Forward Modeling of Rift and Passive Margin Formation

Implications for South, North, and Central Atlantic Margins

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Overview

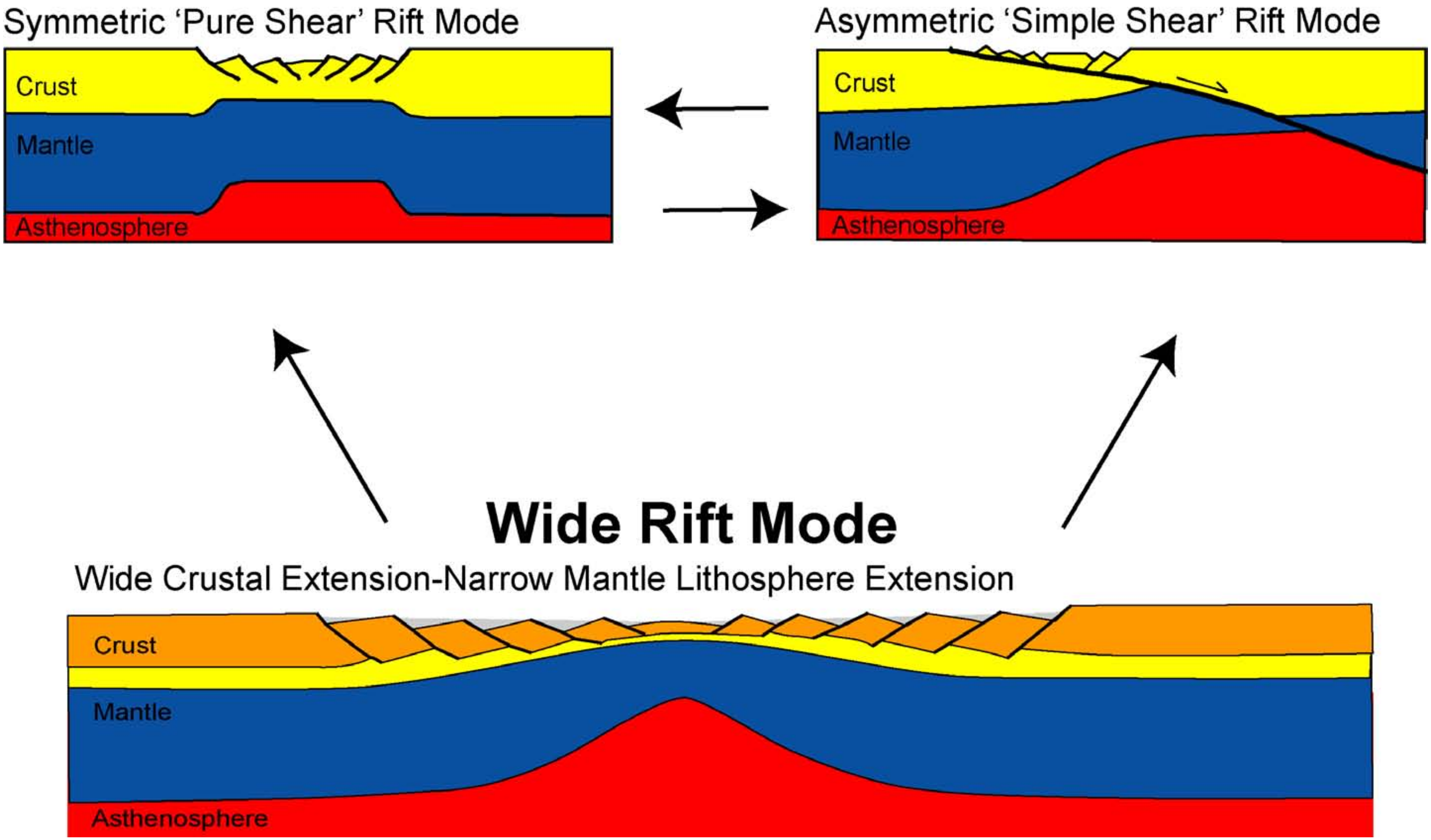
- Styles of rifted margin formation : Variability in natural systems
- First order controls on extension mode
- Type I: Narrow non volcanic rifted margins
- Type II: Wide rifted margins and depth dependent extension

First order rift modes

- Natural systems appear to exhibit a range of styles including:

1. Core complex extension
2. Wide rift and passive margin
3. Narrow rift and passive margin
4. Symmetric rift and passive margin
5. Asymmetric rift and passive margin

Narrow Rift Mode



Symmetric ‘Pure Shear’ Rift Mode

Asymmetric ‘Simple Shear’ Rift Mode

Wide Rift Mode

Wide Crustal Extension-Narrow Mantle Lithosphere Extension

Huismans and Beaumont, 2008

Symmetric Continental Breakup?

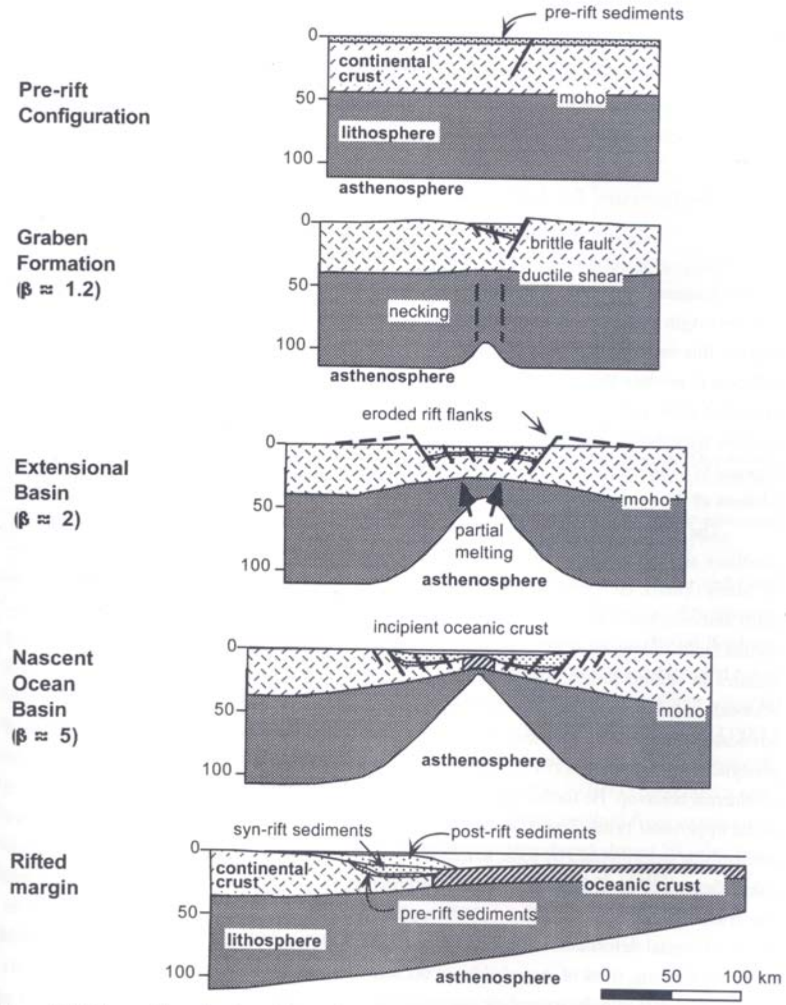
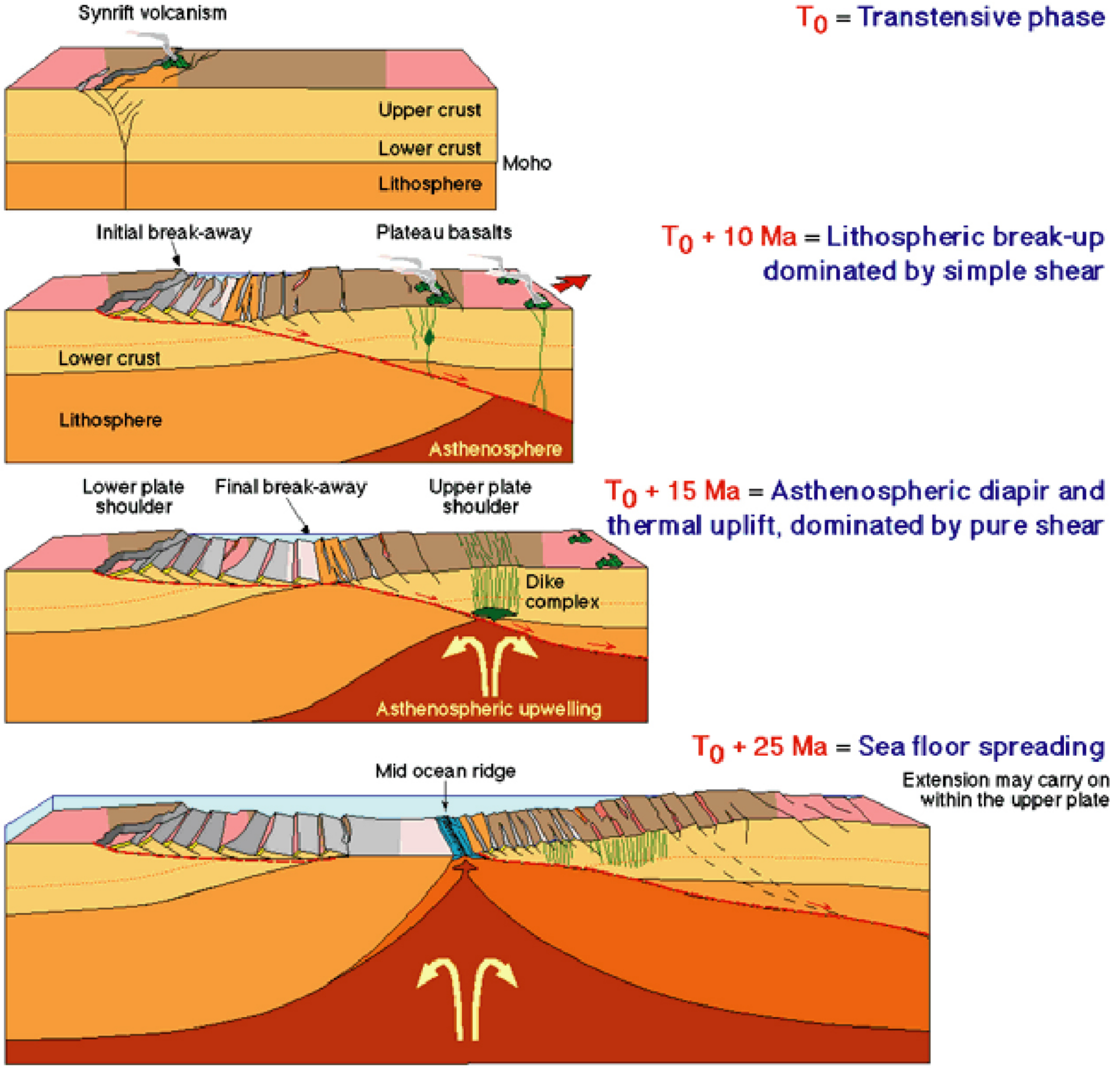


Figure 1.2: Diagram illustrating the evolution of a continental rift to an extensional basin and eventually a rifted continental margin (modified after Salveson, (1978).

Asymmetric continental breakup?



T_0 = Transtensive phase

T_0 + 10 Ma = Lithospheric break-up dominated by simple shear

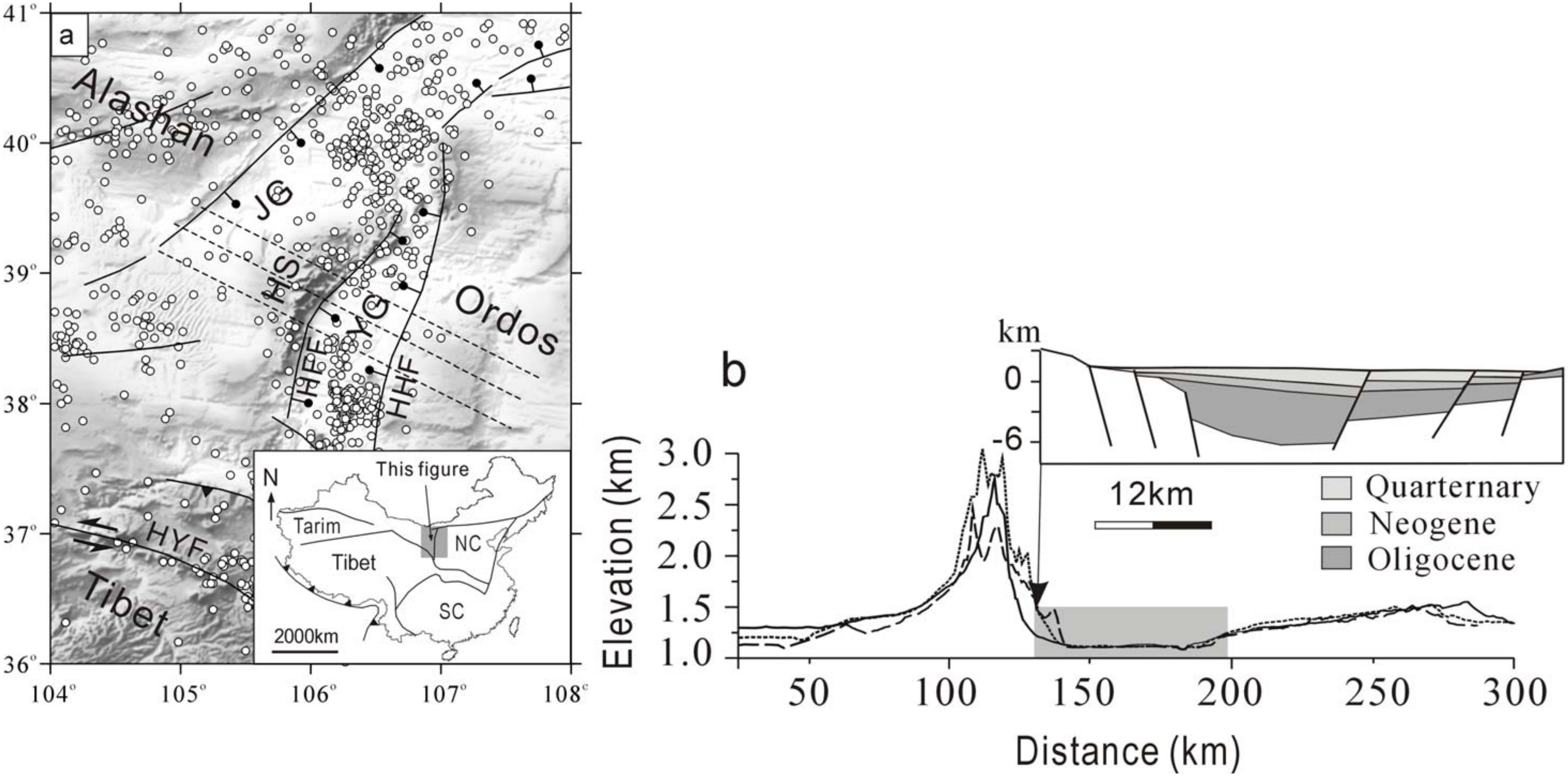
T_0 + 15 Ma = Asthenospheric diapir and thermal uplift, dominated by pure shear

T_0 + 25 Ma = Sea floor spreading

Extension may carry on within the upper plate

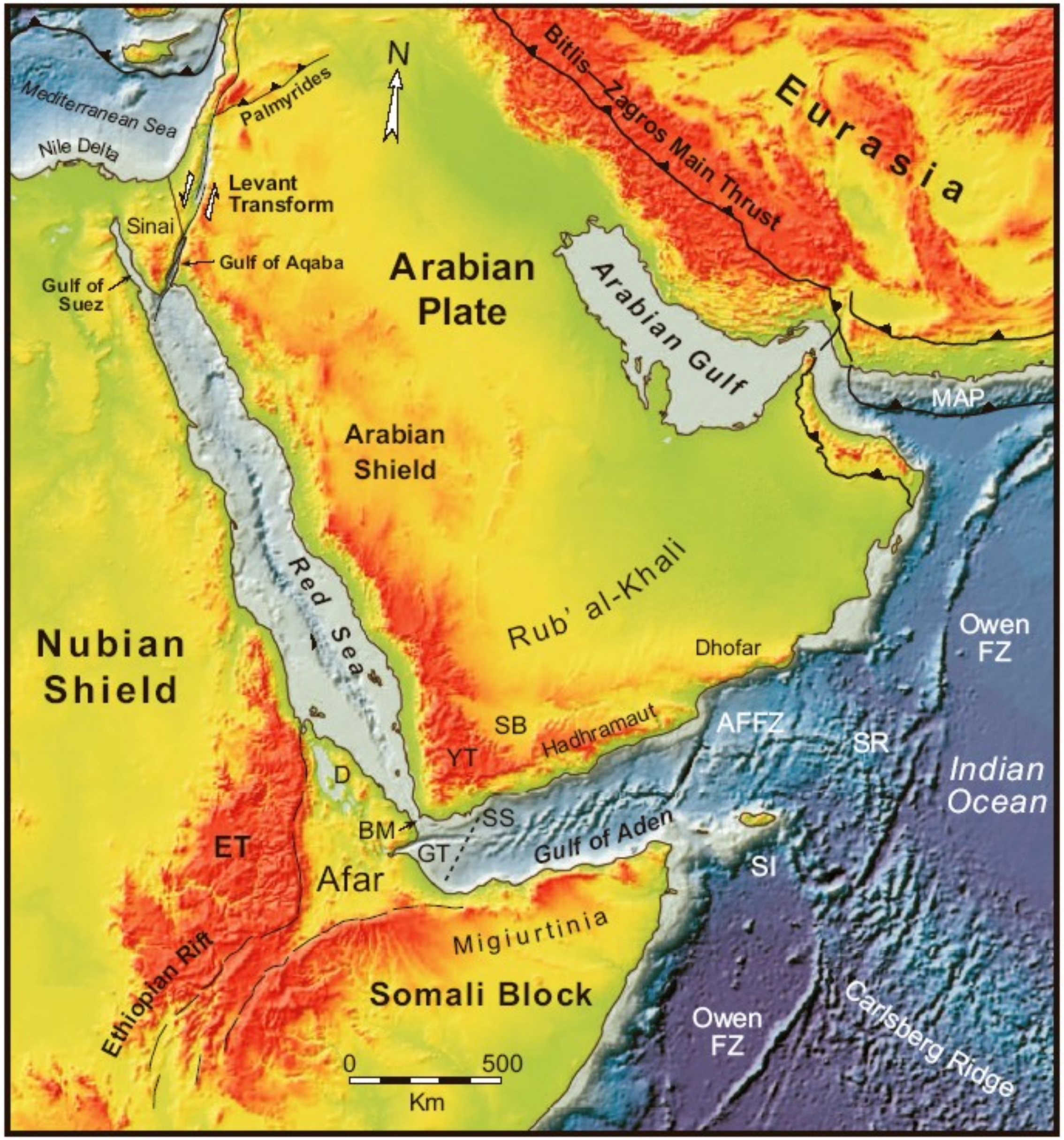
- Stampfli

Narrow asymmetric rifting
Yinchuan graben



He et al., GRL 2003

Narrow (A) Symmetric Rifting



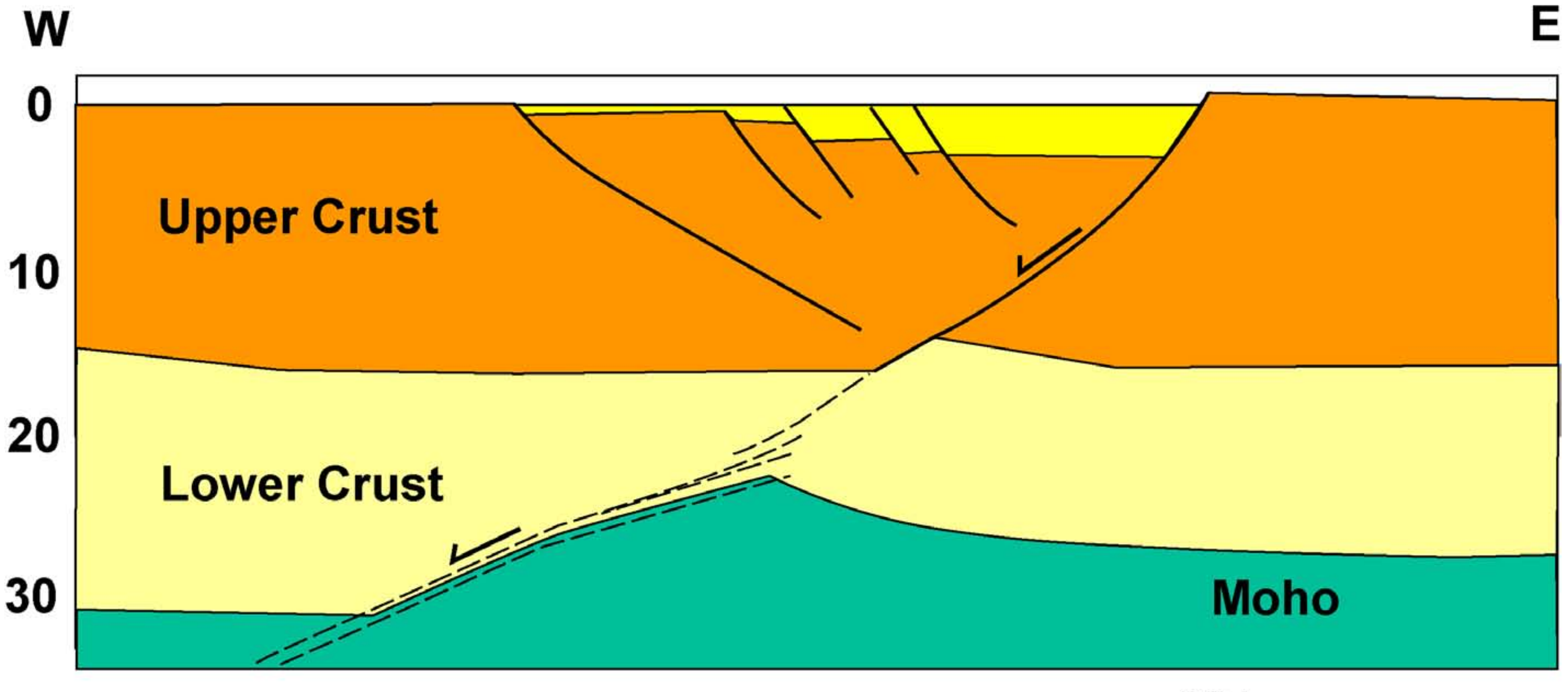
Red Sea / Gulf of Suez

Extension is localized in a Narrow rift system with a width ~ 100 - 150 km

Symmetric or Asymmetric?

