The effects of plumes on the dynamics of supercontinents in a self-consistent plate tectonics setting

ETH zürich

Charitra Jain, Antoine Rozel, Paul Tackley

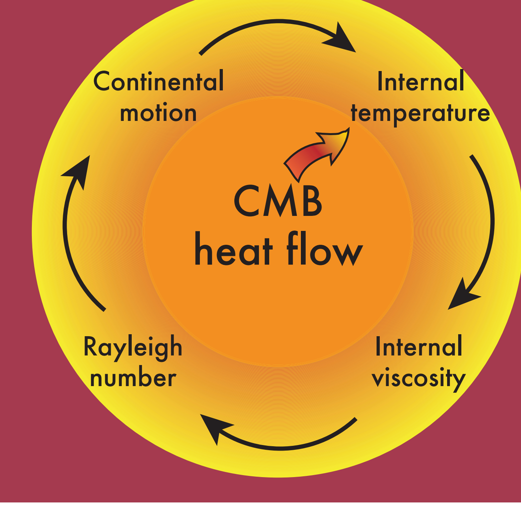
charitra.jain@erdw.ethz.ch

Institute of Geophysics, Department of Earth Sciences, ETH Zürich, Sonneggstrasse 5, 8092 Zürich, Switzerland

Paper number: DI43A-4352

I. Introduction

- Higher core thermal conductivity [1-3] requires a CMB heat flow of at least 12 TW (early estimates around 3-4 TW) [4]. What is the impact of basal heating on mantle dynamics with continents and self-consistent plate tectonics?
- How does the combination of basal and internal heating affect mantle convection?
- Do mantle plumes prefer to develop under continents? [5-7]
- Is there any correlation between continents and elevated temperatures in the subcontinental mantle?



II. Numerical modeling using StagYY

- Boussinesq, incompressible thermo-chemical convection in 2D spherical annulus [8] geometry using StagYY [9]
- Self-consistent plate tectonics with continents [10] which are a compositionally distinct field tracked in time using the tracer ratio method. [11] Continents differ from mantle in terms of density contrast of 100 kg m^{-3} (buoyancy ratio), viscosity contrast, and yield stress
- Viscosity depends on temperature (Arrhenius law), composition, and phase changes at 410, 660 and pPv boundaries. Plastic yielding breaks stagnant-lid and gives plate-like behavior [12,13]

Symbol	Definition	Value	Unit
Ra_0	Rayleigh number	1.0×10^{6}	-
$\Delta\sigma_y$	Compositional yield stress contrast	10	-
$\Delta\eta_C$	Compositional viscosity contrast	100	-
η_0	Reference viscosity (asthenosphere)	1.0×10^{20}	Pa s
α_0	Thermal expansivity	3.0×10^{-5}	K^{-1}
g_0	Gravitational acceleration	9.81	m s^{-2}
D	Mantle thickness	2.89×10^{6}	m
ΔT	Temperature contrast	2500	K
T_s	Surface temperature	300	K
ρ_0	Reference density	3300	kg m^{-3}
κ_0	Thermal diffusivity	1.0×10^{-6}	m^2 s^{-1}

