Comp. by: womat Date:9/2/07 Time:20:06:24 Stage:First Proof File Path://spiina1001z/womat/production/
PRODENV/0000000005/0000001725/0000000022/000000A294.3D Proof by: QC by:

The time span between two successive reversals appears to be random. Many statistical analyses were aimed at detecting periodicities or recurrent features, which would be hidden behind the succession of reversals. The succession of polarity intervals is closely approximated by a Poissonian distribution or at least by a gamma process if one assumes that short events have been missed in the reversal sequence. One can always consider that subsequent refinement of the reversal sequence can change this view. A critical aspect is the presence of field excursions which large deviations from the geocentric axial dipole during periods of very-low-field intensity. Excursions and reversals share common characteristics, which suggest that they could be treated as manifestations of similar processes within the core. In fact many authors proposed that excursions must be seen as aborted reversals whereas others regard them as intrinsic secular variation in presence of a weak dipolar field. In the first case, they should be treated at the same level as reversals in the statistics, which would provide a very different picture of the field. A critical point to answer these problems would be to determine whether excursions existed during the superchrons.

Dating reversals and estimating their duration

The age of the successive reversals is critical for analyzing their succession. As described earlier most reversals were dated by extrapolating the ages of the recent reversals after combining the spreading rates. Very significant progress was accomplished during the past 20 years with the discovery that carbonated sediments revealed the succession of the orbital cyclicities of the Earth (23 ka). The ages of the Pliocene and Pleistocene reversals were refined by using this independent method (Shackleton *et al*., 1990; Tauxe *et al*., 1992, 1996; Channel and Kleiven, 2000) which relies on correlating climate proxies (such as oxygen isotope ratios, susceptibility or density variations . . . or simply counting the astronomical cycles recorded in continuous sedimentary sequences) with calculated variations of the Earth's orbit. Using seafloor spreading rates for five plate pairs, Wilson (1993) has shown that the errors in the astronomical calibration are not greater than 0.02 Ma (which corresponds to a precessional cycle of the Earth's orbit) and also that spreading rate can remain constant for several million years.

A critical question that comes to mind is how long it takes for the field to reverse from one polarity to the other. Before dealing with this aspect, it is important to determine when a reversal starts and when it ends. There are many observations showing successions of large oscillations (Hartl and Tauxe, 1996; Dormy *et al*., 2000) preceding or following polarity changes, and it is not clear whether or not they should be incorporated in the reversal process. Such oscillations can be linked to enhanced secular variation in presence of low dipole field. Alternatively, they can be considered as successive attempts by the field to reverse. Important also is the definition of a transitional direction, which must exceed the normal range of secular variation (i.e., the range of the field variations during periods of polarity). Limits on the virtual geomagnetic pole (VGP) latitudes have been mostly used since it is rare that VGPs reach latitudes lower than 60°, although a strict definition should be restrained to positions lower than 45° (episodes of large secular variation can occasionally reach these latitudes).

The sharp transition between magnetic anomalies of opposite polarities, the very narrow thickness of the intervals recording sedimentary columns as well as the small number of lava flows with directions being unambiguously identified as "intermediate" between the two polarities were rapidly convincing and strong evidences that reversals are short phenomena on a geological timescale. The data recorded from the best continuous and documented sedimentary sequences indicate that the jump between the two polarities is shorter than one precessional cycle (23 ka). If we refer to radiometric dating (e.g., K–Ar or Ar–Ar techniques) of lava flows, the problem is delicate because of the sporadic succession of the flows characterized by pulses of eruptions occurring over a short period and long intervals without any magmatic event. A direct consequence is that sequences of lavas provide only very partial records of one or several phases of the reversal but not the entire process. Finally and even more critical is the fact that uncertainties on the ages cannot be ruled out as this is clearly illustrated by the large number of studies performed on the last reversal (Brunhes–Matuyama). The compilation of K–Ar and/or Ar–Ar dating (Quidelleur *et al*., 2003) for 23 volcanic records indicates an age of 789 ± 8 ka (total error). The tuning of the $\delta^{18}O$ records from sedimentary sequences to orbital forcing models gives an age of 779 ± 2 ka (Tauxe *et al*., 1996). Recently, Singer *et al.* (2005) mentioned that the astronomical determination is close to the age of the lavas from Maui (Hawaii) (776 ± 2 ka), and therefore that the other volcanic records are related to the onset of the transitional process. Consequently they deduce that a field reversal would require a significant period. One can oppose that there is no reason to consider that the onset of the reversal was initiated at the same time everywhere but above all if we consider the total uncertainties on the ages, there is no significant difference. Actually this uncertainty leaves doubts as to the possibility of constraining the duration of the transition with precision. There is also no reason to consider that all reversals have the same duration. Most studies converge to estimates between 5 and 10 ka but durations as short as 1 ka or as long as 20–30 ka have been proposed also. Clement (2004) recently analyzed the four most recent reversals recorded in sediments with various deposition rates and found a mean average duration of 7 ka for the directional changes (Figure G42). An interesting characteristic is that the mean duration seems to vary with latitude, as expected from simple geometrical models in which the nondipole fields are allowed to persist while the axial dipole decays through zero and then builds in the opposite direction.

The reversing field

Recorded by sediments

There has been a great deal of speculations concerning the processes governing field reversals. In order to decipher the mechanisms it was important to focus on the morphology of the field during the transition from one polarity state to the other. The first major step was to determine whether this "transitional" field would keep its dipolar dominant character. To achieve this goal, the paleomagnetists took advantage of

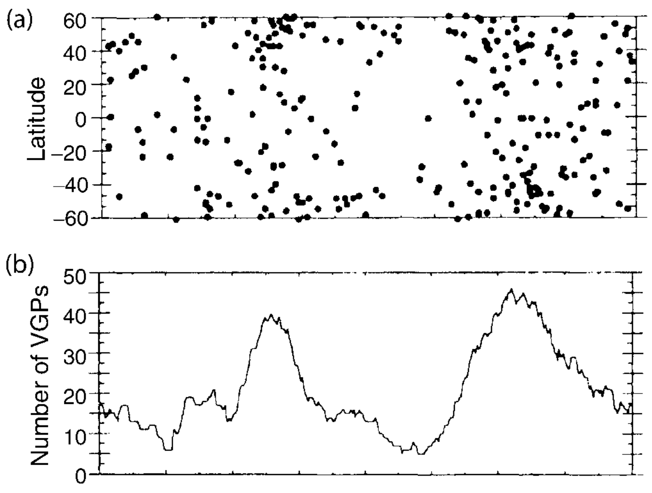

Figure G42 (a) Geographical distribution of Matuyama–Brunhes transitional VGPs derived from a selection of sedimentary records of the last reversal (from Clement, 1991). (b) Longitudinal distribution of transitional VGPs plotted as the number of transitional VGPs in a sliding 30° wide longitude window. Note the presence of two peaks over the American and Asian continents.

