Jour. Geol. Soc. India (2022) 98:1629-1632
https://doi.org/10.1007/s12594-022-2230-8

EDITORIAL

# Geomagnetic Field Polarity Changes

Monika Korte
Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
***E-mail:*** *monika@gfz-potsdam.de*

*Received: 25 July 2022 / Revised form Accepted: 17 August 2022*


The Earth's magnetic field, or geomagnetic field, forms the magnetosphere around Earth, which shields our habitat from cosmic radiation and solar wind. It is generated by dynamic processes in Earth's fluid outer core and changes constantly. These changes are slow on human timescales, but can be drastic on geological scales: over Earth's history, the geomagnetic field has changed its polarity multiple times. While the occurrence of such events is firmly established, the underlying processes in Earth's core and potential consequences for our habitat are not well understood.

**Observations**

The fact that the geomagnetic field reverses polarity is documented in various paleomagnetic records, that are measured on different materials in paleomagnetic laboratories. Transitional and opposite field directions are found both in lava flow samples of different ages as well as time series from sedimentary drill cores. The long-term polarity time scale is also supported by the pattern of stripes of opposite magnetic polarity found at the sea floor on both sides of mid-ocean ridges (see, e.g., Gee and Kent, 2015).

Time intervals of geomagnetic polarity changes are not only characterized by extreme directional field variations, that vary substantially among different regions, but generally have low to very low magnetic intensities. Two varieties of polarity changes are traditionally distinguished: full polarity reversals and so-called excursions. During reversals the field changes polarity globally and remains in stable, but opposite polarity before and after the event for some time, typically at least several thousand years. Excursions, on the other hand, are comparatively brief deviations from stable field polarity, where reverse field directions are found regionally or globally (see Laj and Channell, 2015). It is yet unclear whether excursions can be seen as aborted reversals caused by the same mechanism or whether they have different causes.

The reversal frequency has been highly variable over Earth's history, e.g. with a stable interval of more than 30 Myr during the Cretaceous or high reversal rates between 11 and 12 Myr ago (Fig. 1). Outside of a few extremely long stable field intervals, the field has on average fully reversed every 250,000 to 400,000 years, depending on the considered interval (see e.g. Gee and Kent, 2015). The last full reversal occurred ~780, 000 years ago and is called Matuyama-Brunhes reversal, as the stable polarity intervals (chrons) before and after are named Matuyama and Brunhes chron after a Japanese and French geophysicist, respectively. The last field excursion is called Laschamps excursion after the location in France where it was first found in lava flows, and happened ~41,000 years ago. Several excursions occurred during the Brunhes chron, i.e. over the past ~780,000 years. An exact number cannot be given because it is often not clear whether signatures detected in individual or few and regionally confined data records should be considered as an excursion. Channell et al. (2020) and Panovska et al. (2019) describe details of several excursions over the Quaternary and the past 100,000 years, respectively. Many of the excursions have not been found globally in all locations where data for that time interval exist. Although this seems to suggest that excursions can occur regionally, it has to be noted that sediments, which are a main source of information about excursions as volcanic data are sparse, might fail to record excursion signals. Sediment paleomagnetic records inevitably are smoothed representations of the geomagnetic field variations, and fast changes cannot be recovered in particular if the sedimentation rate is low (see, e.g., Roberts, 2008).

Excursions traditionally have been defined based on directional field behavior. Virtual geomagnetic poles (VGPs) are commonly used in paleomagnetism to describe and compare field directions. VGPs are calculated from declination (deviation of magnetic from geographic north) and inclination (angle at which magnetic field lines penetrate Earth's surface) measurements and give the location where the magnetic pole would be if the field was a dipole centered in the middle of the Earth and tilted with respect to the rotation axis. As the geomagnetic field contains non-dipolar, smaller scale contributions, the scatter of VGPs obtained from different locations at the same time gives an indication how strongly the

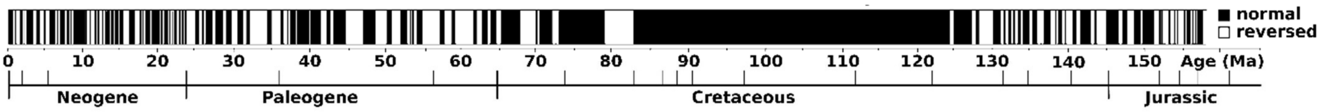


**Fig.1.** The geomagnetic polarity time scale (modified from Lowrie, 1997). Black indicates times of normal polarity, white of reverse polarity.

