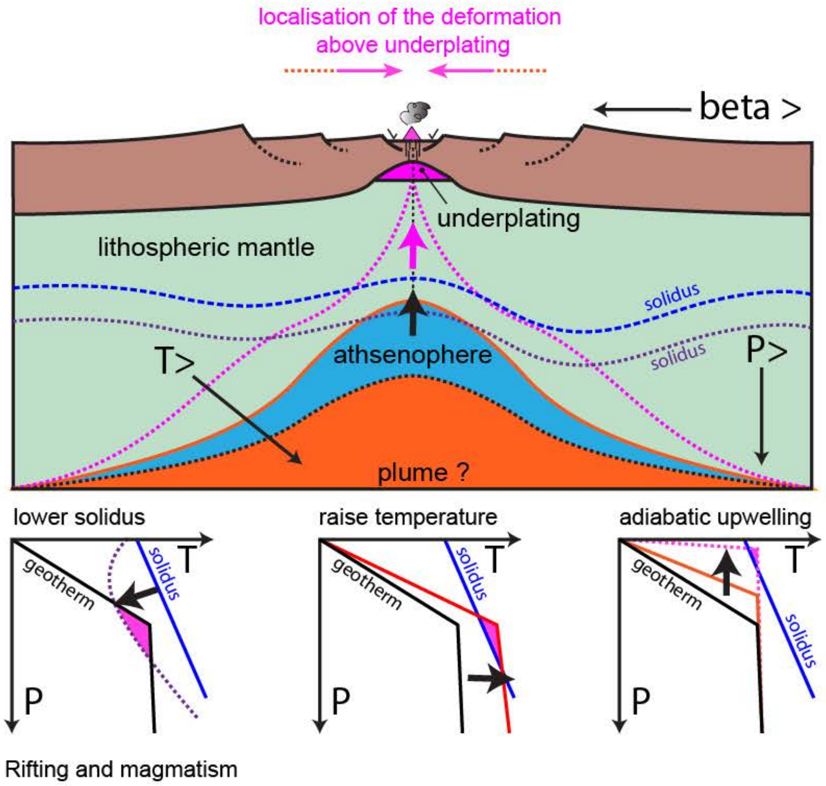
# A modeling perspective on rifting

Luc Lavier, UTIG/DGS
Jackson School of Geosciences
S. Jammes, G. Mohn.

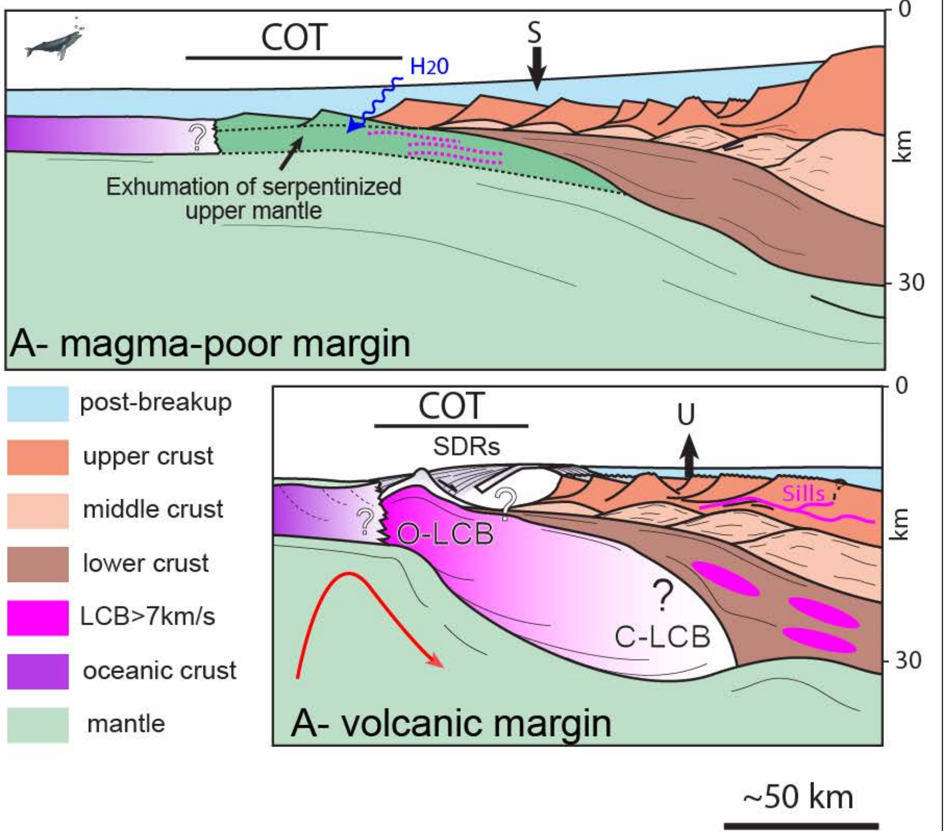
# Magma-”poor” margins versus ”volcanic” margins

What do we really know about volcanic margins ?
Are they really so different from “magma” poor rifted margins ?
What is the origin of the volcanism ? – what are the dynamic processes involved ?
What are the mechanisms leading to breakup ?



Origin of the magmatism

**LCB**: « Lower Crustal Body »
**SDRS**: »Seaward Dipping Reflectors »
COT: Continent-Ocean Transition

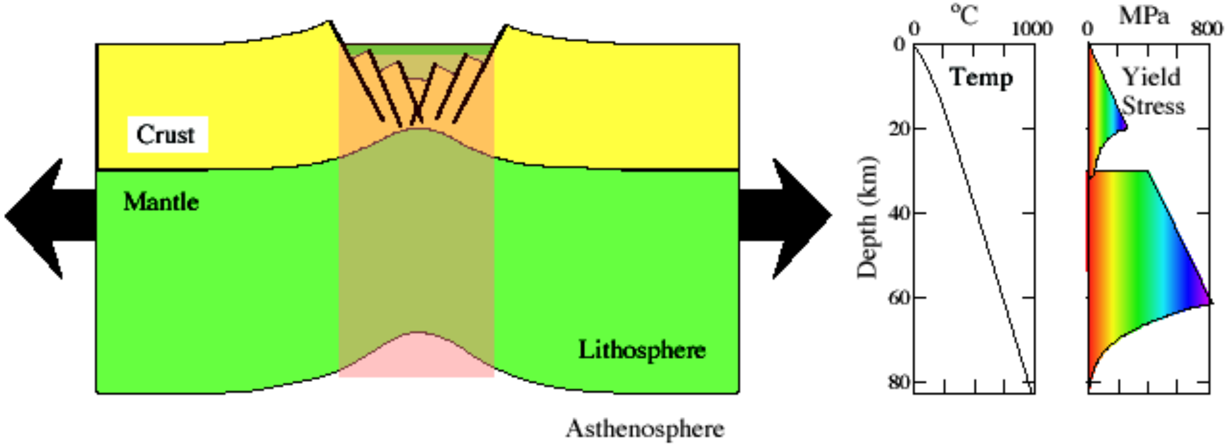


Laurent Geoffroy

# GENERAL FRAMEWORK: WEAKENING OF THE LITHOSPHERE

Tectonic Stretching

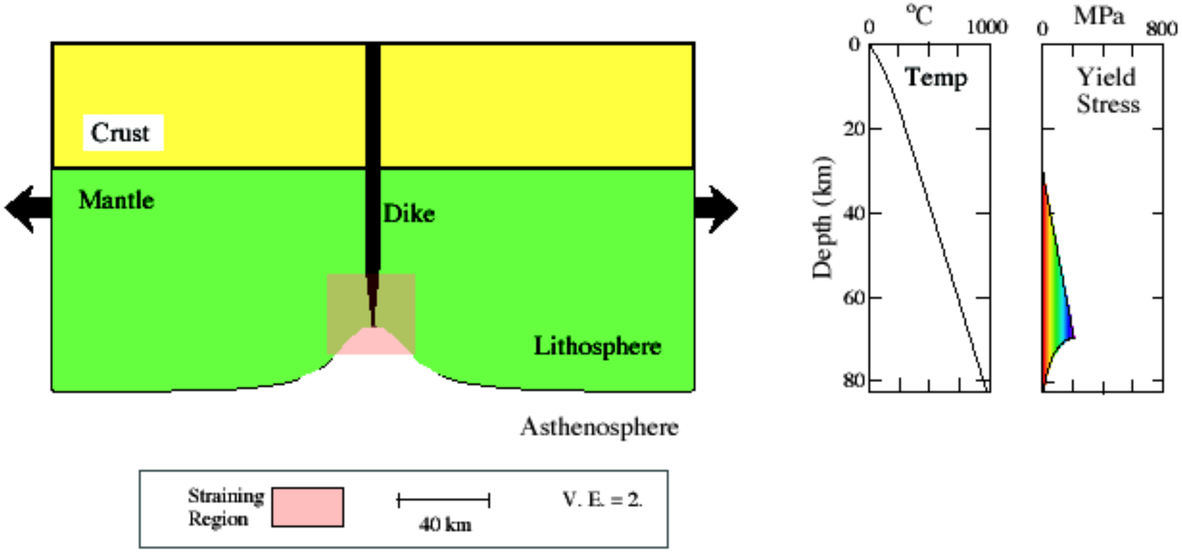
## NEEDS A GRADUAL EVOLUTION OF THE RHEOLOGY



- Detachment faults are present.
- Weakening of the lithosphere by fluids.
- Late serpentinization of the mantle (fluids).
- Storage of melt in the mantle.

Magmatic Extension

## WEAKENING OF THE LITHOSPHERE

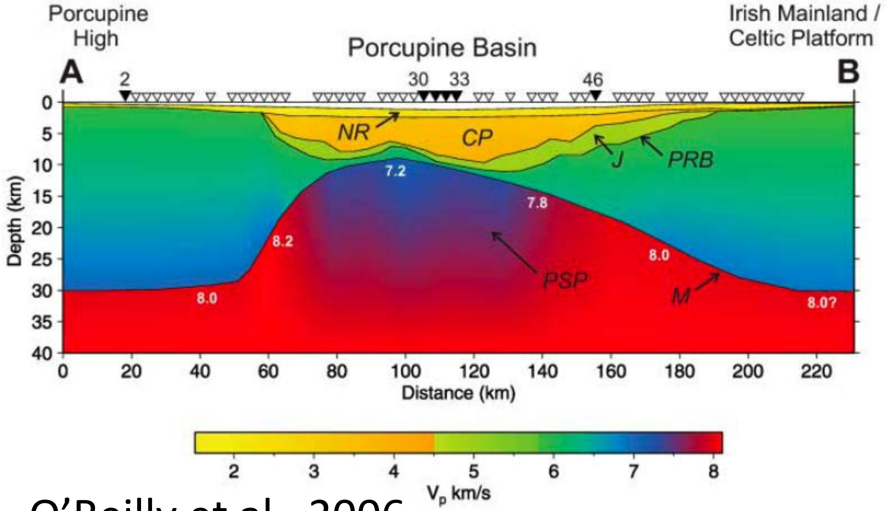


- Needs multiple dikes.
- Normal faulting with dikes.
- A plume head is often present
- Needs 2-3 km of dikes to continue rifting without magma.

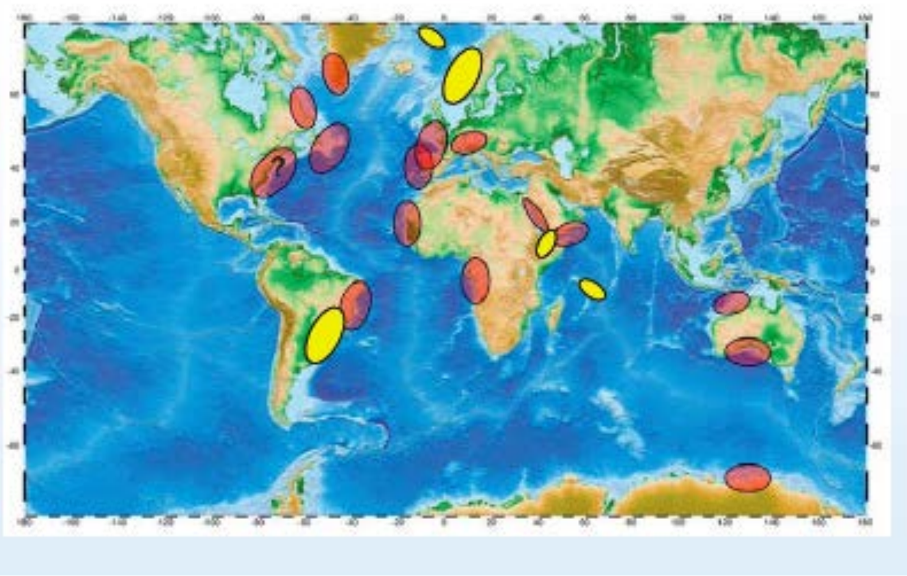
# Some Questions addressed?

