

Modelling fast geomagnetic reversals

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D1252 | EGU2020-10488

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Link to oral presentation:

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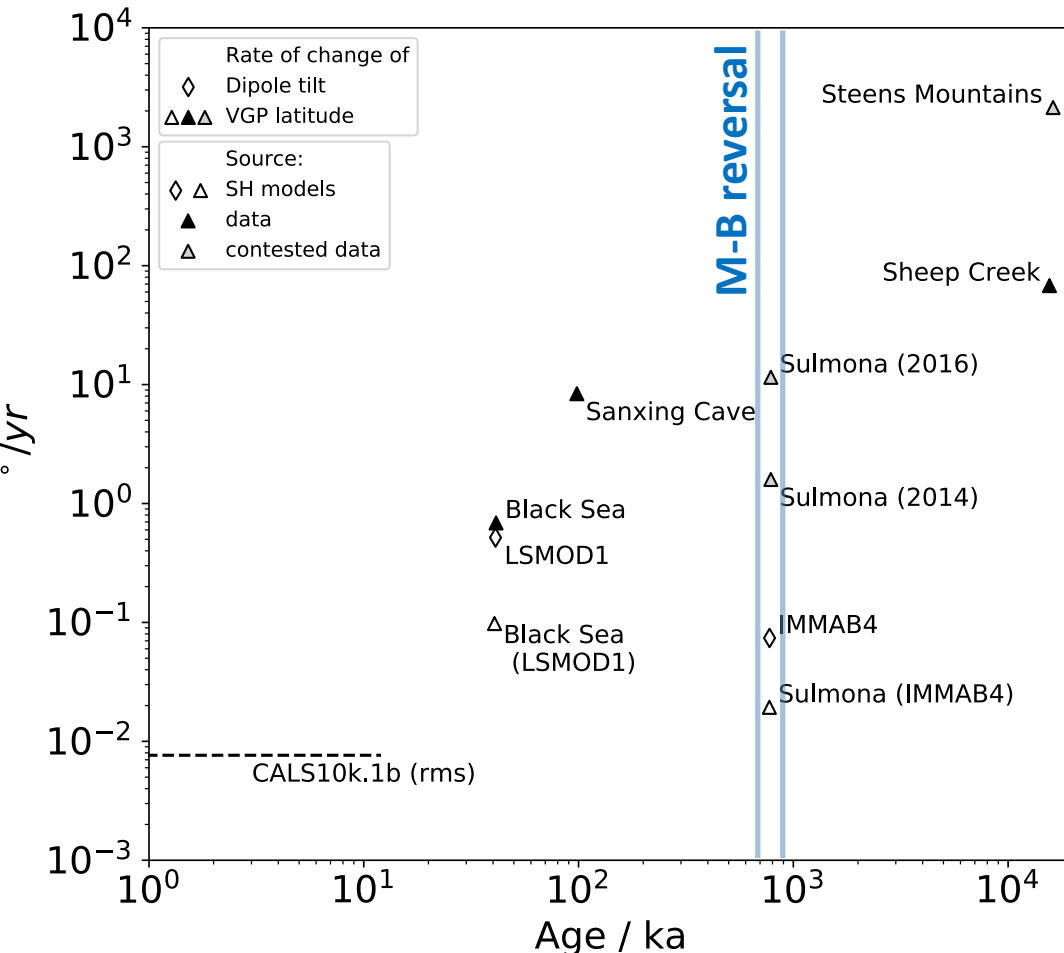


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- Analysis of different paleomagnetic datasets (speleothems, lava flows and sediments) suggest the occurrence of **extremely fast, global geomagnetic field variations**.
 - The **Sulmona basin** (Italy) sediments suggest that the Matuyama-Bruhnes (M-B) reversal took place over **less than a century** (Sagnotti et al., 2014) or over **about a decade** (Sagnotti et al., 2016).
- In contrast, in geodynamo simulations and geomagnetic field models, reversals take place over centuries-to-millennia.
- We calculated optimal flows at the core-mantle boundary that maximise the rate of change of geomagnetic observables. **We find that:**
 - The M-B reversal could not have happened in less than **3.8 centuries**;
 - To reproduce the fast variations of the Sulmona basin the flows drive optimized, local changes and **cannot** have driven a global reversal in the same time.

