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THE STATISTICAL PROPERTIES OF PALAEOMAGNETIC POLARITY–TIME SCALES

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The aim of the statistical investigation of the palaeomagnetic polarity–time scales is to get information about the average behaviour of the reversals in time, and to utilize these to construct models in which the same statistical properties are reflected. The principal problem associated with this objective was the description of the average behaviour in time. After the examination of the newest polarity–time scales we concluded the following:

— the polarity intervals show a non-stationarity which can be approached by linear regression;
— a gamma distribution is shown by the polarity intervals; the parameters of the distribution had changed during the Earth's history;
— the independence of the polarity intervals cannot be investigated with the recent mathematical statistical methods, but it can be proved analytically (if some conditions are fulfilled);
— the stability of the geomagnetic field is the same for the two polarity states: the question is, how the polarity bias is connected with the processes which cause the change of the λ parameter of the gamma distribution.

Keywords: polarity–time scales, polarity intervals, nonstationarity, gamma distribution, paleomagnetism

1. Introduction

It is well-known that the dipole moment of the geomagnetic field has changed polarity many times in the Earth's history. This is not unique in the Universe; the Sun and some other stars change their polarity periodically. At the moment the dipole moment of the Earth is decreasing rapidly. If this decrease continues unchanged then the dipole moment of the magnetic field will vanish within 1000 years. In order to obtain information about the polarity changes, we have to initially investigate the marine magnetic anomalies. In this way, polarity–time scales can be made with a retrospective effect, as from the age of the oldest marine crust. The first polarity–time scale was made at the beginning of the 60's. Lacking the convenient divisions, these timescales were not suitable for statistical investigations. The first timescale which was sufficently long (from 0 to 80 million years), was produced by Heirtzler et al. in 1968. Naturally, its statistical analysis began concurrently. The timescales used in this text are by Heirtzler et al. [1968] (referred to hereafter as HDHPL–68) and Ness et al. [1980] (referred to hereafter as NLC–80).

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The change of magnetic polarity from one stable polarity state to the other is called *polarity transition*. Plotting the normal and reversed polarity intervals against time, we get a *polarity–time scale (Fig. 1)*. The square-like wave illustrates that the polarity changes are momentary. If we investigate the statistical properties of the timescales, we have to assume that a polarity change can occur in an instant. It is acceptable to assume this because the length of the polarity intervals are in hundreds of thousands years, while a polarity change has as a length a multiple of ten thousand years. Futher on, let us see a sufficiently extensive time period with long equidistant samples. Let us determine the original polarity state of the samples. The proportion of samples with normal polarity state to those with reversed polarity state shows the time the field has spent in normal state. This is called the *polarity quotient*, (usually given in percent). *Fig. 2* shows the changing value of the polarity function plotted against geological time [Irving and Pullaiah 1976]. When the polarity quotient is near 50%, then the field oscillates considerably. However when its value is high (90%) or low (10%) for a long period, then no, or only a few reversals occur. Connected with these long intervals some further terms can be defined. When the field has dominantly normal polarization, it is called *normal polarity bias* and when the field is reversed dominantly, it is the *reversed polarity bias*.