- Extreme crustal thinning.
- Mantle exhumation at the Ocean Continent Transition (OCT).
- Detachment fault/low angle normal fault.
- Melt migration or stagnation during rifting.
- Dike (Giant) propagation during rifting and at the transition from continent to ocean.
- The effect of sedimentation and erosion on rifting.
- The subsidence history during rifting.

# Extreme Crustal Thinning



O’Reilly et al., 2006



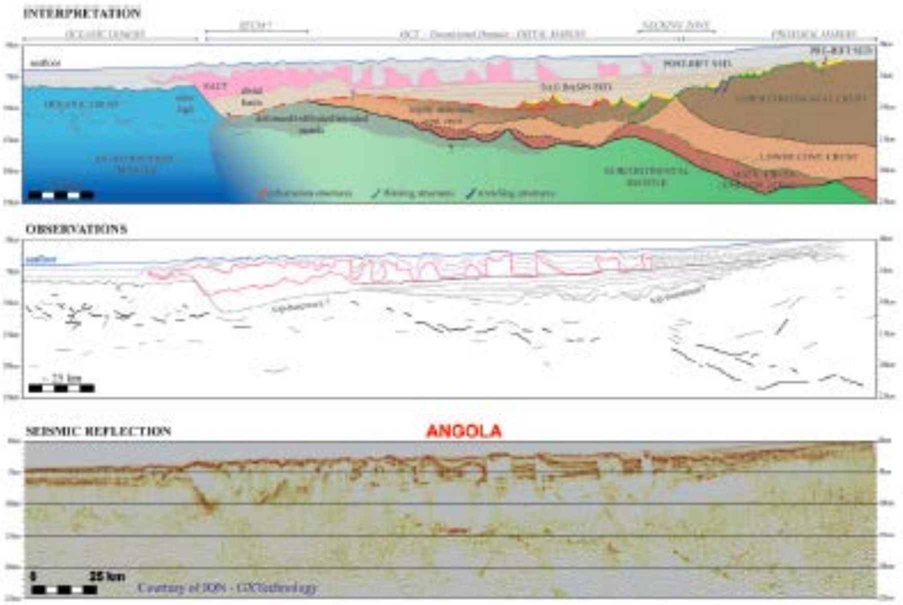


Fig. 2. Angola GXT seismic line. From bottom to top, a depth migrated reflection seismic line, a line drawing and a geological interpretation of one and the same line are shown.

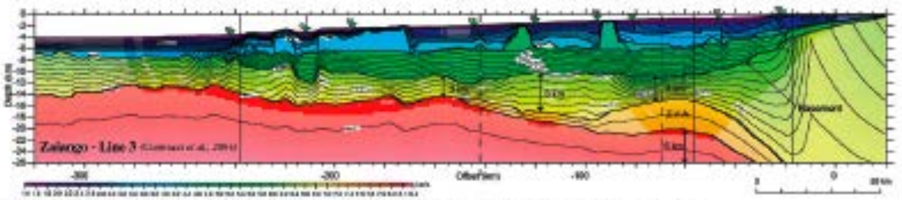
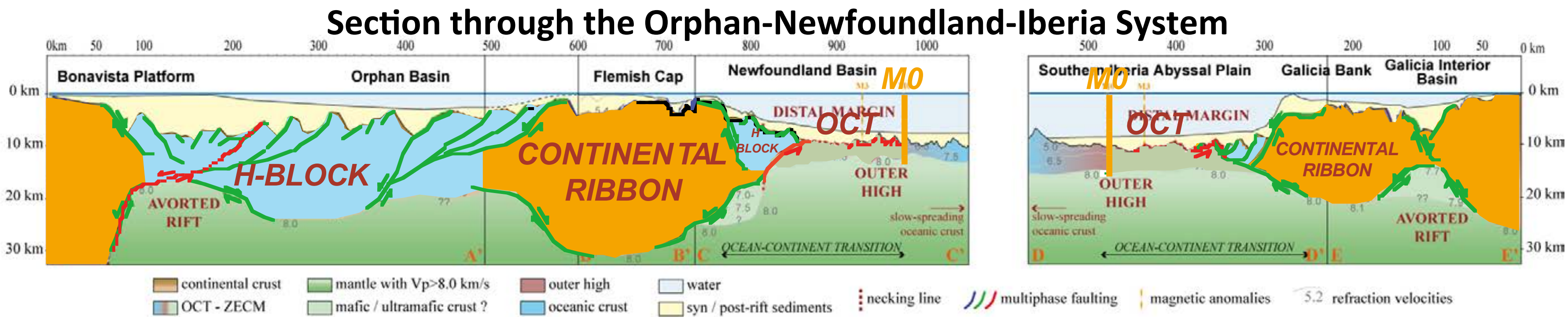


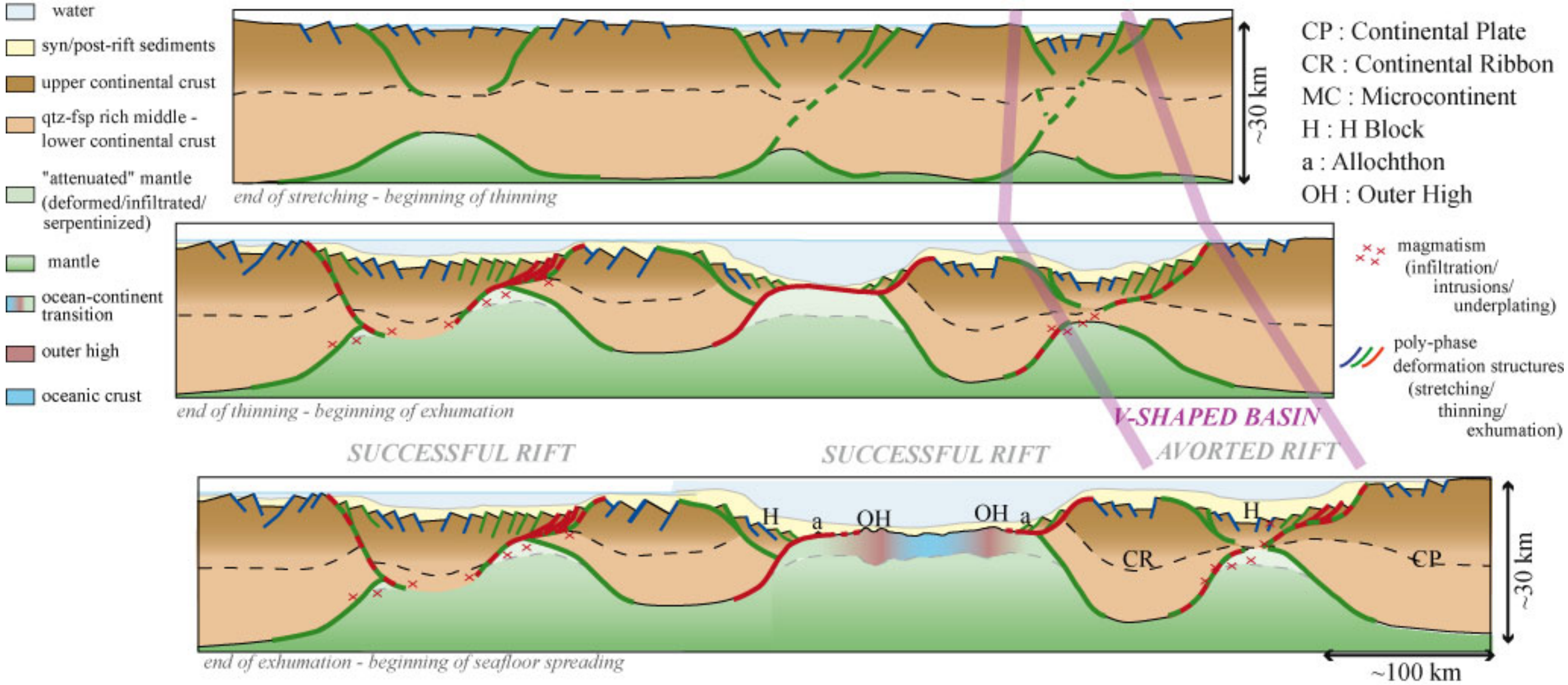
Fig. 3. Seismic refraction model of Contrucci et al. (2004). Location is indicated in Figure 1 as Zaiango profile.

Untherner et al., 2010

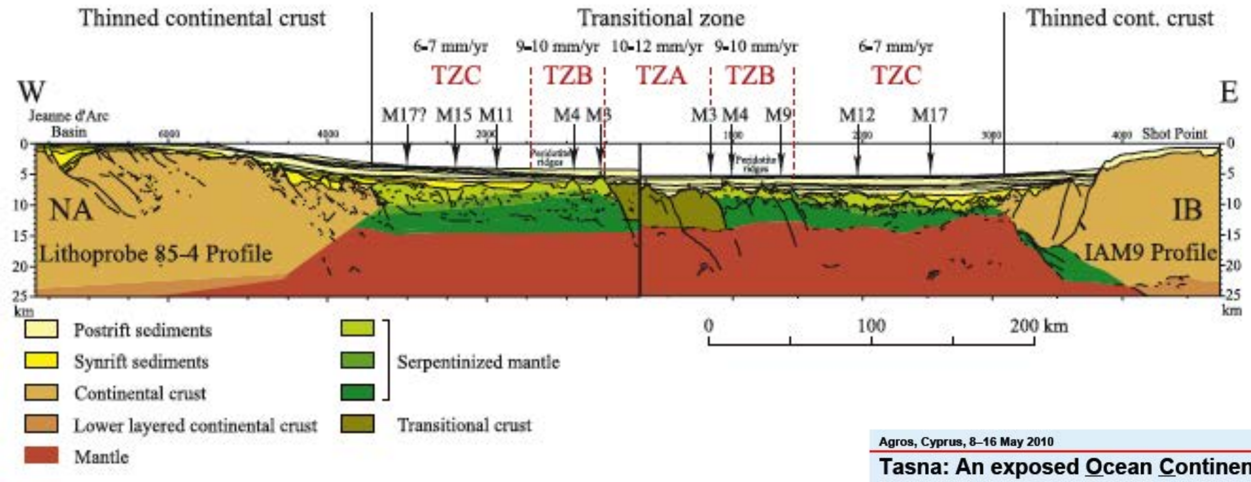
# Detachment fault/low angle normal fault/ Brittle-Ductile weakening/Boudinage.

