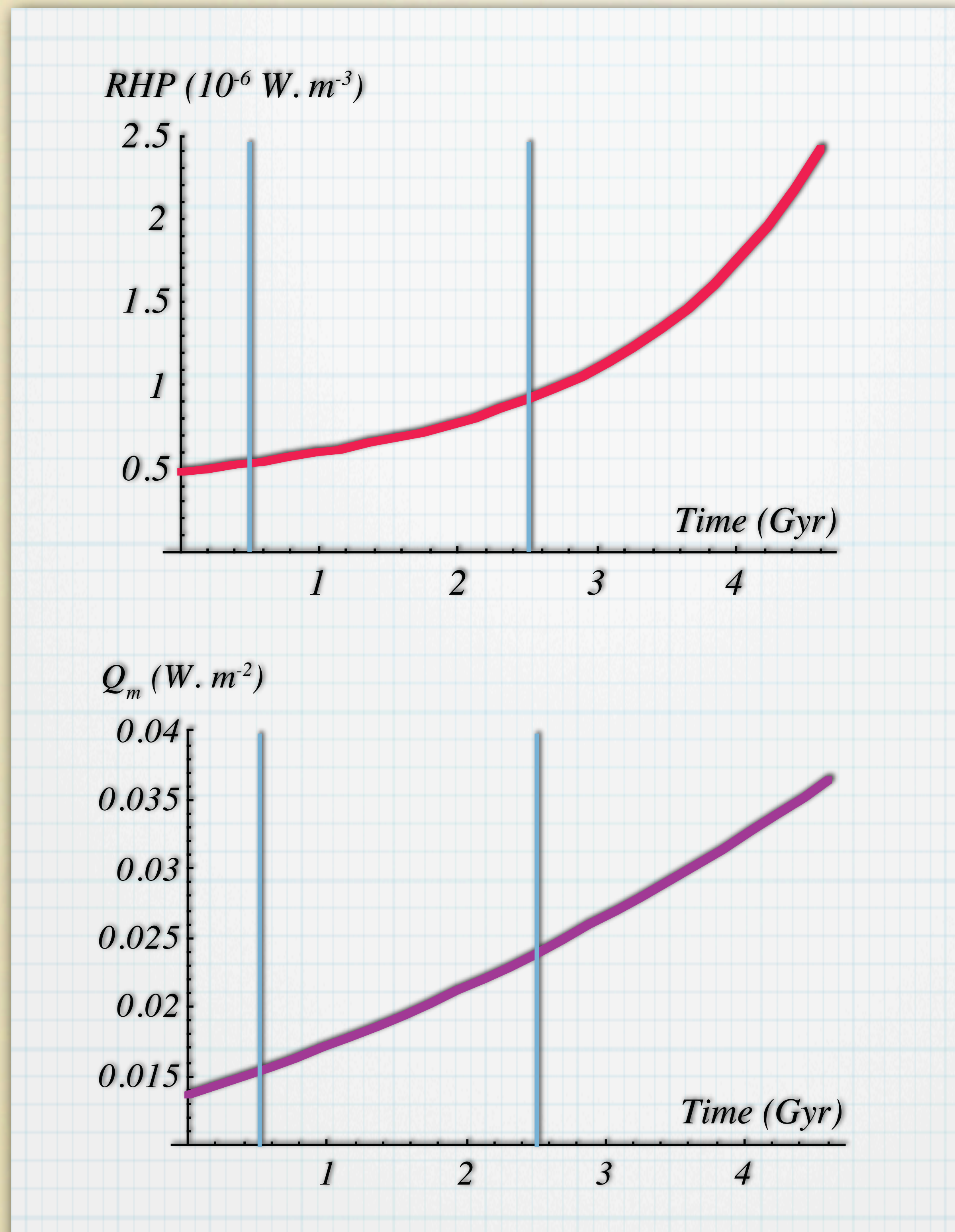


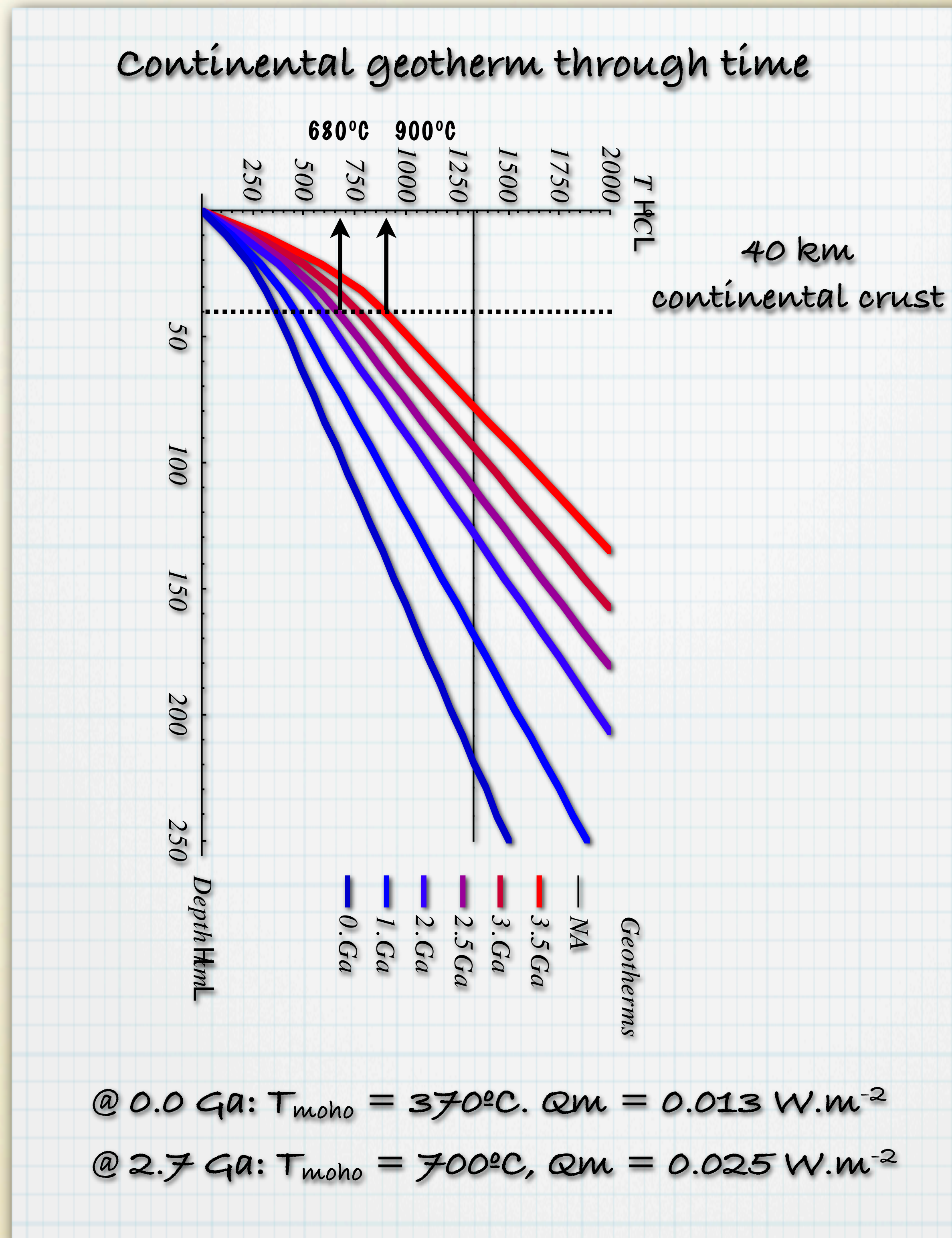


• Continental geotherm through time

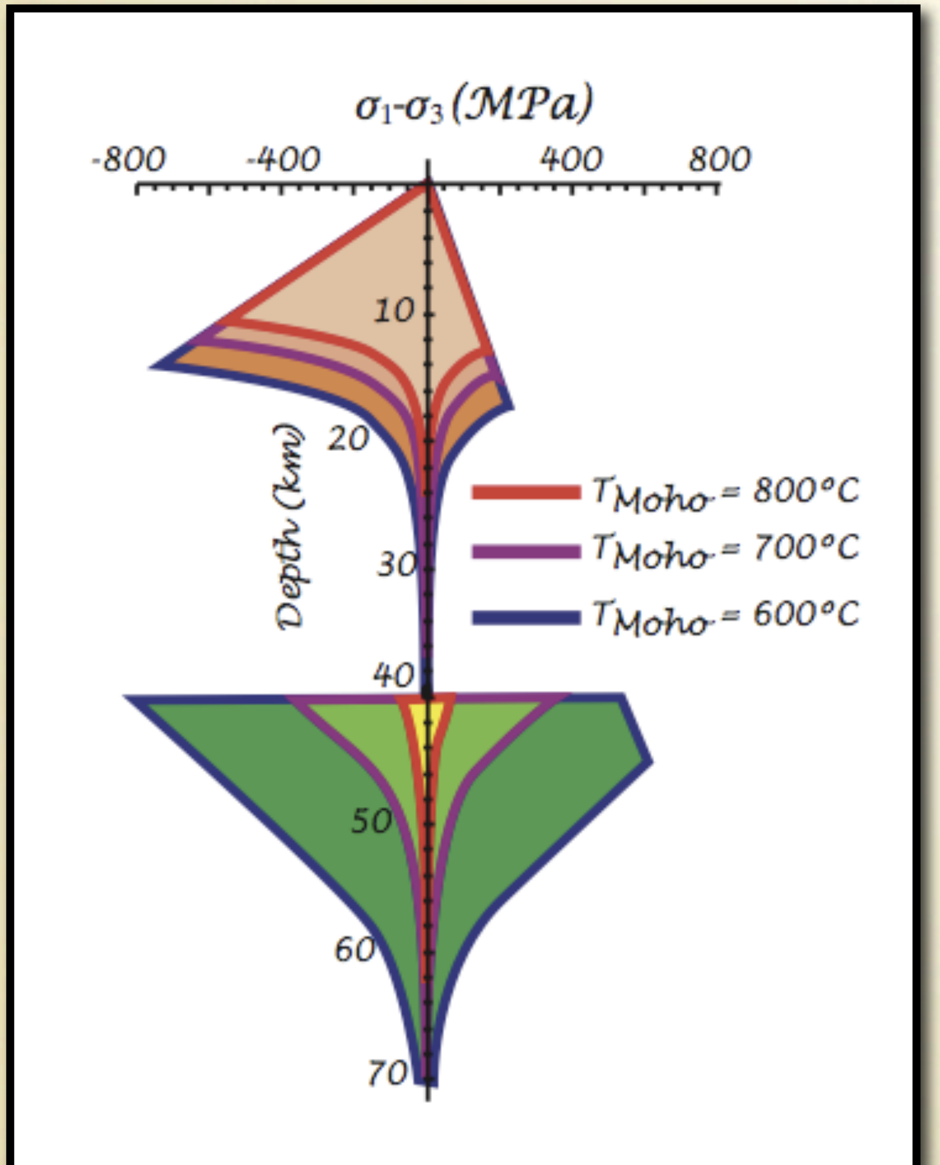


- Continental geotherm through time

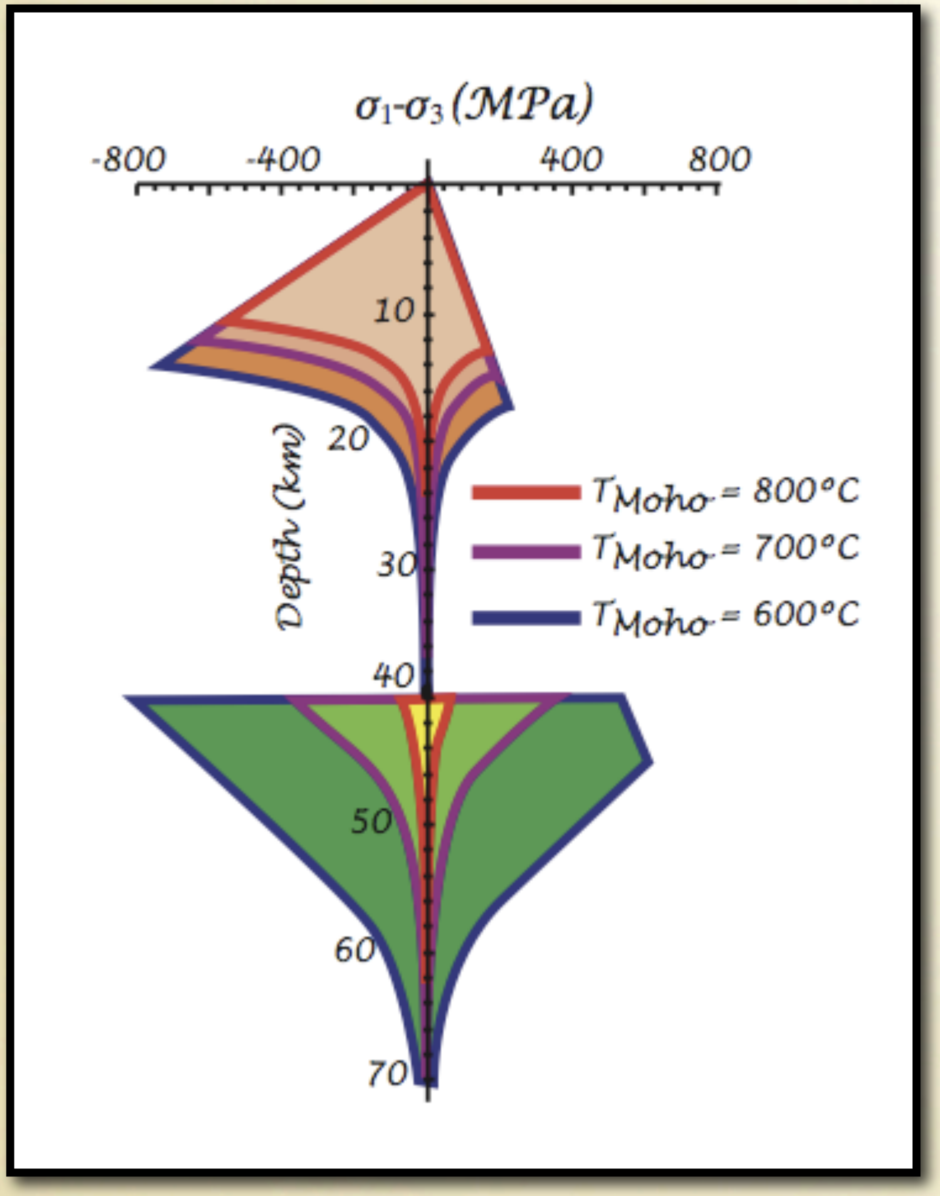


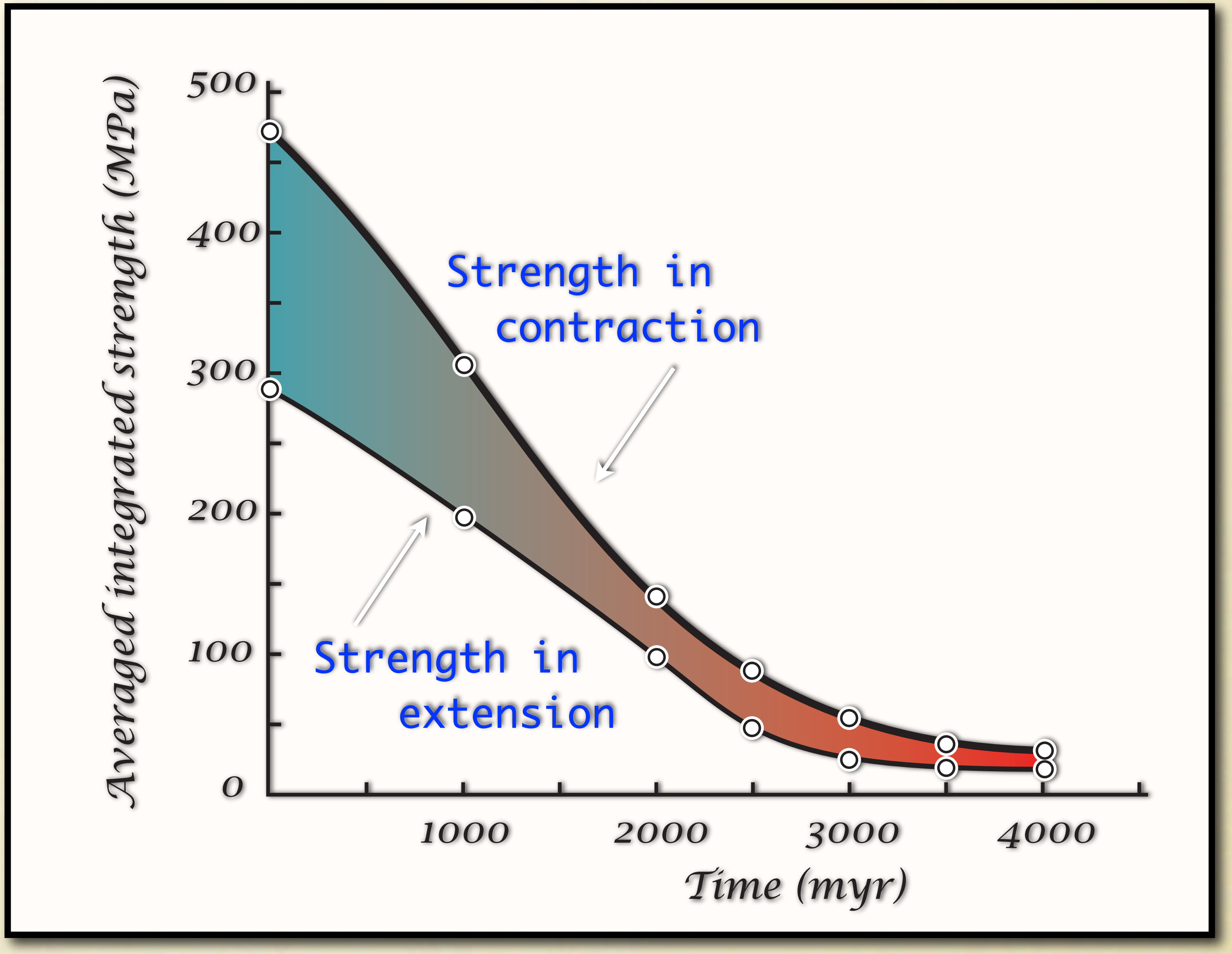


Viscous forces through time

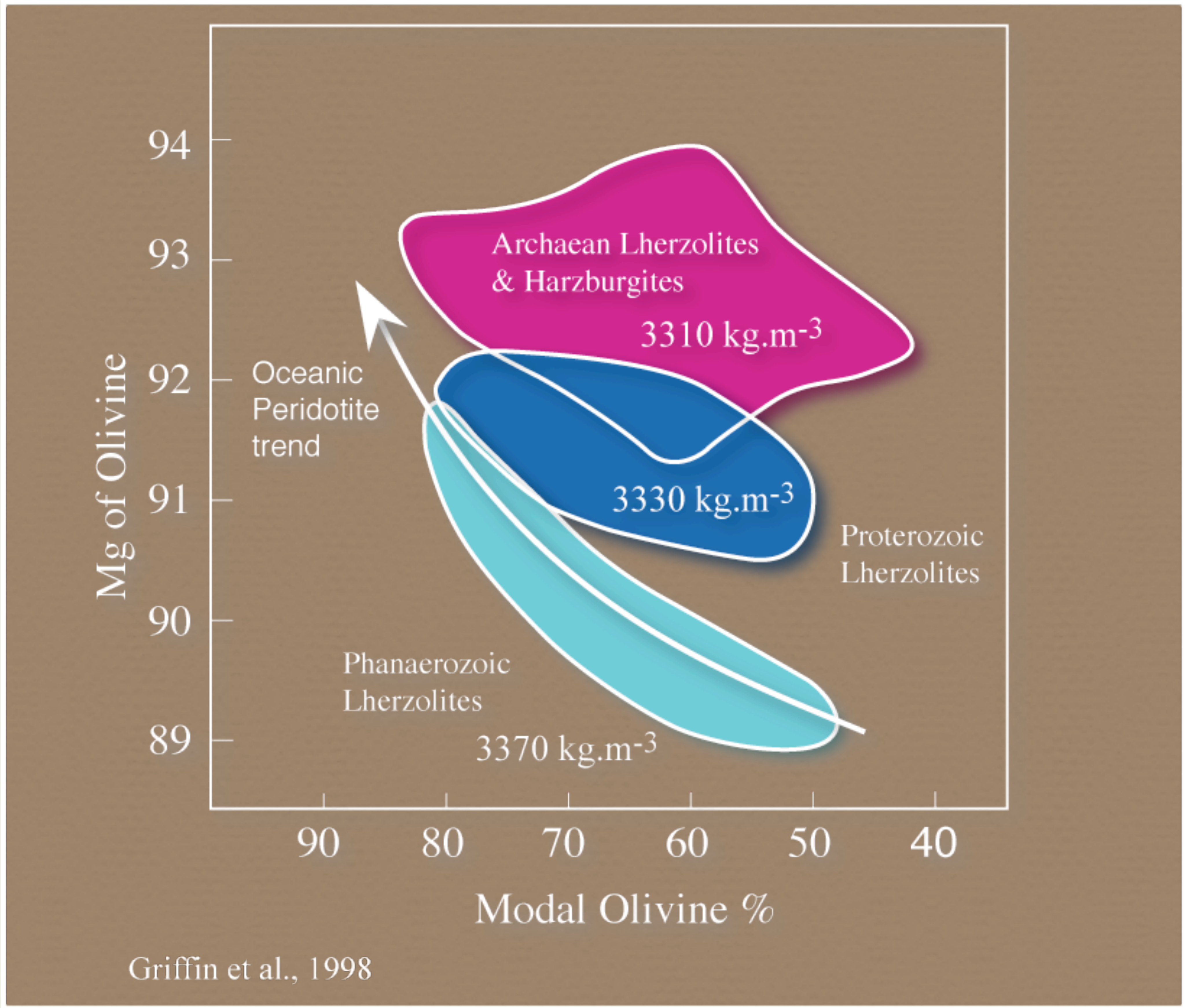


Viscous forces through time

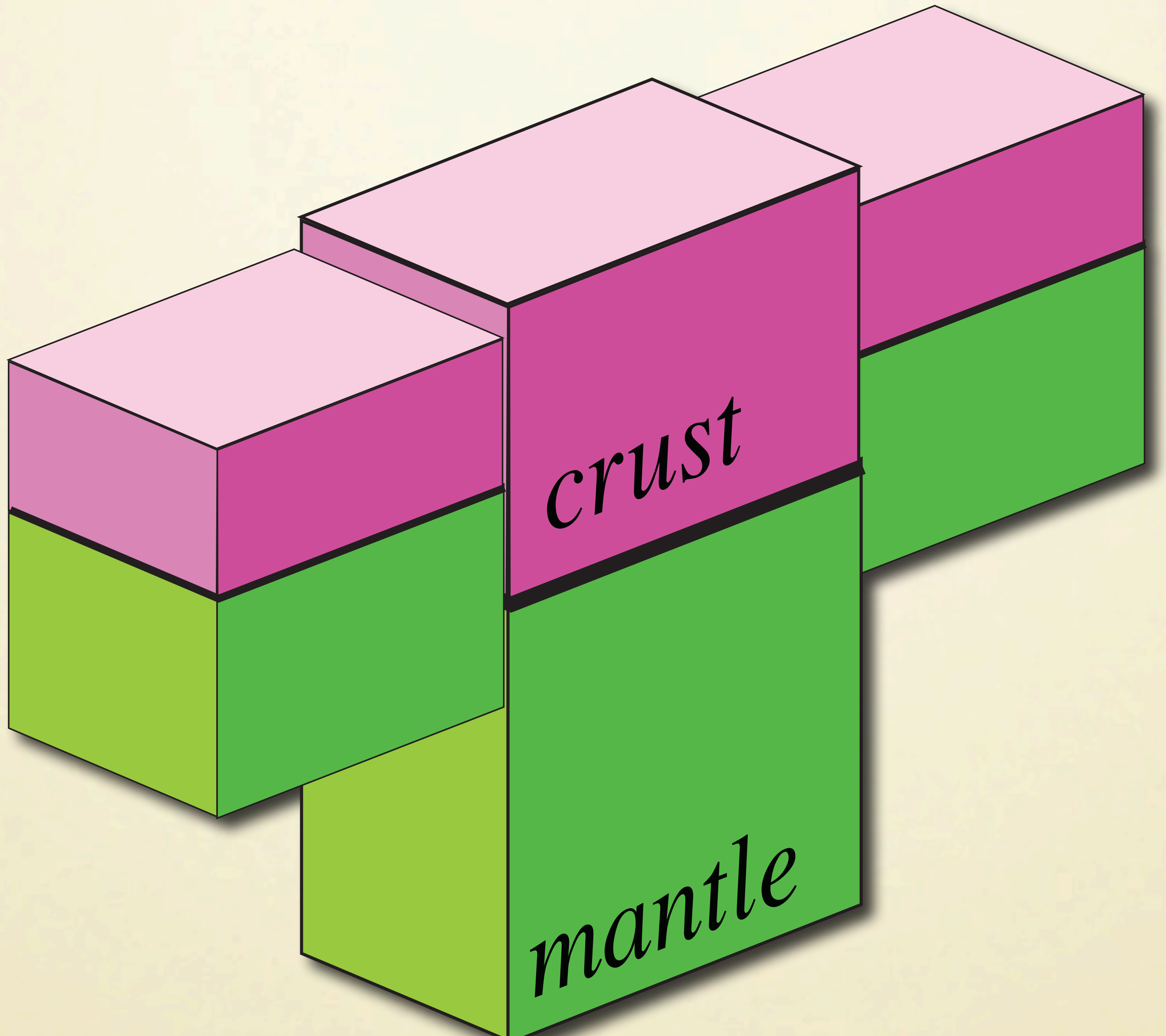




Buoyancy of SCLM

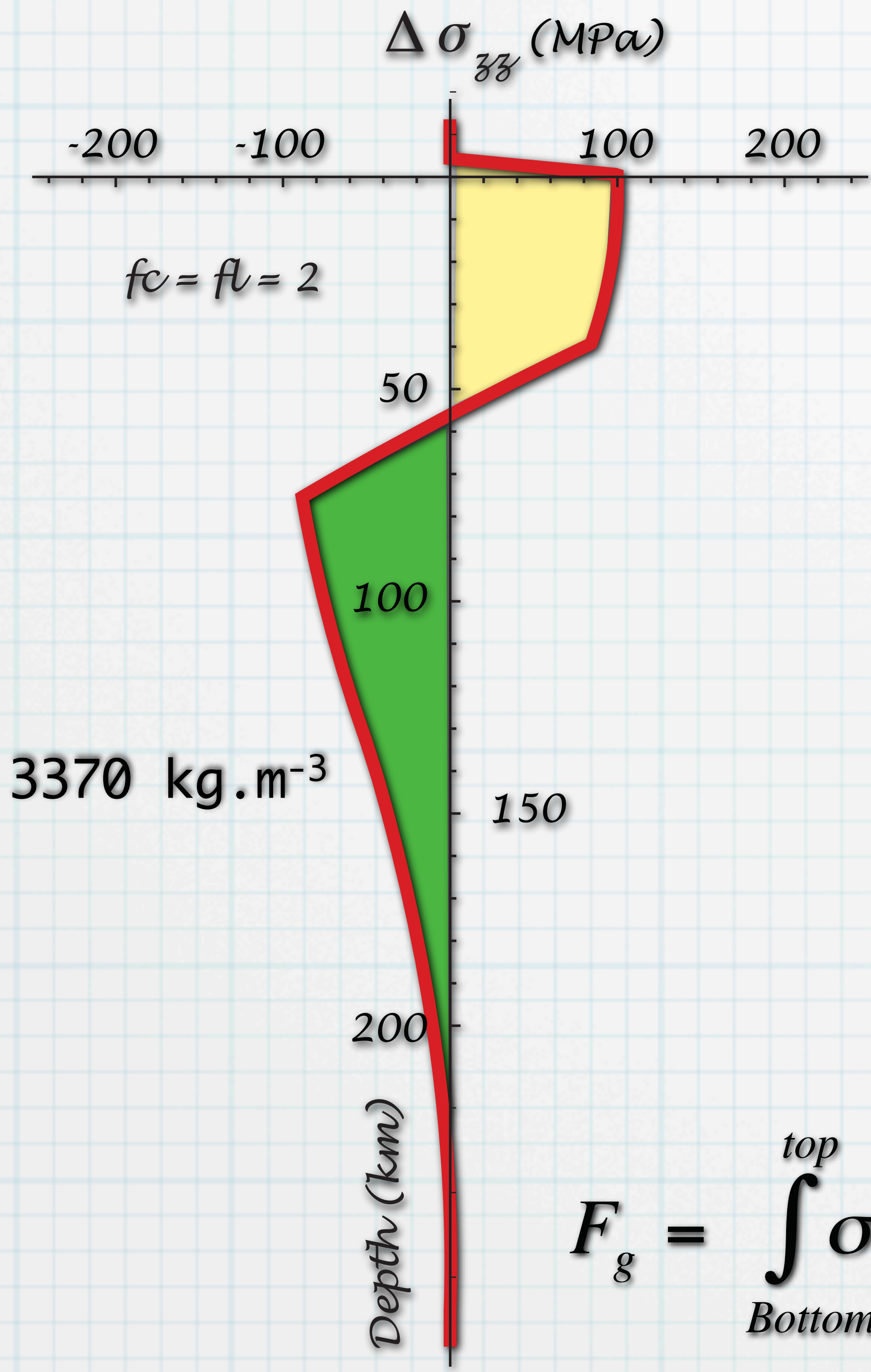


Gravitational forces...

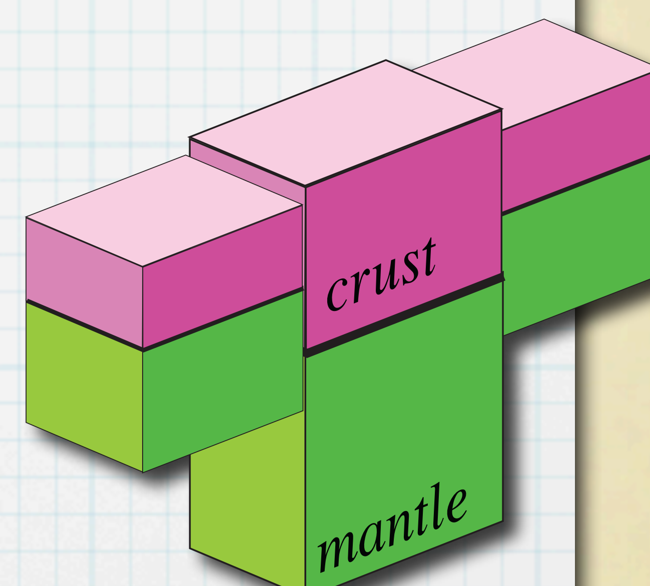


Gravitational forces...

