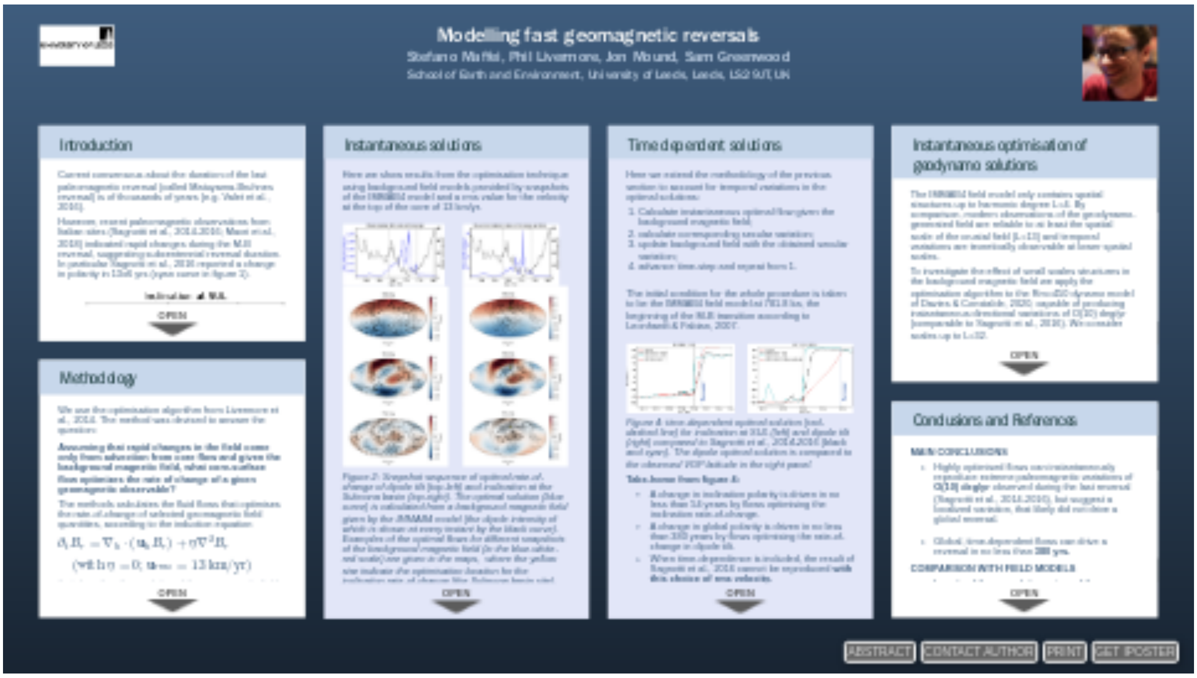
Modelling fast geomagnetic reversals



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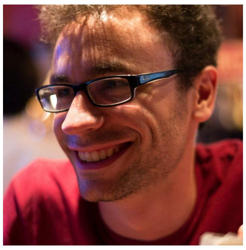

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INTRODUCTION

Current consensous about the duration of the last paleomagnetic reversal (called Matuyama-Bruhnes reversal) is of thousands of years (e.g. Valet et al., 2016).

However, recent paleomagnetic observations from Italian sites (Sagnotti et al., 2014-2016; Macri et al., 2018) indicated rapid changes during the M-B reversal, suggesting subcentennial reversal duration. In particular Sagnotti et al., 2016 reported a change in polarity in 13±6 yrs (cyan curve in figure 1).

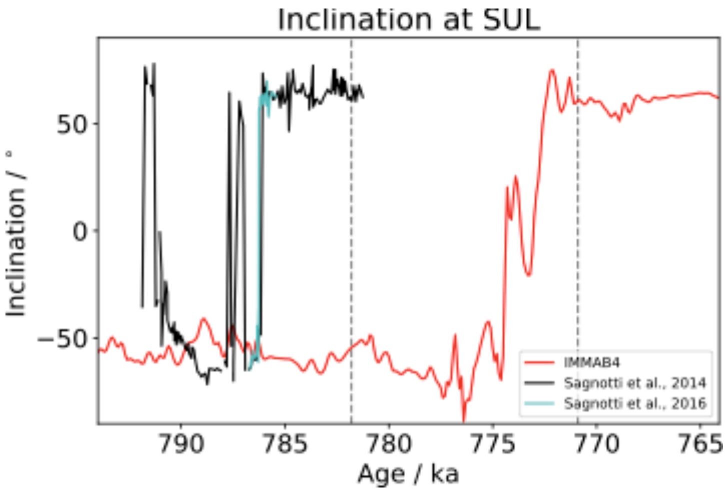


Figure 1: Time-series of inclination at the Sulmona basin location (central Italy) sampled by Sagnotti et al. The black and cyan curves are from Sagnotti et al., 2014 and 2016 studies. The red curve is from the IMMAB4 (Leonhardt & Fabian, 2007) geomagnetic field model. The vertical dashed lines are the limits of the M-B transition period as defined from the initiation and termination of the reversal at the paleomagnetic locations considered in Leonhardt & Fabian, 2007.