*Peron-Pinvidic & Manatschal, subm.*



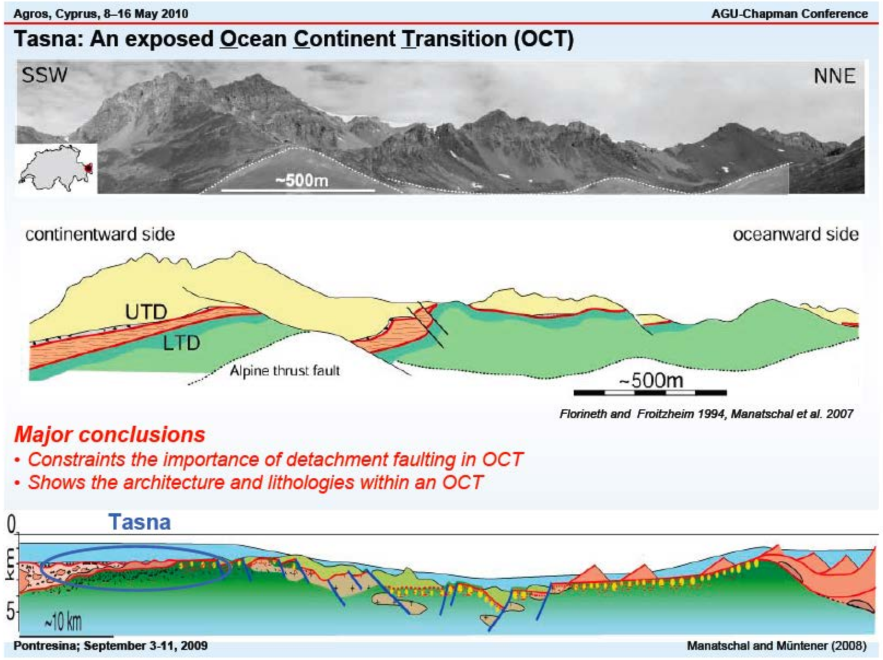


# Mantle exhumation at the Ocean Continent Transition (OCT).



Sibuet et al., 2007

Manatschal et al., 2004


**Agros, Cyprus, 8–16 May 2010** **AGU-Chapman Conference**

**Tasna: An exposed Ocean Continent Transition (OCT)**

*Florineth and Froitzheim 1994, Manatschal et al. 2007*

***Major conclusions***

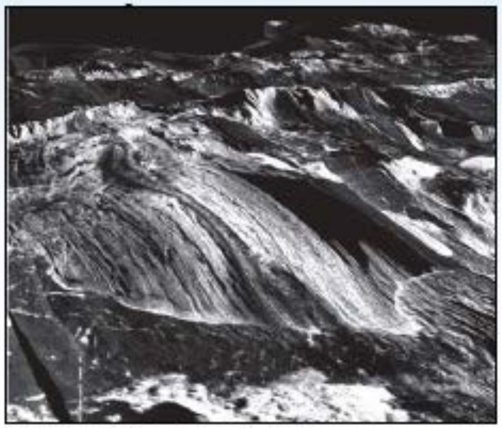
- *Constraints the importance of detachment faulting in OCT*
- *Shows the architecture and lithologies within an OCT*

**Pontresina; September 3-11, 2009** **Manatschal and Müntener (2008)**

# Detachment systems associated with lithospheric extension

**oceanic core complexes**

ocean



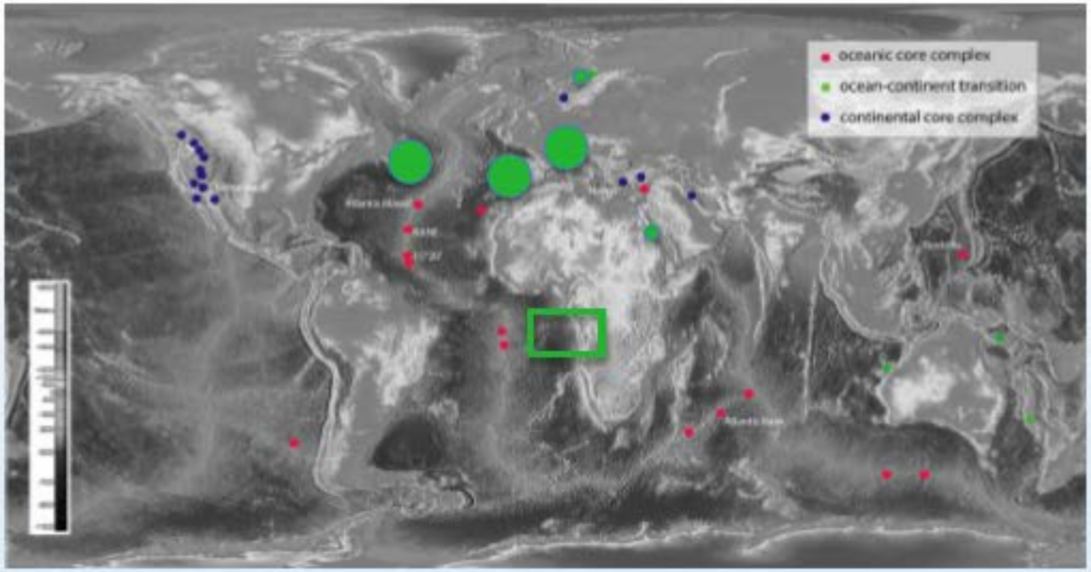
*Mid-Atlantic Ridge*

**Few examples of detachment systems associated with continental breakup have been described**

**metamorphic core complexes**

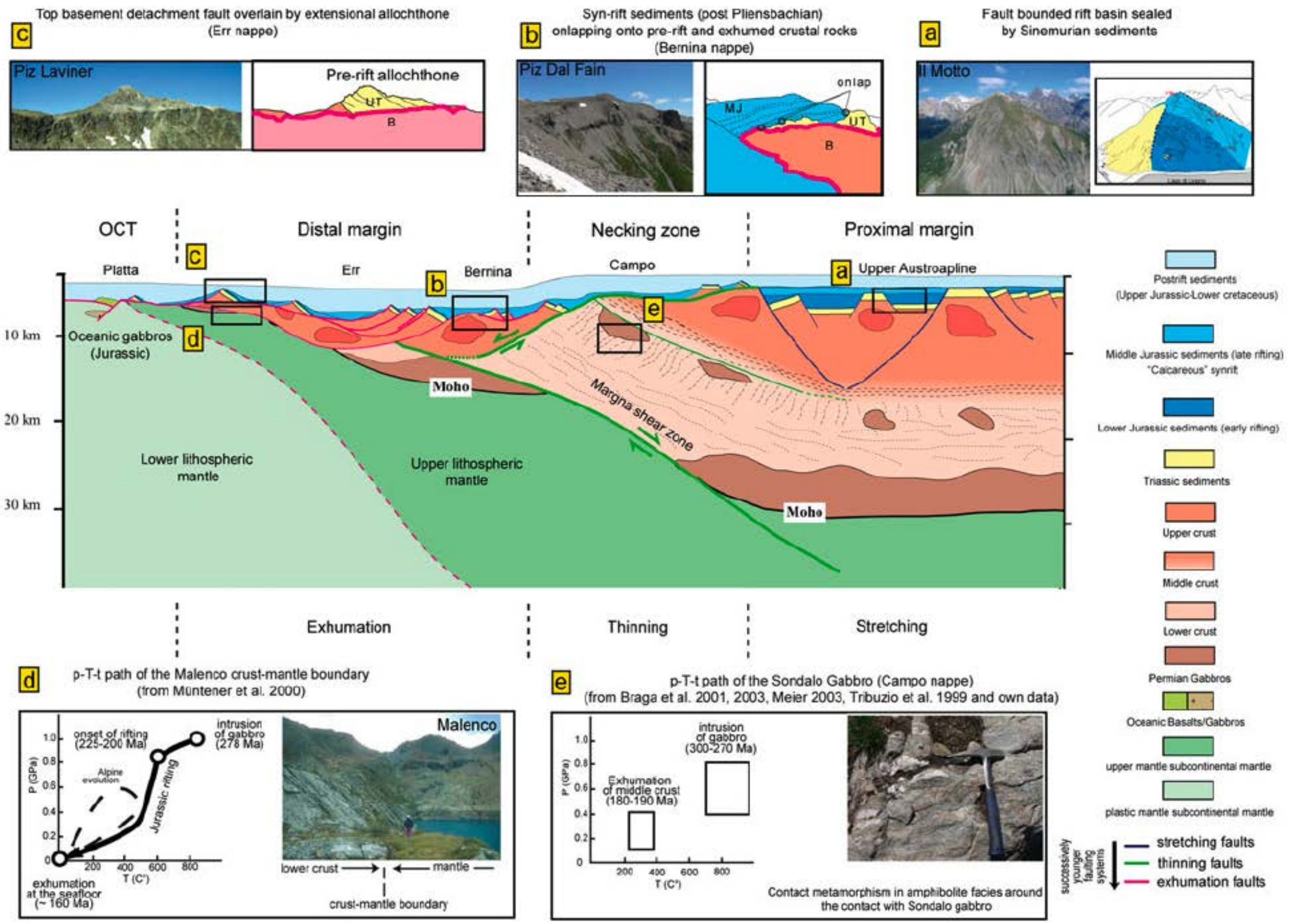
continent

*Death Valley*



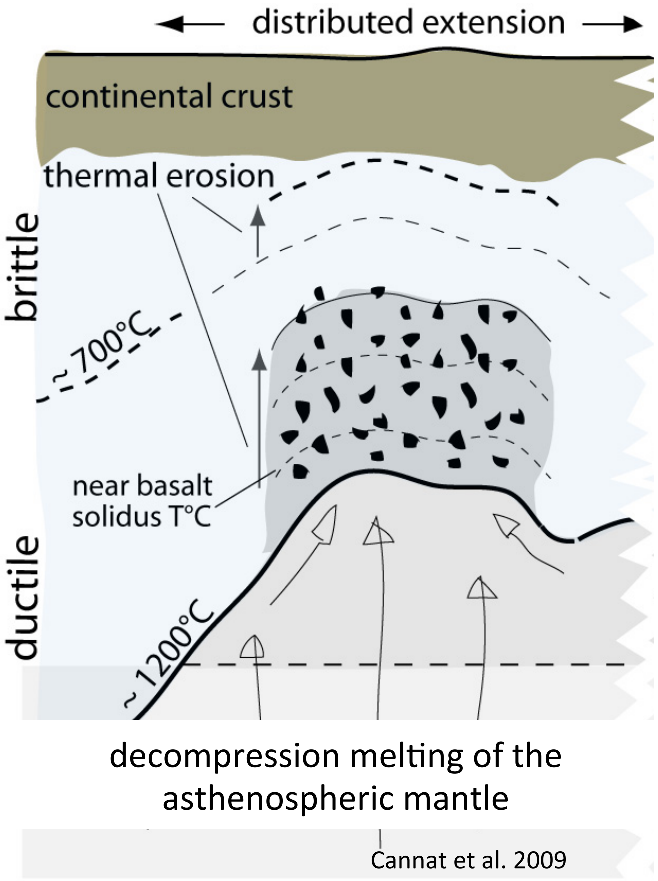
*From Barbara John*

# Field Geology (Alps/Pyrenees-Bay of Biscay) Detachment faults and brittle-ductile weakening associated with necking and crustal thinning.



Mohn et al., 2010

# Melt infiltration and thermal evolution during final rifting



Cannat et al. 2009

***Observation***

Infiltrated sub-continental mantle

***Processes***

melt trapping, leading to thermal erosion of the deep mantle lithosphere during final rifting

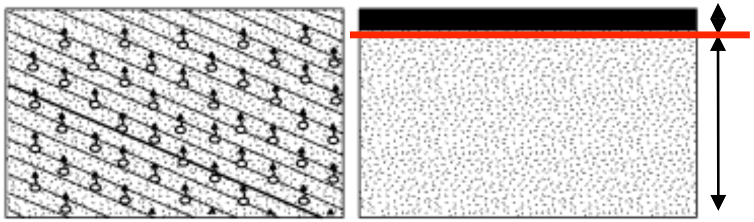
**Consequences**

- *change of the mantle rheology (weakening)*
- *thermal structure (hotter than expected)*
- *subsidence history (retardation of subsidence)*

WHY DOESN'T IT FORM A DIKE?