the concept of the VGP, which defines the position of the pole assuming that the field is dominantly dipolar. The idea was very simple. If the field remained dipolar, then any vector at the surface of the Earth would point toward the same pole following the rotation of the dipole with its north (south) pole passing to the (south), while in the opposite situation the poles would be different at any site. Using the first records from sediments, it was rapidly shown that the field was not dipolar during reversals (Dagley and Lawley, 1974; Hillhouse and Cox, 1976). In the meantime the first records of paleointensity established that the field intensity was systematically very low during the transitions. This decrease in dipole intensity is necessary before directions depart significantly from dipolar ones (Mary and Courtillot, 1993) and therefore consistent with the concept of a nondipolar field. The nature of this nondipolar field is one of the major questions to elucidate.

Two objectives were pursued in order to provide some answers to this question—the first one relied on the acquisition of multiple records of the same transition. It was proposed that because the Earth's rotation keeps a major role in field regeneration the transitions would be dominated by axisymmetrical components (quadripolar or octupolar). This suggestion could be tested at least at the first order by referring again to the useful concept of the VGPs. Indeed to satisfy the axial symmetry, the VGPs always follow the great circle passing through the observation site (or its antipode), which implies to study the same reversals at different sites. Records from sediments were appropriate because the transitions can be identified without ambiguity and thus correlated from widely separated sites. In the meantime the development of cryogenic magnetometers was very helpful as they provided the possibility of measuring weakly magnetized sediments. The results established that the VGP trajectories were effectively constrained in longitude but in many cases 90° away from the site meridian rather than centered above it.

The second objective was to investigate whether successive reversals were characterized by some recurrent or persistent features. This required studying sequences of reversals at the same site. Again long sequences of marine sediments were appropriate for this kind of study as well as the use of VGP paths, despite the dominance of nondipolar components. The most appealing observation emerged from a selection of sedimentary records (Clement, 1991; Tric *et al*., 1991), which were all showing VGP paths within two preferred longitudinal bands, over the Americas and eastern Asia. Going one step further Laj *et al*. (1992) noted that these areas coincide with the cold circum Pacific regions in the lower mantle (outlined by seismic tomography), thereby suggesting that density or temperature conditions in the lower mantle could control the geometry of the reversing field. However, this observation was controversial because it relied on a selection of records. Another intriguing characteristic (Valet *et al*., 1992; McFadden *et al*., 1993) was the fact that these VGP paths were also found 90° away from the longitude of their sites despite their relatively wide geographic distribution (Figure G43), which could suggest some artifacts in the recording processes. Several studies effectively questioned the fidelity of sediments as recorders of the field variations, particularly during periods of low field intensity. Many factors (compaction, alignment of the elongated particles) reduce the inclination of the magnetization, a process that moves the VGPs paths far away from the longitude of the observation sites (Rochette, 1990; Langereis *et al*., 1992; Quidelleur and Valet, 1994, 1995; Barton and McFadden, 1996,). There is also some indication that for some sediments the magnetic torque generated by a weak field is too low to provide accurate orientation of the magnetic grains, leaving in this case a prominent role to the hydrodynamic forces. These problems suggest that sediments could not be as appropriate as it was originally thought to study reversals.

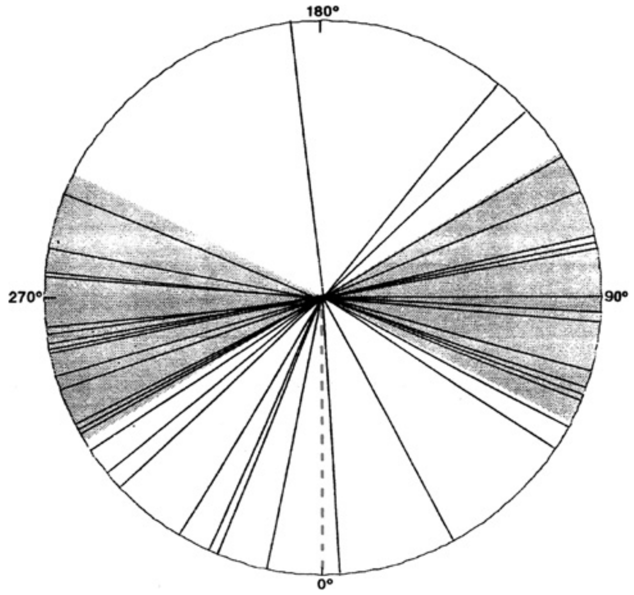

Figure G43 Distance between the mean longitudes of the virtual geomagnetic poles (VGPs) and their site meridian. Note that most lie 90° away from their site longitude.

Recorded by volcanic lava flows

One must thus turn toward volcanic records keeping in mind that in this case we are faced to the very discontinuous character of the eruption rates. Following the presentation of preferred longitudinal bands, Prévot and Camps (1993) compiled all volcanic records with VGPs latitudes lower than 60°, considering only one position for poles that were identical or very close to each other. They observed that no preferred longitudinal band emerged from this database. Love (1998) questioned this interpretation, arguing that similar directions from successive flows should not be averaged, because they do not necessarily result from a very rapid succession of eruptions. Instead he treated each individual flow as a single time event (implying no correlation between successive flows (Figure G44), or identically that the duration between flows was larger than the typical correlation times of secular variation). Because VGPs obtained from volcanics can reach latitudes as low as 45–50° during episodes of large secular changes (and of course excursions), it is also important to restrain the analysis to the most transitional directions, i.e., those with VGP latitudes less than 45°. Unfortunately in this case the number of points becomes too small to perform any robust analysis. This illustrates the difficulties of finding detailed records of reversals but also implies and confirms that indeed transitions occur very rapidly.

