Successes and Future Challenges of Mantle Modelling

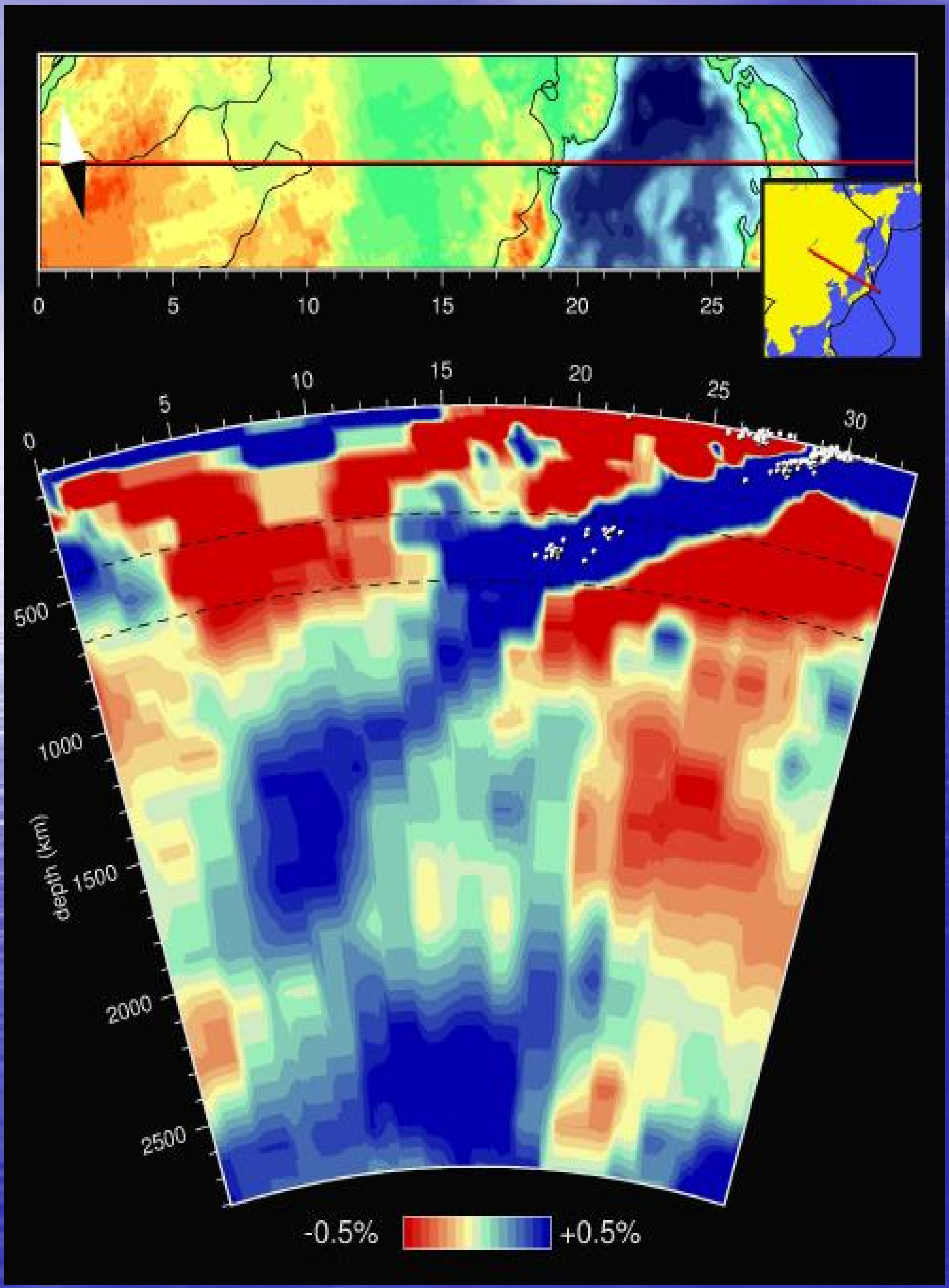
Yanick Ricard
CNRS/ENS-Lyon/Universite-Lyon

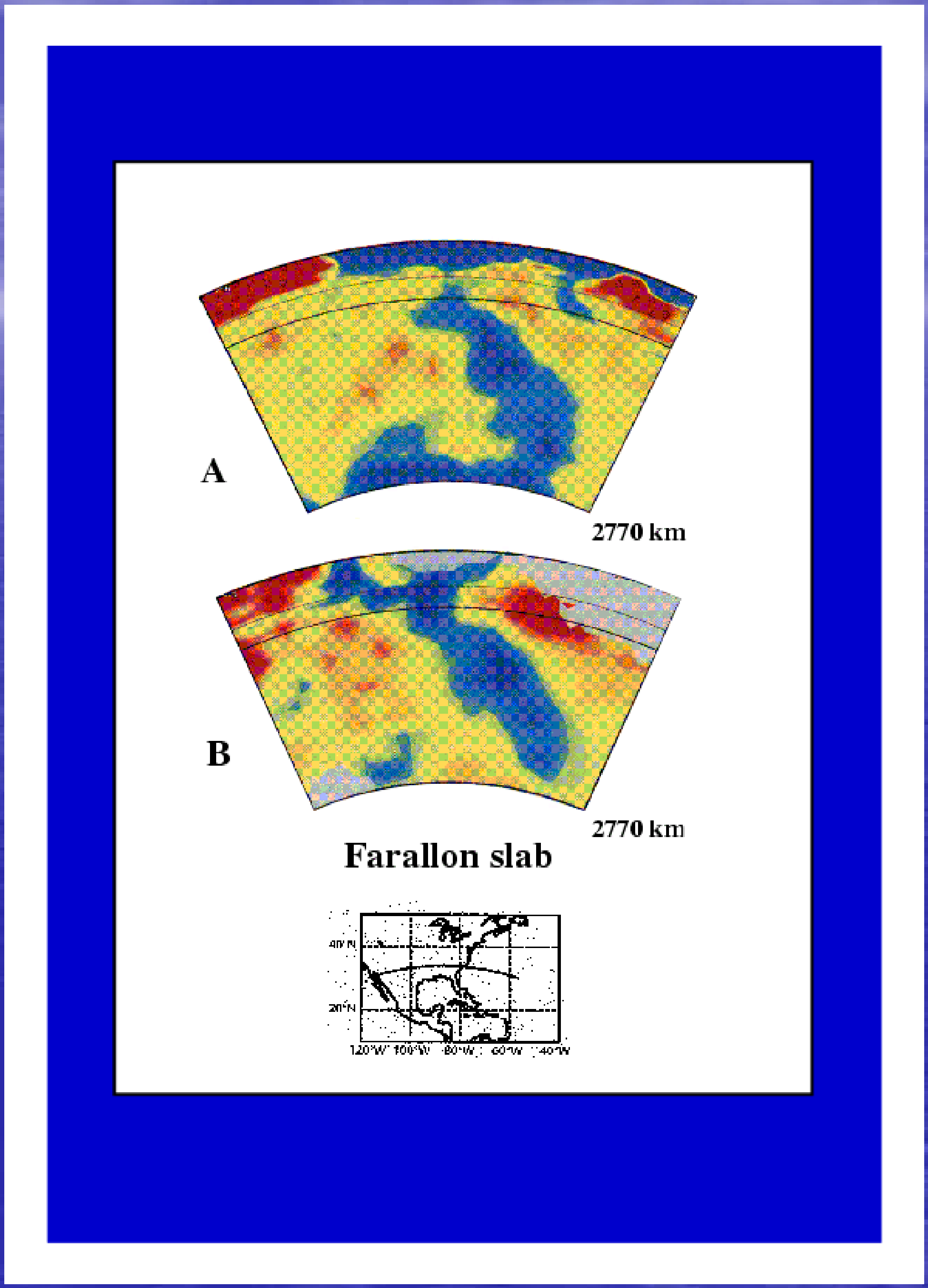
1) Density anomalies

2) Rheology

3) Mixing/geochemistry

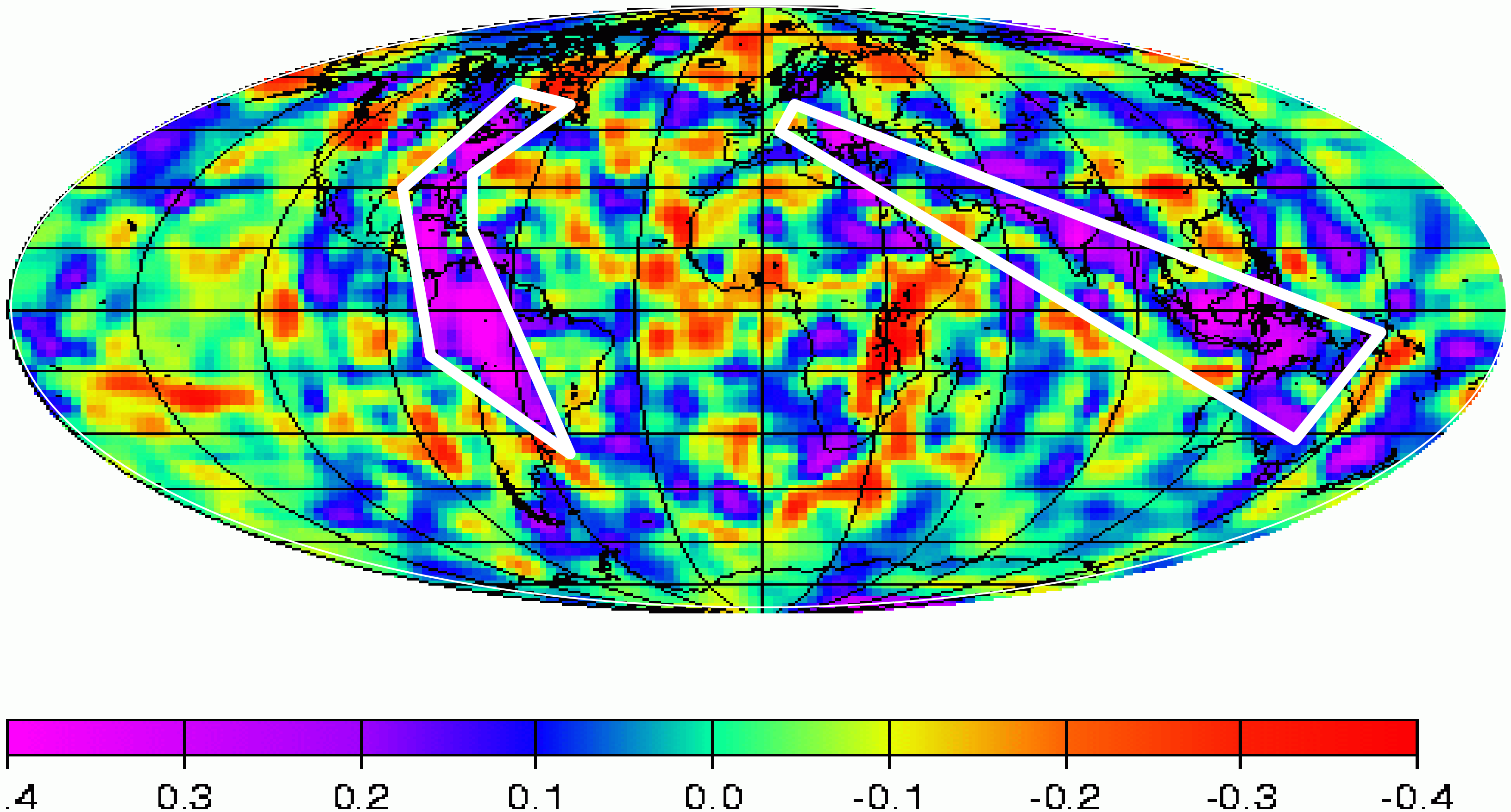
In the last 10 years the links between plate tectonics and mantle convection became much more obvious…