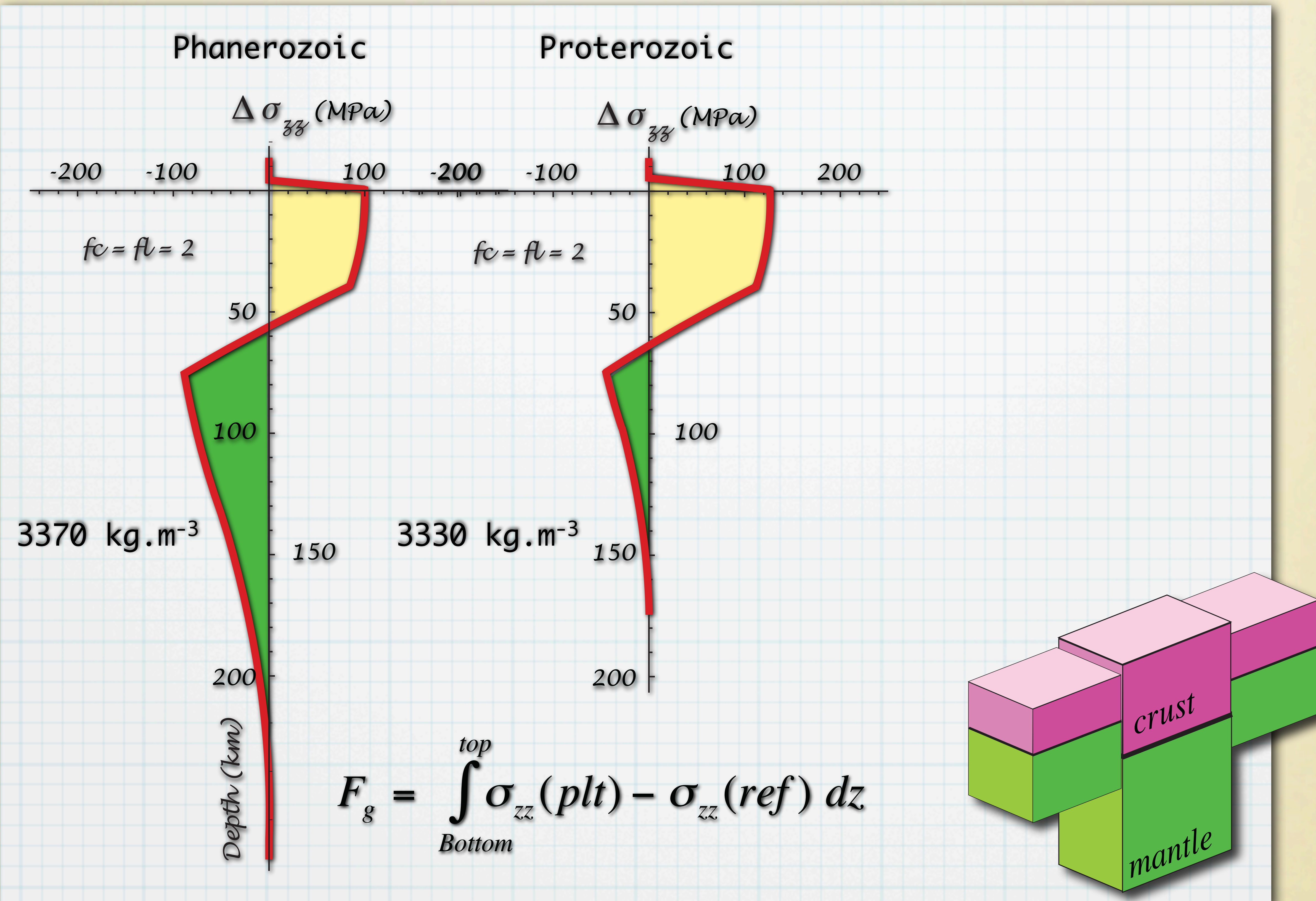
Phanerozoic



$$F_g = \int_{Bottom}^{top} \sigma_{zz}(plt) - \sigma_{zz}(ref)\, dz$$

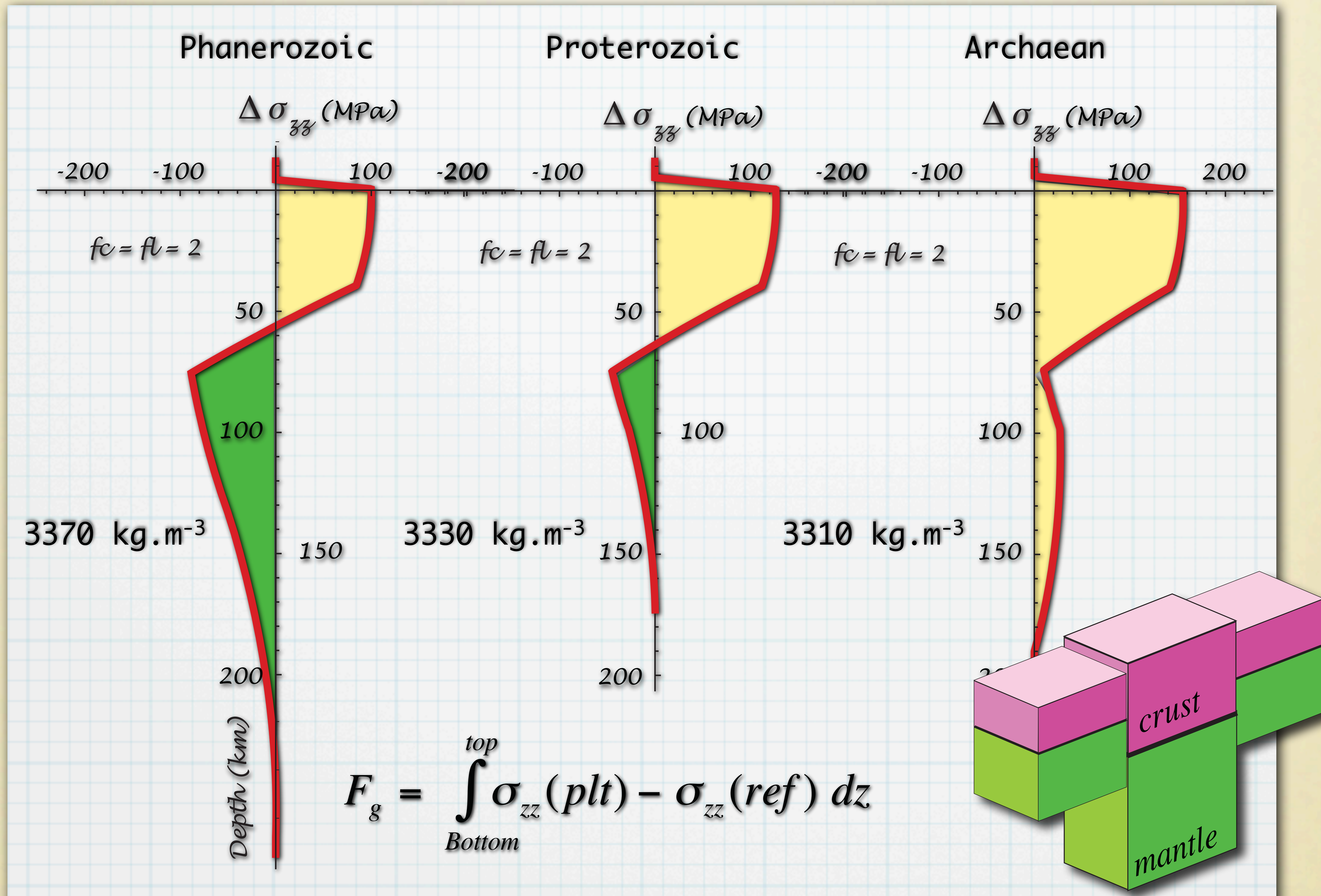


Gravitational forces...



$$F_g = \int_{Bottom}^{top} \sigma_{zz}(plt) - \sigma_{zz}(ref)\, dz$$

Gravitational forces...



$$F_g = \int_{Bottom}^{top} \sigma_{zz}(plt) - \sigma_{zz}(ref)\, dz$$

Thin viscous sheet equations in a triaxial situation

$$\sigma_{xx} - \sigma_{yy} = 2\,\eta\,(\dot{\varepsilon}_{xx} - \dot{\varepsilon}_{yy})$$

$$\sigma_{zz} - \sigma_{yy} = 2\,\eta\,(\dot{\varepsilon}_{zz} - \dot{\varepsilon}_{yy})$$

$$\sigma_{zz} - \sigma_{xx} = 2\,\eta\,(\dot{\varepsilon}_{zz} - \dot{\varepsilon}_{xx})$$

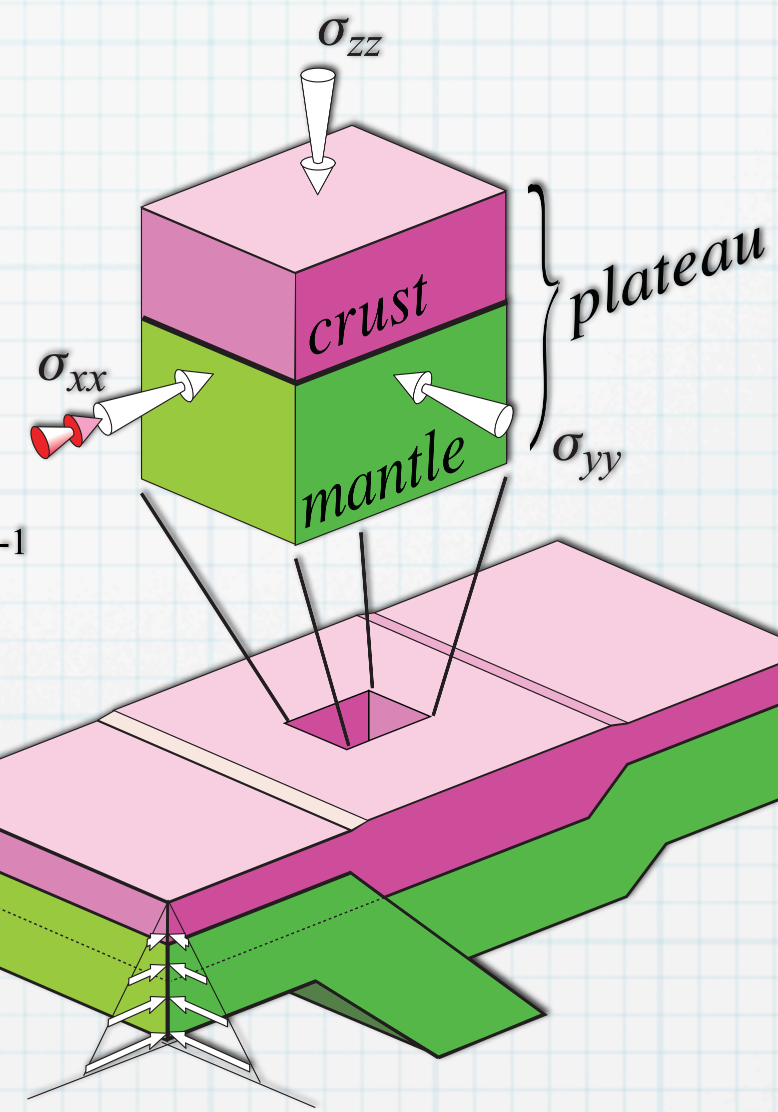
$$\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy} + \dot{\varepsilon}_{zz} = 0$$

$$\dot{\varepsilon}_{zz} = \frac{1}{6\,\eta}(2\,\sigma_{zz} - \sigma_{xx} - \sigma_{yy})$$

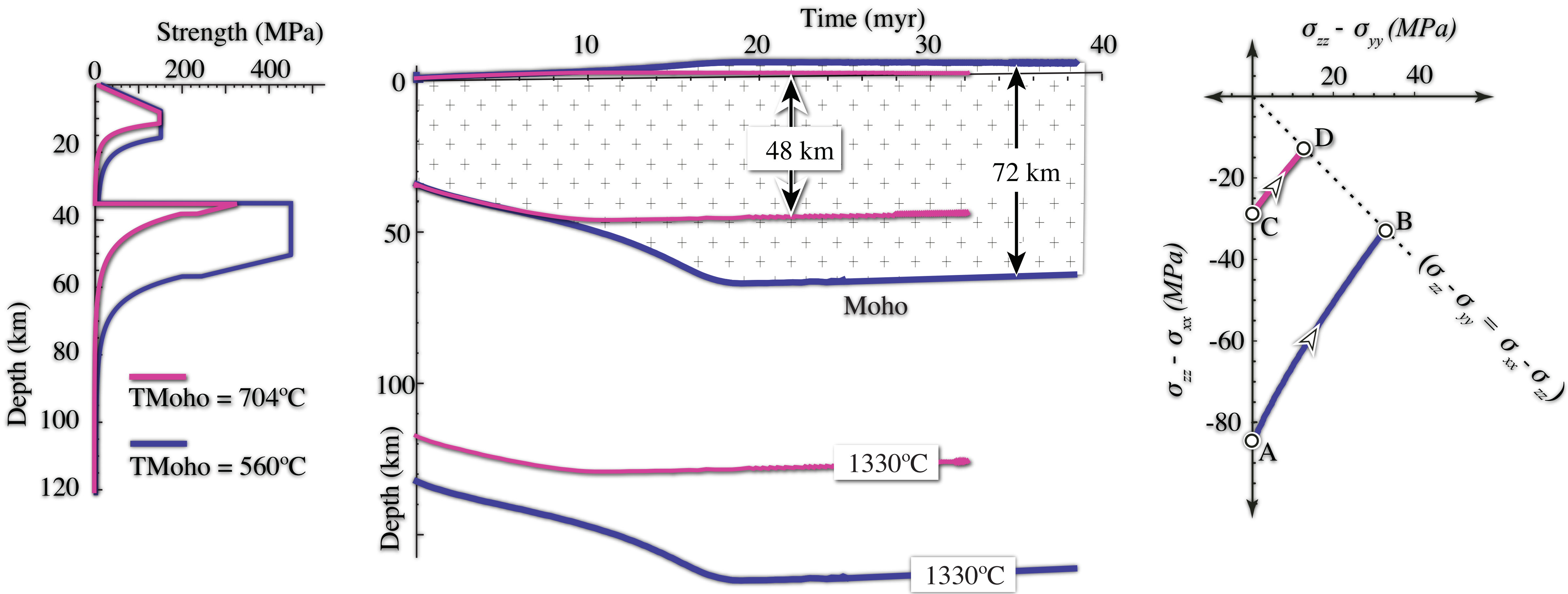
$$\dot{\varepsilon}_{yy} = \frac{1}{6\,\eta}(2\,\sigma_{yy} - \sigma_{zz} - \sigma_{xx})$$

$$\dot{\varepsilon}_{xx} = \frac{1}{6\,\eta}(2\,\sigma_{xx} - \sigma_{zz} - \sigma_{yy})$$

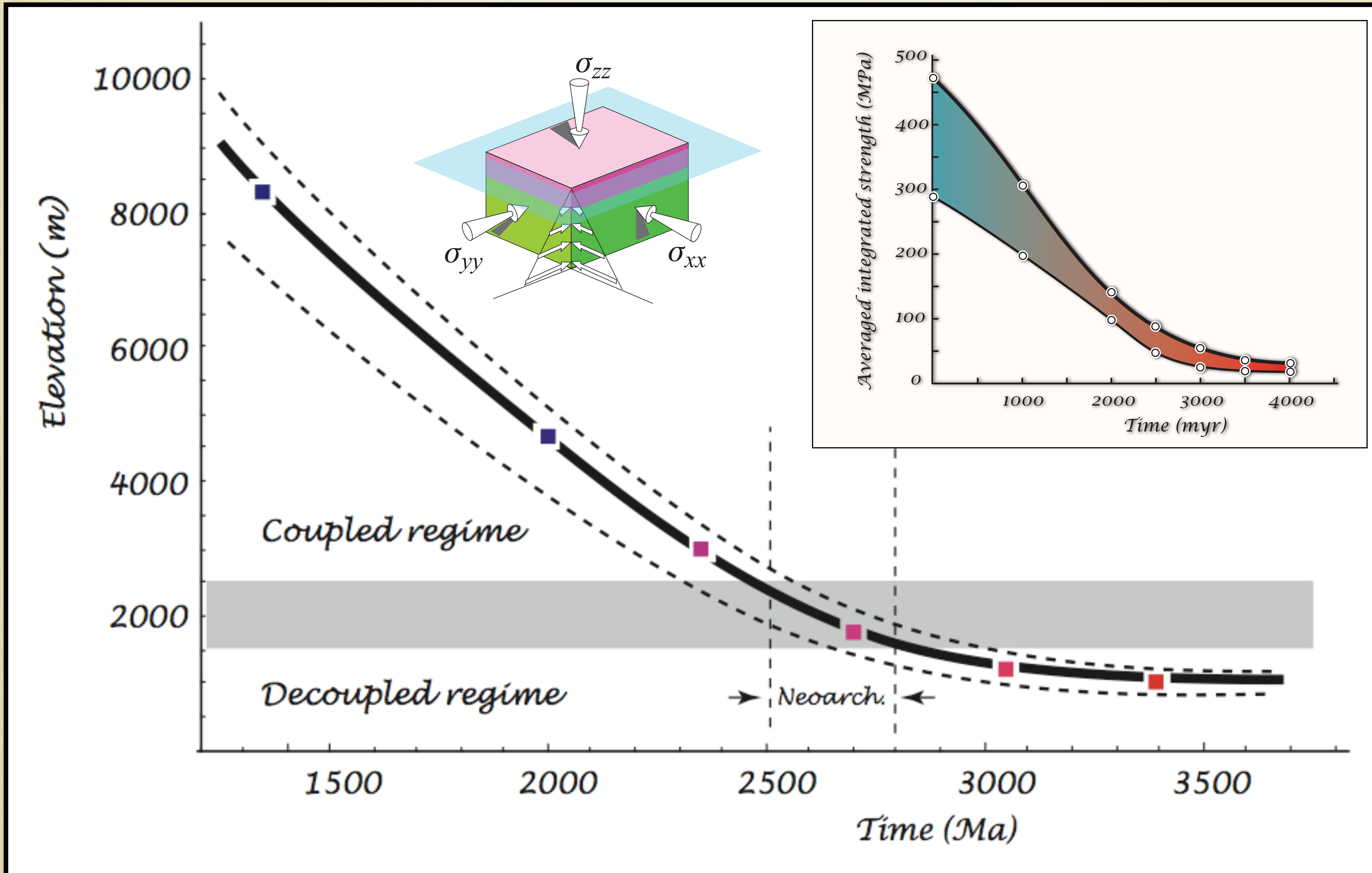
$(\varepsilon_{xx})_{init} = 5 \times 10^{-15}\ s^{-1}$



Triaxial stress, Local isostasy, Radiogenic heating



Strength (MPa)
0
200
400
20
40
60
80
100
120
Depth (km)
TMoho = 704ºC
TMoho = 560ºC
Time (myr)
10
20
30
40
0
50
100
48 km
72 km
Moho
1330ºC
1330ºC
Depth (km)
σzz - σyy (MPa)
20
40
-20
-40
-60
-80
σzz - σxx (MPa)
A
B
C
D
(σzz - σyy = σxx - σzz)



Elevation (m)
10000
8000
6000
4000
2000
σ_{zz}
σ_{yy}
σ_{xx}
Coupled regime
Decoupled regime
Neoarch.
1500
2000
2500
3000
3500
Time (Ma)
Averaged integrated strength (MPa)
500
400
300
200
100
0
1000
2000
3000
4000
Time (myr)

The Archean Flat Earth Hypothesis

Lithospheric scale gravitational flow: the impact of body forces on orogenic processes from Archaean to Phanerozoic

PATRICE F. REY[1] & GREGORY HOUSEMAN[2]

Geological Society, London, Special Publications, **253**, 2006.

Orogen-parallel flow during continental convergence: Numerical experiments and Archean field examples

Duclaux, Rey, Guillot, Ménot

GEOLOGY, August 2007

Neoarchean lithospheric strengthening and the coupling of Earth's geochemical reservoirs

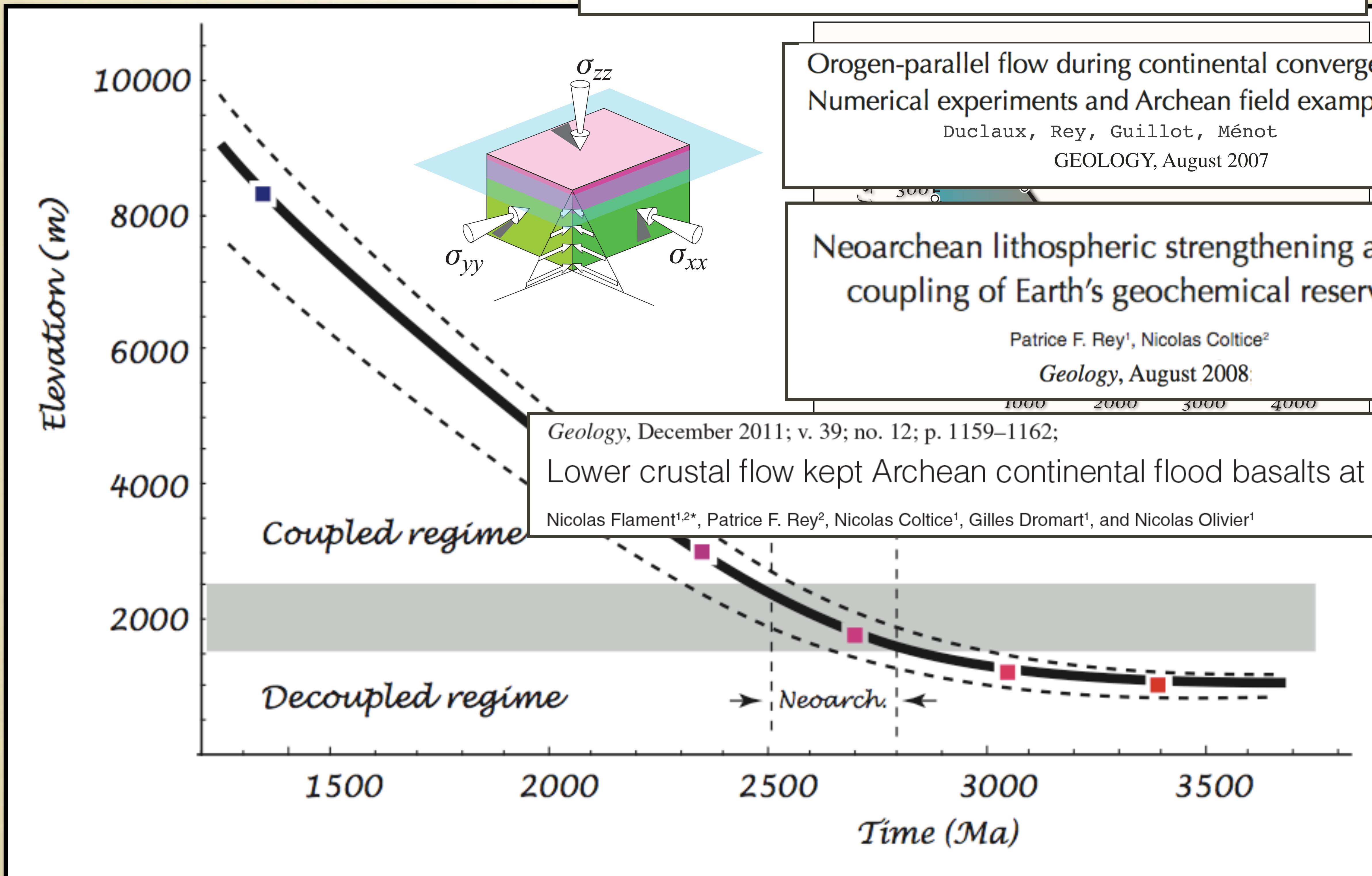
Patrice F. Rey[1], Nicolas Coltice[2]

Geology, August 2008

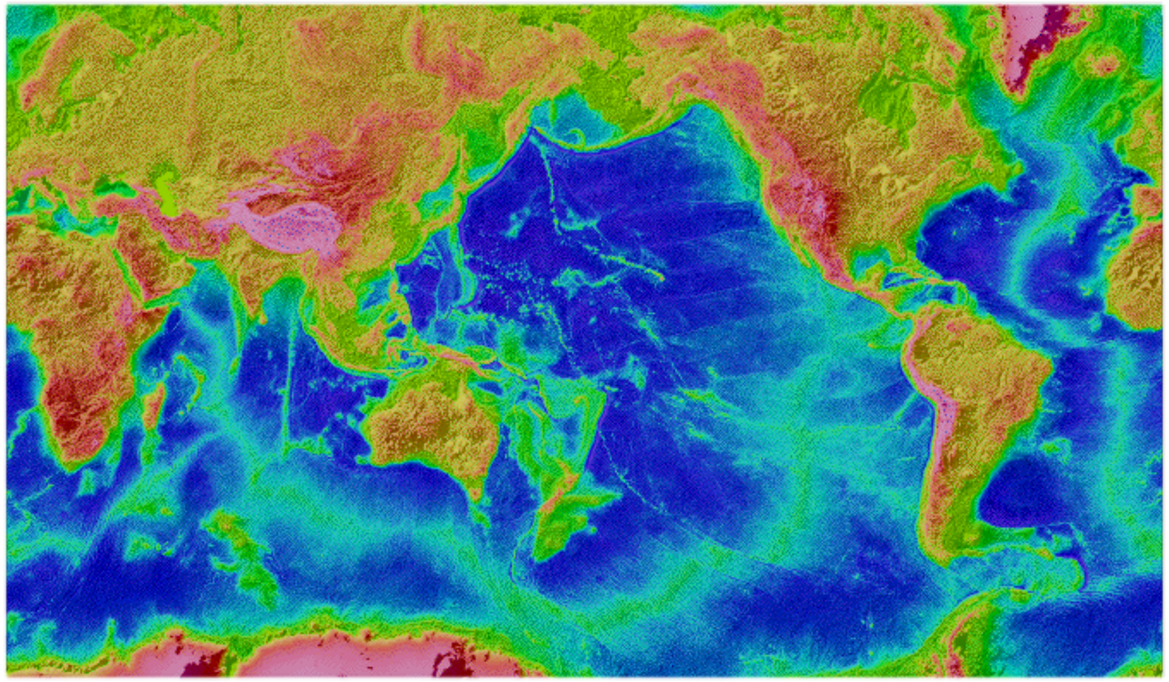
Geology, December 2011; v. 39; no. 12; p. 1159–1162;

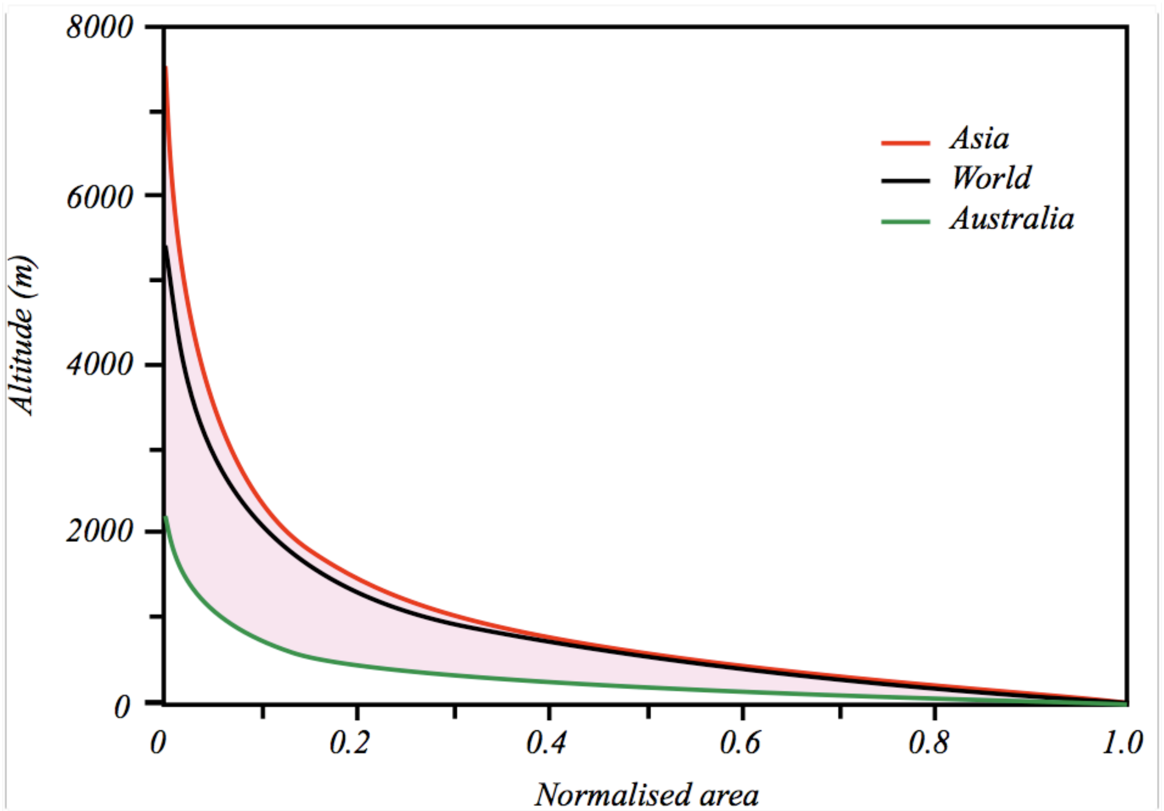
Lower crustal flow kept Archean continental flood basalts at sea level

Nicolas Flament[1,2]*, Patrice F. Rey[2], Nicolas Coltice[1], Gilles Dromart[1], and Nicolas Olivier[1]

