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Triplet de changements de phases

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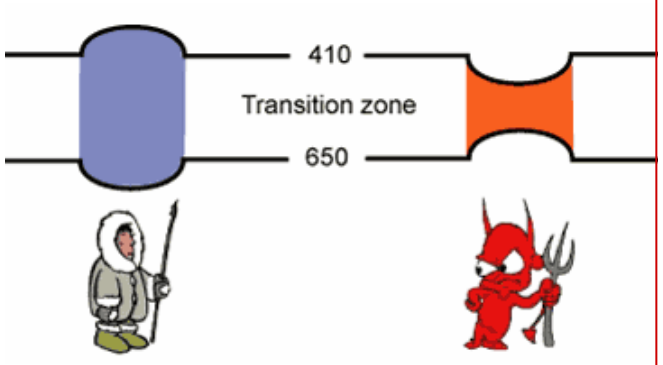
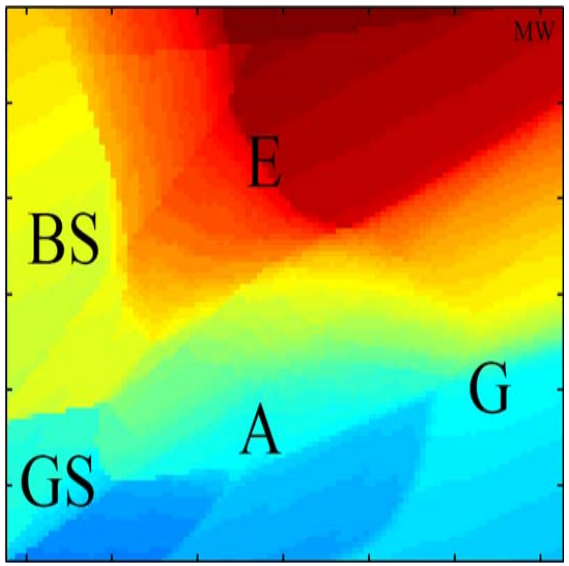
Triplet de changements de phases

zone de transition du manteau



modélisation géodynamique



prismation des orgues de lave

Triplet de changements de phases

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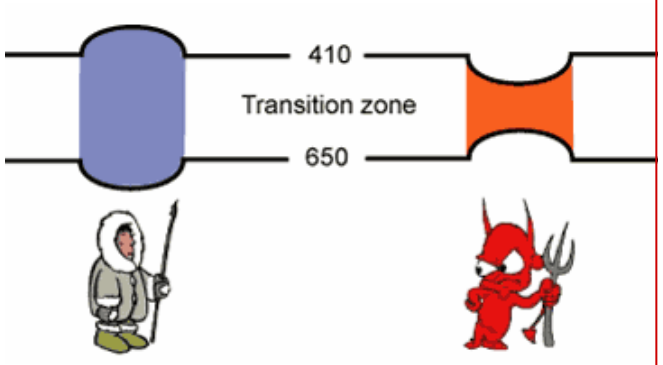

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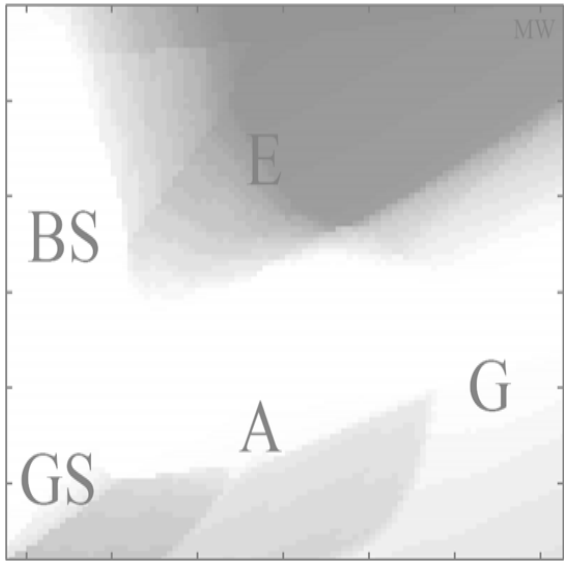
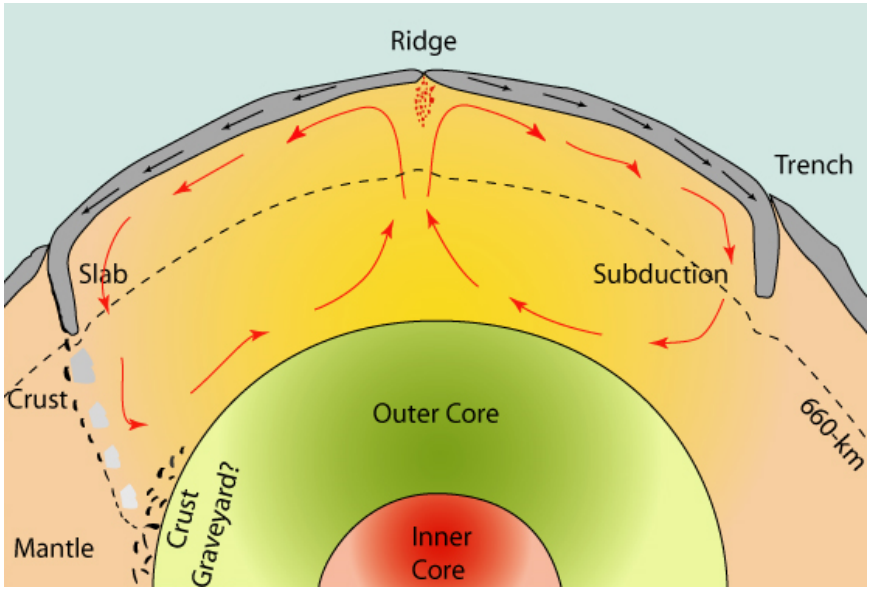
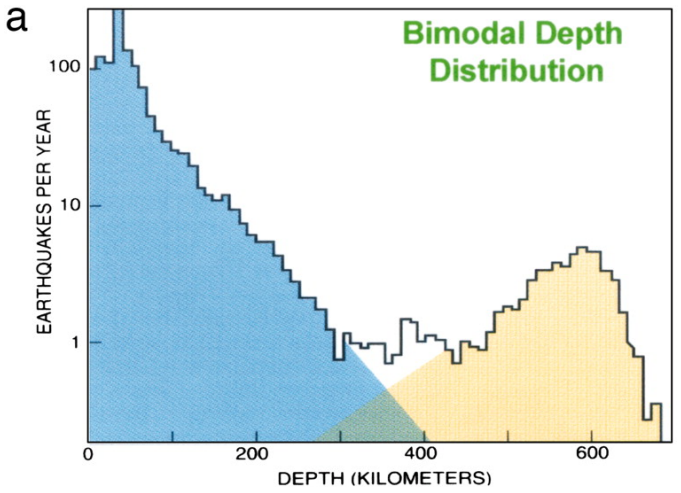


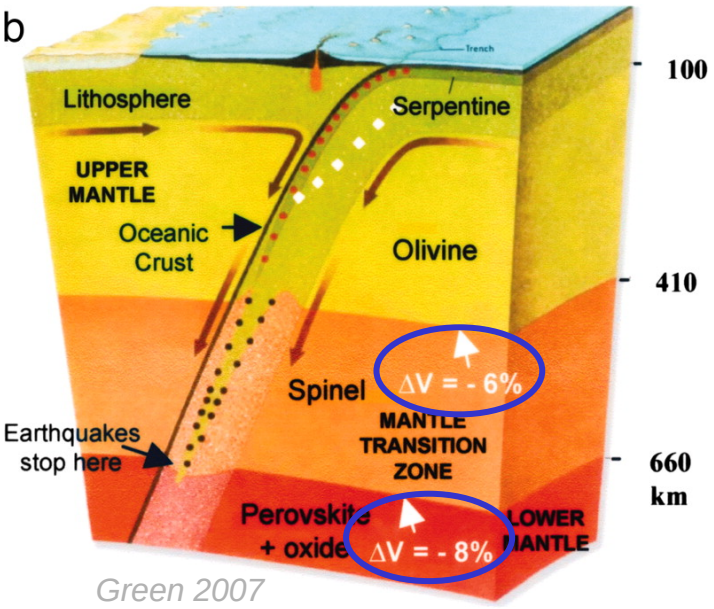
prismation des orgues de lave

Mantle structure and transition zone



S. Rost



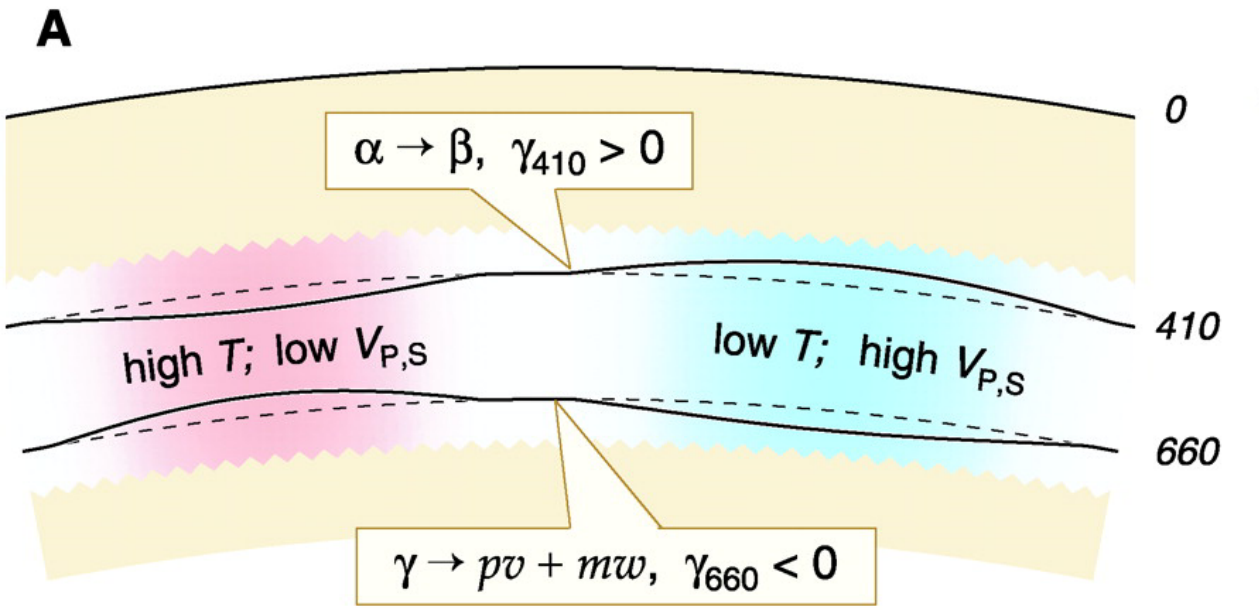


Green 2007

iasp91	Δv_P	Δv_S
410 km:	+3.65%	+4.11%
660 km:	+5.78%	+6.25%

Kennett & Engdahl 1991

Transition zone in an olivine-dominant mantle



Lebedev et al. 2002

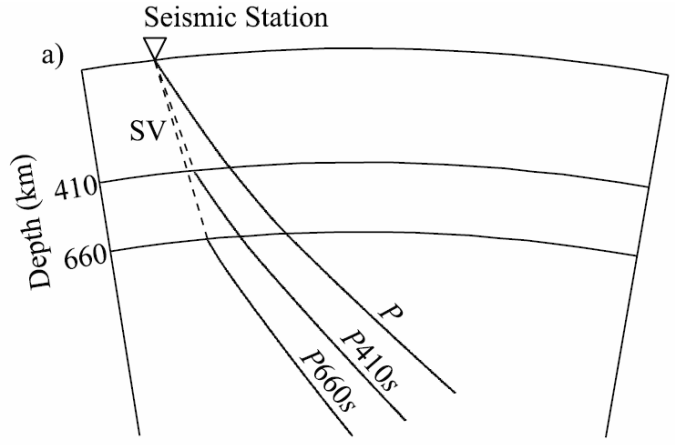
410 km: olivine (α) → wadsleyite (β)

520 km: wadsleyite (β) → ringwoodite (γ)

660 km: ringwoodite (γ) → perovskite + magnesiowüstite

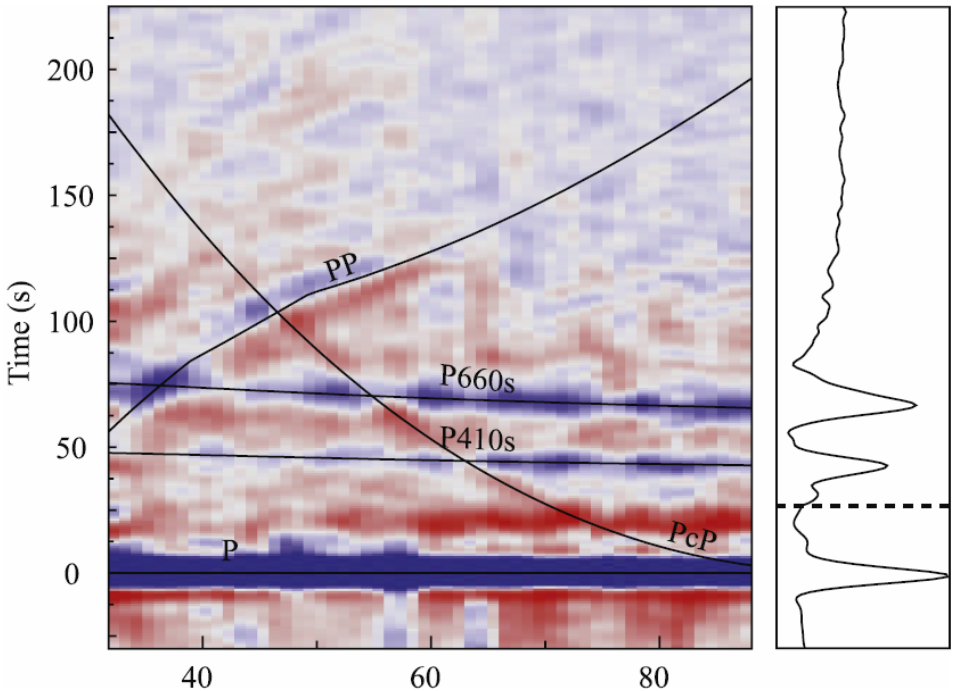
Temperature effect: opposite Clapeyron-slope ($\partial P/\partial T$) signs and deflections

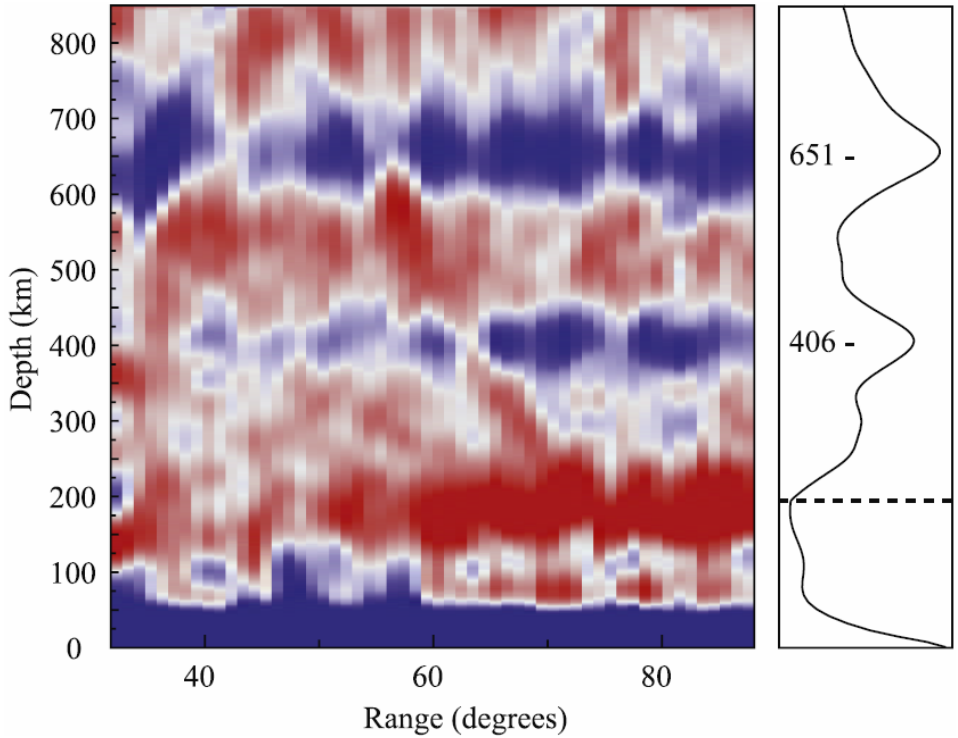
Observations by seismology



Receiver functions

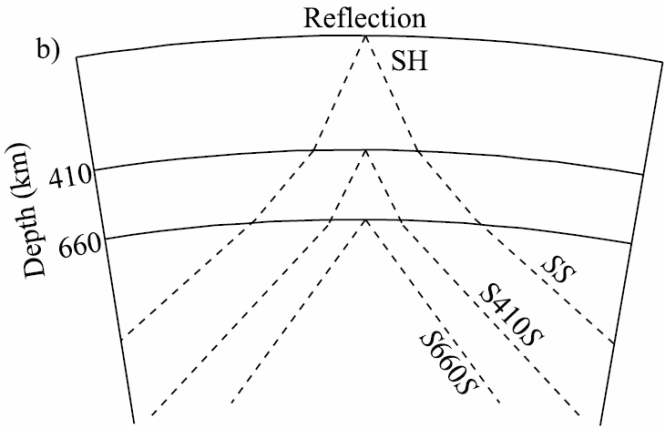
- P-to-S wave conversion
- delay proportional to depth
  (and velocity anomalies)