Using another selection of records, Hoffman (1991, 1992, 1996) pointed out the existence of clusters of VGPs in the vicinity of South America and above western Australia. Because of the apparent longevity of these directions they were interpreted as indicating the existence of a persistent inclined dipolar field configuration during the reversal process. This is an attractive suggestion, which would establish some link between the sedimentary and the volcanic records but limited to a selection of data.

It is striking that these interpretations depend on the chronology of the lava flows. Volcanism is mostly governed by short periods of intense eruptions alternating with quiet intervals. It is usually admitted that the active periods can be very short with respect to the intervals of quiescence. An indirect "magnetostratigraphic" indication has been given by three parallel sections of Hawaii (Herrero-Bervera and Valet, 1999, 2005), which are not distant, by more than a few kilometers. They all recorded the same reversal but do not show the same successions of transitional directions. Clusters of similar directions can be present in one section without being recorded 2 km away. Similarly apparent rapid changes can be observed in detail in one case and be absent 2 km away. In the first case, the field remained in the same position during a period short enough for not being recorded in the nearby section. In the second case, the field variations occurred either over a short time interval or the field moved very rapidly and was thus recorded only at a single location. Thus we cannot rule out that the apparent concentrations of VGPs close to South America and western Australia can be purely coincidental so that it cannot be considered yet as certain that long-lived transitional states represent an actual characteristic of the reversing field.

Another approach is to rely exclusively on volcanic records with well-defined pre- and posttransitional directions and a sufficient number of intermediate directions. These records are more significant in terms of transitional field characteristics because they are not associated with uncertainties about the origin of the directions and their stratigraphic relation. The distribution of poles extracted from this limited database does not display any preferred location, nor does it show any evidence for systematics in the reversal process (Figure G45). Note also the presence of clusters at various longitudes and latitudes.

Despite the difficulties inherent to the interpretation of sedimentary and volcanic transitional directions, the two kinds of data may share some common characteristics. We already noted a possible link between the volcanic clusters and the preferred VGP paths in sediments but outlined some difficulties in reconciling these two aspects. Another important issue is that the two kinds of records are associated with very different timing in the acquisition of their magnetization, the almost instantaneous cooling of the lavas being almost opposite to the slow processes governing the lock-in of magnetization in sediments. It is thus more justified to attempt a comparison by considering sediments with very high deposition rates in order to reach a better resolution (for magnetization acquisition) thus closer to the volcanic characteristics. A few detailed sedimentary records with deposition rates exceeding 5 cm per 1 ka have been published (Valet and Laj, 1984; Clement and Kent, 1991; Channell and Lehman, 1997). A dominant and common characteristic is that they display a complex structure with large directional variations preceding and/or following the transition which reminds the features seen in the volcanics (Mankinen *et al*., 1985; Chauvin *et al*., 1990; Herrero-Bervera and Valet, 1999). These large loops share similarities with the secular variation of the present field. This observation reinforces the simplest model initially suggested by Dagley and Lawley (1974) of a rather complex transitional field which would be dominated by nondipole components following the large drop of the dipole field (Valet *et al*., 1989; Courtillot *et al*., 1992).

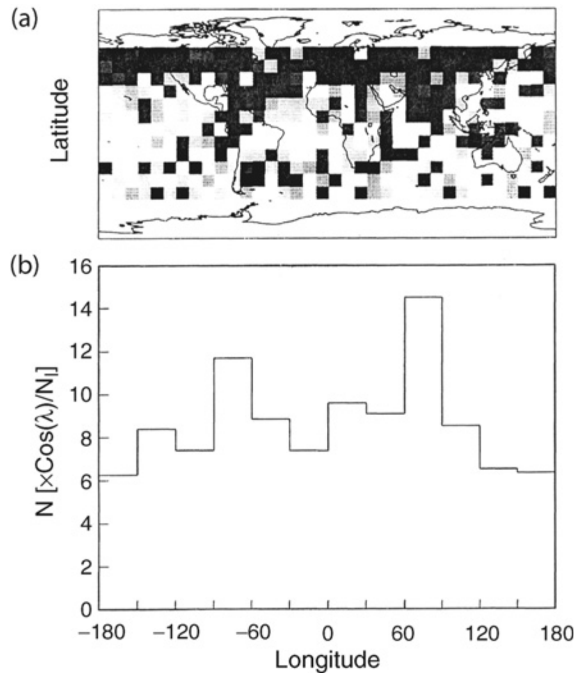

Figure G44 (a) Map of gray-scale histogram of the VGPs from volcanic lava flows with latitudes that are low enough for being considered as transitional (from Love *et al*., 1998). (b) Histogram showing their longitudinal distribution. All lava flows were considered and thus not necessarily incorporated within a sequence of overlying flows. The similar directions that could be linked to a phase of rapid volcanic eruptions were considered as a result of a random process and thus were all taken in consideration. The database is strongly dominated by Icelandic lava flows.

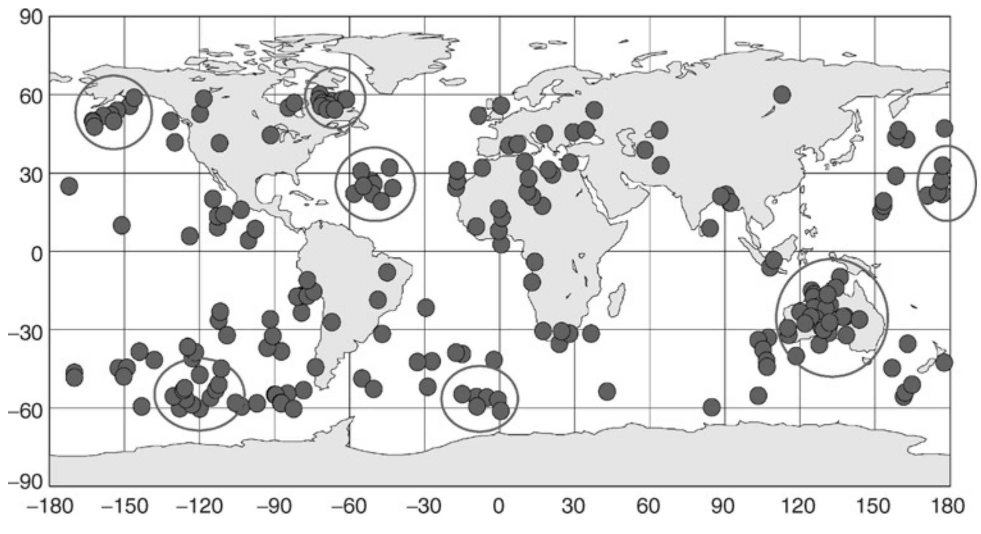

Figure G45 Positions of the VGPs derived from the most detailed volcanic records of reversals published so far. In contrast with Figure G44 no Icelandic sequence of superimposed flows met the selection criteria. Note also the large number of clusters (surrounded by circles) at various locations of the globe.

