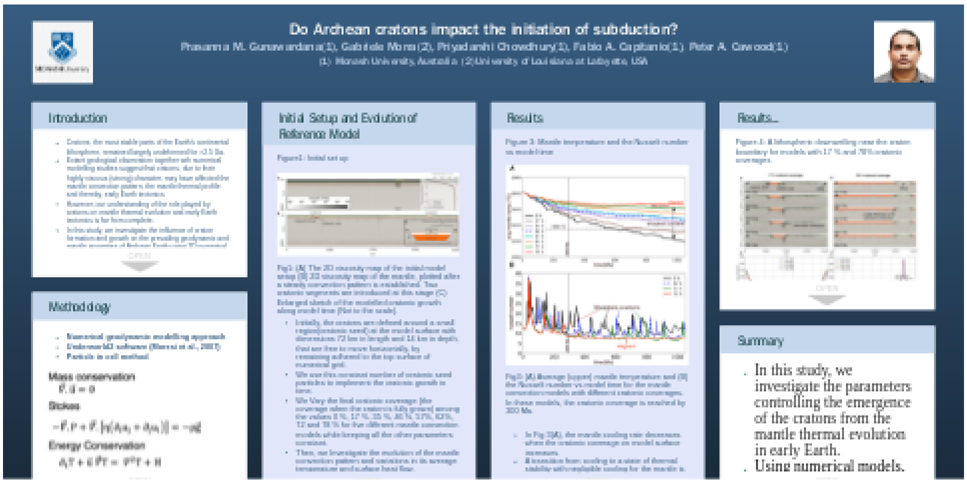
Do Archean cratons impact the initiation of subduction?



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PRESENTED AT:

INTRODUCTION

- Cratons, the most stable parts of the Earth's continental lithosphere, remained largely undeformed for >2.5 Ga.
- Extant geological observation together wth numerical modelling studies suggest that cratons, due to their highly viscous (strong) character, may have affected the mantle convection pattern, the mantle thermal profile and thereby, early Earth tectonics.
- However, our understanding of the role played by cratons on mantle thermal evolution and early Earth tectonics is far from complete.
- In this study, we investigate the influence of craton formation and growth on the prevailing geodynamic and mantle properties of Archean Earth using 2D numerical modelling.
- We model the effects of cratons on mantle convection by varying the cratonic coverage (surface area covered by the craton as a percentage of whole Earth surface area).

METHODOLOGY

- **Numerical geodynamic modelling approach**
- **Underworld2 software (Moresi et al., 2007)**
- **Particle in cell method**

Mass conservation

$$\vec{\nabla}.\vec{u} = 0$$

Stokes

$$-\vec{\nabla}.P + \vec{\nabla}.\left[\eta\left(\partial_i u_j + \partial_j u_i\right)\right] = -\rho\vec{g}$$

Energy Conservation

$$\partial_t T + \vec{u}\,\vec{\nabla}T = \nabla^2 T + H$$

Diffusion creep

$$\eta_T = \eta_o.\exp\left[\frac{E + dV}{T + 1} - \frac{E}{2}\right]$$

Crustal weakening - Yield stress (Plasticity)

$$\sigma_Y = (\sigma_Y^o + z.\sigma_Y')$$

Density

$$\rho = \rho_o[1 - \alpha\Delta T]$$

Partial Melting

Melt Fraction

$$M_o = \begin{cases} 0, & T < T_{solidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}, & T_{solidus} < T < T_{liquidus} \\ 1, & T > T_{liquidus} \end{cases}$$

Melt depletion

$$M = M_o - \sum_n M_{ext}$$

Density of melt bearing lithology

$$\rho_{eff} = \rho_{solid}(1 - M) + \rho_{melt}M$$

Residue formation and eclogitization

$$\rho_{solid}^{Peridotite} = 1\text{–}0.04\left(\sum_n M_{ext}\right)$$

$$\rho_{solid}^{hydrated\ basalt} = \rho_o(1 + coef_{res} + coef_{ecl})$$

$$coef_{res} = 0.4(\textstyle\sum_n M_{ext}), \quad coef_{ecl} = 16\ \%$$

(Sizova et al., 2015)