dipole dominates; larger VGP scatter indicates stronger influence of non-dipole field contributions. Common definitions of excursions or transitional field behaviour are deviations of the VGP by more than 45° from the geographic pole or deviation of VGPs from the normal range of secular field variation (see, e.g., Roberts, 2008). Given that low field intensity seems to play a relevant role in the occurrence of transitional field (Roberts, 2008), it seems preferable to involve this field component in the characterization of transitional field, excursions and reversals. Panovska and Constable (2017) suggested a paleosecular variation index to describe the activity of the magnetic core field, that takes VGP deviation from the geographic pole and field intensity normalized by the present-day field into account. The smaller the dimensionless index, the more dipole dominated and stable is the field, with a threshold of 0.5 for transitional field configuration.

**The Global View**

Two different main mechanisms might cause geomagnetic polarity changes: either a rotation of the dipole dominated field, or a decay and recovery of the axial dipole contribution, in opposite direction for a full reversal. For excursions, a third mechanism might be a temporary strong increase of non-dipole field contributions, which might also explain regional excursions if the underlying perturbation in Earth's outer core is not global (Roberts, 2008).

Ideally, we would like to observe the full global details of polarity reversals in order to understand the mechanism, but data records only come from some individual locations. A traditional way of trying to get a better idea of the global processes is the study of VGP distributions and VGP paths. Longitudinal preferences of transitional VGP paths during excursions and reversals (see Laj and Channell, 2015; Gubbins and Love, 1998) might be seen as indicators of a relatively simple geometry of the transition process, such as mainly a rotating dipole. However, some data clearly deviate from the preferred paths.

As the number of published records is growing, the global reconstruction of polarity reversals by models based on spherical harmonic basis functions, similar to the present day International Geomagnetic Reference Field (IGRF, Alken et al., 2021), becomes feasible and has been attempted since the mid-1990ies. Recently, new models spanning the Laschamps and Mono Lake / Auckland excursion (Brown et al., 2018; Korte et al., 2019) and additionally the Norwegian-Greenland Sea (~60-80 ka, Panovska et al., 2021) and Post Blake (~90 -100 ka, see Panovska et al., 2019) excursions have been derived. All these models suggest that the driving mechanism is mainly a decay and recovery of the axial dipole field contribution, while smaller (non-dipole) scale secular variation continues as during stable periods (Fig. 2). These models, as well as simple simulations of excursions in spherical harmonic models (Valet and Plenier, 2008, Brown and Korte, 2016) indicate that such a mechanism cannot only explain global excursions, when the axial dipole drops to nearly zero or below, but also leads to only regionally observable excursions when the axial dipole drops not quite as low. A similar result of strongly dropping dipole energy during the Matuyama-Brunhes reversal (though accompanied by an increase of non-dipole field) and results from numerical dynamo simulations (Wicht and Meduri, 2016) further support the hypothesis that regional and global excursions and full reversals are all part of a wide range of geomagnetic axial dipole variations. It should be noted again that if individual sediment records fail to record an excursion, this information would also lack in global field reconstructions. However, if axial dipole decay is the main driver of field transitions, global reconstructions will still recover general properties of excursions faithfully if sufficient data have the low intensity values to resolve the global dipole drop.

When the axial dipole drops with respect to the non-dipole field contributions, the field becomes complex with multiple poles as shown in the example for the Laschamps excursion in Fig. 2. Models suggest that in the middle of this excursion, found all over the globe, the field intensity was very low globally (Fig. 2) and the axial dipole strength dropped to around zero and probably even reversed slightly before recovering. Some indications of preferred transitional VGP longitudes are also found in global reconstructions (Korte et al., 2019; Panovska et al., 2019). The field geometry during the transition and thus the VGP positions might be influenced by lateral heat flow heterogeneities through the core-mantle boundary, probably associated with zones of low seismic velocity (large low velocity provinces, LLVPs) found by seismological observations and clearly seen in seismic tomography models (e.g., Garnero et al., 2016).