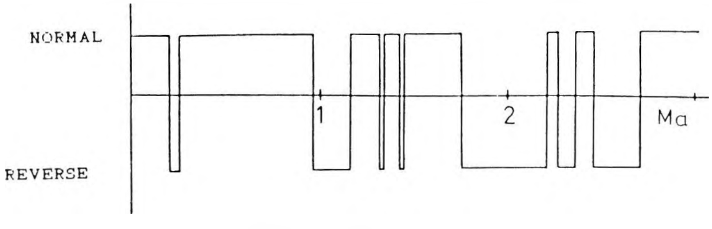

Fig. 1. Polarity–time scale for the last few million years

1. ábra. Polaritás–idő skála az elmúlt néhány millió évre

Рис. 1. Шкала полярность–время для последних нескольких млн. лет

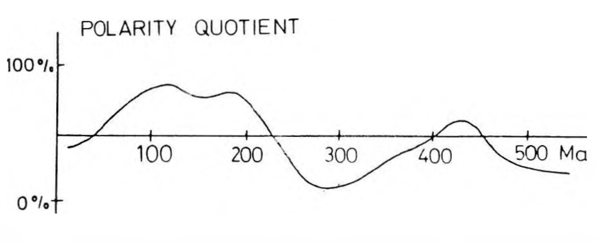

Fig. 2. The change of the polarity quotient as a function of time [after Irving and Pullaiah 1976]

2. ábra. A polaritáshányados változása a geológiai idő függvényében [Irving és Pullaiah 1976 nyomán]

Рис. 2. Изменение доли полярности как функция геологического времени [по Irving and Pullaiah 1976]

The dates of the polarity transitions are given by the polarity–time scales. The time between two succesive polarity transitions is called the "polarity interval". This polarity interval series can be made for the whole time scale. It is not the polarity–time scales which are investigated directly, but the polarity interval series, which were produced from them.

2. The analysis of the polarity intervals

In the mathematical sense, the polarity intervals form a time series. Consequently the polarity intervals can be analysed using time series analysis, X_t ($t = 1, 2, \ldots$) representing the polarity intervals from the present to the past.

2.1 The stationarity of the polarity intervals

Assume that X_t polarity intervals ($t = 1, 2 \ldots$) form a stochastic process, which consists of three parts:

$$X_t = \varphi_t + d_t + Y_t \quad (t = 1, 2 \ldots) \tag{1}$$

where Φ_t is the trend, d_t is a periodical function and Y_t is a stationary time series. Further on, we assume that the periodical component is equal to zero [Phillips and Cox 1976 and Lutz 1985]. Consequently, only trend and stochastic components are contained in our time series.

The first to try to determine the trend with the moving average method was Naidu [1971], who analysed the HDHPL–68 timescale. He had investigated the changeability of the mean and the variance of the intervals in independent, 8 million year long, windows. The mean and the variance was found constant between 0 and 48 million and between 56 and 72 million years, while a discontinuity was found between 48 and 56 million years. The same was found by Phillips et al. [1975] and Phillips [1977], when they investigated the same timescale using the moving average method. *Fig. 3* shows the moving average of the HDHPL–68 timescale with 95% confidence intervals. (Normal distribution was assumed for the polarity intervals, when the confidence intervals were constructed—this is valid when the sample is large.) The HDHPL–68 timescale shows an almost constant behaviour between 0 and 40 and between 50 and 65 million years. The moving average of the NLC–80 timescale is shown in *Fig. 4*. A linear trend can clearly be seen. Other timescales—not demonstrated here —show similar properties: the moving average of the timescales made before 1974 are similar to the moving average of the HDHPL–68 and the moving average of the timescales since 1974 are also similar to the NLC–80 timescale. Perhaps the reason for the difference is the better definition of the new time scales. It must be said that the series of the trend values, so determined, gives a rough picture about the phenomenon in time. We cannot use it for a more complete analysis or for forecasting. For these aims, the trend must be determined as an analytical function of time [Éltető et al. 1982]. After this a linear trend is fitted for different ranges of some time scales. Let us assume that the time series has the next form:

$$X_t = at + b \qquad (t = 1, 2 \ldots) \qquad (2)$$

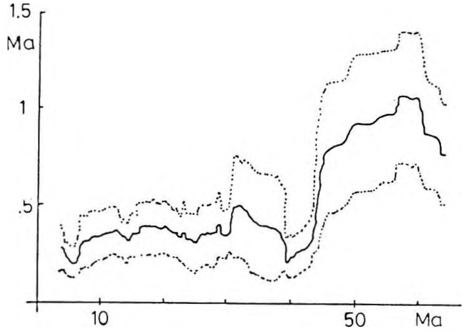

Fig. 3. The moving average of the HDHPL–68 timescale. Sliding window includes 20 intervals of each polarity and shifts by one interval of each polarity each time. The dashed lines show the 95% confidence interval

