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# Endogenic Cycles and the Problem of Crustal Growth

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**Abstract**—The statistical analysis of geochronological data (more than 14200 dates) has been carried out by using the method of the probabilistic description of summary information on the crust and mantle and separately on both of the Earth's upper shells considered together over the whole geological history. Various lines of evidence are presented for the necessity of using the whole set of geochronological methods to reveal any systematic pattern in the evolution of crust formation and to demonstrate the uselessness of utilizing selected data obtained by any one of the methods because of the limited analytical capability of each of them. These constraints, together with compositional variations of the dated rocks and the variable amount of the initial information, lead to uncertainty in estimation of megacyclicity as a sum of contrasting dynamics of endogenic events occurring in the crust and the mantle. It has been shown that mantle processes become more intense during periods of the synchronous activation of endogenic events in both shells; mantle activity sharply decreases in the epochs when endogenic processes in these shells are waning. This difference may serve as an objective criterion for estimating the maximum duration of cycles of mantle activity, which is distinct in the Early–Middle Archean, Late Archean– Proterozoic, and Phanerozoic. These conclusions are supported by examples of geochronological systematics for cratons of northeastern Labrador, western Greenland, and western Australia.

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## INTRODUCTION

More than 40 years have elapsed since the nonuniform character of the evolution of the continental crust growth was pointed out for the first time [1], with this nonuniformity referred to as megacyclicity thereafter [2]. Over these years, the problem of crustal growth has been actively discussed, and if the unusual assumption that the entire crust had been formed during the early stage of the Earth's evolution [3] is abandoned, megacyclicity is commonly considered (first of all, on the basis of geochronological data) to be a reflection of the progressive but nonuniform growth of the crust over the geologic time. In the 1960s–1980s, geochronological information was very limited and compelled to combine the dates of the crustal and upper mantle rocks and minerals into a common "system." This approach actually postulated the geochronological identity of endogenic events in both of the upper shells, or involuntarily ignored the possible differences and, thus, yielded only tentative estimates of the boundaries of the inferred megacyclicity. The difficulties in interpretation of geochronological results were redoubled by variations of the peaks and boundaries between megacycles, which depended on the use of data obtained with K–Ar, U–Th–Pb, and Rb–Sr methods of dating, which could not always be compared with integral statistics based on all methods [1]. The discrepancy was confirmed by new statistical overviews with the involvement of Sm–Nd [4] and U–Pb [5] data and their comparison with previous publications [1, 2, and others]. This was the reason for undertaking this study, which makes use of the probabilistic description of endogenic events in the mantle and the crust for statistical processing of geochronological information.

## PROBABILISTIC DESCRIPTION OF GEOCHRONOLOGICAL DATA

Geochronological dates are highly variable in accuracy: their uncertainties may be as great as tens and hundreds of million years. Another problem is the unequal representativeness of data on discrete types of rocks. The recognition of these principal complications in the analysis of geochronological data stimulated the application of some new approaches to the processing of information concerning the age of rocks. Different variants of the systematics of dates were proposed, from the standard summation with a given discrete step of averaging [4–7] to attempts of accounting for variable errors of individual dates by means of plotting histograms [1, 2, 8, 9]. In recent years, these approaches have been supplemented by the statistic systematics of temporal information [10–13] based on expansions on infinite and finite bases, including the analysis of the correlation dimension of random processes.

The methods of analysis of temporal information that take into account both of the aforementioned problems related to the heterogeneity of initial geochronological data have been realized in the presented study.

First, the problems concerning the unequal representativeness of geochronological measurements that follows from their spatial irregularity may partly be solved by selecting measurement sets only for similar rocks or their natural associations. In this case, the obtained integer-valued selections $N_m(\mathrm{t}_k)$ of geochronological events at time moment $\mathrm{t}_k$ for rock type $m$ should be analyzed separately. Strictly speaking, a uniform selection of rocks requires normalizing to the intensity of rock occurrence (variation in the volume of the rocks) with time. However, assuming that geologic events occur systematically in the Earth's history, it may be deemed that the relative maximums in a specific integer-valued selection $N_k$ characterize the intensity of rock occurrence. Indeed, these selections must be representative enough and comprise as completely as possible all known geologic units in the Earth's upper shells.

Second, the description of a particular integer-valued selection of geochronological data should also naturally include the characteristics of the dating accuracy. The normal law of distribution of time errors is commonly suggested for geochronological data, and the measurement results are accompanied by the estimation of this error at a level of $2\sigma$. In this case, instead of separate discrete events—geological dates on the scale of time—a probability density of such events may be considered. In terms of this approach to geochronological information, the dates may be regarded as normal random processes that are realized over a determined interval [14].