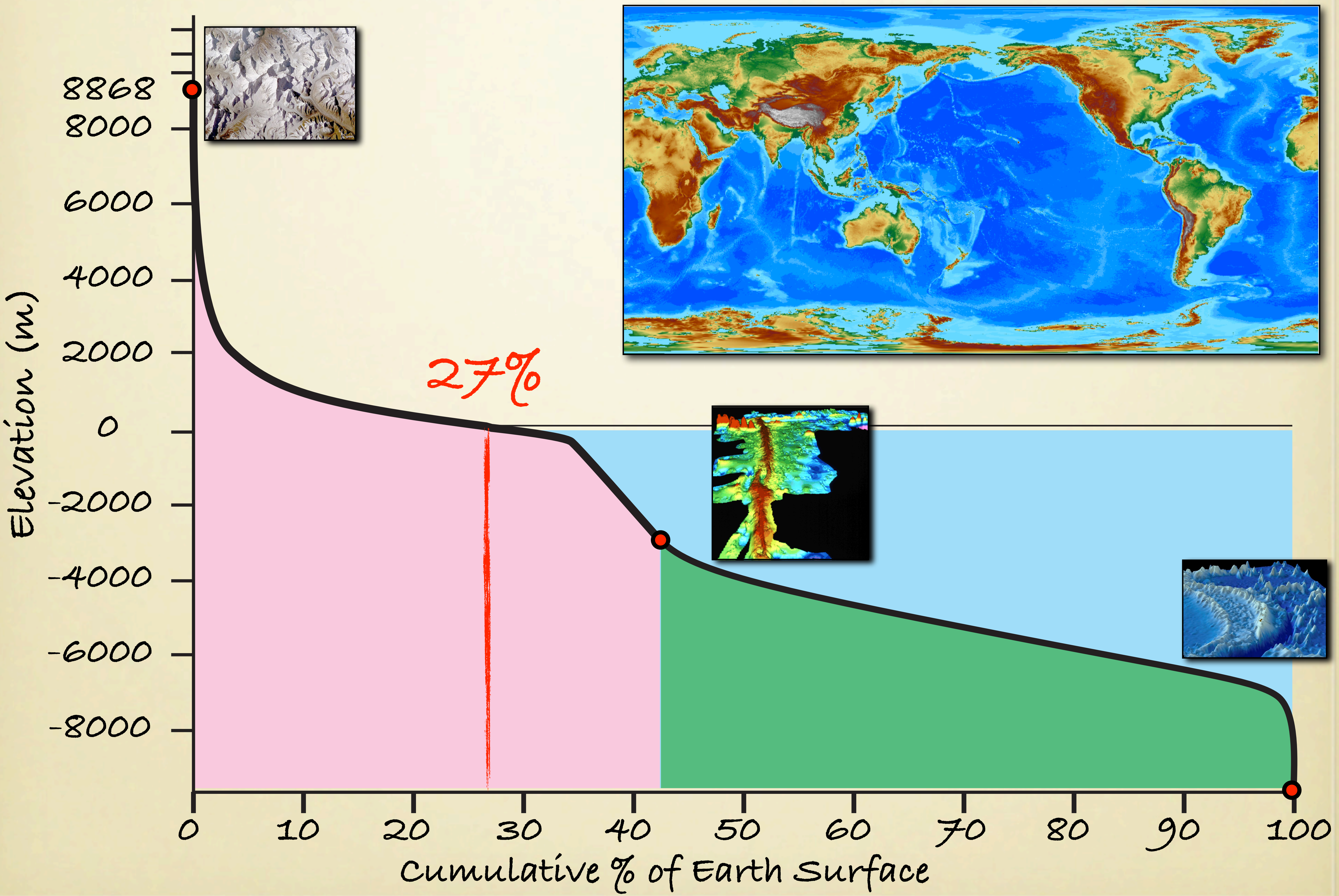


Earth's hypsometry through times: The Archean Flat Earth's Hypothesis





Present-day Earth Hypsometry



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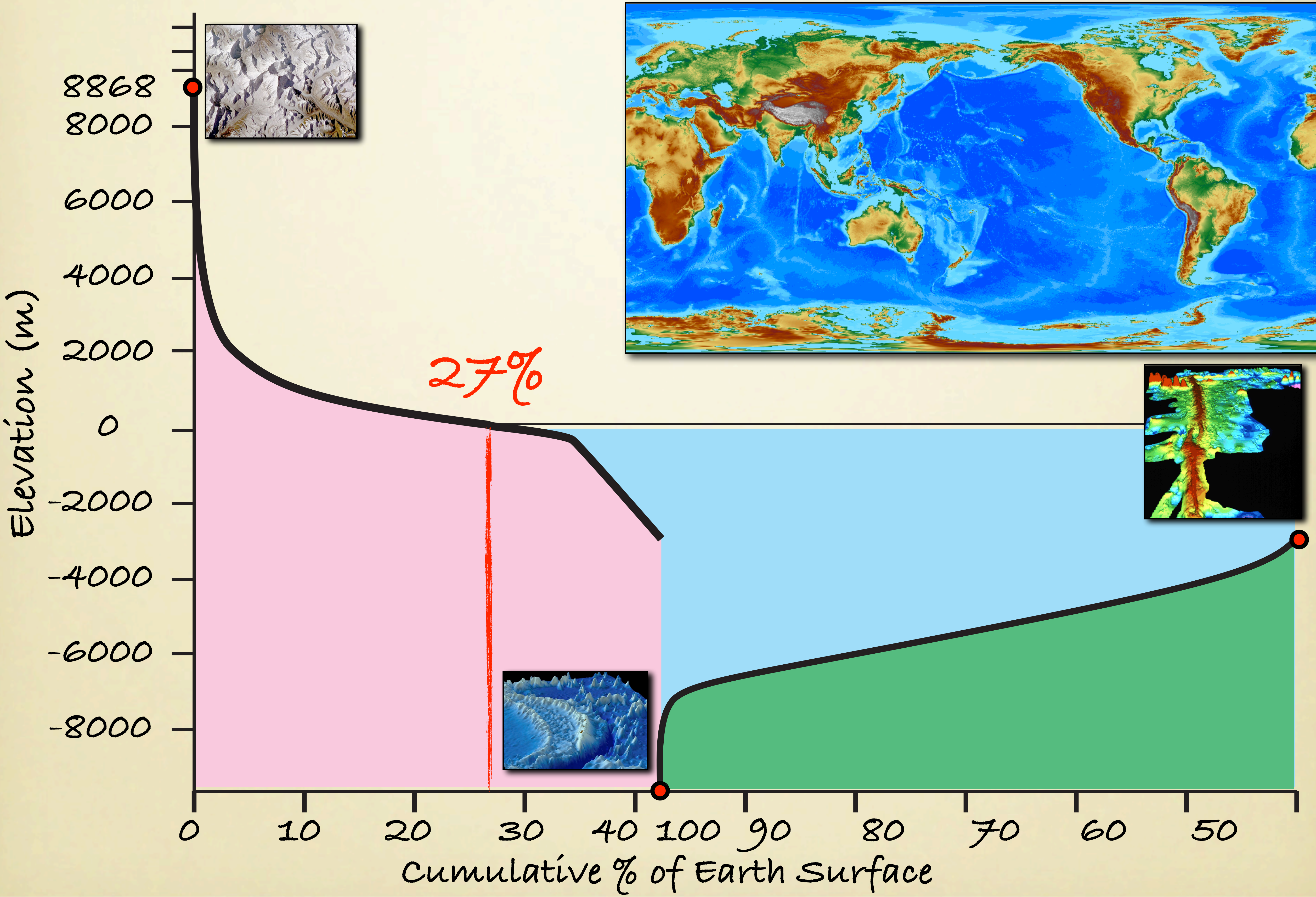
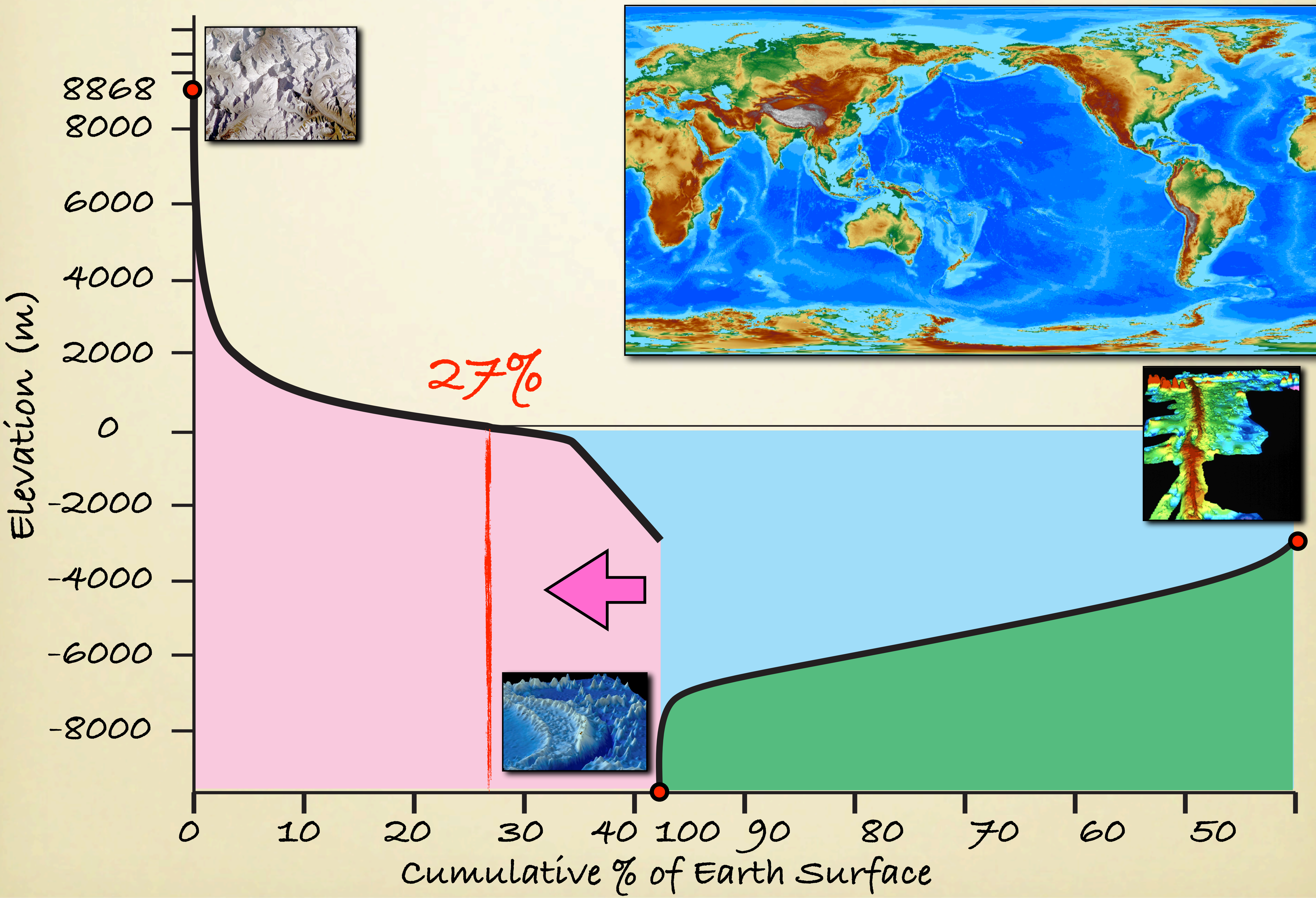
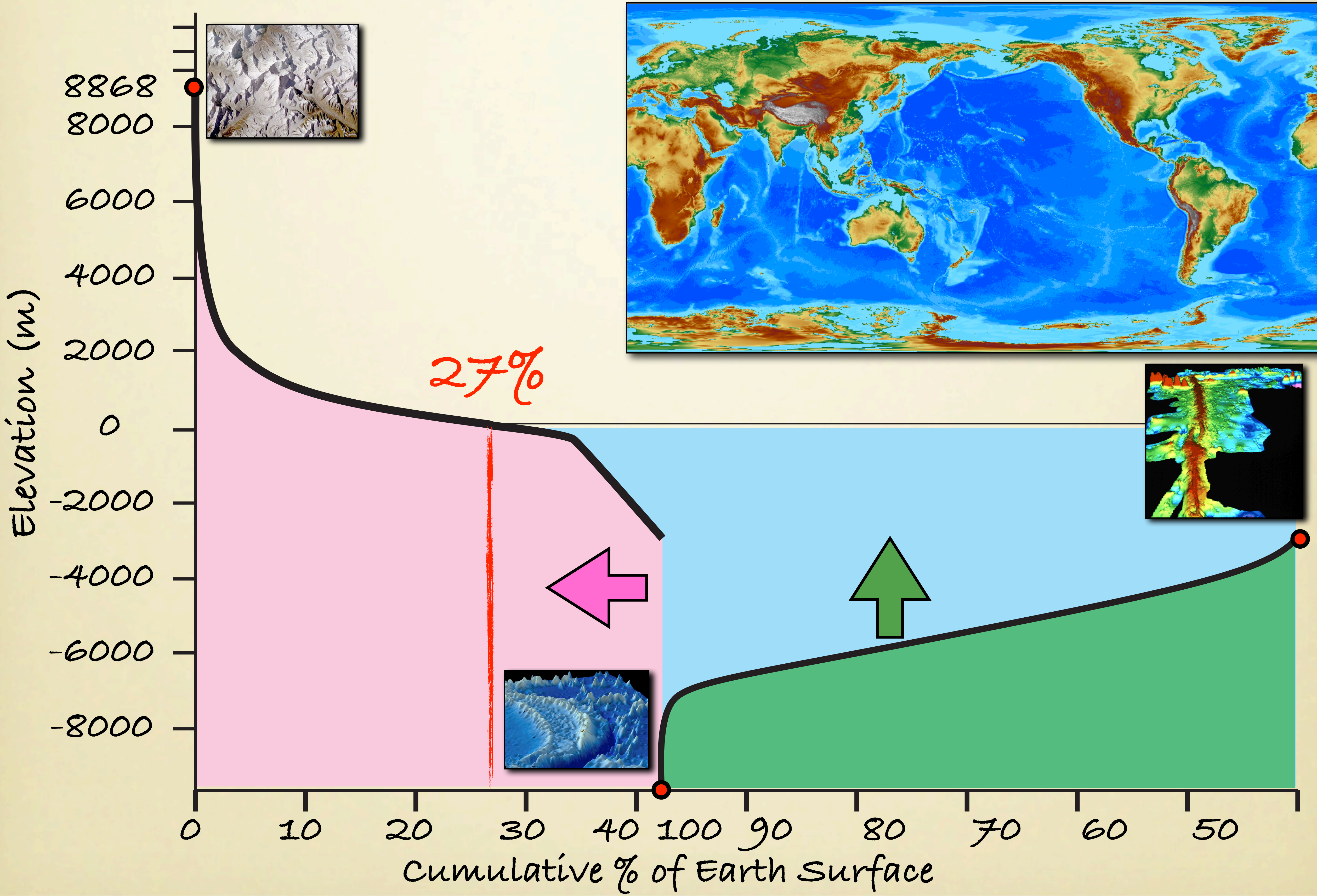


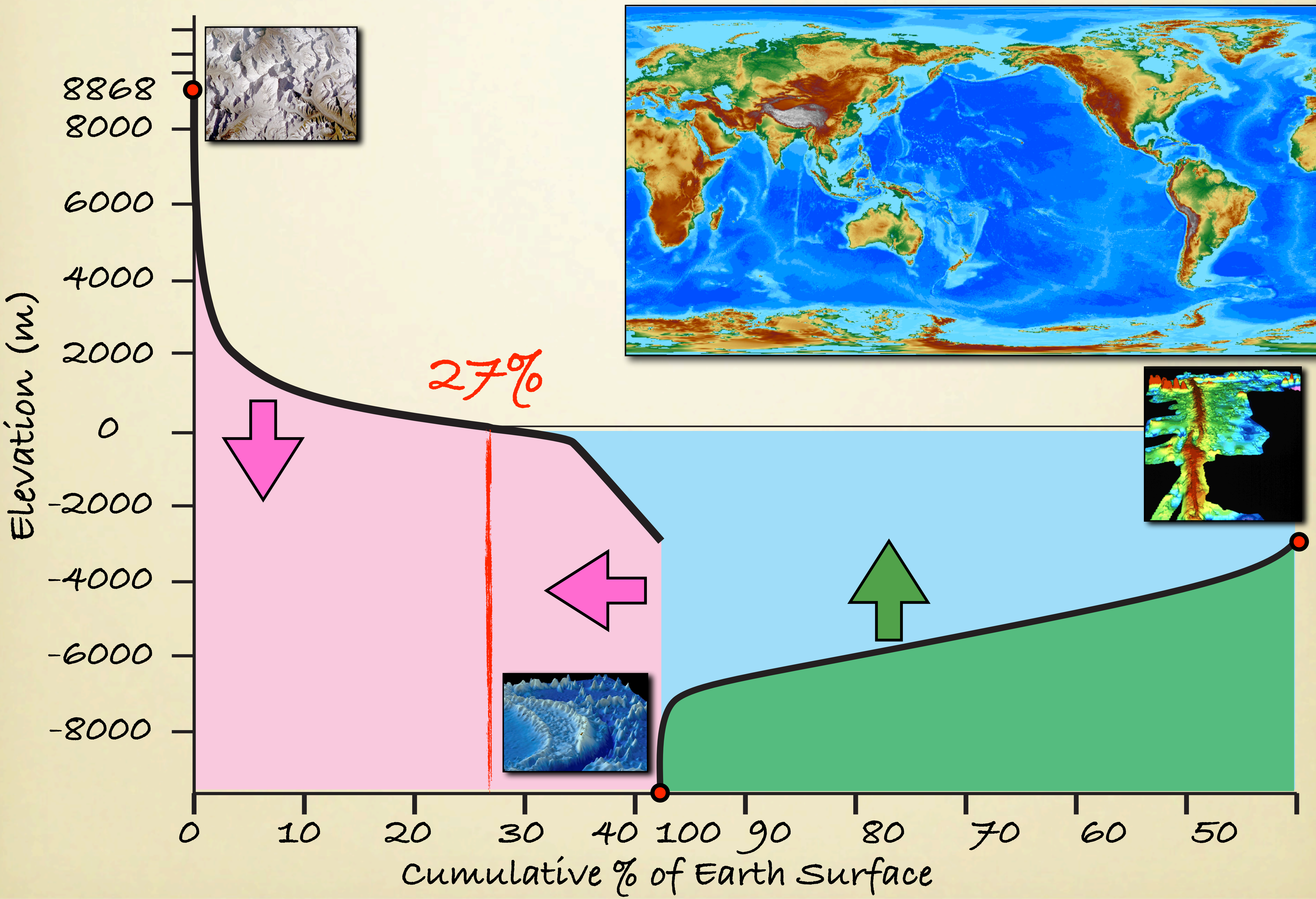
Present-day Earth Hypsometry



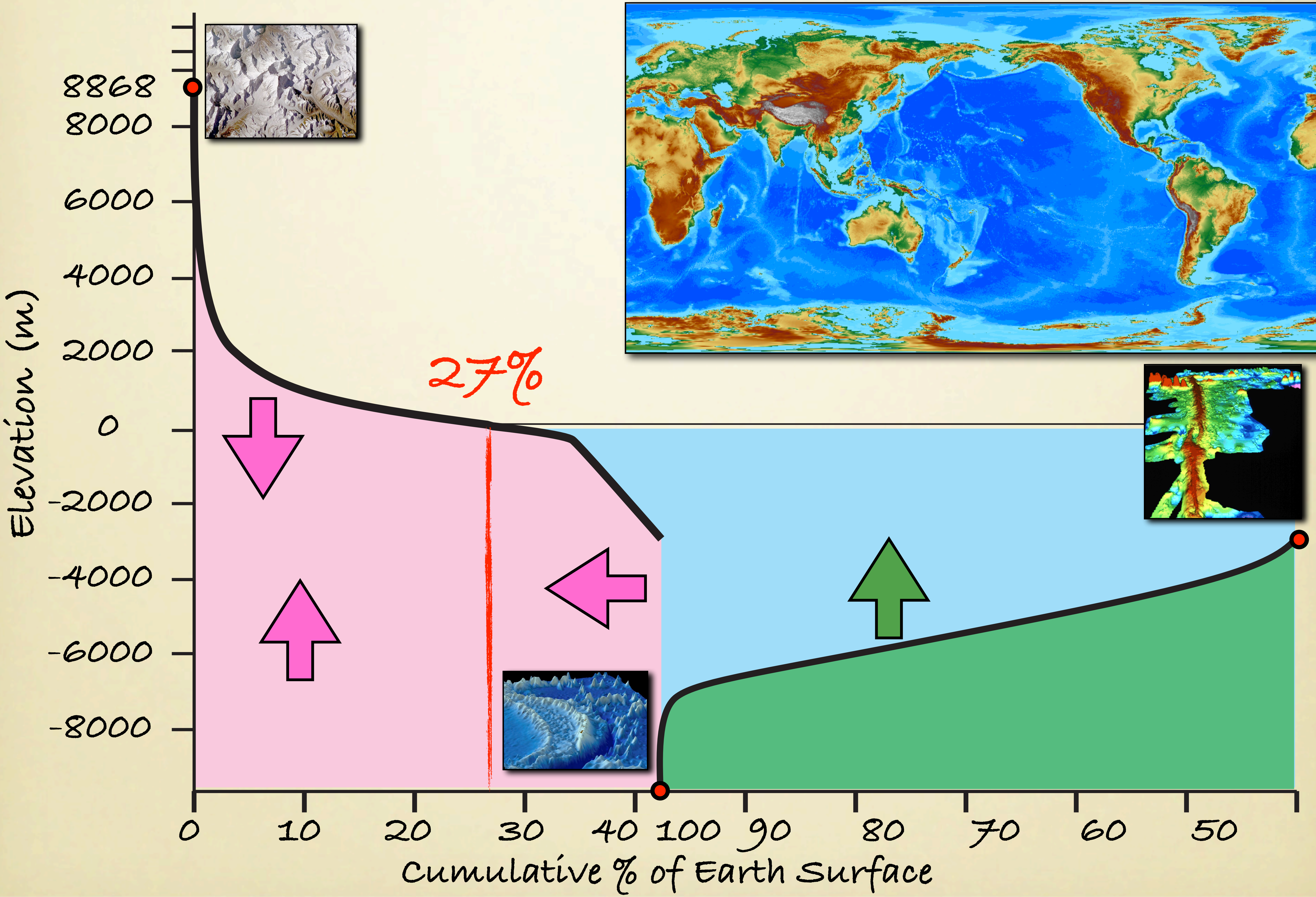
Present-day Earth Hypsometry



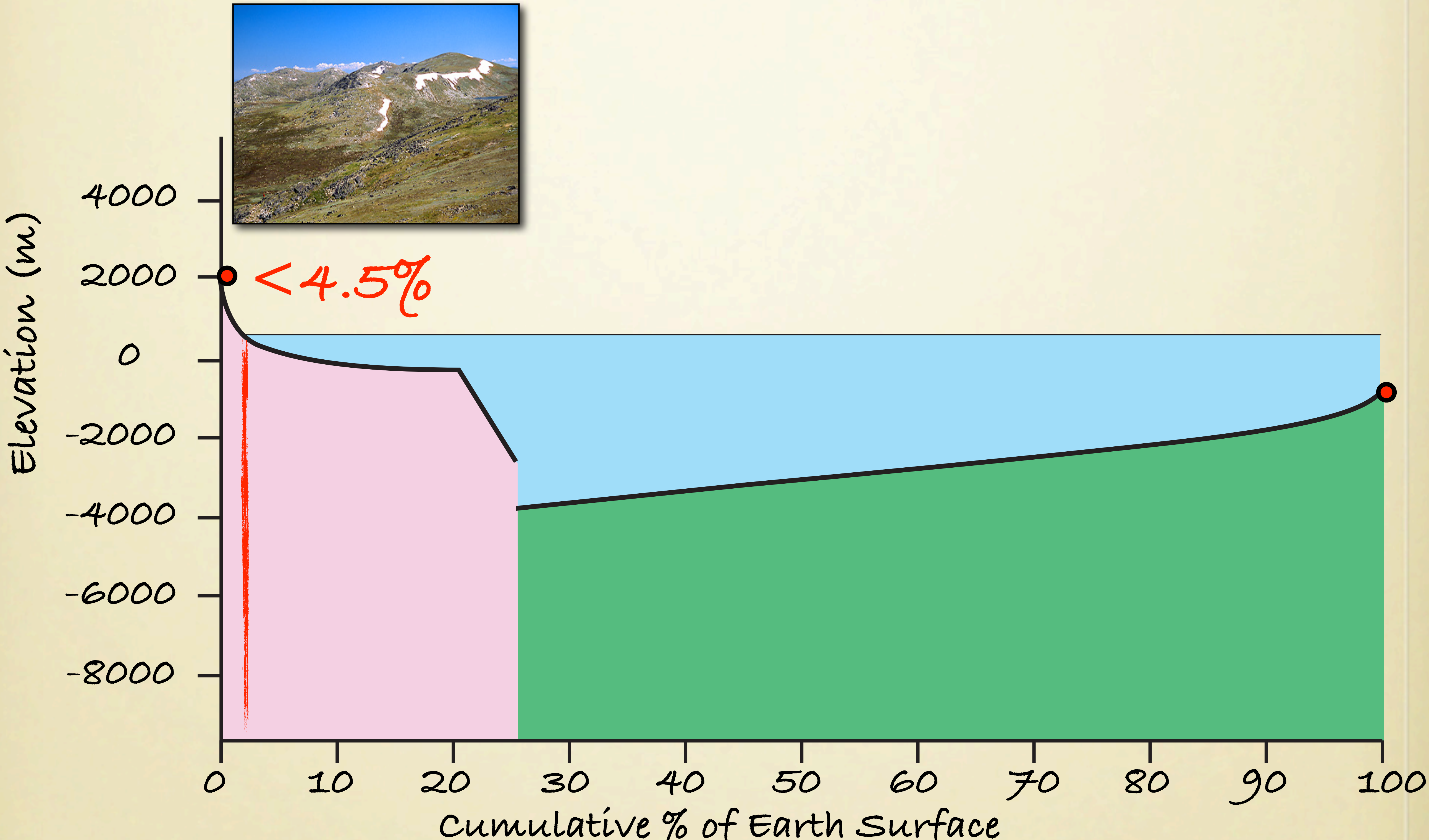
Present-day Earth Hypsometry



Present-day Earth Hypsometry



Late Archean Hypsometry: The Archean Water World Hypothesis



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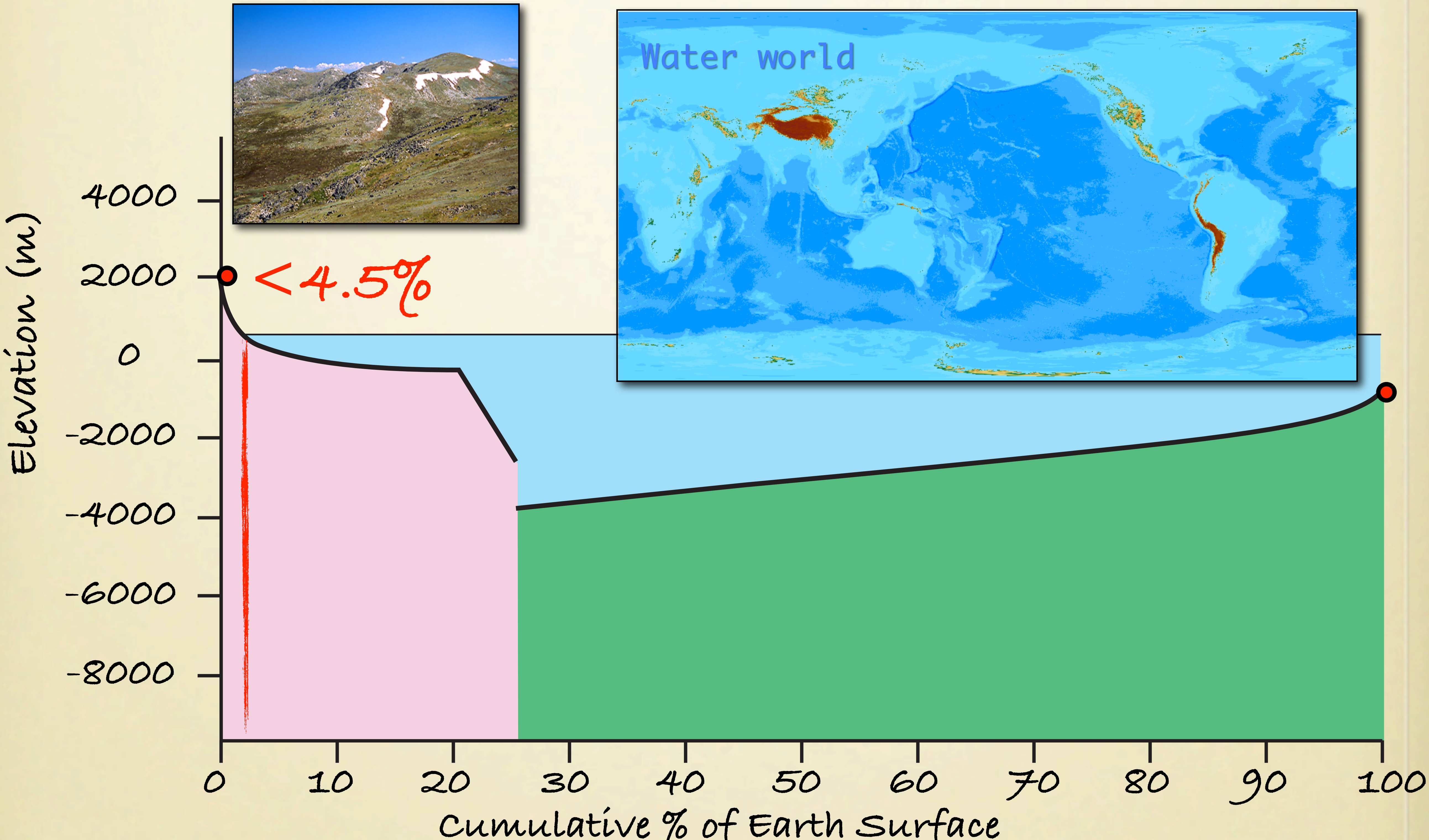

