Growth and Decay Asymmetry in Earth's Axial Dipole Field as a Criterion for Modeling the Geodynamo

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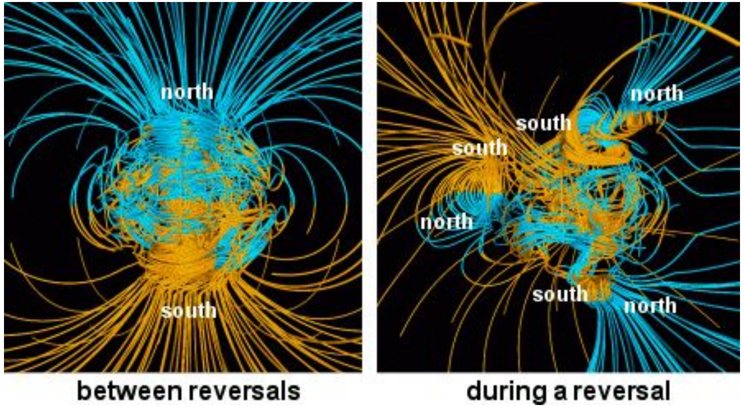
Outline

- Deciphering data
- Deciphering the geodynamo from data
- Towards a tidally driven geodynamo
- Summary



After Glatzmaier & Roberts (1995, *Nature*, **377**, 203)

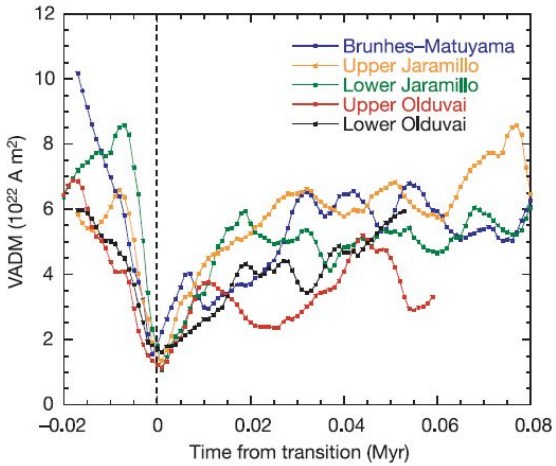
“Deciphering Records of Geomagnetic Reversals”

1. Large and systematic field intensity decreases occur during all polarity transitions
2. Strong indications that the geomagnetic field was not dipolar during the last reversal
3. The existence of preferred longitudinal bands of transitional VGPs and their relationship with convective patterns in Earth’s lower mantle remains a point of debate
4. The existence of recurring VGP clusters in some volcanic data and their possible relationship with lower mantle structures remains controversial
5. Transitional field geometries remain poorly constrained - despite attempts to compile and model data for the last reversal
6. The complex dynamical structure of reversals is supported by sedimentary and volcanic records
7. The existence of rapid field changes during transitional periods has proven to be a challenge for both experimentalists and theoreticians
8. **A saw-toothed pattern of field intensity across reversals is not always present in sedimentary records**

Valet & Fournier (2016, *Rev. Geophys.*, **54**, 410, DOI)

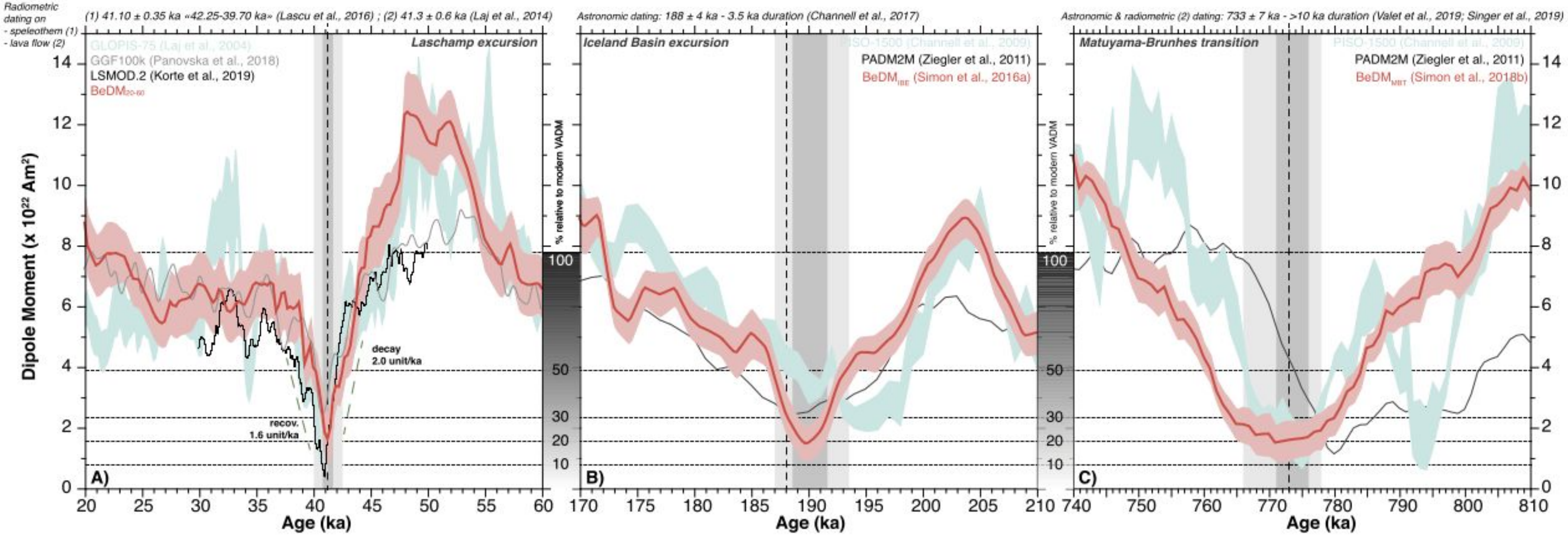
A saw-toothed pattern of field intensity across reversals is not always present in sedimentary records

- Difficulty "... estimating the amplitudes of variations that depend on factors *other* than field intensity"
  - Gating factor for fully validating this observation
- Non-monotonic decay of the field during a reversal
  - "... complexity of the field decay phase depicted by a succession of oscillations makes it difficult to observe an overall decreasing trend."
- Asymmetry present even when the field is *not* reversing
  - Evidence in both volcanic and sedimentary records
  - Processes: "... the emergence, diffusion, and transport of reverse flux patches at the CMB."