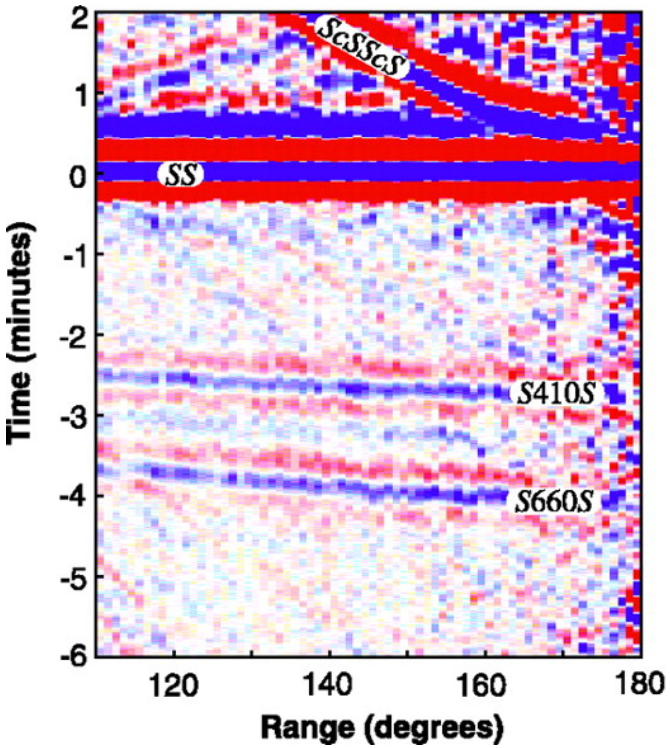
Lawrence & Shearer 2006

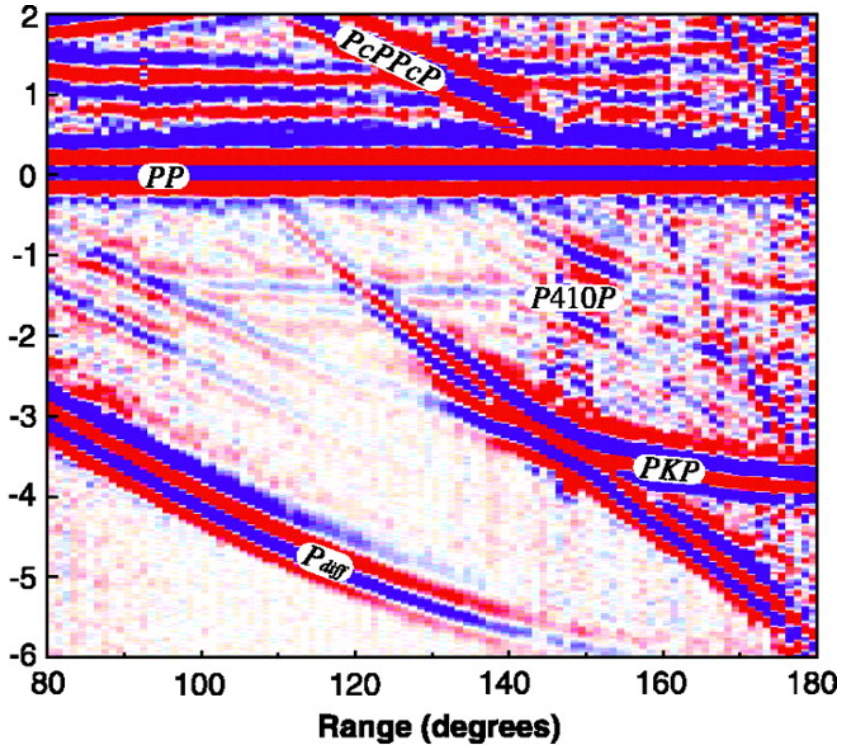
Observations by seismology



Underside reflections / pre-cursors

- with S- or P-waves
- long-wavelength variations

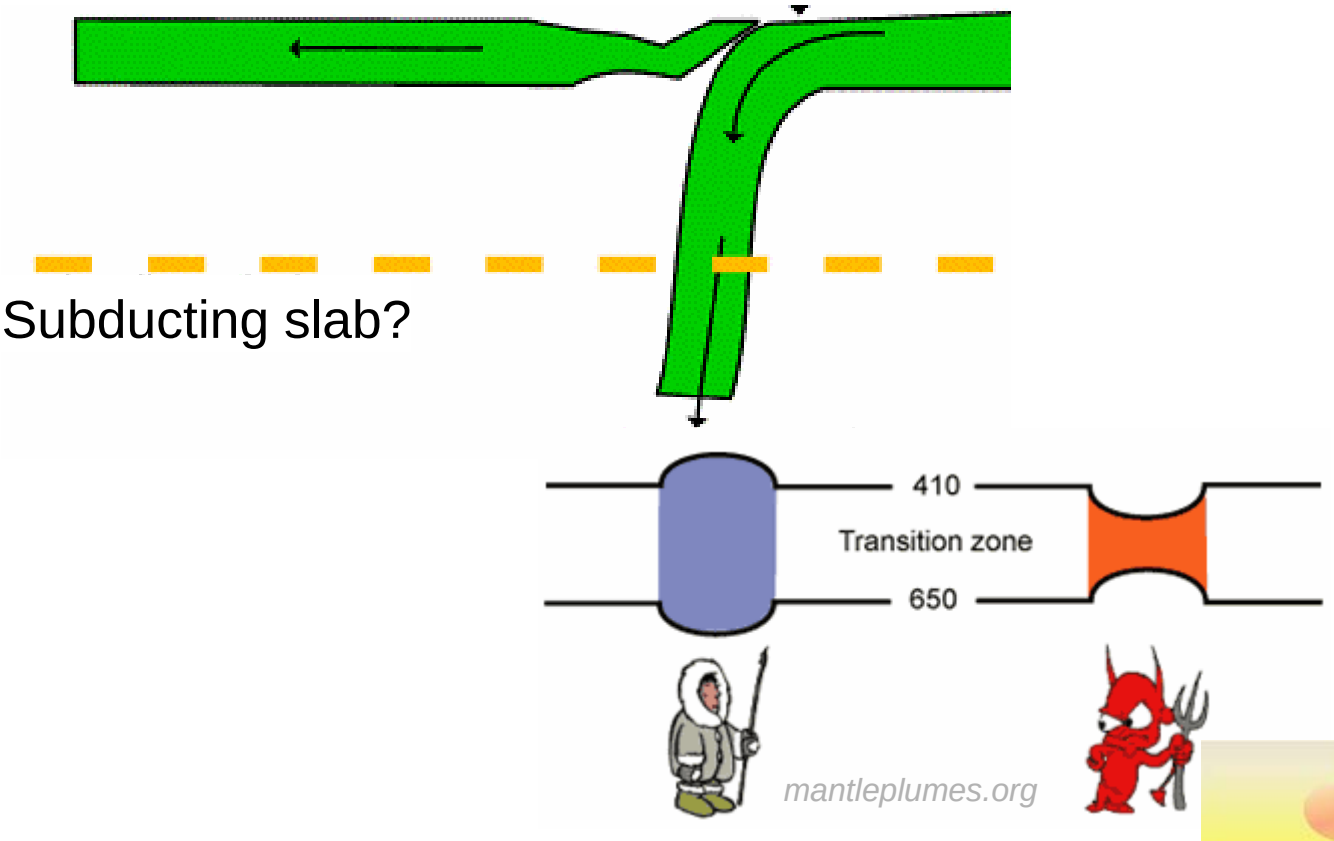




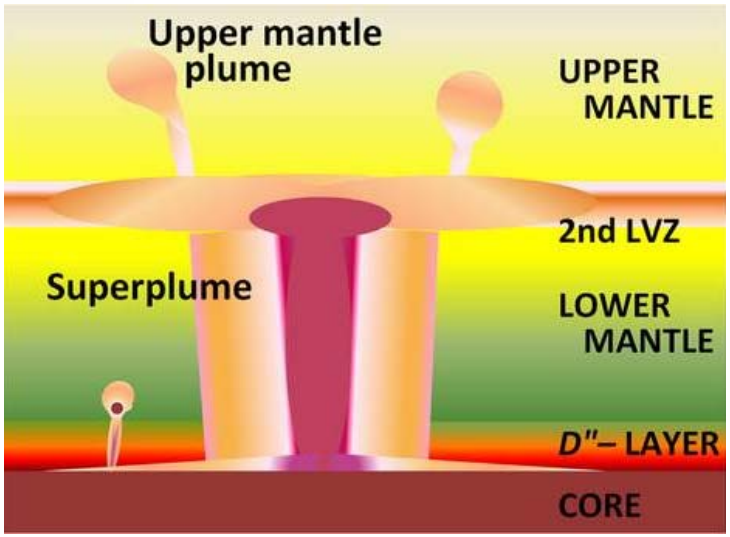
Shearer & Lawrence 1999

Geodynamic interpretation

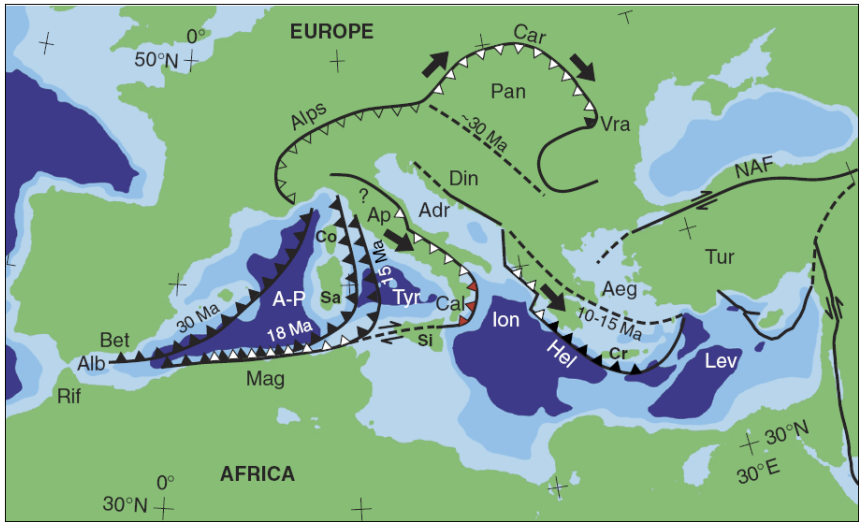
Subducting slab?

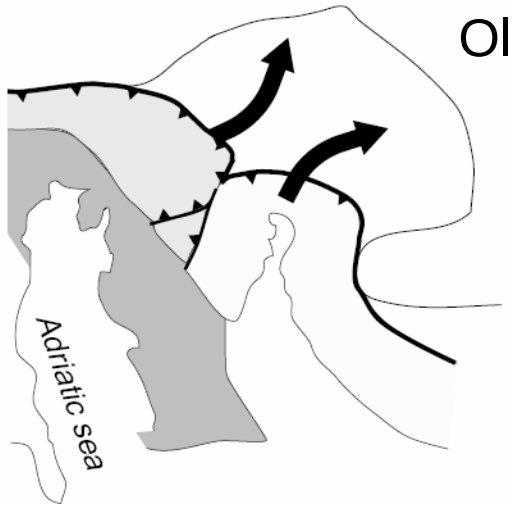


Plume?



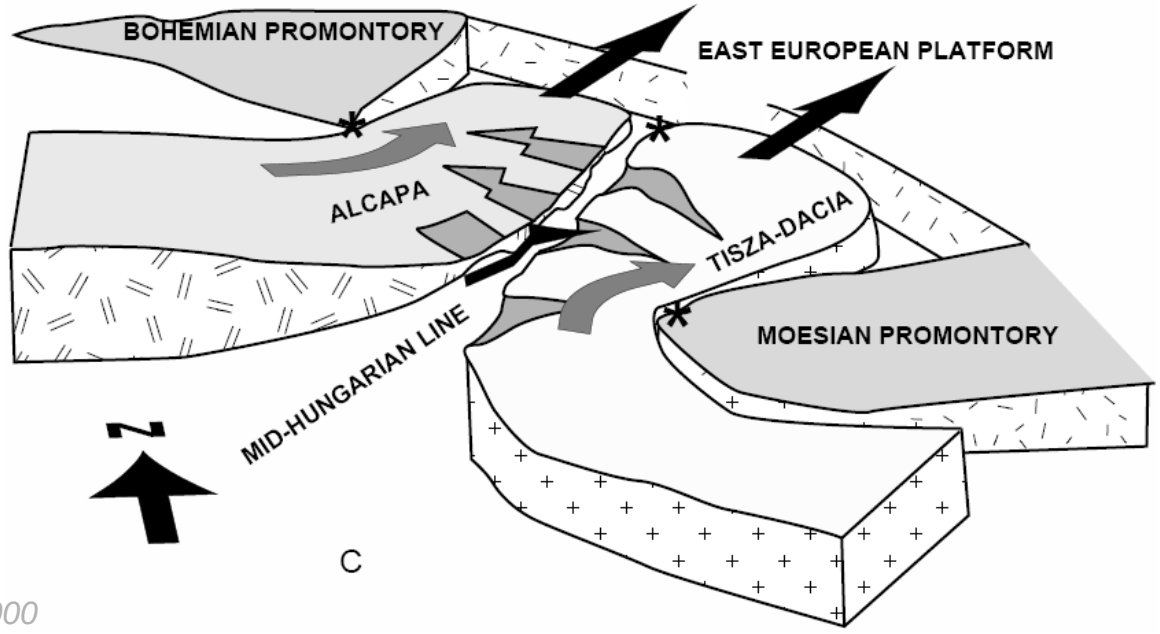
Pannonian Basin





Today:

- thin crust (25km) and lithosphere (55km)
- high heat flow (90mW/m^2)
- minor surface deformation (GPS ~mm/yr)
- minor seismic activity (M4-5-…)

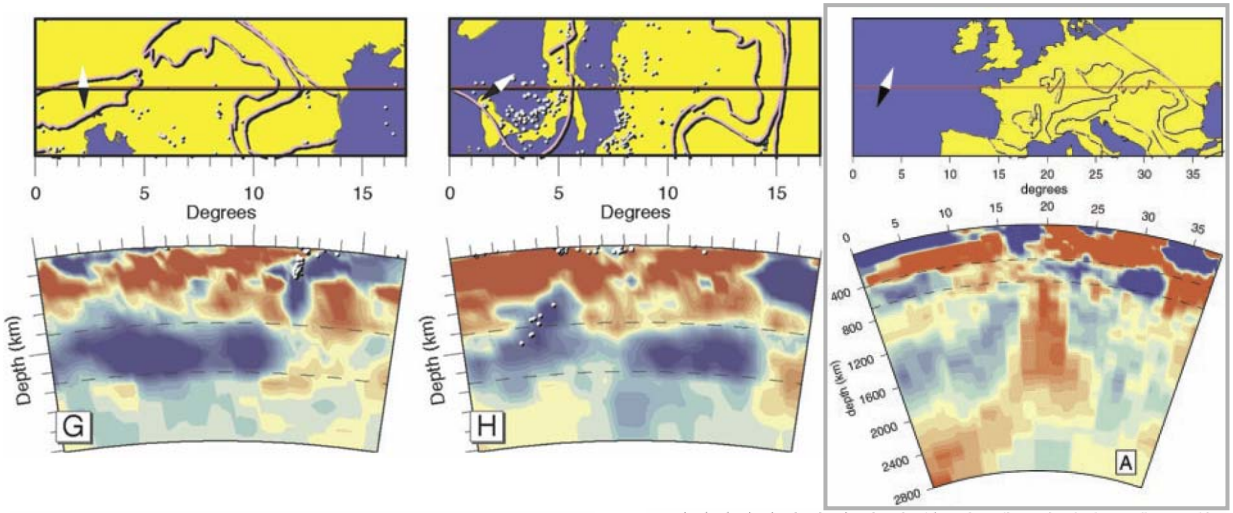


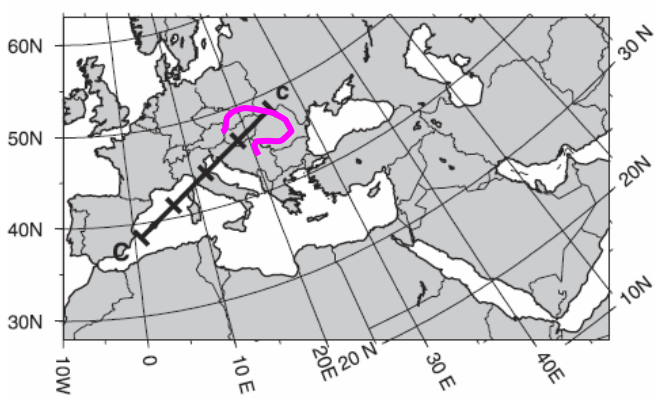
Csontos & Nagymarosy 1998; Wortel & Spakman 2000

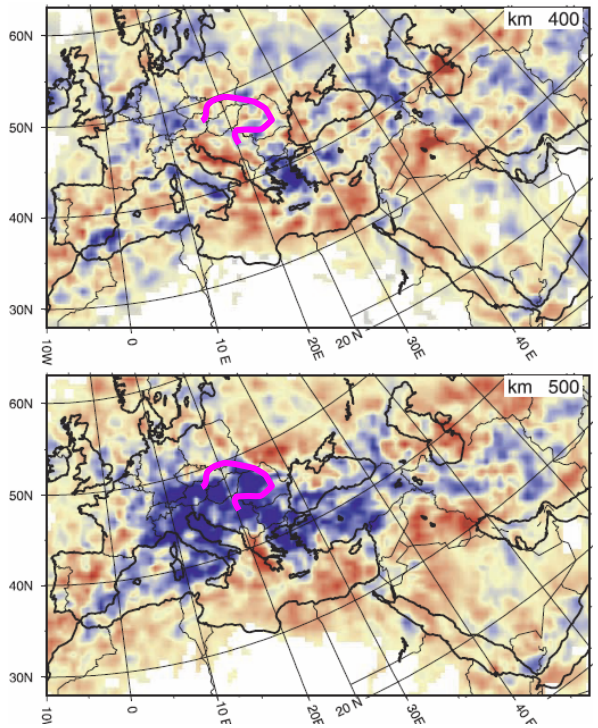
Pannonian Basin

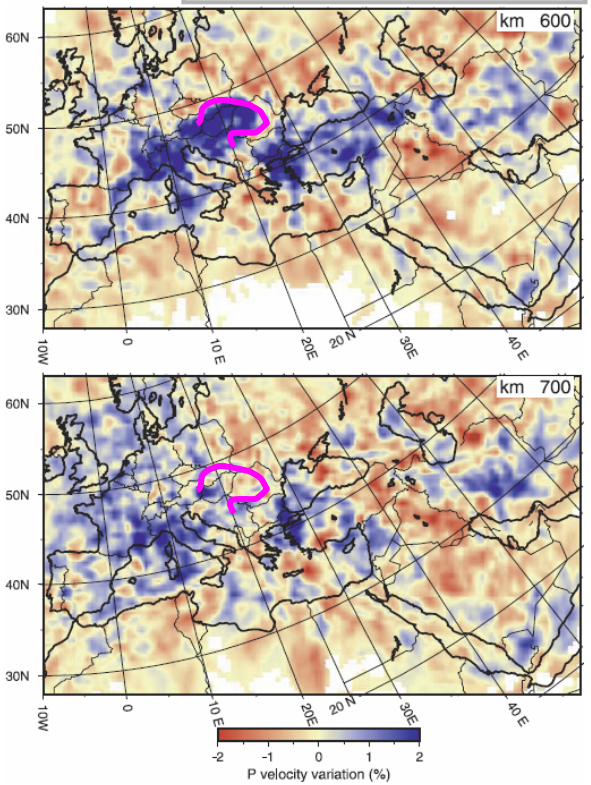
…today:

- fast anomaly in mantle transition zone
- European ‘superplume’