*10% infiltration in*
*10 km thick mantle*
*no seismically*
*'visible' Moho*

*'non-volvanic' ?* *'volcanic'*



*1 km 'true' oceanic crust*

*seismically 'visible' Moho*

*9 km depleted mantle*

Muentener et al., 2009

# Observed magmatic processes in magma-poor rifted margins

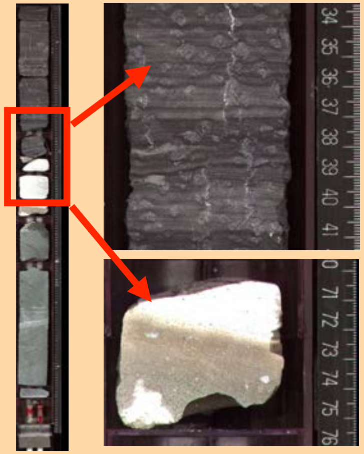
## (2) syn-exhumation

*MOR-gabbro in serpentinized mantle*

*ODP Site 1070 9R-1*

## (3) Breakup and post-breakup

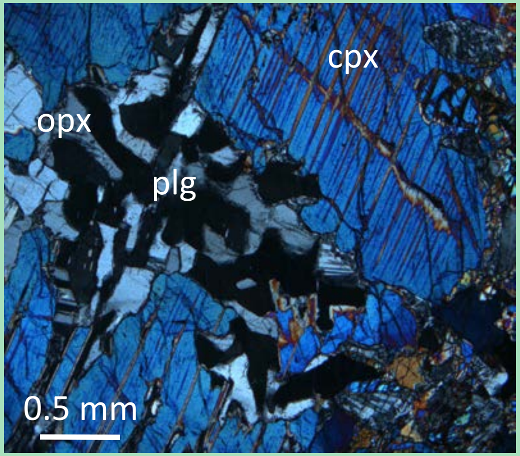
*Alkaline sills in post-rift sediments*



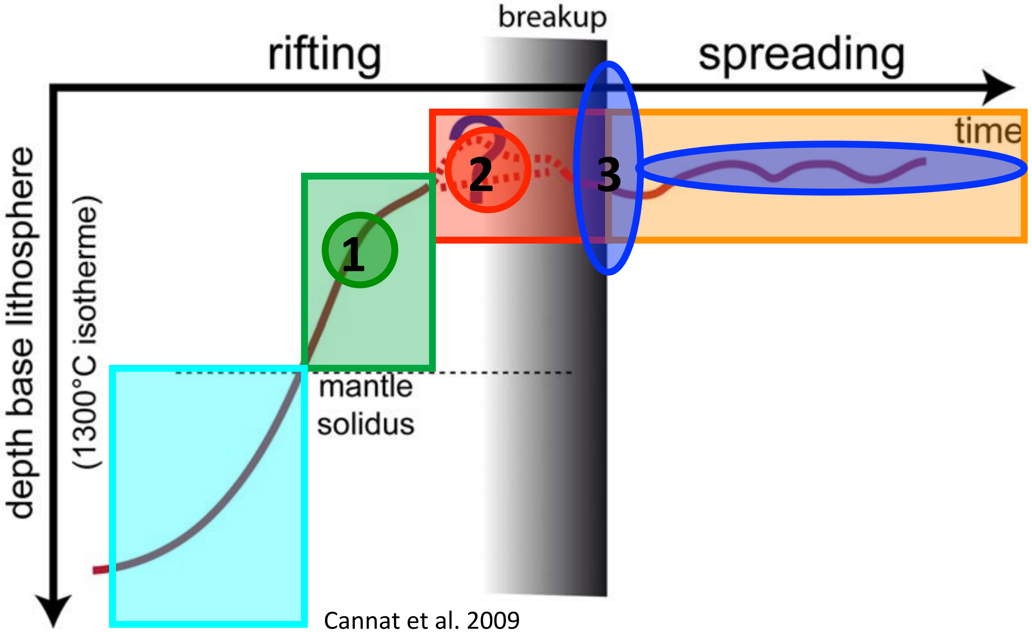
ODP Site *1276-87R-6*

## *(1) pre-breakup*

*melt infiltration in sub-continental mantle*



*ODP Site 897 4R-1*



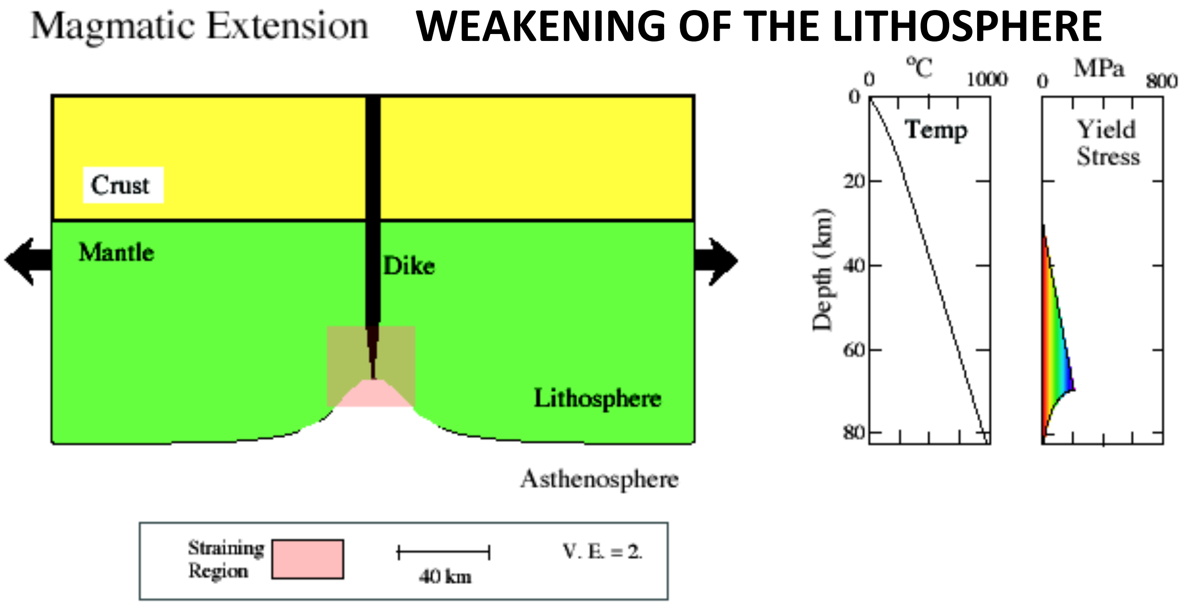
Cannat et al. 2009

# Numerical technique

- Same conservation of momentum and energy.

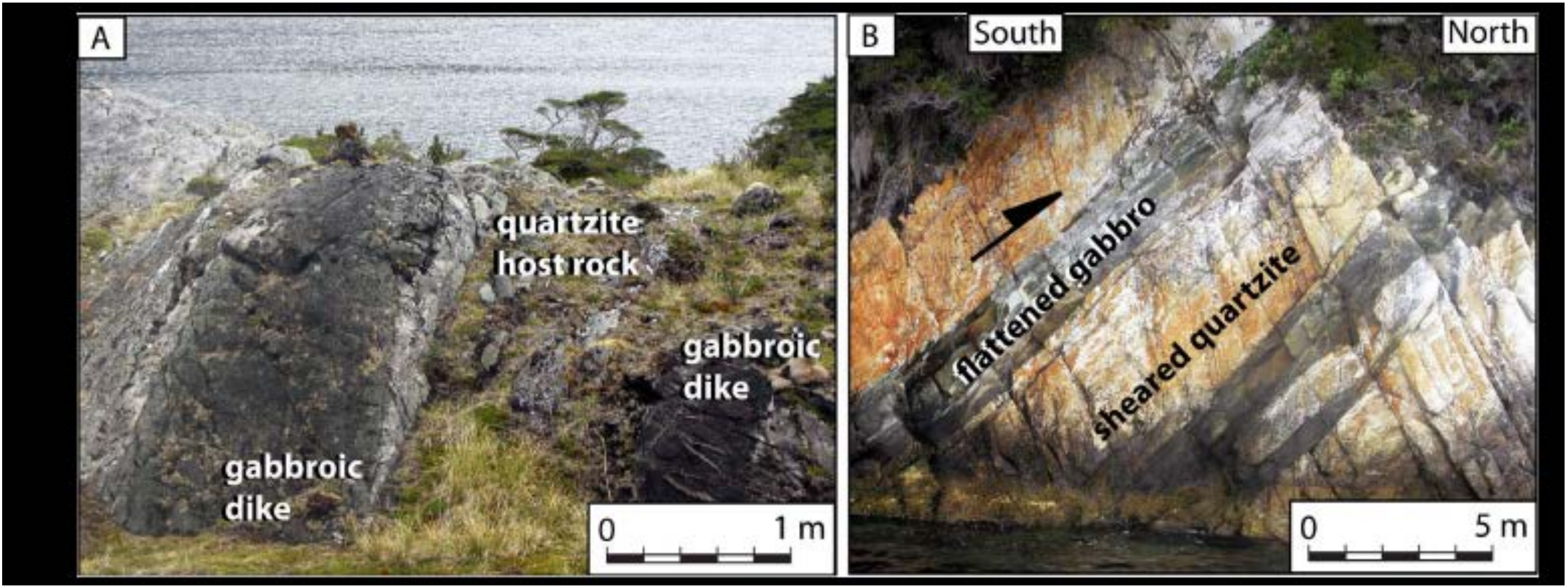
- Differ in their constitutive updates
  - Viscoplastic
  - Elastoplastic
  - Elastoviscoplastic.
  - Different approaches for localization in the brittle and ductile media.
  - It is very difficult to account for melt production and migration in a large deformation code.
  - Diking can be modeled by boundary elements.

# WEAKENING OF THE LITHOSPHERE

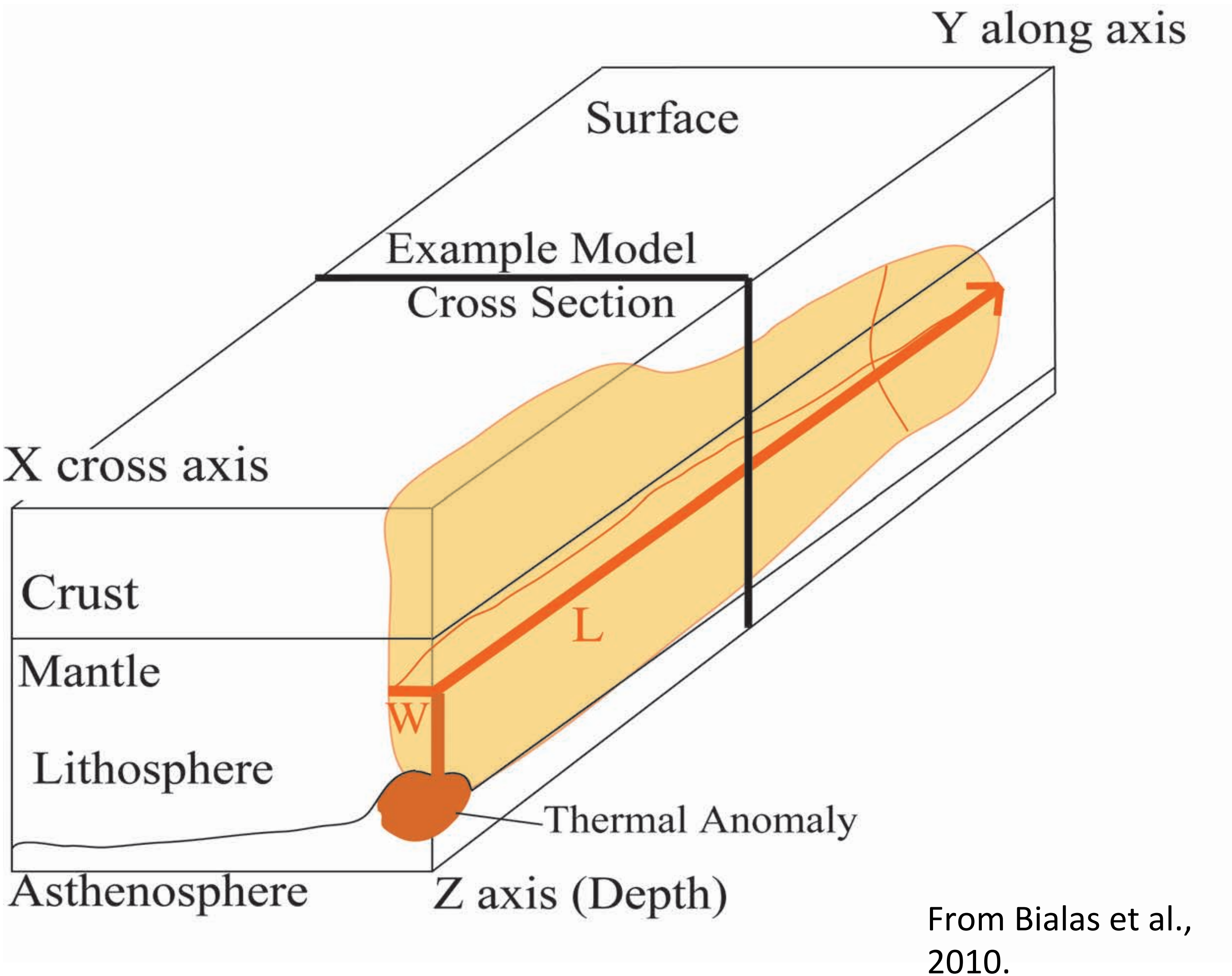


- •Needs multiple dikes.
- •Normal faulting with dikes.
- •A plume head is often present
- •Needs 2-3 km of dikes to continue rifting with magma.