3. ábra. A HDHPL–68 időskála 20 intervallumon keresztül végzett mozgó átlagolás után. A szaggatott vonalak a 95%-os konfidencia-intervallumok

Рис. 3. Шкала HDHPL–68 после скользящего усреднения по 20 интервалам. Прерывыстые линии – 95%-ные интервалы доверия

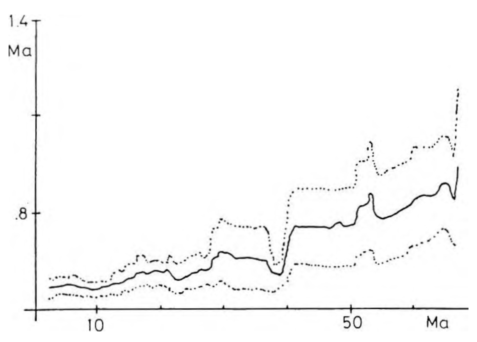

Fig. 4. The moving average of the NLC–80 timescale. Sliding window includes 20 intervals of each polarity and shifts by one interval of each polarity each time. The dashed lines show the 95% confidence interval

4. ábra. Az NLC–80 időskála 20 intervallumon keresztül végzett mozgó átlagolás után. A szaggatott vonalak a 95%-os konfidencia-intervallumok

Рис. 4. Шкала NLC–68 после скользящего усреднения по 20 интервалам. Прерывыстые линии – 95%-ный интервал доверия

The results by the least square method are shown in *Table I*. It can be seen from the data that the trend changes at around 40 million years, and becomes steeper by one order between 40 and 80 million years. McFadden [1984] also investigated the nonstationarity of the time scales. We shall deal with this in the chapter on the distribution of polarity intervals.

If the trend is subtracted from the original time series, we shall get the stationary random component. *AR*, *MA* or *ARMA* models can be fitted for this. But, we shall see later that data for the time series do not exhibit the same distribution function. Therefore if we fit a stochastic model it will be impossible to interpret. At present the application of these stochastic models may only be done if the data for the stochastic process show the same distribution.

We can conclude the following: non-stationary behaviour is shown by the newest timescales. The moving average method is not a perfect test for stationarity, because it gives little independent information about the data set. For example if we have 100 samples and use a moving window with 25 data, we shall get only 4 independent data items for the time series. This problem—as we shall see in the next chapter—was solved by McFadden [1984] using the maximum likelihood principle.

TIMESCALE	INTERVAL[Ma]	a	b
HDHPL–68	0–40	$8.73 \cdot 10^{-4}$	0.28
HDHPL–68	0–72	$3.14 \cdot 10^{-3}$	0.17
NLC–80	0–40	$1.58 \cdot 10^{-3}$	0.15
NLC–80	40–80	$2.1 \cdot 10^{-2}$	0.38
NLC–80	0–80	$4.52 \cdot 10^{-3}$	−0.02
LA–81	0–80	$3.25 \cdot 10^{-3}$	0.13

Table I. The linear trends which were fitted to some different parts of some timescales ($X_t = at + b$)

I. táblázat. Néhány időskála különböző tartományaira illesztett lineáris trend ($X_t = at + b$)

Таблица I. Линейный тренд ($X_t = at + b$) различных интервалов некоторых шкал времени

2.2 The distribution of the polarity intervals

If rough histograms of the length of the polarity intervals were made, we could see that the exponential distribution fits very well (*Fig. 5*). However, using a finer scale, the histogram changes according to *Fig. 6*. On the basis of this, Naidu [1971] generalized the exponential distribution into the gamma distribution. However, whether exponential or gamma distributions describe the polarity intervals, only a gamma distribution can be observed, because there are a lot of undetected polarity changes, which thin the original process.