Table1: Physical properties used in numerical modelling

Symbol	Definition	Non-D Value	Dimensional value
α	Thermal expansivity	10^7	$3x10^{-5}$ 1/K
g	Gravitational acceleration	1	9.81 m/s^2
d	Mantle thickness	1	660 km
T_o	Surface temperature	0	0 ^oC
ΔT	Temperature drop across the model	Vary based on Tp (1 for present Earth)	1680 ^oC for present Earth
H	Internal radiogenic heating	10	$18.77x10^{-12}$ W/kg
K	Thermal conductivity		3 W/m/K
$\rho_{o(peri)}$	Reference density for Peridotite	1	3300 kg/m^3
$\rho_{o(basalt)}$	Reference density for Basalt		3000 kg/m^3
$\rho_{o(crat\_crust)}$	Reference density for cratonic crust		2900 kg/m^3
$\rho_{o(crat\_seeds)}$	Reference density for cratonic seeds		2900 kg/m^3
$\rho_{o(crat\_Litho)}$	Reference density for cratonic Lithosphere		3300 kg/m^3
κ	Thermal diffusivity	1	10^{-6} m^2/s
η_o	Reference viscosity	1	10^{21} Pas
$\eta_{o(craton)}$	Reference viscosity of craton	10	10^{22} Pas
E	Activation energy		320 KJ/mol
R	Universal gas constant		8.314 J/mol/K
σ_Y'	Yield stress gradient	10^7	~35 MPa/km
σ_Y^o	Surface yield stress	10^5	225 MPa
$\sigma_{Y(craton)}^o$	Surface yield stress for cratonic material	10^7	

