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Wavelet Analysis of the Geomagnetic Field during the Neogaea

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Abstract—The purpose of this work is to study the main characteristics of the Neogaean geomagnetic field, including the paleointensity modulus and its variations, the total amplitude of variations in the field direction, and the sequence and frequency of field reversals. We show that the Neogaean geomagnetic field reveals no stationary periodic variations in recorded parameters. The study time series contain relatively short oscillatory processes (cycles) whose duration is mostly comparable to the oscillation "period" itself and rarely reaches three to five periods. The periods of oscillations recognizable from peaks in the corresponding spectra form groups of 40–45, 60–70, 80–100, 130–140, 160–180, 250–260, 300–320, 420, and 500–600 Myr. Furthermore, spectral peaks of various parameters occur asynchronously. According to the behavior of the inferred oscillations, the Neogaea can be divided into three intervals: (a) the Phanerozoic–Vendian (ca. 650–0 Ma), (b) the uppermost Late Riphean (850–650 Ma), and (c) the lowermost Late Riphean–uppermost Early Riphean (1450–850 Ma). These intervals appear to be characterized by different modes of the geomagnetic field generation.

INTRODUCTION

In recent years, researchers have repeatedly addressed the generalization and analysis of the behavior of geomagnetic field characteristics in time intervals as long as hundreds of millions of years. A 170-Ma interval or more rarely the Phanerozoic (about 560 Ma) are usually considered with regard to the geomagnetic field polarity [e.g., Didenko, 1998; Gaffin, 1987; Merrill and McElhinny, 1983] and (more rarely) to other field characteristics [Pechersky and Nechaeva, 1988; Irving and Pullaiah, 1976].

To date, the time series of Neogaean geomagnetic field characteristics have been obtained for variations in the field polarity, intensity, and direction [Pechersky, 1996, 1997, 1998]. Each of these characteristics reflects processes in the Earth's core and in the region of its interaction with the mantle. It is undoubtedly interesting to jointly consider these characteristics, to reveal their interrelation, to trace their evolution during the Neogaea, and to compare them with processes in the lithosphere. This paper makes an attempt to solve in part this problem, namely, to perform a joint spectral analysis of the characteristics mentioned above and to reveal their periodicity.

The spectral Fourier analysis, conventionally used to search for periodicities, is efficient in the treatment of signals with a pronounced periodicity and gives characteristics of the entire time series. However, the Neogaea encompasses a huge time interval of 1700 Myr, and the geomagnetic field evolution should undoubtedly reveal some variations during this time. Also, based on the available data, one cannot expect to discover any well-pronounced periodicities (such as the 11-year cycle). Therefore, we used wavelet analysis, which is a relatively new method of analyzing quasi-stationary and quasi-periodic processes. This method allows the recognition of periodicities only in a fragment of a time series and localizes the fragment itself. In addition, the method allows one to examine signals whose period slowly changes with time [e.g., Holschneider, 1995].

WAVELET ANALYSIS

Wavelets are a set of oscillating self-similar functions of various scales, localized in both the physical and Fourier spaces. The wavelet analysis allows one to study processes characterized by nonstationary spectra, to trace the phase behavior of a component of a quasi-periodic process, and to estimate its energy characteristics. The wavelet analysis is also advantageous in that it can be modified to treat time series including gaps in observations [Galyagin and Frick, 1996]. We define the continuous wavelet transformation of a function $f(t)$ as follows:

$$\omega(a, t) = a^{-1}\int_{-\infty}^{\infty}\psi\left(\frac{t'-t}{a}\right)f(t')dt', \qquad (1)$$

where a is a parameter characterizing the time scale (period of oscillations), $\psi(t)$ is a function, called the analyzing wavelet, for which the condition

$$C_\psi = \int_{-\infty}^{\infty} |\omega|^{-1}|\hat{\psi}(\omega)|^2 d\omega < \infty, \quad (2)$$

provides the uniqueness and invertibility of the transformation, and $\hat{\psi}(\omega) = \int_{-\infty}^{\infty}\psi(t)e^{-i\omega t}dt$ is the Fourier image of $\psi(t)$. Condition (2) leads to the requirement $\int_{-\infty}^{\infty}\psi(t)dt = 0$; i.e., the average wavelet value must be zero. The wavelet transformation maps a function of one variable t onto the plane of two variables, t and a. An analogue of the Fourier spectrum is the so-called integral wavelet spectrum obtained by integration of the squared wavelet transformation modulus over the time interval under consideration T: $S(a) = T^{-1}\int_0^T|\omega(a, t)|^2 dt$. The resulting spectrum, in which multiple and combination frequencies are suppressed, is smoother than the Fourier spectrum.