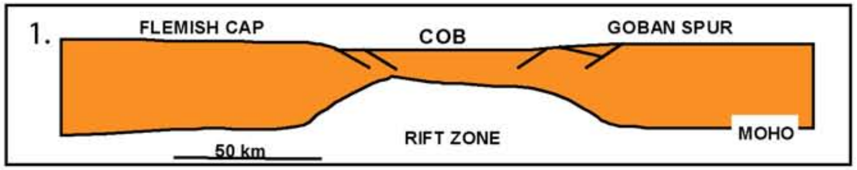
Narrow Rifting

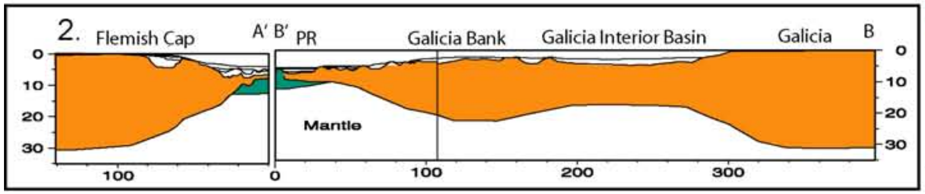
Upper Rhine Graben Section

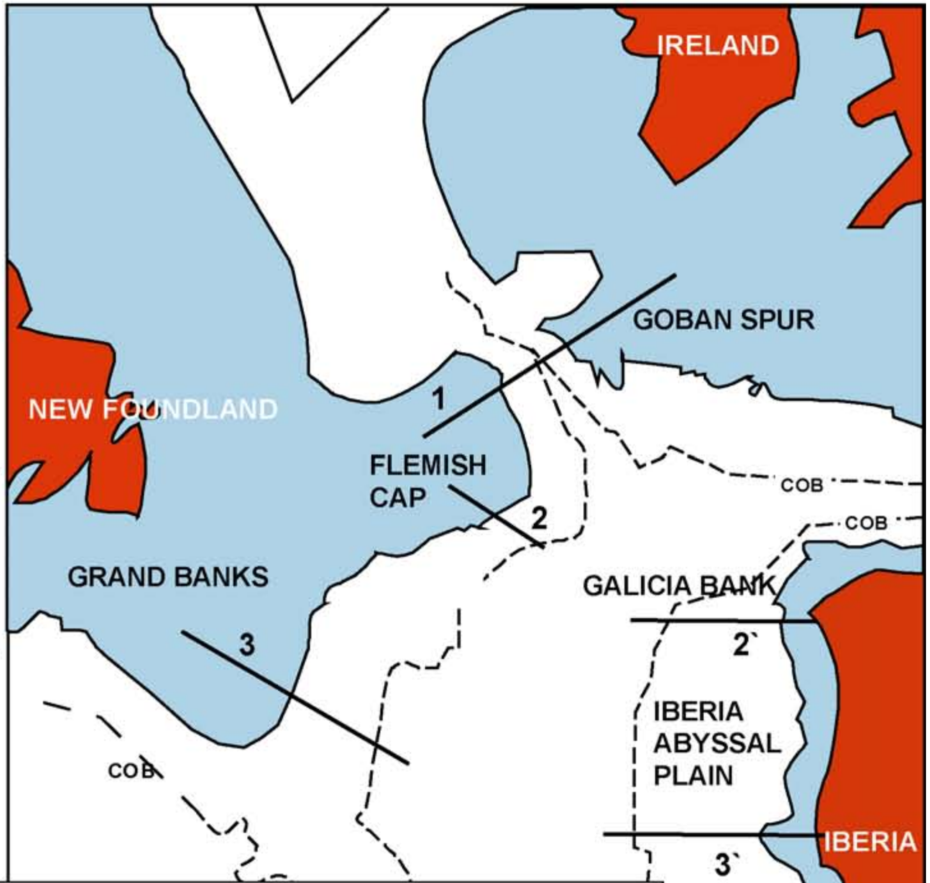


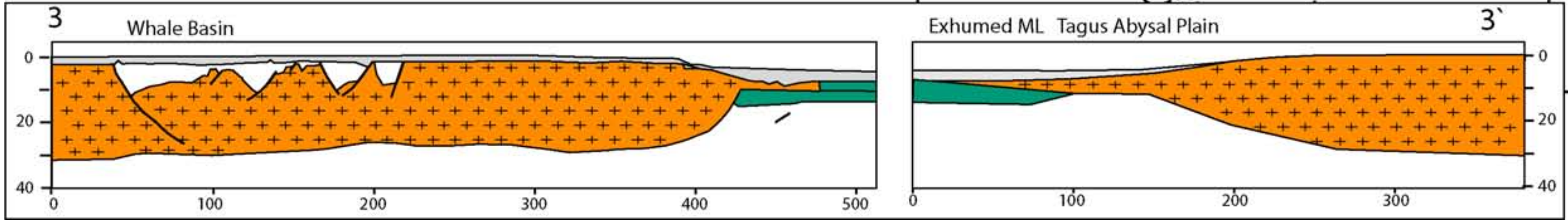
- Brun et al.

Central Atlantic Passive Margins



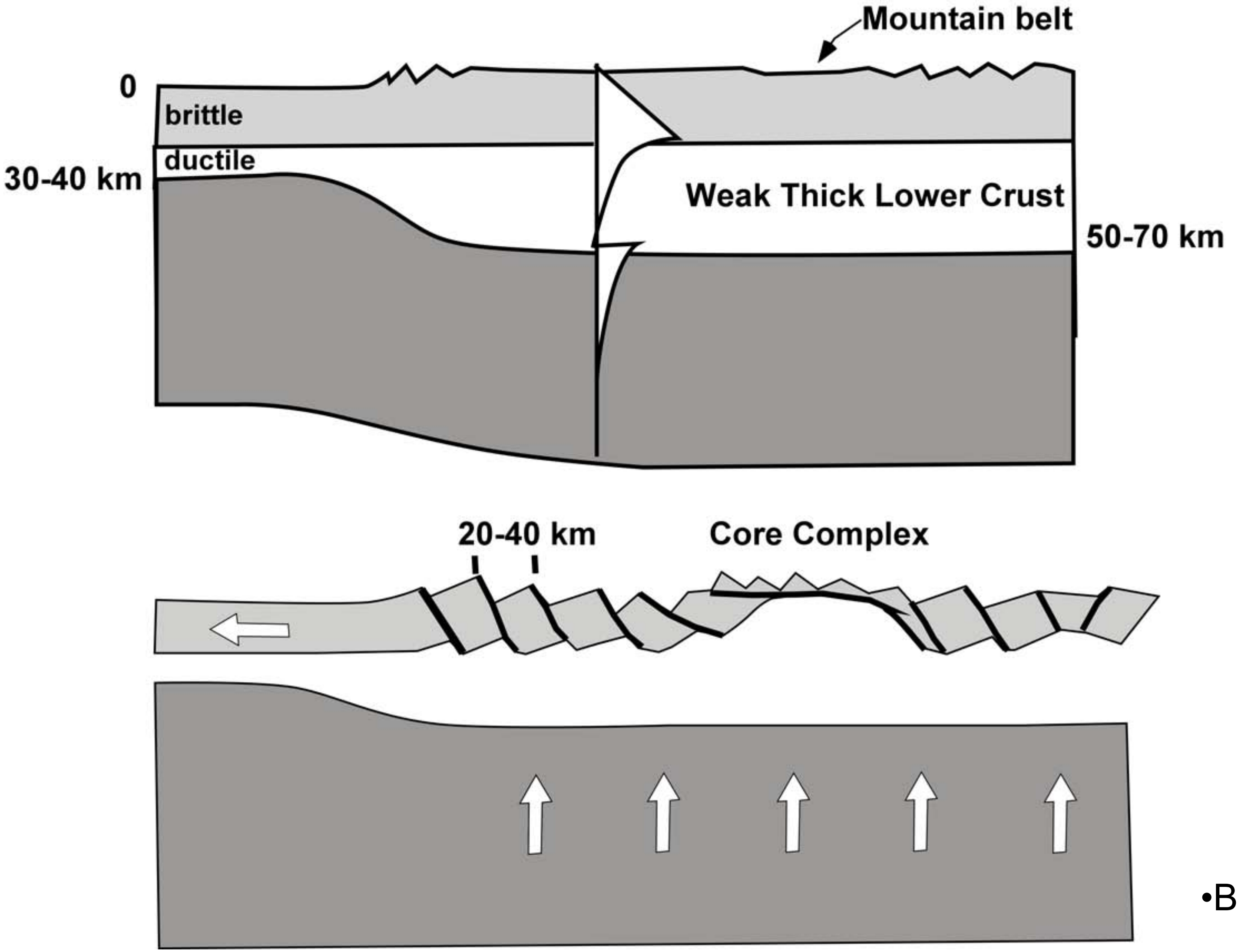






Huismans and Beaumont, 2008

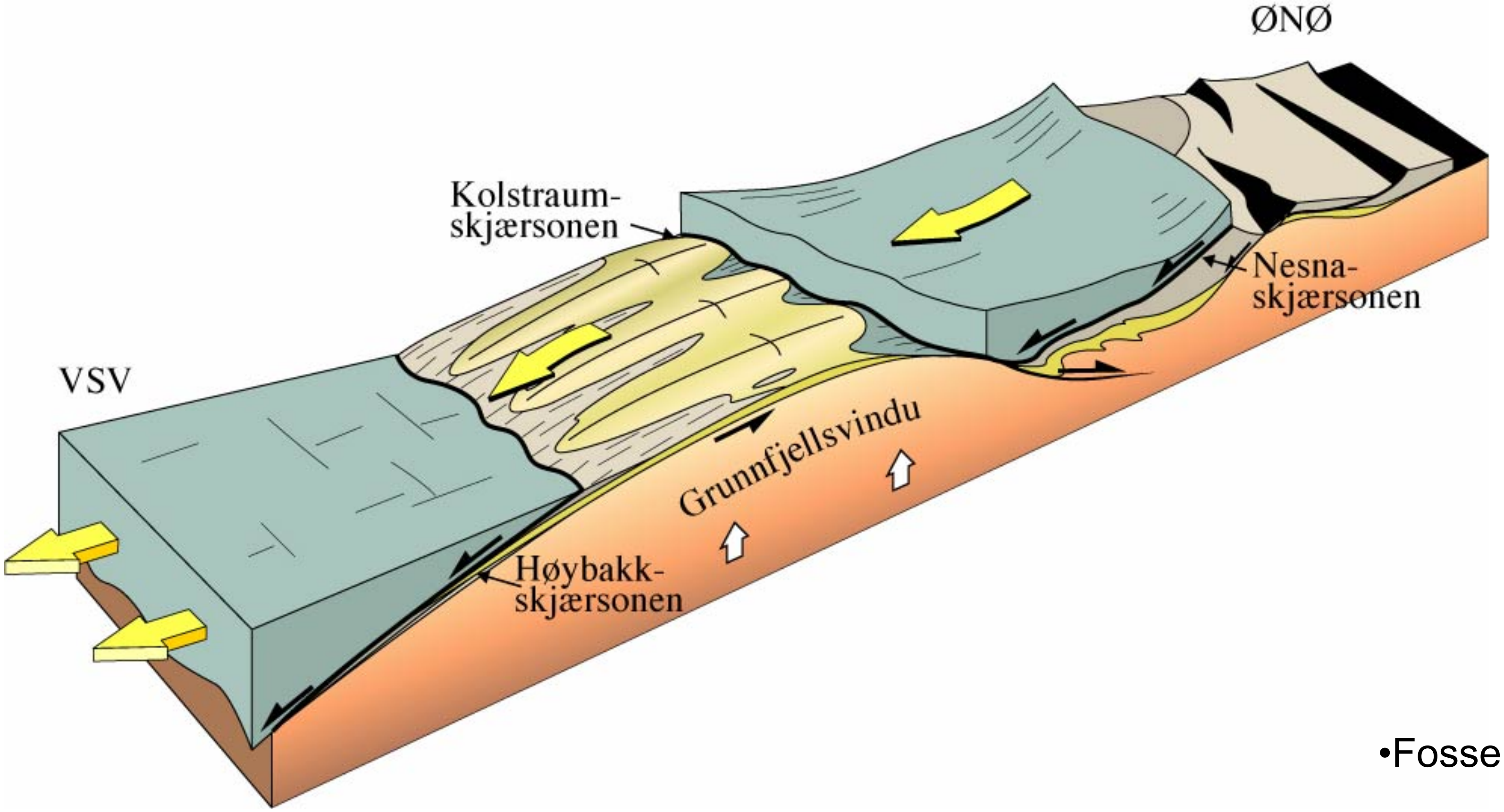
Core Complex to Wide Rift Extension



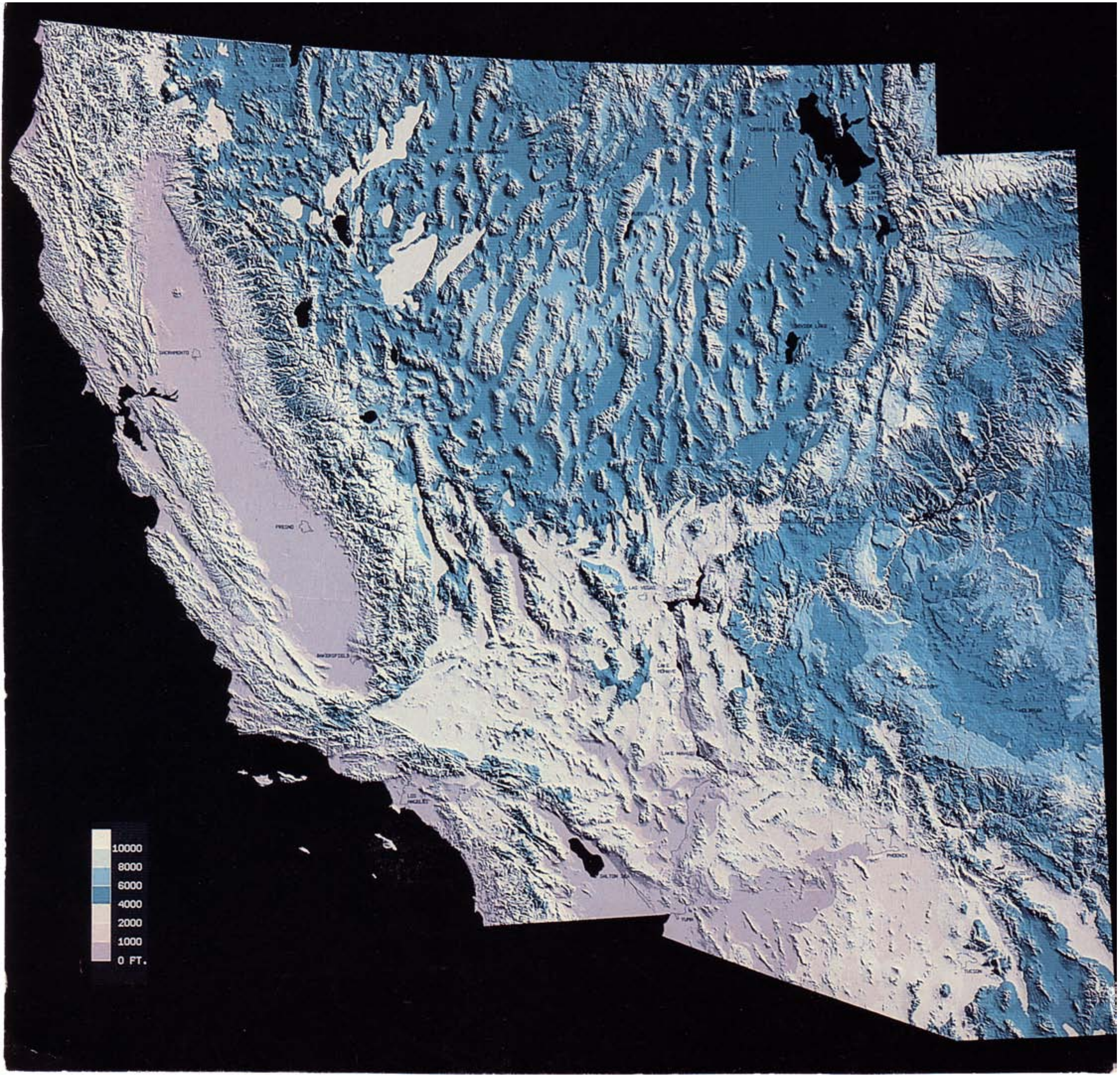
•Brun et al., 1999

•Core Complex Style Extension

- •Extension with a high grade metamorphic core exhumed to the surface
- •Juxtaposition of low and high grade materials
- •Single detachment faults with large offset



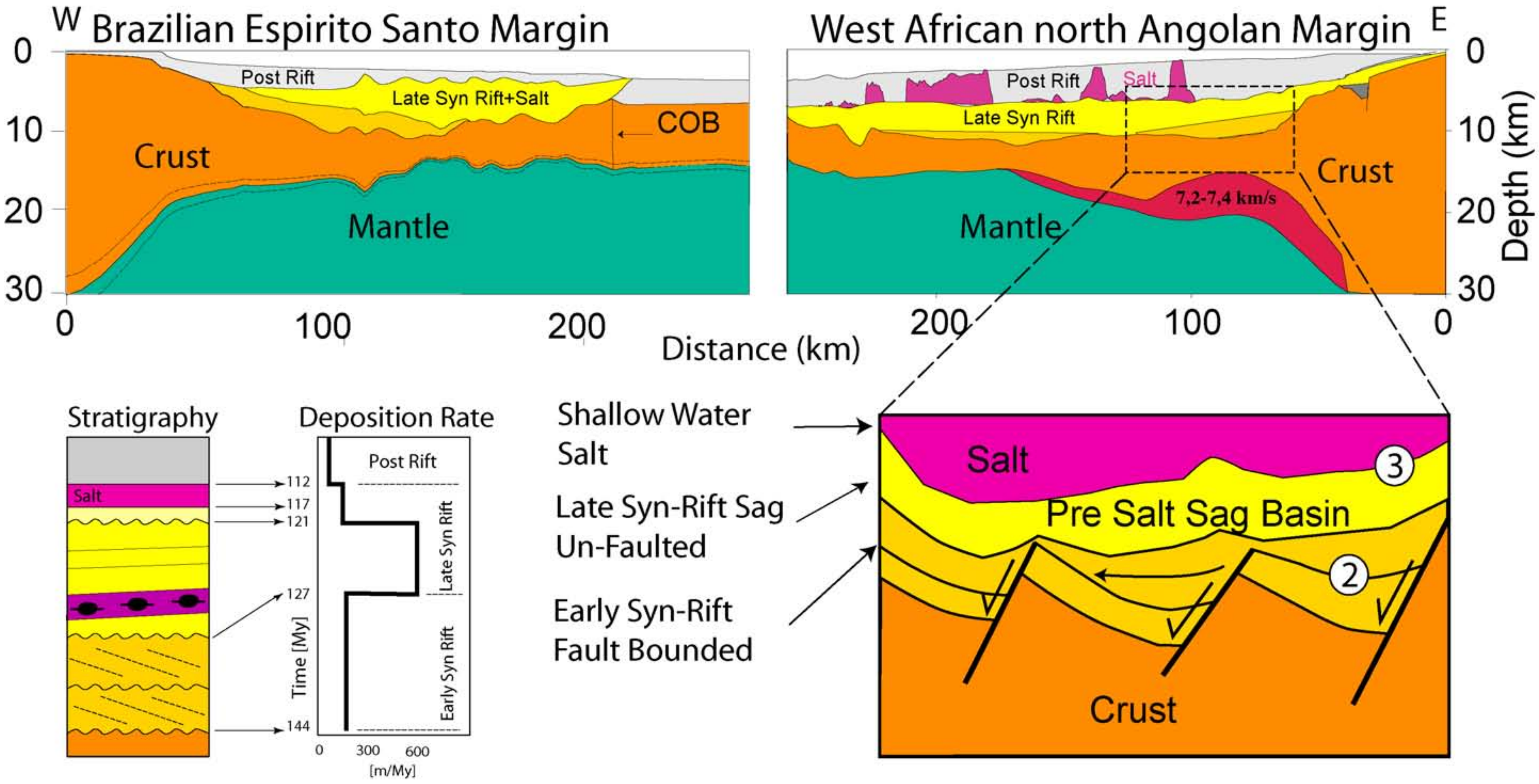
•Fossen



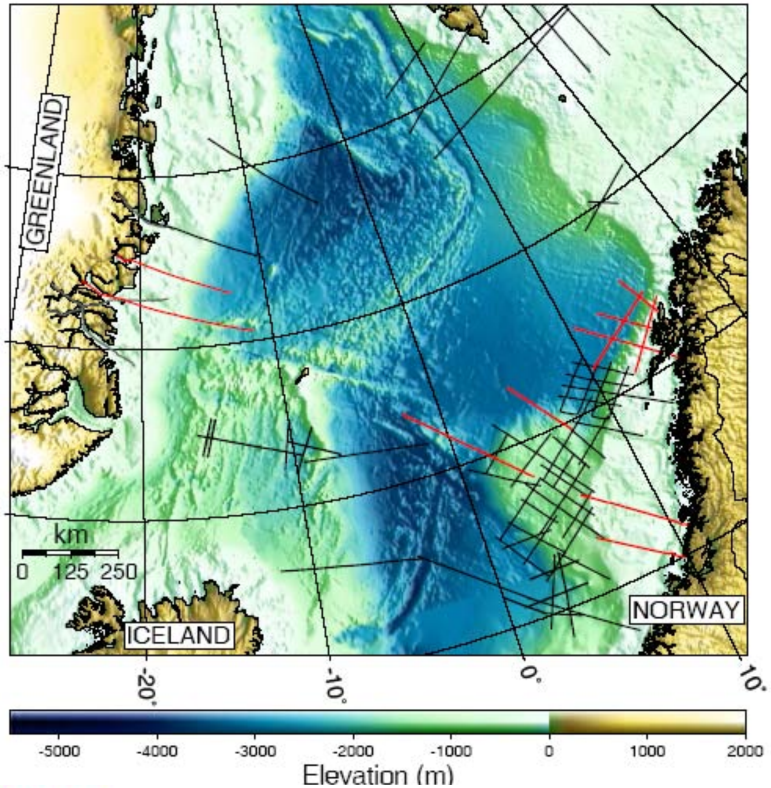
- Basin and Range
- wide rift (800 km)
- Multiple horst and
- grabens
- Distributed
- Extension