INITIAL SETUP AND EVOLUTION OF REFERENCE MODEL

Figure1: Initial set up

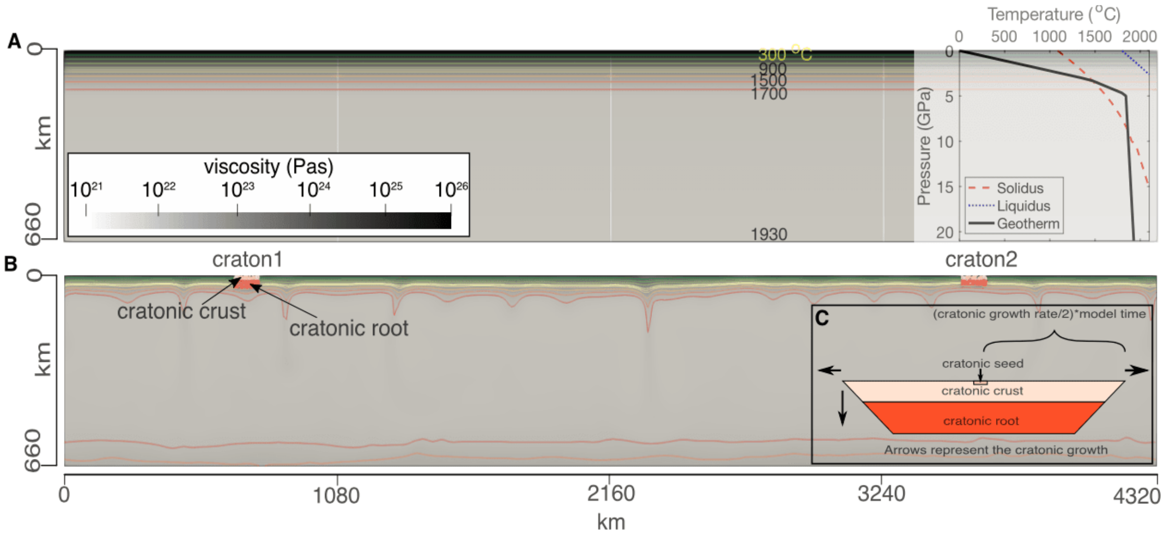
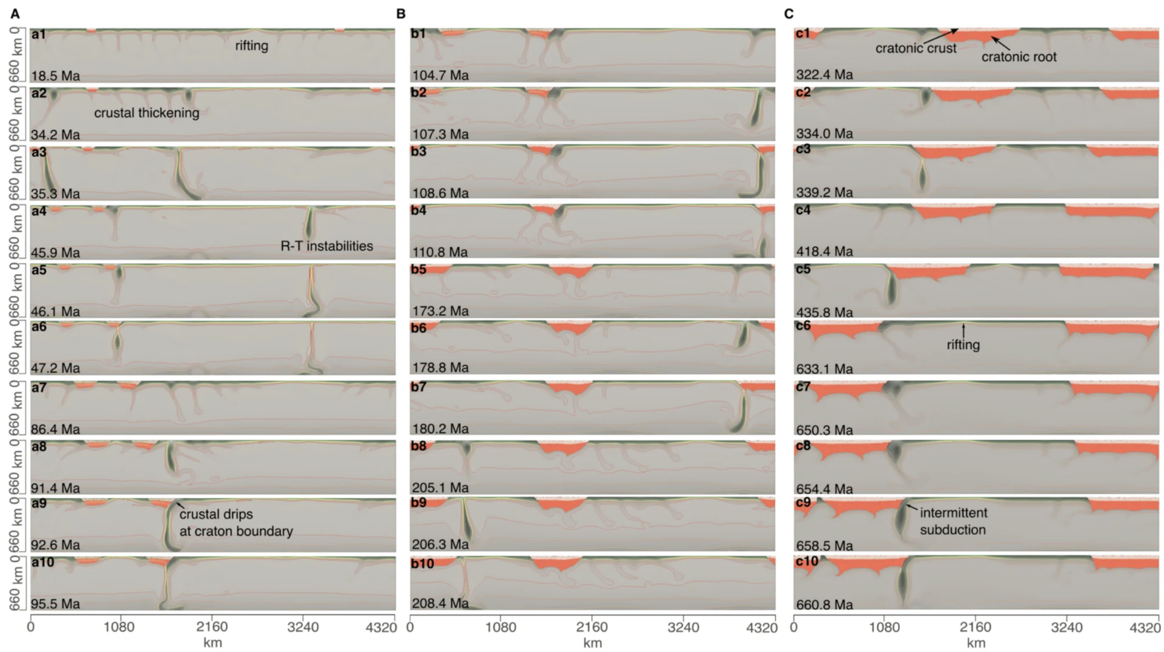


Fig1: (A) The 2D viscosity map of the initial model setup (B) 2D viscosity map of the mantle, plotted after a steady convection pattern is established. Two cratonic segments are introduced at this stage (C) Enlarged sketch of the modelled cratonic growth along model time (Not to the scale).

- Initially, the cratons are defined around a small region(cratonic seed) at the model surface with dimensions 72 km in length and 14 km in depth, that are free to move horizontally, by remaining adhered to the top surface of numerical grid.
- We use this constant number of cratonic seed particles to implement the cratonic growth in time.
- We Vary the final cratonic coverage (the coverage when the craton is fully grown) among the values 0 %, 17 %, 35 %, 46 %, 57%, 62%, 72 and 78 % for five different mantle convection models while keeping all the other parameters constant.
- Then, we Investigate the evolution of the mantle convection pattern and variations in its average temperature and surface heat flow.

Figure2: Evolutionary time steps of the reference model where final cratonic coverage reach 46% by 300 Ma.



- Until 500 Ma, the high temperature conditions produce relatively small convective cells
- Therefore, crustal drips are equally prominent near craton boundaries and away from the cratons.
- When the mantle temperature decreases with the time, the vigour convection subsides due to decreasing buoyancy and increasing viscous force.
- This results in formation of large convective cells.
- The craton coverage also increases with time and influence the convective cell size
- Crustal drips more often develop near the edges of the cratons.

