

Temporal variation of geodynamical properties due to tidal friction

P. Varga*

Geodetic and Geophysical Research Institute, Seismological Observatory, Mérédek 18, H-1112 Budapest, Hungary

Abstract

Fossils and tidal deposits as well as the possibility to compute values of the lunar tidal torque for different geological epochs allow us to model the variations in time of the Earth's figure, assuming that the latter remains, on a global scale, close to a hydrostatic equilibrium figure. On this basis, one can infer the variations of the Earth's most important geodynamic parameters over much of the geological past. Thus, the geometrical flattening has decreased from 5×10^{-3} to 3×10^{-3} , the normal gravity on annual average increase at the equator by ~ 2 nanogal. In present study, first the influence of the tidal friction on the length of day (LOD), geometrical flattening and the Earth–Moon distance during the history of the Earth will be discussed. The different despinning rates during the Phanerozoic (Pz: 0–0.56 Ga BP) and Proterozoic (Ptz: 0.56–2.5 Ga BP) will be also demonstrated. For understanding the development of the dynamics of the early Earth and the Earth–Moon system the length of day during Katarchean (3.00–4.55 Ga BP) shortly after the Earth formation was also estimated.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Geodynamics; Earth–Moon system; LOD; Geometrical flattening; Tidal friction

1. Introduction

On the basis of geochemical and geophysical investigations, it can be concluded that the formation of the Earth runs comparatively quickly. Our planet was separating out the continental crust during early Katarchean, 4.4 Ga BP (100 million years after the Earth formation) (Kerr, 2000). The formation of the life began early, perhaps 3.8 Ga BP ago (Marais, 2000). Eriksson and Simpson (2000) detected in the sedimentary rocks from South Africa tidal formations dating 3.2 billion years ago. Their analysis implies that tides were not unusually strong then and that the Archean (3.8–2.5 Ga BP) lunar orbit was similar to that seen today. Presumably the operation of plate tectonic was present 2.7 Ga BP (Kerr, 2000). In spite of these facts, it also can be concluded that our knowledge on the development of the Earth during its history is incomplete. The study of the Earth's despinning history can help, however, to understand processes governing formation of our planet.

Fossils and tidal deposits as well as the possibility to compute values of the lunar tidal torque for different geological epochs on the basis of paleocotidal maps serve as basis of our investigation. On this ground, Varga et al. (1998) inferred the variations of the rotation speed during the last 3 Ga BP and the most important geodynamical parameters were determined over much of the geological past.

To illustrate the relative importance of despinning of Earth rotation caused by the tidal friction the following rough estimates of the annual variations of the energetic household of the Earth can be given:

* Tel.: +36 1 2482 321.

E-mail address: varga@seismology.hu.

Solar energy (J/a)	$\sim 2.1 \times 10^{24}$
Atmospheric circulations (J/a)	$\sim 6.3 \times 10^{22}$
Loss by heat flow (J/a)	$\sim 1.0 \times 10^{21}$
Oceanic circulations (J/a)	$\sim 3.2 \times 10^{19}$
Rotational energy (J/a)	$\sim 1.6 \times 10^{19}$
Energy of earthquakes (J/a)	$\sim 9.5 \times 10^{18}$
Volcanic energy (J/a)	$\sim 2.0 \times 10^{18}$
Geomagnetic storms (J/a)	$\sim 3.2 \times 10^{13}$

2. Despinning of the Earth angular rotation and the Earth–Moon system through the geological history

The tidal despinning is mainly generated by a fictitious Moon, which revolves around the Earth on a circular orbit in a plane, which coincides with the terrestrial equator (it is the case of semidiurnal M_2 tidal wave). Using this assumption the angular speed (ω) and the despinning rate ($\frac{d\omega}{dt}$) is obtained for the geological history, then the flattening (f) and the Earth–Moon distance (c) can be calculated for different geological epochs with the use of relatively simple equations (see Denis, 1986; Zharkov et al., 1996)

$$\frac{df}{dt} = (1 + k_s) \frac{R^3}{GM_E} \omega \frac{d\omega}{dt} \quad (1)$$

$$\frac{dc}{dt} = \frac{2(M_E + M_M)}{M_E M_M} C(cn)^{-1} \frac{d\omega}{dt} \quad (2)$$

where M_E and M_M are the masses of the Earth and the Moon; n is the orbital speed of the Moon; k_s is the secular Love number; C is the polar moment of inertia; G is the gravitational constant; R is the mean radius of the Earth.