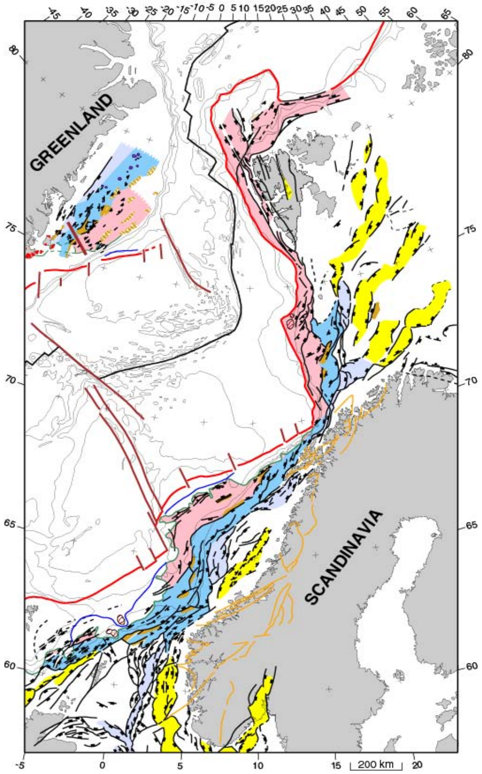
Wide (Non)-Volcanic Rifting

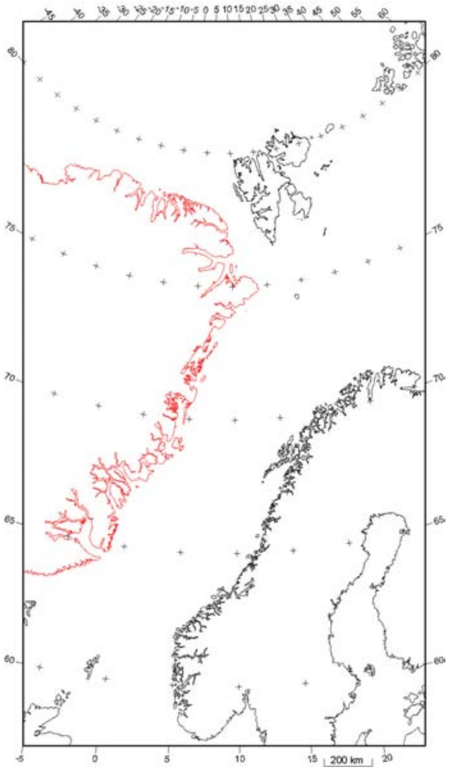
South Atlantic Salt Basin

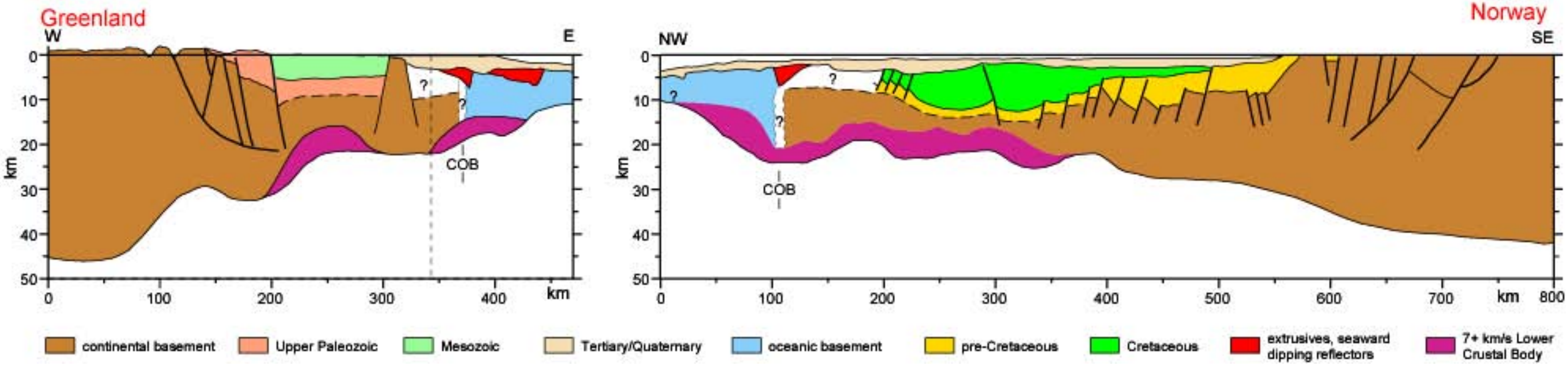


Wide Volcanic Rifting in the North Atlantic

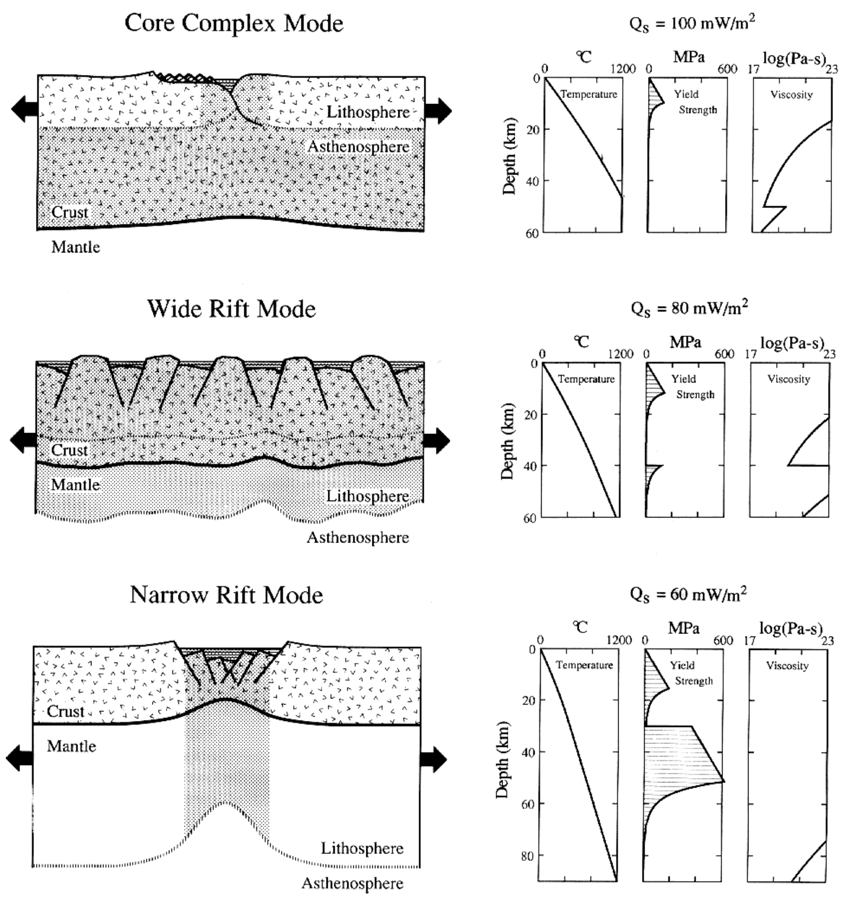


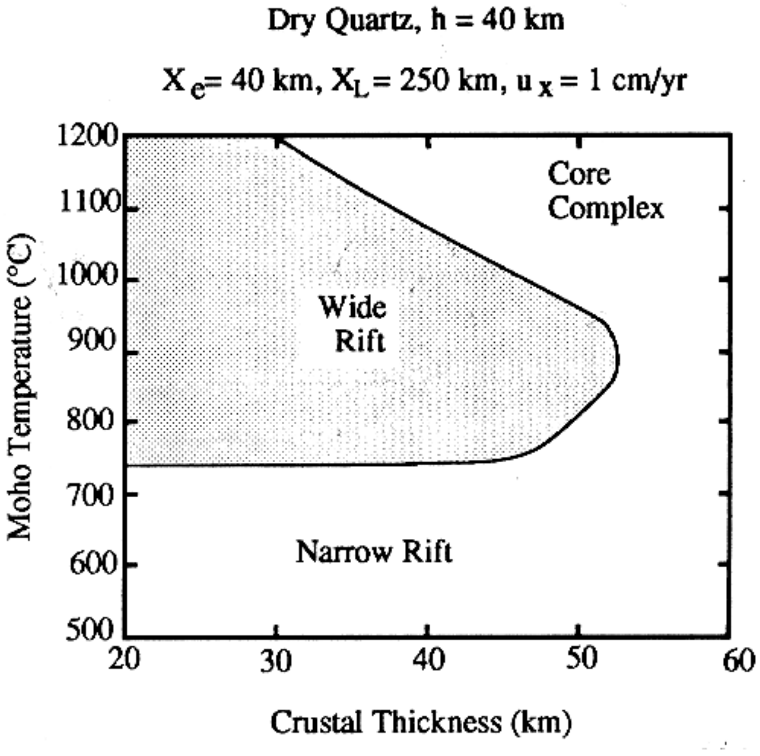






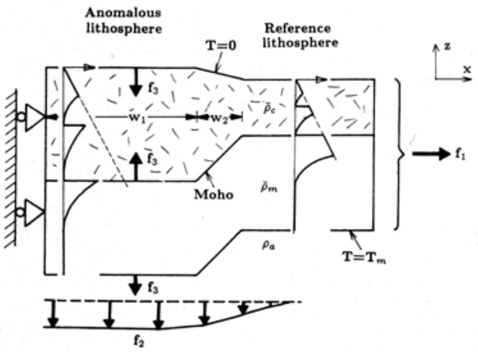
First order control on modes of extension

