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Geomagnetic field reversals: Main results and basic problems

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[1] The aim of this paper is to analyze the data available for the characteristics of the geomagnetic field during its reversals using the latest results. The main attention is given to the problems that arise during the interpretation of these data, the solution of which calls for particular attention. *INDEX TERMS:* 1500 Geomagnetism and Paleomagnetism; 1510 Geomagnetism and Paleomagnetism: Dynamo: theories and simulations; 1560 Geomagnetism and Paleomagnetism: Time variations: secular and longer; *KEYWORDS:* Geomagnetic polarity reversals, Dynamo, Magnetic moment.

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In memory of G. N. Petrova

Introduction

[2] The geomagnetic field reversals seem to be among the most interesting phenomena discovered by the science in the 20th century. Naturally, the process of their operation attracted the attention of geoscientists who began to study them at the end of the 1950s to the beginning of the 1960s [*Momose,* 1958; *Nomura,* 1963; *Petrova and Rybak,* 1963; *Sigurgeirsson,* 1957; *Van Zijl et al.,* 1962]. The characteristics of the geomagnetic field during its reversals, that is, during its transitions from one polarity to another, were and still are of great interest to the geoscientists, because the phenomenology of the processes of the destruction and reconstruction of the stationary magnetic moment, apparently reflecting the characteristics of the processes that violate the mechanism of its generation and reconstruction, might provide information for the operation of the dynamo mechanism, might help to understand its physical essence and broaden our knowledge about the structure of the Earth's deep envelopes, and of the processes operating in them in the scale of geological time. Moreover, the discovery of the fact that each individual inversion has its own distinctive features which can be used to recognize it in the paleomagnetic rock sequences, would increase the value of the magnetostratigraphic scale. The second line of research did not give the expected results: inversions turned out to be indistinguishable in terms of the patterns of their operations, which are necessary for using them in stratigraphic studies. Yet, the work done in this line of research resulted in the collection of information which is of great interest for developing a generation theory and verifying its fundamental positions.

[3] The accumulation of data for transitional conditions is a slow process: the detailed records of the polarity reversal process are found rather rarely. Moreover, the correct interpretation of the results calls for the detailed study of not only the transitional interval itself, but also of the adjacent stationary intervals. The latter circumstance was not taken into consideration immediately by the researchers engaged in the studies concerned. Another important circumstance was associated with the fact that studies of this kind called for a significantly larger volume of work. This is especially obvious for the studies of transitional zones in sedimentary rocks, with the high rates of their accumulation. The data available for these zones allow one to characterize the transitional-state field in a required detail.

[4] Naturally, the records of the magnetic field characteristics, which had been imprinted in sedimentary rocks during the magnetic field inversions, contain a great number of discrepancies. The most substantial of them is the potential smoothing (distortion) of the record owing to the different ages of the sedimentation and postsedimentation components of the orientation magnetization and to the presence of some secondary chemical component with the same carrier of these components of natural remanent magnetization (NRM). This problem was discussed in detail by many researchers [*Bolshakov,* 1995; *Khramov,* 1986; *Kok and Tauxe,* 1996a, 1996b; *Langereis et al.,* 1992; *Quidelleur and Valet,* 1994; *Rochette,* 1990; *Tauxe,* 1993], to name but a few. In his paper, *Rochette* [1990] suggests the lowest sedimentation rate of the rocks, suitable for studying transitional conditions, to be 5 cm for 1000 years. At the same time, the use

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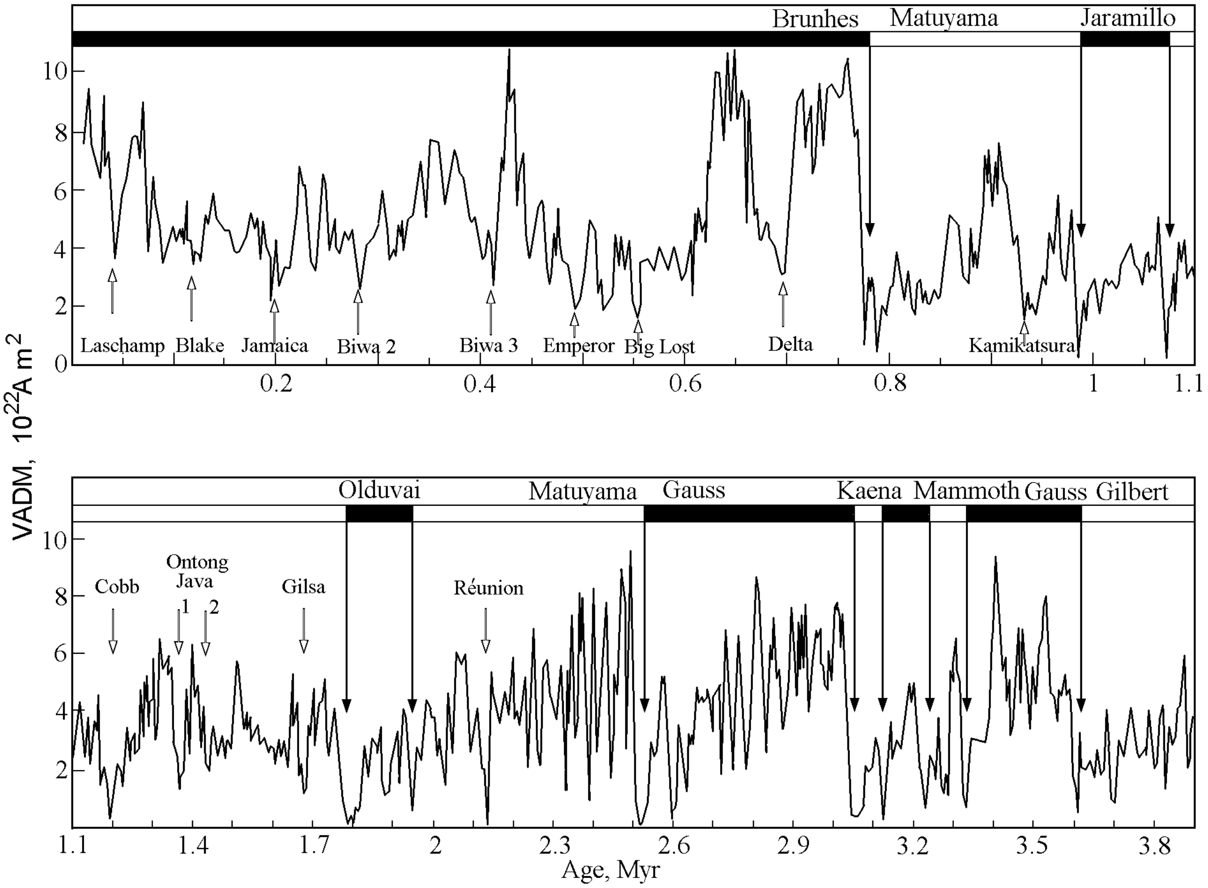

Figure 1. An example of the asymmetrical saw-tooth pattern of the relative paleointensity of the magnetic field during the last 4 million years (cited after Figure 3 from [*Valet and Meynadier,* 1993]).

of the modern techniques of laboratory paleomagnetic studies allows one to obtain data that in many cases most truly reflect the real characteristics of the inverted field.

