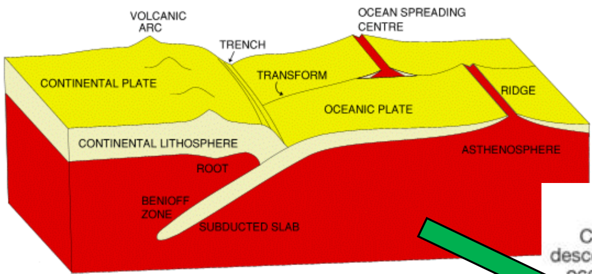
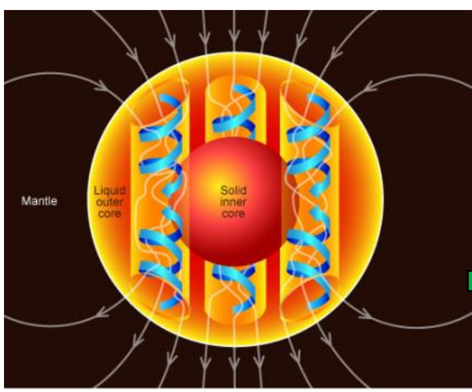
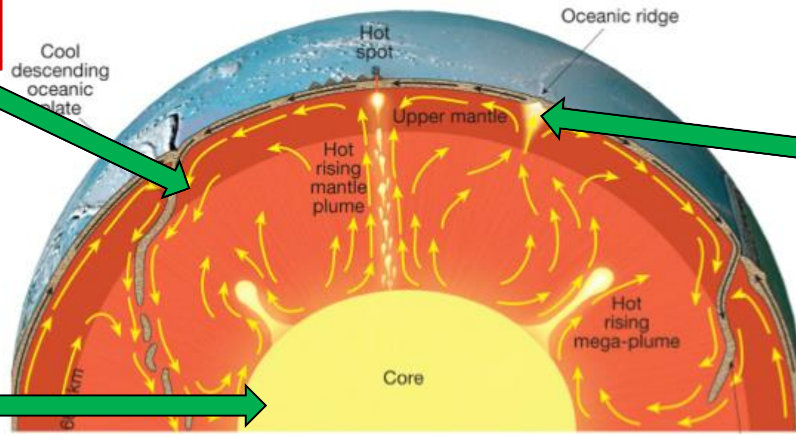
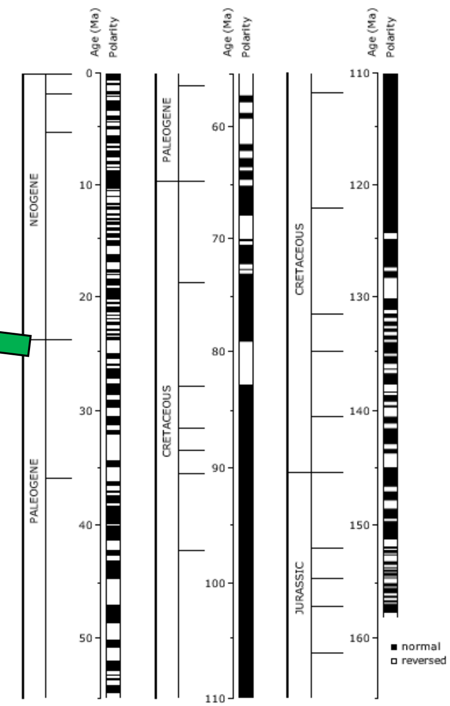
Constraining mantle convection models with palaeomagnetic reversals record and numerical dynamos









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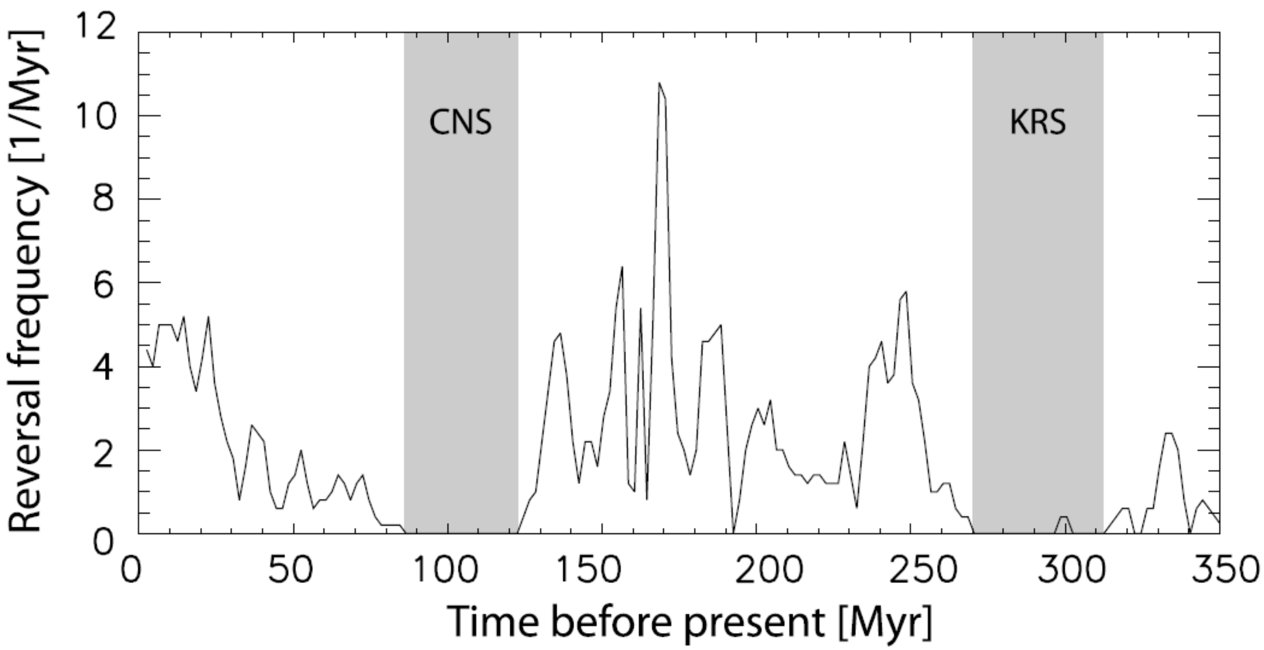
Motivation

The paleomagnetic record contains enigmatic **strong variability** from long **superchrons** to **hyper-reversing** periods. Similarity between mantle overturn timescale and superchrons duration may suggest that **variability in mantle convection** (vigor and/or pattern) **causes changes in reversal frequency.**



Time-dependent reversal frequency based on the geomagnetic polarity time scale of Gradstein et al. (2012). From Amit and Olson (2015).