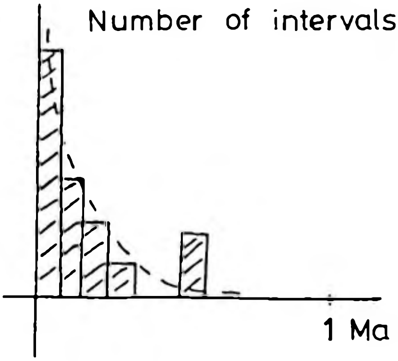

Fig. 5. The distribution function of polarity intervals, with rough division. The exponential distribution fits well

5. ábra. A polaritás-intervallumok gyakorisági görbéje, durva felbontásban. Az exponenciális eloszlás jól illik rá

Рис. 5. Гистограмма интервалов постоянной полярности при грубом разрешении. Достаточно хорошо описывается експоненциальным распределением

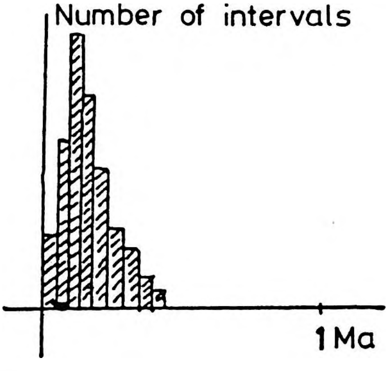

Fig. 6. The distribution function of polarity intervals, with fine division. The gamma distribution fits well

6. ábra. A polaritás-intervallumok gyakorisági görbéje nagyobb felbontásban. A gamma-eloszlás jól illik rá

Рис. 6. Гистограмма интервалов постоянной полярности при большем разрешении. Хорошо описывается гамма-распределением

Let us determine the parameters of the supposed distribution. The maximum likelihood estimation, suggested by Cox and Lewis [1966], was made unbiased by McFadden [1984] for the two parameters of the gamma distribution. The PDF (probability density function) of the gamma distribution is

$$f(x) = \frac{1}{\Gamma(k)} \lambda(\lambda x)^{k-1} e^{-\lambda x} \tag{3}$$

where $x>=0$, λ, $k \in R^+$, $\Gamma(k)$ the gamma function. The mean is

$$\mu = \frac{k}{\lambda} \tag{4}$$

For this reason we may turn to $\mu = k/\lambda$ parameter instead of λ. The maximum likelihood estimations of μ and k and their variance are:

$$\hat{\mu} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \text{var}\,(\hat{\mu}) = \frac{\hat{\mu}^2}{N\hat{k}} \tag{5}$$

$$\ln \hat{k} - \psi(\hat{k}) = \frac{N}{N-1}\ln \hat{\mu} - \frac{1}{N-1}\sum_{i=1}^{N} \ln x_i$$

$$\text{var}(\ln \hat{k}) = \frac{1}{N\hat{k}^2\left[\psi'(\hat{k}) - \frac{1}{\hat{k}}\right]} \tag{6}$$

where $\psi(k)$ is the digamma function, $\psi'(k)$ is the trigamma function [ABRAMOVITZ and STEGUN 1970].

The $\hat{k}$ parameter can not be expressed in an explicit way because $\psi(k)$ is not an analytical function. Therefore we have to approximate it numerically. So, can we estimate the μ and k parameters independently? Yes, because the covariance matrix is diagonal with regard to μ and k. Therefore there is no correlation between them. Let us assume after this that k and λ can change in time, and let us calculate the change of $\hat{k}$ and $\hat{\lambda}$ in time, in 8 million-year-long disjunct intervals *(Fig. 7)*. It can be seen that $\hat{k}$ is approximately constant, while $\hat{\lambda}$ decreases linearly between 0 and 80 million years and it increases almost linearly between 120 and 160 million years.

