Reversals & Excursions:

Extreme Behavior of the Geomagnetic Field

Cathy Constable
Institute of Geophysics & Planetary Physics
Scripps Institution of Oceanography
University of California at San Diego

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Outline

- Reminder of paleomagnetic basics
- Definitions of reversals & excursions
- Time scales - how often do reversals and excursions occur & how long do they last?
- The Matuyama-Brunhes reversal
- What does the field look like during an excursion?
- The Laschamp Excursion
- Consequences for the Earth System

In Paleomagnetism and Archeomagetism we use sediments, lavas and pots as magnetometers

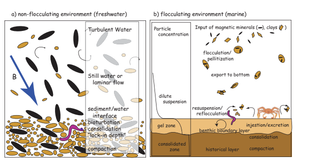
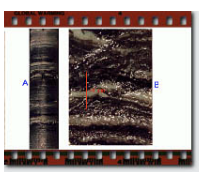
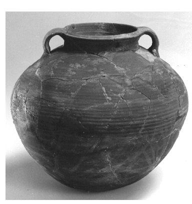
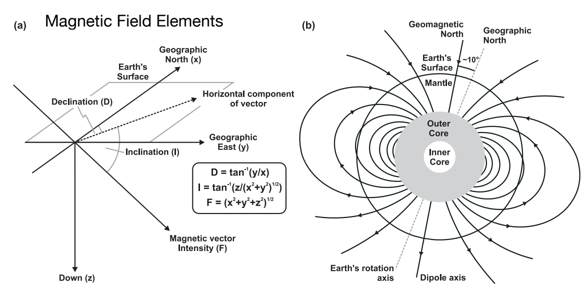


Figure 13.12: a) Schematic drawing of traditional view of the journey of magnetic particles from the water column to burial in a non-flocculating (freshwater) environment. Magnetic particles are black. (Redrawn from Tauxe, 1993.) b) View of depositional remanence in a flocculating (marine) environment. (Redrawn from Tauxe et al. 2006.)



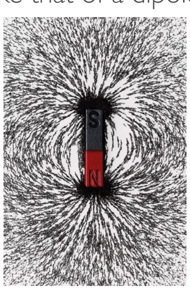


Magnetic Field is a Vector Quantity

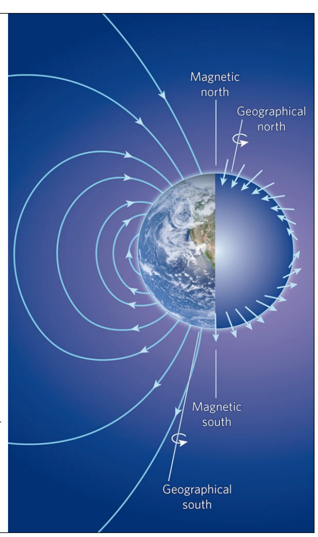


Korte et al., 2018, https://doi.org/10.1016/j.quageo.2018.11.004

On average Earth's field is a lot like that of a dipole - bar magnet



William Gilbert (1544-1603) - Earth itself is a great magnet



Geomagnetic Field Reversals

- A reversed field has the opposite polarity to what we see today - positions of the magnetic north and south poles are interchanged.
- In 1906, French geophysicist **Bernard Brunhes** (3 July 1867 - 10 May 1910) found volcanic rocks magnetized in opposite direction to the existing field.
- **Motonori Matuyama** (松山 基範 , October 25, 1884 – January 27, 1958) was the first to surmise that the Earth's magnetic field had undergone reversals in the past. (Matyuama, M. (1929). "On the Direction of Magnetization of Basalt in Japan, Tyosen and Manchuria". *Proceedings of the Imperial Academy of Japan*. **5**: 203–205.)

https://en.wikipedia.org/wiki/Bernard_Brunhes

Genbudo Cave in Toyooka City

http://sanin-geo.jp/en/info-index001

Geomagnetic Polarity Time Scale (GPTS)