Rapid paleomagnetic variations



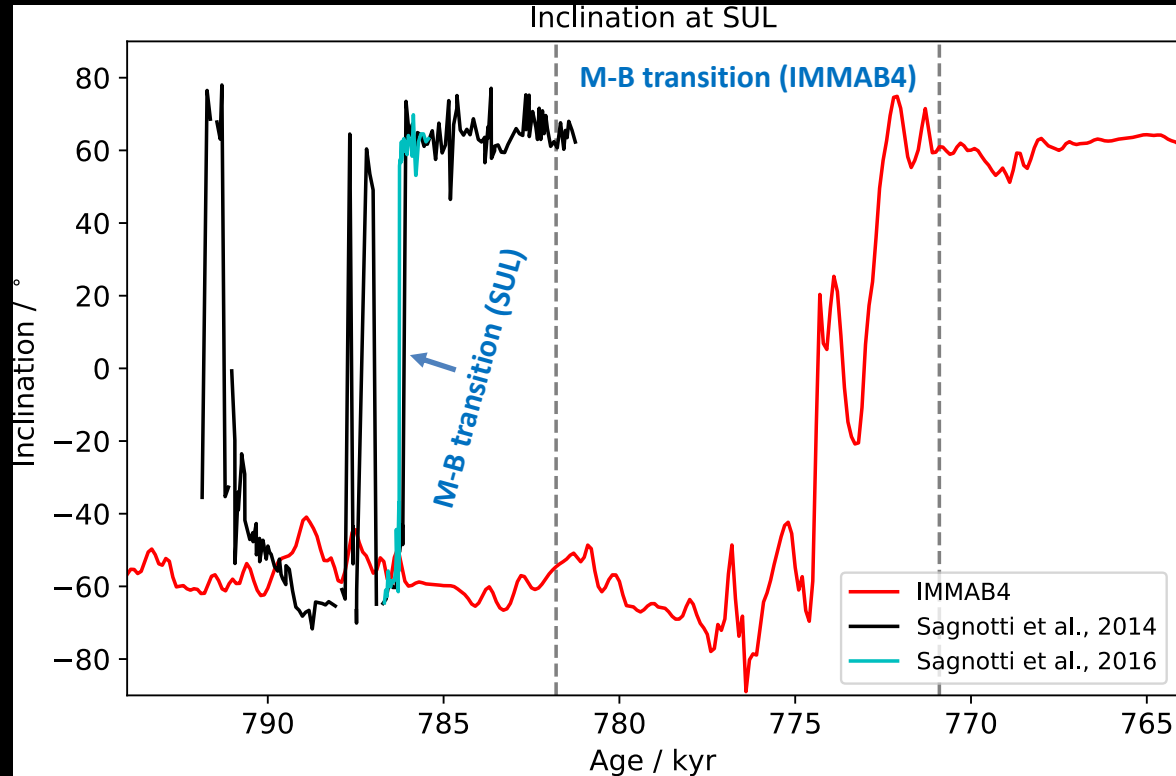
The figure shows a summary of observed data at the locations indicated and published geomagnetic field models: Maximum values of rates of change (in degrees per year) of Virtual Geomagnetic Pole (VGP) latitude (triangles), and dipole axis tilt (diamonds).

Paleomagnetic measurements are marked with black and grey symbols and spherical harmonics geomagnetic field models with white symbols. Grey symbols indicate datasets which reliability has been challenged in the literature.

References:

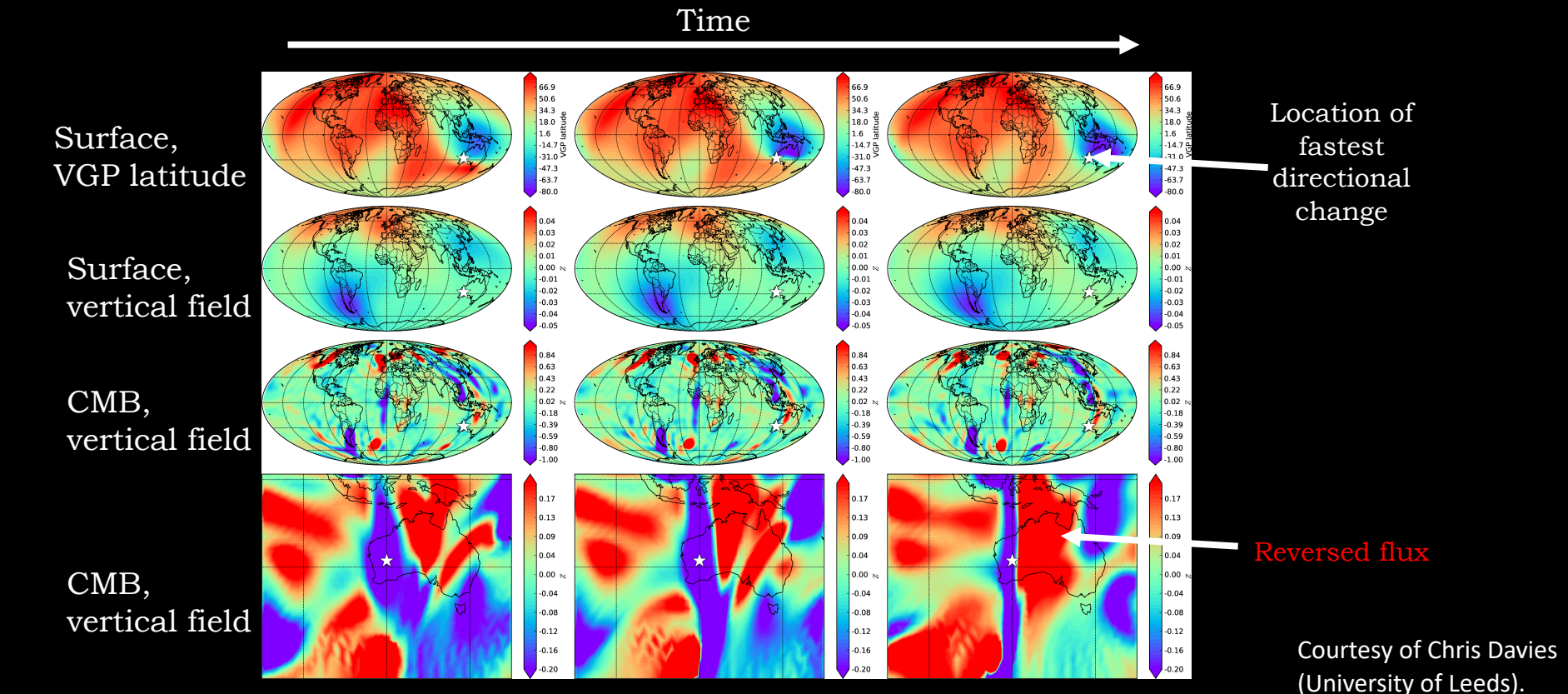
Sources of paleomagnetic observations: Coe et al., 1995 (Steens Mountains), Bogue et al., 2010 (Sheep Creek), Nowaczyk et al., 2012 (Black Sea), Sagnotti et al., 2014, 2016 (Sulmona), Chou et al. 2018 (Sanxing Cave).
Field models: LSMOD1 (Brown et al, 2018), IMMAB4 (Leonhardt et al., 2007) and the CALSK10K1B (Constable et al., 2016), which rms rate of change of dipole tilt is illustrated for comparison.

Matuyama-Brunes reversal



Geomagnetic inclination measured from sediments at the Sulmona basin (SUL) from Sagnotti et al., 2014-2016, and calculated from the IMMAB4 model coefficients (Leonhardt et al., 2007). Vertical grey lines indicate global reversal boundaries. The 2014/2016 studies suggest the reversal took place in less than a century/13 years, respectively.

Numerical simulations can reproduce localized rates-of-change in VGP location of ~ 10 deg/yr, driven by flux patches at the outer core surface.
 However, these variations are not resulting in global reversals.



Goals of the research

- Data suggesting a reversal could take place in less than a century challenge our understanding of the geodynamo mechanism
- Our purpose is to investigate
 - **the maximum rate of change** of observed paleomagnetic quantities (inclination and declination) that can be driven by fluid flows on the top of the outer core
 - **the minimal amount of time** in which these flows can drive a geomagnetic reversal

Is there any way flows at the top of the outer core can drive extreme variations of the magnitude observed in some paleomagnetic studies?

Instantaneous optimal solutions

Instantaneous optimal solutions

- We use the optimization algorithm from Livermore et al., 2014.
- The method was devised to answer the question

*By assuming that rapid changes in the field come only from advection from core flow
and given **the background geomagnetic field**,*

*what **core-surface flow** optimizes **the rate of change of a given geomagnetic observable**?*

$$\partial_t B_r = \nabla_h \cdot (\mathbf{u}_h B_r) + \eta \nabla^2 B_r \quad (\text{with } \eta = 0; \mathbf{u}_{rms} = 13 \text{ km/yr})$$

- Geomagnetic quantities expressed in terms of spherical harmonics are amenable to this optimization algorithm
 - We focus on:

Dipole colatitude (dipole tilt). A global quantity

$$\theta_d = \cos^{-1} \left(g_{10} / \sqrt{g_{10}^2 + g_{11}^2 + h_{11}^2} \right)$$

Geomagnetic inclination at specified location. A local quantity, directly observed