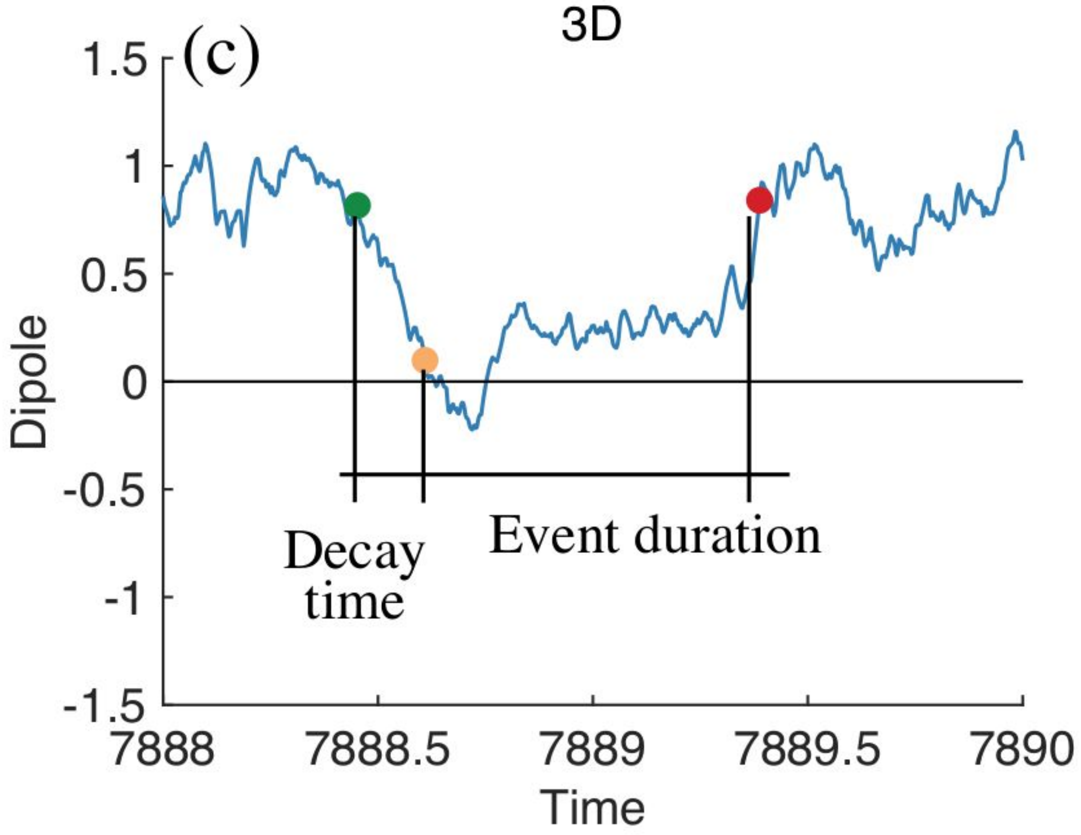
Valet et al. (2005, *Nature*, **435**, 802, DOI, Fig. 4)
Valet & Fournier (2016, *Rev. Geophys.*, **54**, 410, DOI)

Reversals & Excursions from RPI & Be-Ratio Stacks



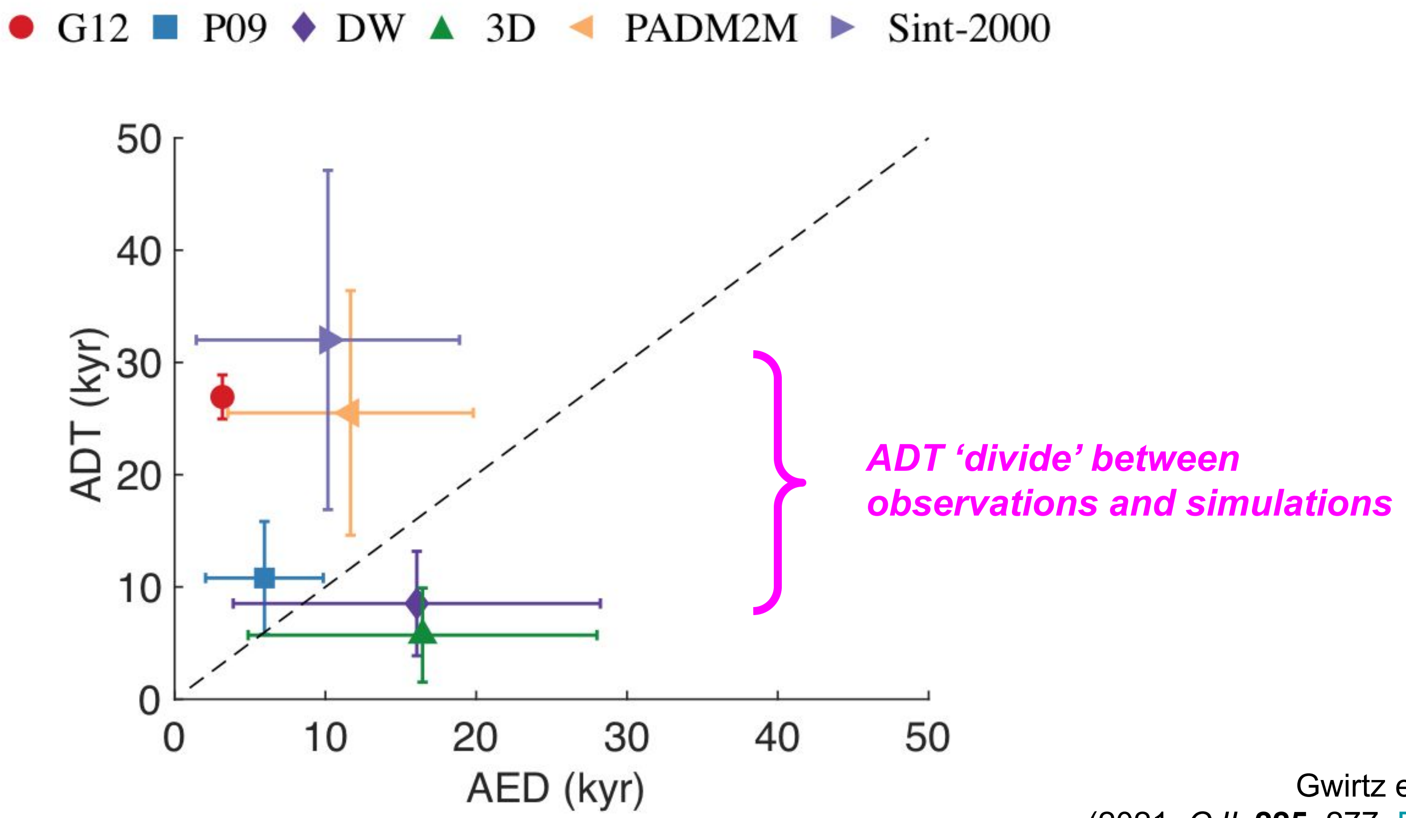
Simon et al. (2020, *EPSL*, **550**, 116547, DOI)