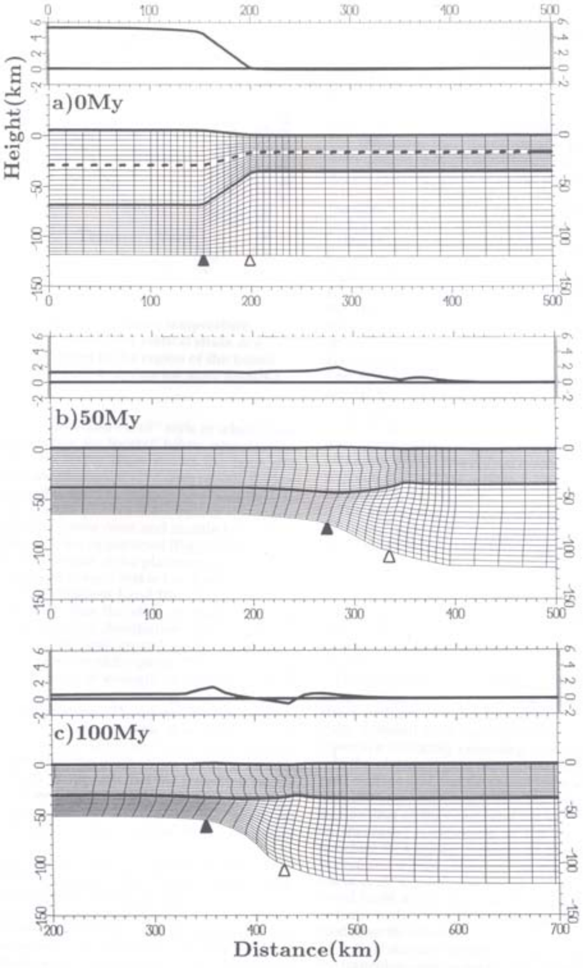


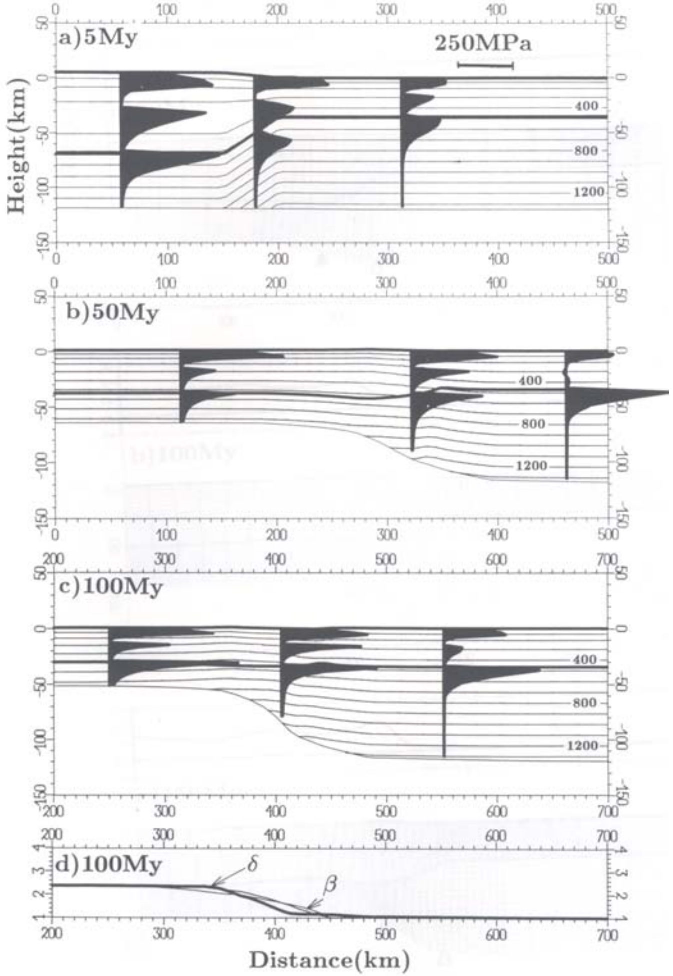


Buck, 1991

Dynamic Extension Models
Contrasting Styles

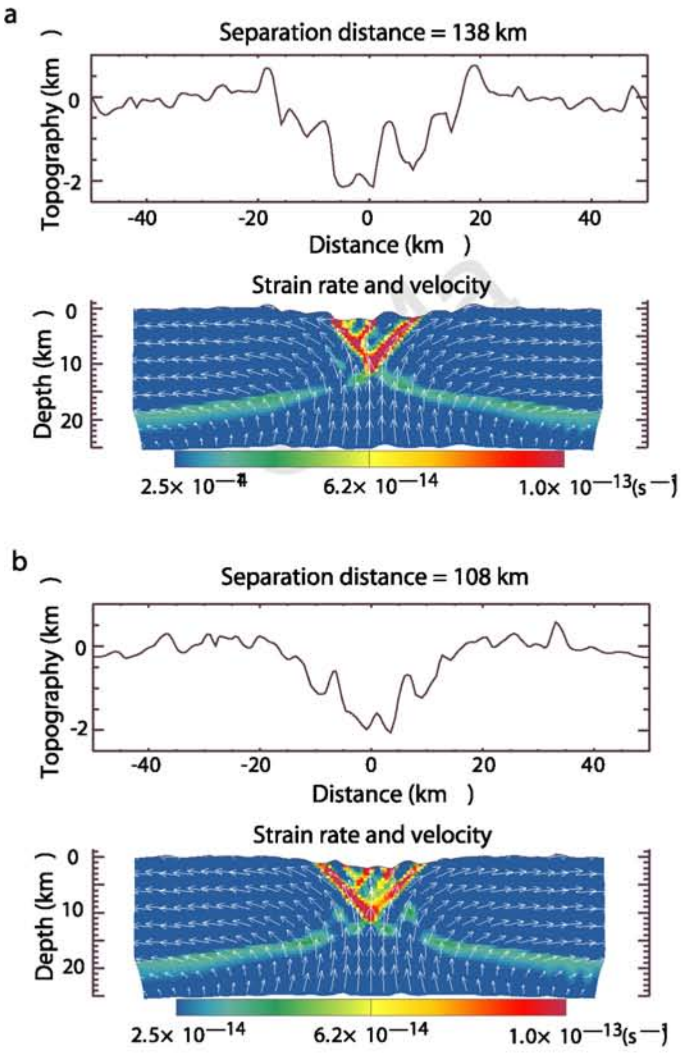




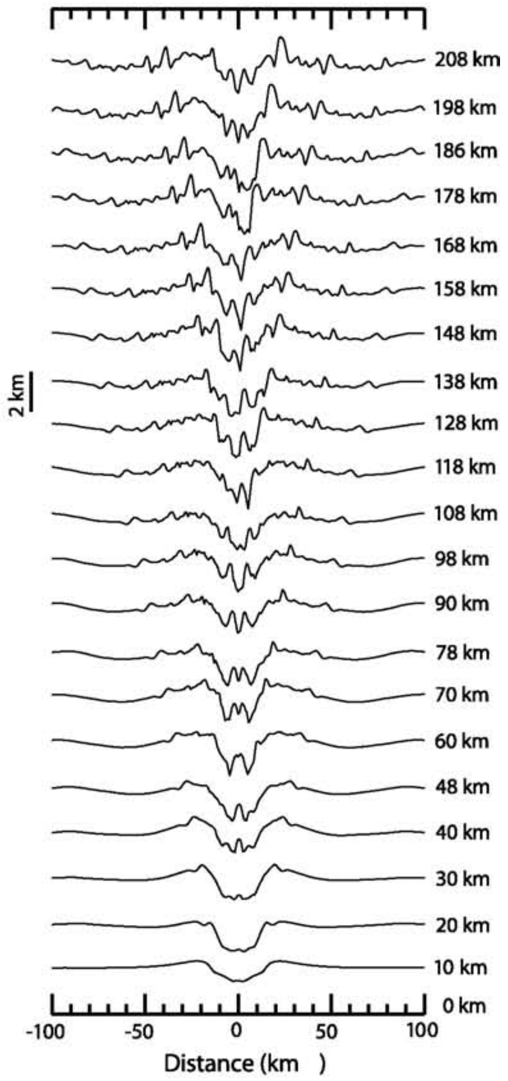


Braun and Beaumont, 1989

Plastic strain weakening allows efficient localisation

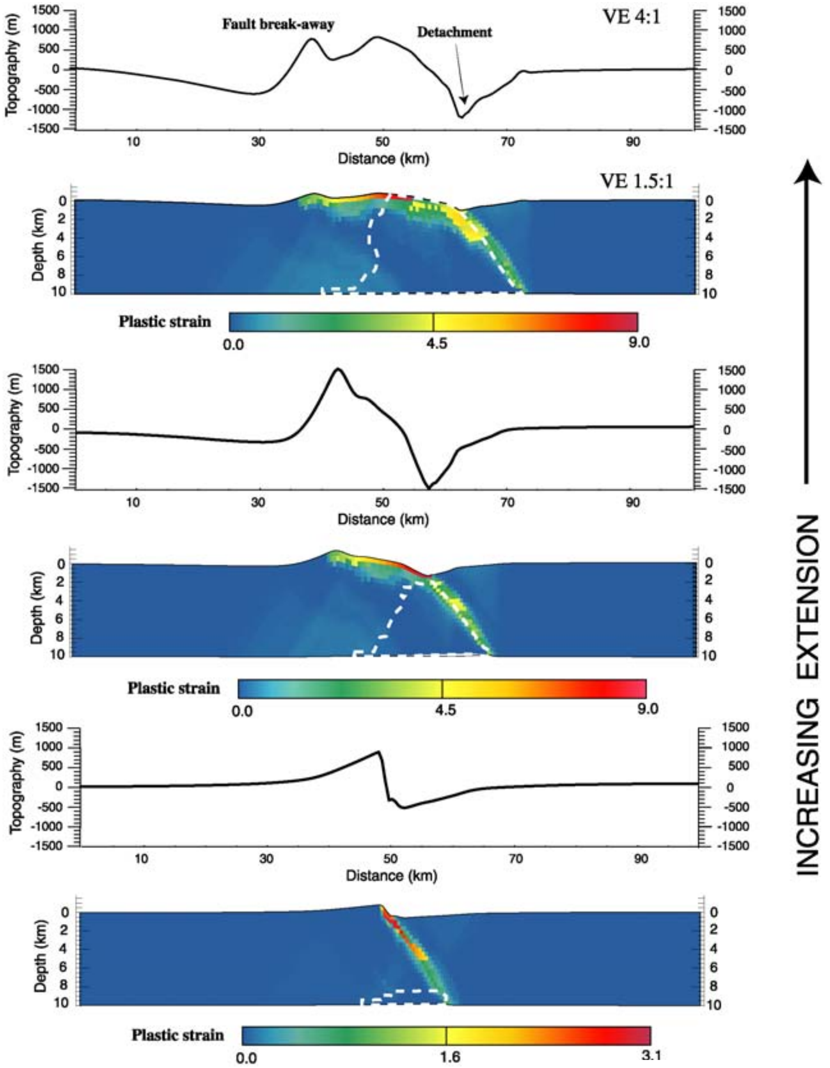


Buck et al, Nature 1998



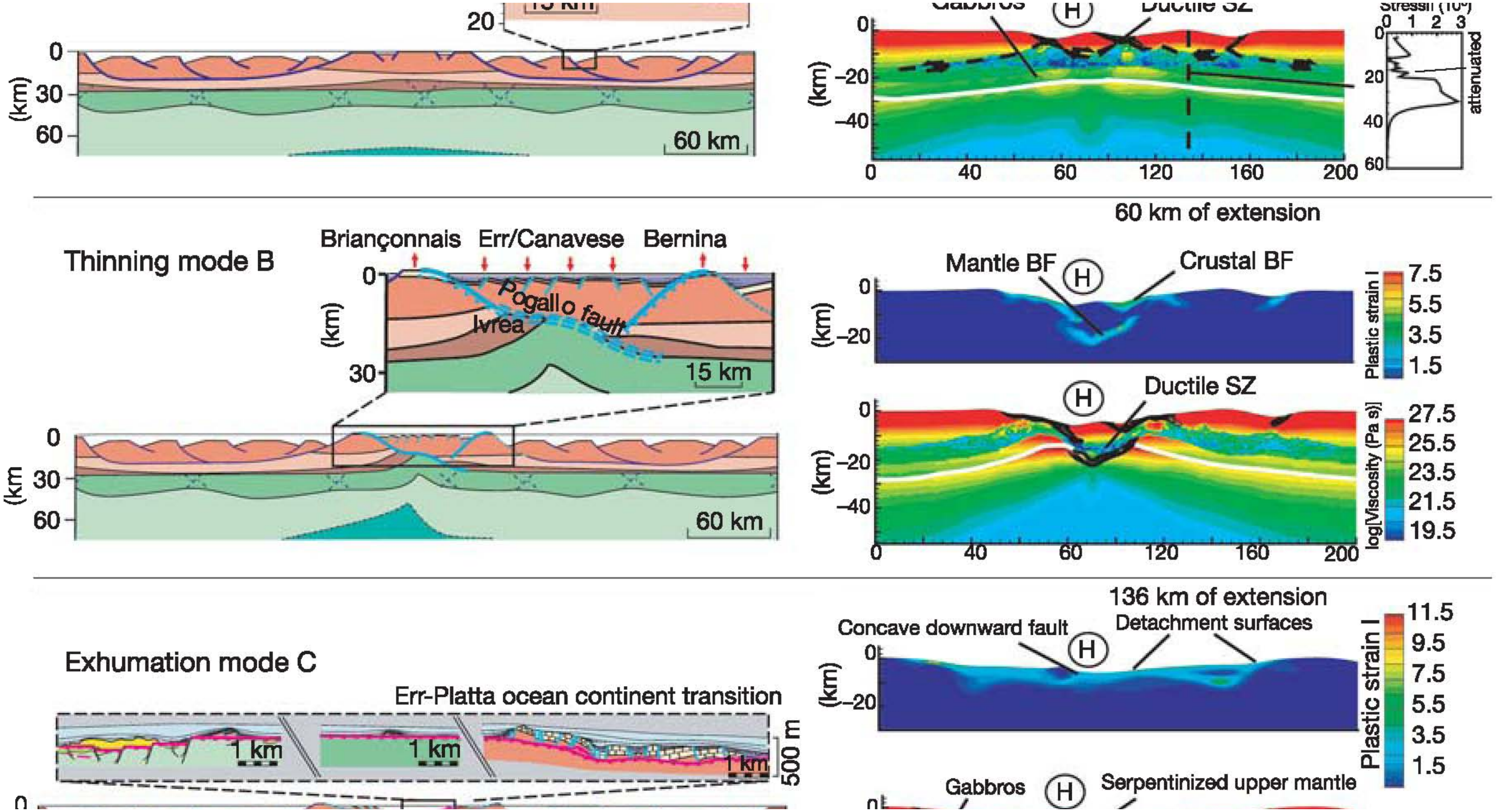
Buck et al Nature 1998

Plastic Strain weakening allows efficient localisation



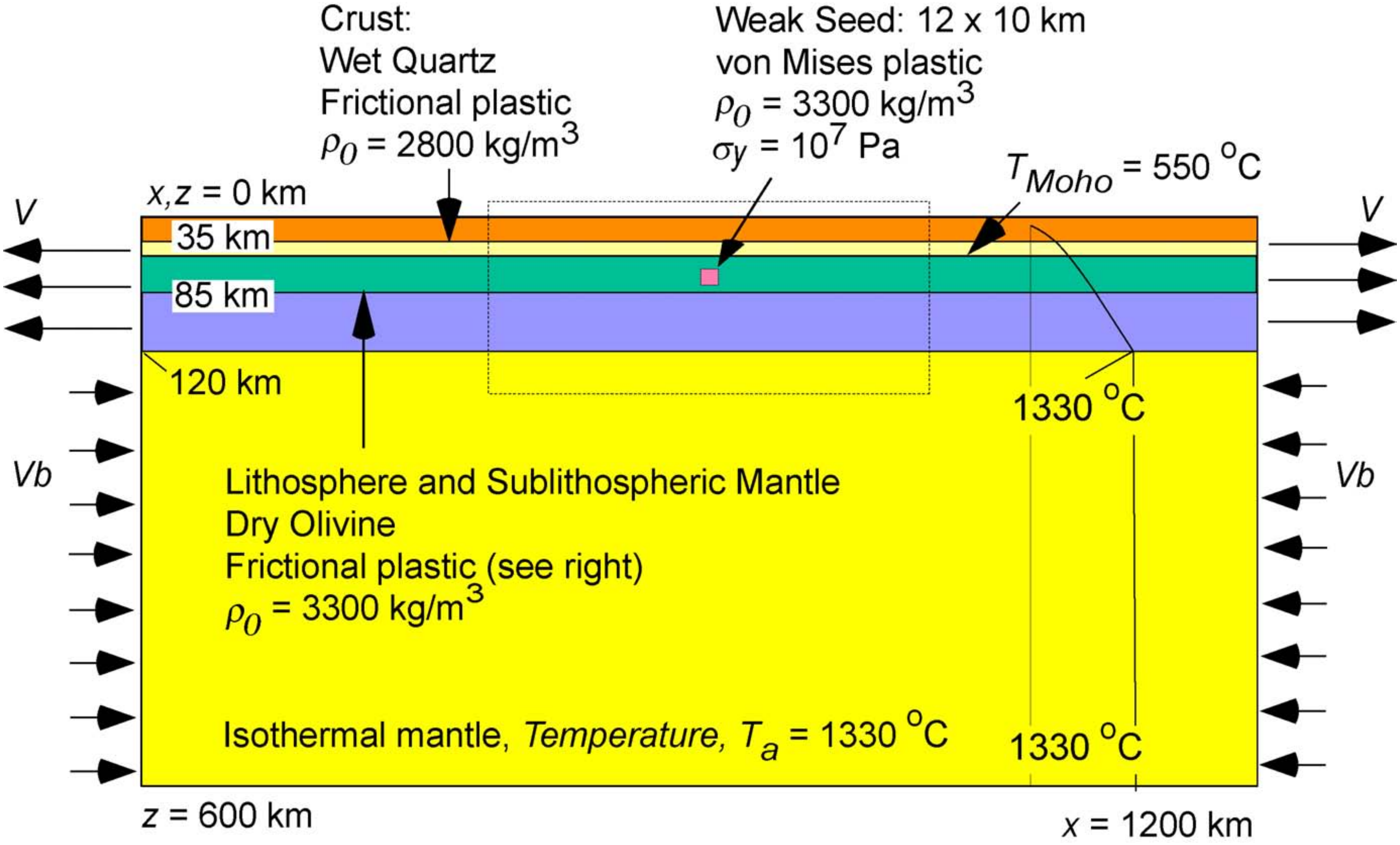
Lavier et al., Geology 1999

Narrow Non Volcanic Margin Formation



Lavier and Manatschal, Nature 2006

Thermo-Mechanical Model Setup



Crust:
Wet Quartz
Frictional plastic
ρ_0 = 2800 kg/m^3

Weak Seed: 12 x 10 km
von Mises plastic
ρ_0 = 3300 kg/m^3
σ_y = 10^7 Pa

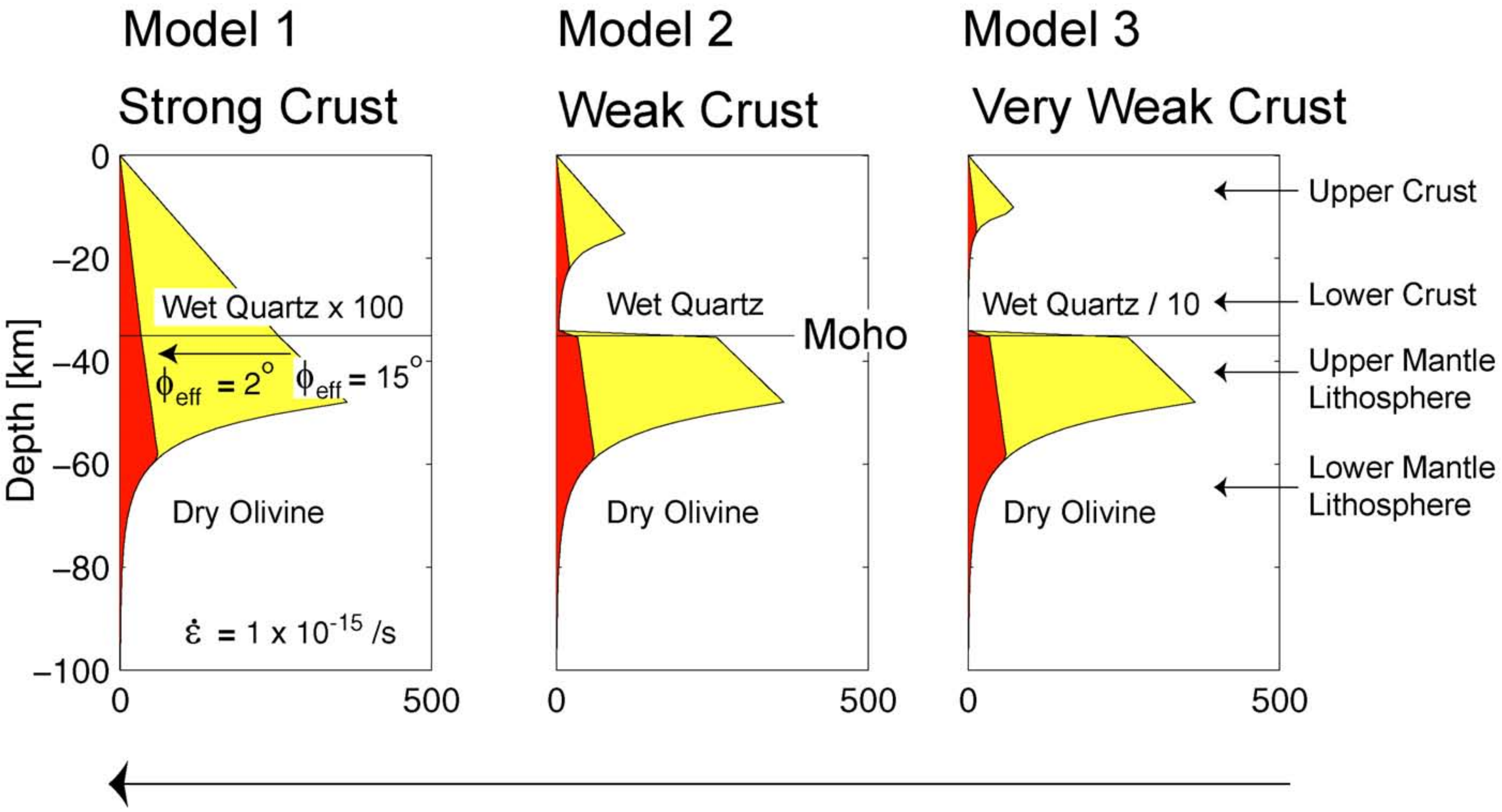
T_{Moho} = 550 °C

Lithosphere and Sublithospheric Mantle
Dry Olivine
Frictional plastic (see right)
ρ_0 = 3300 kg/m^3

Isothermal mantle, *Temperature*, T_a = 1330 °C

Huismans and Beaumont, 2002

Model Crust Strength Variation

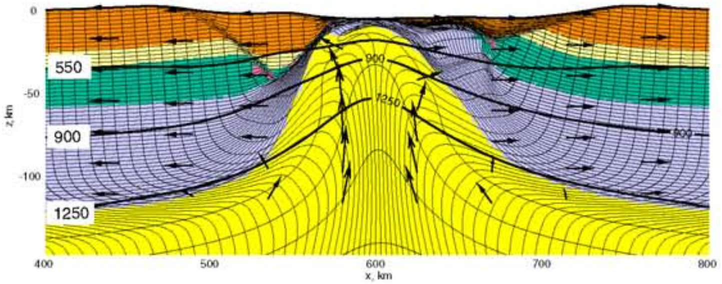


Strength Lower Crust

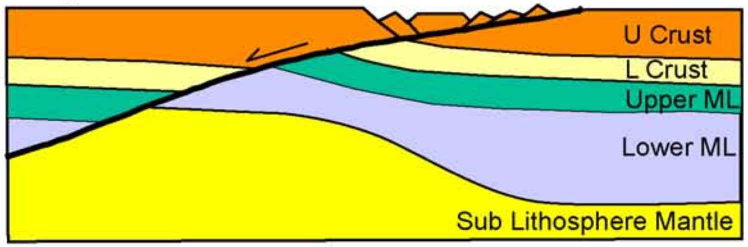
Huismans and Beaumont, 2005

Sensitivity of Rift Mode to Strength Lower Crust

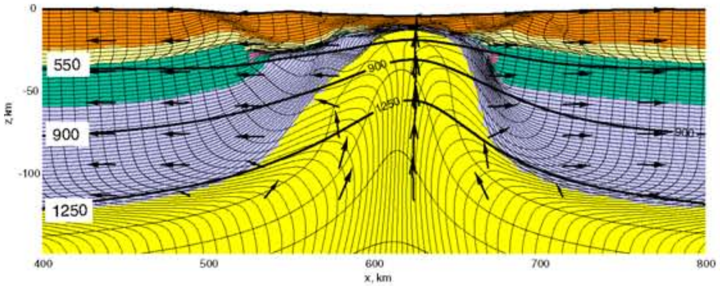
Strong Lower Crust



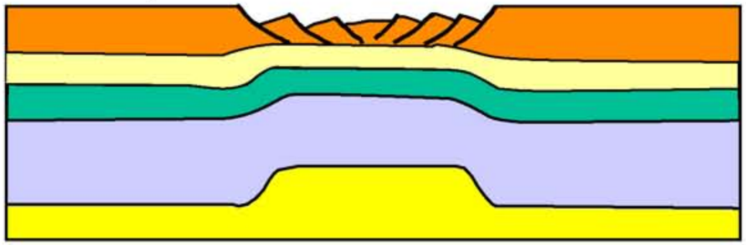
Asymmetric Mode of Extension



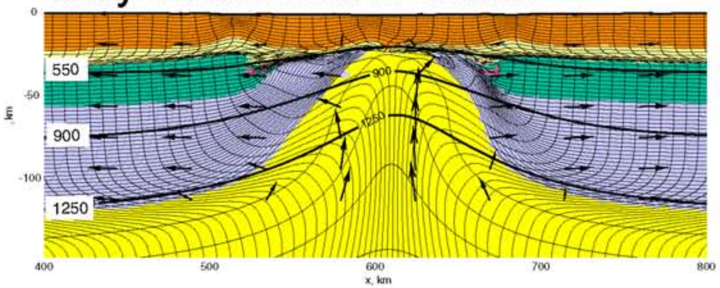
Weak Lower Crust



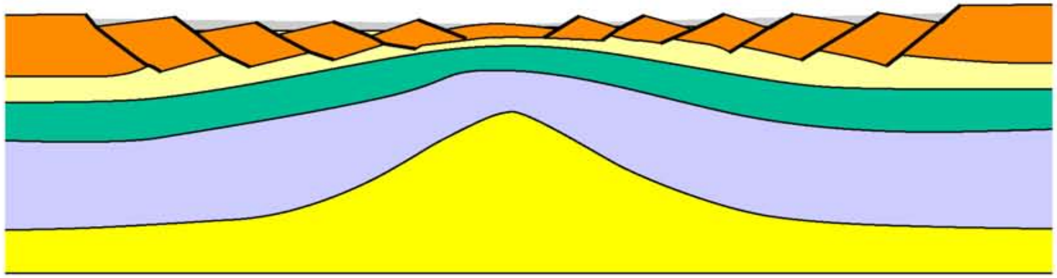
More Symmetric Mode of Extension



Very Weak Lower Crust

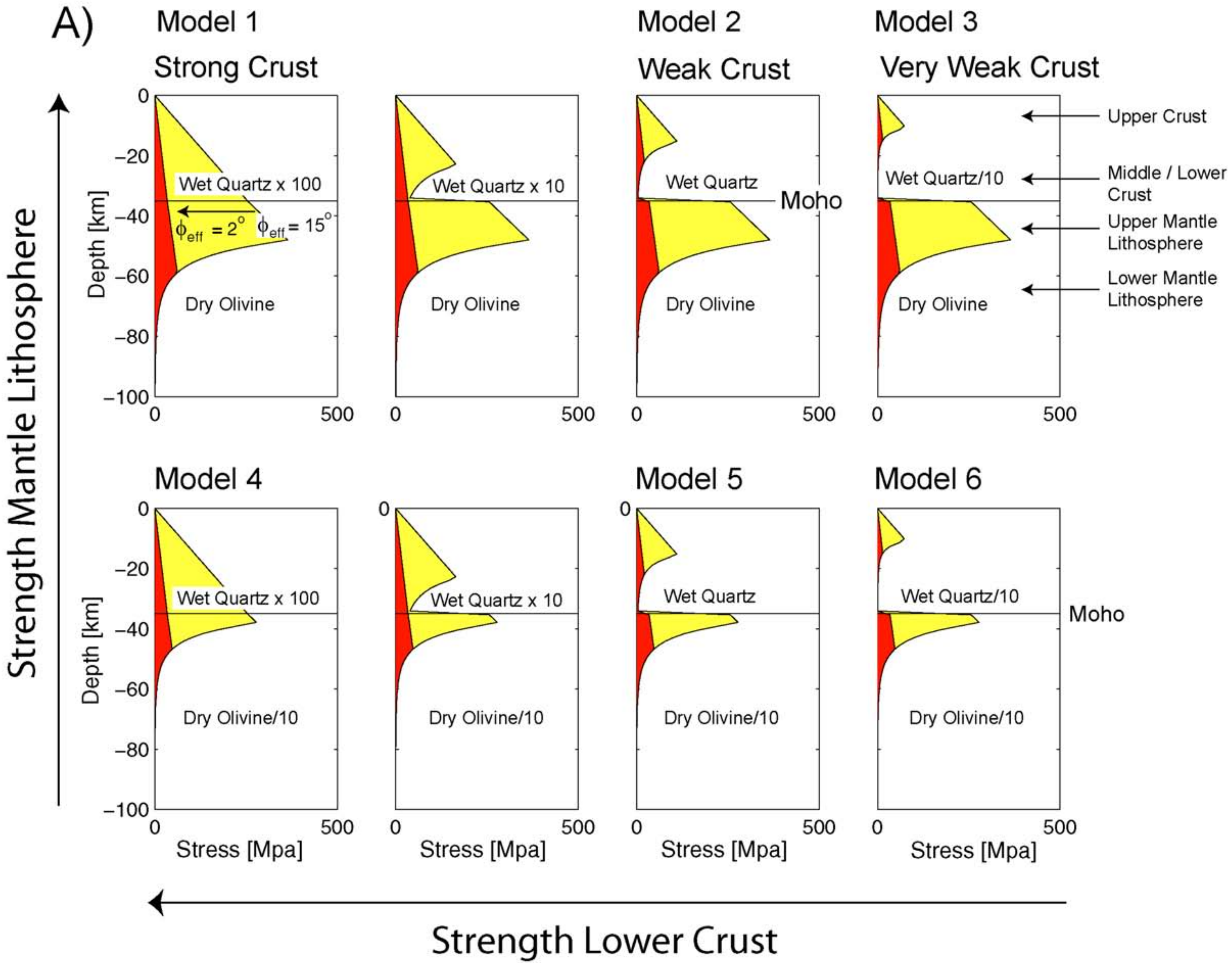


Wide Crustal Rifting / Narrow Mantle Lithosphere Rifting



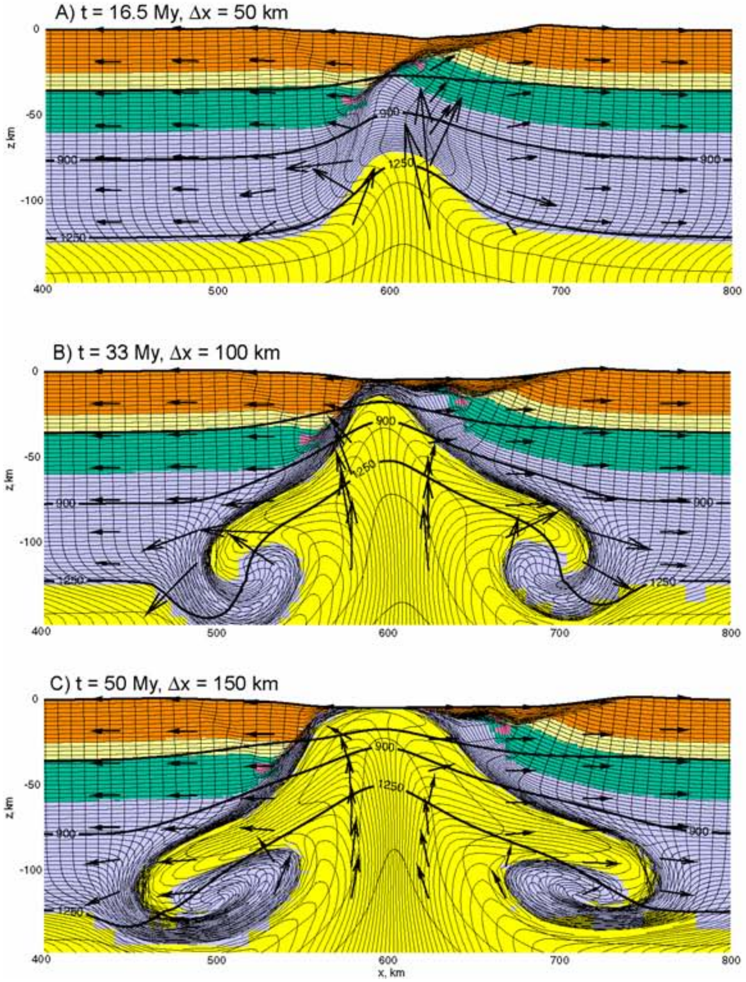
Huismans and Beaumont, 2001, 2002, 2005, 2008