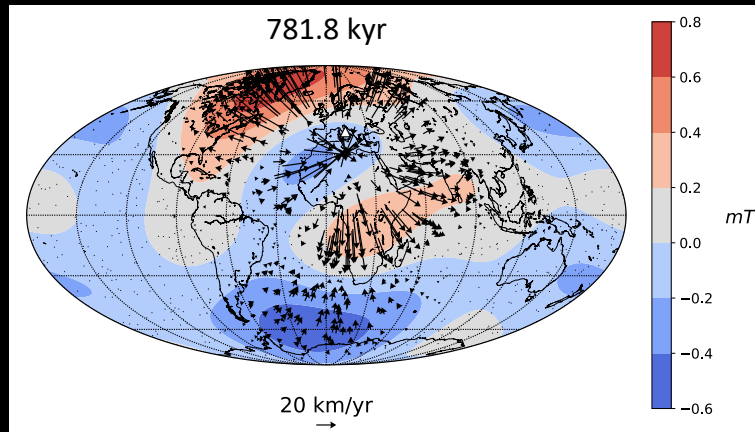
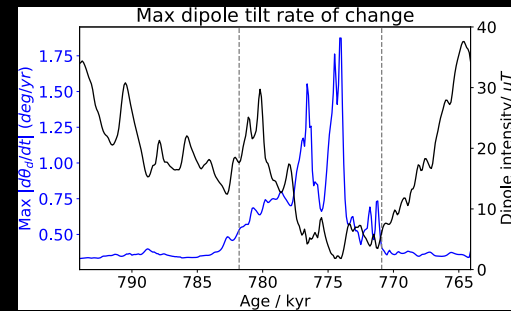
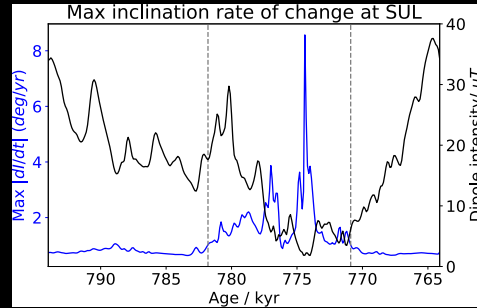
$$I = \tan^{-1} \frac{-B_r}{\sqrt{B_\theta^2 + B_\phi^2}}$$

Instantaneous optimal solutions

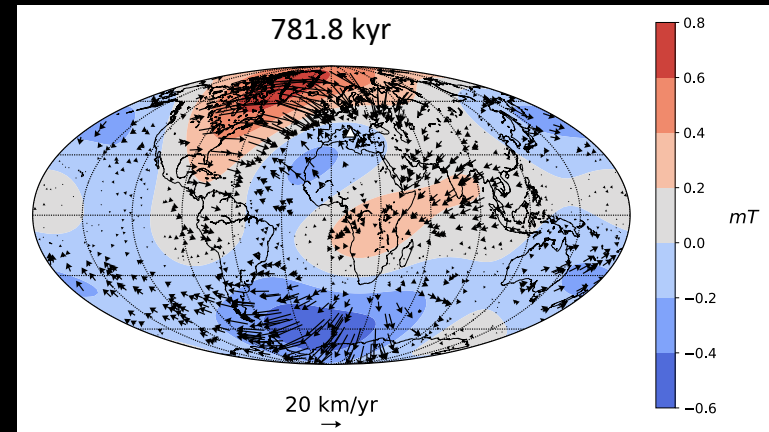
- The optimal solutions are bounded by the energy of the flows at the top of the core
 - We consider a rms value of **13 km/yr** (as in Livermore et al., 2014)
- It is possible to prescribe geometrical restrictions to the flows (e.g.: purely toroidal, purely poloidal, equatorially symmetric). Results shown here assume an unrestricted toroidal/poloidal flow
- The optimal flows are **not** meant to provide a realistic picture of flow at the top of the core
 - They provide **energetically justified upper bounds** to the rate of change of geomagnetic quantities given a prescribed geomagnetic field (from field models)
- Optimal flows to investigate what is the minimal amount of time required for a full reversal are calculated from background fields provided by the IMMAB4 model (Leonhardt et al., 2007)
 - We compare the optimal solution to the paleomagnetic data from Sagnotti et al., 2014-2016

Instantaneous optimal solutions

Flow optimization of IMMAB4 (sampled every 100 yrs) that maximise rate of change of Inclination at Sulmona (left) and dipole tilt (right) at every instant. IMMAB4 dipole intensity is shown in black. Optimal flows are shown with radial magnetic field at CMB at the beginning of the M-B transition (781.8 kyr).