Characterizing Reversals (1)



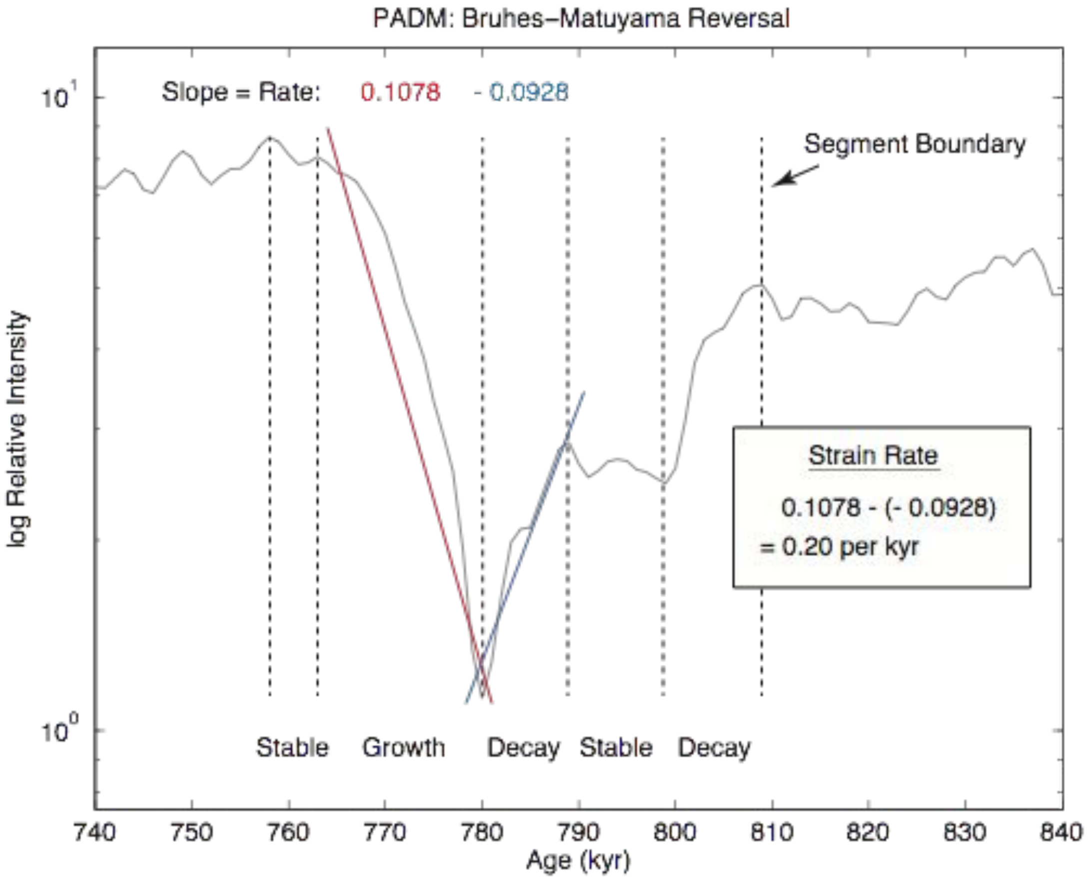
Gwirtz et al.
(2021, *GJI*, **225**, 277, DOI)

Characterizing Reversals (2)



Gwirtz et al. (2021, *GJI*, **225**, 277, DOI)

Estimating Growths & Decays in RPI Data



Aldridge & McMillan
(2017, *EGU Vienna*)

Aldridge & Baker
(2003, *PEPI*, **140**, 91, DOI)

Tidally Driven Elliptic Instability

- Suppose the RPI data has captured the signature of a mechanically generated instability in Earth's fluid outer core
- Suppose the source of the excitation for this instability is the lunisolar tide

