Paleomagnetic evidence for a reversing dynamo and active plate tectonics by 3.47 Ga

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Plate tectonics on the modern Earth touches virtually every aspect of its surface and interior by governing the planetary heat flux, modulating crustal recycling, and moderating surface temperature, among other effects. The existence of modern-style plate tectonics during the Earth's first ~2 billion years, however, is still an open question. Some theoretical arguments have suggested that a hotter, weaker crust and upper mantle did not provide sufficient driving force to sustain subduction while other studies have reached the opposite conclusion, predicting rapid lateral plate motions and vertical cycling driven by a variety of force balances. I will present our paleomagnetic studies of well-preserved 3.18 to 3.48 Ga volcanic rocks from the Pilbara Craton, Australia. We show that this landmass underwent sustained motion at modern-like velocities of >0.55° per My between 3.35 and 3.18 Ga, while older rocks between 3.48 and 3.46 Ga record an episode of even more rapid motion. Importantly, geometric considerations and contemporaneous paleomagnetic poles from South Africa indicate that these motions involved independently moving plates instead of whole-lithospheric rotations such as true polar wander.

A parallel set of paleomagnetic research has focused on revealing the existence and behavior of the earliest geodynamo, which hold broad implications for the thermal history of the Earth and role of light element exsolution in core evolution. I will first discuss the zircon paleomagnetic record, which, if validated, can potentially record the geodynamo as early as 4.2 Ga. However, our studies have shown that ferromagnetic inclusions in >3.5 Ga zircons are highly susceptible to post-crystallization alteration and, in all samples we have studied to-date, are incapable of retaining a truly ancient record. Instead, I will focus on our work with whole rock samples between 3.48 and 3.25 Ga, which reveal a reversing geodynamo with modern-like dipolar morphology during this time.

Recapitulating these results on both plate tectonics and geodynamo activity in the early to middle Archean, the Earth was, within the inherent limits of paleomagnetic observations, remarkably similar to its present-day state, with only faster-than-typical velocities providing some tantalizing hint of non-uniformitarian behavior.

Millennial scale variations in the geomagnetic field and the core surface flow

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One of the most striking developments in Earth's magnetic field change over the past two centuries is the growth of a region weak field intensity, the so-called South Atlantic Anomaly. It has been suggested that the South Atlantic Anomaly is a recurrent feature, possibly controlled by heat-flux heterogeneities at the core-mantle boundary. Another hypothesis is that the anomaly is linked to an eccentric planetary-scale gyre, revealed in modern core surface flow reconstructions, which has persisted for at least the past 140 years. To investigate the occurrence and longevity of weak field anomalies, such as the South Atlantic Anomaly, and potential relationships to the eccentric planetary gyre, we turn to archaeo-/palaeomagnetic archives providing information on geomagnetic field changes on millennial timescales. A number of recent studies have made use of statistics derived from geodynamo simulations to constrain the flow at the top of the Earth's core. Here we adapt these methods to infer possible core surface flow solutions over the past 9000 years, using archaeomagnetic data. We present new results from this integrated core-field and core-flow modelling approach and discuss them in the context of previous observations of westward drift and recurrent weak field anomalies.

Interactions between Mantle Convection and the Geodynamo: How Variability in Core–Mantle Boundary Heat Flux Affects the Earth's Magnetic Field

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Mantle convection and plate tectonics play an essential role in keeping Earth's surface conditions suitable for life. A key aspect of this process is the extraction of heat from Earth's outer core, influencing the geodynamo that creates the Earth's magnetic field. Because of this interaction, we can relate changes in the paleomagnetic record to the dynamics of the Earth's mantle and core in the past.

In this study, we combine a plate reconstruction, 3-D global mantle convection models, and geodynamo simulations to quantify how mantle heat transport affects Earth's surface magnetic field. To constrain the heat flux across the core–mantle boundary (CMB), we use the geodynamic modeling software ASPECT to create compressible global mantle convection models. These models incorporate a temperature- and pressure-dependent thermal conductivity and density based on a mineral physics database, and they use a plate reconstruction throughout the last 1 billion years—covering more than one supercontinent cycle—to determine the location and convergence rate of subduction zones. When the associated subducted slabs descend to the lowermost mantle, they impact the pattern and amplitude of the CMB heat flux. Depending on the material properties and the adiabatic heat flux out of the core, we estimate that the resulting ratio of peak-to-peak amplitude to average heat flux driving the flow is at least 2, but can easily reach values >30. Our models also show that the distribution of hot and cold structures at the base of the mantle changes throughout the supercontinent cycle in terms of location, shape and number and might have looked very differently in Earth's past.