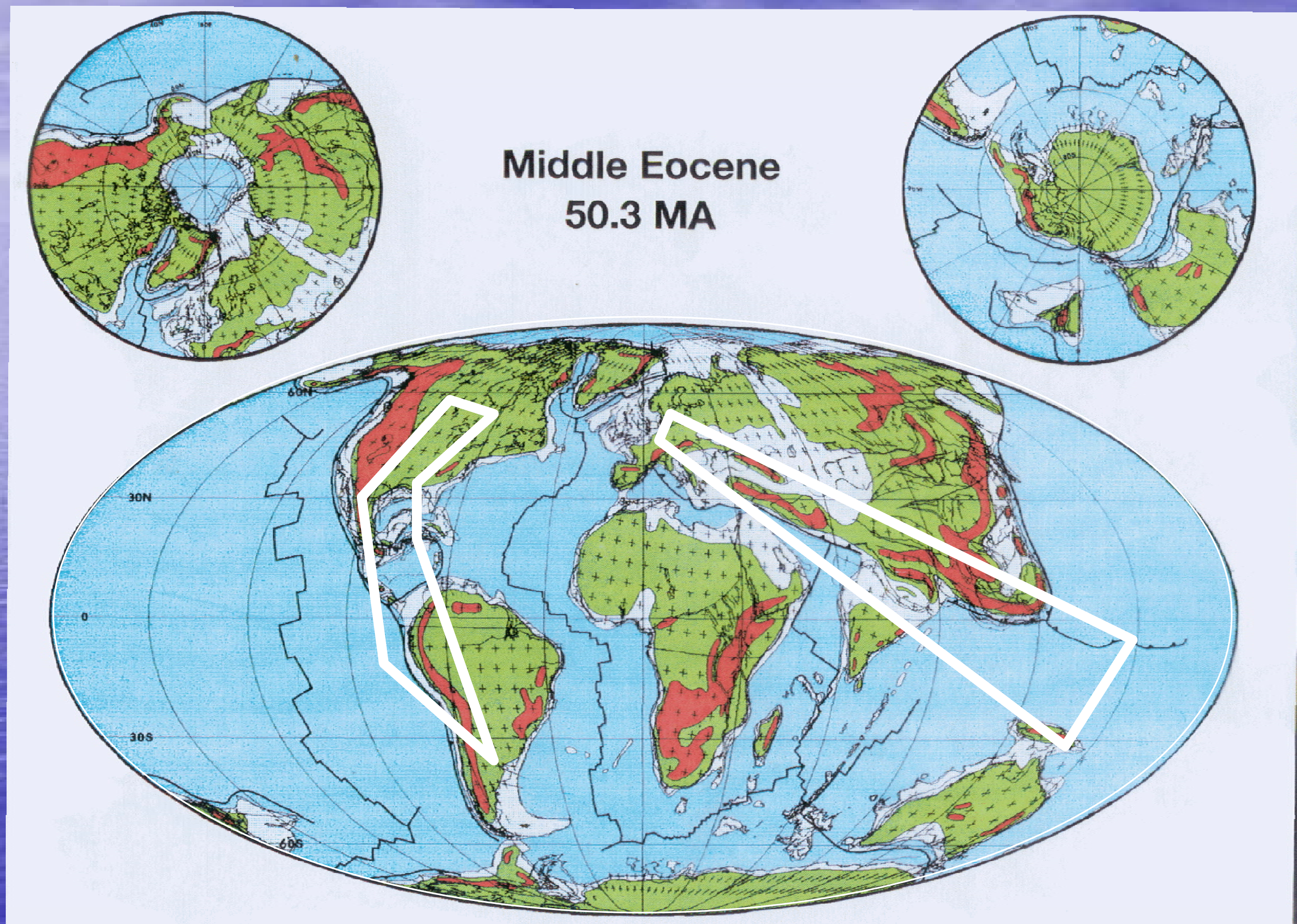


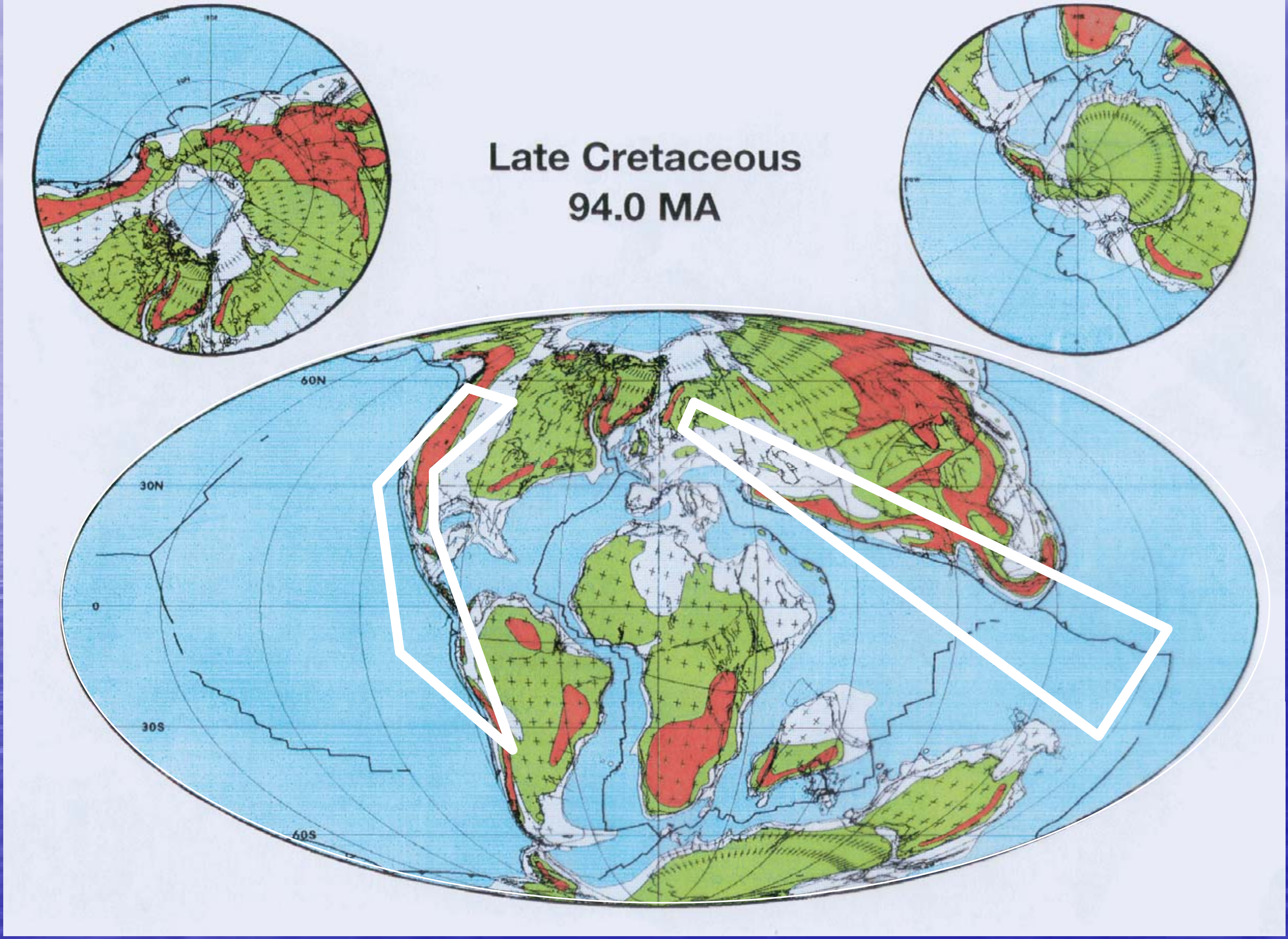
From van der Hilst, Grand, Spakman…

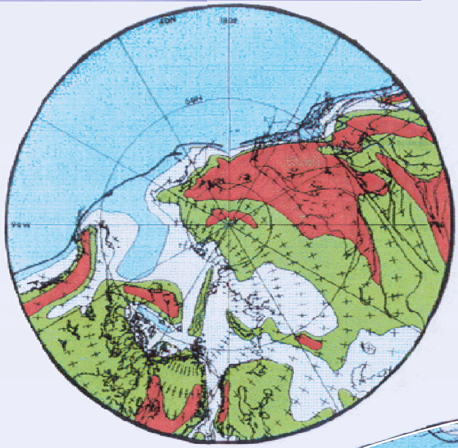
(Grand, 1997) 1100 km



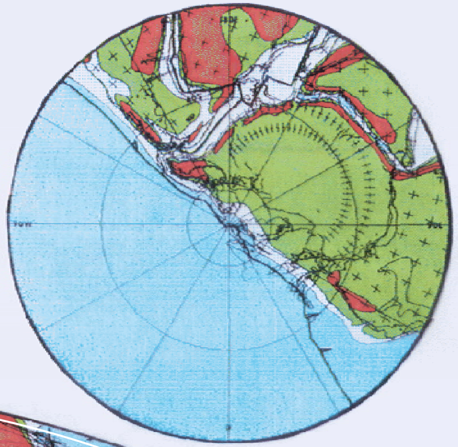
Anomalie de Vitesse (%)