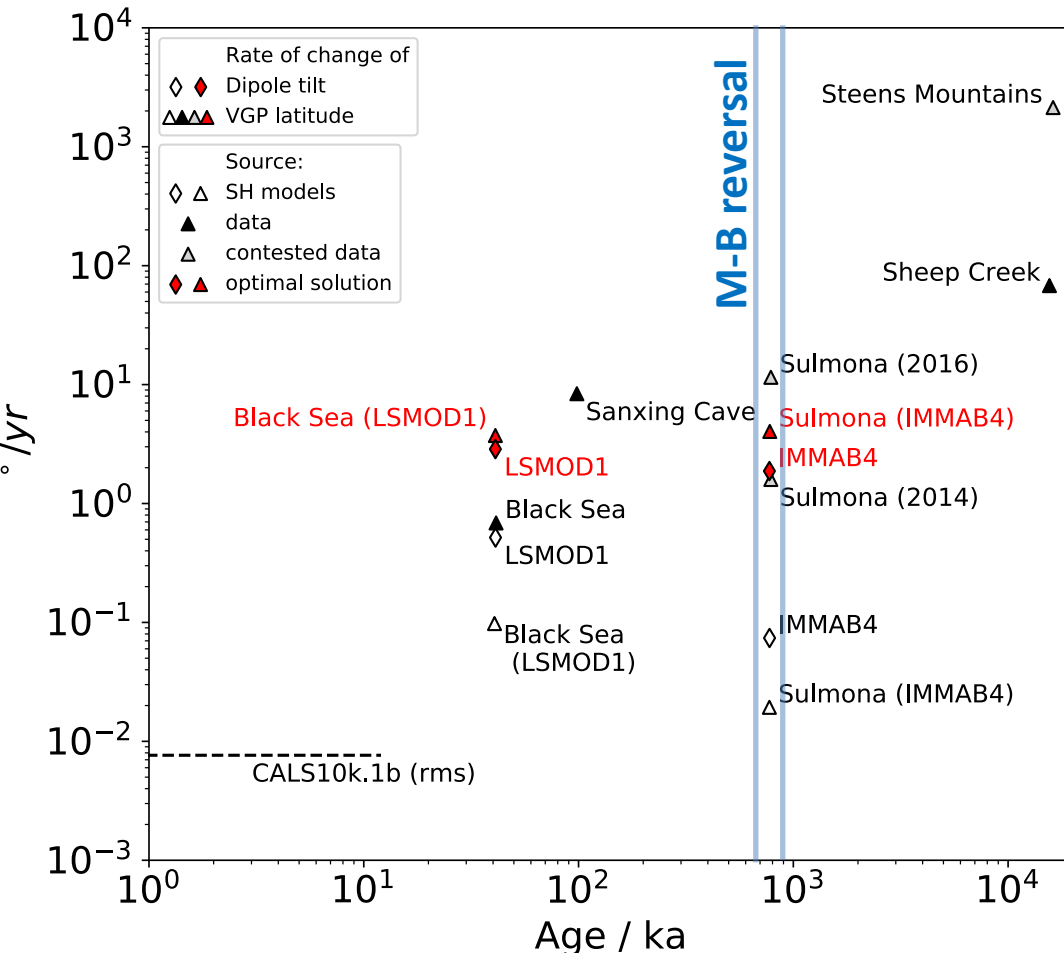


Optimal rate of change of Inclination at SUL:
localized flow. Flux patches (here very large scale) being moved.
Is a full reversal possible?



Optimal rate of change of dipole tilt:
presence of a large scale, global circulation

Rapid paleomagnetic variations



The figure shows a summary of observed data at the locations indicated and published geomagnetic field models: Maximum values of rates of change (in degrees per year) of VGP latitude (triangles), and dipole axis tilt (diamonds).

Optimal calculations (red) are based on a background field given by the field models indicated in the figure. Optimal solutions from IMMAB4 calculations are presented in the previous slides.

Optimal variations for the M-B reversal have magnitude between the Sagnotti et al., 2014 and 2016 studies.

Instantaneous optimal solutions: summary

- Reversal times inferred from extreme, instantaneous values:
 - Sagnotti et al., 2014: **< 100 yrs**
 - Sagnotti et al., 2016: **~13 yrs**
 - Optimal dipole tilt rate-of-change: **80 yrs**
 - Optimal rate-of-change of inclination at SUL: **30 yrs**
- Further questions:
 - Optimizing the rate-of-change of inclination results in localized flows. Do they drive a global reversal?
 - Flows will change the background magnetic field and in turn the optimal solution itself. Can we account for it?
 - Above values are found only for lowest dipole field strengths. Can we obtain more realistic, time-dependent behaviors?