A wide range of estimates has been given for the duration of polarity field changes (see, e.g., Roberts, 2008; Glatzaier et al., 2015). Some of them are not as incompatible as they might seem from individual records when a global view is taken. Particularly fast estimates reporting durations in the order of a few centuries or even less come from individual directional records (e.g., Sagnotti et al., **2016**), while the longest estimates > 10 000 years come from global analyses (e.g., Singer et al., 2019). Regional differences of excursion duration, in particular if only directional variations are considered, can be readily understood from the proposed mechanism of axial dipole

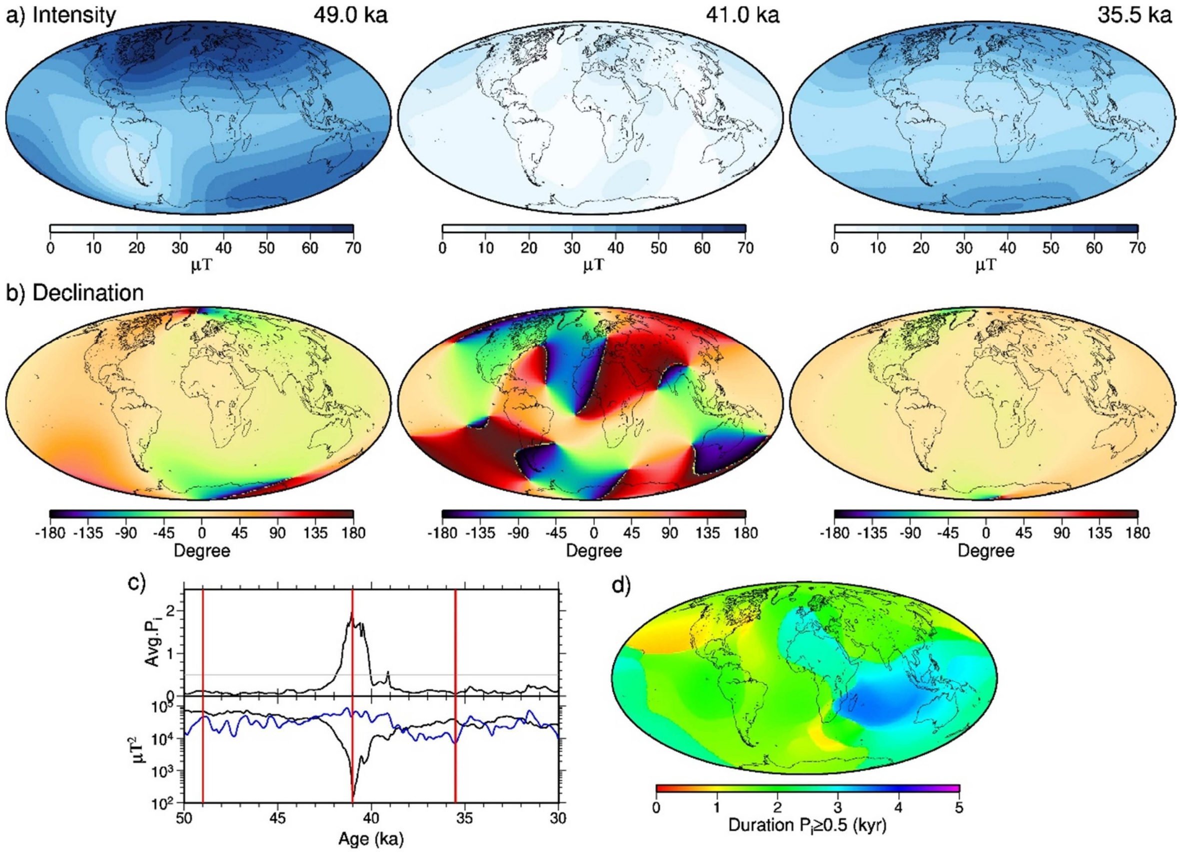


**Fig.2.** Field intensity (a) and declination (b) before (49 ka), during (41 ka) and after (35.5 ka) the Laschamps excursion. In the middle of the excursion the intensity is globally low with multiple poles, indicated by large declination values. Note an intensity minimum resembling the present-day South Atlantic anomaly at 49 ka, long before the excursion. Panel c) gives the globally averaged paleosecular variation index Pi with 0.5 threshold indicated by grey line (top panel), and the power in dipole (black) and non-dipole (blue) field at the core-mantle boundary (bottom panel). The dipole power drops significantly, while the non-dipole power varies nearly in its general range during the excursion. The regional duration of the Laschamps excursion according to the Pi index exceeding the threshold of 0.5 (d) varies from <1 to >4 kyrs.

decay. When the field is not dipole-dominated at Earth's surface any more, the field directions can change quickly. Korte et al. (2019) found regional durations for the Laschamps excursion, based on their global field reconstruction and the paleosecular variation index, between less than 1 and nearly 4 kyrs (Fig. 2), while the globally averaged duration came out as 1.8 kyr. Full polarity reversals seem to take notably longer than excursions. A recent estimate by Singer et al. (2019) based on a good global data distribution from volcanic, sediment and ice core records gave a duration of 22 ka for a complex process that includes a precursor (or preceding excursion).

