



HAL
open science

Geomagnetic Field, Polarity Reversals

Carlo Laj

► **To cite this version:**

Carlo Laj. Geomagnetic Field, Polarity Reversals. Encyclopedia of Solid Earth Geophysics, pp.1-8, 2020, 10.1007/978-3-030-10475-7_116-1 . hal-02885356

HAL Id: hal-02885356

<https://hal.science/hal-02885356>

Submitted on 13 Aug 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Geomagnetic Field, Polarity Reversals

Carlo Laj
Laboratoire des Sciences du Climat, Unité mixte
CEA-CNRS-UVSQ, Gif-sur-Yvette, France

Introduction: The Discovery of Geomagnetic Reversals

Bernard Brunhes (1906) was the first to measure magnetization directions in rocks that were approximately antiparallel to the present Earth's field. Brunhes (1906) recorded magnetizations in baked sedimentary rocks that were aligned with reverse magnetization directions in overlying Miocene lavas from central France (Puy de Dome). In so doing, Brunhes (1906) made first use of a field test for primary thermal remanent magnetization (TRM) that is now referred to as the "baked contact" test. Matuyama (1929) was the first to attribute reverse magnetizations in (volcanic) rocks from Japan and China to reversal of geomagnetic polarity, and to differentiate mainly Pleistocene lavas from mainly Pliocene lavas based on the polarity of the magnetization. In this respect, Matuyama (1929) was the first person to use the sequence of geomagnetic reversals as a means of ordering rock sequences.

The reality of geomagnetic reversals was then progressively established with the studies of Hospers (1951, 1953) in Iceland, and Roche (1950, 1951, 1956) in the Massif Central of France. The work of Hospers on Icelandic lavas was augmented by Rutten and Wensink (1960) and Wensink (1966) who subdivided Pliocene-Pleistocene lavas in Iceland into three polarity zones from young to old: N-R-N. Magnetic remanence measurements on basaltic lavas combined with K/Ar dating, pioneered by Cox et al. (1963) and McDougall and Tarling (1963a, b, 1964), resulted in the beginning of development of the modern geomagnetic polarity timescale (GPTS). These studies, and those that followed in the

mid-1960s, established that rocks of the same age carry the same magnetization polarity, at least for the last few million years. The basalt sampling sites were scattered over the globe. Polarity zones were linked by their K/Ar ages, and were usually not in stratigraphic superposition. Doell and Dalrymple (1966) designated the long intervals of geomagnetic polarity of the last 5 Myrs as magnetic epochs, and named them after pioneers of geomagnetism (Brunhes, Matuyama, Gauss, and Gilbert).

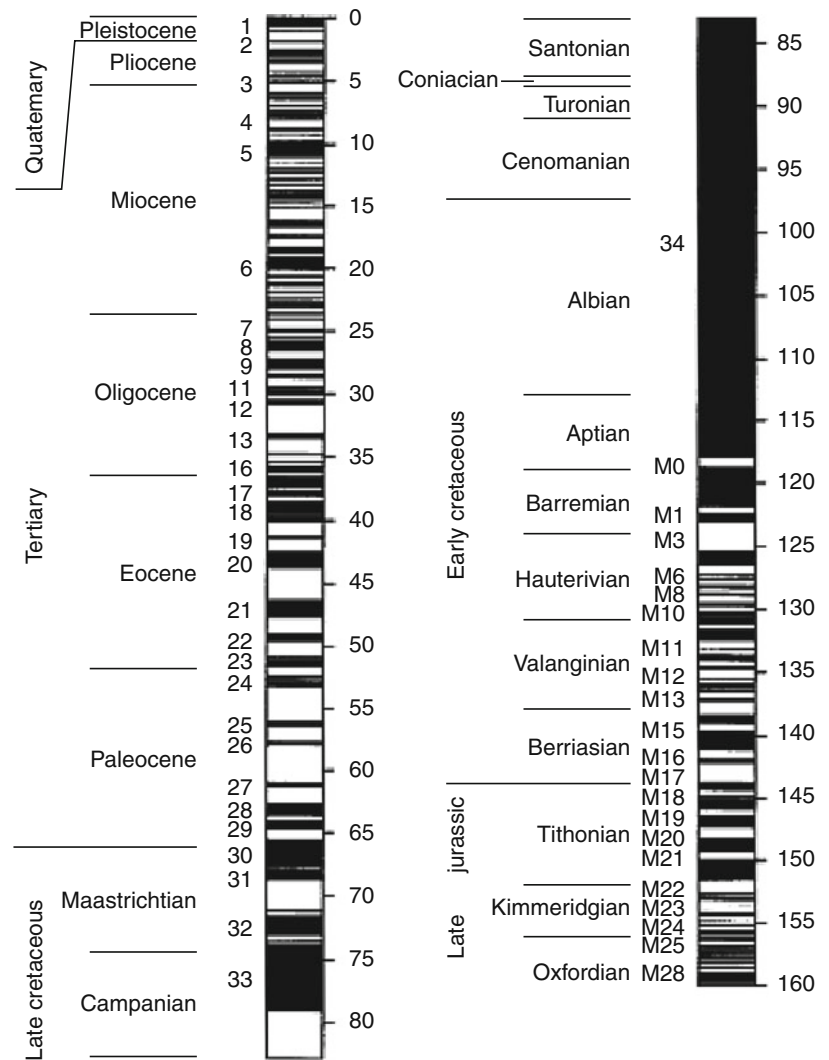
Then, the discovery of marine magnetic anomalies confirmed seafloor spreading (Vine and Matthews 1963), and the GPTS was extended to older times (Vine 1966; Heirtzler et al. 1968; Lowrie and Alvarez 1981). Since then, the succession of polarity intervals has been extensively studied and used to construct magnetostratigraphic timescales linking biostratigraphies, isotope stratigraphies, and absolute ages (see Opdyke and Channell 1996, "Magnetic stratigraphy", for a review).