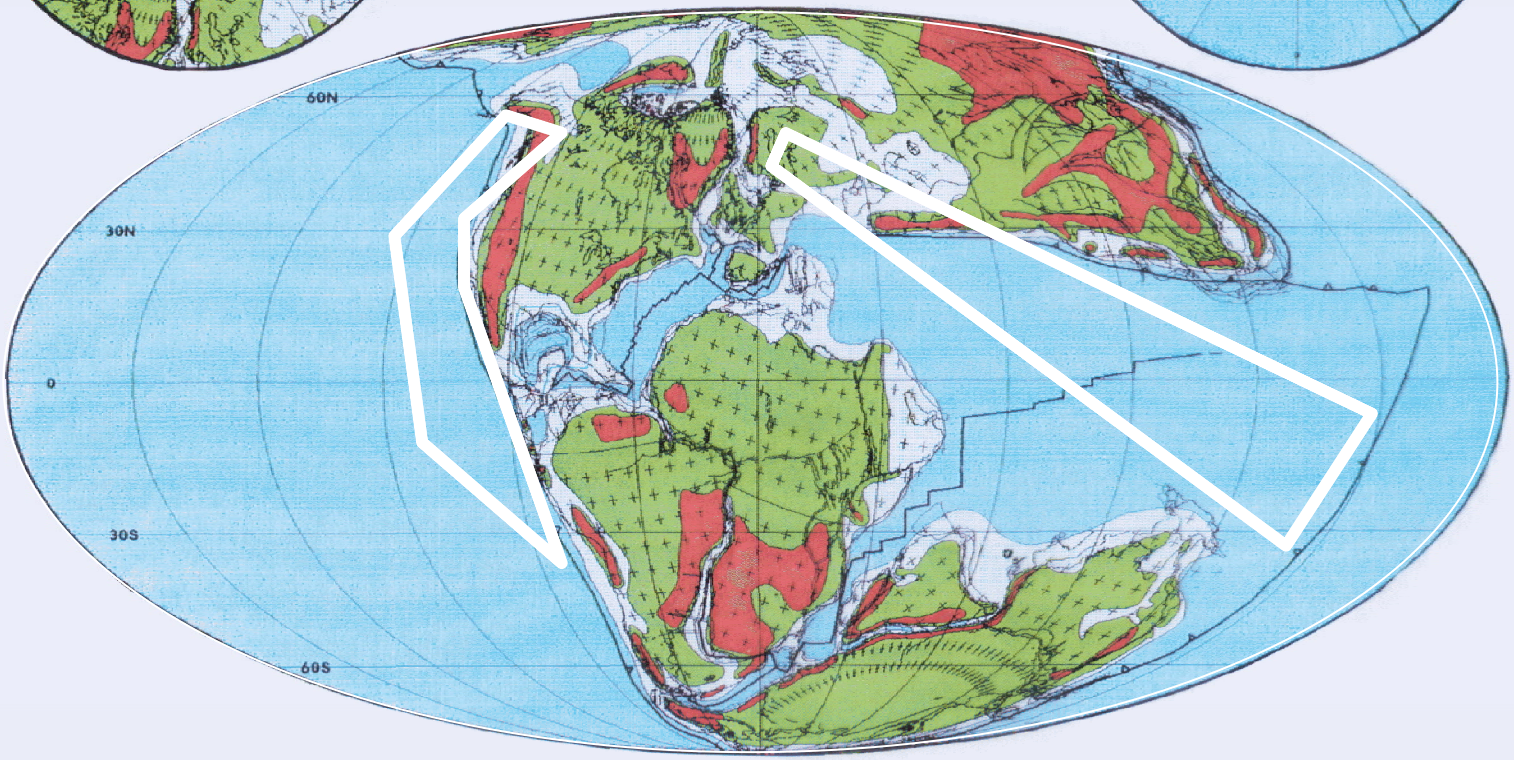

Middle Eocene
50.3 MA
60N
30N
0
30S
60S


Late Cretaceous
94.0 MA
60N
30N
0
30S
60S

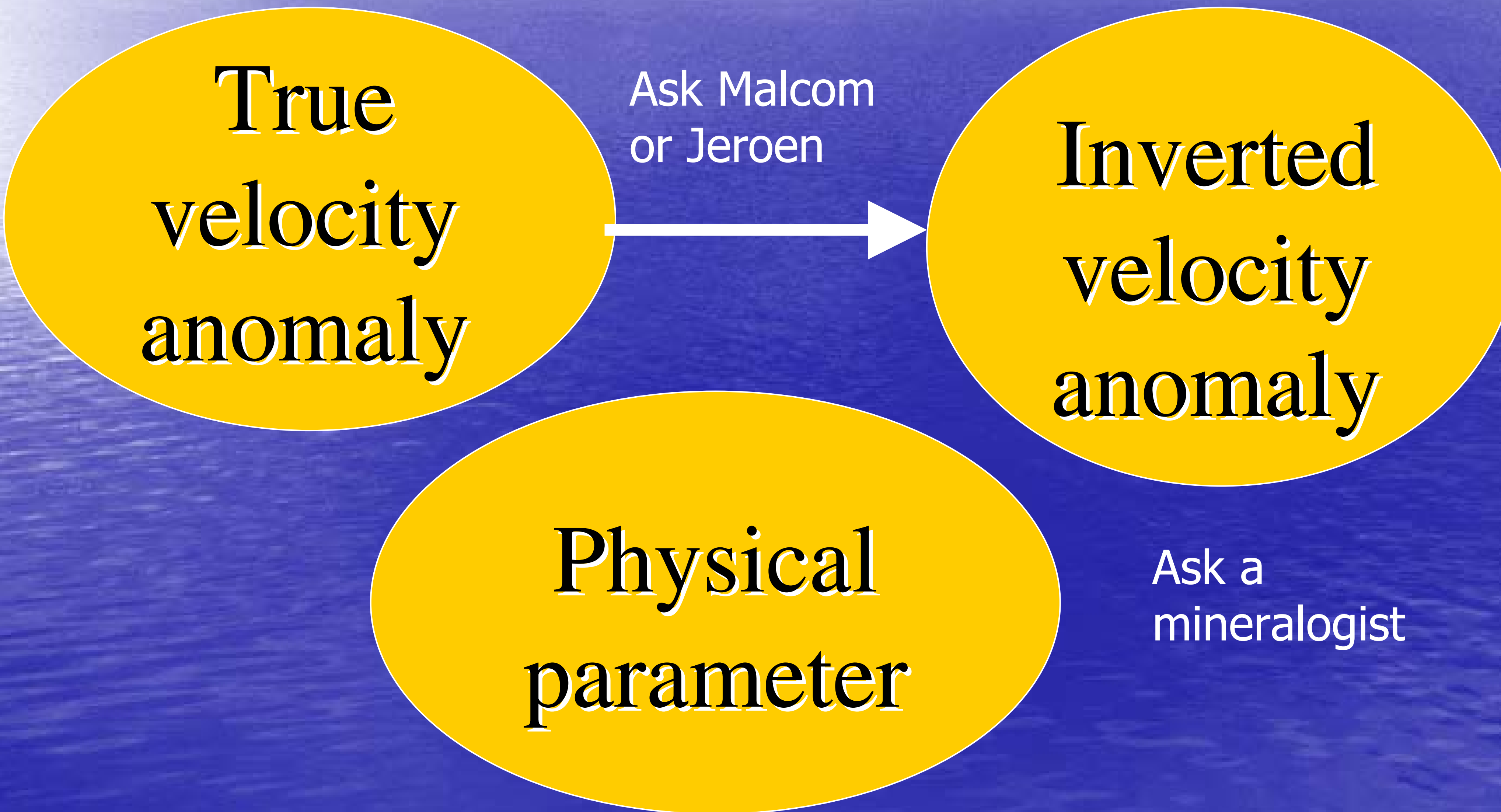


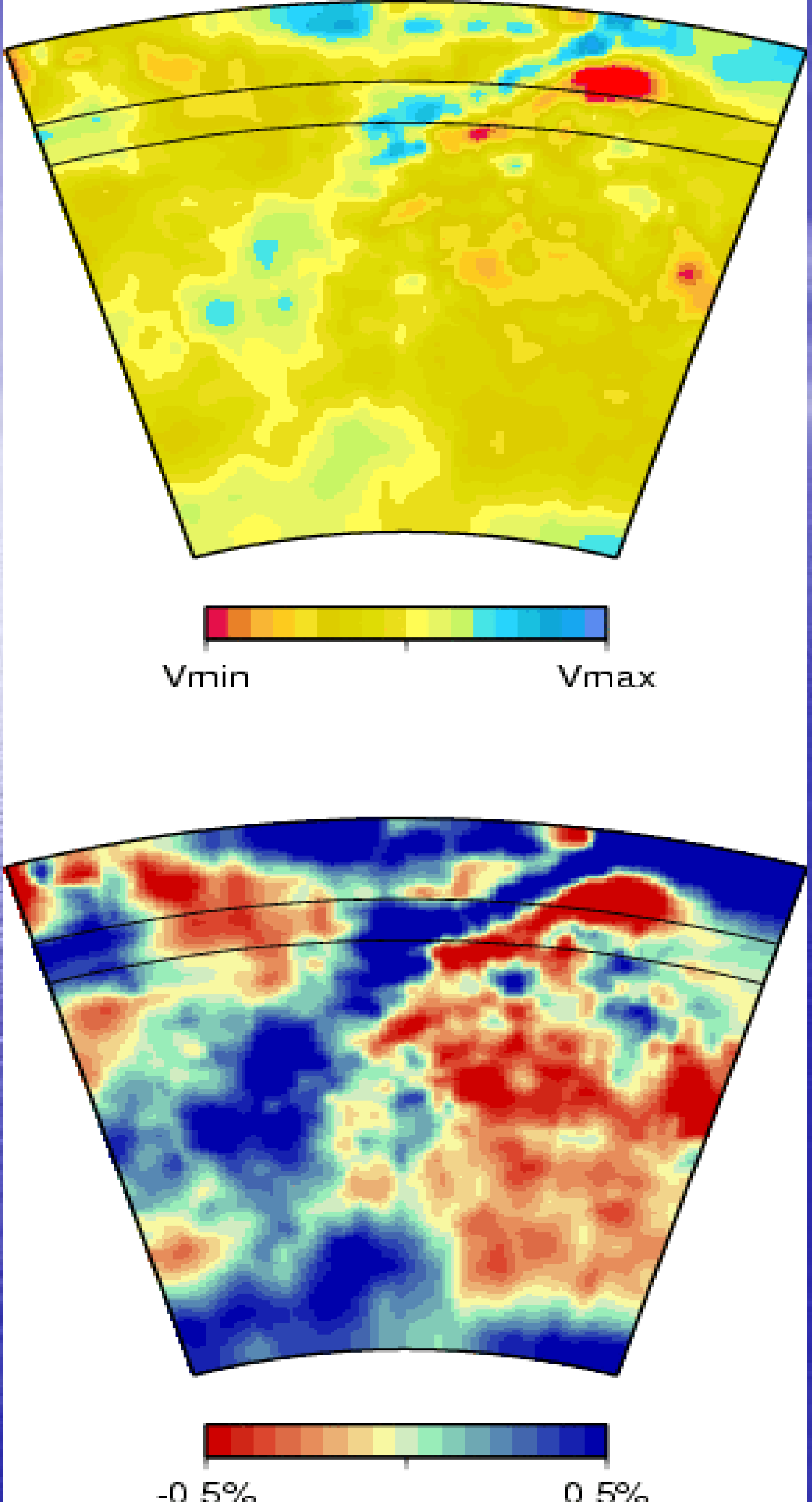
Early Cretaceous
130.2 MA





But what do we really see in the mantle?





Do we see slabs in the lower mantle?

From Rob van der Hilst

Example of a priori density variations

A geodynami… of temperatur… pressure

…mposition

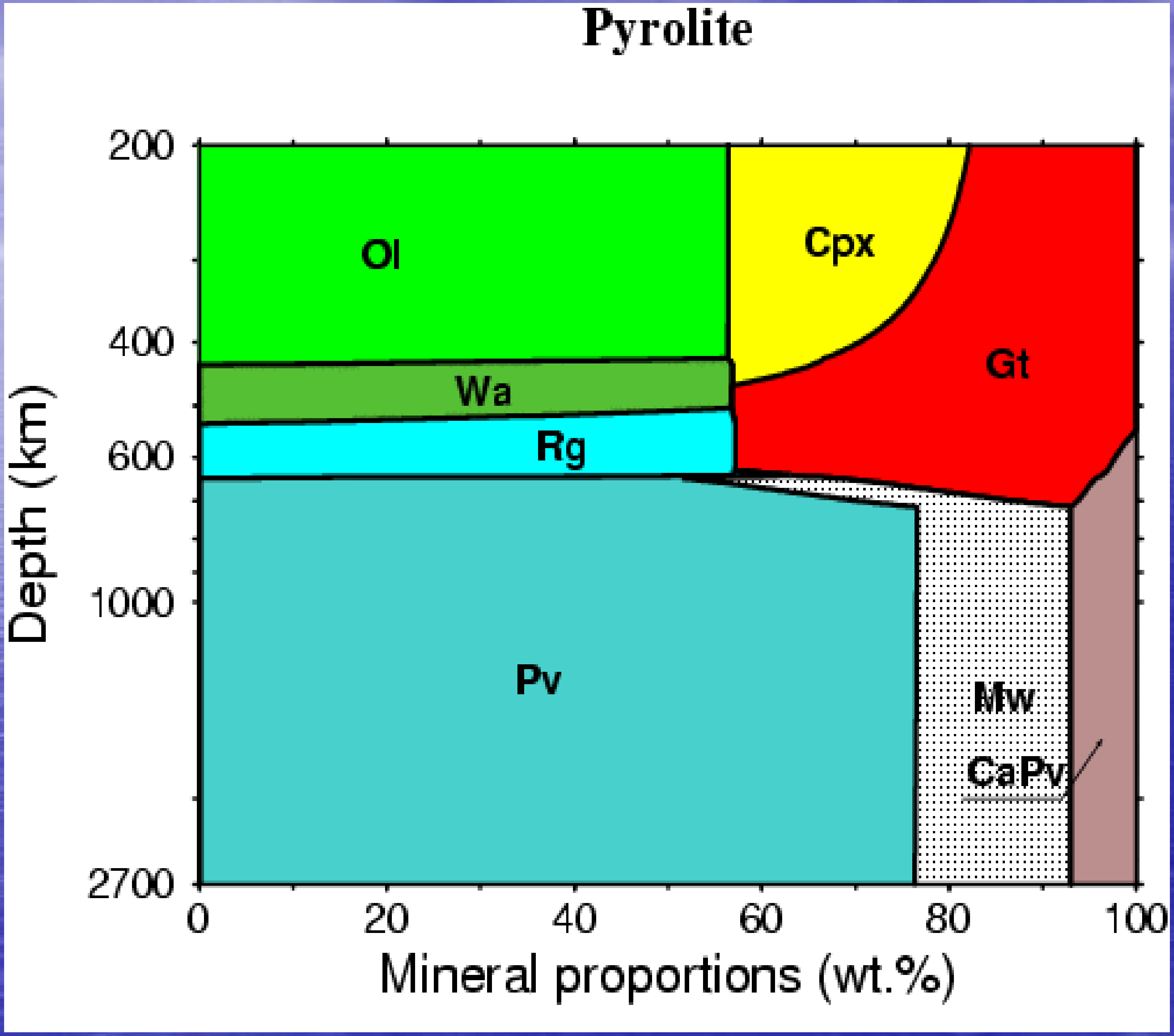
…Si, O

A list of phas… end-member… thermo-elasti… parameters

…zation …ttern…)