The choice of a specific wavelet form depends on the purpose of the wavelet analysis. The Morle wavelet $\psi(t) = e^{-t^2/2}e^{i2\pi t}$, mainly used in this paper, is often applied in spectral analysis problems.

The wavelet representation allows one to assess the degree of correlation between various processes on various time scales (periods). We define a complex correlation between processes $f_1(t)$ and $f_2(t)$ whose wavelet representations are, respectively, $\omega_1(a, t)$ and $\omega_2(a, t)$ as follows:

$$C(a) = \frac{\int\omega_1(a, t)\omega_2^*(a, t)dt}{\left(\int|\omega_1(a, t)|^2dt\int|\omega_2(a, t)|^2dt\right)^{1/2}}. \quad (3)$$

The correlation degree of two processes on a given time scale a determines the modulus of $C(a)$, ranging from zero to unity. The phase $\Delta\varphi$ of the correlation $C(a)$ gives a shift (in radians) between the corresponding spectral harmonics of the two processes.

We also use the wavelet transformation algorithm proposed by Galyagin and Frick [1995] and by Frick *et al.* [1997] in order to analyze data containing significant gaps. The idea of the method is to correct the wavelet falling into the range with gaps so as to satisfy condition (2) providing the average zero value of the wavelet. The algorithm largely suppresses artifacts caused by the pattern of gaps in the time series analyzed.

FIELD REVERSALS (GEOMAGNETIC POLARITY TIME SCALE)

Frequency of Geomagnetic Reversals

In the first approximation, the geomagnetic field is generated by an axial dipole whose direction can be reversed (geomagnetic field reversals). The reversals themselves are believed to be described by a random law [Cox, 1968, 1981; Merrill and McElhinny, 1983]. The sequence of polarity reversal moments constitutes the geomagnetic polarity time scale. The most widespread approach is to study spectral characteristics of variations in the reversal frequency (the number of reversals in the unit time), which appear to reflect variations in the thermal regime at the core–mantle boundary [e.g., Jacobs, 1994]. Such studies were performed for the past 170 Myr (the time scale of linear magnetic anomalies) [Gaffin, 1987; Harland *et al.*, 1990; Lutz and Watson, 1988; Marzocchi and Mulargia, 1992; Mazaud *et al.*, 1983], for the Paleozoic [Didenko, 1998], and for the entire Phanerozoic [Pechersky and Nechaeva, 1988; Irving and Pullaiah, 1976]. The periods identified more or less reliably are 15, 30, 50–60, 70, 100–110, 125, 170, 220, 280, and 390 Myr.

The plot of the number of reversals $F(t)$ versus time (Fig. 1a) shows that both the Phanerozoic and Precambrian sharply differ in the frequency of reversals: of 570 reversals during the Neogaea, 370 fall into the Phanerozoic period. A peak at about 130 Myr and a number of peaks of a smaller amplitude (at 25–30, 65–70, and 420 Myr) are identified from the integral wavelet spectrum of the $F(t)$ series (Fig. 2a); on the whole, this coincides with the previously obtained Fourier spectrum (see above). To answer the question of whether these peaks correspond to actual periodic processes, we show the wavelet spectrum evolution during the Phanerozoic (Fig. 3a) and the entire Neogaea (Fig. 3b). As seen from Fig. 3, the Phanerozoic–Vendian and the Riphean exhibit essentially different patterns. Also, the most intense 130-Myr peak in the integral spectrum is caused by a strong short oscillation represented in the wavelet plane by a clear spot centered near $t = 60$ Myr (in the wavelet plane, this structure reflects two strong peaks at the beginning of the series presented in Fig. 2a).