The Geomagnetic Polarity Timescale

The fit of the land-derived polarity timescale, from paleomagnetic and K/Ar studies of exposed basalts, with the polarity record emerging from marine magnetic anomalies (MMA) (Vine and Matthews 1963; Vine 1966; Pitman and Heirtzler 1966; Heirtzler et al. 1968) resulted in a convincing argument for synchronous global geomagnetic polarity reversals, thereby attributing them to the main axial dipole. This intense research effort has culminated with the work of Cande and Kent (1995) based on the Marine Magnetic Anomalies record, using the South Atlantic as the fundamental template with inserts from faster spreading centers in the Indian and Pacific oceans. Cande and Kent (1995) adopted the astrochronological age estimates for the Pliocene-Pleistocene polarity reversals and fixed the age tie-point at the Cretaceous-Tertiary boundary at 65 Ma (Fig. 1).

Geomagnetic Field, Polarity Reversals, Fig. 1

The geomagnetic polarity timescale for the last 160 My. Numbers indicate the marine magnetic anomalies



The Changing Frequency over Time and the Duration of Geomagnetic Reversals

Examination of the geomagnetic polarity timescale reveals some of the major characteristics of geomagnetic reversals. First, a clear characteristic is the widely different duration of periods of stable polarity separating geomagnetic reversals. Long periods of time during which there were no reversals have been clearly identified, such as the Cretaceous Long Normal Chron (also called the Cretaceous Superchron, about 118–183 million years ago) or the Kiaman Superchron, which lasted approximately from the late Carboniferous to the end of the Permian.

The frequency of reversals decreased prior to the Cretaceous Superchron, and slowly increased over the 80 million years from the end of this Superchron to the present. It has been suggested (Mazaud et al. 1983; Mazaud and Laj 1991) that in this last period the frequency does not increase randomly but presents a dominant frequency corresponding to a

period of approximately 15 million years. This suggestion has, however, been received with some skepticism (McFadden 1987). The most recent analyses seem to converge toward a nonstationary Poisson process or at least a gamma process with k only slightly greater than 1 (Lowrie and Kent 2004).

Another characteristic, revealed from the very beginning by the studies of reversals, is that the Earth’s magnetic field strength drops to low levels during polarity reversals. There has been some debate on whether this drop is symmetrical or not on each side of the reversal. Valet and Meynadier (1993) suggested that the dipole intensity slowly decreases over a long period of time preceding a reversal and rapidly increases immediately after (the so-called sawtooth hypothesis). These authors also suggested that there is a positive correlation between the magnitude of the increase in intensity and the length of the subsequent polarity interval.

The sawtooth pattern, however, is not present in many sedimentary records (Tauxe and Shackleton 1994; Tauxe

and Hartl 1997; Laj et al. 1996; Channell and Kleiven 2000; Channell et al. 2009). Interpretations of the sawtooth pattern, other than true geomagnetic behavior, have been given, either assuming sedimentary postdepositional artifacts (Mazaud 1996) or the presence of a cumulative viscous component not removed by alternating field demagnetization (Kok and Tauxe 1996a, b). Moreover, McFadden and Merrill (1998) have strongly questioned the suggestion that the duration of polarity intervals could be determined by the amplitude of the field recovery after the reversal. The fast recovery of the field intensity after the reversal does not appear either in a recent reconstruction of the Brunhes–Matuyama transition, based on four independent records, where the pre- and posttransitional intensity records appear symmetric about the reversal (Leonhardt and Fabian 2007). In summary, the experimental evidence for the sawtooth hypothesis is controversial.

Also clearly apparent from the geomagnetic polarity time-scale is the extremely short duration of polarity reversals compared to periods of stable polarity. The time it takes for the reversal to happen has been roughly estimated from the early works (Harrison and Somayajulu 1966; Cox et al. 1963, 1964; Cox 1969) to be between 10^3 and 10^4 years, with some estimates up to 28,000 years. In a recent article, Clement (2004) presents an analysis of available sedimentary records and shows that these records yield an average estimate of 7000 years for the duration of a reversal. Moreover, the duration varies with site latitude, with a shorter duration observed at low-latitude sites. This short duration has been one of the most delicate factors to overcome in studying the detailed structure of reversals.

The Morphology of Geomagnetic Reversals

Because of its importance to dynamo theory, the morphology of the geomagnetic field during reversals and whether or not it displays statistical asymmetries has been a subject of continuous research for many years. Records of geomagnetic field changes during a polarity transition have, however, been difficult to obtain, not only because of their short duration mentioned above, but also because the magnetizations of the rocks is weak due to the low intensity of the transitional field. It is only with the advent of sensitive magnetometers that the number of published transitional records has rapidly increased.

