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# Evolution of Rotation Structures in the Earth's Geological History

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## 1. Introduction

The behavioral study of the Earth's magnetic moment or palaeointensity, inversion frequency and other geomagnetic field characteristics in the remote past could have provided the basis for estimation of the time taken by global space and intraterrestrial processes. However, at many international conferences earth scientists are not unanimous as to whether endogenic and cosmic processes are interrelated. In the past few years, the Research Team of the Geophysical Observatory at the Institute of Physics of the Earth, RAS, headed by V.V. Shcherbakova has developed a global IAGA Palaeointensity Database and obtained new extensive reliable data on the magnetic virtual dipole moment (VDM) of the Earth by estimating the degree of validity of each value. The database is available at the website:

[ftp://ftp.ngdc.noaa.gov/Solid\\_Earth/Paleomag/access/ver3.5/access2000/PINT00.MDB](ftp://ftp.ngdc.noaa.gov/Solid_Earth/Paleomag/access/ver3.5/access2000/PINT00.MDB).

It contains about 3900 VDM values and more geomagnetic field palaeointensity values from 3 billions of years ago (Ga) to the present, but most of the data are confined to the last 100 million years (Ma). This work provides an impetus to the palaeomagnetic study of the oldest localities. New evidence for the Earth's evolution, the timing of internal core formation etc. can be obtained by studying geomagnetic field intensity in the geological past. One of the Earth cooling models shows that the Earth's internal core could be younger than it has been assumed earlier (Labrosse et al., 2001). Obviously, voluminous data on geomagnetic field intensity in Palaeoarchaeon-Proterozoic time are needed to check this and other hypotheses. However, slightly more than 30 intensity determinations, consistent with modern reliability criteria, are available for this time span of about 3 Ga in geological history. Some determinations have been made by the authors under INTAS Project 03-51-5807 at the Salmi suite and at the Ropruchei sill on the Fennoscandian Shield (Pavlov et al., 2004; Shcherbakova, Pavlov et al., 2006).

An interesting hypothesis of periodical variations in the Moon's orbit radius and tidal forces during the Phanerozoic was proposed by Y.N. Avsyuk (1993). Variable tidal forces would have made the Earth rotate now rapidly, now slowly. If this hypothesis is valid, the retardation and acceleration of the Earth's rotation also could have affected the behaviour of the main geomagnetic field and folding phases. Variations in palaeointensity, geomagnetic field inversion frequency and Bertrand cycles were correlated with the phases of variations in the Moon's orbit radius after Avsyuk, but no significant correlations have been revealed (Kurazhkovskii et al., 2008), although in the same publication the authors have concluded

that mean palaeointensity is related to the Earth's volcanic activity. Furthermore, Avsyuk's basic assumption is inconsistent with the hypotheses of the Moon origin as a mega-impact (Zharkov, 2003) and as a result of the gravitational trapping of the Moon to the Earth's orbit (Malcuit et al., 1992; Zemtsov, 2007) and with astronomical observations of the constancy of the angle of inclination of the Earth's rotation axis to ecliptics (Shcheglov, 1974; Zharkov et al., 1996; Zharkov, 2003). It seems that the evolution of the Moon's orbit since its emergence has not obeyed the periodic law and has been more complex.

In geodesy and astronomy, the angular rotation velocity (ARV) of the Earth is understood as one full revolution of the Greenwich (zero) meridian and its average ARV value ( $\omega$ ), if the period (T) of rotation of the planet  $T=86164.09891$  [s] is measured in solar seconds (Lambert, 1961), is ((Eq.(1)):

$$\omega = 2\pi/T \approx 7.29115 \cdot 10^{-5} \text{ [s}^{-1}\text{]}. \quad (1)$$

Obviously, determination of the geographic longitude of a point on the Earth's surface as an angle counted from the zero meridian is connected with the problem of calculating super-precise time and its recording for further calculations (Zemtsov, 2007). According to satellite data, the Moon's orbit radius is now increasing by  $3.82 \pm 0.07$  cm/yr (Dickey et al., 1994), which must result in the decreased Earth's rotation velocity. The secular deceleration of the Earth's rotation ( $d\omega/dt = -6.07 \times 10^{-22} \text{ s}^{-2}$ ), predicted earlier theoretically (Christodoulis et al., 1988), almost does not differ from the one estimated from satellite data (Zharkov, 2003). Hence, the vector  $\omega$  of the ancient Earth can be calculated, assuming the deceleration of its rotation is linear. Thus, it decreased by about  $0.2 \times 10^{-5} \text{ s}^{-1}$  every 100 Ma, i.e. 550 Ma ago astronomical day or the Earth's rotation period (T) in Lower Cambrian - Neoproterozoic time was probably 3.5 h shorter than the present, and the Earth's ARV value could have been  $\omega=8.34 \times 10^{-5} \text{ s}^{-1}$  (Zemtsov, 2009a). Astronomers measure T very precisely. During the 20<sup>th</sup> century T or LOD (length of day) had generally increased by about 0.002 s, but 2-3 LOD anomalies of up to 0.004 s, caused by the Earth's deceleration, are distinguished. These fluctuations reduce the Earth's rotation energy and are consistent with the Earth's high global seismic activity intervals (Fig.1). Furthermore, it has been shown (Varga et al., 2004) that the Earth's rotation energy is the main internal component, and its annual variations are about twice the annual energy of all earthquakes. The authors have concluded (p. 120) that a seismic event, even the most powerful one, cannot influence the rotation speed of the Earth. Variations in rotation speed cause stress, which is due to relevant smoothing variations, and is related to the E-W distribution of seismicity and seismic energy. Seismicity does not seem to generate LOD anomalies. On the contrary, LOD or T variations affect the Earth's seismic activity. Interestingly, a great event can be followed by a slight acceleration of the Earth's rotation (Chao & Gross, 1995). Actually, according to NASA data of 3 March, 2010, a magnitude 8.8 earthquake on the Richter scale, which broke out on 27 February, 2010 in the ocean near Chile, was followed by the shift of the Earth's crust and the decrease of T by  $1.26 \times 10^{-6} \text{ s}$ . LOD observations have shown that "the Earth was rotating most rapidly in 1870, when the day length was 0.003 s shorter than the standard, and most slowly in 1903" (Sidorenkov, 2004). The author also notes that "the Earth's rotation velocity is slowest in April and November and most rapid in January and July. The January maximum is much smaller than the July maximum...The reason for this instability should be sought for in the Earth's rotation mechanisms". It is essential, therefore, to record considerable non-regular T fluctuations that last at least 20 years (see

Fig.1) to make long-term predictions of the intervals of the most powerful earthquakes and to estimate the time spans of anomalously high  $T$  in geological history as the Earth's highest palaeoseismicity epochs.

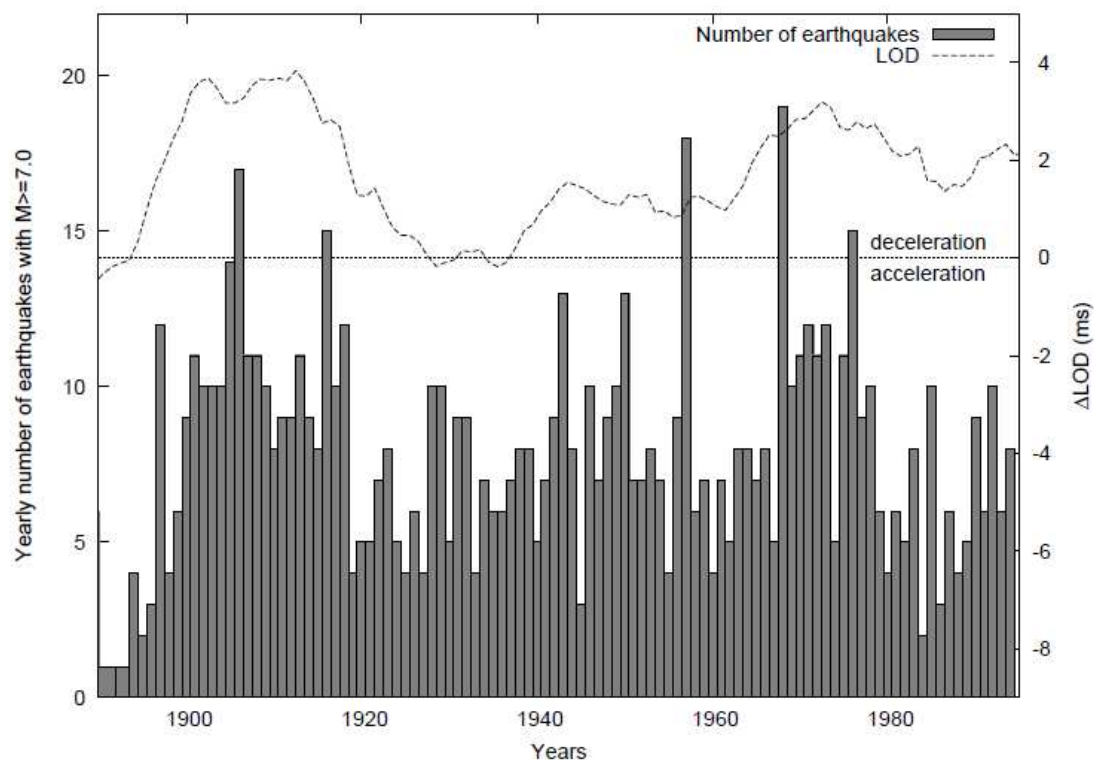


Fig. 1. The annual number of seismic events with magnitude  $M > 7$  and variations in day length (LOD) in the 20<sup>th</sup> century (Varga et al., 2004)

Rotation events have been given little attention in earth sciences. In plate tectonics and in plume tectonics the effects related to the rotation of the Earth and its lithosphere are not taken into account. Do these global processes affect deep geodynamics and tectonics? According to V.E. Khain, some essential geodynamic processes in plate tectonics have not been discussed but “the role of a rotation factor in the endogenic, and not only endogenic, Earth's dynamics is practically undisputable” (Khain & Lomize, 2005, p. 549). In the past few decades new concepts of global tectonics, such as plume tectonics, hot-spot tectonics and wrench tectonics, have been developed (Dobretsov et al., 2001; Fukao et al., 2003; Ley & Zhao, 2006; Pavlenkova, 2006; Storetvedt, 2003, 2005; Zonenshain & Kuzmin, 1993).

Based on proved physical phenomena and palaeomagnetic data, in this chapter the author used M.A. Sadovsky's idea of the hierarchical structure of the geophysical medium to describe an individual continent as a third-order structure and to discuss (Zemtsov, 2005; 2006; 2007) simplified models of the mechanical rotation of the continents located in the Northern and Southern Hemispheres. The first model was discussed at the 32-nd International Geological Congress (Zemtsov, 2004b). Modern Eurasia and the ancient lithospheric blocks it is made of were used subsequently as an example to analyze the continent rotation pattern which retards the mantle rotation (Zemtsov, 2009a). However, as the energy aspects of continental lithosphere-mantle interaction were not discussed in this publication, the reasons for changes in  $T$  and the disintegration of supercontinents are not

quite clear. These problems were discussed briefly at the 8th International Conference "Problems of Geocosmos" (Zemtsov, 2010).

## 2. The Earth's rotation, modern structure and energetics

The proper rotation of the Earth, like that of many other planets and stars, is one of the essential physical properties of this body. The Earth's shape and rotation regime must have been changing substantially in geological history (Zemtsov, 2007, 2009a; Zharkov et al., 1996). According to Robert Malcuit and co-workers, the main event in a series of events could have been related to the gravitational trapping of the Moon at ca. 3.9 Ga (Malcuit et al., 1989, 1992). If the Earth is understood as a homogeneous first-order body after M.A. Sadovsky, then its rotation could be described by a certain angular velocity. At a second level, the question "What is the Earth's angular rotation velocity?" becomes physically incorrect. There exist at least several ARV values of the different Earth's shells (Fig. 2):

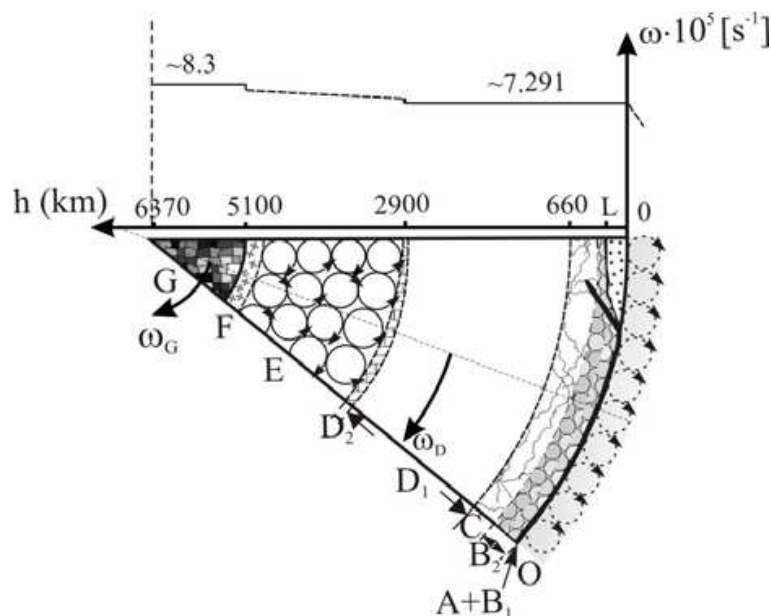


Fig. 2. Cross-section through the Earth's shells and divisions A-O after V.A. Zemtsov (2007), based on geophysical data (using the publications of Dobretsov et al., 2001; Dziewonski & Anderson, 1981; Starchenko, 2000; Zemtsov, 2005, 2007; Zharkov, 1986), in the equatorial plane on the South Pole side and a plot of variations in their angular rotation velocities  $\omega$ , with depth,  $h$  (km). The  $\omega$  vectors are shown arbitrarily as if they coincide with the linear velocity directions.