# Cordillera Darwin (Patagonia)
Rocas Verde rift basin (Jurassic)

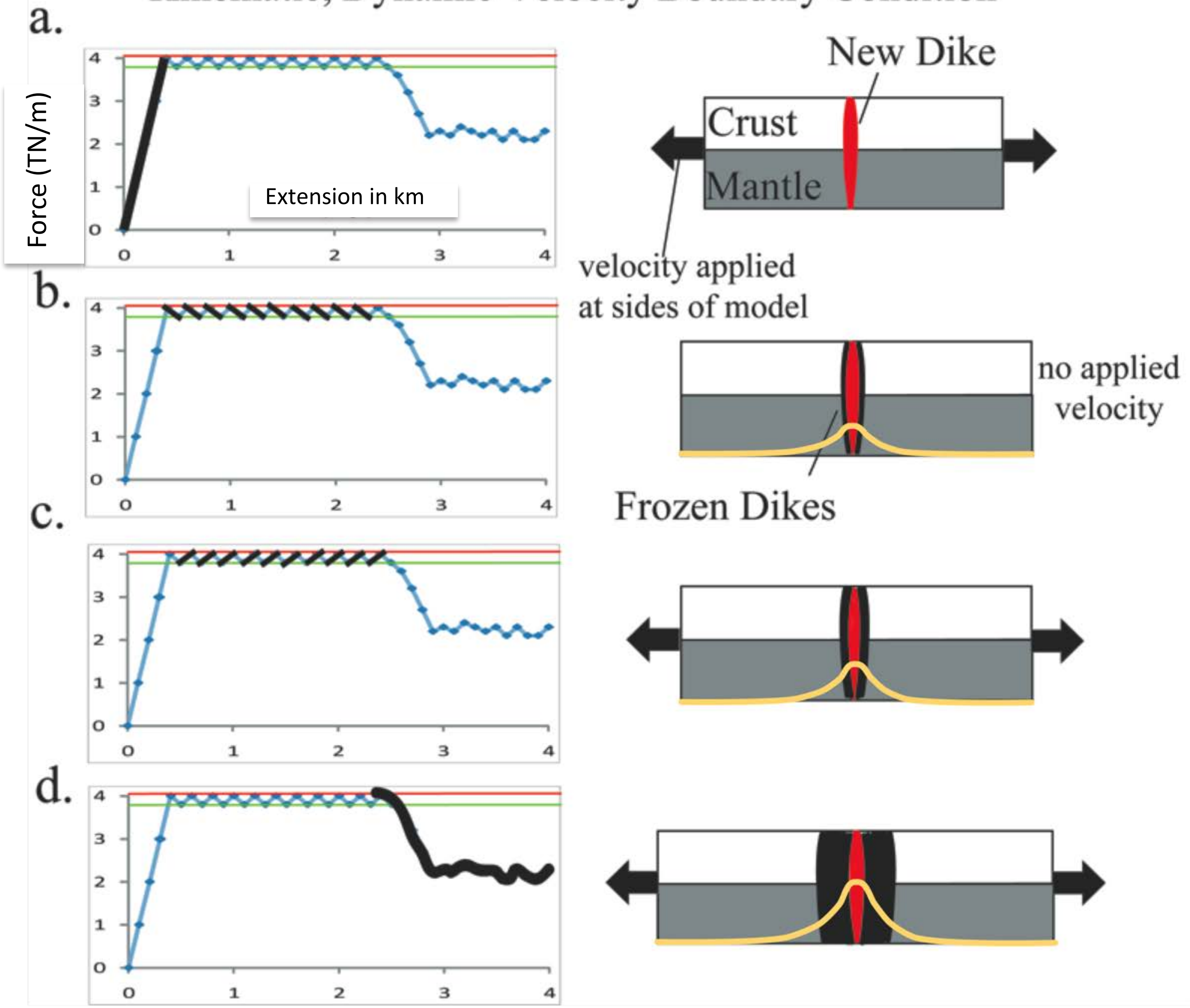


Klepeis et al., 2010



From Bialas et al., 2010.

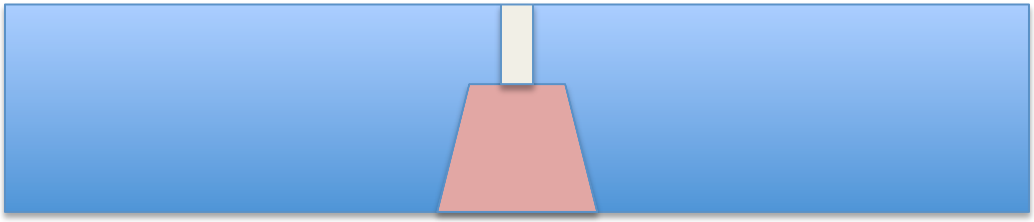
# Kinematic, Dynamic Velocity Boundary Condition



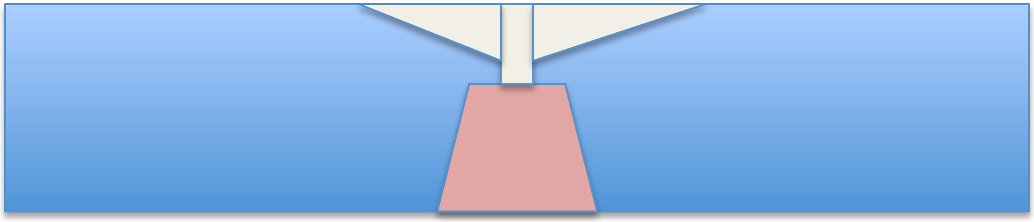
Bialas, Buck and Qin, 2010

Magma Injection Weakens Lithosphere

Weak Lithosphere Extends Tectonically



Sometimes a Pulse of Extrusion Makes a Volcanic Margin



From Roger Buck

# Intrusion of giant dikes explains:

1. Opening of rifts in normal continental areas

2. No opening of rifts where mantle lithosphere is thick:
    Cratons or old oceanic crust

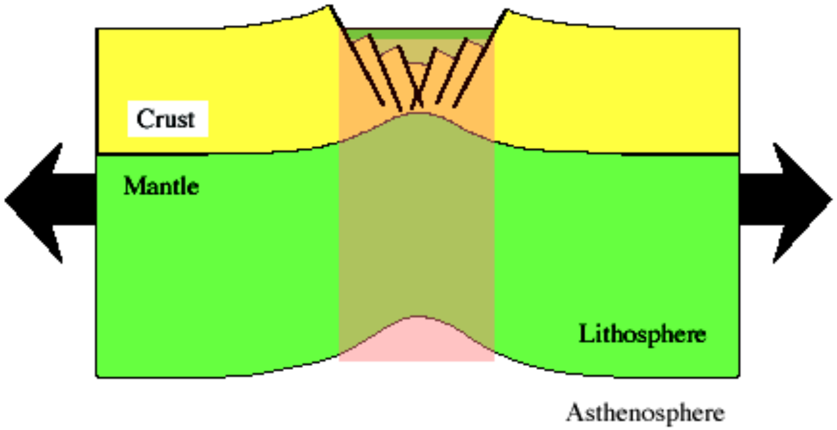
3. Only a few kilometers of magmatic rifting may
    weaken lithosphere enough for extension to
    continue at moderate stress levels

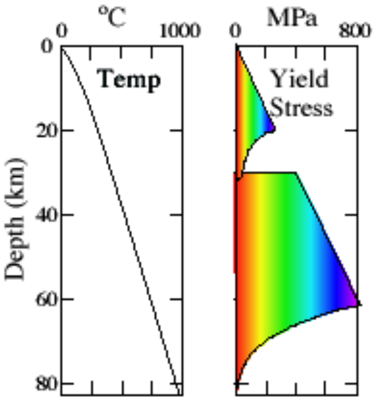
4. Magma does not have to reach the surface to
    weaken lithosphere. Need seismics to ‘see’ magma

From Roger Buck

Tectonic Stretching

# NEEDS A GRADUAL EVOLUTION OF THE RHEOLOGY





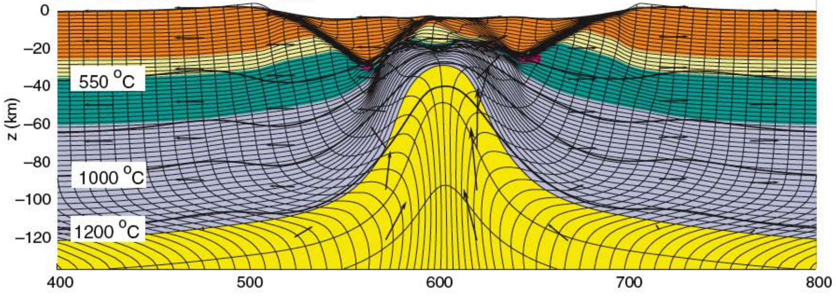
- Detachment faults are present.
- Weakening of the middle-lower crust by fluids.
- Late serpentinization of the mantle (fluids).

# Viscous strain softening

**Strong Crust, Sensitivity to Velocity**

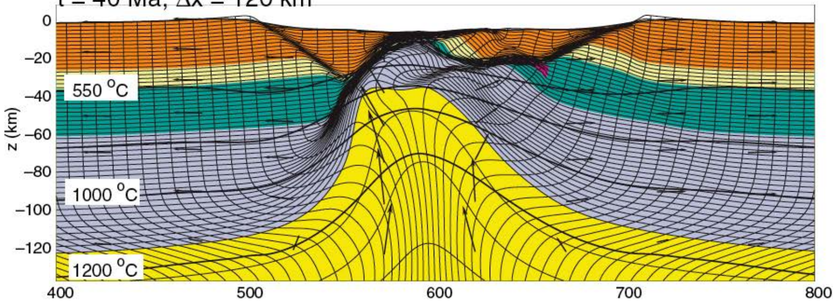
(**a**) High Velocity, $V = 10$ cm/a

t = 12 Ma, Δx = 120 km



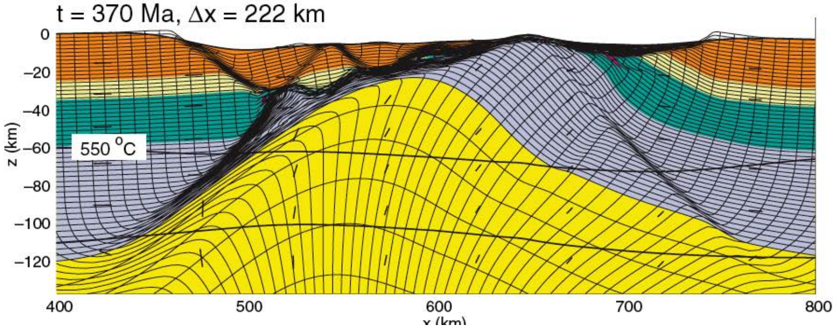
(**b**) Moderate Velocity, $V = 0.3$ cm/a

t = 40 Ma, Δx = 120 km



(**c**) Very Low Velocity, $V = 0.06$ cm/a

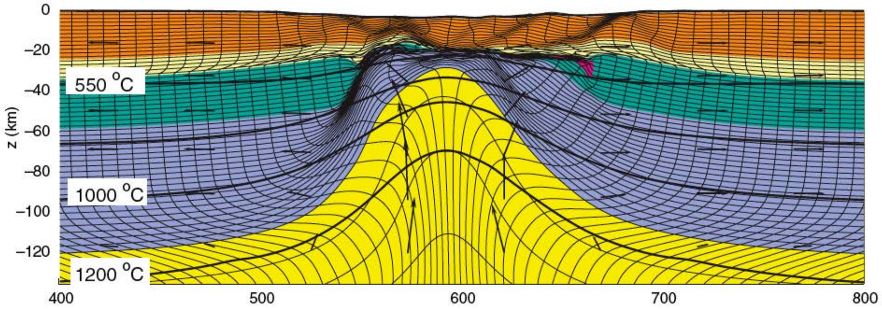
t = 370 Ma, Δx = 222 km



**Effect Strength Lower Crust**

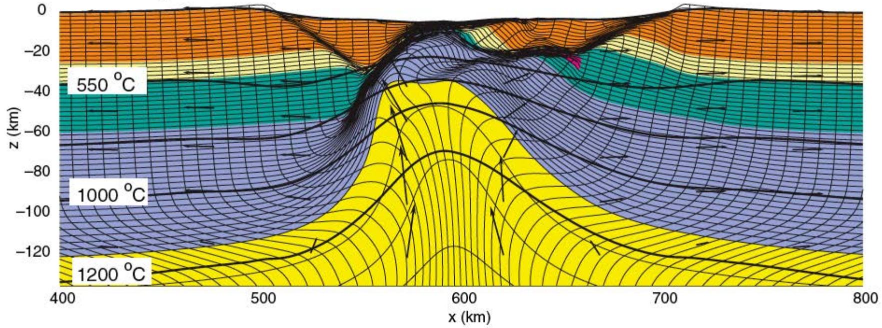
(**a**) Weak Lower Crust, $V = 0.3$ cm/a