Comp. by: womat Date:9/2/07 Time:20:06:27 Stage:First Proof File Path://spiina1001z/womat/production/
PRODENV/0000000005/0000001725/0000000022/000000A294.3D Proof by: QC by:

Fast impulses during reversals?

The existence of fast impulses during the 16 Ma old reversal recorded at the Steens Mountain in Oregon (Mankinen *et al*., 1985) was suggested from a puzzling progressive evolution of the paleomagnetic directions in the interiors of two transitional lava flows (Coe and Prévot, 1989; Camps *et al*., 1999). Each lava unit recorded a complete sequence of directions going all the way from that of the underlying flow to the direction of the overlying flow. In the absence of any clear evidence for anomalous rock magnetic properties, these features have been interpreted in terms of very fast geomagnetic changes, which would have reached 10° and 1000 nT per day. For comparison values typical of the present-day secular variation of the field (of internal origin) are of the order of 0.1° and 50 nT per year, i.e., some 10^4 times slower. In this specific case the timing of these fast changes can be constrained by estimates of the cooling times of individual flows.

However, such rapid changes do not seem to be compatible with accepted values of mantle conductivity (Ultré *et al*., 1995). As a consequence this interpretation of the magnetization generated exciting controversy. Additional detailed investigations have been conducted in order to see whether this situation could not have arisen because of remagnetization of the flows. Remagnetizations of lava flows, yielding complex or unusual directions, have been detected at several locations where reversals have been recorded. A first interesting example was given by Hoffman (1984) from Oligocene basaltic rocks. Valet *et al*. (1998) observed the coexistence of both polarities (with similar characteristics as for the directions recorded at Steens Mountain) within flows marking the last reversal boundary (0.78 Ma) at the Canary Islands, and also in a lava flow associated with the onset of the upper Réunion subchron (2.13 Ma) in Ethiopia. In these cases, a purely geomagnetic interpretation would imply that a full reversal took place in only a few days. Similarly to the Steens Mountain, there is no striking difference between the rock magnetic properties of these units and the rest of the sequence, but a scenario involving thermochemical remagnetization is not incompatible with the results. Thermochemical magnetic overprinting can be particularly serious when it affects a flow emplaced at a time of very low field intensity, sandwiched between flows emplaced at a time of full (stable polarity) intensity. Recent investigation of additional flows at Steens did not shed more light on this problem but rather casts doubts on a geomagnetic interpretation of the paleomagnetic directions (Camps *et al*., 1999). Therefore, the existence of very large and rapid changes that have been documented from a single site by a unique team remains controversial. In the meantime no alternative explanation has been completely accepted yet.

Field intensity variations across reversals

Variations in field intensity accompanying the reversals provide important and unique information concerning the transition itself but also the evolution of the dipole prior and after the reversals. We mentioned earlier that a significant decrease of the dipole was reported since the earliest studies. It is well established, based on all sedimentary as well as volcanic records that field intensity drops significantly and in most cases these changes last longer than directional changes (see e.g., Lin *et al*., 1994; Merrill and Mc Fadden, 1999). Note that similar drops have been mentioned in all records of excursions with one exception (Leonhardt *et al*., 2000). Initially, the records were restrained to the transitional interval or to a few thousand years preceding and following the reversal. Several long records of relative paleointensity have now been obtained using sequences of deep-sea sediments, which make possible to observe the evolution of the field over a long period. These independent records from sediment cores in different areas of the world can be stacked together to extract the evolution of the geomagnetic dipole moment (Guyodo and Valet, 1996, 1999; Laj *et al*., 2000). There is a remarkable consistency between the first stacks published for the past 200 and 800 ka and a similar approach performed from field measurements immediately above bottom seafloor magnetic anomalies (Gee *et al*., 2000). There is also a good agreement with the cosmogenic isotopic records (Frank *et al*., 1997; Baumgartner *et al*., 1998; Carcaillet *et al*., 2003, 2004; Thouveny *et al*., 2004). Apart many other interesting observations a dominant feature is the existence of a large drop of intensity about every 100 ka, which coincide with excursions reported from various sequences in the world.

The most recent curve of relative paleointensity was extended to the past 2 Ma (Valet *et al*., 2005) and is in good agreement with the absolute dipole moments derived from volcanic lavas, which were used for calibration. It shows that the time-averaged field was higher during periods without reversals but the amplitude of the short-term oscillations remained the same. As a consequence, few intervals of very low intensity and thus less instability are expected during periods with a strong average dipole moment, whereas more excursions and reversals are produced during periods of weak field intensity. Prior to reversals, the axial dipole decays during 60 to 80 ka, but rebuilds itself in the opposite direction in a few thousand years at most (Figure G46). The most complete volcanic records confirm that recovery following a transition is short and culminates to very high values. The detailed volcanic records including determinations of absolute paleointensity provide support for such an asymmetry. Strong posttransitional field values have been reported in a Pliocene reversal recorded at Kauai (Bogue and Paul, 1993) and in the upper Jaramillo (0.99 Ma) subchron recorded from Tahiti (Chauvin *et al*., 1990) as well as for the lower Mammoth reversal (3.33 Ma) from Hawaii. The same characteristics emerge also from the 60 Ma oldest record obtained so far in Greenland (Riisager and Abrahamsen, 2000), from the 15 Ma old Steens Mountain reversal (Prévot *et al*., 1985) and from the last reversal (0.78 Ma) recorded from La Palma in the Canary Islands (Valet *et al*., 1999).