The tidal torque – which determines the despinning of the Earth – is composed of three components. The atmospheric tidal torque has an overall accelerating effect and amounts to $+0.4 \times 10^{16}$ J. The torque produced by the solid Earth tide depends on the phase difference between the observed and theoretical tides. Due to the fact that this phase difference is small ($\leq 0.05^\circ$) the corresponding tidal torque is $\geq -0.5 \times 10^{16}$ J. The oceanic tidal torque is the most significant component of the tidal torque and amounts to -5.1×10^{16} J. The oceanic tidal torque at present epoch is composed first of all of the semidiurnal tidal wave M_2 (83%). The input of M_2 strongly depends on the distribution of continents and oceans and probably it was different in the geological past. On the basis of analysis of paleo-cotidal maps it seems, however, that the role of M_2 wave was always determinant. The tidal torque of the oceans influences the rotation speed first of all through the tides of the shelf areas (Varga et al., 1998).

Length of day (LOD) values and f and c data derived from it are plotted in Figs. 1 and 2. The length of data is sparse and they were collected together from different sources in Varga et al. (1992, 1998). Information came from fossils, stromatolites and paleodeposits of the Phanerozoic and Proterozoic. Concerning the LOD curves of Figs. 1 and 2 two questions must be answered:

- What is the accuracy of paleontological and paleosedimentological data used for determination of temporal variation of length of day?
- Are the changes reflected by this curve significant in statistical sense?

An estimate of error in LOD can be obtained from a comparison of daily growth rings of recent corals and the astronomical datum. This way the relative error value of length of day data is around 2%. The error bounds of the absolute age determination based on radiometric dating usually are not indicated. When they are provided the typical errors are smaller than 10% and only rarely approach 20%.

To answer the second question on statistical significance of the non-linearities in the despinning a robust statistical modelling was carried out. The robust estimation is a convenient statistical parameter estimation technique when the distribution of errors cannot be a priori supposed as normal. Thus the robust estimation is a generalization of least-squares method. A common feature of most robust estimation techniques is to reduce the influence of outliers and to allow optimal solution in case of different error distributions. In case of paleontological and paleosedimentological data the Laplace-type robust estimations of degree $n \leq 3$ are suitable. The condition for modelling the paleorotation periods