III. Results

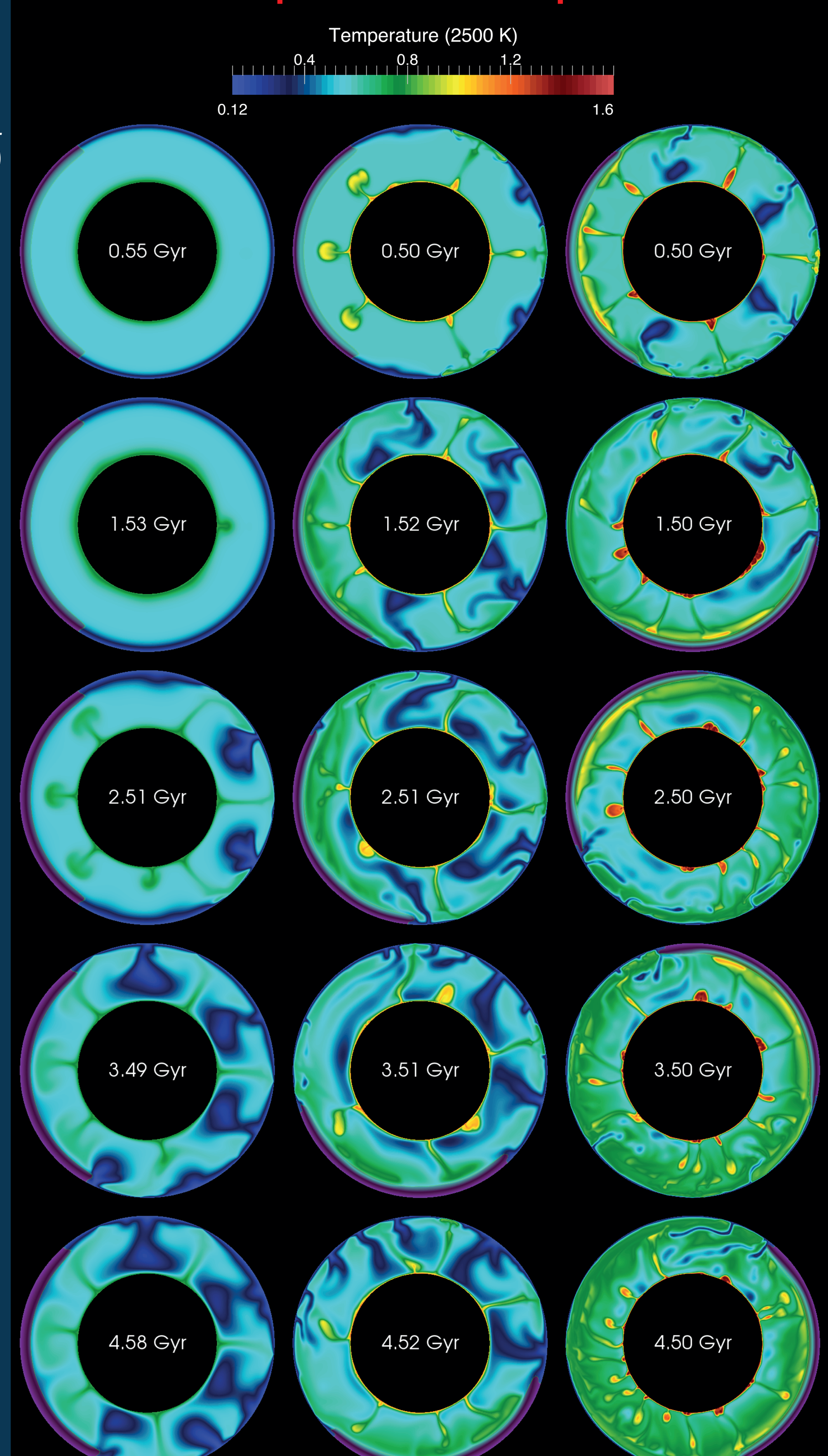
Time (Gyr)

CMB Temperature

basal heating, 1 supercontinent

2000 K | 3000 K | 4000 K

Continents are represented by compositional field (violet) superimposed over temperature field

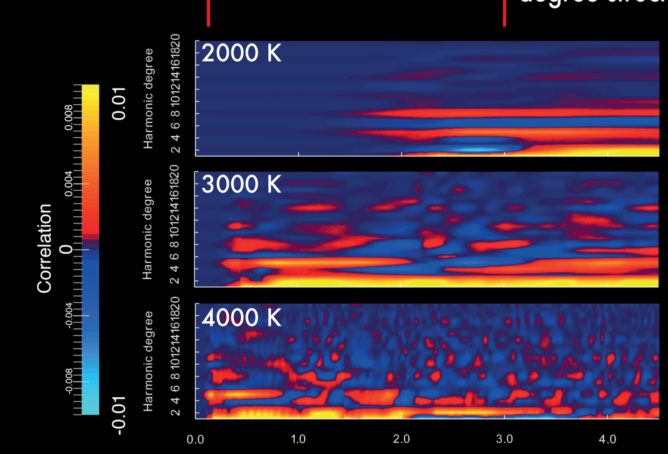


2000 K:
- plumes form slowly with degree 2, 5, 8
- lack of higher degree structures

3000 K:
- harmonic degree 1 structure

4000 K:
- plumes form faster with degree 1, 2
- anticorrelation due to multi-layered convection around 2 Gyr
- short lived higher degree structures