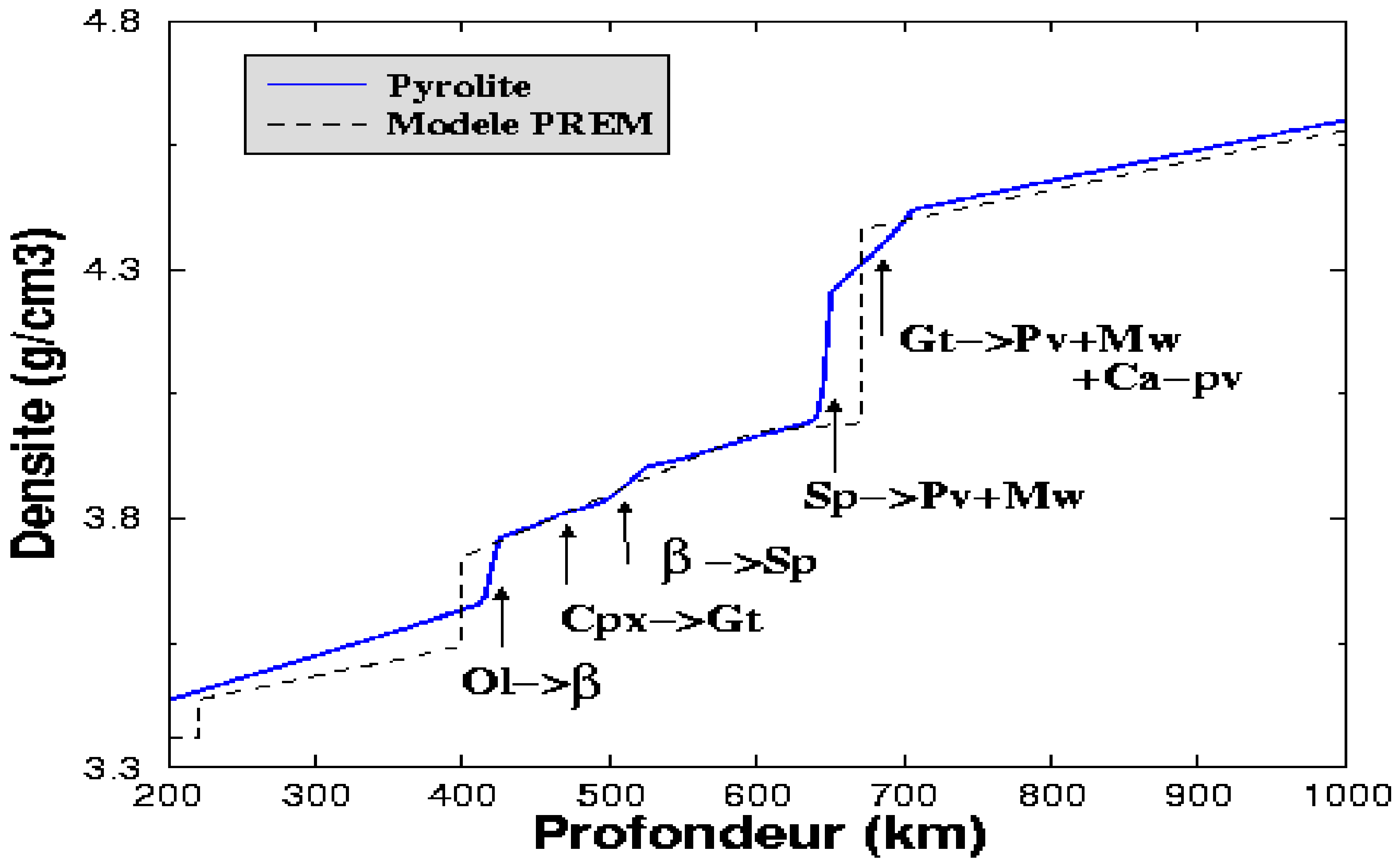
…neralogy

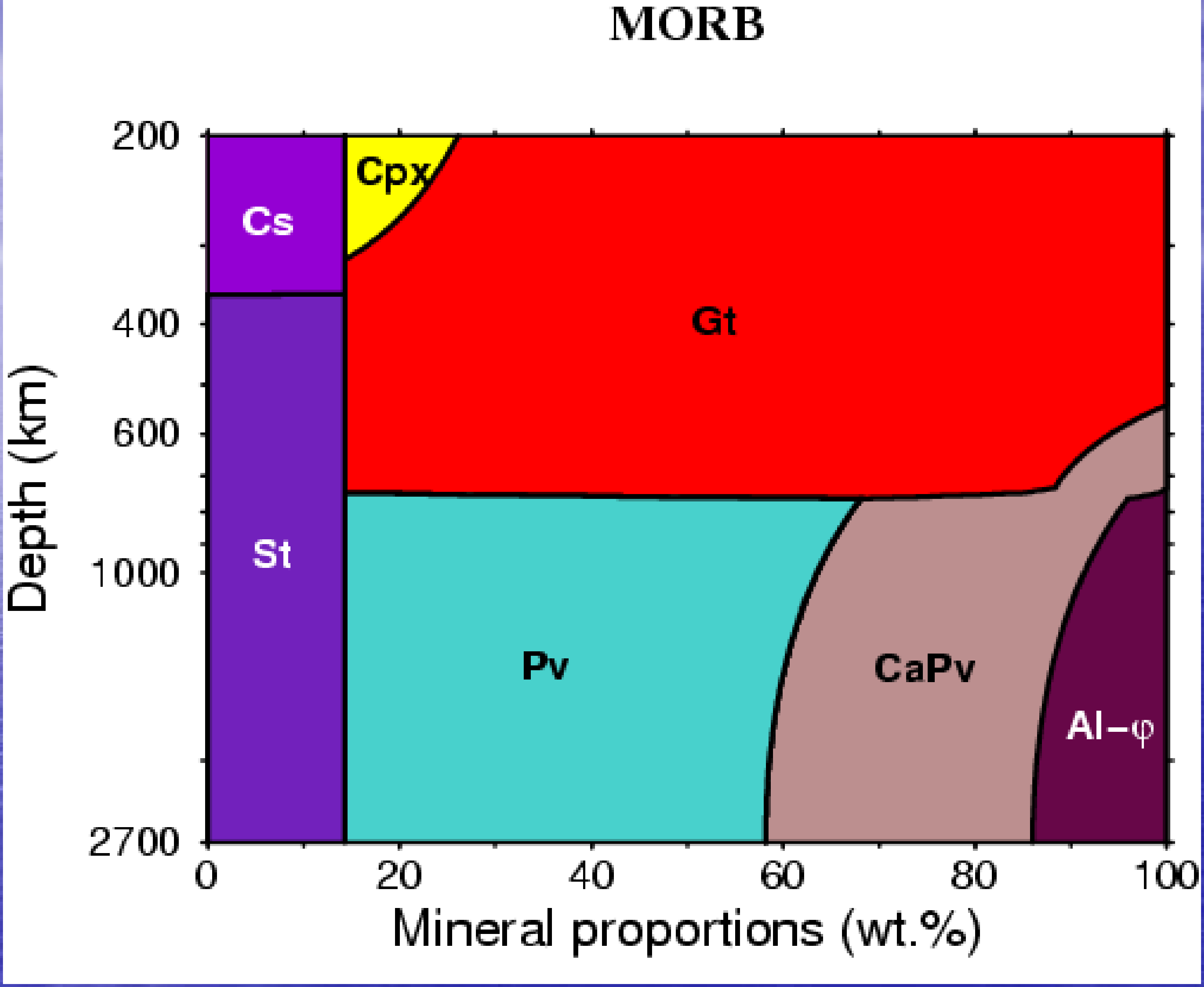
Olivine (α)	Forsterite	Mg_2SiO_4
$(Mg,Fe)_2SiO_4$	Fayalite	Fe_2SiO_4
Olivine (β)	Mg-Wadsleyite	Mg_2SiO_4
$(Mg,Fe)_2SiO_4$	Fe-Wadsleyite	Fe_2SiO_4
Ringwoodite (γ)	Mg-Ringwoodite	Mg_2SiO_4
$(Mg,Fe)_2SiO_4$	Fe-Rinwooditeite	Fe_2SiO_4
Magnesiowustite	Periclase	MgO
$(Mg,Fe)O$	Wustite	FeO
Perovskite	Mg-Perovskite	$MgSiO_3$
(Mg,Fe,Al)	Fe-Perovskite	$FeSiO_3$
$(Al,Si)O_3$	Al-Perovskite	Al_2O_3
Akimotoite	Mg-Akimotoite	$MgSiO_3$
$(Mg,Fe)SiO_3$	Fe-Akimotoite	$FeSiO_3$
Orthopyroxene	Orthoenstatite	$MgSiO_3$
$(Mg,Fe)SiO_3$	Orthoferrosilite	$FeSiO_3$
Clinopyroxene	Diopside	$CaMgSi_2O_6$
(Ca,Mg,Fe)	Hedenbergite	$CaFeSi_2O_6$
(Mg,Fe,Al)	Ca-Tschermak	$CaAl_2SiO_6$
$(Al,Si)_2O_6$	Clinoenstatite	$Mg_2Si_2O_6$
	Clinoferrosilite	$Fe_2Si_2O_6$
Grenat	Pyrope	$Mg_3Al_2Si_3O_{12}$
$(Ca,Mg,Fe)_3$	Almandin	$Fe_3Al_2Si_3O_{12}$
$(Mg,Fe,Al,Si)_2$	Grossulaire	$Ca_3Al_2Si_3O_{12}$
Si_3O_{12}	Mg-Majorite	$Mg_4Si_4O_{12}$
	Fe-Majorite	$Fe_4Si_4O_{12}$

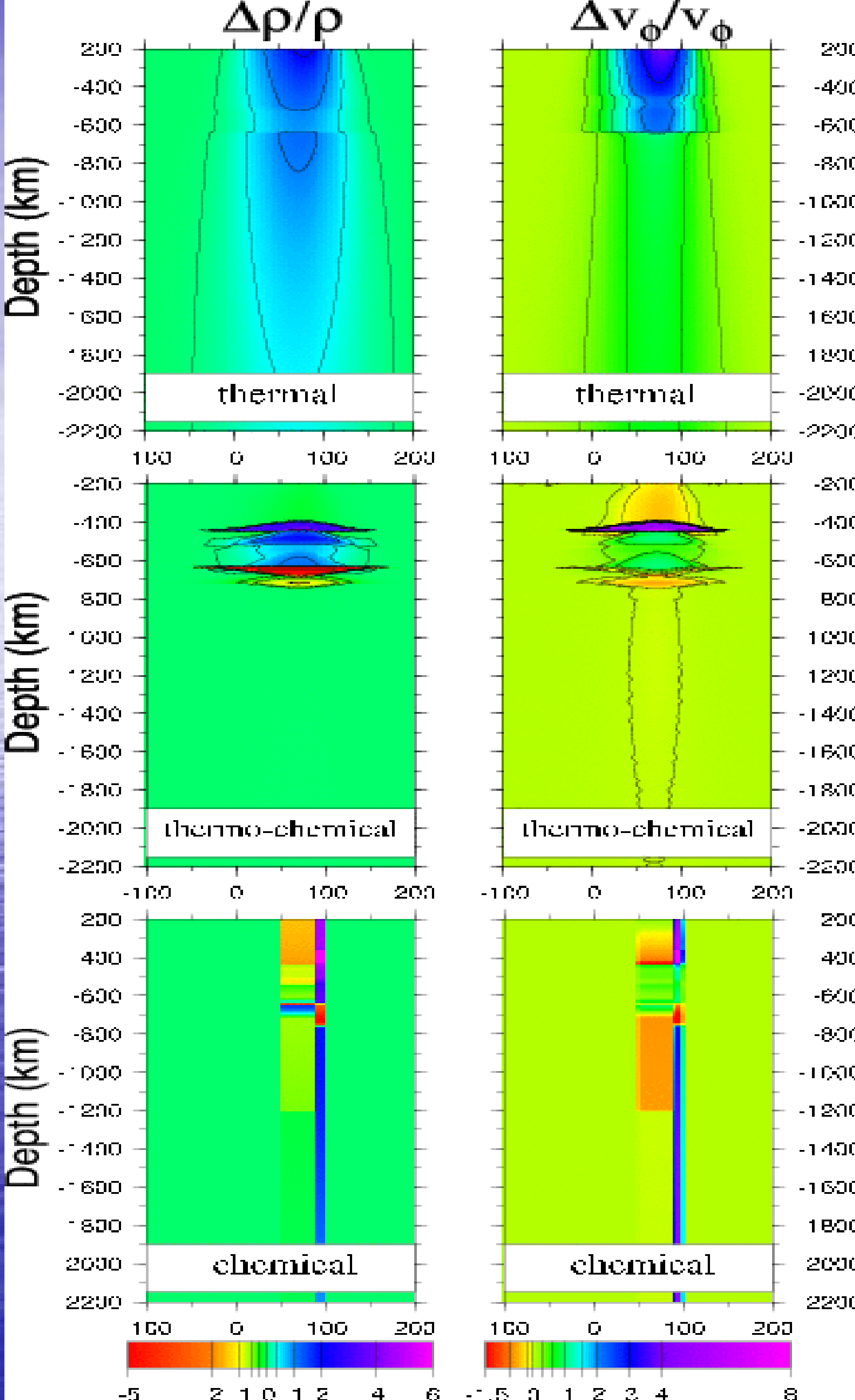


Matas, Ricard et al.

Mineralogy vs. Seismology




MORB
200
400
600
1000
2700
Depth (km)
Cs
St
Cpx
Gt
Pv
CaPv
Al−φ
0
20
40
60
80
100
Mineral proportions (wt.%)



Example of a vertically sinking slab:

Basalt+harzburgite+pyrolite

Intrinsic thermal effect

+

Changes in mineralogy to maintain equilibrium

+

Changes in mineralogy according to changes in elemental composition

- The thermal anomalies,
- the thermo-chemical anomalies,
- the compositional anomalies

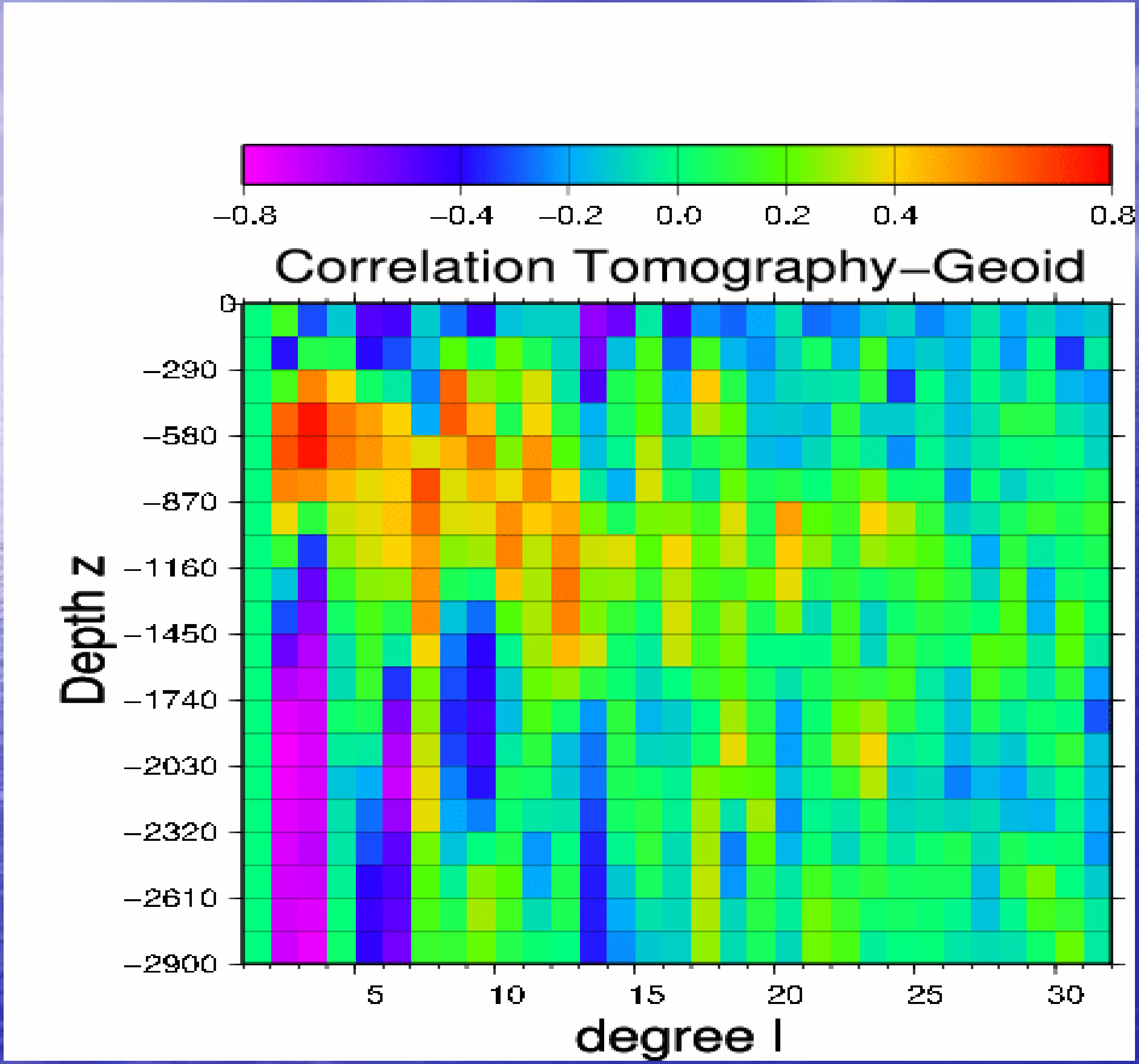
have similar amplitudes…

The end of purely thermal convection models?...