A - the Earth's crust;  $B_1$  - subcrustal mantle;  $A+B_1$  - lithosphere: continental (dots) and oceanic (black); L (220 km) - Lehmann's boundary;  $B_2$  - upper asthenosphere (small grey circles against black background); C - lower asthenosphere (crack);  $B+C$  - upper mantle;  $D_1$  - lower mantle (white);  $D_2$  (CMB) - transition zone, Gutenberg's boundary (bricks); E - outer core (whirls); F (ICB) - transition zone (small crosses); G - inner core (stone wall); O - outer layer (grey whirls)

Earlier geophysical models did not reflect the deep-level Earth's rotation dynamics. They did not have an outer layer (O), which is essential for the correct understanding of the Earth's evolution and energetics.



In the Earth's outer core (E-layer), the relative velocities of longitudinal currents are at least  $1 \times 10^{-3}$  m/s (Starchenko, 2000; Zharkov, 1983, 2003). These velocities are millions of times the velocities of tectonic movements. The linear movement velocities of the Earth's outer core (V) at the CMB and ICB boundaries (see Fig. 2) can be estimated from the differential equations of magnetic hydrodynamics in Archimedes' heat layer of known thickness. Considering these velocities as heat wind, S.V. Starchenko estimated current velocity at the CMB boundary:  $V \approx 4 \times 10^{-3}$  m/s (Starchenko, 2000). If liquid flow on the outer core surface is laminar, then the core will slip relative to the mantle (Zemtsov, 2007) with a rapid increase in  $ARV = \Delta\omega$  ((Eq. (2)):

$$\Delta\omega = V/r \approx 1 \times 10^{-9} [\text{s}^{-1}], \quad (2)$$

where  $r$  is the core radius.

The positive flow velocity in the liquid core relative to the lower mantle shows unambiguously that the flow velocity on the hard core surface is even higher and that the inner core has a higher ARV than the mantle ARV ( $\omega_D$ ). Calculations made by magnetologists have shown that an increment in ARV by virtue of the rapidly rotating core can be as large as  $\Delta\omega \leq 1 \times 10^{-5} \text{ s}^{-1}$ , although the marginal ARV of the inner core is not required for the generation of a planetary magnetic field (Braginsky & Roberts, 1995; Glatzmaier & Roberts, 1995; Zemtsov, 2007). A positive difference in ARV of the inner core and the mantle is characteristic of planets and stars that have their own magnetic fields and is supported experimentally by seismological observations (Song & Richards, 1996; Zharkov, 2003).

Obviously, the high-velocity proper rotation of the Earth as a first-order tectono-dynamic structure, which rotates at angular velocity  $\omega$ , is expected to have greater energy (E), which can be estimated using the well-known physical Eq. (3):

$$E = \frac{\omega^2}{2} \cdot J, \quad (3)$$

where  $J$  is the Earth's inertia moment.

It should be noted that as the Earth is not an absolutely solid body, its dimensionless inertia moment, estimated at 0.3308, is less than 0.4. Conversely, the well-known compression of the Earth from the poles, slightly increases the estimated inertia moment. Therefore, in the PREM model  $J = 8.0391 \times 10^{37} \text{ kgm}^2$  (Dziewonski & Anderson, 1981). "The moment of inertia of a rotating body is a way of expressing the concentration of its mass about the centre of gravity. The greater the concentration of mass, the greater its moments of inertia, and the faster the body will spin. Thus, any net inward motion of mass increases the Earth's moment of inertia and, therefore, increases its rate of rotation; similarly, any net outward mass transport decreases the moment of inertia and reduces the planet's spin rate" (Storetvedt, 2005, p. 180), and its rotation energy must decrease also (see Eq. 3). More recently, astronomers not only confirmed the accuracy of this above cited calculation of the Earth's polar moment of inertia, but also estimated the inertia moment value for the Earth's mantle  $J = 7.04 \times 10^{37} \text{ kgm}^2$  (Moritz & Müller, 1992),  $J = 7.0426 \times 10^{37} \text{ kgm}^2$  (Zharov, in print). To estimate the inertia moments of second-order structures, one needs to calculate their masses, and the mass of the entire Earth can subsequently be taken as equal to  $6 \times 10^{24} \text{ kg}$  (Fig. 3). The inertia moment of the inner core can be calculated using a formula for a homogeneous solid ball with radius  $r$ :  $J = 0.4mr^2$ . We can borrow data from V.E. Zharov:  $J = 5.873 \times 10^{34} \text{ kgm}^2$  and the mass  $m = 9.851 \times 10^{22} \text{ kg}$  (Zharov, in print), but to estimate inner core energy, one has

to use the assumed  $\omega$ . The rotation energy of the entire core or outer core is even harder to estimate, for its dimensionless inertia moment is also unknown, because the outer core is in semi-liquid state. The estimates of the rotation energetics of some Earth's structures are presented in the Table 1 below, where well-known data on other types of energy and their annual variations are considered for comparison.

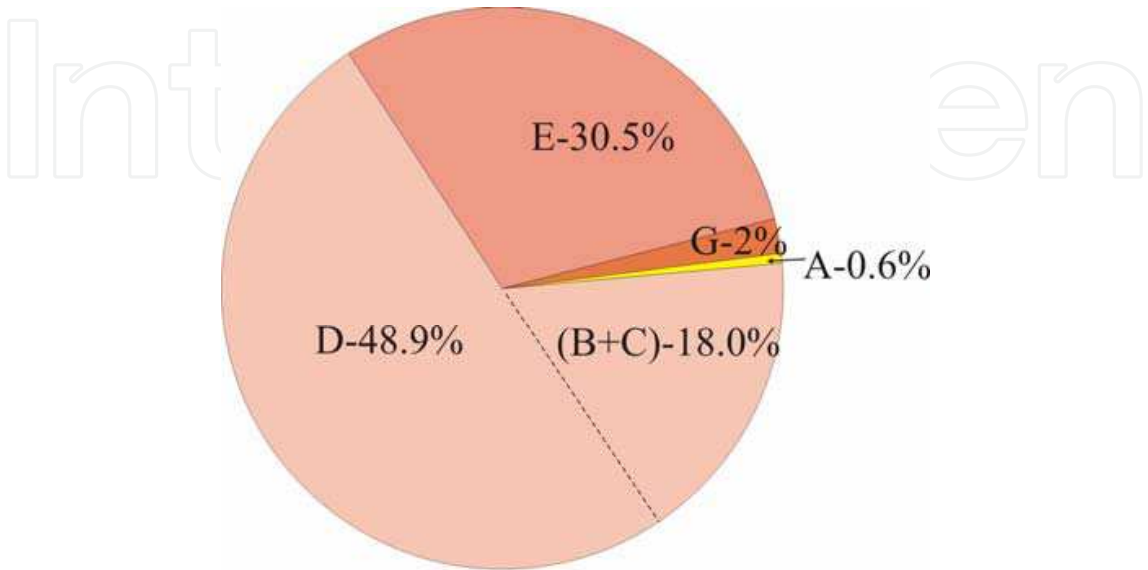


Fig. 3. The relative masses of the Earth's layers (using the publications of Allegre et al., 1995; Dobretsov et al., 2001). For symbols, see Figure 2

Annual energy variations, J/yr	Some types of energy, J
Solar energy received- $2.1 \times 10^{24}$	<i>Earth's rotation - <math>2.13 \times 10^{29}</math></i>
Atmospheric circulations - $6.3 \times 10^{22}$	<i>Mantle rotation - <math>1.9 \times 10^{29}</math></i>
Loss by heat flow - $1.0 \times 10^{21}$	<i>Outer core rotation - <math>3 \times 10^{28}</math> (?)</i>
Oceanic circulations - $3.2 \times 10^{19}$	<i>Inner core rotation - <math>2.04 \times 10^{26}</math></i>
<i>Mantle rotation energy - <math>1.6 \times 10^{19}</math></i>	<i>Earth's crust rotation - <math>2.2 \times 10^{27}</math></i>
Earthquake energy - $9.5 \times 10^{18}$	Main geomagnetic field - $8 \times 10^{22}$
Volcanic energy - $2.0 \times 10^{18}$	Local geomagnetic field - $4 \times 10^{18}$
<i>Plume energy - <math>7.6 \times 10^{15}</math></i>	
Geomagnetic storms - $3.2 \times 10^{13}$	

Table 1. The Earth's energy budget (Varga et al., 2004), with more precise definitions and addenda (in italics)

It follows from the Table 1 that even small fluctuations in the Earth's rotation velocity have tremendous energy, which exceeds the total energy of all earthquakes and all tectono-magmatic processes. Annual fluctuations in mantle rotation energy are comparable in magnitude to oceanic circulation energy. Consequently, they can disturb this circulation,

inevitably invoking global climatic changes. The assumed relationship between observed T fluctuations and climatic changes are discussed in the paper (Sidorenkov, 2004).

### 3. Anomalies in the rotation period and magnetic moment of the Earth in geological history

The secular deceleration of the Earth's rotation also took place in the geological past. One of the first attempts to correlate geomagnetic inversions in the Phanerozoic with the retardation of the Earth's rotation was made using "fossil clocks" as early as 1975 (Creer, 1975; Panella, 1975). It appeared that the number of days in a year in the geological past can be estimated by calculating growth rings in fossil shells. Creer has revealed the total long-term planetary deceleration of the Earth's rotation in Palaeozoic time. He tried to attribute this fact to the Earth's expansion, but this is not quite obvious. Such regularity has not been established unambiguously for Mesozoic time. Other data (Williams, 1989) show that in the Mesozoic the Earth's ARV value increased slightly (Storetvedt, 2010). P. Varga summed up all available data (Lambeck, 1978, 1980; Panella, 1975; Scrutton, 1978; Sonett et al., 1996; Vanyo & Awramik, 1982; Varga, 1996) on "fossil clocks" from regular laminations in palaeobiological residua (fossil corals, bivalves, stromatolites, and notably tidalites). These combined and new data point to the steady and predictable LOD evolution and Earth-Moon distances over the last 1–2 Ga (Kvale et al., 1999; Lathe, 2004, 2006; Varga et al., 2006; Williams, 1997, 2000; Zharkov, 2003). "The oldest LOD value we know of for the moment has been determined for the cyclic banded iron formation of WeeliWolli, Western Australia (Walker & Zahnle, 1986; Williams, 1989, 1990). With an age of about 2.45 Ga that places it close to the beginning of the Proterozoic eon, it is comprised almost surely between 17 and 19 h" (Varga et al., 2006). In Phanerozoic time, the growth of the Earth's rotation period (T) was near-linear (Fig. 4) and was consistent with the  $d\omega/dt$  value estimated from satellite data (Zemtsov, 2008; 2009a; 2009b). In these works and below the author used a new Geologic Time Scale (Gradstein et al., 2004). At the turn of the Phanerozoic, 550 Ma ago T was  $3\pm 1$  hours shorter than the present, and the angular rotation velocity of the Earth's mantle was higher by 14%:  $\omega = 8.34 \times 10^{-5} \text{ s}^{-1}$ , i.e. it could exceed a corresponding value for the inner core (Zemtsov, 2009a; 2010). In this case, a geomagnetic field cannot be generated.

Assuming the core radius to remain constant in time, average mantle retardation energy over the entire Phanerozoic ( $\Delta E$ ) can be estimated using the equation ((Eq.(4)), known in theoretical mechanics, for the inertia moment (J) of an hollow sphere with the radii of the Earth ( $R_E$ ) and the core ( $R_c$ ) (Zemtsov, 2010)..

$$\Delta E = -\frac{\Delta\omega^2}{2} \cdot J = -\frac{\Delta\omega^2}{2} \cdot \frac{2}{5} m \frac{R_E^5 - R_c^5}{R_E^3 - R_c^3} \approx -0.5 \cdot 10^{28} \text{ J}, \quad (4)$$

where  $\Delta\omega \approx 1 \times 10^{-5} \text{ s}^{-1}$  is the decrease in the ARV value of the Earth's mantle in the Phanerozoic;  $m \approx 4 \times 10^{24} \text{ kg}$  is mantle mass.

Part of this tremendous dissipation energy could have been a source of generation of the main geomagnetic field in Phanerozoic time. Knowing its duration, we can calculate the power of a possible additional energy source at the CMB boundary, which could be as high as  $\approx 0.3 \cdot 10^{12} \text{ W}$ , while the power of a modern dynamo is known to be  $10^9 \div 10^{12} \text{ W}$ . However, what part of mantle retardation energy could be absorbed by the core is unknown.