Model Crust and Mantle Lithosphere Strength Variation

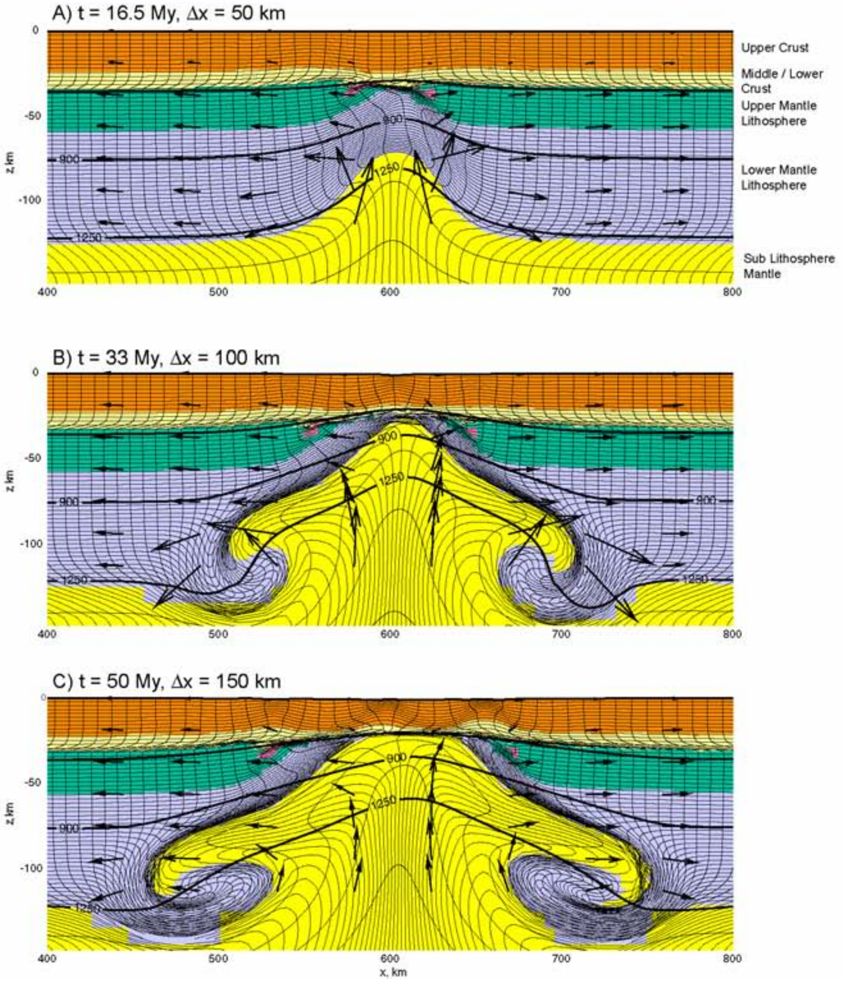


Effect of Weak Mantle Lithosphere

Model 4. Strong Crust, Weak Mantle Lithosphere



Model 6. Very Weak Lower Crust, Weak Mantle Lithosphere



Huismans and Beaumont, 2005

Effect of Brittle Ductile Couping: Prediction of mode transition

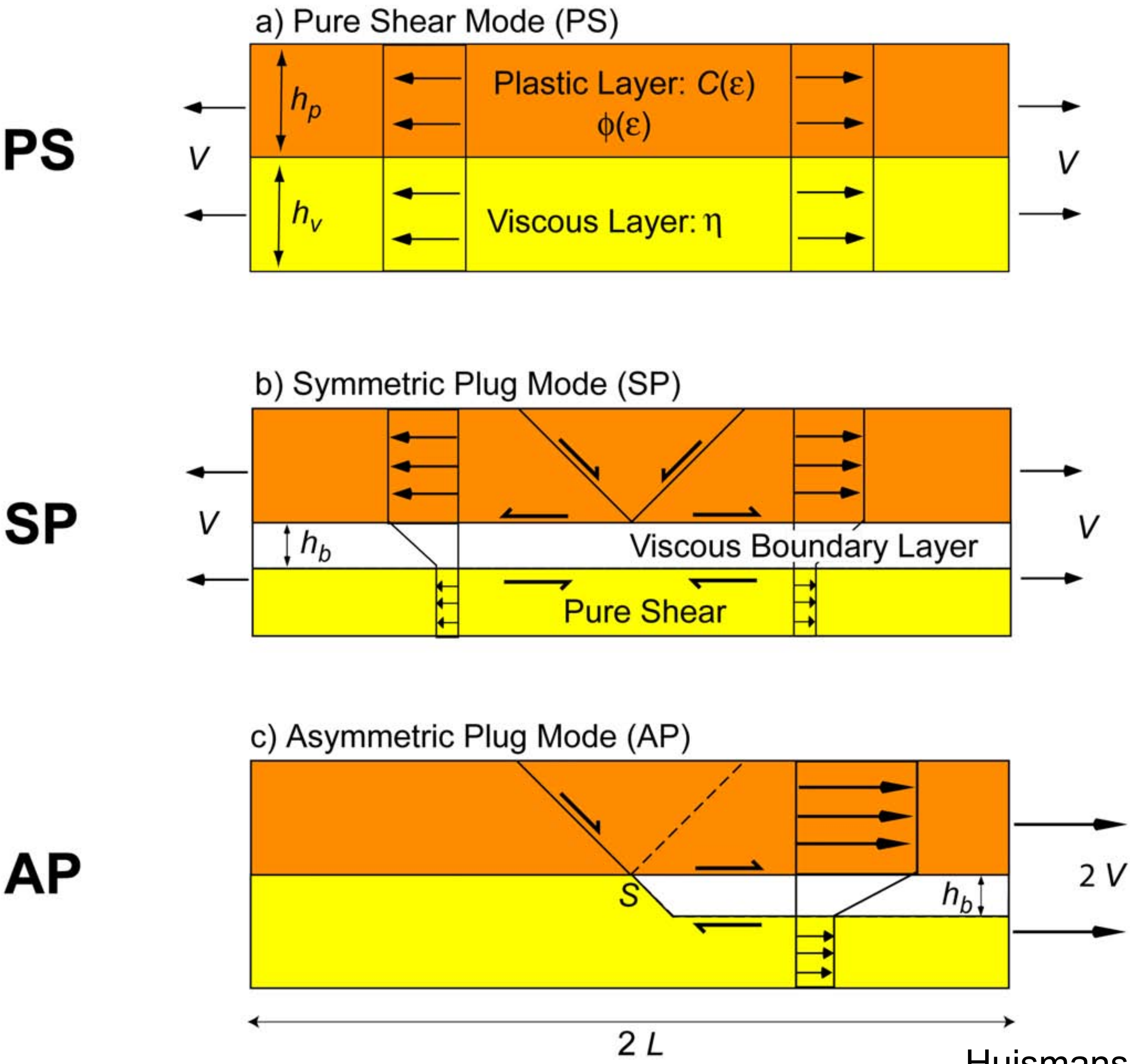
- Ratio of Brittle / Ductile Stress
  - Mode boundary not defined

- Compare Integrated Force for different modes, e.g. mode transition when:
  - $F_{mode1} = F_{mode2}$ and $F_{mode2} = F_{mode3}$
  - Well defined mode transition, but does resolve not higher order features, e.g. difference between symmetric – pure shear mode

- Compare Rate of Work for different modes, e.g. mode transition when:
  - $W_{mode1} = W_{mode2}$ and $W_{mode2} = W_{mode3}$

Huismans et al.,JGR, 2005

Modes for Dissipation Analysis



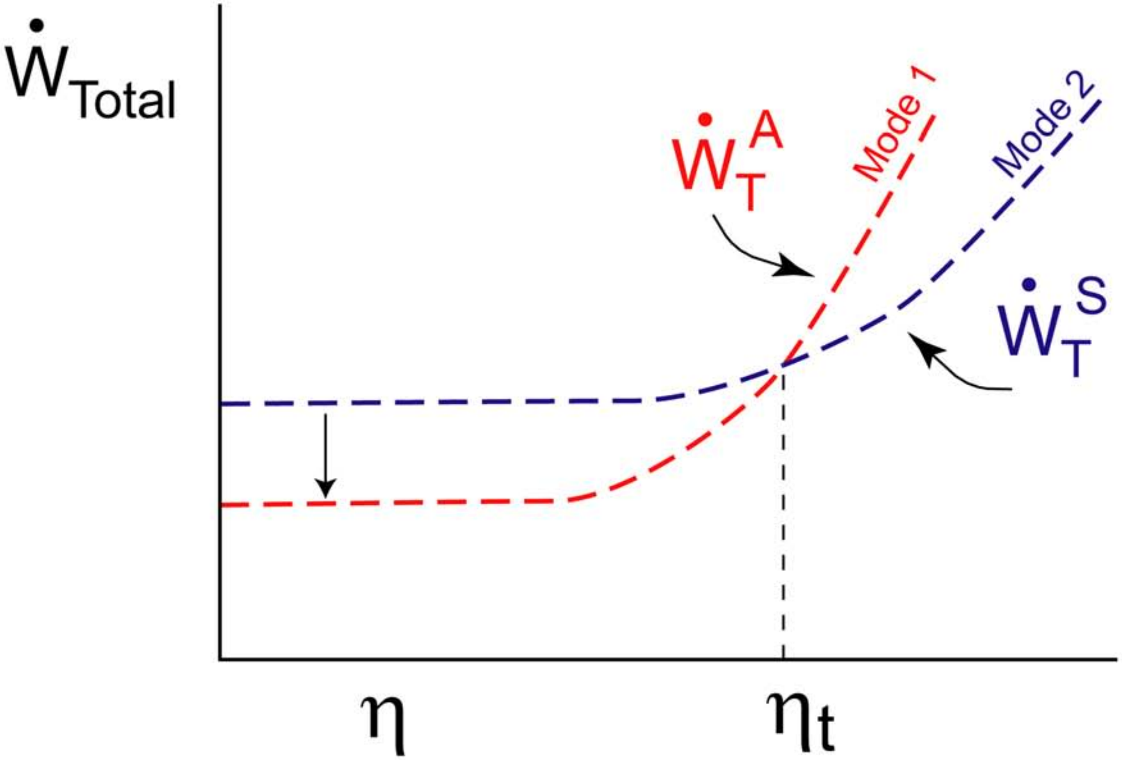
Huismans et al.,JGR, 2005

RATE OF DISSIPATION ANALYSIS

Mode 1 $\dot{W}_p^A + \dot{W}_v^A = \dot{W}_p^S + \dot{W}_v^S$ Mode 2

At the mode transition

$$\dot{W}_T = \int_A \dot{\varepsilon} \cdot \sigma \, dA$$



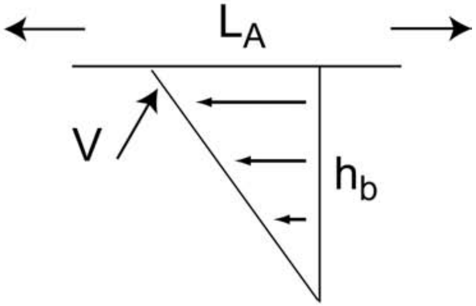
Huismans et al.,JGR, 2005

Symmetric versus Asymmetric Mode
Von Mises Plastic Layer, Cohesion C

Transition viscosity

$$\boxed{\eta_t = \frac{3\ h_b}{L_A\ V}\ h_p\ (C_S - C_A)}$$

$$\eta_t\ L_A\ \frac{V}{h_b} = 3\ h_p\ (C_S - C_A)$$



Simple Shear
Boundary
Layer

$$\boxed{L_A\ \eta_t\ \dot{\varepsilon}_A = 3\ h_p\ (C_S - C_A)}$$

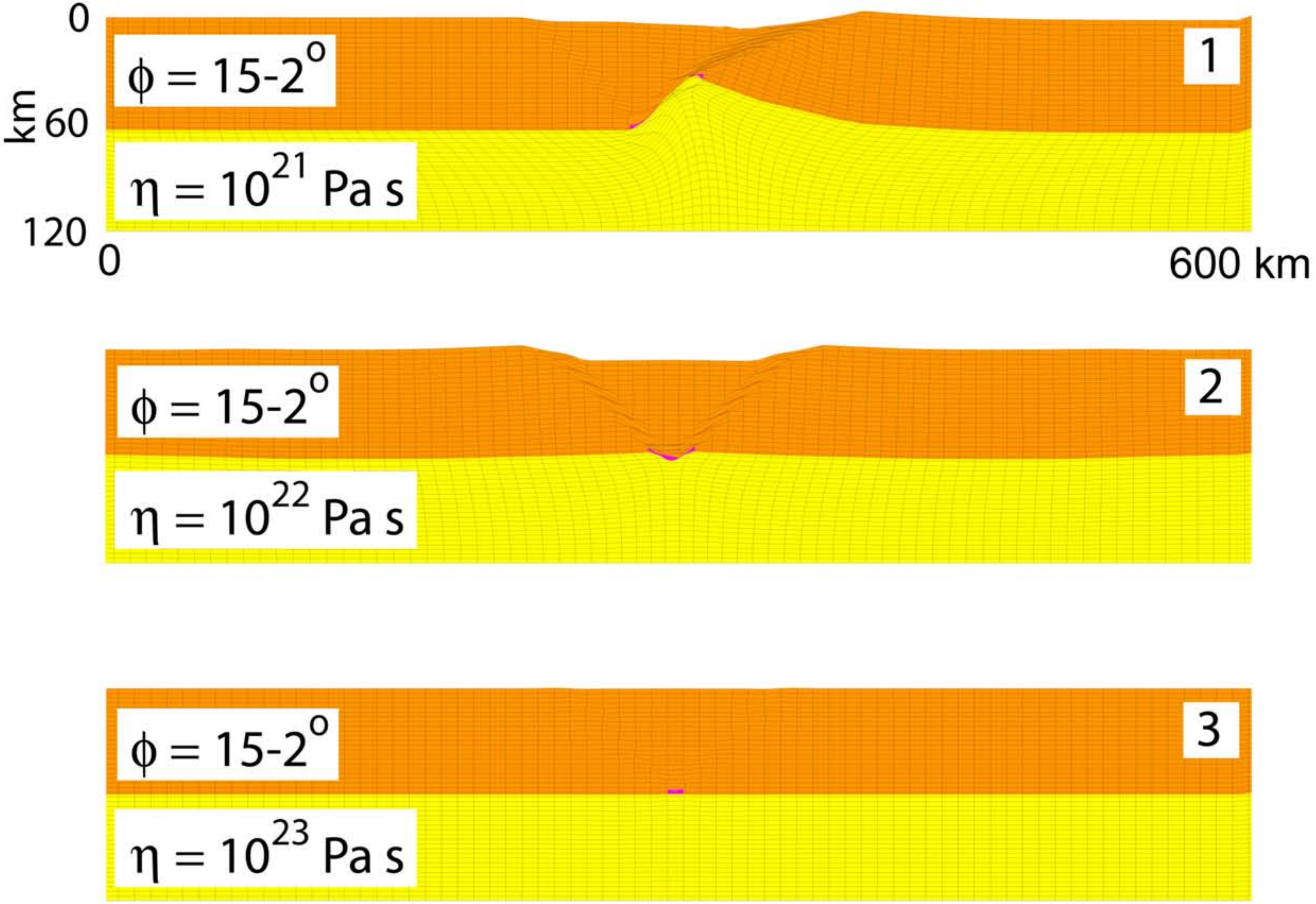
$$\Delta F_v = \Delta F_p$$

Differential viscous penalty force | Differential plastic gain force

Huismans et al.,JGR, 2005

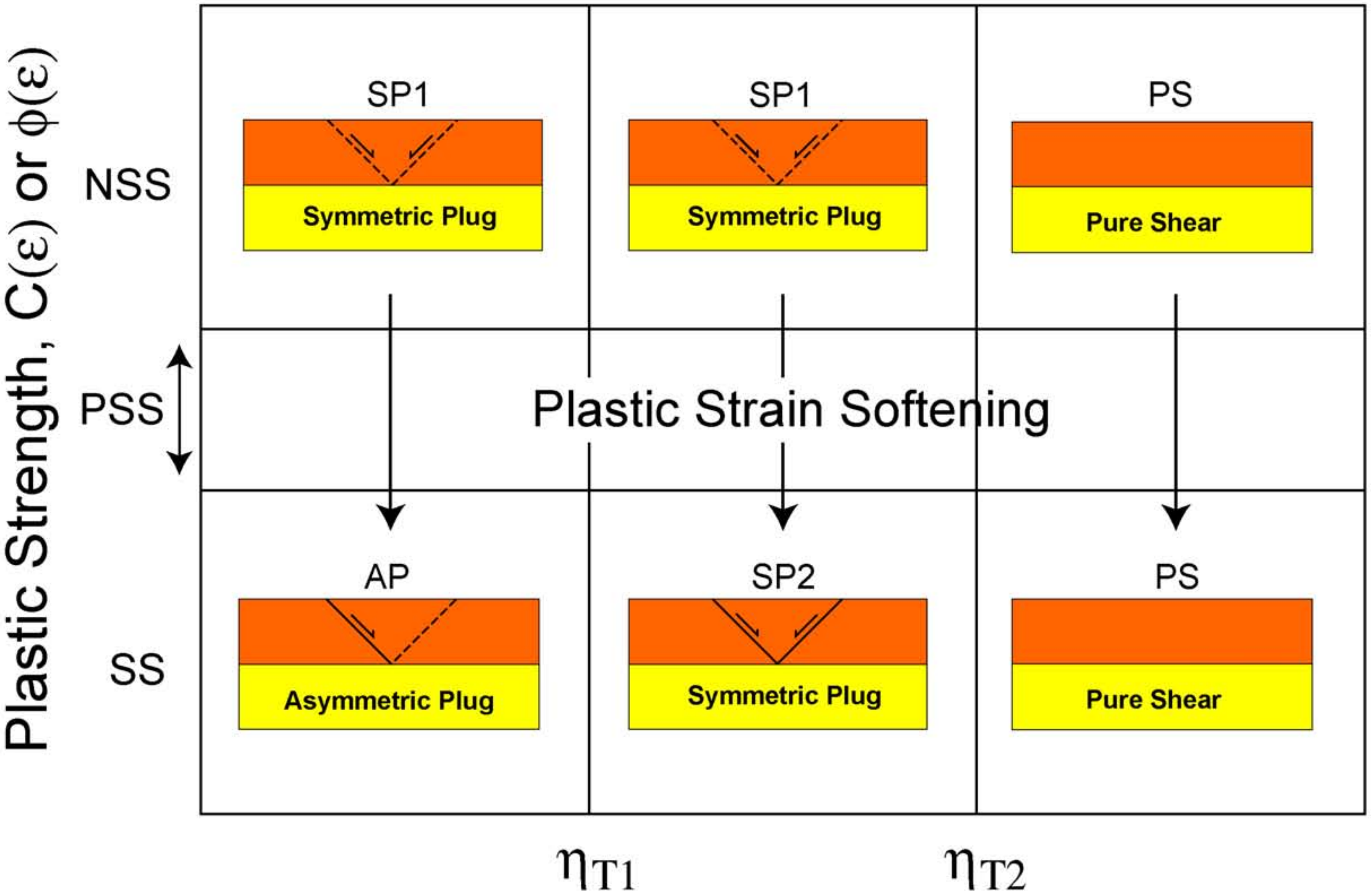
MS2: Two Layer Model, Frictional-Plastic Strain Softening