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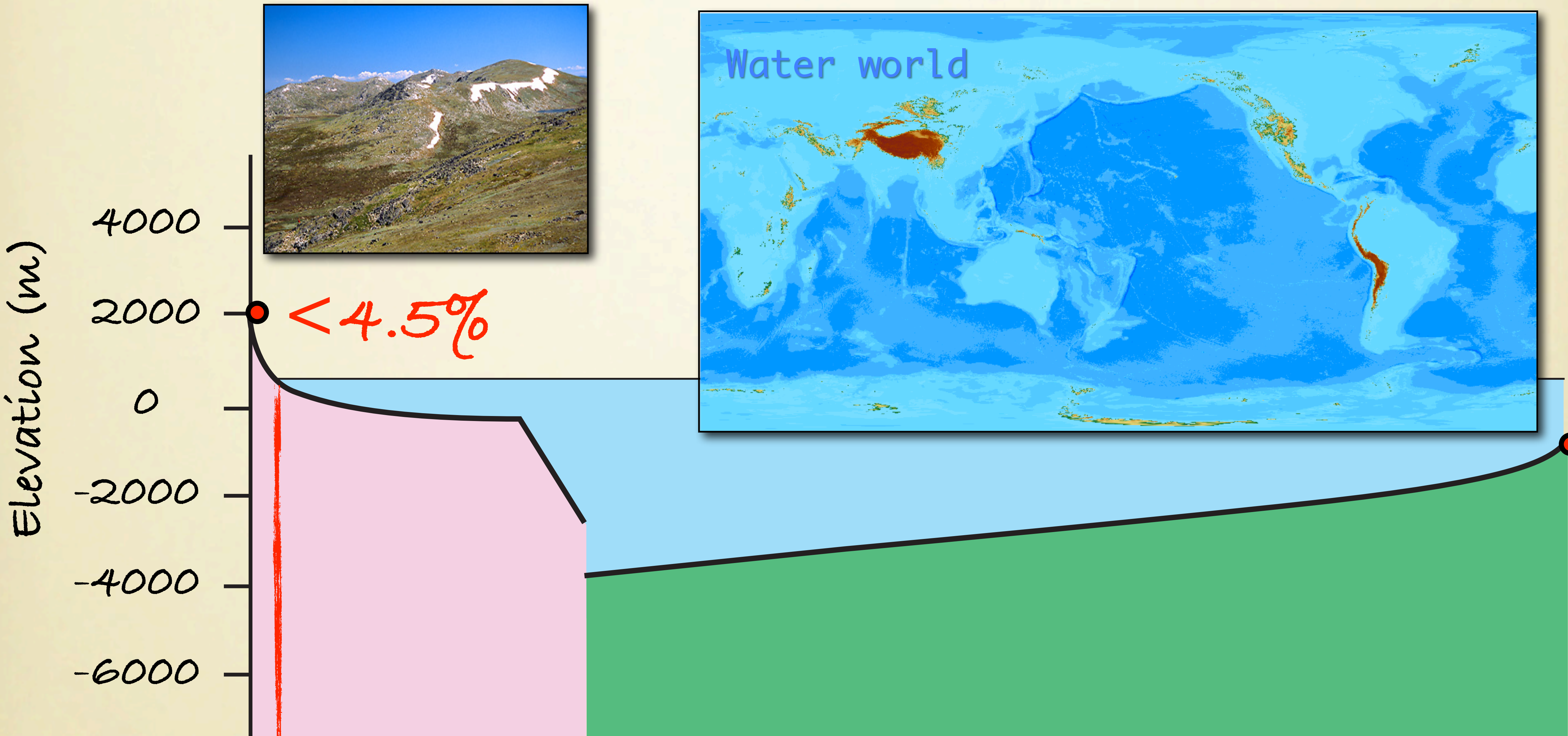
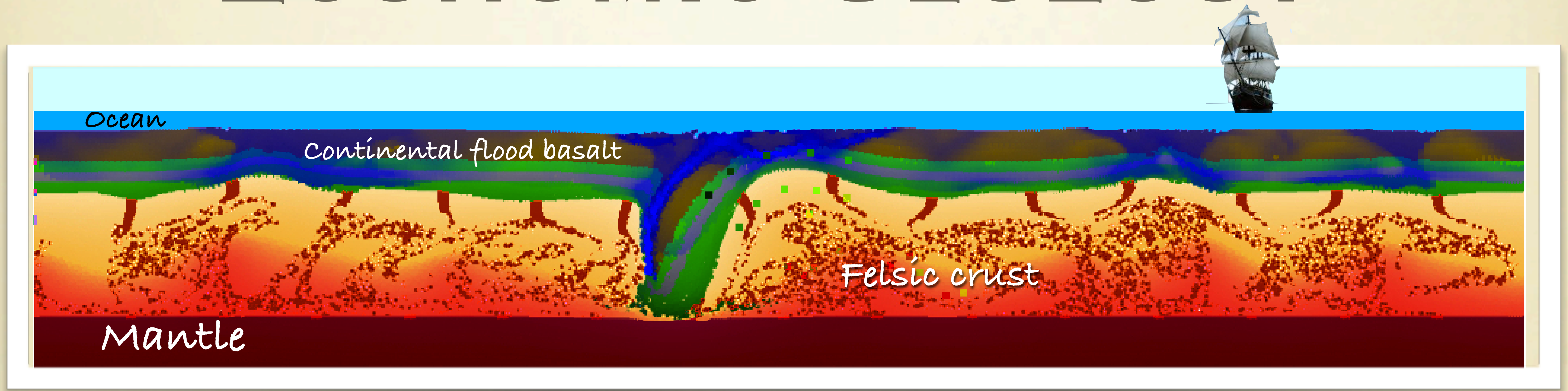


Earth and Planetary Science Letters 275 (2008) 326–336

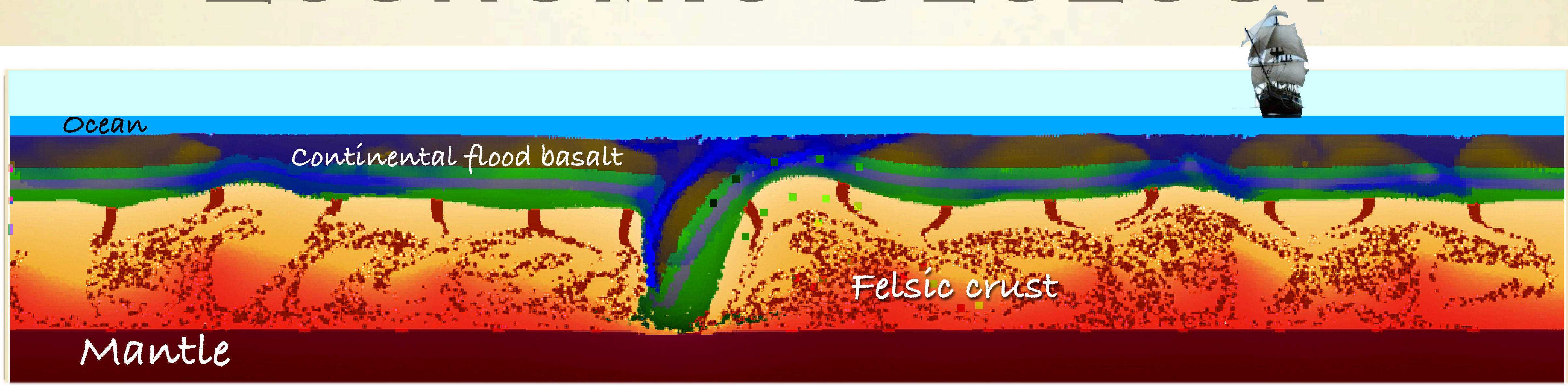
A case for late-Archaean continental emergence from thermal evolution models and hypsometry

Nicolas Flament [a,b,*], Nicolas Coltice [a], Patrice F. Rey [b]

Consequences for Economic Geology



Consequences for Economic Geology



Precambrian Research 229 (2013) 93–104

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

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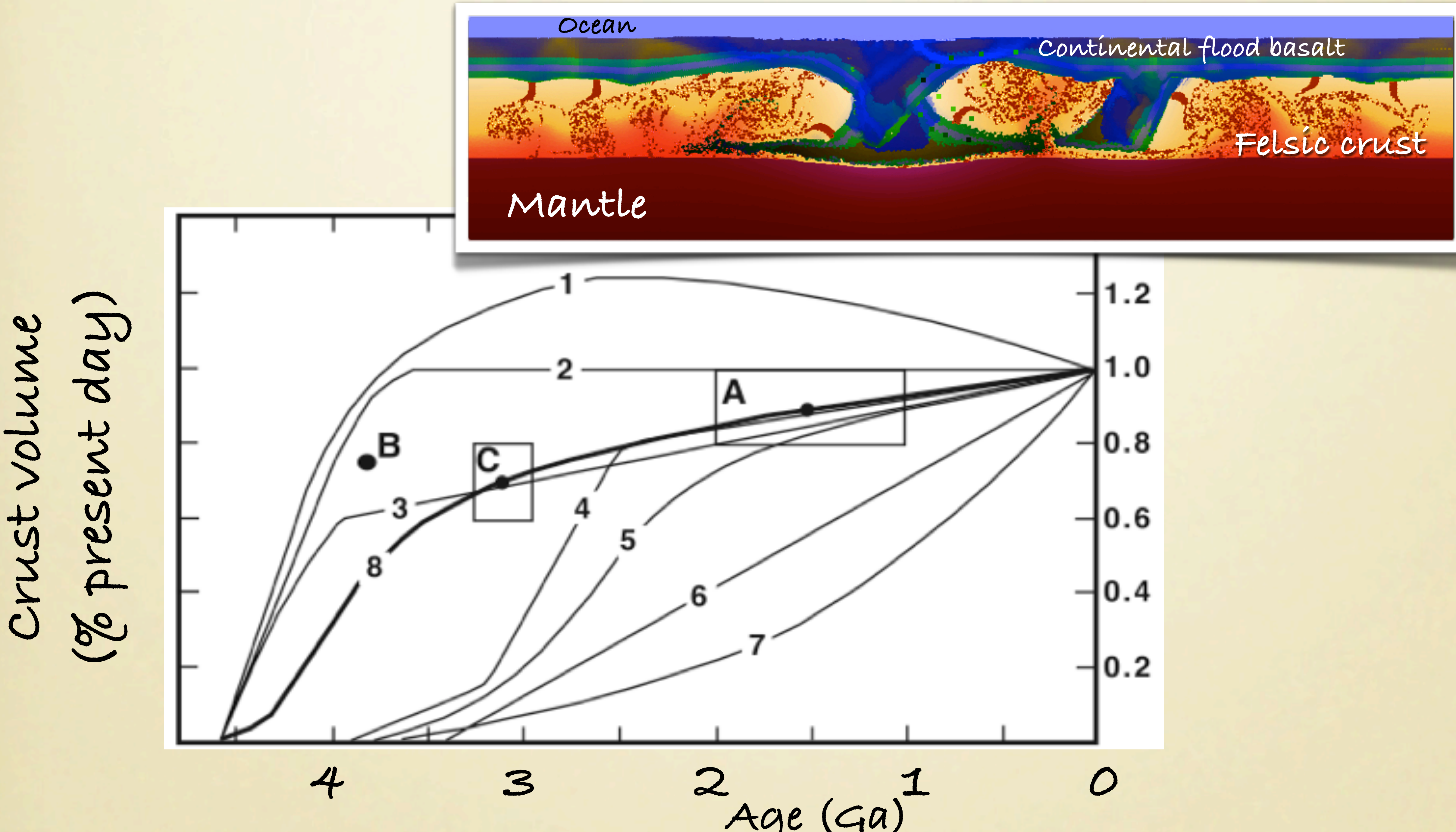
PRECAMBRIAN RESEARCH

Archean gravity-driven tectonics on hot and flooded continents: Controls on long-lived mineralised hydrothermal systems away from continental margins

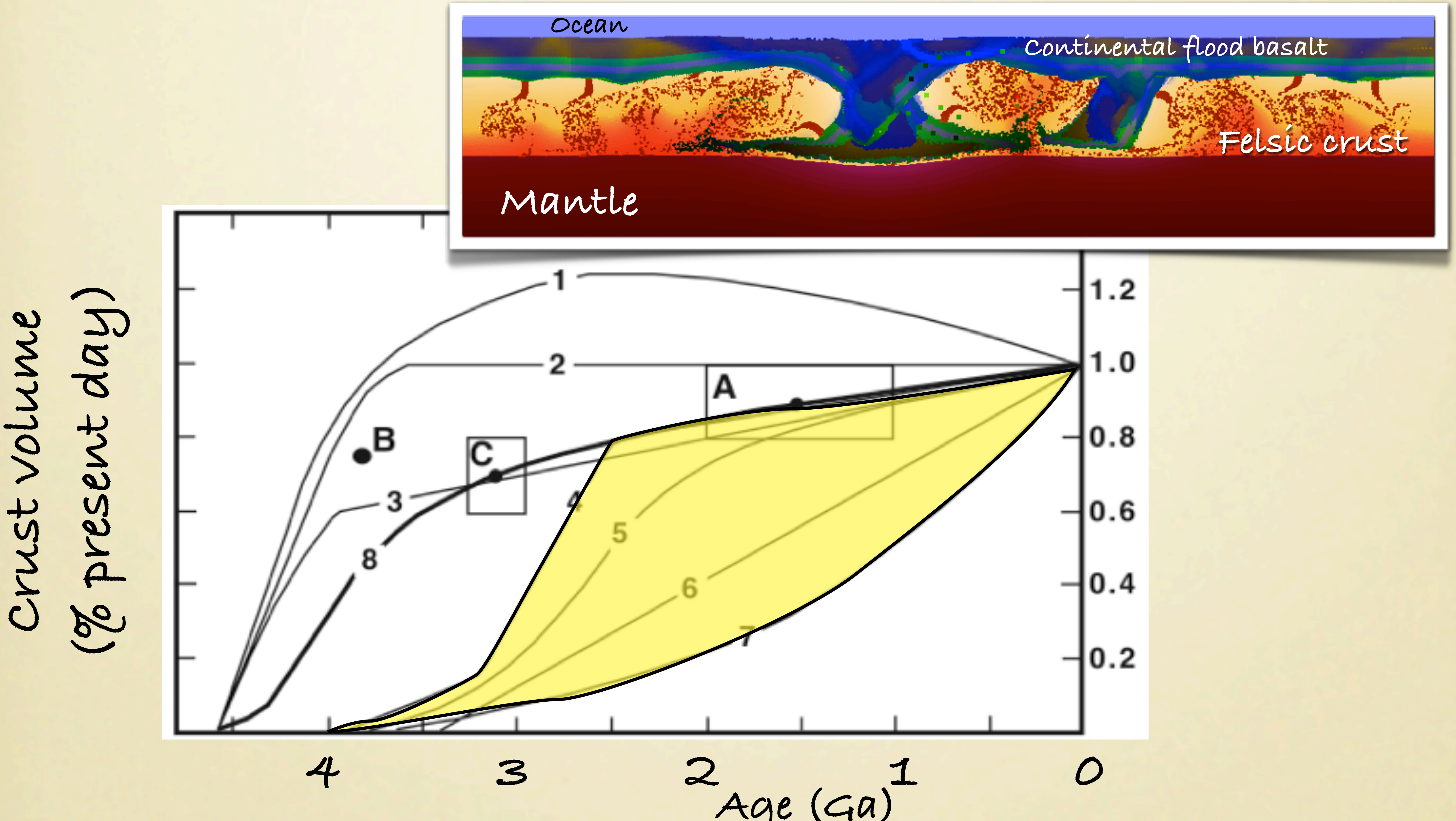
N. Thébaud[a,*], P.F. Rey[b]

Consequences for Everyone Else



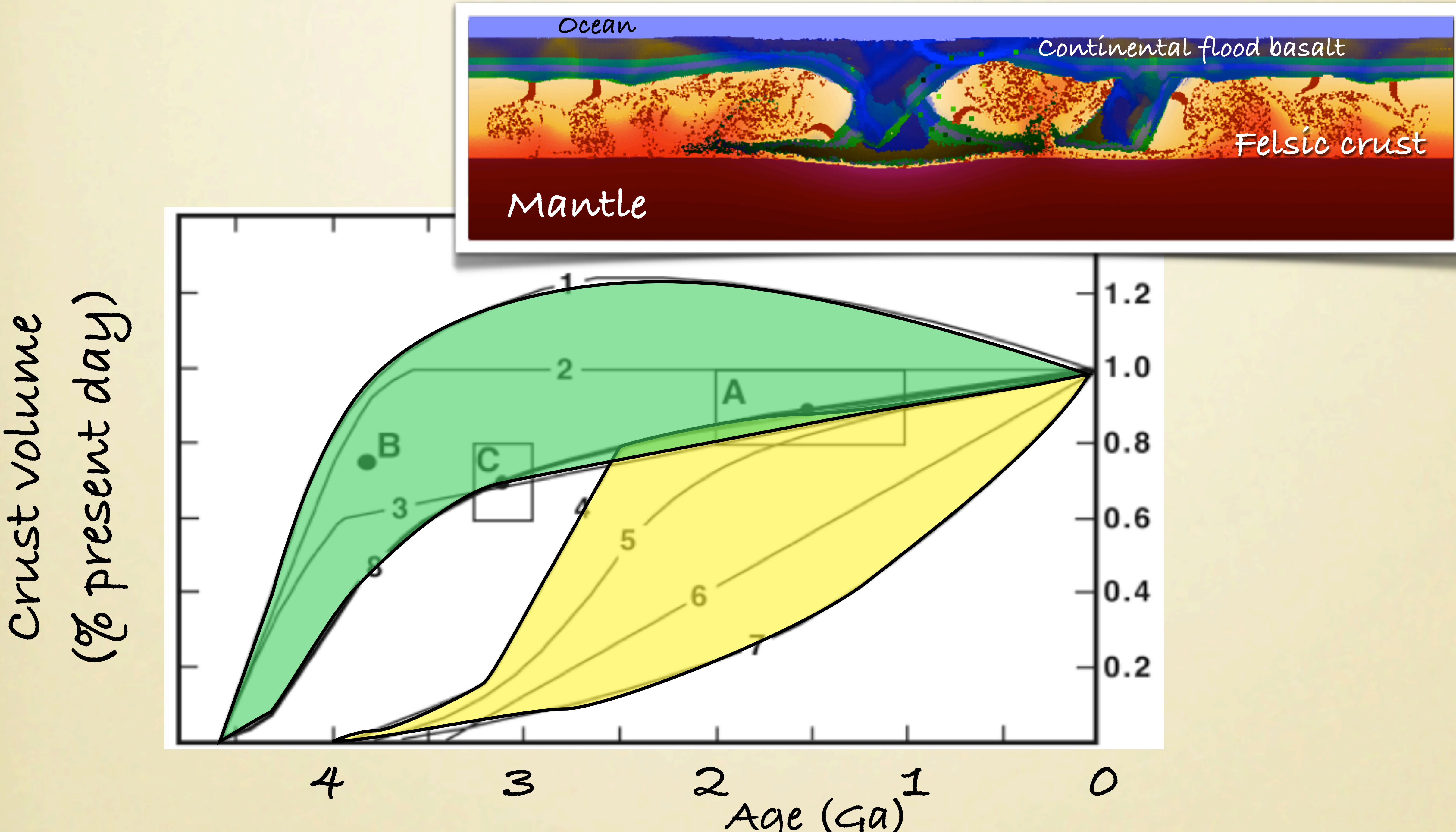
Campbell, Am. J. E. Sc., 2003

Consequences for Everyone Else



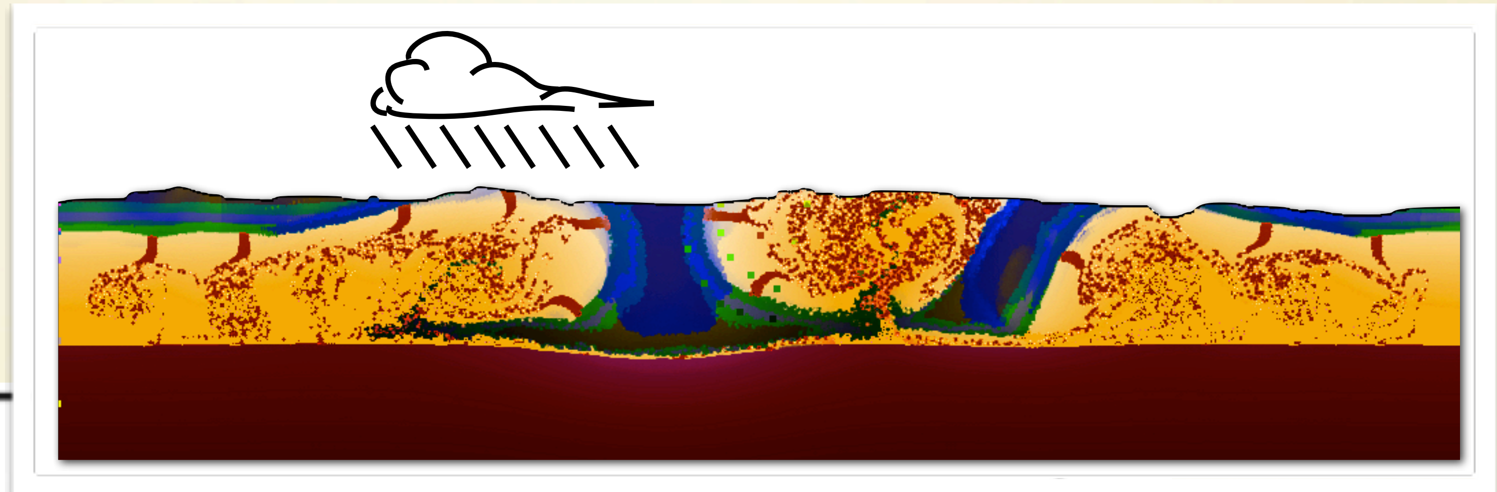
Campbell, Am. J. E. Sc., 2003

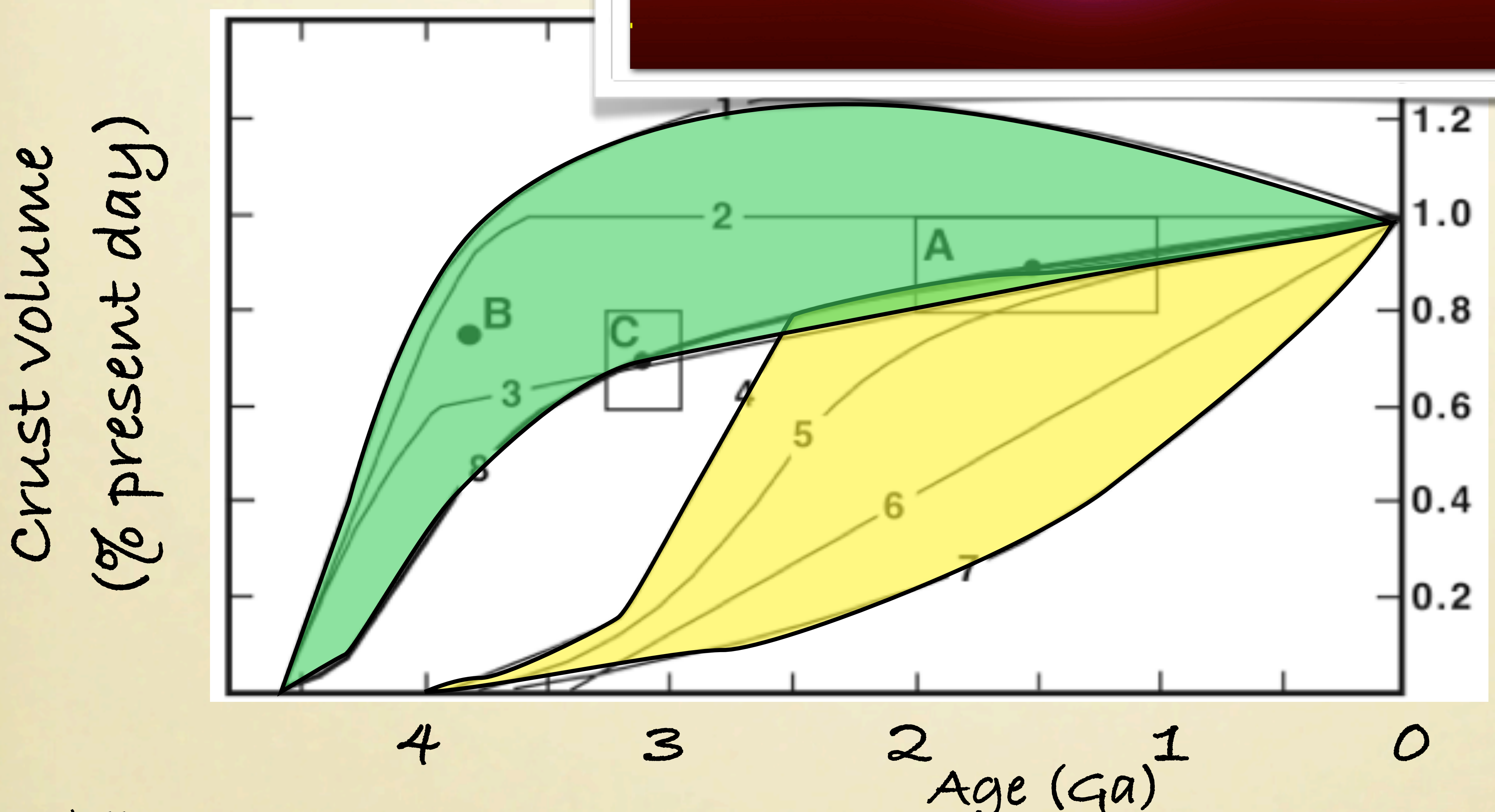
Consequences for Everyone Else



Campbell, Am. J. E. Sc., 2003

Consequences for Everyone Else





Campbell, Am. J. E. Sc., 2003

HOT CONTINENTS CHANGE EVERYTHING...

HOT CONTINENTS CHANGE EVERYTHING...

Hypsometry
&
Tectonics

HOT CONTINENTS CHANGE EVERYTHING...

Hypsometry & Tectonics → Earth's geochem

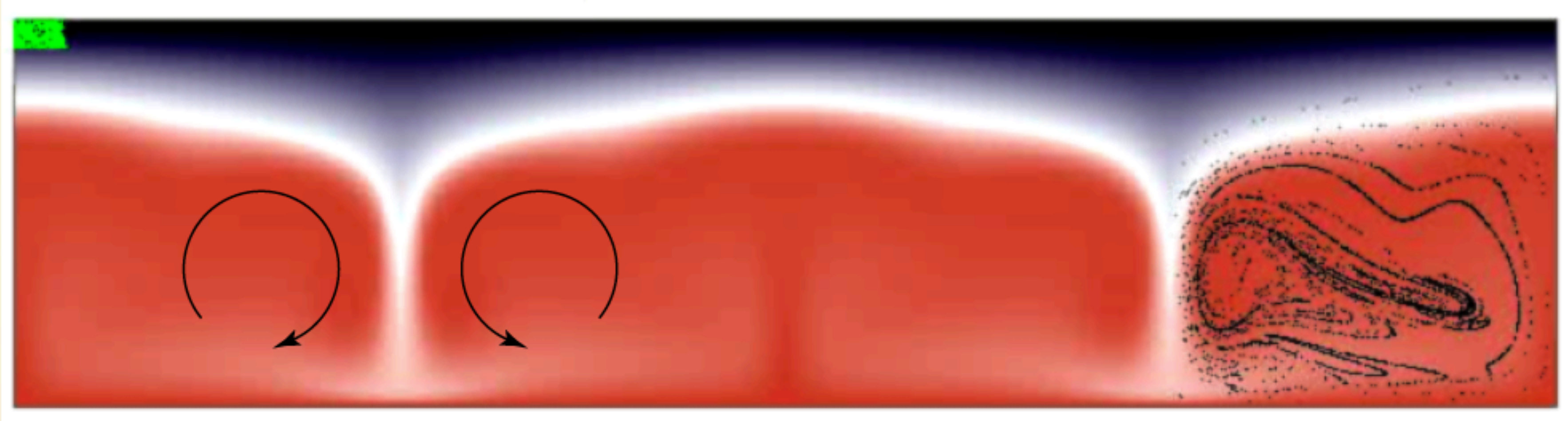
Hypsometry & Tectonics → Biosphere

Hypsometry & Tectonics → Economic geology

EARLY CONTINENTS AND PLATE TECTONICS

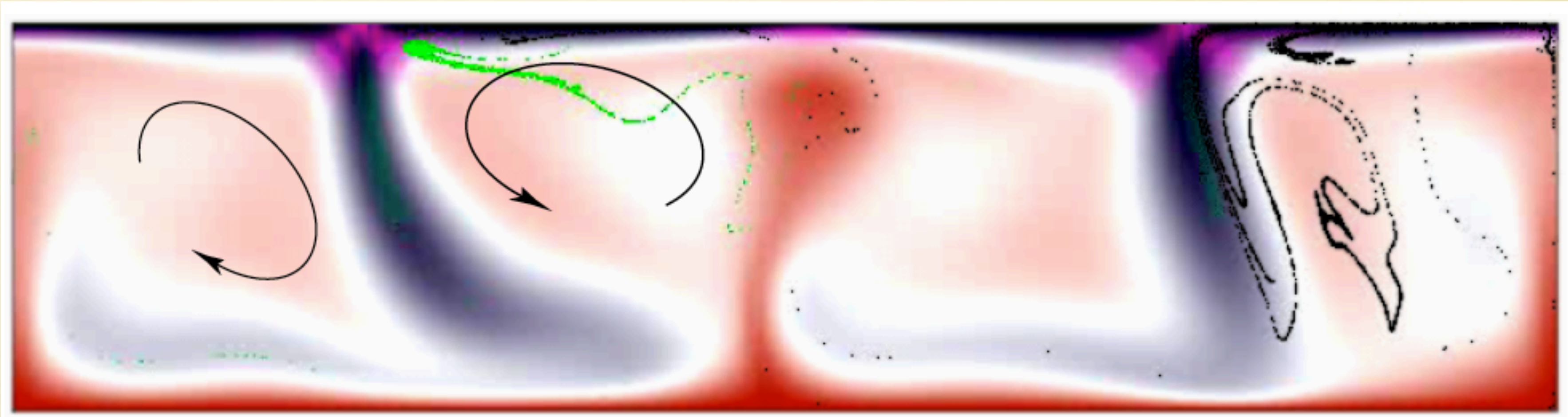
STAGNANT LID

Convective stress
<
Yield stress

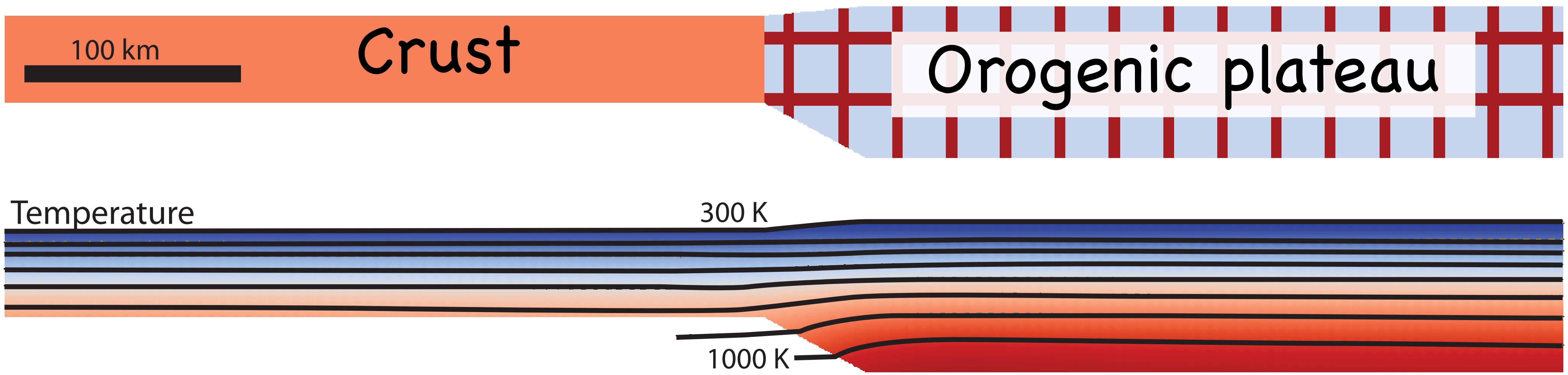


MOBILE LID

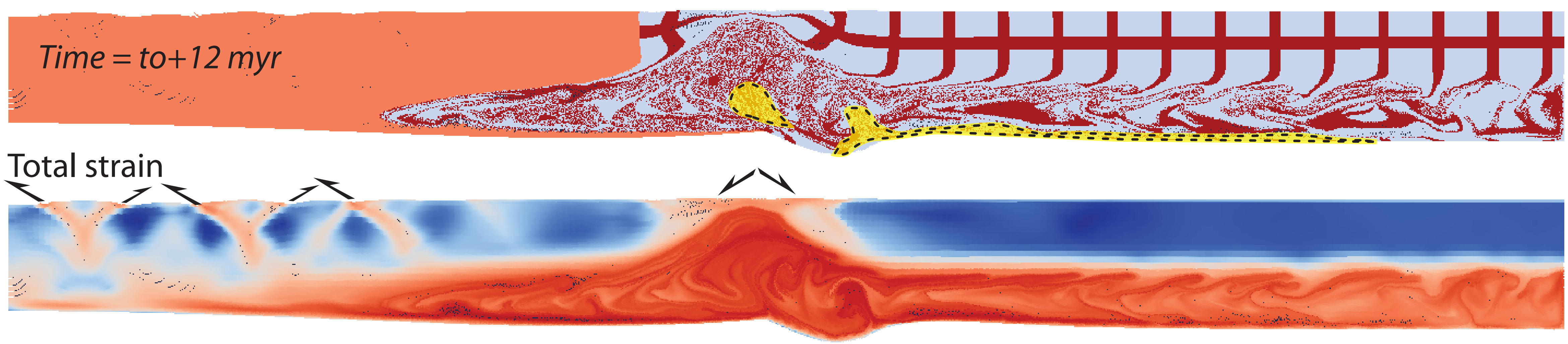
Convective stress
>
Yield stress



Moresi, Zhong & Gurnis, 2000



Fix foreland, melt with buoyancy



Convective system without and with continents ...