Concept

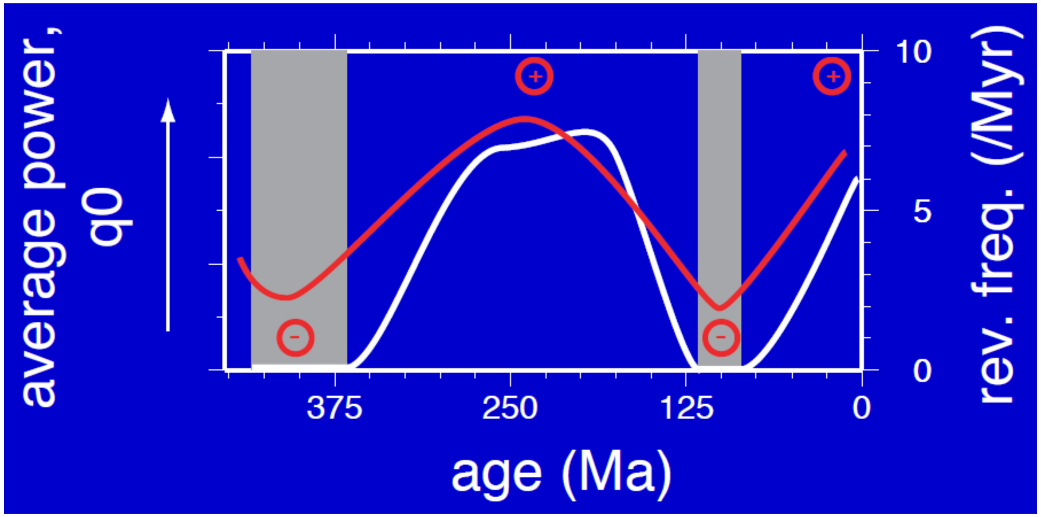
- 450 Myrs plate velocities history imposed on mantle convection models.
- Set of mantle convection models with various rheology, dense basal layer thicknesses, initializations and convection vigors to obtain time-dependent CMB heat flux (amplitude and pattern).
- Infer criteria for reversal frequency from numerical dynamos literature.
- Compare modelled CMB heat flux with palaeomagnetic reversal frequency in light of dynamo criteria.

As in **Zhang and Zhong (2011)**, but:

- **More dynamo criteria** (e.g. Driscoll and Olson, 2009; Olson et al., 2010; Olson and Amit, 2014).
- Many **more mantle convection models**.

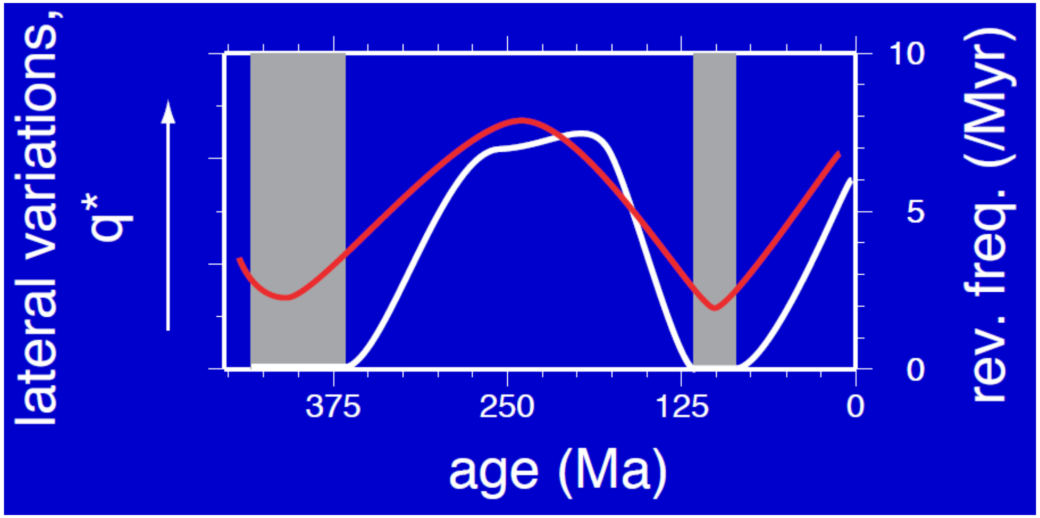
Criteria for reversal frequency from numerical dynamos – mean CMB heat flux

Increased **mean CMB heat flux** increases reversal frequency (Kutzner and Christensen, 2004; Driscoll and Olson, 2009; Olson and Amit, 2014). Stronger core convection increases turbulence, rendering the dipole more vulnerable to reversals. Considered the **most robust** criterion.