In probably the most famous of the early records, Hillhouse and Cox (1976) showed that the Virtual Geomagnetic Pole (VGP) (The Virtual Geomagnetic Pole is defined as the pole of the geocentered axial dipolar field that would give the observed direction of the field at the observation site. If the VGPs observed at several sites at a given time coincide, then the field has a dipolar structure.) path for the Brunhes–Matuyama transition recorded in sediments from

Lake Tecopa (California) was different from the one previously obtained by Niitsuma (1971) from the Boso Peninsula in Japan, thereby providing evidence that the transitional field is not dipolar. Although in a more recent article Valet et al. (1988a) showed that the AF demagnetization used by Hillhouse and Cox (1976) did not completely remove a strong overprint, the conclusion that the transitional field was not dipolar was maintained.

Another famous record was obtained from a Miocene lava sequence at the Steens Mountain (Mankinen et al. 1985; Prévot et al. 1985). The record displays several phases with large swings, one of which occurring at the extremely rapid rate of $50 \pm 21^\circ$ per year, while the intensity change was $6700 \pm 2700 \mu\text{T}$ per year, about 10–50 times larger than the maximum rate of change observed for the non-dipole field in historical records. These amazing rates of change are still a matter of discussion among geophysicists.

Other transitional records were obtained from lava sequences in French Polynesia (Roperch and Chauvin 1987; Roperch and Duncan 1990; Chauvin et al. 1990). These records appear to indicate that a zonal field dominates the beginning of the transition, then non-dipolar terms emerge without any preferred axi-symmetry, consistent with an earlier suggestion by Hoffman (1982).

Transitional records from sequences of relatively high accumulation rate marls in Western Crete (Greece), were reported in a series of papers by Valet and Laj (1981, 1984) and by Valet et al. (1983, 1986, 1988b). The results from multiple records indicated that the reversal process observed for four sequential transitions remained unchanged for about 1.3 Ma. In one record, obtained from a particularly high sedimentation rate section, fast directional fluctuations, reminiscent of the Steens Mountain record, were observed whose amplitude significantly increases during the transition. Slight smoothing of the data reveals that almost periodic fluctuations occurred on a longer timescale during the transition (Valet et al. 1986).

Two landmark papers were published almost simultaneously and independently in 1991. Clement (1991) examined records of the Brunhes–Matuyama transition obtained from the northern, equatorial, and southern latitudes in the Atlantic sector. The VGP paths from the mid-latitudes in the northern and southern hemispheres are nearly coincident and extend over the Americas. Paths from the equatorial site track almost antipodal to the other paths. These results suggest that during the reversal VGPs tend to fall along two longitudinal bands.

From a compilation of all the available sedimentary records from several sites and spanning about 12 million years, Laj et al. (1991) suggested that reversals and excursions exhibit geometric regularity: the VGP paths of these transitions tend to fall along either American or Asian–Australian longitudes, that is, the same as for the

Brunhes-Matuyama reversal (Fig. 2). As remarked by the authors a persistent geometry over 12 Ma has important geomagnetic consequences: since the duration between transitions is longer than both the core's convective and magnetic diffusion timescales, the most plausible mechanism by which the core could retain a memory of previous transitions, particularly preferred longitudinal bands, is through some form of core-mantle coupling. This argument was reinforced by Laj et al. (1991) who noted the apparent correlation between preferred longitudes and lower mantle seismic velocity variations, possibly arising from thermal heterogeneities.

The suggestion of preferred longitudinal bands for transitional VGPs has, however, been met with some skepticism, some authors questioning the adequacy of the geographical distribution of the sites (Valet et al. 1992), or the reliability of transitional records from sediments (Langereis et al. 1992; Barton and McFadden 1996). Statistical analyses of the distribution of path have not given a clear answer (Weeks et al. 1992; McFadden et al. 1993; Quidelleur and Valet 1994). An initial analysis of transitional records from lavas (which are devoid of many of the problems of sedimentary magnetizations) appeared to indicate that transitional VGPs are statistically axi-symmetric (Prévot and Camps 1993). However, a more recent analysis by Love (1998, 2000) using a mathematical approach in which the records are normalized taking into account differences in recording density of the paleomagnetic directions, has concluded that the volcanic transitional VGPs indeed show a significant tendency to fall along American and Asian-Australian longitudes, consistent with the sedimentary data. The existence of preferred longitudinal bands for transitional VGPs must, therefore, be considered as a realistic suggestion.

Alongside with the observations of records of geomagnetic reversals, phenomenological models have been developed to account for at least the main characteristics of the records. As early as 1976, Hillhouse and Cox (1976) suggested that if the usual non-dipole drift remained unchanged during the reversal, then one should observe large longitudinal swings in the reversal PGV paths. As this was not observed, these authors

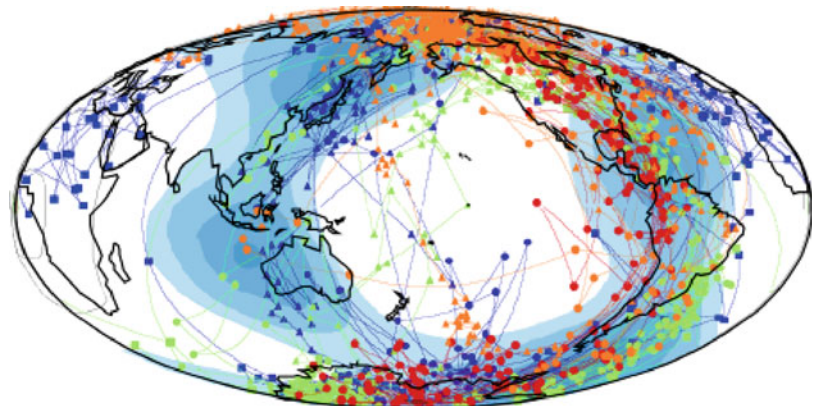
proposed that an invariant component dominates the field when the usual dipole has vanished (the so-called standing field hypothesis). Subsequently, Hoffman and Fuller (1978) and Hoffman (1979) proposed a model in which reversals originate in particular regions of the core and progressively extend to other regions (the so-called flooding model). None of these models was, however, capable of predicting VGP paths from particular sites on the Earth.