[5] As more data were accumulated for the transitional conditions, repeated attempts were undertaken to generalize and interpret them. Naturally, the main features of the transitional conditions did not change from one generalization to another, but acquired a more detailed pattern with the growing certainty of the conclusions. Yet, the interpretation of these regular characteristics underwent substantial changes.

[6] Inversions begin with the decline of the magnetic moment (M). At the background of the lowered magnetic moment the virtual geomagnetic poles (VGP) happen to reside at the intermediate and low latitudes, where the successive changes in their positions show both a normal and a chaotic character, moving later to the high latitudes of the opposite hemisphere. The magnetic moment grows to its stationary value.

[7] Although this schematic pattern is basically correct, many of its aspects call for a more detailed description and discussion, which should be based on the data obtained in the course of studying sedimentary rocks using the results obtained during the last several years.

Magnetic Moment Decline and Restoration. The Duration of Inversions

[8] Using their own paleomagnetic data, different authors estimate a decline in the intensity of the old magnetic field H_{old} (or of the magnetic moment M) during the reversal to be 3 to 10 (and more) times. This difference of their estimates is associated mainly with the absence of any distinct level from which this decline can be estimated. Moreover, it should be taken into consideration that these investigators derive their data of the absolute decline of the magnetic field intensity as a result of studying igneous rocks, because in the case of using sedimentary rocks one can deal only with the variations of the parameters associated with paleointensity. Nevertheless, it should be recognized that the data obtained from the studies of different objects usually show some general agreement.

[9] The paleomagnetic records available show that some H_{old} variations took place both before and after the reversal, and that one can judge about the average M level with a stationary field only after the averaging of the recorded variations. Moreover, as stated by some authors [*Meynadier*

et al., 1994, 1998; *Thibal et al.,* 1995; *Valet and Meynadier,* 1993], to name but a few, the H_{old} variations in the periods between the inversions show "an asymmetric saw-tooth pattern": the H_{old} intensity grows abruptly after the end of the inversion, and then, following high-magnitude variations, declines slowly toward the beginning of the next reversal. The general decline in this case amounts to 1.5–2 times, the variation magnitude being as high as ~0.5 H of the average value and the typical variation times ranging from a few hundred to a few thousand years (Figure 1). At the same time, some authors believe that this variation of the parameters characterizing the behavior of the stationary (one-polarity) field might have been associated with the stable viscous magnetization of the rocks [*Hartl and Tauxe,* 1996; *Laj et al.,* 1996], to name but a few.

[10] The analysis of the paleointensity data variation during and in the vicinity of the reversals showed that the average decline of the magnetic field during its reversals had been as high as seven times [*Gurarii,* 1988]. This estimate was obtained for the reversals of the last 15 million years, using the data published prior to 1986. As new data were published, including the detailed descriptions of the near-reversal variations of the geomagnetic field, this estimate did not experience any substantial changes [*Gurarii et al.,* 2000a, 2002; *Hartl and Tauxe,* 1996], to name but a few.

[11] At the same time, an interesting result was obtained, which calls for its verification at the present-day level of data accumulation. It appears that the coefficient of the magnetic moment decline during reversals is controlled by the M value of the stationary field before its reversal [*Petrova and Sperantova,* 1986]. S. I. Braginskii advanced the suggestion (during some oral discussion) that various parts of the magnetic (dipole and nondipole) field show their different reactions to the reversal. The pre-reversal dipole field of a variable intensity declines slowly almost to zero, and a new field arises in an opposite direction, the nondipole field varying to a significantly lower degree. In other words, no dipole field could exist during the fairly long time of the pole switching. This view offered by S. I. Braginskii agrees with the conclusions advanced by *Gurarii* [1988], *Clement* [2004], and other authors, and is of great interest in terms of the physical nature of the dipole and nondipole field.

[12] As follows from the estimates of most of the authors, the time interval of some low M existence was notably longer than the time of the magnetic field reversal. The modal values of the Late Cenozoic reversals, estimated from the data available prior to 1986, suggested the average duration of the reversals to be 7–8 thousand years (the individual estimates varying from 4 to 25 thousand years), the time interval of the declining magnetic moment being 1.5 to 2.0 time longer, that is, embraced a time interval of up to 16 thousand years [*Gurarii,* 1988]. *Merrill and McFadden* [1999] estimated the time necessary for a complete reversal to be 1 to 8 thousand years. *Clement* [2004] concluded that the period of the four latest reversals had been 7 thousand years. This author noted that the duration of the field sign change had varied as a function of the latitude of the study area, which agrees with the simple model assuming that the dipole field declined to zero during its reversal and recovered again in the continuous presence of some nondipole field. This allows one to assume that the average time of a dipole field absence during inversions (if this is correct) was at least shorter than 7–8 thousand years.

The Behavior of Virtual Geomagnetic Poles (VGP) During Reversals

[13] The background of the often disordered, abrupt changes in the VGP positions during reversals often shows more or less regular changes in the VGP positions which are usually not only interpreted, but also described in different ways. The principal difference in describing VGPs during their reversals is expressed in the terms of "location" and "displacement". The term "displacement" implies some systematic movement, such as, for instance, the rotation of the dipole field axis. The term "location" suggests that there is no systematic displacement. What actually takes place is the breakdown of the dipole field and its reconstruction with some change in the direction of its axis. The different VGP position in this case reflects the different direction of the instantaneous (virtual) geomagnetic field, averaged over the time during which the study rocks had accumulated, or over the time of their magnetization, to be more exact, recalculated to the VGP coordinates using the central dipole formulas. No matter how these two versions are described in words or formulas, we deal with the propositions which are formulated roughly above.

[14] In this connection, before we pass to analyzing the VGP positions during reversals, I would emphasize the following. The position of a virtual geomagnetic pole is usually located using central dipole formulas, and makes sense only in the case of this field. The researchers who deal with the study of geomagnetic reversals realize this fact. At the same time, the representation of the results in the VGP form allows one to identify the dipole character of the magnetic field at hand, the duration or absence of a dipole field, the differences between the inversions of the same age studied in the same region, and to perform many other operations.

[15] During the early studies of geomagnetic reversals, the geophysicists who performed them traced the paths of virtual geomagnetic poles by way of connecting 2 or 3 data points by a line. Later, after new data were obtained, including those for the transitional zones described in detail, that is, containing a great number of virtual geomagnetic poles (VGP) between 60°N and 60°S, a view was advanced concerning the longitudinal sector of the VGP movement, suggesting that these movements have a loop-type pattern, propagating along meridional and latitudinal loops.