4200 km

3000 Co=1 MPa, Bp = 0.015, η= 0.001 η^*

Ct Surf Temp. = 20 ºC

700 km

Plasticity (Co + μ . Pressure) . Weakening

Co=40 MPa, μ = 0.268

Density = 3395 $kg.m^{-3}$ α= 2.8 10^{-5} K^{-1}

Radiogenic Heat: 4.10^{-12} $W.kg^{-1}$

Olivine rheology: T, σ and ε dependent η

(E:520 KJ.mol-1, n=3, 5e6 $MPa^{-n}.s^{-n}$)

Rayleigh nb (Conv. mtle): 10^6 - 10^7

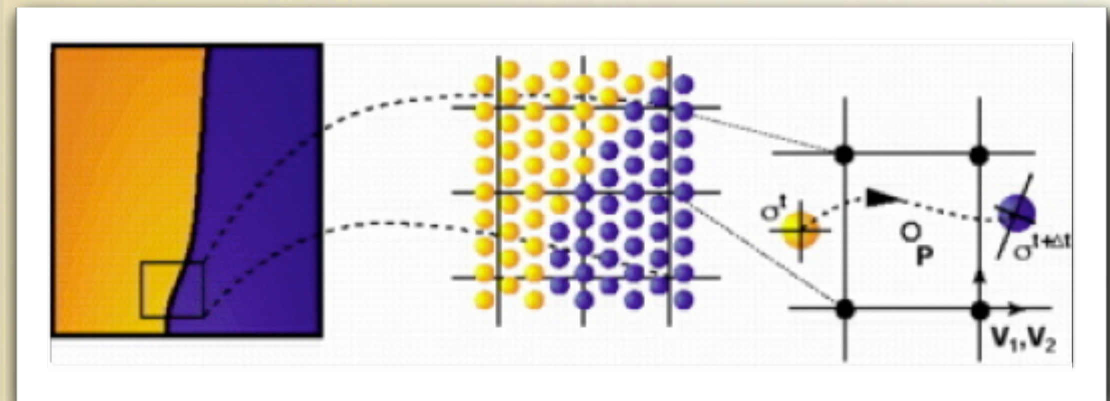
Ct Basal Temp. = 1873 ºC

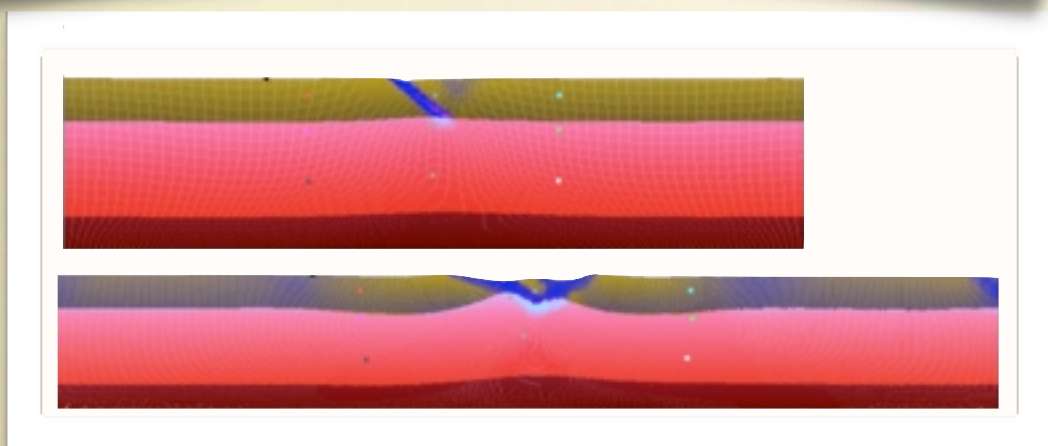
Open source codes: *Ellipsis, Underworld*

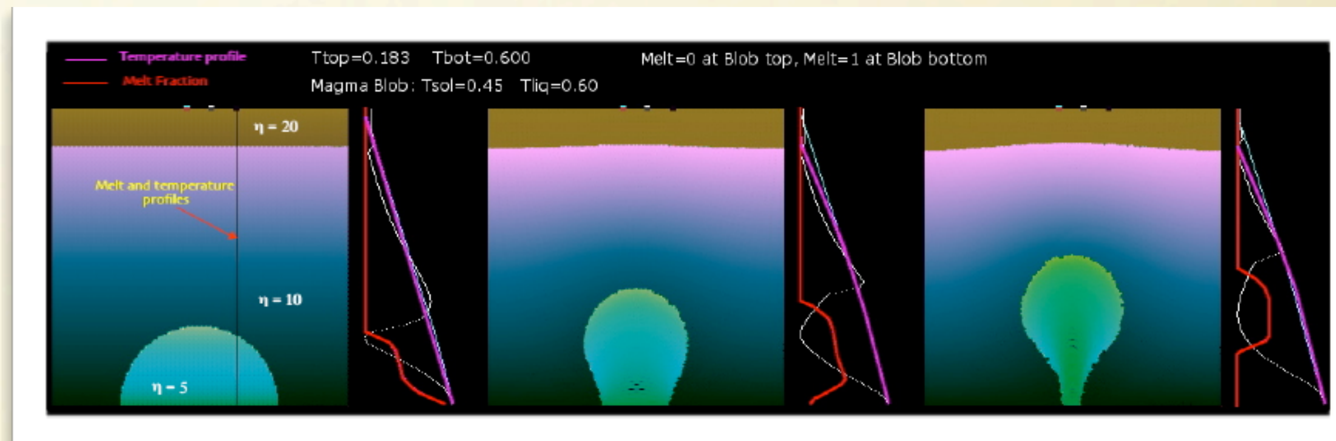
Coupled thermal-mechanical $\rho\ (\mathrm{T, Metam.})$ $\eta\ (\sigma, \varepsilon, \dot{\varepsilon}, \mathrm{T})$

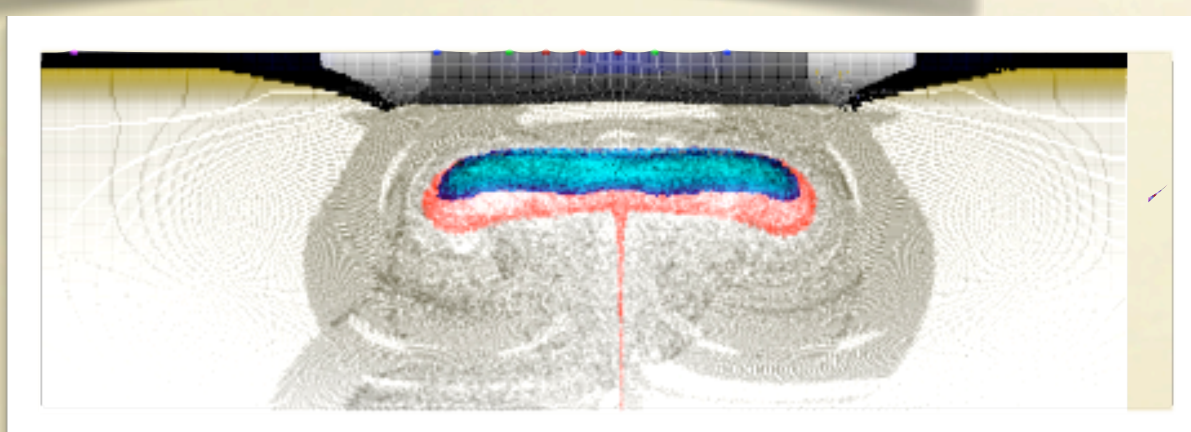
Visco-plastic rheology with strain weakening

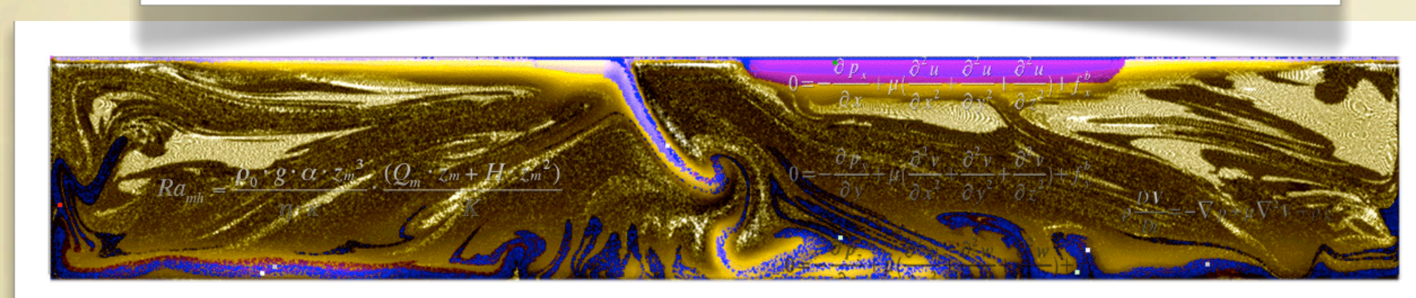
Radiogenic heat, partial melting, eclogitization...

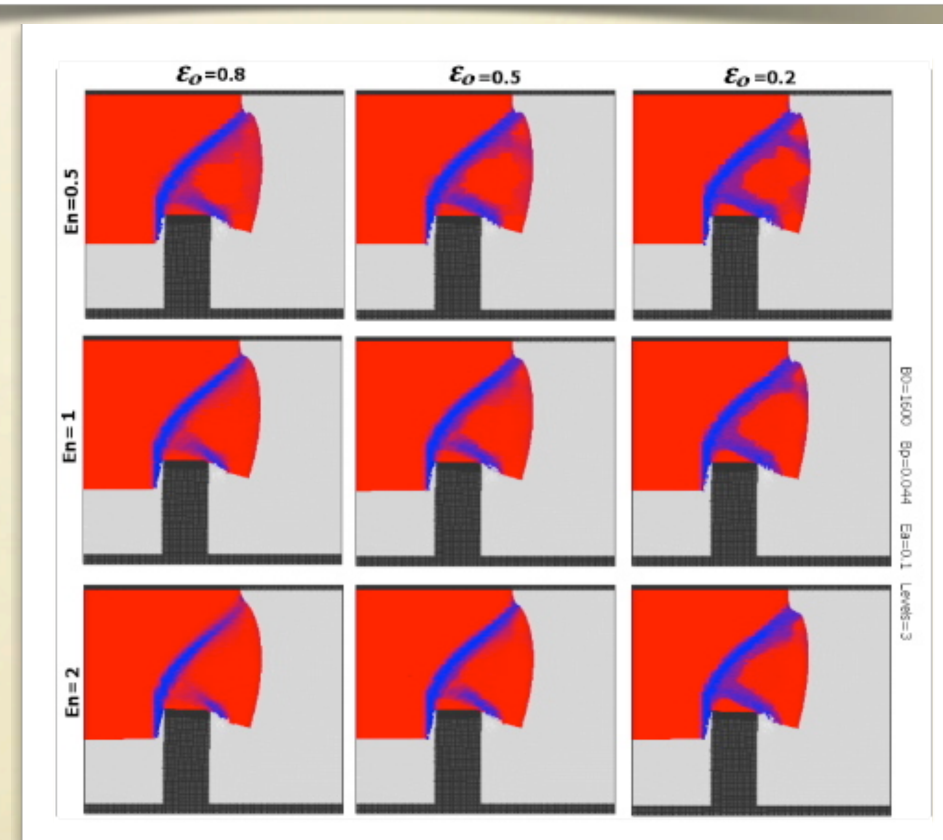




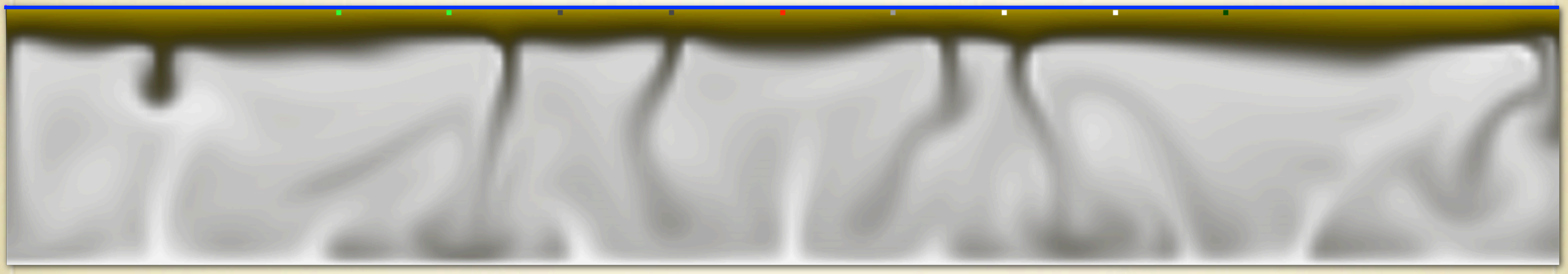




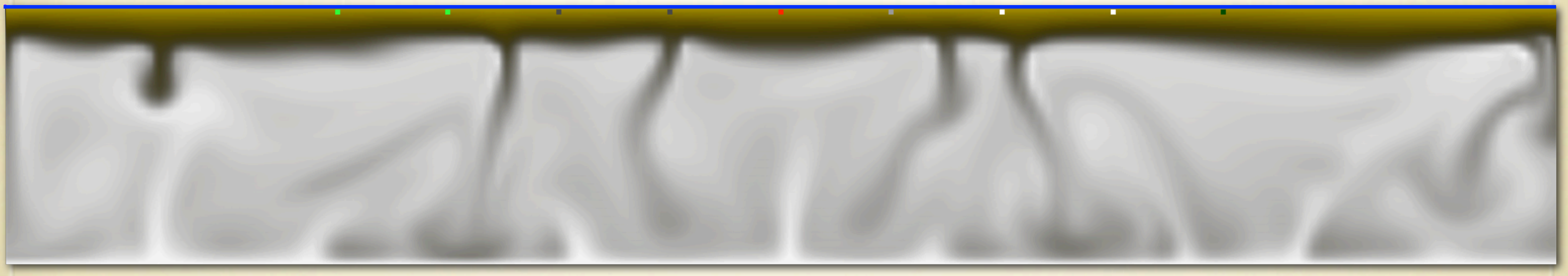




Convective system with no continent ...

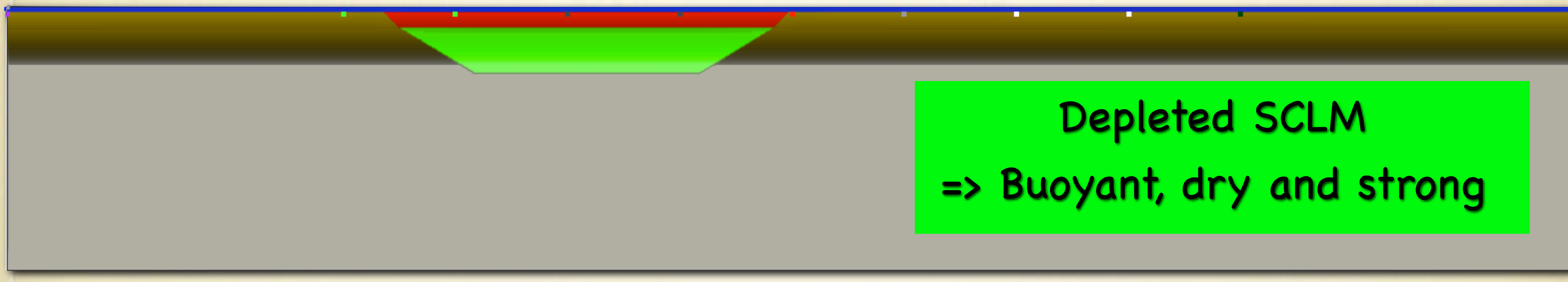


Convective system with continent ...



Convective system with continent ...

Convective system with continent ...



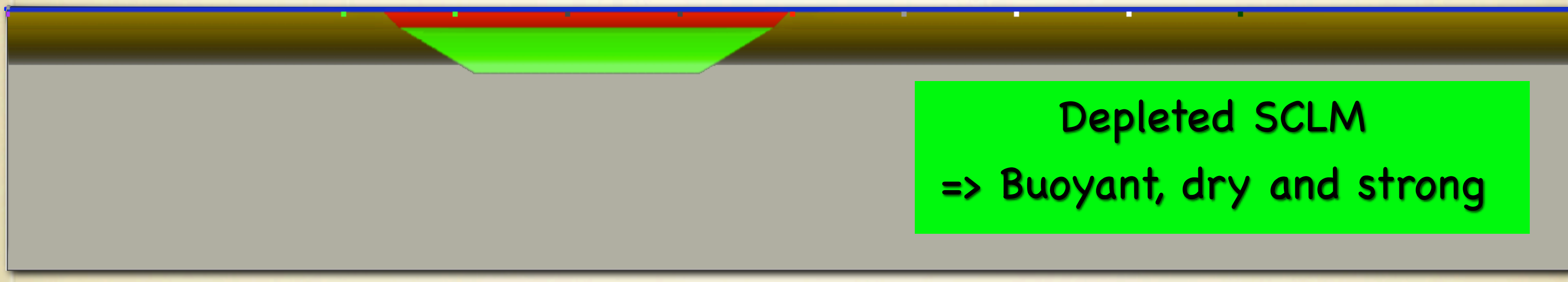
15 km — 3000 kg.m^{-3}

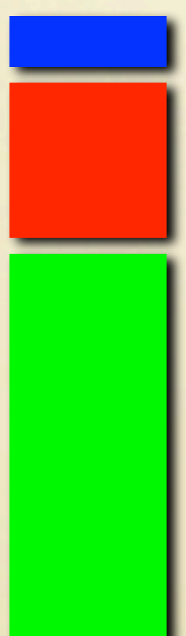
40 km — 2850 kg.m^{-3}

120 km — 3310 kg.m^{-3}

Total thickness: 175 km

Convective system with continent ...





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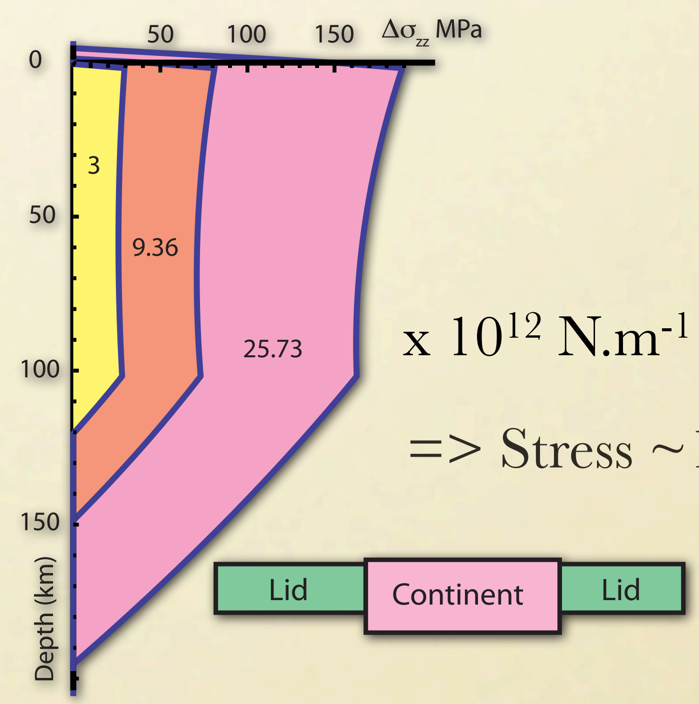
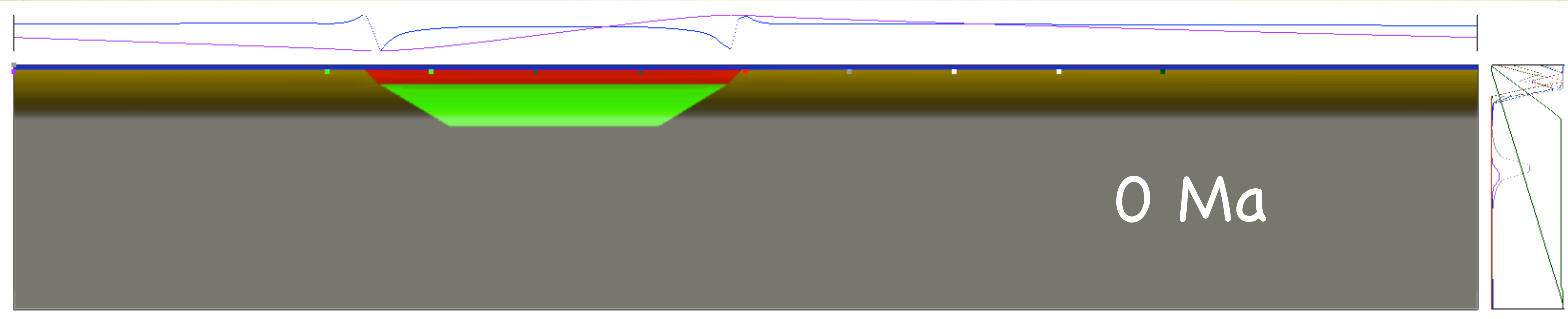
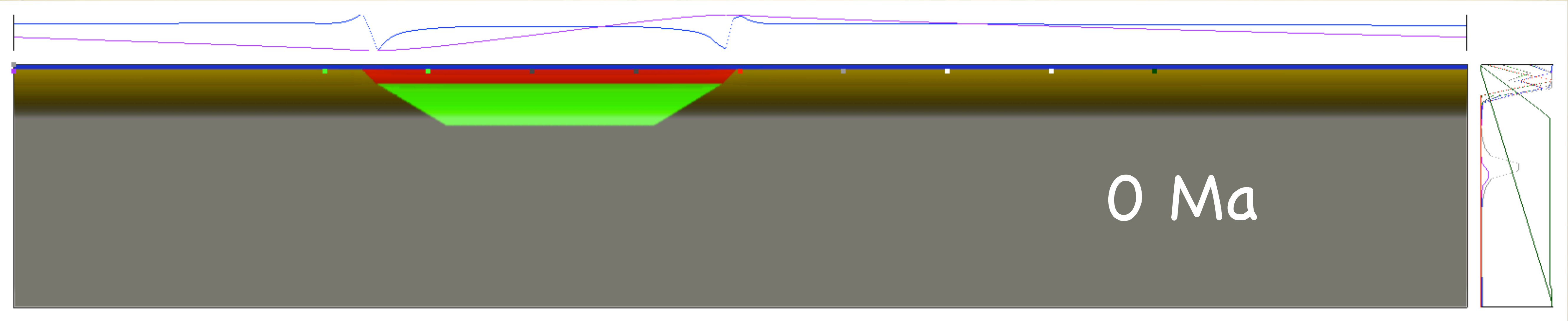
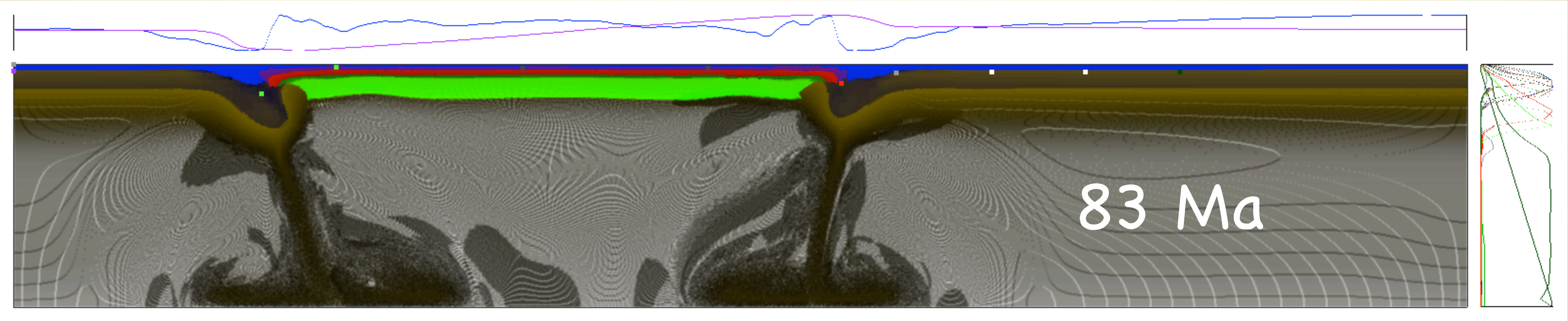