From the standpoint of periodic processes with duration significantly exceeding their period, horizontal structures on the wavelet plane are most interesting (purely periodic processes are represented by strictly horizontal bands). Only the cycle with a period of about 400 Myr, decreasing from over 450 Myr in the Vendian to less than 400 Myr in the Late Cenozoic, is recognizable throughout the Vendian–Phanerozoic interval. The lifespan of the remaining cycles (with periods of 70 to 200 Myr) is much shorter. In particular, the 90- and 180-Myr “periods” are recognized in the interval from 550 to 200 Ma (the periods are poorly resolved in Fig. 2a, but they are clearly seen in Fig. 3a), and both

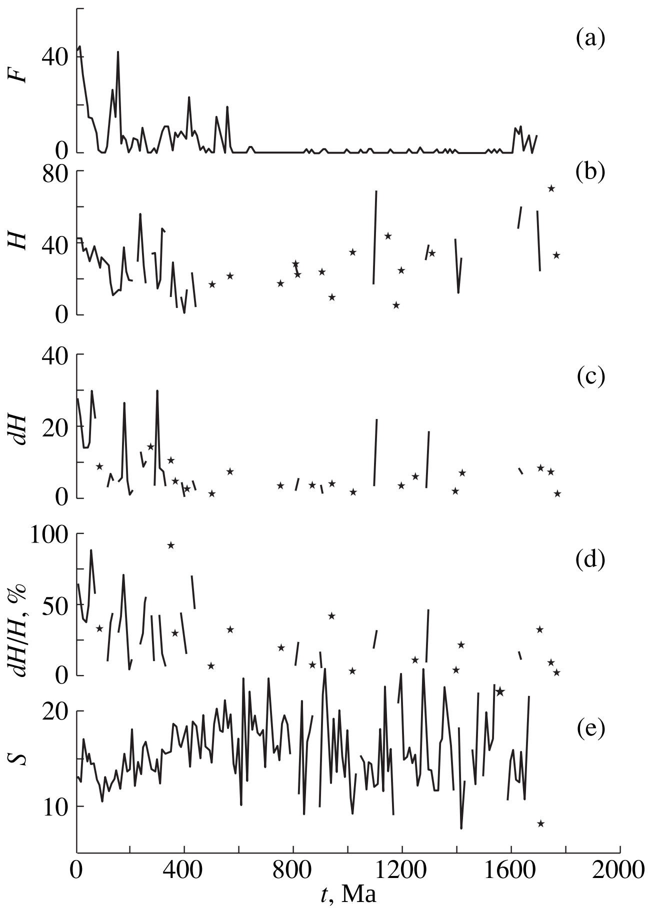

Fig. 1. Evolution of paleomagnetic characteristics (after Pechersky [1997, 1998]): (a) frequency of reversals F; (b) modulus of the geomagnetic field intensity H; (c) absolute amplitude of the field intensity variation dH; (d) relative amplitude of the field intensity variation dH/H; (e) total amplitude of the direction variation S. All data were averaged over 10-Myr intervals.