Time-dependent optimal solutions

Time-dependent optimal solutions

1. Calculate *instantaneous optimal flow* given *background magnetic field*
 - Calculate corresponding *secular variation*
2. Update *background field* for *optimal variation*
3. Advance time-step and repeat from 1

$$\partial_t B_r = \nabla_h \cdot (\mathbf{u}_h B_r) + \eta \nabla^2 B_r \quad \left(\begin{array}{l} \text{with } \eta = 0.7 \text{ m}^2/\text{s}; \\ \mathbf{u}_{rms} = 13 \text{ km/yr} \end{array} \right)$$

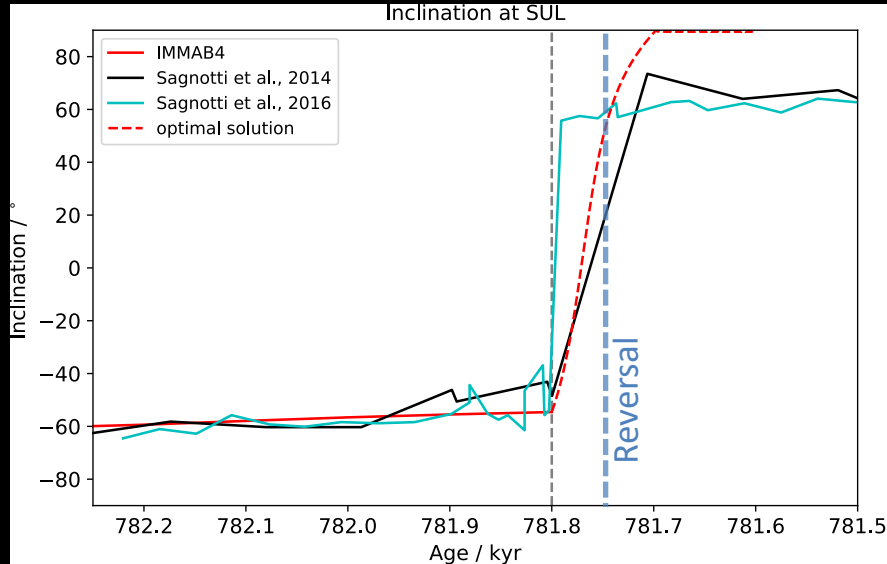
- The flow is allowed to change instantaneously at every temporal step.
- We initialize the method from the IMMAB4 filed at 781.8 ka: the beginning of the M-B transition.

This gives a better answer to the question “how short can a reversal take, given reasonable energetic bounds?”

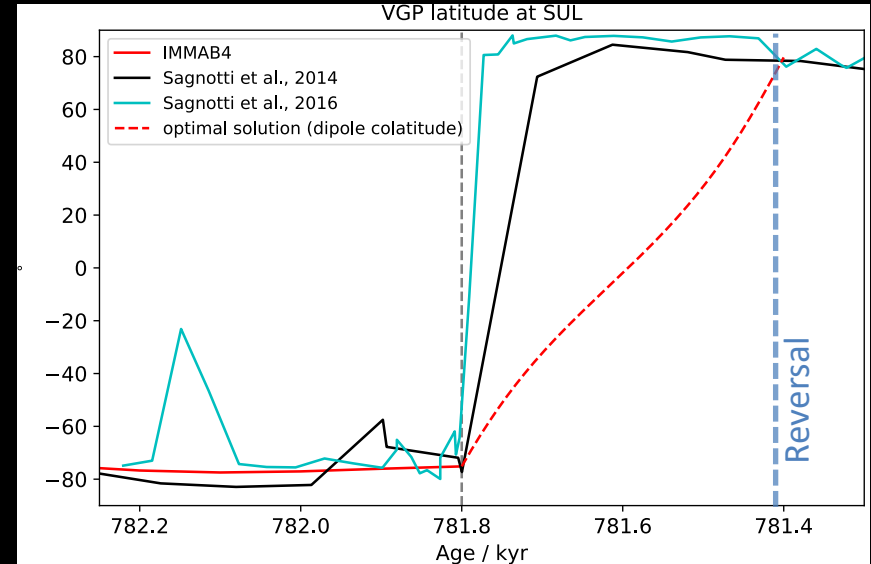
The best answer requires advanced methods (i.e.: variational methods, Long et al., 2018) that are not considered here.