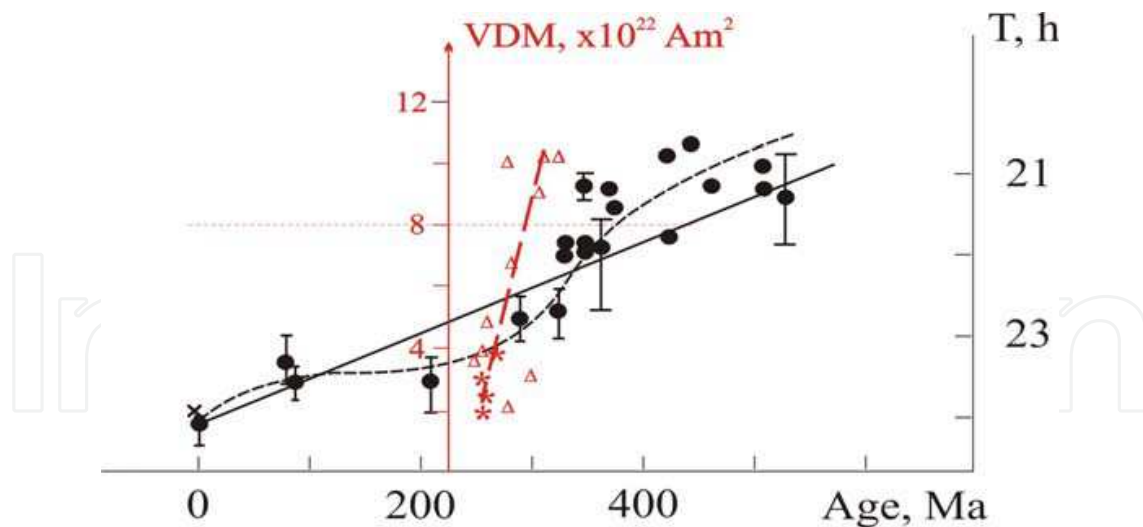


Fig. 4. Variation in the Earth's rotation period (T) during the Phanerozoic (Varga, 1996; Zemtsov, 2008; Zharkov, 2003) and Palaeozoic T- and VDM-anomalies in the Carboniferous-Triassic interval (Zemtsov, 2010). Filled circles are mean T-values; red triangles and stars are VDM values (Shcherbakova, Shcherbakov et al., 2006). Vertical segments are T estimation errors. Red dotted line is present VDM value

Closer examination of the T-curve shows that it has a nonlinear quasi-periodical pattern. In the time span bracketed by 350 and 200 Ma (Lower Carboniferous - Lower Jurassic) the Earth's rotation was slowed down much faster than in the Lower Palaeozoic and especially in the Middle-Upper Jurassic. The decrease in magnetic moment values of the Earth (VDM) over the same interval is directly proportional to the increase in T (LOD), but lags behind by about 100 Ma relative to the decrease in the ARV mantle. Furthermore, the onset of rapid deceleration of mantle rotation in the Lower Devonian about 400 Ma must have been accompanied by a sharp peak in  $\Delta\omega$  between the inner core and the mantle, which is quite consistent with the peak itself and the time lag in the decrease of VDM values. Consequently, a certain part of mantle retardation energy is absorbed by the core one way or another, although it cannot be great because, according to the Table 1, core rotation energy is very small compared to mantle rotation energy. Most of Palaeozoic mantle retardation energy was presumably used to restructure the geoid, oceanic circulations, anomalously high seismicity, tectonics, magmatism, etc. Palaeoseismicity over the interval 400-300 Ma can be estimated indirectly. Figure 4 shows that LOD had increased by about 1.5 h over a time span of 100 Ma. Hence, LOD increased by approximately 5.5 ms per 100 years at that time and by about 2 ms over the last century. This suggests that magnitude 10 earthquakes were not unusual in the Upper Palaeozoic. Known global glaciation (Upper Carboniferous-Lower Permian time) and "The Great Dying" (251.4 Ma ago) have begun later (Erwin, 1993; Jin et al., 2000), in the end of this anomaly interval.

The secular retardation of the mantle rotation was chiefly due to the well-known tidal friction of oceanic north-south wave M2, which rolls over continent and island shores from east to west about twice a day. In Phanerozoic time tidal energy dissipation values were shown by many authors to vary within  $(0.34 \div 4.5) \times 10^{12}$  W (Zharkov, 2003). Strange as it is, the smallest tidal energy values and the low velocities of the Moon's orbit radius growth in time are modelled (Fig. 5) for the time span of interest (350-150 Ma), although the Moon was closer to the Earth by about 4000 km. It is essential that friction energy magnitudes in

geological history were dependent not only on the perimeter of the land that withstood this wave chiefly at tropical latitudes ( $\pm 30^\circ$ ) but also on wave height, which was dependent on the Moon's attraction force, which was inversely proportional to the cubic distance between the centres of the Earth-Moon system (Tsuboi, 1982, p. 176; Zemtsov, 2009a, 2009b). At the turn of the Phanerozoic, Gondwana was located in the polar zone of the Southern Hemisphere, where ocean tide energy power is smallest, but as the Moon's orbit radius was about 12000 km smaller (see Fig.5), ocean tides must have been much higher. For example, in the Palaeoproterozoic the Earth's land area was smaller, but maximum tidal wave amplitude could have been ten times the present value. There may have been other factors which retarded the Earth's rotation, e.g. global glaciations that temporarily reduced world ocean mass, the drifting of lithospheric plates, etc. (Zemtsov, 2010).

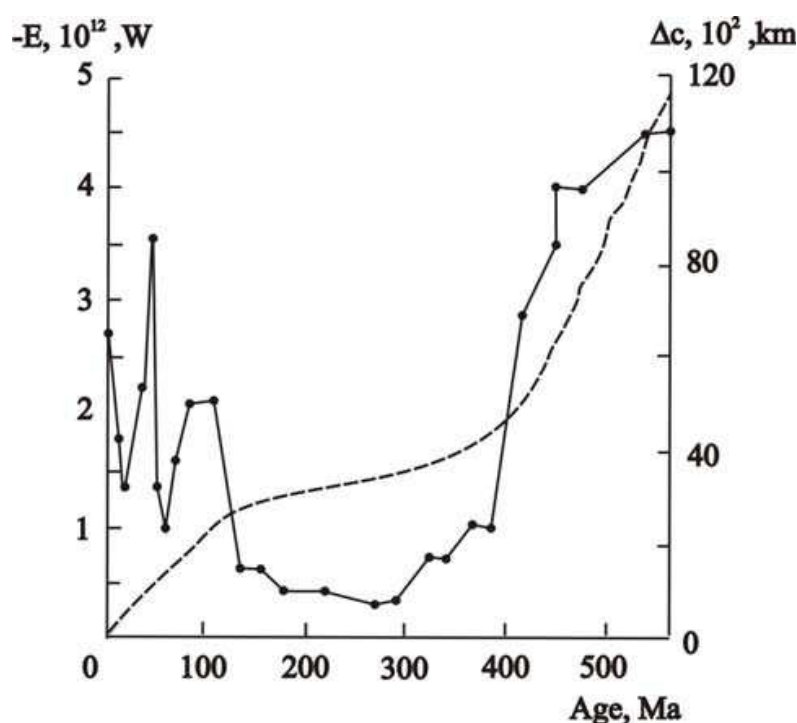


Fig. 5. Ocean tidal power dissipation ( $-E$ ) in Phanerozoic time (solid line) and relative decrease in the Moon's orbit radius ( $\Delta c$ ) with age (Zharkov, 2003)

The Earth's mantle retardation could also be due to the fading-out operation of possible nuclear reactors located on the inner core surface. The authors estimate their power at  $30 \times 10^{12}$  W (Rusov et al., 2007). Interestingly, "in the depth interval 4983.64–5000.0 km (see Fig. 6, BC), the P-wave velocity drops sharply from 10.86 to 9.7 km/s" (Burmin, 2004; 2008), and the author assumed that a ca. 215 km thick, less viscous layer (BCDE) could be located here.

A second similar (see Fig. 4) but less reliable T- and VDM- anomaly is assumed for Precambrian time in the interval 1.0–0.6 Ga, when the accretion of the continental lithosphere continued. Sparse known VDM-values at the end of this interval were probably also much smaller than at the present level and at the preceding time (Fig. 7). The Moon began to move away from the Earth more intensely in the Upper Mesoproterozoic ( $900 \pm 100$  Ma ago). This time is consistent with the disintegration of the assumed Rodinia

supercontinent. However, Palaeozoic supercontinents are known to have existed up to the Jurassic period, when Phanerozoic T-anomaly was completed. The formation pattern and drifting of continents, as third-order structures, will be discussed below in more detail, but at the end of this interval (1.0–0.6 Ga) global glaciation (“snowball Earth”) also re-appeared at 0.73–0.58 Ga (Evans et al., 1997; Kirschvink, 2000), presumably causing a decrease in ocean tidal friction energy.

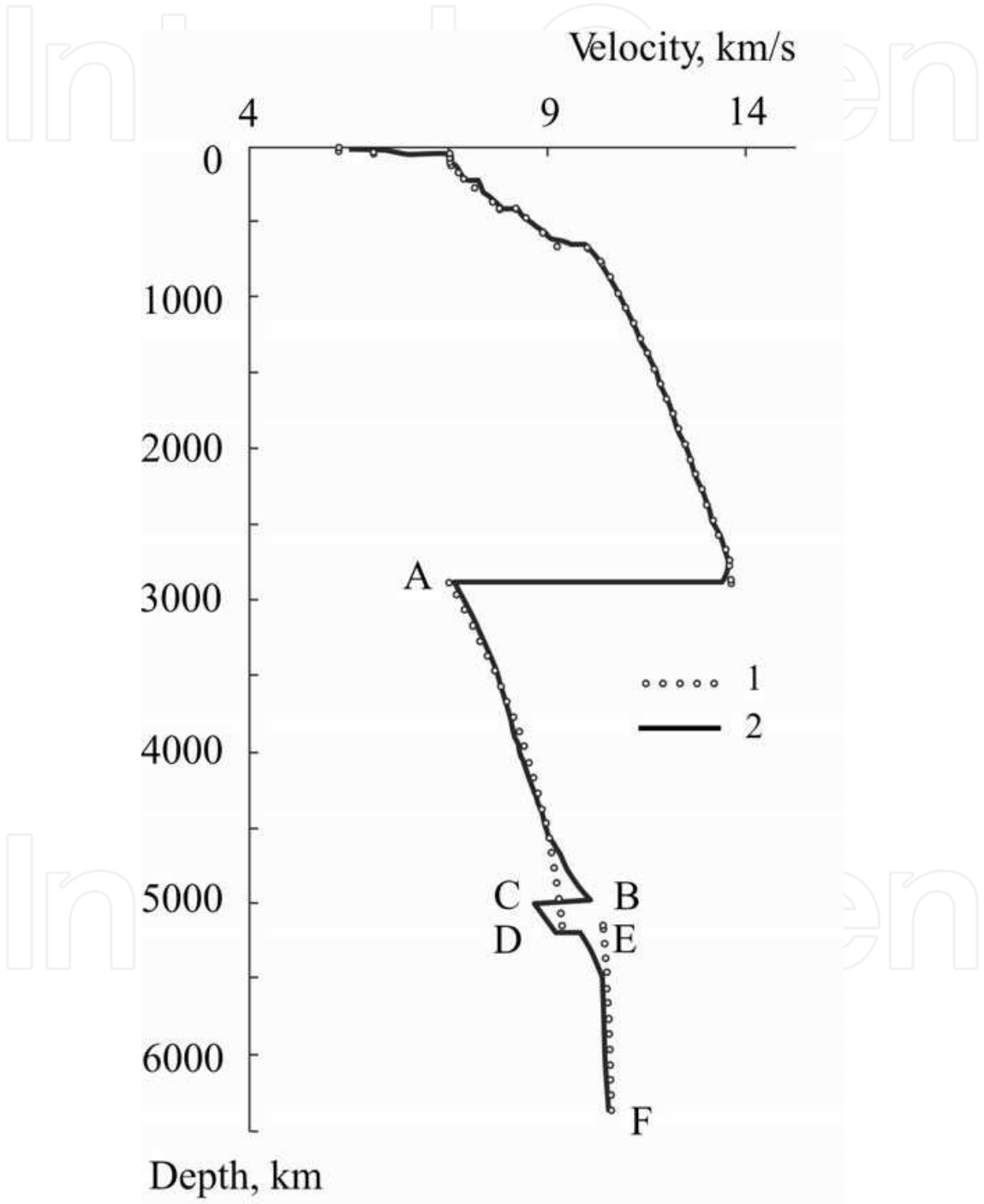


Fig. 6. Distribution of the *P*-wave velocity in the Earth (Burmin, 2004): (1) IASPEI91 model; (2) model with the function  $v(r)/r$  monotonically decreasing in the radius interval 2652–3478 km (depths of 3719–2893 km)