Such rapid variations are a challenge to our current understanding of the geodynamo and only recently have numerical simulations being capable of reproducing analogous magnetic field directional variations (Davies & Constable, 2020).

In this presentation we make use of an alternative methodology aimed at reproducing the fastest magnetic field variations that were energetically allowed during the M-B reversal. The purpose is to attempt at asnwering the following questions:

- What flow on top of the outer core could have driven the observed changes?
- Are the rapid changes observed at the Italian sites consistent with a global reversal? Or were they geographically localised?
- What is the shortest time in which a geomagnetic reversal is energetically allowed to take place?

METHODOLOGY

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

Assuming that rapid changes in the field come only from advection from core flow and given the background magnetic field, what core-surface flow optimizes the rate of change of a given geomagnetic observable?

The methods calculates the fluid flows that optimises the rate-of-change of selected geomagnetic field quantities, according to the induction equation

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

that describes the evolution of the geomagnetic field on top of the core.

We fodus on the following geomagnetic directional quantities:

- 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 in paleomagnetic studies

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

In other words, the method requires a background magnetic field (from a spherical harmonics model such as the IMMAB4 model) and an estimate of the kinetic energy of the flows on top of the outer core. As an output, it gives the horizontal flows that drive the fastest variation in the selected geomagnetic quantitity.

This methodology allows to restrict the flow geometry to the following structure:

- unrestricted: no restriction imposed on the flow
- poloidal: the toroidal flow is set to zero
- toroidal: the poloidal flow is set to zero. This geometry is relevant in the presence of stable stratification on top of the outer core
- columnar: the flow is assumed equatorially symmetric. this geometry simulates columnar flows throughout the outer core, considered appropriate for interannual-to-decadal temporal variations.

Note that the resulting flows are not likey realistic, but give an upper bound to the field variations allowed by core-surface flows with the selected kinetic energy.

INSTANTANEOUS SOLUTIONS

Here we show results from the optimisation technique using background field models provided by snapshots of the IMMAB4 model and a rms value for the velocity at the top of the core of 13 km/yr.