Conclusion and perspectives

Several hundreds reversals have been documented from geological records and it is not unlikely, yet not demonstrated, that reversals always accompanied the existence of the geomagnetic field. Their internal origin neither makes any doubt. Many numerical models for the Earth's dynamo were produced during the last decade, including three-dimensional self-consistent dynamos that exhibit magnetic reversals. However, mostly for computation difficulties the parameters used remain far away from the Earth. This demonstrates the importance of

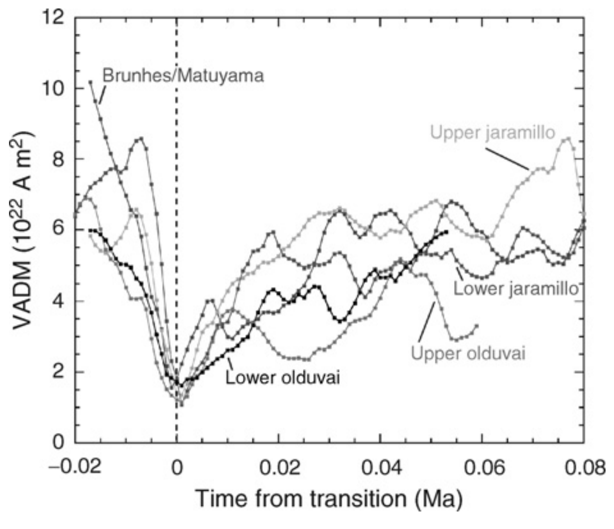

Figure G46 Field intensity variations across the five reversals occurring during the past 2 Ma. In this figure we superimposed the changes in dipole moment during the 80 and 20 ka time intervals, respectively preceding and following each reversal. Note the 60–80 ka long decrease preceding the reversals, and the rapid recovery following the transitions.

accumulating data. For about 30 years the paleomagnetists attempted to acquire as many detailed records as possible using the magnetic memory of sediments and lava flows. One of the first objectives was to determine whether the field keeps its dipolar character when reversing. The complexity of the directional changes shown by the detailed records and the large decrease of the field intensity indicates that the dipolar component strongly decreases by at least 80%, if not vanishing completely. One of the major constraints is the rapidity of the reversal process. There is no clear estimate for reversal duration, which may vary. Indeed it seems easier to isolate transitional directions for some reversals than for some others. There is no estimate for a lower limit of the duration of a transition which could be as short as a few hundreds years, if not less. It is reasonable to consider that the upper limit does not exceed 20 ka. After many years the suitability of sedimentary records (which have the advantage of preserving continuous information on field evolution) has been heavily questioned because their direction of magnetization can be affected by other factors (climate, alignment of the magnetic grains, postdepositional reorientations), particularly in presence of low field intensity. It is thus wise to turn also toward volcanic records despite their intrinsic limits in terms of resolution and dating. If we refer to the existing volcanic database, different views are presently defended regarding the field configuration during the short transitional period. Some claim that there is a dominance of the pole positions within preferred longitudinal bands, particularly within the American and Australian sectors, while others oppose rock magnetic artifacts and defend that the distribution of the transitional directions is typical of a nondipole field that would be similar to the present one. These two views have different implications and impose different constrains. The first one assumes that the lower mantle exerts some control on the reversal processes while the alternative interpretation defends that the transitional field would result from intrinsic processes linked to the dynamic of the core fluid. Another aspect is the existence of precursory events. The complexity of the field evolution prior to reversals depicts some "excursions" of the directions that are interpreted as precursory events. This observation can be linked to the long-term decay of the dipole component prior to the reversal, which is responsible for the complexity of the directional changes observed at the surface. Under this scenario the "precursory" excursions simply reflect the dominance of the nondipole part of the field, which will then prevail during the transition. Finally, a fast and strong recovery takes place immediately after the transition. The amplitude of this restoration phase is certainly critical as recent observations suggest that the dipole field strength could be a dominant factor controlling the frequency of reversals.

Jean-Pierre Valet

Bibliography

Barton, C.E., and McFadden, P.L., 1996. Inclination shallowing and preferred transitional VGP paths. *Earth and the Planetary Science Letters*, **140**: 147–157.

Baumgartner, S., Beer, J., Masarik, J., Wagner, G., Meynadier, L., and Synal, H.-A., 1998. Geomagnetic modulation of the ^{36}Cl flux in the Grip ice core, Greenland. *Science*, **279**: 1330–1332.

Bogue, S.W., and Paul, H.A., 1993. Distinctive field behaviour following geomagnetic reversals. *Geophysical Research Letters*, **20**: 2399–2402.

Brunhes, B., 1903. Sur la direction de l'aimantation permanente dans diversees roches volcaniques. *Comptes Rendus De l Academie Des Sciences Paris*, **137**: 975–977.

Brunhes, B., 1905. Sur la direction de l'aimantation dans une argile de Pontfarein. *Comptes Rendus De l Academie Des Sciences Paris*, **141**: 567–568.

Camps, P., Coe, R.S., and Prévot, M., 1999. Transitional geomagnetic impulses hypothesis: geomagnetic fact or rock magnetic artifact? *Journal of Geophysical Research*, **104**(B8): 17747–17758.

Carcaillet, J., Thouveny, N., and Bourlès, D., 2003. Geomagnetic moment instability between 0.6 and 1.3 Ma from cosmonuclide evidence. *Geophysical Research Letters*, **30**(15): 1792.

Carcaillet, J., Bourlès, D.L., Thouveny, N., and Arnold, M., 2004. A high resolution authigenic ^{10}Be/^{9}Be record of geomagnetic moment variations over the last 300 ka from sedimentary cores of the Portuguese margin. *Earth and Planetary Science Letters*, **219**: 397–412.

Channell, J.E., and Kleiven, H.F., 2000. Geomagnetic paleointensity and astronological ages for the Matuyama–Brunhes boundary and the boundaries of the Jaramillo subchron: paleomagnetic and oxygen isotope records from ODP site 983. *Philosophical Transactions of the Royal Society of London A*, **358**: 1027–1047.

Channell, J.E.T., and Lehman, B., 1997. The last two geomagnetic polarity reversals recorded in high deposition-rate sediments drifts. *Nature*, **389**: 712–715.