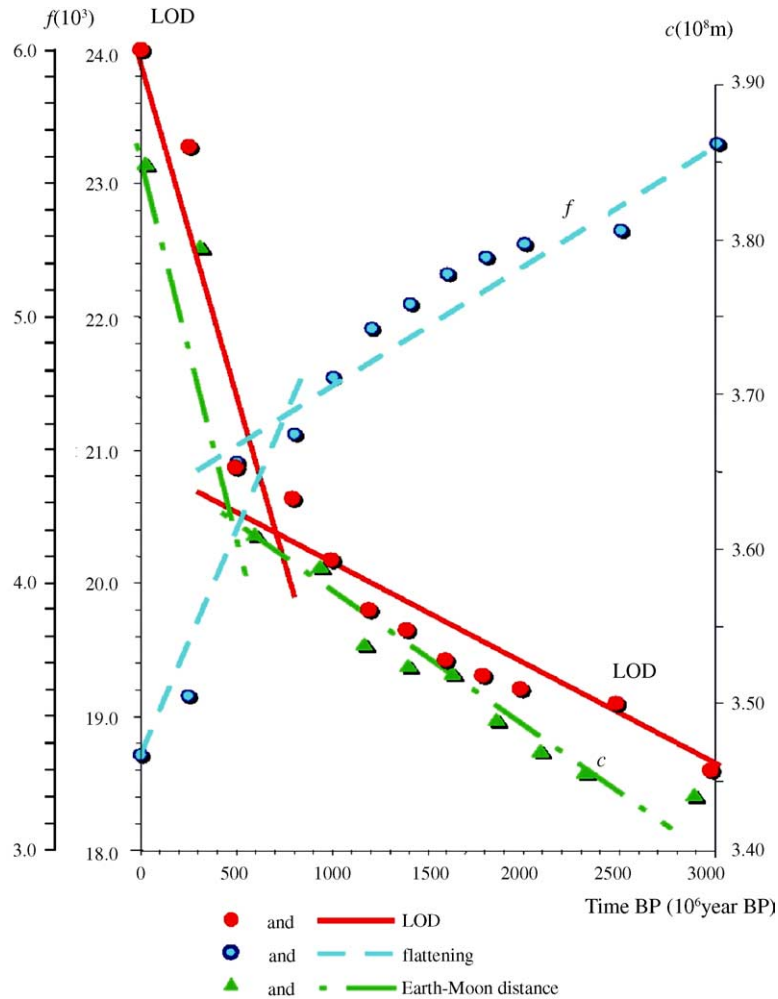


Fig. 1. Variations of LOD (in hours), flattening (f) and Earth–Moon distance (c) during the Phanerozoic and Proterozoic.

was that the deviation from the statistical model should be less than ± 0.5 h. In case of first order ($n = 1$) modelling the length of day variations for the Phanerozoic (Pz) (0–0.56 Ga BP) and Proterozoic (Ptz) and most of the Archean (Arch) (0.56–2.50 Ga BP) give significantly different linear trends (Varga et al., 1992):

$$\begin{aligned} \text{LOD}_{\text{Pz}} &= 24.00 - 4.98t \\ \text{LOD}_{\text{Ptz}} &= 21.44 - 0.97t \end{aligned} \tag{3}$$

where t is the time before present expressed in Ga=eon.

During the Pz the increase of LOD amounted on the average to 1.79 ms/century (4.98 h/eon) and the Ptz can be characterised by 0.35 ms/century (0.97 h/eon).

There are two possible explanations for the approximately five times smaller despinning rate during the time-interval 0.56–2.50 Ga BP than during Pz. Either the tidal retarding torque acting during the Proterozoic and most of the Archean was on the average much smaller than the present day value, or the tidal torque was about the same all the time, but there existed a compensating effect of tidal friction brought about the core and/or continuous mantle differentiation (Denis et al., 2002).

- (1) An important consequence of the data calculated with the use of Eqs. (1) and (2) as plotted in Fig. 1 is that the Moon was only about 4% closer 3×10^9 years ago than today and its orbital radius remaining within about 90% of the present value (4.0–4.5) Ga BP. This means: the development of the Earth–Moon system was probably slow