We select different scenarios of CMB heat flux patterns and amplitudes to apply as boundary conditions in thermally driven numerical geodynamo simulations. To systematically explore the impact of CMB heat flux heterogeneity and to assess how well our simulations reproduce the long-term geomagnetic field behavior, we apply the Quality of Paleomagnetic Modeling criteria. We find that increasing CMB heat flux heterogeneity leads to a more instable and less Earth-like magnetic field. This effect is stronger for heat flux patterns originating from seismic tomography compared to our global mantle convection models, so that the latter models generate a field that is more Earth-like. The effect of changes in CMB heat flux patterns throughout Earth's history is minor compared to changes in the amplitude of the heterogeneity.

Our work shows how integrating multidisciplinary datasets into modeling studies improves our understanding of the mantle's role in regulating the magnetic field throughout Earth's history.

Effect of heterogeneous heat flux at the core-mantle boundary on geomagnetic reversals

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Abstract

Palaeomagnetic evidence shows that the behaviour of the geodynamo has changed during geological times. These behaviour changes are visible through variations in the strength and stability of the magnetic dipole. Variations in the heat flux at the core-mantle boundary (CMB) due to mantle convection have been suggested as one possible mechanism capable of driving such a change of behaviour. Previous studies have notably shown that large-scale heat flux heterogeneities at the CMB can have a large impact on the stability of the magnetic dipole in viscous and moderately viscous dynamo models.

This work aims at acquiring a more complete understanding of how lateral heterogeneities of the CMB heat flux affect the geodynamo while other relevant parameters are pushed to more realistic values. For this purpose, we ran geodynamo simulations with degree 1 and 2 spherical harmonic patterns of heat flux at the CMB. We especially focus on the heat flux distribution between the poles and the equator. We use five different geodynamo models, going from standard numerical dynamos to more extreme parameters by decreasing the Ekman number down to 1e-6 and the magnetic Prandtl number down to 0.2. We separate our five reference dynamo models into two categories: "Strong Field" (SF) for the dynamos that have a ratio of magnetic to kinetic energy larger than 10, and "high Rm" (hRm) dynamos for the dynamos with a magnetic Reynolds number larger than 400.

We show that an equatorial cooling of the core is the most efficient at destabilising the magnetic dipole, while a polar cooling of the core tends to stabilise the dipole. The destabilization is very efficient for high Rm dynamos and occurs for low heterogeneity amplitudes. Heat flux patterns have a more moderate effect on strong field dynamos, with a destabilisation of the dipole only for unrealistically large amplitudes. The different effects of equatorial and polar cooling are explained through the compatibility of convection forced by heat flux heterogeneities with the underlying convection in the core. Polar cooling reinforces westward zonal flow through thermal wind, which stabilises the dipole, while equatorial cooling counteracts this zonal flow, destabilising the dynamo.

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How well do we know the last geomagnetic field reversal?

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The last polarity change of Earth's magnetic field, the Matuyama-Brunhes (MB) reversal, occurred about 780 000 years ago. The polarity time-scale of geomagnetic field reversals throughout Earth's history is fairly well-established from paleomagnetic data and magnetic ocean floor patterns. However, global and regional details of individual reversals are known less well, as paleomagnetic data coverage is limited. Previous global reconstructions of the MB reversal using paleomagnetic data, published over 10 years ago, relied on few records or made strong assumptions about the timing of the event. We have recently developed a new global inverse model of the reversal based on 38 paleomagnetic records with largely independent age control. In addition, we tried to gain a better understanding of the uncertainties of the model and the robustness of geomagnetic field characteristics shown by the model through a comparison to several alternative models with modifications to the underlying dataset. Here, we present and discuss our findings regarding aspects such as duration of the MB reversal, field intensity and dipole moment during the event, the occurrence of a precursor or rebound, the role of dipole and non-dipole field contributions and field morphology.

Geomagnetic jerks as a pulse in flow acceleration

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Secular variation (SV) of the internal geomagnetic field is observed on timescales of millennia to months. The fastest of such variations we observe are so-called geomagnetic jerks – abrupt changes in slope in SV occurring over periods of a few months. Geomagnetic jerks have been deemed spatiotemporally unpredictable, and thus make it difficult to forecast the changes of the magnetic field. Recent results from flow inversions of satellite SV data show that jerks in the equatorial Atlantic (in the CHAMP era) and equatorial Pacific (in the Swarm era) are contemporaneous with localised pulses in the core surface azimuthal flow acceleration.

In order to explore to what extent these pulses could be responsible for the observed equatorial geomagnetic jerks, we create a synthetic acceleration pulse. We use a Fisher–Von Mises probability distribution to define the pulse spatially, and vary its amplitude temporally with a Ricker wavelet. We show that the spherical harmonic series for the poloidal and toroidal acceleration coefficients converge with this spatial probability distribution. We choose the parameters of the Ricker wavelet to match the temporal width of the pulse observed in the Pacific. To recover a dynamic flow, we add normally distributed noise to the toroidal and poloidal coefficients of flow acceleration.

