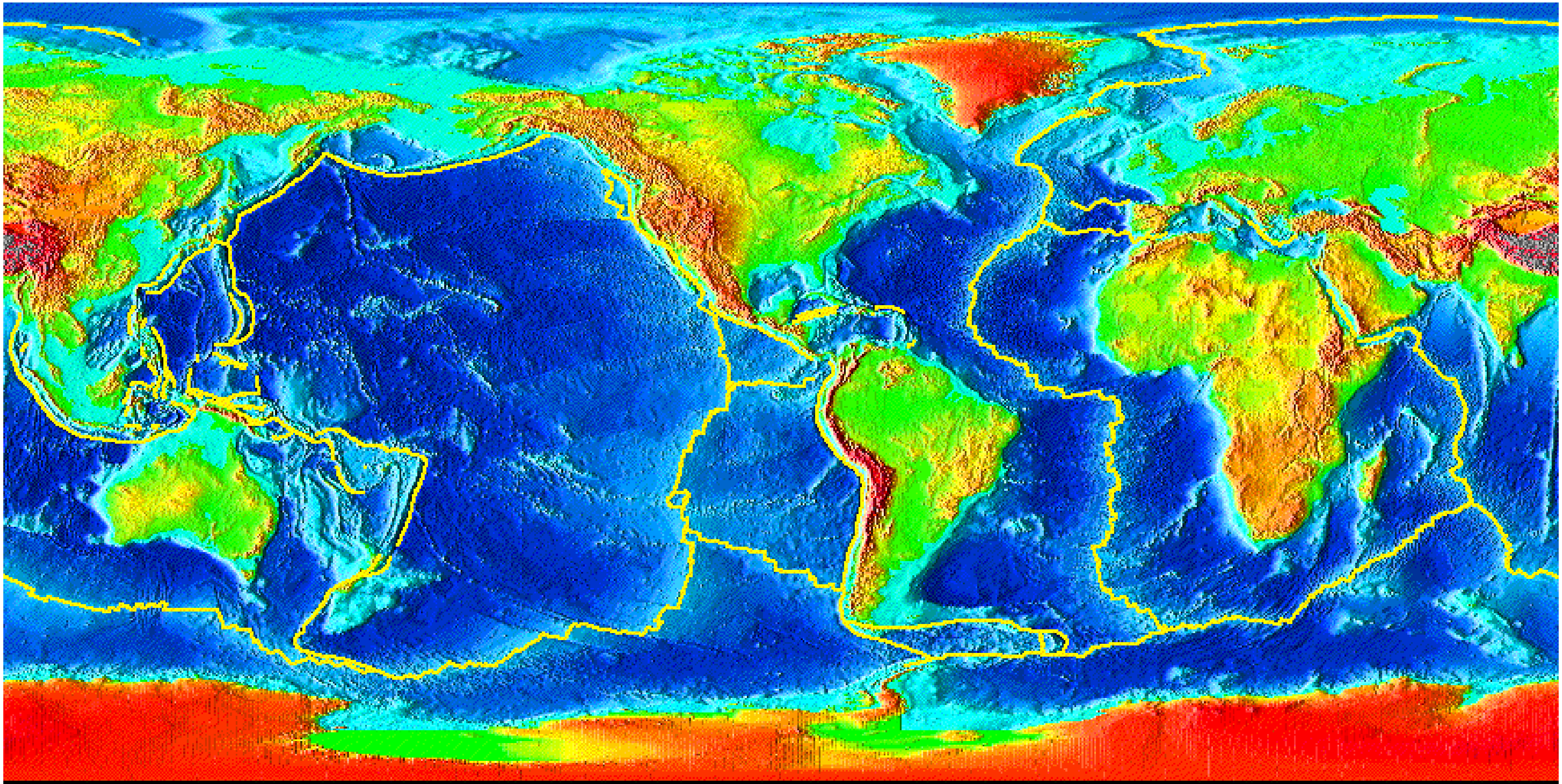
Lecture 4. Beyond the Plate Tectonics: Plumes, Large Ign. Provinces and Mass Extinctions

Outline

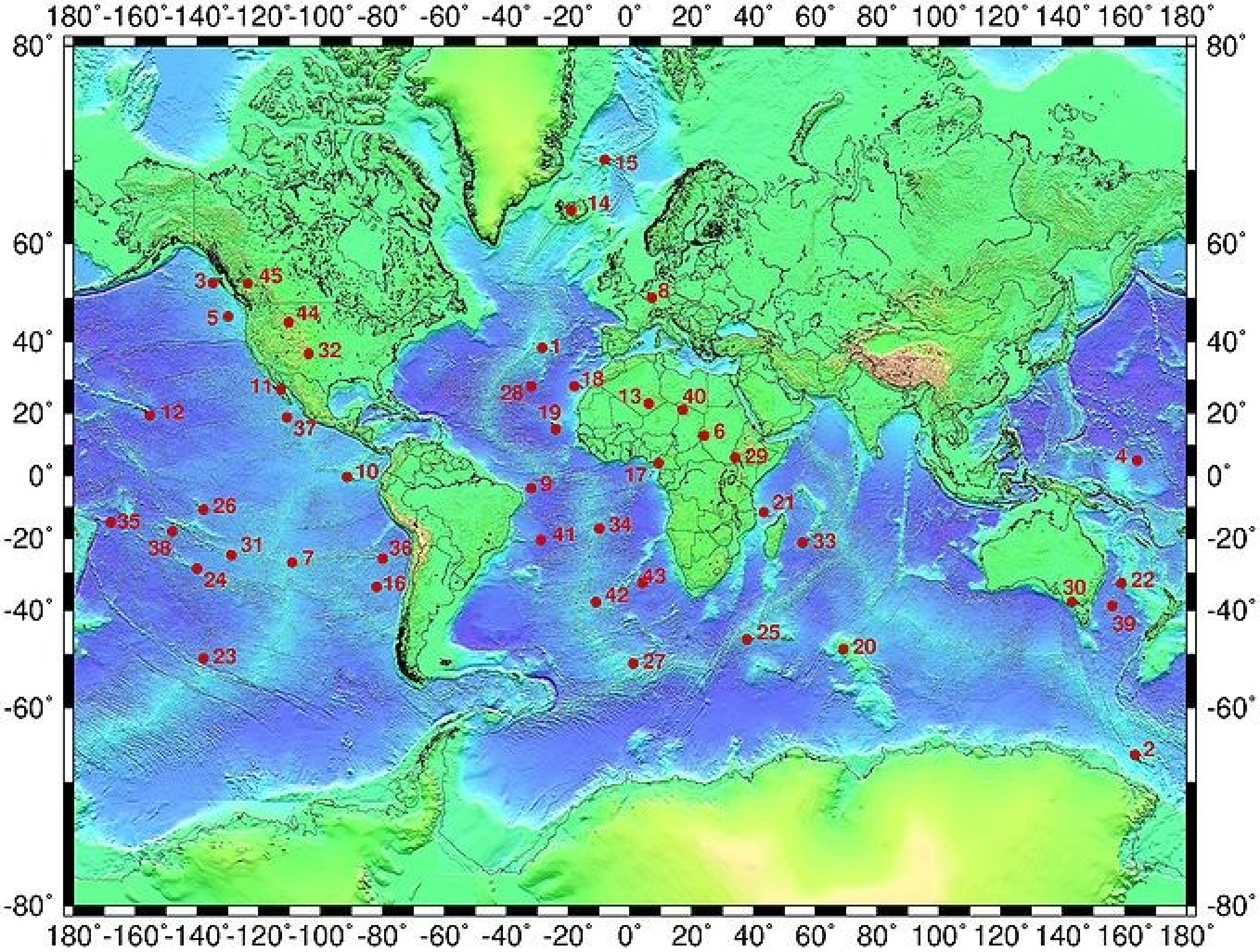
- Hotspots and Large Igneous Provinces (LIPs) general features
- Hot Mantle Plume concept and its problems
- Siberian Traps Model
- Models of Thermo-Chemical Plumes

Plates

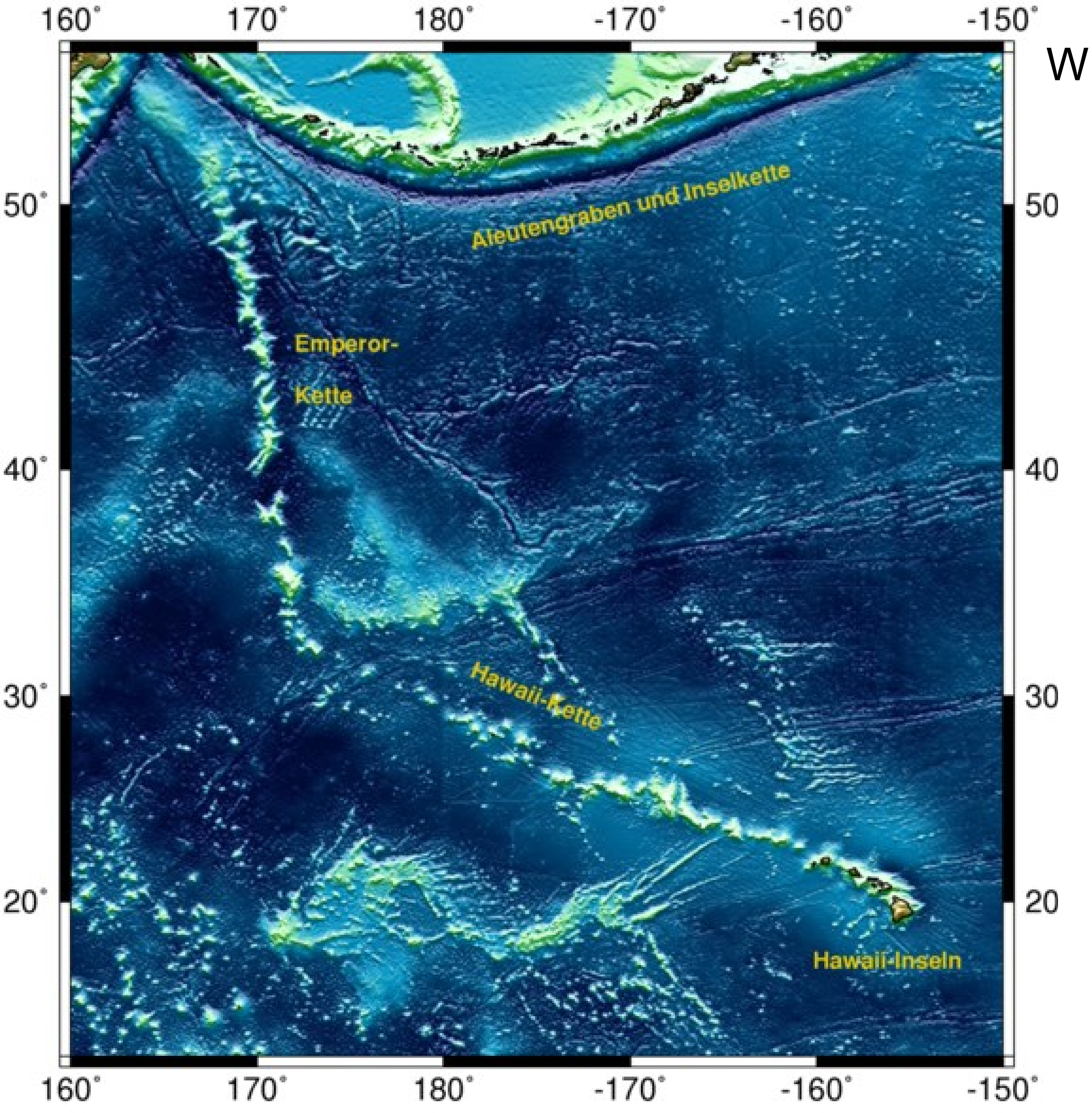


Crustal Plate Boundaries

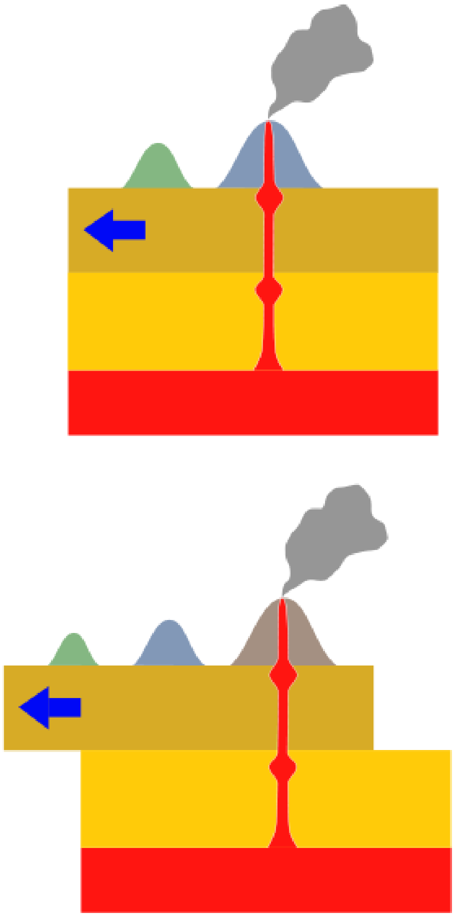
Hot Spots-OIBs



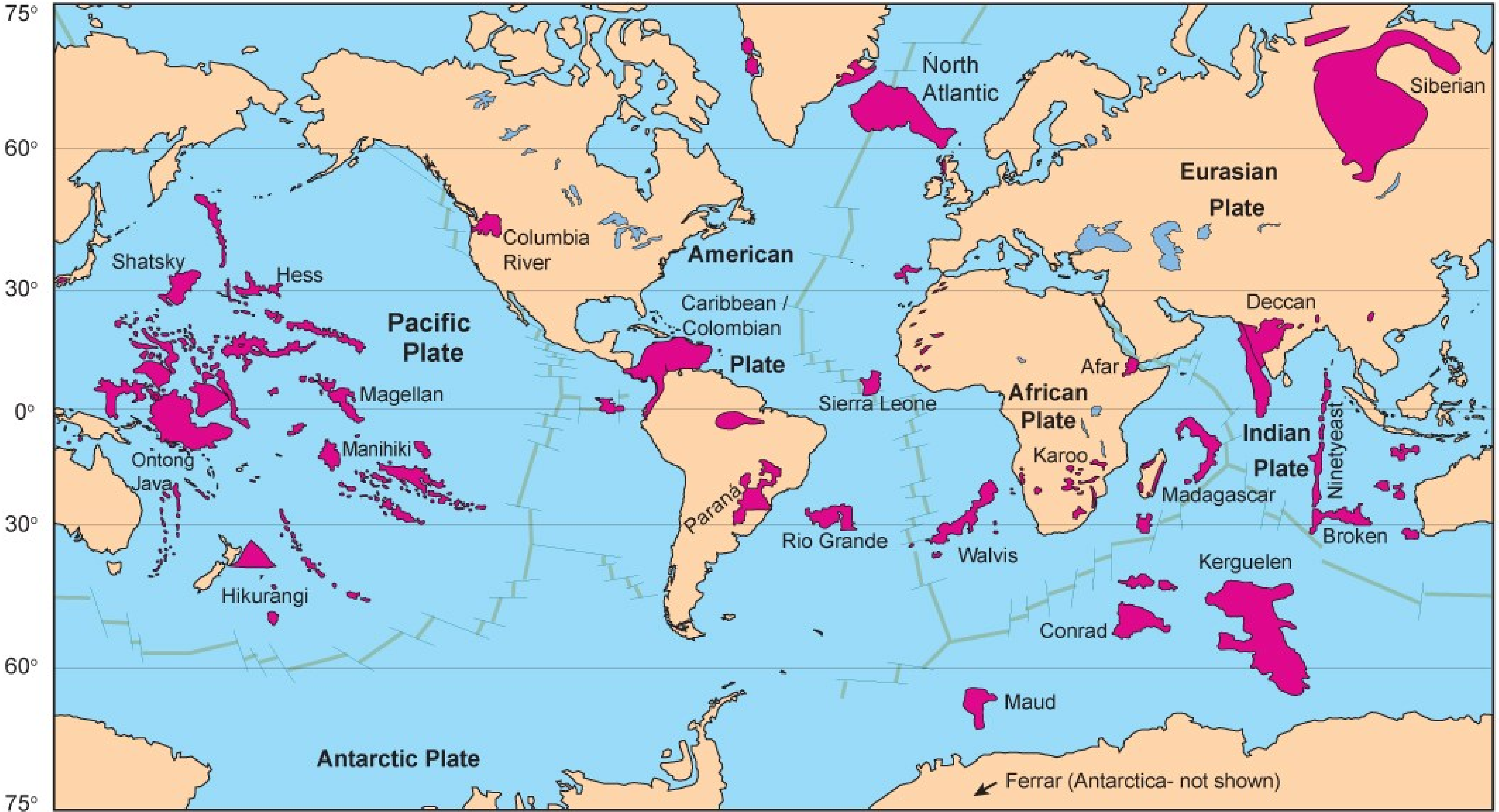
Hot Spot Track



Willson, 1963; Morgan, 1971

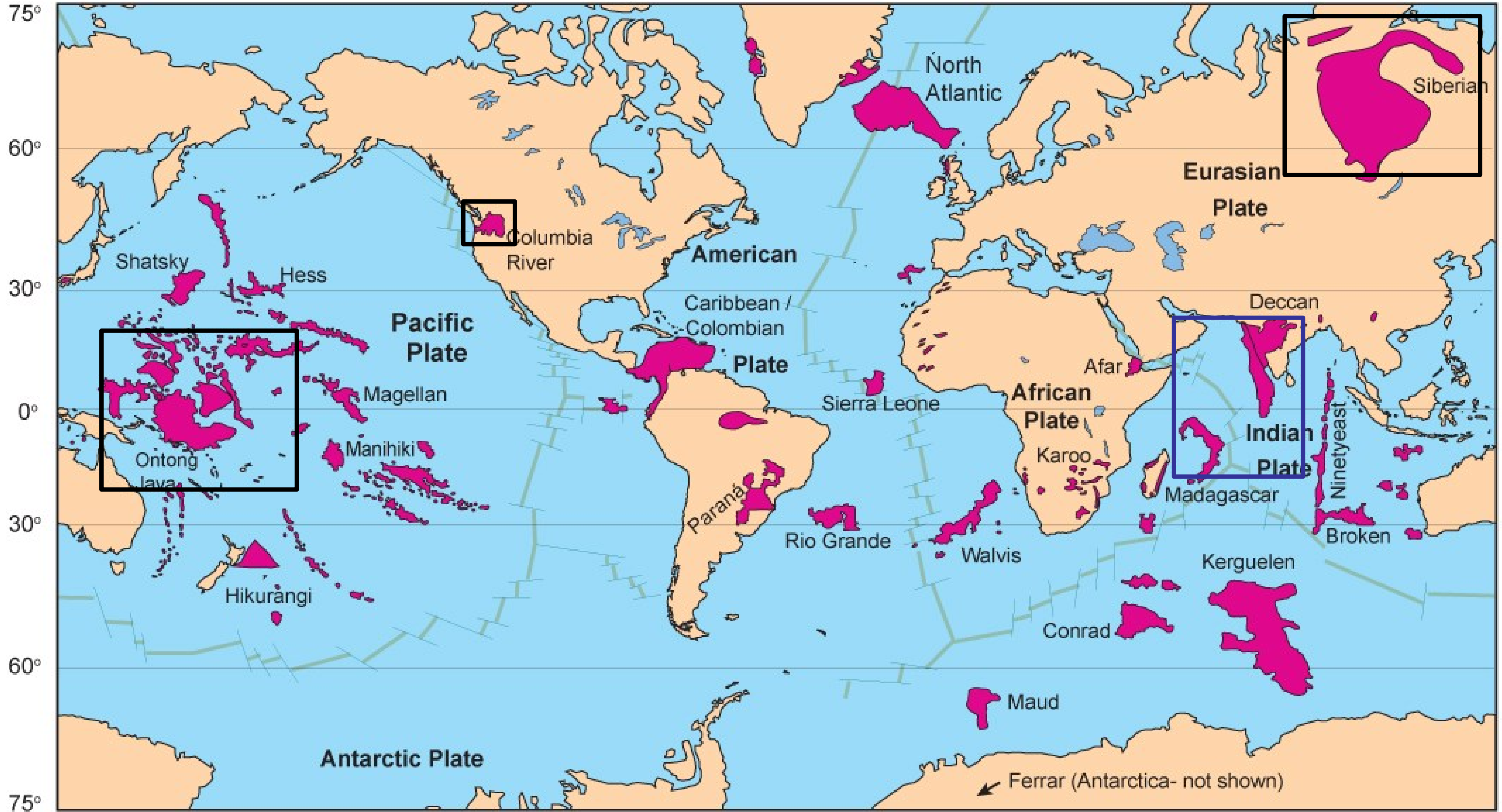


Large Igneous Provinces (LIPs)



After Saunders et al. (1992)

Large Igneous Provinces (LIPs)



After Saunders et al. (1992)