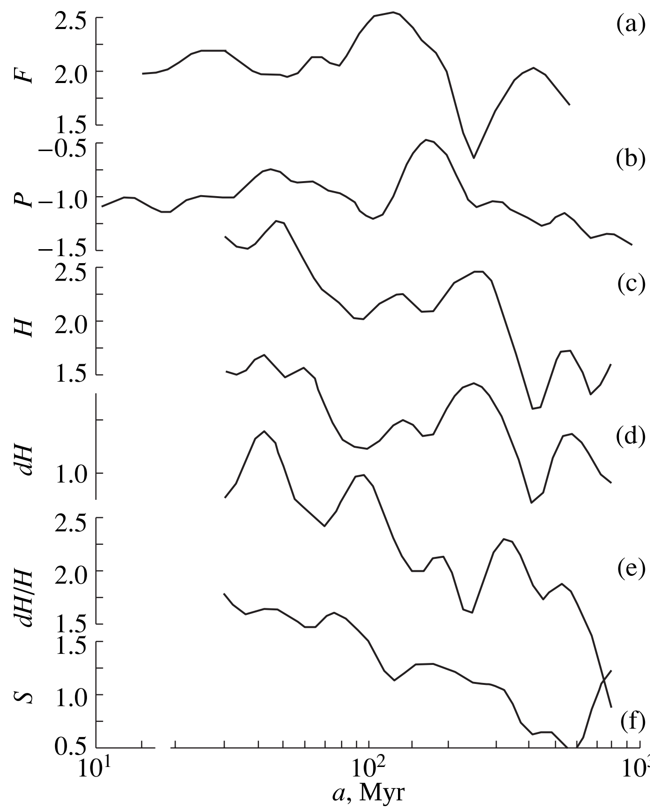

Fig. 2. Integral wavelet spectra: (a) frequency of reversals F; (b) polarity time scale P; (c) geomagnetic field intensity modulus H; (d) absolute amplitude of the field intensity variation dH; (e) relative amplitude of the field intensity variation dH/H; (f) total amplitude of the direction variation S.

periods gradually decrease (from 200 to 170 Myr and from 100 to 90 Myr, respectively).

Of the remaining features on the wavelet plane, we note a horizontal structure extending for the past 160 Myr, with a period decreasing from 70 to 55 Myr, and a series of point-like spikes during the Phanerozoic and at the very beginning of the Riphean (t = 160, 420, 540, and 1650 Ma), which are localized at the lower boundary of the wavelet plane (consequently, these spikes have time scales $T \leq 30$ Myr).

To examine the stability of the results, the wavelet analysis was also performed with 5-Myr (Phanerozoic) and 30-Myr (Neogaean) smoothing windows. Its results are close to those described above.

Field Sign Spectrum

The complete information on geomagnetic field reversals is contained in the original polarity record, rather than in the derived characteristics, of which the reversal frequency discussed above is one. It is therefore interesting to analyze the polarity time scale itself by making use of spectral methods. Such an analysis was recently performed by Galyagin *et al.* [1998]. The problem is that the polarity signal P is a step function of the form (0, 1,…, 0), and its examination by conventional spectral methods (e.g., Fourier analysis or the maximum entropy method) is difficult, because the spectrum of such a function weakly decreases at infinity. To overcome this difficulty, Galyagin *et al.* [1998] used wavelets and obtained the geomagnetic polarity time scale spectrum in the interval from 100 Ma to 20 ka. Furthermore, they found a break in the integral wavelet spectrum on a scale of $a \approx 1$ Myr, separating variations with characteristic times smaller than 1 Myr, directly caused by dynamo processes, from slower variations of geological origin [e.g., Pechersky *et al.*, 1997].

In this paper, we are interested in the variations with characteristic times longer than 10 Myr. The corresponding part of the integral wavelet spectrum (Fig. 2b) is appreciably different from the spectrum of the rever-