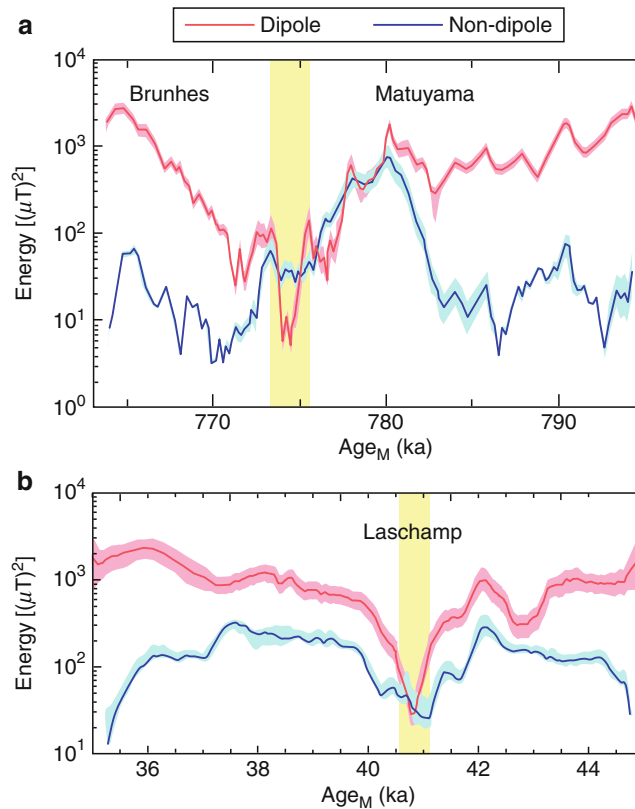
A significant step forward has been made recently, with the development by Leonhardt and Fabian (2007) of a Bayesian inversion method devised to reconstruct the spherical harmonic contents of the geomagnetic field during a reversal from paleomagnetic data. The validity of this inversion technique is proven, in particular, by iteratively combining four geographically distributed high quality paleomagnetic records of the Brunhes–Matuyama reversal into a single scenario without assuming an a priori common age model. The obtained results successfully describe most independent Brunhes–Matuyama transitional records.

Leonhardt and Fabian (2007) were able to discuss many questions about the transitional field, which had been controversially discussed (see, e.g., Merrill et al. (1996)) so far: primarily the question of contribution of dipole versus non-dipole fields during the reversal process. The results of their modeling indicates a strong increase of non-dipolar energy a few kyrs before the reversal. The non-dipole energy prevails on the dipole some 5 kyrs before the dipole minimum, after which both the non-dipole and dipolar energies decrease. Following the minimum in dipolar energy, the non-dipolar energy drops further, while the dipolar energy increases first sharply then progressively recovers (Fig. 3a). The model also shows that, during the reversal, the inverse flux penetrates the tangent cylinder (the imaginary cylinder aligned with the Earth's rotation axis and tangent to the inner core).

Geomagnetic Field, Polarity

Reversals, Fig. 2 The compilation of sedimentary records for the last 12 My (Laj et al. 1991) indicating the existence of preferred longitudinal bands for transitional VGPs. The blue shaded zones are characterized by fast seismic velocities in the lower mantle





Geomagnetic Field, Polarity Reversals, Fig. 3 (a) Evolution of the dipole and non-dipole energies during the Matuyama–Brunhes polarity transition. (b) Evolution of the dipole and nondipole energies during the Laschamp excursion

Dynamo Mechanisms and Reversals

For many years, scientific opinion has been divided on what causes geomagnetic reversals. Initial suggestions have been made that geomagnetic reversals are not due to spontaneous processes in the Earth’s dynamo, but rather that they are triggered by external factors (such as arrival of continental slabs near the core-mantle boundary as a result of plate tectonics, or even mantle-core shear forces linked to external impacts).

Today, most geophysicists believe that reversals are inherent aspects of the dynamo, which generates the geomagnetic field. Recent developments in numerical dynamo models, which take advantage of modern supercomputers, and also an experiment with a laboratory dynamo, point strongly that this is the only sustainable mechanism. In these models the equations describing the time-dependent thermal, compositional, velocity and magnetic field are solved simultaneously in the three-dimensional spherical geometry appropriate to the core. There is no a priori prescription for reversals, so, if they happen, they are an intrinsic property of the mechanisms of the geodynamo.

The first of these numerical models aiming to simulate Earth-like characteristics was published by Glatzmaier and Roberts (1995). This three-dimensional, selfconsistent model

was able to maintain a magnetic field for over 40,000 years. The model, considers a finitely conducting solid inner core, in agreement with findings by Hollerbach and Jones (1993) that a solid inner core tends to stabilize the geodynamo. Over the period of 40,000 year the model undergoes several polarity excursions and finally a reversal is observed. The model, therefore, shares some similarities with real reversals of the geomagnetic field, and therefore may provide insight into the mechanisms of geomagnetic reversals.

