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Interrelationships between Length of the Day, Moon Distance, Phanerozoic Geodynamic Cycles, Tidal Dissipation and Earth's Core: Review and Analysis

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Abstract

The rotation of the Earth and the related length of the day (LOD) are predominantly affected by tidal dissipation through the Moon and the growth of the Earth's core. Due to the increased concentration of mass around the rotation axis of the spinning Earth during the growth of the core the rotation should have been accelerated. Controversially the tidal dissipation by the Moon, which is mainly dependent on the availability of open shallow seas and the kind of Moon escape from a nearby position, acts towards a deceleration of the rotating Earth. Measurements of LOD for Phanerozoic and Precambrian times open ways to solve questions concerning the geodynamical history of the Earth. These measurements encompass investigations of growth patterns in fossils and depositional patterns in sediments (Cyclostratigraphy, Tidalites, Stromatolites, Rhythmites). These patterns contain information on the LOD and on the changing distance between Earth and Moon and can be used as well for a discussion about the growth of the Earth's core. By updating an older paper with its simple approach as well as incorporating newly published results provided by the geoscientific community, a moderate to fast growth of the core in a hot early Earth will be favored controversially to the assumption of a delayed development of the core in an originally cold Earth. Core development with acceleration of Earth's rotation and the contemporaneous slowing down due to tidal dissipation during the filling of the ocean may significantly interrelate.

Keywords

Length of the Day, Moon Distance, Phanerozoic Geodynamic Cycles, Tidal Dissipation, Earth's Core

1. Introduction

The present status of the Earth and the predictable future is only understandable with understanding the past beginning with the planet's origin and all its physical circumstances. This includes transferring into the knowledge base all present day astronomical observations of galaxies (esp. Milky Way), stars, planets and moons as well as geological, geophysical and biological studies of star dust, meteorites, asteroids and investigations on the evolution of life. In this sense the chemical composition of the Earth, the size of the planet, the evolution of the oceans and the origin of the Earth's moon are important issues to be elucidated. The preliminary end of the timeline is today's situation of the Earth's interior with its chemical separation and segregated layers, its thermal status and deep rooted plate tectonics with seafloor spreading and continental growth and drift. The time span between the origin of our rocky planet and its today's life supporting surface has to be analyzed by starting at its ends, back in time from the surface (Phanerozoic eon) and forward from the center (Hadean eon), and filled with reliable assumptions (Archean and Proterozoic eons) constraint by physical laws and the need for a final fit between the forward and backward models. This has been done for decades by a countless number of scientists with an outcome of important geoscientific, chemical, astronomical and mathematical works. Within this framework the study of the thermal history of the Earth, the evolution of the core and its growth, the development of the magnetic field, the effect of the Moon and its escape from the Earth, the rotation of the Earth and the length of the day, the filling of the ocean with water as well as (Milky Way galaxy related?) Phanerozoic geodynamic cycles and tidal dissipation become essential. More or less all of them are strongly interrelated (e.g. see references [1]-[11] and [37]-[51] and references therein).

2. Hadean Eon and Accretion of the Earth

The Solar System developed as a circumstellar disk with the proto-Sun at its center via a gravitational collapse of a molecular nebula cloud that contained an ensemble of all available chemical elements. These have been produced in preceding star explosions (planetary nebulae and supernovae) since the birth of the Milky Way some billion years ago. Dust particles accreted within the disk and finally formed occasionally the planets. This took place through collisions between initially micrometer-sized dust grains that might have guided to the growth of millimeter-to-decimeter-sized pebbles. These pebbles accreted into ~100-km-sized planetesimals in course of the time. Planetesimals further accreted into ~1000-km-sized planetary embryos, some with segregated cores. As the nebula vanished when the gas was dissipated by stellar winds and irradiation by the Sun and nearby stars, gravitational interactions between planetary embryos triggered their orbits to cross, leading to crashes of the involved protoplanets. During that phase Earth collided assumingly with a Mars-sized protoplanet called Theia at ~70 - 120 Myr. The resulting Giant Impact ejecta accreted as the

Moon (**Figure 1**). A small portion (<0.5%) of Earth's mass may have been provided in a possible so called late veneer by a bombardment of much smaller impactors. Due to the absence of early terrestrial geology from the first 500 Myr of the Solar System, only reliable theoretical assumptions may answer some open questions. Some answers were found through the results of Apollo 11 to 17 missions (1969-1972). According to dynamical simulations terrestrial planet formation lasted tens of millions of years. The surprising diversity of recently observed exoplanetary systems suggests that our Solar System structure is extraordinary and probably reflects very specific conditions. According to the evaluation of the ages of magmatic iron meteorites melting and core formation occurred in early protoplanetary objects ≤ 100 km in size by heating from decay of radioactive isotopes ^{26}Al (T½ = 0.72 Myr) and ^{60}Fe (T½ = 2.6 Myr). With advancing accretion the collisional heating became dominant, leading to melting and fluid core formation in larger, later-formed planetary bodies [1].