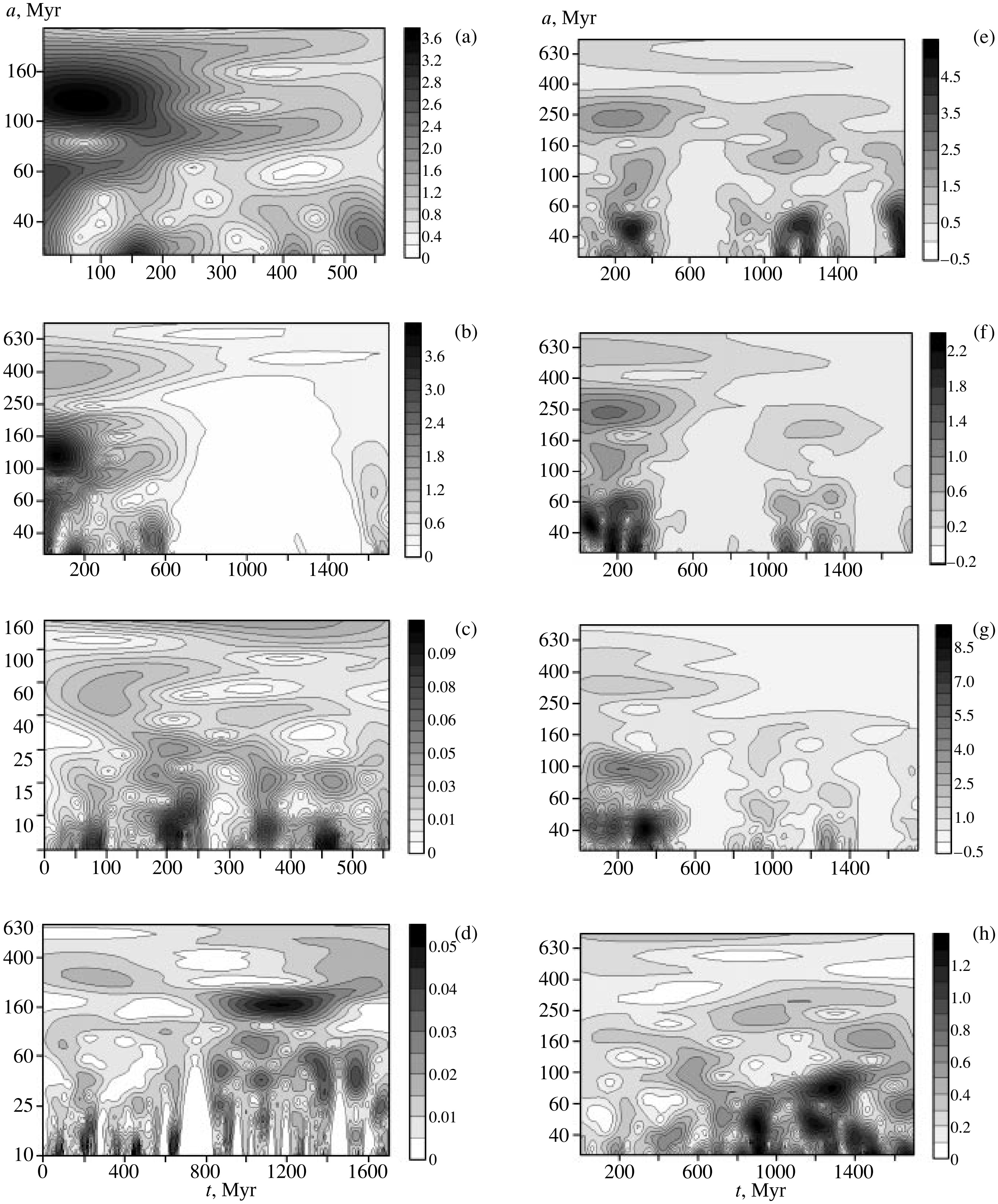

Fig. 3. Wavelet expansion $\omega(a, t)$. The moduli of wavelet coefficients is plotted on the time–scale plane: frequency of reversals F, (a) 560 and (b) 1700 Myr; polarity time scale P, (c) 560 and (d) 1700 Myr; (e) modulus of the field intensity H, 1700 Myr; (f) absolute amplitude of the field intensity variation dH, 1700 Myr; (g) relative amplitude of the field intensity variation dH/H, 1700 Myr; (h) total amplitude of the direction variation S, 1700 Myr.

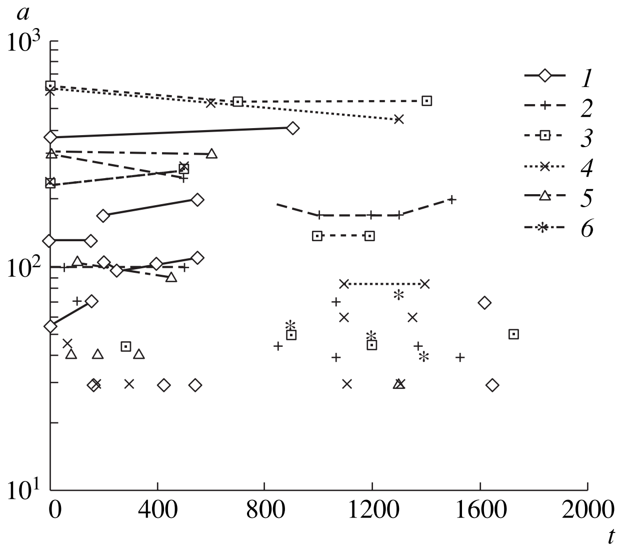

Fig. 4. Main structures obtained from the wavelet expansion of geomagnetic field characteristics in the Neogaea: (*1*) *F*; (*2*) *P*; (*3*) *H*; (*4*) *dH*; (*5*) *dH*/*H*; (*6*) *S*.