After this let us handle separately the normal and reverse polarity intervals. MCFADDEN [1984] proved that there is no reason to reject the hypothesis that the value of $\hat{k}$ and $\hat{\lambda}$ are the same for both polarity states. (This assertion will be taken into account in the chapter which deals with the stability of the polarity states.) The change in time of the $\hat{k}$ and $\hat{\lambda}$ parameters for both polarity states is very similar to that shown in Figure 7.

Let us return to the investigation of non-stationarity, mentioned by MCFADDEN [1984]. The λ parameter can be replaced with a linear trend

$$\lambda = \alpha + \beta t \tag{6}$$

in equation (3), and the value of $\hat{k}$, $\hat{\alpha}$, $\hat{\beta}$ were determined by the maximum likelihood method. It is obvious, that the non-stationary nature was described here in an analytical way without the moving average method and all data were used in the computations. In conclusion we can say that the observed polarity intervals show gamma distribution, and that its two parameters (k and λ) have changed in geological history.

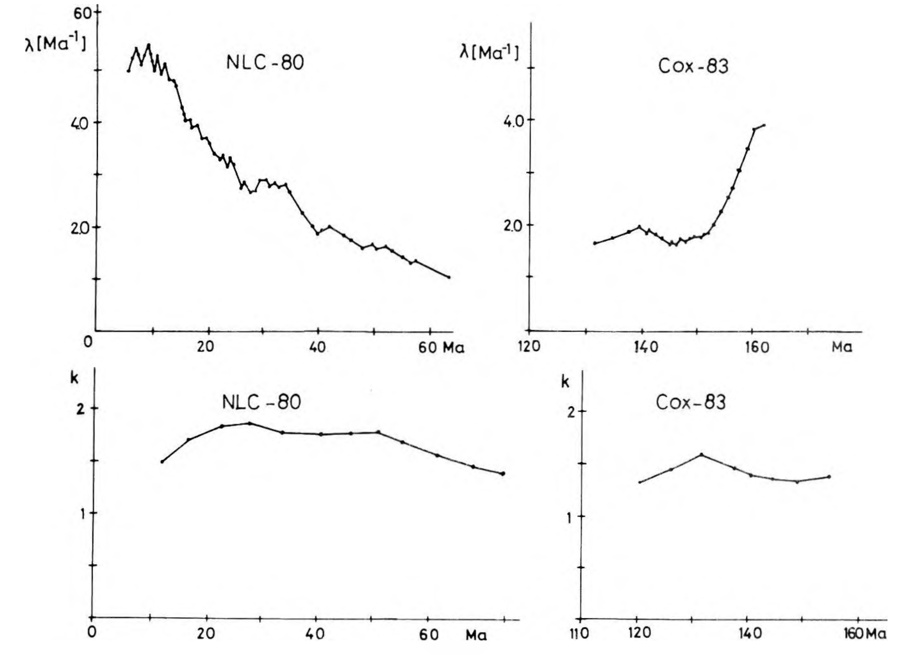

Fig. 7. The change of λ and k in time for the NLC–80 (from 0 to 80 million years) and for the Cox–83 (from 120 to 160 million years) timescales [McFadden and Merrill 1984]

7. ábra. λ és k időbeli változása az NLC–80 (0–80 millió év) és a Cox–83 (120–160 millió év) időskálára [McFadden and Merrill 1984]

Рис. 7. Изменение λ и κ во времени по шкалам NLC–80 (0–80 млн. лет) и Cox–83 (120–160 млн. лет) [McFadden and Merrill 1984]

2.3 The independence of the polarity intervals

A very important question in the statistical investigation of time series is whether or not the time intervals between the polarity reversals are independent. First Naidu [1974, 1975] made tests for the independence. The autocorrelation function of the polarity intervals was constructed for the HDHPL–68 timescale from 0 to 72 million years *(Fig. 8)*. It can be seen that the autocorrelation function significantly differs from the autocorrelation function of the white noise. Therefore the independence can be rejected. The idea of Naidu was correct, but as has been shown by Ulrych and Clayton [1976], the autocorrelation analysis can be used only when the process is stationary. Therefore the autocorrelation function was made for the HDHPL–68 timescale from 0 to 48 million years. We can assume the stationarity for this time interval as per chapter 2.1. As *Fig. 9* shows, we can accept the independence of the intervals