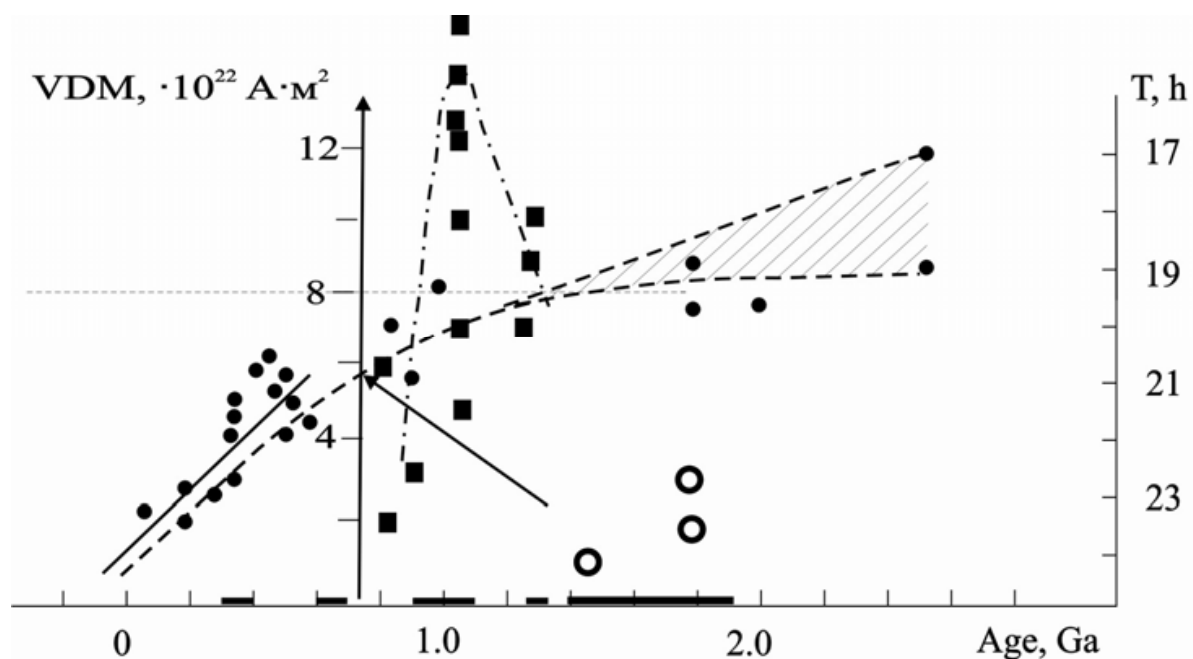


Fig. 7. A plot of variation in the Earth's rotation period ( $T$ ) with age (Varga, 1996; Varga et al., 2006) – dotted line is shown by arrow; assumed Precambrian anomaly in VDM (Zemtsov, 2010) – dotted-point line; and magmatic activity cycles (Baluev & Moralev, 2001; Zemtsov, 2007; 2010). Filled circles are  $T$ -values; squares are VDM-values in Mezo-Neoproterozoic time; open circles are the VDM-values obtained from Karelia (Shcherbakova, Pavlov et al., 2006); bold segments are magmatic activity cycles; line shaded area is possible  $T$  values in Palaeoproterozoic time. Horizontal dotted line is present VDM value (approximately  $8 \times 10^{22} \text{ Am}^2$ )

The common characteristics of both  $T$ -anomalies seem to be more essential as they mark magmatic and seismic activation cycles in the Earth and presumably result from the global restructuring of the geoid, because the degree of compression of the Earth depends on  $\omega^2$  of the mantle (Tsuboi, 1982; Zemtsov, 2010). As a result, huge lithospheric masses are transported to polar regions, the Earth's moment of inertia increases, the lithosphere is split up repeatedly and igneous and seismic processes are activated. In the meantime, the Earth's core is, of course, transformed as well, though with a minor lag. The Earth's VDM values first increase and then decrease rapidly. At least four magmatic activation cycles are known in the Proterozoic history of the Earth (Baluev & Moralev, 2001; Zemtsov, 2007), but the oldest  $T$ - and VDM-anomalies are impossible to trace as reliable data are meagre. It seems likely that no consensus will be obtained without further investigations to resolve these crucial issues.

#### 4. Continent drift patterns

Strictly speaking, the mantle ARV is an unknown value. The ARV of the Greenwich meridian may differ slightly from it because the asthenosphere has a degree of plasticity which can be recognised from the physical properties of peridotite at upper mantle temperatures and from the propagation of seismic waves (Lithgow-Bertelloni & Richards, 1998; McNamara et al., 2001). However, its viscosity is much greater than that of the liquid outer core (see, layer E, on Fig. 2). "The linear equatorial velocity of the upper asthenosphere

relative to the lithosphere, which is connected with the Earth's rotation, can thus be evaluated at  $V \approx 18 \text{ mm/yr}$  (Zemtsov, 2007, p. 244). This qualitative estimate shows that the lithosphere could have slipped relative to the lower mantle if it had been integral instead of comprising an assemblage of plates. Thus, relative longitudinal eastward drift of the asthenosphere seems to occur, although it cannot have a strong influence on continental motions because continents as a rule move much faster, as will be shown below.

#### 4.1 Variations in the pole of rotation of the Earth

As early as the 19<sup>th</sup> century, astronomers discovered Chandler oscillation, which was visible in the Northern Hemisphere by a small variation in the zenith angle of the Polar Star, and identified the secular movement of the Earth's rotation pole. The curve for the migration of the terrestrial pole (Fig. 8), called the polhode, gained practical importance for correcting coordinates. The pole position, the International Arbitrary Beginning (IAB), is recognized as the mean value of instant poles in 1903 since at that time the Chandler oscillation had its smallest recorded amplitude.

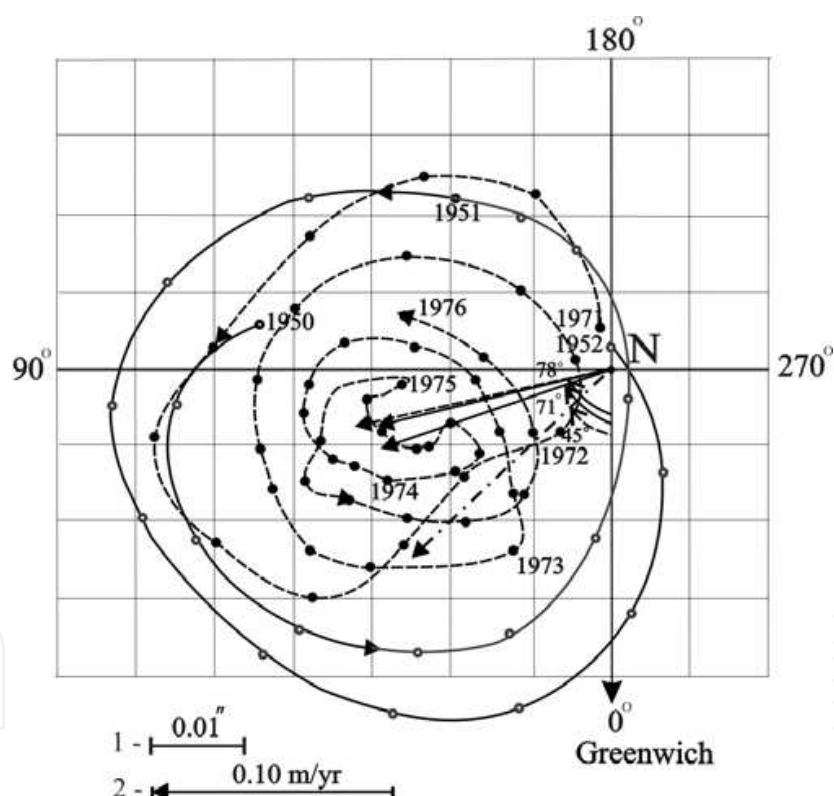


Fig. 8. Curves of variations in the North Pole of rotation of the Earth (polhode) relative to the International Arbitrary Beginning in 1903 (N) after (Zemtsov, 2007) and the mean vectors of the secular migration of the pole in 1930-1952 after (Shcheglov, 1974) – solid line; in 1971 – 1976 after (Tsuboi, 1982) – dotted line; in 1900 – 1925 after (Wegener, 1929, 1984) – dotted-point line. Instant positions of the pole = circles. A side of small squares is 3 m. 1 – horizontal scale in degrees; 2 – direction and value of secular course velocity

The analysis of the polhodes clearly shows that in the "Earth's body" there are two more movements that differ in pattern and velocity and are related to the secular course of the



pole. The secular course is the slow and apparent movement of the pole along the meridian; it manifests itself in that as time goes by, the instant poles make Chandler oscillations and move further away from IAB. From 1903 to 1976, the secular course of the North Pole (NP) was almost constant at  $(100\div120) \pm 20$  mm/yr. However, at first it was directed towards the 45<sup>th</sup> meridian (in the west system), in the 1950s towards the 71<sup>st</sup> meridian and in 1976 it moved towards the 78<sup>th</sup> meridian, turning opposite to the real rotation of the Earth (Zemtsov, 2004a, 2007). Astronomers agree that this secular course cannot be explained by periodic changes in the axis of rotation of the Earth in space or by changes in the angle of its inclination to the ecliptic. "In the Earth's coordinate system the axis is immobile, whereas the Earth's body is moving slowly on it" (Shcheglov, 1974), i.e. pole migration is interpreted as slow rotation of the entire lithosphere of the Northern Hemisphere in a direction opposite to the apparent movement of the pole. From the physical point of view, such a generalization is unreal. Firstly, the complex secular movement of NP in the 20th century to the west, from the 71<sup>st</sup>- to the 78<sup>th</sup>- meridian and along them, can be alternatively interpreted as the rotational-forward drift of both Eurasia and North America relative to IAB in the direction opposite to the secular course vector. All five observatories of the Latitude Service were located on continental lithosphere, and the results of their measurements pertain only to the continents of Eurasia and North America as third-order tectono-dynamic structures. It is no accident that sections of the Earth at the 71<sup>st</sup>-78<sup>th</sup> - meridians and in the opposite meridians extend across these continents. This means that both continents rotate clockwise, but Eurasia moves away from the NP and North America moves toward the NP. Secondly, the Earth is not a perfect sphere, and its lithosphere will tend to split up as it moves along a meridian. If one mentally rotates the polar lithosphere to the latitude of the equator and considers it purely as a brittle cap with the polar radius smaller than the equatorial radius by about  $\Delta r = 21.4$  km, then the total thickness of fractures in the lithosphere will be  $2\pi \times \Delta r \approx 135$  km. In this case, the thin oceanic lithosphere would be expected to be the first to split up. Thirdly, common forward continental drift in the Northern Hemisphere can occur only when shear movements take place simultaneously along transform faults in the Arctic, Atlantic and Pacific Oceans (Zemtsov, 2007). Finally, the North Pacific plate, as a fourth-order tectono-dynamic structure located between Eurasia and North America rotating clockwise, should rotate in the opposite direction, as was described in (Vikulin, 2002). Thus, the geographic coordinates of any point on the Earth's surface are not constant in time.

#### 4.2 Global Positioning System (GPS) data

The instantaneous ARV vector ( $\omega$ ) is the main characteristic of a rotating plate. In this case, at any instant of time the  $\omega$  value has to be invariable at any point of the plate with regard to the axis of its rotation. Physically, the  $\omega$  vector will be directed along the rotation axis of the plate by the right-hand screw rule. Thus, a degree of continental elasticity can be estimated for different points of its surface calculating some  $\omega$  values from a vector product (Eq. (5)):

$$\mathbf{V} = \omega \times \mathbf{r}, \quad (5)$$

where  $\mathbf{V}$  is the linear velocity vector at the definite point M on the plate surface and  $\mathbf{r}$  is the radius-vector which is equal to the shortest distance from this point M to the rotation axis of the plate, i.e. perpendicular to the rotation axis. The  $\omega$  sign is chosen according to the right screw rule (Fig. 9).