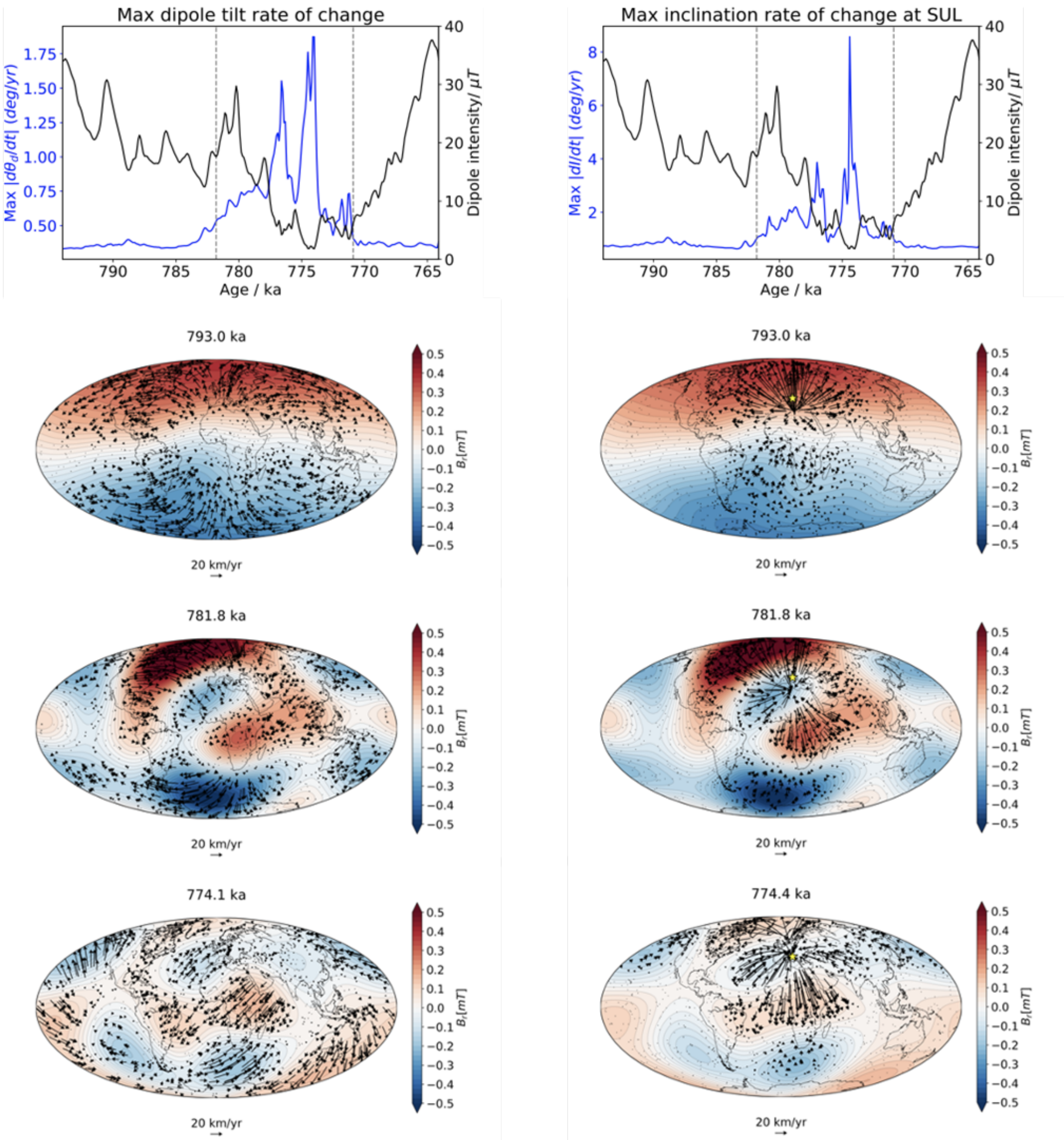


Figure 2: Snapshot sequence of optimal rate-of-change of dipole tilt (top-left) and inclination at the Sulmona basin (top-right). The optimal solution (blue curve) is calculated from a background magnetic field given by the IMMAB4 model (the dipole intensity of which is shown at every instant by the black curve). Examples of the optimal flows for different snapshots of the background magnetic field (in the blue-white-red scale) are given in the maps, where the yellow star indicate the optimisation location for the inclination rate-of-change (the Sulmona basin site).

Take-home from figure 2:

- Strongly non-dipolar magnetic field and weak dipolar fields promote extremely high values of optimal rates-of-change. This suggests flux patches at the top of the core are important in driving rapid magnetic field variations (in agreement with Livermore et al., 2014 and Davies & Constable, 2020).
- As expected, fluid flows that optimise the dipole tilt rate-of-change have a global nature, while flows optimising magnetic inclination at SUL have a highly localised nature.

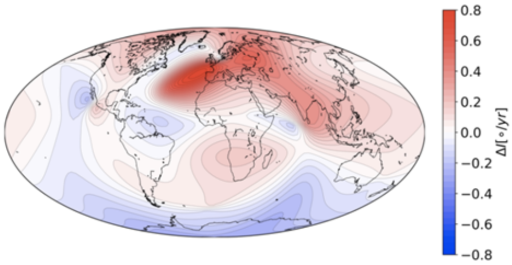
	$d\theta_d/dt\|_{max}$ / (°/yr)	$dI/dt(SUL)\|_{max}$ / (°/yr)	$d\lambda/dt_P(SUL)\|_{max}$ / (°/yr)
Unrestricted	1.87	8.57	6.21
Poloidal	1.53	6.23	4.51
Toroidal	1.40	5.88	4.27
Columnar	1.27	5.54	4.50
Sagnotti et al., 2014	-	1.65	1.30
Sagnotti et al., 2016	-	8.44	11.16
IMMAB4, M-B avg	0.074	0.039	0.019
IMMAB4, max	0.41	0.42	0.34

Table 1: Numerical values of maximal rate-of-change in dipole tilt (first column), and inclination (middle column) and VGP latitude (third column) at Sulmona for optimal flow calculations (indicated by the different flow geometries), from the measurements at Sulmona (Sagnotti et al., 2014-2016) and predicted the IMMAB4 geomagnetic field model (Leonhardt & Fabian, 2007). These are the numerical values of the maximum values of the time-series shown in figure 2. Values from Sagnotti et al., 2014-2016 refer to the the polarity transition which takes place between two contiguous data-points. Values indicated with 'IMMAB4, M-B avg' are calculated across the M-B reversal. Values indicated with 'IMMAB4, max' refer to the maximum rates-of-change calculated via first differences.