RESULTS

Figure 3: Mantle temperature and the Nusselt number vs model time

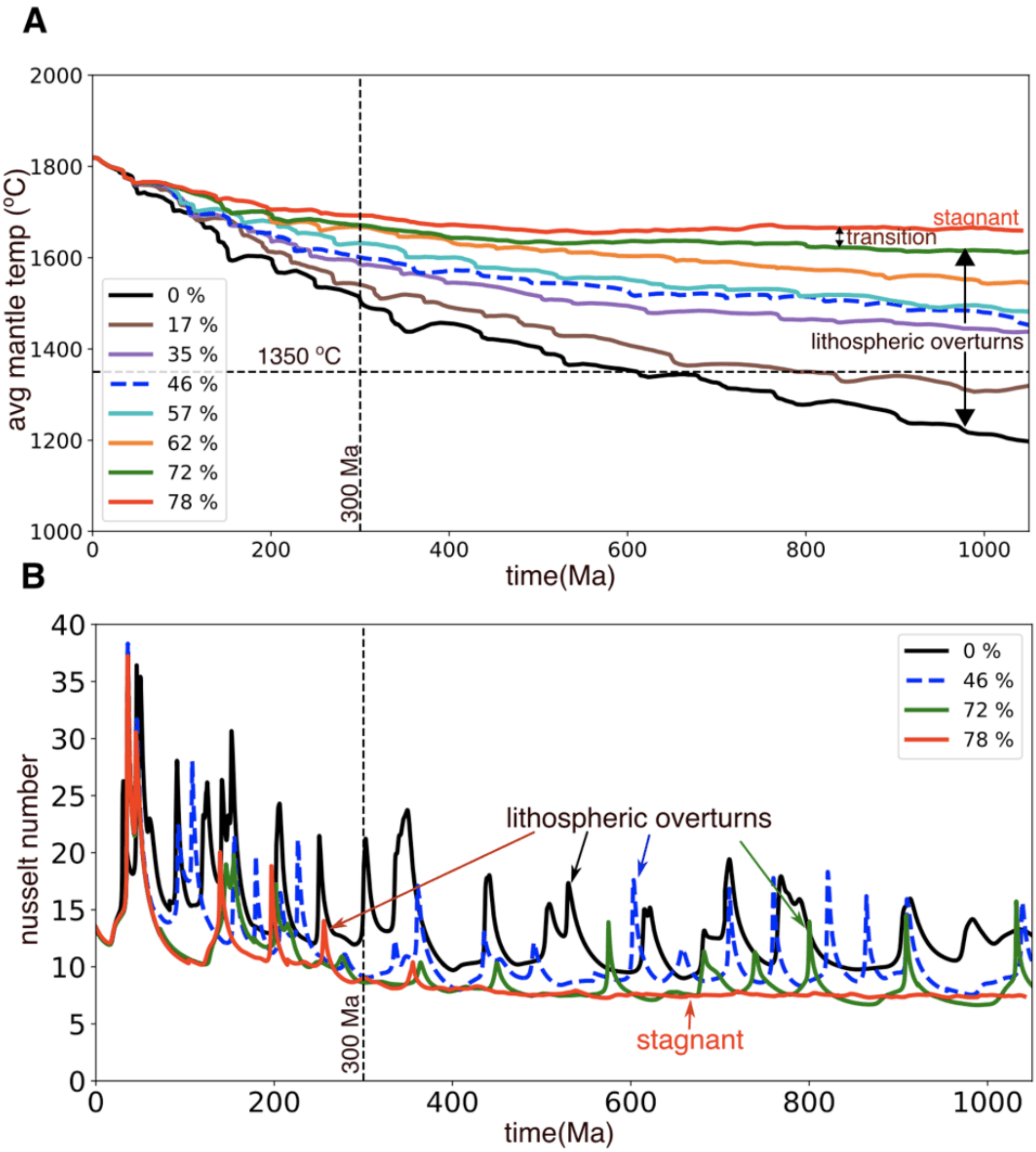


Fig3: (A) Average (upper) mantle temperature and (B) the Nusselt number vs model time for the mantle convection models with different cratonic coverages. In these models, the cratonic coverage is reached by 300 Ma.