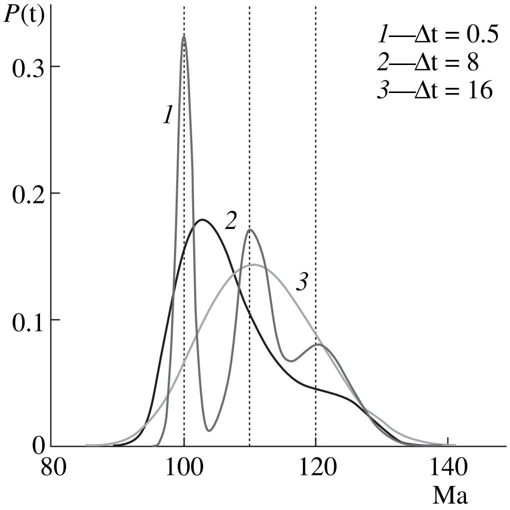

**Fig. 1.** Example of probabilistic calculation of a peak of dates carried out with different steps of averaging.

The probability density of a normal random process [14] with dispersion $\sigma_k$ and average value $\mathrm{t}_k$ equals

$$P_k(\mathrm{t}) = \frac{1}{\sigma_k\sqrt{2\pi}}\exp\left(-\frac{(\mathrm{t}-\mathrm{t}_k)^2}{2\sigma_k^2}\right), \qquad (1)$$

under condition of natural normalizing

$$\tilde{P} = \int_{-\infty}^{\infty} P_k(\mathrm{t})d\mathrm{t} = 1. \qquad (2)$$

The total probability density of the sequence consisting of $N$ normal events (geochronological dates) is expressed as

$$P(\mathrm{t}) = \sum_{k=1}^{N} P_k(\mathrm{t}). \qquad (3)$$

The condition of normalizing (2) also applies to (3) in the form $\tilde{P} = N$.

Such a representation of geochronological dates naturally comprises both the age estimates $\mathrm{t}_k$ and their dispersions $\sigma_\mathrm{k}$. Modern methods of the analysis of stationary and intermittent processes [15, 16] commonly used in the study of signals may be applied to the resulting transform (3).

Some remarks should be made about the practical usage of this approach, first of all, the normalizing of the initial data. Strictly speaking, this normalizing can be realized only approximately, because the interval of determination for (1) and (3) is specified. The entire interval of estimates (present time–the time of formation of the Earth's primary shells) naturally always exists, and therefore only rather long series of measurements can yield unbiased estimates of the characteristics of the random processes under study. Second, the numerical implementation of (3) is possible only at a discrete step Δt, which must be chosen from *a priori* reasoning about the representativeness of the used integer-valued geochronological data. Needless to say, the chosen step must fit the stated problem of signal analysis. For example, if analysis with a step of 10–20 Ma is acceptable for revealing statistic patterns for the Precambrian and corresponds to the average accuracy of individual age estimates of Precambrian endogenic events, then the processing with a step of 2–5 Ma is required for the Phanerozoic (the step should be even diminished when we are dealing with the Miocene or Quaternary). Such a step is consistent with the accuracy of modern chronostratigraphic charts.

Taking into account the accepted premises and constraints, the application of the proposed approach to the analysis of sequences of geochronological data can be illustrated by a simple example. Consider only three dates with given errors: $\mathrm{t}_1 = 100 \pm 2.5$ Ma, $\mathrm{t}_2 = 110 \pm 5$ Ma, and $\mathrm{t}_3 = 120 \pm 10$ Ma (Fig. 1). These ages are shown in the figure, however their averaging based on the common rules yields only an average value of 110 Ma. In terms of the proposed approach, different estimates can be obtained for the probability density of a sequence of geochronological dates. It is self-evident that the resulting graph of the probability density depends on the temporal lag $\Delta t$, whose values are shown in the figure. However, the main point of this presentation is the possibility of applying all capabilities of the modern analysis of signals, e.g., plotting of wavelet spectrograms for the probability density of a process [15, 16], to the obtained probabilistic estimates $P(t)$.

## TWO TYPES OF MEGACYCLICITY?

Extensive geochronological information accumulated over the past 10–15 years allows us to revise the problem of megacyclicity on the basis on newly obtained data. This is especially topical, because the current achievements in studying the deep structure and geodynamics of the Earth [17–21] urge us to upgrade tectonic, petrologic, and geochemical concepts of the evolution of the crust and mantle. Thus, nowadays the necessity arises to correlate various aspects of geological knowledge with geochronology, which provides a quantitative measure for judgments about crustal growth in terms of plate and plume tectonics and its relations to the energy budget of the Earth's inner shells and core and to possible external impacts on particular shells.

Before considering these problems, it is necessary to discuss the possibilities and constraints of the application of geochronological methods to the phenomenon of megacyclicity. In this paper, we used the basic dataset that includes more than 14 200 published dates obtained with various methods: U–Th–Pb (shortly U–Pb)—8229, Rb–Sr—3330, K–Ar + ${}^{40}$Ar/${}^{39}$Ar + FT (shortly K–Ar)—2054, and Sm–Nd—650 dates. The great number of dates obtained by each method allow us to draw reasoned conclusions based on the probabilistic description of endogenic events. The results of systematization show (Fig. 2) that the informational fields for each method substantially differ from one another. As could be expected, the data obtained with U–Pb method are the most comprehensive, except for the Mesozoic and Cenozoic. On the contrary, K–Ar and Rb–Sr methods yielded the bulk of information on Phanerozoic endogenic events. Information derived with the use of these methods drastically diminishes with the transition from the Phanerozoic to the Proterozoic–Late Archean and is hardly representative to detect peaks of megacyclicity for ages older than 3.1 Ga. In this context, it is pertinent to mention information on the U–Pb dates of juvenile processes presented in [5] and reflecting the integral effect of subduction and plume magmatism at the surface and the deep tectonics of the Earth over the geologic time. Although, strictly speaking, the selective usage of the U–Pb method distorts the systematics of Phanerozoic magmatism and the integration of subduction-related and plume magmatism introduces uncertainty in the assessment of their contributions, the results (the identification of megacyclic peaks at 2.7 and 1.9 Ga) are consistent with the general systematics of U–Pb data (Fig. 2).