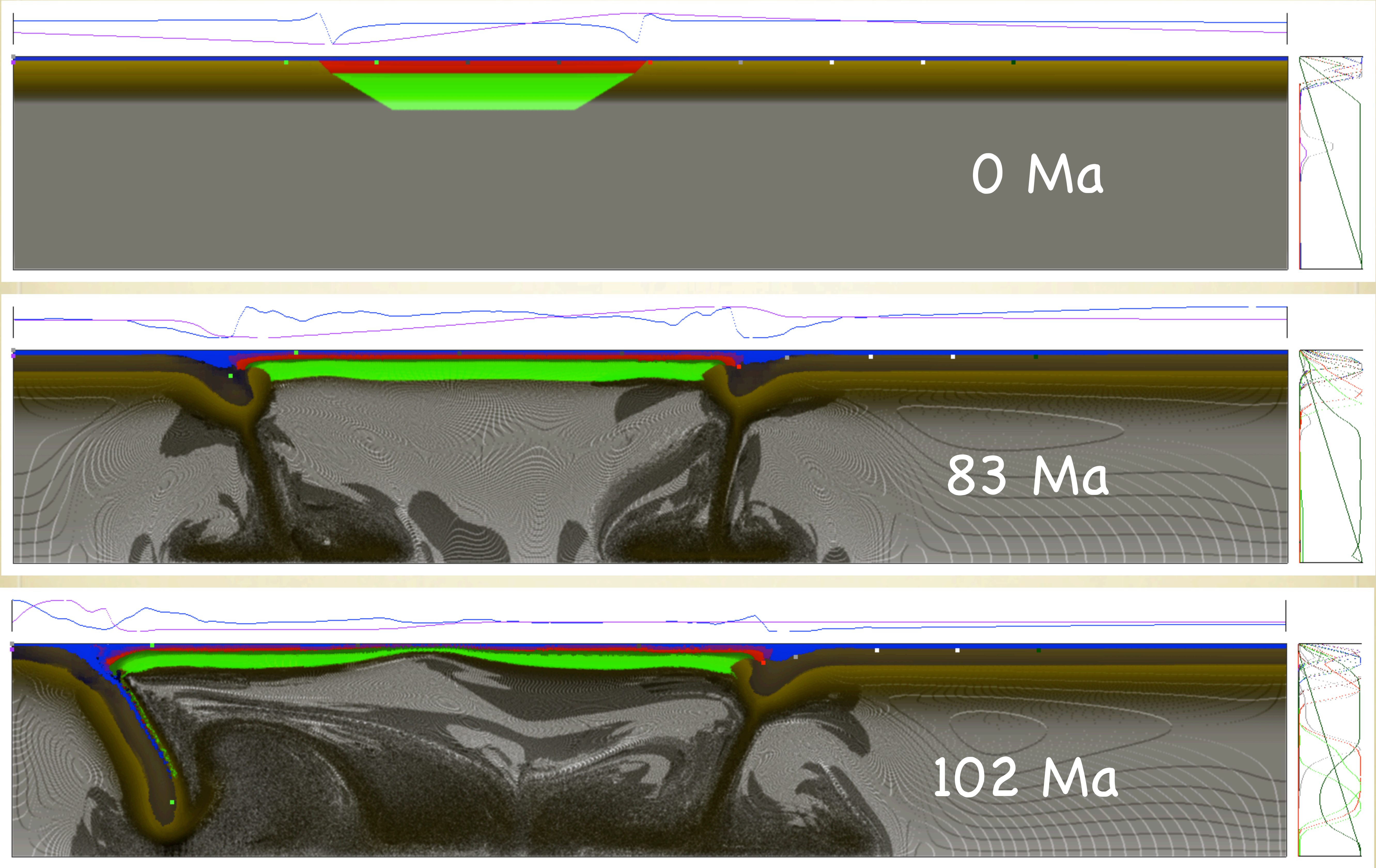
x 10^{12} $N.m^{-1}$

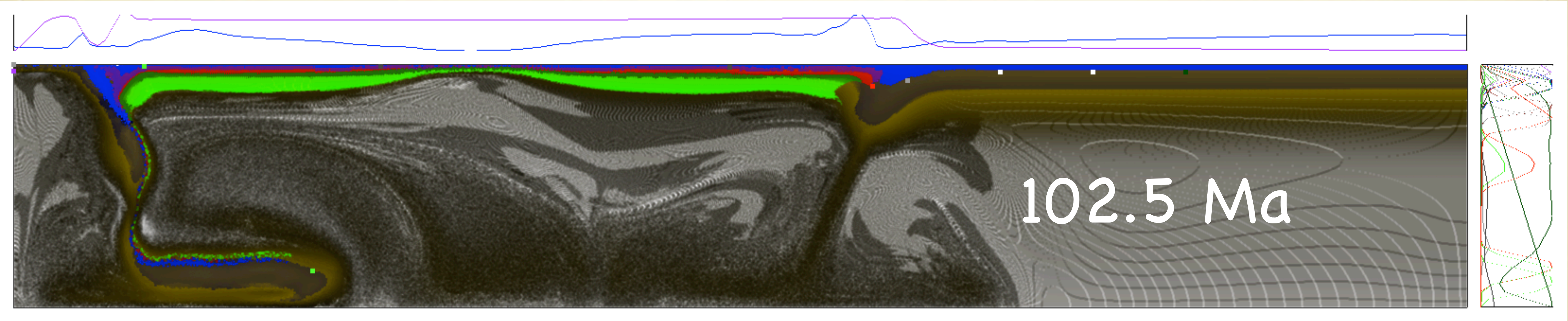
=> Stress ~100 MPa

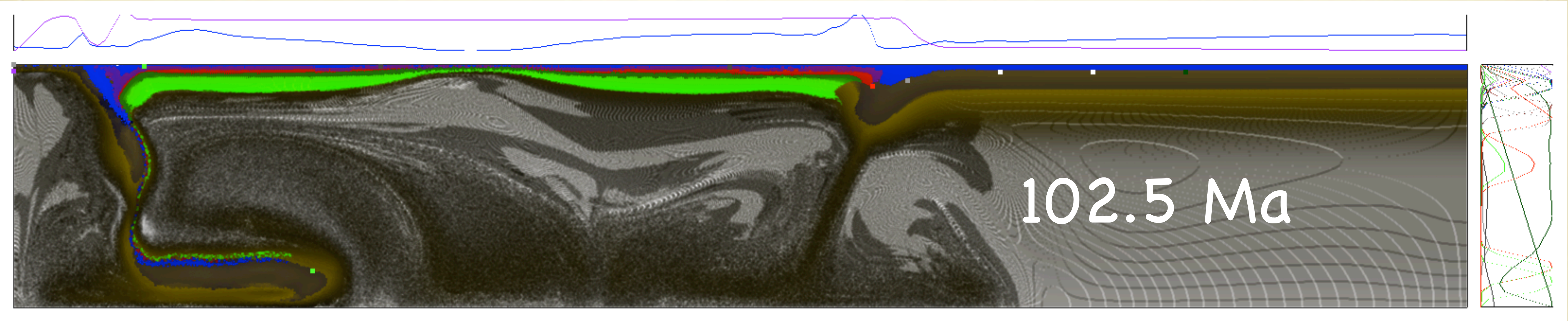

0 Ma

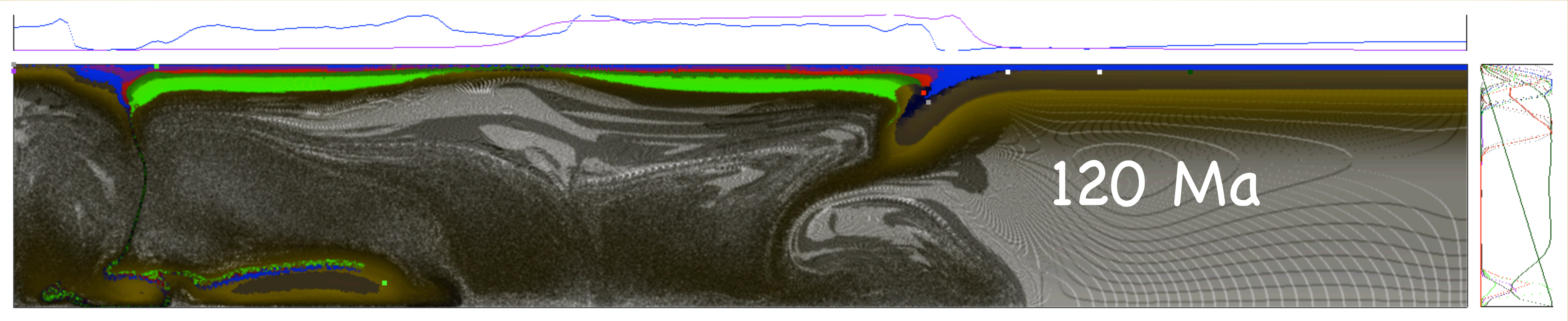

0 Ma

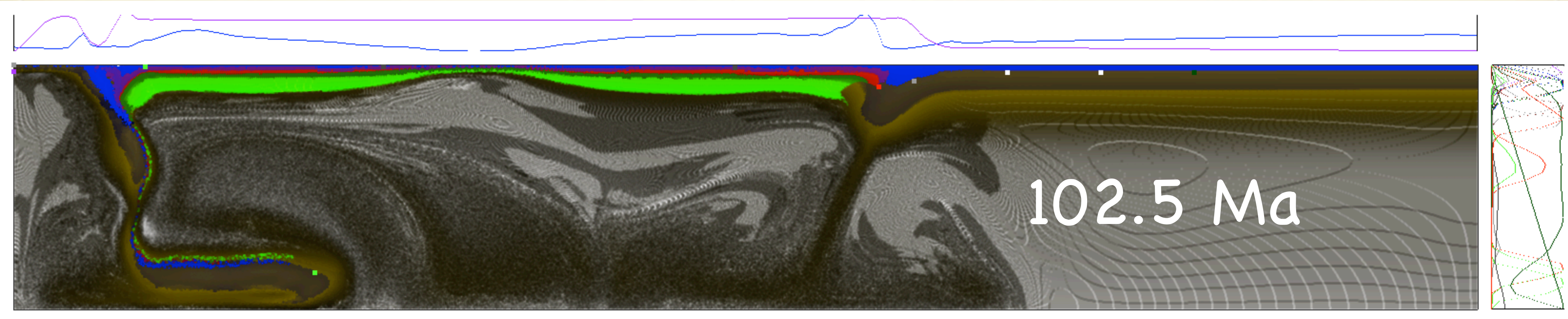

83 Ma

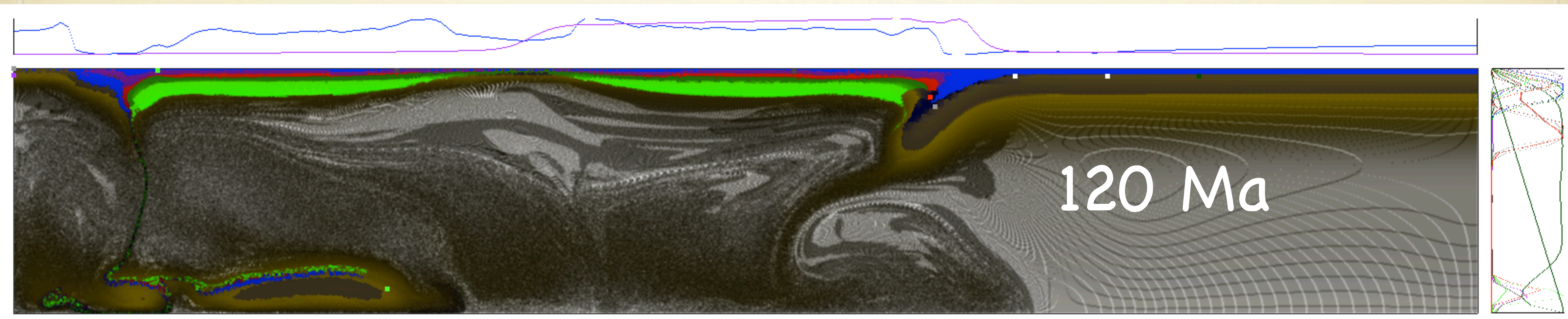

0 Ma
83 Ma
102 Ma

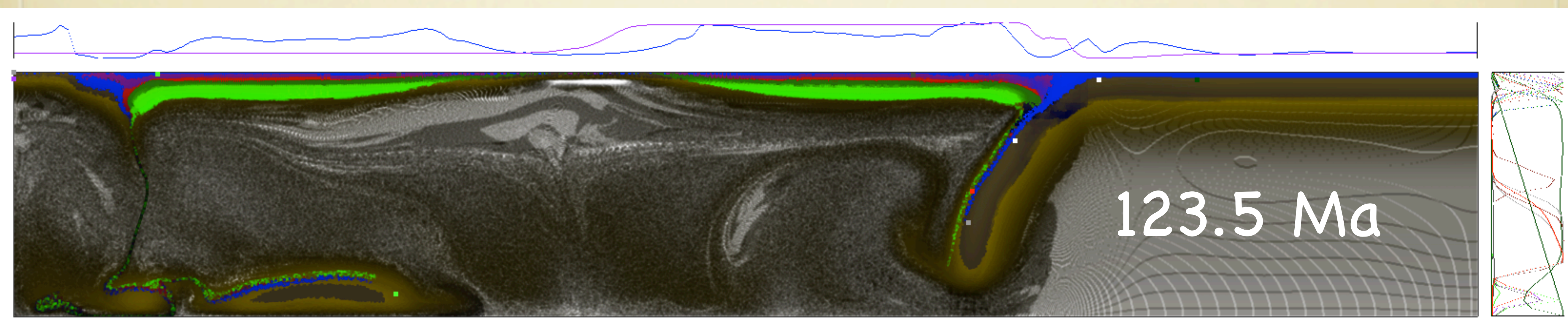

102.5 Ma

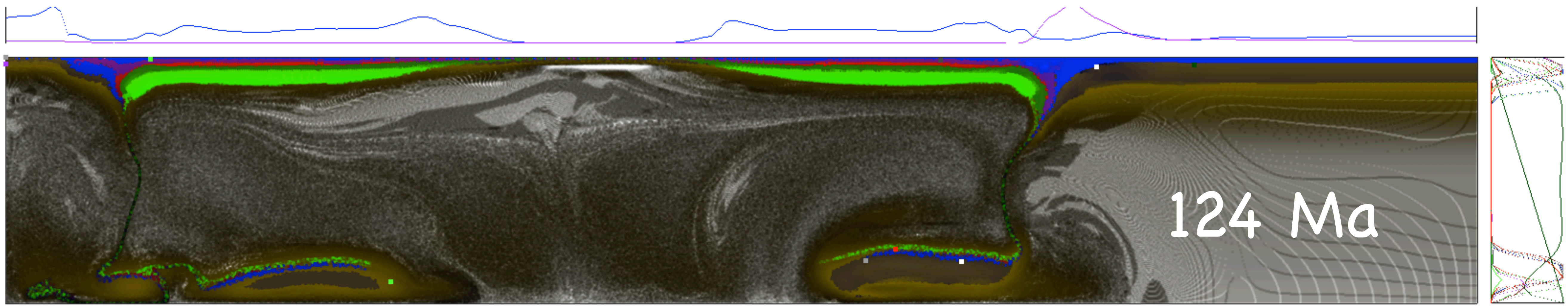

102.5 Ma

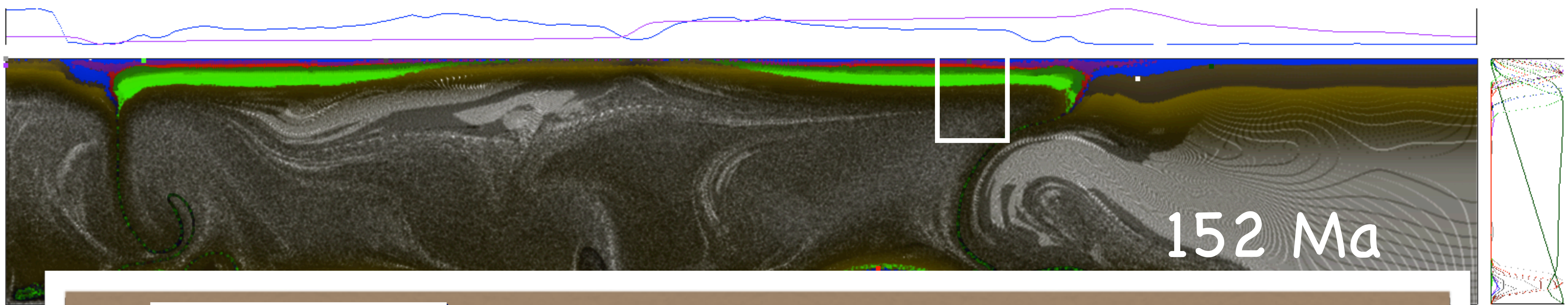

120 Ma

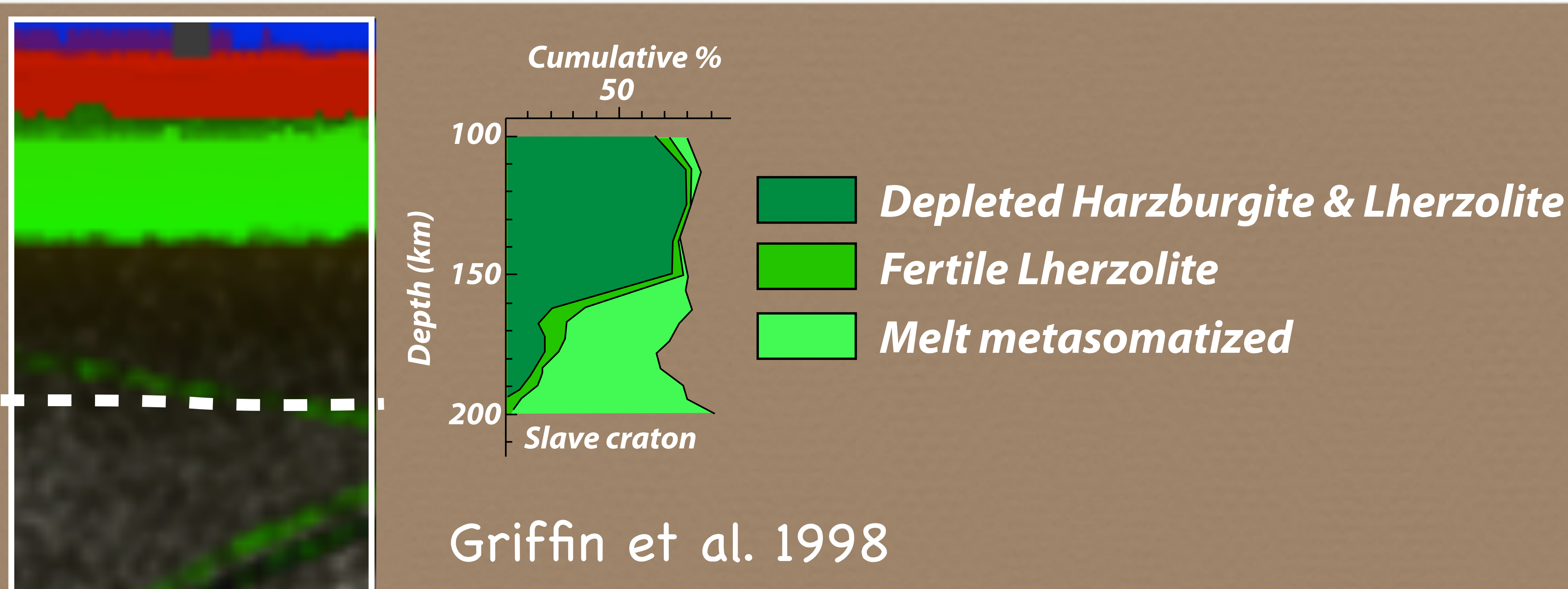

102.5 Ma


120 Ma

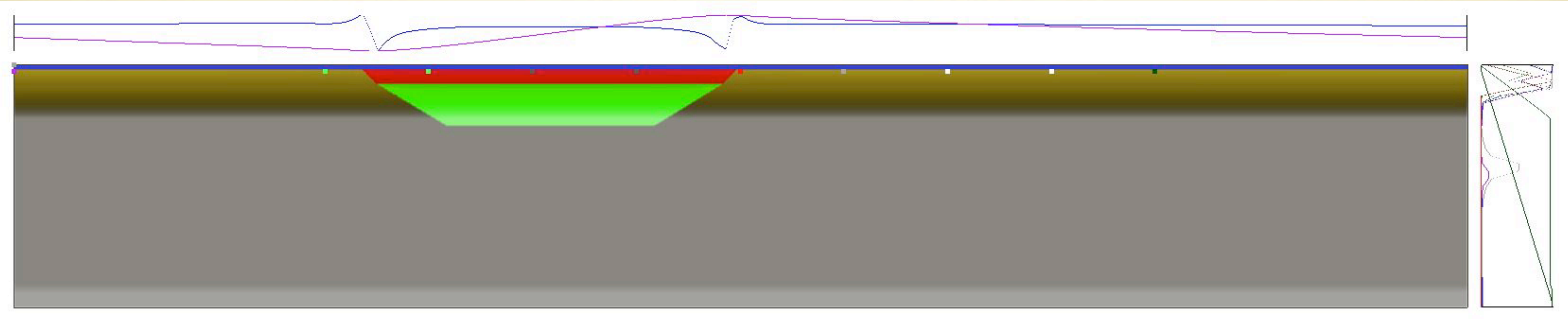

123.5 Ma



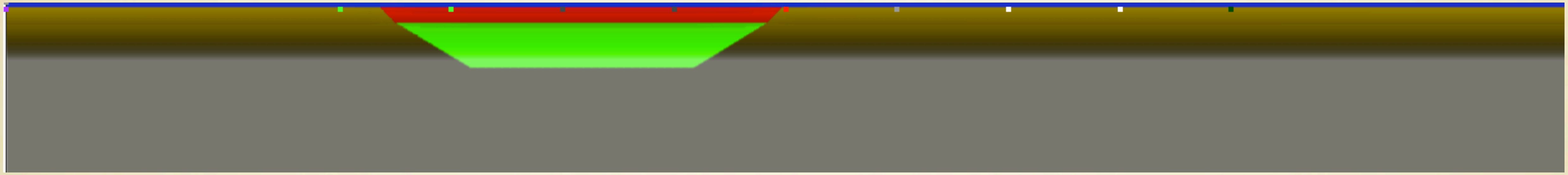


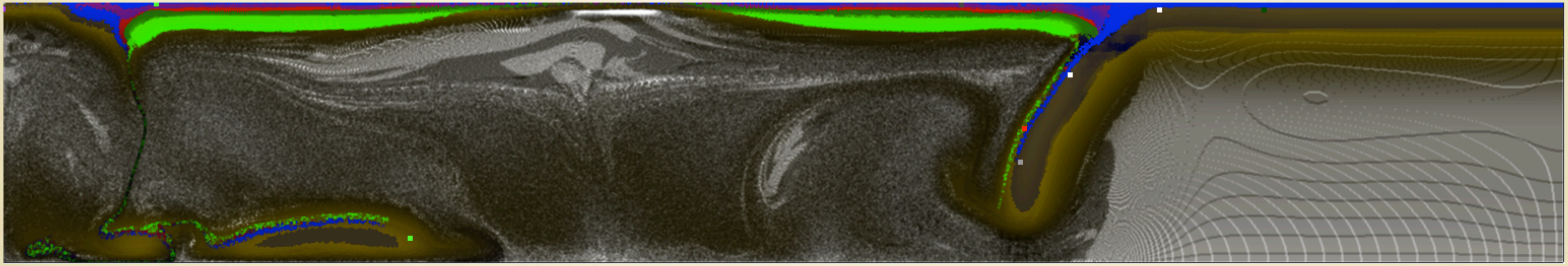


Griffin et al. 1998

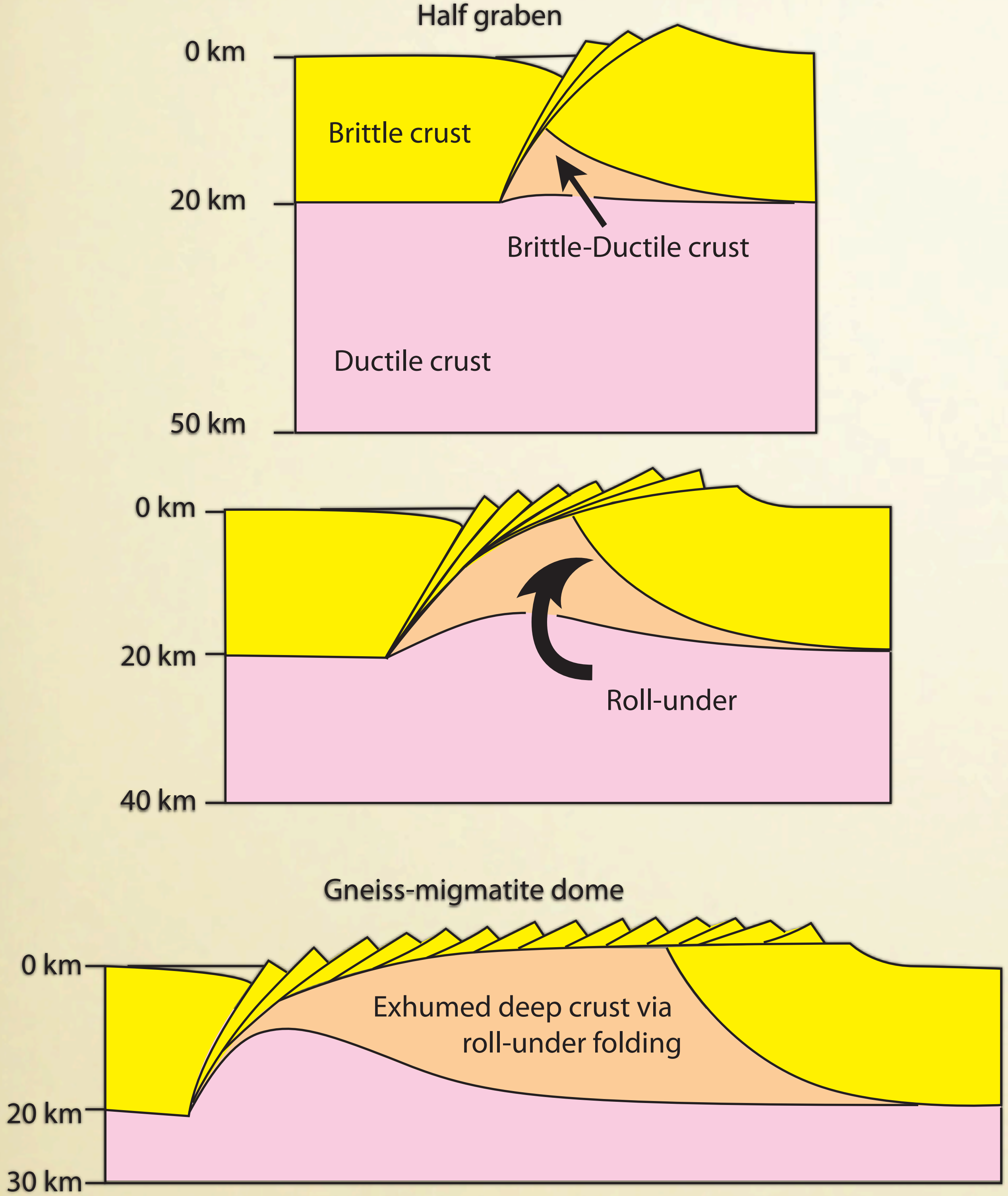


Did early continents crank-start plate tectonics?