40 km extension at 1 cm/yr



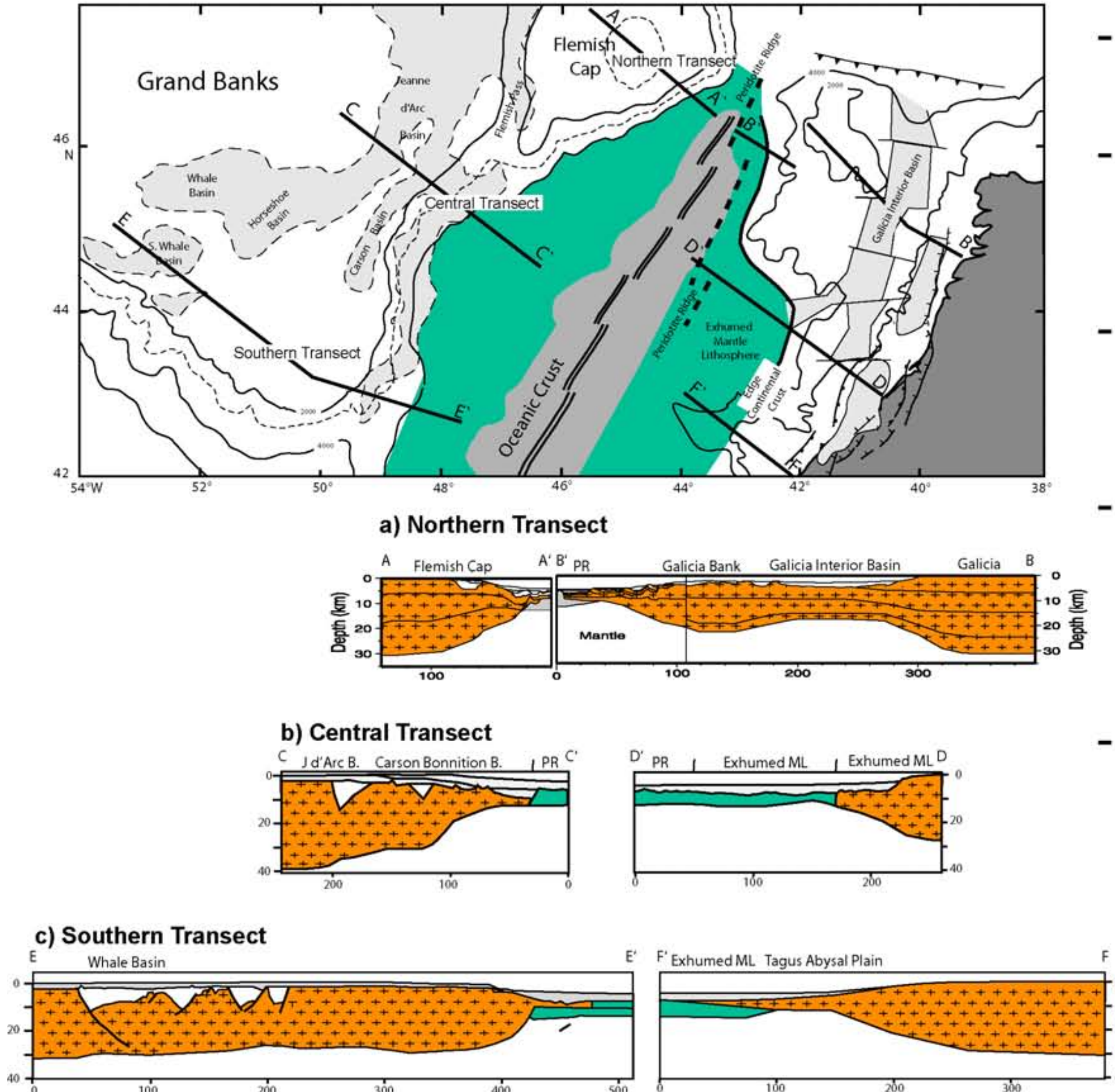
Huismans et al.,JGR, 2005

Rift Mode Space



Huismans et al.,JGR, 2005

Cold Non Volcanic Margins
Iberia - Newfoundland



- Magma starved rifting

- Exhumation of Mantle Lithosphere to seafloor

- Final rift stage very narrow with very narrow crustal necks <100km

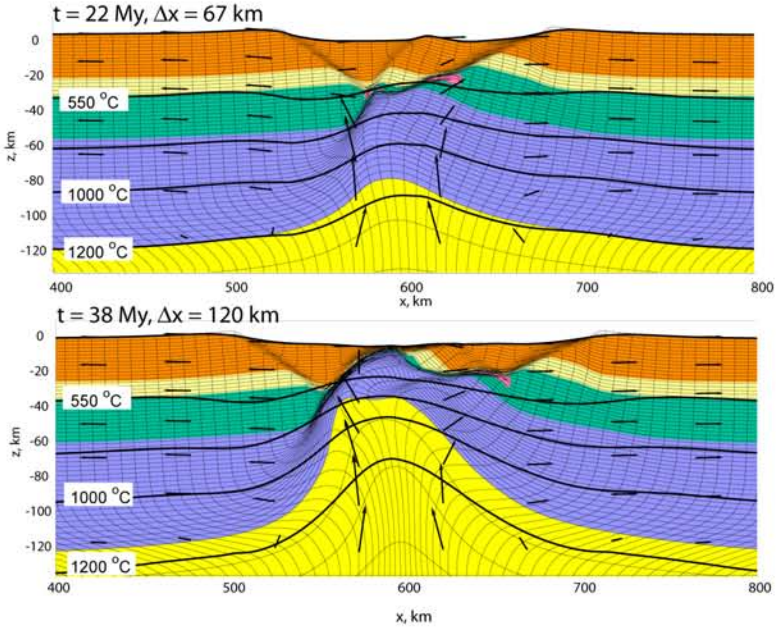
- Mantle lithosphere exhumation decreases with increasing crustal neck width

- Progressive deeper levels of ML in distal positions

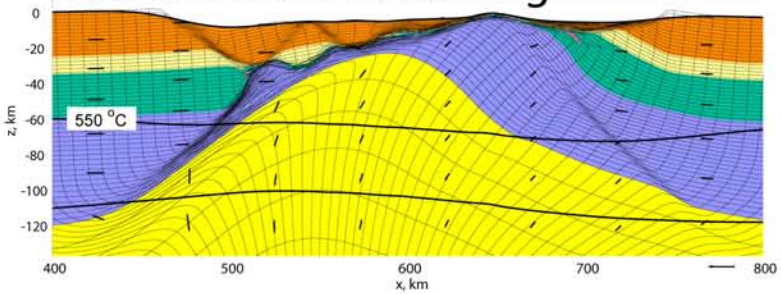
Huismans and Beaumont, 2004, 2007

Iberia-Newfoundland, Models & Interpretations

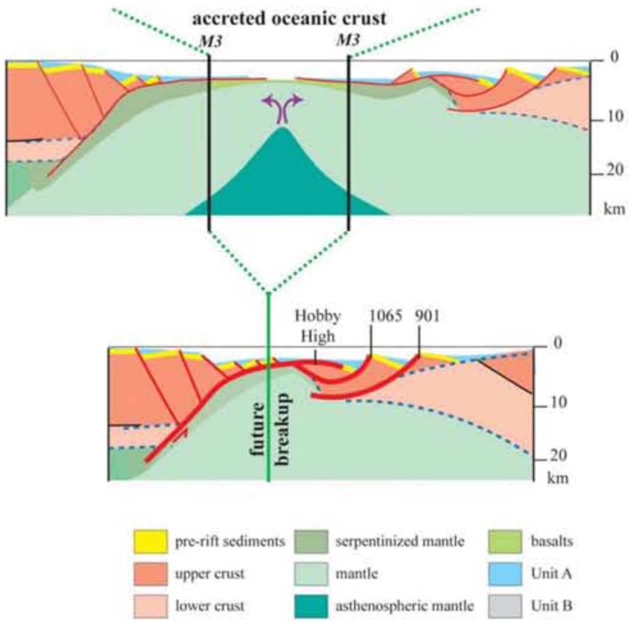
Stretching Cold Lithosphere



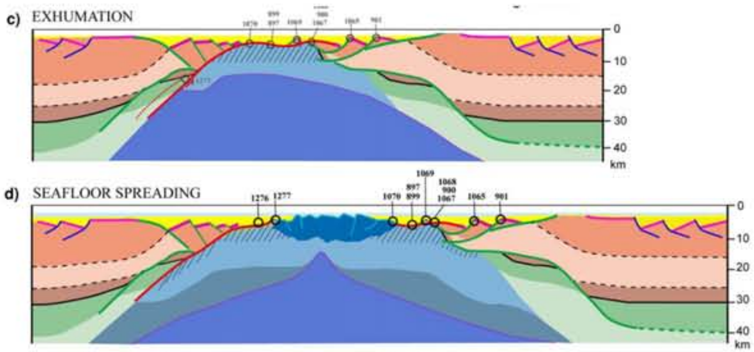
Cold and Slow Stretching



Huismans and Beaumont, 2002, 2003

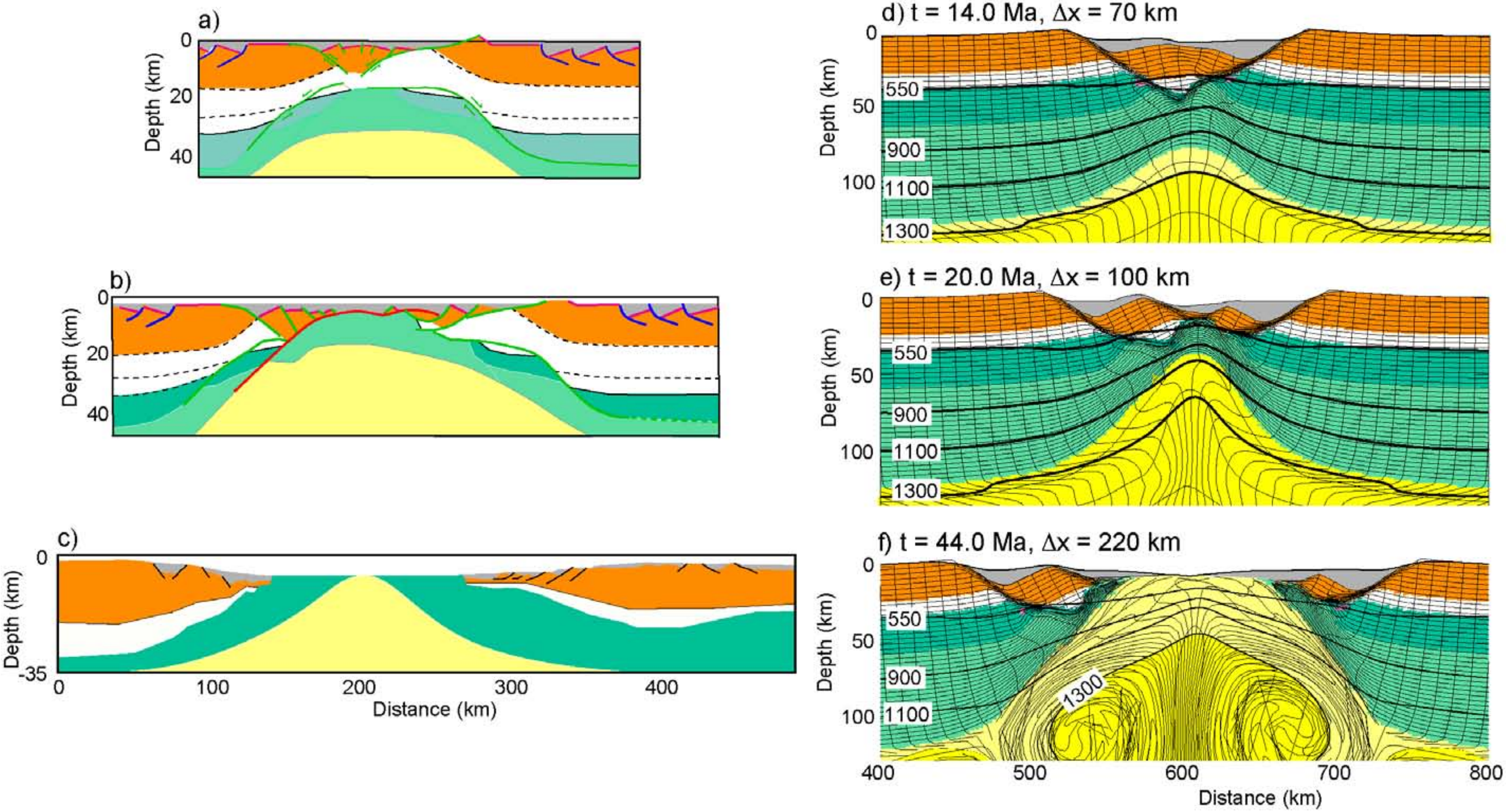


Peron-Pinvidic et al, Tectonics 2007



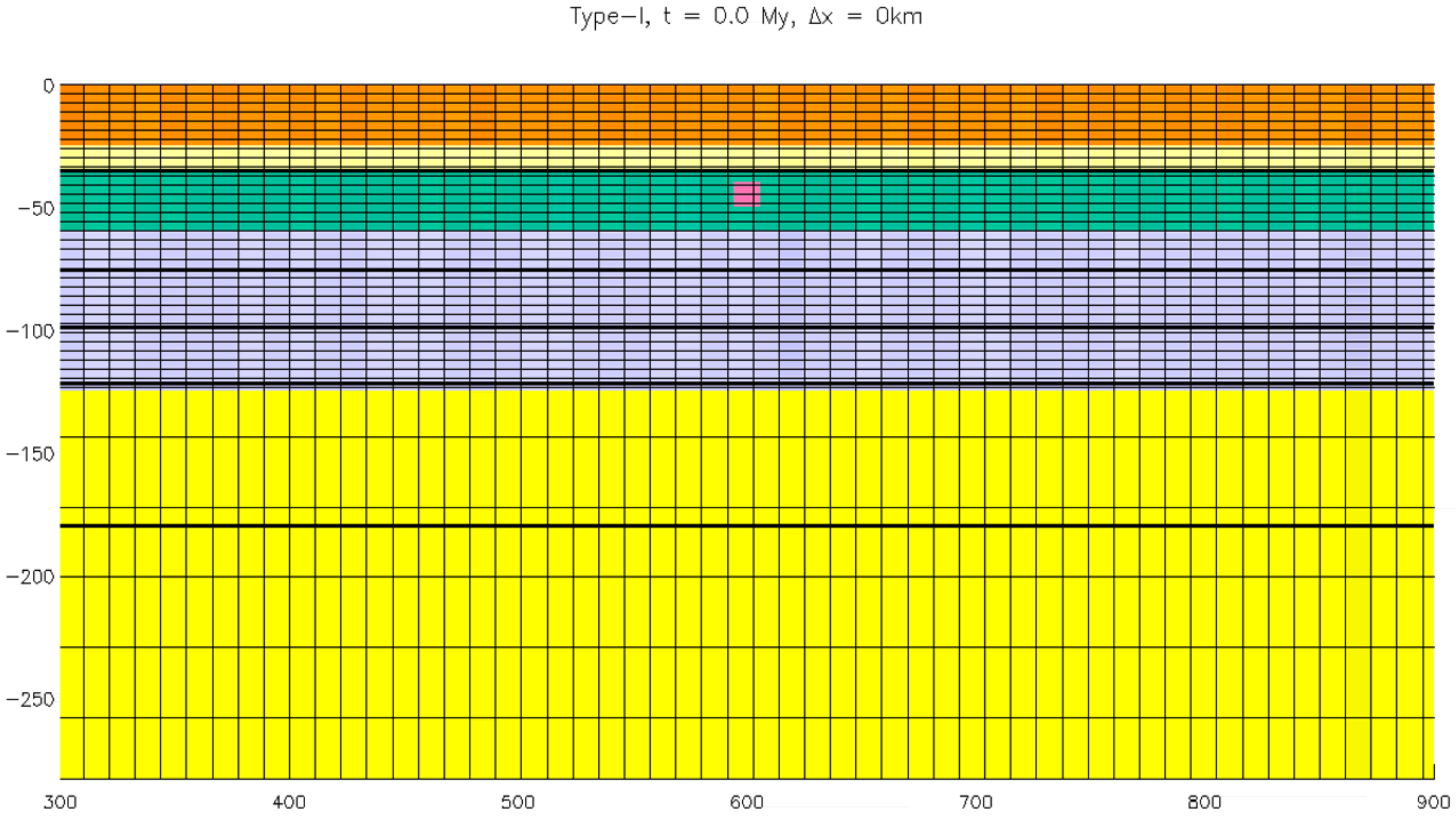
Peron-Pinvidic and Manatschal, Int J Earth Sci, in press

Iberia Type I margin



Huismans and Beaumont, Nature 2011

Iberia Type I margin



Animation, see: http://folk.uib.no/rhu002/huismans_beaumont_nature2011.html

Huismans and Beaumont, Nature 2011

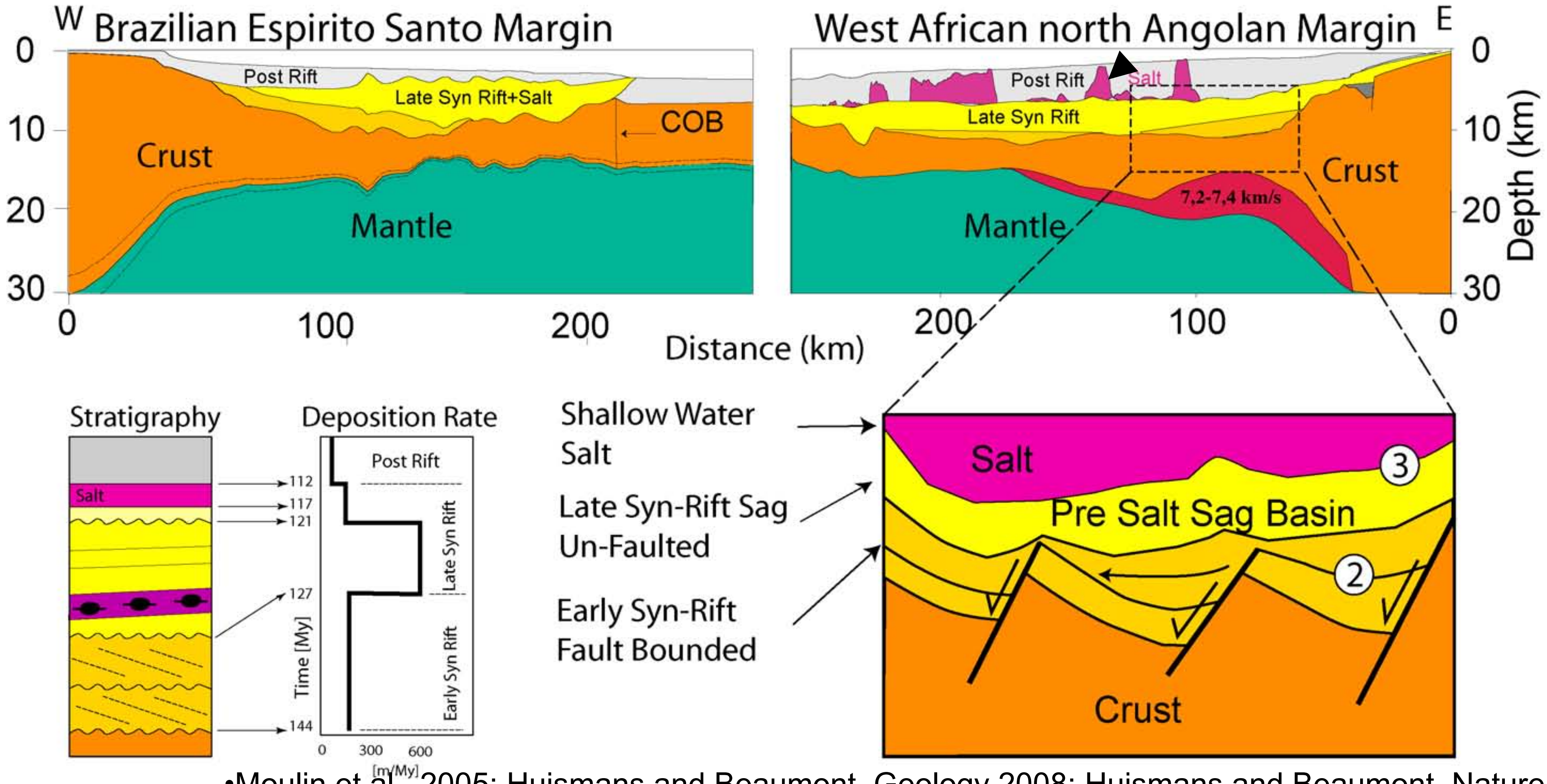
Type I Margins

- During last phase of rifting the crust breaks before the mantle lithosphere
- Largely a-magmatic
- Type I margin:
  - Crust breaks first, mantle lithosphere necks later
  - Exhume mantle lithosphere
  - Favored by stronger crust

Wide Hot Rifted Margins with Anomalous Vertical Motions, Depth Dependent Stretching (and Magmatism ?)