sal frequency (Fig. 2a) and has a relatively smooth shape, against the background of which a pronounced peak ($a \approx 180$ Myr) and a number of weak peaks (12, 23, 43, 60, 100, 300, and 600 Myr) are observed. Addressing the wavelet plot (Figs. 3c and 3d), one can see that the 180-Myr peak is associated with a horizontal structure extending for the time interval from 1450 to 850 Ma (including the upper half of the Early Riphean, the Middle Riphean, and the lower half of the Late Riphean), which is adjacent to weaker horizontal structures associated with the 100- and 300-Myr peaks. The remaining peaks observed in the integral spectrum are caused by local events whose duration is of the order of the time scale. A certain regularity is recognizable in the time distribution of these local events (Figs. 3c and 3d), which may be subdivided into three intervals: (a) the Vendian–Phanerozoic (630–0 Ma), within which five spikes separated, on average, by intervals of 125 Myr are fixed; (b) middle of the Late Riphean–middle of the mid-Riphean (1260–800 Ma), where five spikes with an average spacing of 80 Myr are observed; and (c) Middle–Early Riphean (1670–1260 Ma), with three spikes separated by average intervals of 140 Myr. Note that, although the general structure of the wavelet plot for the reversal time scale has nothing in common with the wavelet plot for the reversal frequency, the Phanerozoic–Precambrian boundary is also clearly seen in the former plot (compare Figs. 3b and 3d, keeping in mind that the smallest scale in the last case is 10 Myr, rather than 30 Myr).

CHARACTERISTICS OF THE GEOMAGNETIC FIELD INTENSITY

The geomagnetic field polarity considered above does not provide the full information on the field behavior, because the field is a three-dimensional vector. Galyagin *et al.* [1998] examined the possibilities of determining the spectral properties of variations in the magnetic field itself from the corresponding polarity time scale. Using model examples, they showed that the slope of the reversal time scale spectrum is always greater than the slope of the spectrum of a signal itself and can coincide with the latter in the case of a relatively simple signal structure (for example, in the Rikitaki dynamo model). In this section, we consider the spectral properties of the main characteristics of the geomagnetic field, derived from the available data [Pechersky, 1996, 1997, 1998]: the modulus of the field intensity, its variations, and the total amplitude of variations in the field direction.

Intensity Modulus

As compared with the geomagnetic polarity time scale, the time series of the intensity modulus is less complete, containing significant gaps in data (Fig. 1b). A special technique of wavelet analysis was used to analyze such series [Galyagin and Frick, 1996; Frick *et al.*, 1997].

The peaks at 45, 140, 260, and 560 Myr are identified in the integral spectrum of *H* (Fig. 2c). Previously, a reliable period of 270 Myr and two less reliable periods of 115 and 90 Myr have been identified in the Phanerozoic [Pechersky and Nechaeva, 1988]. The wavelet plot for *H* (Fig. 3e) substantially differs from those discussed above. Three intervals are distinguished in this plane: 450–0, 1450–850, and 1700–1600 Ma, with no data being available between these intervals (Fig. 1b). Local peaks are observed within these intervals, and the strongest peak has a time scale $a \approx 45$ Myr. The intervals are contiguous at times $a \approx 200$–250 Myr.

Variations in the Modulus of the Geomagnetic Field Intensity

We consider that the field variation is represented by the time behavior of the standard deviation *dH* of the paleointensity modulus *H* and of the ratio *dH*/*H* (Figs. 1c, 1d). The integral spectrum of *dH* is very similar to the spectrum of *H* (Figs. 2c, 2d) and contains only one additional peak at 60 Myr. The spectrum of *dH*/*H* (Fig. 2e) is somewhat different and has peaks at 40, 100, 180, 320, and 500 Myr. As well as in the case of the integral spectra (Figs. 2c, 2d), the wavelet expansions of *H* and *dH* (Figs. 3e and 3f) have very similar structures. Accordingly, we may conclude that the variations become greater as the intensity of oscillations increases. The wavelet expansion of *dH*/*H* (Fig. 3g) retains the general structure of the *H* and *dH* expansions. Nevertheless, some of the local peaks are absent, as is also demonstrated by a change in the position of several peaks in the integral spectrum (Fig. 2e).