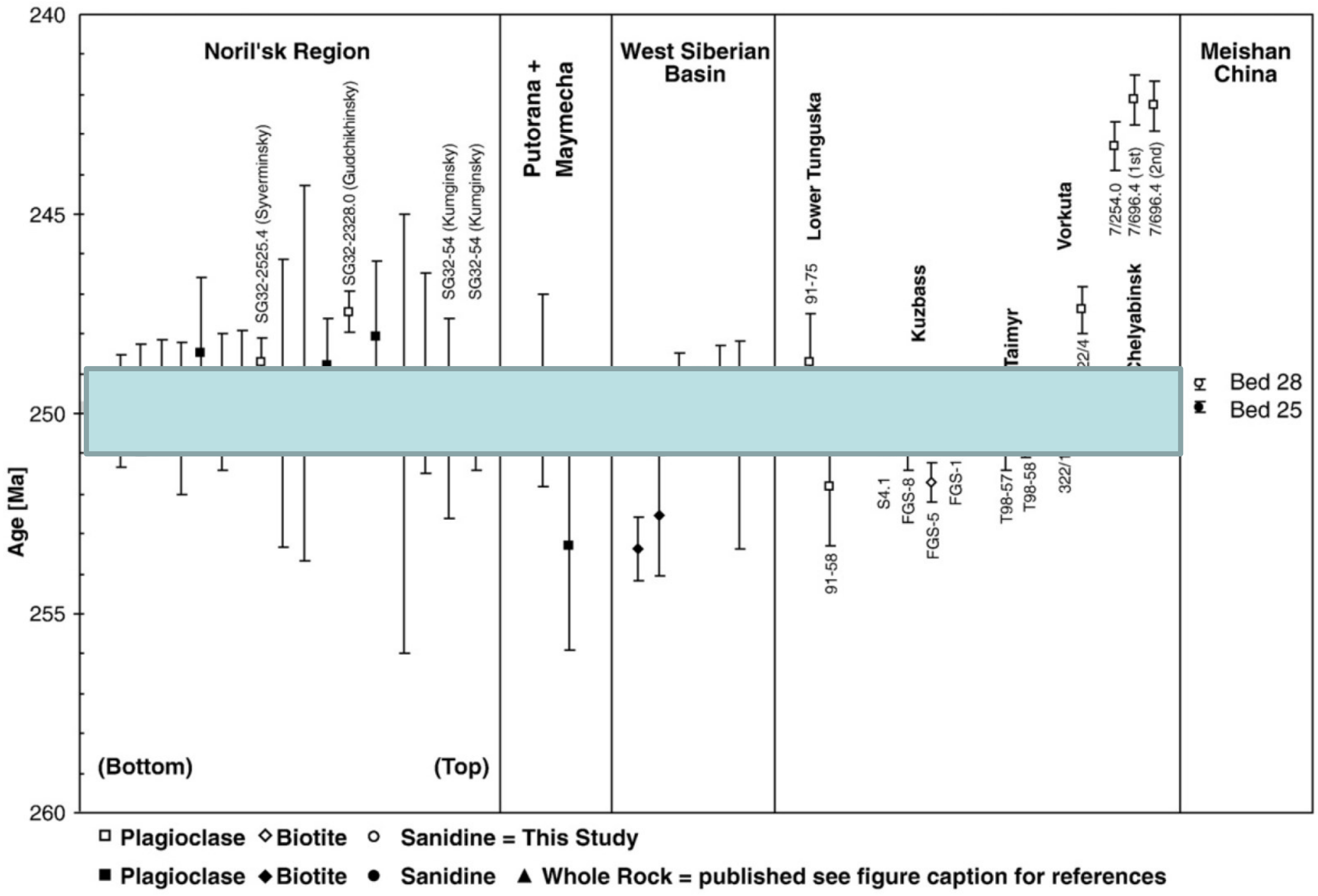
Large Magma Volume

- Siberian Flood Basalts- over **4 mln. km^3**
- Deccan Traps- **2 mln. km^3**
- Columbia River Province- **0.3 mln. km^3**
- Plato Onthong-Java- over **40 mln. km^3**

Short Time Scales of Major Magmatic Phases

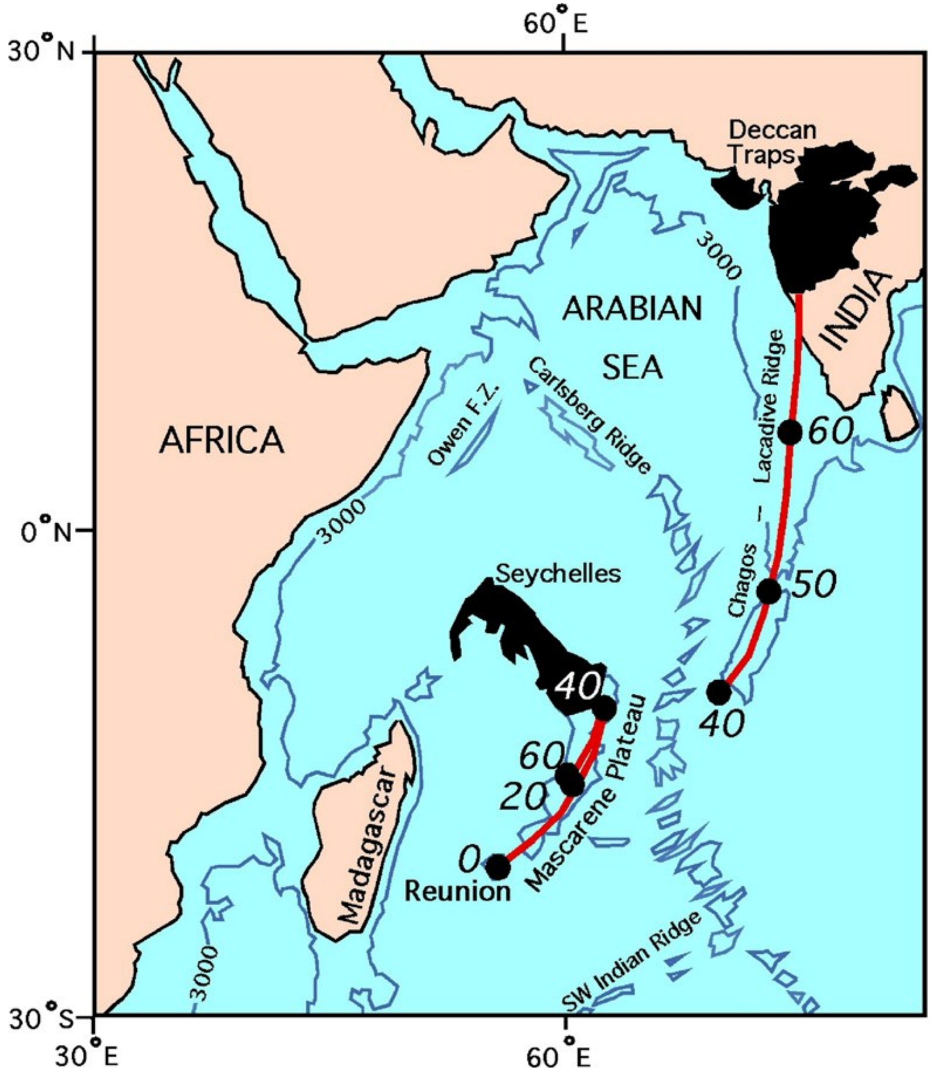
- The most precise dating gives age ranges for the main magmatic phase within method accuracy ±1 mln.y.
- The full range of magmatic activity may exceed 10 mln.y.

Ar-Ar age of Siberian Flood Basalts 250±1.1 Ma

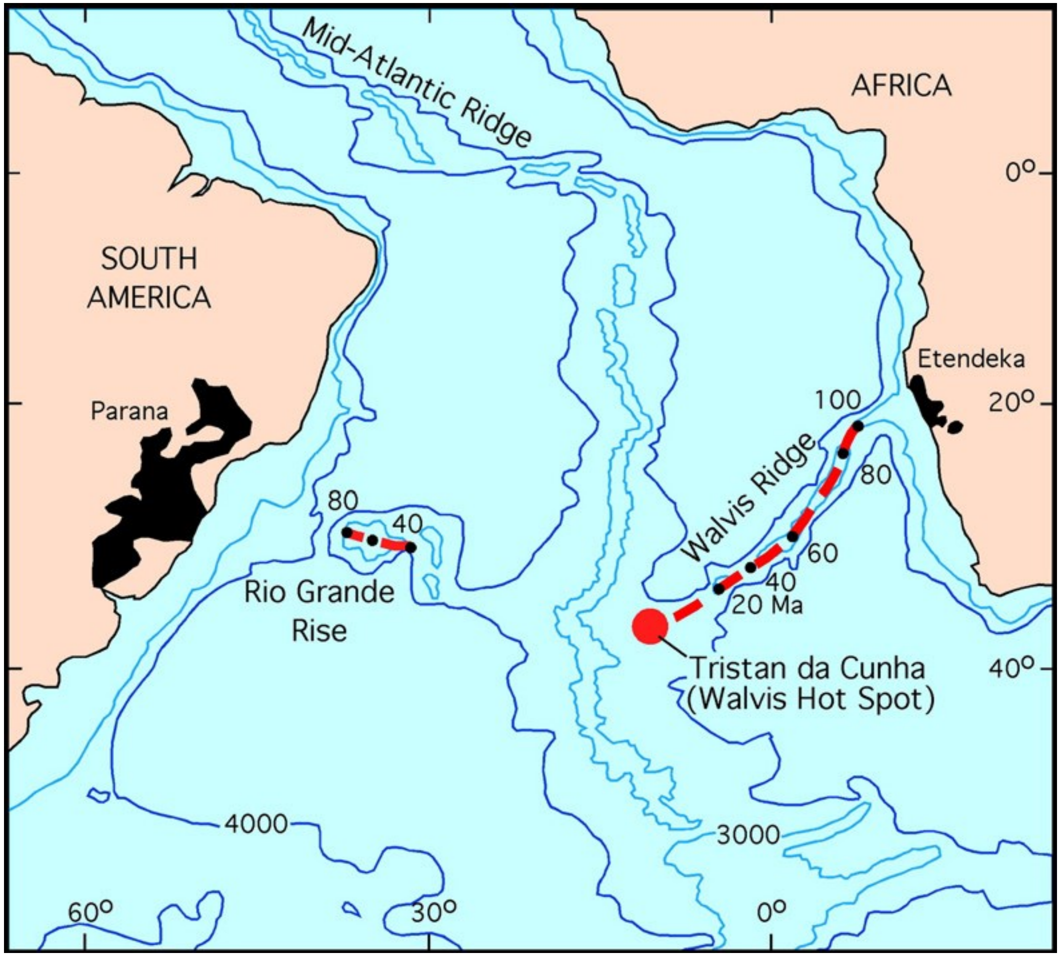


Reichow et al, 2009

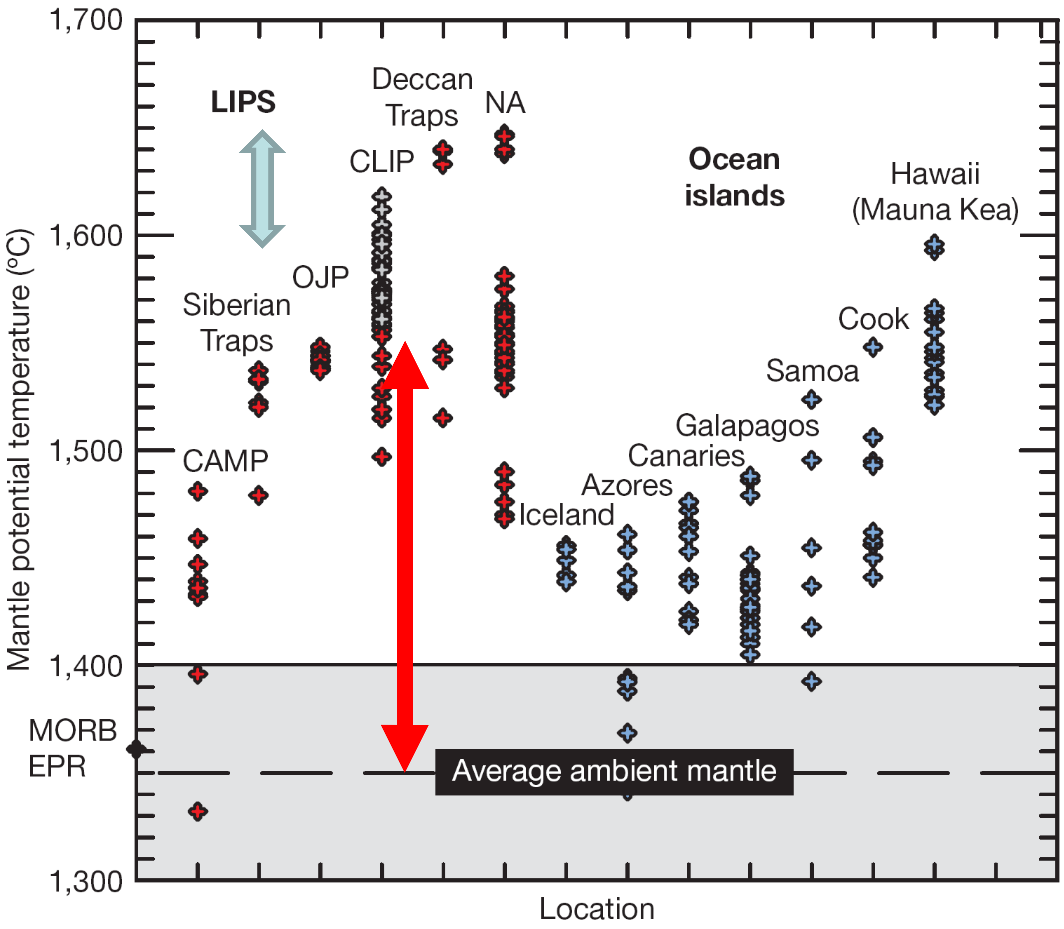
LIPs are related to hot spots Deccan Traps—Reunion HS



Parana-Etendeka—Tristan HS

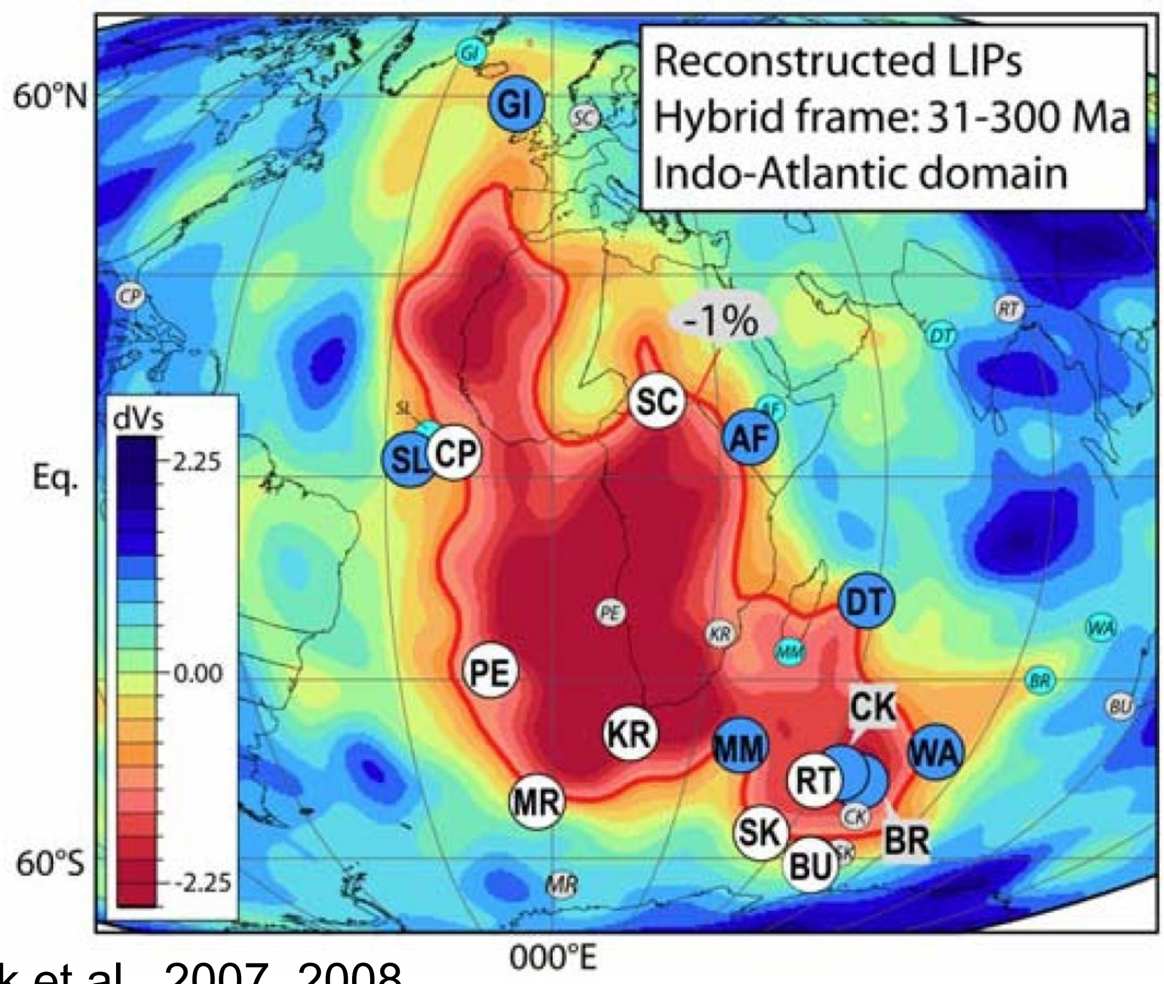


LIPs source has high temperature



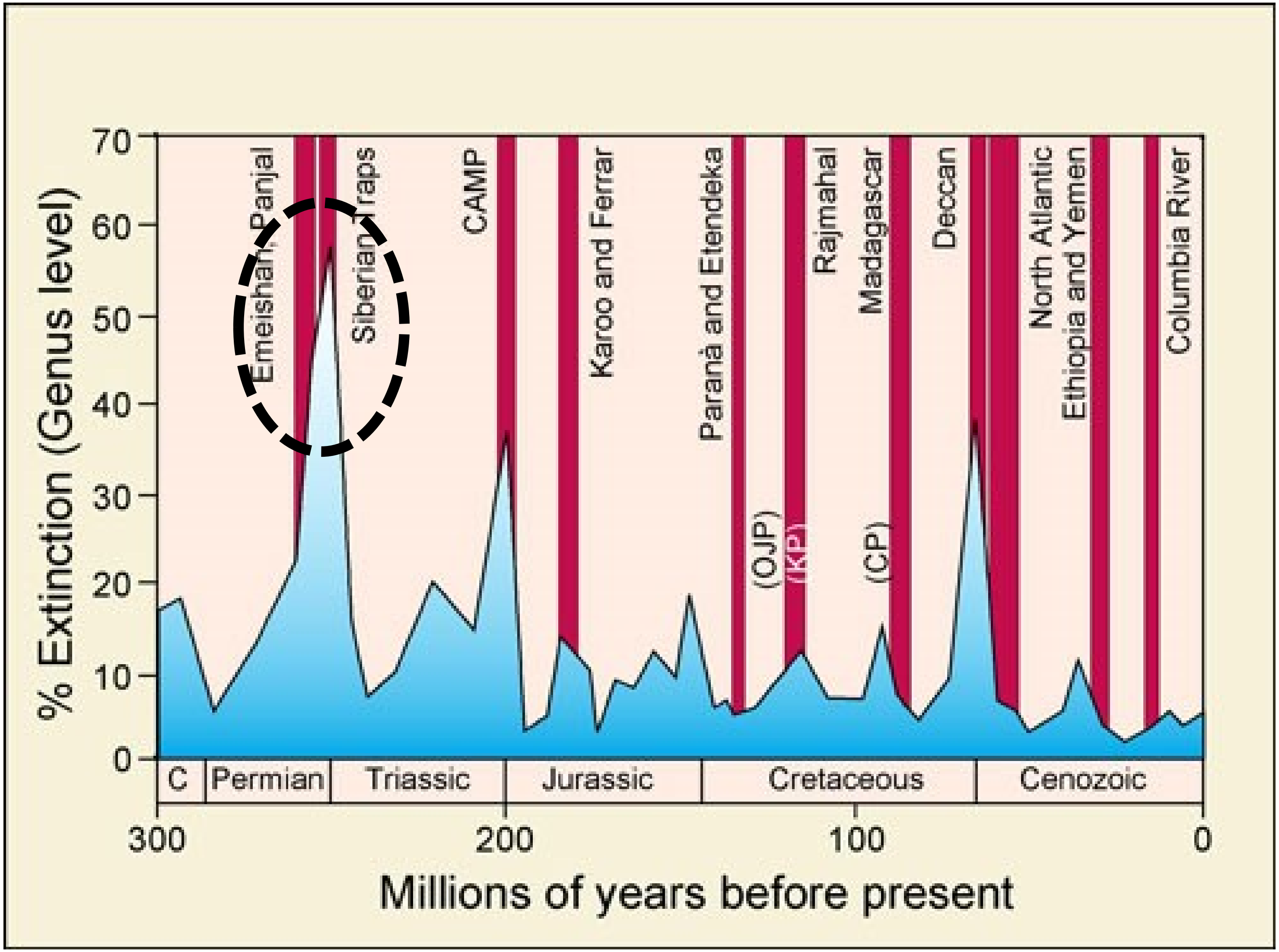
Herzberg & Gazel, 2009

LIPs sources are in the Lower Mantle ?