[16] Views differ as to the location of the longitudinal sectors. Some authors suggested the presence or obvious predomination of one [*Laj et al.,* 1991, 1992] or two sectors in the area of 120–180°E and, approximately, in the opposite sector of 300–360°E [*Clement,* 1991]. The reality of this predomination, that is, any association with the geomagnetic field, was doubted by *Langereis et al.* [1992]. Another group of authors supported the idea of the "near" and "distant" sectors. The near sector was supposed to include the coordinates of

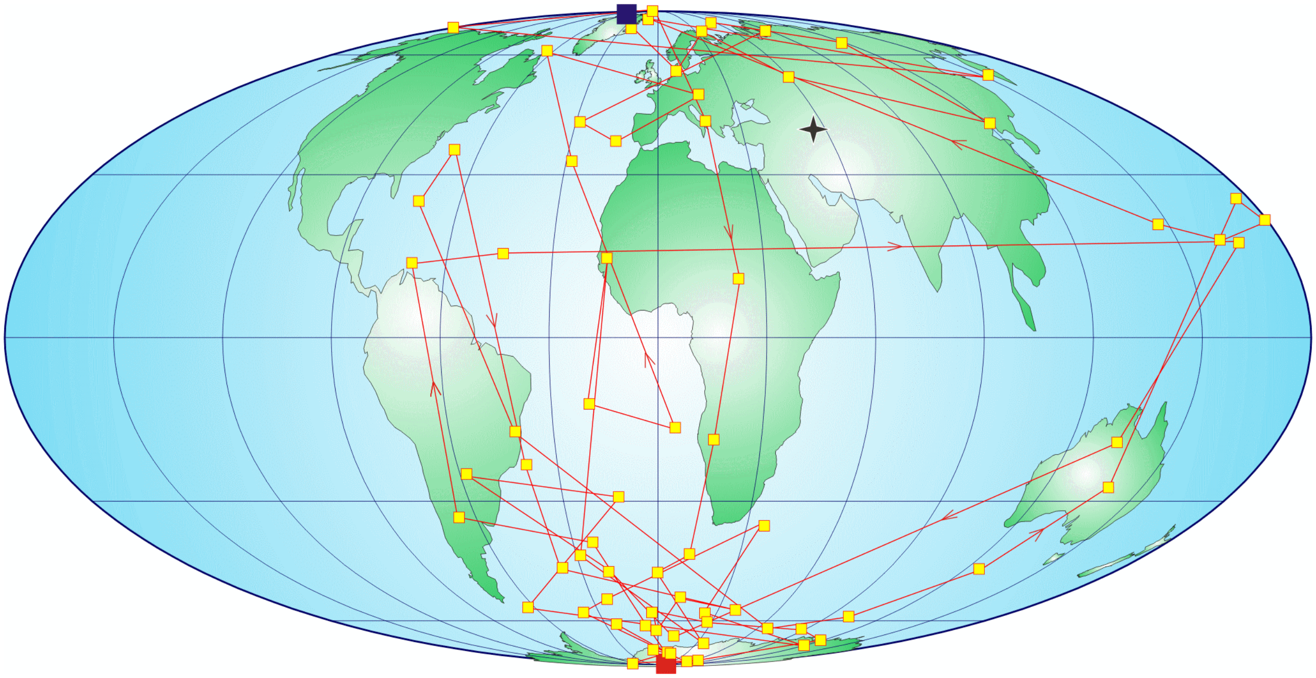

Figure 2. The position of the virtual geomagnetic poles (VGP) during the Early Jaramillo reversal for the Adjidere rock sequence, West Turkmenia; the declination and inclination values are shown in Figure 6 for the respective transitional zone. The red and black squares show the initial and final VGP positions, respectively. The VGP coordinates were calculated using the close average values obtained for declinations and inclinations using 2 to 73 sampling depths. The arrows show changes in the pole positions. The arrow marks the study area.

the sampling site, the remote sector was supposed to be opposite [*Fuller et al.,* 1979; *Hoffman,* 1977]. The researchers of both groups offered convincing arguments to prove that they were right, which proved not only the erroneous character of one view (or of both of them), but also the absence of any distinct concept during the data interpretation. Both groups of the researchers offered convincing illustrations of their correctness, this suggesting not only the fallibility of one or both of their views, but also the difficulty of the problem and the absence of any unique concise concept in terms of data interpretation. In one of my previous studies [*Gurarii,* 1988] I checked the agreement between the VGP trajectory distributions during the Late Cenozoic inversions in a region bordering the equator and their uniform distribution in terms of the Kuiper criterion [*Kuiper,* 1960; *Stephens,* 1965] for 32 inversions and found a significant probability of their uniform distribution, that is, my results did not prove the presence of any "predominant sectors". The mathematical processing of the experimental data, based on combining, for a certain inversion, the VGP trajectories (geomagnetic field trends), located at statistically insignificant distances from one another, into one group (as it is done in cluster analysis), revealed the following regularity: two types of processes, chaotic and quasistationary ones, operate during inversions, at least during some of them. In the case of chaotic conditions the typical duration of a trend change is <100 years. In the case of quasistationary conditions, the characteristic time periods of which show main spectrum variations (archaeomagnetic data), the virtual geomagnetic poles (VGP) remain in one limited area $\sim(20^\circ\times20^\circ)$, the field trend varying insignificantly at the measurement site. The coordinates of these quasistationary regions vary, after the chaotic conditions, both in one hemisphere and between the two of them [*Vadkovskii et al.,* 1980]. This coincides perfectly with the results obtained as a result of studying most of the transitional zones in igneous rocks. The study of the inversion recorded in the Stin Mountain lavas, USA, [*Coe and Prevot,* 1989] revealed a very rapid change in the direction of the geomagnetic field between its quasistationary states without any chaotic state of the field between them. A similar result was reported by *Leonhardt et al.* [2002] and other researchers, and was also discovered during the study of the Twera-Gilbert inversion in the sedimentary rocks of East Georgia, Caucasus [*Gurarii and Kudasheva,* 1995a].

[17] The location of these quasistationary areas shows a kind of order. These areas are located usually in the longitudinal sectors which had been earlier assigned to the VGP trajectories. *Petrova* [1987] noted another regularity: the quasistationary regions surround global magnetic anomalies, being located at their slopes. Most of the quasistationary regions are located in the areas of the magnetic center projection on the Earth surface, this center, in turn, being located not far from the intersection of the third (equatorial) radius of the geoid. This could be associated with the asymmetry of the Earth core, namely, with its displacement which has long been discussed by geomagnetologists and gravity re-