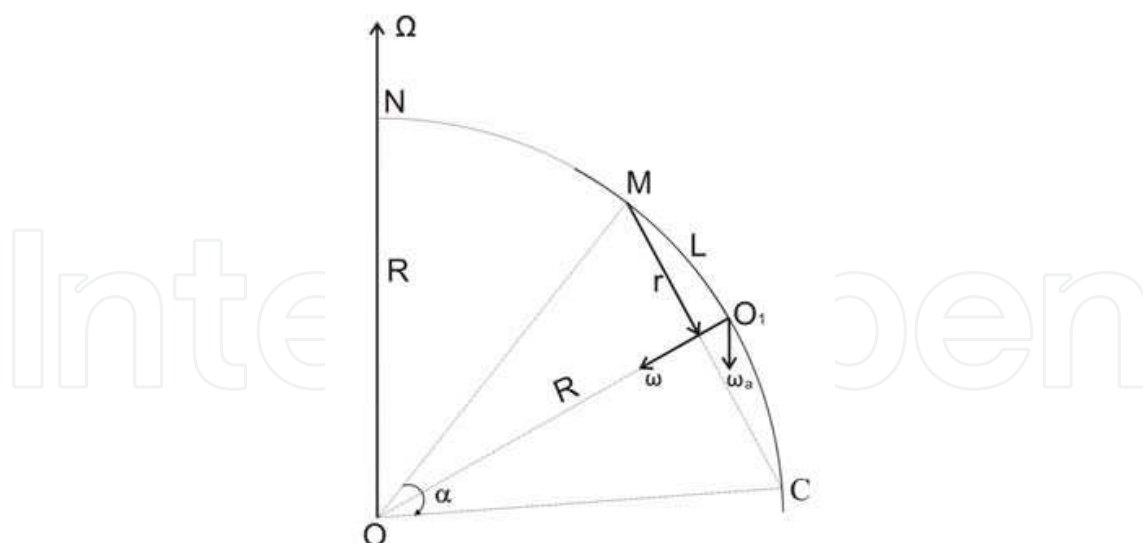


Fig. 9. Segment of the central angle  $\alpha$  of a spherical Earth rotating with an angular velocity vector ( $\Omega$ ) after (Zemtsov, 2009a), where O is the Earth's centre, N is the North pole of rotation, R is the Earth's radius,  $r$  is the radius vector of point M, L is the arc distance from point M to the rotation axis of a continental plate  $OO_1$ ,  $\omega$  is the ARV vector for point M,  $\omega_a$  is the axial component of this vector

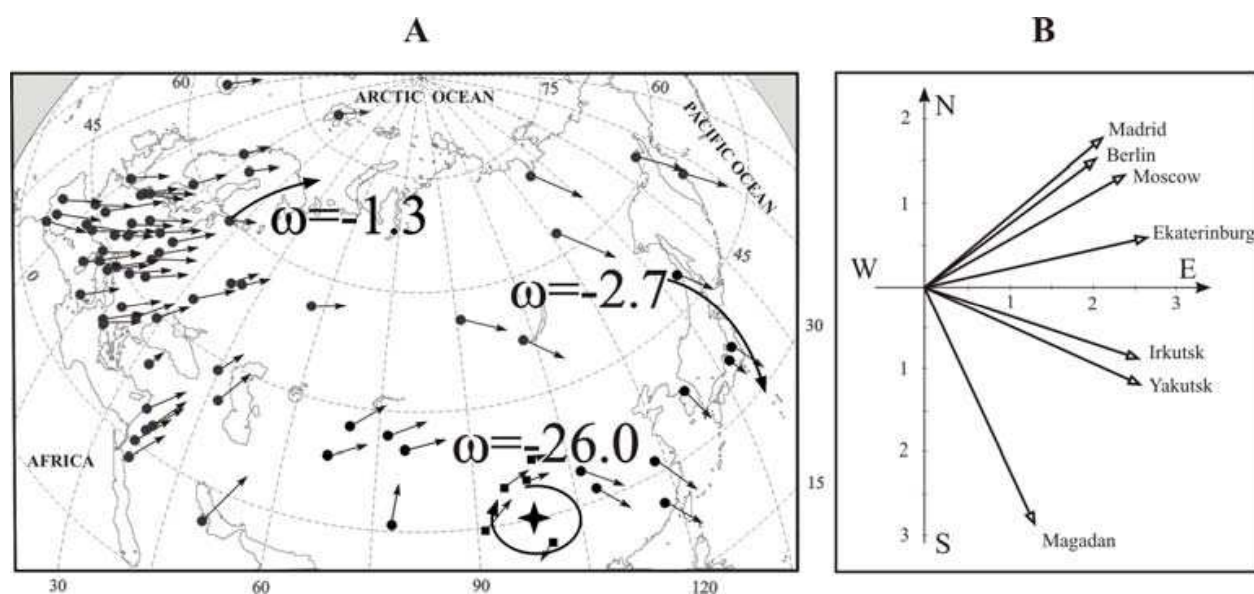


Fig. 10. (A) - scheme showing the horizontal linear velocity vectors (arrows) of GPS stations in Eurasia and the instantaneous ARV ( $\omega \times 2\pi 10^{16} \text{ s}^{-1}$ ) at some domains of continent after (Zemtsov, 2007) and (B) - some linear velocity vectors of GPS stations after (Utkin, 2002), cm/yr. Positions of GPS stations after (Utkin, 2002) = solid circles; positions after (Yuping et al., 2004) = solid squares; assumed centre of continental rotation = asterisk

The Earth's sphericity has nearly no effect on the  $\omega$  modulus if  $r < 1200 \text{ km}$ . In this case,  $r$  can be calculated from coordinates of points with the Williams Aviation Formulary V1.42 program (see <http://williams.best.vwh.net>), which yields the arc distance between the GPS point and the axis of rotation with a relative error smaller than 1%. The error in  $r$  increases

nonlinearly at great arc distances. For example, a central angle of  $45^\circ$  is matched by a distance of 5000 km on the Earth's surface, while  $r = 4500$  km, i.e., the error is 10%. The calculated value of  $\omega$  modulus will be underestimated. We can apply a necessary correction using known mathematical tables specifying the segment elements of a circle (Zemtsov, 2009a). Such a method is used to estimate the degree of elasticity (plasticity) of the Eurasian plate at various points of its surface (Zemtsov, 2007, 2008, 2009a) as it is now covered with a fairly dense permanent satellite geodetic network (GPS monitoring). The sum of the data obtained in the past few decades indicates that the general direction of plate motions is NE for Europe, SE for NE Asia and from SW to SE directions for SE Asia. The modern clockwise rotational drift of the Eurasian plate is clear (Fig. 10). In any case, the ARV vectors  $\omega$  of the Eurasian domains, owing to the clockwise continental rotation, have a negative sign because of the ARV constant constituent directed into the Earth on the Northern Hemisphere, in the opposite direction to its own ARV vector  $\Omega$  (see Fig. 9).

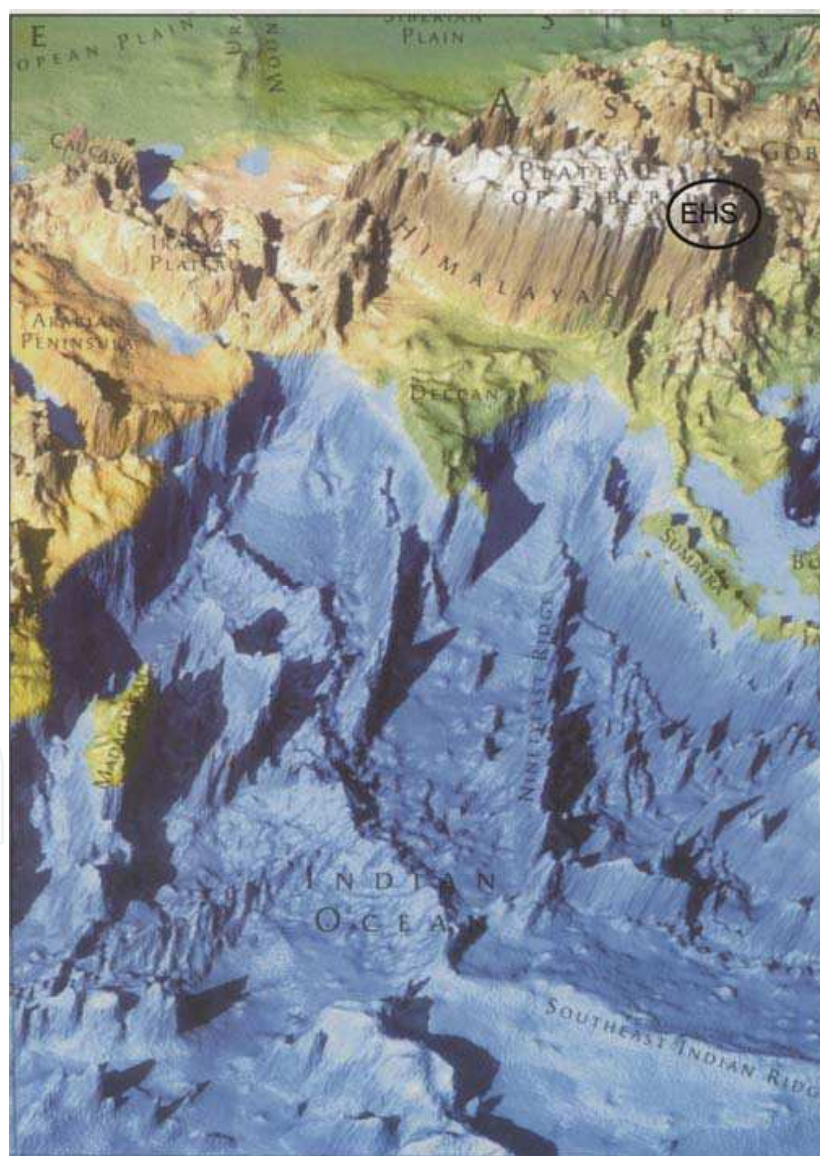


Fig. 11. Scheme showing bathymetric features in the Indian Ocean and the altitudes of surrounding land (Naqvi, 2005). EHS = the novel central domain of Eurasia's rotation



However, contrary to V.I. Utkin (2002), the centre of rotation is not a point. The central block of rotation of contemporary Eurasia (the eastern Himalayan Syntaxis (EHS)) seems to be located in the eastern Himalayas at the approximate coordinates  $E98^{\circ}N31^{\circ}\pm 4^{\circ}$  (Zemtsov, 2005, 2007, 2008). It manifests itself in the regional morphology (Fig. 11), being edged by the bend in the Litankhe River in the east, whose riverbed has the shape of a comma in its headstream, and with a clearly defined ring-shaped boundary intersecting known geologic structures (Yuping et al., 2004; Zhiliang et al., 2004). However, the authors of these detailed GPS studies, conducted in eastern Tibet in recent decades, restrict themselves to a consideration of the linear velocity field and have made only qualitative inferences about the most rapid rotation of "the EHS ring" as compared to that of its "skirt." They did not even understand that the EHS ring is the central, fastest-rotating block in all contemporary Eurasia but horizontal displacements into the EHS block likely into the rigid indenter have to be equal to zero. The most important vectors of linear velocities obtained for Tibet and its surroundings are presented in Table 2. Although colleagues (Zhiliang et al., 2004) noted, however, that there is a series of sub-order vortexes rotating around the EHS and that their velocities decline systematically from the inner ring to the outer one. They tentatively interpret these vortex motions and crustal deformations as a reflection of the lower crust rock rheology. According to Table 2, only the CSD point has very small horizontal displacement the reason for which is hard to find. It is located in close proximity to the source of the recent destructive earthquake that occurred in southwestern China (Zemtsov, 2009a).

The tectonics and seismicity of the Himalayas has been the subject of intense investigations by many geoscientists during the past few decades (Kayal, 2001; Ramesh et al., 2005; Saklany, 2005). Most of the earthquakes were assigned to a fixed depth (33 km) as recorded in the catalog of the International Seismological Centre. It has not been possible to correlate the observed seismicity and tectonic features of the Himalayas with any realistic model, particularly the great earthquakes in this region are yet to be understood well. Recent data shed some new light on tectonics of the Himalayas that differs from west to east (Kayal, 2001). "The analysis of the seismicity in central Asia shows its distribution within a "triangle" of maximum inner-continental seismic activity, which is situated between the south edge of Lake Baikal and the Himalayas. The "triangle" coincides with the central Asian transition zone which divides the north Eurasian and Indian lithosphere plates and provides the transfer and relaxation of tectonic stresses that arise between them. The Central Asian transition zone consists of numerous crust blocks of different sizes. The blocks' boundaries are often represented by not only single faults but relatively wide interblock zones characterized by intensive shattering of rocks and releasing a significant quantity of seismic energy. The most active interblock zones limited the Pamirs, Tien Shan, Shan, and Bayanhar blocks as well as the north boundaries of the Indian Plate. The quantity of the seismic energy released along each of them reaches  $\geq 5 \times 10^{15}$  J, while the energy flowing along other boundaries does not exceed  $3 \times 10^{12} - 2 \times 10^{15}$  J. The majority of the most intensive seismic events took place just in these interblock zones. The total quantity of seismic energy generally diminishes away from the boundary of the Indian Plate, but sometimes the maximal quantity releases in the inner parts of the transit zone at a distance of 500-1500 km from the plate boundary. The most active interblock zones of central Asia differ from subduction and collision zones in the depth of their penetration into the lithosphere and at the same time are rather near to them by the volume of energy realized. The examination of

interblock zones shows that the majority of intensive earthquakes occur within them in regions with sharp changes in geodynamic conditions. As a whole, most of Central Asia is influenced by the Indian indenter, which is responsible for the prevalence of transpression tectonics” (Gatinsky et al., 2011).