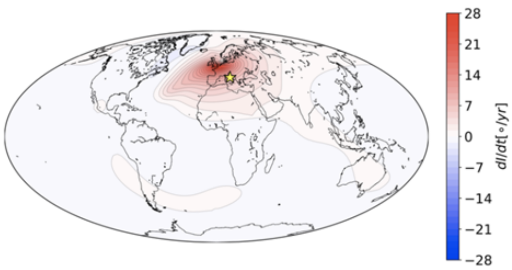
Take-home from table 1:

- As expected, optimised rates-of-change are order of magnitude larger than geomagnetic field model predictions.
- **Optimal solutions can reproduce the extreme values of inclination variation obtained by Sagnotti et al., 2014.**

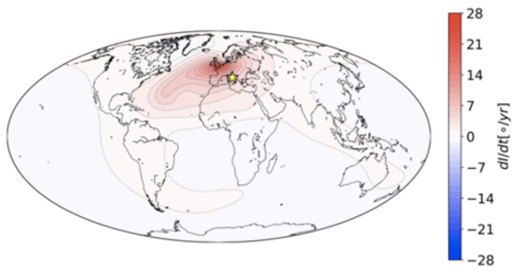
Given that the optimal rates-of-change are linearly dependent on the rms velocity during the M-B reversal (a highly unkown quantity), it is difficult to clearly establish what flow geometry was the most likely to cause the measured paleomagnetic variations.



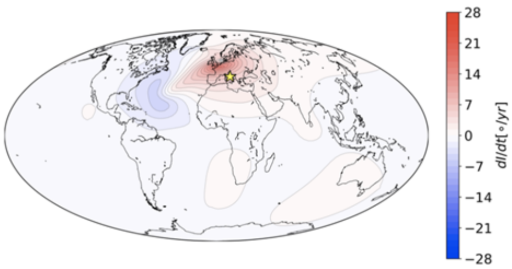
(a) IMMAB4 (774.5 ka)



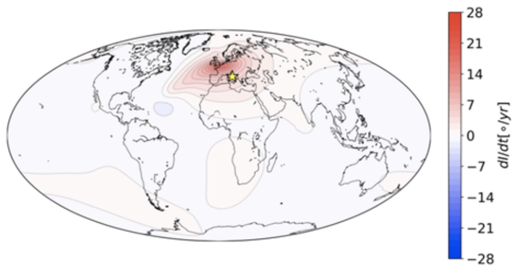
(b) Unrestricted



(c) Poloidal



(d) Toroidal



(e) Columnar

Figure 3: inclination rate-of-change at the Earth surface for the IMMAB4 geomagnetic field model at epoch 774.5 ka (a) and driven by optimal flows with unrestricted (b), poloidal (c), toroidal (d) and columnar (e) geometry.

Take-home from figure 3:

- Different numerical values aside, the rate-of-change of inclination driven by the optimal flows across the globe is qualitatively similar for different flow geometries. Again, this makes it difficult to establish what flow geometry was most likely during the M-B reversal.
- The actual inclination rate-of-change during the M-B reversal (estimated throught the M-B model) shows strong qualitative similarities with the optimal solution. Namely: strong variations in the European region.

TIME DEPENDENT SOLUTIONS

Here we extend the methodology of the previous section to account for temporal variations in the optimal solutions:

1. Calculate instantaneous optimal flow given the background magnetic field;
2. calculate corresponding secular variation;
3. update background field with the obtained secular variation;
4. advance time-step and repeat from 1.

The initial condition for the whole procedure is taken to be the IMMAB4 field model at 781.8 ka, the beginning of the M-B transition according to Leonhardt & Fabian, 2007.