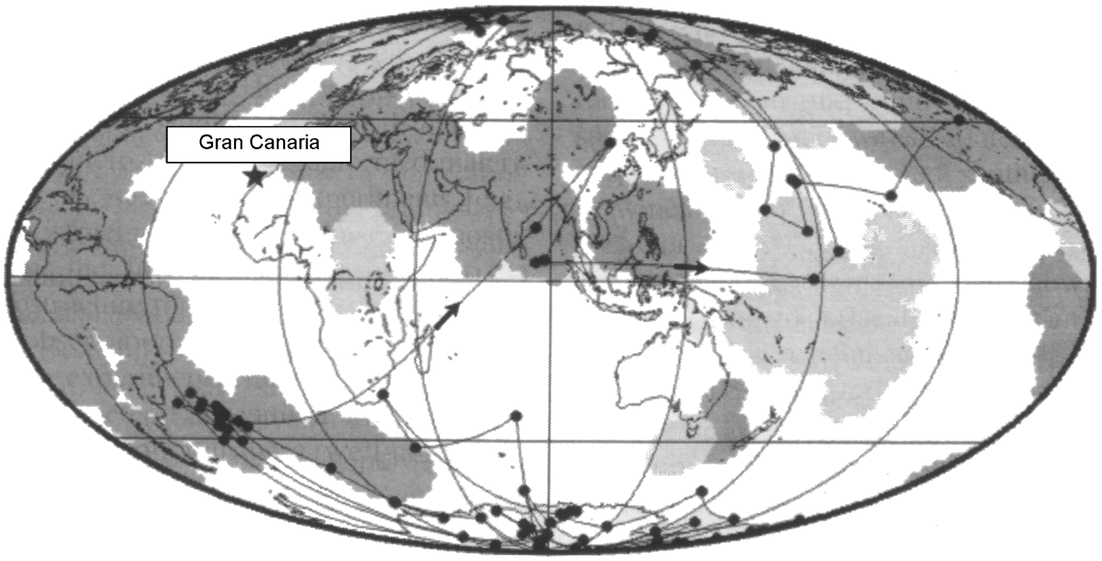

Figure 3. The VGP positions during the Middle Miocene reversal, shown after Figure 9 from [*Leonhardt et al.,* 2002].

searchers, and is acknowledged now by seismologists. At the same time, proceeding from the conventional VGP position in the inversion state of the field, which has been mentioned above, this assumption should be treated with extreme care.

[18] *Hoffman* [1992, 1993, 1996] supported the conclusion concerning the concentration of the largest number of virtual geomagnetic poles (VGP) during their inversions in the limited number of areas in the Earth ("patches"). Yet, he believes that these concentrations do not correlate with the global anomalies. On the other hand, B. M. Clement, who compared the data available for the VGP positions during the Matuyama-Brunhes inversion, which was studied in several different areas of the world ocean, and the data obtained in the course of studying several Early Pliocene reversals in remote territories (sedimentary rocks and lavas), emphasized their good agreement and restriction to the same longitudinal stripe, this suggesting, in his opinion, the significant role of a dipole during these reversals [*Clement,* 1991; *Clement et al.,* 1998]. It should be noted that in his recent paper [*Clement,* 2004] he arrived at the opposite conclusion. The restriction of the VGP bulk to a certain longitudinal sector during some definite inversion, or during a few successive ones, is associated by some geoscientists [*Constable,* 1992; *Gubbins,* 1994] with the potential existence of some not axially symmetric parts of the geomagnetic field, which may not vary during some long period of time. The existence of such a field, which is comparable, in the simple case, with the field of some additional dipole, including the equatorial one, was recorded during some particular studies [*Gurarii et al.,* 2000a; *Rodionov et al.,* 1998]. Assuming that the field of such a dipole is preserved during inversions, the transitional virtual geomagnetic poles must be located in one longitudinal sector, or in two sectors, differing roughly by 180°, in the case of its inversion.

[19] The authors of the paper published by *Gurarii et al.* [2002] proved that the presence of such a nonaxial dipole was confirmed by the results of studying the rocks located in the direct vicinity of the Early Jaramillo transitional zone (West Turkmenia). They confirmed that nearly all of the main features of the field during this reversal could be explained by changes in the values and polarities of these dipoles (Figure 2). Of great interest is the fact that the results, coinciding in many respects with the results of our work in terms of the positions of two VGP crowdings, were obtained by *Leonhardt et al.* [2002] (Figure 3) as a result of studying a Middle Miocene inversion, using the magnetization of lavas. The data we obtained in our 2003–2004 studies suggest the existence of such an additional field in the territory of West Turkmenia throughout the Matuyama Chron (see the Table 1).

[20] The assumed presence of an additional dipole of this kind suggests the following sequence of the field variations during the reversals: the magnetic moment of the main dipole, associated with the main system of convective movements in the core, declines to zero and then grows to its normal value again either in the opposite direction (inversion) or in the previous direction (unfinished inversion or excursion).

[21] As the magnetic moment of the main dipole decreases at the Earth surface, an increasingly important role is played by the field of an additional dipole (or dipoles), the sources of which can be the rock material movements associated with the heterogeneities of the core-mantle boundary, or with those in the upper part of the core and in the lower mantle. The number of the additional dipoles and their dispositions and orientations control the distribution of the magnetic field elements at the Earth surface, as well as their variation from one inversion to another.

Table 1. The average NRM directions for some intervals of three rock sequences in West Turkmenia after complete thermal demagnetization and component analysis

Location	Chron (age or duration)	N	Dec°	Inc°	k	α_{95}°	Δ°
Adjidere	Jaramillo, after Early Jaramillo reversal (∼9 thousand years)*	225	351	54	57.8	1.4	170
	Matuyama, prior to Early Jaramillo reversal (∼3 thousand years)*	60	185	−61	50.6	2.8	
	Jaramillo (∼ −1.038 to −1.029 Ma)*	237	353	61	40.6	1.4	175
	Matuyama (∼ −1.152 to −1.140 Ma)*	255	179	−57	43.4	1.4	
	Jaramillo (∼ −1.06 to −0.99 Ma)*	73	349	58	40.8	2.6	171
	Matuyama (∼ −1.17 to −1.08 Ma)*	69	187	−57	31.7	3.1	
	Matuyama (∼ −1.70 to −1.40 Ma)**	71	187	−52	26.5	3.3	
Monzhukly	Matuyama (∼ −1.70 to −1.40 Ma)**	110	193	−55	23.5	2.8	
Pirnuar	Matuyama, after Gauss-Matuyama reversal (∼18.5 thousand years)**	230	218	−53	27.5	2.0	
	Average "+"	3	351	57.5	489.9	5.6	171.7
	Average "−"	6	186	−56.5	354.0	4.1	

Note: N is the number of the studied time intervals (sampling levels), * and ** indicate that each sampling level was represented by 5 and 3 samples, respectively; Dec and Inc are given in stratigraphic coordinate system; Δ° – denotes the angle between the average directions of the normal and reverse magnetization in large circle degrees. The time characteristics are certainly given in approximate values.

[22] The use of additional sources provides a good explanation of differences in the magnetic field behavior during its excursions, studied at different sites of the ground surface, namely, from the field intensity decline, unaccompanied by any changes in the field direction, to a short time reversal. This model can be used to explain different relationships between the time periods, marked by a low magnetic field, and the periods marked by changes in the direction of the field in the course of studying one and the same reversal in different areas or studying reversals of different ages. This model can be used to explain a drastic change in the characteristics of the same reversal studied at the sites spaced less than a few hundred kilometers apart. The high efficiency of this model has been proved by the mathematical modeling of the field at the Earth surface using a central axial dipole and an additional differently oriented dipole located at the core-mantle boundary.