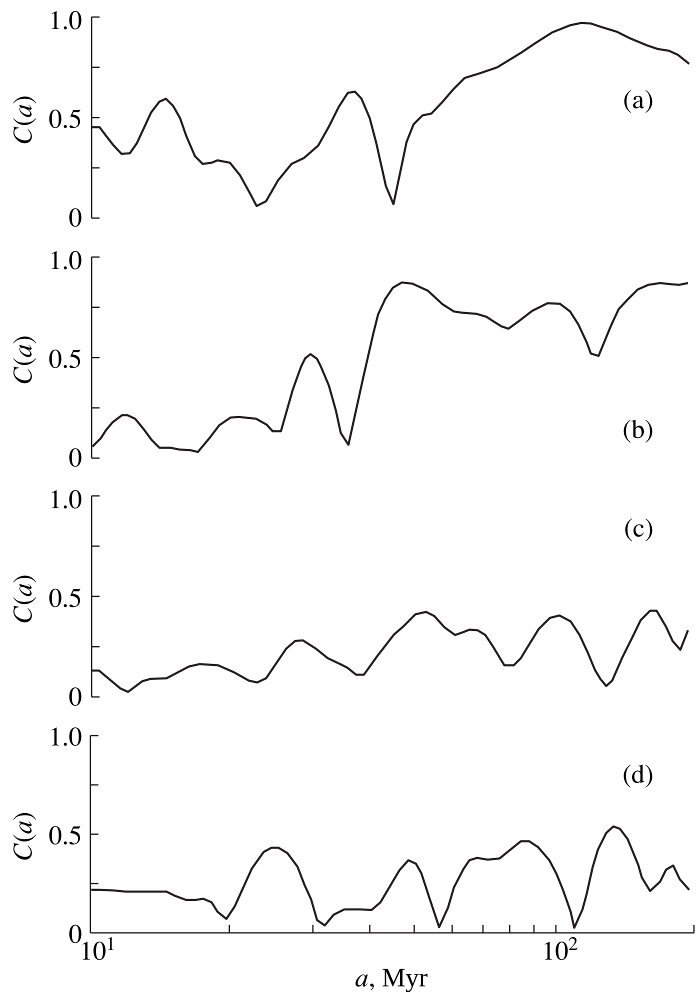

Fig. 5. Correlation modulus $C(a)$ for pairs of time series: (a) *dH–H*; (b) *F–dH/H*; (c) *S–dH/H*; (d) *S–H*.

Total Amplitude of Variations in the Field Direction

Based on the data synthesis of paleovariations in the field direction, their total amplitude was found from the standard deviation of the paleomagnetic direction *S* [Pechersky, 1996, 1997]. Paleomagnetic data immediately determine the geomagnetic field direction in a given geological time moment. The precision parameter of the unit vectors involved in this determination was estimated for each paleomagnetic direction in a given object and was used to find the standard deviation of the paleomagnetic direction, which is the total amplitude of field direction paleovariations. We emphasize that this procedure incorporates variations in the full direction vector, i.e., variations in both the inclination and declination of the paleomagnetic field. Weak peaks at 45, 80, 160, 300, and 450 Myr are observed in the relatively smooth integral wavelet spectrum (Fig. 2f). Moreover, the original data (Fig. 1e) yield evidence of an oscillation with a period of $\approx 10^3$ Myr, associated with an increase in the spectrum on maximum time scales. As seen from the wavelet plane (Fig. 3h), all of these periods give local maximums. The pattern looks quite uniform in a large scale range ($a > 100$ Myr). The difference in the field generation modes between the Phanerozoic and Precambrian is evident at times shorter than 100 Myr; at these times, an interval of higher intensity of variations is distinguished in the Precambrian.