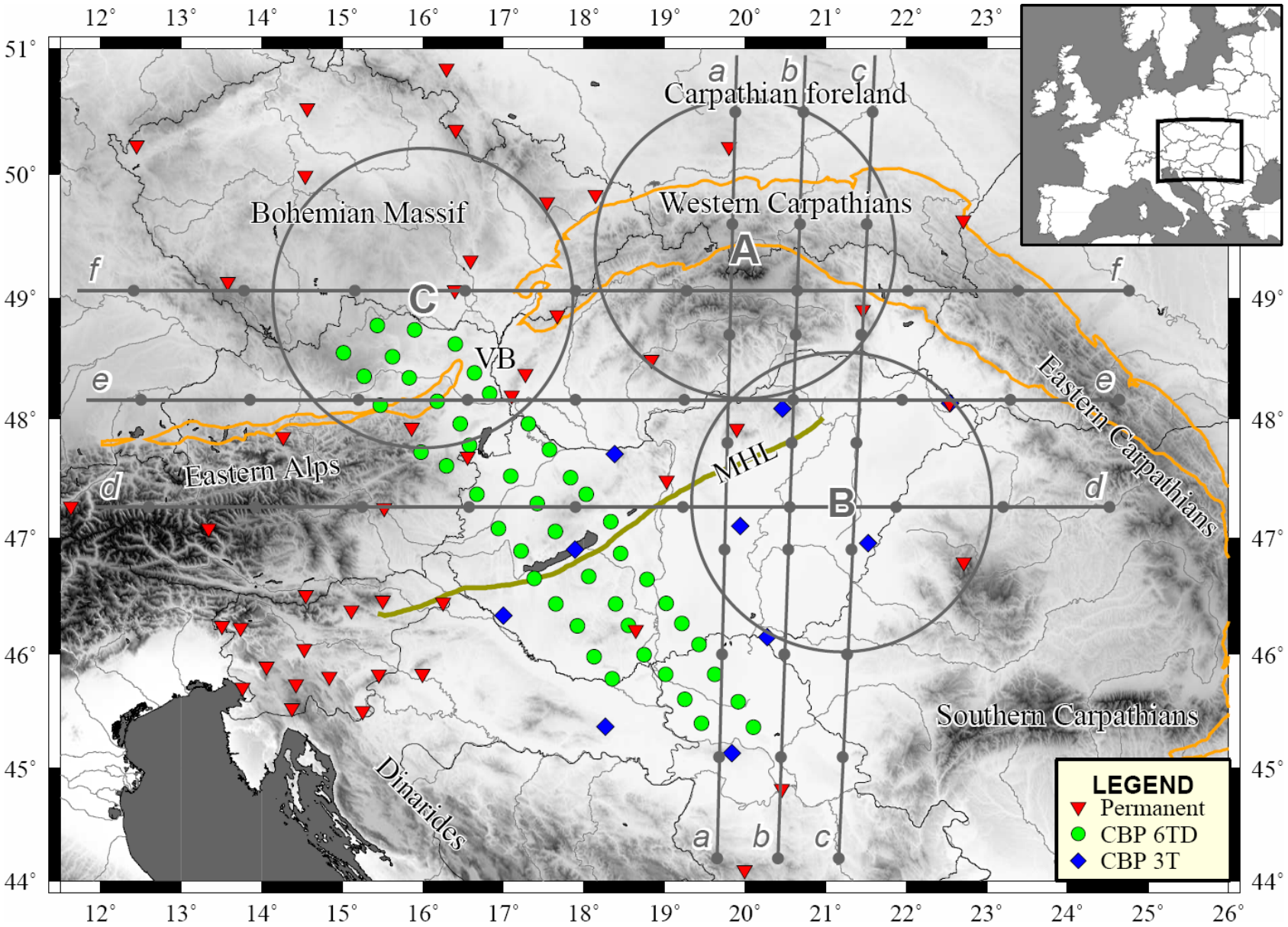






Goes et al. 1999; Wortel & Spakman 2000; Piromallo & Morelli 2003

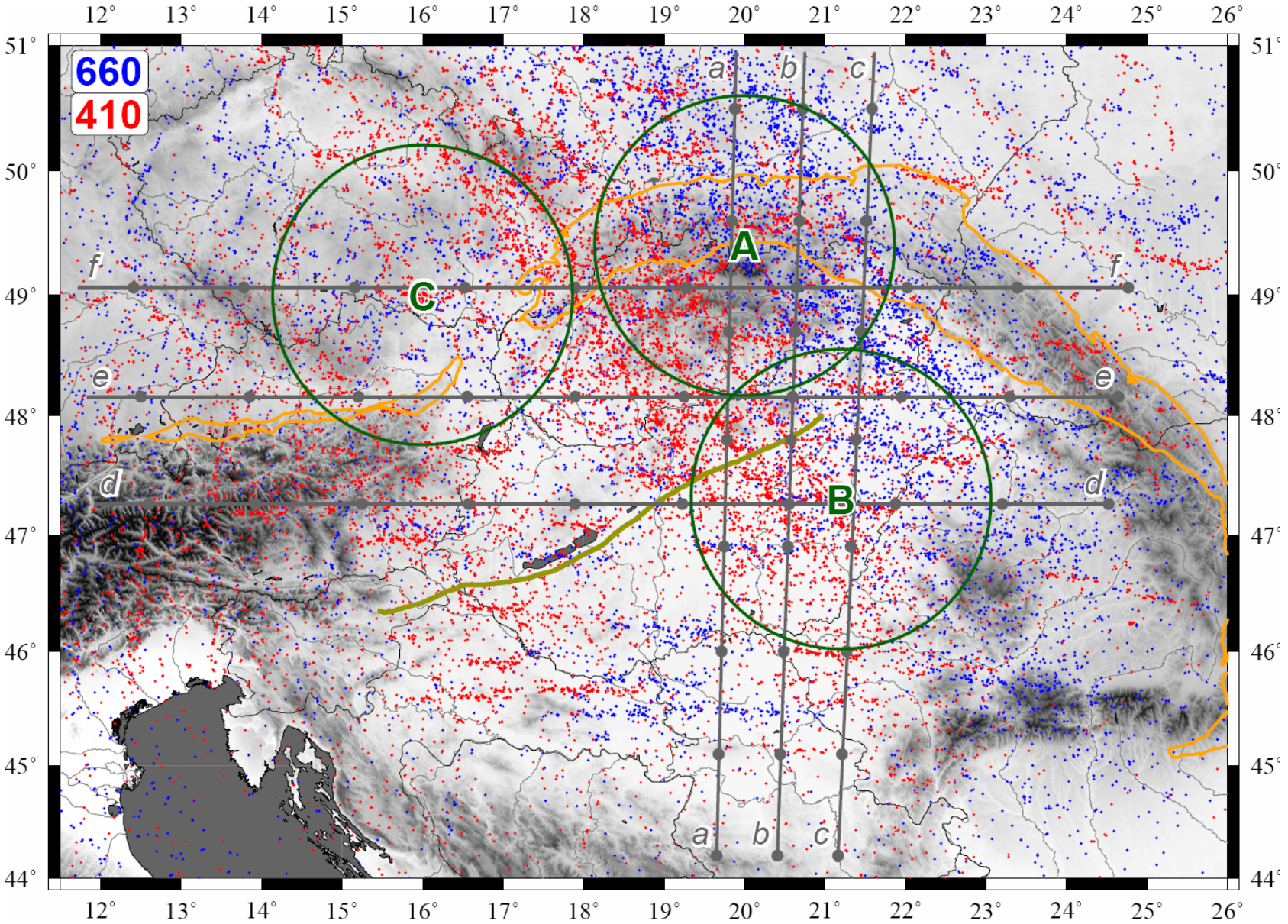
Pannonian Basin



Collaboration: Greg Houseman, Graham Stuart (Univ. Leeds) & CBP

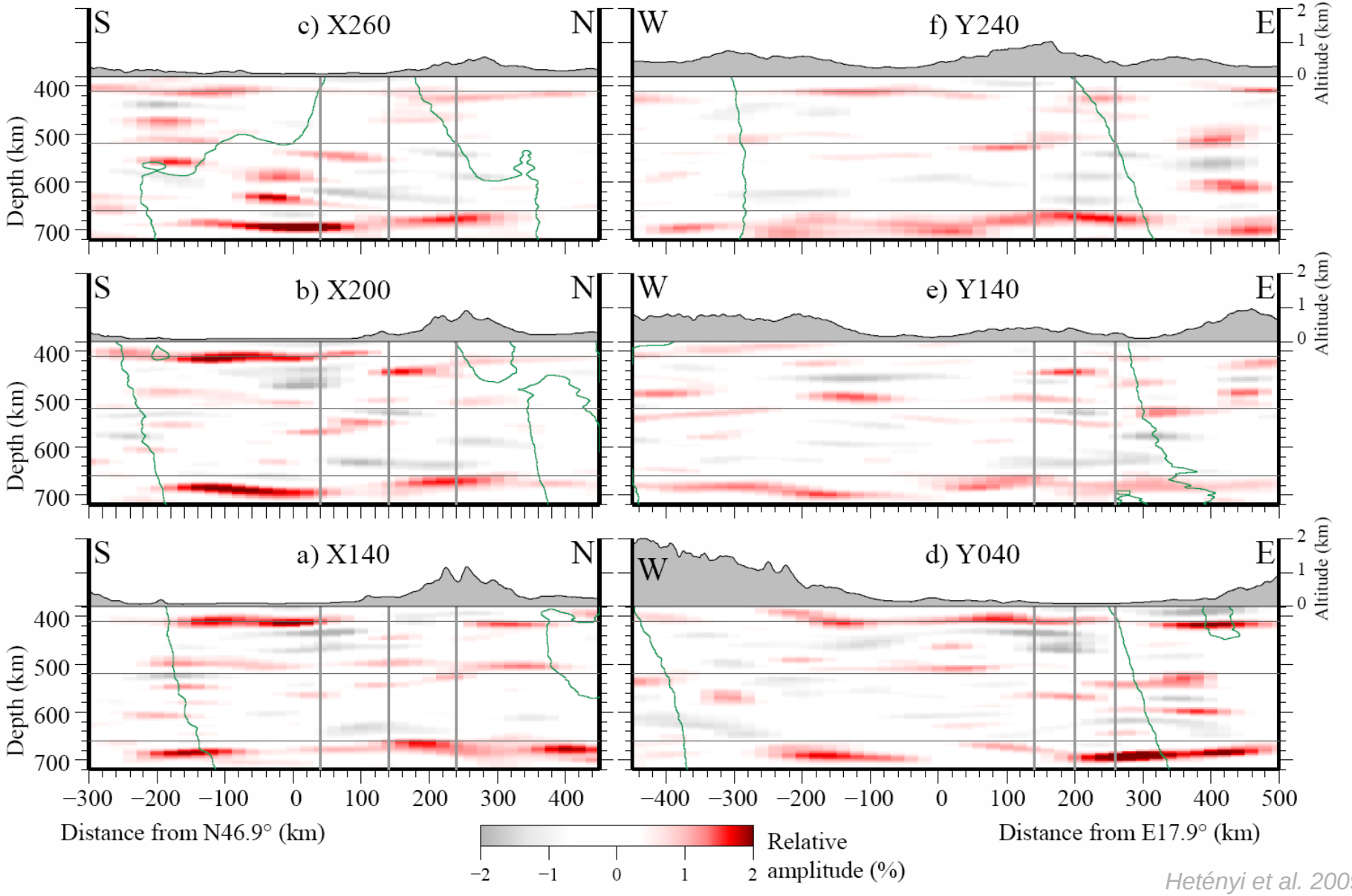
Hetényi et al. 2009

Pannonian Basin



Hetényi et al. 2009

Pannonian Basin

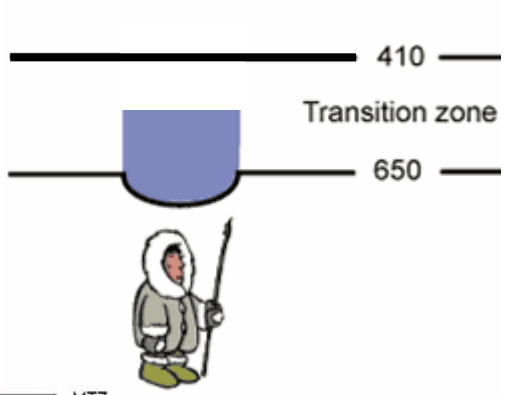


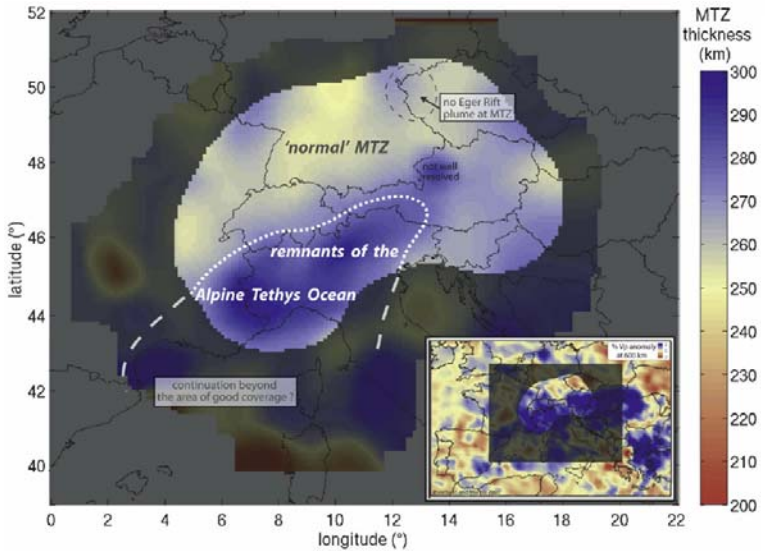
Hetényi et al. 2009

RF, 30-4 sec, CCP migration with regional tomographic model, 20% of max. resolution

Pannonian Basin

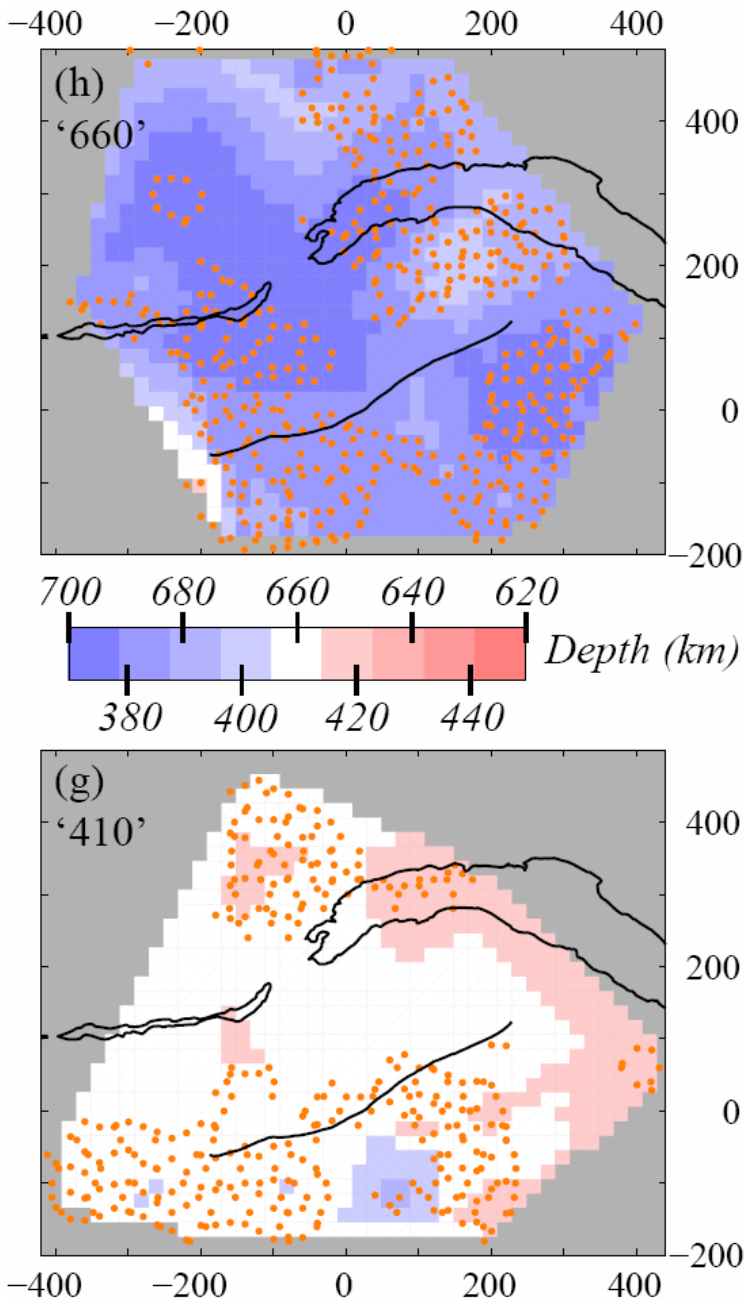
- ‘410’ horizontal, normal depth
- ‘520’ no clear signal
- ‘660’ deepened, significant depth-variation





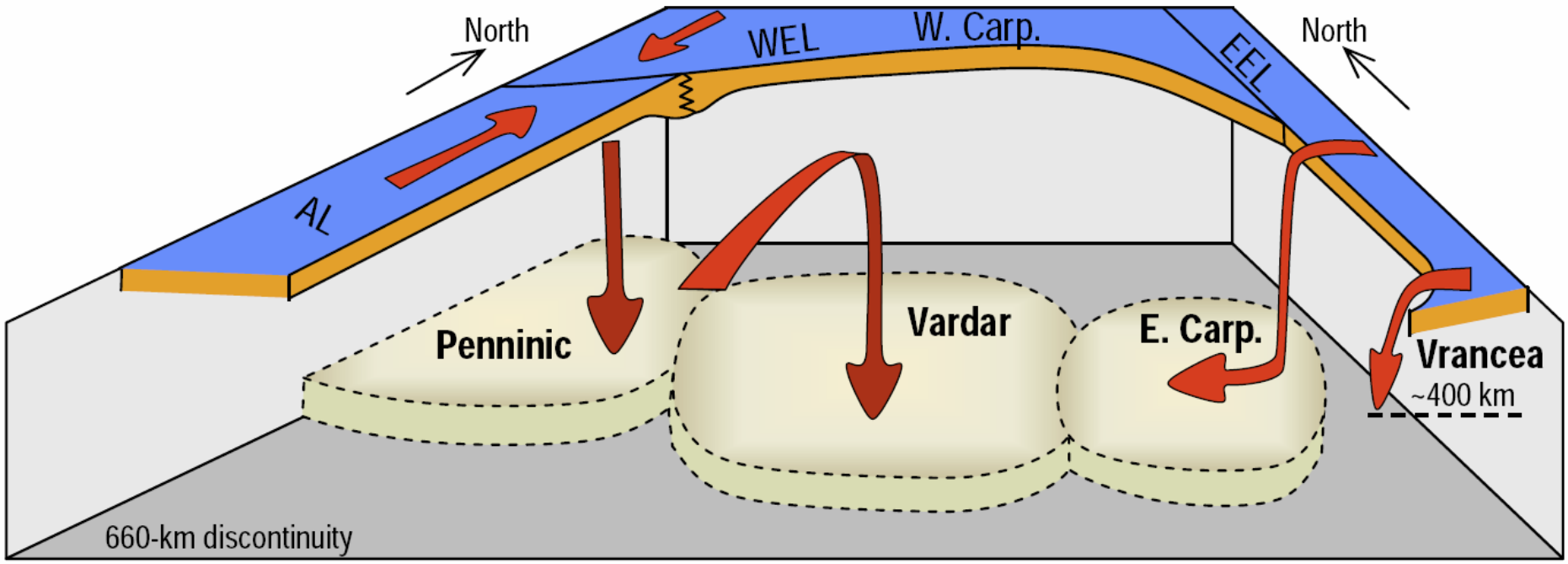
Lombardi et al. 2009

Hetényi et al. 2009



Pannonian Basin

- different Neo-Tethys sub-basin fragments accumulate since Cretaceous



Hetényi et al. 2009

- 40 km thickening = 300 K temperature anomaly throughout the MTZ
- normal ‘410’ + deflected ‘660’: 800 K ???
- how to explain the strong lateral variations ???

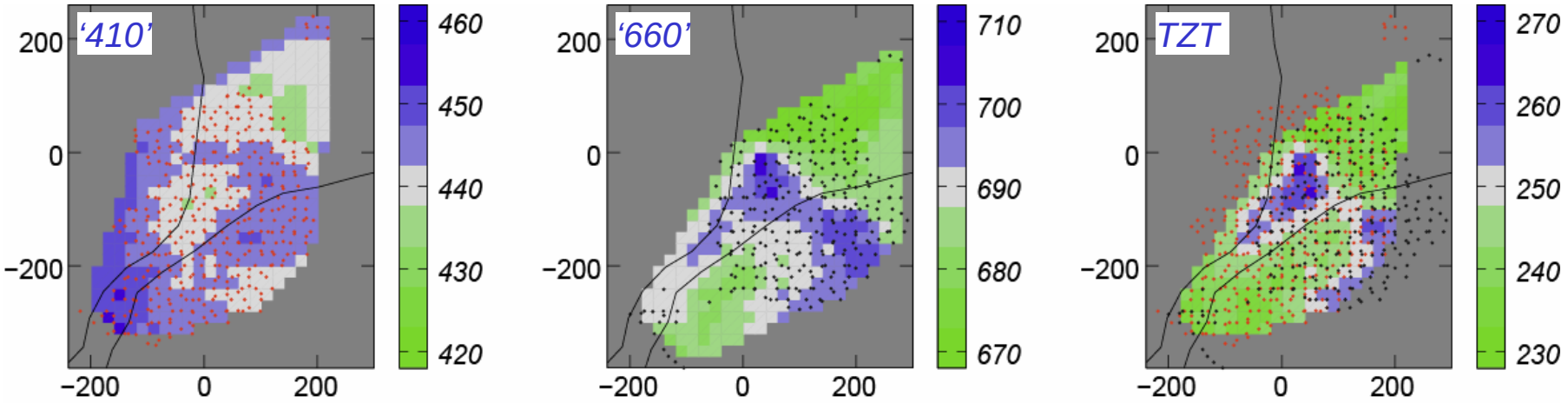
Other transition zone thickness variations

Tauzin et al. 2008 [RF]:
- overall MTZ thickness variations: 35-40 km
- no clear evidence for thinning at hotspots: '410' deepened, '660' less T-sensitive

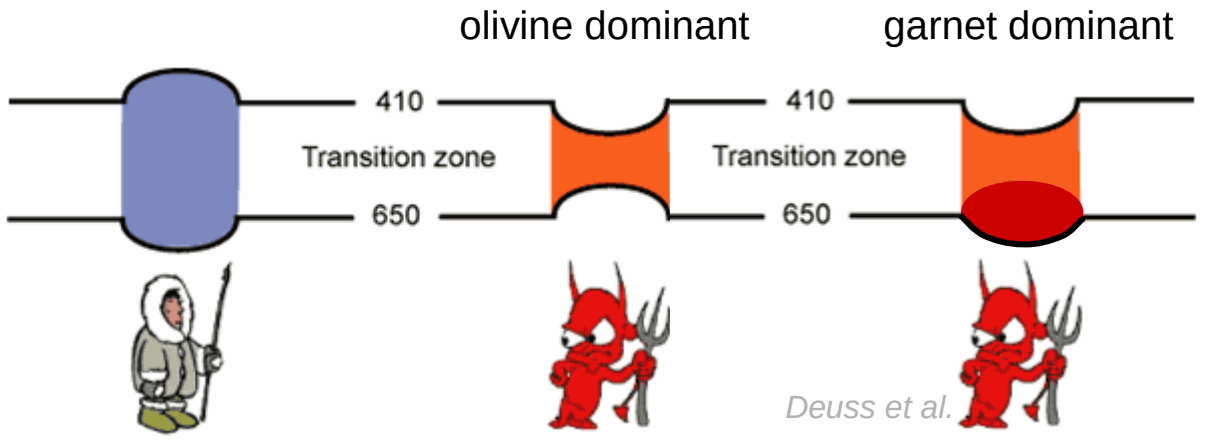
Huerta et al. 2009 [RF]:
- East-African rift: '410' depressed (350°C hot anomaly), '660' also depressed