[23] At the same time, changes in the field during the inversions of different ages, studied in the region discussed, changes in the duration of the inversions over long periods of time, changes in the characteristics of the inverted field from one region to another, as well as the character and scale of these variations, can be used as the indicators of the state and structure of a boundary between the core of the Earth and its lower mantle [*Gurarii,* 1988].

[24] It is significant that *Gubbins* [1994] arrived at similar conclusions. It should be noted that a similar interpretation for the positions of the virtual geomagnetic poles (VGP) during the reversals was offered by *Creer and Ispir* [1970].

Secular Variations in the Trend of the Geomagnetic Field at the Time of its Reversal

[25] Since the early studies of transition conditions many authors emphasized the growing disturbance of the geomagnetic field or, to be more exact, of the parameters characterizing its direction, during its inversions. Using the term "disturbance", they meant the growth of the variation magnitude and numerous outbursts and loops of large magnitude, often measuring 180° along the large circle arc.

[26] It is possible that a change in the magnitude of the regular variations of the field direction is a seeming effect. The angular elements of the geomagnetic field vector, Dec. and Inc., are calculated using their X, Y, and Z components. It is obvious that under the conditions of the low medium field intensity, the same increments of these components lead to a greater change in the angular elements compared to the case of high field intensity.

[27] According to the modern views, the main variation spectrum is a principally important characteristics of a dynamo mechanism. The periods of the variations included into the main spectrum (archaeomagnetic data) correspond to the periods of MAC waves in terms of their theoretical estimates [*Braginskii,* 1974]. MAC waves are an integral part of the generation mechanism being the manifestation of its principal instability. It is a change in the MAC wave spec-

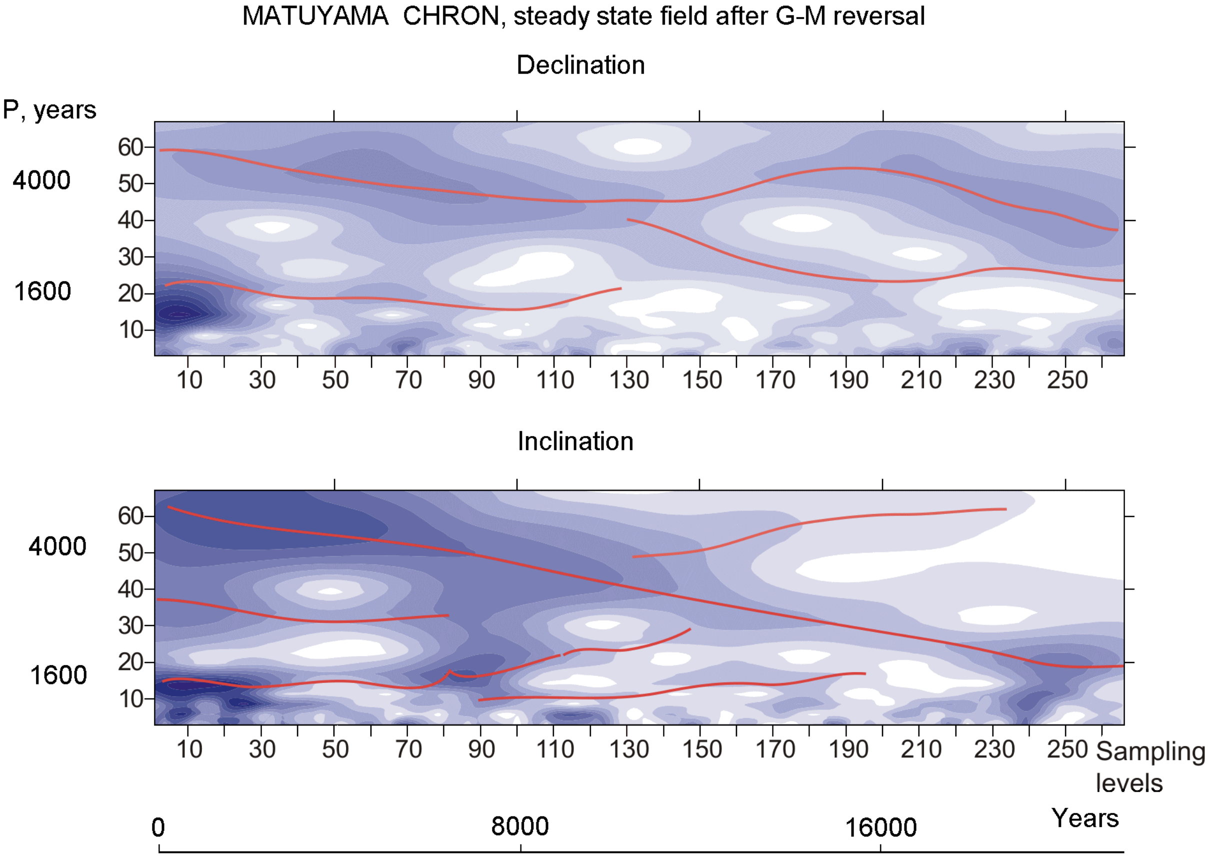

Figure 4. The wavelet diagrams of the NRM declination and inclination of the Matuyama chronozone located at a distance of about 26 m above the Gauss-Matuyama transition zone, this distance being approximately equivalent to 100 thousand years. The declination and inclination values analyzed represent, in the stratigraphic system of the coordinates, the average values for three specimens after their complete thermal demagnetization and component analysis. The P letter marks the most characteristic variation times. The red lines mark variations in the data series following from our interpretation. The time characteristic is approximate, varying with the number of the depth levels from which the samples were collected.

trum, that is, in the periods of secular variations, that record variations in the dynamo process.

[28] The identification of the main-spectrum variations with the MAC waves is based not only on the proximity of their theoretical and experimental periods, but also on some specific variations of the basic spectrum variations stemming from the results of arhaeomagnetic investigations. First, the main-spectrum variations have a running and a standing component, both being pertinent to MAC waves. Secondly, some variations, like, for example, the well-known variation with a period of 1200 years, show distinct global features [*Burlatskaya,* 1999].

[29] The secular variations recorded during polarity reversals were studied using the Gauss-Matuyama, Matuyama-Jaramillo and Matuyama-Brunhes reversals [*Petrova et al.,* 1980, 1992]. These authors came to the conclusion that the secular variation spectrum had not varied throughout the inversion process. Moreover, the comparison of their results with the data reported by *Gurarii et al.* [1994] suggested the conclusion that the basic spectrum of the geomagnetic field variation had not changed during the last 5.5 million years, that is, the dynamo mechanism operated continuously.