Joerg, Al…


Ra=1000.000000 Ras=3000.000000 Numx = 257 Numy = 129
Step: 1
Time: 0.000000
Temp
Min: 0.
Max: 1.
Chem
Min: 0.000000
Max: 2.667106
Uran min/max 0.00 / 5.00
Min: 1.849999
Max: 1.850000
He4 min/max 0.00 / 5.00
Min: 3.699998
Max: 3.700001

2. Rheology

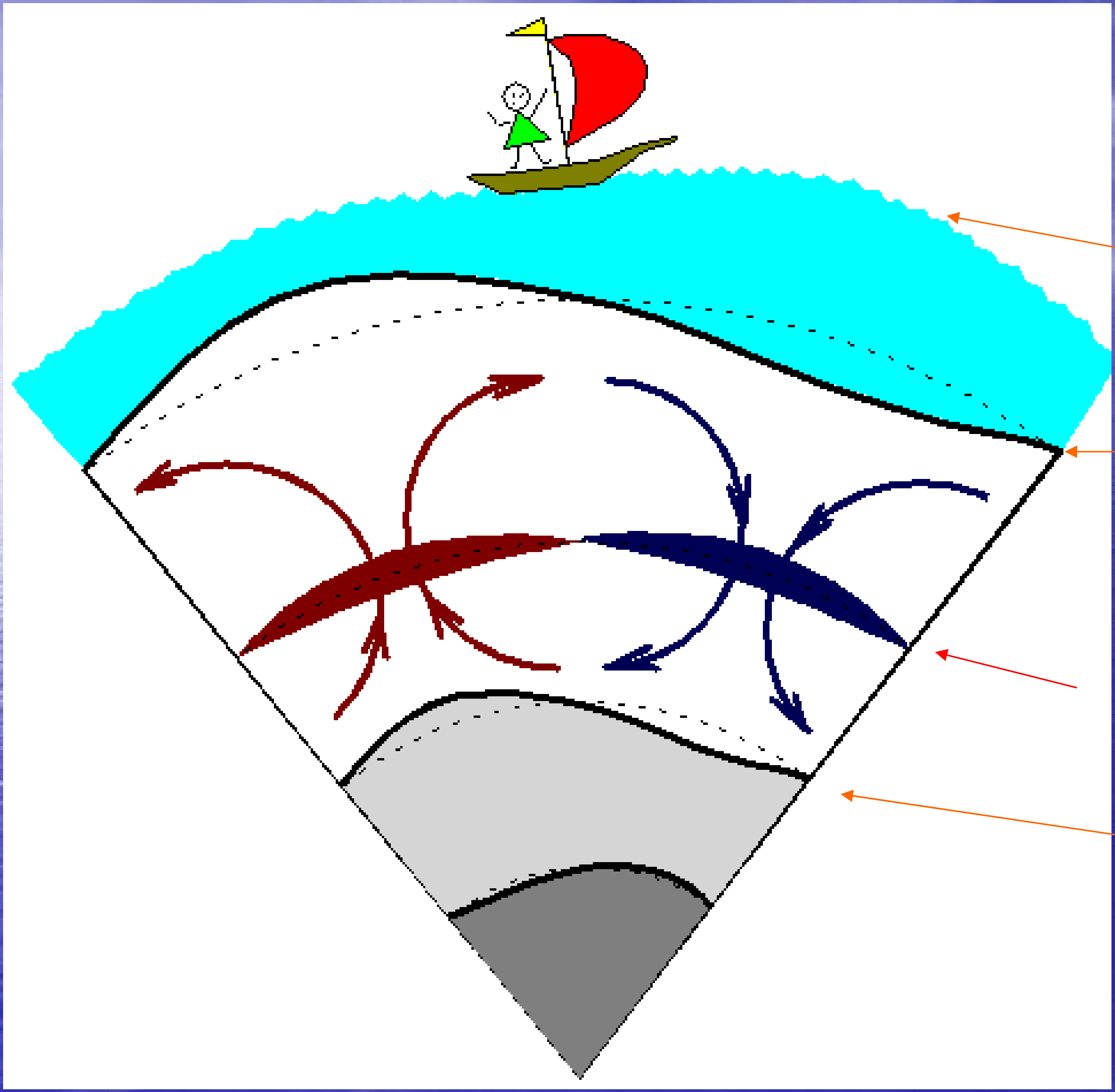


Negatif

Positif

Negatif

Thorsten, Ondrej…



Geoid

Deflexion

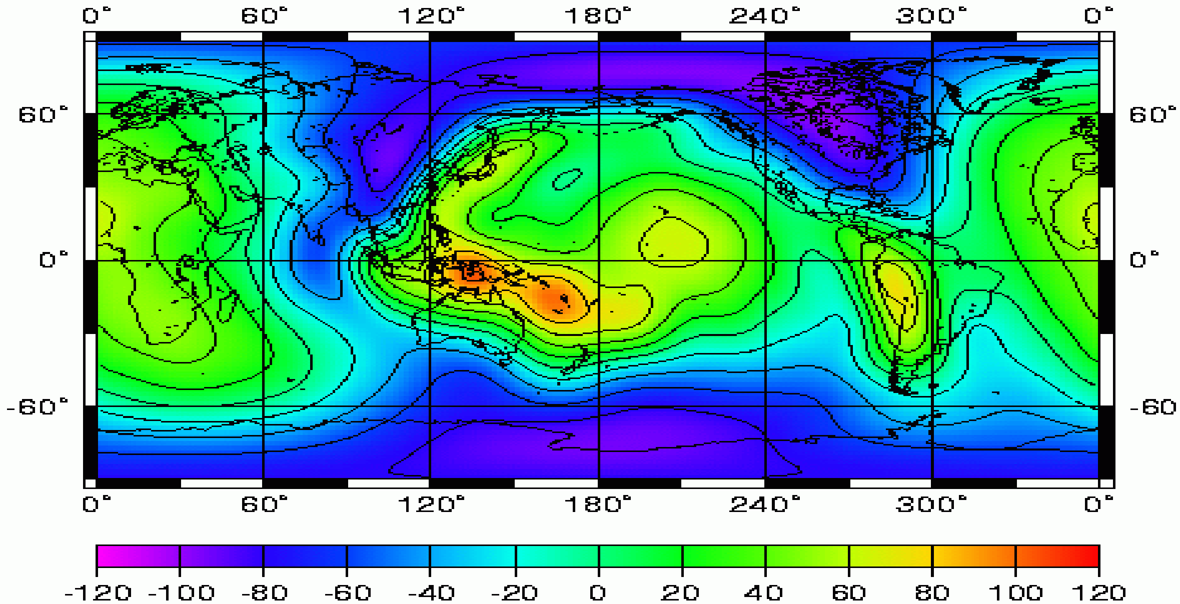
"Dynamic Topography"

Loads

Deflexion

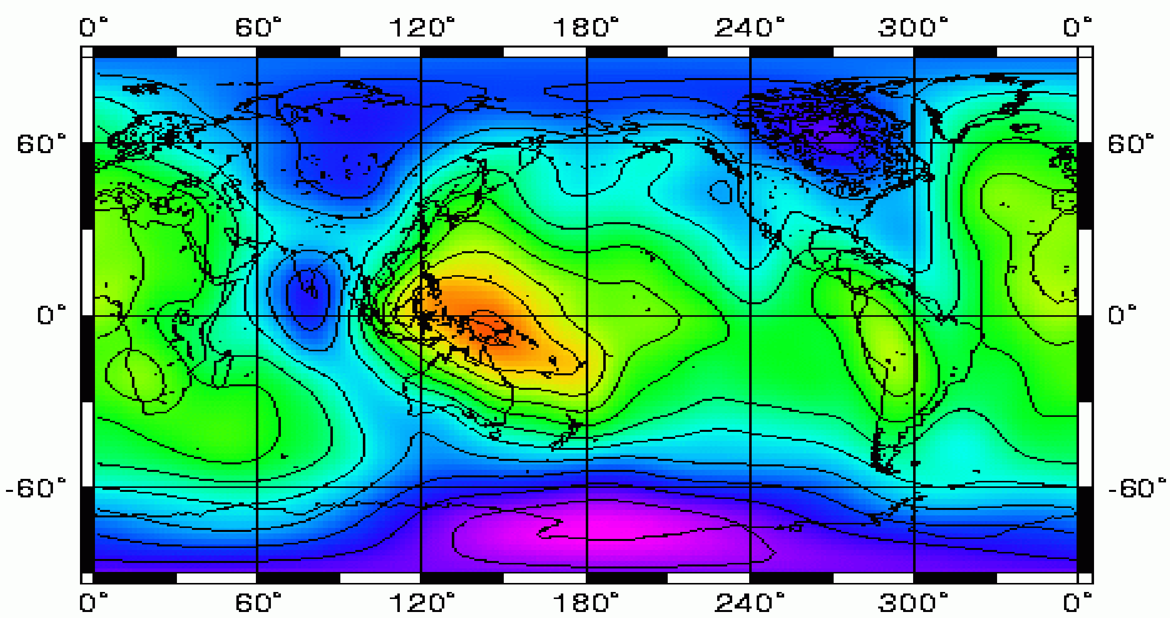
The gravity is anti-correlated with the internal density, except in the vicinity of a factor 10-100 viscosity increase…

GEOIDE SYNTH.

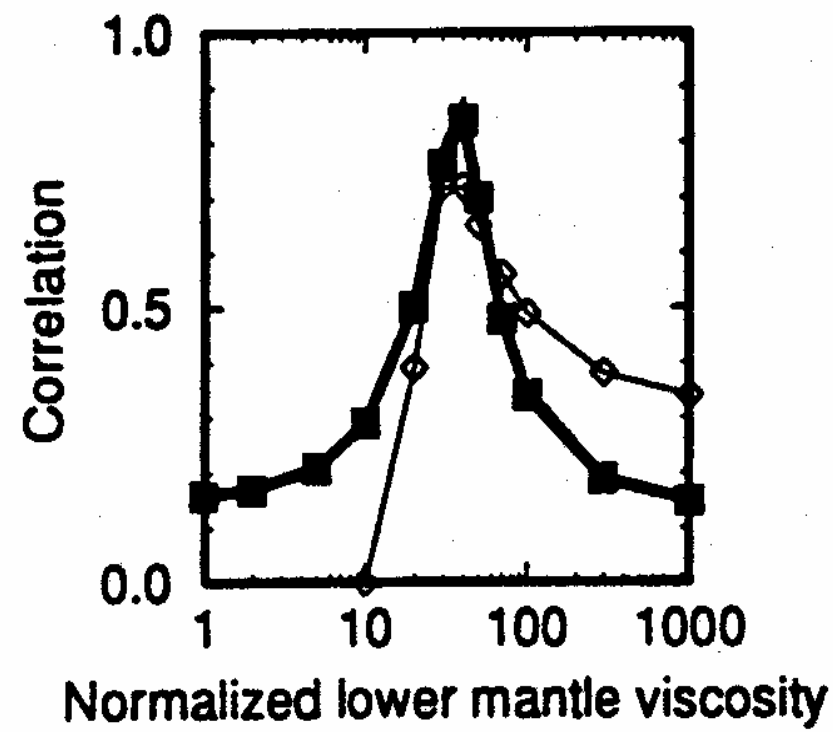


metres

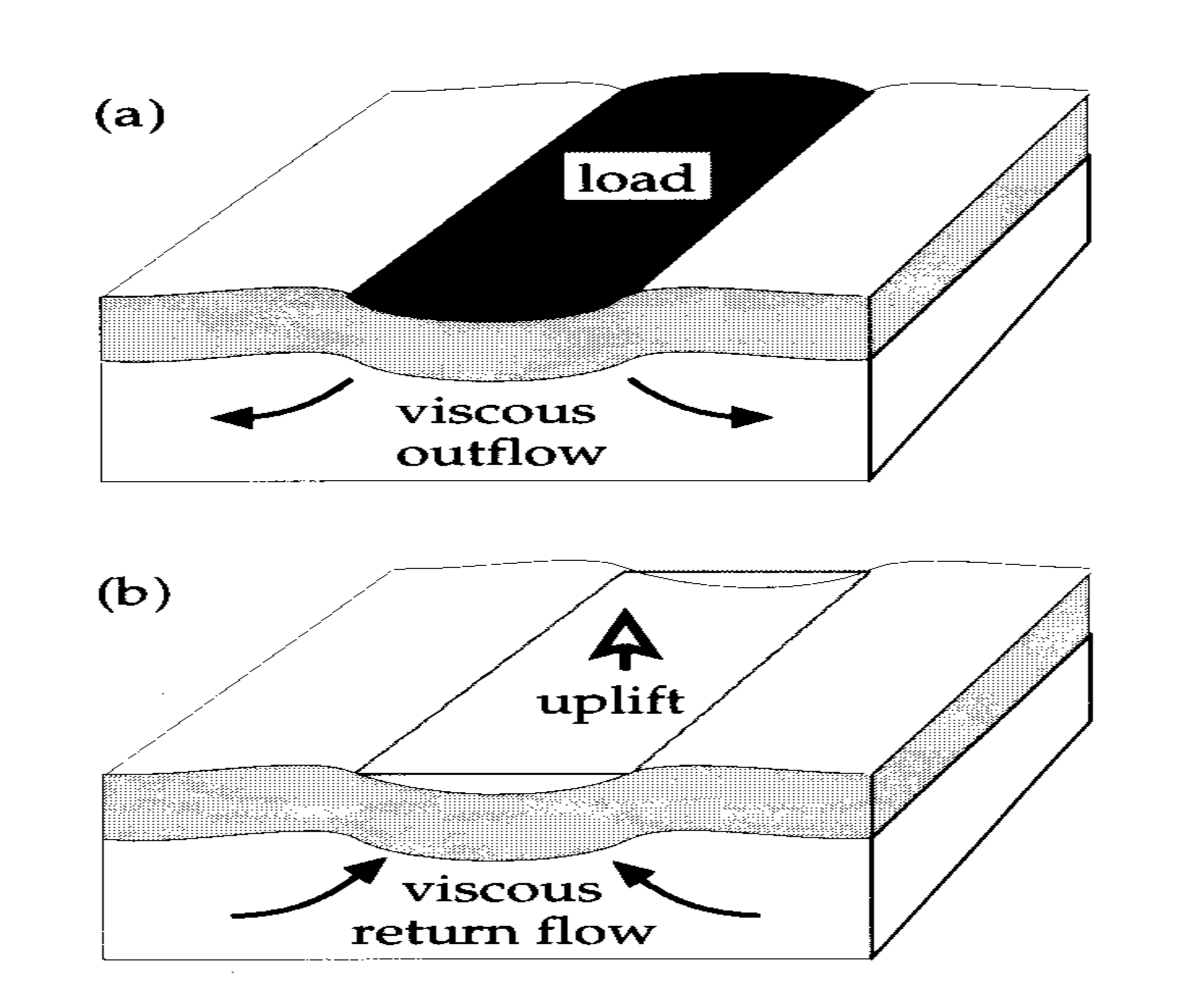
GEOIDE



COMP. VS. OBS. GEOID



…which is in agreement(?) with post-glacial rebound modeling…



Kurt…

Finland

Hudson

Scotland

Bretagne

- But do we see the dynamic topography?

  not a lot!

- But should the rheologyy be only linear visco-elastic, depth-dependent?