We obtain flow by integrating its acceleration with respect to time, using a snapshot from an inversion of core-surface flow from 2015 as our starting point. We can then get SV from the flow using the diffusionless induction equation, and by assuming a magnetic field structure similar to Earth's, using a snapshot of the CHAOS model. By plotting the expected SV at satellite altitude, we successfully replicate geomagnetic jerks, similar to those observed by Swarm in the Pacific in 2017 and 2020. This pulse-like source of jerks is in agreement with results from numerical dynamo simulations, which suggest that jerks can originate from Alfvén wave packets emitted from the inner-outer core boundary. Our results further suggests that waves propagating along the core-surface are not required for jerks to occur.

Using SOLA for investigating rapid fluctuations of outer core surface flow

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The SOLA (Subtractive Optimally Localised Averages) methodology allows us to create point estimates of radial field SV at any desired location at the CMB by considering a weighting of global satellite measurements. The achieved resolution of the estimates involves a spatio-temporal trade-off. Producing localised-average estimates at the CMB bypasses problems with global downward continuation of magnetic data. We incorporate SOLA outputs (including the localising kernel) into the *pygeodyn* code and produce new core surface flow models. This approach may provide additional information (finer temporal and spatial resolution) on wave-like flow motions at the top of the Earth's core, where these motions are thought to be most prominent. Here we compare rapid core surface motions inverted from SOLA solutions over the period 2000-2024 with reconstructions obtained using conventional field models, e.g. CHAOS-7.

Rapid Changes in Strength and Direction of Earth's Magnetic Field Over the Past 100,000 Years

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Previous studies of rapid geomagnetic changes have highlighted the most extreme changes in direction and field strength found in paleomagnetic field models over the past 100 ky. Here we study distributions of rates of change in both time and space. Field models based on direct observations provide the most accurate values for rates of change, but their short duration precludes a complete description of field behavior. Broader representation is provided by time-varying paleofield models including GGF100k, GGFSS70, LSMOD.2, CALS10k.2, HFM.OL1.A1, and SHAWQ-iron age although variability across models and lack of temporal and spatial resolution of fine scale variations make direct comparisons difficult. For the paleofield we define rapid changes as exceeding the peak overall value of 0.4 °/yr for directional changes and 150 nT/yr for intensities as established by the *gufm1* model spanning 1590-1990 CE. We find that rapid directional changes are associated with low field strength and can spread across all latitudes during such episodes. Distributions of directional rates of change exhibit high skewness for models that include excursions. Rates of change in field intensity exceeding 150 nT/yr arise in brief intervals during the Holocene particularly associated with the strong field Levantine Iron Age Anomaly. Around the Laschamp excursion there are also rare localized occurrences of rapid intensity change. Limitations in current models make it difficult to define absolute rates for past changes, but we see that rapid changes are essential field characteristics not observed in the modern field that should nevertheless be regarded as an essential for Earth-like dynamo simulations.

Detecting waves in core surface flow acceleration derived from 26 years of secular variation

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Fluid motion in the liquid outer core of the Earth produces major parts of the Earth's magnetic field, and its time changes over timescales of one year or longer, the secular variation. Thus, it is possible to infer estimates of the fluid flow from observations of the field and the secular variation.

Data from the satellite missions Swarm, Ørsted, CHAMP, and CryoSat-2 are combined to yield a secular variation dataset spanning almost 26 years, from late 1997 to early 2023. The data are represented by geomagnetic virtual observatory (GVO) time series at 4-month intervals. Over the entire time span, the satellite data are additionally supplemented with ground observatory data.

These secular variation data were inverted for velocity profiles of the fluid flow at the core- mantle boundary assuming it is purely advective, with the main field specified by the CHAOS- 7.16 field model. The inversion is regularized both in time and in space: In time, the difference in velocity between individual epochs, that is, the acceleration, was minimized. In space, small- scale velocity structures are penalized by using the "strong norm".

From the obtained velocities, flow acceleration is calculated by taking the first differences of the velocities at successive epochs. Time-longitude diagrams show sloping features in the azimuthal acceleration at low latitudes, interpreted as signatures of propagating waves. Waves propagating both eastwards and westwards were observed, with propagation velocities of approximately 1700 km/yr which is in agreement with previous inferences of fast core waves. The linear best-fit to the acceleration data was removed to detrend in time prior to power spectral density (PSD) analysis. PSD plots additionally reveal that there is a higher energy content in the westward propagating waves than in those travelling eastwards. The energy is concentrated in modes with periods of 6-7 years, and wavenumbers -5, -2 and 2.