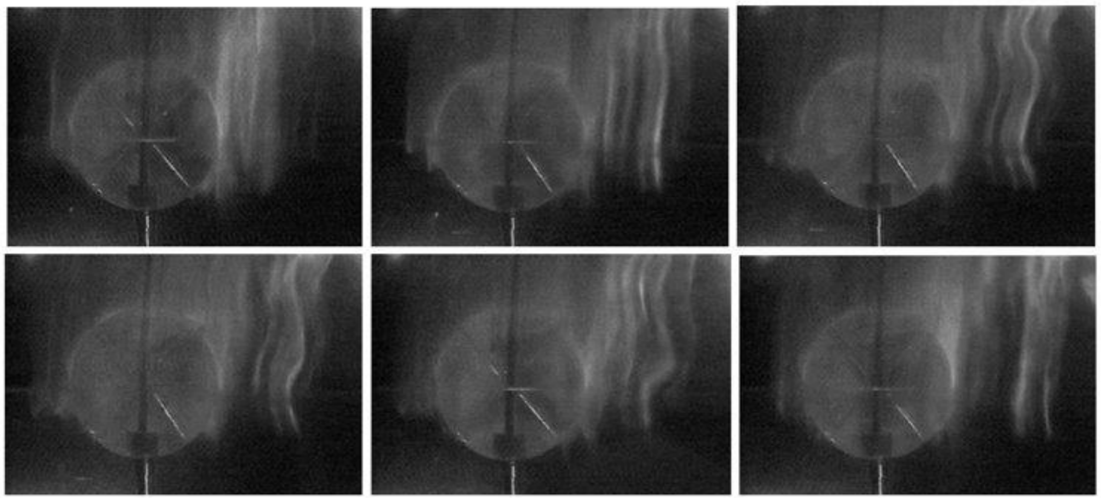
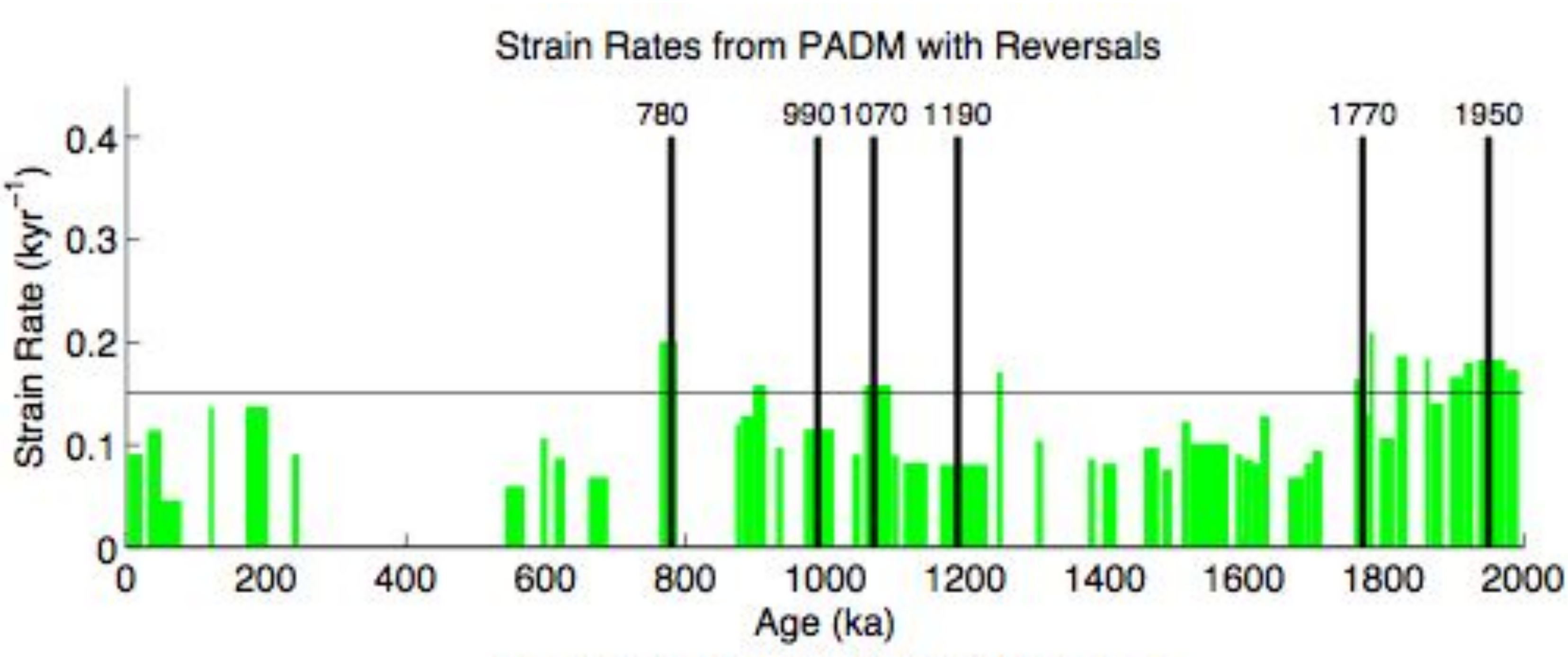


Figure 4. Images of instability in a shell; sequence runs left to right, top to bottom and spans 40 s.

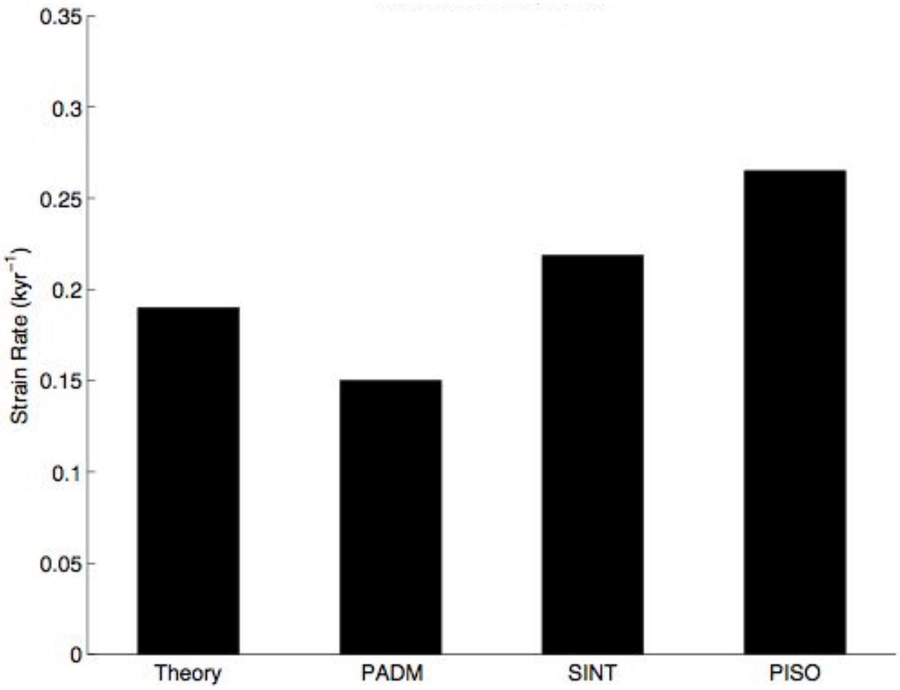
Aldridge et al.
(*GAFD*, **101**, 507, 2007, DOI)

Reversals and Tidal Strain Rates

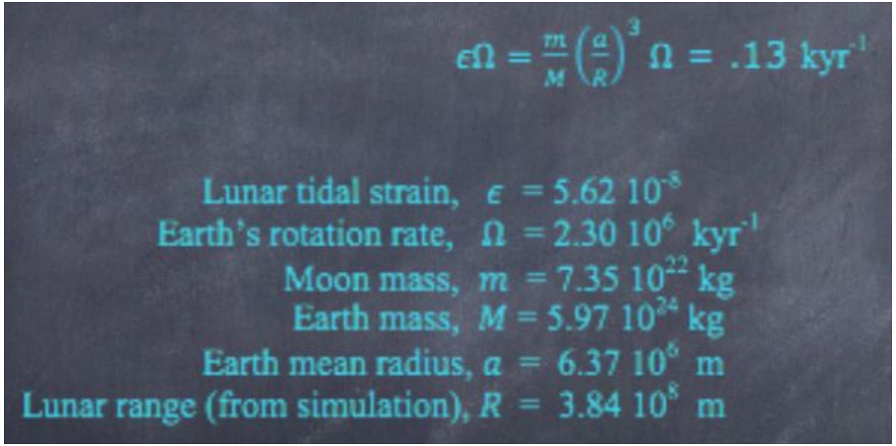


Aldridge & McMillan (2017, *EGU Vienna*)