GPS stations	Longitude, deg.	Latitude, deg.	Linear velocity, mm/yr	Azimuth of motion, deg.
Lhasa (LHS)	91.1	29.66	26.75±1.27	45.61
GLM-1	94.8	36.2	16.65±1.90	49.77
XRH-1	98.2	36.43	12.27±1.57	50.81
CSD	99.08	40.28	2.76±1.45	78.53
OLZ-3	98.43	25.04	10.0	212
Bangalore (IISC)	77.6	13.1	41.68±2.21	26.18

Table 2. Geographic coordinates of GPS stations (in the east system) and their linear velocity vectors in the Tibet Plateau and its environs, based on the data of (Yuping et al., 2004; Zemtsov, 2007, 2009a)

The estimates of ARV vectors  $\omega$ , obtained for various Eurasian domains in (Zemtsov, 2006, 2007, 2009a), show that the  $\omega$  modulus varies several times (see Fig. 10), increasing from the periphery of the continent (it is  $(1.2\div1.4)\times10^{-16}$  1/s at European stations) to the EHS-block boundary, where it reaches  $(26\div29)\times10^{-16}$  1/s. The real value of  $\omega$  is somewhat smaller than the one calculated as there is an additional component of E to SE Eurasian drift. Greatly different ARV values show that Eurasia, the largest modern continent, does not possess the main property of a rotating solid body, i.e. it is not a rigid plate, to a second approximation, but rather a complex structure comprising domains exhibiting differential rotational drift, which cannot be accounted for by plate tectonics or by subduction ideas of vertical density heterogeneities in the lithosphere. However, the general pattern of the Eurasian linear velocities includes local anomalous areas (the Altai, the Carpathians, etc.) characterized by a high seismicity (Goldin et al., 2005; Mocanu, 2008; Timofeev et al., 2006). As a matter of fact, all determining ARV values for the Eurasian domains are  $30\div300$  billion times smaller than the proper ARV of the contemporary Earth but, rotating clockwise, the continent extracts a fraction of the total energy of the Earth’s rotation because a moment of forces preventing the Earth’s rotation acts at its assumed basement (Zemtsov, 2006, 2007, 2009a). Unfortunately, such an analysis of the drift of GPS stations cannot be performed for other continents because similar systematic studies are at the initial stage there. In particular, local GPS networks are concentrated in the United States, mainly in western North America, and are used primarily to trace earthquakes. Like Europe, this part of the continent drifts NE (Melbourne et al., 2004). However, these data and the results of the interpretation of the secular apparent North Pole wander passes over the last century suggest that this continent rotates clockwise (Zemtsov, 2004a, 2007). The data obtained for the continent of Antarctica are very contradictory (Bouin & Vigny, 2000). Due to severe conditions, French scientists obtained only one reliable vector, which suggests that this huge continent apparently rotates counterclockwise.



### 4.3 Driving forces of continental motions

It seems that large-scale forces, rotating the continents in the direction opposite to the rotation of the Earth, permanently exist when the centres of the continents are far away from the equator. To understand the physical nature of these forces, we can draw analogies with atmospheric vortexes (anticyclones) and the rotation pattern of floating ice in the Arctic Ocean (Zemtsov, 2004a). Anticyclones arise at Arctic and temperate latitudes and rotate clockwise in the Northern Hemisphere, but counter-clockwise in the Southern Hemisphere and form vortexes that are about 1000 km across. Descending on the interface of the rotating Earth, a heavy air column begins to whirl, presumably by virtue of frictional torque forces as described in textbooks on theoretical mechanics. This physical problem has not yet been solved analytically as, unlike absolutely rigid bodies that can touch each other at a single point, natural bodies always touch one another at a site that, in principle, can rotate. In non-linear mechanics, a combination of such problems, in which the radii of curvature of the contact surfaces are considered, is known as a contact problem in the theory of elasticity, plasticity and creep (Zemtsov, 2007), although a rough physically determined model of such torsion can be created (Fig. 12). If a site at which rotating bodies touch each other is horizontal, and the force which presses the upper body against the lower one is equal to the weight of the upper body ( $P$ ), then the problem is simpler although friction-sliding forces on the bottom of the upper body will have different directions and magnitudes and, if summed up, will give a torque friction force moment. If the moment of these forces is too low to overcome frictional resistance, the upper body will not move relative to the lower one. The limit of the torque friction force moment ( $M$ ) depends on the distribution of pressure on the bottom of the upper body, and such factors as the shape, size and elastic properties of bodies (Eq. (6)):

$$M = \mu P, \quad (6)$$

where  $\mu$  is the torque friction coefficient and has the dimension of length.

This coefficient, in turn, depends on the dimensionless sliding friction coefficient ( $f$ ) and the area of contact of bodies. For a cylinder with radius ( $a$ ) it can be estimated theoretically as ((Eq. (7)):

$$\mu = \pi f a / 4 \approx 0.79 f a, \quad (7)$$

Analysis of the simplified Eqs. (7) and (8) leads to an important geophysical conclusion. As the torque friction coefficient on the bottom of a cylinder increases with increase in its radius,  $M$  is an approximate function of  $a^3$  and  $P$  is an approximate function of  $a^2$ . Thus, for any value of  $f < 1$  and constant height of the cylinder  $h$ , there exists a critical radius  $a$  at which  $(M/\mu) \geq P$ , i.e. the upper body will be detached from the lower one and will begin to move on the rotating surface of the lower body (Zemtsov, 2007). The pattern of this movement becomes obvious (see Fig. 12): when both cylinders will rotate primarily in the direction opposite to the rotation of the disc retarding it, but the upper cylinder will rotate clockwise and the lower cylinder will rotate counterclockwise. The effect of torque frictional forces can be modelled, for example, when making polished sections on a grinding wheel. Fig. 12 can, therefore, be regarded as a rough model of a continent with radius  $a$  and thickness  $h$ , which drifts on the surface of the homogeneous mantle. The rotation of Eurasia is likely to follow the same physical pattern, i.e. it has to rotate clockwise as it is located in the Northern Hemisphere likely to the upper cylinder. In reality, of course, each continent has a huge

mass, its surface is not flat at the base and a number of secondary interactive geodynamic forces operate.

Using this continental model and (Eq. 3), the rotation energy ( $E$ ) of an individual continent, e.g. Eurasia, can be estimated, assuming that it is similar to the upper cylinder, which has thickness  $h \approx 200$  km and radius  $a \approx 3000$  km and rotates on the mantle surface at ARV  $\omega \approx 4 \times 10^{-16} \text{ s}^{-1}$ , then  $E \approx 2.5 \times 10^6 \text{ W}$ . Thus, the energy of continental motion is ca. a million times smaller than ocean tidal retardation energy. Such small values can be neglected (Zemtsov, 2010).

The spherical interface between the continental lithosphere and the asthenosphere is probably formed spontaneously by virtue of a change in the elastic properties of the mantle and its partial melting associated with a natural rise in temperature with depth at the expense of the heat released from the core and lower mantle so that, at a relatively small depth of 100 km, the temperature can be as high as 1500 K. If the moment  $M$  on the bottom of the continent exceeds the force of attraction attributed to its base area, it will begin to rotate spontaneously in the direction opposite to the rotation of the base. The temperature of the base may be expected to rise as a result of the torque friction.

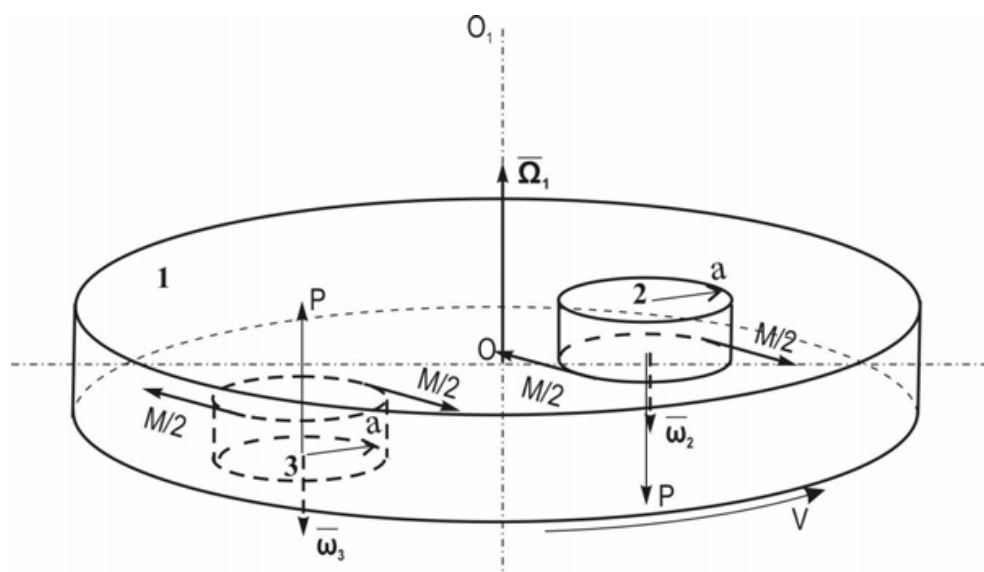


Fig. 12. Spontaneous momenta of spinning friction forces ( $M$ ) of vertical cylinders (2 and 3) of radius  $a$  pressed down to a massive horizontal disk (1) with the force  $P$ . The disk rotates about the vertical axis  $OO_1$  with a linear velocity  $V$ . Angular velocity vectors of these bodies are, respectively,  $\bar{\Omega}_1$ ,  $\bar{\omega}_2$ , and  $\bar{\omega}_3$ , after (Zemtsov, 2008, 2009a, 2009b)

The depth  $h$  appears to be located within zones with the minimum mechanical quality factor of the Earth's mantle, which has a layer of low mechanical strength at a depth of  $90 \div 450$  km (Zharkov, 1983). For the largest continents, such as Eurasia, Africa and South America, Lehmann's seismic discontinuity is located in this interval at a depth of ca. 220 km. The nature of this interface can be explained by a transition from anisotropic lithosphere to essentially isotropic upper mantle. Therefore, seismically anisotropic mantle zones located at higher levels indicate that rock flow can occur in them (Gaherty & Jordan, 1995). Furthermore, the possibility cannot be ruled out that several, rather than one, subparallel zones of shearing with differentiated rotation are present at the base of the continental lithosphere. DSS data also show that at a depth of 90–120 km in the sub-continental mantle a

second global layer with elastic wave velocity inversion and high electrical conductivity (i.e. fluid-saturated) is present, and at similar depths substantial crust-mantle heterogeneous masses are isostatically balanced (Pavlenkova, 2006). High seismicity qualitatively corroborates both of these mantle interfaces: following the Harvard catalogue, Rodkin (2004) has studied the possible depths of mantle earthquakes and attributed seismicity to the “ripping up” of the upper mantle or an upward breakthrough of fluids to a zone of smaller lithostatic pressures. A maximum torque moment seems to arise in a continent if the centre of its mass is located at the poles of planetary rotation. For example, the modern Antarctic Continent has a huge area and tendency to retain quiescence in the inertial coordinate system, i.e. it would spontaneously rotate counterclockwise in the opposite direction to the Earth's rotation (Zemtsov, 2007).

#### 4.4 Ancient rotations of Eurasia and its domains from palaeomagnetic data

A similar rotation pattern of the continental lithosphere can be recognized in the Phanerozoic history of the Earth from palaeomagnetic data. The eastern Siberian domain, located in a temperate latitude band, was the central Eurasian block in the Mesozoic, but the velocities of differential rotations of more distant domains insignificantly exceed contemporary values ( $-3.0 \times 10^{-16}$  1/s in western Siberia,  $-2.5 \times 10^{-16}$  1/s in the Altai-Sayan folded region, and  $-2.0 \times 10^{-16}$  1/s in the Urals) (Fig. 13).

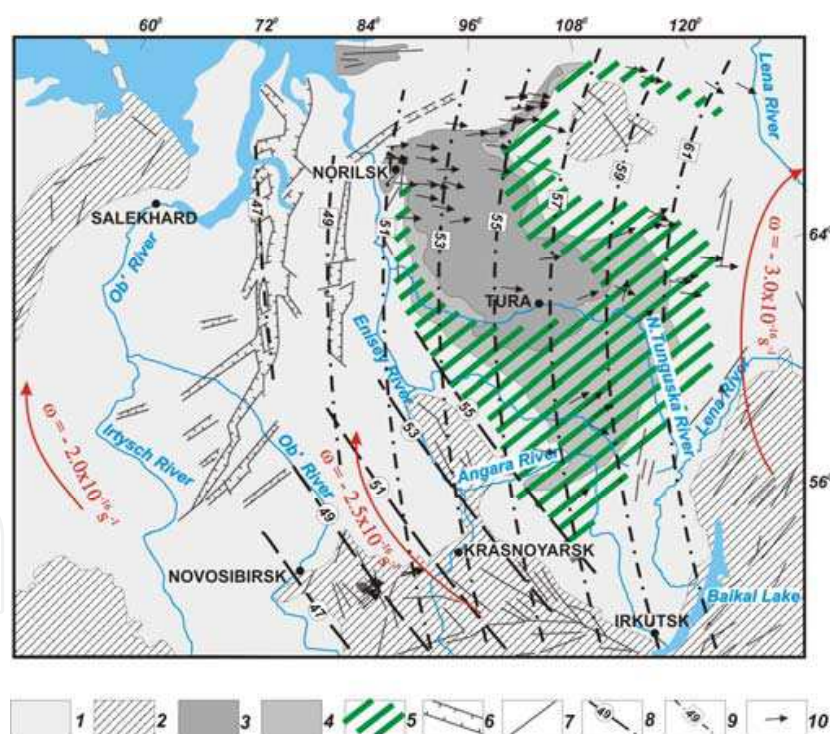


Fig. 13. Geological scheme of Siberia (Almukhamedov et al., 1999) with the Mesozoic palaeolatitudes (Kazansky et al., 2005) and the angular rotation velocity (ARV) values for some regions (Zemtsov, 2008). Legend: 1 - Phanerozoic sedimentary cover; 2 - foldbelts and Precambrian basement; 3 - basalt; 4 - basaltic tuff and tuffite; 5 - intrusive trap development areas; 6 - Pre-Jurassic basement rift structures of the West Siberian Plate; 7 - major faults; 8 - palaeolatitudes determined from trap basalt of the Kuznetsk basin; 9 - those from East Siberian traps; 10 - Permian-Triassic palaeomagnetic directions (to the North Pole)

The differentiated rotations of the continental domains of the future Eurasia were typical of the Palaeozoic until the collision between the East European plate (Baltica) and Siberia (Didenko & Ruzhentsev, 2001; Filippova et al., 2001; Zemtsov, 2007; 2008), although V.I. Utkin discussed the rotational drift of Eurasia and assumed it to be “historically inherited” (Utkin, 2002). He postulated that a change in the rotation of the Eurasian plate (EAP) occurred in Lower Permian time and attributed it to the completion of magmatism in the Urals. He argued that the subsequent behaviour of the plate was affected by a change in the structure of convective cells in the mantle. However, his arguments were based on old palaeomagnetic data, and the interpretation seems unlikely because it conflicts with the modern forward drift of the EAP and available palaeomagnetic data from the Siberian and Kazakhstan blocks, which indicate long-term clockwise rotation before the Permian (Filippova et al., 2001; Sennikov et al., 2004; Smethurst et al., 1998; Van der Voo, 1988). Hence, it is not quite correct to consider the drift of the EAP as historically inherited (Zemtsov, 2007).