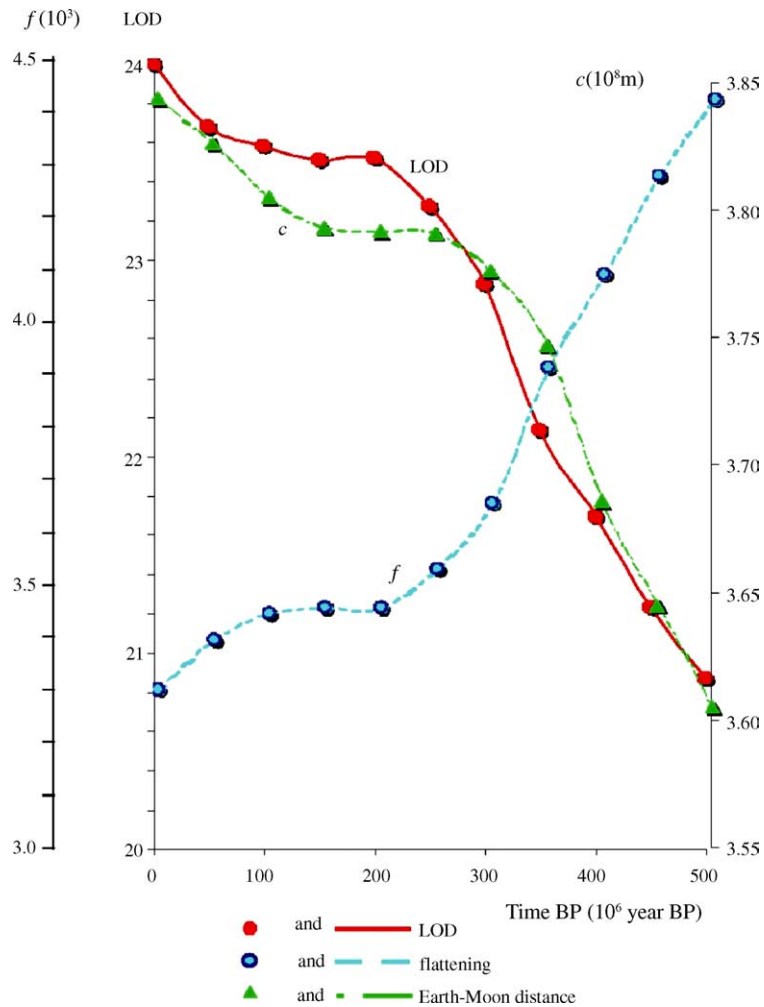


Fig. 2. Variations of LOD (in hours), flattening (f) and Earth–Moon distance (c) during the Phanerozoic.

and gradual during almost the whole history of the Earth, namely after the Katarchean (3–4.55 Ga BP) except the time-interval very close to formation of the Moon.

- (2) The statistically significant low during the Mesozoic (0.35 and 0.15 Ga BP) shown in Fig. 2 coincides with the time of Pangea super continent, i.e. when the area of continental shelf was significantly reduced. It was shown by paleotidal torque estimations that around the same time-interval the value of the oceanic tidal torque had its relative minimum too (Zharkov et al., 1996). The anomaly in the despinning during the Mesozoic is correlated with the low of the magnetic field (Denis et al., 2002). This coincidence suggests that the anomaly of the rotation speed in the middle of the Phanerozoic to some extent is related to the processes of the Earth interior (to the phenomena which have their origin in the core).

3. Time variation of geodynamical processes

With the use of Eqs. (1) and (2) one can calculate the variation of the Earth’s geodynamic parameters over a large part of the life span of our planet assuming that for the considered time scales, the Earth evolving shape can be described as a succession of hydrostatic equilibrium figures. It is also necessary to suppose that the core formation was essentially completed $(2.5\text{--}3.0) \times 10^9$ years ago, the gravitational constant (G), the mass (M_E) and the mean radius of the Earth (R) did not change appreciably.

It can be concluded that the geometrical flattening (f) of the Earth has decreased by about 70% during the last $(2.5\text{--}3.0) \times 10^9$ years. This modification of f was more or less stable during the Pz and it led to elastic stress accumulation in the outer most part of the Earth (depth interval 0–100 km). This process is continuing recently (Varga et al., 1998). Using the LOD valid for different epochs of the geological past it can be concluded that $(2.5\text{--}3.0)$ Ga BP the reduction of the gravity at the poles was ~ 90 mgal, and the increase at the equator amounts to about 340 mgal. From this consideration follows: the equatorial average increase rate is about 2 nanogal/year.