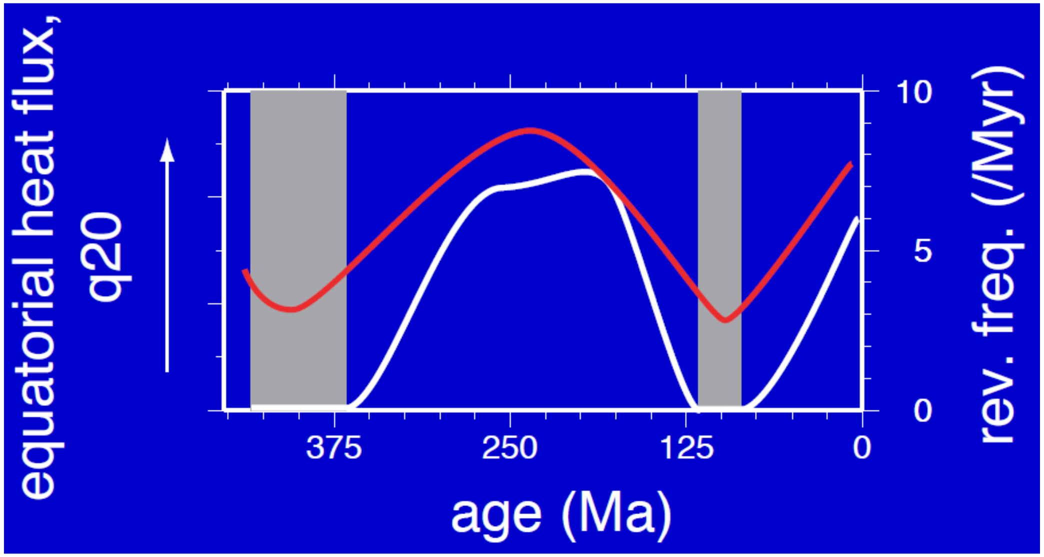
Criteria for reversal frequency from numerical dynamos – amplitude of CMB heat flux heterogeneity

Increased **amplitude of CMB heat flux heterogeneity** increases reversal frequency (Olson et al., 2010; Heimpel and Evans, 2013; Olson and Amit, 2014). Reversals are triggered locally where CMB heat flux is anomalously large.



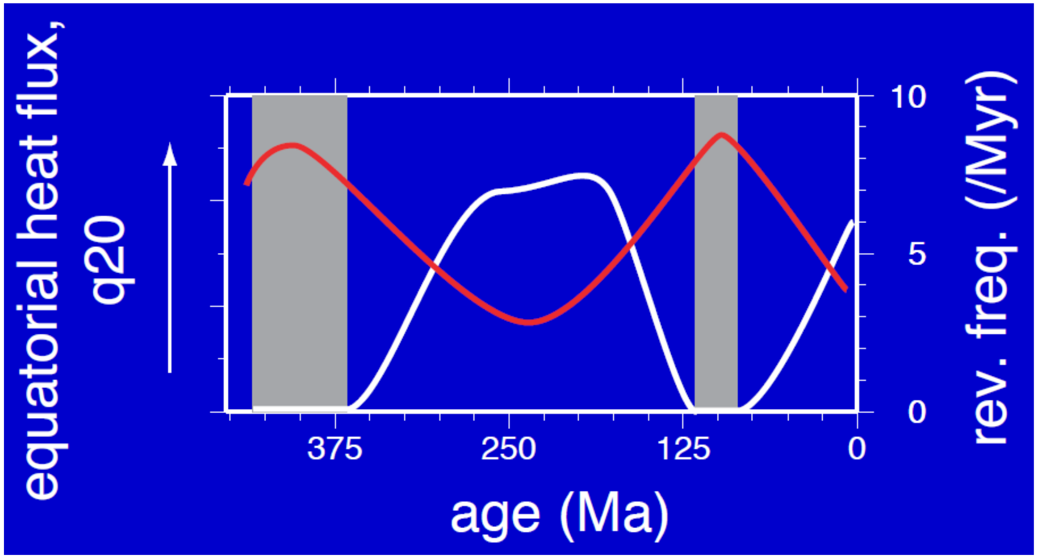
Criteria for reversal frequency from numerical dynamos – equatorial vs. polar cooling (geographic control)

Increased **equatorial cooling** increases reversal frequency (Glatzmaier et al., 1999; Kutzner and Christensen, 2004; Olson et al., 2010). Concentration of magnetic flux at low-latitudes destabilizes the dipole (Amit et al., 2010).



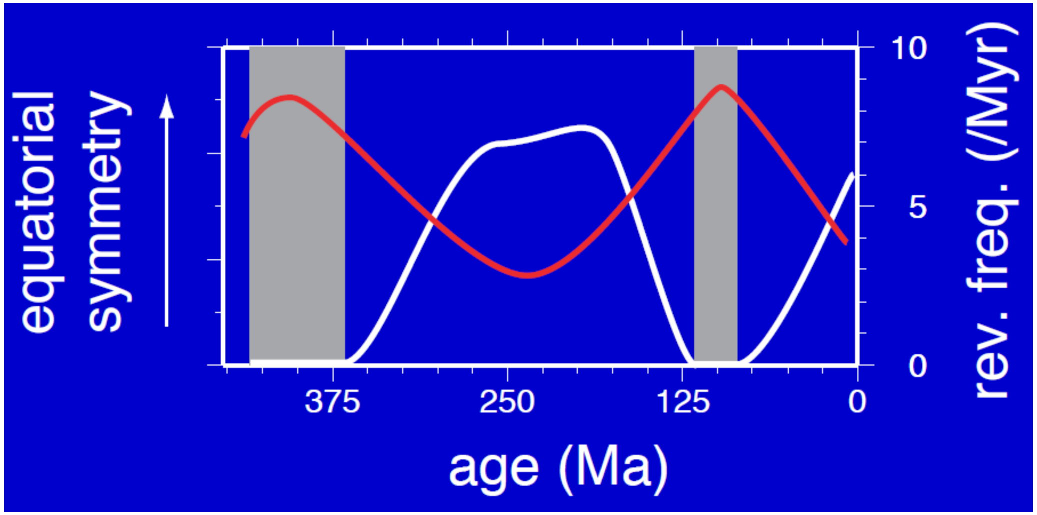
Criteria for reversal frequency from numerical dynamos – equatorial vs. polar cooling (inertial control)

Increased **polar cooling** increases reversal frequency by enhancing the background meridional circulation and hence the inertia (Olson and Amit, 2014). Such ‘inertial control’ is found when the system is far from the non-reversing regime.