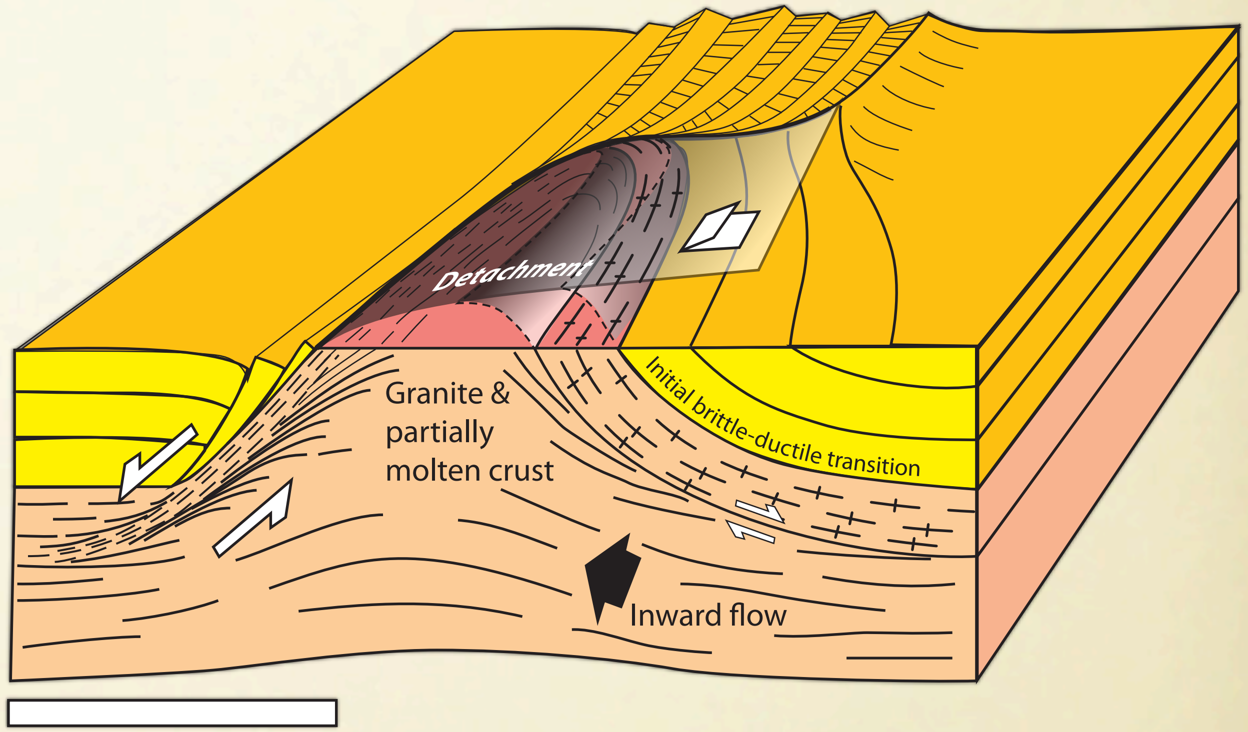




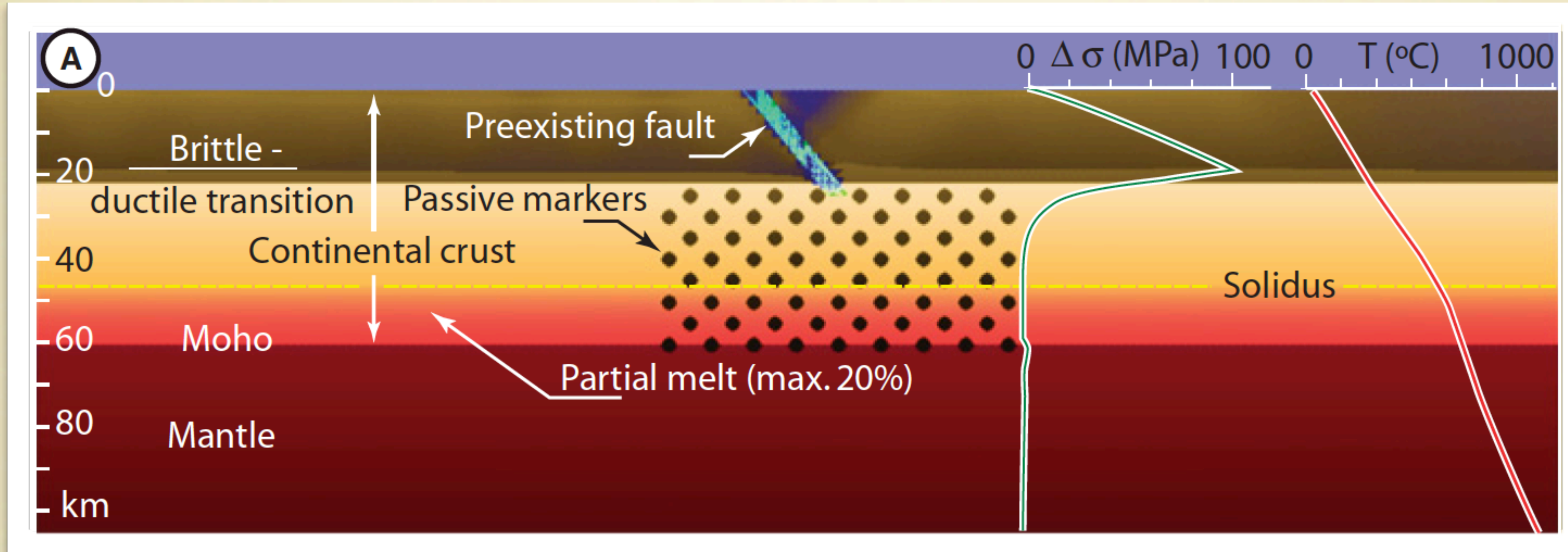
Strain regimes in hot crusts



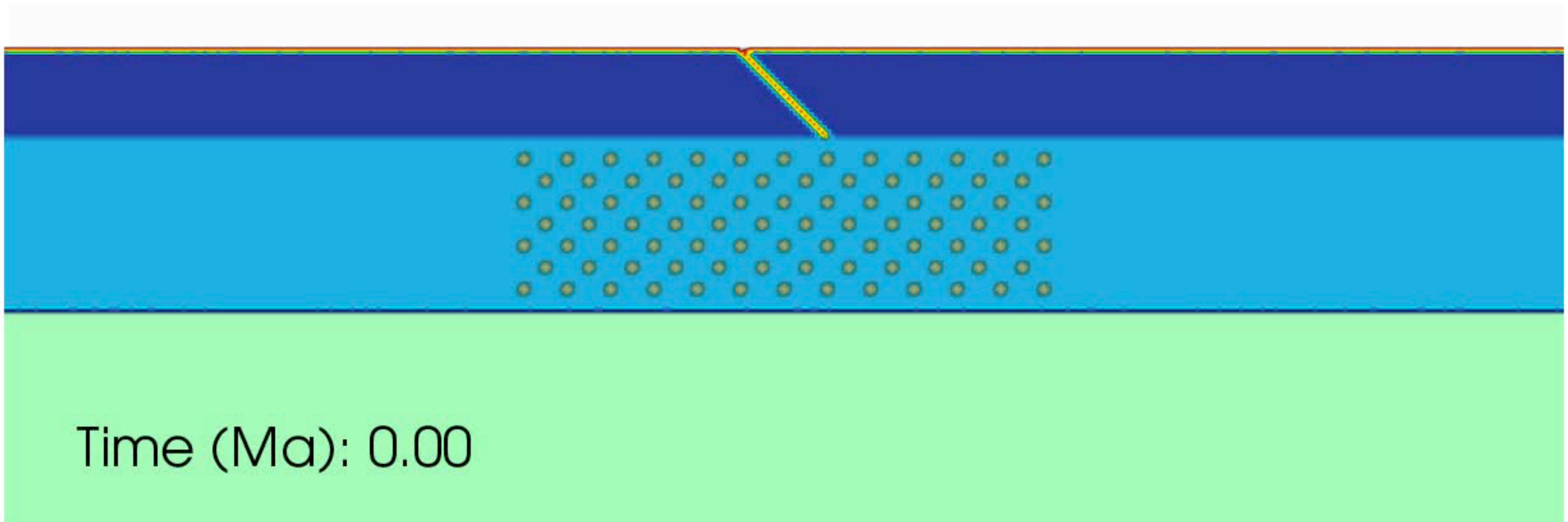
Van den Driessche & Brun, 1992



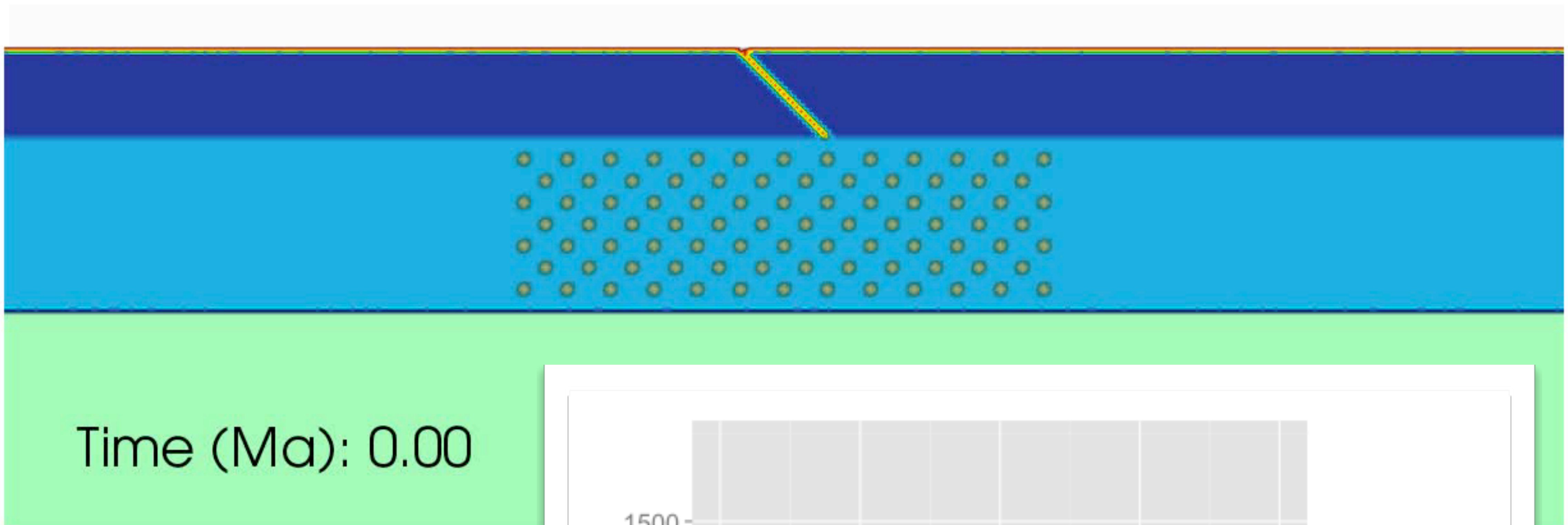
Brun & Van den Driessche, 1994


A
0
20
40
60
80
km
Brittle -
ductile transition
Continental crust
Moho
Mantle
Preexisting fault
Passive markers
Partial melt (max. 20%)
Solidus
0 Δ σ (MPa) 100
0 T (ºC) 1000

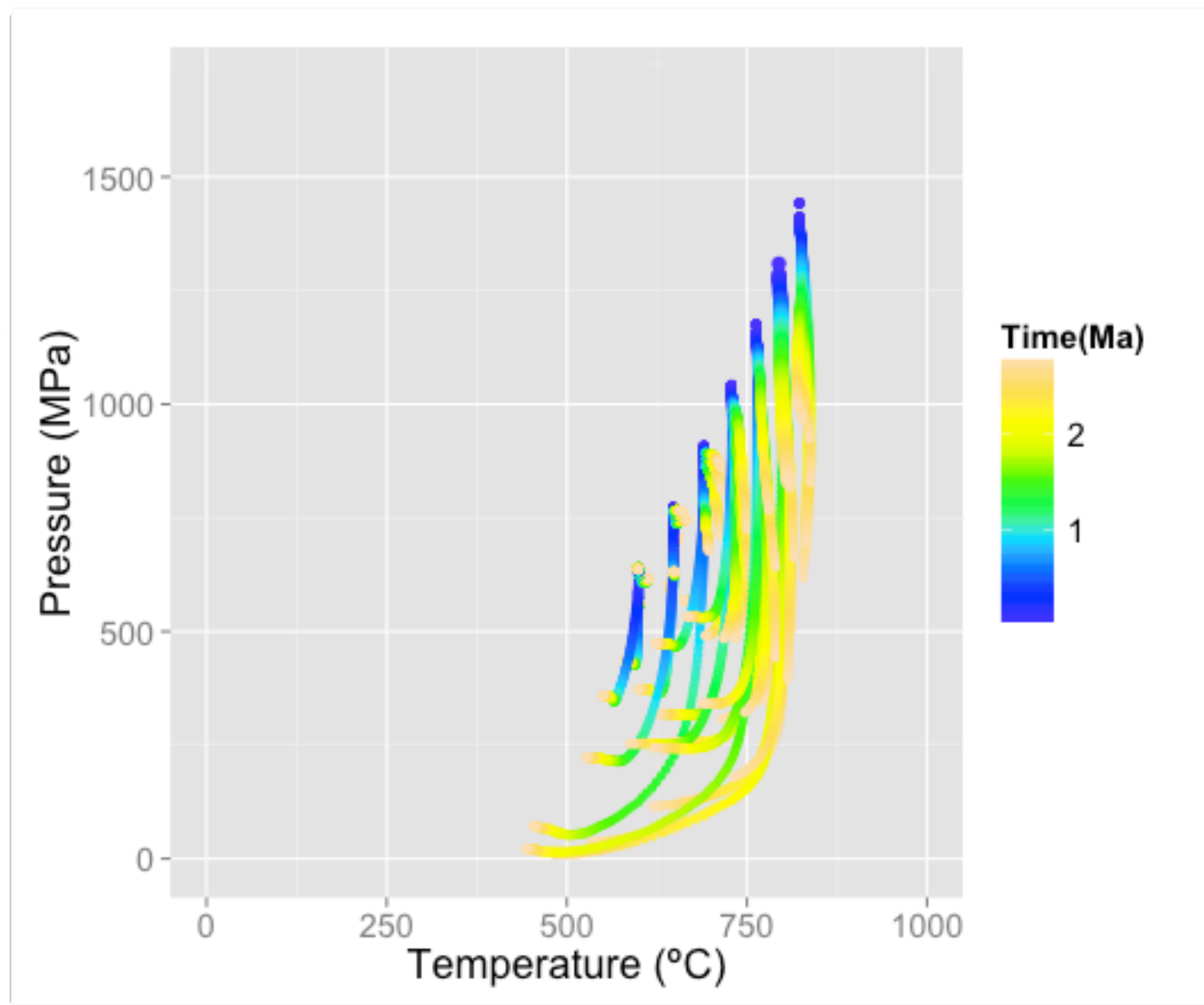
1.8 cm / yr



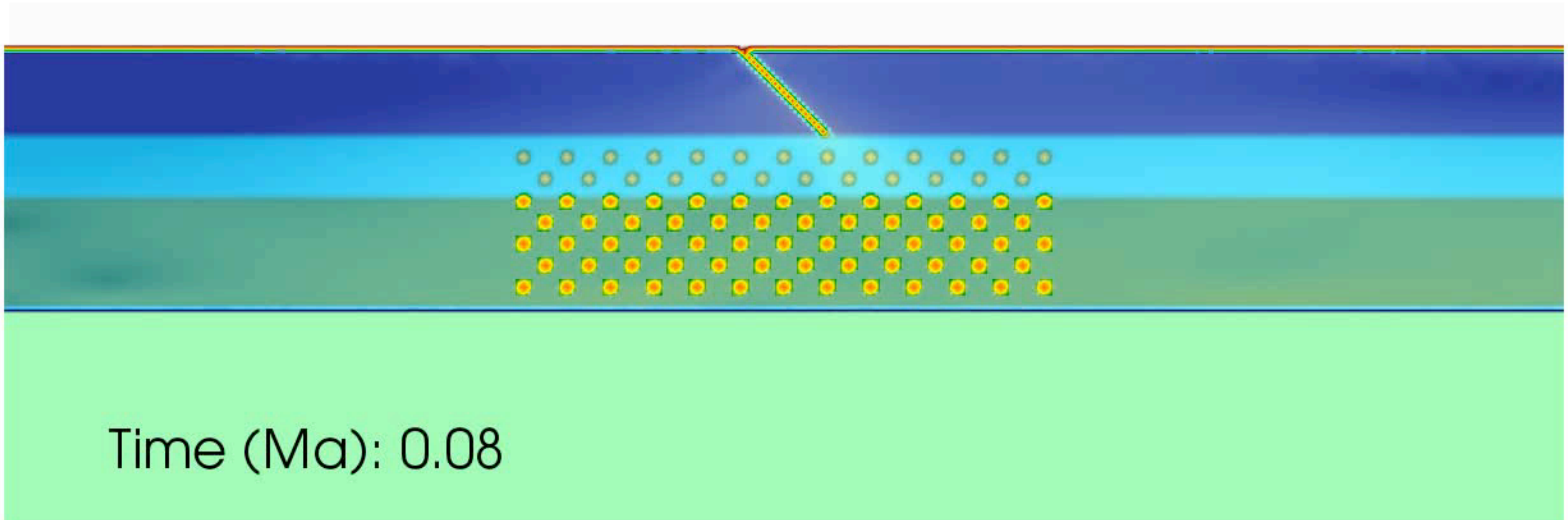
1.8 cm / yr


Time (Ma): 0.00

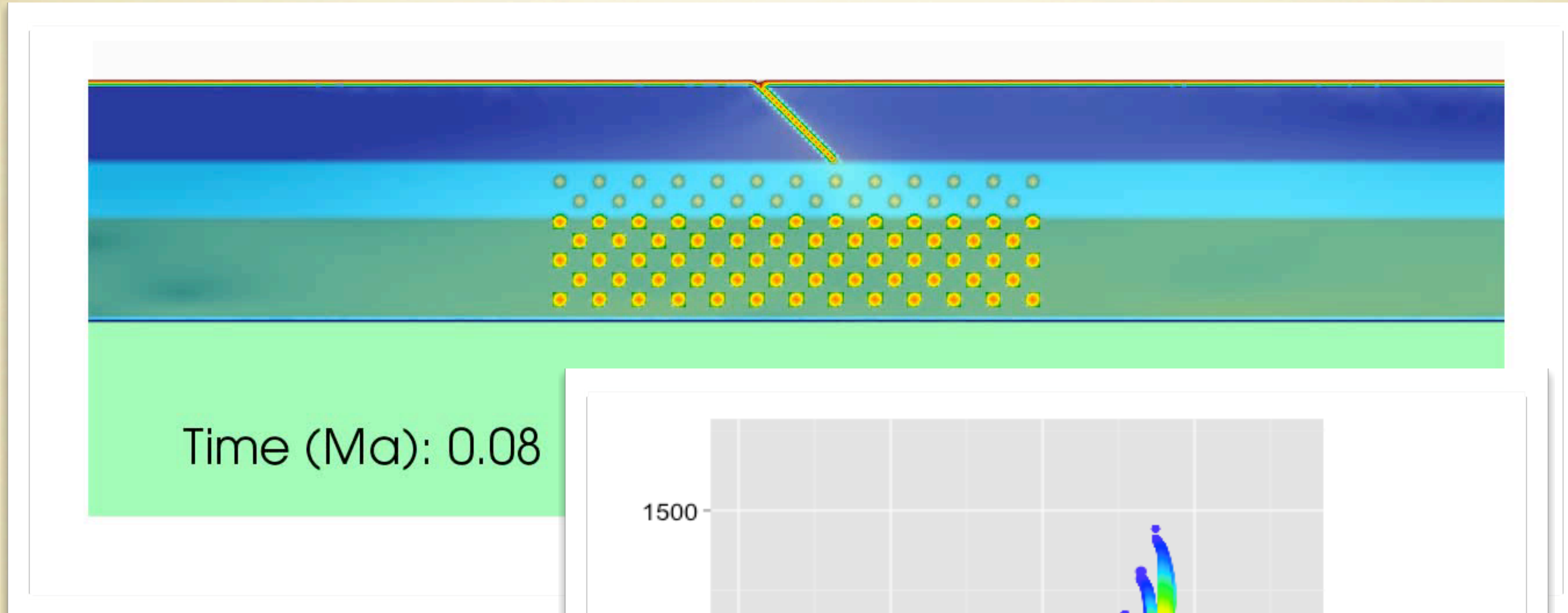
1.8 cm / yr


Pressure (MPa)
1500
1000
500
0
0
250
500
750
1000
Temperature (°C)
Time(Ma)
2
1

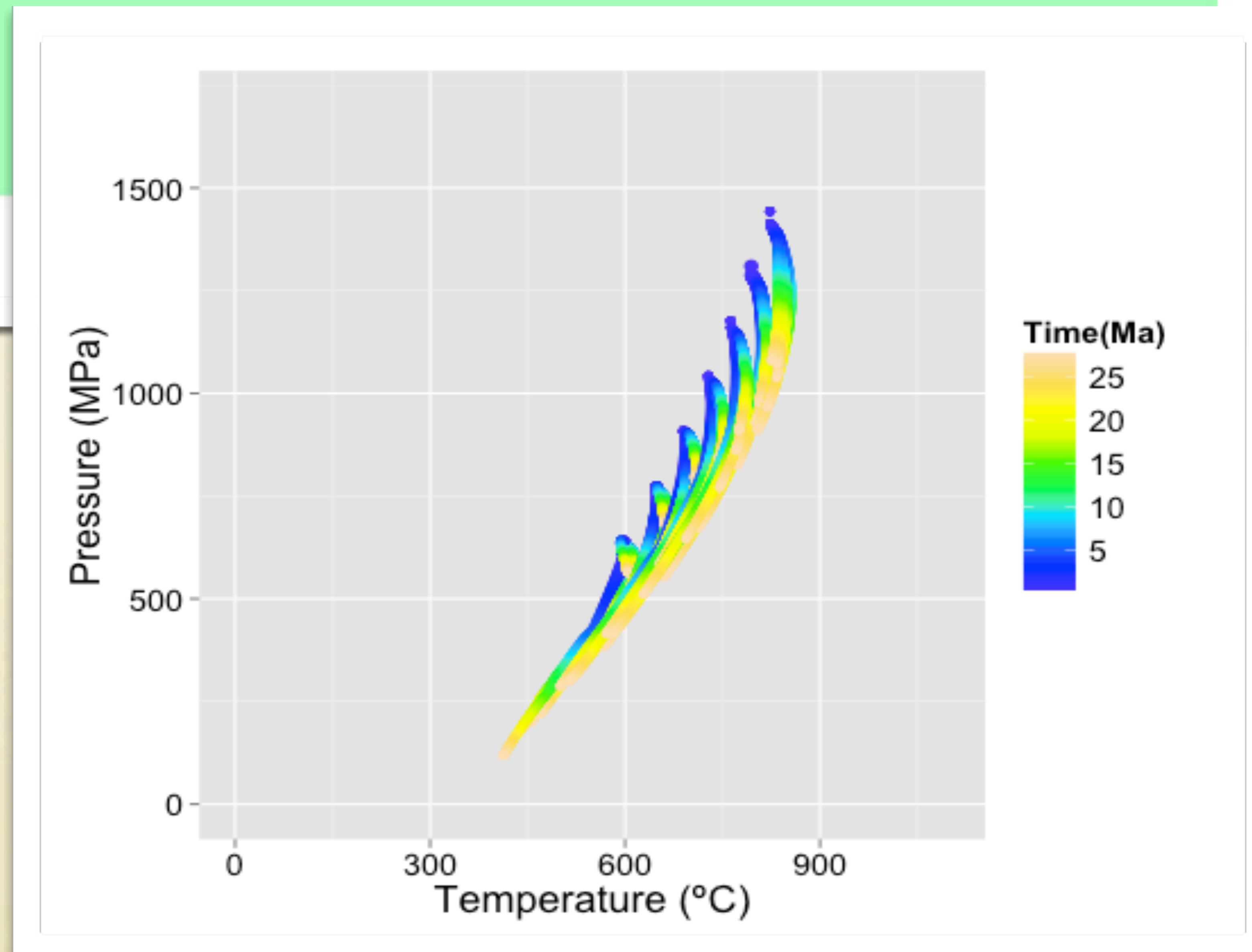
1.8 mm / yr

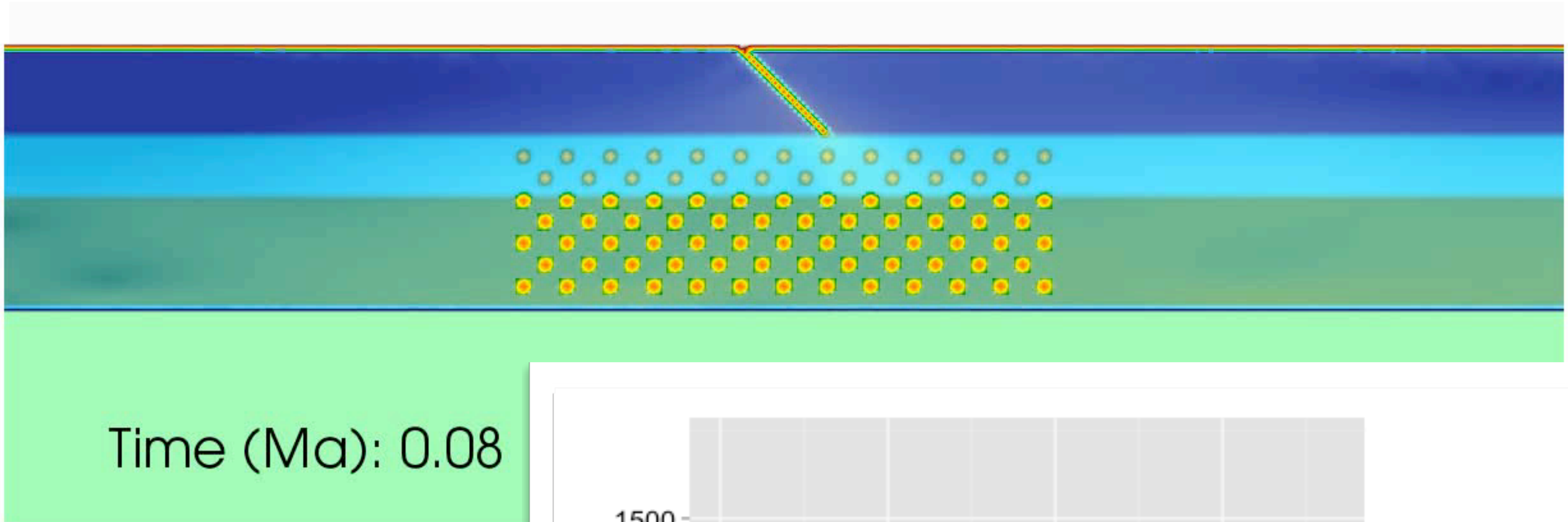


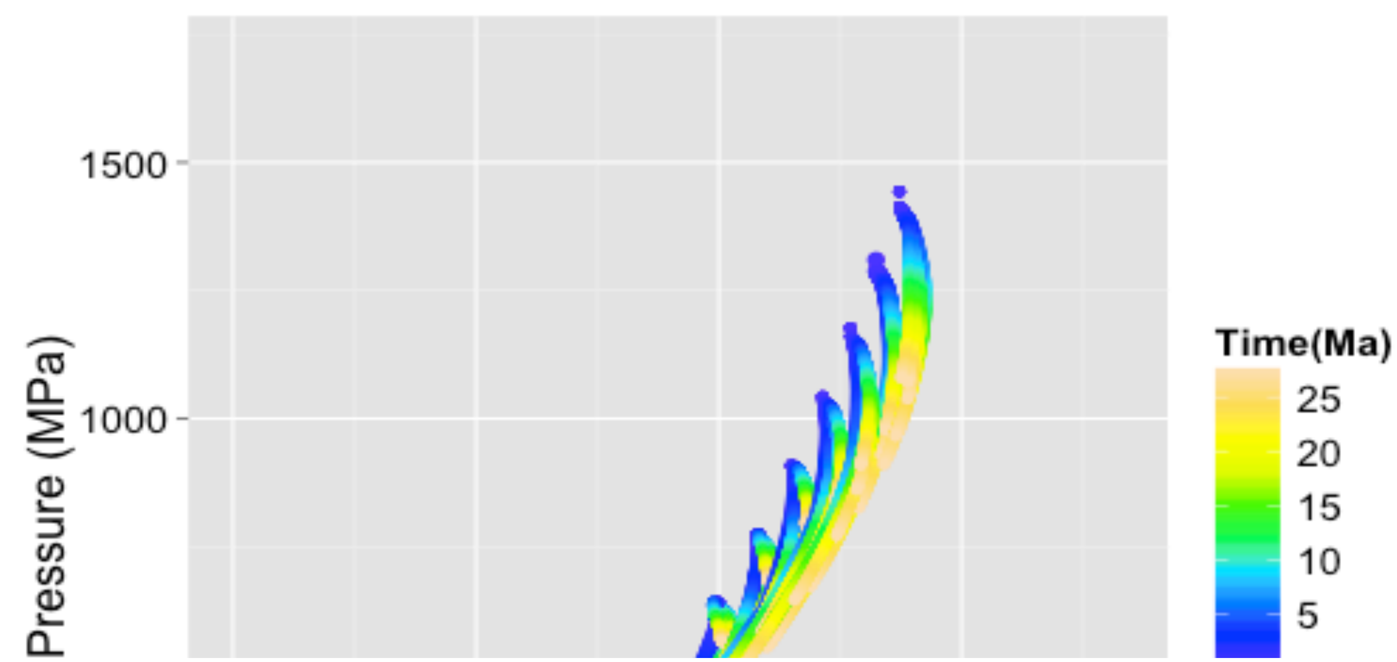
1.8 mm / yr


Time (Ma): 0.08

1.8 mm / yr


Pressure (MPa)
1500
1000
500
0
0
300
600
900
Temperature (°C)
Time(Ma)
25
20
15
10
5





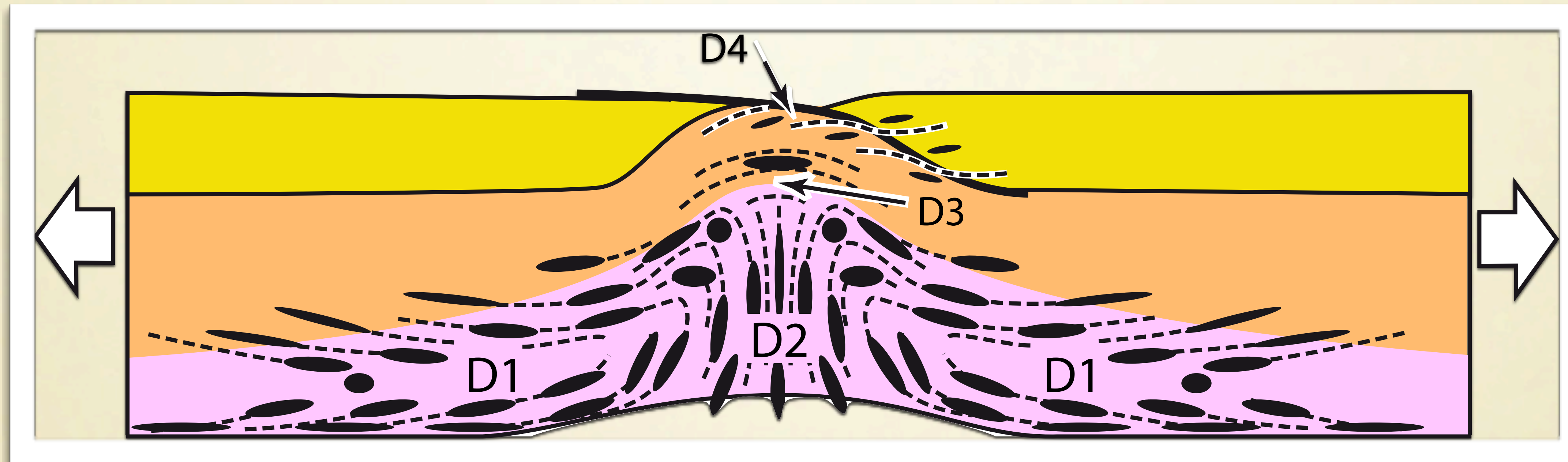
1.8 mm / yr

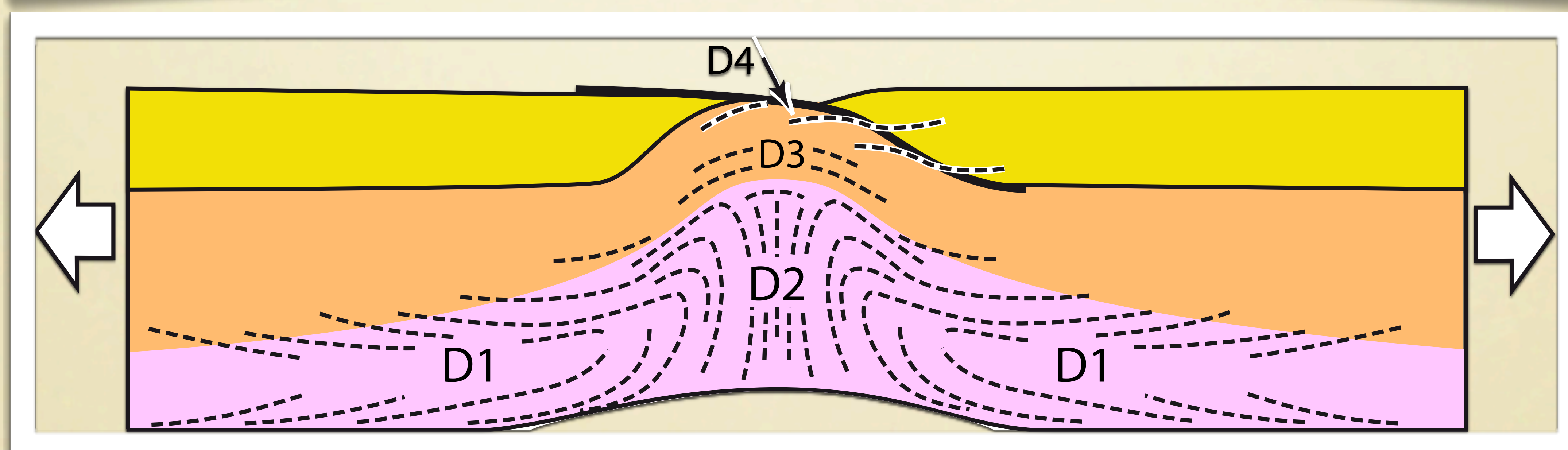
Viscous collision in channel explains double domes in metamorphic core complexes

Patrice F. Rey[1], Christian Teyssier[2], Seth C. Kruckenberg[3], and Donna L. Whitney[2]