- In Fig 3(A), the mantle cooling rate decreases when the cratonic coverage on model surface increases.
- A transition from cooling to a state of thermal stability with negligible cooling for the mantle is observed when the model reaches a cratonic coverage of 78%.
- In Fig 3(B), the spikes of the Nusselt number plot represent the lithospheric overturns.
- For the model that reach the cratonic coverage of 78%, the crustal drips are prominant until the cratonic coverage reaches 78% of the model surface.
- Possibly at some values between 72 % and 78 % cratonic coverage, but certainly by 78 % the model behaves as a stagnant lid.

RESULTS...

Figure 4: A lithospheric downwelling near the craton boundary for models with 17 % and 78% cratonic coverages

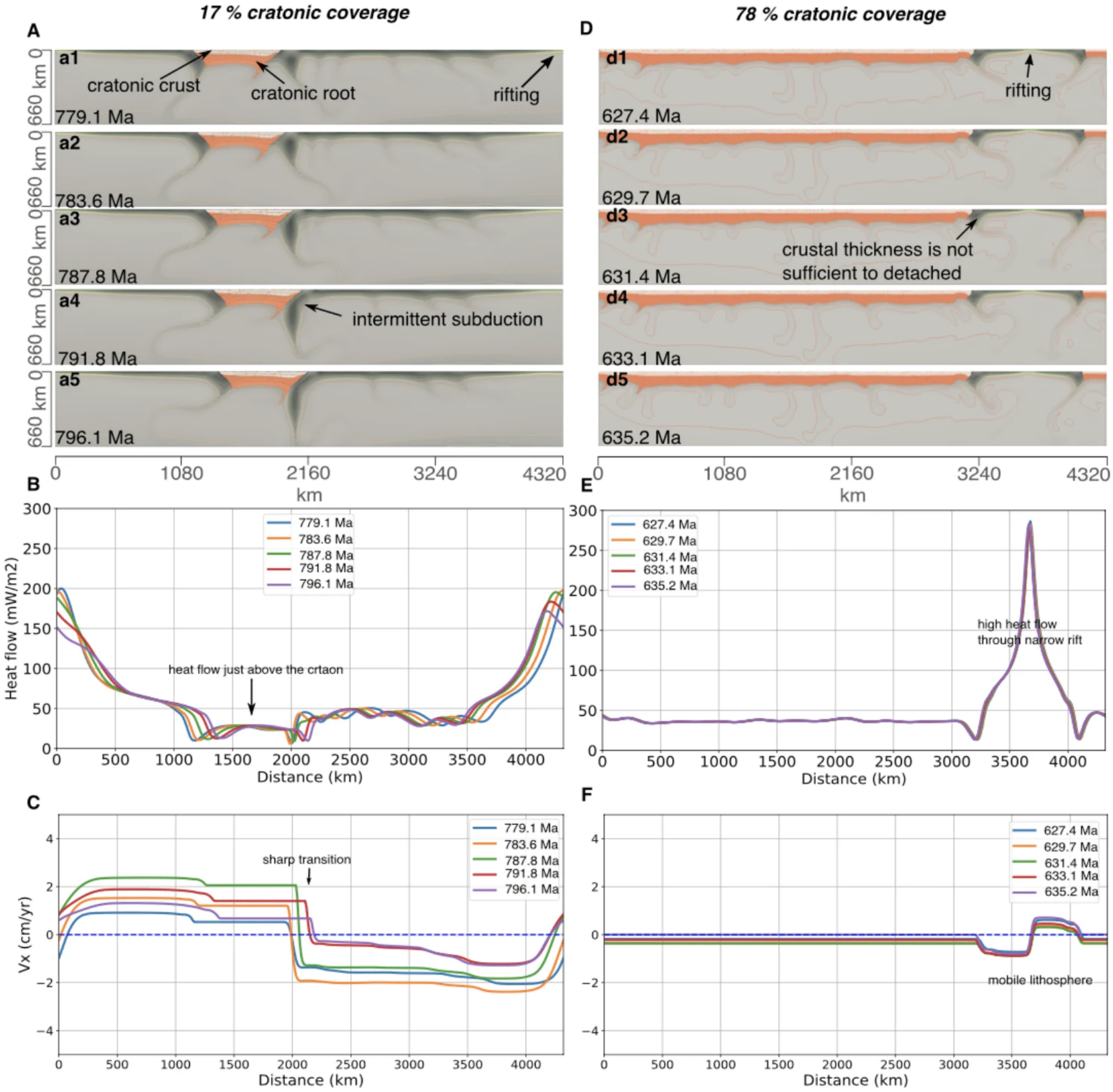


Fig 4: (A) The snapshots of a lithospheric downwelling near the craton boundary for model with 17 % cratonic coverage. (B) The surface heat flow profiles and, (C) surface horizontal velocity profile for each time snapshot in (A). (D) The snapshots of mantle convection model that has 78 % cratonic coverage and reach the thermal stability. (E) The surface heat flow profiles and (F) surface horizontal velocity profile for each time snapshot of (D).

- When the cratonic coverage < 46 % (Fig4 (A));
  - drips often resemble subduction.
  - observed a substantial cooling of the mantle.
- Subduction-like downwellings as in Fig. 4(A) are not observed when the cratonic coverage increases towards 78 % (Fig4(B)).
- In 78% model,
  - the region that is not covered by a craton has a large heat flow and a significantly low crustal mobility.
  - the lithosphere does not reach a suffcient thickness to form Eclogites for yieding
  - the rift region gets narrow making ineffcient heat release.

SUMMARY

- In this study, we investigate the parameters controlling the emergence of the cratons from the mantle thermal evolution in early Earth.
- Using numerical models, we simulate the effects of strong and buoyant cratons on mantle convection by varying the cratonic coverage.
- We then identify the implications of cratonic coverage on upper mantle cooling rate, lithospheric tectonics and mantle convection pattern.
- We find that, if the cratonic coverage is less than 72 %, the mantle cooling process is dominated by lithospheric overturns in the form of crustal drips; however, the cratons may restrict the drips by their large strength.
- A cooler mantle is characterized by large convective cells, which more often terminate near the cratonic edge.