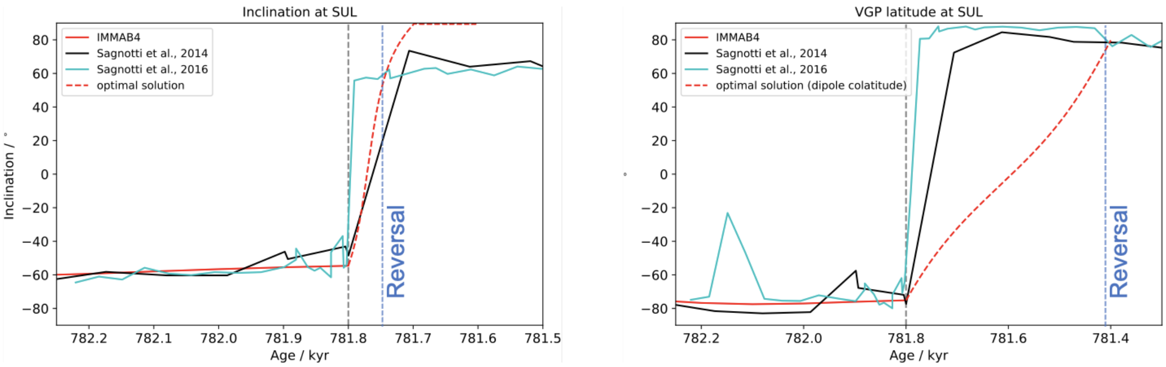


Figure 4: time-dependent optimal solution (red-dashed line) for inclination at SUL (left) and dipole tilt (right) compared to Sagnotti et al., 2014-2016 (black and cyan). The dipole optimal solution is compared to the observed VGP latitude in the right panel.

Take-home from figure 4:

- A change in inclination polarity is driven in no less than 54 years by flows optimising the inclination rate-of-change.
- A change in global polarity is driven in no less than 380 years by flows optimising the rate-of-change in dipole tilt.
- When time-dependence is included, the result of Sagnotti et al., 2016 cannot be reproduced **with this choice of rms velocity.**

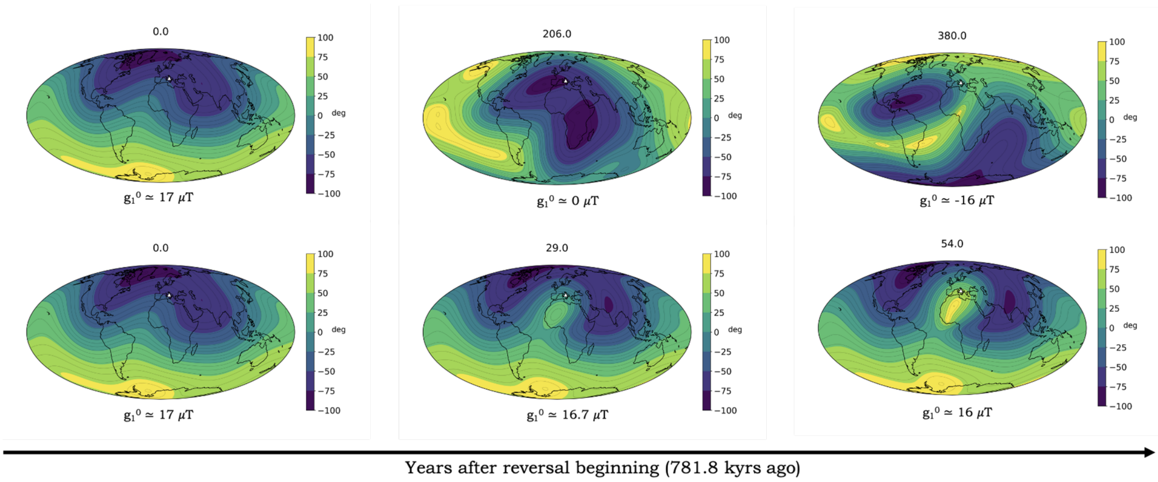


Figure 5: maps of inclination from the time-dependent optimal solution that maximises the rate-of-change of dipole tilt (top) and inclination at SUL (bottom). Also illustrated is the axial dipole coefficient numerical value.

Take-home from figure 5:

- As expected, the solution optimising the rate-of-change of inclination at SUL does **not** drive a global polarity reversal

- Therefore **the lower limit for a true global reversal is 380 years**

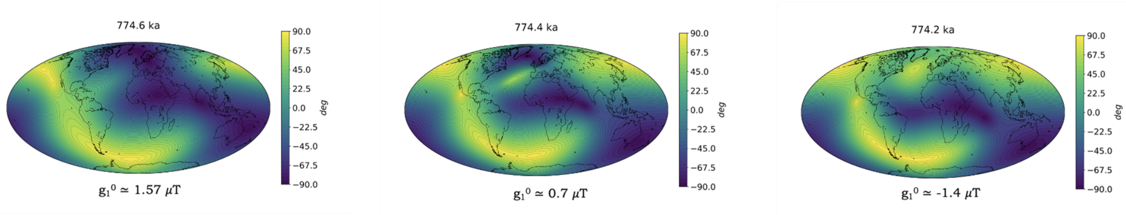


Figure 6: snapshot of inclination as predictex by the IMMAB4 field model between 774.6 and 774.2 ka.