- Radiometric dating was used to establish the geomagnetic polarity time scale starting in the 1950s
- Current records come from marine magnetic anomalies associated with seafloor spreading, and from paleomagnetic records in volcanic rocks and sediments
- Geomagnetic reversals have occurred often in the past - 183 times in the interval 0-84 Ma. The most recent reversal, the Matuyama-Brunhes transition was at 0.78 Ma.
- Reversals form an important part of the geological time scale

Marine magnetic anomalies and seafloor spreading provide a record back to 160 Ma

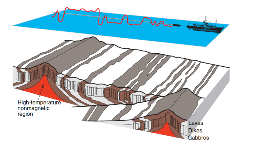


Figure 10 3-D perspective cartoon of ocean crust (after Johnson *et al.*, 1997), showing spreading centers separated by a transform fault. Crust generated during normal/reverse geomagnetic polarity (shown as shaded/unshaded regions) can be inferred from magnetic anomalies, for example, as measured from ship-towed magnetometers. Magnetization polarity boundaries are expected to be vertical in sheeted dikes and are likely to slope but in opposite directions in extrusive basalt layer (due to successive emplacement of lavas) and in intrusive gabbroic layer (due to progressive cooling with depth of gabbros).

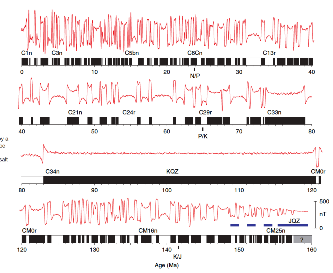
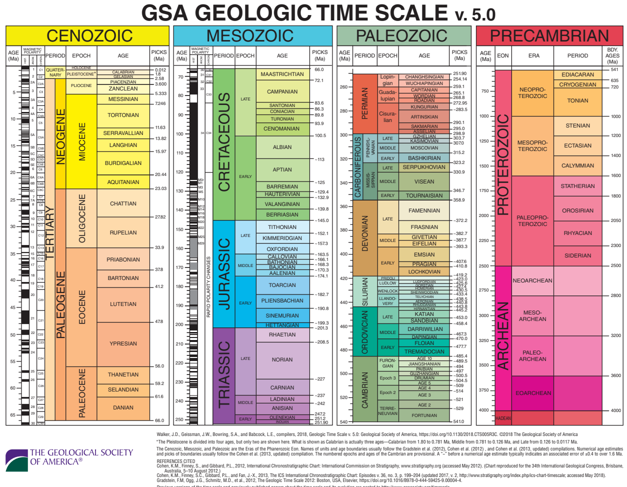


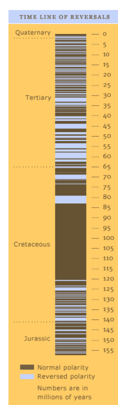
Figure 1 Geomagnetic polarity timescale from marine magnetic anomalies for 0–160 Ma. After Lowrie and Kent (2004); largely based on Cande and Kent (1995) and Channell *et al.* (1995). Filled and open blocks represent intervals of normal and reverse geomagnetic field polarity. (**Table 1**); key chrons that were used as calibration tiepoints are identified above the bar graph (C1n, C3n, etc.) and correlated positions of geologic period boundaries are indicated by ticks below the bar graph (N/P, Neogene/Paleogene; P/K, Paleogene/Cretaceous, K/J, Cretaceous/Jurassic). Idealized magnetic anomaly profile uses this polarity pattern in a 1 km thick source layer that has a mean magnetization of 5 A m^{-1} with gaussian variation ($\sigma = 42\%$ of mean) to mimic paleointensity variations, and vertical magnetization boundaries. The anomaly is calculated at the pole (no skewness, magnetization and ambient field direction vertical) at a full-spreading rate of 140 km My^{-1}, with depth to the upper surface that increases with $age^{0.5}$ (Ma) (Stein and Stein, 1994). Note the amplitude modulation, which primarily reflects the sequence effect since source properties otherwise stay constant other than modest monotonic change in water depth, except for magnetization ramp from JQZ into M-sequence (dashed line; factor of 5 increase from 157 Ma to 143 Ma) that is likely due to a systematic increase in geomagnetic intensity (Cande *et al.*, 1978; McElhinny and Larson, 2003).