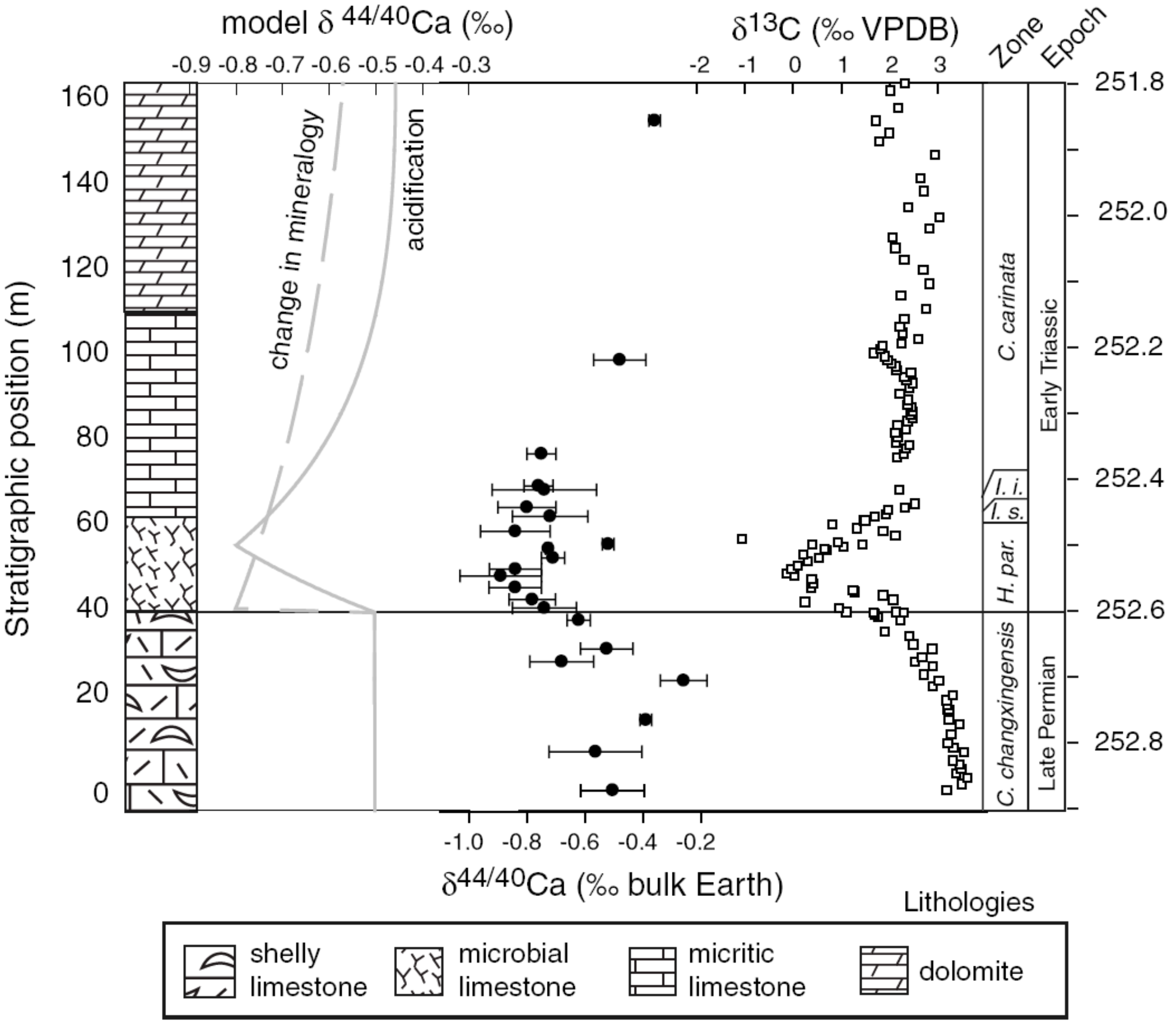
Torsvik et al., 2007, 2008

LIPs correlate with mass extinction events



White and Saunders (2005)

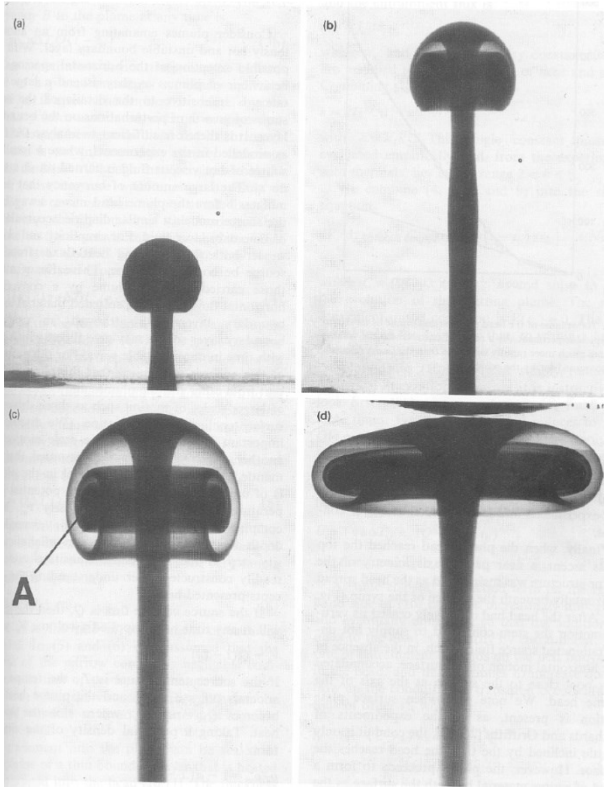
Change of isotopic composition of atmosphere and ocean



Payne et al, PNAS, 2010

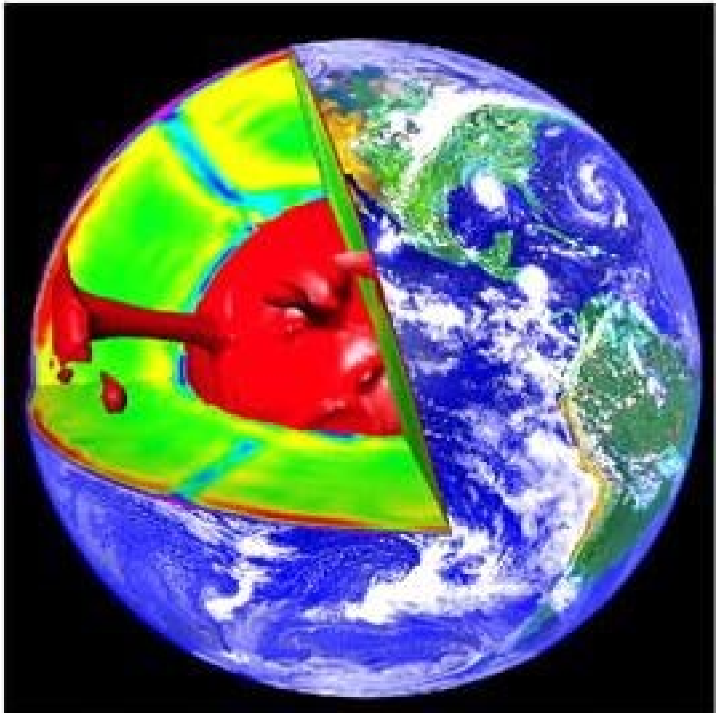
Plume-model to explain hotspots and LIPs

White and McKenzie, 1989; Richards et al.,1989, Campbell and Griffiths, 1990



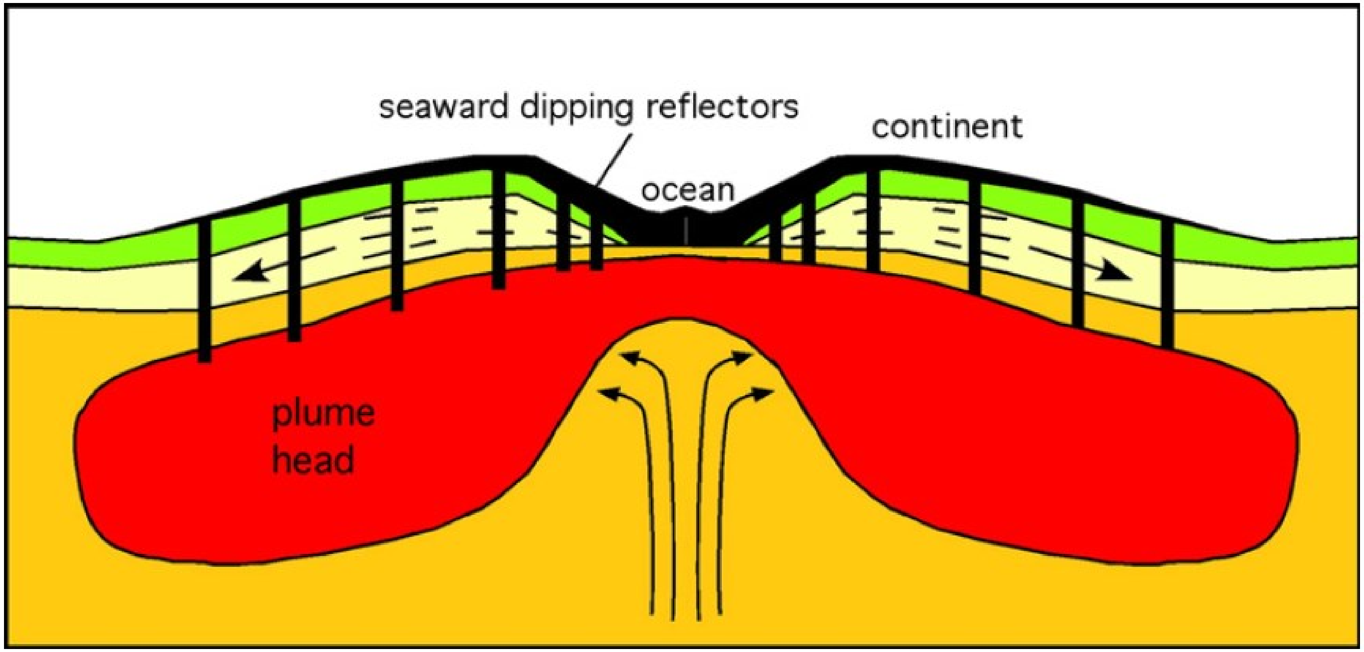
An experimental starting plume (in glucose syrup)

Hot mantle plume



Problems of classical plume model

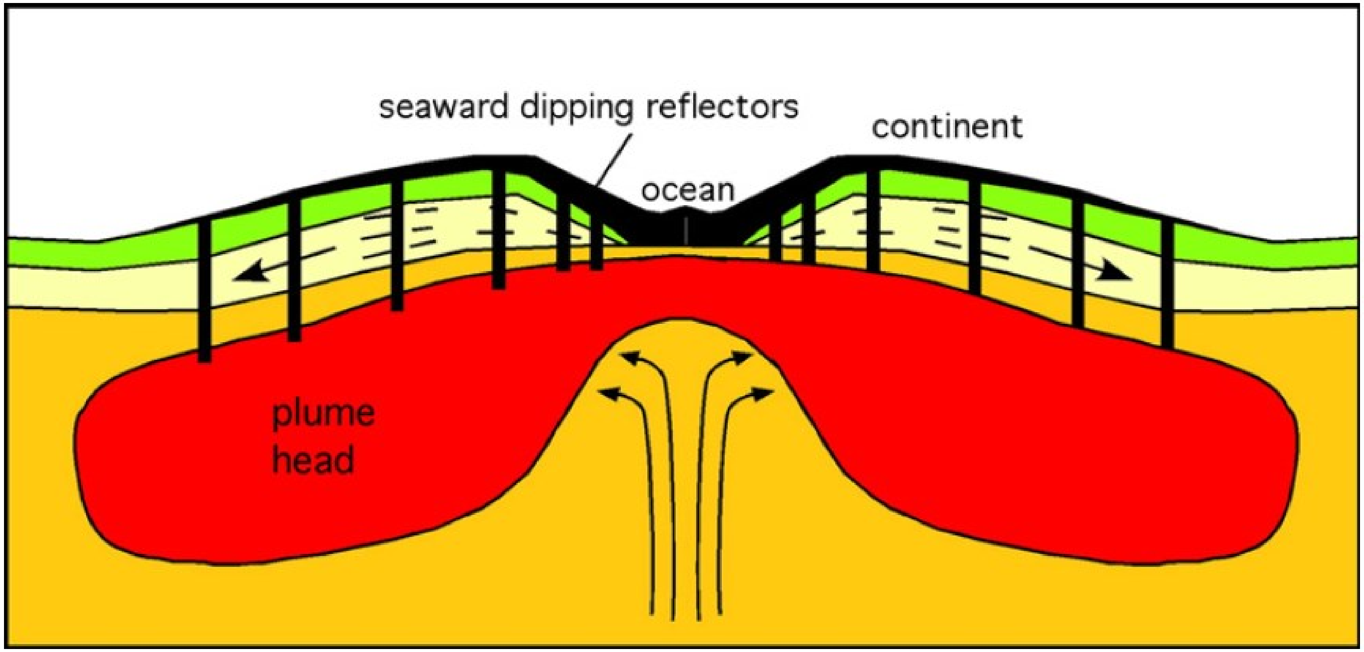
I.H. Campbell / Chemical Geology 241 (2007) 153–176



Prediction: Surface uplift = 0.7-1.0 km/100°, i.e. 1.4-3 km for DT= 200-300°

Problems of classical plume model

I.H. Campbell / Chemical Geology 241 (2007) 153–176

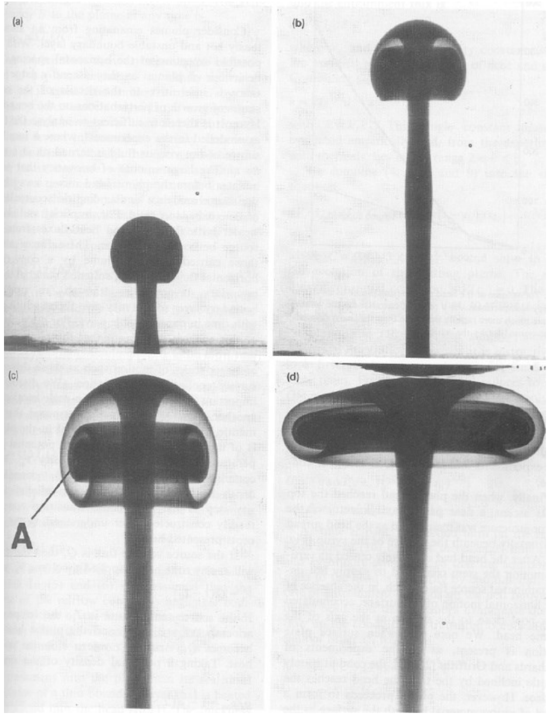


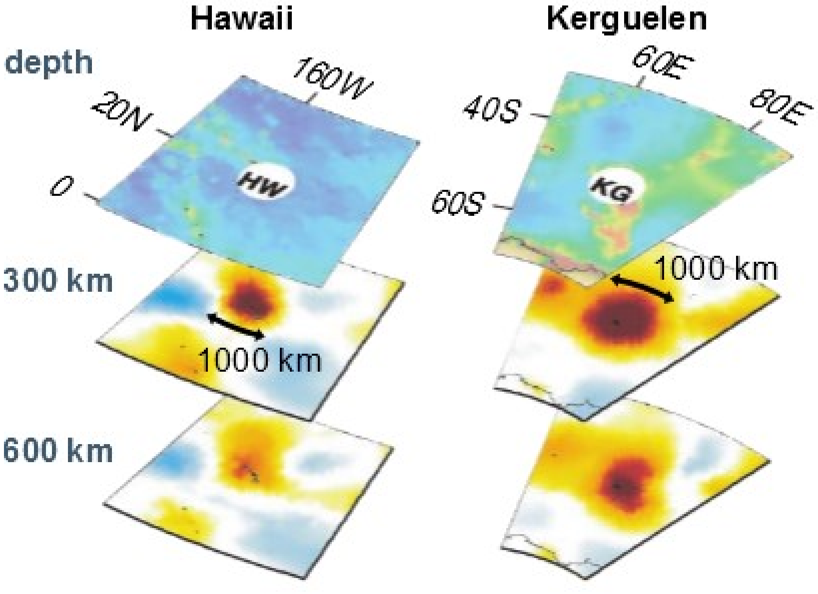
Observation: Often less than 1 km or even not detectable surface uplift

Problems of classical plume model

Prediction: narrow (R=100km) plume conduits (tails)

Seismic observations: wide (R=500km) plumes

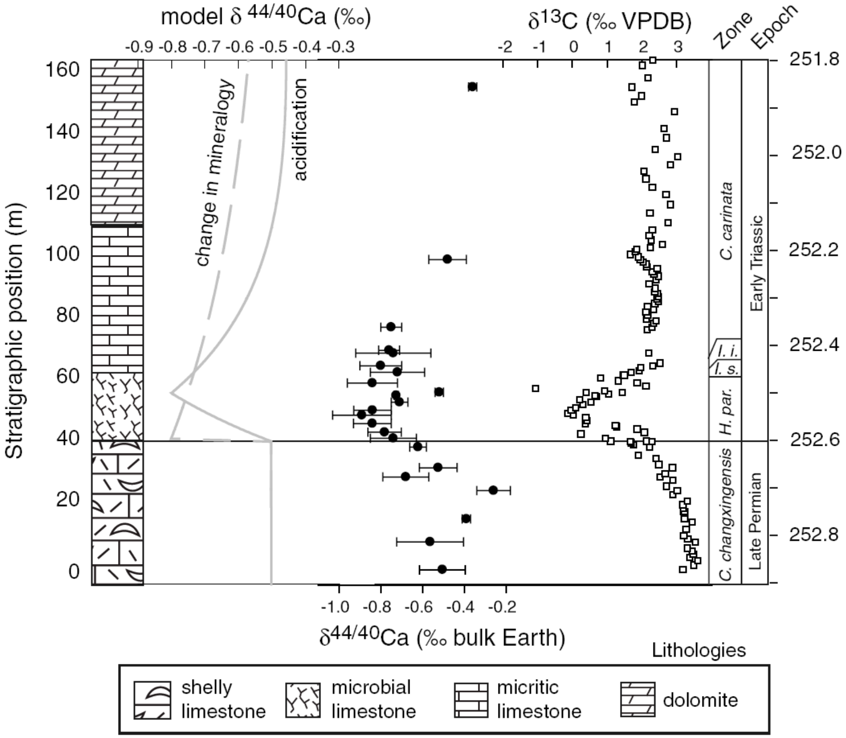




From Montelli et al., 2006

Problems of classical plume model

Volumes and isotopic composition of gases expected from eruptions above plume heads are not sufficient to explain observations for mass extinctions