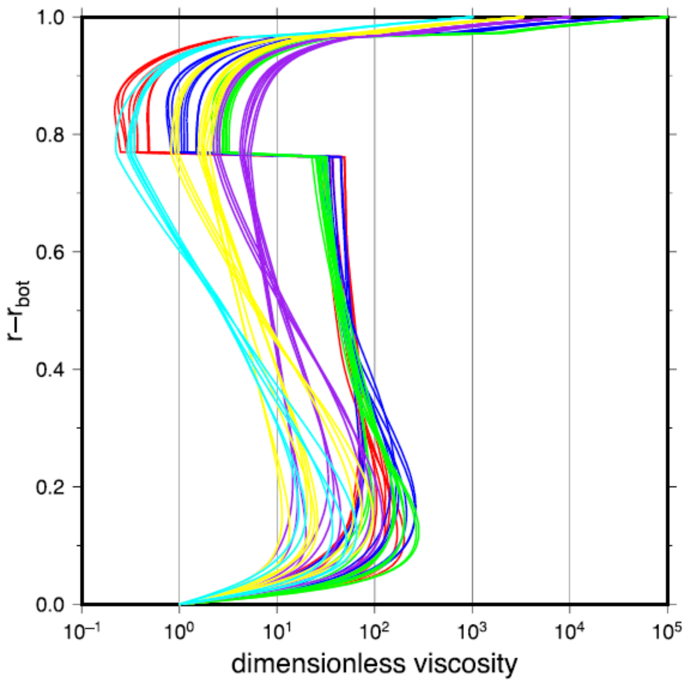


Criteria for reversal frequency from numerical dynamos – equatorial symmetry

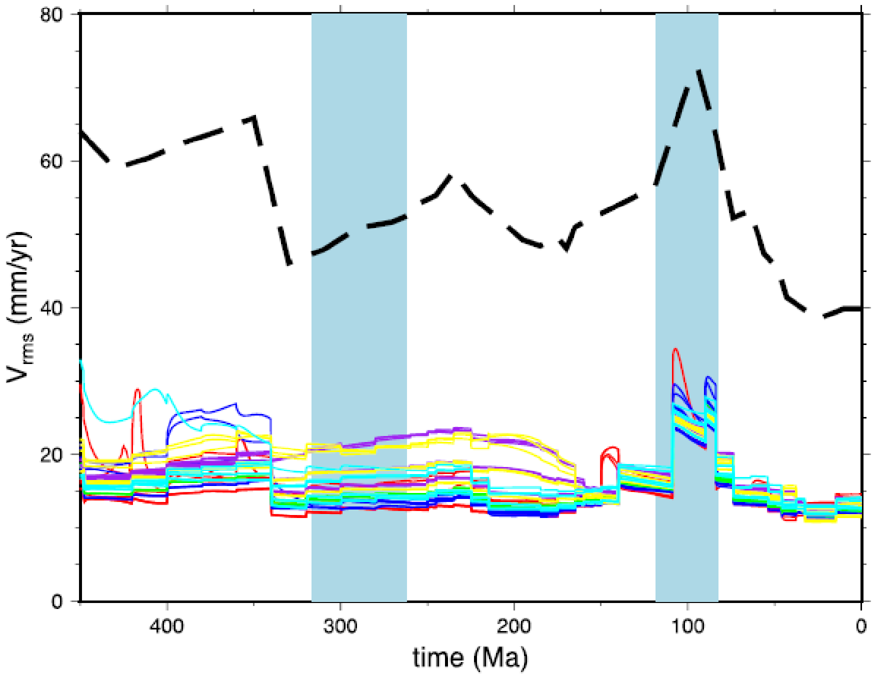
Increased **equatorial symmetry** decreases reversal frequency (Pétrélis et al., 2009, 2011; Biggin et al., 2012). Equatorially symmetric convective columns characterize rapidly rotating systems. Breaking these columns by equatorially anti-symmetric CMB heat flux triggers reversals.



Mantle convection models setup



Viscosity profiles in the mantle models. Each color represents a group of similar rheology models. **Upper to lower mantle jump** is either gradual or discontinuous, with 3 possible amplitudes.