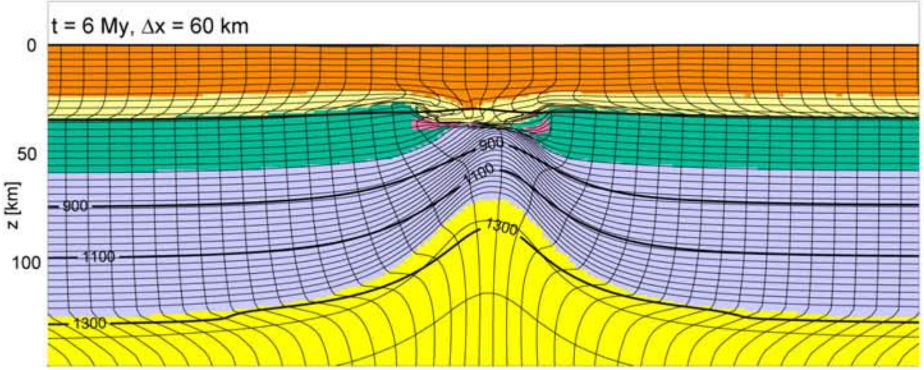
Late shallow water salt on thin crust indicates depth dependent thinning between crust and mantle

South Atlantic Salt Basin

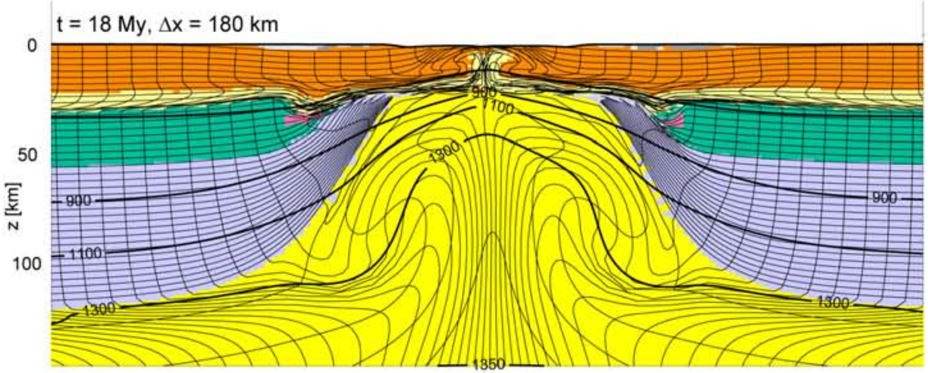


•Moulin et al., 2005; Huismans and Beaumont, Geology 2008; Huismans and Beaumont, Nature

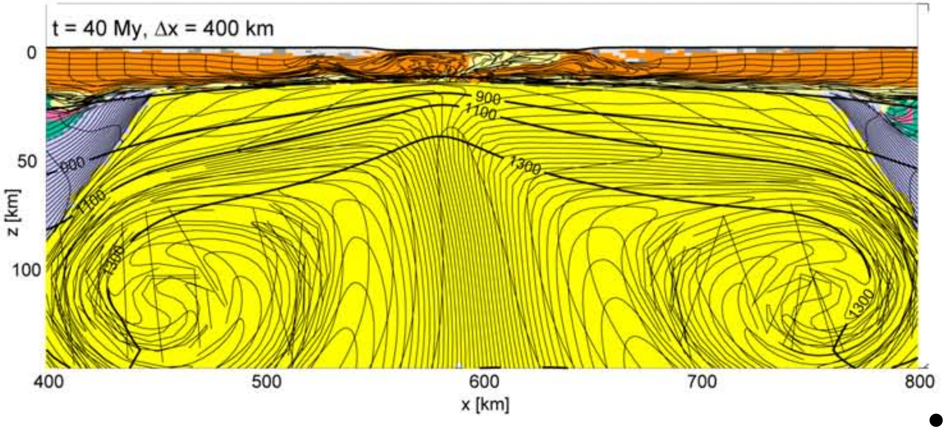
Weak Lower Crust, Seed in Mantle



- Narrow rifting of mantle lithosphere
- Distributed extension in crust
- Lower crustal flow to thinning area



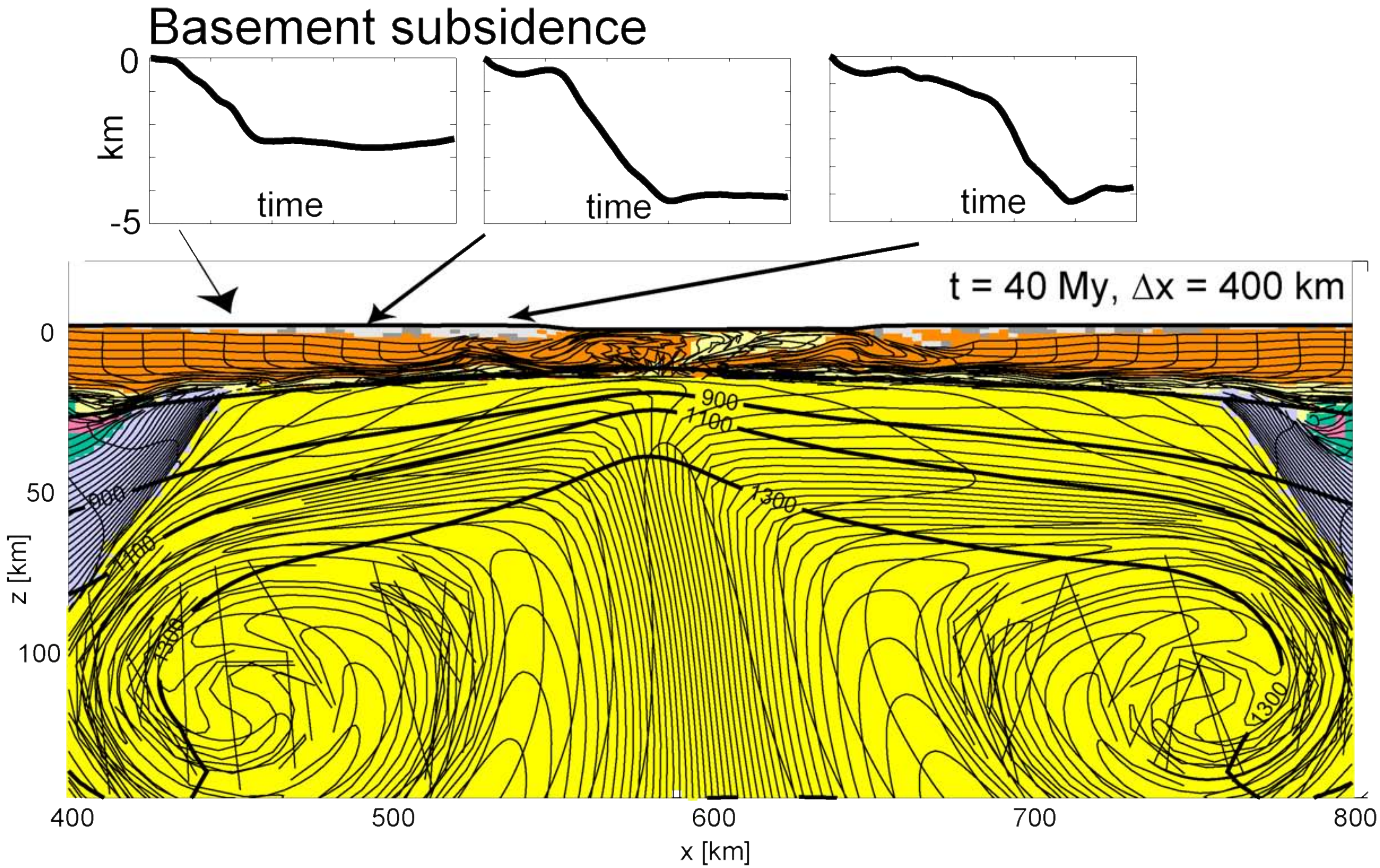
- Narrow rifting of mantle lithosphere
- Lower crustal flow to thinning area
- Regional 'sag' subsidence



- Very wide upper crustal sections
- Lower crustal flow to distal margin
- Regional 'sag' subsidence
- Little deformed upper crustal section

- Huismans and Beaumont, Nature 2011

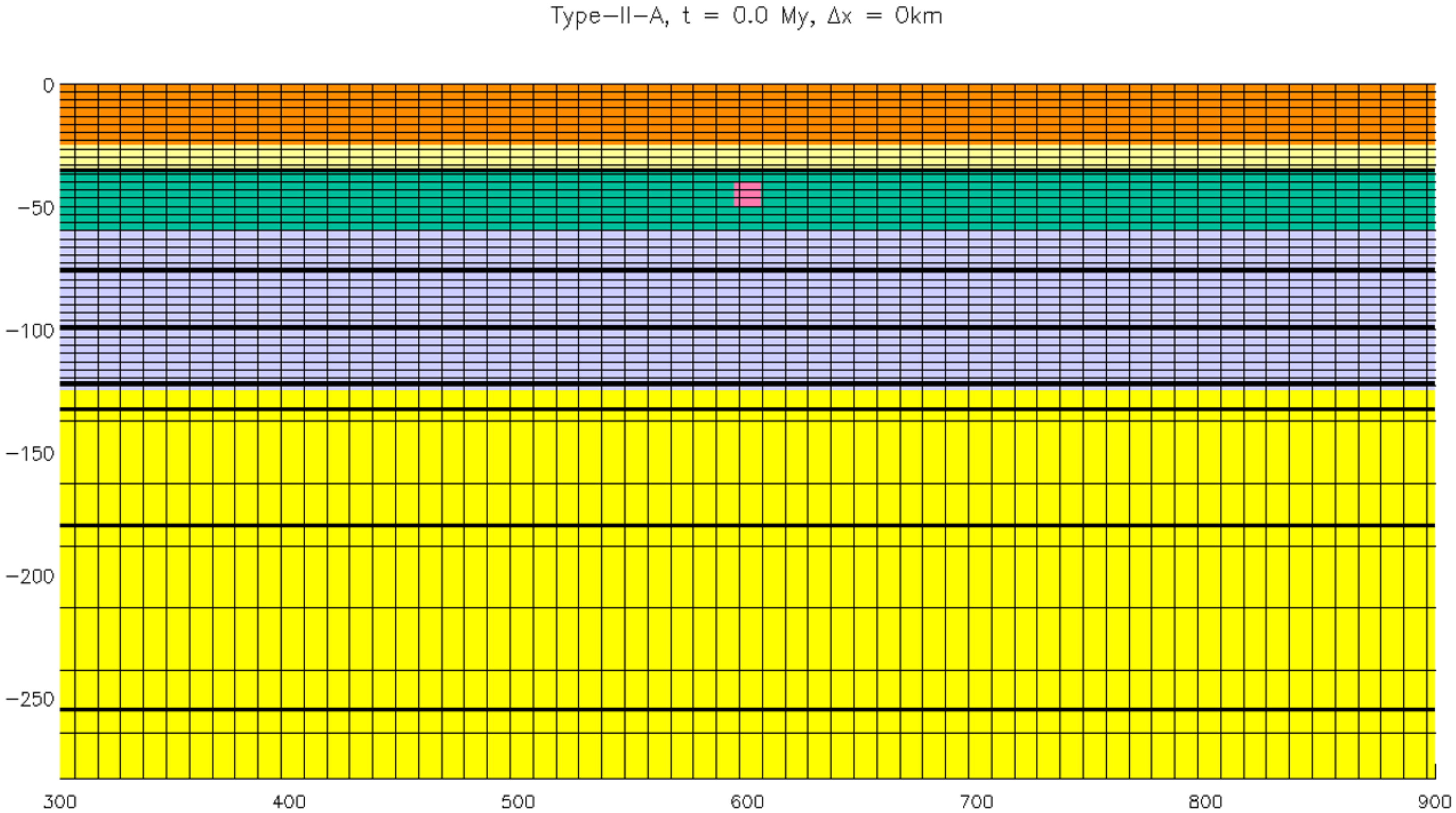
Very Weak Lower Crust



- Lower crustal flow to distal margin
- Diachronous ‘sag’ subsidence

•Huismans and Beaumont, Nature 2011

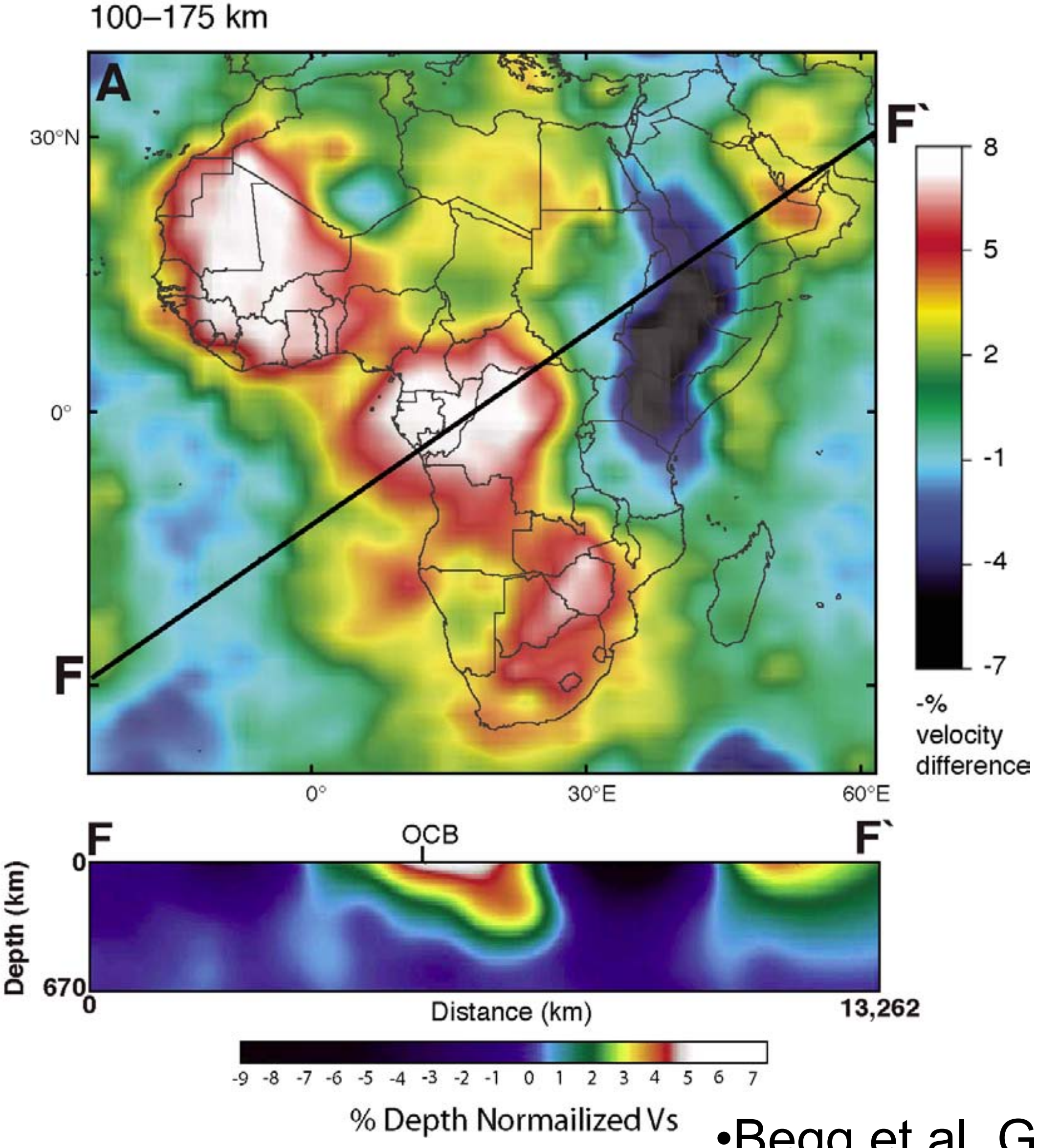
Type II-A



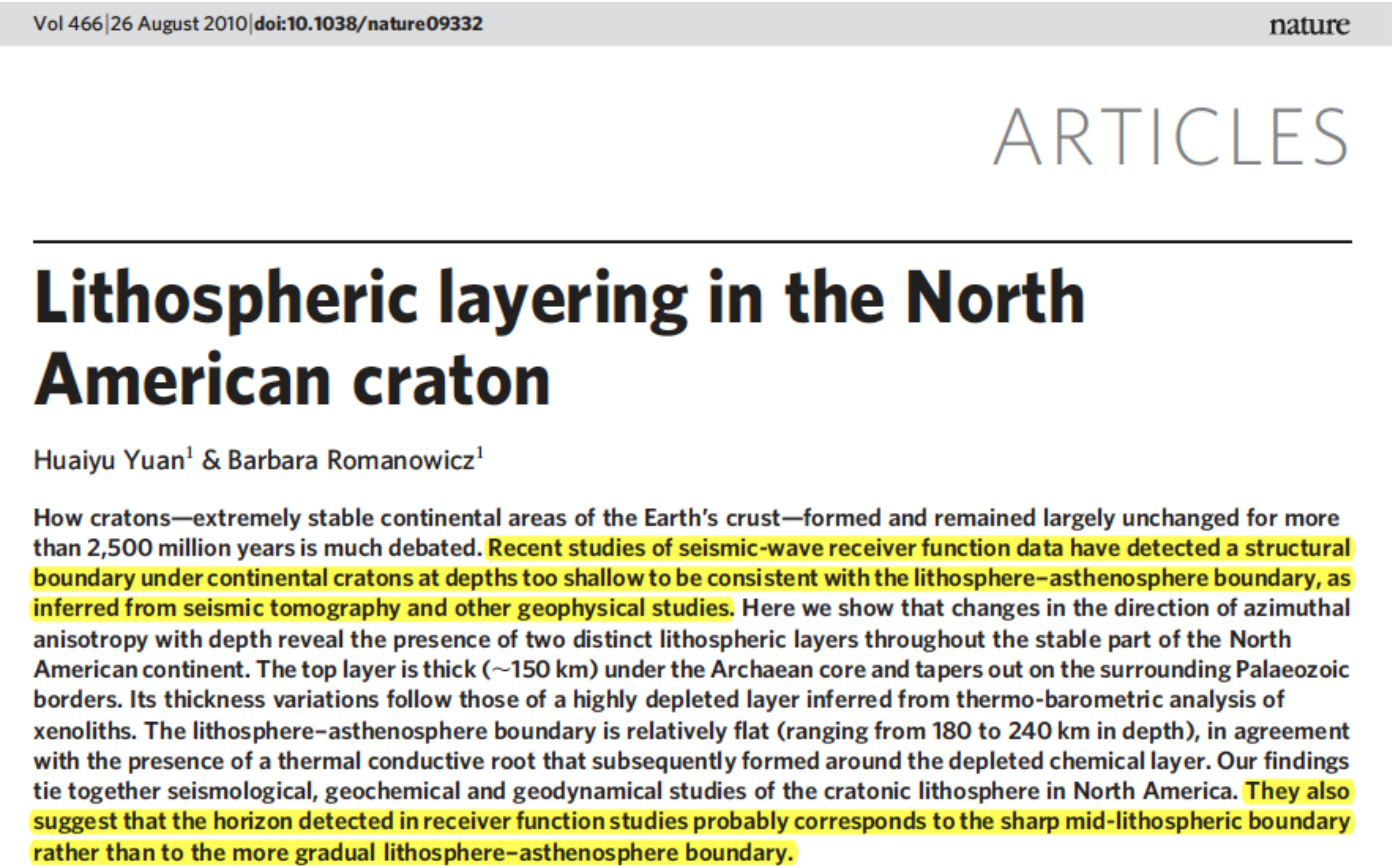
Animation, see: http://folk.uib.no/rhu002/huismans_beaumont_nature2011.html

•Huismans and Beaumont, Nature 2011

Tomography



- Begg et al, Geosphere 2009



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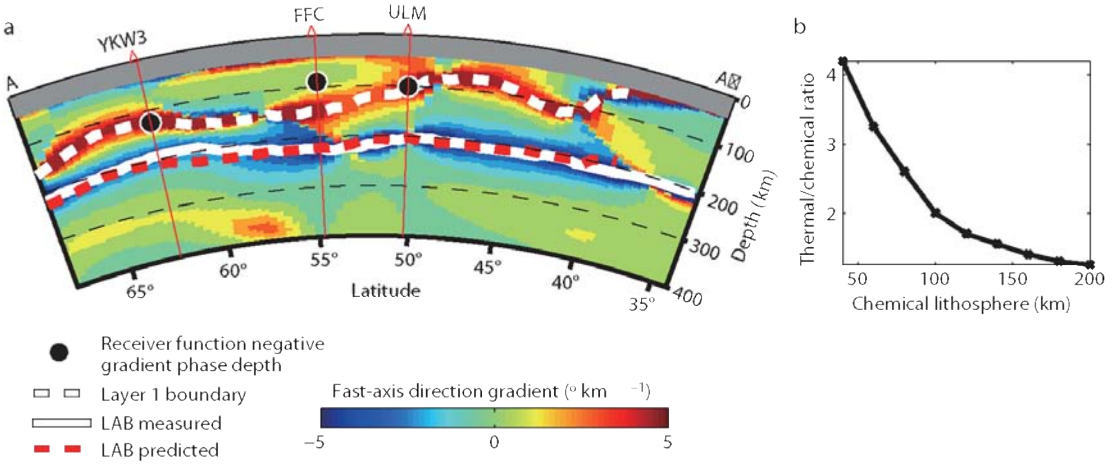
ARTICLES

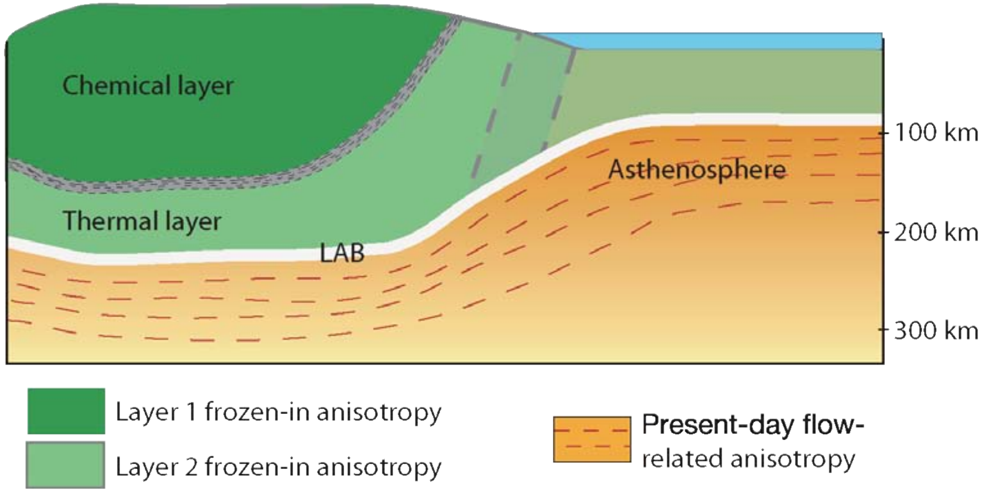
Lithospheric layering in the North American craton

Huaiyu Yuan[1] & Barbara Romanowicz[1]

How cratons—extremely stable continental areas of the Earth's crust—formed and remained largely unchanged for more than 2,500 million years is much debated. Recent studies of seismic-wave receiver function data have detected a structural boundary under continental cratons at depths too shallow to be consistent with the lithosphere–asthenosphere boundary, as inferred from seismic tomography and other geophysical studies. Here we show that changes in the direction of azimuthal anisotropy with depth reveal the presence of two distinct lithospheric layers throughout the stable part of the North American continent. The top layer is thick (~150 km) under the Archaean core and tapers out on the surrounding Palaeozoic borders. Its thickness variations follow those of a highly depleted layer inferred from thermo-barometric analysis of xenoliths. The lithosphere–asthenosphere boundary is relatively flat (ranging from 180 to 240 km in depth), in agreement with the presence of a thermal conductive root that subsequently formed around the depleted chemical layer. Our findings tie together seismological, geochemical and geodynamical studies of the cratonic lithosphere in North America. They also suggest that the horizon detected in receiver function studies probably corresponds to the sharp mid-lithospheric boundary rather than to the more gradual lithosphere–asthenosphere boundary.