Gee & Kent, 2007, Treatise on Geophysics, 2nd edition
http://dx.doi.org/10.1016/B978-0-444-53802-4.00106-8

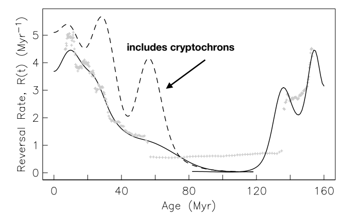
GSA GEOLOGIC TIME SCALE v. 5.0

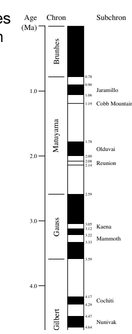


Geomagnetic polarity time scale & reversal rate



- **Reversals** occur at irregular intervals and the rate varies over time. Because they occur irregularly they are often treated as a random process with a time varying rate.
- **Cryptochrons** are very short events that may reflect rapid successive reversals or excursions in the magnetic anomaly record.





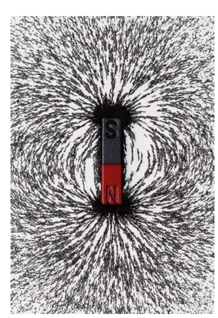
Constable (2000) PEPI, 118, 181-193

What does the geomagnetic field look like during reversal?

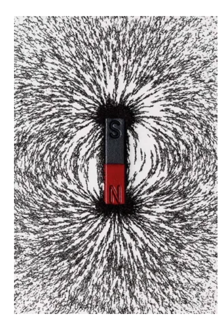
- Field strength at Earth's decreases over time.
- When dipole strength drops low enough, directions generally become non-dipolar, and highly variable in space.
- Dipole strength recovers with opposite polarity (reversal) or returns to the same polarity (excursion)

Simple Reversing Dipole

Normal polarity axial dipole

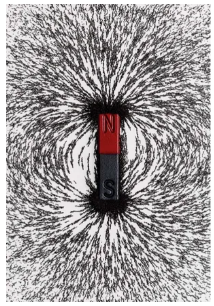


transition by rotating

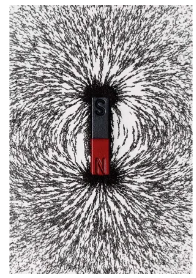


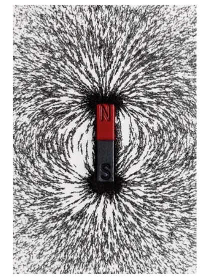
Normal polarity axial dipole

Reverse polarity axial dipole



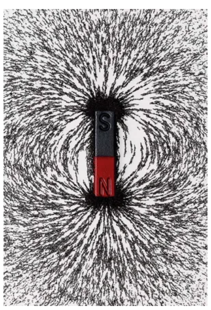
Shrinking, Reversing, and Growing Dipole





Excursion of the Axial Dipole

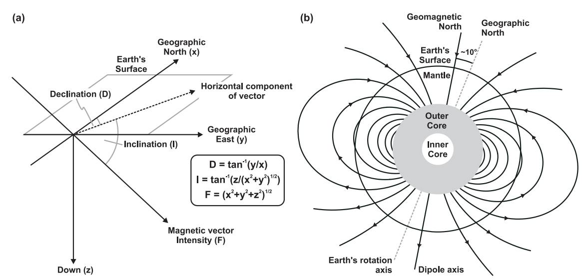
Normal polarity axial dipole



Deviation from axial dipole

How far must the dipole rotate to produce an excursion or transitional field?
How can we tell if/when the field is going to reverse completely?