Temperature (T) and composition (C) fields are decomposed into fourier harmonics. Positive (yellow) and negative (light blue) values indicate correlation and anticorrelation between continental material at the surface and elevated temperatures underneath it respectively

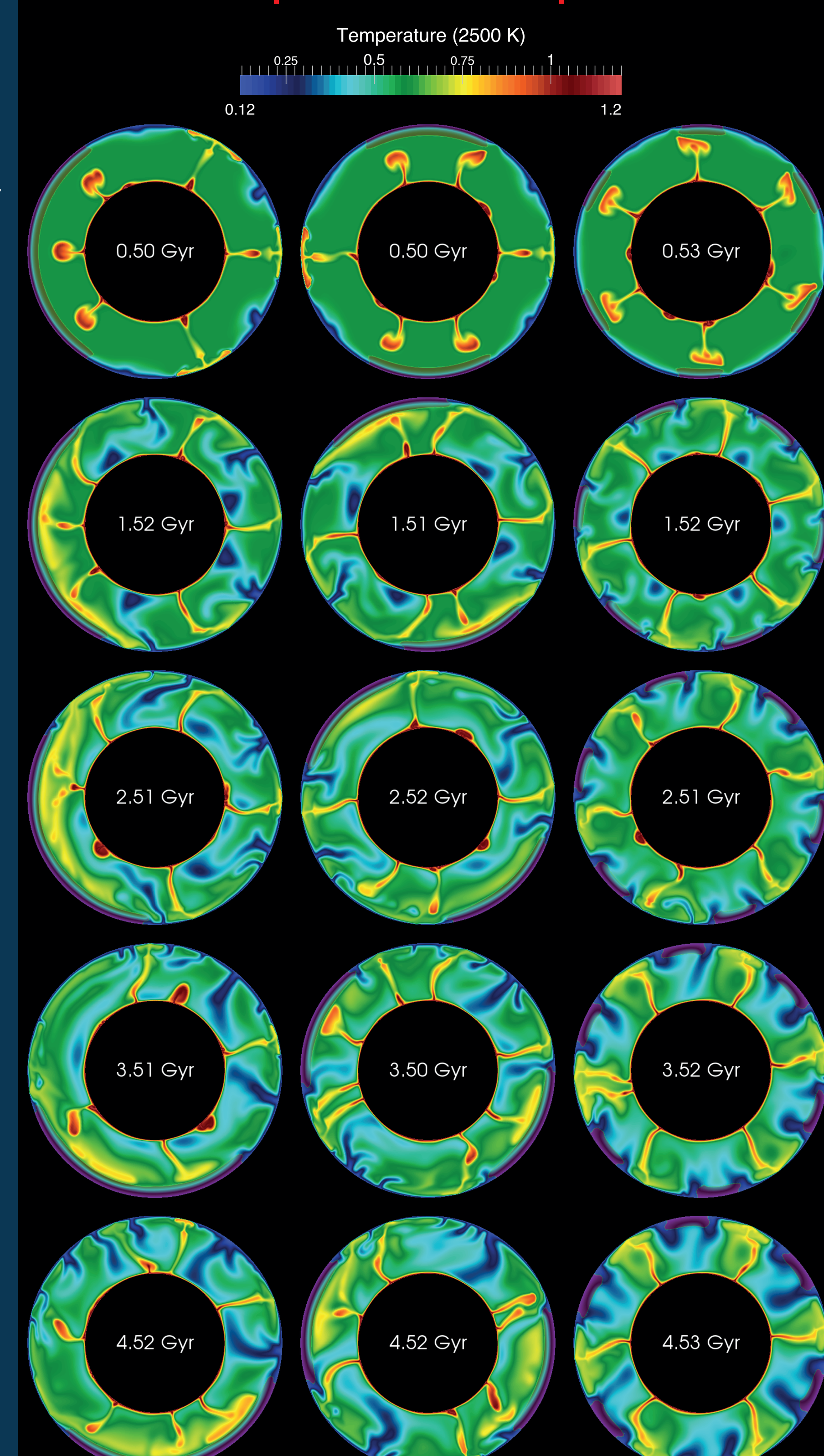


Continental configuration

basal heating, 3000 K CMB temperature

1 continent | 2 continents | 6 continents

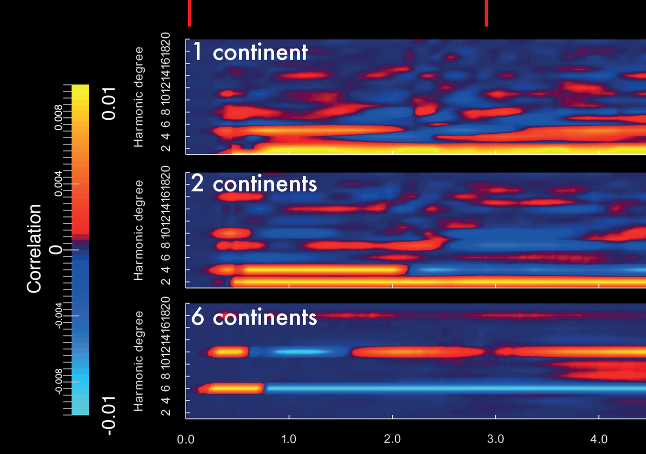
While keeping the total continental coverage same as 30% of earth's surface area, three different configurations are tested



1 continent:
- harmonic degree 1 structure

2 continents:
- degree 2 prominent
- degree 4 until 2 Gyr

6 continents:
- degree 6, 12
- continents not free from subduction
- anticorrelation due to very small continents