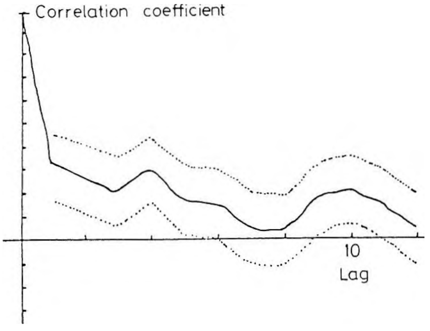

Fig. 8. The autocorrelation function for the whole HDHPL–68 timescale. The dashed lines show the 95% confidence interval [after ULRYCH and CLAYTON 1976]

8. ábra. A HDHPL–68 időskála autokorrelációs függvénye a teljes időskálára. A vízszintes tengelyen az eltolás, a függőleges tengelyen a korrelációs együttható látható. A pontozott vonal a 95%-os konfidencia-intervallumot jelöli [ULRYCH and CLAYTON 1976 nyomán]

Рис. 8. Функция автокорреляции временной шкалы HDHPL–68 по всей шкале времен. На горизонтальную ось нанесены смещения, а на вертикальную – коэффициенты корреляций. Пунктирной линией обозначен 95%-ный интервал доверия [по ULRYCH and CLAYTON 1976]

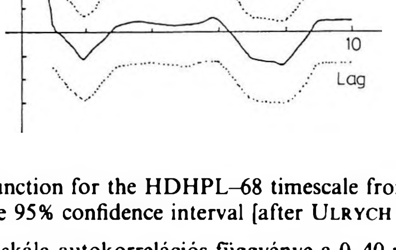

Fig. 9. The autocorrelation function for the HDHPL–68 timescale from 0 to 40 million years. The dashed lines show the 95% confidence interval [after ULRYCH and CLAYTON 1976]

9. ábra. A HDHPL–68 időskála autokorrelációs függvénye a 0–40 millió éves időszakra. A vízszintes tengelyen az eltolás, a függőleges tengelyen a korrelációs együttható látható. A pontozott vonal a 95%-os konfidencia-intervallumot jelöli [ULRYCH and CLAYTON 1976 nyomán]

Рис. 9. Функция автокорреляции временной шкалы HDHPL–68 по интервалу времени 0–40 млн. лет. На горизонтальную ось нанесены смещения, а на вертикальную – коэффициенты корреляций. Пунктирной линией обозначен 95%-ный интервал доверия [по ULRYCH and CLAYTON 1976] for a 95% confidence limit. In his reply, NAIDU [1976] admitted the validity of ULRYCH and CLAYTON's result, but maintained that the polarity intervals are not independent between 48 and 72 million years. Practically the same investigation was made by PHILLIPS et al. [1975]. They concluded that for the stationary time intervals from 0 to 45 and from 45 to 76 million years, the intervals are independent. LAJ et al. [1979] found the same result for the whole HDHPL–68 timescale, with another method of building the autocorrelation function. It will be worth investigating why the discontinuity does not appear around 48 million years. We can see that the newer timescales are not stationary (therefore autocorrelation analysis cannot be carried out on them). Furthermore the samples do not originate from the same distribution, consequently statistical tests for the independence cannot be carried out on them (for example difference-test [MESZÉNA and ZIERMANN 1981]), because these tests assume that the samples originate from the same distribution. Consequently we can say nothing about the independence of the polarity intervals with the mentioned methods.