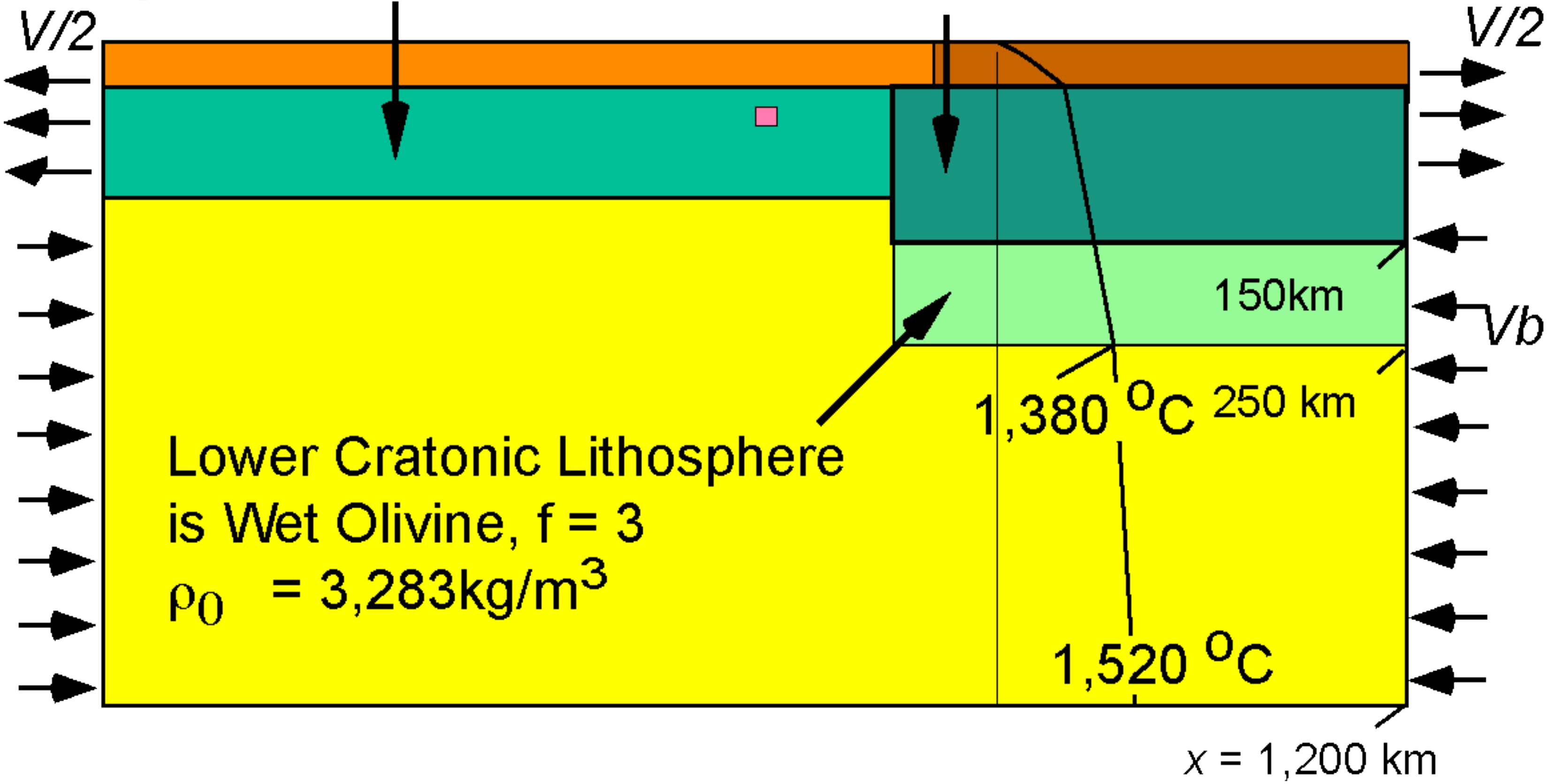
Lower Lithospheric Mantle Layer





Yuan and Romanovich, Nature 2010

Type-II Craton



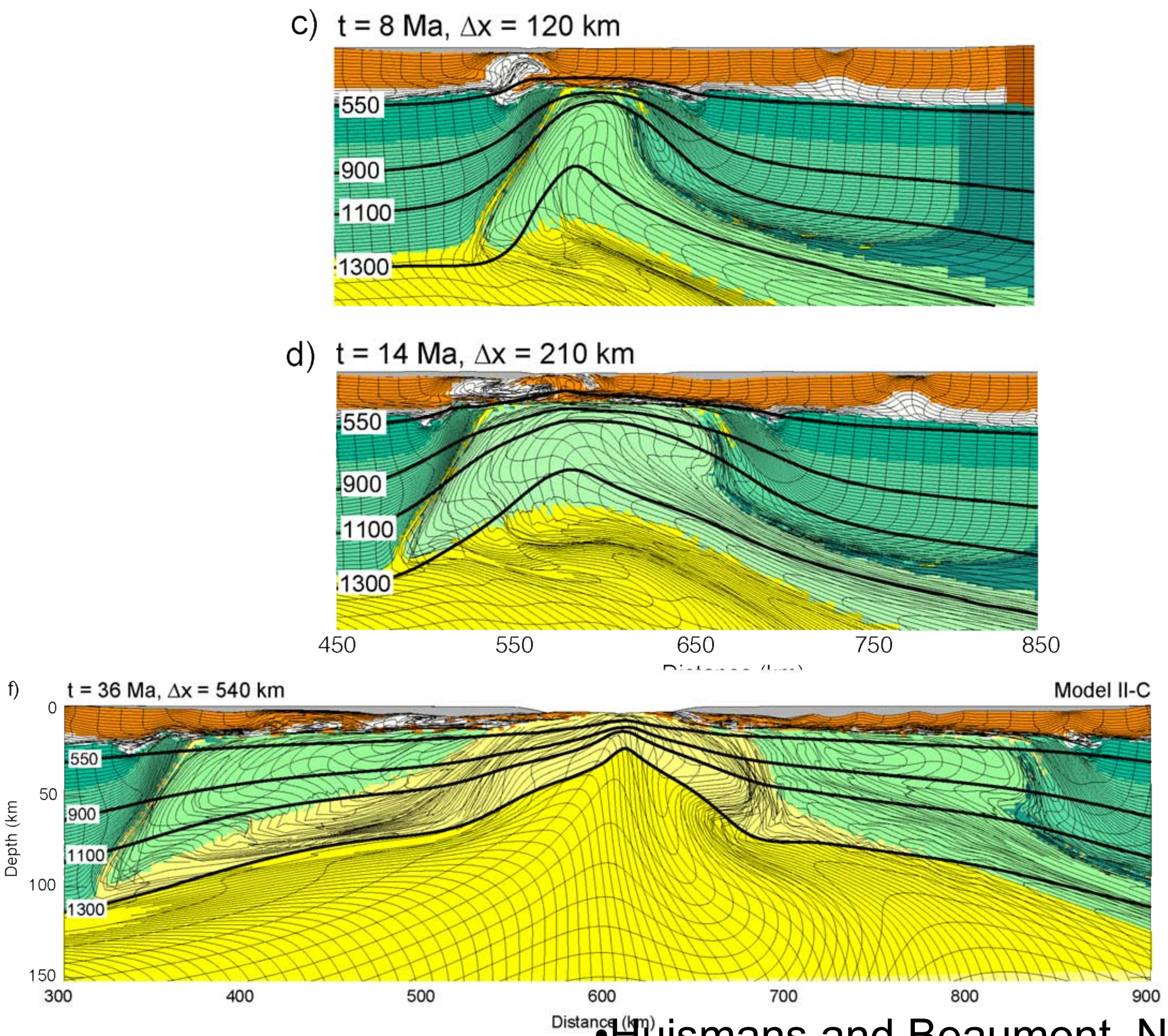
Lithospheric Mantle
Wet Olivine, f = 5
$\rho_0 = 3{,}300\ \mathrm{kg/m^3}$

Upper Cratonic Lithosphere
Wet Olivine, f = 5
$\rho_0 = 3{,}285\ \mathrm{kg/m^3}$

Lower Cratonic Lithosphere
is Wet Olivine, f = 3
$\rho_0 = 3{,}283\mathrm{kg/m^3}$

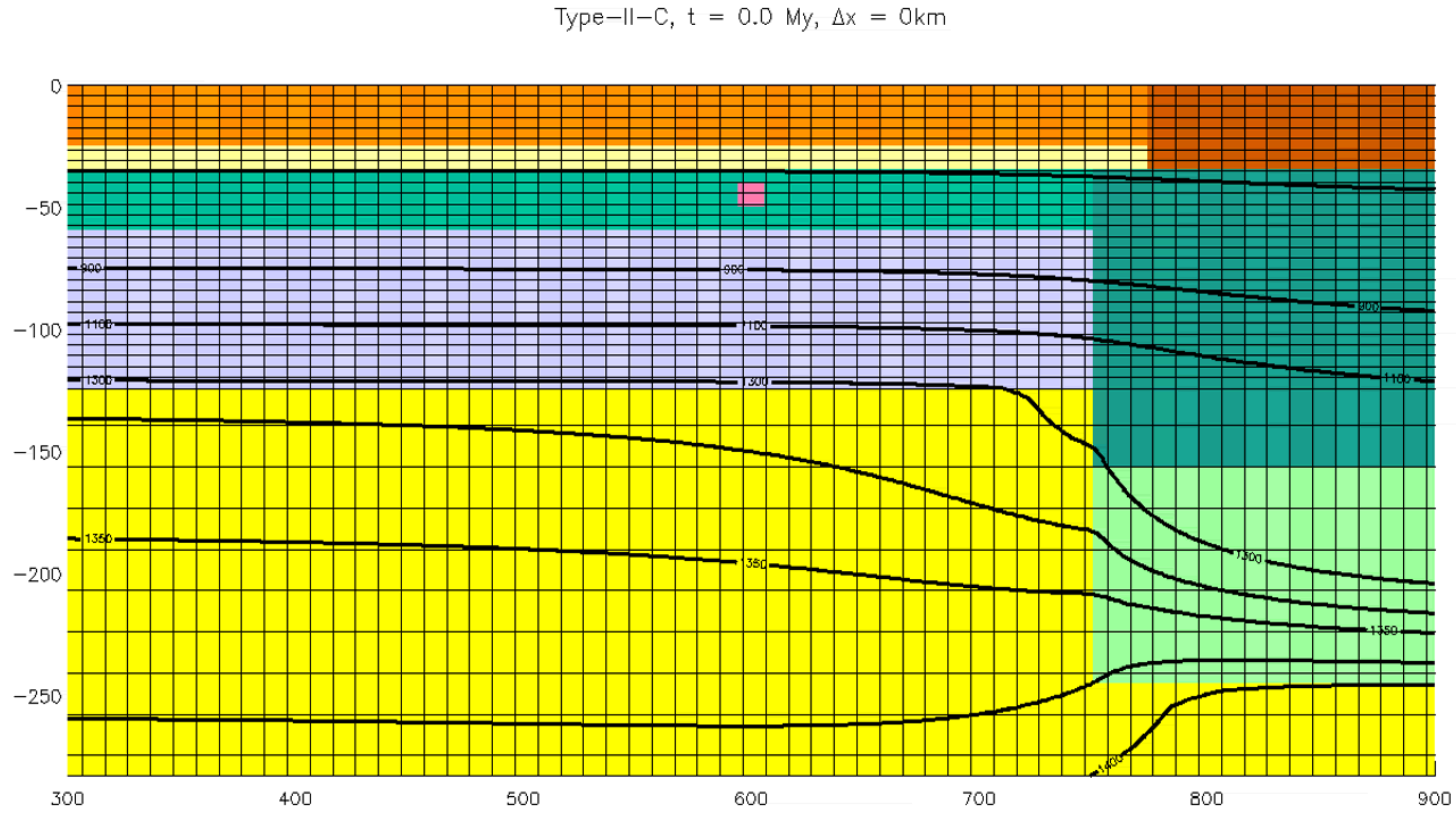
•Huismans and Beaumont, Nature 2011

Type II-Cratonic inflow



- Huismans and Beaumont, Nature 2011

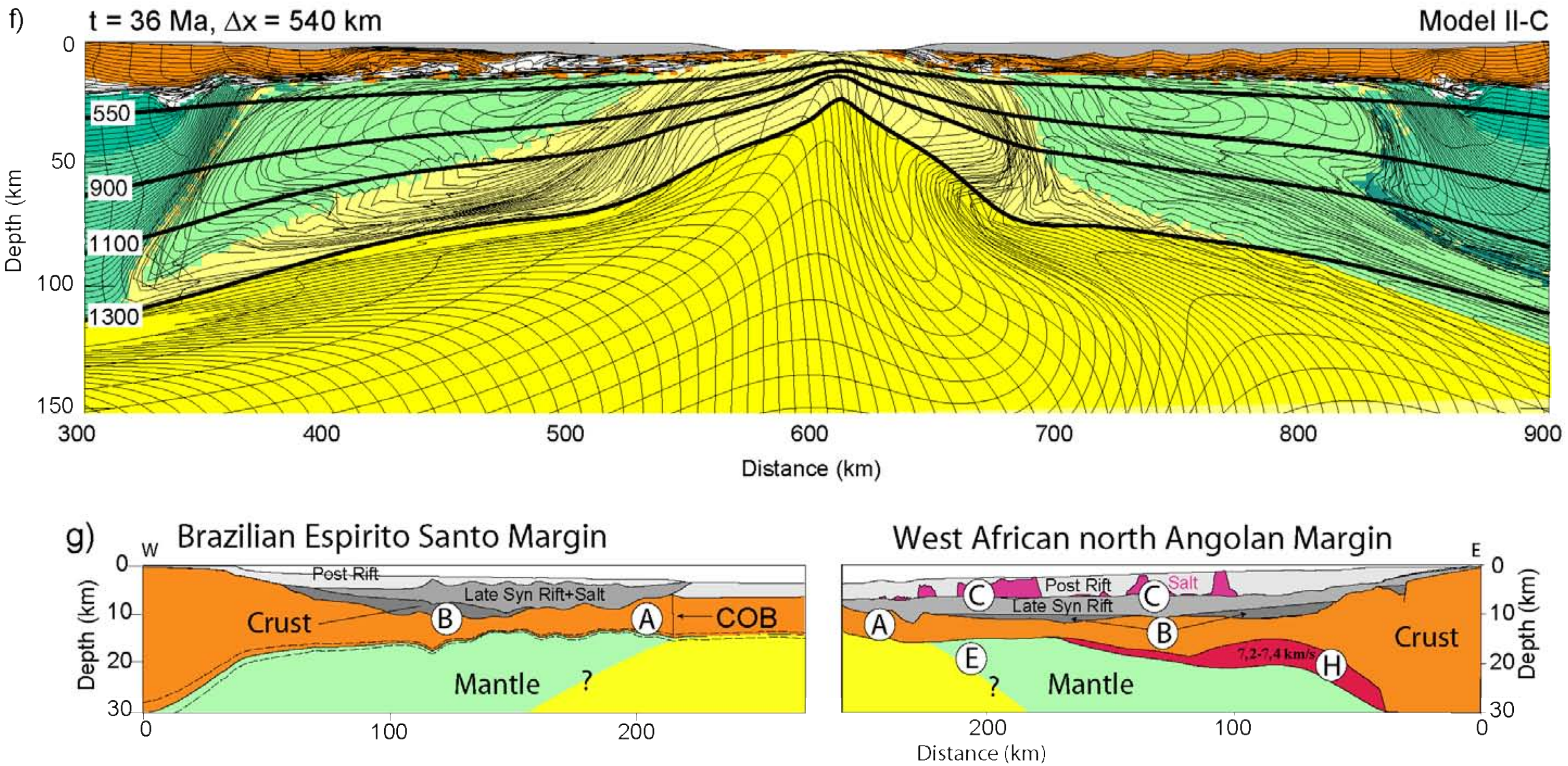
Type II-C



Animation, see: http://folk.uib.no/rhu002/huismans_beaumont_nature2011.html

•Huismans and Beaumont, Nature 2011

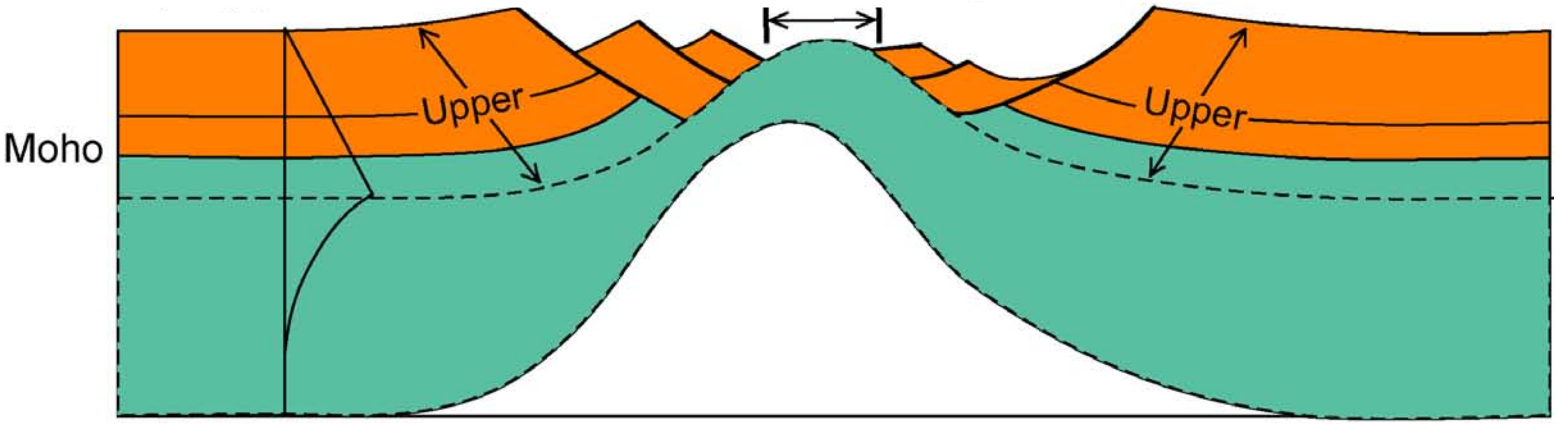
Type II-Cratonic Inflow



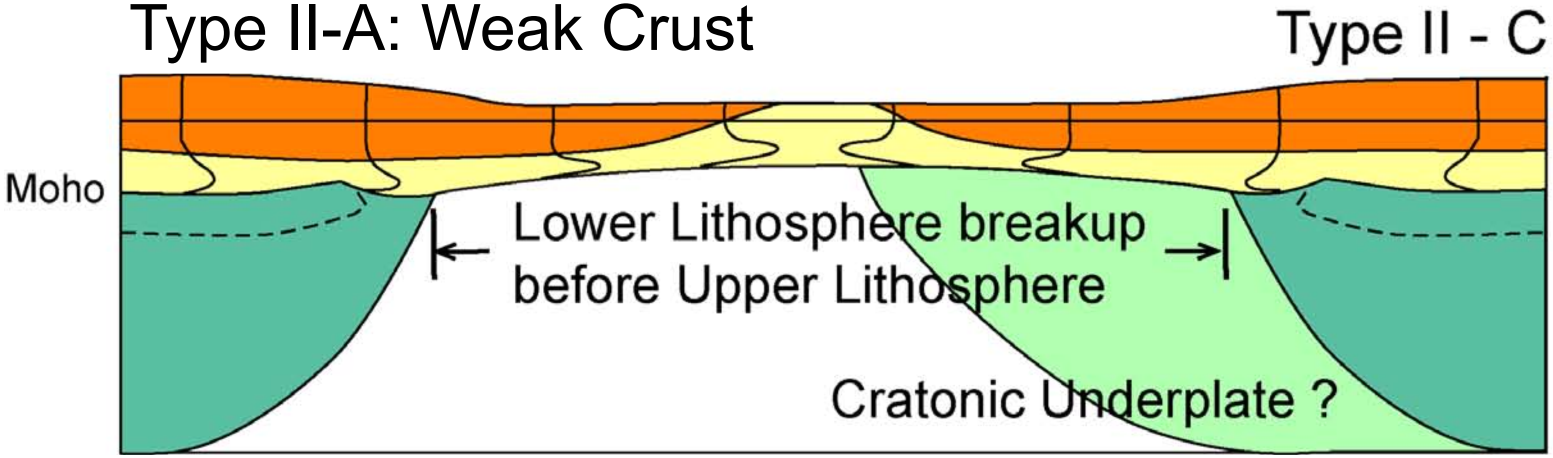
- Huismans and Beaumont, Nature 2011

Type I & II Contrasting Styles

Type I: Strong Crust



Type II-A: Weak Crust



Huismans and Beaumont, Nature 2011

Conclusions

- Type I margins:
  - Crust breaks first, mantle lithosphere necks later
  - Exhume mantle lithosphere
  - Favored by stronger crust

- Type II-A margins:
  - Mantle lithosphere necks first, crust breaks later
  - No mantle lithosphere exhumation
  - Favored by weak crust

- Type II-C margins:
  - Cratonic lower mantle lithosphere flows into necking area
  - Low density owing to depletion promotes shallow water depth
  - Depleted nature inhibits magmatism

- Lower mantle lithosphere inflow may explain large tracts of exhumed mantle in narrow Type I margins