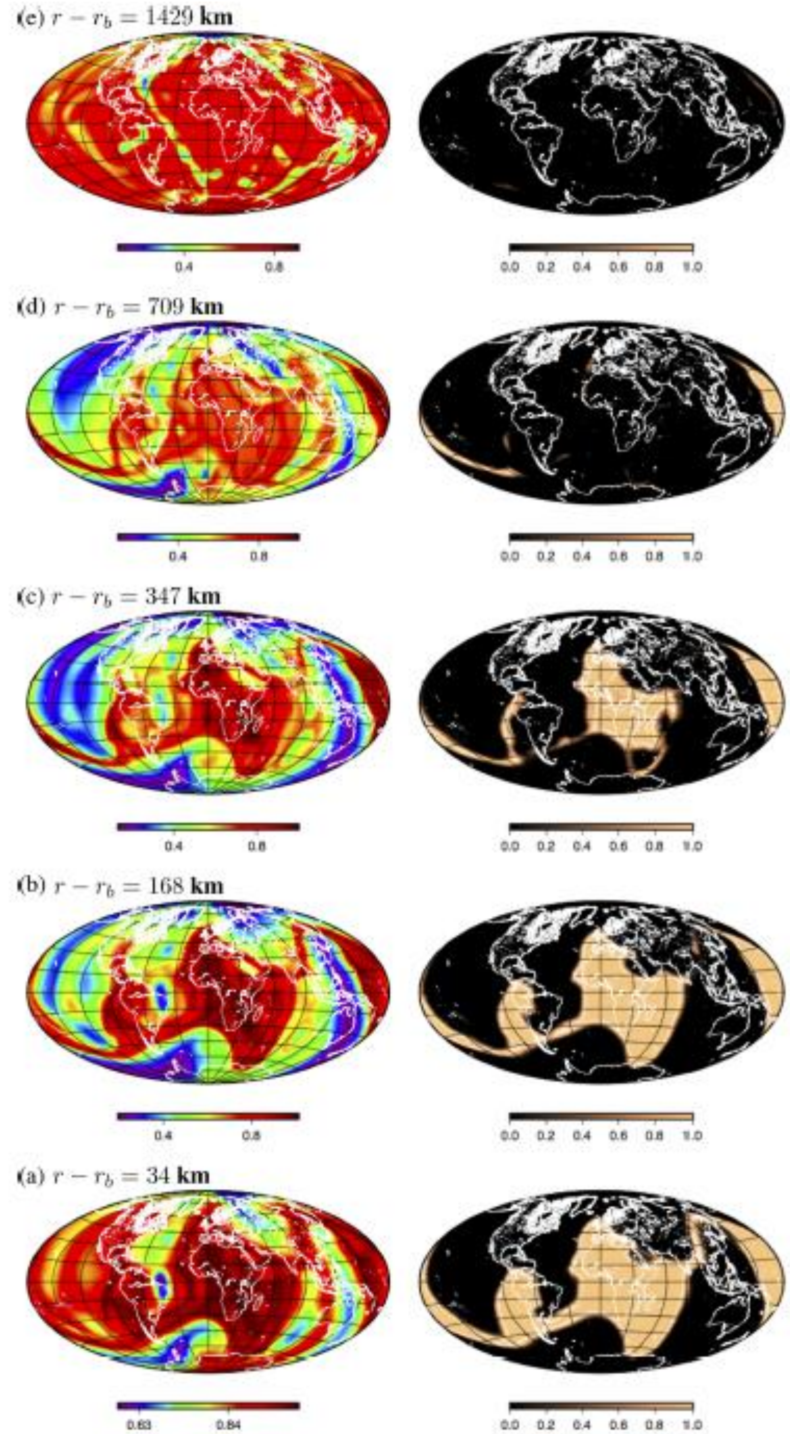


Imposed time-dependent rms plate velocity and resulting rms bulk velocity in 54 mantle convection models.

Problem: **During the CNS fast plates** yield large CMB heat flux and **frequently reversing** dynamos (Olson et al., 2013).

Radial dependence above the CMB

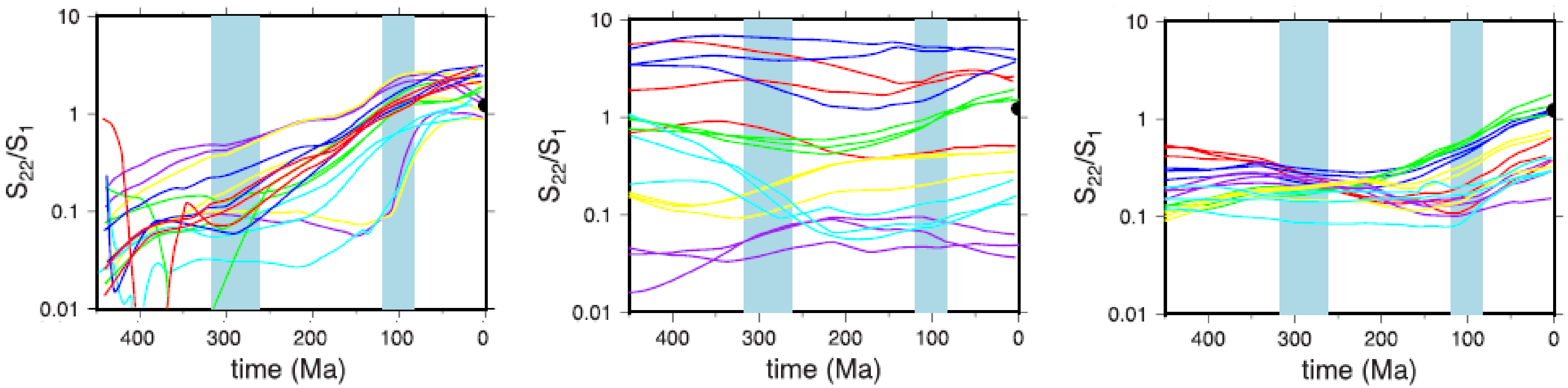
- Deepest **compositional field** (right a) is in agreement with observed locations of LLSVPs and is **well correlated with global tomography** (Masters et al., 2000).
- Deepest **temperature field** (left a) is more complex. Here e.g. coldest dense basal material has the same temperature as hottest normal mantle. Consequently **correlation with tomography is inferior** - piles are compositionally distinct more than hotter.
- Coldest regions in the lowermost mantle (left a-c) reflects interplay of earlier plate motions and mantle dynamics (dense piles and normal mantle).



Temperature (left) and composition (right) at various depths (bottom closest to CMB) at present-day in one of the models.

Persistent two mantle piles?