t = 40 Ma, Δx = 120 km



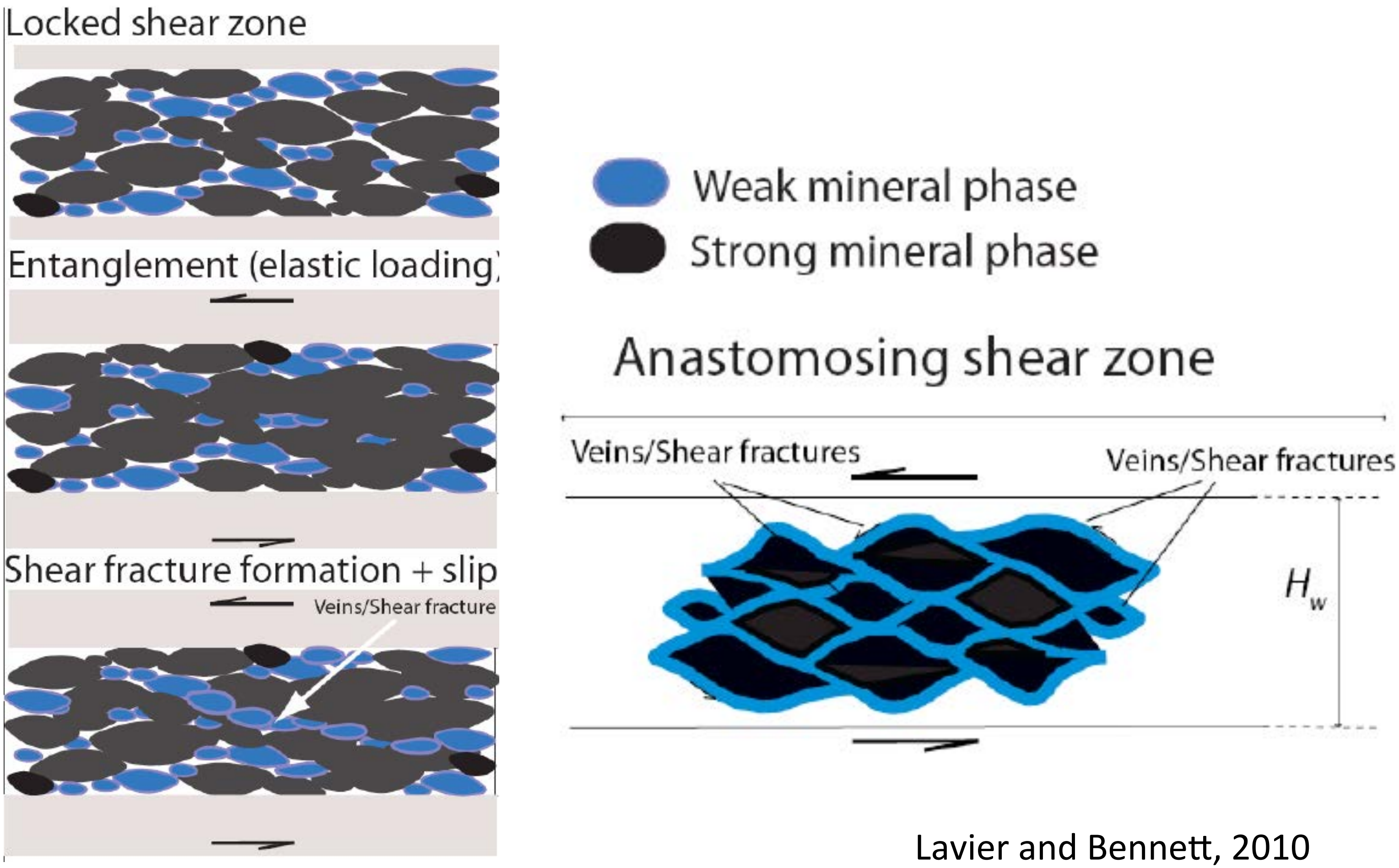
(**b**) Strong Lower Crust, $V = 0.3$ cm/a

t = 40 Ma, Δx = 120 km



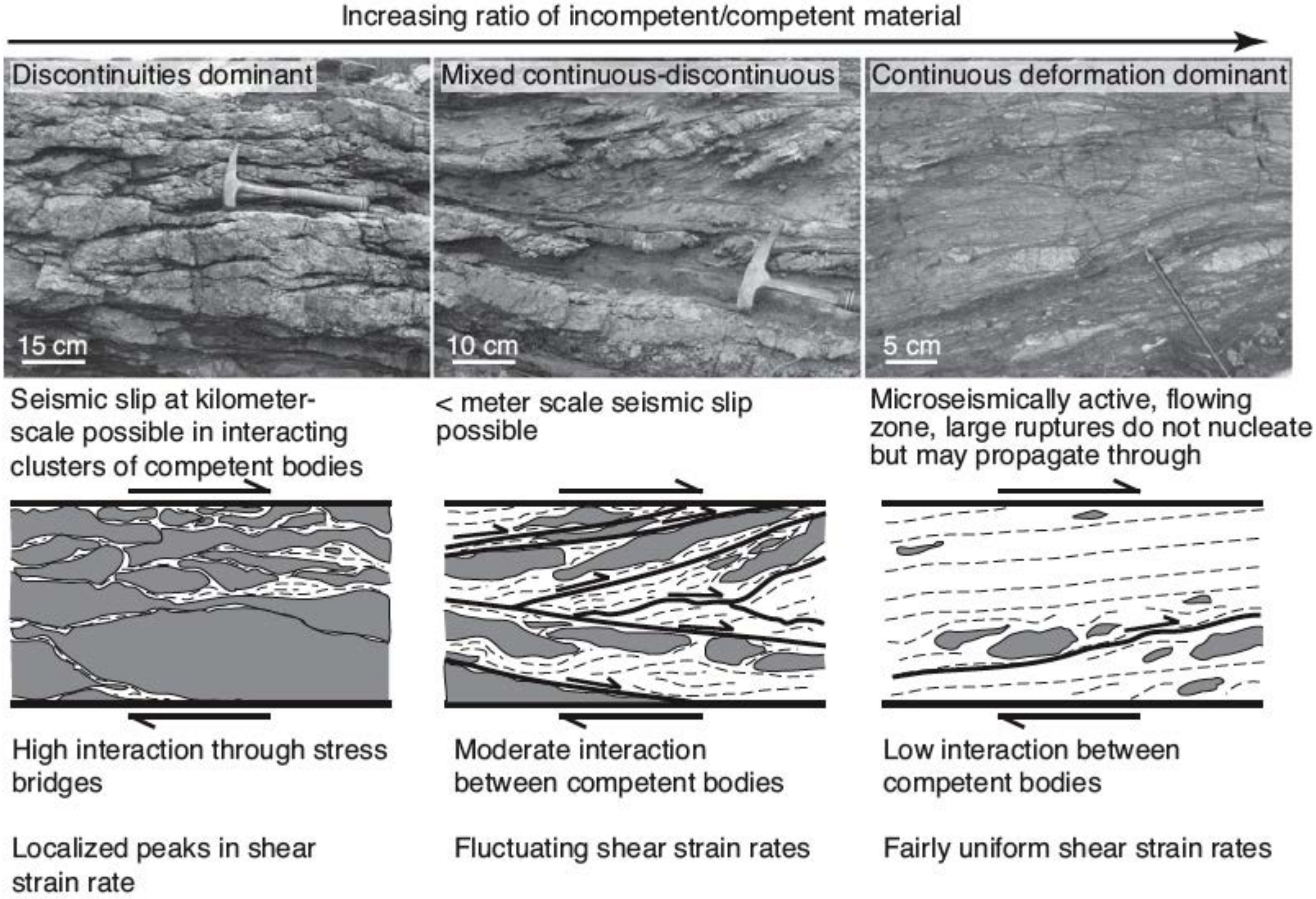
Huismans and Beaumont, 2007

# Physical Model: Both brittle and ductile deformation. Triggered by fluids/metamorphic reaction.



Lavier and Bennett, 2010

# Semibrittle media



Seismic slip at kilometer-scale possible in interacting clusters of competent bodies

< meter scale seismic slip possible

Microseismically active, flowing zone, large ruptures do not nucleate but may propagate through