Chauvin, A., Roperch, P., and Duncan, R.A., 1990. Records of geomagnetic reversals from volcanic islands of French Polynesia. *Journal of Geophysical Research*, **95**: 2727–2752.

Clement, B.M., 1991. Geographical distribution of transitional VGPs: evidence for non zonal equatorial symmetry during the Matuyama–Brunhes geomagnetic reversal. *Earth and Planetary Science Letters*, **104**: 48–58.

Clement, B.M., 2004. Dependence of the duration of geomagnetic polarity reversal. *Nature*, **428**: 637–640.

Coe, R.S., and Prévot, M., 1989. Evidence suggesting extremely rapid field variation during a geomagnetic reversal. *Earth and Planetary Science Letters*, **92**: 292–298.

Courtillot, V., Valet, J.-P., Hulot, G., and Le Mouël, J.-L., 1992. The Earth's magnetic field: which geometry? *EOS Transactions, American Geophysical Union*, **73**(32): 337.

Cox, A., Doell, D.R., and Dalrymple, G.B., 1963. Geomagnetic polarity epochs and Pleistocene geochronometry. *Nature*, **198**: 1049.

Dagley, P., and Lawley, E., 1974. Paleomagnetic evidence for the transitional behaviour of the geomagnetic field. *Geophysical Journal of the Royal Astronomical Society*, **36**: 577–598.

Dormy, E., Valet, J.-P., and Courtillot, V., 2000. Observational constraints and numerical dynamos. *Geochemistry, Geophysics and Geosystems*, **1**: Vol1, N°10, doi:10,1029/2000GCD00062.

Frank, M., 1997. A 200 ka record of cosmogenic radionuclide production rate and geomagnetic field intensity from ^{10}Be in globally stacked deep-sea sediments. *Earth and Planetary Science Letters*, **149**: 121–129.

Gee, J., Cande, S.C., Hildebrand, J.A., Donnelly, J.A., and Parker, R.L., 2000. Geomagnetic intensity variations over the past 780 ka obtained from near-seafloor magnetic anomalies. *Nature*, **408**: 827–832.

Guyodo, Y., and Valet, J.P., 1996. Relative variations in geomagnetic intensity from sedimentary records: the past 200 thousand years. *Earth and the Planetary Science Letters*, **143**: 23–26.

Guyodo, Y., and Valet, J.P., 1999. Global changes in intensity of the Earth's magnetic field during the past 800 ka. *Nature*, **399**: 249–252.

Hartl, P., and Tauxe, L., 1996. A precursor to the Matuyama/Brunhes transition-field instability as recorded in pelagic sediments. *Earth and the Planetary Science Letters*, **138**: 121–135.

Herrero-Bervera, E., and Valet, J.-P., 1999. Paleosecular variation during sequential geomagnetic reversals from Hawaii. *Earth and the Planetary Science Letters*, **171**: 139–148.

Herrero-Berrvera, E., and Valet, J.P., 2005. Absolute paleointensity from the Waianae volcanics (Oahu, Hawaii) between the Gilbert-Gauss and the upper Mammoth reversals. *Earth and the Planetary Science Letters*, **234**: 279–296.

Hillhouse, J., and Cox, A., 1976. Brunhes–Matuyama polarity transition. *Earth and the Planetary Science Letters*, **29**: 51–64.

Hoffman, K.A., 1984. Late acquisition of "primary" remanence in some fresh basalts: a case of spurious paleomagnetic results. *Geophysical Research Letters*, **11**: 681–684.

Hoffman, K.A., 1991. Long-lived transitional states of the geomagnetic field and the two dynamo families. *Nature*, **354**: 273–277.

Hoffman, K.A., 1992. Dipolar reversal states of the geomagnetic field and core–mantle dynamics. *Nature*, **359**: 789–794.

Hoffman, K.A., 1996. Transitional paleomagnetic field behavior: preferred paths or patches? *Surveys in Geophysics*, **17**: 207–211.

Hulot, G., and Gallet, Y., 2003. Do superchrons occur without any paleomagnetic warming? *Earth and the Planetary Science Letters*, **210**: 191–201.

Laj, C., Mazaud, A., Weeks, R., Fuller, M., and Herrero-Bervera, E., 1992. Geomagnetic reversal paths. *Nature*, **351**: 447.

Laj, C., Kissel, C., Mazaud, M., Channell, J.E.T., and Beer, J., 2000. North Atlantic paleointensity stack since 75 ka (NAPIS 75) and the duration of the Laschamp event. *Philosophical Transactions of the Royal Society of London A*, **358**: 1009–1025.

Langereis, C.G., van Hoof, A.A.M., and Rochette, P., 1992. Longitudinal confinement of geomagnetic reversal paths. Sedimentary artefact or true field behavior? *Nature*, **358**: 226–230.

Love, J.J., 1998. Paleomagnetic volcanic data and geometric regularity of reversals and excursions. *Journal of Geophysical Research*, **103**(B6): 12,435–12,452.

Leonhardt, R., Hufenbecher, F., Heider, F., and Soffel, H.C., 2000. High absolute paleointensity during a mid Miocene excursion of the Earth's magnetic field. *Earth and the Planetary Science Letters*, **184**(1): 141–154.

Lin, J.L., Verosub, K.L., and Roberts, P.A., 1994. Decay of the virtual dipole moment during polarity transitions and geomagnetic excursions. *Geophysical Research Letters*, **21**: 525–528.

Mankinen, E.A., Prévot, M., Grommé, C.S., and Coe, R.S., 1985. The Steens Mountain (Oregon) geomagnetic polarity transition. 1. Directional history, duration of episodes and rock magnetism. *Journal of Geophysical Research*, **90**: 10393–10416.

Mary, C., and Courtillot, V., 1993. A three-dimensional representation of geomagnetic field reversal records. *Journal of Geophysical Research*, **98**: 22461–22475.

Matuyama, M., 1929. On the direction of magnetisation of basalt in Japan, Tyosen and Manchuria. *Proceedings of the Imperial Academy of Japan*, **5**: 203.

McFadden, P., and Merrill, R., 1995. Fundamental transitions in the geodynamo as suggested by paleomagnetic data. *Physics of the Earth and Planetary Interiors*, **91**: 253–260.