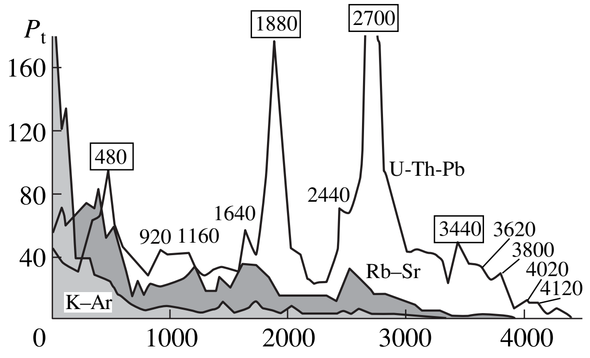

**Fig. 2.** Histogram of numbers of dates obtained with three geochronological methods for rocks and minerals from the crust and the upper mantle. The statistic time-base sweep ($P_t$ is number of dates) was carried out with a 20-Ma step of averaging. The maximal $P_t$ values within an interval 0–4400 Ma were used to compile a histogram for each method. Numerals in rectangles are the highest U–Pb peaks of megacyclicity.

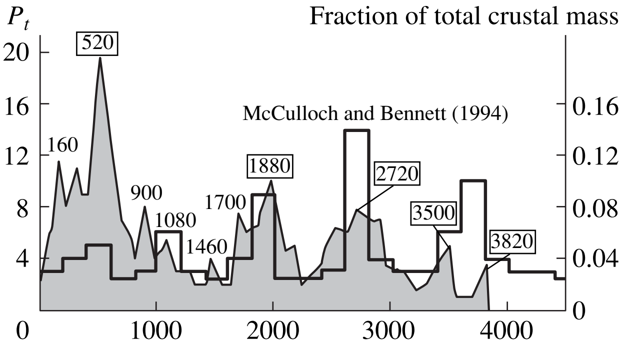

**Fig. 3.** Correlation of Sm–Nd data carried out by using nonparametric statistics ($P_t$) within an interval of 0–4.5 Ga for all maxima revealed by averaging with a 20-Ma step and with a model method of statistical averaging with a step of 200 Ma [4]. In the latter case, the heights of peaks are expressed in fractions of the total crustal mass formed over 4.5 Ga. Numerals in rectangles are the ages of the highest peaks of megacyclicity obtained from new data.

A single histogram that records the discontinuous growth of the continental crust on the basis of the Sm–Nd method was published by McCulloch and Bennett [4] for Australia. Comparison of the respective selection from our database (650 estimates for various provinces) with the data on Australia reveals a satisfactory similarity despite the difference in the step of averaging (Fig. 3). Thereby, the ages of Sm–Nd maximums may be specified.

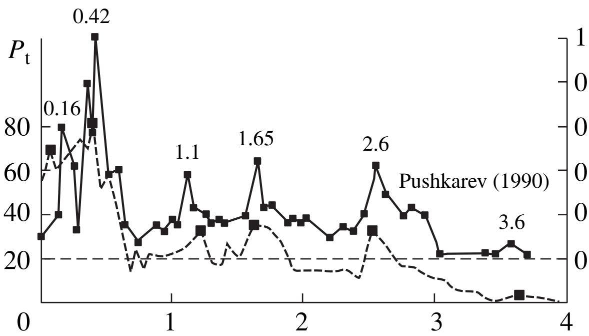

**Fig. 4.** Correlation of Rb–Sr data carried out by using nonparametric statistics ($P_t$) within the interval 0–4 Ga for all maxima revealed by averaging with a 20-Ma step and with a method of sliding averaging for elementary quadrangle with a side of 200 Ma [2] and conditional normalizing to the highest peak accepted as unity.

The main Sm–Nd peaks, Ma (3820, 3500, 2720, 1880, and 520) are well correlated with the highest U–Pb peaks (3800, 3440, 2700, 1880, and 480).

The Rb–Sr megacyclic peaks were outlined on the basis of 3330 dates collected in our database, which is three times more than the 1108 dates used for the same purpose by Yu.D. Pushkarev [2]. Nevertheless, both systematics reveal, despite different processing methods, a similar distribution of the highest peaks of megacyclicity over the entire interval of geologic time (Figs. 4, 5). The ages (Ma) of peaks after our data/data from [2] are as follows: 3660–3620/~3600; 2520/2600; 1620–1720/1650; 1220/1100; 405/420; 125/160.

The ages (Ma) of the highest K–Ar peaks are 2600, 2020, 1720, 1440, 330, 125, 80, 0–15 (Fig. 5). The highest Rb–Sr and K–Ar peaks do not fit the U–Pb and Sm–Nd systematics and are markedly shifted toward younger ages by 50–200 Ma. This conclusion is not original and was evident from the very first publication on the "distribution of mineral dates in time and space" [1].