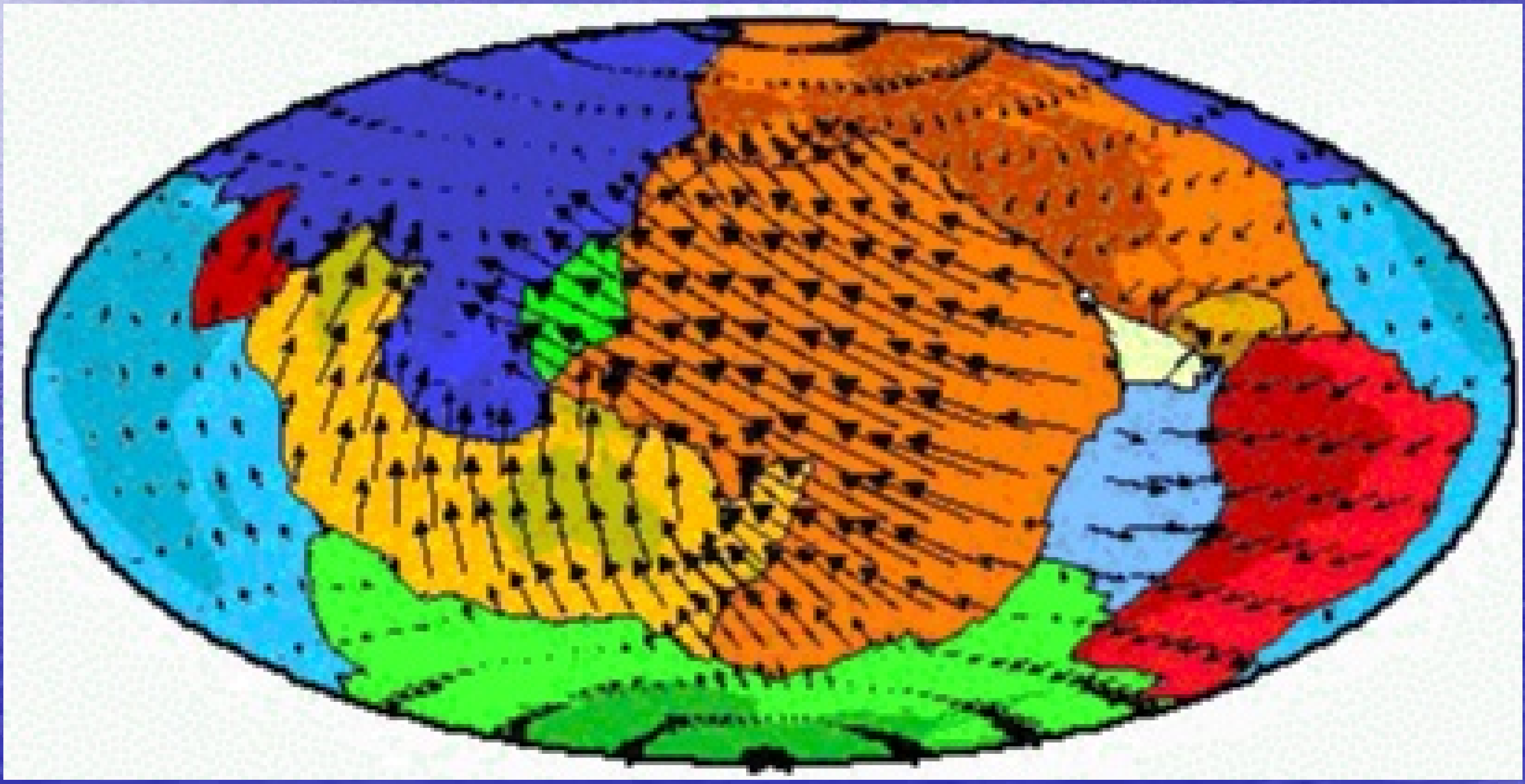
  no 1)

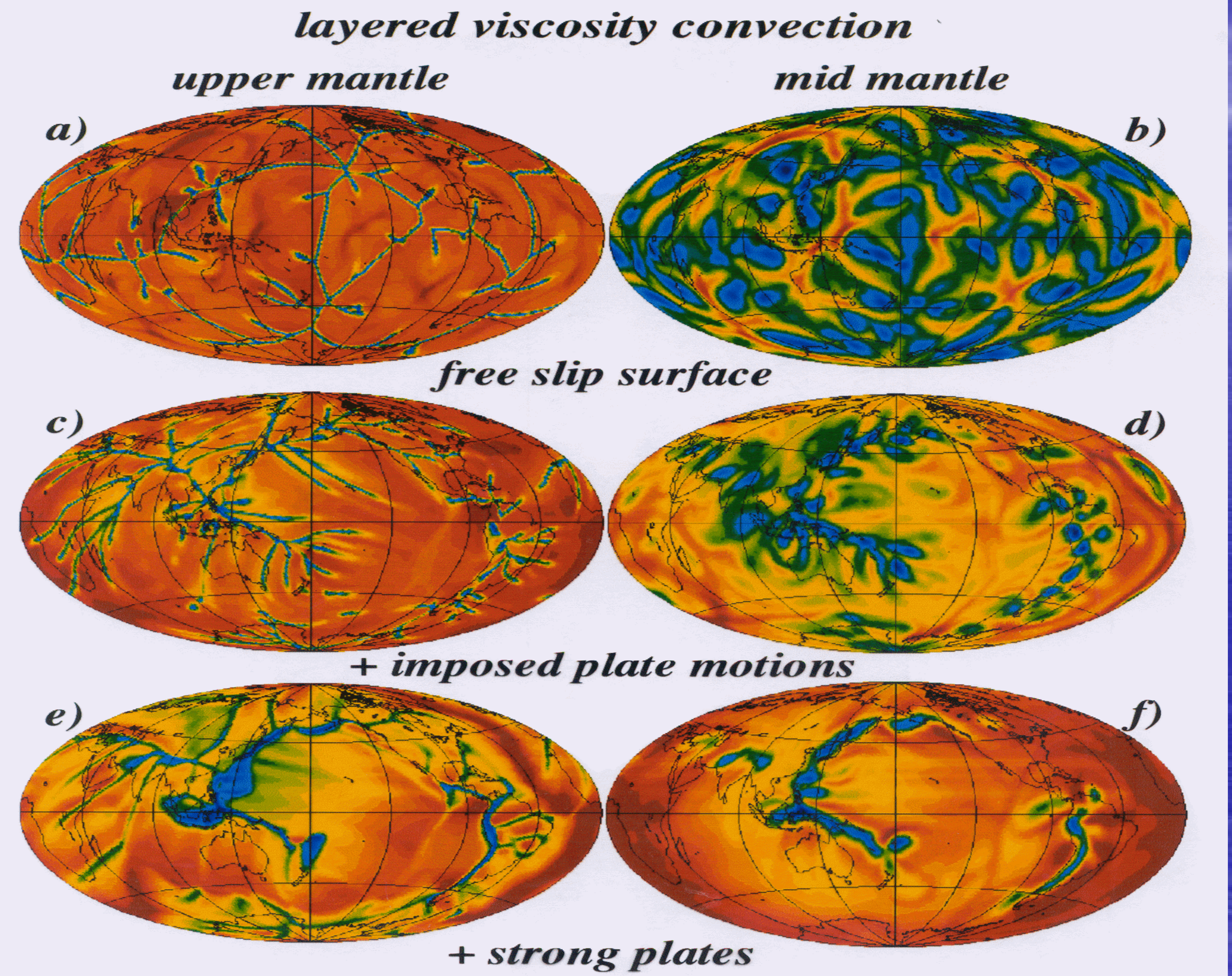
Rheology depends on stress, temperature, melt, water content, grain size, composition…

Patrick, Greg, Mark…

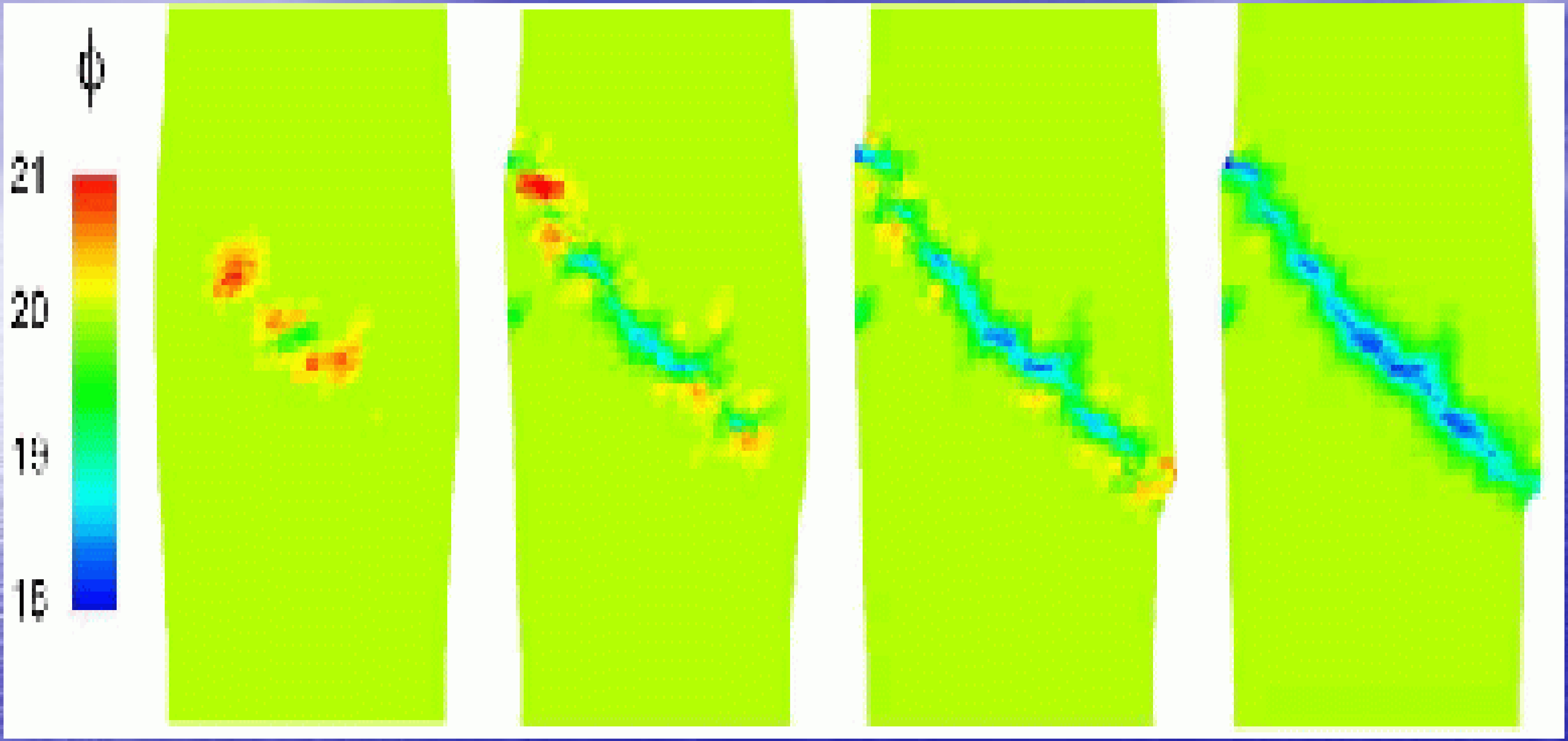
- But should the rheology be only depth dependent?

no 2)



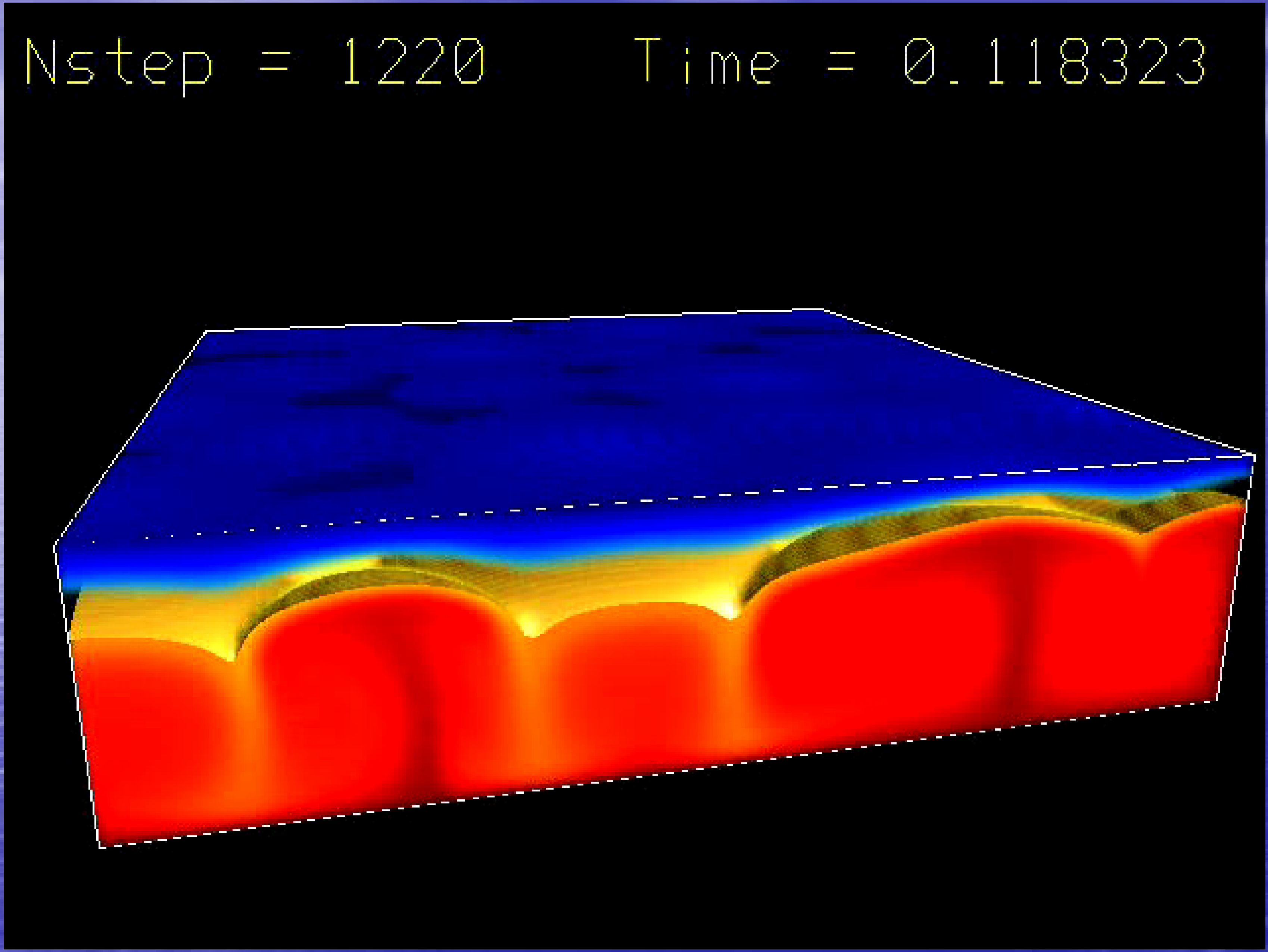

layered viscosity convection
upper mantle
mid mantle
a)
b)
free slip surface
c)
d)
+ imposed plate motions
e)
f)
+ strong plates

LOCALISATION



The rheology has a memory.