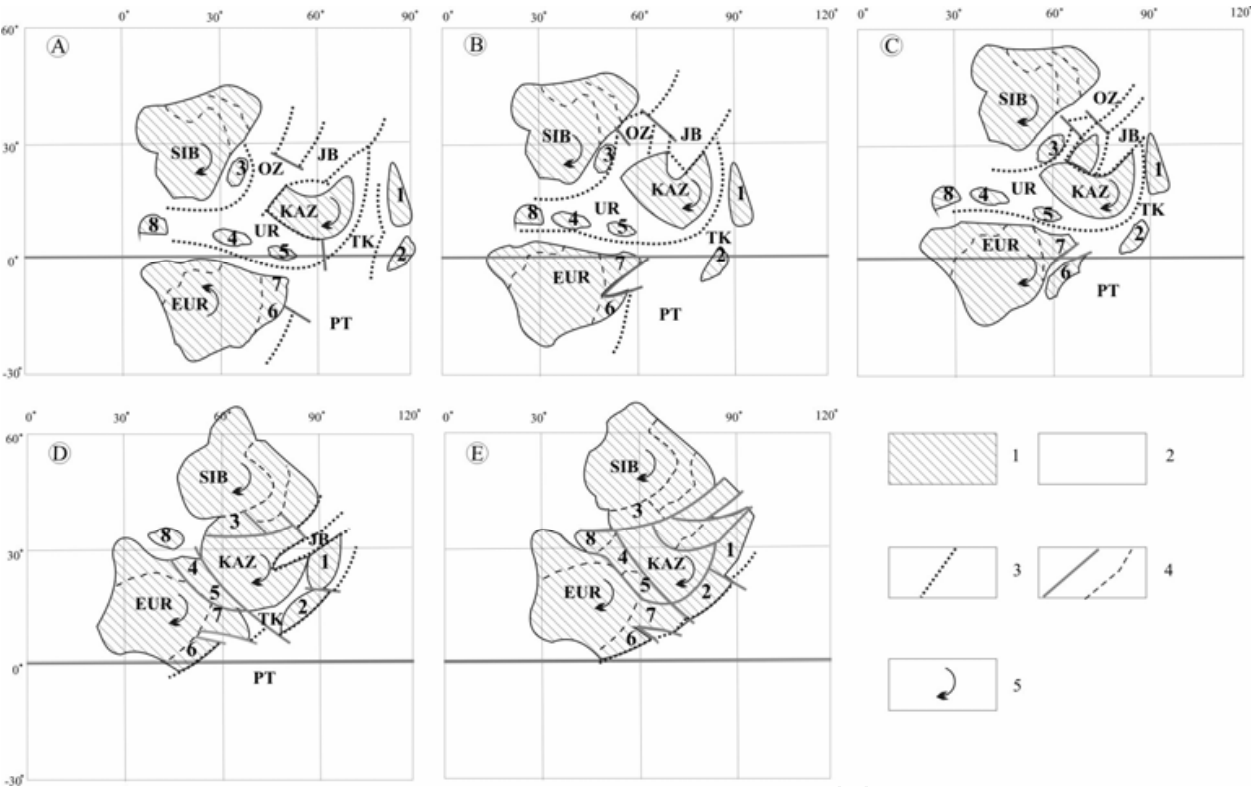


Fig. 14. Schemes showing the geodynamic evolution of the Central Asian foldbelt omitting contiguous areas (Filippova et al., 2001) with some reductions: A – Lower Devonian, B – Middle Devonian, C – Upper Devonian, D – Lower Carboniferous, E – Lower Permian. Symbols: 1 – continents and microcontinents, 2 – oceans and back-arc basins, 3 – subduction belts, 4 – other structural sutures and principal strike-slip faults, 5 – sense of rotation of continental blocks. Acronyms denote continent (EUR = European, SIB = Siberian, KAZ = Kazakhstan) and oceans (UR = Uralian, TK = Turkestan, JB = Junggar-Balkhash, OZ – Ob-Zaisan, PT = Paleo-Tethys). Numerals mark microcontinents and continental blocks: 1 – Tarim, 2 – Baisun, 3 – Vartovsk-Nyuroika, 4 – Khanty-Mansi, 5 – East Urals, 6 – Bechasyn-Karabogaz, 7 – Ustyurt-Karakum-Amu-Darya, 8 – Baydaratsky



Interestingly, differential rotations, slow for the ancient European continent (Baltica) and fast for Siberia, had existed in Lower Devonian time, and after the Upper Carboniferous collision (Fig. 14) and can presently be observed. Secondly, Figure 14 shows that as early as the Middle Devonian the ancient European continent (Baltica) intersected the equator and moved from the Southern to Northern Hemisphere whilst changing the direction of its rotation in Lower Carboniferous time. When it was south of the equator during the Lower Palaeozoic, it was rotating counterclockwise, whereas upon transition to the Northern Hemisphere the sense of rotation became clockwise. Volcanic activity in the Urals had already ceased by Permian time, and by the Upper Carboniferous the Baltica, Siberia and the Kazakhstan blocks had joined to form ancient Eurasia, which then continued drifting northwards and rotating clockwise. The faster rotation of Siberia in Devonian and Carboniferous time was apparently related to its distant position to the north of Baltica and the Kazakhstan plate (Zemtsov, 2009a).

Thirdly, an updated correct version of the Apparent Pole Wander Path (APWP) was obtained for the more ancient Baltica from detailed paleomagnetic studies of Lower Silurian–Middle Devonian sedimentary rocks from Podolia (Lubnina et al., 2007). At that time, after the supercontinent Gondwana disintegration, Baltica was at tropical latitudes of the Southern Hemisphere approaching gradually the equator (Fig. 15). The drift of Baltica, which began in the Upper Ordovician (449 Ma) and continued up to the Lower Devonian (400 Ma), was not as complex as it was interpreted previously (Bakmutov et al., 2001; Smethurst et al., 1998). It can be represented as a smooth counterclockwise rotation of the whole continent by  $30^\circ$  over 21 Ma at the ARV equal to ca.  $(-7.90 \pm 0.15) \times 10^{-16} \text{ 1/s}$  (Zemtsov, 2008, 2009a, 2009b). Approximately after this time (400 Ma ago) the rotation of the Earth's mantle as a second-order structure, was slowed down much faster than in the Lower Palaeozoic (see Fig. 4 and Fig. 14, C).

It is essential that the palaeomagnetic angular error amounts to  $5^\circ \div 10^\circ$ . The determination uncertainty of ancient ARV is small and is about  $\pm(\pi/30)(1/t)$ , because Ma is taken as a geologic time unit, where  $t$  is time calculated in seconds according to the International Stratigraphic Chart (Gradstein et al., 2004) with regard for the determination uncertainty of absolute age. As the relative determination uncertainties of age intervals seldom exceed 1% for entire Phanerozoic time, disregarding these uncertainties cannot considerably affect ARV values.

A change in the direction of rotation for Baltica and for other large continents on intersecting the equator has been established reliably and is apparently a general geophysical pattern of plate motion in geologic time (Fillipova et al., 2001; Zemtsov, 2006, 2007). Naturally, the traversal of the equator did not occur instantly, but took a relatively short interval of the Upper Devonian (less than 27 Ma). This event was accompanied (in ancient coordinates) by latitudinal shear deformations directed along the equator and an ultramafic diamond-bearing magmatism in the northern Fennoscandian Shield, which at that time was what is contemporary Africa, at the Aswan meridian, near Khartoum, in the modern coordinate system, and Baltica, traversing the equator under N-S compression conditions, experienced one of the last tectonic and magmatic activations (Zemtsov, 2008, 2009a). The diamond kimberlite pipes on the Terskii coast of the White Sea form a separate series in the Kandalaksha graben. They have a K-Ar age of 380–360 Ma (Kalinkin et al., 1993).



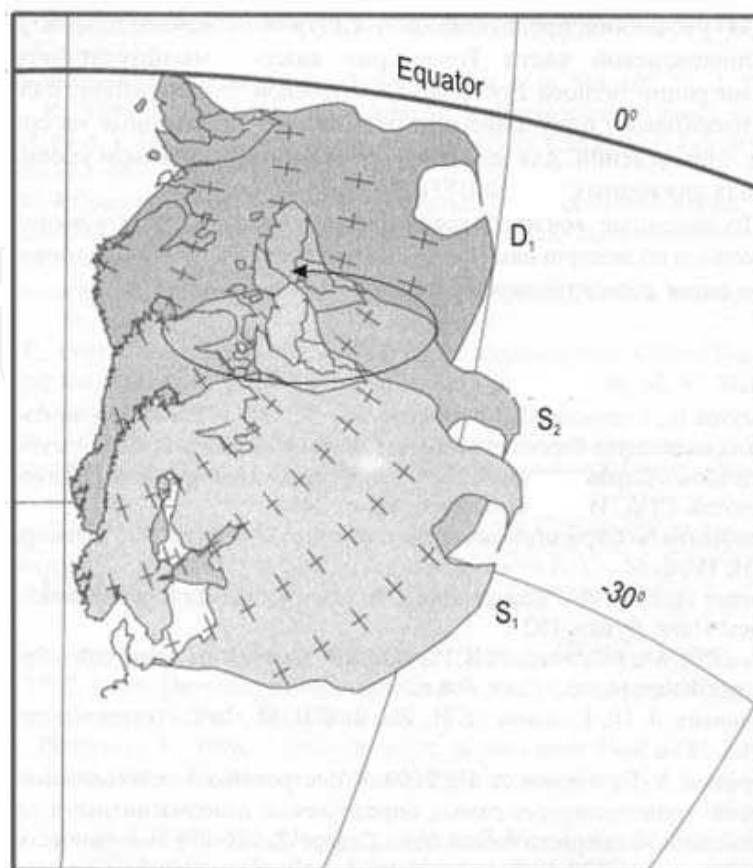


Fig. 15. A drift for the East-European Plate (Baltica) during the Silurian (Wenlock) – Lower Devonian (Pragian) after (Lubnina et al., 2007). The sense of continent rotation is shown by arrow

New interesting palaeomagnetic data have been obtained for the Middle Ordovician–Lower Devonian from the Tas-Khayakhtakh terrain (TKT) of the Verkhoyansk-Kolyma folded area (Rodionov et al., 2007). The authors assumed that as early as Mid-Ordovician time, according to the International Palaeomagnetic Database (McElhinny & Lock, 1966), the East-Siberian Plate and TKT were located at equatorial latitudes. During the Middle Ordovician interval, Central Siberia was shifted northwards from 5 to 30 degrees N. At the same time, the continent rotated slightly (by about 6 deg.) counterclockwise. The TKT also moved northwards from 8 to 27N but rotated clockwise by ca. 10 degrees. The results for this interval can thus be interpreted as a joint kinematic drift of the East Siberian Plate and TKT from the equator to the tropical latitudes of the Northern Hemisphere over a distance of ca. 30 degrees, combined with a TKT minimum relative clockwise rotation. During Lower Silurian - Lower Devonian time Siberia continued to drift northwards to the 42-nd latitude, rotating slightly clockwise. The relative positions of the continent and TKT were as stable as those at the beginning of Lower Silurian time, i.e. TKT was “soldered in” the lithosphere of the front-continental basin. During the Lower Devonian – Lower Carboniferous interval the clockwise rotation of Siberia at an angle of approximately 90° began to accelerate, and the speed of its forward movement northwards diminished (see Fig. 15). During this period the Earth’s rotation was slowed down much faster than earlier (see Fig. 4) and Siberia drifted from the 42-nd latitude to the 50-th latitude. The TKT also moved slightly northwards, but it

retained the Lower Silurian orientation. Therefore, since the beginning of Lower Devonian time Siberia was rotating rapidly relative to the almost immobile Verkhoyansk-Kolyma folded area (or had already ceased to rotate). The Siberian continent seems to have detached from the front-continental basin in the Lower Devonian, but it may have occurred later, in the Mid- and even Upper Devonian. Such a differential rotation of Siberia could be accompanied by a growing number of slip-strike crust deformations at the passive boundary surrounding the continent. Unfortunately, the time of the Siberia's detachment from the Verkhoyansk-Kolyma folded area was determined incorrectly. According to (Rodionov et al., 2007), this could have occurred even in the Upper Devonian. Therefore, the averaged ARV value for Siberia is estimated over the time of the continent rotation with a large error: (from  $-7.4$  to  $-16.5$ ) $\times 10^{-16}$  1/s; i.e., it exceeded the contemporary value for the East Siberian domain of Eurasia by about three to six times (Zemtsov, 2009a).