However we can say something about the independence in an analytical way. The sequence of ideas was suggested by MCFADDEN in private communication. For simplicity let us assume that the reversals are generated by a Poisson–process. Therefore the probability $P(t)$ that a reversal will happen in the interval $[t, t+dt]$ is:

$$P(t)\,\mathrm{d}t = \lambda \cdot \mathrm{e}^{-\lambda t}\,\mathrm{d}t \tag{7}$$

Further, let us assume that the λ is a function of time, for example: $\lambda = \alpha+\beta t$. Let us start from time $t=0$, and wait for the first reversal, which will have happened in t_1 time moment. On the basis of equation (7) the probability density function relating to t_1 time moment is:

$$P(t_1) = \alpha \cdot e^{-\alpha t_1} \tag{8}$$

The probability density function for the next interval length t_2 upon condition t_1 is given by

$$P(t_2|t_1) = (\alpha+\beta t_1)\exp\{-(\alpha+\beta t_1)t_2\} \tag{9}$$

It is obvious, that we can not get rid of t_1 in equation (9), since interval t_2 will depend on the previous t_1 interval. Thus the intervals are not independent.

3. The stability of the polarity states

To determine the stability of the polarity states we shall provide an equation which gives the probability of the next reversal as a function of the passed time from the previous reversal. Therefore we have to consider that the elements of the time series do not originate from the same distribution, namely k and λ change with time. Let us assume an event (for example normal polarity state) which is in process at the time t_0. What is the probability that the event will be over before $t_0 + t$? (i.e. will a polarity change happen?) *(Fig. 10).*

$$P(x \leqq t_0 + t \mid x \geqq t_0) = ?$$

where X is the length of the polarity interval. After a simple calculation:

$$P(x \leqq t_0 + t \mid x \geqq t_0) = \frac{\gamma[\lambda(t_0 + t), k] - \gamma[\lambda t_0, k]}{1 - \gamma[\lambda t_0, k]} \tag{10}$$

where $\gamma[\lambda, k]$ is the incomplete gamma function [Harter 1964]. Let us call this probability the *probability of reversals.* Let us choose t_0, that "first" time moment which will follow after a reversal with an infinitesimal time, and let us describe the probability of reversals for different geological dates with the help of the values λ and k, which can be seen on Fig. 7 *(Fig. 11)*. It can be seen that

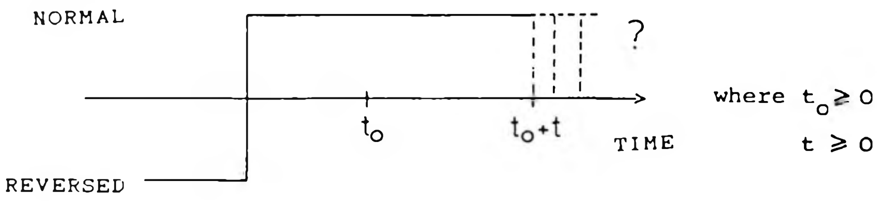

Fig. 10. A description of the polarity change

10. ábra. Polaritásváltás

Рис. 10. Перемена полярности

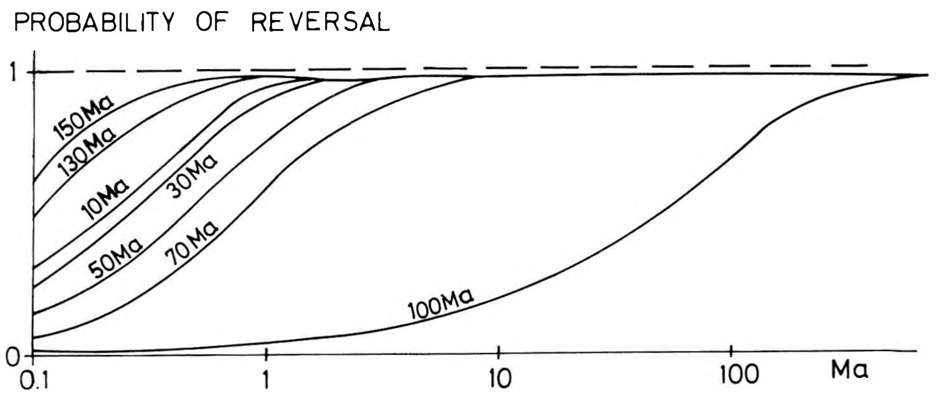

Fig. 11. The change of the probability of reversals with time, for different geological dates