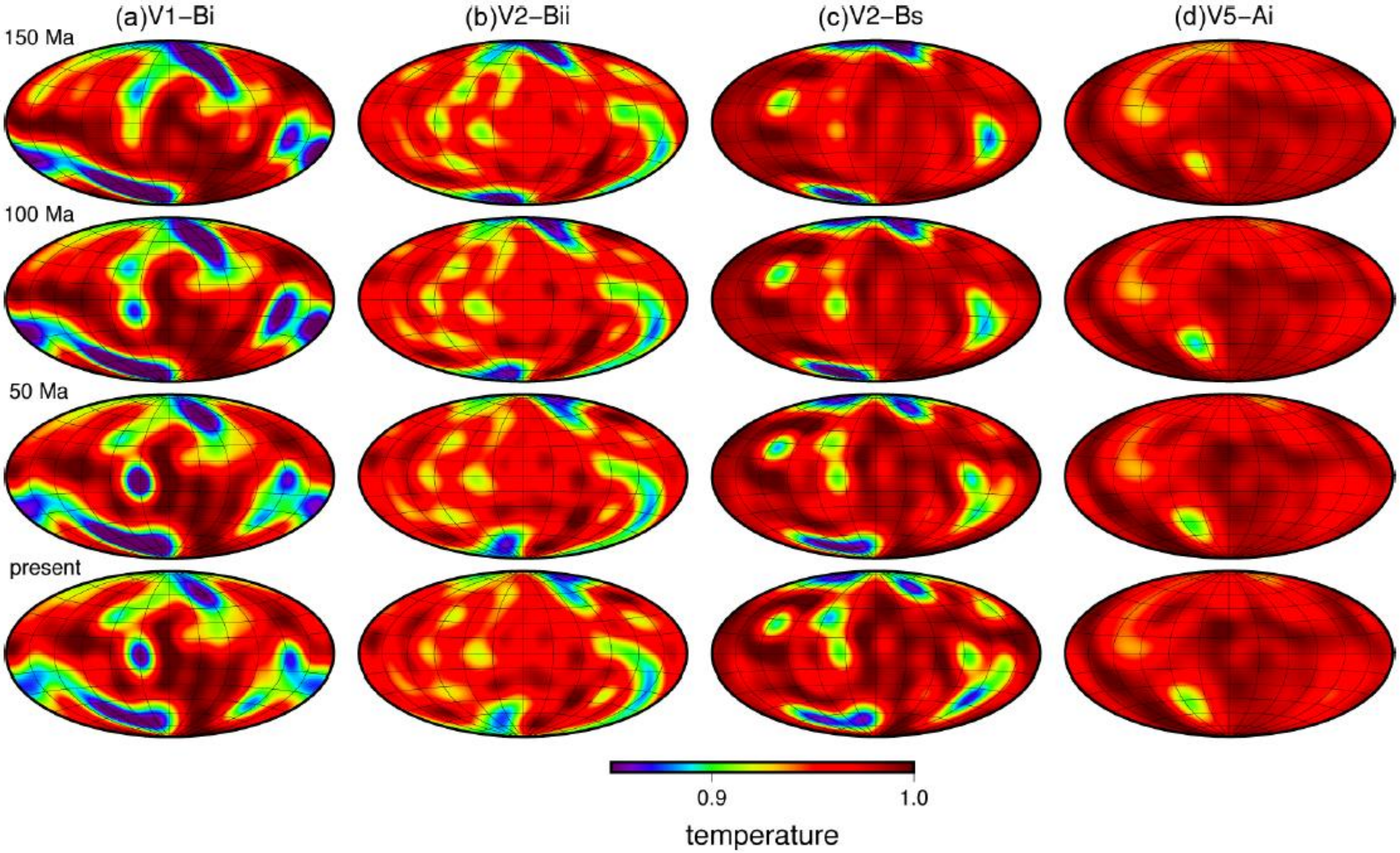
Large-scale convection pattern is **time-dependent**. Strong dependence on rheology (colors) and initialization (three subplots), weak dependence on dense basal material.



Time evolution of S22/S1 compositional field at the lower mantle for different initializations (subplots). Disks correspond to lower mantle tomography (Masters et al., 2000).

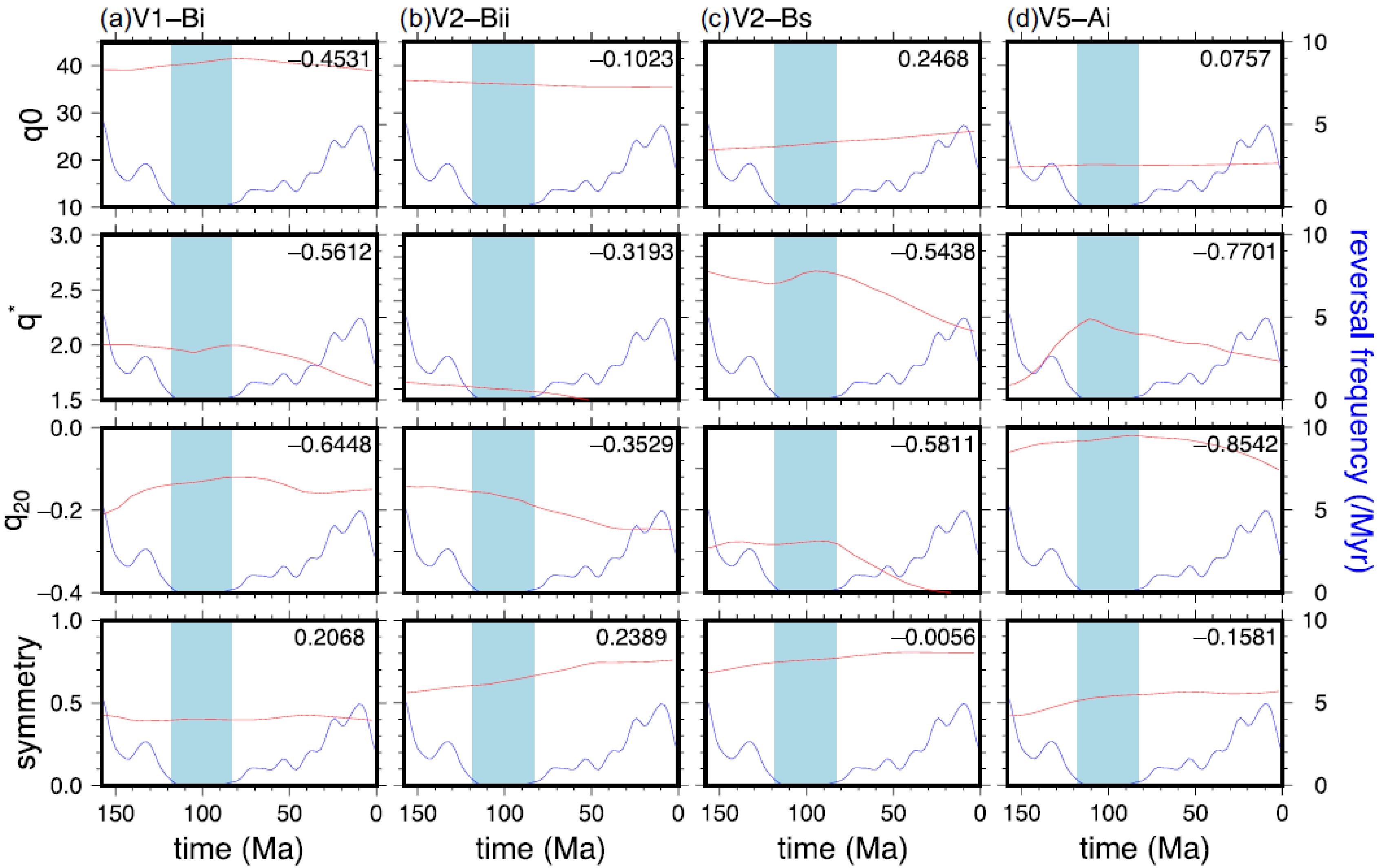
Time-dependent CMB heat flux and dynamo criteria - examples

CMB temperature (inverse proportional to heat flux) in four models (columns) at four snapshots (rows). Timeseries of such maps are used to calculate the time-dependent dynamo criteria.