Time-dependent optimal solutions

Optimal rate of change of Inclination at SUL:
localized flow. Inclination reversal in **54 yrs**. It is
a global reversal under the Global Axial Dipole
(GAD) assumption.



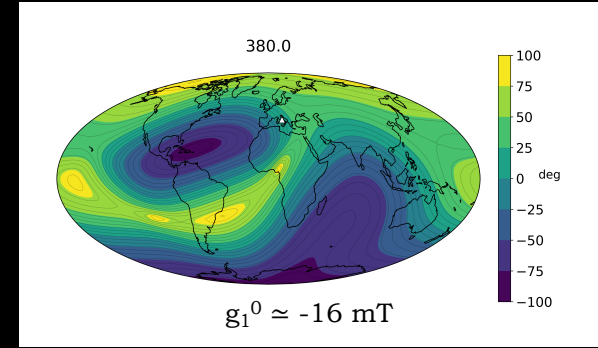
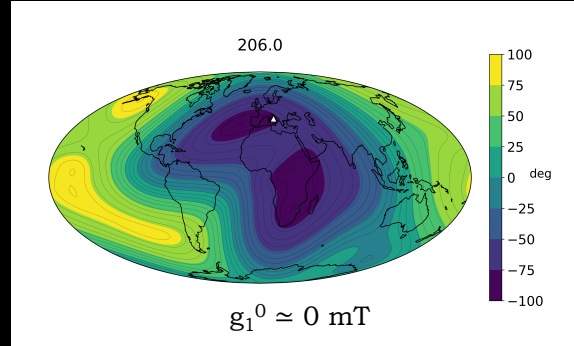
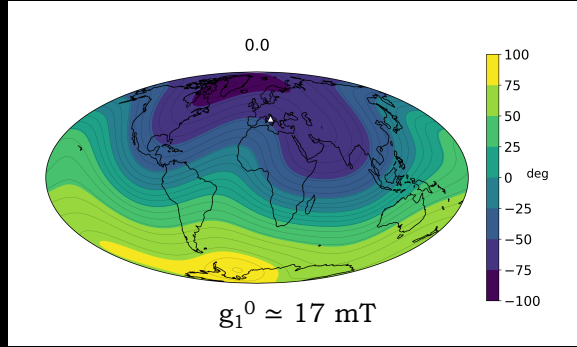
Optimal rate of change of dipole tilt, compared
with the VGP latitude at SUL. Full reversal in
380 yrs



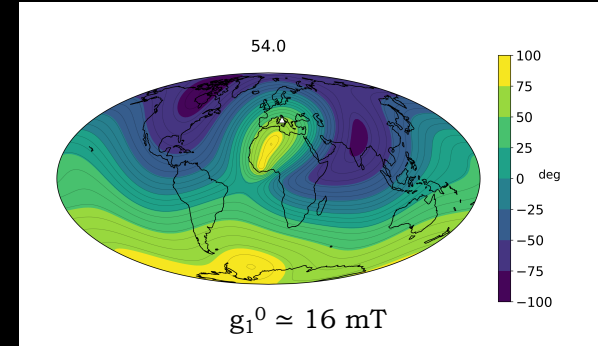
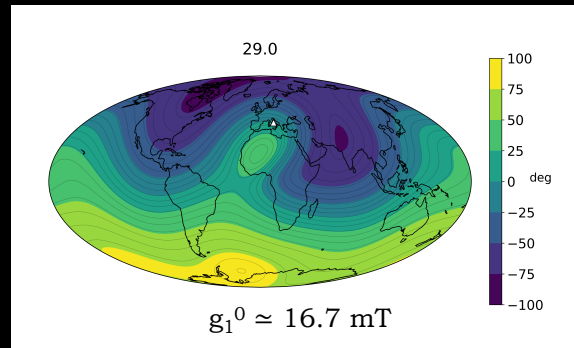
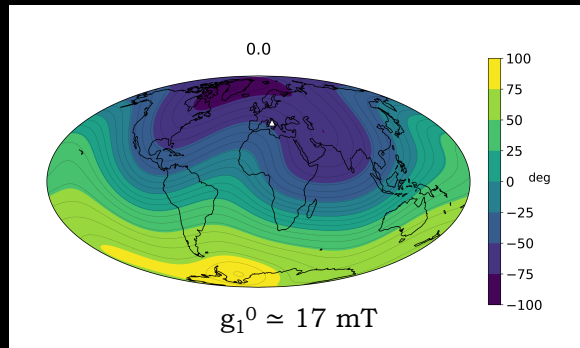
Time-dependent optimal solutions

Maps of **geomagnetic inclination** as a function of time and location show that:

- Flows that optimize the rate-of-change of dipole tilt (previous slide, right panel) actually **drive a global reversal**.