Interannual Magneto-Coriolis modes and their sensitivity on the magnetic field within the Earth's core

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Linear modes for which the Coriolis acceleration is almost entirely in balance with the Lorentz force are called Magneto-Coriolis (MC) modes. These MC modes are thought to exist in Earth's liquid outer core and could therefore contribute to the variations observed in Earth's magnetic field (Hide, 1966; Malkus, 1967). More recently, it has been suggested that quasi-geostrophic MC modes can reach interannual periods, observable from satellite observation (Gerick et al. 2021; Gillet et al. 2022). We study the effect of a range of both axisymmetric and non-axisymmetric background magnetic fields on the MC modes. We filter the spectrum of modes for those that are (i) in principle observable, (ii) those which match a proxy for interannual geomagnetic signal over 1999-2023, and (iii) those which align with core-flows based on recent geomagnetic data. We found that the background field plays a crucial role in determining the structure of the modes. In particular, we found no examples of axisymmetric background fields that support modes consistent with recent geomagnetic changes, but that some non-axisymmetric background fields do support geomagnetically consistent modes.

Mantle-driven north–south dichotomy in geomagnetic polar minima

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The geomagnetic field on the core-mantle boundary (CMB) is characterized by weak or even reversed field in the polar regions and intense flux patches at the edges of the intersection of the inner-core tangent cylinder (TC) with the CMB. This high-latitude field morphology is in agreement with thermal wind theory inside the TC in which polar upwellings disperse magnetic field lines. Furthermore, inferences from the geomagnetic secular variation hint to the presence of a westward jet at high latitudes of the northern hemisphere, also in agreement with the TC dynamical theory, but not in the southern hemisphere. Here we study polar minima in an ensemble of geomagnetic field models that span the historical era and in a set of numerical dynamo simulations with a heterogeneous outer boundary heat flux inferred from a tomographic model of lowermost mantle seismic anomalies. We quantified the polar minima using a previously-proposed expression as well as a new measure which may better capture this phenomenon. We found that throughout the historical era the geomagnetic field is characterized by stronger polar minima and more reversed flux inside the northern TC than inside the southern TC. Likewise, almost all dynamo models exhibit on average stronger polar minima in the northern hemisphere. This north/south dichotomy is explained in terms of the pattern of lowermost mantle seismic anomalies, in particular the southern centers of the two Large Low Shear-wave Velocity Provinces below Africa and the Pacific. We also investigated polar minima in planets where magnetic field models at the top of the dynamo region are available. We speculate that the absence of polar minima in Mercury's field is likely due to the thick stratified layer at the top of its core, while the strong polar minima in Jupiter's field might have a different dynamical origin than the geomagnetic polar minima.

Common features and characteristics of archeo- and paleomagnetic field models

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Abstract

Archeo- and paleomagnetic field models show a wide range of temporal variability and of spatial content. While the temporal variability may reflect true geomagnetic field variation, the different spatial content of individual models could be explained by different modeling strategies and data sources, but most likely by data uncertainties. To overcome these problems, we derive a time-dependent mean, median and robust Huber models over the last 100 kyrs from a large suite of different archeo- and paleomagnetic field models (AFM-M, AFM-Md and AFM-H, respectively). These models allow to identify common features of the past field and to qualitatively assess the robustness and the significance of these spatial features throughout time. We evaluate each model over the entire period and compute structural criteria that quantify axial dipole dominance, equatorial symmetry, zonality and radial flux concentration at the CMB. These criteria are used to quantify the Earth-likeness of numerical dynamo simulations. Over 100 kyrs, the criteria show larger fluctuations than previously assumed, which implicates a wider range of numerical dynamo simulations to be considered as Earth-like.

Regional outer core kinematics from the time dependence of intense geomagnetic flux patches

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Abstract

Observations of the geomagnetic field by surface observatories and dedicated satellite missions such as the Swarm constellation provide constraints on the dynamics in Earth's outer core. In particular, global core flow models estimated by inversion of the radial magnetic induction equation provide an image of the circulation of the electrically conductive fluid at the top of the core. However, in these models the poloidal flow is much less robust than the toroidal core flow. Here, we infer regional outer core kinematics from the temporal variability of high-latitude intense geomagnetic flux patches. We develop an algorithm to fit anisotropic 2D-Gaussians to the shape of those flux patches in order to infer their area, amplitude and level of anisotropy. The temporal variabilities of these properties are used to quantify contraction, expansion, amplification, weakening and horizontal shear. Comparisons with idealized kinematic scenarios based on synthetic field and flow models allow to infer regional outer core kinematics. We found that some geomagnetic flux patches exhibit expansion and weakening