Magnetic Field is a Vector Quantity



Korte et al., 2018

Transforming Local Field Vector into Virtual Geomagnetic Pole and Virtual Dipole Moment removes the geographic variation due to the dipole part of the field

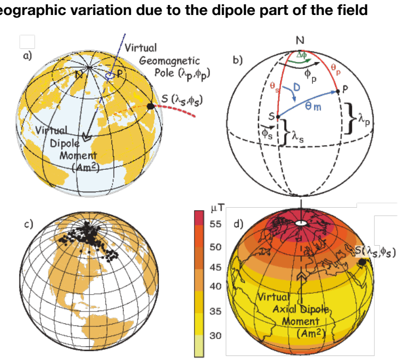


Figure 2.9: Transformation of a vector measured at S into a virtual geomagnetic pole position (VGP) and virtual dipole moment (VDM). a) Red dashed line is the magnetic field line observed at S (latitude of λs, longitude of ϕs). This field line is the same as one produced by the VDM at the center of the Earth. The point where the axis of the VDM pierces the Earth's surface is the VGP. b) Observed declination (D) and inclination (converted to θm using the dipole formula (see text) defines angles D and θm. θs is the colatitude of the observation site. N is the geographic North Pole (the spin axis of the Earth). The position of the pole at P (θp,ϕp) can be calculated with spherical trigonometry. c) VGP positions converted from directions shown in Figure 2.7b. d) The virtual axial dipole moment giving rise to the observed intensity at S.

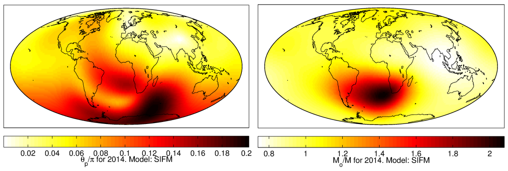
https://earthref.org/MagIC/books/Tauxe/Essentials/WebBook3ch2.html

Defining a transitional field state

- A transitional field can be an excursion (recovery to initial polarity) or can lead to a full reversal
- VGP latitude less than 45 degrees is one definition of a transitional field.
- Low field strengths are also seen - so another criterion is for VDM <0.5 that of current field
- Can also use a criterion called the paleosecular variation (PSV) index that combines both direction and intensity change

How different from the current axial dipole are the virtual dipoles for the modern field?

Normalized VGP colatitude - **Normalized VDM**



<36 degrees from geographic axis

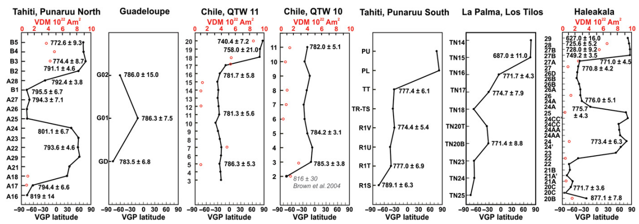
VDM is less than half the current dipole moment in the South Atlantic

Normalized VDM is more geographically variable than VGP direction for the modern field

VGPs and VDMs from

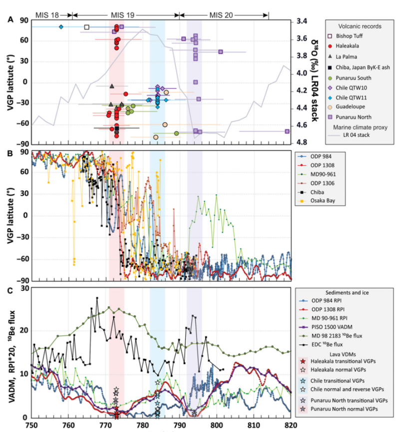
ava flow sequences that record transitional geomagnetic field behavior associated with the Matuyama-Brunhes reversal.

Lava flows are expected to provide the most accurate records of the field - but they are sparse and limited in temporal sampling