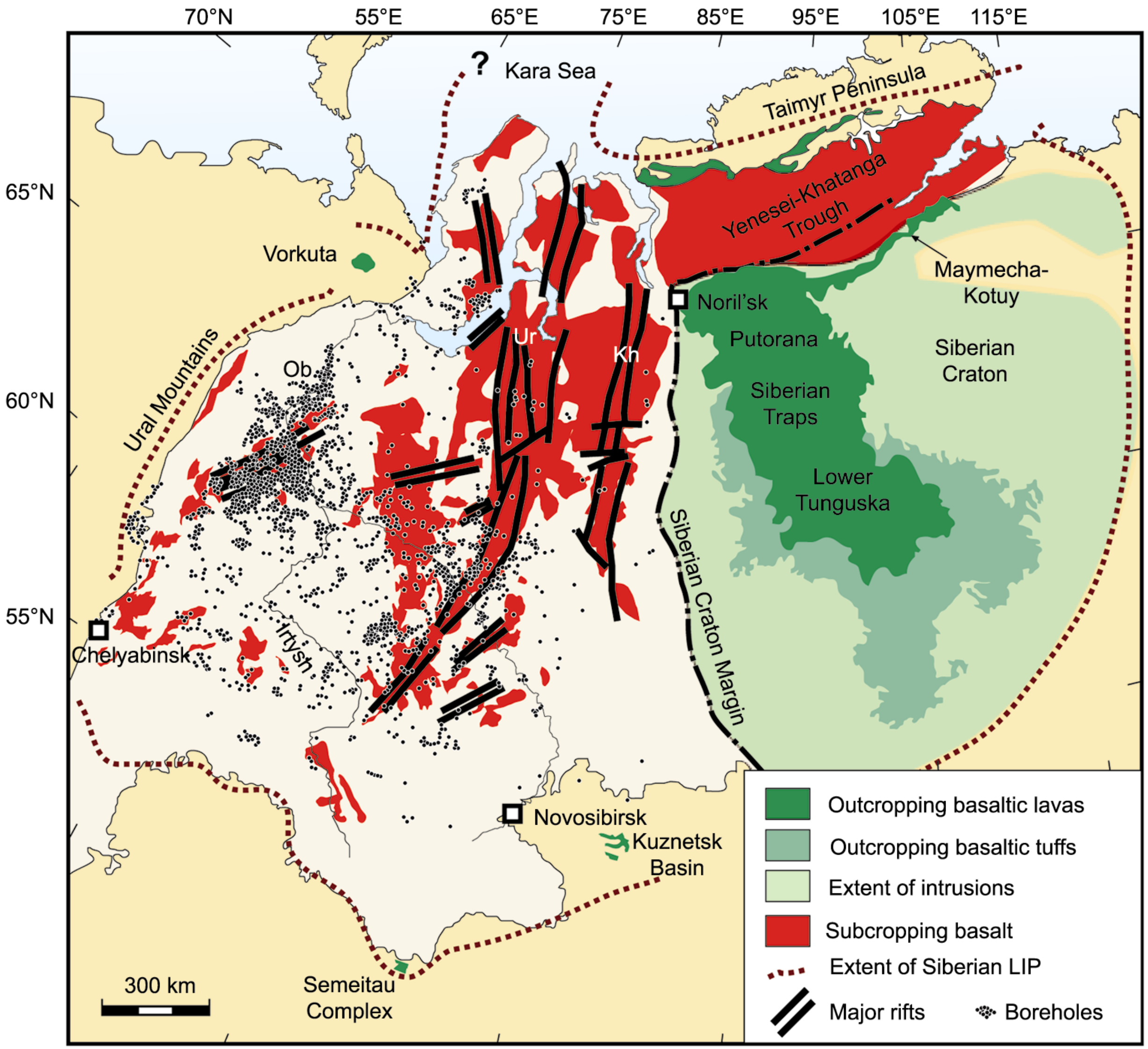


Siberian LIP

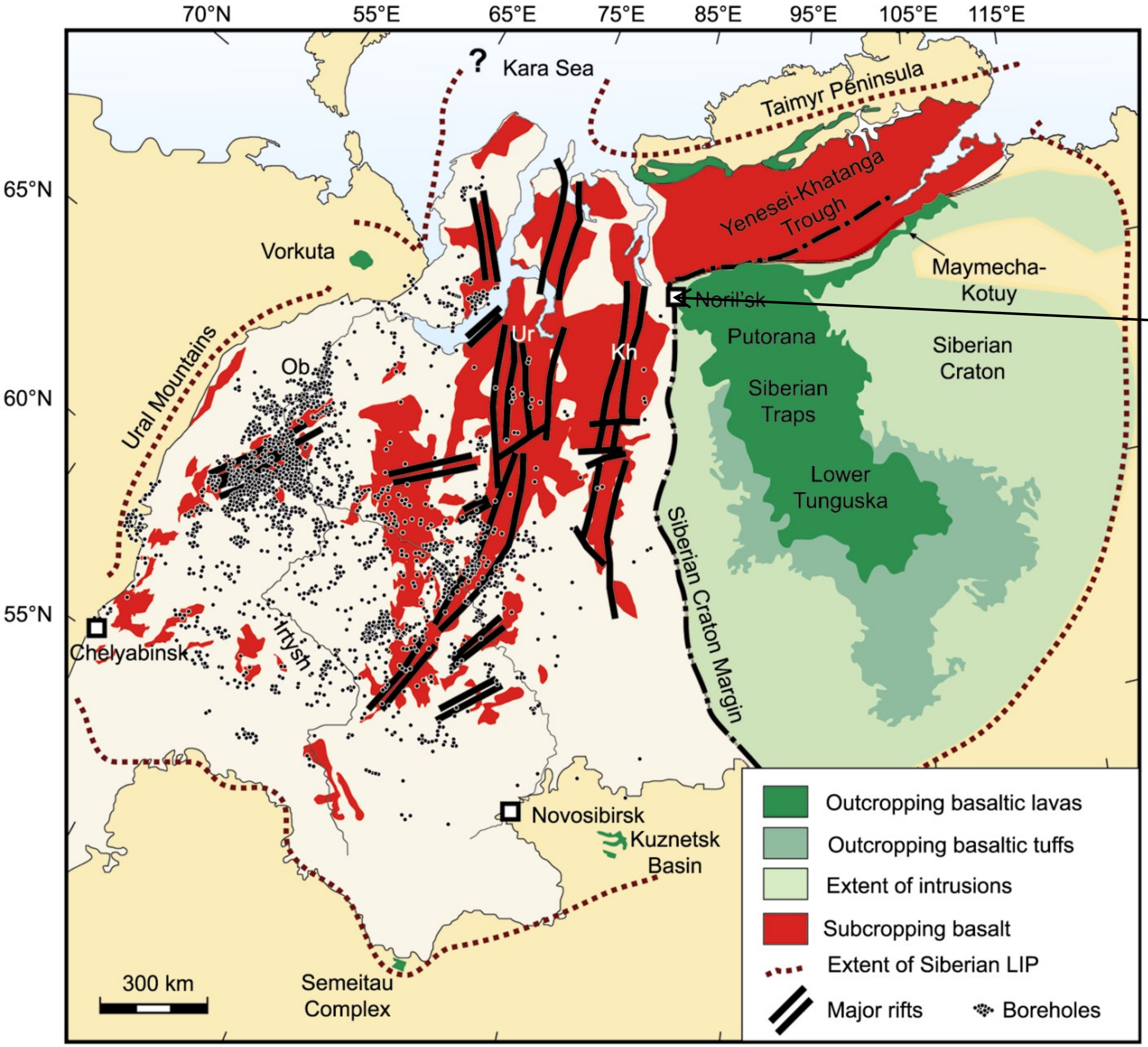
- Over **4 mln. km^3** of magmas produced in less than **1 ma** at the area of about 2 mln km2
- The age of province is about **252 ma and coincides with P-T** mass extinction
- No pre-magmatic uplift

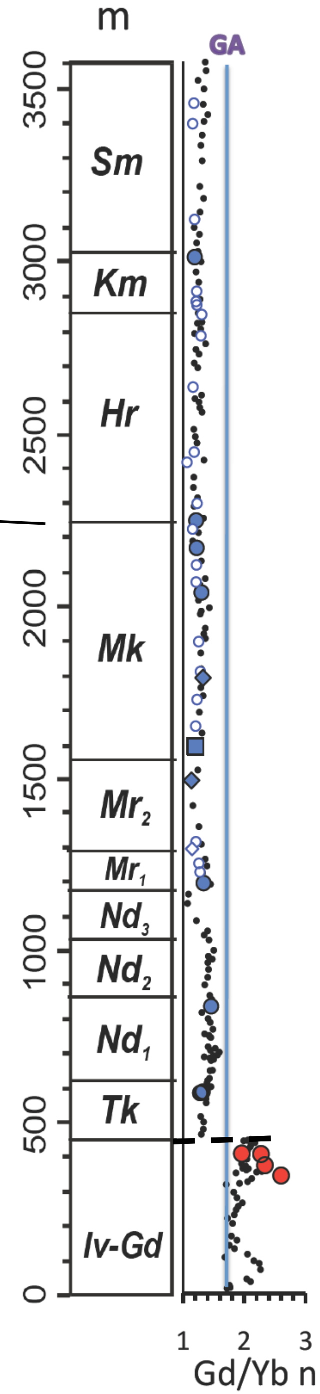
Reichow et al, 2009

Siberian LIP



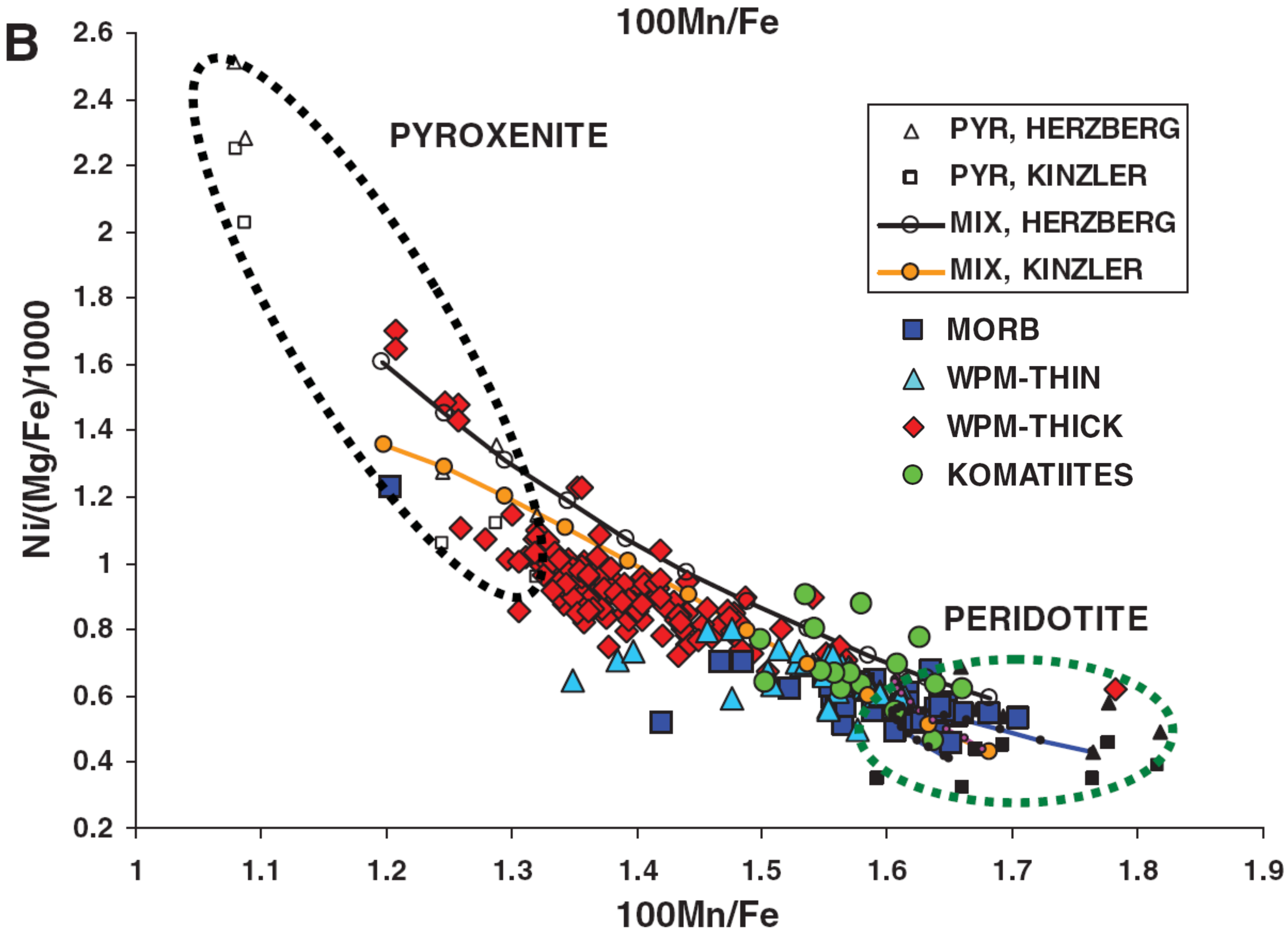
Siberian LIP



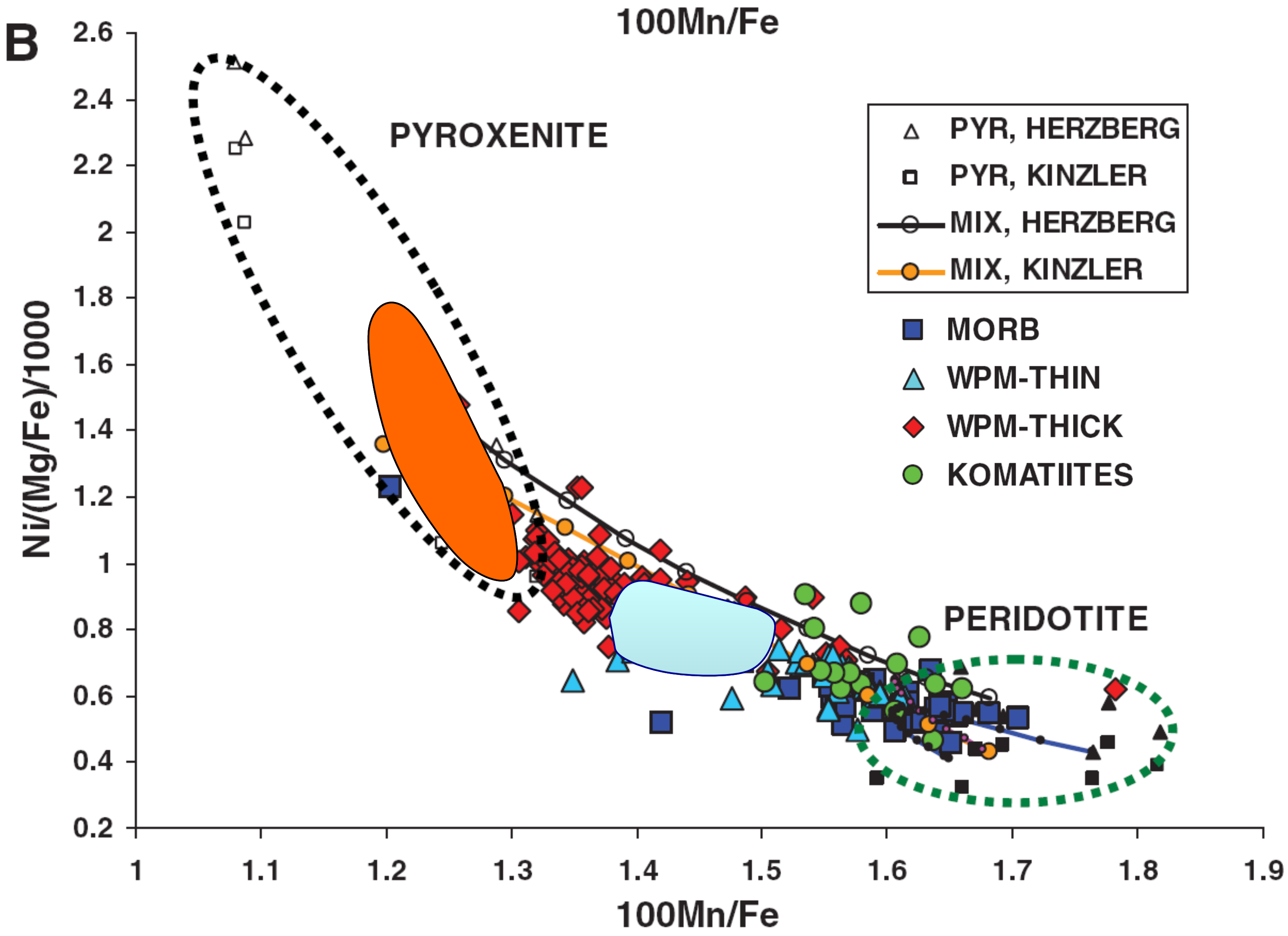


Questions

- Why no pre-magmatic uplift?
- How lithosphere was thinned by >50 km during only few 100 thousand years?
- What was the source of large volumes of CO2 and other gases that triggered P-T mass extinction?