corresponding to fluid upwellings, whereas other patches exhibit contraction and intensification corresponding to downwellings. In both cases the patches' area and amplitude relations follow hyperbolic curves. Our results show that the geomagnetic flux patches are affected by upwelling more often than by downwelling during the historical period. Equatorially symmetric poloidal flow prior to ≈ 1910 is inferred for the western intense patches. Kinematic scenarios where the field and flow structures centers coincide failed to reproduce the geomagnetic flux patches behavior. We recover the flux concentration efficiency of intense geomagnetic flux patches with an upwelling that resides two times its radius size away from the center of the flux patch. We also found a significant level of anisotropy over long periods for the historical geomagnetic flux patches. Anisotropic magnetic flux patches that are elongated in the direction of the shear flow may explain the east-west oriented present-day field at high latitudes of the southern Hemisphere. Overall, stretching effects at the top of the core can be deduced from our analysis of regional SV and allow further inferences on the poloidal part of the core flow.

Using stochastic models to study variability in Earth's magnetic field

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Abstract

The fluid flow in the Earth's outer core presents rich dynamics, from the propagation of magnetohydrodynamic waves on decadal timescales to fluid patterns able to sustain the geodynamo over millions of years. On these long timescales, one of the most striking features of the magnetic field are its reversals. Given the erratic pattern of magnetic reversals seen in the paleomagnetic record, as well as the turbulent nature of core flows, it appears justifiable to use stochastic models for studying the evolution of Earth's magnetic field over long timescales.

While a stochastic treatment cannot tell us about the deterministic evolution of the magnetic field, it provides probabilistic information. Since our knowledge of geomagnetic reversals is at best probabilistic, this seems to be a promising way of studying this curious behaviour.

We consider a stochastic model for magnetic field generation based on the kinematic dynamo equation, where the fluid velocity acts as a random forcing obeying Gaussian statistics. Making use of techniques borrowed from field theory, we compute the magnetic field's variance, and present a framework that allows us to establish how statistical properties of the velocity distribution affect the probability of magnetic reversals in this simplified system.

Keywords: Geodynamo, Statistical dynamos

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What is up with the length of day? An interruption in the six-year oscillation

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Intradecadal variations in the length-of-day (ΔLOD) can reveal changes in angular velocity interpreted as due to Earth's core. Previous studies have identified periodic oscillations of around 6 and 8 years. To complement widely used Fourier methods, we investigate the ΔLOD record from 1962—2023 in the time domain, seeking smooth variations using cubic splines.

We analyse in several ways. A penalised least-squares spline fit allows isolation of coherent variations from analysing the first and second derivatives. Alternatively, a smooth (but not band limited) curve fit with least-squares splines allows removal of the long-term behaviour of ΔLOD. We then fit the residual with a pure cosine-wave of varying period but examine the data fits carefully in case the signal is non-stationary (for example from impulsive forcing).

All approaches show clear evidence of signals with periods around 6—and in the case for the time derivatives—8 years. We find that the pure 6-year oscillation breaks down in 2010, with a one-off peak to peak variation of 4 years. After 2014, the variation is once again consistent overall with an approximate 6-year oscillation. Such a discontinuous, non-stationary effect is not well-characterised by frequency-domain based methods.

Seeking to understand this brief interruption of the 6-year oscillation, we create a ΔLOD series from lunar occultation data extending back to 1800, and find it suitable to repeat our spline-based analysis from 1900 onwards. From this, we find the 6-year oscillation stable throughout the entire 20th century, with the exception of 1906–1910, where we observe a similar interruption of the 6-year variation into a 4-year oscillation. The origin of this interruption is unknown, but similar behaviour is recorded in the geomagnetic field, and core surface flow studies. This points towards a source mechanism located in the outer core.

Regionally-triggered geomagnetic reversals

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Abstract

Systematic studies of numerical dynamo simulations reveal that the transition from dipole-dominated non-reversing fields to models that exhibit reversals occurs when inertial effects become strong enough. However, the inertial force is expected to play a secondary role in the force balance in Earth's outer core. Here we show that reversals in numerical dynamo models with heterogeneous outer boundary heat flux inferred from lower mantle seismic anomalies appear when the amplitude of heat flux heterogeneity is increased. The reversals are triggered at regions of large heat flux in which strong small-scale inertial forces are produced, while elsewhere inertial forces are substantially smaller. When the amplitude of heat flux heterogeneity is further increased so that in some regions sub-adiabatic conditions are reached, regional skin effects suppress small-scale magnetic fields and the tendency to reverse decreases. Our results reconcile the need for inertia for reversals with the theoretical expectation that the inertial force remains secondary in the force balance. Moreover, our results highlight a non-trivial non-monotonic behavior of the geodynamo in response to changes in the amplitude of the core-mantle boundary heat flux heterogeneity.