Brad S. Singer et al. Sci Adv 2019;5:eaaw4621

The View of the M-B transitions from Sediment Records

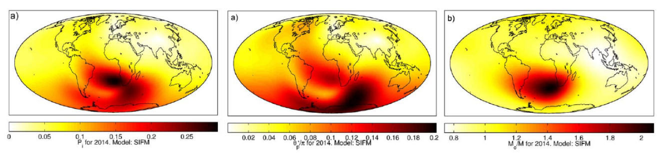


more detailed and quite complex

Singer et al., 2019, Science Advances

PaleoSecular Variation Index: Combining normalized VGP co-latitude and VDM

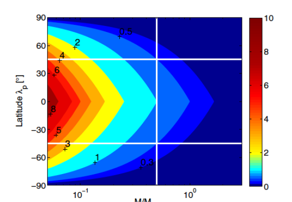
P_i θ_p/π M_0/M



Combined VGP part VDM part

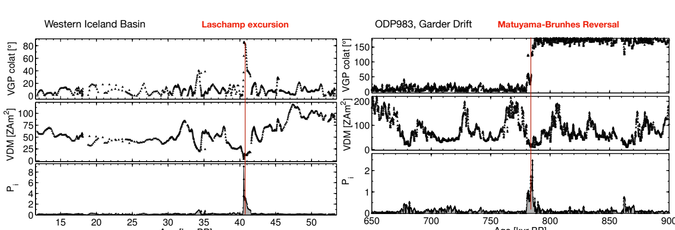
$$P_i(\theta,\phi,t) = \frac{|\pi/2 - \lambda_p(\theta,\phi,t)|/\pi}{M(\theta,\phi,t)/M_0} = \frac{|\pi/2 - \lambda_p(\theta,\phi,t)|\, M_0}{\pi\, M(\theta,\phi,t)}$$

Excursional behavior for $P_i > 0.5$



Panovska & Constable, 2017, doi: 10.1002/2016GC006668 22

Paleomagnetic records from sediments

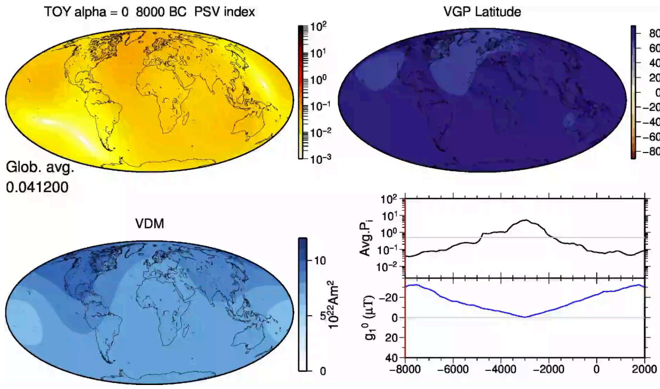


Laschamp Excursion at 41 ka **M-B Reversal at 780 ka**

Panovska & Constable, 2017, doi: 10.1002/2016GC006668

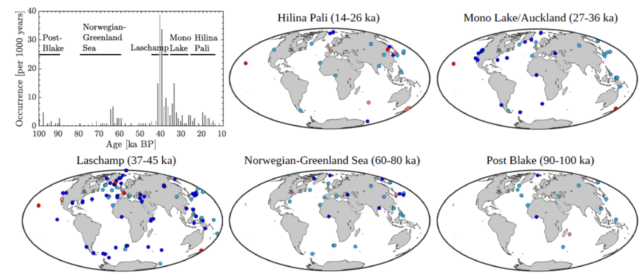
- How long does a reversal or excursion take? That depends on where you look and the definition used.
- VGP latitude less than 45 degrees is one definition of a transitional field. But that will occur at different times in different locations. And it ignores changes in VDM. Can use PSV index instead.
- Are excursions “failed reversals” or are excursions and reversals both part of a continuum of field behavior, representing very strong paleosecular variation (PSV)?

Toy model that simulates an excursion by forcing the axial dipole to decay to zero and then recover while preserving ordinary secular variation in the background



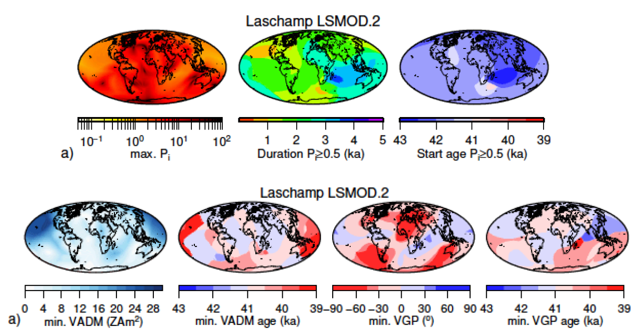
Brown & Korte, 2016, http://dx.doi.org/10.1016/j.pepi.2016.03.003