Strain-Rate Comparison



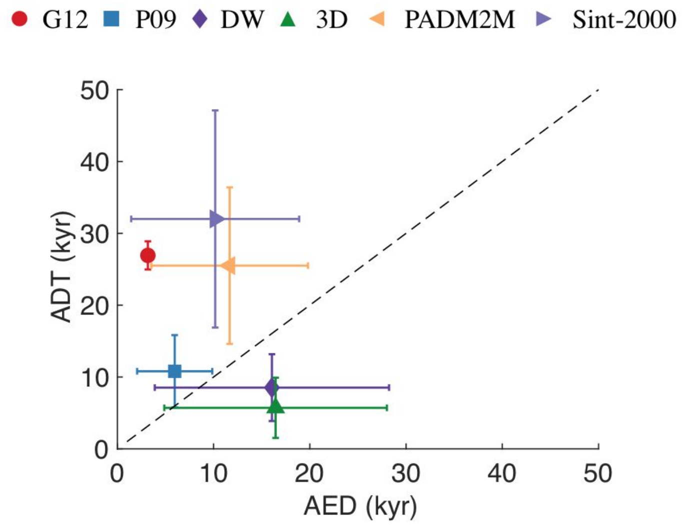
Theory



Aldridge & McMillan (2017, *EGU Vienna*)

Characterizing Reversals Revisited

- RPI *and* Be-ratio stacks quantify the geomagnetic field during reversals
- Beyond AED vs. ADT
  - AED vs. ADT is an excellent starting point
    - Observation-simulation ‘divide’
  - Account for **growths** (AGT) as a third dimension
  - Acquire additional data points - particularly ‘alternative’ geodynamo mechanisms
    - Consider low-dimensional models for geodynamos driven by elliptic instability
  - Consider **excursions** in addition to reversals - compelling data available!



Gwirtz et al.
(2021, *GJI*, **225**, 277, DOI)

Summary

- Nuances of RPI and Be-ratio stacks present interesting possibilities for *connecting* geomagnetic field observations and processes
  - Asymmetric growths and decays of the field around reversals and excursions merit focus
- Tidally driven elliptic instability model for the geodynamo is illustrative
  - Reversals occur near maximum tidal strain rates
  - RPI-extracted strain rates compare favourably with theory
- Advancements require efforts on prioritized fronts
  - Observational - reduce ‘ambiguities’ in asymmetry estimates
  - Modeling and simulation - geodynamo driven by elliptic and shear instabilities

Q & A

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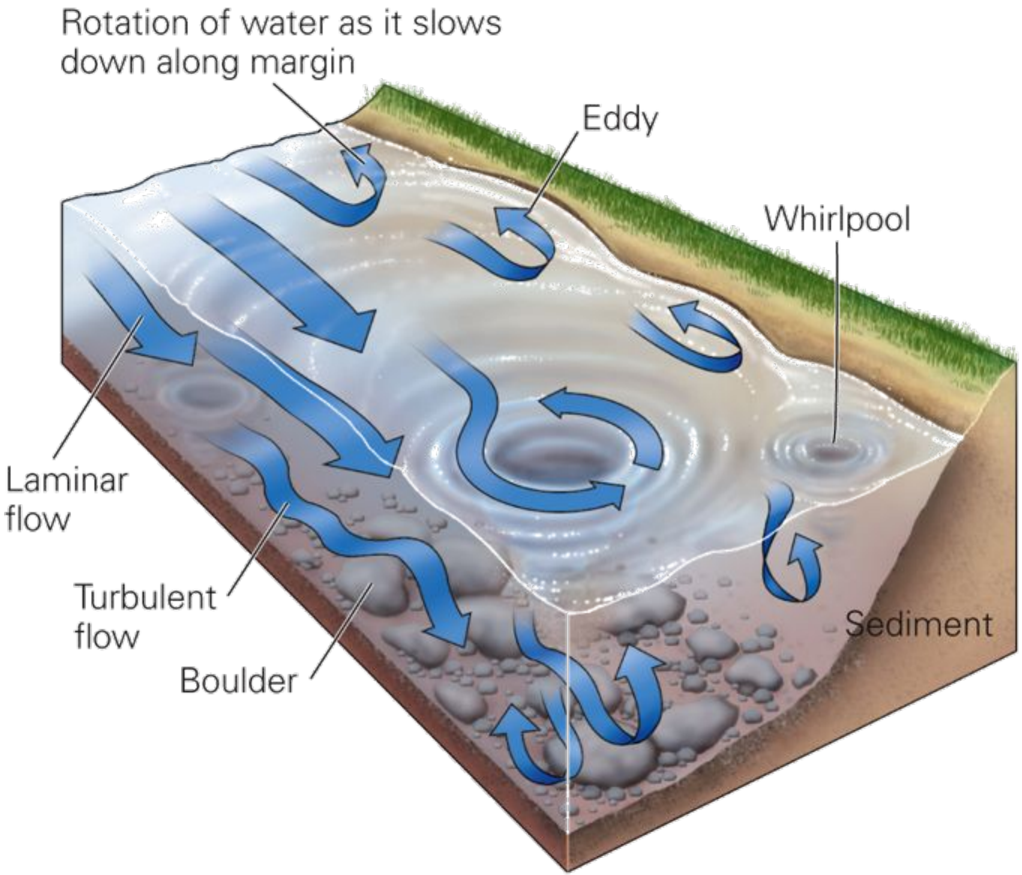
Supplement