In this respect, Glatzmaier et al. (1999) and Coe et al. (2000) have run numerical simulations of the Glatzmaier–Roberts dynamo using a variety of thermal boundary conditions. The model displays a range of behavior that resembles records of real reversals of the Earth’s magnetic field. Reversals occurred during both the homogeneous and tomographic simulation (in this last case the heat flux at the Core-Mantle Boundary is patterned after a seismic velocity model from tomographic investigation of the lower mantle). All reversals appear spontaneously, with no external triggering required. The tomographic model of Glatzmaier et al. (1999) also appears to offer some support for the hypothesis that VGPs during reversals correlate with areas of higher than average heat flux.

The question of how well the geodynamo model represents the Earth’s field is of course fundamental. Indeed, if the

Earth's values for the radius and the rotation of the core are used, then, owing to computation limitations, viscous diffusivity values at least three to four orders of magnitude larger than those of the Earth must be used. So, while some modelers have argued that the field produced by models should be fairly realistic, other modelers are less confident that the results can be directly extrapolated to the Earth, even at the large scales. In the author's opinion, numerical models have very largely improved our understanding of the mechanisms inherent to the production of the Earth's magnetic field.

Finally, a benchmark experiment showing how magnetic field reversals can be generated without any external triggering in a turbulent conducting field has been obtained recently in a laboratory environment, the so-called VKS experiment (this acronym stands for Von Karman Sodium) (Berhanu et al. (2007)). In 2000 experiments in Riga (Gailitis et al. 2001) and Karlsruhe (Stieglitz and Müller 2001) showed that fluid dynamo could be generated by fluid sodium flows, when a favorable geometry is imposed to the flow. In the more recent VKS experiment, a turbulent flow is produced in a copper cylinder filled with liquid sodium whose flow is created by two counter-rotating impellers. When the speed of the impellers exceeds a critical value, the flow spontaneously generates a magnetic field that is self-sustained by the flow itself. This field undergoes large fluctuations, originating from the high level of turbulence. The most spectacular result was observed when the two impellers were counter-rotated at different speeds: in this case the temporal evolution of the field is characterized by a series of erratic reversals of polarity. These reveal remarkable similarities with the Earth's magnetic field, in the sense that the duration of the transitions is very short compared to the periods of stable polarity. In addition, excursions are also present, during which the field

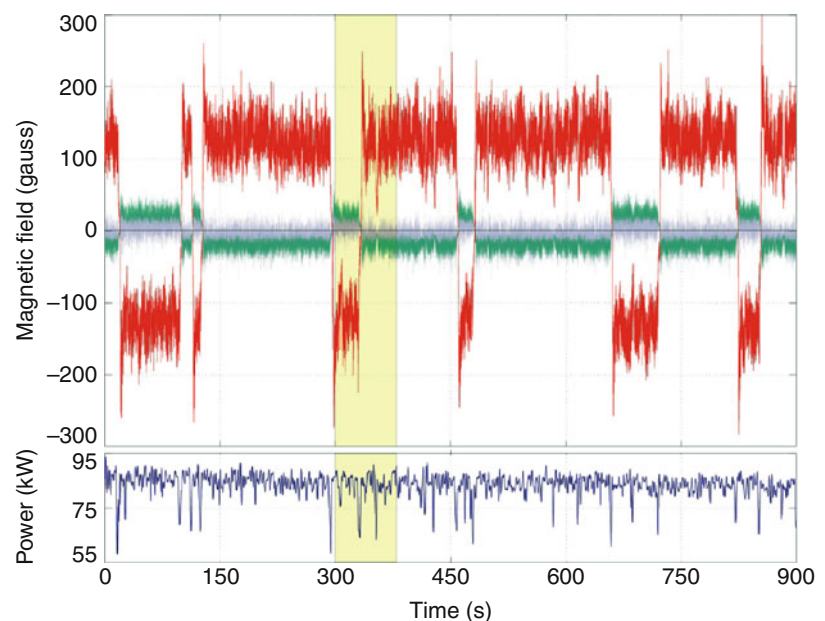
decays to very low values before growing again without a change in polarity (Fig. 4). Although similarity to the Earth's magnetic field should not be overstressed, this laboratory experiment clearly shows that reversals can appear spontaneously, as a consequence of the complexity of the fluid flow, without any necessity for an external triggering.

Outlook: The Future of Geomagnetic Reversals

The geomagnetic dipole has decreased in recent historical times at a rate of 5% per century, which is about 10–12 times the rate of free Ohmic decay of the geomagnetic dipole field in the core. Additional evidence for this rapid decrease is the poleward migration of large patches of reverse magnetic field at the core-mantle boundary that have largely contributed to the historical dipole field drop (Olson and Amit 2006). Therefore, this is a very rapid change for the geodynamo, which has led to speculations about the possibility of an impending field reversal (Constable and Korte (2006); Olson and Amit (2006)). Because an intensity drop is also associated with excursions this second possibility should also be considered.