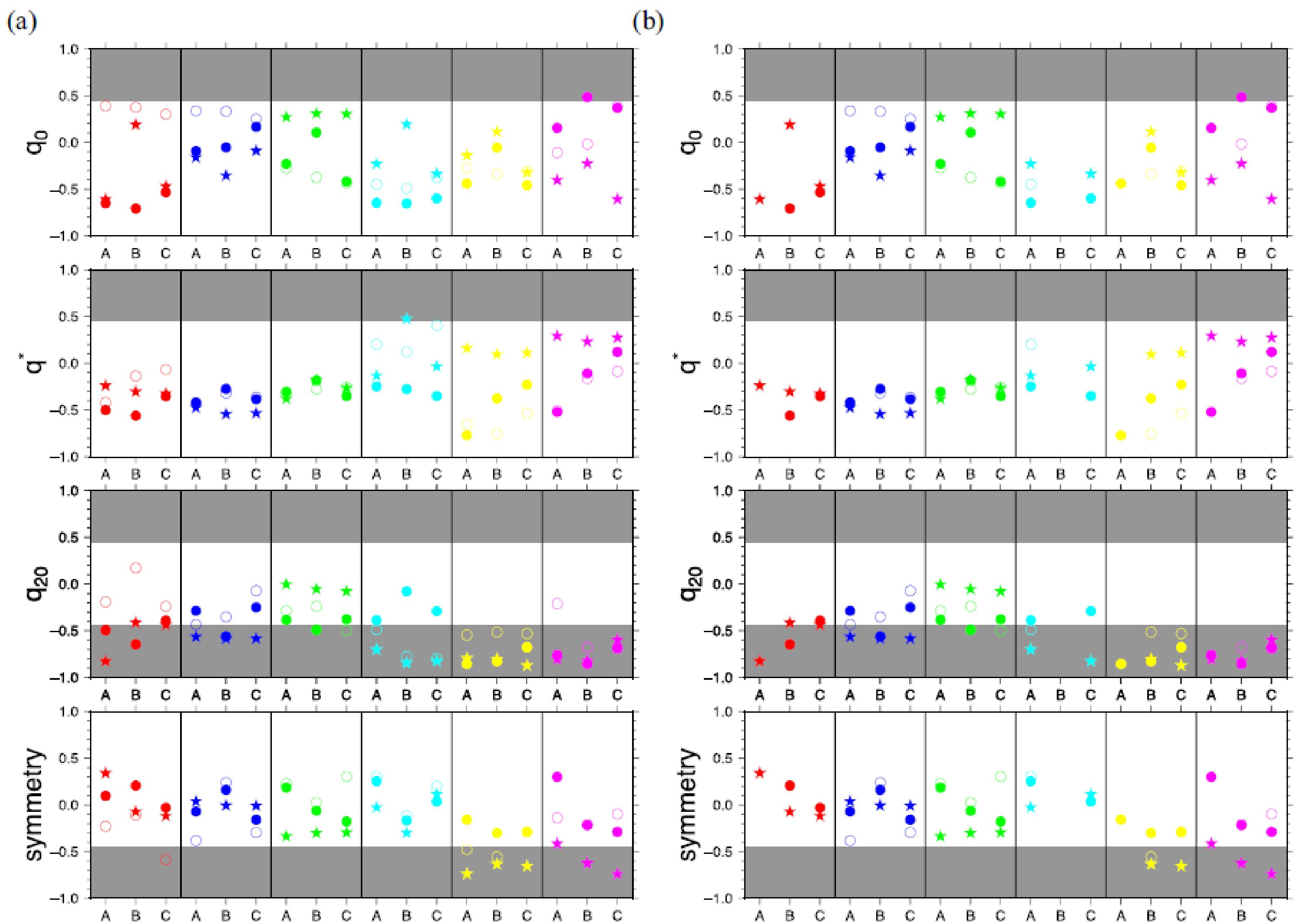
Time-dependent CMB heat flux and dynamo criteria - examples

Successful model correlates with at least one dynamo criteria, i.e. during CNS: Minimum mean CMB heat flux, minimum heterogeneity amplitude, extreme q20 (minimum or maximum), maximum equatorial symmetry. Note weak time-dependence of mean…