Take-home from figure 6:

- The solution that optimises the inclination rate-of-change contains aspects of the field evolution during the M-B reversal, predicted by the IMMAB4 model.
- This suggest that a component of the core-surface flow during the reversal was close, at least in shape, to the optimal flows calculated here.

INSTANTANEOUS OPTIMISATION OF GEODYNAMO SOLUTIONS

The IMMAB4 field model only contains spatial structures up to harmonic degree L=4. By comparison, modern observations of the geodynamo-generated field are reliable to at least the spatial scale of the crustal field (L=13) and temporal variations are teoretically observable at lower spatial scales.

To investigate the effect of small scales structures in the background magnetic field we apply the optimisation algorithm to the Rm=450 dynamo model of Davies & Constable, 2020, capable of producing instantaneous directional variations of O(10) deg/yr (comparable to Sagnotti et al., 2016). We consider scales up to L=32.

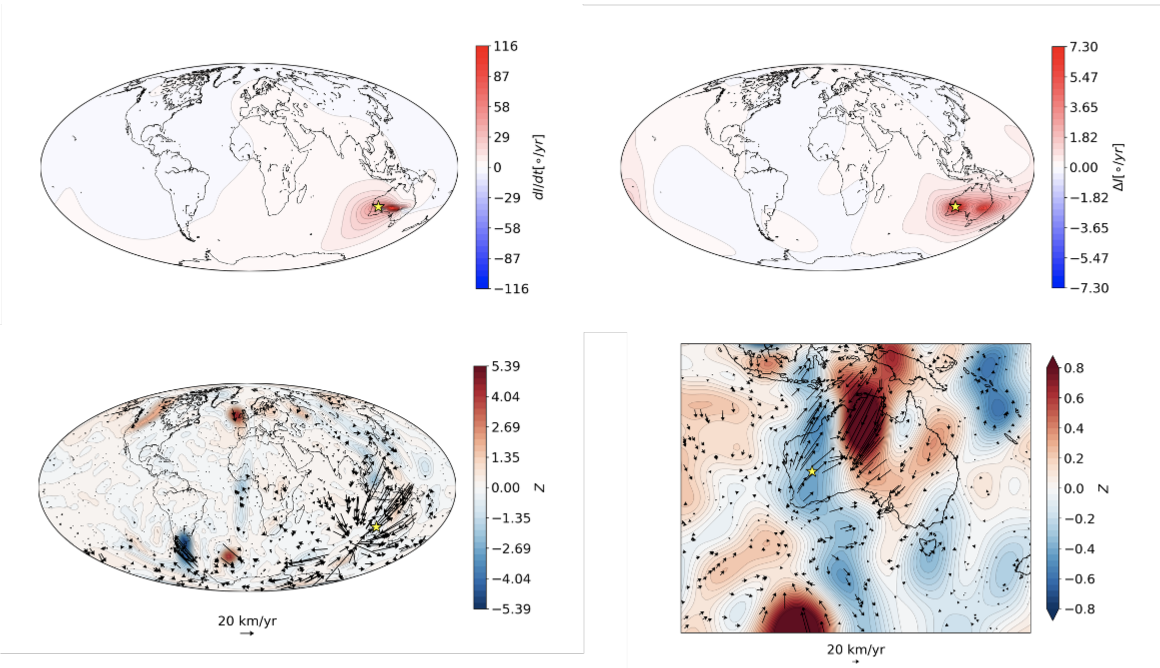


Figure 6: Result of the optimisation of the inclination rate-of-change with the Rm=450 geodynamo model from Davies & Constable, 2020. (top-left) Optimal inclination rate-of-change; (top-right) inclination rate-of-change calculated with first-differences from the $Rm=450$ model output; (bottom-left) optimal flow calculated from the background magnetic field shown by the colormap; (bottom-right) detail of background field and optimal flow around the optimisation location (the yellow star), which is the same location in which extreme directional changes are observed in Davies & Constable, 2020. Note that the geographical longitude is chosen arbitrarily in this numerical model, and the outline of the continent is shown solely for reference.