McFadden, P.L., Barton, C.E., and Merrill, R.T., 1993. Do virtual geomagnetic poles follow preferred paths during geomagnetic reversals? *Nature*, **361**: 342–344.

Mercanton, P.L., 1926. Inversion de l'inclinaison magnétique aux âges géologiques. Nouvelles constattations. *Comptes Rendus De l Academie Des Sciences. Paris*, **192**: 978–980.

Merrill, R.T., and McFadden, P.L., 1999. Geomagnetic polarity transitions. *Reviews of Geophysics*, **37**: 201–226.

Néel, L., 1955. Some theoretical aspects of rock magnetism. *Advances in Physics*, **4**: 191.

Pavlov, V., and Gallet, Y., 1998. Upper Cambrian to Middle Ordovician magnetostratigraphy from the Kulumbe river section (northwestern Siberia). *Physics of the Earth and Planetary Interiors*, **108**(1): 49–59.

Prévot, M., and Camps, P., 1993. Absence of longitudinal confinement of poles in volcanic records of geomagnetic reversals. *Nature*, **366**: 53–57.

Prévot, M., Mankinen, E.A., Coe, R.S., and Grommé, C.S., 1985. The Steens Mountain (Oregon) geomagnetic polarity transition. Field intensity variations and discussion of reversal models. *Journal of Geophysical Research*, **90**: 10417–10448.

Quidelleur, X., and Valet, J.-P., 1994. Paleomagnetic records of excursions and reversals: possible biases caused by magnetization artefacts? *Physics of the Earth and Planetary Interiors*, **82**: 27–48.

Quidelleur, X., Valet, J.-P., Le Goff, M., and Bouldoire, X., 1995. Field dependence on magnetization of laboratory redeposited deep-sea sediments: first results. *Earth and the Planetary Science Letters*, **133**: 311–325.

Quidelleur, X., Carlut, J., Soler, V., Valet, J.-P., and Gillot, P.Y., 2003. The age and duration of the Matuyama–Brunhes transition from new K–Ar data from LaPalma (Canary Islands) and revisited $^{40}Ar/^{39}Ar$ ages. *Earth and the Planetary Science Letters*, **208**: 149–163.

Riisager, P., and Abrahamsen, N., 2000. Paleointensity of west Greenland Paleocene basalts: asymmetric intensity around the C57n-C26r transition. *Physics of the Earth and Planetary Interiors*, **118**: 53–64.

Rochette, P., 1990. Rationale of geomagnetic reversal versus remanence recording process in rocks: a critical review. *Earth and the Planetary Science Letters*, **98**: 33–39.

Shackleton, N.J., Berger, A., and Peltier, W.R., 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions of the Royal Society of Edinburg Earth Science*, **81**: 251–261.

Singer, B.S., Hoffman, K.A., Coe, R.S., Brown, L.L., Jicha, B.R., Pringle, M.S., and Chauvin, A., 2005. Structural and temporal requirements for geomagnetic reversal deduced from lava flows. *Nature*, **434**: 633–636.

Tauxe, L., Deino, A.D., Behrensmeyer, A.K., and Potts, R., 1992. Pinning down the Brunhes/Matuyama and Upper Jaramillo boundaries: a reconciliation of orbital and isotopic timescales. *Earth and the Planetary Science Letters*, **109**: 561–572.

Tauxe, L., Herbert, T., Shackleton, N.J., and Kok, Y.S., 1996. Astronomical calibration of the Matuyama Brunhes Boundary: consequences for magnetic remanence acquisition in marine carbonates and the Asian loess sequences. *Earth and the Planetary Science Letters*, **140**: 133–146.

Thouveny, N., Carcaillet, J., Moreno, E., Leduc, G., and Nérini, D., 2004. Geomagnetic moment variation and paleomagnetic excursions since 400 ka BP: a stacked record of sedimentary sequences of the Portuguese margin. *Earth and Planetary Science Letters*, **219**: 377–396.

Tric, E., Laj, C., Jehanno, C., Valet, J.-P., Mazaud, A., Kissel, C., and Iaccarino, S., 1991. A detailed record of the upper Olduvai polarity transition from high sedimentation rate marine deposits of the Po valley. *Physics of the Earth and Planetary Interiors*, **65**: 319–336.

Ultré-Guérard, P., and Achache, J., 1995. Core flow instabilities and geomagnetic storms during reversals: the Steens mountain impulsive field variation revisited. *Earth and the Planetary Science Letters*, **139**: 91–99.

Uyeda, S., 1958. Thermoremanent magnetism as a medium of paleomagnetism with special references to reverse thermoremanent magnetism. *Japanese Journal of Geophysics*, **2**: 1–123.

Valet, J.-P., and Laj, C., 1984. Invariant and changing transitional field configurations in a sequence of geomagnetic reversals. *Nature*, **311**(5986): 552–555.

Valet, J.-P., Tauxe, L., and Clement, B.M., 1989. Equatorial and mid-latitudes records of the last geomagnetic reversal from the Atlantic Ocean. *Earth and the Planetary Science Letters*, **94**: 371–384.

Valet, J.P., Tucholka, P., Courtillot, V., and Meynadier, L., 1992. Paleomagnetic constraints on the geometry of the geomagnetic field during reversals. *Nature*, **356**: 400–407.

Valet, J.-P., Kidane, T., Soler, V., Brassart, J., Courtillot, V., and Meynadier, L., 1998. Remagnetization in lava flows recording pretransitional directions. *Journal of Geophysical Research*, **103**(B5): 9755–9775.

Valet, J.P., Meynadier, L., and Guyodo, Y., 2005. Geomagnetic field strength and reversal rate over the past 2 Million years. *Nature*, **435**: 802–805.

Wilson, D., 1993. Confirmation of the astronomical calibration of the magnetic polarity timescale from seafloor spreading rates. *Nature*, **364**: 788–790.