Thus, formal evidence for existence of two types of megacyclicity are available. The U–Pb and Sm–Nd isotope systems are considered by most geochronologists to be less susceptible to the effects of late superimposed processes than the Rb–Sr and K–Ar systems, a fact that is especially important for the Precambrian. Looking for reasons for the duality of megacyclicity, one can hypothesize that the shift in the K–Ar and Rb–Sr dates most likely reflects their relations to the effect of metamorphism. However, in fact, such a tendency is not traceable. On the contrary, in the sum of U–Pb dates, the ratio of igneous processes (Ig) occurring in the crust and in the mantle to the other processes (MMM), including metamorphism, migmatization, metasomatism, ore formation, and hydrothermal activity turned out to be minimal; 5560/2669 = 2.08; for the Rb–Sr dates; Ig/MMM = 2346/984 = 2.38; and for the K–Ar dates; Ig/MMM = 1544/510 = 3.03. Furthermore, the percentage of mantle-derived rocks dated with the U–Pb method does not exceed 14%; for the Rb–Sr method, this percentage amounts to 32.6% and attains 67.9% for the K–Ar method. The percentages of dates related to tonalites, granodiorites, and diorites are close to 14.6, 5.2, and 5.7% and to granites and gneisses, to 14.1, 26.4, and 11%, respectively. This implies that the dates obtained by various methods provide records of various endogenic events in different proportions. To some extent, the observed differences mirror the progress in techniques of mass-spectrometric analysis and the trends in scientific interests over recent decades. For example, the prevalence of granites and metagranites as targets of Rb–Sr dating in the 1970s–1980s may be explained by the fact that these rocks with high Rb/Sr ratios were then the most suitable for this method of dating. The predominance of the Phanerozoic mantle-derived rocks dated by the K–Ar method corresponds to the recent expansion of works aimed at the dating of

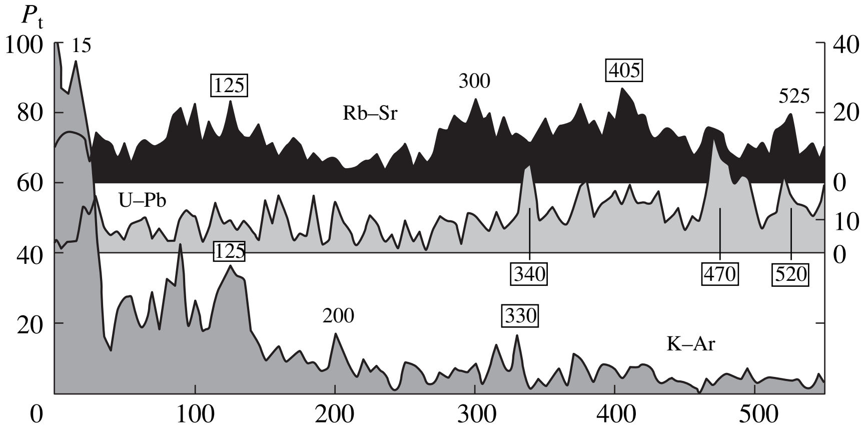

**Fig. 5.** Location of the most important peaks of the Phanerozoic megacyclicity obtained by different geochronological methods and specified by using nonparametric statistics ($P_t$) with a 5-Ma step.

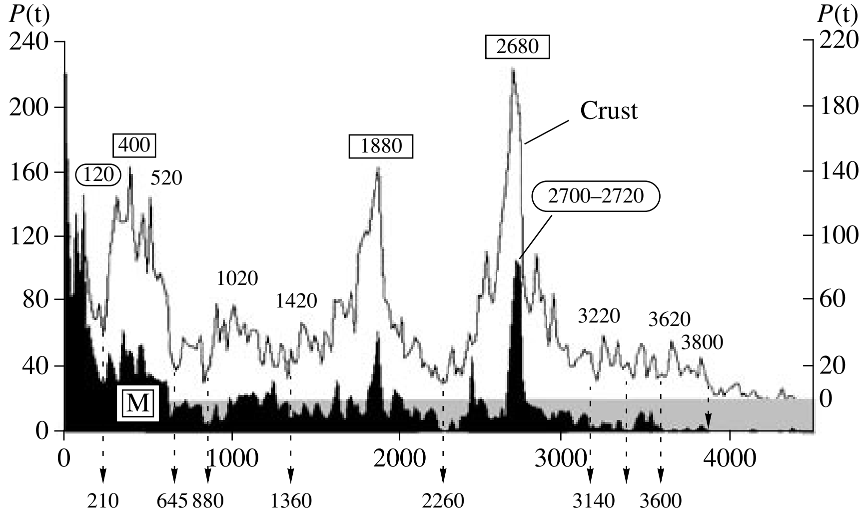

**Fig. 6.** General trends in the evolution of endogenic events in the mantle (M) and crust that record nonuniform crust formation with alternation of maximal and minimal activation in both of shells. Dashed arrows indicate the most distinct minima coinciding in the mantle and in the crust. The diagram is plotted by statistical parameter *P*(t) with a 20-Ma step of averaging. Numerals in rectangles are the ages of megacyclic peaks for the crust, Ma; numerals in ovals are the same for the mantle.

young marine and continental volcanics. The U–Pb data on Precambrian rocks are largely related to tonalite, granodiorite, and gray gneisses as a whole, as well as to the oldest detrital zircon that bear information on the oldest stages of formation and evolution of the crust. The comparison of the observed data on megacyclicity with the modern concepts [17] of deep geodynamics indicates that such megacyclic duality does not provide insights into two major processes of plume and plate tectonics. The search for substantiation of these geodynamic ideas on the basis of integrated information on geochronology of the upper shells is not promising.