The optimal inclination rate-of-change is produced by advection of local flux patches in a similar way as the flows in the geodynamo simulation do (red patch advected westward, blue patch advected eastward).

More details on the comparison of the optimal solution with the geodynamo solution will follow.

Given the small scale nature of the geodynamo field, we can run convergence studies, with the purpose of establishing if optimal calculations based on observed/measured geomagnetic fields are converged.

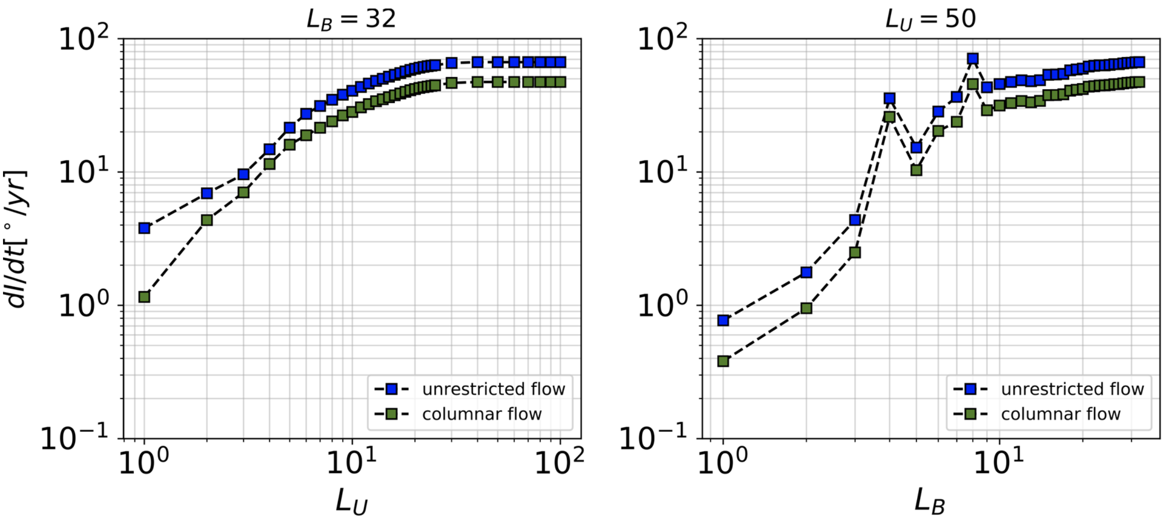


Figure 7: *convergence study for the optimal calculation of inclination rate-of-change. The panels show the optimal inclination variation at the same location varying (left) the spatial resolution of the fluid flows and (right) the spatial resolution of the background magnetic field.*

Take-home from this box:

- Extreme directional variations in numerical simulation also appear to contain a component of optimal flow, corroborating the validity of the technique for the study of extreme geomagnetic field variations.
- While convergence appears to be obtained by setting the resolution of the fluid flows to be $L_U=10+L_B$ (as in Livermore et al., 2014 and in the present study) convergence as a function of the resolution of the background field is harder to achieve.

CONCLUSIONS AND REFERENCES

MAIN CONCLUSIONS

- Highly optimised flows can instantaneously reproduce extreme paleomagnetic variations of **O(10) deg/yr** observed during the last reversal (Sagnotti et al., 2014-2016), but suggest a localized variation, that likely did not drive a global reversal.

- Global, time-dependent flows can drive a reversal in no less than **380 yrs.**

COMPARISON WITH FIELD MODELS

- In spite of the speculative nature of these calculations, field models of the last reversal (Leonhardt & Fabian, 2007) show some similarities with the localised optimal solutions. In particular the IMMAB4 model shows short-lived, fast directional variations localised over Europe.
- This corroborates the findings of local, sub-centennial polarity reversal in the Italian peninsula (Sagnotti et al., 2014-2016, Macri et al., 2018).
- Data points responsible for the presence of this feature in the IMMAB4 model are currently being investigated.

A WORD OF CAUTION

- The methodology presented here is geared towards finding upper bounds for the allowed directional variations, given a specified energy of the core-surface flows. However, given that the presented calculations are likely not converged (due to the low resolution of the background model), care needs to be taken in interpreting the results.
- The optimal variations are linearly dependent on the rms velocity on top of the core. Given the uncertainty in the estimation of this value, high uncertainty in the magnitude of the optimal solutions is expected.

