

Modelling moving force of tectonic plates with the use of length of day variation

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Length of day variations in Phanerozoic and during earlier eons

The despinning caused by the tidal friction results in an extension of the length of the day (LOD). The LOD database for Proterozoic (Ptz, 2500 Ma BP-540 Ma BP) and Phanerozoic (Pz, 540 Ma BP-Present) (Varga, Fodor, 2021) gives for the slope a ($LOD = a \cdot t + b$)

$$- (0.00503 \pm 0.00072) \text{ h/Ma for Ptz} \quad (1)$$

$$- (0.00059 \pm 0.00060) \text{ h/Ma for Pz.} \quad (2)$$

The significance of the trend estimate of LOD assuming normally distributed data has been verified using F statistical hypothesis test using using a confidence level of $\alpha = 5\%$ and it was found that the slope is statistically significant in both cases.

With the use of results of statistical analysis of LOD data, it has been found that during the Pz the LOD increased on average at a rate of 5.0 h/Ga (1.80 ms/century) (Eq. 1 and Figure 1) while during the Ptz, the average rate was only 0.5h/Ga (0.18 ms/century) (Eq. 2 and Figure 2), i.e. 10 times smaller (Varga et al., 1998, Varga 2006, Zhenyu et al., 2007, Zhang 2012).

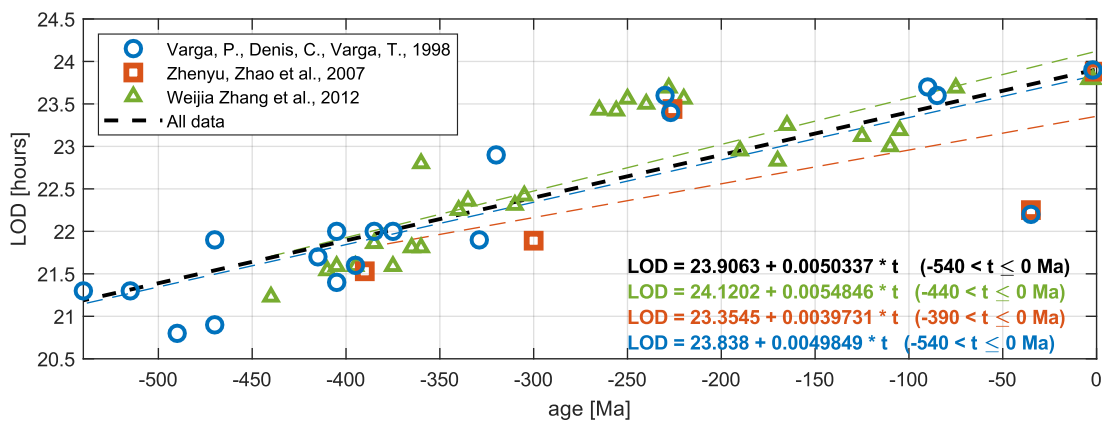


Figure 1. Length of day during Phanerozoic (Varga & Fodor, 2021)

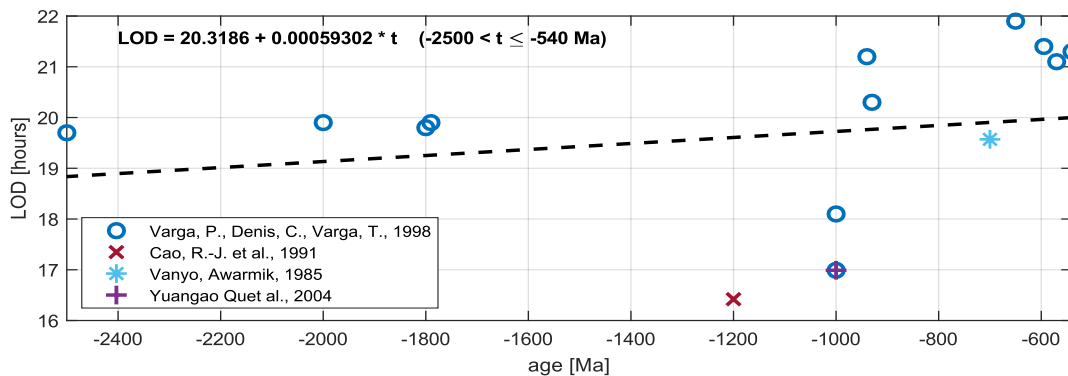


Figure 2. Length of day during Proterozoic (Varga & Fodor, 2021)

The effectiveness of tidal friction in regulation of LOD can be investigated with the use of total tidal energy E , determined as a sum of three energies (energy of axial rotation of the Earth, Moon's orbital energy around the common centre of mass and the mutual potential energy):

$$E = \frac{1}{2} C \omega^2 + \frac{1}{2} a_m^2 n_m^2 \cdot \left(\frac{M \cdot M_m}{M + M_m} \right) - G \frac{M \cdot M_m}{a_m} \quad (3)$$

Here C , ω and M are the polar moment of inertia, the angular speed and the mass of the Earth, a_m , n_m and M_m are the Earth-Moon distance, the Moon's orbital speed and the mass of the Moon respectively. G is the gravitational constant. Using Kepler's third law

$$n_m^2 a_m^3 = G(M + M_m) \quad (4)$$

we get for the tidal energy

$$E = \frac{1}{2} (C \omega^2 - \frac{M \cdot M_m}{a_m}) \quad (5)$$

The basic equation for tidal dissipation can be obtained as a time derivative of this equation:

$$\dot{E} = C \omega \dot{\omega} + \frac{1}{2} G \frac{M M_m}{a_m^2} \dot{a}_m \quad (6)$$