It depends on ~~stress~~, ~~temperature~~, melt, water content, grain size, composition…



Joerg

Damage variable x

Rheology=F(x)

Dx/dt=damage-healing

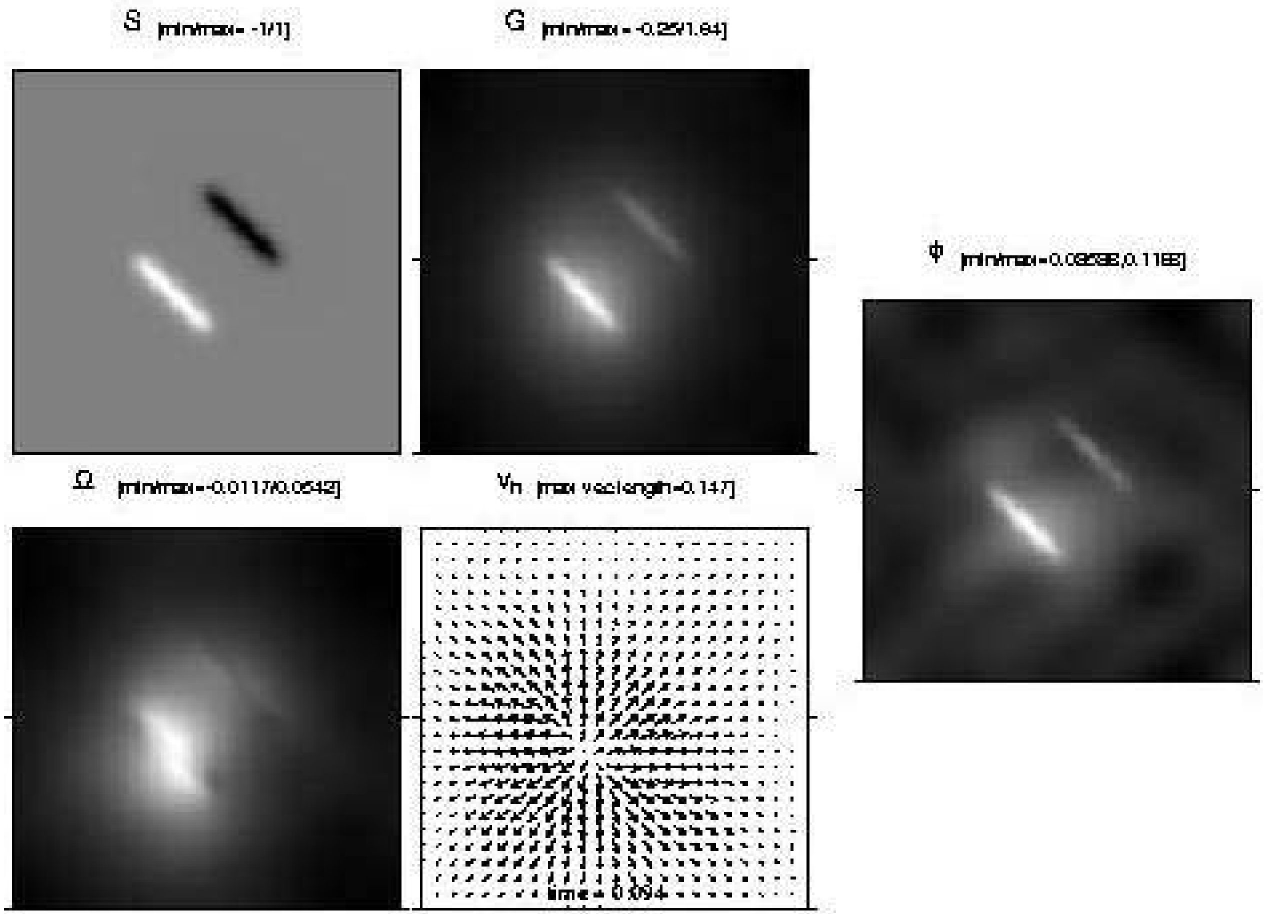
Ex:

DT/Dt=shear_heating-diffusion

D <grain size>/Dt=fracture_nucleation-coarsening

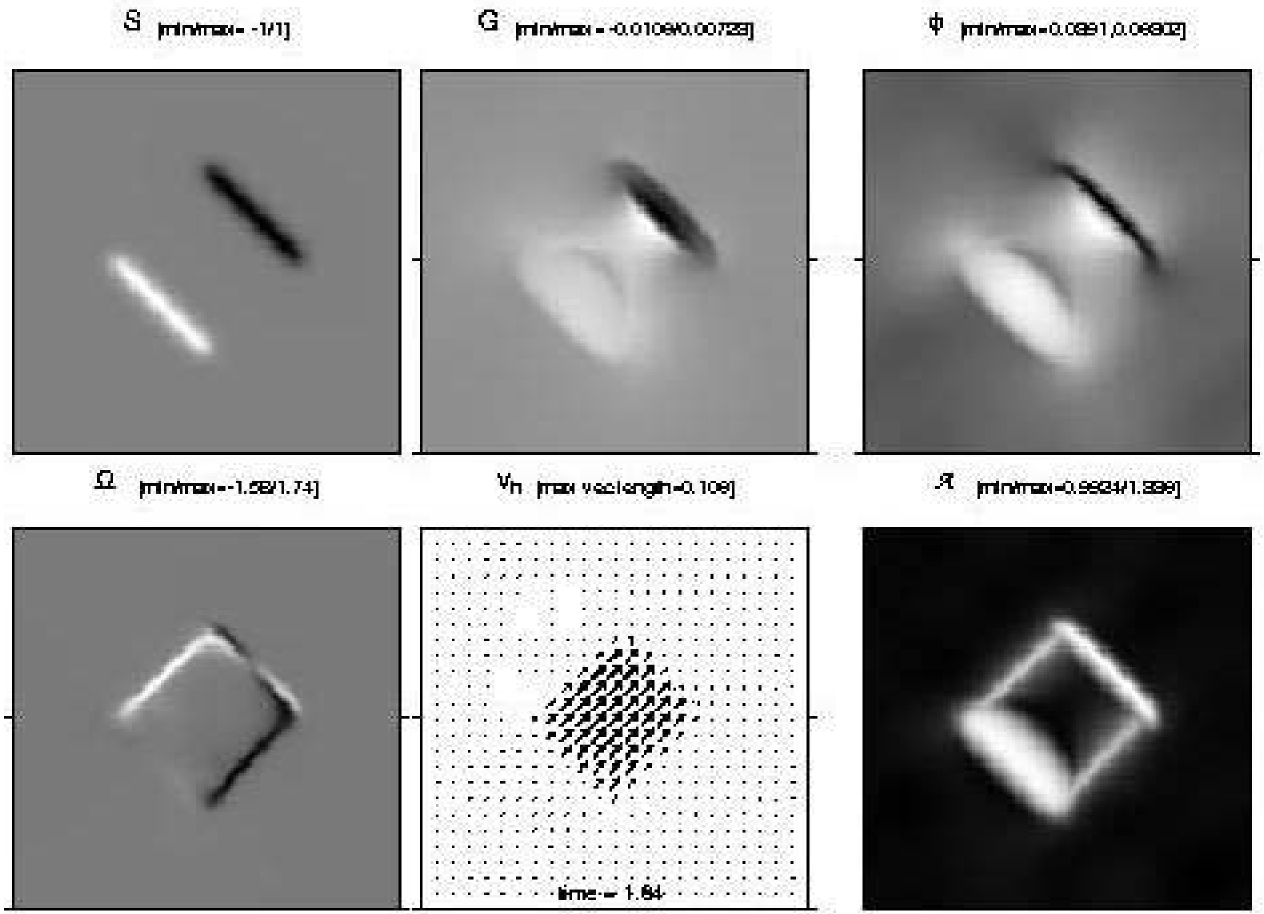
D porosity/Dt=microcracking-compaction

Porosity Related Damage $f_{\alpha_0} = 0, f_\phi \neq 0$



Dave

Grain Size Related Damage $f_{\alpha_0} \neq 0, f_\phi = 0$

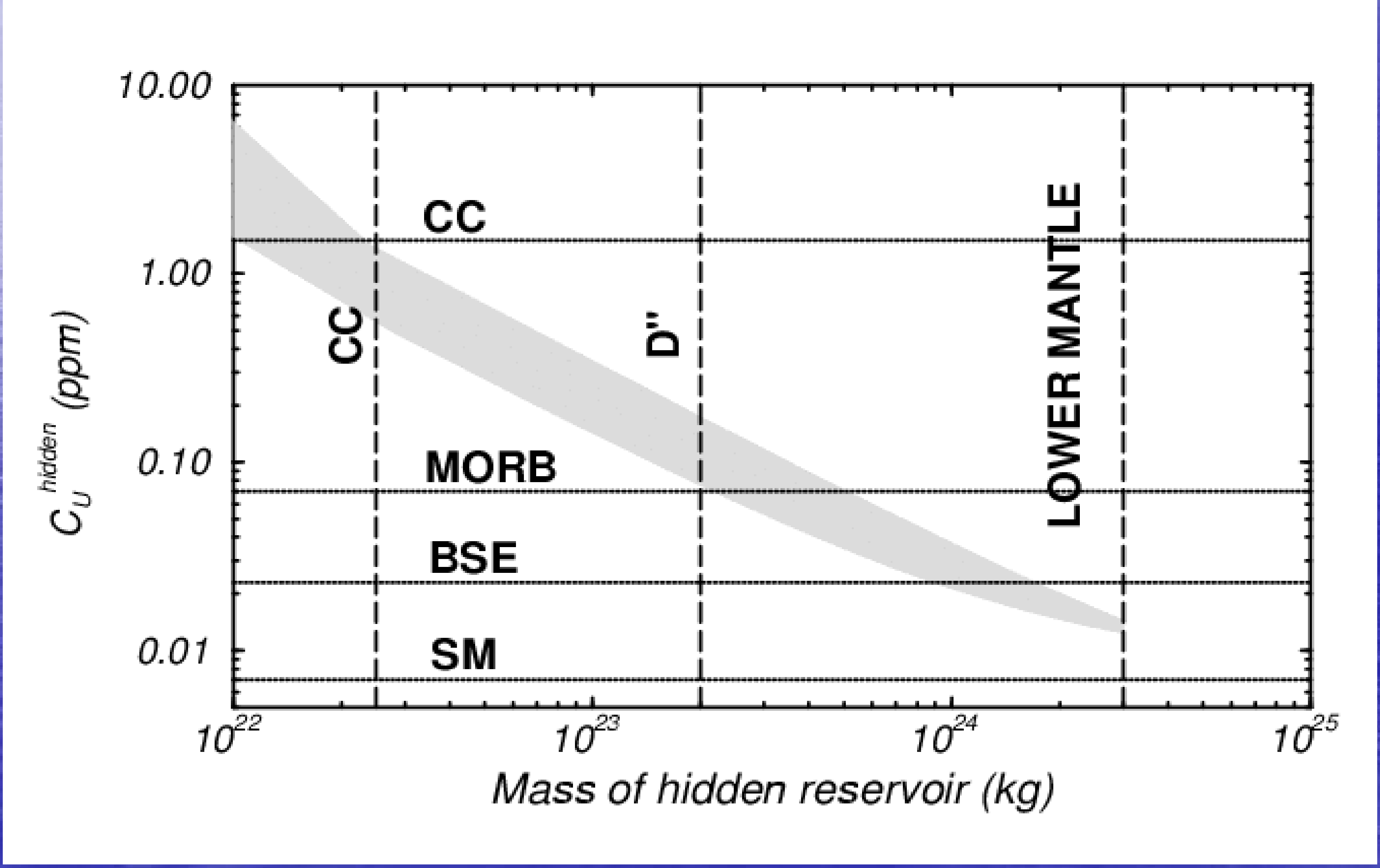


The end of models with linear depth dependent models…

Mixing/geochemistry

Mass Balance for trace elements

Bulk Sil. Earth = Crust+Morb source+Hidden res



There is a hidden reservoir…

- ✓ Slightly depleted=lower mantle
- ✓ Primitive=50% of the mantle
- ✓ With higher concentration of incompatible elements than BSE (D" with oceanic crust composition)

^{40}Argon

Produced in the Earth 940 pmol/g

Atmosphere 44%

Crust 3.5%

Upper mantle .9 % (25 pmol/g)

Lower mantle 52 % (720 pmol/g)

But K/U??

50-200 pmol/g

Another K-rich reservoir?