- Localized flows that optimize the rate-of-change of inclination (previous slide, left panel) **do not**.



Years after reversal beginning (781.8 kyrs ago) →

Conclusions

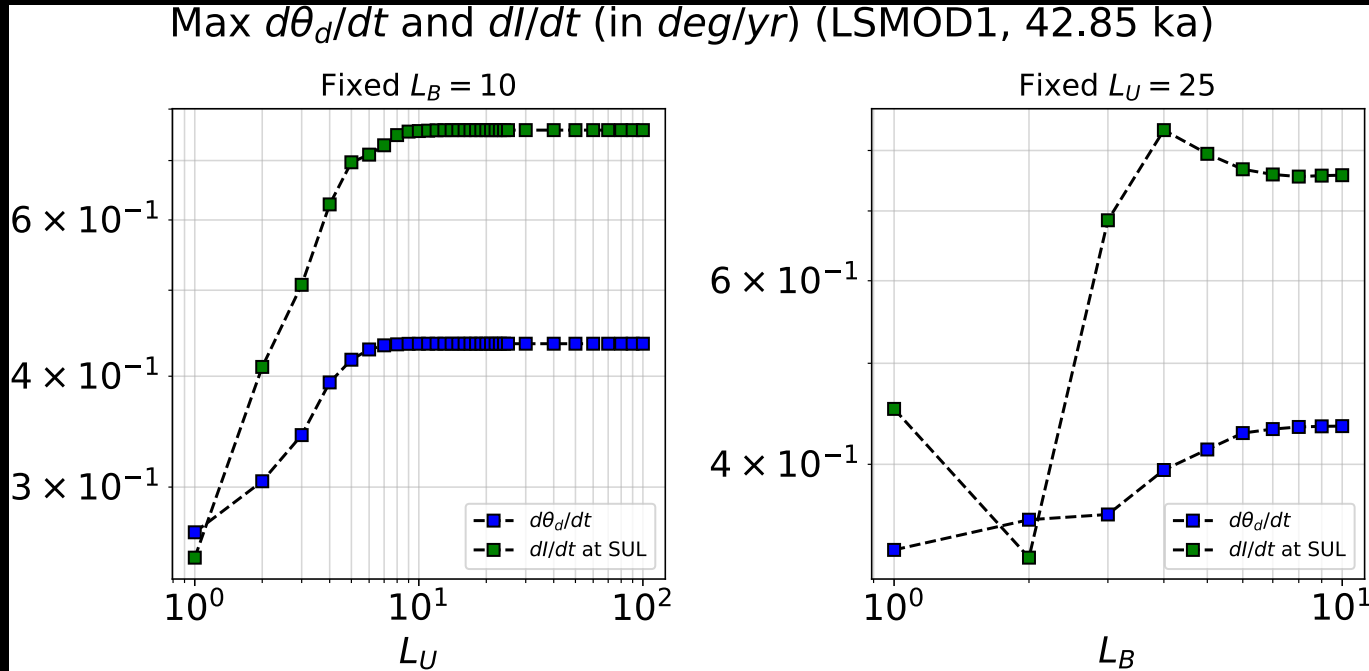
- Highly optimized flows can reproduce extreme temporal variations from paleomagnetic observations for the latest reversal (Sagnotti et al. 2014-2016), but suggest a localized variation.
- In particular:
 - Reported changes in inclination of **~10 deg/yr** can be obtained by highly localized flows that do not drive a global reversal
 - Global flows drive a global reversal in no less than **380 yrs**

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Extra slides

Convergence of the optimal solutions

- Livermore et al., 2014: the higher the degree of the background field model (L_B), the higher the optimal rate-of-change (IMMAB4 has only $L_B=4$).
- To illustrate: optimal solutions for various values of L_B , L_U (max degree of velocity field) for LSMOD1 model (Brown et al., 2018), right before the Laschamp excursion.



Convergence of the optimal solutions

- We illustrate with LSMOD1 model (not covering the M-B reversal) because it has $L_B > 4$: it allows convergence study with realistic background fields.
- Convergence w.r.t. flow field is achieved (theoretically expected for dipole tilt optimization)
- Convergence w.r.t. background field is less trivial:
 - Global and local optimization behave differently as L_B increases
 - In this particular case convergence is achieved at $L_B > 4$ (above max degree of IMMAB4).
- Results of convergence studies do depend on the optimization instant.
- Future calculations need to parameterize the effect of unobserved magnetic scales ($L_B > 13$).