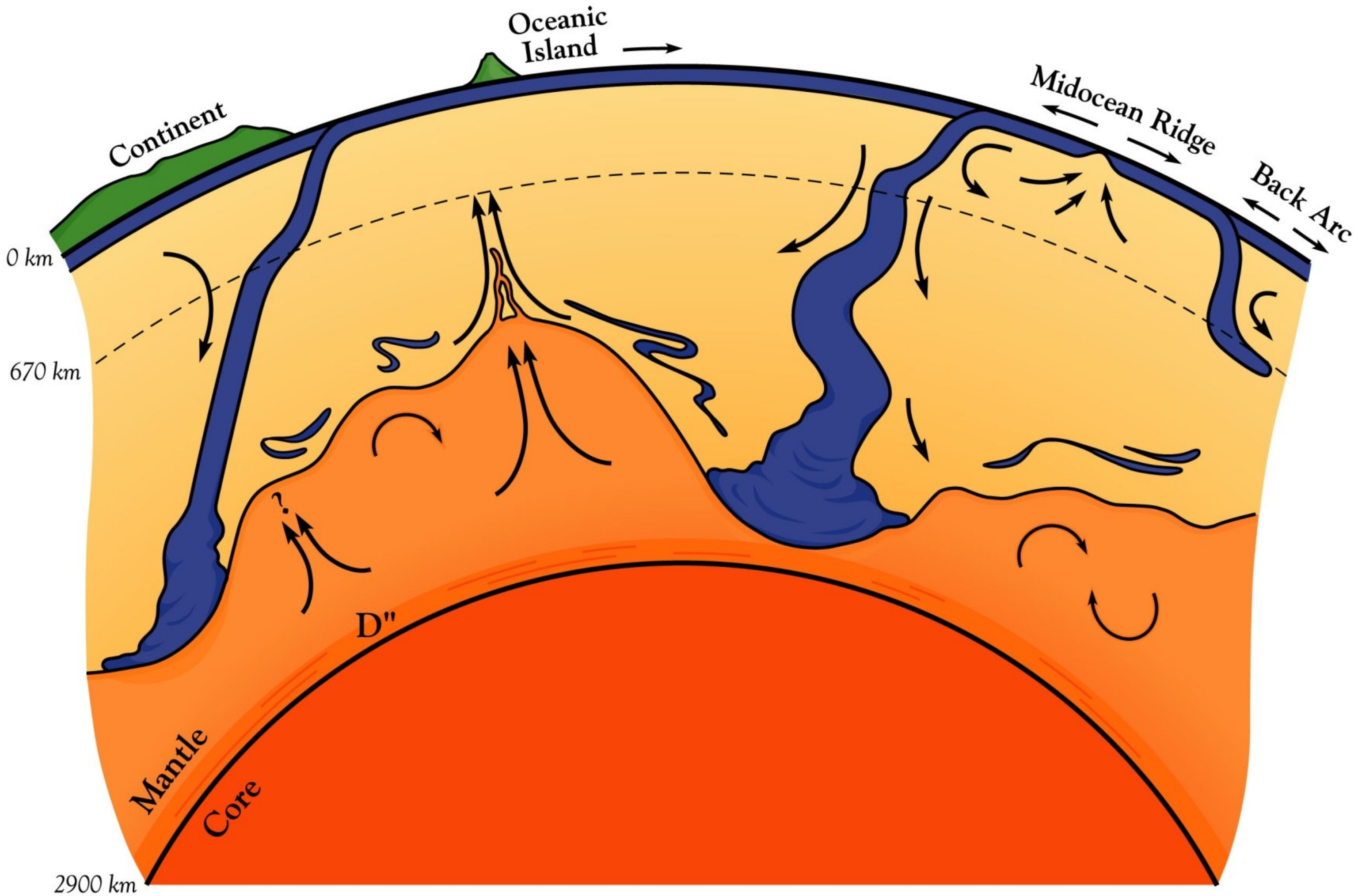


Sobolev et al, *Science*, 2007



Sobolev et al, *Science*, 2007

Crustal recycling
Hofmann and White, 1980-1982



Kellogg et al., 1999

Eclogite: clinopyroxene ≥ garnet ± SiO_2 phase

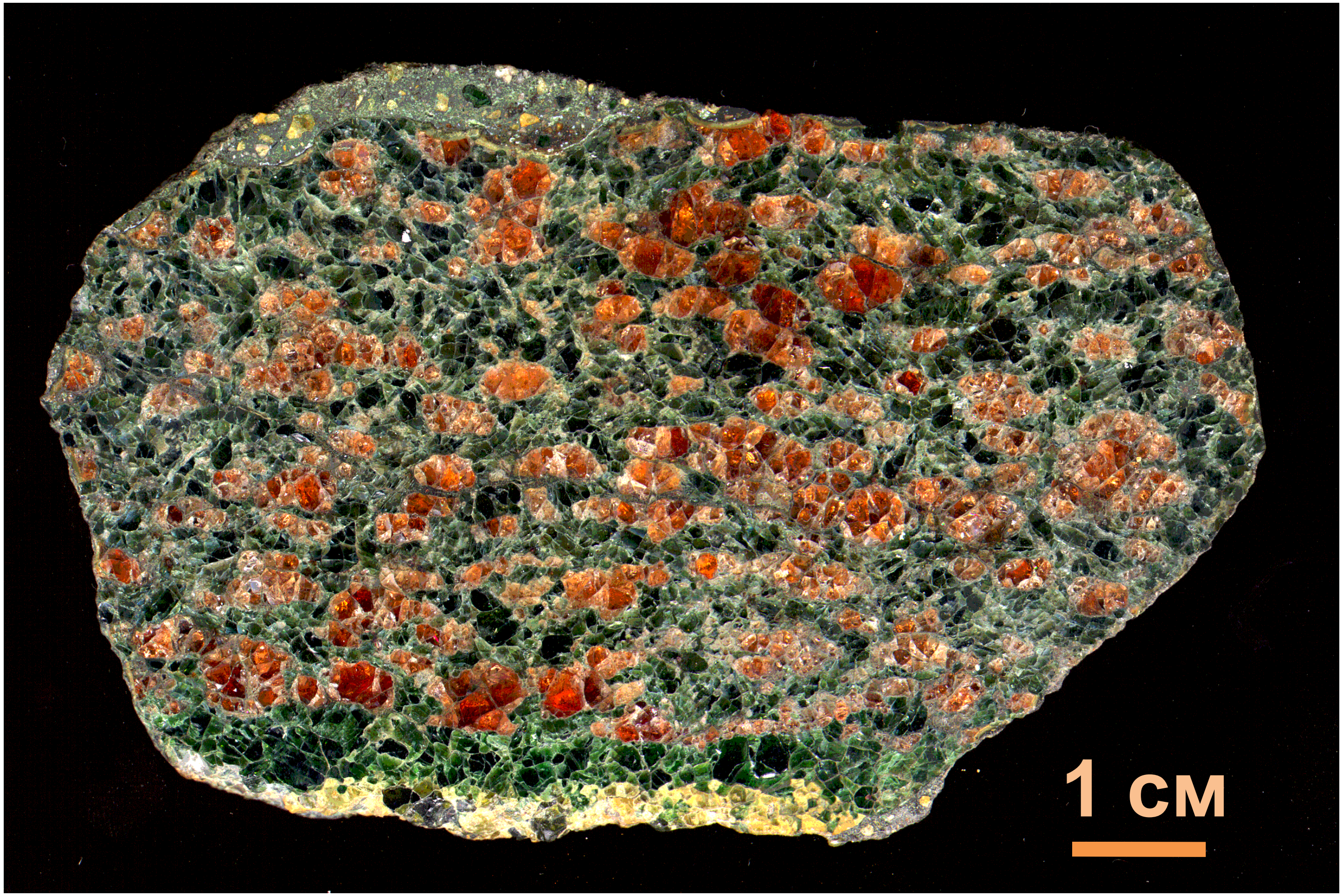


Photo and sample of I. Aschepkov

Petrological constraints

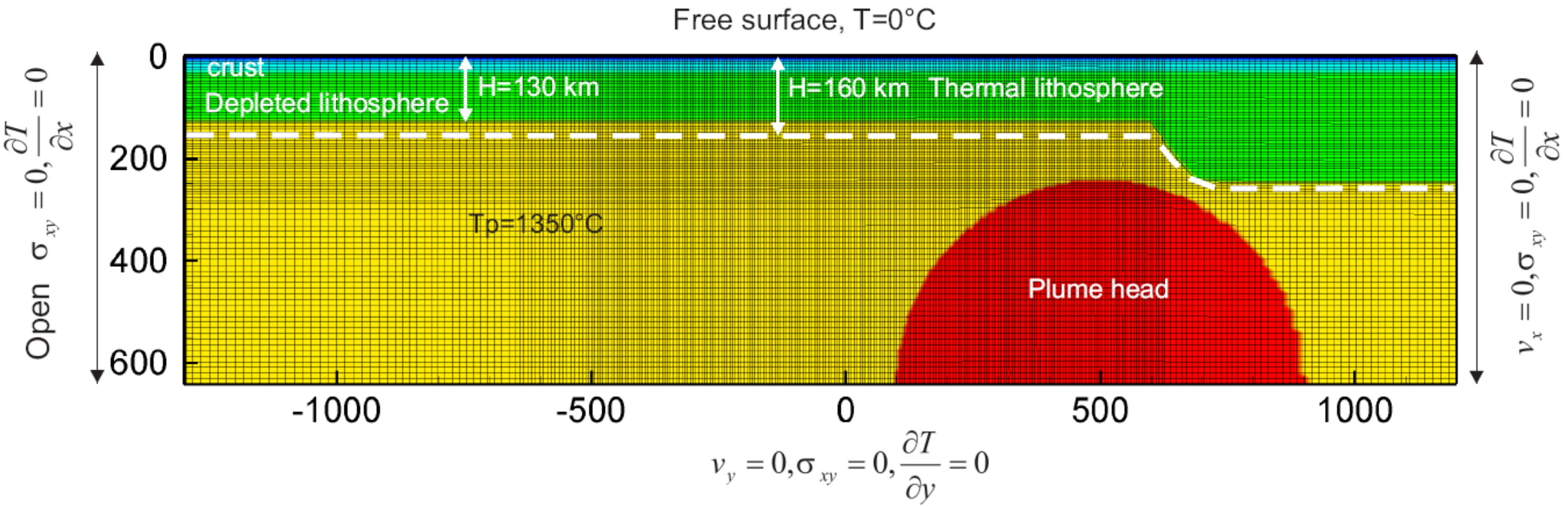
- Plume potential temperature Tp=1600°C
- Eclogite content in plume 10-20wt% (15wt%)
- Initial lithospheric thickness >130 km

Improvements of tne thermomechanical modeling technique

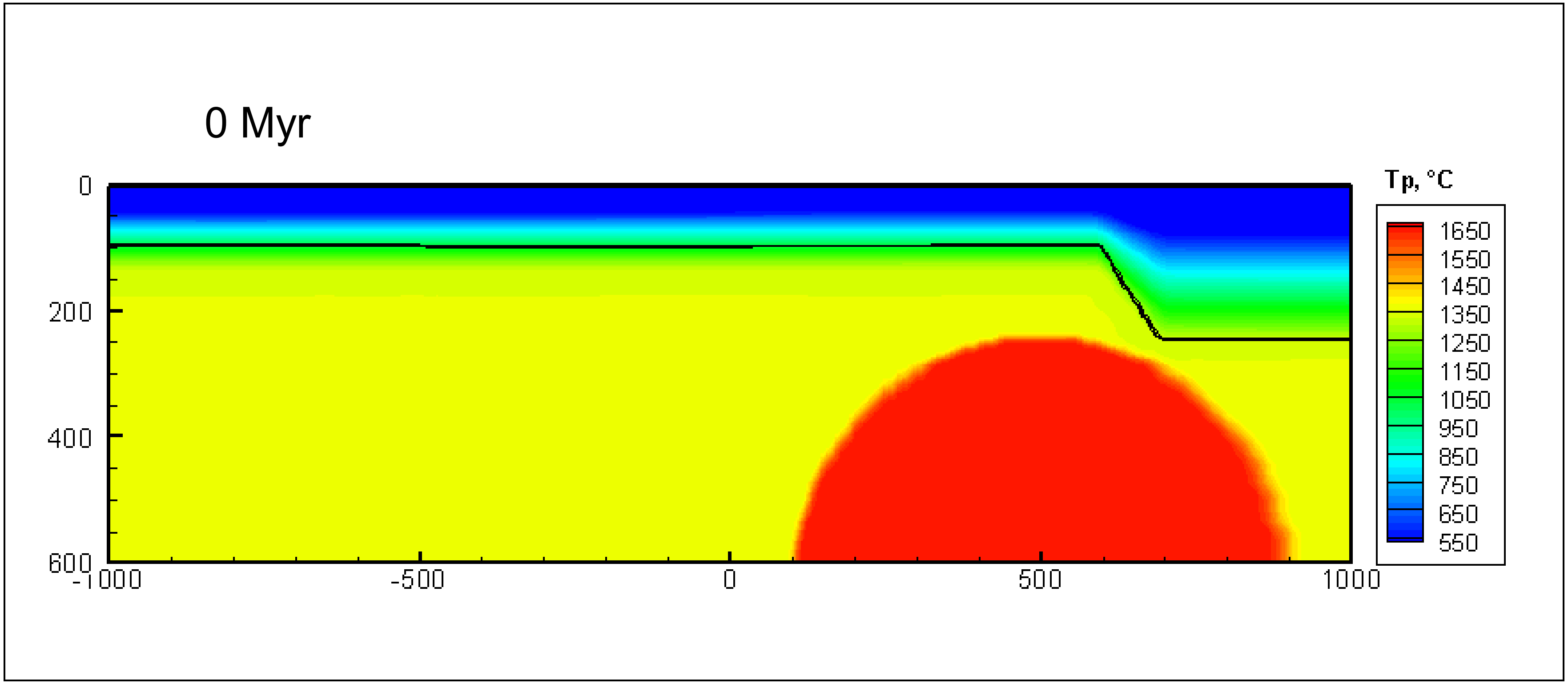
Melting of peridotite (Katz et al, 2003), of eclogite and pyroxenite (based on experiments of Yaxley, and Hirschmann group, Sobolev et al, 2007

Melt transport procedure (fast compaction porous-flow-like in the melting region and intrusion in the lithosphere)

Model setup

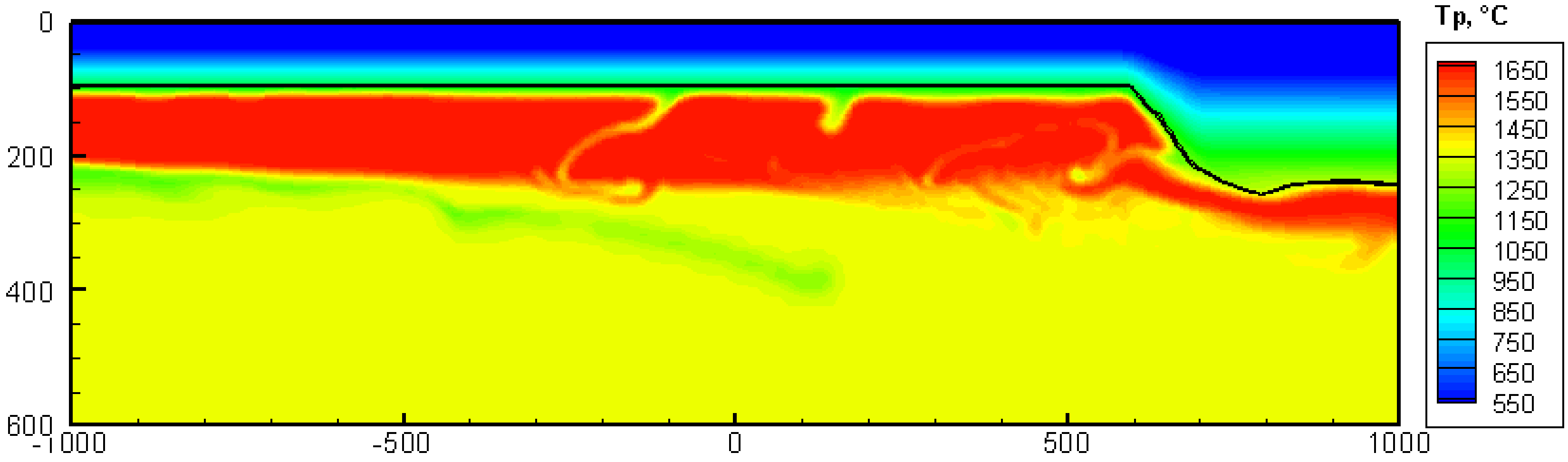

Free surface, T=0°C
crust
Depleted lithosphere
H=130 km
H=160 km
Thermal lithosphere
Tp=1350°C
Plume head
0
200
400
600
-1000
-500
0
500
1000
Open $\sigma_{xy} = 0, \frac{\partial T}{\partial x} = 0$
$v_x = 0, \sigma_{xy} = 0, \frac{\partial T}{\partial x} = 0$
$v_y = 0, \sigma_{xy} = 0, \frac{\partial T}{\partial y} = 0$

Thermal plume(Tp=1650°C)
no melting

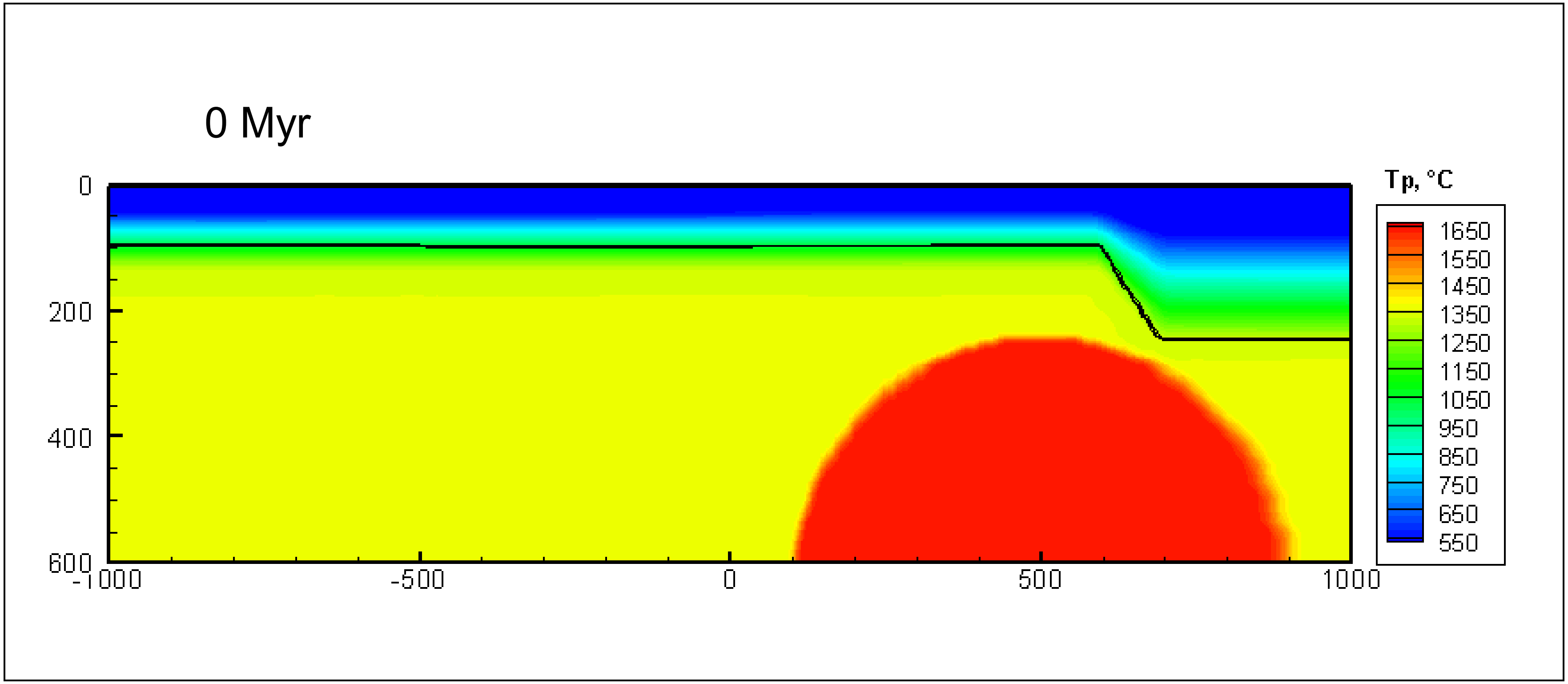


Thermal plume
no melting

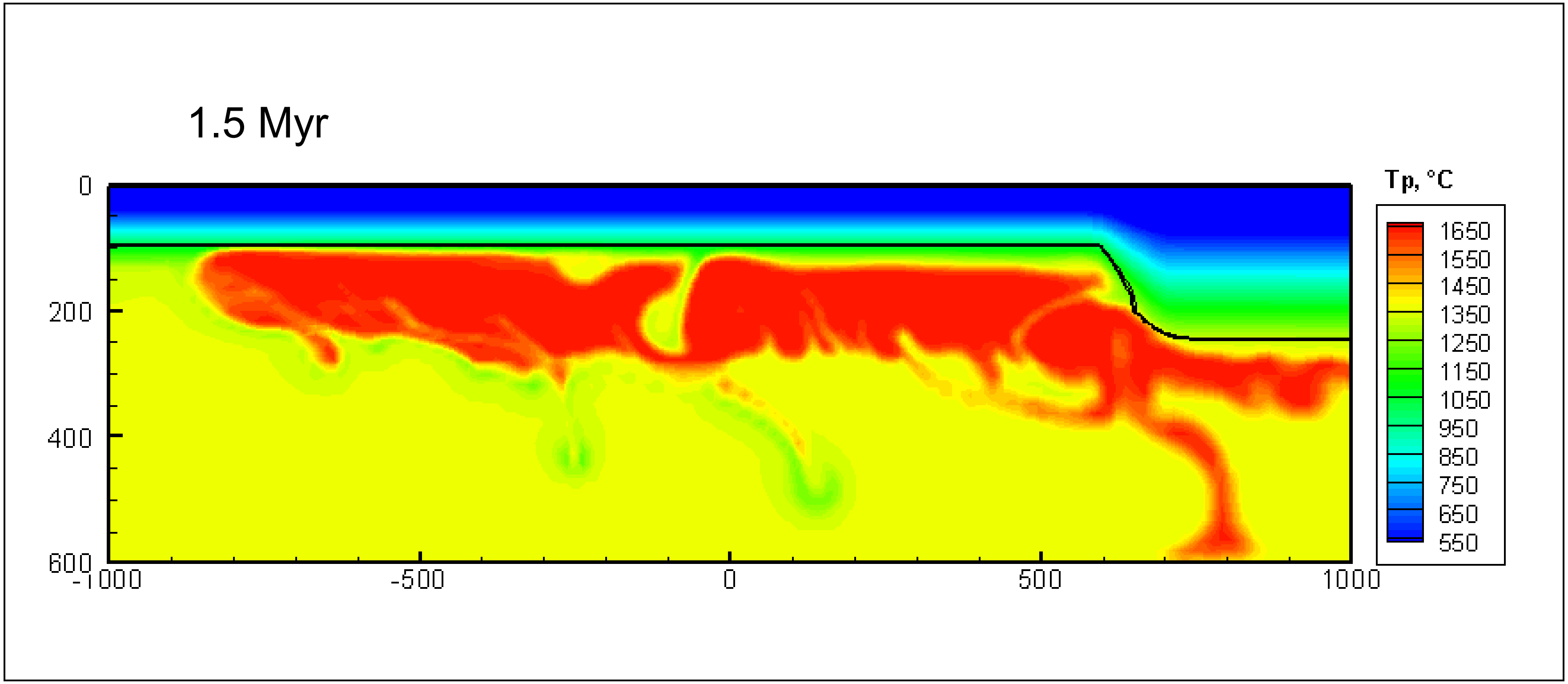
0.5 Myr



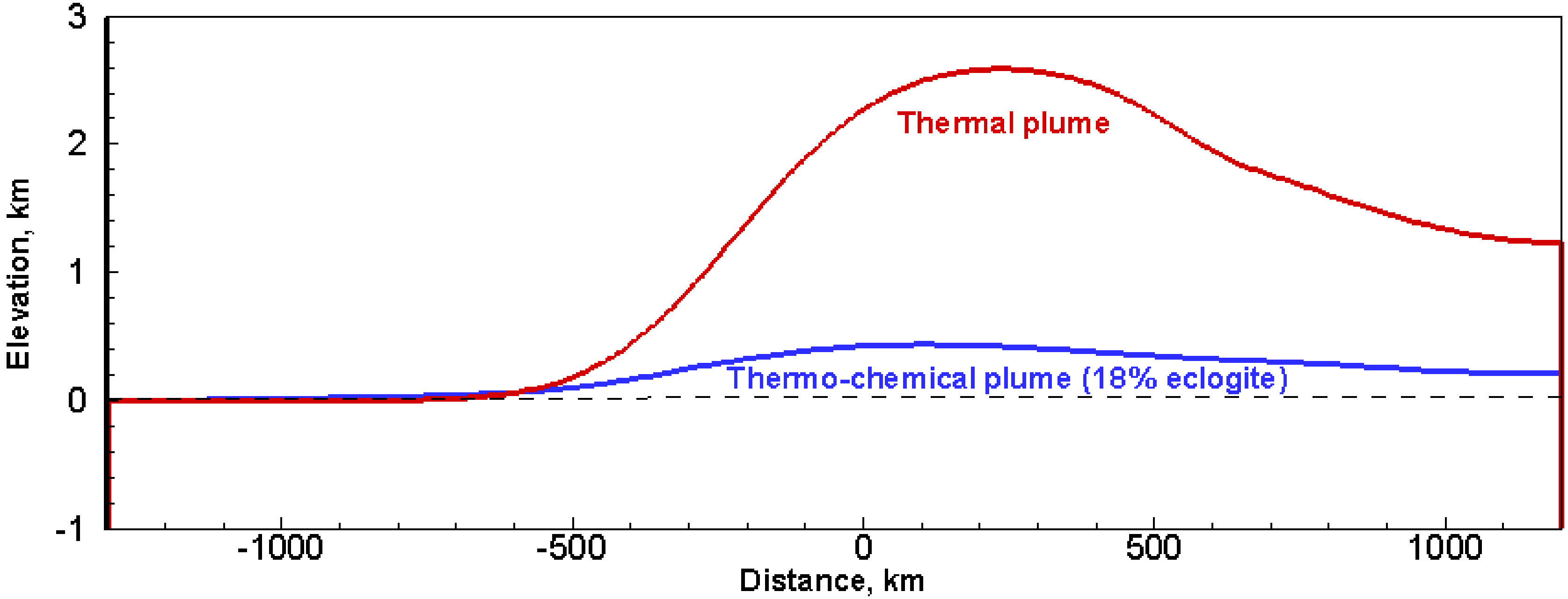
Thermo-chemical plume
(Tp=1650°C,18% eclogite)
no melting



Thermo-chemical plume
no melting



Elevation


Thermal plume
Thermo-chemical plume (18% eclogite)
Elevation, km
3
2
1
0
-1
-1000
-500
0
500
1000
Distance, km

Thermomechanical model of Siberian LIP constrained by petrological data based on 2011 paper