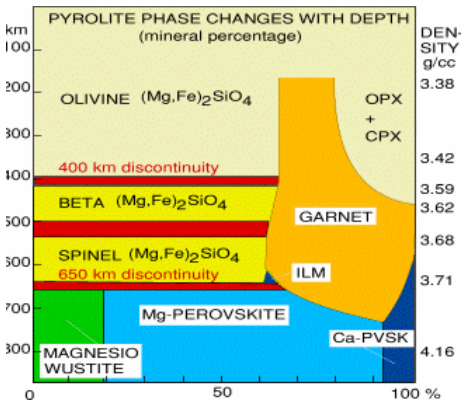
Day & Deuss 2010 AGU [PP and P'P' precursors]:
- '660': up to 35 km depth variation within few hundred lateral km
- double peak: 720 km depth: majorite garnet → Ca-perovskite phase change

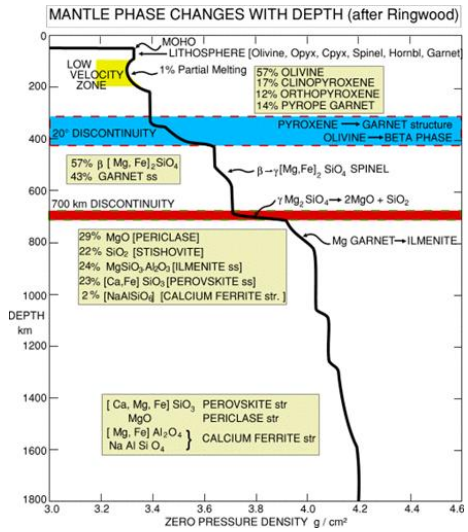
Cornwell et al. (2010 AGU; paper in prep.) [RF]:
- Ethiopia: depressed '410', '660' also deepened and shows lateral variations

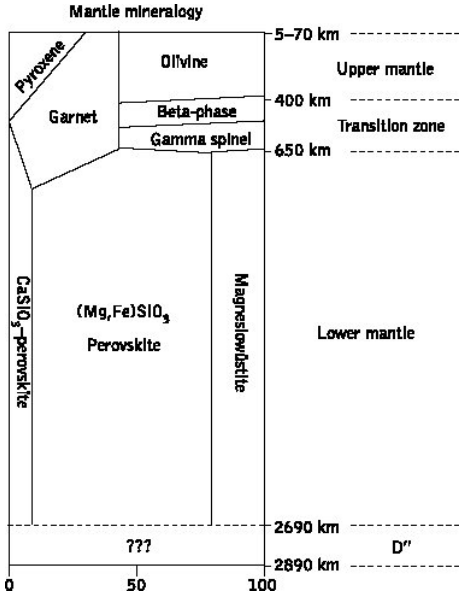


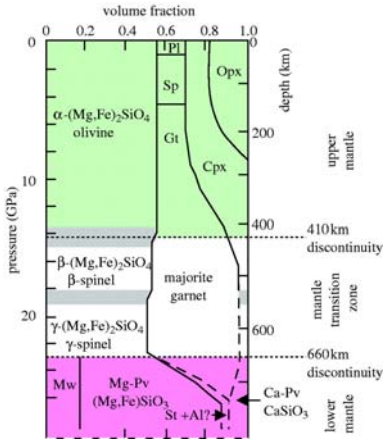
Phase changes control the transition zone



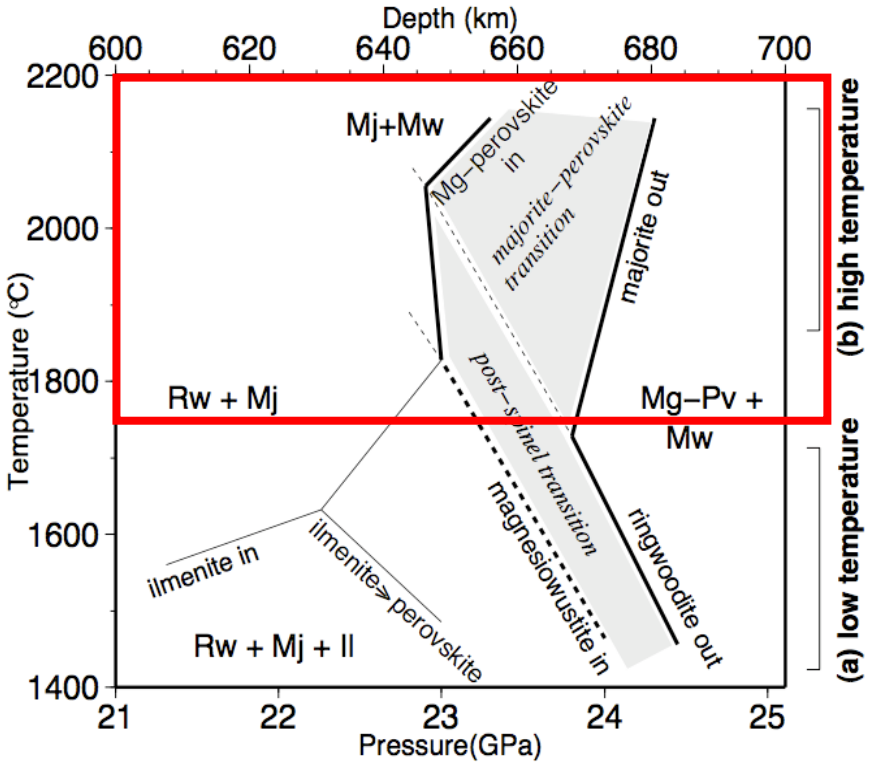




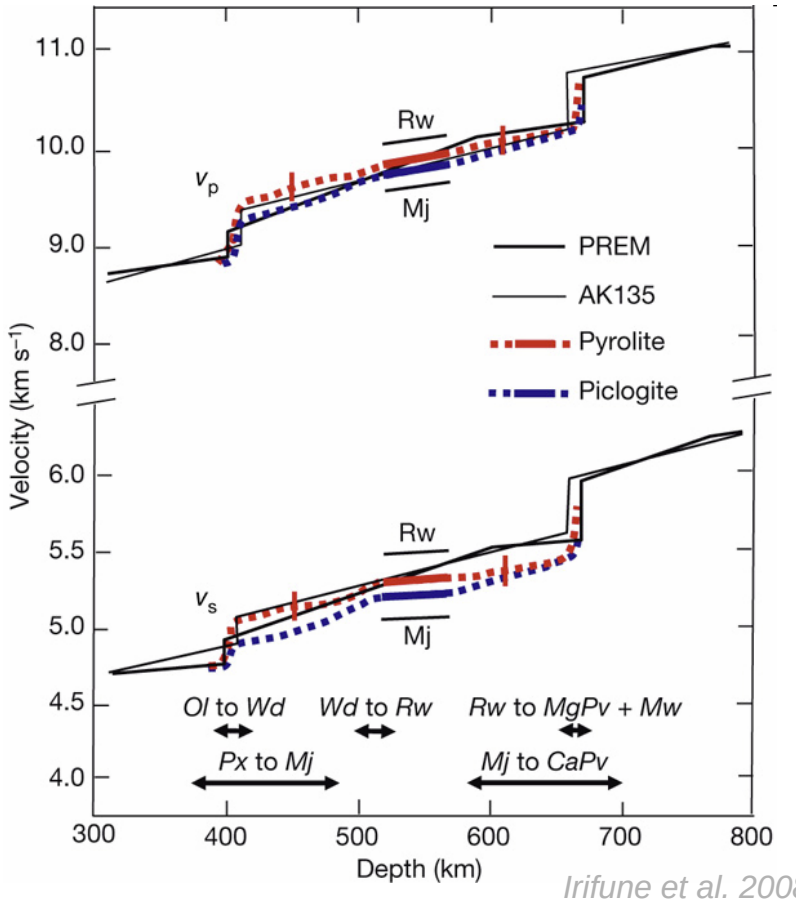




Phase changes control the transition zone



Hirose 2002



Irifune et al. 2008

1) Phase changes of olivine and garnet shape the depth of discontinuities
2) Garnet Clapeyron-slope is positive → '660' more complex
3) Lateral variations likely to be explained by compositional heterogeneities

Triplet de changements de phases

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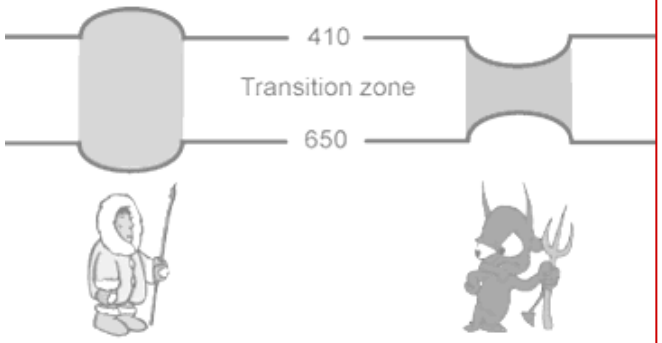
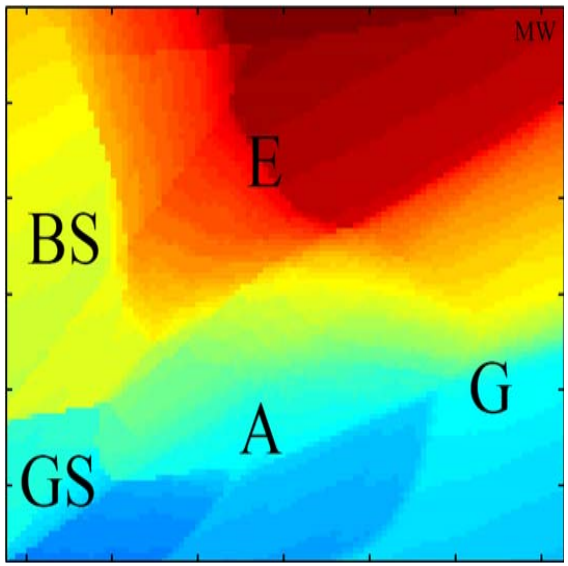


modélisation géodynamique

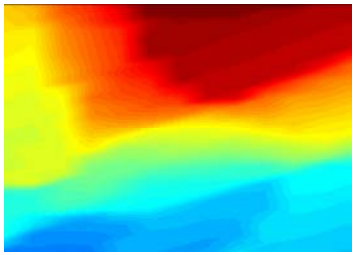


prismation des orgues de lave

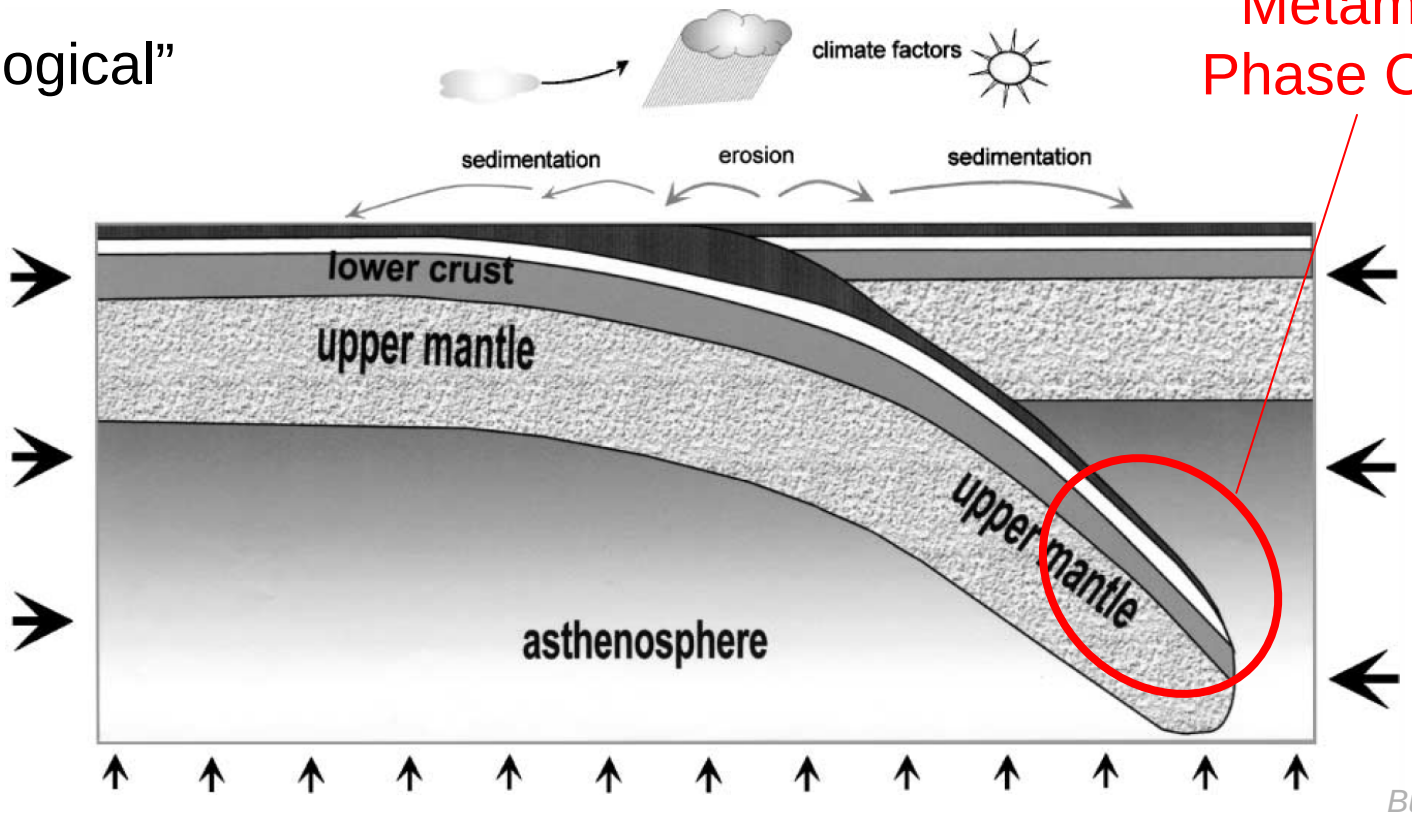
Consistent implementation of phase changes into geodynamic models

Physical processes and laws

- mechanical
- thermal
- “geological”



Metamorphic Phase Changes

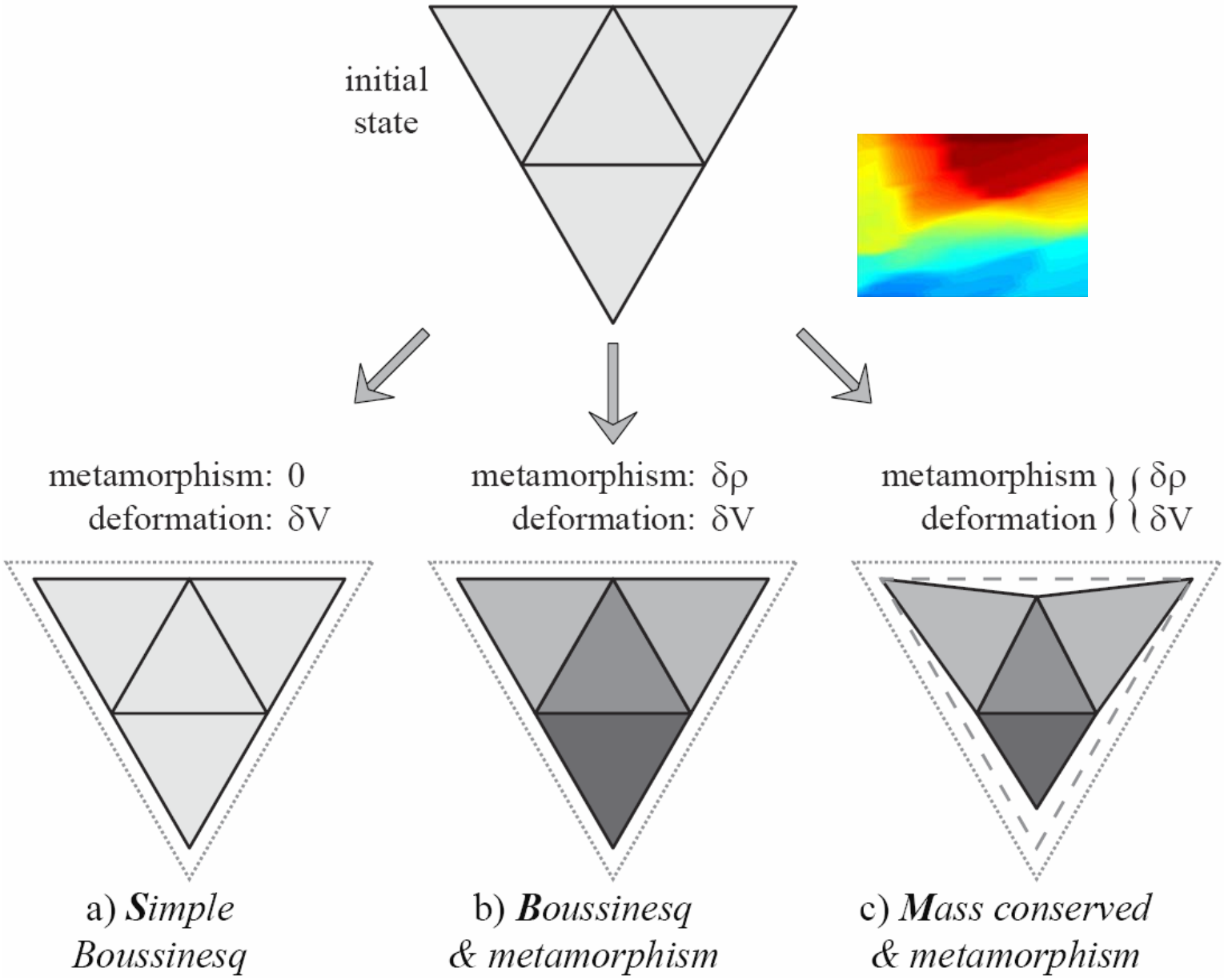


Burov et al. 2001

Collaboration: Vincent Godard (CEREGE), Rodolphe Cattin (Géosciences Montpellier), James A. D. Connolly (ETH)

Metamorphism and deformation

$t_0(P_0,T_0)$



$t_1(P_1,T_1)$

Equations to solve

- equilibrium: conservation of momentum

$$\nabla \cdot \sigma_{ij} + \mathbf{f} = m\mathbf{a}$$

✓

- heat: conservation of energy

$$\frac{\partial T}{\partial t} - \kappa \cdot \Delta T - A + \mathbf{v} \cdot \nabla T = 0$$