The principle of combined information on the crust and the upper mantle looks today obsolete and unfit for deciphering the processes that govern the cyclicity of the crust formation. This conclusion seems to be evident from a number of contradictions. The first is related to the substantial difference in quantities of dates obtained with certain geochronological methods, which results in different estimates of ages of megacyclic peaks, and especially in the assessment of their contrast and the relative intensity of endogenic events, e.g., by recording Phanerozoic megacycles. Moreover, published geochronological information on various types of igneous rocks is inconsistent with the appreciable variations in the global and regional abundances of the most important rock types. For example, the approximate ratios of abundances for territories of Russia and the United States (%) are as follows: granitoids—49/35, basalts and silicic volcanics—35/45 and 13.5/12.5, respectively, foidolites and foidites—0.4/0.1 [22]. Second, the sharp contrast in rock abundances between Precambrian and Phanerozoic provinces is not taken into account. This leads to inaccurate generalization of geochronological information that obliterates the significance of specific geological processes. The same pertains to attempts to find a global 100-Ma periodicity in relative abundances of rocks by using the integrated data on the crust and the mantle [8, 9]. It turned out that “anomalous” peaks within 100-Ma intervals that are higher than the neighboring ones or equal to them in height are prevalent during the last 2 Ga and were never identified in older Precambrian rocks. Consequently, no unequivocal conclusions about the types of processes were drawn, as none were reached by analyzing the larger scale phenomenon of megacyclicity. It can be only theorized that such a pattern arose owing to the superposition of diachronous events in the crust and mantle and/or within each of the geospheres. Thus, it is necessary to study the crustal and mantle events separately and in more detail.

## THE CRUST–UPPER MANTLE SYSTEM

Inasmuch as sufficient information is now available separately on the crust and mantle, it seems to be reasonable to consider, as the first step, endogenic events in each of the Earth’s upper shells separately to settle the question concerning the similarities and differences in the dynamics of their evolution. Note that the generalization of geochronological data on discrete shells does not rule out all the contradictions mentioned above for the bulk analysis of the data on the crust and mantle considered together, but provides for correction for the types of processes in each shell.

The summary histogram of dates (Fig. 6) obtained by all methods separately for the crust (9808 dates) and mantle (4435 dates) clearly indicates that megacyclicity is recorded in both of the upper shells as the main

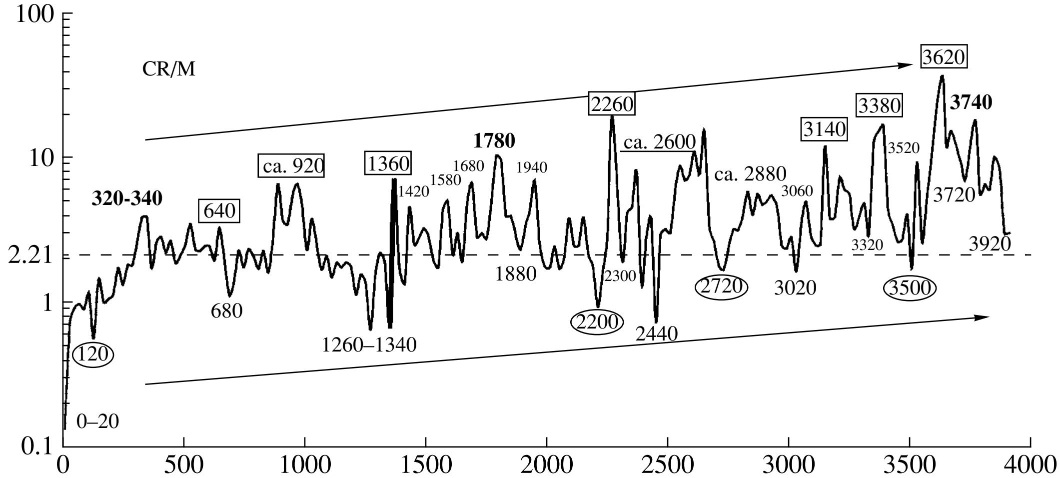

**Fig. 7.** Variations in the CR/M ratio (dates of crustal rocks/dates of mantle rocks) within interval 0–4000 Ma. Numerals in ovals are the ages of megacyclic peaks; numerals in rectangles are the ages of minima of endogenic activity in both shells (see Fig. 6). The arrow shows increase in CR/M from the Phanerozoic to Early Precambrian. The step of averaging is 20 Ma.