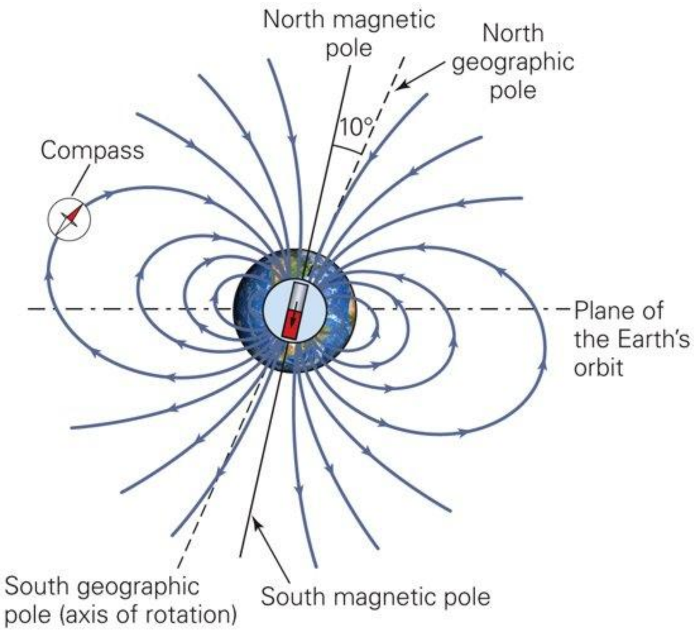


[Minden Whitewater Preserve]

Marshak, 6th Edition, Earth: Portrait of a Planet (W W Norton & Co., Inc.)

Earth’s Magnetic Field

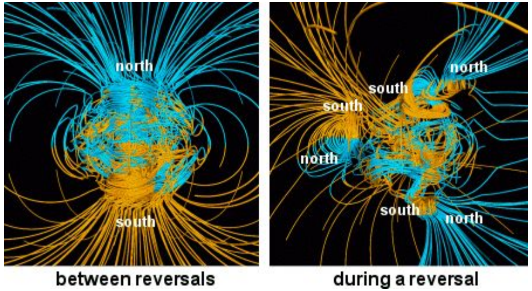
- Evidence for its ongoing existence over ~ 4 Ga
- ‘Strong’ dipolar main field
    - Originates within Earth’s interior
    - Protects the biosphere and atmosphere
        - Deflects the solar wind
        - Traps cosmic rays
    - Leveraged for navigation
- Evidence for variations
    - Intensity - space (SAA) and time
    - Direction - e.g., reversals, excursions, …
    - Drift
- *Requires* a self-sustaining mechanism



A Field Guide to the Magnetic Solar System (Eos, January 2021)

Mechanisms for Driving the Geodynamo

- Alternative: Mechanical turbulence - emphasizes nonlinear effects
  - **Tidal deformation**, libration, or impacts - elliptical instability
  - Precession, impacts - shearing instability
  - Shearing >> elliptical
- Conventional: Thermochemical convection
  - Dependent upon Earth's evolving thermal state - *especially* the age of the inner core



After Glatzmaier & Roberts (1995, *Nature,* **377**, 203)

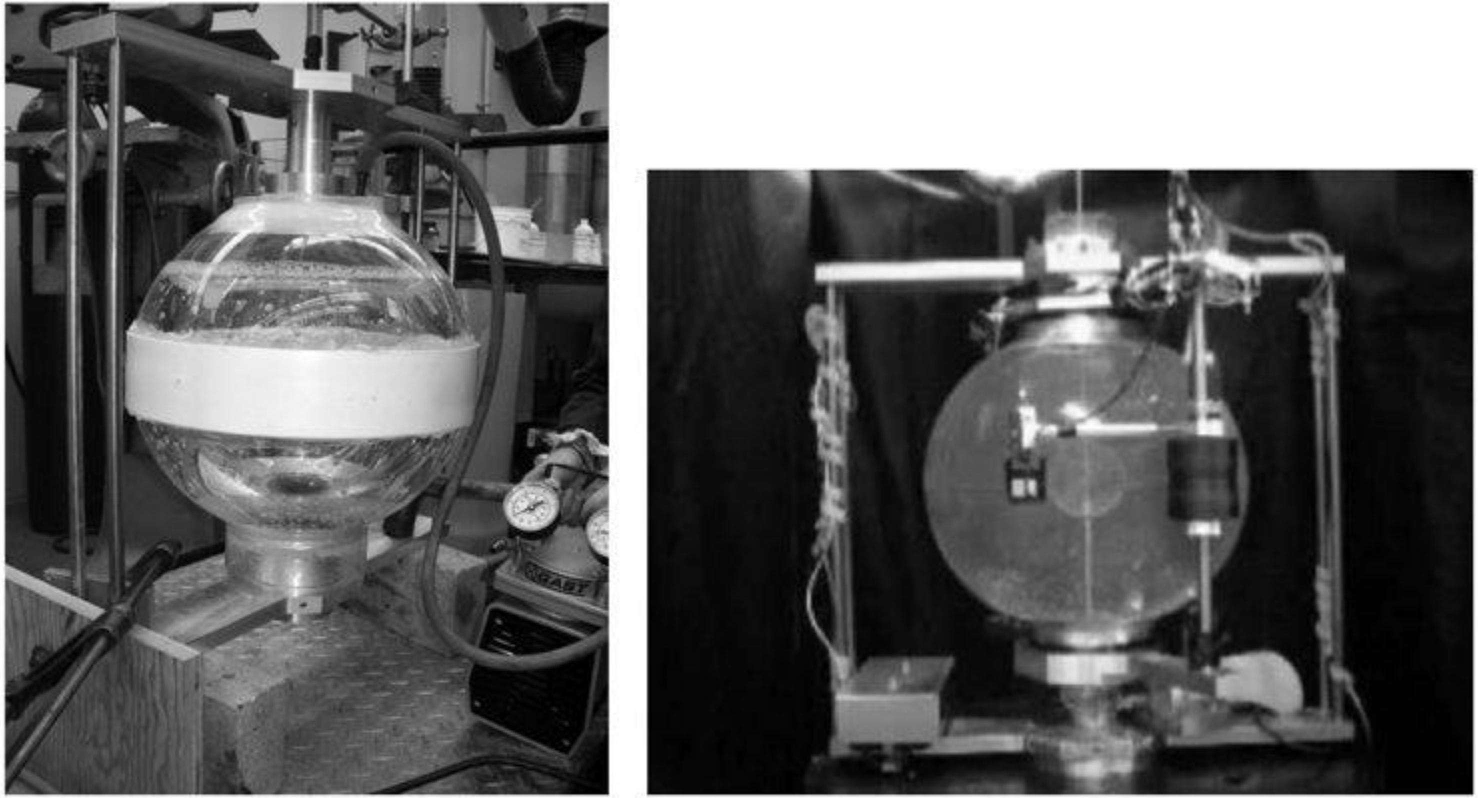


Figure 1. Apparatus to excite parametric instability. Fabrication of elastic container (left) and completed system including perturbation (right) with inner core installed.