DISCUSSION

A number of the averaged characteristics of the Neogaean geomagnetic field were considered: the frequency of reversals, a polarity signal, the intensity modulus, and variations in the field direction and magnitude. The time series and their evolution were treated in terms of the wavelet analysis. The majority of peaks detected in the integral spectra were shown to be caused by local events on the corresponding time scales, rather than by any pronounced periodic processes.

The following facts are evidence of the general instability of the geomagnetic field.

(a) The wavelet spectra markedly differ in their structure for all of the geomagnetic parameters considered (Figs. 3 and 4). However, the parameters H and dH are characterized by two time intervals similar in both the duration and behavior of the related processes (Figs. 3e and 3f). These intervals are the last 400–500 Myr and the period of the same duration centered at 1200 Myr. Other characteristics show different behavior. Whereas the frequency F has a much more pronounced structure in the first of the intervals mentioned above, the total amplitude of variations in the field direction S and the change of sign in the geomagnetic polarity P demonstrate a considerably higher "activity" in the second interval.

(b) The overwhelming majority of the inferred periods are short "spikes" about as long as one complete oscillation (or not longer than two oscillations). There are about 40 such periods. Three oscillations at a given period were only observed in four cases: for F, with $a \approx$ 100 Myr in the interval $470 > t > 160$ Ma; for P, with $a \approx 60$ Myr in the interval $430 > t > 280$ Ma; and for dH/H ($a \approx 40$ in the interval $120 > t > 70$ Ma and $a \approx$ 100 Myr in the interval $450 > t > 150$ Ma). The only cases of longer duration are the oscillations of P, lasting for four periods ($1500 > t > 800$ Ma, of $a \approx 180$ Myr), and the oscillations of S, lasting for five periods (1500 to 1100 Ma, $a \approx 100$ Myr).

(c) Oscillations of different field characteristics with similar periods are usually asynchronous. The following preferred intervals of "periods" are distinguished: 40–45 Myr (F, P, H, dH, dH/H, S); 60–70 Myr (F, P, dH); 80–100 Myr (F, dH/H, S); 130–140 Myr (F, H, dH); 160–180 Myr (F, P, dH/H, S); 250–260 Myr (H, dH); 300–320 Myr (dH/H, S); and 500–600 Myr (P, H, dH, dH/H).

(d) The oscillation "periods" often vary smoothly with time, which is illustrated in Figs. 3 and 4. This fact is largely responsible for marked ranges of variations in period values (see (c)). Most periods decrease with time, indicating a general acceleration of the process: for example, the period of F decreases from 100 to 85 Myr or from 70 to 60 Myr during the time periods from 470 to 160 Ma or from 150 Ma to the present, respectively; the period of S decreases from 100 to 70 Myr in the interval from 1500 to 1100 Ma, etc. Less frequent are the cases when the period increase, which indicates a deceleration of the process: for example, the period of P increases from 200 to 280 Myr, or the period of dH/H increases from 80 to 100 Myr in the time period from 450 to 150 Ma, etc.

The wavelet representations of nearly all of the temporal series considered above reveal the Phanerozoic–Riphean boundary, which is best resolved in the wavelet plane of the reversal frequency series (Figs. 3a and 3b), where the Phanerozoic is sharply distinguished from the preceding time.

To elucidate the relation between the geomagnetic field characteristics, we calculated the cross correlations of the spectral coefficients $\omega(a, t)$ in (3) for all possible combinations of five parameters considered (F, H, dH, dH/H, and S). The following results are noteworthy. As mentioned above, the expansions of the intensity modulus H and its variations dH have similar patterns. This is additionally supported by the behavior of the curve $C(a)$ (Fig. 5a) showing that the correlation coefficient is nearly unity on scales $a \approx 100$ Myr and larger (the phase shift is close to zero in this case). A high correlation coefficient was found for the pair of F–dH/H on time scales of 40 Myr and more (Fig. 5b). Of the remaining results, we only note a strong peak in the S–dH/H correlation on a time scale of 250 Myr (Fig. 5c). Other fields have similar structures in the vicinity of $a \approx 250$ Myr, although they are less reliably resolved. Finally, Fig. 5d shows a characteristic example of the absence of cross correlation between the H and S series.

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