Global characteristics of geomagnetic field reversals from data based spherical harmonic models

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The geomagnetic field has changed its polarity several times throughout the Earth's history. When the field geometry significantly departs from the axial dipole and interchanges the position of its poles, it is called geomagnetic reversal. Excursions are comparatively brief periods of transitional or reversed field that do not lead to lasting polarity changes.

The last two full field reversal occurred ~2.6 Ma and ~780 ka ago -Gauss-Matuyama (GM) and Matuyama-Bruhnes (MB) reversal. Many short term polarity changes happened in between, e.g. the Laschamps(~41 Ka), Mono Lake/ Aukland (~33 Ka), etc. The global reconstruction of transitional events by models based on spherical harmonic basis functions gives us the opportunity to study the behavior of geomagnetic field through the field transitions and thereby understand the geodynamo better. In the present study, we will derive and analyze global quantities such as surface field intensity, dipole moment and virtual geomagnetic pole paths (VGP) using the models like LSMOD.2 (Laschamps excursion) and GGFMB (MB reversal) to answer open questions such as whether there is a fundamental difference between excursions and reversals. The first step of the study is to examine the time series of dipole moment and the paleo-secular variation (PSV) index (a dimensionless index which represents deviation from a geocentric axial dipole field) of different models over a short term and a long term polarity transition period to compare the rate of decay and growth in their plots.

The broader aim of the study is to compare the characteristics of several events. To this aim, we will also derive the first global model of the GM reversal in this project and will use it in combination with the existing models of the MB reversal and recent excursions to investigate the similarities and differences among the events.

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Assessing How Core-Mantle Boundary Properties Influence Geomagnetic Reversal Frequency

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Over the past decade, advancements in data assimilation techniques combined with the rapid increase in computational power have allowed for increasingly realistic dynamo simulations. One of the key parameters controlling the dynamics of the magnetic field is the amount of heat loss through the core-mantle-boundary (CMB), highlighting the crucial role of the lower mantle in the dynamo processes. Previous work suggest that variations at the lower mantle may explain the observed changes in reversal frequency on time scales of some 10 million years.

To study the effect of the mantle on reversals, we use the numerical code MagIC, simulating the dynamo process over geological timescales. The long required simulation time forces us to use a relatively large Ekman number of $E = 3 \cdot 10^{-4}$. Following (Kutzner and Christensen, 2004), we explore the impact of several fundamental heat-flux pattern (spherical harmonic degree Y_{10}, Y_{20}, Y_{22} ...) and amplitudes imposed at the outer boundary. We also vary the degree of compositional to thermal driving, expecting a smaller impact of the pattern for growing compositional contribution.

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Toy model for migrating magnetic flux patches across the core-mantle boundary

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Earth's axial dipole moment (ADM) varies across different time scales, with the largest rates of change occurring on centennial to multi-millennial time scales. One proposed mechanism for dipole growth and decay is meridional flux advection, that is magnetic flux patches migrating toward or away from the poles. In the present field, a planetary-scale gyre transports normal polarity magnetic flux toward the equator and reverse polarity flux (e.g., South Atlantic Anomaly) toward the south pole, which can account for the recent decay in the dipole field. In contrast to this the Levantine Iron Age Anomaly marks a strong regional increase in the paleofield intensity around 3000 BP. Some studies attribute this to a spike at the core-mantle boundary (CMB) that migrates northwest, therefore contributing to the growth of the dipole field strength in the third millennium BP. In this study, we create a toy model using a spherical triangle tessellation basis to create a spike at the CMB and force the spike to migrate in an anti-cyclonic motion (Fig. 1(a-f)). We show the variations of the axial dipole moment (Fig. 1(g)), field directions, and strength as spikes migrate poleward or equatorward. This toy model will be used to help us assess whether the planetary gyre is a persistent feature in the magnetic field that can be detected with a limited number of paleomagnetic records from sediment cores and archeological artifacts.