Aldridge et al., *Geophysical and Astrophysical Fluid Dynamics,* **101**, 507–520, 2007.

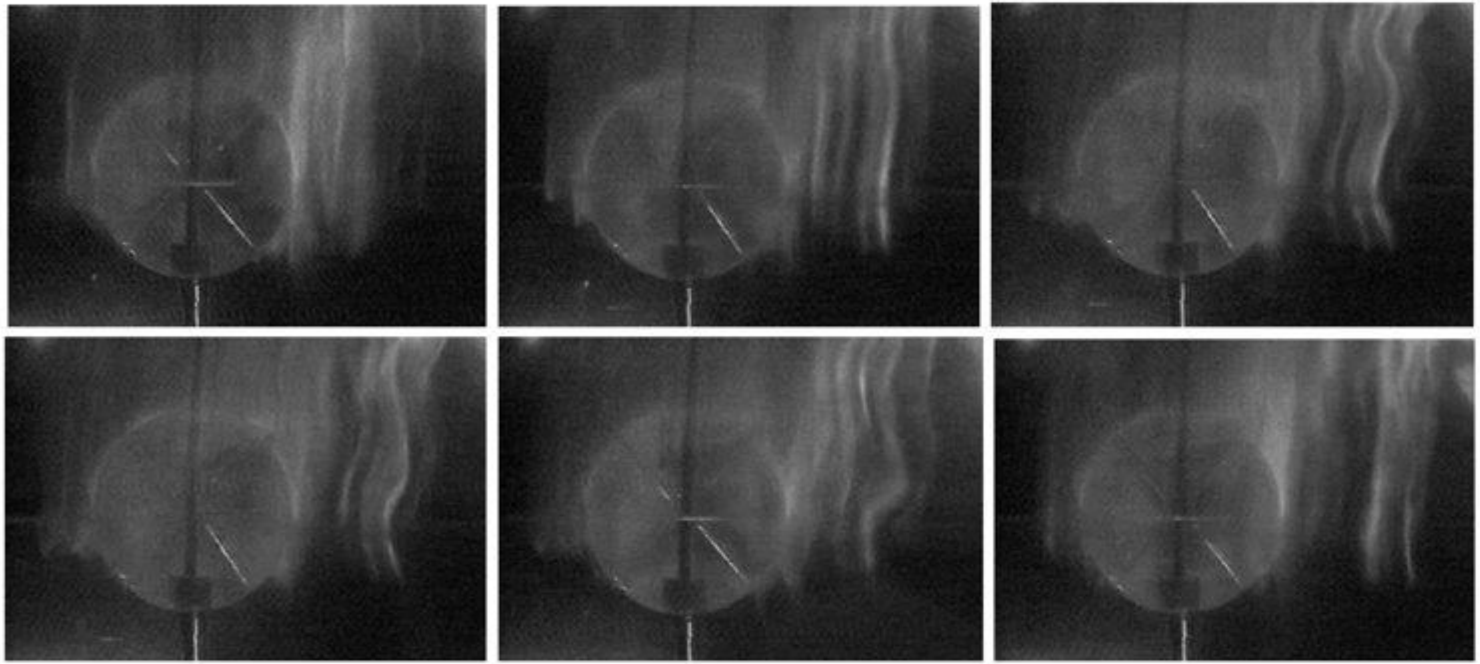


Figure 4. Images of instability in a shell; sequence runs left to right, top to bottom and spans 40 s.

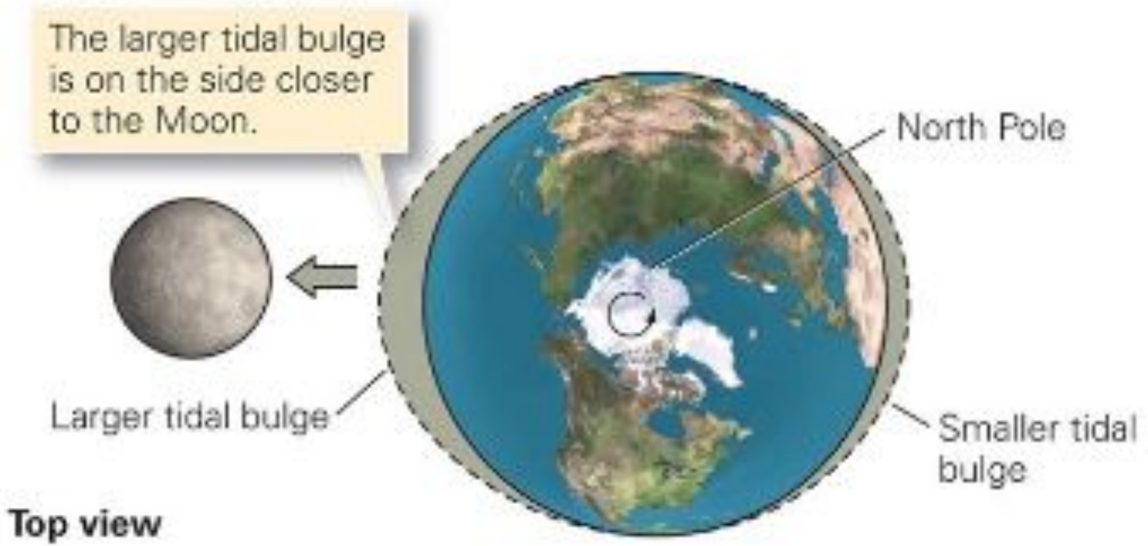
Aldridge et al., *Geophysical and Astrophysical Fluid Dynamics,* **101**, 507–520, 2007.