## Consequences of Polarity Reversals

It is unclear what, if any, consequences past geomagnetic polarity reversals had on environment, climate and/or life on Earth. Glassmeier and Vogt (2010) provide a comprehensive review of studies of potential consequences, including changes to the magnetosphere and shielding against solar wind, potential influences of an increased influx of energetic particles into the atmosphere, radiation enhancements and potential correlations of geomagnetic reversals and biological mass extinctions. They conclude that a simple direct link to environmental or biogenic changes cannot be expected, but that the complex and non-linear chains of processes that might be caused by the strongly enhanced energetic particles entering the atmosphere during a polarity transition are unclear and should be studied in interdisciplinary approaches. This has recently been done by Cooper et al. (2021), who conclude that the Laschamps excursion caused major environmental changes associated with extinction events. However, the study is strongly disputed (Picin et al., 2021, Hawks, 2021) and it should also be noted that the geomagnetic field strength variations considered there only come from one local record, ignoring regional differences or the fact that one record does not represent a global average.

What seems clear is that direct impacts of enhanced influx of energetic particles or radiation to the biosphere at Earth's surface are unlikely because the atmosphere remains an effective shield. However, the shielding effect of the magnetosphere for our modern technology against harmful space weather influences would likely be clearly diminished during a geomagnetic polarity transition.

## Outlook

Both the current decrease of the geomagnetic dipole strength, that has been ongoing at least since the beginning of direct magnetic field observations in historical times, and the evolution of a region of unusually weak geomagnetic field intensity known as the South Atlantic Anomaly have been interpreted as indications for the beginning of the next geomagnetic polarity transition (see, e.g., Olson, 2006; Laj and Kissel, 2015; Pávon-Carrasco and De Santis, 2016). However, the present dipole field strength seems to lie well above the paleomagnetic average, and a probabilistic model of dipole fluctuations suggests that an imminent reversal is unlikely (Buffet and Davis, 2018). The South Atlantic Anomaly seems to have been a recurring feature in the paleomagnetic field, but previous occurrences do not directly precede field excursions (Fig. 2, Brown et al., 2018, Panovska et al., 2019).

Even though the next polarity field change will definitely not occur within our or the next generation's life time (as the physical processes in the core at least require a few hundred years from now), understanding the causes and consequences of such events is relevant to predict the future geomagnetic field evolution and its shielding for our habitat. The most important ingredient is more high quality paleomagnetic data with accurate age control from all areas that currently are devoid of it, in particular large parts of the southern hemisphere. Moreover, it takes improved data-based reconstructions of several extreme magnetic field changes and comparisons to results from numerical dynamo simulations to fully understand the underlying mechanisms and potentially better predict future geomagnetic field changes by data assimilation methods. Further collaborations with the magnetospheric physics, atmospheric chemistry and climate modelling communities are required to better understand environmental and societal consequences of geomagnetic polarity changes.

## References


Alken, P., Thébault, E., Beggan, C. D., Amit, H., Aubert, J., Baerenzung, J., ... and Zhou, B. (2021) International geomagnetic reference field: the thirteenth generation. Earth, Planets and Space, v.73(1), pp.1-25.

Brown, M.C. and Korte, M. (2016) A simple model for geomagnetic field excursions and inferences for palaeomagnetic observations. Phys. Earth Planet. Inter., v.254, pp.1-11.

Brown, M., Korte, M., Holme, R., Wardinski, I. and Gunnarson, S. (2018) Earth's magnetic field is probably not reversing. Proc. Natl. Acad. Sci., v.115(20), pp.5111-5116.

Buffett, B. and Davis, W. (2018) A probabilistic assessment of the next geomagnetic reversal. Geophys. Res. Lett., v.45(4), pp.1845-1850.