LETTER

doi:10.1038/nature10385

Linking mantle plumes, large igneous provinces and environmental catastrophes

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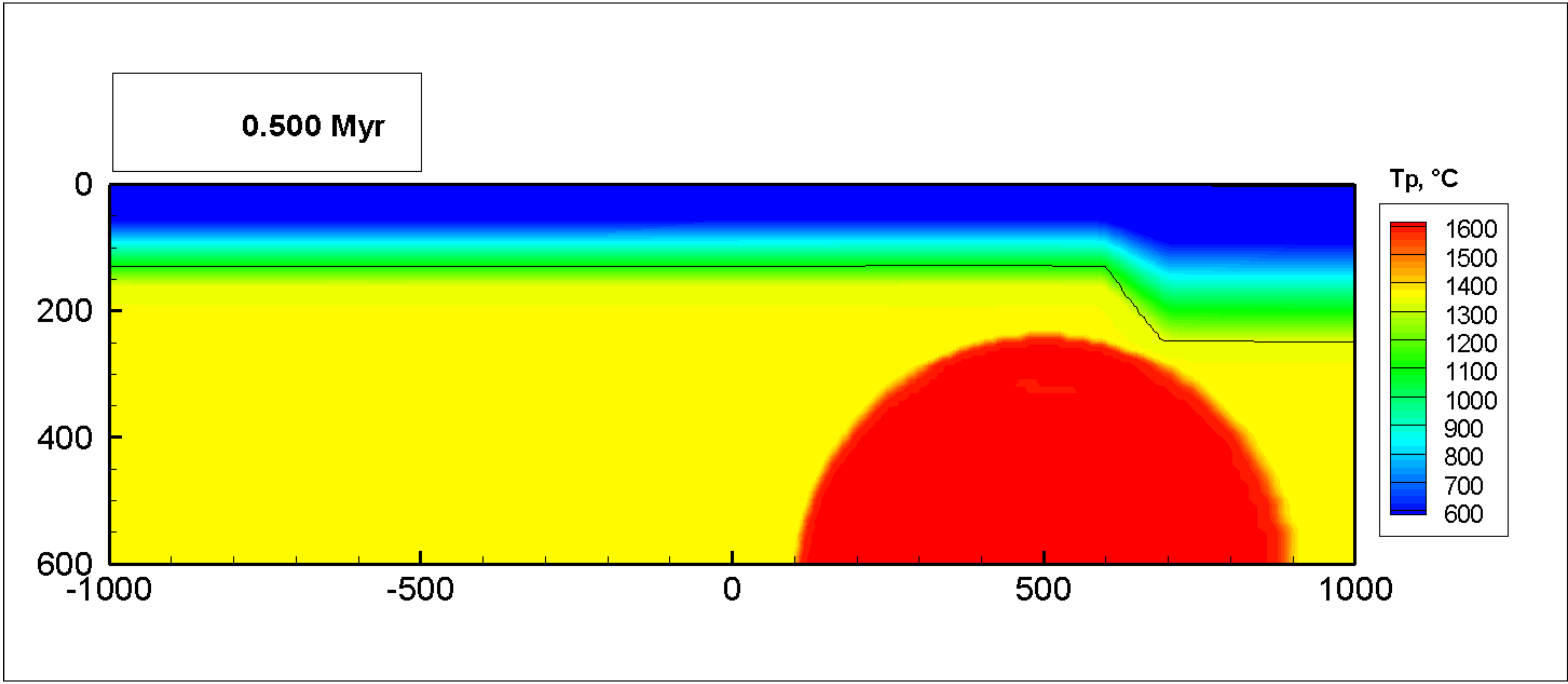
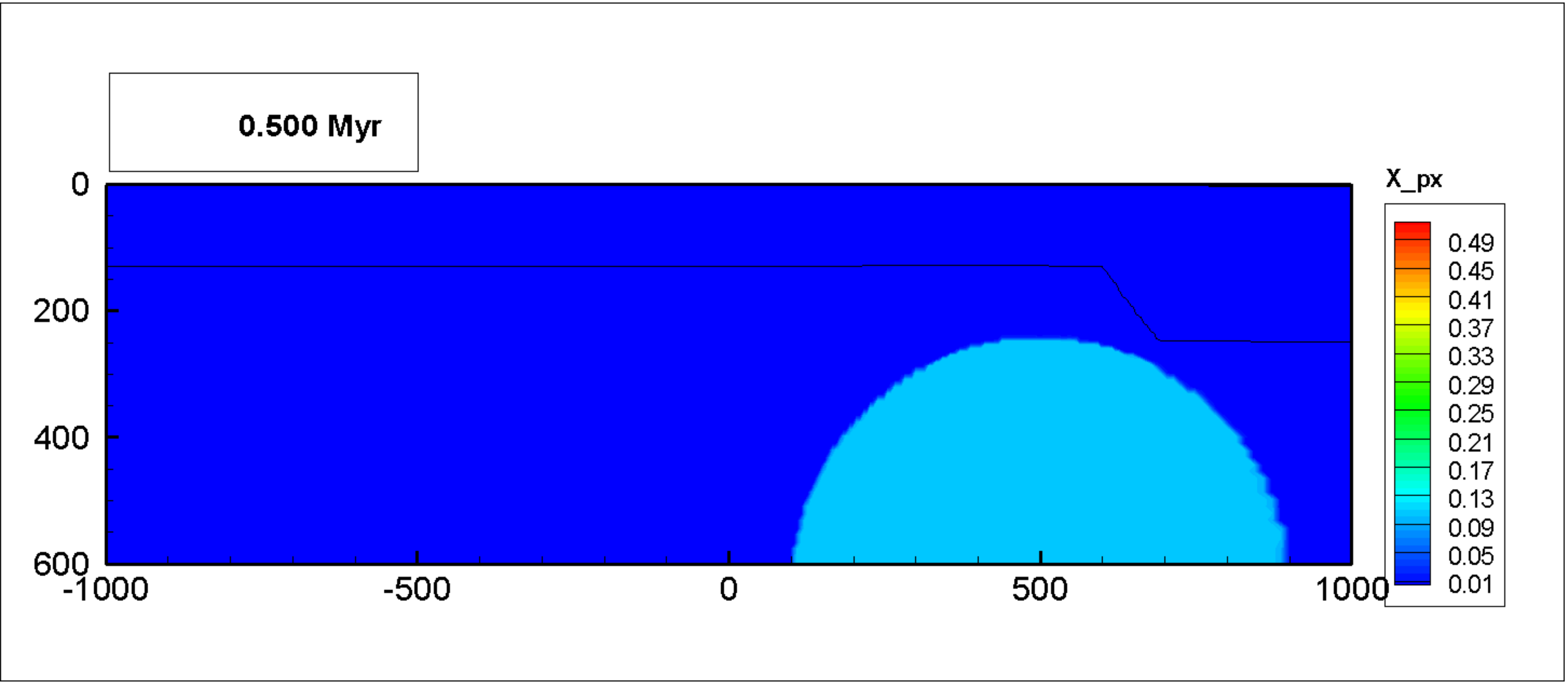
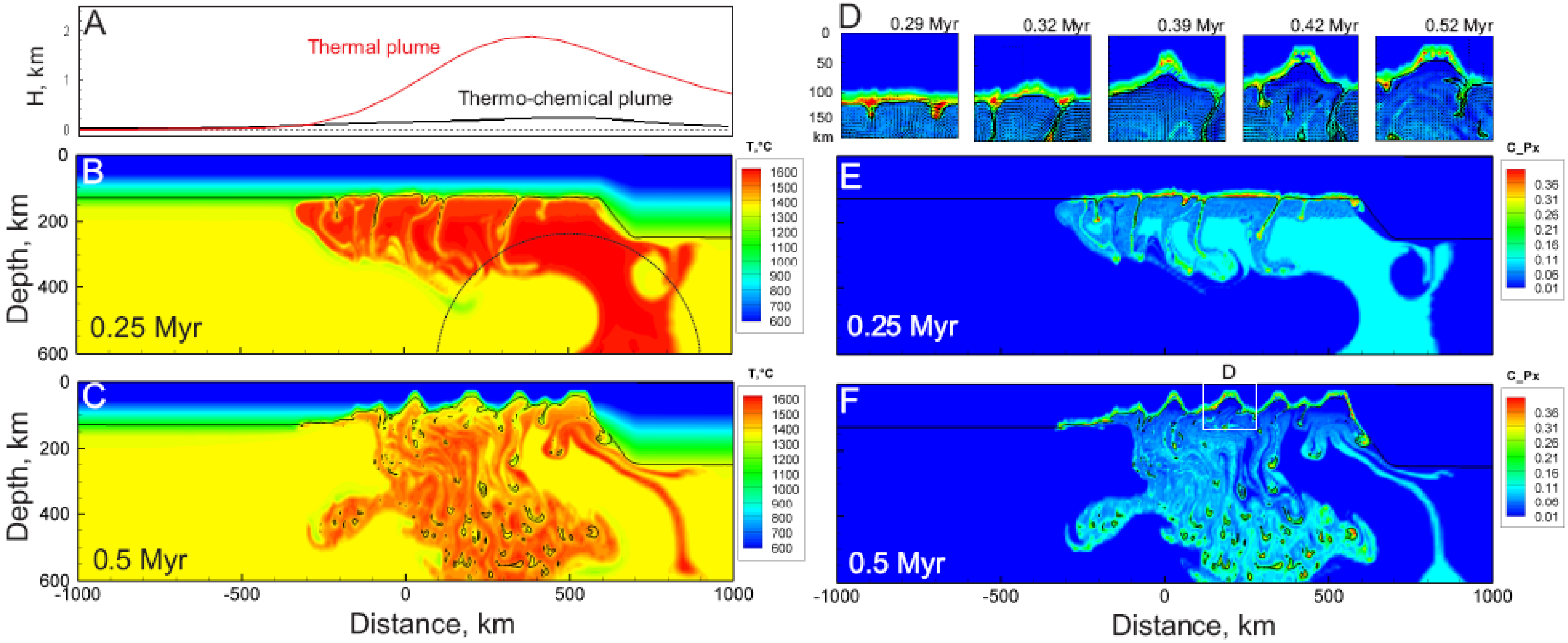
Temperature



Composition

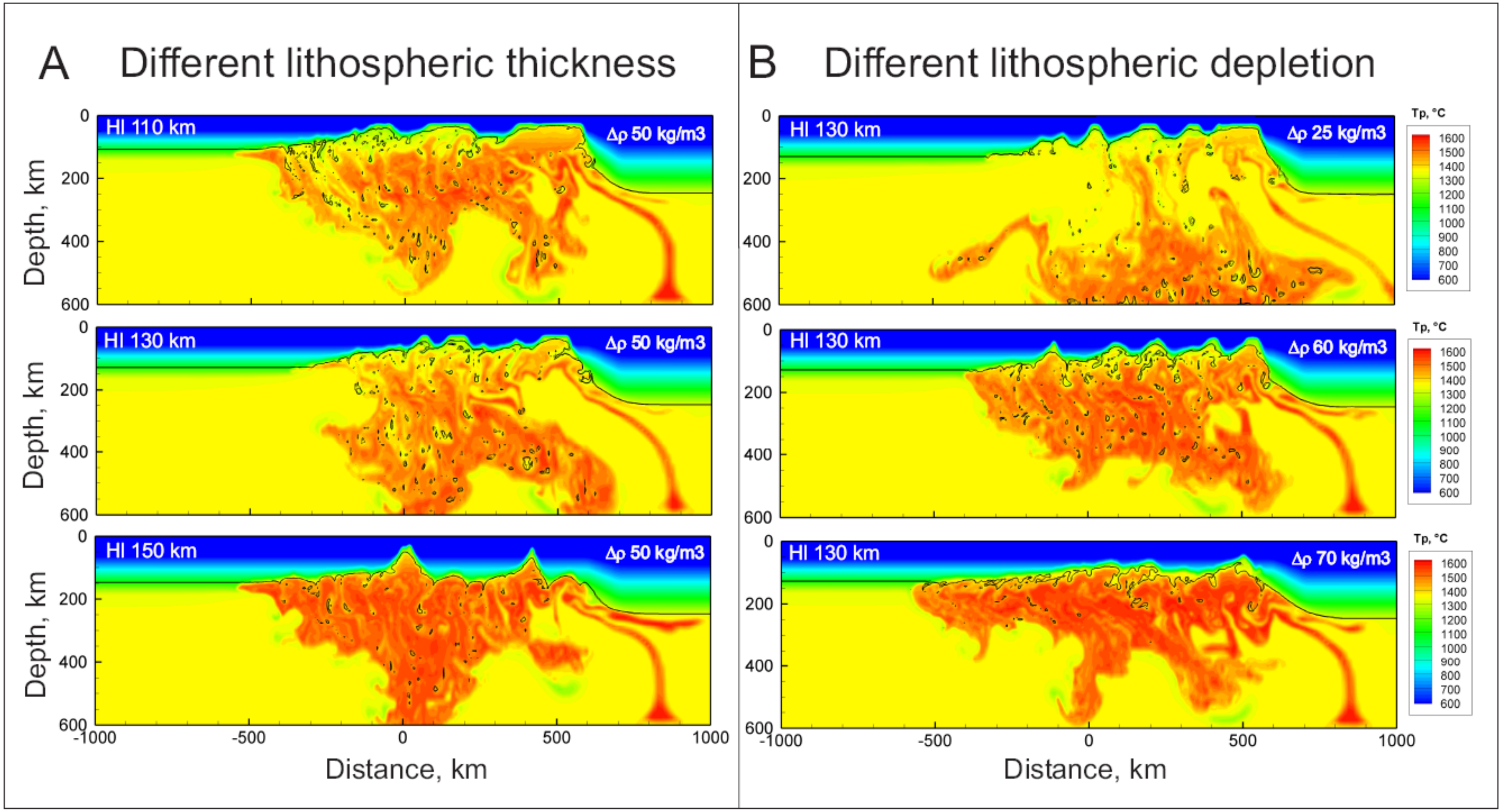


Numerical model



Sobolev et al. submitted

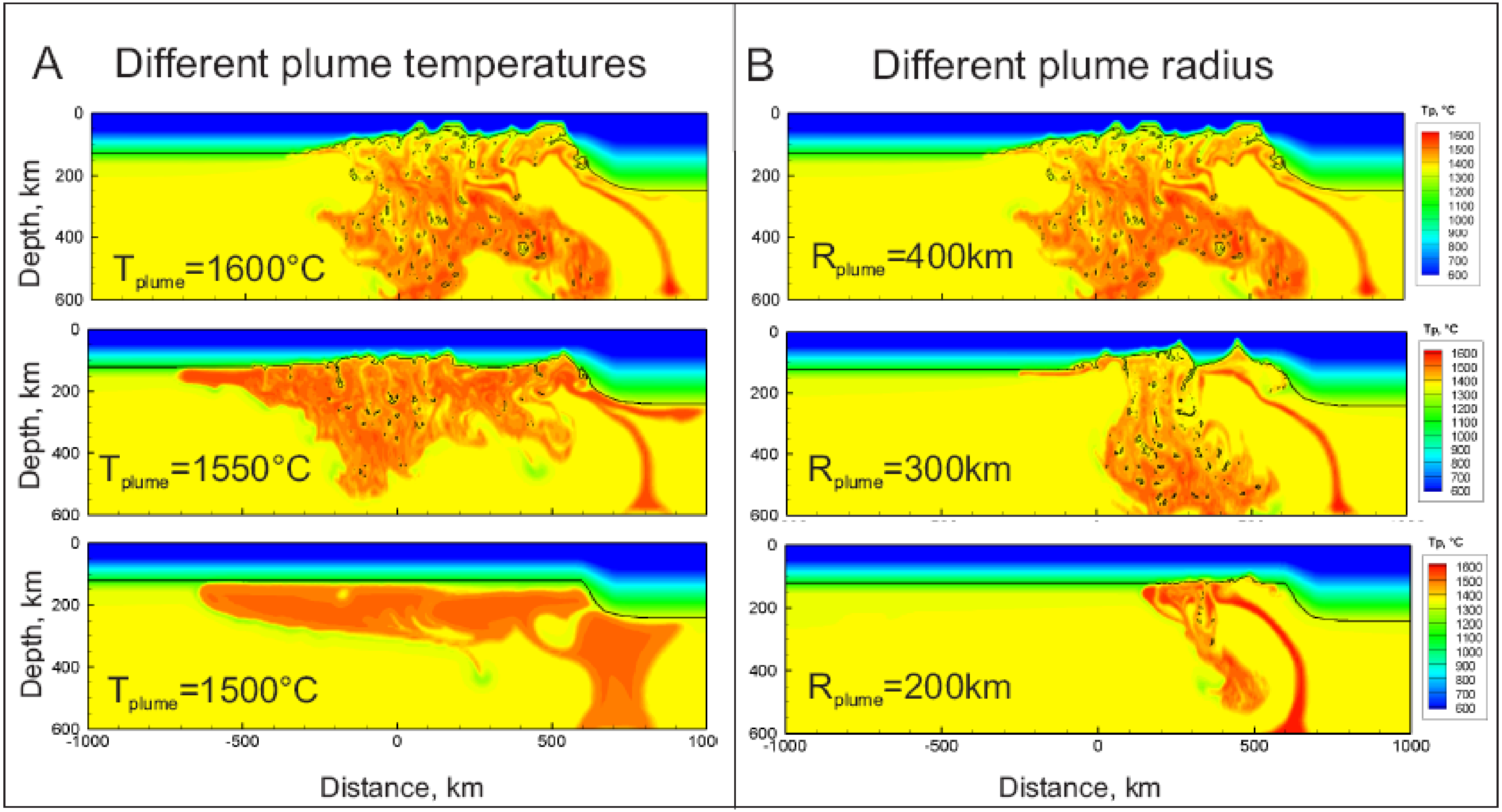
Effect of lithosphere



A Different lithospheric thickness

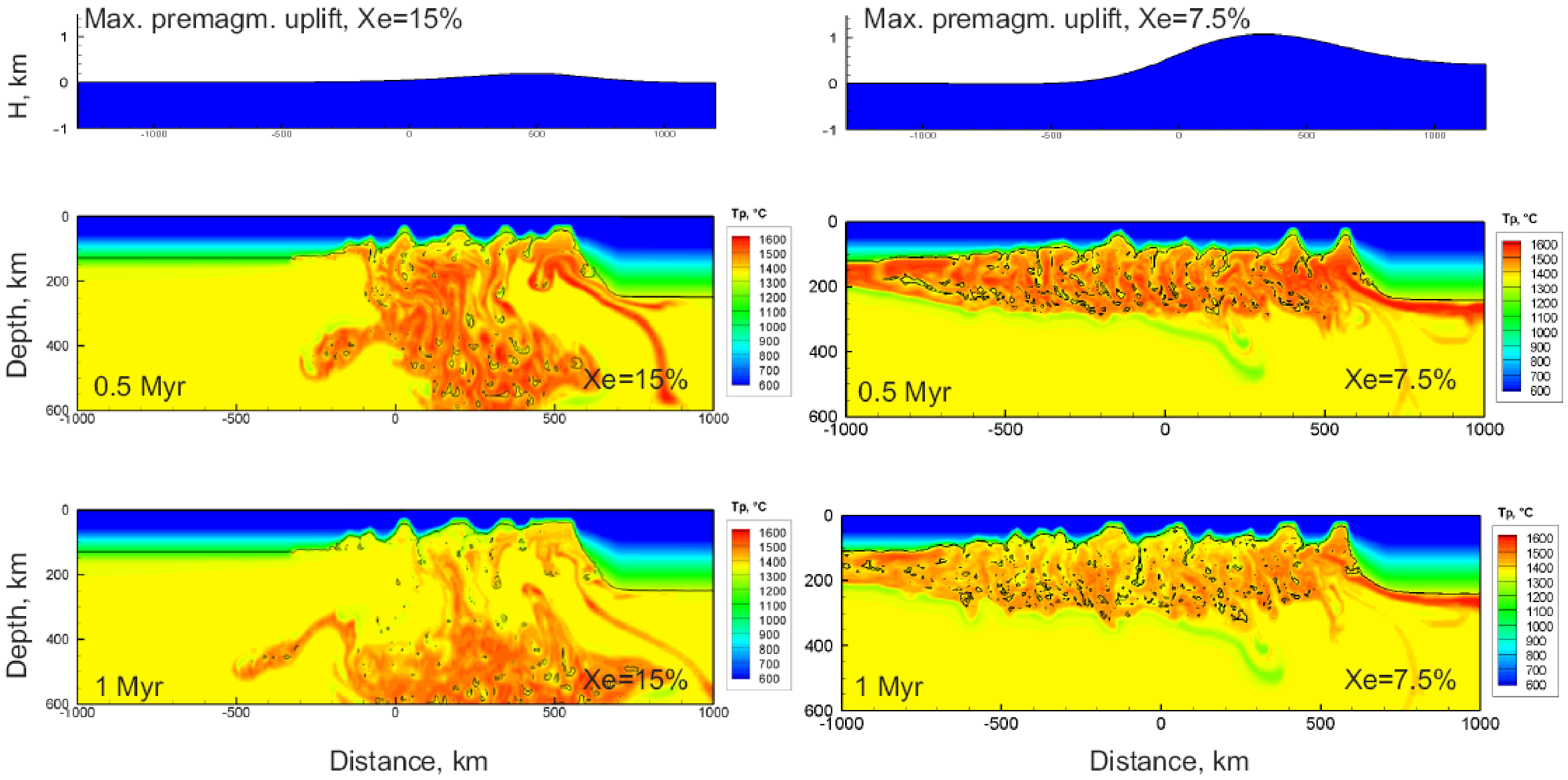
B Different lithospheric depletion

Effect of plume



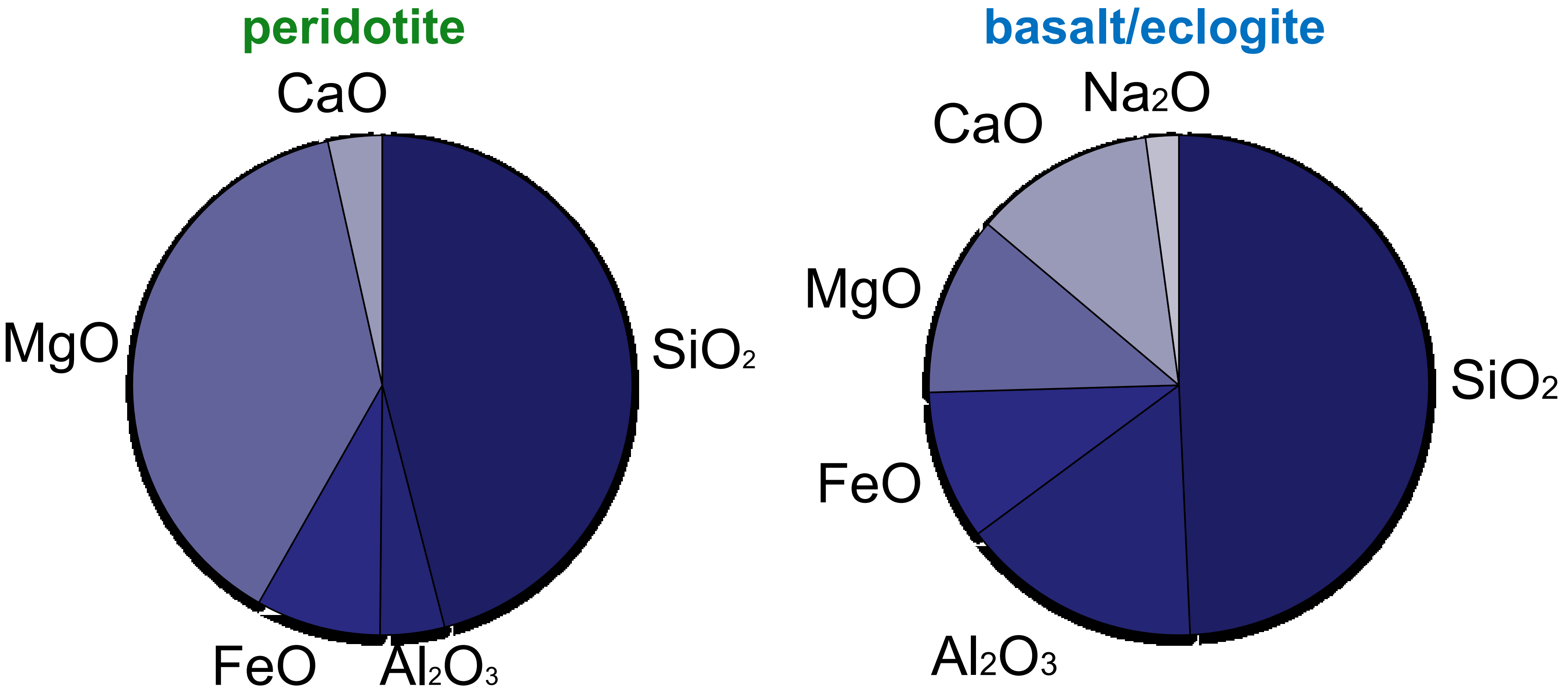
Effect of plume

Different plume composition



What about relation with Mass Extinctions?