The time derivative of Kepler's law

$$\dot{a}_m = -\frac{2}{3} \frac{a_m}{n_m} \dot{n}_m \quad (7)$$

The principle of conservation of momentum of the Earth-Moon system is

$$C \omega + \frac{M M_m}{M + M_m} a_m^2 = \text{const.} \quad (8)$$

With a simple combination of the two last equations one gets

$$\dot{\omega} = \frac{1}{3} \frac{M_m}{M + M_m} \frac{M a_m^2}{C} \dot{n}_m \quad (9)$$

Using $\dot{a}_m$ and $\dot{\omega}$ together with Kepler's law this leads to $\dot{E} = C(\omega - n_m) \dot{\omega}$.

Because $\omega = 7.2685 \cdot 10^{-5} \text{ s}^{-1} > n_m = 2.425 \cdot 10^{-6} \text{ s}^{-1}$ it can be assumed that

$$\dot{E} \approx C \omega \dot{\omega} \approx C \omega^2 \frac{\Delta \text{LOD}}{\text{LOD}} \quad (10)$$

Using this equation it can be concluded that the energy dissipation $\dot{E}$ during the Pz was $3.2 \cdot 10^{12} \text{ W}$, while prior to Pz it amounted to $0.7 \cdot 10^{12} \text{ W}$ (Varga et al., 1998).

The kinetic energy of rotation is

$$E_K = \frac{C \cdot \omega^2}{2} = C \cdot \frac{2\pi^2}{\text{LOD}^2} = \frac{C \cdot r \cdot v(r)_T^2}{2} \quad (11)$$

(r is the distance from the centre of the Earth and $v(r)_T$ is the tangential velocity).

With the use of equation (11) and data in Table 1 it can be concluded that during the last 3 Ga the Earth-Moon distance increased by about 12%, the day became six hours longer. Earth lost 33% of its rotational energy and the rotational energy loss rate was 4.1 times higher during the Pz than earlier in the Arch and Ptz, what means that near the boundary of Ptz and Pz there took place a significant alteration in the despinning of the Earth's axial rotation.

Age	C in $10^{37} \text{ kg} \cdot \text{m}^2$	a_m in 10^8 m	ω in 10^{-5} s^{-1}	LOD in hours	E in 10^{29} Joule
Present epoch	8.038	3.84402	7.292	24	1.757
600 Ma	7.111	3.6	8.242	21.2	2.008
3000 Ma	6.106	3.4	9.599	18.2	2.382

Table 1. Polar moment of inertia (C), Earth-Moon distance (a_m), angular speed (ω), length of day (LOD) and total tidal energy for the last 3 Ga.

Effect of tidal friction on the motion of tectonic plates

The low-velocity zone (LVZ) at 100-200 km depth interval, close to the boundary between the lithosphere and the asthenosphere characterized by a negative anomaly of shear wave velocities. Consequently the LVZ can result in a decoupling effect (see e.g. Scheidegger, 1960; Doglioni et al., 2011). The motion of the oceanic plate is compared to a stationary one, which is the top of the Earth's mantle at the bottom of LVZ. The two plates are separated by a viscous layer of asthenosphere (thickness h). The force required to move the plate (F_{plate}) over the stationary one at constant speed against the resistance of the viscous fluid is proportional to the area A of the plate and to the velocity gradient $\frac{dv}{dr}$. The constant of proportionality η is called the viscosity expressed in $N \cdot s \cdot m^{-2} = Pa \cdot s$.

$$F_{plate} = \eta \cdot A \cdot \frac{dv}{dr} \approx \eta \cdot A \quad (12)$$

The uncertainty in the determination of the force in (12) is due to the currently inaccurate knowledge of the viscosity value η .

According to Zaccagnino et al. (2020) the probable value of viscosity in the LVZ is between 10^{13} and $10^{15} \text{ Pa} \cdot \text{s}$. Using equation (12), we assume that $\eta = 10^{14} \text{ Pa} \cdot \text{s}$ the area of A is $\approx 5 \cdot 10^7$ square kilometres (which corresponds to the area of a significant oceanic tectonic plate) and $h = 100 \text{ km}$. For calculation of F_{plate} the tangential speed difference at the surface of the Earth and at the depth 200 km is needed: $v = 15 \text{ m} \cdot \text{s}^{-1}$. If for the speed of the oceanic tectonic plates 1 cm/yr is assumed the energy required to move the plate with aforementioned area is $8 \cdot 10^{18} \text{ Joule}$.

At the same time, the annual rotational energy change over the last 600 Ma period (see Table 2) annually is $\Delta E = (2.008 - 1.757) \cdot 10^{29} \text{ Joule} / 6 \cdot 10^8 \text{ year} = 4.188 \cdot 10^{19} \text{ Joule}$. This annual energy is on the order of magnitude of that required to move the plate along the surface of the Earth.

For the pre-Phanerozoic case is $\Delta E = (2.382 - 2.008) \cdot 10^{29} \text{ Joule} / 2.4 \cdot 10^9 \text{ year} = 1.658 \cdot 10^{19} \text{ Joule}$ was obtained, which is 2.5 times less than the value for the Phanerozoic, but it is still large enough to move continents.

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