4. Estimation of the length of day and the Earth–Moon distance near to the time of formation of the Moon

With the use of the second equation of (3) at the time of Earth formation (4.5 Ga BP) the result will be 17.5 h. This value should be an extreme short one and serves as a lower bound because the despinning of the Earth's axial rotation is due to oceanic tides first of all and the solid Earth tides has only a reduced despinning effect. It can be supposed, however, that the first oceans were formed significantly later than 4.5 Ga BP. Another estimation became possible if the database described in Varga et al. (1998) for the time interval from the present epoch till 3.0 Ga BP is used in a robust estimation process. The database can be modelled in this case by an exponential expression, which gives

$$\text{LOD} = 4.68 e^{-0.00166t} + 19.65$$

using a robust estimation procedure.

With the use of this model the length of day between 3.0 and 4.5 Ga BP is practically constant and amounts to 19.6 h. This value can serve as an upper bound for the LOD 4.5 Ga BP, because in this case it is supposed that there was no tidal friction at all during the first 1.5 Ga of Earth history. From the already mentioned paper by Eriksson and Simpson (2000), it can be concluded that the length of day 3.2 Ga BP was closer to 15 h than to 24 h, which means: LOD at that time was less than 19.5 h.

To estimate the original LOD value (T_0) the equation for the characteristic time of the lunisolar despinning τ_{TID} can also be of use (Hubbard, 1984):

$$\tau_{\text{TID}} = \frac{2\pi M_E c^6}{3k_s T_0 G M_M^2 R^3 \delta} \quad (4)$$

Here, δ is the tidal delay of the lunisolar bulge, which was 6.8° for Pz and 1.5° for the Ptz (Varga et al., 1998). For the earlier parts of the Earth history, we can suppose $\delta \leq 0.5^\circ$ because during the early history (before 3 Ga BP) of our planet its surface not consists of worldwide oceans in the present day sense. For the use of Eq. (4) to estimate T_0 , i.e. LOD around 4.5 Ga BP the value of c is needed in the remote past. Using the data obtained from Eq. (2) one gets:

$$\begin{aligned} c &= 3.3844 \times 10^8 \text{ m, for present epoch;} \\ c &= 3.4500 \times 10^8 \text{ m, for 3.0 Ga BP;} \\ c &= 3.2000 \times 10^8 \text{ m, for 4.5 Ga BP.} \end{aligned}$$

For the characteristic time of tides τ_{TID} – to a certain extent arbitrary – we suppose three values: 10 Ga; 7.5 Ga; 5×10^9 Ga. In case of the real Earth $\tau_{\text{TID}} > 5$ Ga and with high probability $\tau_{\text{TID}} > 7.5$ Ga. This assumption is based on the fact that at present epoch T_0 is significantly shorter than the lunar month and using for extrapolation the despinning rate $d\omega/dt$ valid for Pz it can be assumed that this situation remains for the next 2.5 Ga too.

In Table 1, LOD values are estimated for 4.5 Ga BP in the case of different phase delays (δ), for the Earth–Moon distances (c) of present epoch (3.844×10^8 m), of 3 and 4.5 Ga BP (3.450×10^8 and 3.200×10^8 m, respectively), furthermore for the three characteristic time values of the lunisolar damping τ_{TID} mentioned above.

In Table 1, values listed in rows for $c = 3.844 \times 10^8$ (present epoch) are unrealistic in case of LOD for 4.5×10^9 BP. The results in the last column can also be excluded because $\tau_{\text{TID}} > 5 \times 10^9$ year. According to result of Eriksson and Simpson (2000), LOD 3.2 Ga BP was already shorter than 19.5 h. It was mentioned above that in case of the linear extrapolation of the paleorotational data we got the lowest bound for LOD at 4.5 Ga BP (16.5 h). So only one possible solution remains for T_0 : it should be between 15.15 and 20.22 h 4.5 Ga BP ($\delta = 0.5^\circ$, $c = 3.2 \times 10^8$ m and $\tau_{\text{TID}} = (10\text{--}7.5) \times 10^9$ years). This result coincides in an acceptable degree with the upper and lower bound values obtained earlier.