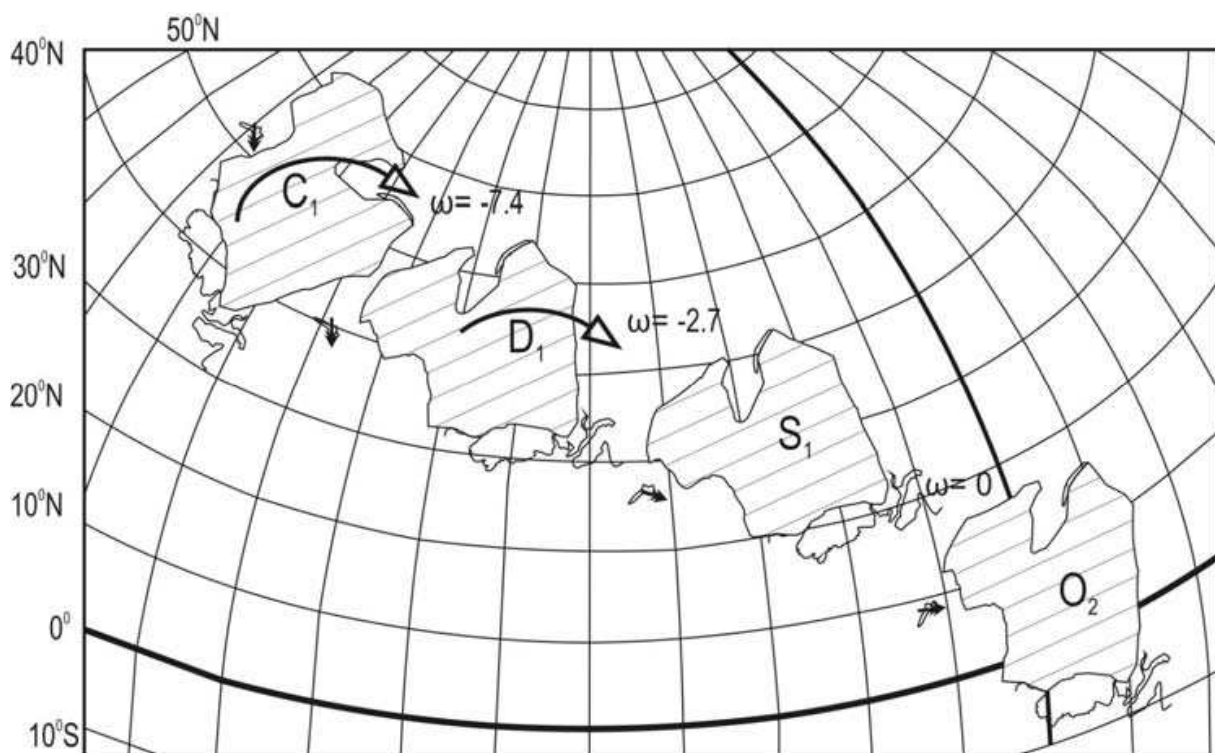


Fig. 16. Geographic position of the ancient East-Siberian Plate after (Van der Voo, 1993; McElhinny & Lock, 1996) with regard to the Tas-Khayakhtakh terrain (TKT) of the Verkhoyansk-Kolyma folded area during the Middle Ordovician (O<sub>2</sub>) - Lower Carboniferous (C<sub>1</sub>) interval after (Rodionov et al., 2007) and the angular rotation velocity (ARV) values ( $\omega \times 10^{16} \text{ s}^{-1}$ ) for Siberia (round arrows) after (Zemtsov, 2008). Modern directions to the north for the TKT-block = little arrows

During the Middle Carboniferous - Lower Permian interval the Paleozoic basement of the Kolyma structure was finally formed (Rodionov et al., 2007) and by the Upper Carboniferous Baltica, Siberia and the Kazakhstan blocks had joined to form Eurasia (see Fig. 14), which then continued drifting northwards and rotating clockwise. Palaeomagnetic data suggest that the total rotation of the Urals during the past  $255 \pm 5$  Ma has amounted to  $55-60^\circ$  (Didenko & Ruzhentsev, 2001) and, to a first approximation; the average ARV values for the Uralian domain of Eurasia during this great interval was  $-(1.3 \pm 0.2) \times 10^{-16} \text{ s}^{-1}$

(Zemtsov, 2007). This value seems to be underestimated, because the rotation of the Uralian domain had almost ceased by the end of the Cretaceous Period (Zemtsov, 2009a).

The number of reliable determinations in the Precambrian APWP is insufficient even for Baltica. However, joint interpretation of palaeomagnetic data and dating of large tectonomagmatic events that occurred in ancient continents, such as rapakivi-granitic magmatism, different orientation of dike swarms of different ages, and others, make it possible to consider separate episodes of continent geodynamics and to estimate their ARV in the Precambrian. Such calculations were performed for the putative Columbia supercontinent in a time interval of 1570–1430 Ma (Zemtsov, 2009a). Columbia was in the Southern Hemisphere, at that time rotating counter-clockwise, but its ARV decreased from  $-32 \times 10^{-16} \text{ 1/s}$  to  $-4.5 \times 10^{-16} \text{ 1/s}$  as the supercontinent split up successively.

The Indian Shield is composed of weakly metamorphosed rocks and had apparently very slow rotation at the ARV value  $\approx -0.8 \times 10^{-16} \text{ 1/s}$  in an interval of 2500–2000 Ma (Zemtsov, 2009a, 2009b), although in Basu's opinion (Basu, 2001), it hardly rotated at all throughout the Palaeoproterozoic. But in the Bundelkhand Craton of the Indian Shield the NE-SW trending shear-zones with quartz reefs (2200–2100 Ma), spaced ca. 20 km apart, show sinistral displacement (to 6 km), producing clockwise rotation and compression along shear-zones and point to differential sliding movement along shear walls (Basu, 2007). Apparently, having a small size, the Indian Shield retained the properties of the Archaean microcontinent for the longest period of time.

It becomes obvious from the above examples that the absolute ARV values of large continents approaching the equator or moving away from it were latitude dependent. According to global wrench tectonics, the basis of which was laid more than 100 years ago by revolutionary scientists Damian Kreichgauer (Kreichgauer, 1902), shear deformations are also latitude-dependent and have the maximum effect directed along the (palaeo)equator (Storetvedt, 2003, 2005, 2010). However, deformations in Palaeozoic Siberia at temperate latitudes apparently have a different pattern of dominantly annular shear deformations that arose under lithospheric tension conditions and are related to spontaneous rotation of the continent. The increase in the Earth's polar radius, caused by historical lengthening of the earth day, also indirectly corroborates the fact that the lithosphere at temperate latitudes ( $\pm 50^\circ$ ) had to experience a gradual extension in the Phanerozoic. In addition, analysis of absolute ARV values suggests that the Palaeozoic velocities of the Eurasian domains were higher than contemporary ones. It follows from the model that this can be associated with the movement of young Eurasia's rotation centre to the equator (from Siberia in the Himalayas), as well as with an increase in the rotation period and deceleration in the Earth's mantle rotation (see Fig. 4). However, the retardation energy of continental motion, for example Eurasia as a third-order structure, is ca. a million times smaller than tidal retardation energy. Such small values can be neglected, as shown above.

## 5. Conclusions

The above examples of palaeoreconstructions show that average ARV values for ancient continents depend primarily on their geographic position and size. Note that counter-clockwise rotation was typical of the continents located in the Southern Hemisphere, while those located in the Northern Hemisphere rotated clockwise; i.e., they had, in accordance with the model proposed (see Fig. 12), a component opposed to the terrestrial ARV vector. This pattern is important for an unambiguous determination of the polarity of the pole in

the APWP, especially for the Precambrian. If the centre of the continent is located near the equator, for example, the Upper Devonian Baltica or contemporary Africa, it does not rotate. In this case, the force exerted on the mantle by the continent is perpendicular to the terrestrial ARV vector. A continent rotates faster as its distance from the equator increases, which is corroborated by differential acceleration of Siberian and Baltica rotation in the Palaeozoic. Such differential continental rotations could be accompanied by a growing number of slip-strike crust deformations at the passive boundary surrounding continents. In this period the Earth's mantle rotation was slowed down much faster than earlier, there were great anomalies in the Earth's rotation period (T) and magnetic moment of the Earth (VDM); igneous and seismic processes were activated. On the contrary, as a rule, continent rotation slowed down as the equator was approached. In particular, available palaeomagnetic data (Irvig et al., 1976; McElhinny & Lock, 1996) corroborate the fact that when Africa was, after the disintegration of Gondwana and Pangea, in the Southern Hemisphere, it rotated counter-clockwise, relatively rapidly approaching the equator, as well as the Baltica, in the Early Palaeozoic; having reached the equator in the Cenozoic, it slowed down and stopped, similar to Upper Devonian Baltica. It is important that the epicentre of the present rotation of Eurasia seems to be located in the Eastern Himalayas, far from the geometrical centre of the continent. Eurasia does not possess and did not possess the main property of a rotating solid body during the Earth's geological history, and it is not a rigid plate, to a second approximation. Within the continent, the instantaneous ARV values change several times, increasing in absolute value from the periphery of the continent to the central domain of rotation. The continent has a complex structure with domains that have a differential rotational drift complicated by external factors.

In any case, for the largest continents, such as Eurasia, Africa and South America, Lehmann's seismic discontinuity is located at a depth of ca. 220 km. The nature of this interface can be explained by the transition from the anisotropic lithosphere to the essentially isotropic upper mantle. Therefore, seismically anisotropic mantle zones, located at higher levels, indicate that rock flow can occur in them (Gaherty & Jordan, 1995). Furthermore, the possibility cannot be ruled out that several, rather than one, subparallel zones of shearing with differentiated rotation are present at the base of the continental lithosphere. Deep seismic sounding (DSS) data also indicate that at a depth of 90-120 km in the sub-continental mantle a second global layer with elastic wave velocity inversion and high electrical conductivity (i.e. fluid-saturated) is present, and at similar depths substantial crustal-mantle heterogeneous masses are isostatically balanced. More recently, further evidence has been obtained concerning the presence of major electrical and seismic discontinuity around these depth ranges (Arora et al., 1995; Ramesh et al., 2005; Pavlenkova, 2006; Zemtsov, 2007). In Karsten Storetvedt's opinion, the only way into the future is through application of well-established facts, primarily based on rock evidence and other various surface data. But to go from there to aspects of real understanding, we need a functional thought construction – a Theory. And a theory is an invention made to explain the diversity of observations and phenomena – and their interrelationship. Therefore, a successful theory of the Earth will automatically establish an extensive phenomenological prediction confirmation sequence, spanning at least a major part of geological history. The ability of such a system must be its capacity to evolve in one direction only – from the characteristics of the Archaean to the features of the modern Earth for which uplift of



mountain ranges worldwide probably stands out as the most prominent event (Storetvedt, 2010).

But the evaluation of an average mantle deceleration energy over the entire Phanerozoic (Eq. 4) and annual energy variations (Table 1) show that even small fluctuations in the Earth's rotation velocity have tremendous energy, which exceeds the total energy of all tectono-magmatic processes and all earthquakes and annual fluctuations in mantle rotation energy are comparable in magnitude to oceanic circulation energy. Consequently, they can disturb this circulation, inevitably invoking global climatic changes. Part of this tremendous dissipation energy could have been a source of generation of the main geomagnetic field. The common characteristics of both the last anomalies in the Earth's rotation period and in the magnetic moment of the Earth in geological time seem to be more essential as they mark magmatic, geomagnetic and seismic activation cycles into the Earth and presumably result from the global restructuring of the geoid, because the degree of compression of the Earth depends on  $\omega^2$  of the mantle rotation and the evolution of the Moon orbit. As a result, huge lithospheric masses are transported to polar regions, the Earth's moment of inertia increases, the lithosphere is split up repeatedly and igneous and seismic processes are activated. In the meantime, the Earth's core is, of course, transformed as well, though with a minor lag. The Earth's magnetic moment first increases and then decreases rapidly. At least four magmatic activation cycles are known in the Proterozoic history of the Earth (Baluev & Moralev, 2001; Zemtsov, 2007), but the oldest T- and VDM-anomalies are impossible to trace as reliable data are meagre. Finally, it becomes apparent that no consensus will be obtained without further investigations to resolve these crucial issues.

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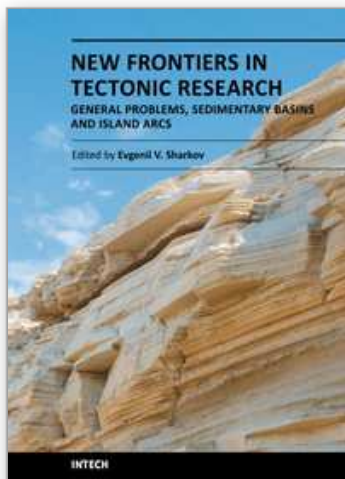
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