The inverse model of Leonhardt and Fabian (2007) may allow to have a deeper insight on this scenario. Indeed, when applied to the study of the Laschamp excursion (Leonhardt et al. 2009) the model indicates that both dipolar and non-dipolar energies at the Earth's surface decrease at approximately the same time with similar rates. The dipolar energy reaches its minimum slightly later than the non-dipolar energy. Then, for a brief interval the non-dipolar energy prevails, contrary to the Brunhes–Matuyama reversal discussed above where the non-dipole energy prevails on the dipole

Geomagnetic Field, Polarity Reversals, Fig. 4 Evolution of the magnetic field measured inside the flow vessel during the VKS experiment. The main component (red) is the azimuthal one. Note that all components decay to zero at a reversal. The bottom graph shows the evolution of the power driving the flow. (Adapted from Berhanu et al. 2007)



some 5 kyrs before the dipole minimum, after which both the non-dipole and dipolar energies decrease (Fig. 3b). The time evolution of the dipole versus non-dipole fields is different for a reversal or an excursion and could, therefore, be an indicator for an incoming reversal or excursion.

At present, however, the non-dipole field energy is about one order of magnitude smaller than the dipolar term. This latter is still larger than the dipole energy calculated before either a reversal or an excursion using the Leonhardt and Fabian approach. So despite the decreasing trend of dipole energy, there is no indication in the present field that would point toward either type of instability. Together with Olson and Amit (2006), Leonhardt et al. (2009) therefore consider that it is not justified to consider the present decrease in dipole energy and an indication of an imminent reversal. We will have to wait some more time to know whether we are heading toward a reversal, an excursion, or whether we are simply undergoing an intensity fluctuation.

Acknowledgments I thank Alain Mazaud for helpful discussions during the writing of the manuscript.

Bibliography

- Barton CE, McFadden PL (1996) Inclination shallowing and preferred transitional VGP paths. *Earth Planet Sci Lett* 140:147–157
- Berhanu M, Monchaux R, Fauve S, Mordant N, Pétéelis F, Chiffaudel A, Daviaud F, Dubrulle B, Marié L, Ravelet F, Bourgoign M, Odier PH, Pinton J-F, Volk R (2007) Magnetic field reversals in an experimental turbulent dynamo. *Europhys Lett* 77:59001–59005
- Brunhes B (1906) Recherches sur la direction de l'aimantation des roches volcaniques. *J Phys V*:705–724
- Cande SC, Kent DV (1995) Revised calibration of the geomagnetic polarity timescale for the late cretaceous and cenozoic. *J Geophys Res* 100:6093–6095
- Channell JET, Kleiven HF (2000) Geomagnetic palaeointensities and astrochronological ages for the Matuyama-Brunhes boundary and the boundaries of the Jaramillo Subchron: palaeomagnetic and oxygen isotope records from ODP site 983. *Phil Trans R Soc A* 358:1027–1047
- Channell JET, Hodell DA, Lehman B (1997) Relative geomagnetic paleointensity and $\delta^{18}\text{O}$ at ODP site 983 (Gardar Drift, North Atlantic) since 350 ka. *Earth Planet Sci Lett* 153:103–118
- Channell JET, Xuan C, Hodell DA (2009) Stacking paleointensity and oxygen isotope data for the last 1.5 Myr (PISO-1500). *Earth Planet Sci Lett* 283:14–23
- Chauvin A, Duncan RA, Bonhommet N, Levi S (1989) Paleointensity of the Earth's magnetic field and K-Ar dating of the Louchadière volcanic flow (central France): new evidence for the Laschamp excursion. *Geophys Res Lett* 16:1189–1192
- Chauvin A, Roperch P, Duncan RA (1990) Records of geomagnetic reversals from volcanic islands of French polynesia, 2-paleomagnetic study of a flow sequence (1.2 to 0.6 Ma) from the Island of Tahiti and discussion of reversal models. *J Geophys Res* 95:2727–2752