(maximal) megacyclic peaks that are generally close to the U–Pb systematics for the total data on the crust and upper mantle. This is probably a consequence of the quantitative prevalence of U–Pb dates among those obtained by different methods. Almost all other Precambrian maxima are coordinated in both shells. In the Early and Middle Archean, the ages of the maxima are close (crust/mantle, Ma): 3800/3820, 3620/3640, 3520/3500, 3300/3310, and 3220/3220. The crustal peaks are almost similar in height, and it is hardly possible to select a main peak among them; the highest peaks in the mantle fall onto 3440 and 3500 Ma. One megacyclic maximum at 2680/2710 and two less pronounced peaks at 2920/2920 and 2820/2810 are identifiable in the Late Archean. In the Proterozoic, one megacyclic peak at 1880/1880 is recorded, along with many smaller peaks at 2520/2500, 2420/2440, 2320/2320, 2220/2200, 2100/2100, 2020/1980, 1720/1720, 1660/1640, 1500/1520, 1420/1440, 1300/1340, 1220/1260, 1140/1140, 1020/1000, 920/920, 820/800, and 720/740. It is impossible to select reliable megacyclic peaks among them, because such maxima may differ in age and intensity, e.g., for the interval of 1400–900 Ma. The scale with a step of 20 Ma is too crude for the Phanerozoic, and only one megacyclic peak at 400/410 Ma can be recognized. At a step of 5 Ma, similarities occur for peaks at 475/475, 400/410, 375/375, and 90/90 Ma. Other maximal peaks for the crust and mantle do not coincide; e.g., an individual peak at 120 Ma was identified in the mantle. This testifies to certain autonomy in the evolution of endogenic processes within the shells during the Phanerozoic. Note that the most pronounced megacyclic peak of the late Archean is separated into two dating, about 2710 Ma for the mantle and 2680 Ma for the crust (Fig. 6).

In order to solve the second problem, i.e., to estimate the duration of megacycles, it makes sense to use the episodes of an abrupt decrease in or the complete disappearance of endogenic activity in the crust and mantle. Such episodes are tentatively divided into two groups (Fig. 6). One of them corresponds to the nearly contemporaneous attenuation of endogenic activity in both shells (see vertical arrows in Fig. 6) and the other mostly corresponds either to the crust or to the mantle. In formal terms, the ages of the first group of minima may be regarded as natural boundaries of megacycles. A similar interpretation of these "boundaries" was proposed previously [2]. If the data on the first group are used, the following series of dates is outlined (Ma): ~3900, ~3600, 3380, 3140, 2260, 1360, 940–960, 880, 645, 210, and 60. This series may be expanded or shortened at discretion of researchers. This approach rules out completely or partly the data on the second group and thus gives rise to subjectivity in the recognition of the boundaries. To reveal a real pattern in the variations of the intensity of endogenic events in both shells, we can make use of crustal/mantle (CR/M) peak ratios within the interval of 0–4 Ga (Fig. 7). This approach makes it possible to get rid of the visual effect of the preferential influence of the megacyclic reactivation of processes in the mantle upon the intensity of endogenic events in the crust (Fig. 6). The average ratio of crustal/mantle dates (9808/4935 = 2.21) may serve as a reference value for the comparison of specific CR/M ratios and their variations over the geologic time. First of all, note that the maximum CR/M values correspond to the dates of synchronous minima on the histograms for the crust and mantle, while the minimum values fit the megacyclic crustal–mantle maxima (Fig. 7). At the same time, Fig. 7 demonstrates a series of other peaks in both of the zones, which do not coincide with the extreme CR/M ratios (Fig. 6). It may be seen that so-called megacyclic peaks do not differ any significantly from a series of others. Moreover, some megacyclic peaks have less contrasting CR/M values. However, it is more important that the intervals of the synchronous

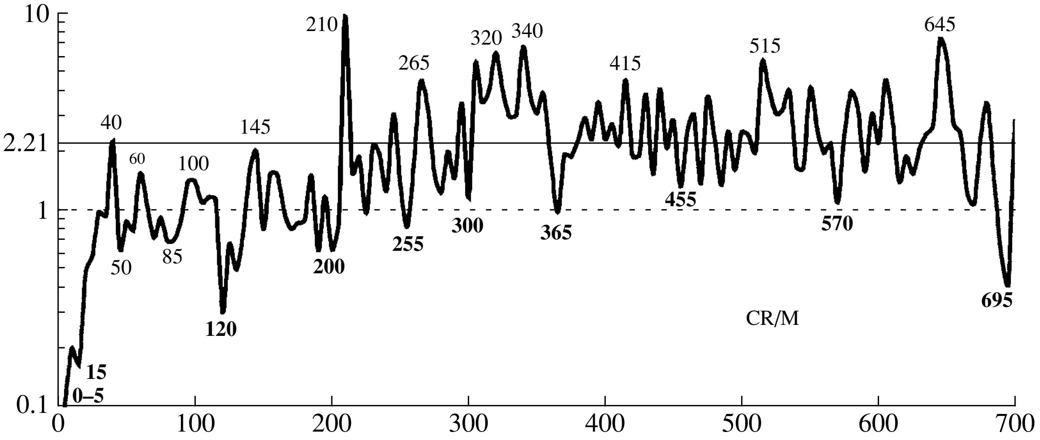

**Fig. 8.** Detailed variations in the CR/M ratio in the Phanerozoic. The step of averaging is 5 Ma.

attenuation of activity in both of the shells testify to the primary attenuation of the mantle endogenic activity. In other words, crustal processes continue when mantle processes abruptly wane. On the contrary, the intervals with the minimum CR/M peaks, including the megacyclic peaks, indicate the sharp prevalence of endogenic processes in the upper mantle over the crustal ones.