11. ábra. A térfordulási valószínűségek alakulása az időben, különböző geológiai időpontokban

Рис. 11. Изменение вероятности перемены полярностей во времени для различных моментов геологического времени until the Cretaceous Normal Interval (between 80 and 120 million years) the rate of increase of the probability of reversals decreases, and after the Cretaceous Normal Interval it starts to increase quickly (see Fig. 11). On the basis of this we can understand, in a qualitative way, the existence of the long intervals with the same polarity, because, if λ approaches zero, the mean length of the polarity intervals will become infinite. It may also be assumed that it is by chance as to what kind of polarity will be a long polarity interval. Since according to chapter 2.2, the value of k and λ are the same for both polarity states, the probability of reversals (or the stability of the two polarity states) are also the same.

Some remarks about the polarity bias. Until now, this problem was connected with the question of the difference in stability between normal and reverse polarity states [PHILLIPS 1977]. If the stability of the two polarity states are the same, then the phenomena is due entirely to other reasons, and will not be valid for the models connected with this (e.g. the models of Cox [1981]). On the basis of these calculations, the question of the polarity bias is connected with those processes which cause the change of the λ parameter of the gamma distribution.

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A PALEOMÁGNESES POLARITÁS–IDŐ SKÁLÁK STATISZTIKAI TULAJDONSÁGAI

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A paleomágneses polaritás–idő skálák statisztikai vizsgálatának célja, hogy információt szerezzünk a térfordulások átlagos időbeli viselkedéséről, és ezek felhasználásával olyan modellt készítsünk a jelenségről, amely ugyanezeket a statisztikai tulajdonságokat tükrözi. E feladatok közül a dolgozat az átlagos időbeli viselkedés leírását tűzte maga elé. A legújabb időskálák vizsgálatával a következő eredmények adódnak:

— a polaritásintervallumok időben nem-stacionárius viselkedést mutatnak, amely lineáris regresszióval közelíthető;
— az észlelt polaritásintervallumok gamma-eloszlást követnek; az eloszlás paraméterei változtak a földtörténeti múltban;
— a jelenlegi matematikai statisztikai módszerekkel nem vizsgálható az intervallumok függetlensége, analitikus úton — megfelelő feltételek esetén — azonban bizonyítható;
— a tér stabilitása mindkét polaritásállapotra azonos; a polaritásállapotok túlsúlyának kérdése összekapcsolódik a gamma-elosztás λ paraméterének változását előidéző folyamatokkal

СТАТИСТИЧЕСКИЕ СВОЙСТВА ПАЛЕОМАГНИТНЫХ ШКАЛ ПОЛЯРНОСТЬ–ВРЕМЯ

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Цель статистического исследования палеомагнитных шкал полярность–время заключается в извлечении информации о среднем поведении изменений полярности во времени и в создании с ее помощью модели, отражающей те же статистические свойства. Из этих задач в данной статье рассматривается характеристика среднего поведения во времени. При изучении новейших шкал времени можно придти к следующим выводам:

— интервалы постоянной полярности обнаруживают не стационарное во времени поведение, которое может быть аппроксимировано линейной регрессией;
— наблюдаемые интервалы постоянной полярности распределены по гамма-закону; параметры распределения менялись в ходе геологической истории;
— независимость интервалов не может быть изучена известными математическими методами, но—при надлежащих условиях—может быть доказана;
— стабильность поля одинакова в обоих состояниях полярности; вопрос о преобладании состояния той или иной полярности связана с процессами, вызывающими изменения параметра λ гамма-распределения.