✓

- continuity: conservation of mass

$$\frac{d\rho}{dt} + \nabla \cdot (\rho \mathbf{v}) = 0$$

✘

Simplification

» Cette indépendance subsiste même quand, supposant le fluide incompressible (ce qui n'est nullement obligé, même pour un liquide), on s'impose de ne choisir que des déformations compatibles avec la conservation parfaite des volumes aux divers instants. En effet, celle-ci revient, comme on sait, à établir, entre les vitesses effectives de dilatation dans les sens des axes, la relation linéaire

$$\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz} = 0; \tag{4}$$

Boussinesq 1897

$$\cancel{\frac{d\rho}{dt}} + \nabla \cdot (\cancel{\rho}\mathbf{v}) = 0$$

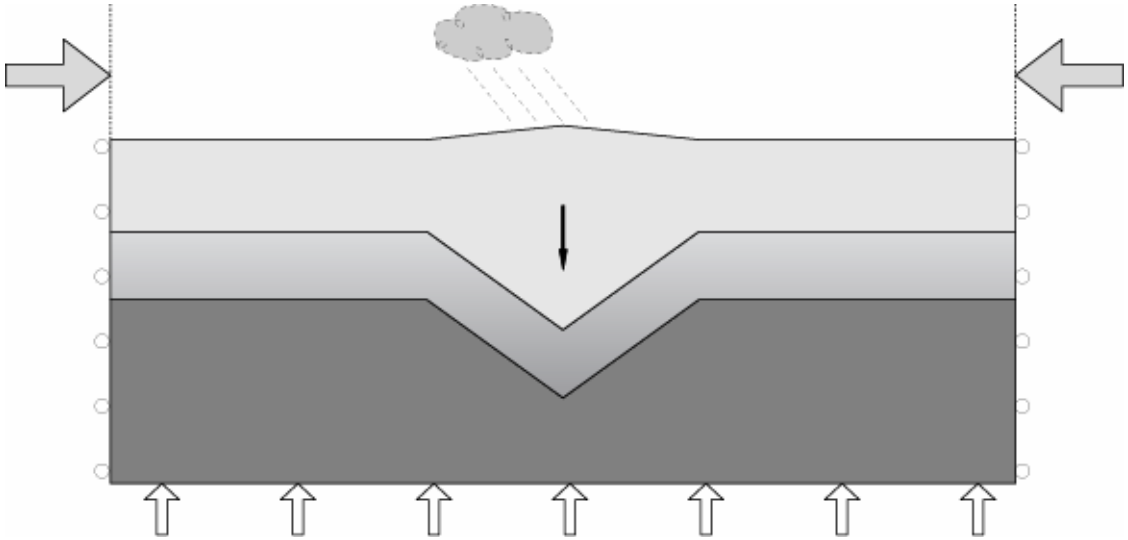
incompressibility

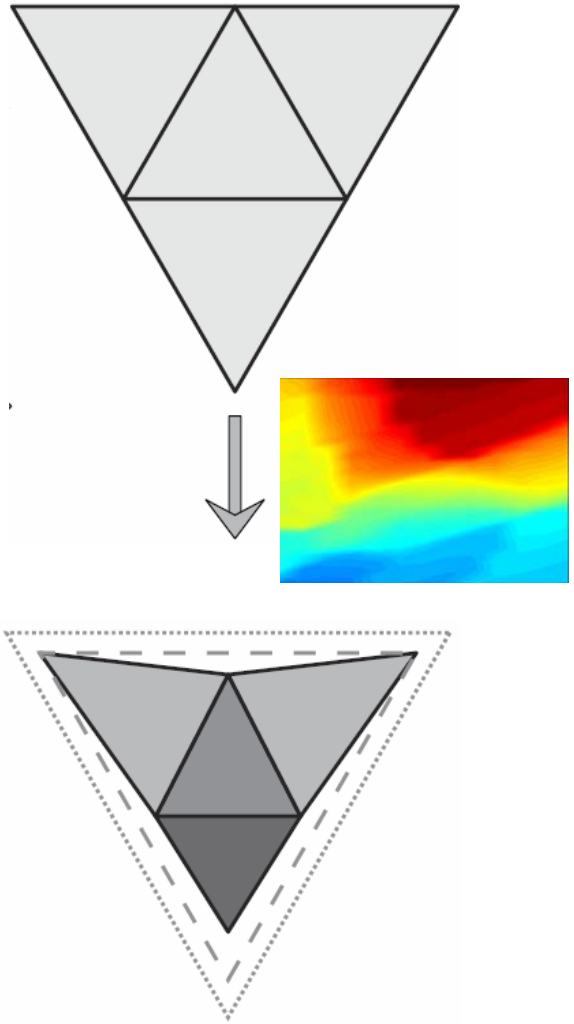
Goal

- implement

$$\frac{d\rho}{dt} + \nabla \cdot (\rho \mathbf{v}) = 0$$ ✓

- explore the consequences





Modelling tool: Castem

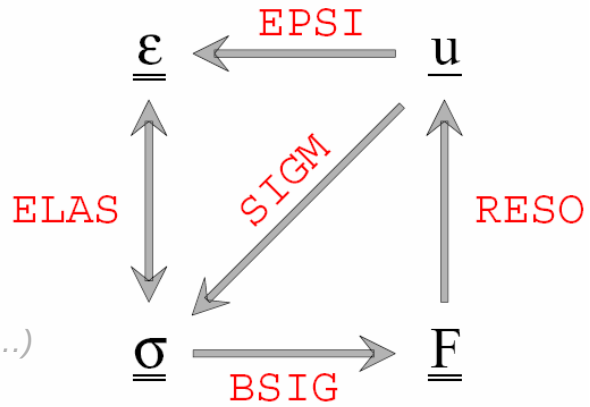
- finite element modelling tool (2D, 3D)
- mechanical and thermal problems
- pre-defined operators: flexibility ☺, efficiency ☹

Cast3M

http://www-cast3m.cea.fr

Geodynamics toolbox *(Godard, 2006)*

- rheologies (elastic, viscous, plastic)
- erosion (diffusive, fluvial incision)
- benchmarked against ADELI *(J. Chéry, R. Hassani, …)*
- re-meshing



Implementation of mass conservation

Mass to conserve:

$m_c = \rho_1 V_1 = \rho_0 V_0$

$\Delta V / V = -\Delta\rho / \rho$

$\Delta V / V = tr\ \underline{\varepsilon} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$

$\varepsilon_{ii} = \Delta V / 3V = -\Delta\rho / 3\rho$

Stress modification:

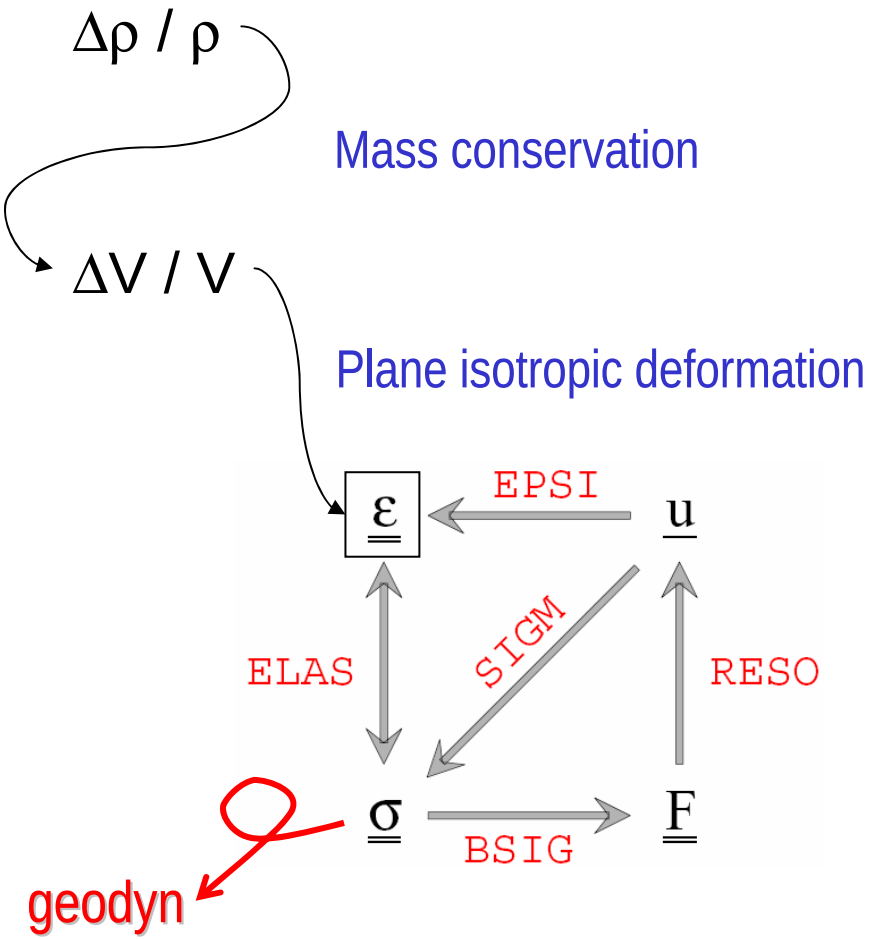
- substract from internal stress field

$$\underline{\sigma}_{int} = \underline{\sigma}_{int} - \underline{\sigma}_{MPC}$$

- “numerical” damping

$$\underline{\sigma}_{int} = \underline{\sigma}_{int} - \underline{\sigma}_{MPC} / \boldsymbol{F}$$

- stability tests

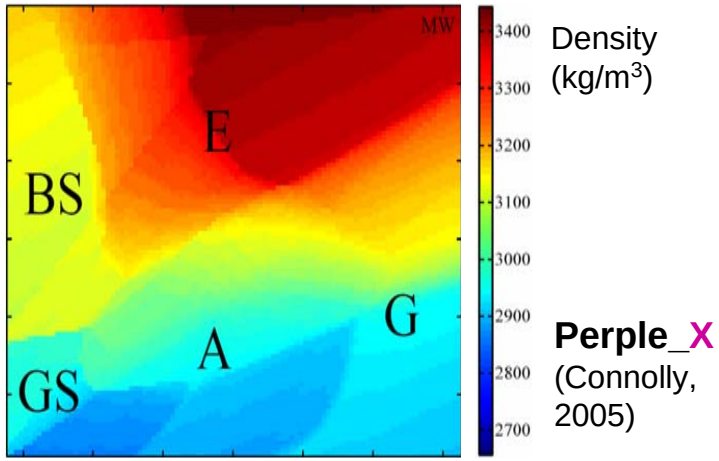


Benchmark setup

2D continental lithosphere with topography & isostatic crustal root

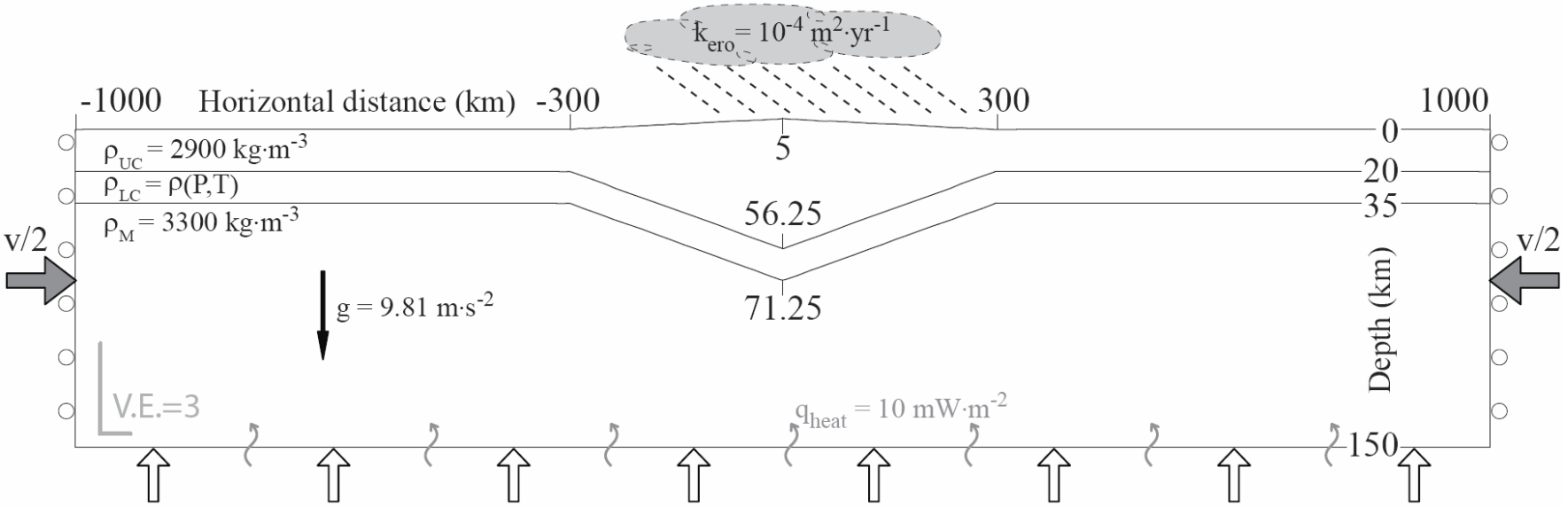
- visco-elastic rheology
- horizontal convergence: 20 mm/yr
- lower crustal metamorphism
- linear diffusive erosion

$$\frac{\partial h}{\partial t} = -k_{ero} \cdot \frac{\partial^2 h}{\partial x^2}$$



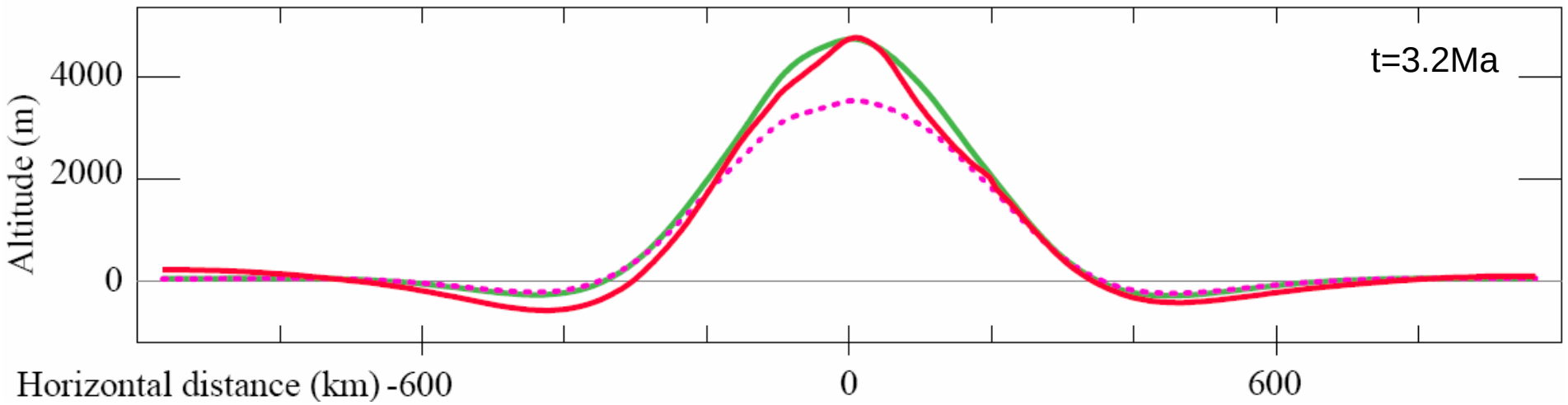
Density (kg/m^3)

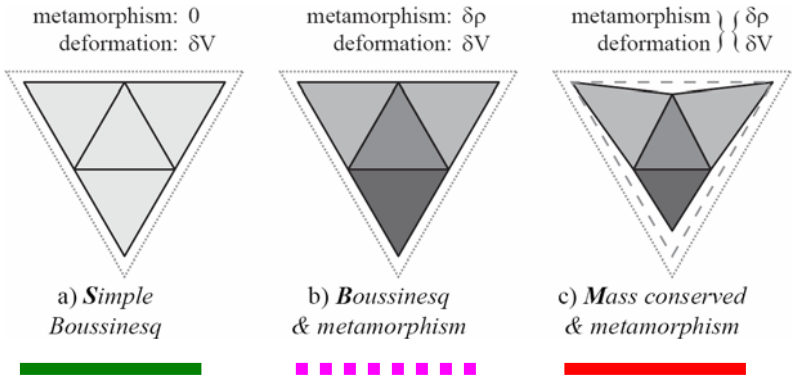
Perple_X (Connolly, 2005)

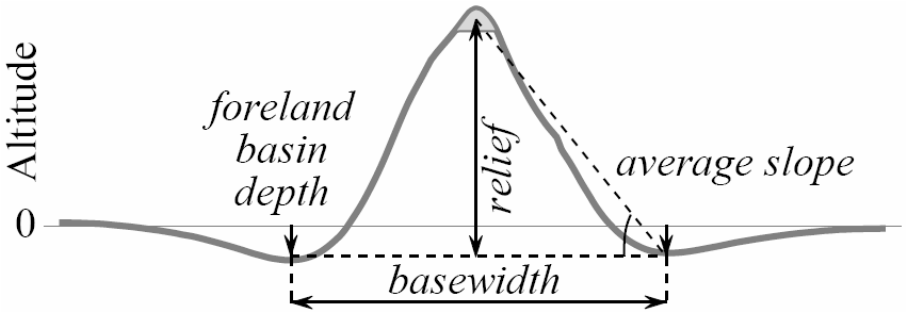


Effect of metamorphism

with visco-elastic rheology, erosion, convergence



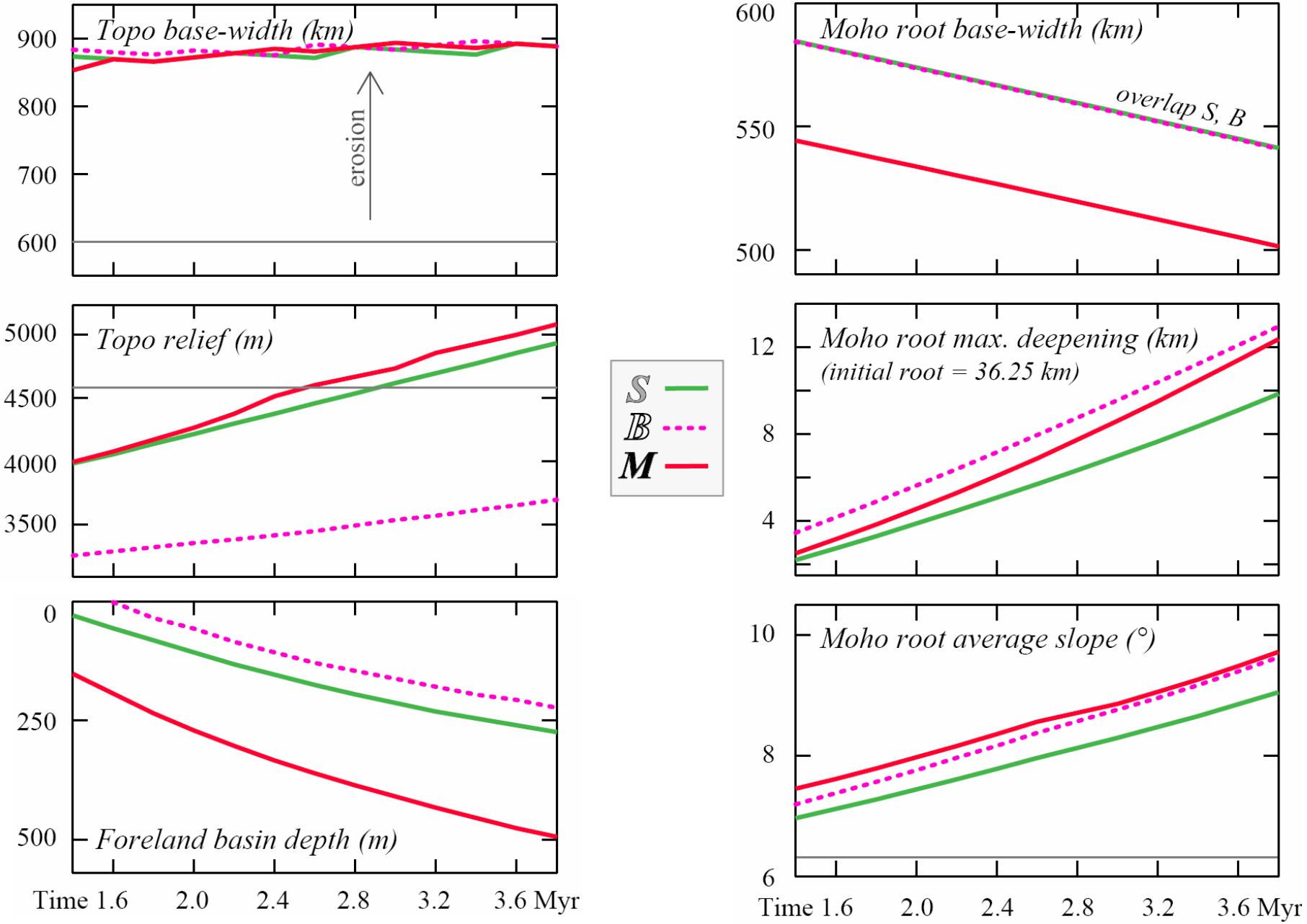




Topography

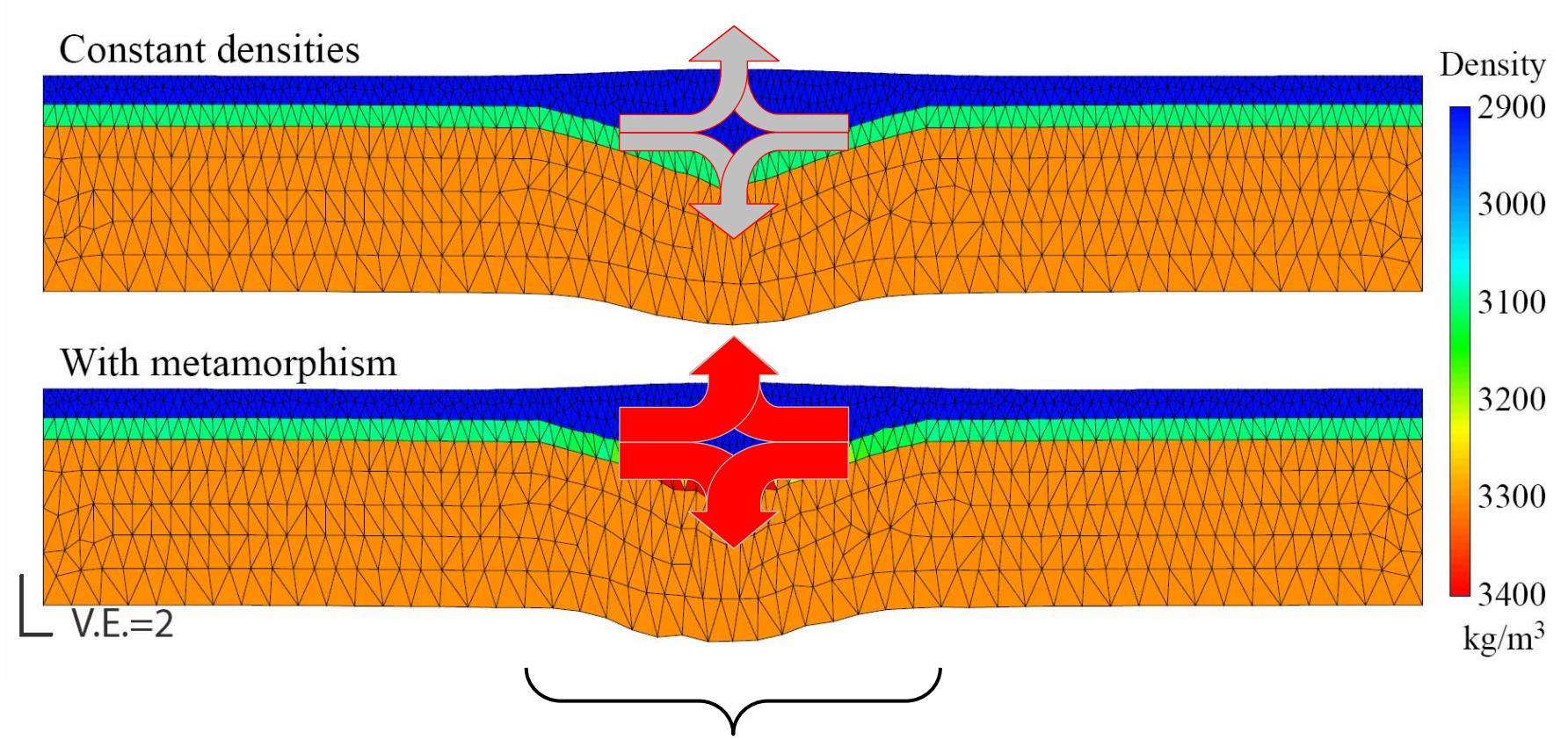
Effect of metamorphism

Crustal root



Effect of metamorphism

Density profiles



average Bouguer anomaly difference: ~70 mgal

Conclusions and implications

Metamorphism in orogeny:

- deformation localization
- amplitudes similar to erosion

May need revision:

- erosion rates
- basin evolution
- flexural studies

Respect continuity !!!

Earthquake triggering ($\underline{\sigma}_{MPC} \approx$ few bars)

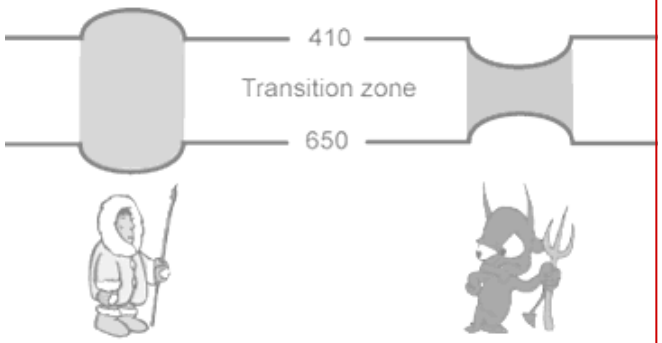
[e.g., eclogitization beneath Tibet]

Delamination / break-off

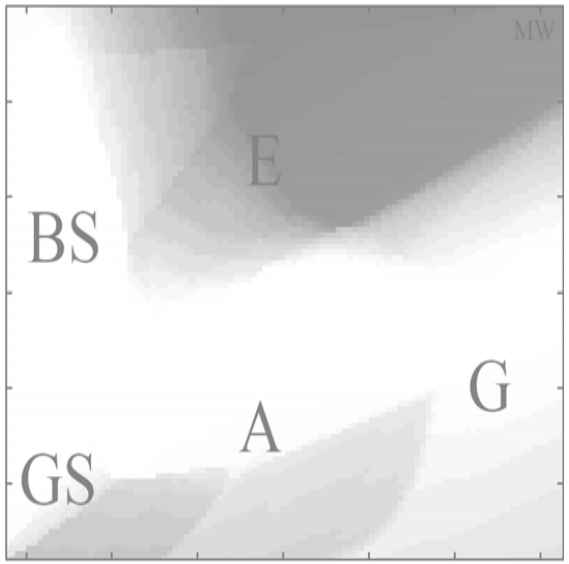
…

Triplet de changements de phases

zone de transition du manteau

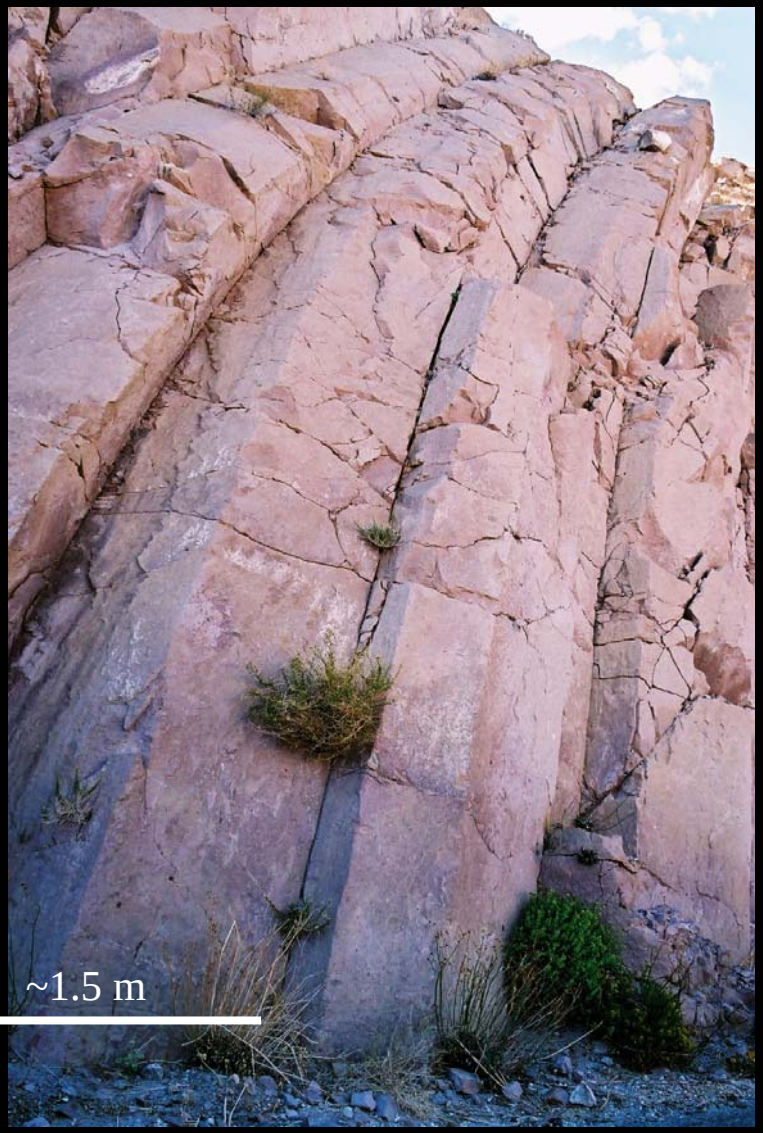


modélisation géodynamique



prismation des orgues de lave

Where this study has started…

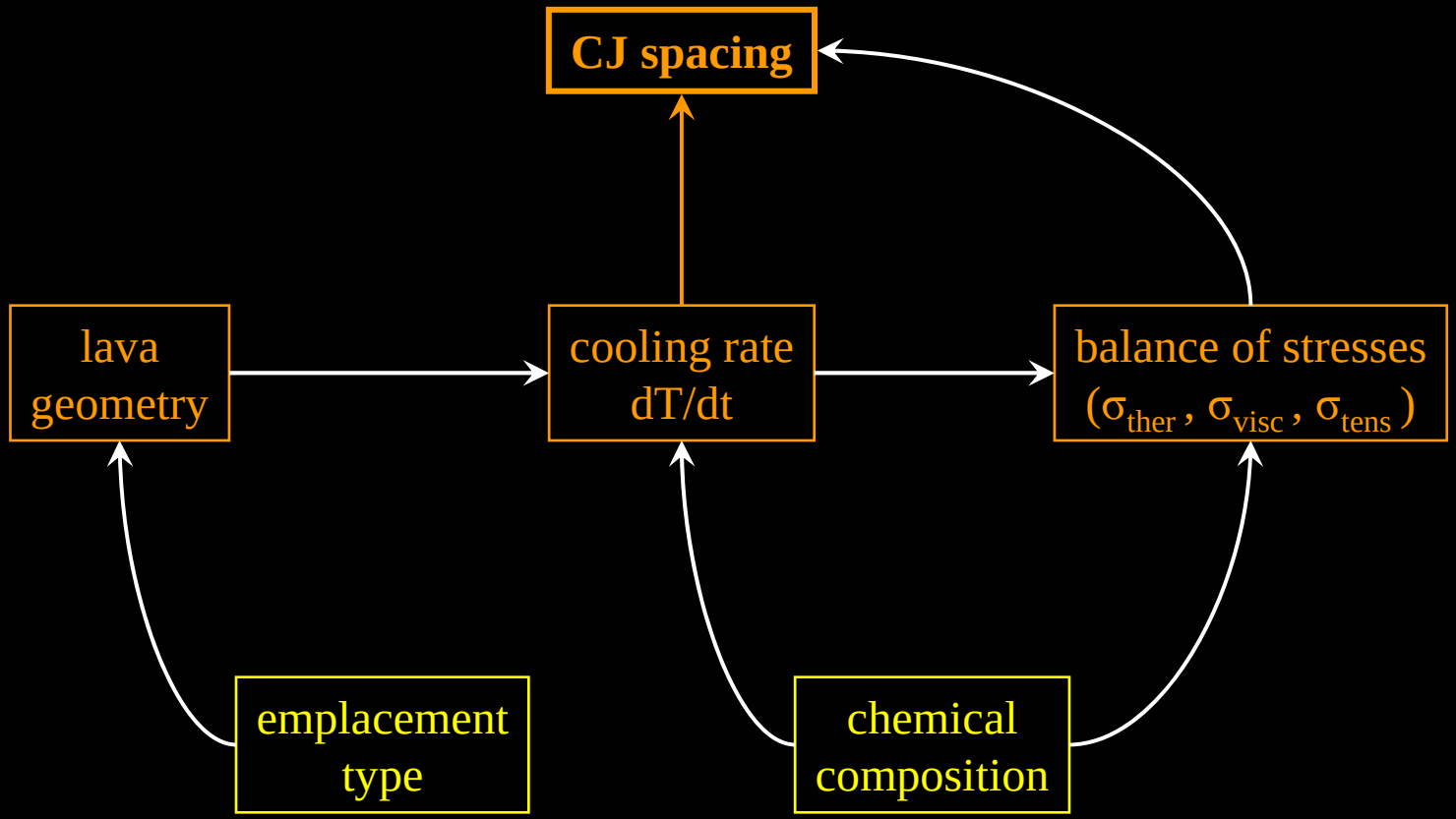


Bishop Tuff (CA, USA) – rhyolite

Somoskő [Šiatorská Bukovinka] (H-SK) – basalt

Szanda (H) – andesite

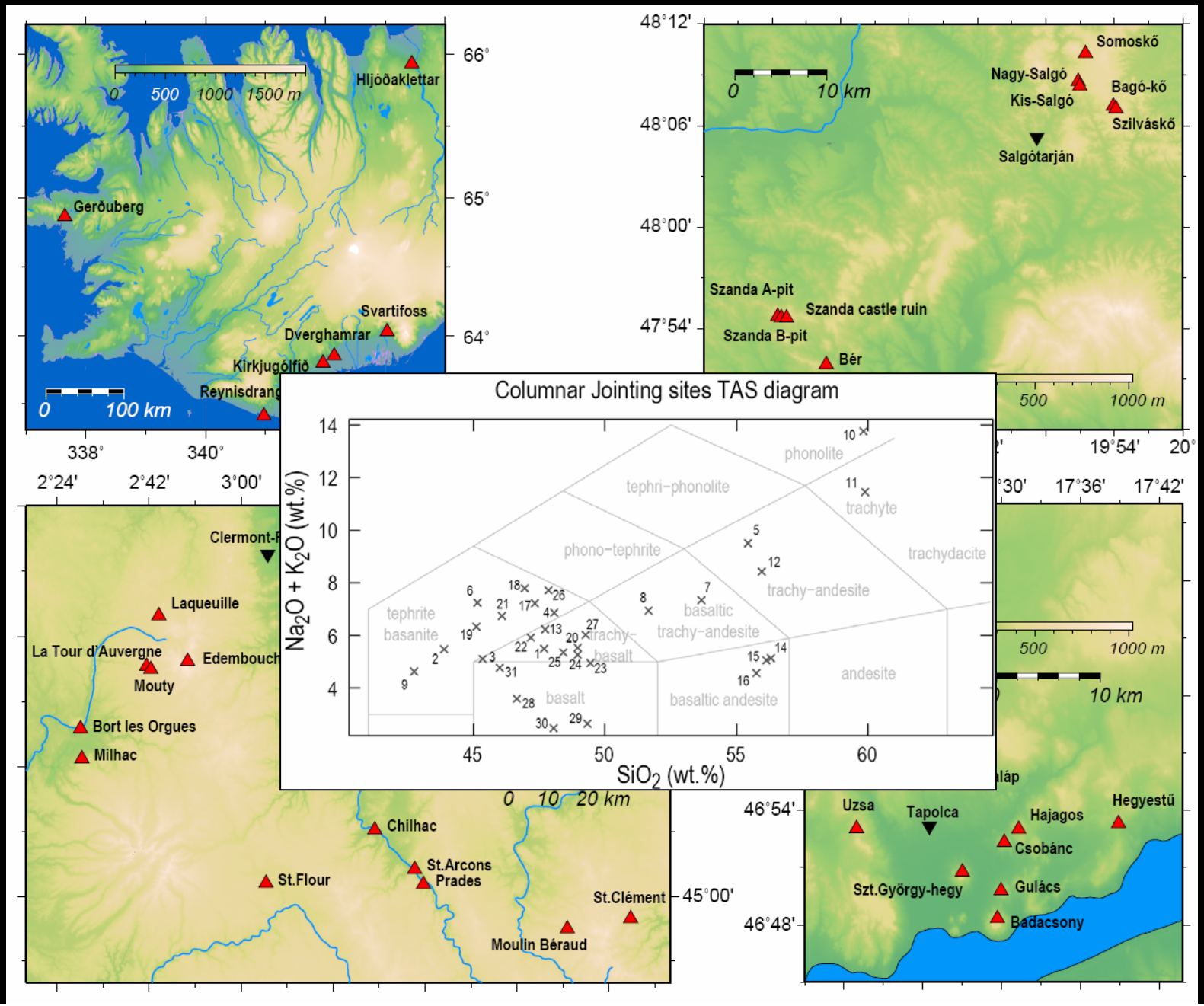
What controls the size of columns?



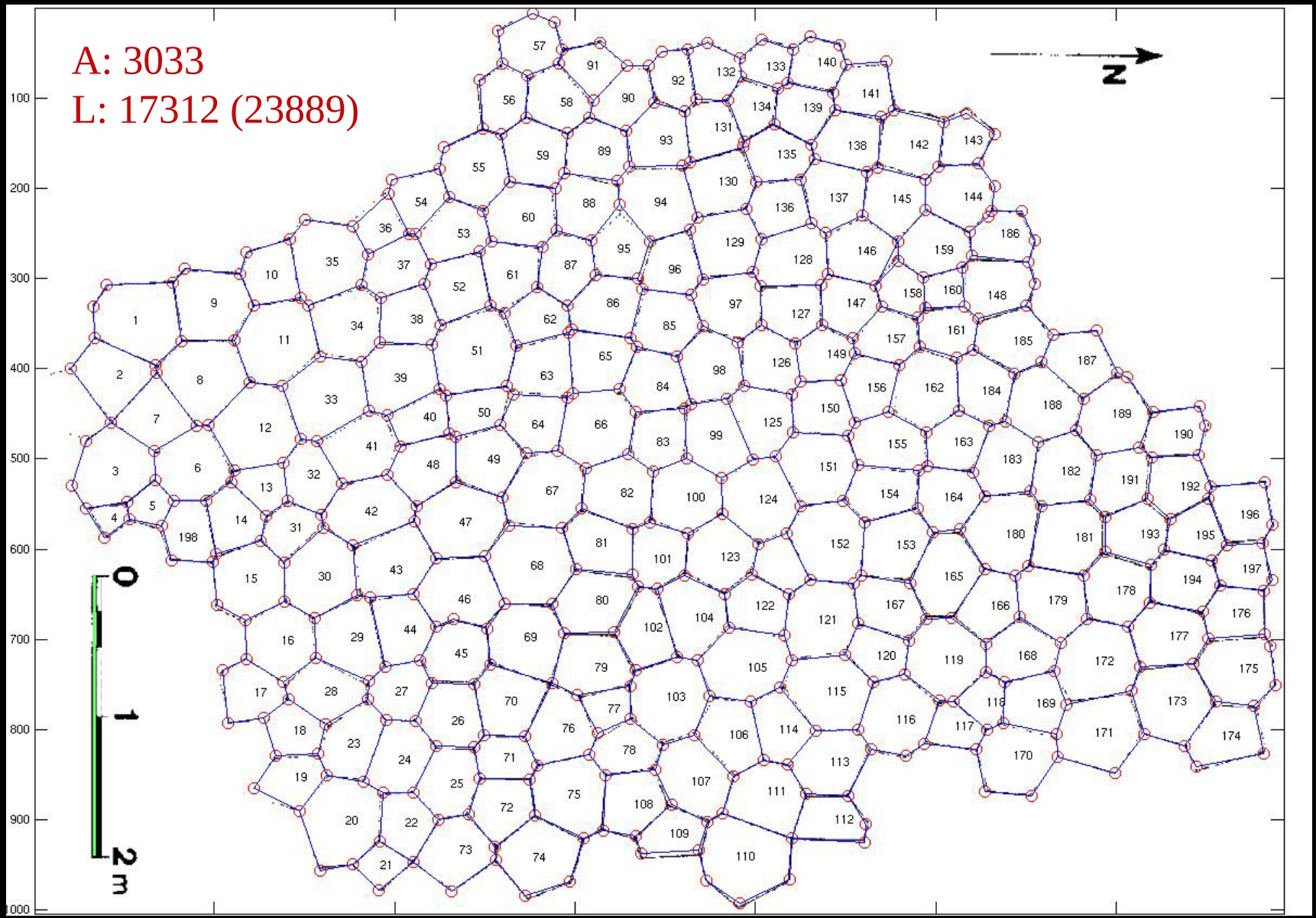
Field studies in search for: characteristic size, emplacement type, composition…

Collaboration: Etienne Médard (Clermont-Ferrand), Fanny Garel and Benoît Taisne (IPGP)