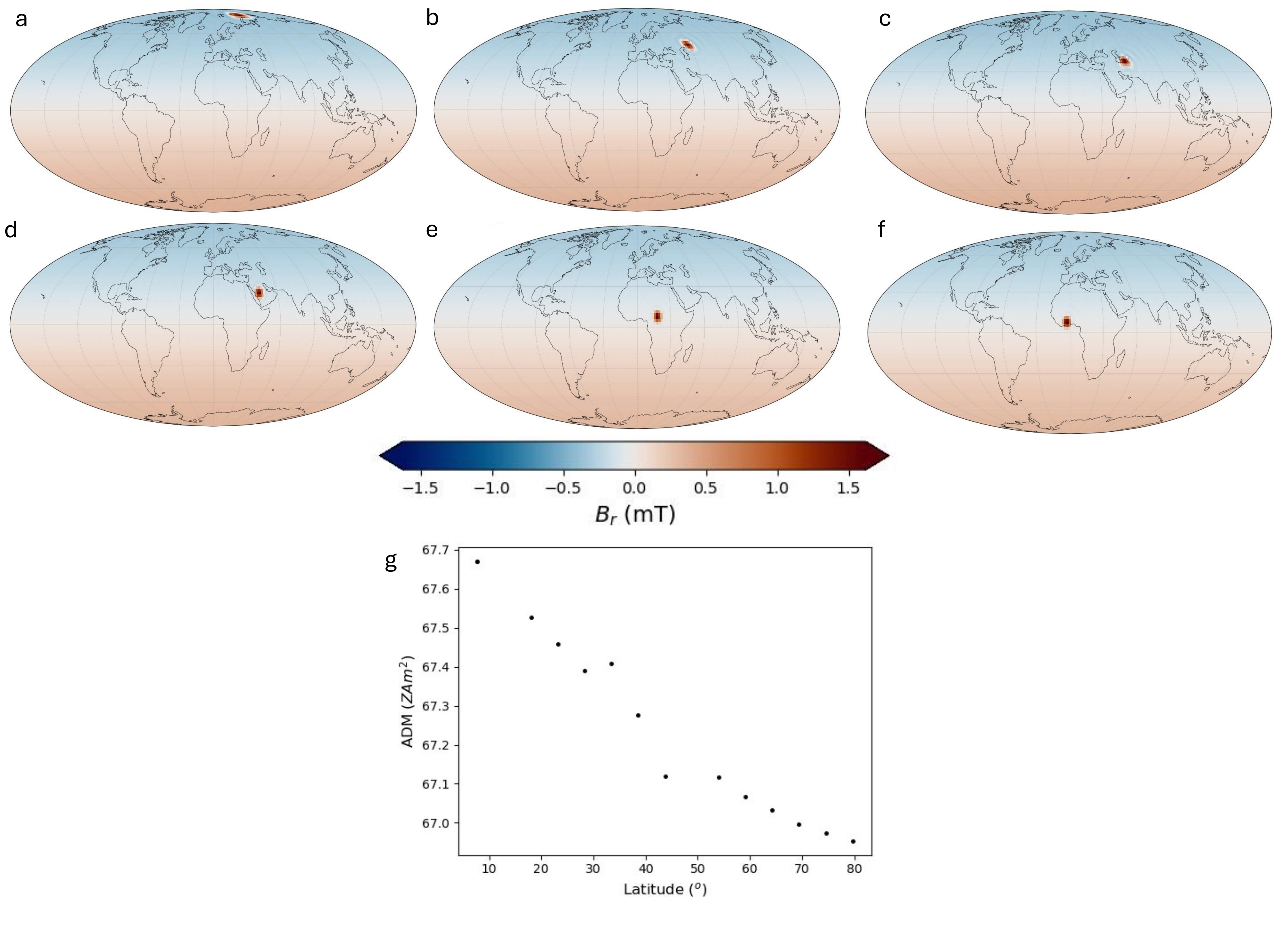

Figure 1: Radial magnetic field at the core-mantle boundary (a-f) with a background dipolar field ($g_1^0 = -0.026$ mT) and a migrating reverse flux spike (2 mT). Axial dipole moment as a function of the spike's latitude (g).

Weather at the core: Defining and categorizing geomagnetic excursions

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Paleomagnetic records provide us with information about the extreme geomagnetic events known as excursions and reversals, but the sparsity of available data limits detailed knowledge of the process and timing. To date there are no agreed on criteria for categorizing such events in terms of severity or longevity. In an analogy to categorizing storms in weather systems, we invoke the magnitude of the global paleosecular variation index P_i to define the severity of the magnetic field state, ranging in level from 0 to 3, and defined by instantaneous values of P_i with level 0 being normal ($P_i < 0.5$) to extreme ($P_i \geq 15$). We denote the time of entry to an excursional (or reversal) event by when P_i first exceeds 0.5, and evaluate its duration by the time at which P_i first returns below its average or median value, termed the end of event threshold. We categorize each excursional event according to the peak level of P_i during the entire event, with a range from Cat-1 to Cat-3. We explore an extended numerical dynamo simulation containing more than 1200 events and find that Cat-1 events are the most frequent (72%), but only rarely lead to actual field reversals where the axial dipole, g_1^0, has reversed sign at the end of the event. Cat-2 account for about 20% of events, with 34% of those leading to actual reversals, while Cat-3 events arise about 8% of the time but are more likely to produce reversals (43%). Higher category events take as much as 10 times longer than Cat-1 events. Two paleomagnetic field models separately cover the Laschamp excursion and Matuyama-Brunhes (M-B) reversal which are Cat-2 events with respective durations of 3.6 and 27.4 ky. It seems likely that Cat-2 may be an underestimate for M-B due to limitations in the paleomagnetic records.