- Clement BM (1991) Geographical distribution of transitional V. G.P.'s: evidence for non-zonal equatorial symmetry during the Matuyama-Brunhes geomagnetic reversal. *Earth Planet Sci Lett* 104:48–58
- Clement BM (2004) Dependence of the duration of geomagnetic polarity reversals on site latitude. *Nature* 428:637–640
- Coe RS, Hongre L, Glatzmaier GA (2000) An examination of simulated geomagnetic reversals from a paleomagnetic perspective. *Phil Trans R Soc A* 358:1141–1170
- Constable CG, Korte M (2006) Is the Earth's magnetic field reversing? *Earth Planet Sci Lett* 246:1–16
- Cox A (1969) Geomagnetic reversals. *Science* 163:237–245
- Cox A, Doell RR, Dalrymple GB (1963) Geomagnetic polarity epochs and Pleistocene geochronometry. *Nature* 198:1049–1051
- Cox A, Doell RR, Dalrymple GB (1964) Reversals of the Earth's magnetic field. *Science* 144:1537–1543
- Doell RR, Dalrymple GB (1966) Geomagnetic polarity epochs: a new polarity event and the age of the Brunhes-Matuyama boundary. *Science* 152:1060–1061
- Gaillitis A, Lielausis O, Platacis E, Dement'ev S, Cifersons A, Gerbeth G, Gundrum T, Stefani F, Christen M, Will G (2001) Magnetic field saturation in the Riga dynamo experiment. *Phys Rev Lett* 86:3024–3027
- Glatzmaier GA, Roberts PH (1995) A three-dimensional self-consistent computer simulation of a geomagnetic field reversal. *Nature* 377:203–209
- Glatzmaier GA, Coe RS, Hongre L, Roberts PH (1999) The role of the Earth's mantle in controlling the frequency of geomagnetic reversals. *Nature* 401:885–890
- Gubbins D (1999) The distinction between geomagnetic excursions and reversals. *Geophys J Int* 137:F1–F3
- Harrison CGA, Somayajulu BLK (1966) Behaviour of the earth's magnetic field during a reversal. *Nature* 212:1193–1195
- Heirtzler JR, Dickson GO, Herron EM, Pittman WC III, LePichon X (1968) Marine magnetic anomalies, geomagnetic field reversal and motions of the ocean floor and continents. *J Geophys Res* 73:2119–2136
- Hillhouse J, Cox A (1976) Brunhes-Matuyama polarity transition. *Earth Planet Sci Lett* 29:51–64
- Hoffman KA (1979) Behaviour of the geodynamo during a reversal: a phenomenological model. *Earth Planet Sci Lett* 44:7–17
- Hoffman KA (1982) The testing of geomagnetic reversal models/récent developments. *Philos Trans R Soc Lond A* 306:147–159
- Hoffman KA, Fuller M (1978) Polarity transition records and the geomagnetic dynamo. *Nature* 273:715–718
- Hollerbach R, Jones CA (1993) Influence of the Earth's inner core on geomagnetic fluctuations and reversals. *Nature* 365:541–543
- Hospers J (1951) Remanent magnetization of rocks and the history of the geomagnetic field. *Nature* 168:1111–1112
- Hospers J (1953–1954) Reversals of the main geomagnetic field I, II, and III. *Proc K Ned Akad Wet C* 56:467–491; 57:112–121
- Kok YS, Tauxe L (1996a) Saw-toothed pattern of relative paleointensity records and cumulative viscous remanence. *Earth Planet Sci Lett* 137:95–100
- Kok YS, Tauxe L (1996b) Saw-toothed pattern of sedimentary paleointensity records explained by cumulative viscous remanence. *Earth Planet Sci Lett* 144:9–14
- Laj C, Mazaud A, Fuller M, Herrero-Bervera E (1991) Geomagnetic reversal paths. *Nature* 351:447
- Laj C, Kissel C, Garnier F, Herrero-Bervera E (1996) Relative geomagnetic field intensity and reversals for the last 1.8 My from a central Pacific core. *Geophys Res Lett* 23:3393–3396
- Langereis CG, Van Hoof AAM, Rochette P (1992) Longitudinal confinement of geomagnetic reversal paths: as a possible sedimentary artefact. *Nature* 358:226–230
- Leonhardt R, Fabian K (2007) Paleomagnetic reconstruction of the global geomagnetic field evolution during the Matuyama/Brunhes transition: iterative Bayesian inversion and independent verification. *Earth Planet Sci Lett* 253:172–195