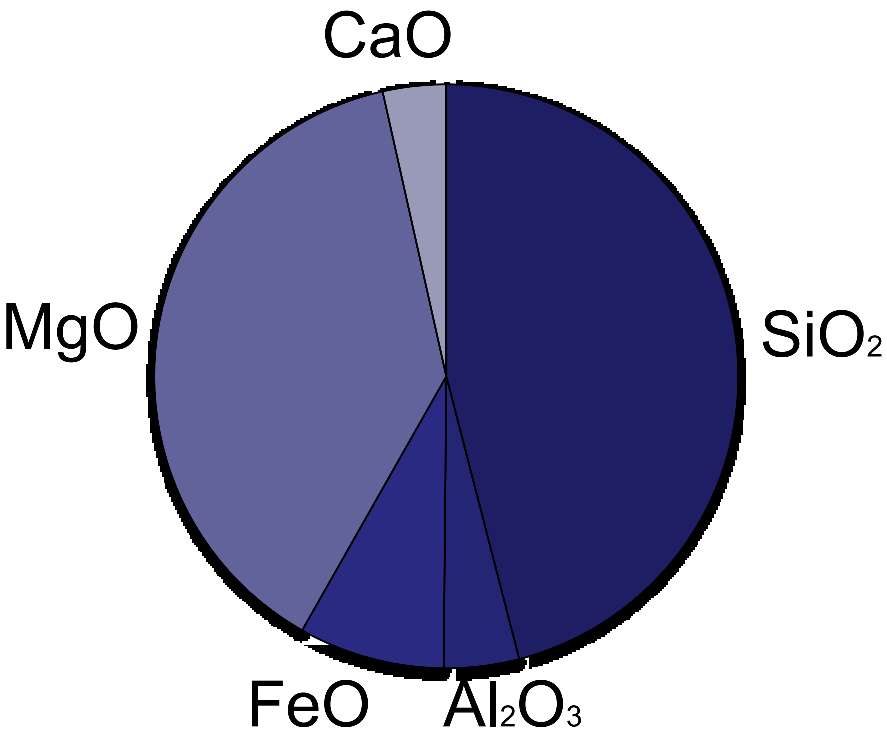
Thermo-chemical plume



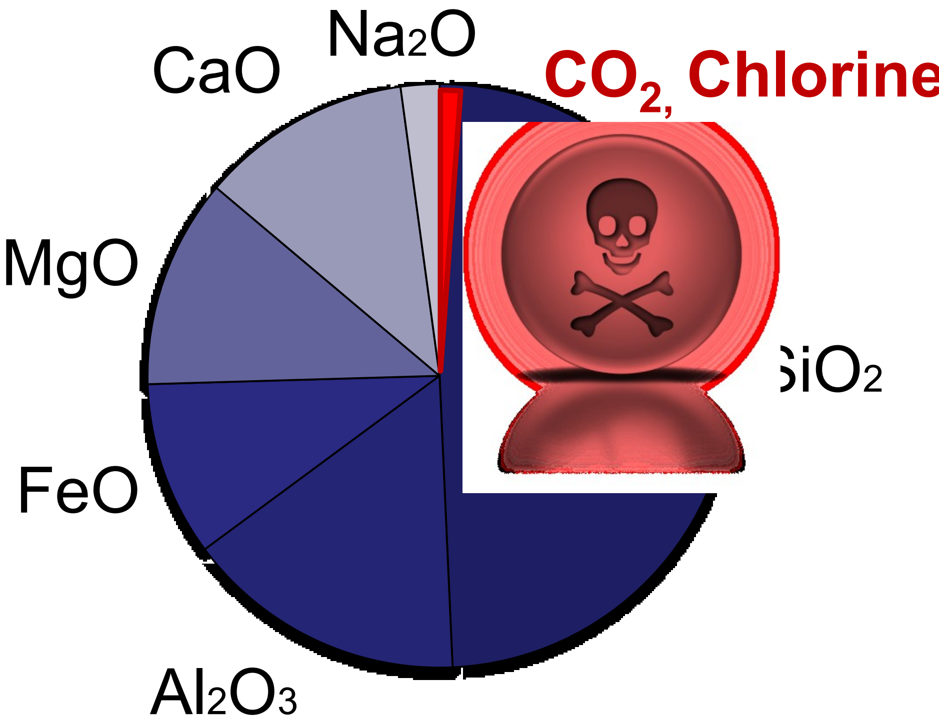
Data from Ganguly et al., (2009)

Thermo-chemical plume

peridotite

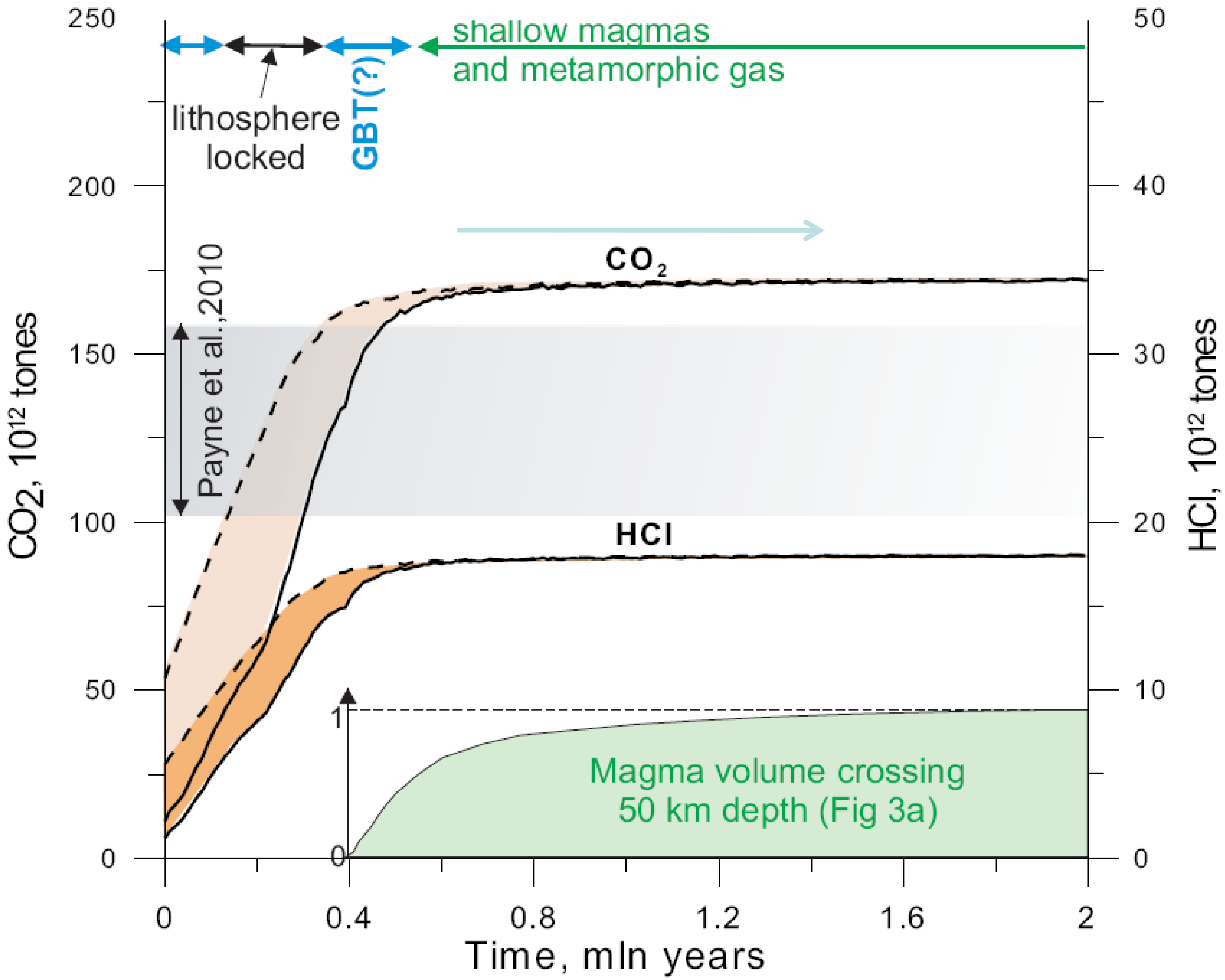


basalt/eclogite

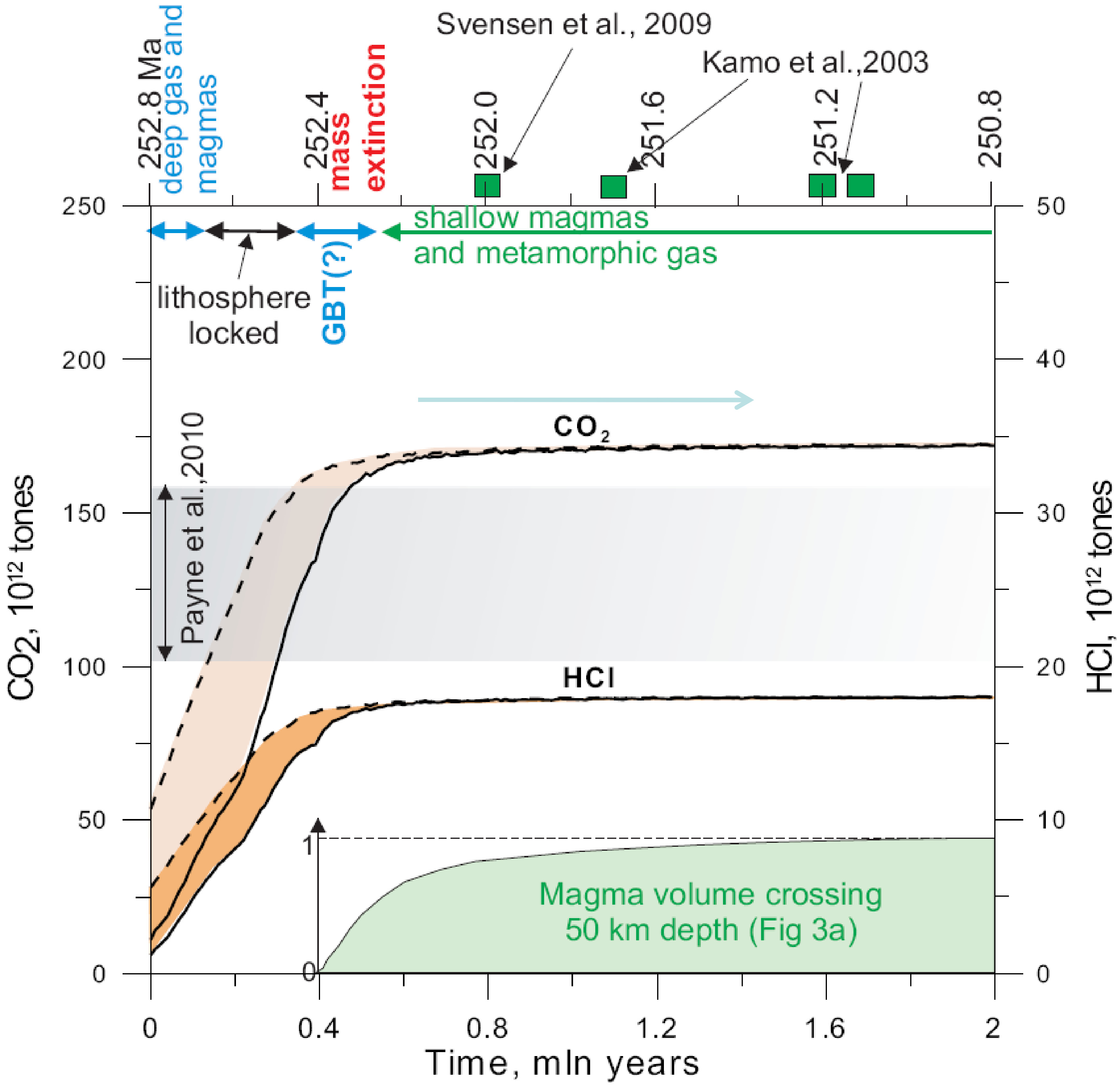


Data from Ganguly et al., (2009)

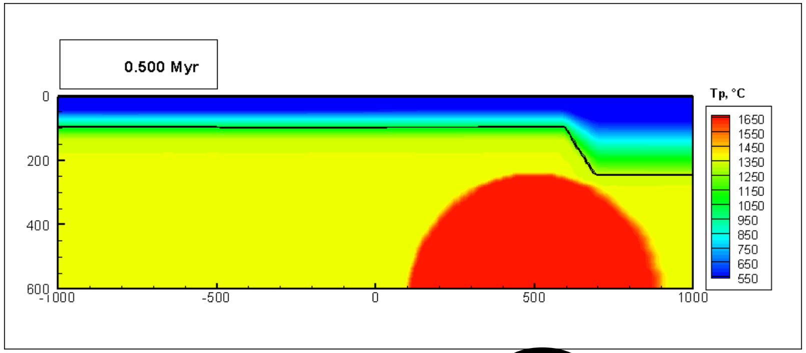
Modeled Plume degassing



Model prediction: degasing and extinction <u>before</u> main magmatic phase

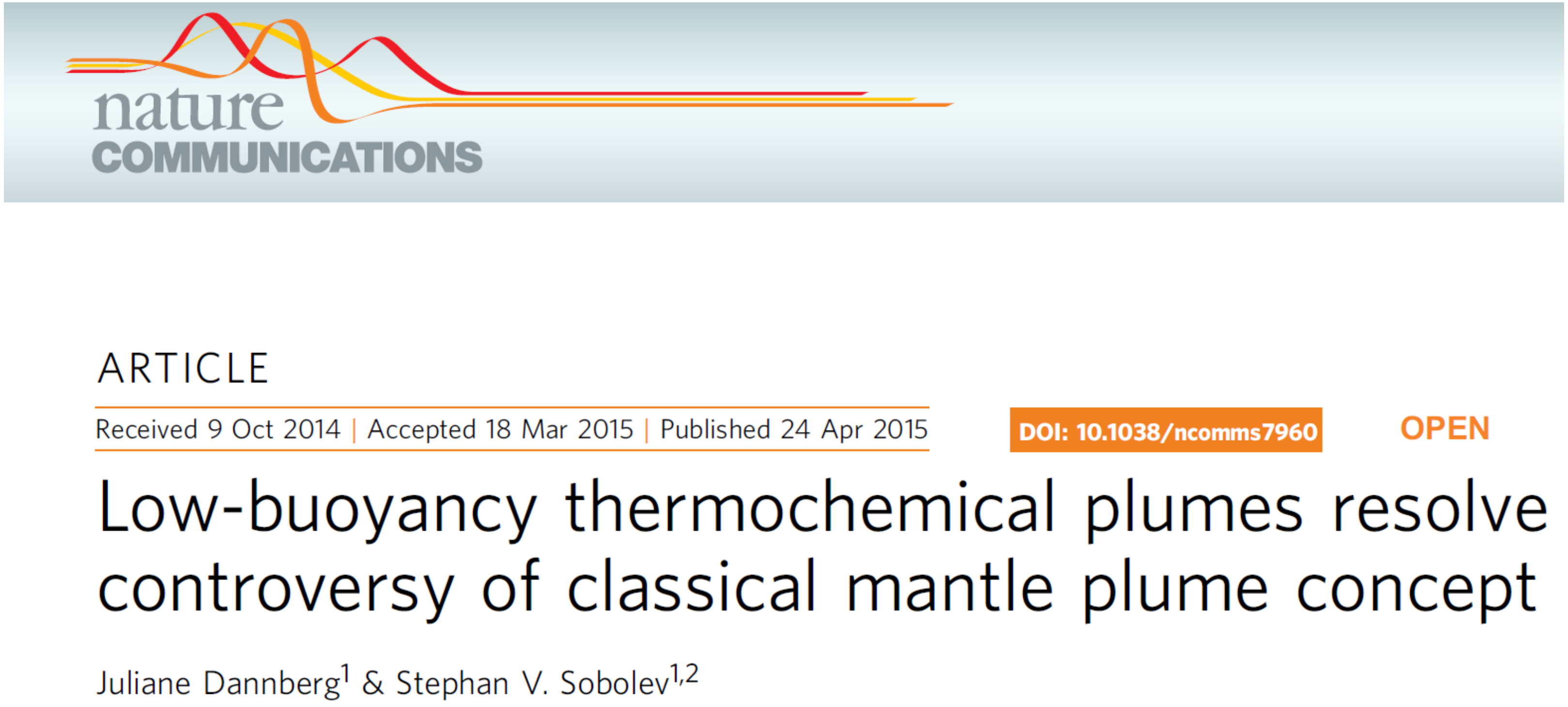

252.8 Ma
deep gas and magmas
252.4
mass extinction
252.0
251.6
251.2
250.8
Svensen et al., 2009
Kamo et al.,2003
lithosphere locked
GBT(?)
shallow magmas and metamorphic gas
Payne et al.,2010
CO_2
HCl
Magma volume crossing 50 km depth (Fig 3a)
1
0
CO_2, 10^{12} tones
HCl, 10^{12} tones
250
200
150
100
50
0
50
40
30
20
10
0
0
0.4
0.8
1.2
1.6
2
Time, mln years

But what happens with thermochemical plumes in deep mantle?



?