The extreme deviations from the average CR/M ratios (Fig. 7) make it possible to describe rather rigorously the number of cycles and their boundaries. Thereby, the cycles themselves acquire another sense and indicate a relative activation of processes in the crust or mantle. If the age sequence of the maximum CR/M ratios is used, which corresponds to a decrease in activity of mantle endogenic events and, hence, records the boundaries of mantle cycles, then the obtained series of intervals (shown in parentheses) are subdivided into three groups.

(1) According to refined data (Fig. 8), the dates of mantle magmatism with CR/M < 2.21 are strongly predominant in the Phanerozoic group within an interval of 0–330 Ma. This hampers the reliable estimations of the cycles. The youngest (Cenozoic) cycles are fairly arbitrarily subdivided into episodes at 0–10 (10), 15–30 (15) and 35–40 (5) Ma. The episodes at 40–60 (20), 60–100 (40), 100–145 (45), 145–210 (65), 210–265 (55), 265–330 (65), 330–415 (85), 415–515 (100), and 515–645 (130) Ma are recognized more reliably by maxima of the CR/M ratios. In general, this sequence demonstrates a general decrease in duration of mantle cycles with time.

(2) The Proterozoic intervals are limited by intervals 640–920 (280), 920–1360 (440), 1360–1780 (420), 1780–2260 (480), and 2260–2600 (340) Ma that determine arbitrarily average durations of arbitrarily cycles at about 390 Ma. These cycles are close in duration to Wilson cycles recognized in geotectonics.

(3) The Archean cycles make up a series of 2600–2880 (280), 2880–3140 (260), 3140–3380 (240), 3380–3620 (240), and 3620–3920 (300) Ma; the average interval equals 265 Ma. Scanty information on the Early Archean makes the estimates of the two oldest large cycles quite uncertain, as is their extrapolation to 3900–4100 Ma. The data on detrital zircons suggest the possible existence of 100- or 200-Ma cycles.

Thus, periods of endogenic activity in the crust and the upper mantle alternate, and the duration of mantle cycles changes through the geological history, indicating the contrasting dynamics of the Earth's upper shells. As a first approximation, the cyclicity may reflect a delayed and a relatively slow (extended in time) reaction of the crust to the processes initiated in the upper mantle. The mantle processes themselves had a different duration in various geological periods.

It is worth noting the shift of all CR/M ratios from the Phanerozoic to the Early Precambrian toward the prevalence of crustal activation (Fig. 7). This shift probably depends on the intensity of the secondary reworking of the crust and on the worse preservation or denudation of the primary mantle-derived rocks in the oldest cratons. It was established long ago that granitoids and gneisses are spread most widely in the Early Precambrian of the Karelian, Kola, Ukrainian, Aldan, Canadian, and other shields [22].

The differences in dynamics of mantle and crustal processes may be specified on the basis of regional materials (Figs. 9, 10).

(1) The boundaries of the largest mantle cycles established by extreme CR/M ratios on the integrated diagram (Fig. 7) clearly record a series of discrete events in the mantle magmatism on both of the regional diagrams. As could be expected, none of the igneous mantle episode would fall within boundary zones, in contrast to the crustal peaks, some of which correspond in age to these boundaries.

(2) In many cases, the crustal peaks are markedly shifted toward younger ages relative to the mantle peaks. This shift is especially distinct for the megacy-

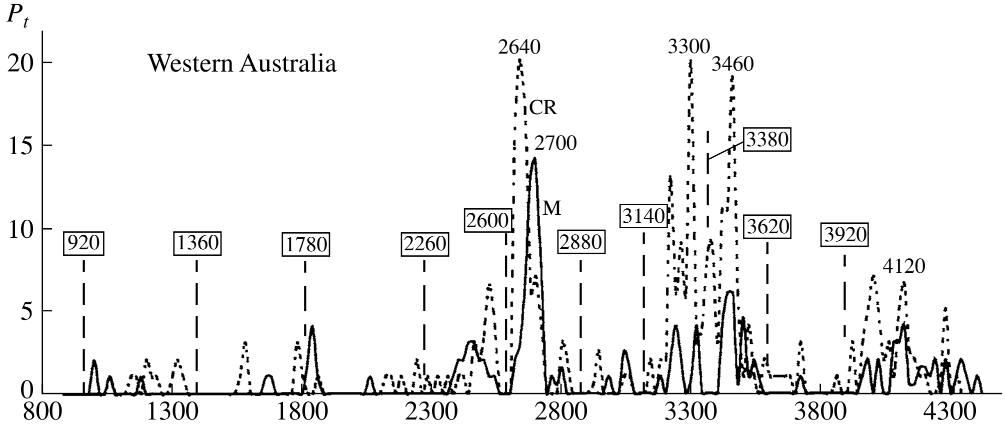

**Fig. 9.** Evolution of mantle magmatism (M) and endogenic events in the crust (CR) in the Pilbara and Yilgarn blocks, western Australia. Numerals in rectangles are the ages of mantle cycles, and dashed lines are their boundaries that correspond to Fig. 7.