Columnar jointing sites and compositions

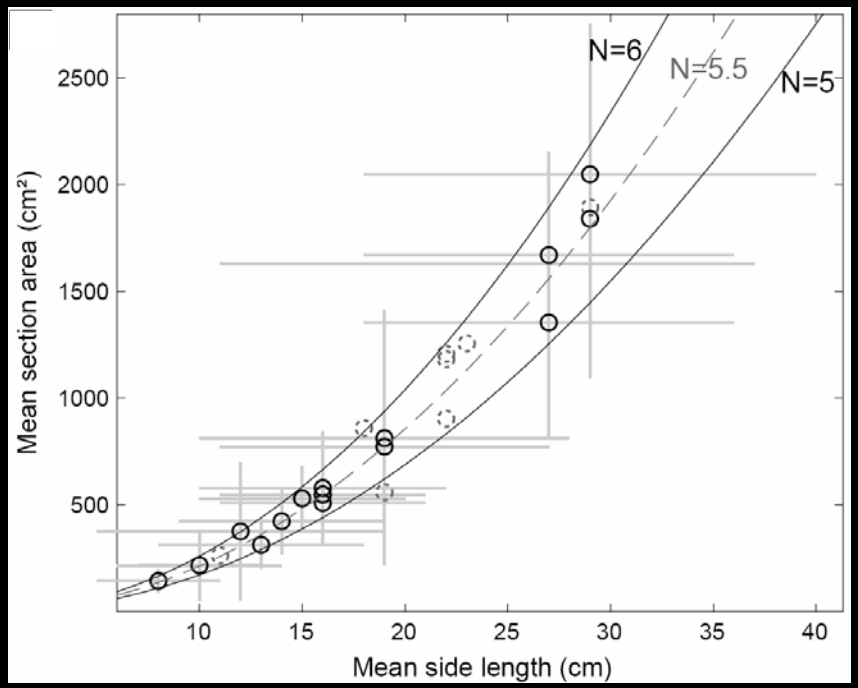


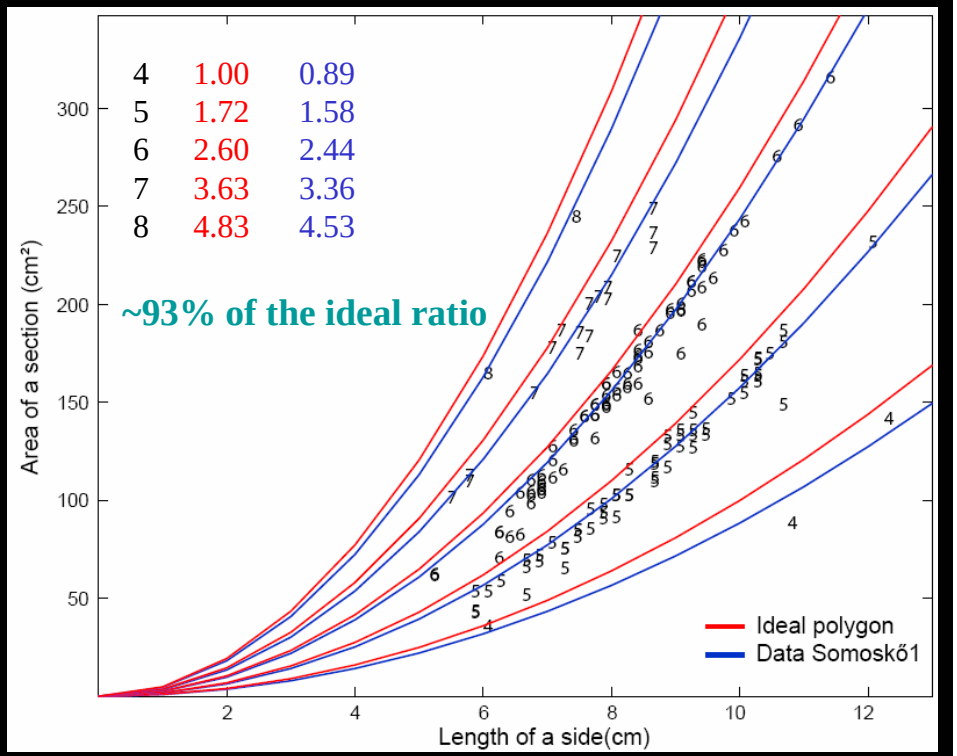
Field measurements: photos → software → statistics on L, A, N

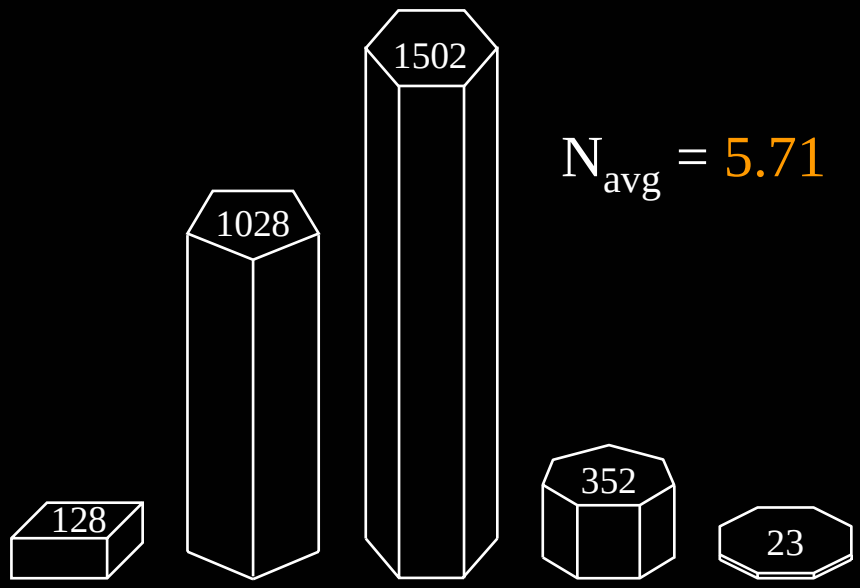


Background drawing from O'Reilly, 1879 (Trans. R. Irish Acad., 26: 641-728; cited in Budkewitsch & Robin, 1994)

Some results on geometry







N_{avg} = 5.71

- areas reduced compared to ideal polygons (“distorted” columns)
- $N_{avg} < 6$

→ energy spent on creating joints is not minimized

→ dynamic process

Field measurements: simple flow

Saint-Flour (F)

Field measurements: ponded flow

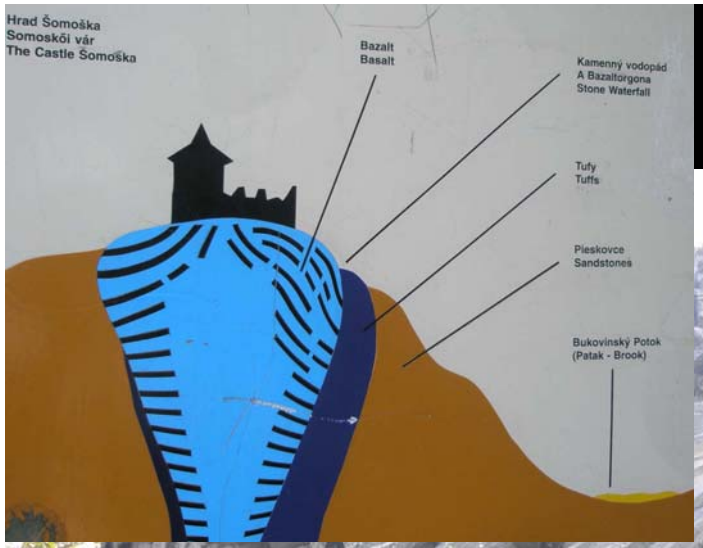
Prades (F)

Field measurements: dyke

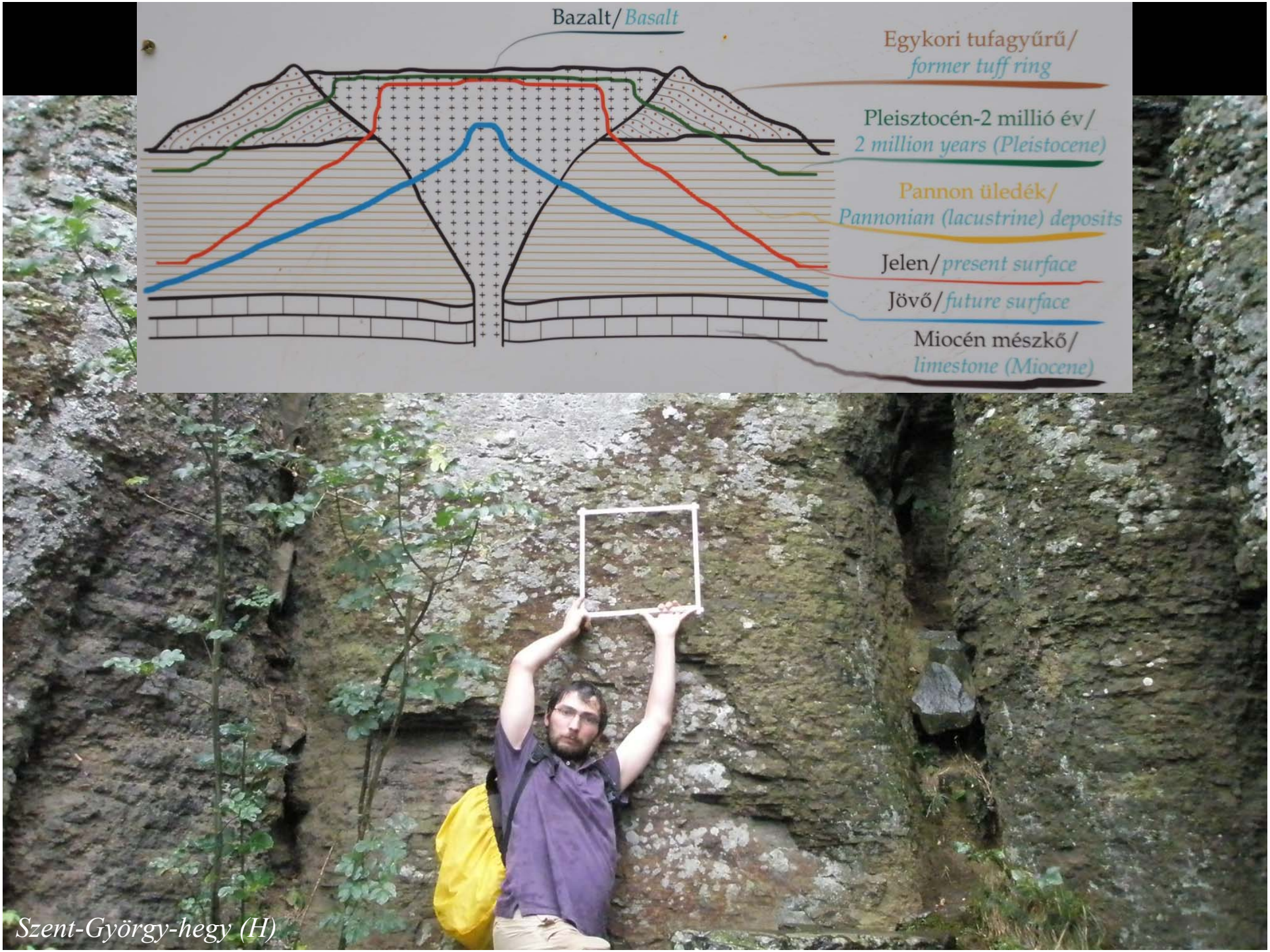
Moulin Béraud (F)

Field measurements: neck/plug

Field measurements: neck/plug



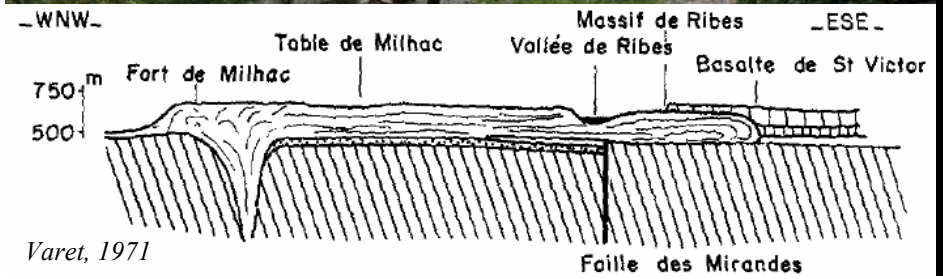
Somoskő [Šiatorská Bukovinka] (H-SK)



Szent-György-hegy (H)

Field measurements: viscous flow and lava lake

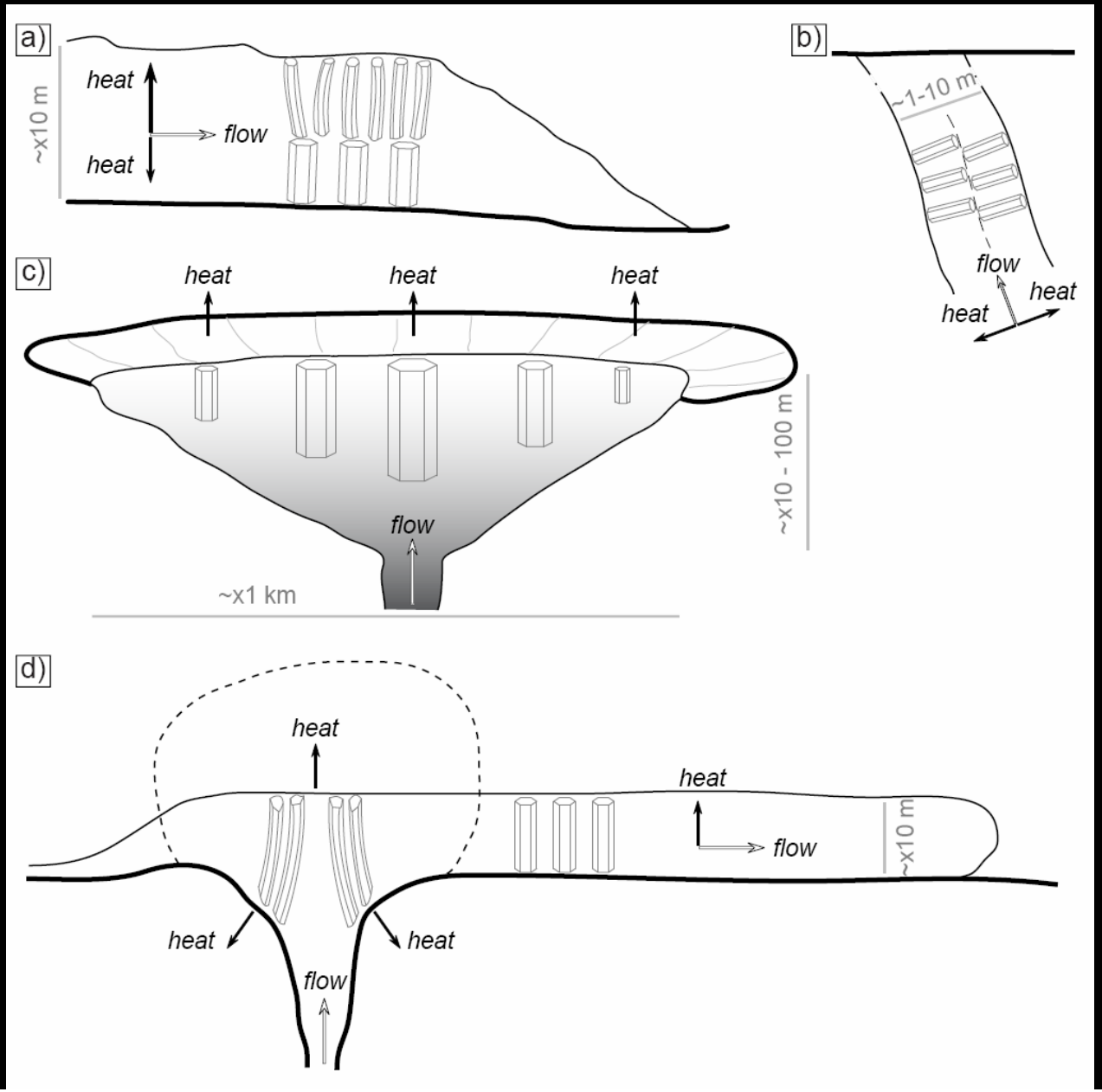

St.Clément (F)



Varet, 1971


Szent-György-hegy (H)

Solidification geometry affects the shape of columns



flow (ponded)

dyke (sub-surface)

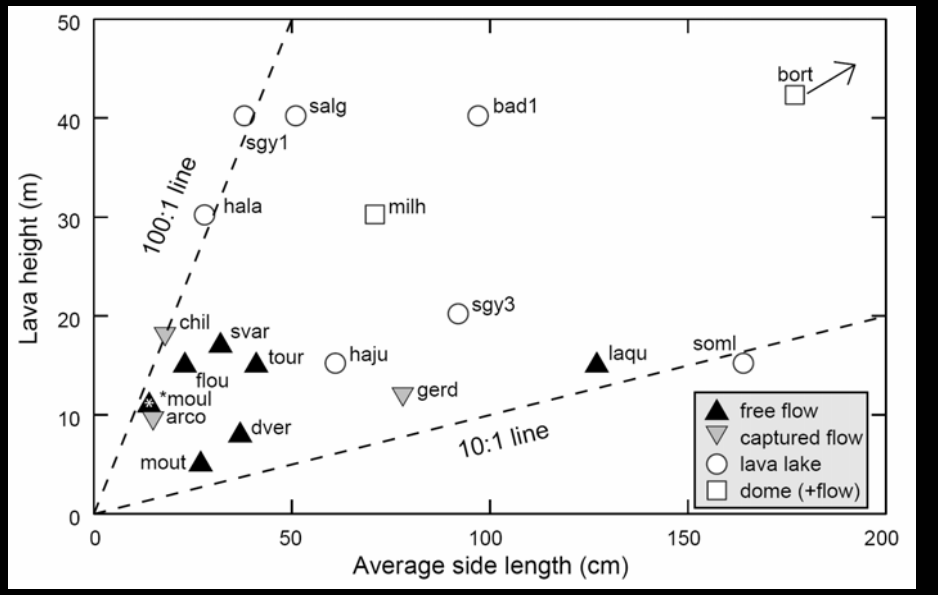
lava lake

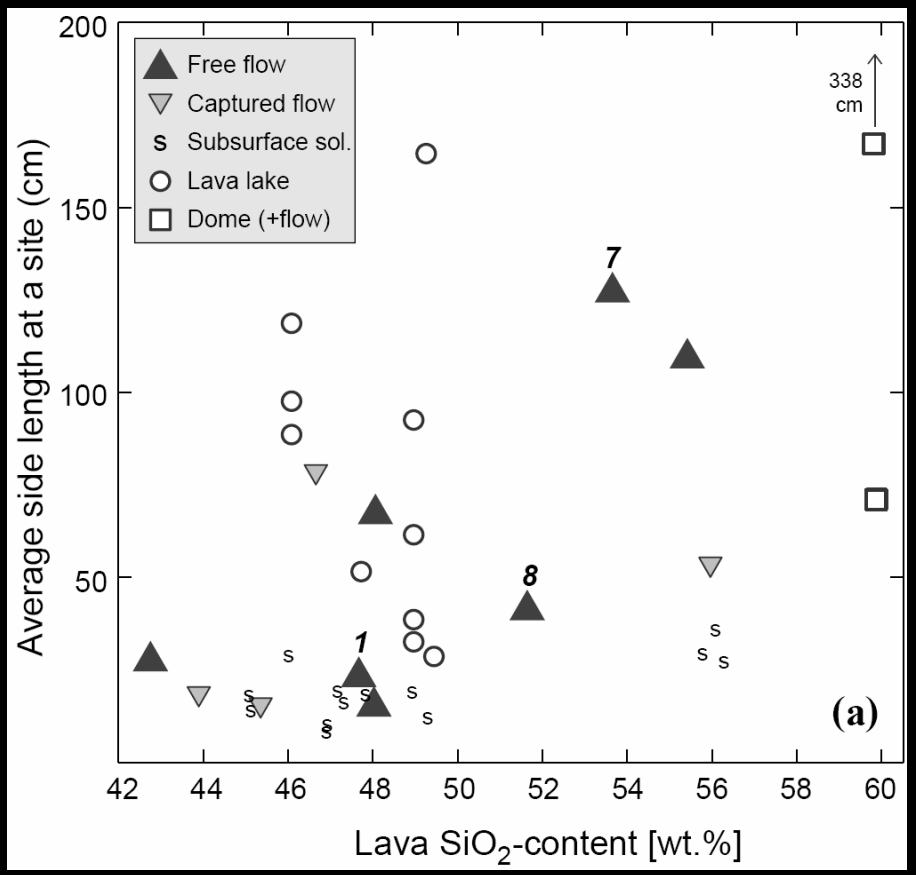
dome (+flow)