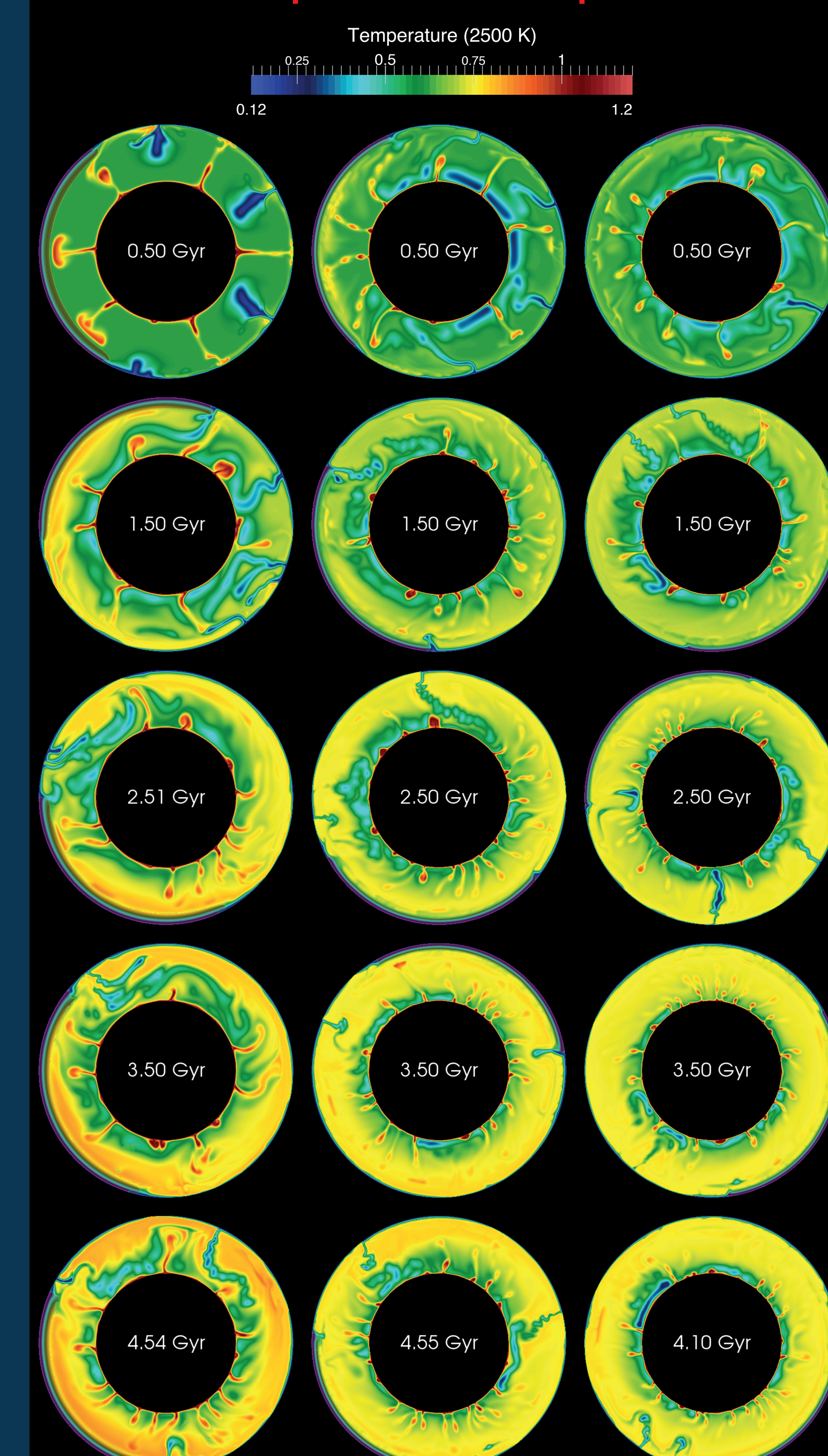


Rayleigh number

basal heating + internal heating, 1 supercontinent, 3000 K CMB temperature

Time (Gyr)

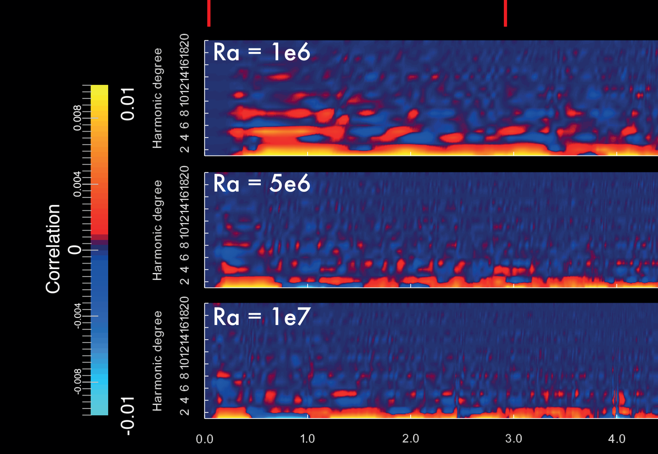
Ra = 1e6 | *Ra* = 5e6 | *Ra* = 1e7



Ra = 1e6:
- internal heating accounts for 65% of surface heat flow
- degree 1 and 2

Ra = 5e6:
- internal heating accounts for 57% of surface heat flow
- episodicity between correlation-anticorrelation

Ra = 1e7:
- internal heating accounts for 50% of surface heat flow
- degree 1 correlation with episodicity



IV. Conclusions

- Irrespective of variations in basal heating or continental size (except for very small continents), correlation between continents and elevated temperatures in the subcontinental mantle is observed. With increasing *Ra*, continents become very mobile and an episodicity can be seen between correlation-anticorrelation
- Anticorrelation is observed for cases with multi-layered convection. In most cases, plumes focus under continents
- With increase in CMB temperature, plumes form much quicker. They are short-lived and larger in number (higher degree)
- With internal heating, convection is more vigorous and continents move faster

V. Future directions

- Moving to compressible mantle convection models
- Run cases with different continental yield stress values
- Combine free surface boundary condition
- Self-consistent evolution of continents

References

[1] deKoker et al. (*PNAS*, 2012)
[2] Pozzo et al. (*Nature*, 2013)
[3] Gomi et al. (*PEPI*, 2013)
[4] Lay et al. (*Nature Geoscience*, 2008)
[5] Heron and Lowman (*GRL*, 2010)
[6] Heron and Lowman (*Tectonophysics*, 2011)
[7] O'Neill et al. (*Gondwana Research*, 2011)
[8] Hernlund and Tackley (*PEPI*, 2008)
[9] Tackley (*PEPI*, 2008)
[10] Rolf et al. (*EPSL*, 2012)
[11] Tackley and King (*G3*, 2003)
[12] Moresi and Solomatov (*GJI*, 1998)
[13] Tackley (*G3*, 2000)