Table 1
LOD values in case of different phase delays (δ), Earth–Moon distances (c) and characteristic times of lunisolar despinning (τ_{TID})

c (m)	$\tau_{\text{TID}} = 10^{10}$ (year)	7.5×10^9 (year)	5×10^9 (year)
$\delta = 2^\circ$			
3.844×10^8	11.39	15.19	22.78
3.450×10^8	5.95	7.94	11.91
3.200×10^8	3.79	5.05	7.58
$\delta = 1.5^\circ$			
3.844×10^8	15.19	20.25	30.38
3.450×10^8	7.94	10.59	15.88
3.200×10^8	5.05	6.74	10.11
$\delta = 1.0^\circ$			
3.844×10^8	22.78	30.37	45.46
3.450×10^8	11.91	15.88	23.82
3.200×10^8	7.58	10.11	15.16
$\delta = 0.5^\circ$			
3.844×10^8	45.57	60.75	91.12
3.450×10^8	23.82	31.75	47.65
3.200×10^8	15.15	20.22	30.30

In past the Earth spun faster and the Moon was closer to the Earth. The Earth spin state at very early times is uncertain. When the Moon was much closer to the Earth the tidal interactions were complex (see, e.g. [Lissauer et al., 2000](#)). Estimation of the time-interval during which this violent dynamical development took place is an important task. The giant impact theory is the leading hypothesis for the origin of the Moon. This event occurred near to the end of terrestrial accretion, when more than 95% of the Earth mass was accreted. The single impact theory was proposed in 1975 and the numerical solutions of collision of a 1/10 Earth mass planetesimal with the Earth were carried out at the end of eighties ([Canup, 2004](#)). [Kokubo et al. \(2000\)](#) show that the formation timescale of the Moon is of the order of 1 month and it took place at a distance 1.3 Roche limit ($\sim 2.5 \times 10^3$ km). The numerical simulations carried out describe many details of the Moon formation. It is generally accepted that the present high angular momentum of the Earth–Moon system can be explained by the collision with a Moon-sized projectile with the Earth. There is no doubt that on average more than 80% of the Moon's composition comes from impactor's mantle. Moon is made predominantly from outer regions of the impactor, which not collide directly with Earth. According to [Palme \(2004\)](#) "... after the initial impact they expand to distances of several Earth radii where they are placed into stable Earth orbits by gravitational torque". The impact event could not have remelted the Earth substantially, generating a magma ocean, but imprints of such geochemical fractionation of elements into solid or liquid phases have not been observed ([Sankaran, 2002](#)).

The question how long lasts this dynamical stage of the development of the Earth, Moon and the Earth–Moon system is still open. The formation of the Moon according to [Kokubo et al. \(2000\)](#) and [Palme \(2004\)](#) took place at the distance from the Earth, which is significantly smaller than the present Earth–Moon distance, which was more or less the same during the predominant part of the Earth lifetime. It follows from results described in present study that 3–3.5 Ga BP the Moon was only about 4% closer than today and it can be also supposed that its orbital radius remains within about 90% of the present value (4.0–4.5) Ga BP.

5. Conclusions

At present, we can accept that the values between 19.5 and 17.5 h are giving realistic estimation for the rotation period in time just after of Earth formation. This means that during the whole history of the Earth the LOD has changed only $\sim 30\%$. The corresponding change in the rotational energy $E = \frac{C\omega^2}{2}$ is more than 50%. Most of this rotational energy loss ($\sim 1.7 \times 10^{29}$ J) is connected with Pz, i.e. with 13% of the total lifetime of our planet. What was the impact of this energy loss into the development of the Earth and of the Earth–Moon system? This question should be answered by future investigations.