- Leonhardt R, Fabian K, Winklhofer M, Ferk A, Laj C, Kissel C (2009) Geomagnetic field evolution during the Lascamp excursion. *Earth Planet Sci Lett* 278:87–95
- Love JJ (1998) Paleomagnetic volcanic data and geometric regularity of reversals and excursions. *J Geophys Res* 103:12435–12452
- Love JJ (2000) Statistical assessment of preferred transitional VGP longitudes based on paleomagnetic lava data. *Geophys J Int* 140:211–221
- Lowrie W, Alvarez W (1981) One hundred million years of geomagnetic polarity history. *Geology* 9:392–397
- Lowrie W, Kent DV (2004) Geomagnetic polarity timescales and reversal frequency regimes. In: Channell JET et al (eds) *Timescales of the geomagnetic field*. AGU geophysical monograph series, vol 145, pp 117–129
- Mankinen EA, Prévot M, Grommé CS, Coe RS (1985) The Steens Mountain (Oregon) geomagnetic polarity transition. 1. Directional history, duration of the episodes, and rock magnetism. *J Geophys Res* 90:393–416
- Matuyama M (1929) On the direction of magnetization of basalts in Japan, Tyosen and Manchuria. *Proc Imperial Acad* 5:203–205. (Tokyo)
- Mazaud A (1996) Sawtooth variation in magnetic intensity profiles and delayed acquisition of magnetization in deep sea cores. *Earth Planet Sci Lett* 139:379–386
- Mazaud A, Laj C (1991) The 15 m.y. geomagnetic reversal periodicity: a quantitative test. *Earth Planet Sci Lett* 107:689–696
- Mazaud A, Laj C, De Seze L, Verosub KL (1983) 15-Myr periodicity in the frequency of geomagnetic reversals since 100 Myr. *Nature* 304:328–330
- McDougall I, Tarling DH (1963a) Dating of reversals of the Earth's magnetic field. *Nature* 198:1012–1013
- McDougall I, Tarling DH (1963b) Dating of polarity zones in the Hawaiian Islands. *Nature* 200:54–56
- McDougall I, Tarling DH (1964) Dating geomagnetic polarity zones. *Nature* 202:171–172
- McFadden PL (1987) Comment on "a periodicity of magnetic reversals?". *Nature* 330:27
- McFadden PL, Merrill RT (1998) Sawtooth paleointensity and reversals of the geomagnetic field. *Phys Earth Planet Inter* 103:247–252
- McFadden PL, Barton CLE, Merrill RT (1993) Do virtual geomagnetic poles follow preferential paths during geomagnetic reversals? *Nature* 361:342–344
- Merrill RT, McElhinny M, McFadden PL (1996) The magnetic field of the earth, international geophysics series, vol 63. Academic, San Diego, p 531
- Meynadier L, Valet J-P, Weeks R, Shackleton NJ, Hagee VL (1992) Relative geomagnetic intensity of the field during the last 140 ka. *Earth Planet Sci Lett* 114:39–57
- Meynadier L, Valet J-P, Shackleton NJ (1995) Relative geomagnetic intensity during the last 4 MY from the equatorial Pacific. *Proc ODP Sci Res* 138:779–793
- Niitsuma N (1971) Detailed studies of the sediments recording the Matuyama-Brunhes geomagnetic reversal. *Tohoku Univ Sci Rpt 2nd Ser (Geology)* 43:1–39
- Olson P, Amit H (2006) Changes in the Earth's dipole. *Naturwissenschaften* 93:519–542
- Opdyke ND, Channell JET (1996) *Magnetic stratigraphy*. Academic, San Diego, p 346
- Pitman WC III, Heirtzler JR (1966) Magnetic anomalies over the Pacific-Antarctic Ridge. *Science* 154:1164–1171
- Prévot M, Camps P (1993) Absence of preferred longitudinal sectors for poles from volcanic records of geomagnetic reversal. *Nature* 366:53–57
- Prévot M, Mankinen E, Coe RS, Grommé CS (1985) The Steens Mountain (Oregon) geomagnetic polarity transition. 2. Field intensity variations and discussion of reversal models. *J Geophys Res* 90:10417–10448
- Quidelleur X, Valet J-P (1994) Paleomagnetic records of excursions and reversals: possible biases caused by magnetization artefacts. *Phys Earth Planet Inter* 82:27–48
- Roche A (1950) Sur les caractères magnétiques du système éruptif de Gergovie. *C R Acad Sci* 230:113–115
- Roche A (1951) Sur les inversions de l'aimantation remanente des roches volcaniques dans les monts d'Auvergne. *C R Acad Sci* 223:1132–1134. Paris
- Roche A (1956) Sur la date de la dernière inversion du champ magnétique terrestre. *C R Acad Sci* 243:812–814. Paris
- Roperch P, Chauvin A (1987) Transitional geomagnetic field behavior: volcanic records from French Polynesia. *Geophys Res Lett* 14:151–154
- Roperch P, Duncan RA (1990) Records of geomagnetic reversals from volcanic islands from French Polynesia 1. Paleo-magnetic study of a polarity transition on a lava sequence from the island of Huahine. *J Geophys Res* 95(B3):2713–2726
- Rutten MG, Wensink H (1960) Paleomagnetic dating glaciations and chronology of the Plio-Pleistocene in Iceland. *Int Geol Congress* IV:62–70. Sess 21
- Stieglitz R, Müller R (2001) Experimental demonstration of a homogeneous two-scale dynamo. *Phys Fluids* 13:561. <https://doi.org/10.1063/1.1331315>
- Tauxe L, Hartl P (1997) 11 million years of oligocene-geomagnetic field behavior. *Geophys J Int* 128:217–229
- Tauxe L, Shackleton NJ (1994) Relative paleointensity record from the Ontong-Java plateau. *Geophys J Int* 117:769–782
- Valet J-P, Herrero-Bervera E (2003) Some characteristics of geomagnetic reversals inferred from detailed volcanic records. *C R Geosci* 335:79–90
- Valet J-P, Laj C (1981) Paleomagnetic record of two successive Miocene geomagnetic reversals in Western Crete. *Earth Planet Sci Lett* 54:53–63
- Valet J-P, Laj C (1984) Invariant and changing transitional field configurations in a sequence of geomagnetic reversals. *Nature* 311:552–555
- Valet J-P, Meynadier L (1993) Geomagnetic field intensity and reversals during the last four million years. *Nature* 366:234–238
- Valet J-P, Laj C, Langereis CG (1983) Two different R-N geomagnetic reversals with identical VGP paths recorded at the same site. *Nature* 304:330–332
- Valet J-P, Laj C, Tucholka P (1986) High resolution sedimentary record of a geomagnetic reversal. *Nature* 322:27–32
- Valet J-P, Laj C, Langereis CG (1988a) Sequential geomagnetic reversals recorded in upper Tortonian marine clays in Western Crete (Greece). *J Geophys Res* 93:1131–1151
- Valet J-P, Tauxe L, Clark DR (1988b) The Matuyama-Brunhes transition recorded from Lake Tecopa sediments 5 (California). *Earth Planet Sci Lett* 87:463–472
- Valet JP, Tucholka P, Courtillot V, Meynadier L (1992) Paleomagnetic constraints on the geometry of the geomagnetic field during reversals. *Nature* 356:400–407
- Vine FJ (1966) Spreading of the ocean floor: new evidence. *Science* 154:1405–1415
- Vine FJ, Matthews DH (1963) Magnetic anomalies over oceanic ridges. *Nature* 199:947–949
- Weeks R, Fuller M, Laj C, Mazaud A, Herrero-Bervera E (1992) Sedimentary records of reversal transitions – magnetization smoothing artefact or geomagnetic field behaviour? *Geophys Res Lett* 19:2007–2010
- Wensink H (1966) Paleomagnetic stratigraphy of younger basalts and intercalated Plio-Pleistocene tillites in Iceland. *Geol Rundsch* 54:364–384