- These crustal drips are features of subduction, but they do not replicate the exact behaviour of subducting plates on contemporary Earth.
- Increasing the cratonic coverage above ~72 % inhibits intermittent subduction and causes slower mantle cooling, which in turn creates a runaway effect and eventually push the planet towards a stagnant lid domain.
- Based on these results, we conclude that the cratonic coverage in the Archean Earth played a crucial role on mantle thermal evolution and impacted early Earth tectonics, especially the time of subduction initiation.
- Our results suggest that a significant cratonic coverage in the Archean Earth would have delayed the initiation of subduction.
- In future studies, we will investigate the implications of cratonic growth rate on early Earth tectonics.

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ABSTRACT

Cratons are stable parts of the Earth's continental lithosphere that have remained largely undeformed for several billion years. These consist of crustal granite-greenstone terrains coupled to roots of strong, buoyant cratonic lithospheric mantle that extend up to several hundreds of kms depth. Due to their stability, cratons preserve a record of the tectonics and the thermal evolution of the mantle in the early Earth. These observations suggest that the highly viscous (strong) character of cratons hampered the viability of early Earth tectonics, thereby affecting mantle convection patterns and cooling. In this study, we investigate the controls of stiff cratons on the initiation of subduction and mantle thermal evolution on the early Earth. Using numerical models, we simulate the effects of strong and buoyant cratons on mantle convection. We vary a set of parameters including (i) width and thickness of cratons, and (ii) viscosity ratio between cratonic lithosphere and cratonic crust. We test initial conditions varying the number of cratons, which is unconstrained for early Earth and associated it to mantle cooling rates. Our preliminary results show that the mantle cooling rate decreases with increasing number of cratons. Because mantle cooling rates affect the early Earth transition from a basaltic drip regime to initiation of subduction, we show that the craton coverage on the early Earth controls the time of onset of plate tectonics. Furthermore, we observe that cratons will remain separate or combine depending on the convective cell size, which is function of mantle cooling.

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