Rise of the thermochemical plumes through the mantle



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ARTICLE

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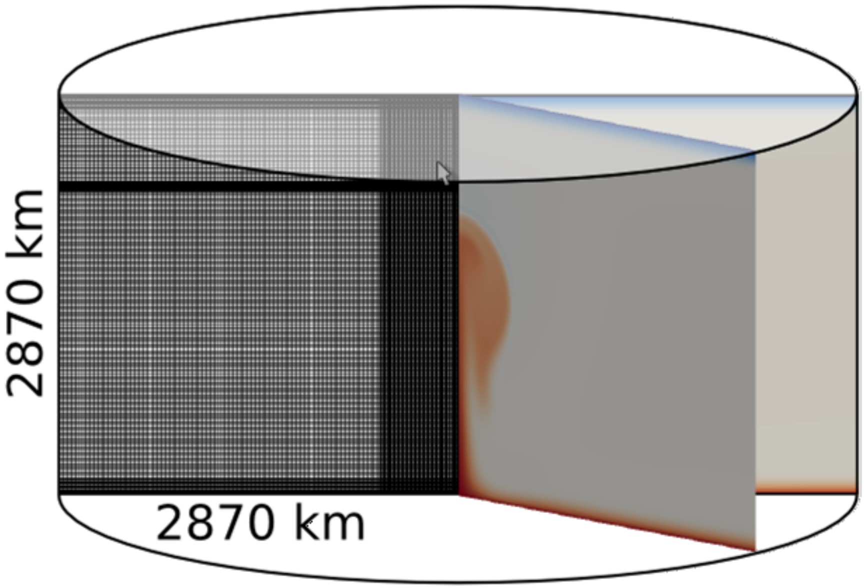
OPEN

Low-buoyancy thermochemical plumes resolve controversy of classical mantle plume concept

Juliane Dannberg[1] & Stephan V. Sobolev[1,2]

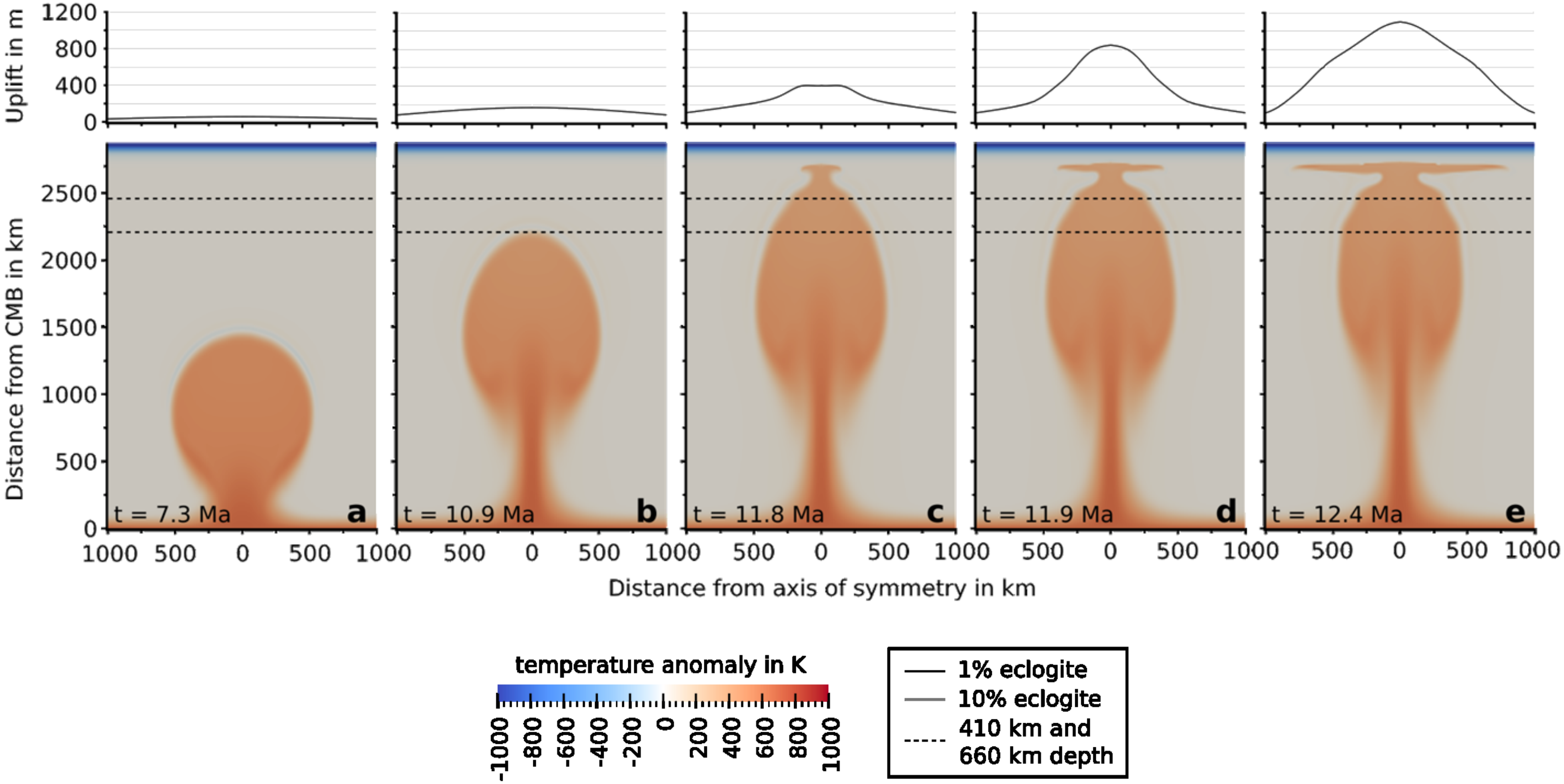
Whole Mantle Model of Thermo-Chemical Plume



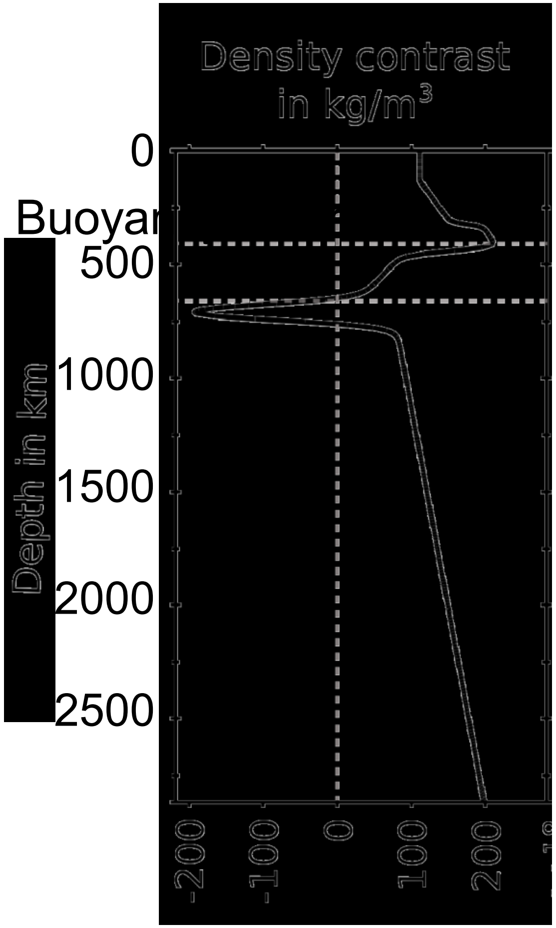
- Software:
  Citcom (2D axisymmetric)
  Aspect (3D models)

- Compressible mantle
- Adiabatic heating & shear heating
- Effect of phase transitions

Thermal plume

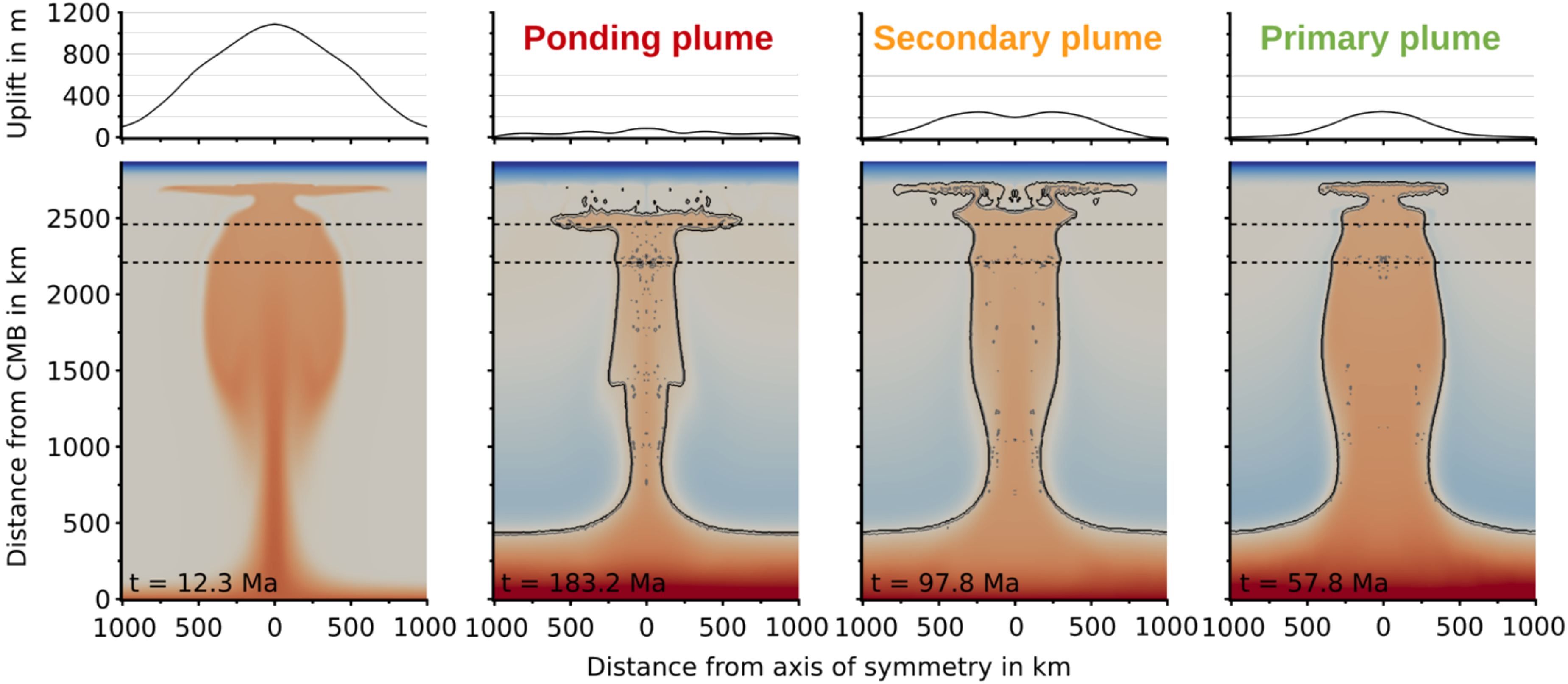


Plume buoyancy



Experimental data on eclogite-peridotite density difference after Aoki & Takahashi, 2004; Litasov & Ohtani, 2005; Hirose et al., 2005

Plume regimes



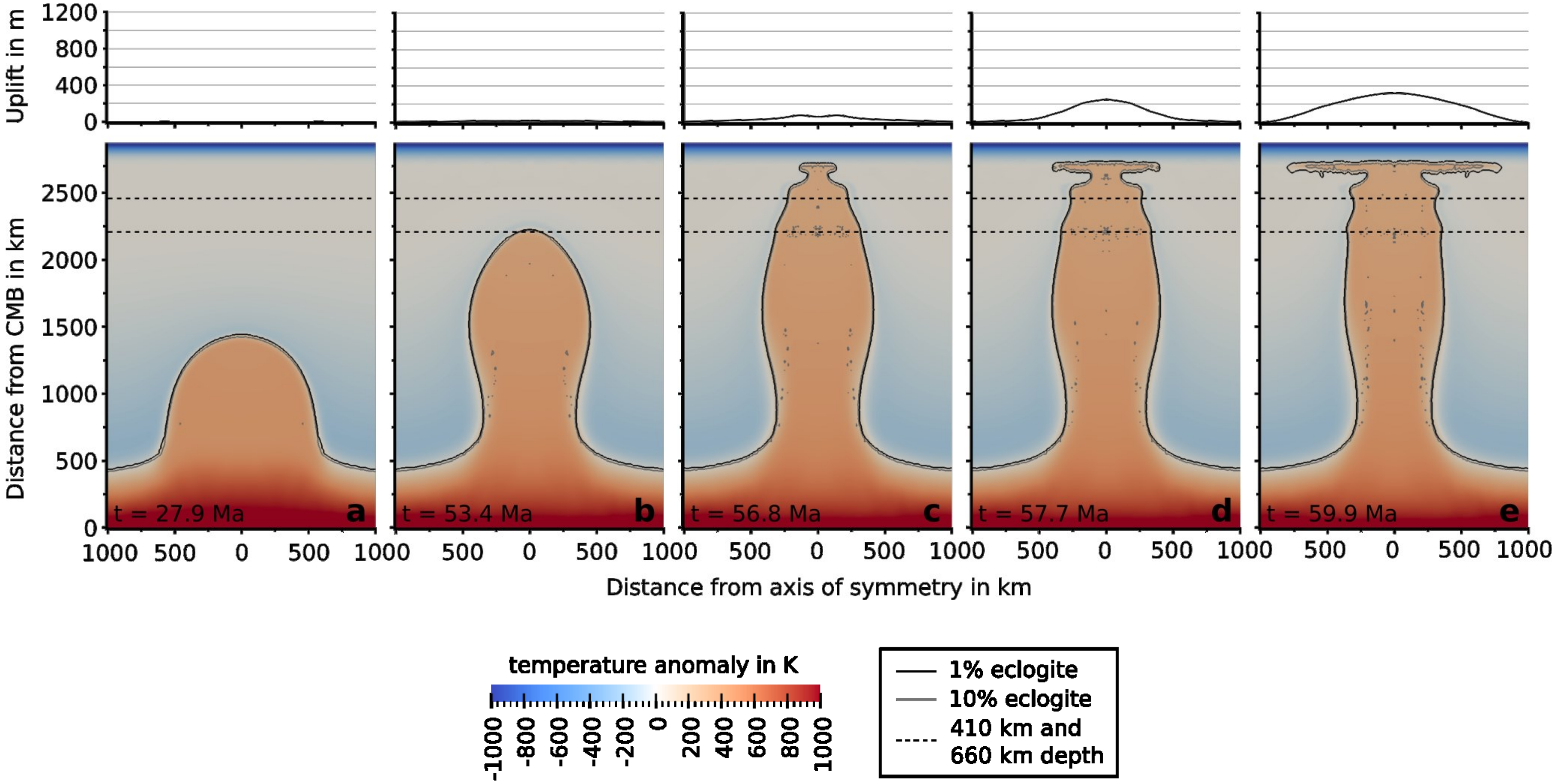
(a) thermal plume, R_0=685 km.

(b) thermo-chemical plume, R_0=685 km.

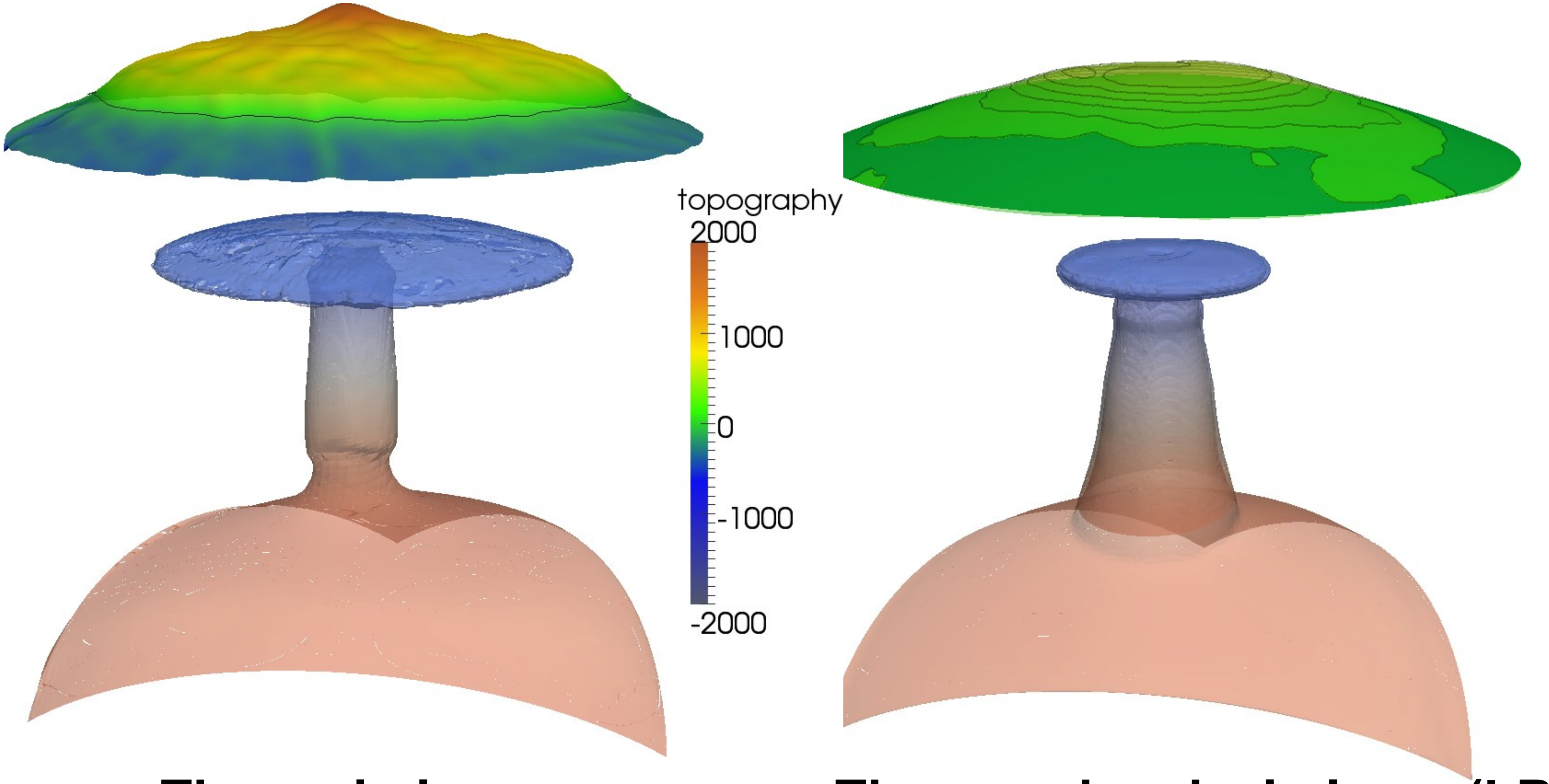
(c) thermo-chemical plume, R_0=760 km.

(d) thermo-chemical plume, R_0=840 km.

Thermo-chemical plume



Thermal vs. Thermo-chemical plume in 3D (modeling with ASPECT)



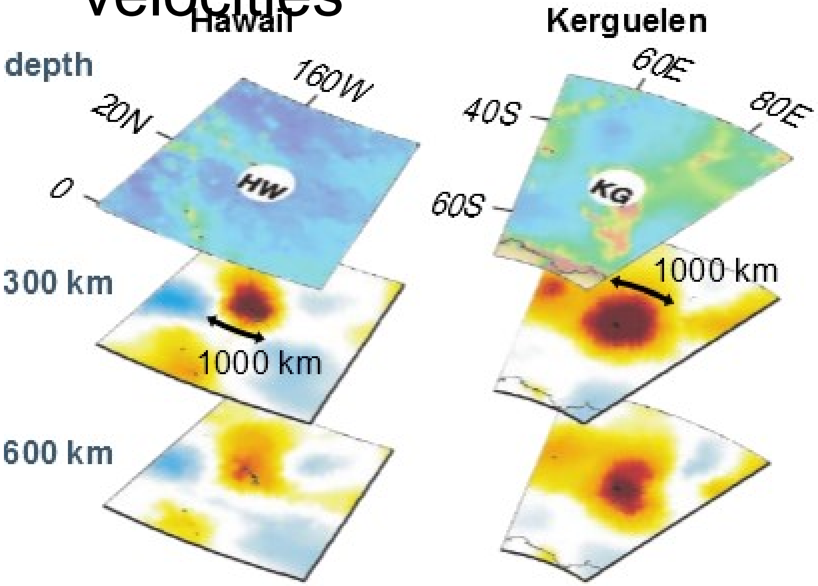
Thermal plume

Thermo-chemical plume (LBP)

Comparison to observations

Observation:

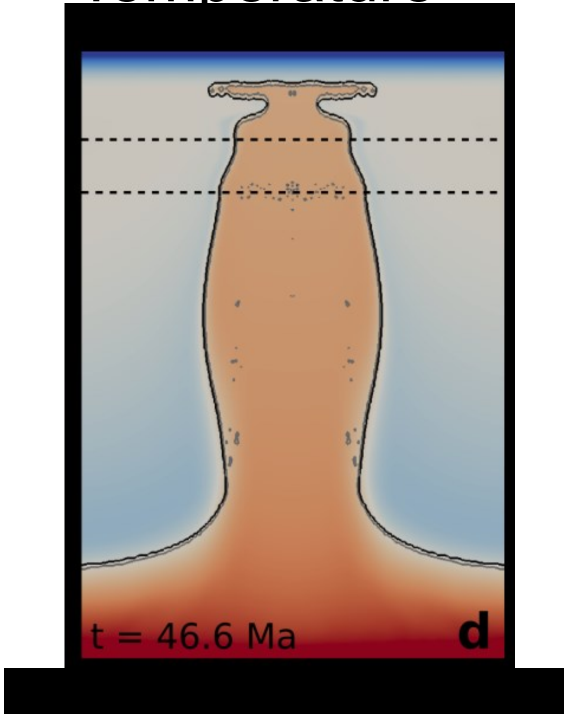
seismic velocities



From Montelli et al., 2006

Model:

Temperature



Conclusions

✓Large thermochemical plume inriched in recycled oceanic crust can rise from the deep mantle and generate LIP without significant pre-magmatic uplift of the lithosphere

✓Such a plume is able to thin dramatically cratonic lithosphere without extension and to generate several mln km3 of melt in few 100 thousand years

✓Massive CO2 and HCl degassing from the plume could alone trigger the Permian-Triassic mass extinction <u>before</u> the main volcanic phase