Total Heat Sources U, Th, K…

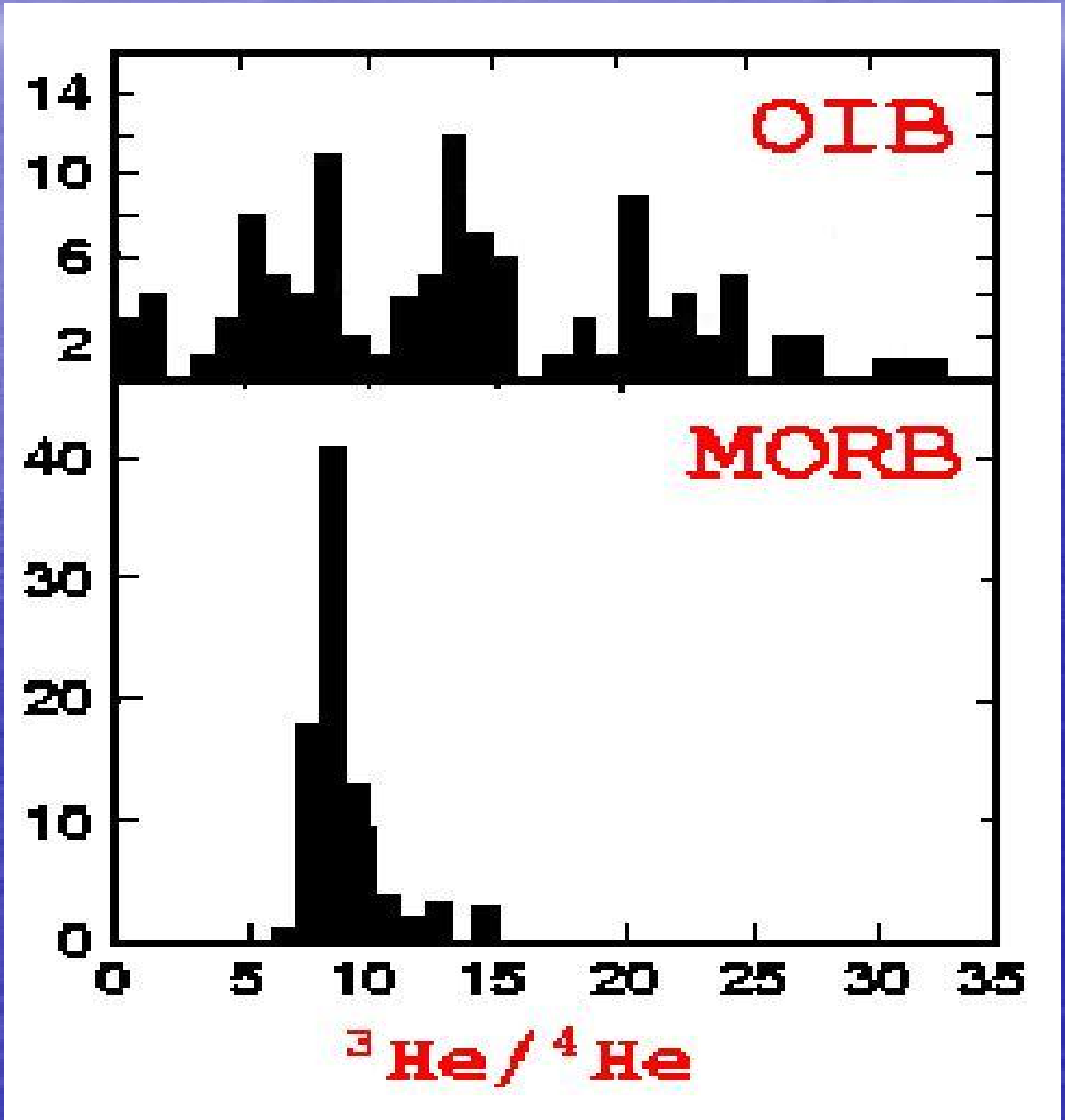
H=20 TW

Q=43 TW

Cooling=Production-Surface heat loss

Cooling 23 TW !

Rare Gas



From Hart & Zindler

✓OIBs are more heterogeneous than MORBs (but there is a continuous range between OIBs and MORBs)

Erasing heterogeneities

Mixing = stirring + diffusion

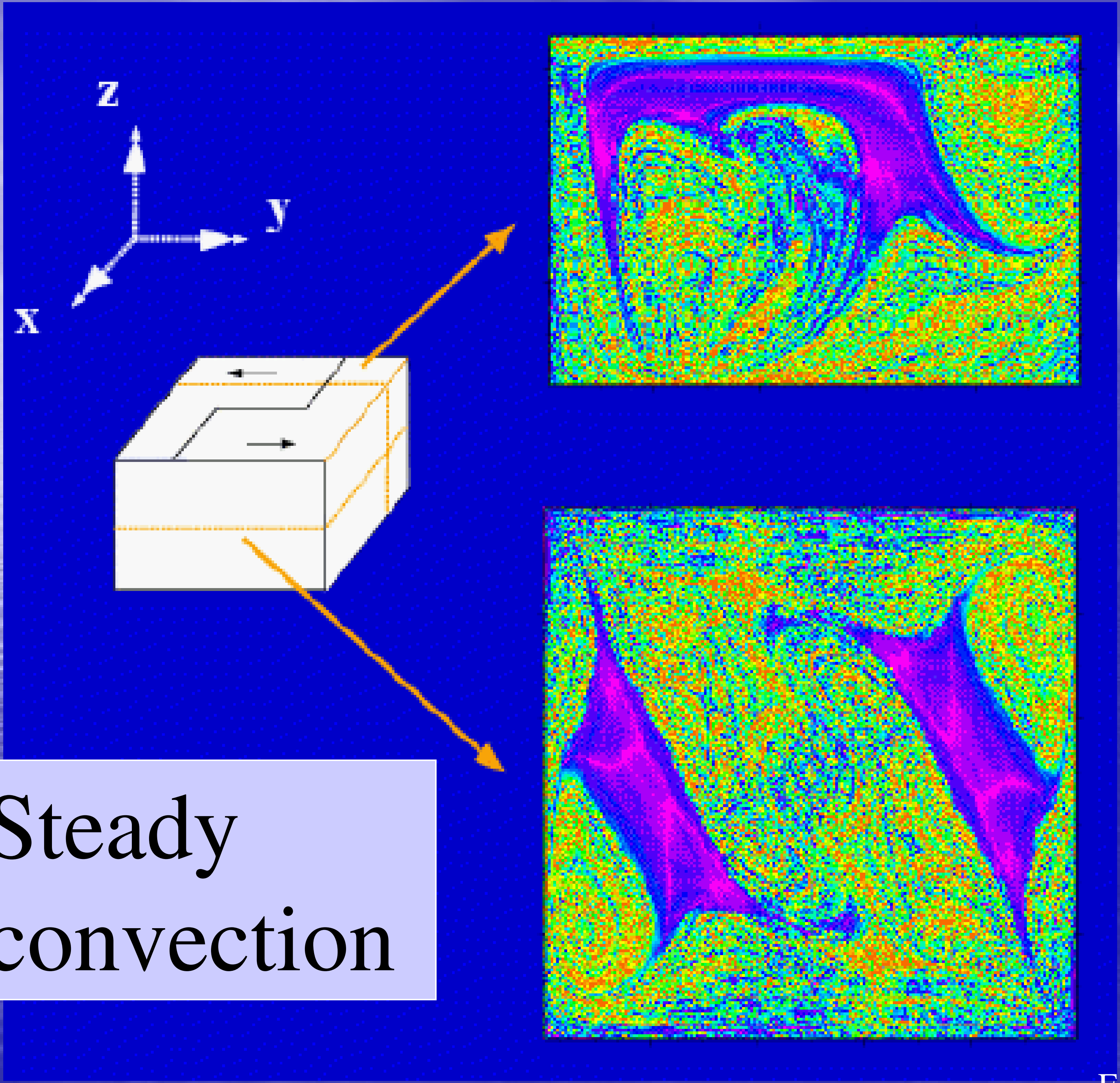
Diffusion… $L^2 = 2\,D\,t$

$\mathrm{Log}(\dot{\varepsilon}\,L^2/D)/2\dot{\varepsilon}$

advected

totally mixed

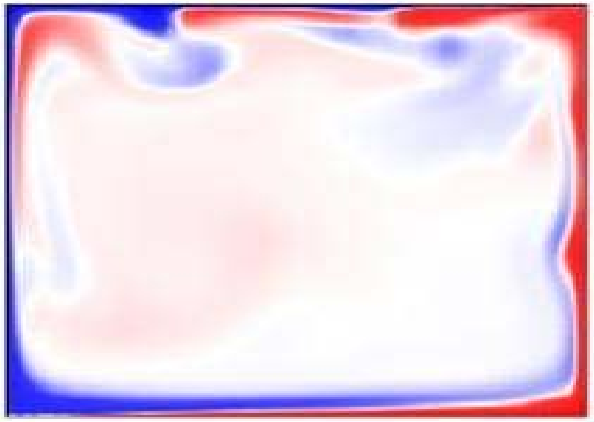
- ✓ Erasing U in the oceanic crust: 2 byrs (?)
- ✓ Erasing He in the oceanic crust: 1 byr (?)

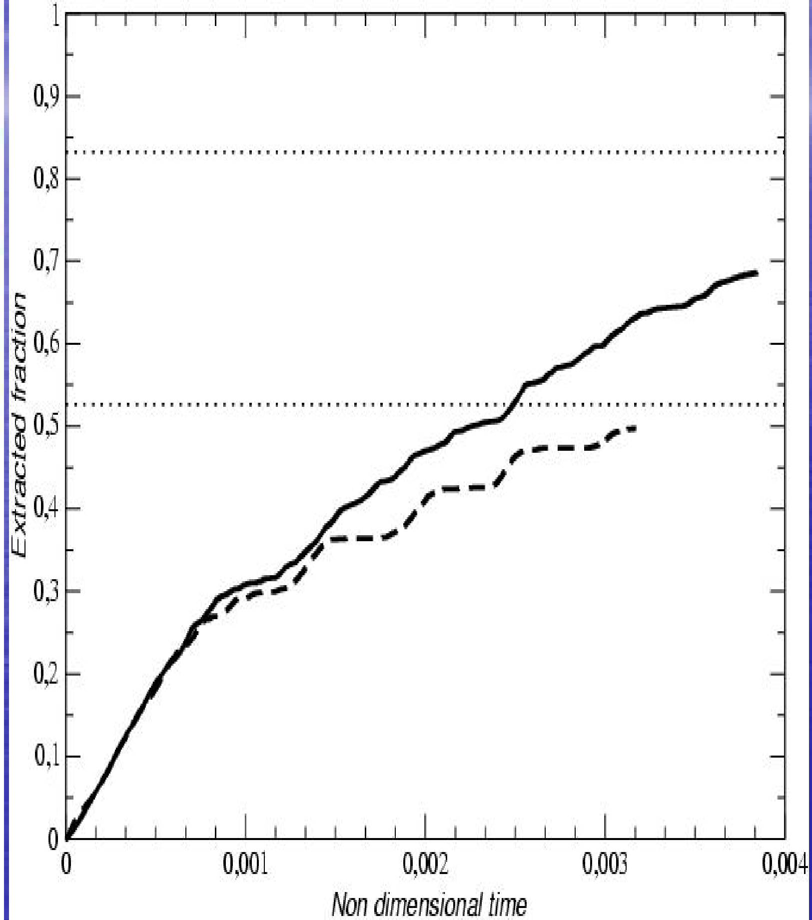


Steady convection

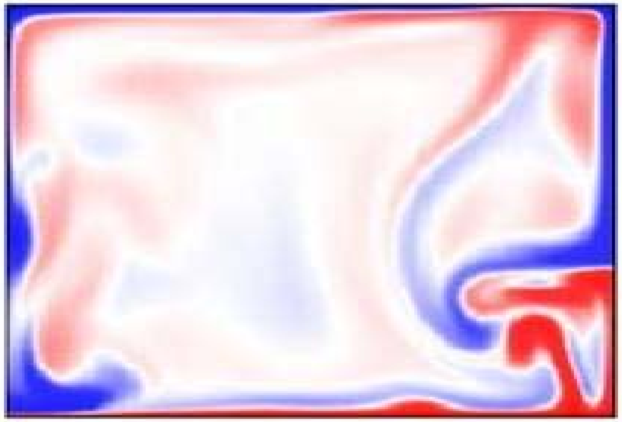
Ferrachat & Ricard

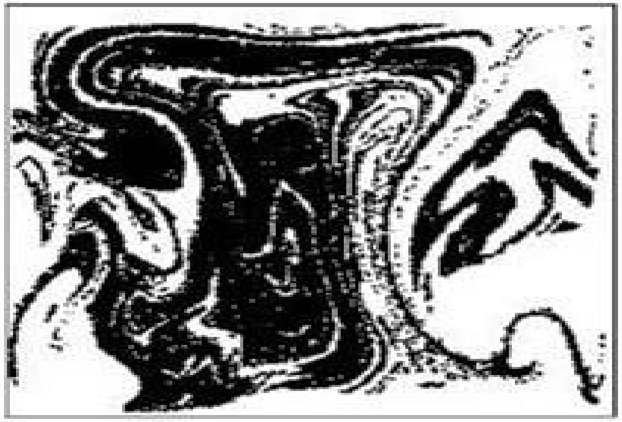
An efficient mixing is not necessarily due to a strong temporal variability





Extracted fraction
Non dimensional time
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
0,001
0,002
0,003
0,004





In whole mantle convection models when the volume of remaining primitive material decreases, its probability to be processed under a ridge also decreases

3-20 % of primitive mantle (filaments, lumps…)

Davies, van Keken, Becker, Kellogg, Coltice…

Various MORB and OIB recipes

Stratified Cake:

MORB are from the SM (shallow mantle)

OIB are a mixture between SM and primitive mantle

Marble Cake:

The whole mantle is made of recycled oceanic crust + peridotite (recycled lithosphere+primitive mantle)

The difference between MORB and OIB are mostly due to mixing differences

Various MORB and OIB recipes

Cake with raisins:

MORB are from the dough

OIB taste from the raisins

Water filter:

Fast (OIB) and slow upwellings are filtered by water extraction at 400 km.

	PRIMITIVE MANTLE	ORIGIN OF ANOMALIES
Stratified cake	LARGE QUANTITY	INITIAL
Marble Cake	SMALL QUANTITY	CONSEQUENCE OF TECTONICS
Cake with raisins	SMALL QUANTITY	INITIAL
Water filter	SMALL QUANTITY	CONSEQUENCE OF TECTONICS

	SLABS IN THE LM	DIFF. LM/UM
Stratified cake	NO	YES
Marble Cake	YES	NO
Cake with raisins	YES	NO
Water filter	YES	YES

Still a lot to do….

The possibility of confronting seismic images, mineralogic and geochemical data with geodynamic models is still rather new

Knowing the limits of our knowledge is a first step to have new ideas…