Core surface flow ingredients: sensitivity to geodynamo priors and geomagnetic secular variation data

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High quality continuous satellite magnetic data gives unprecedented insights into core surface motions but the inversion process remains under-determined, thus requiring additional information. We make use of the *pygeodyn* inversion tool, in which the core surface dynamics is forecasted with stochastic equations anchored to prior information from a geodynamo free run. However, there is no clear overview of the relative importance of the different 'ingredients' entering in the core flow inversion process, or the robustness of the inferred flow features. We document the sensitivity to three factors: (1) choice of geodynamo prior, (2) choice of geomagnetic field model, and (3) choice of maximum secular variation spherical harmonic degree. We analyse the influence of six dynamo priors by varying the input parameters towards Earth-like values, or changing the conditions (isotropic or not, stratified or not), and the torques at play.

We quantitatively show that over the satellite era, changing the prior has a greater impact on the core surface flow than the choice of magnetic field model used as observations. This difference becomes less pronounced in the past due to the data quality decreasing and the field models showing more divergence. Furthermore, we find a larger sensitivity for instantaneous flow models than for their transient component. Transient flow motions appear very coherent for all considered dynamo priors and field models. The recovery from satellite measurements of subdecadal wave dynamics and of a growing eastward motion under the Pacific are robust and appear data driven. Finally, we quantify the efficiency of core flows for generating magnetic variations as a function of frequency. Normalized to their magnitude, rapid changes generate relatively more magnetic signal than slow variations. This is interpreted as the signature of a slow core dynamics tending towards a Ferraro's state: towards long periods, a larger part of core surface motions enters the null-space of the core flow inverse problem.

Insights into the last 100 ky of geomagnetic field variability using numerical dynamo simulations

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Recent observational models covering the last 100ky of the geomagnetic field have identified features not captured in the modern day record, which have to yet be directly compared with numerical dynamo simulations. We will present results from a new suite of dynamo simulations with an Earth-like magnetic Reynolds number and a force balance that is consistent with the expected regime of the geodynamo, allowing comparison of simulated data and observational models. We find that such simulations are able to simultaneously reproduce the observed extreme rates of change in intensity and direction as well as the general amplitude of field variability over the last 100 ky. We use the paleosecular variation (PSV) index to identify a broad spectrum of polarity excursions and show that the PSV index is closely linked to the dipolarity of the simulation. Simulated excursional events are mostly associated with a decrease in the axial dipole moment with generally modest changes in dipole tilt. The excursions range from global events characterised by a reduction in the field contribution from solely the axial dipole component and a decrease in mean VDM in the manner of the Laschamp excursion, to localised events with anomalous activity in small regions reminiscent of the Mono Lake/Auckland excursion.

Title: Local Estimation of the Flow at the top of the Earth's Liquid Core

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The Earth's geomagnetic field arises from the constant motion of the fluid outer core. By assuming that these motions are advection-dominated, rather than diffusion, one can relate this motion at the core surface to the secular variation of the geomagnetic field, providing an observational approach to understanding the motions in the deep earth. Existing methods predominantly employ global inversions, assuming large-scale solutions where all observed secular variations are attributed to the flow. In contrast, this work introduces a novel technique based on machine learning, specifically Physics-Informed Neural Networks, to perform local flow inversions. Our approach incorporates a loss function comprising of both data loss and Physics-based partial differential equations (PDEs) loss, in which different flow assumptions can be swapped in and out when needed. This poster presents the set-up, underlying assumptions, and preliminary results of this methodology using Tangentially Geostrophic flow constraints. Furthermore, we discuss the technical and scientific next steps to advance this method as a powerful tool in understanding the dynamics of the Earth's core.

Evolution of the oxygen level on Earth's surface mirrors that of the geomagnetic field since late Paleozoic

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Earth is currently the only known rocky planet to support complex life forms, and to have possessed a strong magnetic field for much of its history, prompting a long-standing conjecture that the magnetic field is important, or even necessary, to Earth's habitability over geological time scales. We search for possible observational evidence by examining evolutions of the virtual geomagnetic axial dipole moment (VGADM) from paleomagnetic records, and of the atmospheric oxygen level derived from a variety of proxies over the past 540 million years. We find that both exhibit a strong linearly increasing trend, superimposed by a strong surge in magnitude between 330 to 220 million years ago. Our time series analysis and statistical tests show that both are highly correlated, with the maximum correlation reached when there is no time lag between the two series. This correlation suggests a direct connection between geophysical processes in the deep interior, Earth's atmospheric redox budget, and surface biosphere. Further investigations are necessary to understand possible mechanisms responsible for the observed correlations.