The set of data used in present study contains information derived from paleontological and paleosedimentological data about long-term variations of the spin of the Earth. From this data, we infer that Earth's rotational history has been essentially not linear. The Earth–Moon distance has increased slowly in Ptz relative to its present day value. It was mentioned in Section 2 that an important consequence of data plotted in Fig. 1 is that the Moon was only about 4% closer 3 Ga BP than today and its orbital radius remaining within $\sim 90\%$ of present value (4.0–4.5) Ga BP. It is shown by model calculations based on the giant impact theory that the formation of the Moon was a fast process at distances probably significantly smaller than the present value (Kokubo et al., 2000; Palme, 2004). Our results suggest that the dynamical part of the development of the Earth–Moon system should be complete soon after the formation of the Moon, and since 4.0 Ga BP the evolution of the system is slow.

For interpretation of the Earth rotation history, it is important to consider the characteristic time (τ_{TID}). The straightforward use of Eq. (4) given by Hubbard (1984) in case of $\delta = 0.5^\circ$, we got $\tau_{\text{TID}} = (10-7.5) \times 10^9$ years. If instead of the secular love number k_s , the elastic love number k is used as in Hubbard (1984) we get for the characteristic time $(3.0-2.5) \times 10^9$ years, which is evidently too small for the Earth. If the same calculation is carried out for the Moon, we obtain for the τ_{TID} 10 and 3 million years in case of k_s and k , respectively. This means that the tidal evolution of the Moon was complete very soon after the formation of the Earth–Moon system.

Acknowledgements

Author thanks the two anonymous reviewers for valuable comments on the manuscript. This work received financial support from the Hungarian Science Found OTKA (Project No.: T038123). Author acknowledges with thanks stipend obtained in the frame of the bilateral project of the Deutsche Forschungsgemeinschaft and of the Hungarian Academy of Sciences (436 UNG 113/133/0-2).

References

- Canup, R.M., 2004. Simulation of late lunar-forming impact. *Icarus* 164 (2), 433–4456.
- Denis, C., 1986. On the changes of kinetical parameters of the earth during geological times. *Geophys. J. R. Soc.* 87, 559–568.
- Denis, C., Schreider, A.A., Varga, P., Závoti, J., 2002. Despinning of the Earth rotation in the geological past and geomagnetic paleointensities. *J. Geodyn.* 34, 667–685.
- Eriksson, K.E., Simpson, E.L., 2000. Quantifying the oldest tidal record: 3.2 Ga Moodies Group, Barberton Greenstone Belt, South Africa. *Geology* 28 (9), 831–834.
- Hubbard, W.B., 1984. *Planetary Interiors*. Van Nostrand Reinhold Company.
- Kerr, R.A., 2000. Geologists pursue solar system's oldest relics. *Science* 290, 2239–2242.
- Kokubo, E., Ida, S., Makino, J., 2000. Evolution of a circumterrestrial disk and formation of a single Moon. *Icarus* 148, 419–436.
- Lissauer, J.J., Dones, L., Ohtsuki, K., 2000. Origin and evolution of terrestrial planet rotation. In: Canup, R.M., Righter, K. (Eds.), *Origin of the Earth and the Moon*. University of Arizona, Tucson, pp. 101–112.
- Marais, D.J.D., 2000. When did photosynthesis emerge on the Earth? *Science* 289, 1703–1705.
- Palme, H., 2004. The giant impact formation of the Moon. *Science* 304, 977–979.
- Sankaran, A.V., 2002. Impact origin of the Moon—the probable scenario. *Curr. Sci.* 82 (4), 389–391.
- Varga, P., Denis, C., Varga, T., Závoti, J., 1992. Statistical modelling of the tidal history of the Earth–Moon system. *J. Luxemburgeosies Geodyn.* 73, 1–7.
- Varga, P., Denis, C., Varga, T., 1998. Tidal friction and its consequences in paleogeodesy, in the gravity field variations and in tectonics. *J. Geodyn.* 25, 61–84.
- Zharkov, V.N., Molodensky, S.M., Brzezinski, A., Groten, E., Varga, P., 1996. *The Earth and its Rotation*. Low Frequency Geodynamics. Wichmann Verlag, Heidelberg.