Time-dependent CMB heat flux and dynamo criteria - summary

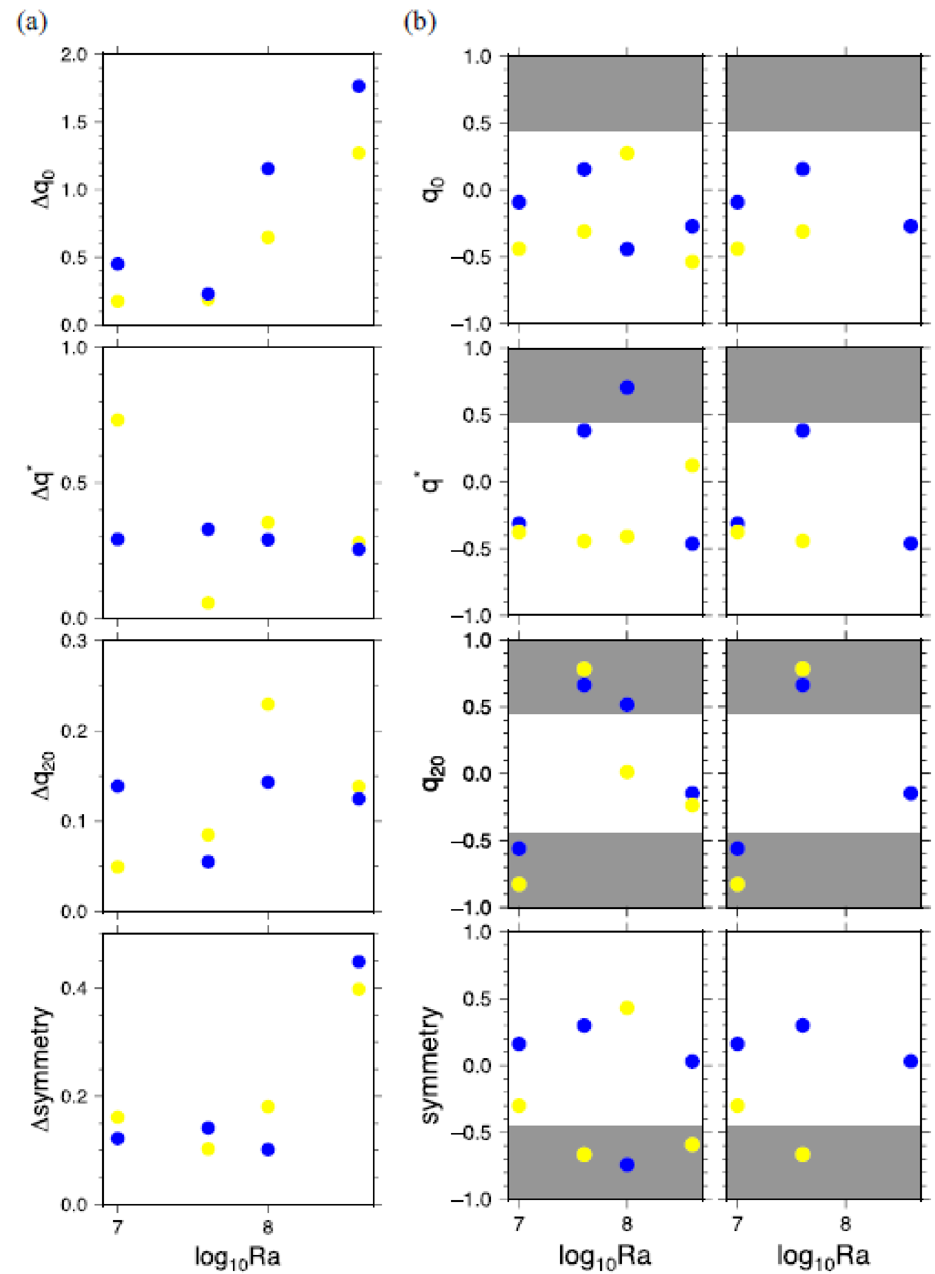
All models (a) and only those that agree with present-day mantle tomography (b). Shadings denote statistical significance. Successful scenarios for CNS: **Minimal polar cooling** (‘inertial control’; Olson and Amit, 2014) and some **maximal equatorial symmetry** (Pétrélis et al., 2011).



Influence of mantle convection vigor

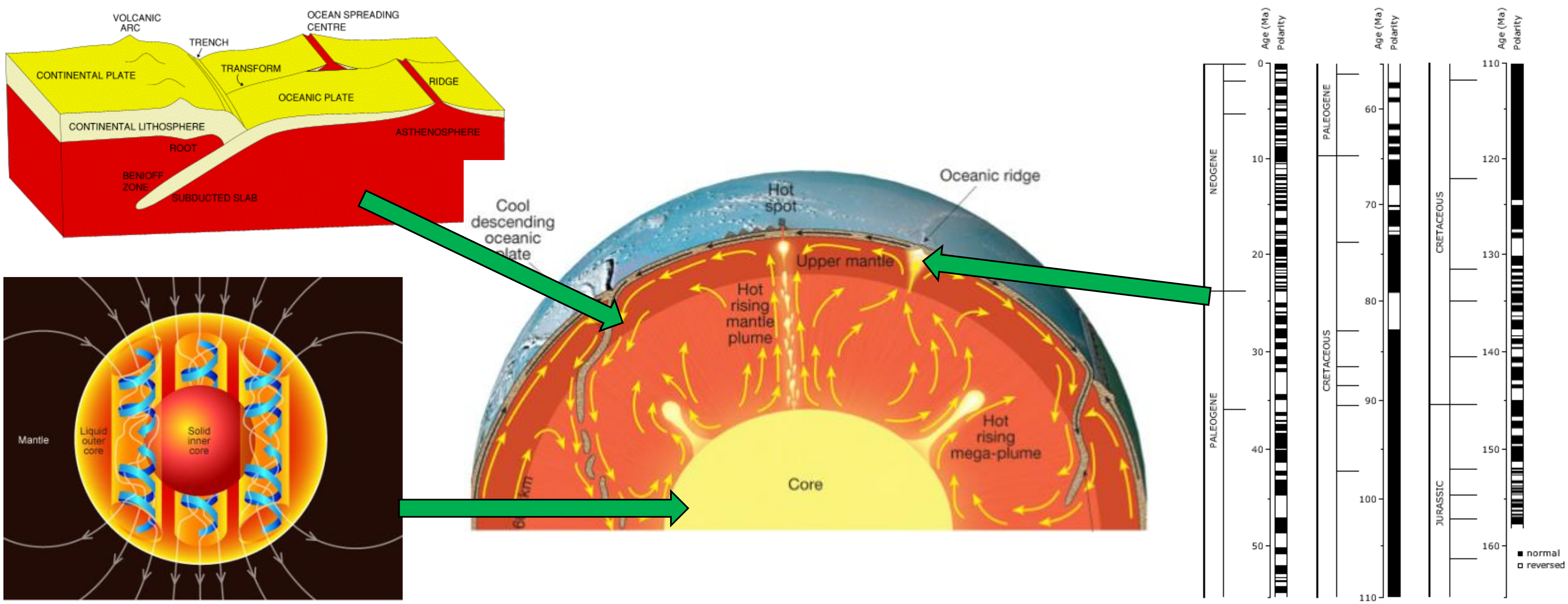
Uncertainties in slab velocities permit a range of plausible Ra numbers. Increasing Ra gives:

- **Stronger time-dependence** (a), especially **for the mean** CMB heat flux (top).
- Some cases with **maximal polar cooling** during CNS ('geographic control').
- More models pass equatorial symmetry criterion.



Conclusion

The **paleomagnetic reversal frequency** record + accounting for criteria from **numerical dynamos** may **constrain mantle convection models.**



Other ingredients in mantle convection models should be tested against the history of reversal frequency.