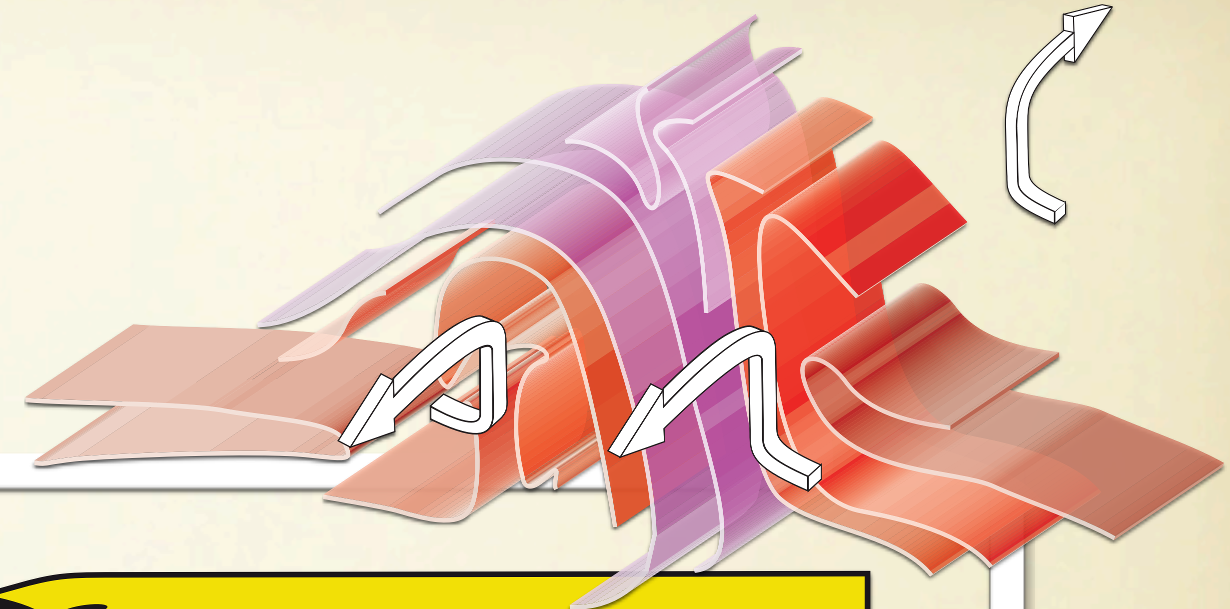
GEOLOGY, April 2011

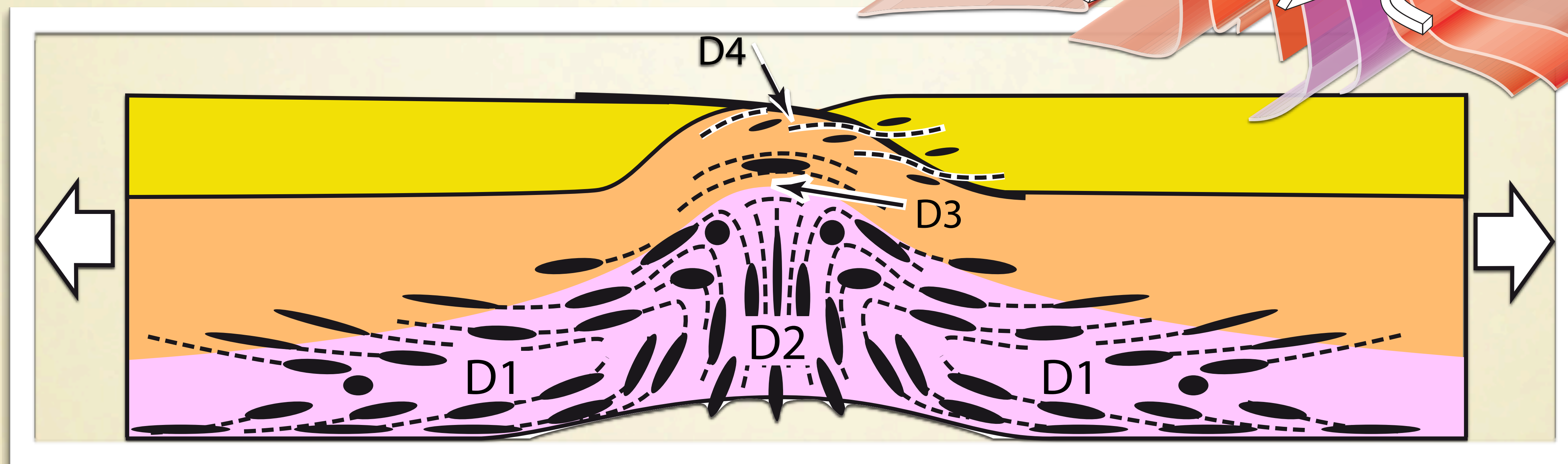
Strain regime partitioning

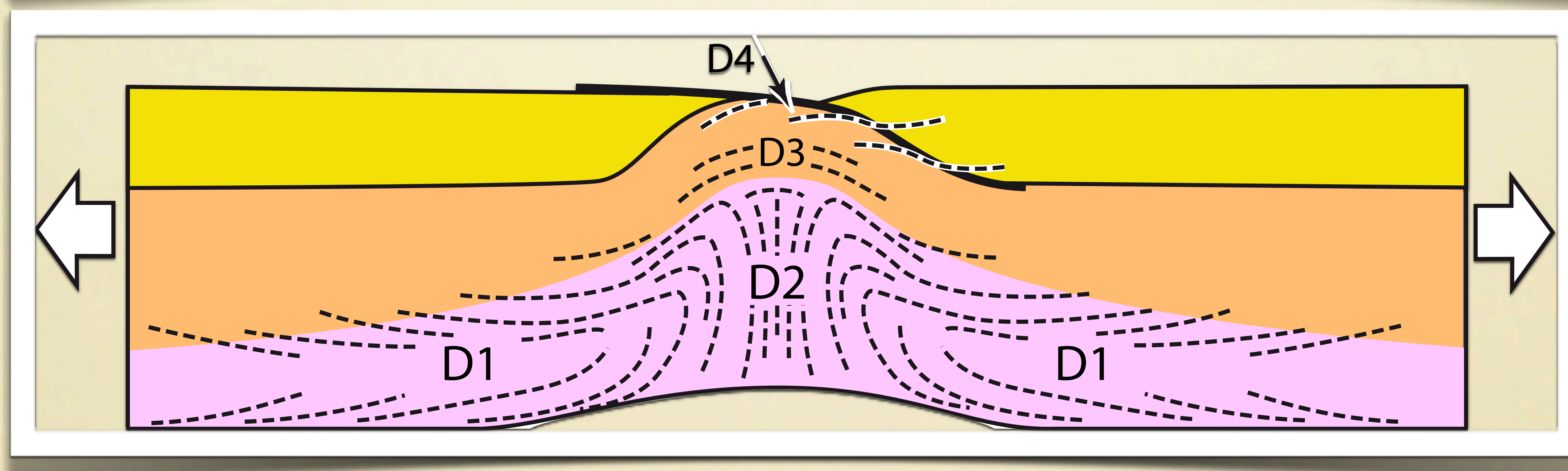


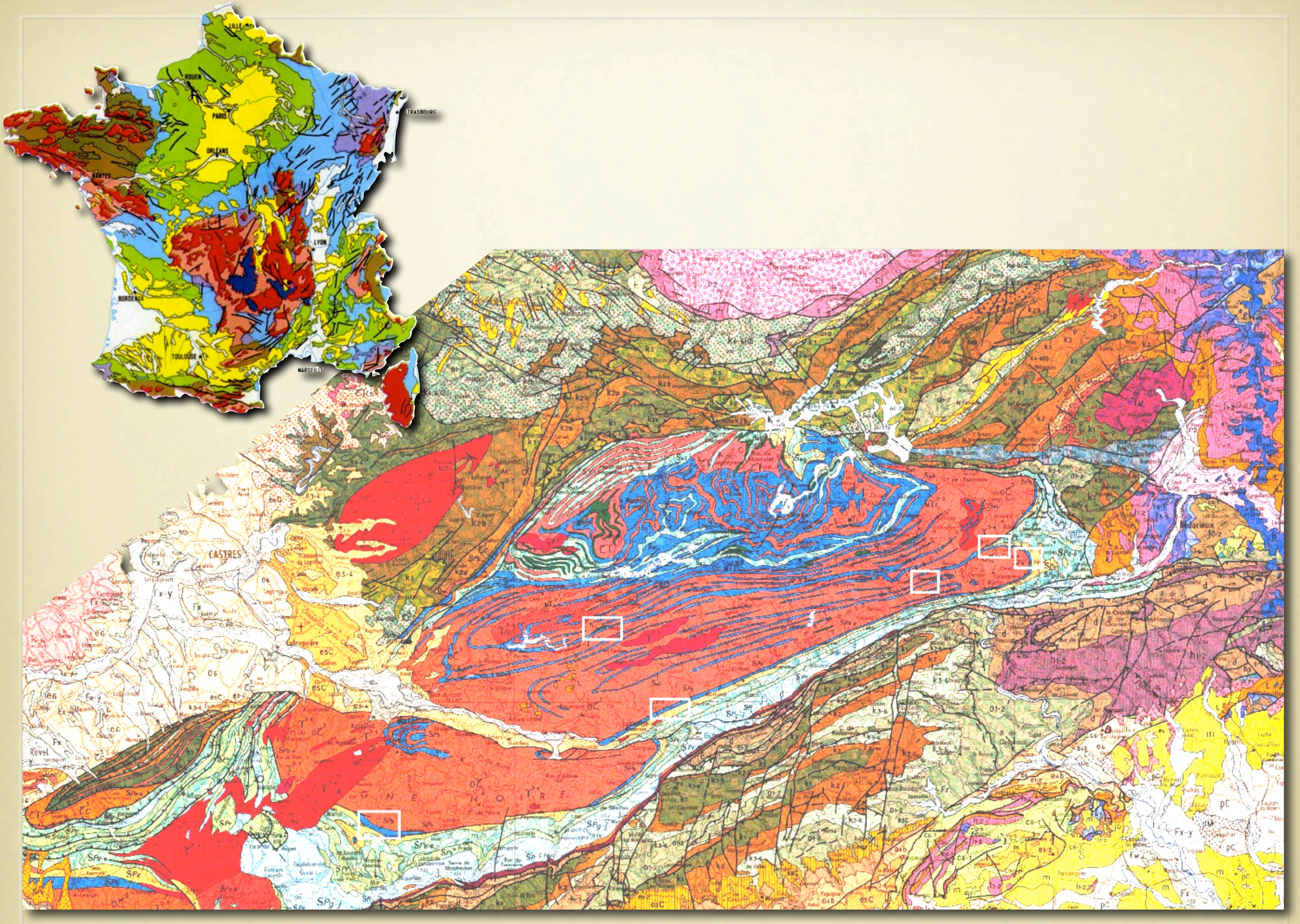


Strain regime partitioning

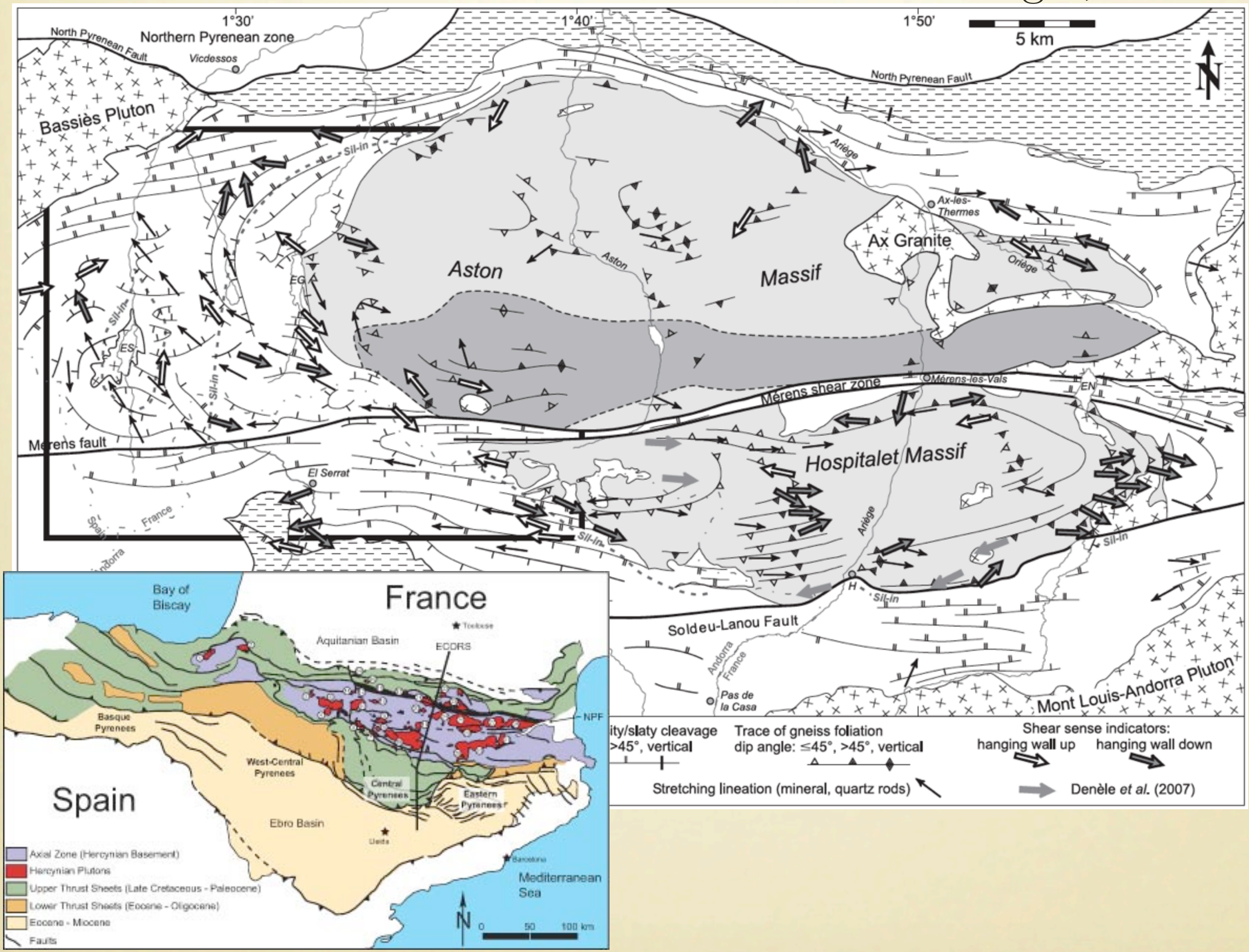




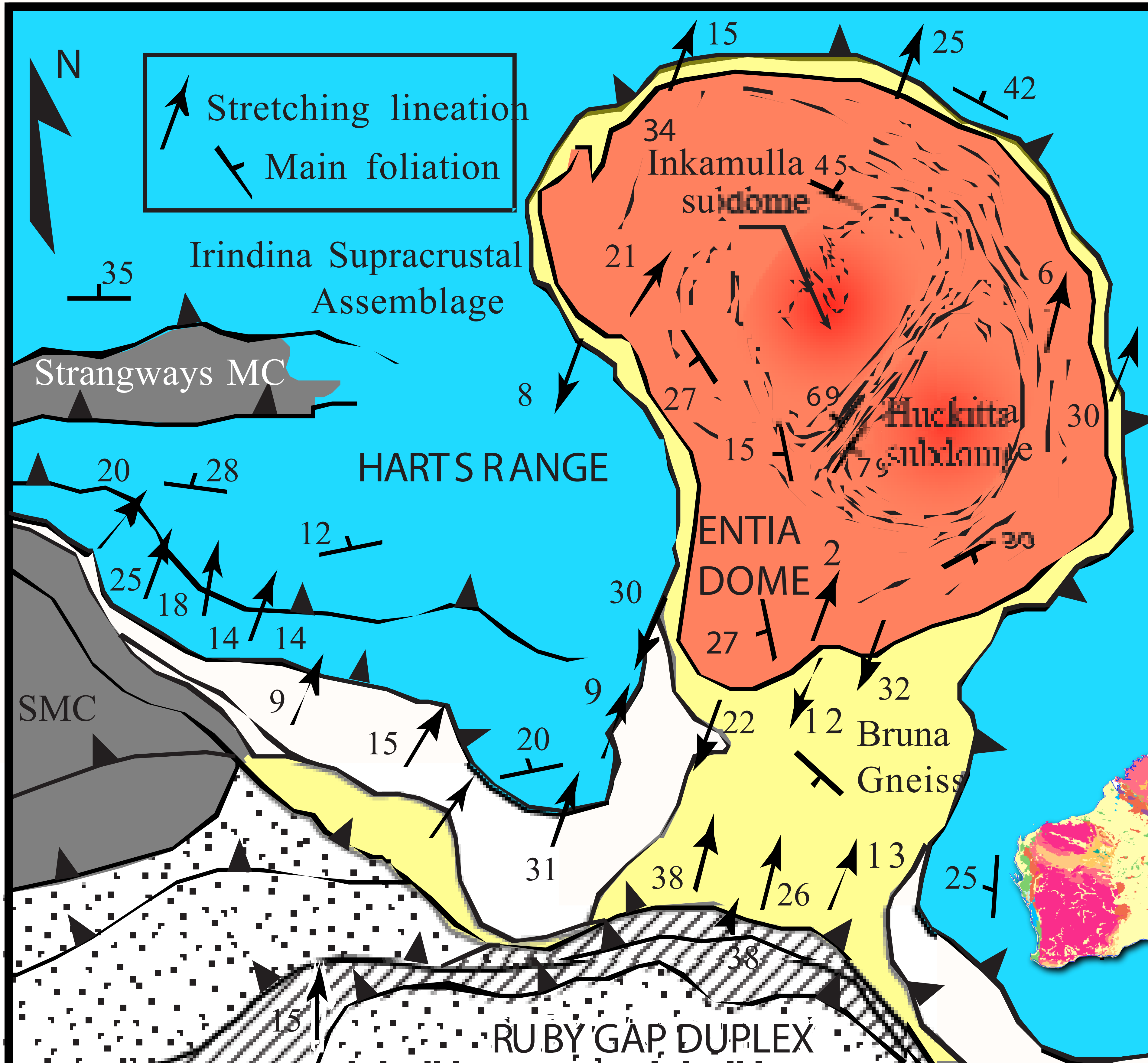


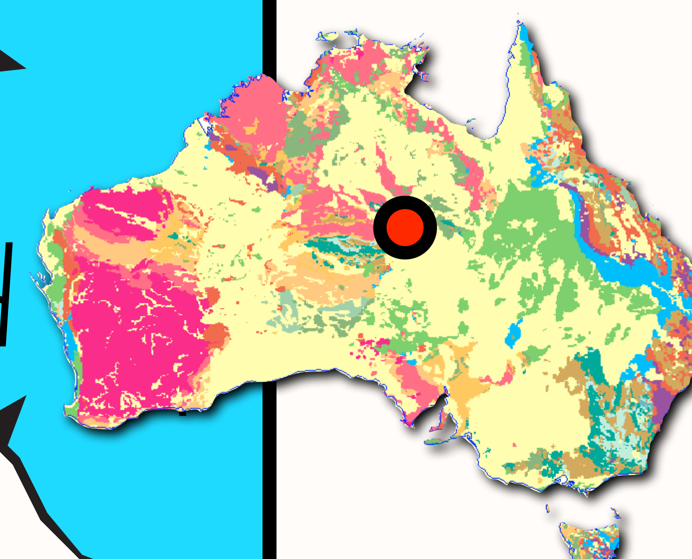

LILLE
ROUEN
PARIS
ORLÉANS
NANTES
LYON
BORDEAUX
TOULOUSE
CASTRES

Mezger, 2004

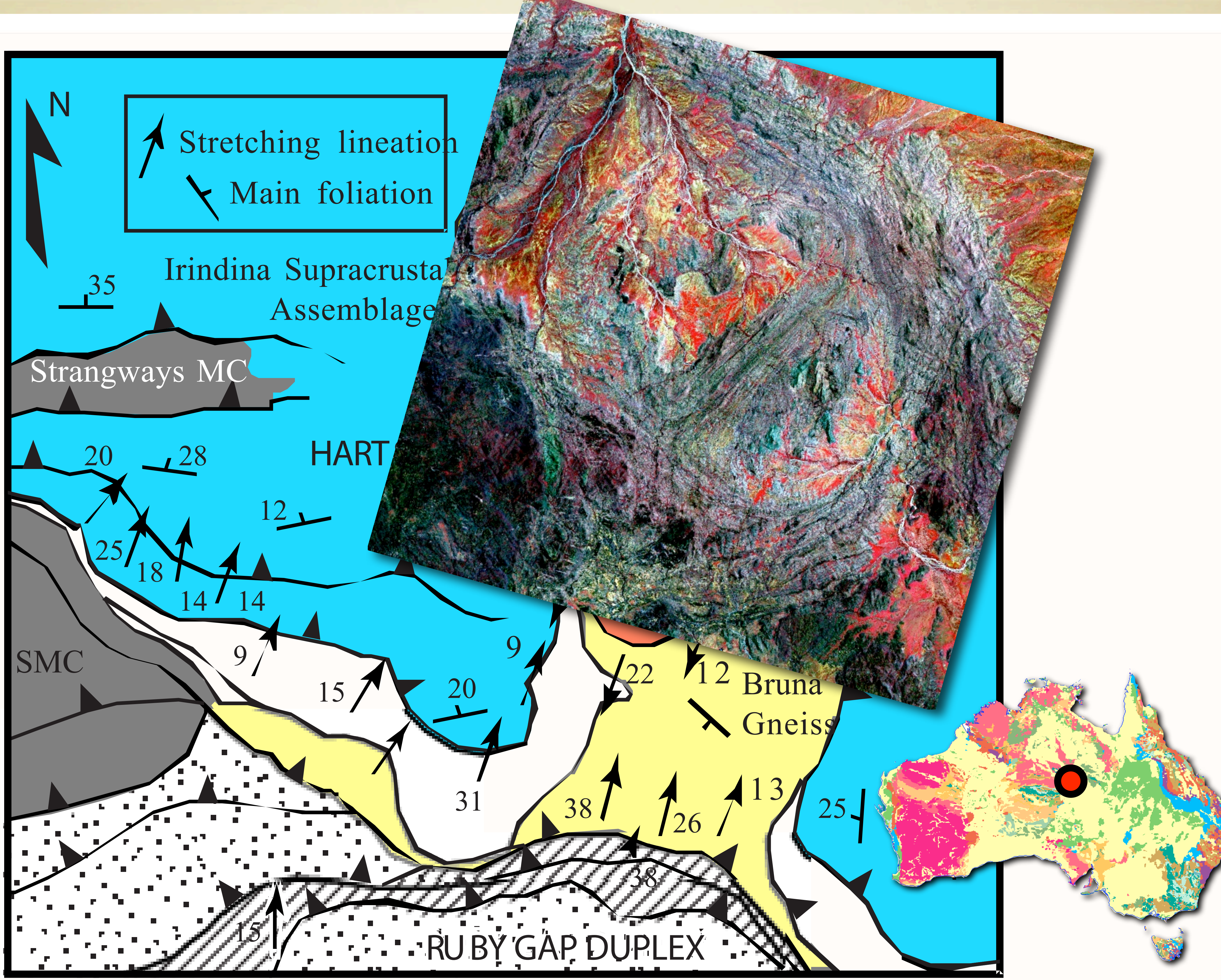


1°30'
1°40'
1°50'
5 km
North Pyrenean Fault
Northern Pyrenean zone
Vicdessos
Bassiès Pluton
Aston
Massif
Ax Granite
Ax-les-Thermes
Oriège
Ariège
Mérens shear zone
Mérens-les-Vals
Mérens fault
El Serrat
Hospitalet Massif
Soldeu-Lanou Fault
Pas de la Casa
Mont Louis-Andorra Pluton
Sil-in
Trace of gneiss foliation
dip angle: ≤45°, >45°, vertical
Shear sense indicators:
hanging wall up
hanging wall down
Stretching lineation (mineral, quartz rods)
Denèle et al. (2007)
Bay of Biscay
France
Aquitanian Basin
ECORS
Basque Pyrenees
West-Central Pyrenees
Central Pyrenees
Eastern Pyrenees
Spain
Ebro Basin
Mediterranean Sea
Axial Zone (Hercynian Basement)
Hercynian Plutons
Upper Thrust Sheets (Late Cretaceous - Paleocene)
Lower Thrust Sheets (Eocene - Oligocene)
Eocene - Miocene
Faults
0 50 100 km





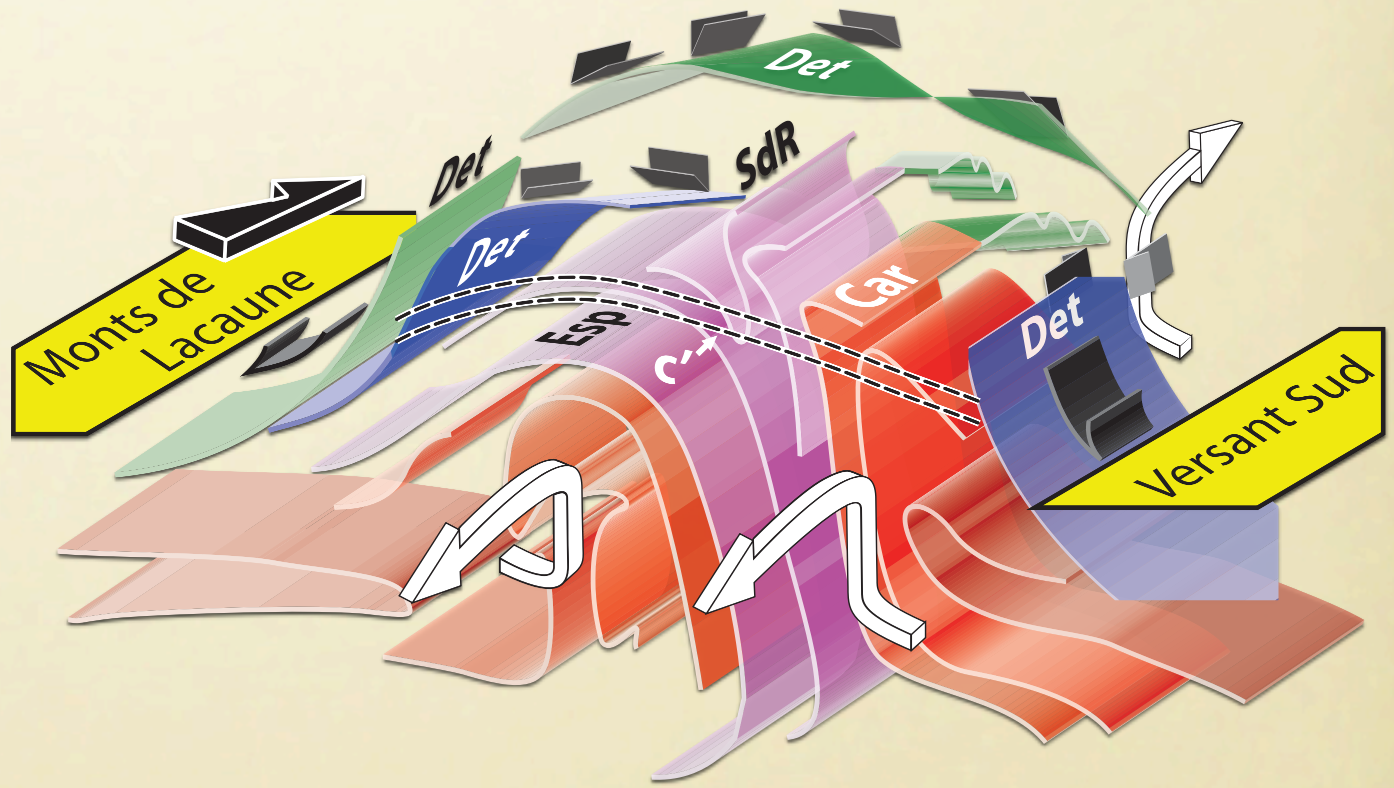
Wednesday, 6 November 13

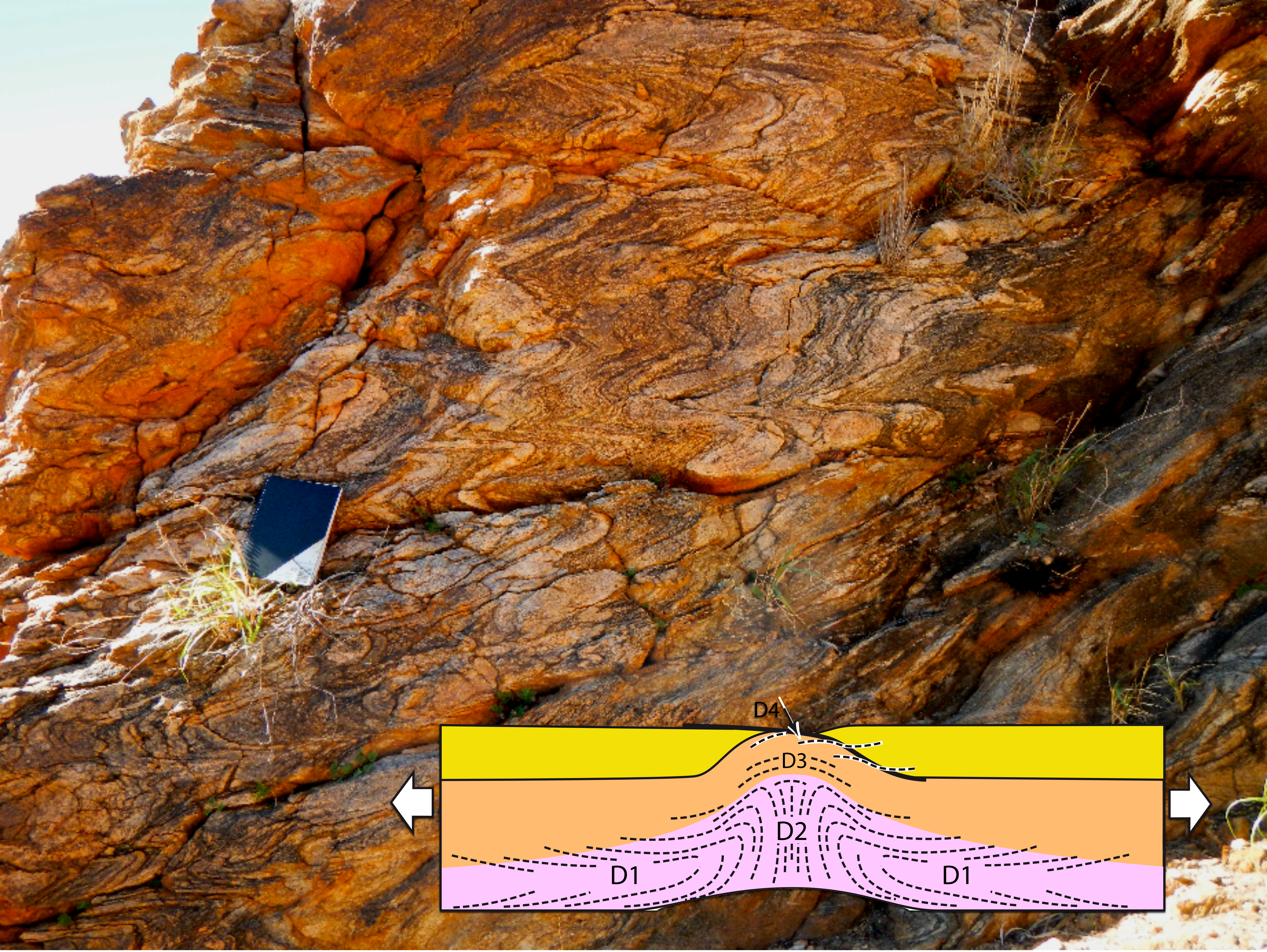

N
Stretching lineation
Main foliation
Irindina Supracrustal
Assemblage
Strangways MC
HART
SMC
Bruna
Gneiss
RUBY GAP DUPLEX
35
20
28
12
25
18
14
14
9
15
20
9
22
12
31
38
26
13
25
38
15

Strain regimes in hot crusts:

Coeval contractional, extensional and shear fabrics develop in various parts of hot extending crusts.

During extension, hot rocks are advected through regions of contrasting "tectonic regimes".




D4
D3
D2
D1
D1