High interaction through stress bridges

Moderate interaction between competent bodies

Low interaction between competent bodies

Localized peaks in shear strain rate

Fluctuating shear strain rates

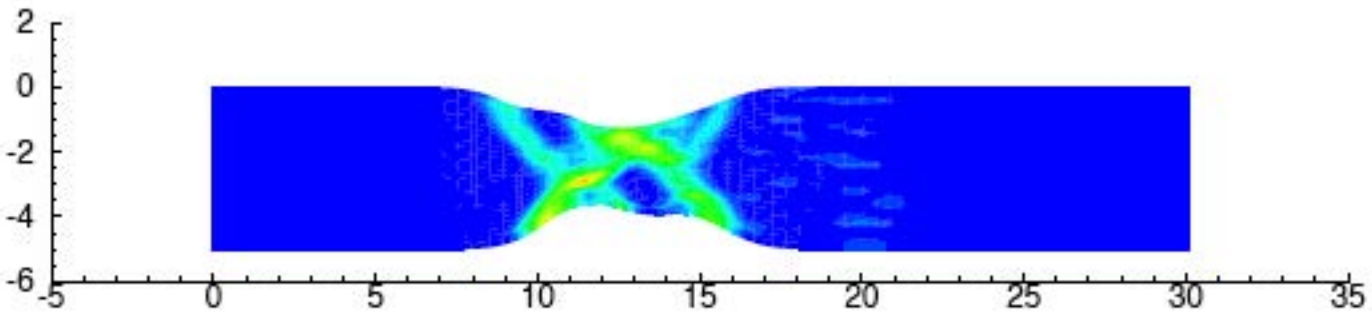
Fairly uniform shear strain rates

**Chrystalls Beach Complex, California.**

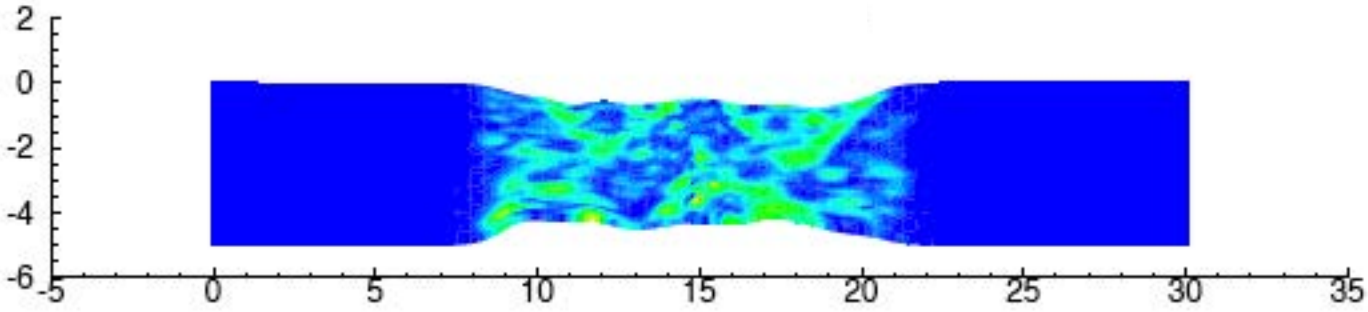
Fagereng and Sibson, 2010

# Partitioning between pure and simple shear.

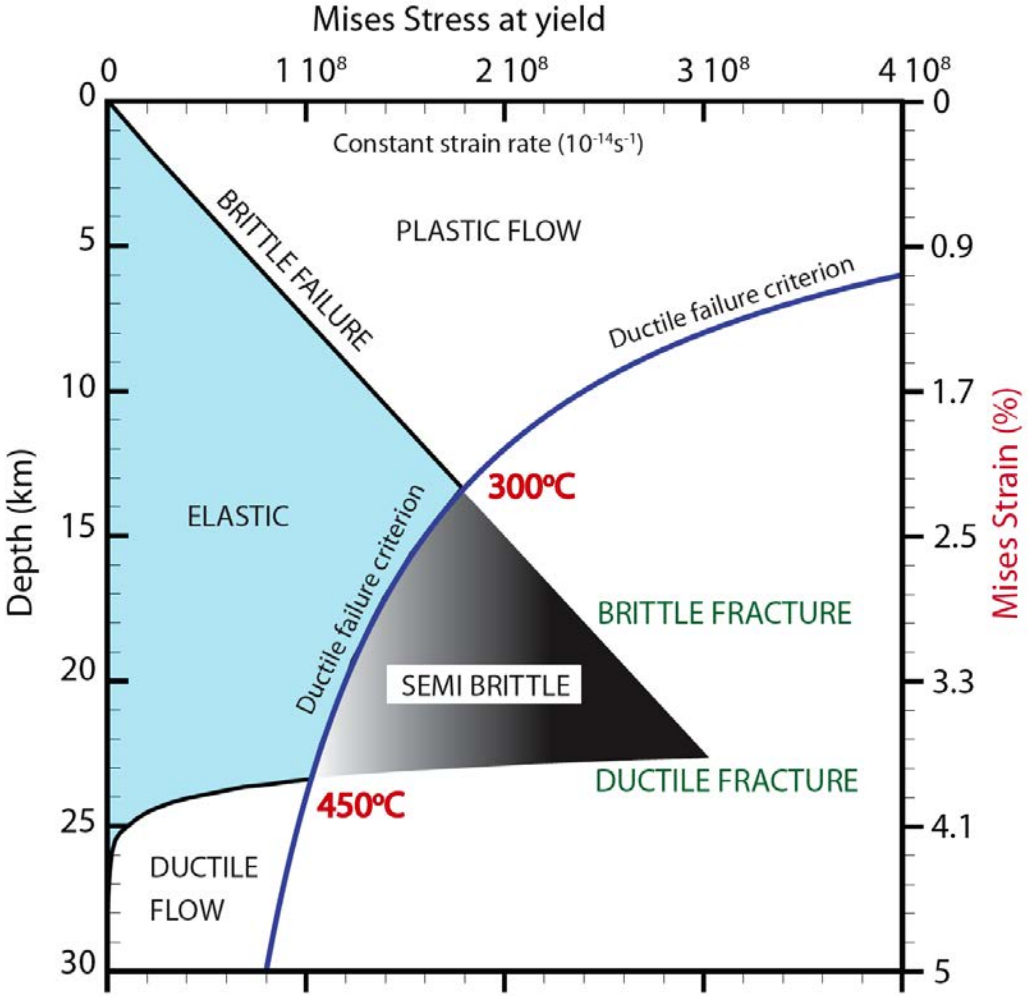
66% of brittle material



33 % of brittle material (Macroductile)



# Failure envelope in the models: Middle crust is weakened.



**Competent**: Anorthosite
**Incompetent**: Quartz.

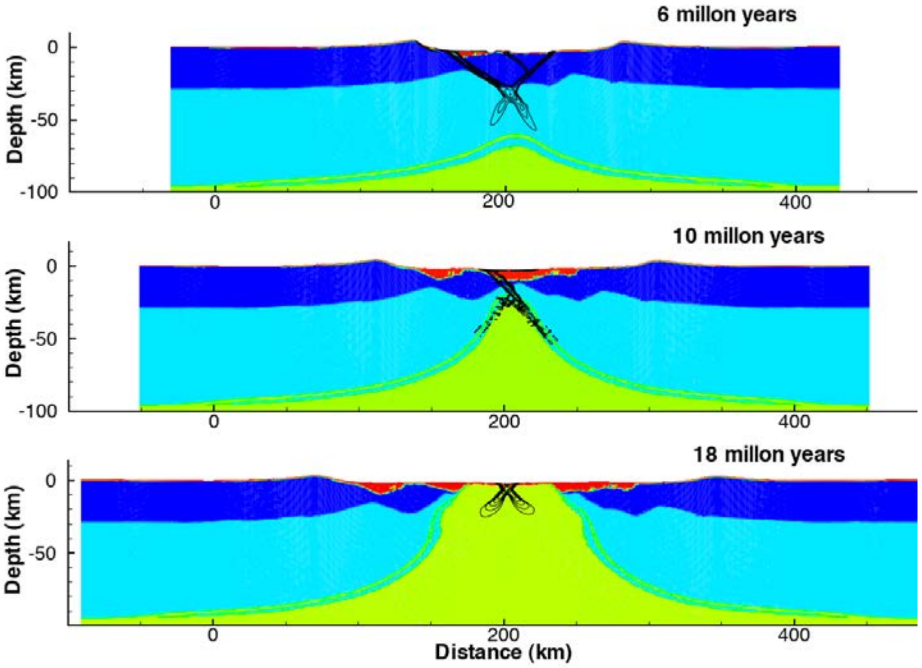
**Competent**: Olivine
**Incompetent**: Serpentine.

We can use similar mechanism for the mantle to decrease the strength in the mantle with serpentinization.

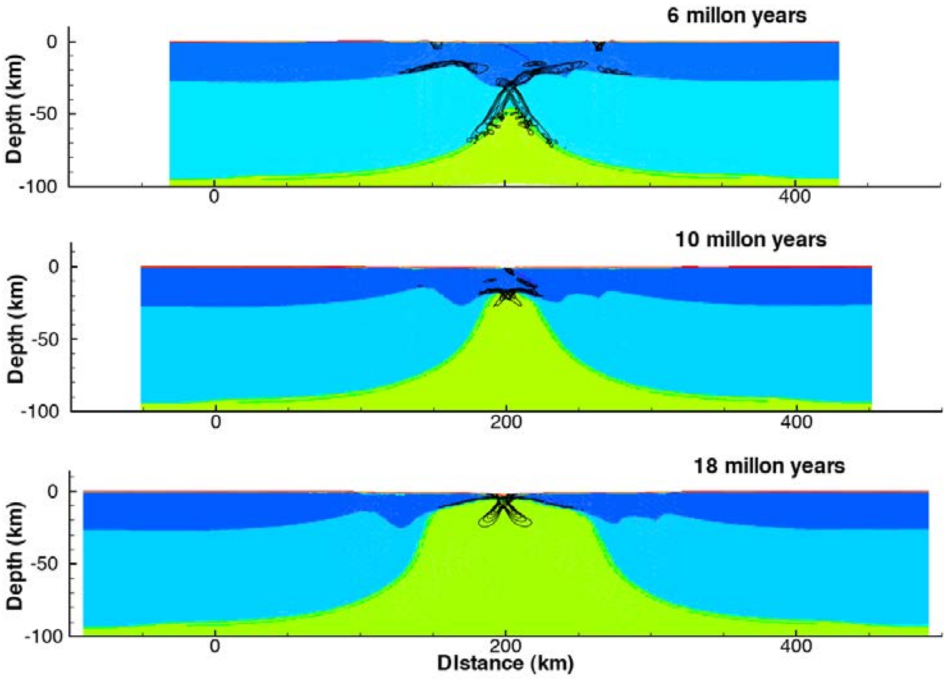
Jammes, Lavier. Manatschal, 2010

# Wet vs. dry and not so wet rifts: Relation to subsidence.

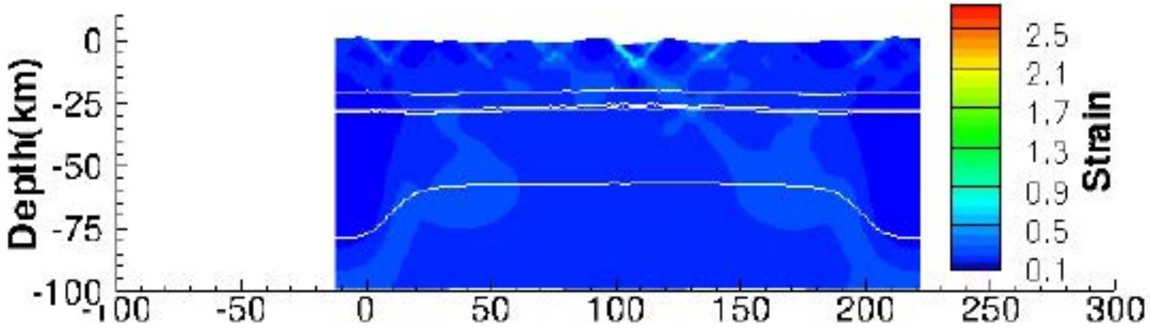
DRY RIFT/ NORMAL FAULTS
Very strong subsidence
Rift flanks
Normal fault (60-30°)



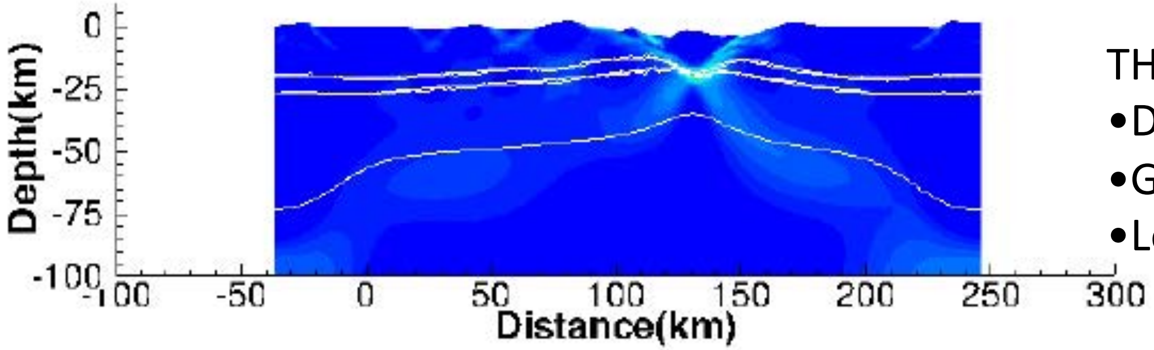
WET RIFT/ NO NORMAL FAULTS
Little subsidence
Weak ductile shear zones
Flow of the lower crust



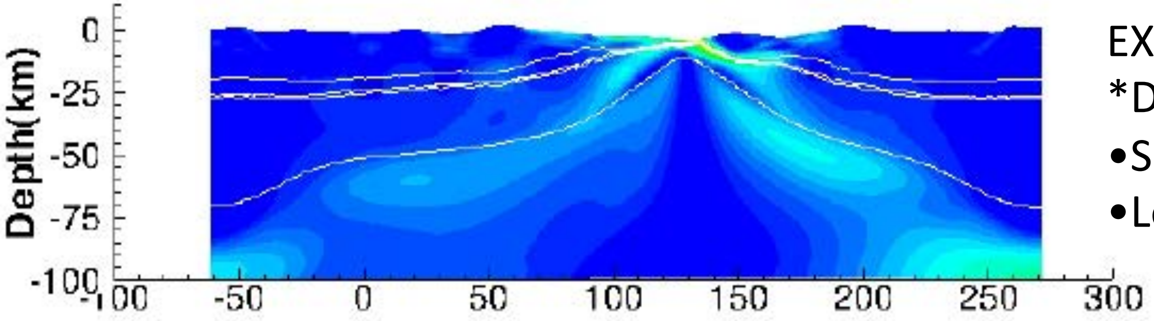
# Rheological evolution (progressive weakening of the lithosphere)