[30] However, the latest data suggest that both the above conclusion and the term "basic spectrum" should be treated with care, where the latter implies not merely the presence of the oscillations of certain periods (characteristic time intervals), but also the persistence of these periods throughout the long time of the existence of a certain-polarity field. *Gurarii et al.* [2000b] proved that this view on the spectrum of these "variations" owes its origin to the method chosen for the processing and analysis of the data available for paleomagnetic time series. The use of the wavelet analysis, as a basic technique, for the processing of the data obtained during the study of the sedimentary rocks in the Ajidere area (West Turkmenia) and characterizing the magnetic field for the period of 0.99–1.17 million years proved the high variation of the characteristic times of the recorded oscillations. This variation was observed in the data series of different durations, characterizing the field of different polarity both in the vicinity of the inversion and at a significance distance from it, this fact being proved by our new results (Figure 4).

[31] These results do not contradict the view proposed by

Braginskii [1974], yet, can be treated as another indication of the permanent instability of the generation mechanism, the extreme manifestation of which is the geomagnetic field reversal.

[32] Therefore, the sole, most substantiated, conclusion that can be offered at the present time is that the study of this problem need be continued.

Changes in the Magnetic Field Trend With the Characteristic Time Interval of ∼100 years

[33] As the magnetic moment declines, outbursts appear and grow in number, attaining their maximum values in the central region of the reversal, when the virtual geomagnetic poles (VGP) reside in the areas of intermediate and low latitudes. After they leave the medium- and low-latitude bands, the number of outbursts declines as the magnetic moment grows higher. The characteristic time of the outbursts lasts about 40–200 years, that is, almost coincides with the time of the accumulation of one to four sampling intervals of the rapidly accumulating rocks. In the central interval of the reversal, the outbursts sometimes follow one another, and the VGP movements grow highly disorderly to the extent that some researchers suggested their independence of the real field variations. The authors of this view believe that under the conditions of the low magnetic moment (0.1 and less of the present day M value) magnetization operated as a random process, and its direction was not controlled by the magnetic field which varied at that time in its direction extremely rapidly and randomly, or was absent at all [*Vadkovskii et al.,* 1980]. This assumption of the absolute absence of the geomagnetic field contradicts the view of S. I. Braginskii, who supposed that the subsurface layer of the core (∼20–30 km thick) was stratified and showed some special characteristics: the liquid core material differentiation resulted in the fact that the density of this layer was somewhat lower (at least by fractions of percent) than that of the major volume of the liquid core. The arising density gradient, which was estimated theoretically to be sufficient for changing the Reynolds magnetic number significantly and, hence, for creating the generation conditions, different from those existing in the major liquid core volume. S. I. Braginskii believes that single oscillations may be generated in this surface layer, distinguished by their characteristic torsion oscillation times and amplitudes typical of the "main spectrum" oscillations. Also possible are periodical M declines to the level close to zero, yet the association of the vertical geomagnetic poles (VGP) movements with the low M value (close to zero) can be treated in a different way.

[34] Oscillations with the typical periods of about 100 years and lower develop (according to S. I. Braginskii) in the surface layer of the liquid core. Since the magnetic field suppresses the movements of the conducting material, the intensity of the processes operating in the subsurface layer grows as the magnetic moment declines. The number of the outbursts grows slowly during the M decline, rather than beginning from some low M level, which is in better agreement with the second interpretation of the pattern observed. However, the combination of both factors is possible, namely, of the growing activity of the processes operating in the subsurface layer and of the low contribution of the magnetic field to the magnetization.

[35] Be it as it may, it is precisely these random, occasionally continuous, processes (if they are real ones, rather than being the products of magnetization in the low magnetic field, or were produced by magnetization in some low magnetic field and by the development of natural remanent magnetization in sedimentary rocks) that often distinguish the inversion conditions from the other states of the geomagnetic field.

Precursors of Polarity Reversals

[36] The theoretical substantiation of the potential precursors as some triggers of the polarity reversals of the stationary geomagnetic field were offered by *Olson* [1983] and *McFadden and Merrill* [1986]. Proceeding from the real paleomagnetic records, some authors emphasized the appearance of a distinct NRM peak before the inversion onset, which was interpreted by them as a reversal precursor [*Burov,* 1979; *Iosifidi and Metallova,* 1988]. However, the analysis of these data revealed that the recorded magnetization growth had been accompanied by the significant growth of magnetic susceptibility, so that the competence of some elementary normalization for the conclusion concerning the growth of the field intensity in such cases is highly doubtful [*Gurarii and Kudasheva,* 1995b]. The analysis of the variation trend and H_{old} values of the old geomagnetic field during its inversion periods and the adjacent time periods showed the absence of any intensive and distinct precursors [*Petrova and Sperantova,* 1986]. Moreover, the exact recording of any confident precursors calls for the meticulous analysis of the stationary field at some distances from its reversals. Unfortunately, the data needed for such analysis are almost lacking in the areas of rapidly accumulating rocks, needed for such analyses, except for some few examples [*Gurarii et al.,* 2000a].

[37] In my opinion, only the data reported in [*Glen et al.,* 1999a, 1999b; *Gurarii et al.,* 2002; *Hartl and Tauxe,* 1996] can be used at the present time as the examples that potentially record the operation of the mechanism that triggers reversals.

[38] 1. In [Hartl et al., 1996] treat, as a precursor, some significant decline in the geomagnetic field intensity before the Matuyama-Brunhes reversal, identified while studying the magnetization of rocks in 12 drill cores collected in different regions of the world ocean (Figure 5). In all cases this decline of the geomagnetic field intensity had preceded the inversion by 15 thousand years, which proves it to be a real fact. The embarrassing fact is the absence of data for the longer period of the Matuyama Chron.

[39] 2. The authors of the paper [*Glen et al.,* 1999a, 1999b discuss, as a potential precursor, three intervals of the low geomagnetic field and anomalous magnetization trends be-