Channell, J.E., Singer, B.S. and Jicha, B.R. (2020) Timing of Quaternary geomagnetic reversals and excursions in volcanic and sedimentary archives. Quaternary Sci. Rev., v.228, pp.106114.

Cooper, A., Turney, C. S., Palmer, J., Hogg, A., McGlone, M., Wilmshurst, J., ... and Zech, R. (2021) A global environmental crisis 42,000 years ago. Science, v.371(6531), pp.811-818.

Gee, J.S. and Kent, D.V. (2015) Source of oceanic magnetic anomalies and the geomagnetic polarity time scale. *In:* G. Schubert (Ed.), Treatise on Geophysics, Second Edition, no.8.11, pp.419-460.

Garnero, E.J., McNamara, A.K. and Shim, S.H. (2016) Continent-sized anomalous zones with low seismic velocity at the base of Earth's mantle. Nature Geoscience, v.9(7), pp.481-489.

Glassmeier, K.H. and Vogt, J. (2010) Magnetic polarity transitions and biospheric effects. Space Sci. Rev., v.155(1), pp.387-410.

Glatzaier, G.A., Coe, R.S. and Schubert, G. (2015) Magnetic polarity reversals in the core.*In:* G. Schubert (Ed.), Treatise on geophysics, Second Edition, no.8.11, pp.279-295.

Gubbins, D. and Love, J.J. (1998) Preferred VGP paths during geomagnetic polarity reversals: Symmetry considerations. Geophys. Res. Lett., v.25(7), pp.1079-1082.

Hawks, J. (2021) Comment on "A global environmental crisis 42,000 years ago". Science, v.374(6570), eabh1878.

Korte, M., Brown, M.C., Panovska, S. and Wardinski, I. (2019) Robust characteristics of the Laschamp and Mono Lake geomagnetic excursions: results from global field models. Front. Earth Sci., v.7, pp.86, doi:10.3389/feart.2019.00086.

Laj, C. and Channell, J.E. (2015) Geomagnetic excursions. *In:* G. Schubert (Ed.), Treatise on Geophysics, Second Edition, no.5.10, pp.343-383.

Laj, C. and Kissel, C. (2015) An impending geomagnetic transition? Hints from the past. Frontiers in Earth Sci., v.3, pp.61.

Lowrie, L. (1997) Fundamentals of Geophyscis. Cambridge University Press.

Olson, P. (2002) The disappearing dipole. Nature, v.416(6881), pp.591-593.

Panovska, S. and Constable, C.G. (2017) An activity index for geomagnetic paleosecular variation, excursions, and reversals. Geochem., Geophys., Geosyst., v.18(4), pp.1366-1375.

Panovska, S., Korte, M. and Constable, C.G. (2019) One hundred thousand years of geomagnetic field evolution. Rev. Geophys., v.57(4), pp.1289-1337.

Panovska, S., Korte, M., Liu, J. and Nowaczyk, N. (2021) Global evolution and dynamics of the geomagnetic field in the 15–70 kyr period based on selected paleomagnetic sediment records. Jour. Geophys. Res.: Solid Earth, v.126(12), e2021JB022681.

Pavon-Carrasco, F.J. and De Santis, A. (2016) The South Atlantic anomaly: The key for a possible geomagnetic reversal. Frontiers in Earth Sci., v.4, pp.40.

Picin, A., Benazzi, S., Blasco, R., Hajdinjak, M., Helgen, K. M., Hublin, J. J., ... and Talamo, S. (2021) Comment on "A global environmental crisis 42,000 years ago". Science, v.374(6570), eabi8330.

Roberts, A.P. (2008) Geomagnetic excursions: knowns and unknowns. Geophys. Res. Lett., v.35., L17307.

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 Sulmona Basin, central Italy. Geophys. Jour. Internat., v.204(2), pp.798-812.

Singer, B.S., Jicha, B.R., Mochizuki, N. and Coe, R.S. (2019) Synchronizing volcanic, sedimentary, and ice core records of Earth's last magnetic polarity reversal. Science Adv., v.5(8), eaaw4621.

Valet, J.-P. and Plenier, G. (2008) Simulations of a time-varying non-dipole field during geomagnetic reversals and excursions. Phys. Earth Planet. Inter., v.169, pp.178–193.

Wicht, J. and Meduri, D.G. (2016) A Gaussian model for simulated geomagnetic field reversals. Phys. Earth Planet. Inter., v.259, pp.45-60.