STRETCHING
- Normal fault/Mohr-Coulomb
- Diffuse stretching



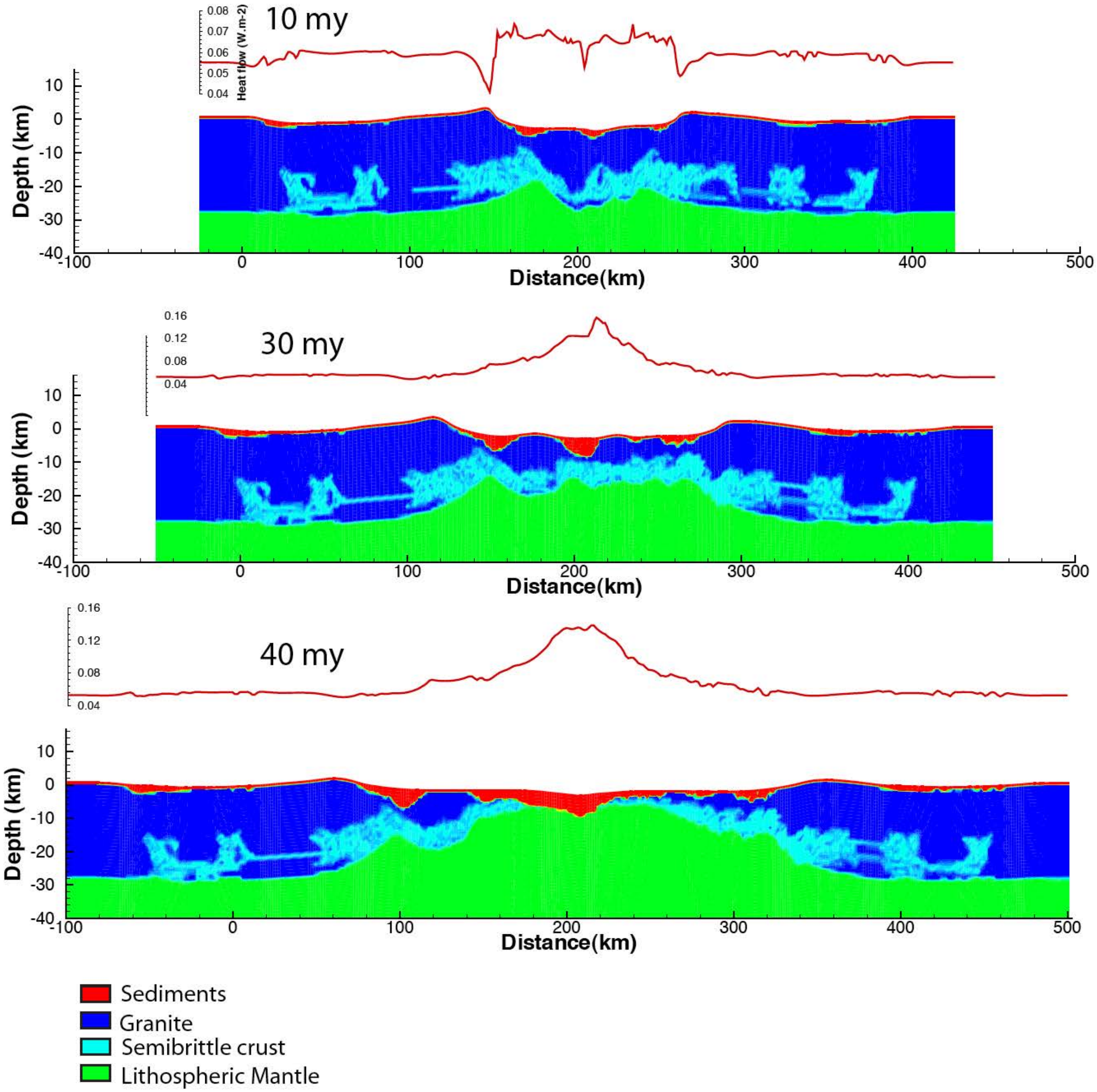
THINNING
- Detachment faults/Semi brittle.
- Granite weakened by fluids.
- Localized thinning.



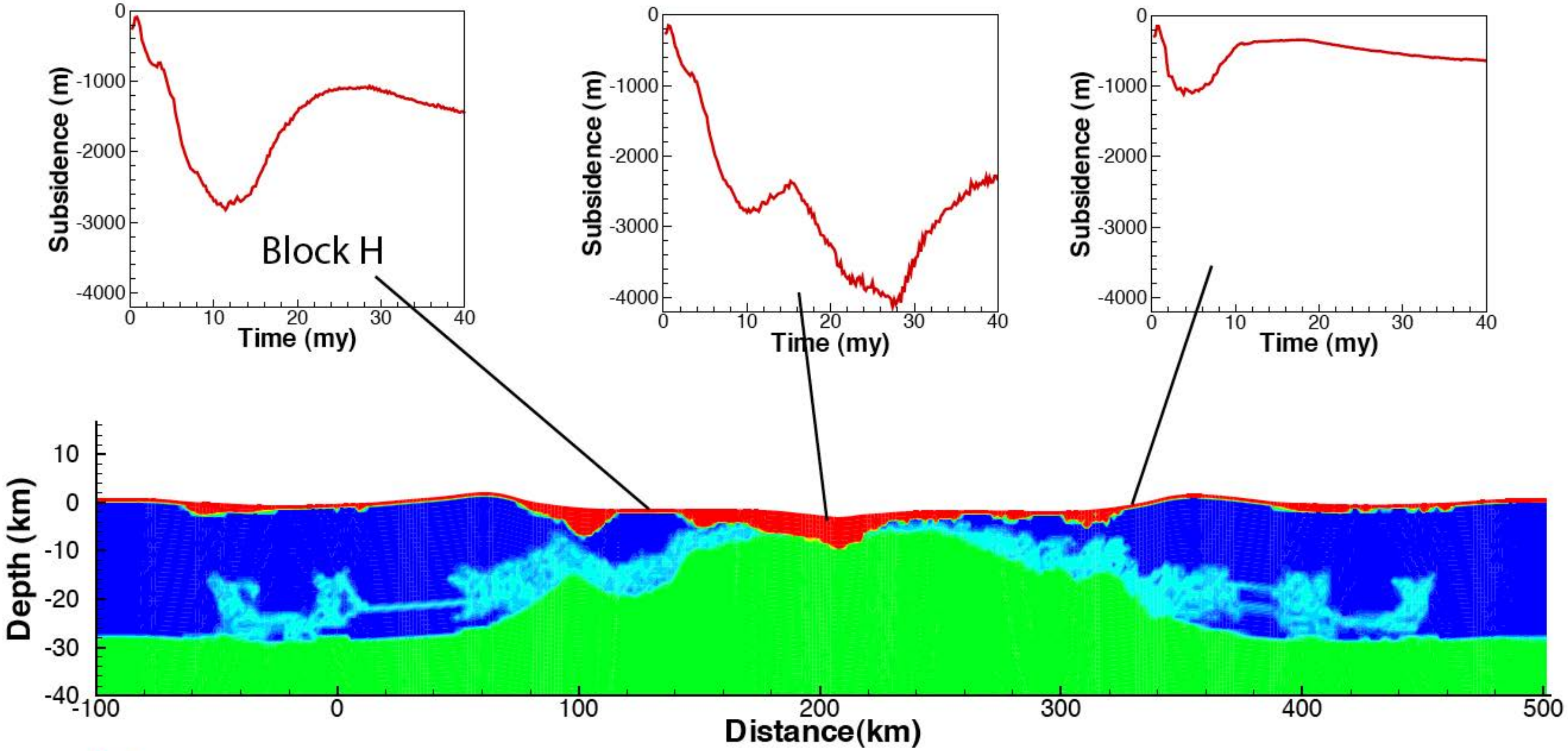
EXHUMATION

*Detachment faults/semi brittle.
- Serpentinized mantle.
- Localized exhumation.

# Typical structural and heat flow evolution



# Typical structural and subsidence evolution

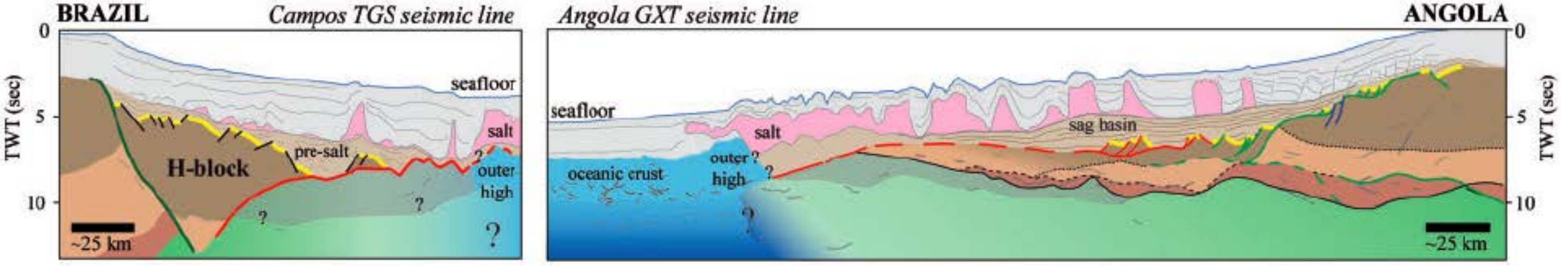


🟥 Sediments

🟦 Granite

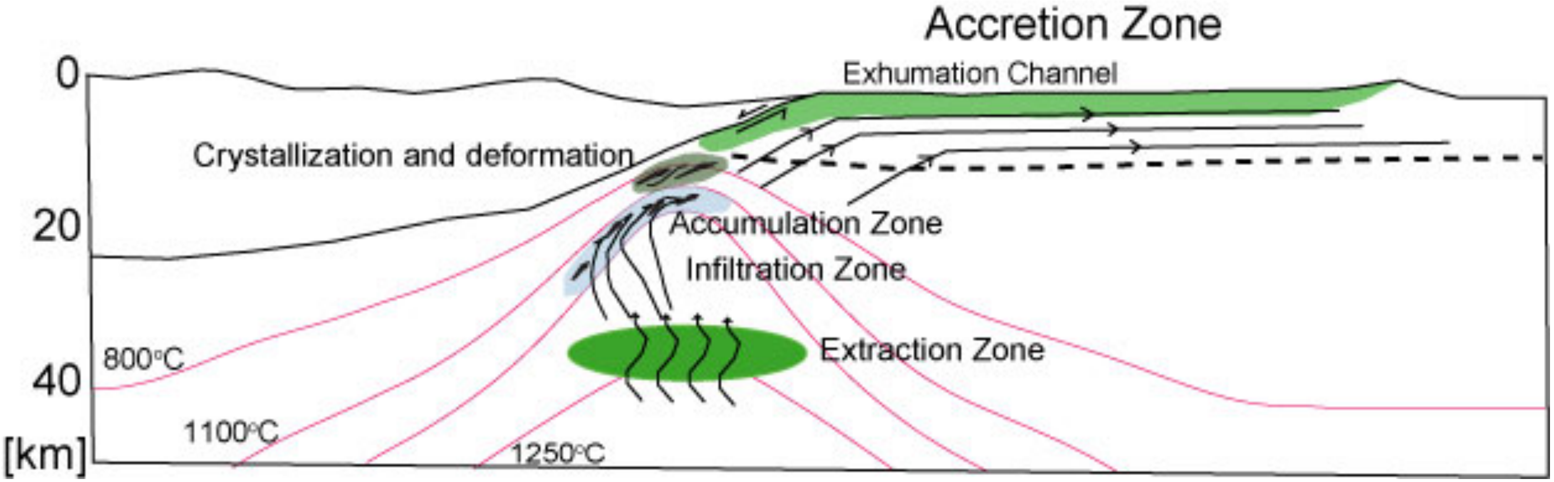
▨ Semibrittle crust

🟩 Lithospheric Mantle

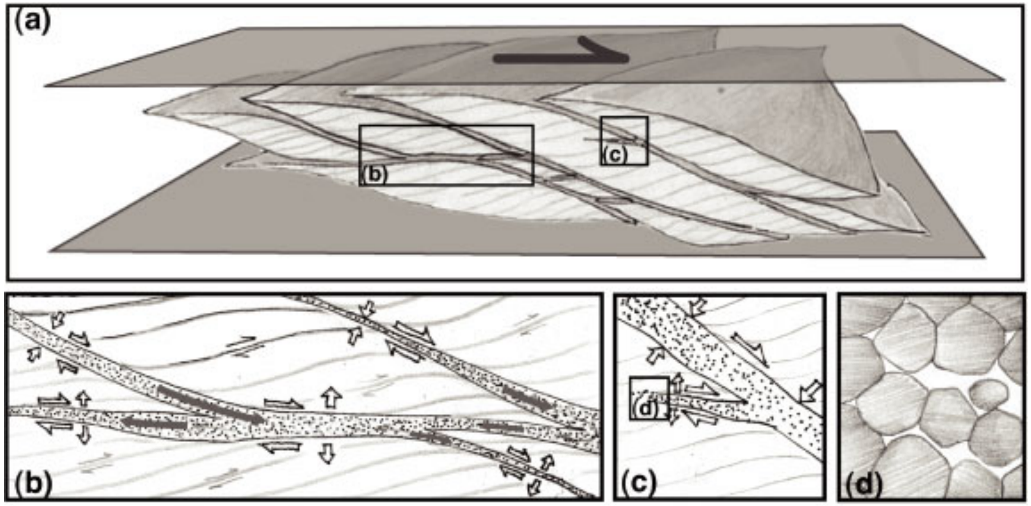


Untherner at al., 2010.

# *Melt focusing mechanisms on top of shear zone.*



Melt-rich shearing (Holtzman et al. 2003, Katz et al. 2006)



Holtzman and Kohlstedt 2007

Lanzo (ask Mary, or see Kaczmarek and Müntener J. Petrol 2008, in press)

Shearing with time:

Melt enhanced shearing and focussing: strain localization in presence of melt
High permeability
- ’melt conductor’

After cooling and crystallization: mylonite and ultramylonite: extreme localization, Low permeability

# The common processes between each questions (fluid-rock interactions).

- The evolution of crustal and mantle rheology during rifting.
- The weakening effect of fluids in the crust and during mantle exhumation.
- The weakening/strengthening effect of melt and diking in both non-volcanic and volcanic environments.
- The evolution of topography (free surface), sedimentation, erosion and geological structures.