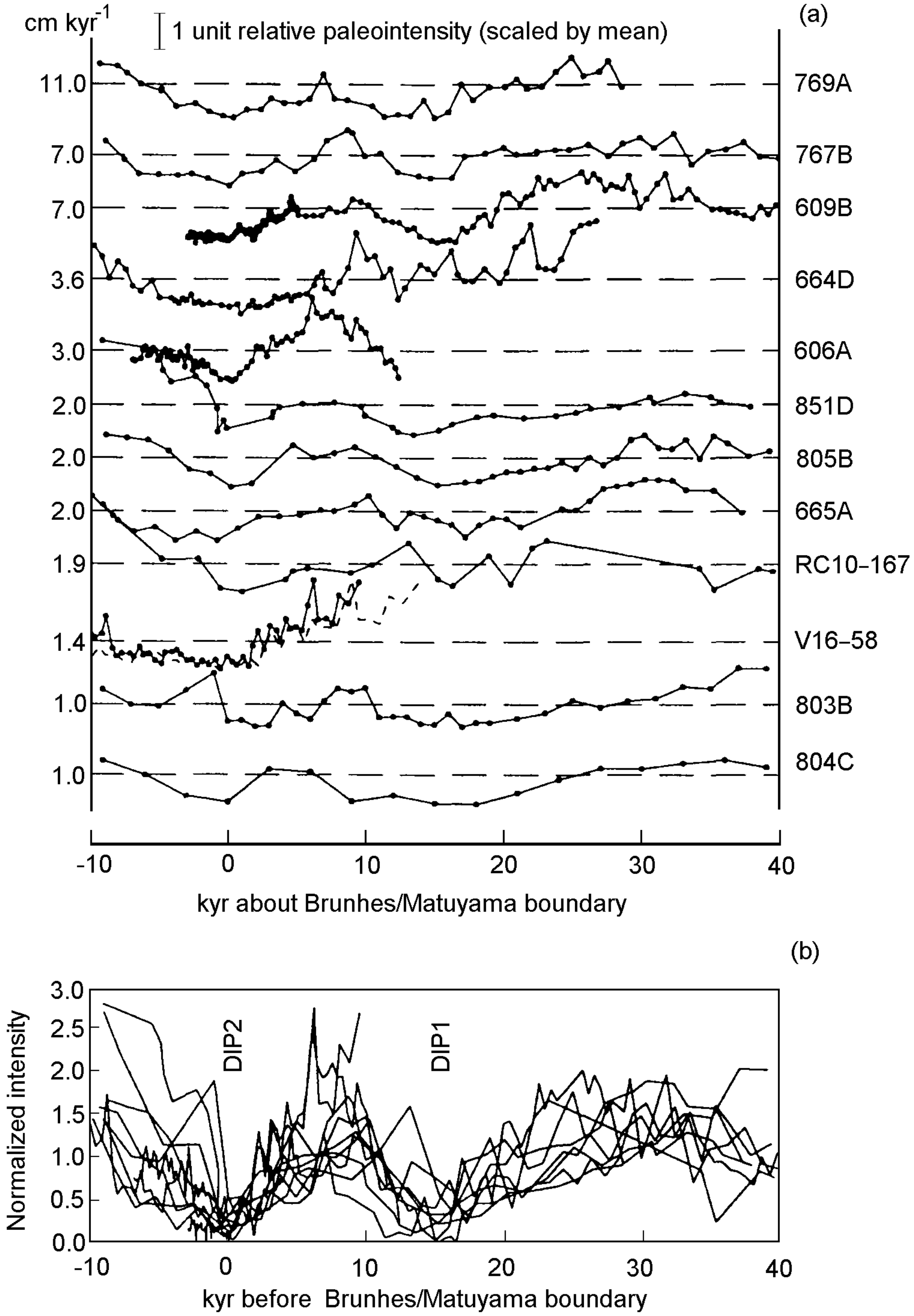

Figure 5. The example of the relative paleointensity variation obtained after studying the magnetization of the rocks from 12 ocean-floor core samples for the time interval of 50 thousand years. The DIP2 paleointensity decline corresponds to the Matuyama/Brunes boundary, the DIP1 reflecting the triggering mechanism of the reversal, as follows from our interpretation of Figure 6 from [*Hartl and Tauxe,* 1996].

fore the Gauss-Matuyama reversal. The subject of their study were the Searles Lake sedimentary rocks in California, the accumulation rate of which varied between 15.5 cm and 20.7 cm for a thousand years. Regrettably, no data are reported in this paper, too, for the characteristics of the Gauss Chron at a distance from the reversal.

[40] 3. The authors of the paper [*Gurarii et al.,* 2002] emphasized the anomalous behavior of the magnetic field char-

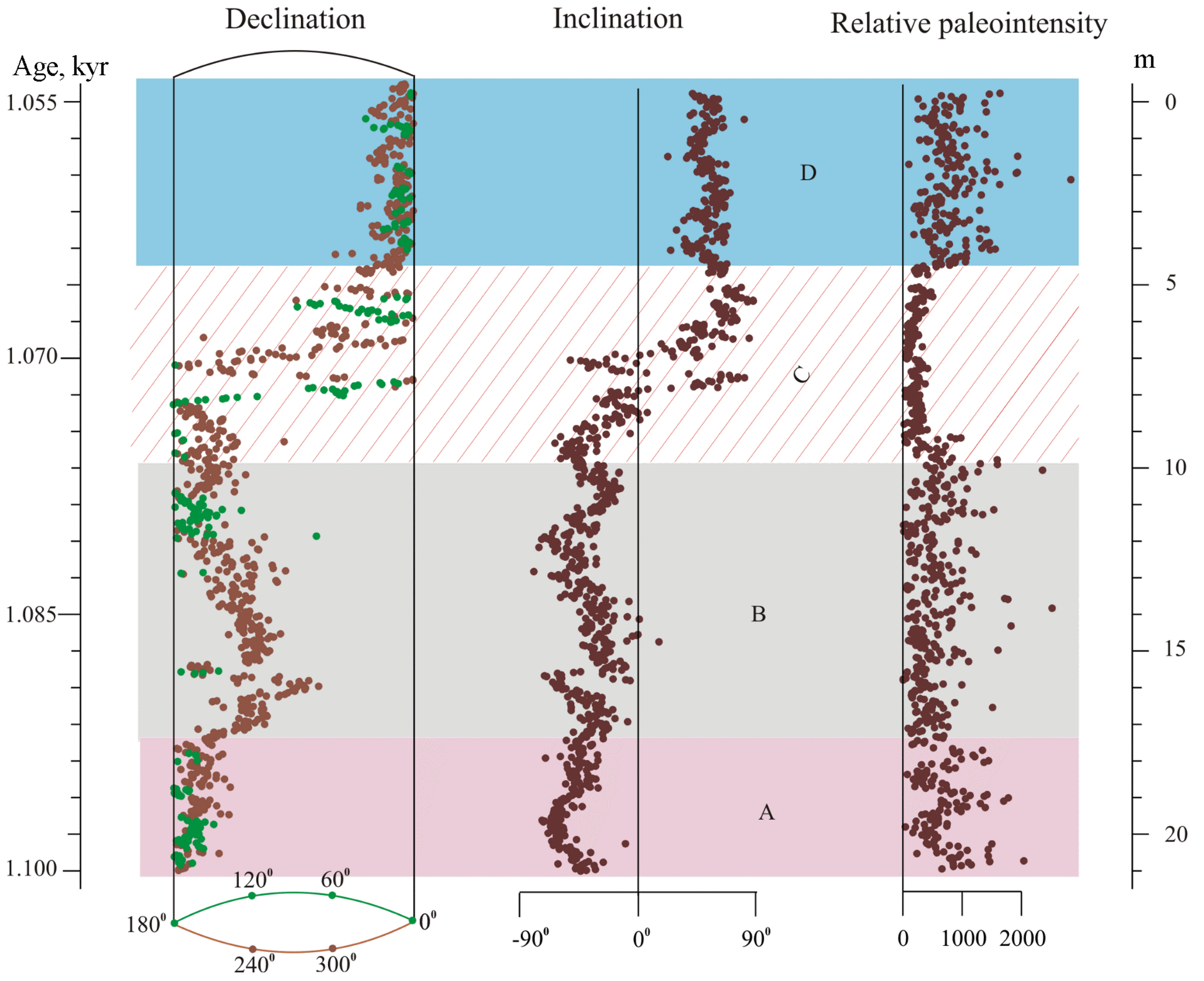

Figure 6. Transitional Lower Jaramillo zone (Adjidere section, West Turkmenia). (A) Matuyama chronozone, (B) reflection of the inversion triggering mechanism or of the early reversal stage; (C) reflection of the reversal, (D) Jaramillo chronozone. Declination and inclination are given in the stratigraphic system of the coordinates, each depth level is characterized by the average value for five specimens after their complete thermal demagnetization and component analyses. The relative paleointensity Rns=(NRM_{300°–NRM_{500°/IRM_{300°–IRM_{500°)×1000, IRM in the field of 0.9 T.