Thermochemical convection

Challenges and Opportunities

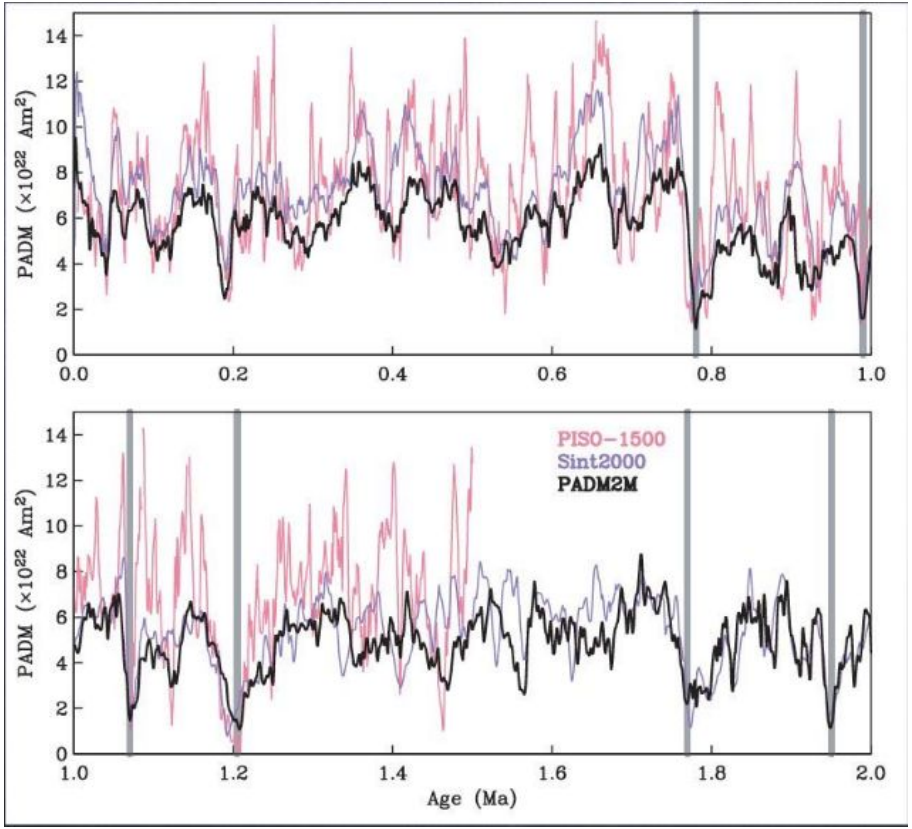
- Evidence for Earth's magnetic field over the past ~ 4 Ga
- Thermochemical convection has only been available for ~ 1 Ga
    - Owing to late-stage solidification of the inner core
    - Can thermal convection alone sustain the geodynamo for ~ 3.5 Ga?
- Motivates the need for alternate mechanisms

https://en.wikipedia.org/wiki/Inge_Lehmann

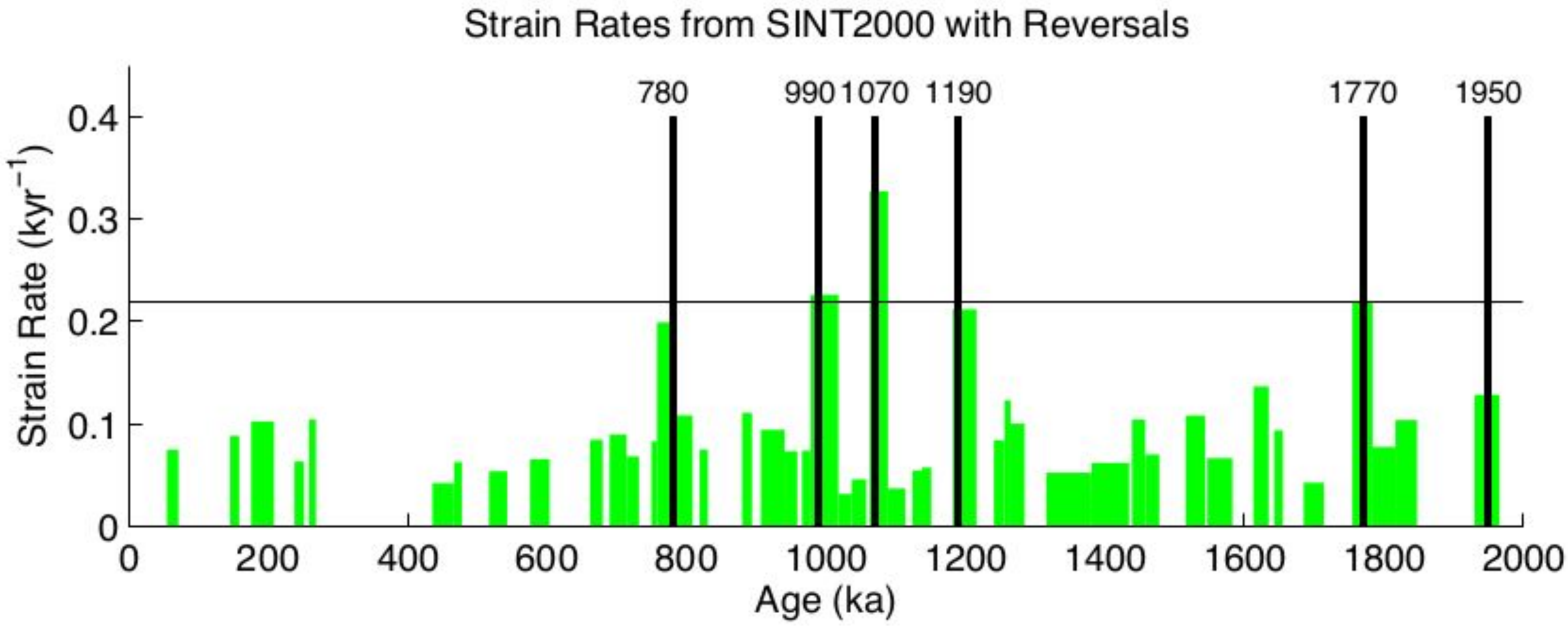


(a) Tides develop as the Earth spins relative to the two tidal bulges.

Marshak, 6th Edition, Earth: Portrait of a Planet
(W W Norton & Co., Inc.) - Figure 18.13(a)



Paleointensity data (Ziegler et al., 2001)



Magnetic field reversals occur near maximum tidal strain rates
(Aldridge & MacMillan, EGU Presentation 2017)

References

- Eos January 2021
- The Spinning Magnet
  - The Spinning Magnet by Alanna Mitchell: 9781101985168 | PenguinRandomHouse.com: Books
  - When our magnetic field flips, say goodbye to modern life

Tracking Magnetic Fields

- A Field Guide to the Magnetic Solar System
- The Herky-Jerky Weirdness of Earth's Magnetic Field
- Habitability and the Evolution of Life Under Our Magnetic Shield
- Modeling Earth's Ever-Shifting Magnetism
- Do Uranus's Moons Have Subsurface Oceans?
- Measuring Massive Magnetic Meteorites
- A Robust Proxy for Geomagnetic Reversal Rates in Deep Time