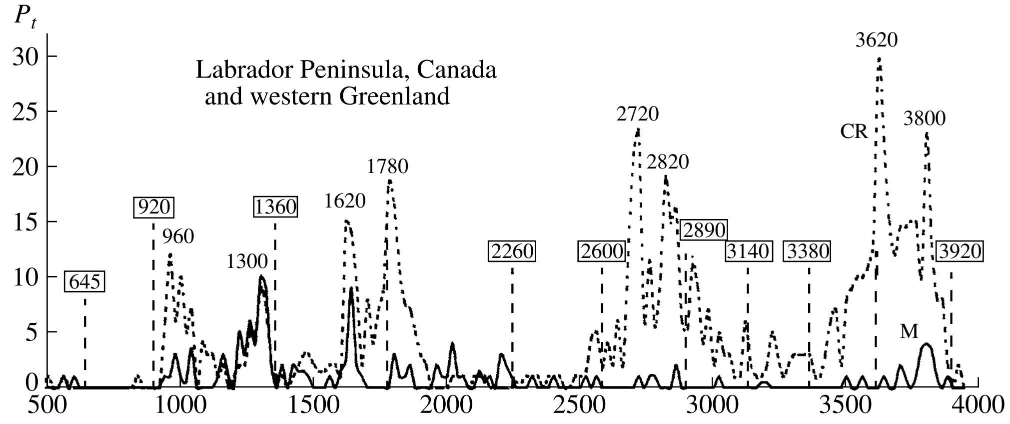

**Fig. 10.** Evolution of mantle magmatism (M) and endogenic events in the crust (CR) in the Labrador Peninsula, Canada and western Greenland, including the oldest Archean cratonized blocks and the zone of Grenville reactivation. Numerals in rectangles are the ages of mantle cycles, and dashed lines are their boundaries that correspond to Fig. 7.

clic peak at 2700 Ma for mantle rocks and 2640 Ma for crustal rocks (Fig. 9).

(3) The data on crustal endogenic events furnish direct evidence for the cycles of intense crustal reworking of the Archean basement beneath the Australian cratons within the intervals of 3600–3140, 2800–2600, and older than 3920 Ma. In the Labrador Peninsula and western Greenland, such reworking took place at 3920–3380 and 3140–2600 Ma. Proterozoic reactivation was superimposed at 1900–1600 and 1360–920 Ma.

Thus, regional information confirms the two conclusions derived from the analysis of integrated data on the crust–upper mantle system. First, it is evident that crustal events are delayed relative to the corresponding mantle events and, hence, the crustal events depend on the mantle activation. Second, direct evidence argues in favor of the vigorous secondary reworking of the Early Precambrian crustal–mantle material in both the Archean and the Proterozoic. As a result of multistage reworking, the peaks of crustal events are more fuzzy and wider than the narrow peaks of mantle events (Fig. 6).

## DISCUSSION

The overview of geochronological data on crustal growth has shown that the selective application of a single geochronological method even to the formal description of the crust growth is hardly acceptable because of different informativeness of the U–Pb, Sm–Nd, Rb–Sr, and K–Ar isotope systems and incommensurable bodies of data obtained with particular methods for various rocks formed during specific time intervals. Because of this, the generalization of the total geochronological information is required to provide insights into the nonuniform growth of the crust. This integration must be accompanied by the separate analysis of information on both of the Earth's upper shells, since the crust and the upper mantle are discrete, although interrelated, systems with different associations of rocks and types of endogenic processes.

As has been shown, mantle processes become more intense during periods of the synchronous activation of endogenic events in both shells; the mantle activity sharply decreases in epochs when endogenic processes in these shells are waning. The different dynamics of activation does not deny the megacyclicity of the crust formation, which is approximately described by the integrated information on both shells and makes it possible to depict the cyclicity of endogenic processes more reliably and to understand its sense, which reflects the delayed reaction of the crust to the processes proceeding in the mantle. As a result, we managed to establish a rather complex character of the dynamics of mantle processes with variable duration of cycles, which, in our opinion, reflects three large-scale epochs of the crust formation: (1) the Early and Middle Archean, with cycles 200–250 Ma long; (2) the Late Archean and Proterozoic with the longest cycles of ~400 Ma; and (3) the Phanerozoic, with cycles of variable duration, from 5–10 to 100–130 Ma. The causes of this nonuniformity are yet to be studied. Analyzing the regular kinematic inversions in mobile belts in the course of their tectonic evolution, Yu.A. Morozov [23] drew a conclusion that the duration of kinematic stages shortens from the Archean and Proterozoic to the Phanerozoic (from 100 to 25–30 Ma). In principle, this is consistent with the geochronological systematics of the Phanerozoic endogenic events in the mantle. The detailed consideration of 100-Ma or any other briefer cyclicity or periodicity that is obviously detected within large cycles of mantle magmatism and endogenic events in the Precambrian crust is out of the scope of this paper and should be the subject of future investigations. The geodynamic interpretation of events that proceed with different rates in both shells and the causes of mantle cycles of various duration is also pending.

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