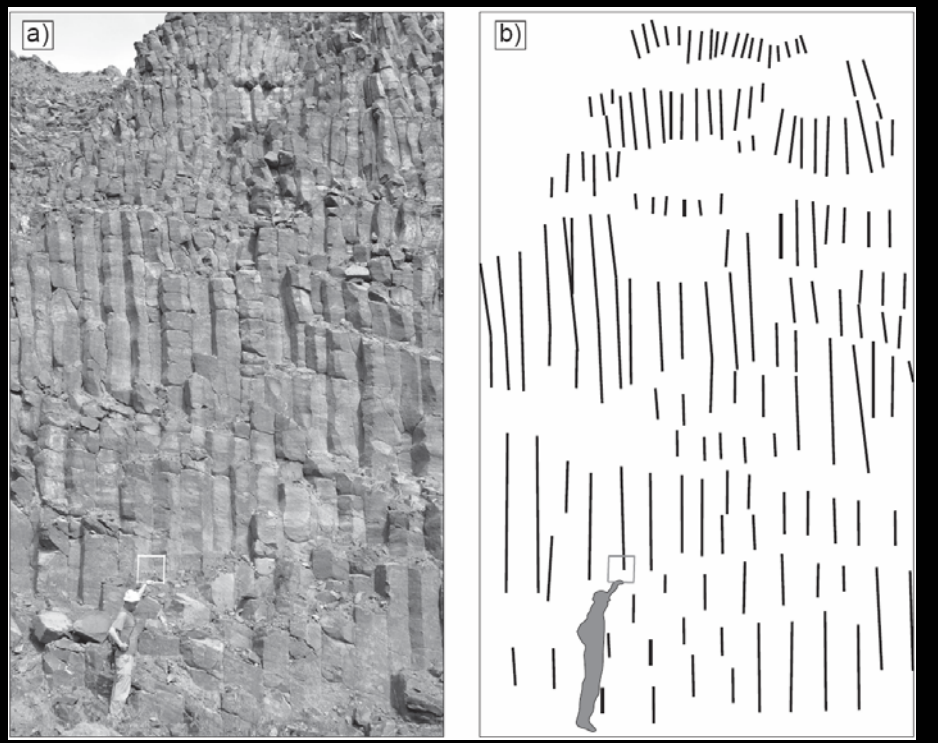
Simple, free flows

Column diameter correlates with:

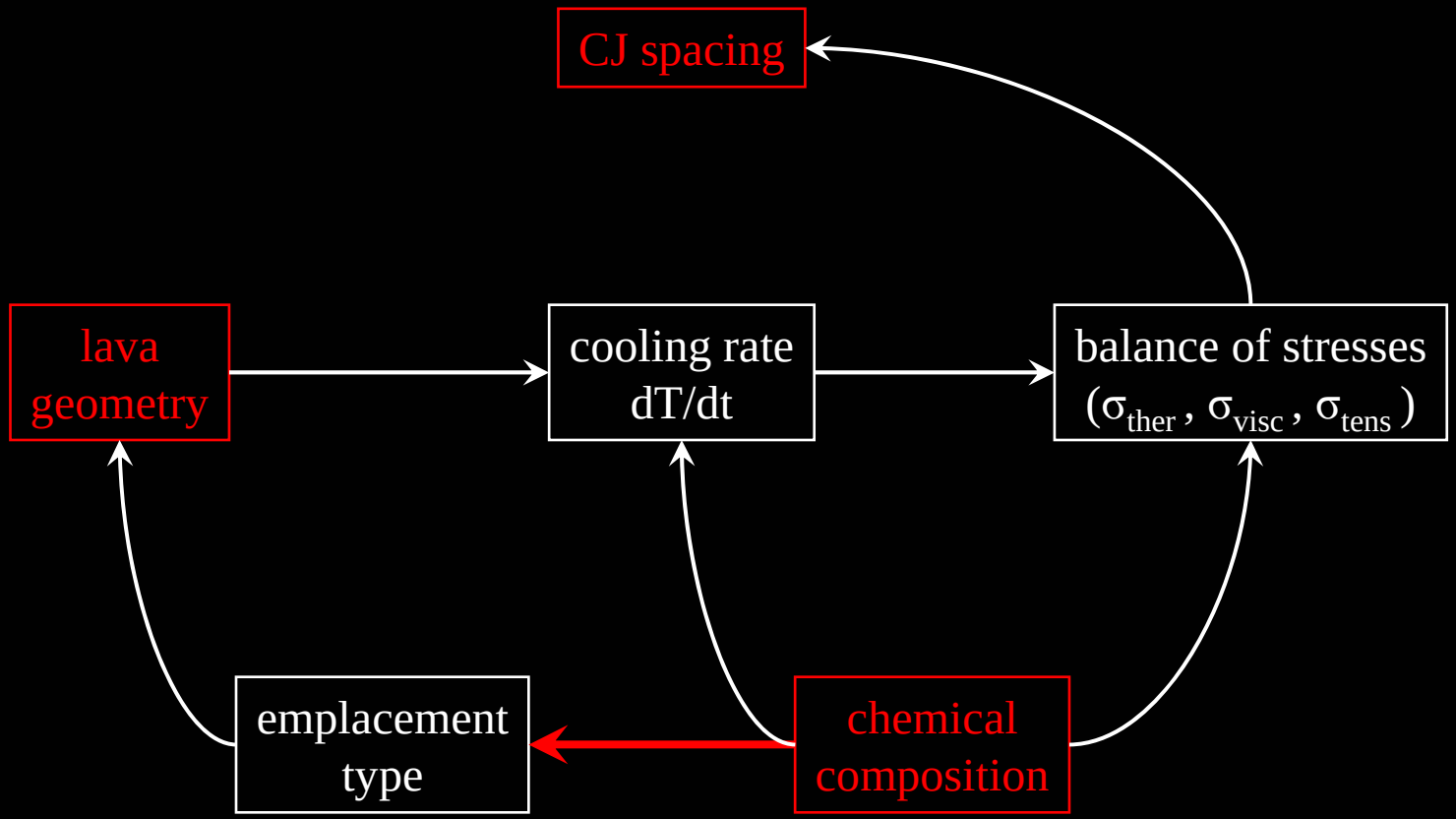
- SiO_2-content
- lava flow thickness







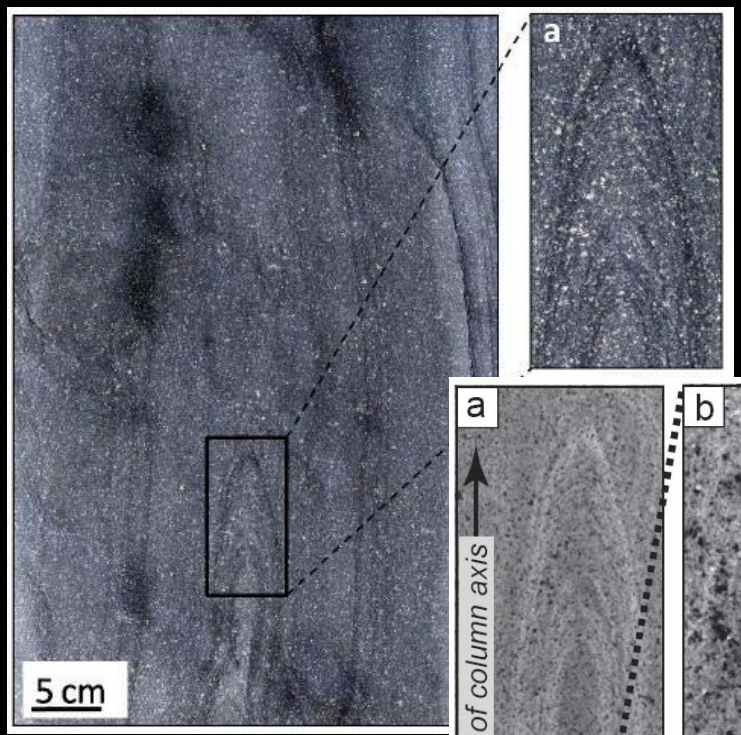
CONCLUSIONS

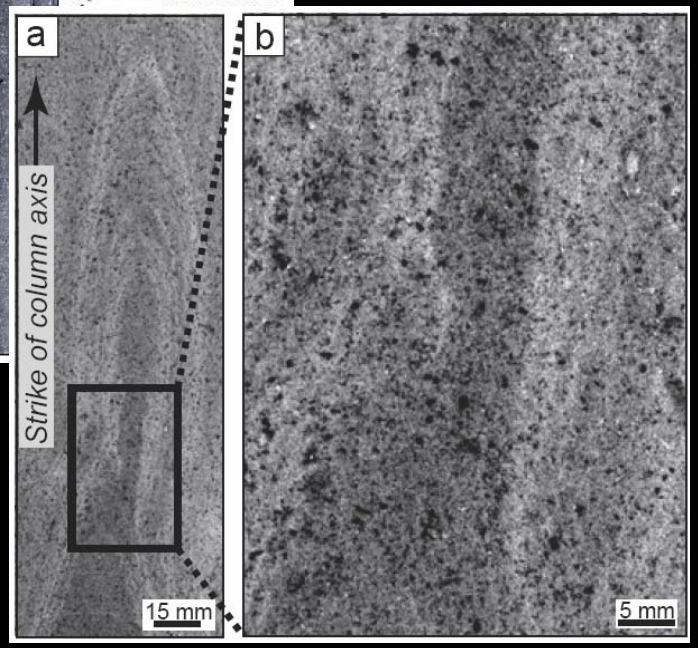


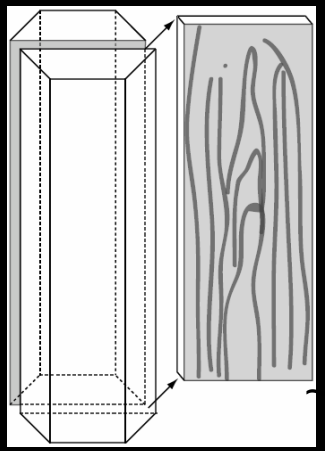
What happens inside a column?

<u>Collaboration:</u> Hannes B. Mattson, Sonja Bosshard, Bjarne Almqvist, Ann M. Hirt (ETH)

What happens inside a column?



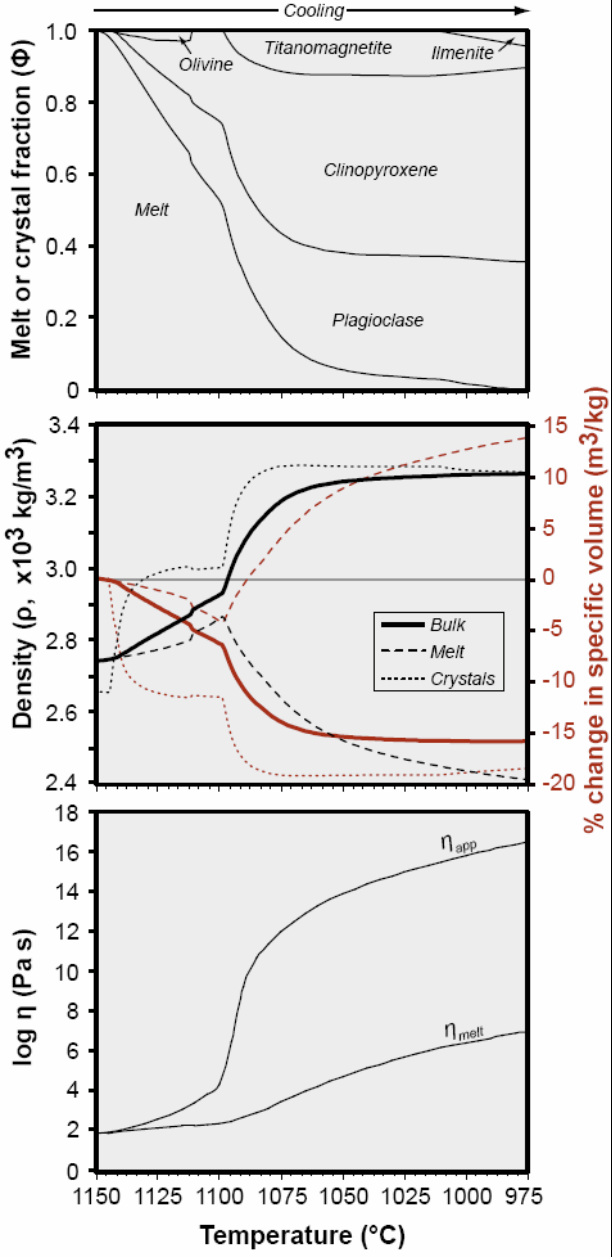




Micro-scale observations across the column

- variation in composition
- variation of the crystal size distribution
- AMS sub-vertical, slight change in the susceptibility-ellipsoid orientation

Thermodynamic model



MELTS model *Ghiorso & Sack 1995, Asimow & Ghiorso 1998*

- crystallization order
- physical properties

→ volume decrease of ~15%

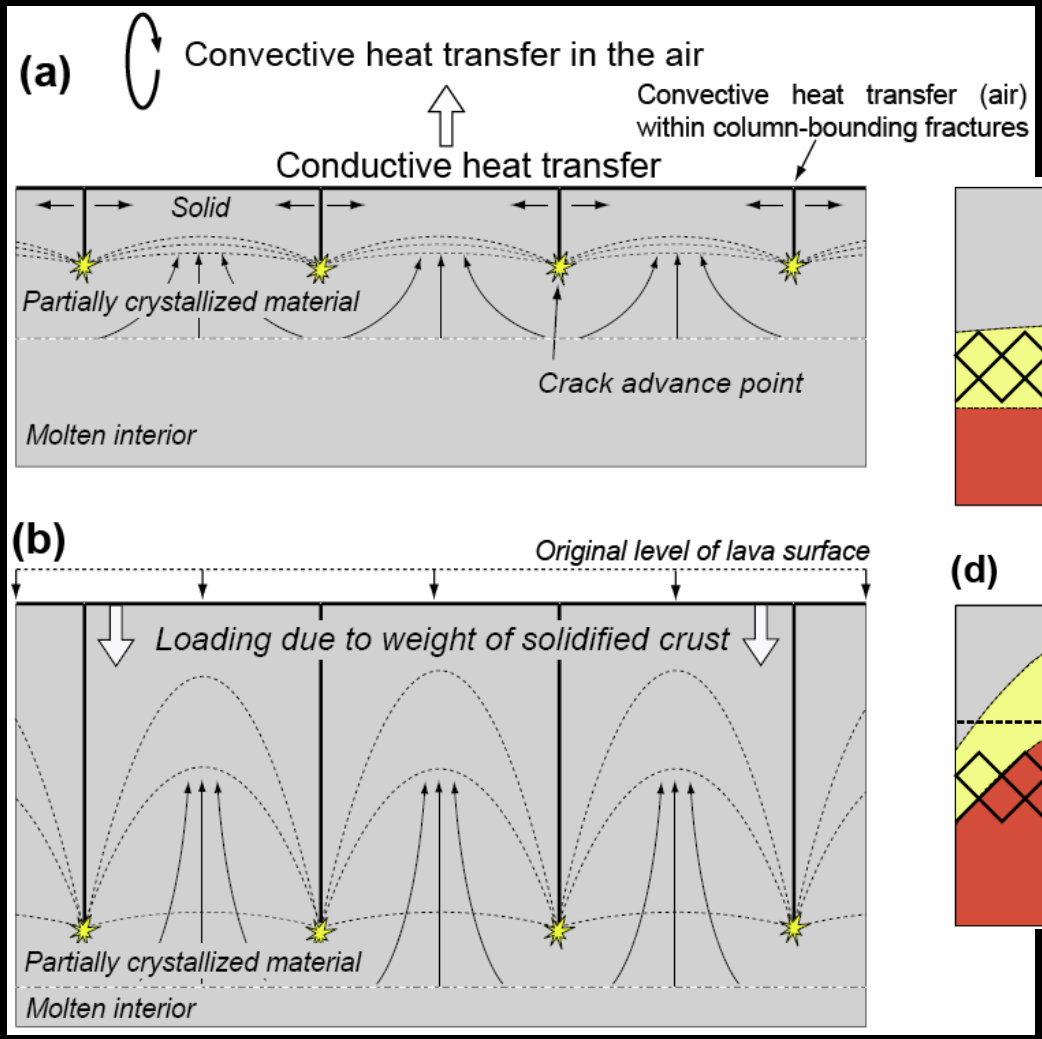
- joints can account for 0.5-1%

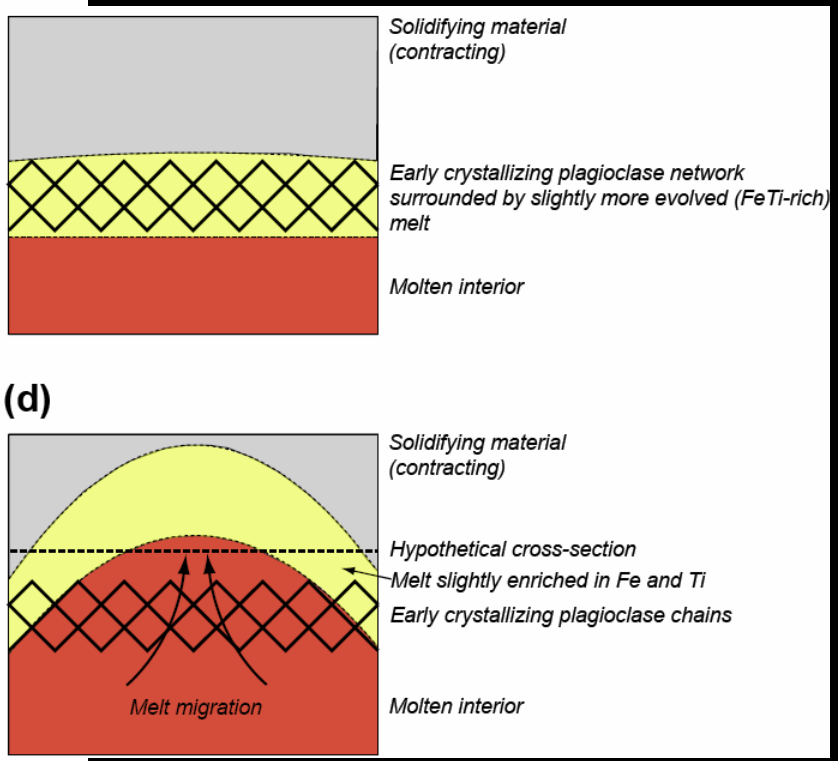
→ significant vertical component

- early crystallization of plagioclase
- late crystallizing titano-magnetite
- important change in physical properties below 1100°C

Model for melt migration within the column

- early crystallization of plagioclase
- late crystallizing titano-magnetite
- important change in physical properties below 1100°C

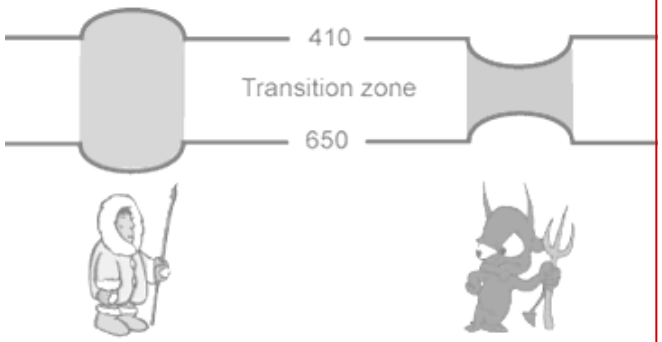




« subsidence » by weight & passive upward melt migration into the column

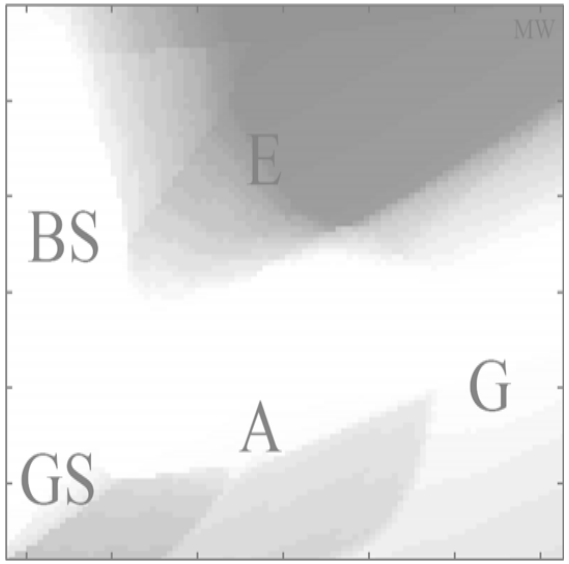
Triplet de changements de phases

zone de transition du manteau



COMPOSITION

modélisation géodynamique



VOLUME

prismation des orgues de lave

COMPOSITION & VOLUME