REFERENCES

Bogue, S. W. and Glen, J. M. (2010). Very rapid geomagnetic field change recorded by the partial remagnetization of a lava flow. Geophysical research letters, 37(21).

Brown, M., Korte, M., Holme, R., Wardinski, I., and Gunnarson, S. (2018). Earth's magnetic field is probably not reversing. Proceedings of the National Academy of Sciences, 115(20):5111–5116.

Chou, Y.-M., Jiang, X., Liu, Q., Hu, H.-M., Wu, C.-C., Liu, J., Jiang, Z., Lee, T.-Q., Wang, C.-C., Song, Y.-F.,et al. (2018). Multidecadally resolved polarity oscillations during a geomagnetic excursion. Proceedings of the National Academy of Sciences, 115(36):8913–8918.

Constable, C., M. Korte and S. Panovska (2016): Persistent high paleosecular variation activity in Southern hemisphere for at least 10000 years. Earth Planet. Sci. Lett.,453,78-86.

Davies, C. J., & Constable, C. G. (2020). Rapid geomagnetic changes inferred from Earth observations and numerical simulations. Nature communications, 11(1), 1-10.

Leonhardt, R. and Fabian, K. (2007). Paleomagnetic reconstruction of the global geomagnetic field evolution during the Matuyama/Brunhes transition: iterative bayesian inversion and independent verification. Earth and Planetary Science Letters, 253(1-2):172–195.

Livermore, P. W., Fournier, A., and Gallet, Y. (2014). Core-flow constraints on extreme archeomagnetic intensity changes. Earth and Planetary Science Letters, 387:145–156.

Macrì, P., Capraro, L., Ferretti, P., & Scarponi, D. (2018). A high-resolution record of the Matuyama-Brunhes transition from the Mediterranean region: The Valle di Manche section (Calabria, Southern Italy). Physics of the Earth and Planetary Interiors, 278, 1-15.

Nowaczyk, N., Arz, H., Frank, U., Kind, J., and Plessen, B. (2012). Dynamics of the Laschamp geomagnetic excursion from black sea sediments. Earth and Planetary Science Letters, 351:54–69.

Sagnotti, L., Giaccio, B., Liddicoat, J. C., Nomade, S., Renne, P. R., Scardia, G., and Sprain, C. J. (2016).How fast was the Matuyama–Brunhes geomagnetic reversal? A new subcentennial record from the sulmonabasin, central italy. Geophysical Journal International, 204(2):798–812.

Sagnotti, L., Scardia, G., Giaccio, B., Liddicoat, J. C., Nomade, S., Renne, P. R., and Sprain, C. J. (2014).Extremely rapid directional change during Matuyama- Brunhes geomagnetic polarity reversal. Geophysical Journal International, 199(2):1110–1124

Valet, J. P., & Fournier, A. (2016). Deciphering records of geomagnetic reversals. Reviews of Geophysics, 54(2), 410-446.

ABSTRACT

Field reversals are some of the most prominent and commonly known temporal variations of the geomagnetic field. Polarity changes have been observed in seafloor magnetisation patterns, volcanic records, sediment sequences, speleothem records, and have been reported in geodynamo simulations. However, open questions remain concerning the phenomenology and underlying causes of this process. In particular, there is currently no consensus about the temporal scales over which geomagnetic reversals occur. Numerical simulations aimed at understanding Earth's million-year evolution have predicted a time scale on the order of thousands of years. On the other hand, analysis of a lacustrine sequence in the central Italian Apennines suggests that the most recent geomagnetic reversal (the Matuyama-Brunhes) took place in as short as 13 years, requiring VGP latitudinal changes of the order of 10 degrees/yr [Sagnotti, L. et al. (2015). GJI, 204(2), 798-812]. This extremely short decadal time scale challenges our current understanding of the geodynamo and present-day numerical models.

Here we derive fluid flows at the top of Earth's outer core that optimise either the rate of dipole decay or directional changes local to the Italian Apennines, subject to a minimal number of physical ingredients. Specifically, we neglect the internal dynamics and prescribe a total flow kinetic energy that is consistent with observational bounds. Our optimal flows can drive an instantaneous VGP latitudinal change of at most 5 degrees/yr during the Matuyama-Brunhes transition. Extending the methodology to account for the spatio-temporal evolution of the magnetic field, we find that this solution does not drive a global reversal, but only changes that are highly localised around the Mediterranean and West-African regions. Solutions that optimise the rate of dipole decay suggest that full reversal would take at least 380 years.