Excursions that have been proposed for 0-100 ka



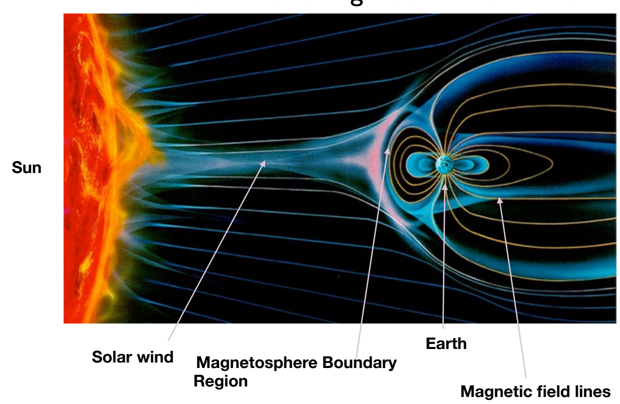
Panovska et al., 2019, doi: 10.1029/2019RG000656

Excursions have variable temporal and spatial structure.
The Laschamp excursion has been mapped globally.



Panovska et al., 2019, doi: 10.1029/2019RG000656

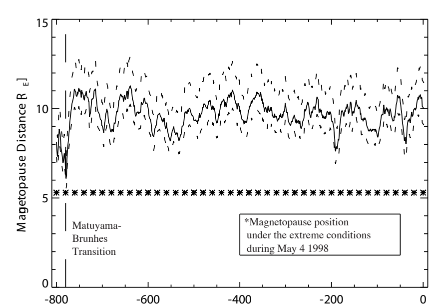
The Normal Geomagnetic Environment



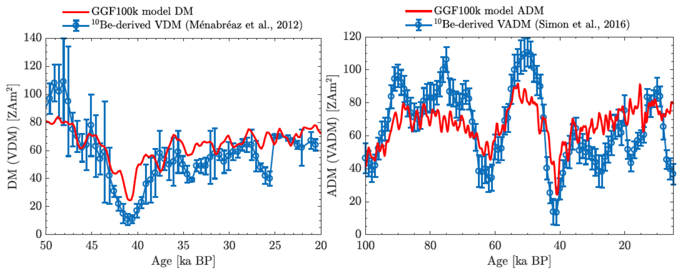
Consequences of Magnetic Excursions or Reversals

- space weather and climate are related to sunspot evolution & related compression of magnetosphere which moves the magnetopause
- solar energetic particle precipitation from solar wind - distributions and amount will change
- possible health effects due to increased atmospheric activity, decreased ozone, and increased cosmic ray flux
- solar magnetic storms may have larger effect than reversals, depending on details of magnetic field structure when field strength is low.

Magnetopause moves inwards during reversals, excursions, and magnetic storms



Dipole Moment - from paleomagnetic field model and cosmogenic isotopes



Summary

- Reversals are studied from marine magnetic anomaly data and paleomagnetic data from igneous and sedimentary rocks which are combined with radiometric dating to provide the magnetostratigraphic time scale.
- On average reversals have occurred at a rate about 2/My, but the rate is highly variable. Their timing is considered random. Long intervals (>20 Myr) with no reversals have occurred several times in Earth's history.
- Estimates of time taken for a reversal range from less than a century to 22,000 years. Very rapid directional changes are possible at times of low field strength.
- Structure of the Laschamp excursion (at ~41 ka) is temporally and spatially variable.
- Large decrease in field strength will affect interactions with the solar wind, changing size and possible shape of magnetosphere, with possible interactions with the upper atmosphere

Extra Reading

For much more on excursions see
Laj & Channell (2017) http://dx.doi.org/10.1016/B978-0-444-53802-4.00104-4

and on reversals
Glatzmaier & Coe (2017) http://dx.doi.org/10.1016/B978-0-444-53802-4.00146-9

Effects on the Biosphere
Glassmeier & Vogt (2010) doi:10.1007/s11214-010-9659-6.