acteristics (magnetic intensity decline and the trend different from the trend of the axial dipole field) before the Early Jaramillo reversal, which was studied in the very rapidly accumulated sedimentary rocks (40–50 cm during a thousand years) of West Turkmenia (Figure 6). This behavior of the geomagnetic field was recorded immediately before its reversal during a period of about 20 thousand years and was not recorded elsewhere in the stationary field of the Matuyama and Jaramillo chrons [*Gurarii et al.,* 2000a].

[41] Further research is needed to answer the following questions: Are there any precursors of inversions? Was the decline in the magnetic field magnitude, reported in Paper 3, one of the declines characteristic of this part of the Matuyama Chron? Weren't the unusual behaviors of the geomagnetic field, reported in papers (1) and (2), parts of reversals, which in this case must have lasted 20–28 thousand years?

Ancient Reversals

[42] The study of the Earth core evolution requires the data available for Precambrian and Paleozoic reversals. It is a change in the characteristic time and magnitude values of the geomagnetic field fine-structure elements that can provide information for changes in the liquid core state for a long period of time. It is believed that the most important parameter in this respect is the MAC wave spectrum. However, the above-mentioned doubts concerning the real existence and persistence of some "basic spectrum" even for the case of the field during the young epochs do not allow us to believe that we can correlate the data available for different periods of time with an accuracy sufficient for judging whether some characteristic variation time periods did actually change during the period of time concerned.

Unfortunately, we can just set hopes only on the correlation between the time periods of the operation and character of the geomagnetic field variations during reversals

[43] The first results for polarity reversals in Paliozoic time were obtained during the early studies of transitional periods [*Gurarii,* 1968; *Khramov,* 1987; *Khramov and Rodionov,* 1980; *Khramov et al.,* 1974; *Kravchinskii,* 1968; *Rodionov,* 1969; *Rodionov and Osipova,* 1985]. However, it was only recently that the repeated studies of some previously investigated reversals and the use of the data obtained for new rock sequences yielded the results which could be used to compare the processes of the reversals that had occurred about 0.6–0.5 billion years ago with those of the Late Cenozoic reversals.

[44] The studies of the reversals recorded in the Middle Ordovician rocks (the south of the Siberian Craton), in the Middle Cambrian rocks (same region), and in the Late Riphean rocks (Southern Ural) [*Komissarova et al.,* 1997; *Rodionov et al.,* 1998; *Surkis et al.,* 1999] allowed the authors to interpret the stationary field of these epochs as the sum of the fields of the basic and equatorial dipoles with the $M_\mathrm{e}/M_\mathrm{a} = 0.2$. During reversals the axial field diminishes and passes across the zero, while the equatorial dipole (and the sectorial harmonics) remains almost unaltered. A similar model was proposed in the description of the Early Jaramillo reversal, and the potential existence of the axial and equatorial dipoles with the M value of the latter being about 8–10% of the M value of the former was confirmed by the results of studying the stationary field both at a distance from and in the vicinity of the Matuyama-Jaramillo reversal [*Gurarii et al.,* 2000a, 2002] which, as mentioned above, agrees with the data reported in [*Constable,* 1992; *Gubbins,* 1994]. The decline of the magnetic moment during the above mentioned ancient reversals was estimated, using the Koenigsberger ratio, to be $\sim$5, 3–5, and 2.5–5, respectively. The duration of the Late Riphean reversal was estimated to be about 20 thousand years, that of the Late Cambrian reversal, to be less than 30 thousand years.

[45] Of particular interest was the attempt to estimate the characteristics of the behavior of the geomagnetic reversals during the periods of their frequent repetitions (Early Ordovician). The study of the four reversals following one another during this time period in the south of Siberia yielded the results that were somewhat different from the previous ones. With the duration of the subchrons between the inversions measuring 13–32 thousand years, the duration of the transitional period was merely 3–4 thousand years, the magnetic moment being 5–10 times lower [*Surkis et al.,* 1999].

[46] To sum up, no significant differences were found in the characteristics of the magnetic field during its ancient and Late Cenozoic reversals.

Conclusion

[47] It is obvious that this paper is not a comprehensive review of the numerous data available for the characteristics of the geomagnetic field during its reversals. The important aspects of this problem, such as the dipole and nondipole fields and their potential sources, inversion models, and others, are not discussed. Although I do not claim to be sufficiently competent for the analysis of this kind, I dare to conclude that the data available at the present time are hardly sufficient to offer any correct conclusions. This does not mean that these problems cannot be discussed, however this must be done by experts.

[48] My goal was to emphasize the intricacy of the general problem: "Geomagnetic field during its polarity reversals" and to "shake" the pessimism existing concerning its solution. It would be too optimistic to expect, as it was at the very outset of its research, that this complex (yet very interesting and important) problem can be solved rapidly.

[49] In conclusion, I would draw the attention of the readers of my paper to some questions, the answers to which should be found by way of initiating some joint projects for performing both the field surveys and laboratory studies of the stationary magnetic field and of the field during its reversals in the course of studying the magnetization of rapidly accumulating rocks, without answering which this extremely important and interesting problem can hardly be solved:

[50] (1) Is the high variation of the characteristic times of the stationary magnetic field elements a real fact, or these results reflect the effects of some extraneous factors?

[51] (2) If the answer is affirmative, can we find some characteristics of these variations which suggest an approaching reversal?

[52] (3) Did the geomagnetic field record any traces of the triggering mechanism of its reversal, and if the answer is "yes", were the characteristics of the magnetic field during these events different from the characteristics of the anomalous field during its general stationary state far before and after the reversals?

[53] (4) Is the regular behavior of the field intensity, namely, its reversal at the background of the low field – the abrupt growth of the field intensity – the slow decline of the intensity of the stationary field of one polarity almost throughout its existence – inversion, and so on, a real fact?

[54] (5) Is it a real fact that the stationary field consisted in some cases of at least two fields, namely, of some central axial dipole and an extra field which could be represented by an independent dipole or by sectorial harmonics? What role did this additional field play during reversals, and so on.

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