Cross-references

Core motions
Geomagnetic dipole field
Geomagnetic excursion
Geomagnetic hazards
Magnetization, chemical remanent (CRM)
Magnetization, depositional remanent (DRM)
Magnetization, natural remanent (NRM)
Non-dipole field
Paleomagnetic secular variation
Paleomagnetism, deep-sea sediments
Polarity transitions: Radioisotopic Dating

GEOMAGNETIC SECULAR VARIATION

Introduction

The term *secular* comes from the Latin *Seculum* which means the duration of the influence of a powerful family becoming steadily less. The Romans accounted 100 years for that, why it also was synonymous for century. In context of geomagnetism it implies a long-term variation of the Earth's magnetic field.

The observed temporal variations of the Earth's magnetic field cover timescales from milliseconds to a few million years and originate in two distinct (external and internal) source regions with respect to the Earth's surface. With this respect the fluctuations of the external field ranges from milliseconds to a few decades, where the longer periods are related to variations of the solar magnetic field, e.g., the turnover of solar magnetic field (about 22 years). Changes of the internal field are of the order of a few years to millions of years. This variation results from the effect of magnetic induction in the fluid outer core and from effects of magnetic diffusion in the core and the mantle. Here, we distinguish geomagnetic secular variation and paleomagnetic secular variation, where the latter includes temporal changes longer than several hundreds of years, such as reversals (see *Reversals, theory*). The overlap of periods of internal and external sources in the range of a few years to decades can be separated in internal and external contributions applying spherical harmonic analysis (see *Internal external field separation*).

The geomagnetic secular variation was first noticed by Gunter and "Gellibrand" in 1635, who collected measurements of magnetic declination made at Limehouse near London between 1580 and 1634. This component gradually changed over the period of 350 years from 11° E to 24° W in 1820, before turning eastward again. Figure G47 shows the declination measured in London and Danzig (Gdansk) for about 350 years. Whereas the main field is dominated by its dipolar nature, the secular variation is clearly nondipolar, which is reflected in regions of different magnitudes of secular variation. For example, in the pacific region the secular variation appears to be crestless. However, the (geomagnetic) secular variation has been observed to be the feature of the main field and not of the local field.

One other prominent feature of the secular variation is the tendency of isoporic foci (areas of maximum secular variation) to drift westward. Analyzes by Vestine *et al*. (1947) and Bloxham *et al*. (1989) found an averaged drift rate of about $0.3° y^{-1}$.

In addition to the slowly varying secular variation event-like features appear, the so-called geomagnetic jerks. Such jerks show up as a change of sign in the slope of the secular variation, a discontinuity in the second time derivative of the field, most clearly seen in the east (Y) component of the geomagnetic field. For the last 100 years at least seven jerks have been reported (1912, 1925, 1969, 1978, 1983, 1991, and 1999), some of them of global extent. The 1969 event (first described by Courtillot *et al*., 1978) was widely investigated; on the basis of observatory records. Courtillot *et al*. (1978) and Malin and Hodder (1982) showed its global extent, although it was not evident in all field components. This fact and the coincidental occurrence of jerks and sunspot maxima set off a lively discussion between Alldredge and McLeod in the 1980s (Alldredge, 1984; McLeod, 1985; Backus *et al*., 1987) about the causative processes of jerks. The general understanding is that jerks are of internal origin, mainly because of two reasons: First, the potential of the solar cycle has approximately the form of zonal spherical harmonics, therefore any contribution to the East component would be small. Jerks are most clearly visible in the East component of European observatories. The second argument is based on a comparison of the strength of the solar maxima adjacent to the 1969 jerk, 1958 and 1980. At both epochs the solar maxima were more pronounced than in 1969, so we would expect two jerks at those epochs, but nothing obvious happened in 1958 and the jerks around 1978 and 1983 do not fit well to the solar maximum in 1980 (see also entry on *Geomagnetic jerks*).

Determination of secular variation models

Before considering the generation of secular variation and its link to other observables of processes in the Earth's core, we shall first describe a modeling approach to map the secular variation at the source region, the core–mantle boundary (CMB).

In principle, the magnetic field and its variation can be separated in parts due to external and internal sources by spherical harmonic analysis (Gauss, 1839). The geomagnetic field is then represented by the so called Gauss coefficients (see entries on *Internal external field separation and Main field modeling*). The variations of the internal field can be modeled by expanding the internal Gauss coefficients in a Taylor series in time about some epoch, t_e, e.g.,

$$g_l^m(t) = g_l^m(t_e) + \dot{g}_l^m(t_e)(t - t_e) + \ddot{g}_l^m \frac{(t - t_e)^2}{2!} + \cdots \qquad \text{(Eq. 1)}$$

where the first time derivative $\dot{g}_l^m$ is the secular variation and the second time derivative $\ddot{g}_l^m$ the secular acceleration. The determinations usually have been truncated after some derivatives. The GSFC(12/66) model (Cain *et al*., 1967) included second time derivatives and the GSFC(9/80) model of the magnetic field between 1960 and 1980 by Langel *et al*. (1982) included third time derivatives. These

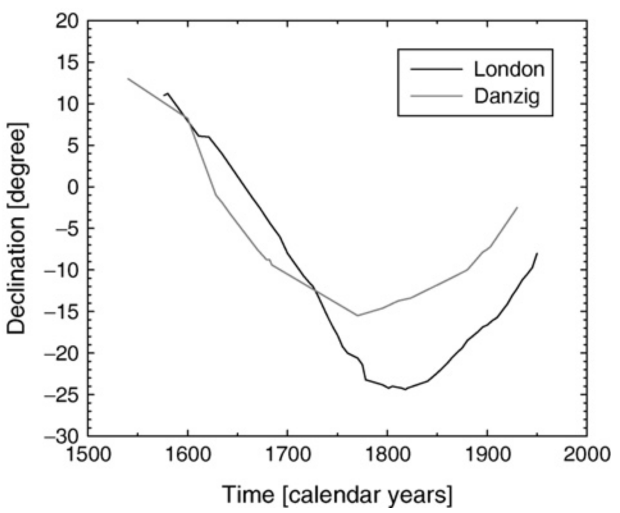

Figure G47 The declination at London and Danzig (Gdansk).

Springer

http://www.springer.com/978-1-4020-3992-8

Encyclopedia of Geomagnetism and Paleomagnetism
Gubbins, D.; Herrero-Bervera, E. (Eds.)
2007, XXVI, 1054 p. 718 illus., 50 illus. in color.,
Hardcover
ISBN: 978-1-4020-3992-8