3. Evolution of the Earth's Core

In course of the time the evolution of the Earth's core delivered an important contribution to the thermal history of the Earth and became the source of the magnetic field that protected the evolution of life on Earth as we know it today. The growth of the core is a current topic of scientific debate whether it took place in a short or long timespan and at which time exactly during the history of

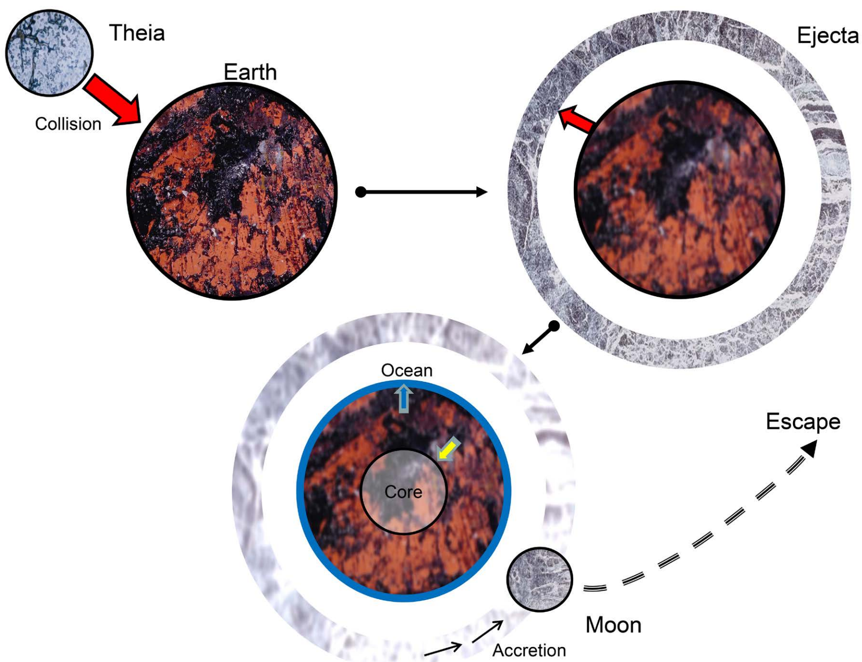

Figure 1. This sketch shows important steps during the very early days of the Earth history about 4.45 Ga ago. The events include the collision of the proto Earth with a Mars like planet called Theia, the development of a belt of ejecta just outside the Roche limit, the following accretion of the ejecta to the Moon and its recession from the Earth and the downwards and upwards segregations to core and ocean. For timing see text. The Hadean eon is estimated to last roughly until 3.8 (classical)/4.0 (newly defined) Ga ago.

the Earth. This event has certainly affected the rotation history of the planet due to the mass increase closer to the rotation axis. Therefore gathering of data that contain some information about the spin rate history of the Earth becomes important. Fossils with growth rings as well as sedimentation patterns (Cyclostratigraphy, Tidalites, Stromatolites, and Rhythmites) have been identified as adequate data sources.

The present internal configuration of the Earth demonstrates that it is a really differentiated body, and the ages of surface rocks indicate that a differentiation took place early in the history of the Earth. The gravitational energy associated with the formation of the Earth, the thermal energy of core formation and heat generation of short to long live radioactive isotopes are the primary sources of energy for the melting and subsequent gravitational separation of the Earth into a core, a chemically inhomogeneous mantle, a crust, and an atmosphere and hydrosphere. The Earth probably accreted in 10^5 years or less. This causes the initial temperatures to be high and results in a fluid core formation to be essentially simultaneous with accretion [2].

Earth models in which the core has been growing slowly since 4.5 Ga ago or 3 Ga ago fail to meet the requirement of a solid mantle. In these models the calculated present surface heat flows are much larger than the observed heat flow. Earth models in which the core was substantially complete at 4.5 Ga ago or 3 Ga ago within a short period less than 100 Ma lead to the observed heat flow [3].

The estimated present growth rate of the Earth's core does not affect significantly the observed deceleration of the Earth's spin caused by tidal braking. However, in the remote geological past, before the Phanerozoic, the effects of core growth may have been much more important, because the total change of length of the day (LOD) associated with core formation has been estimated by [4] already in 1965 to be 2.4 h for an initially undifferentiated cold Earth, and 3.1 h for an initially undifferentiated hot Earth. Scenarios, corresponding to very early and/or very fast core formation and others corresponding to slow and/or late core formation seem to favor slow core formation during the Proterozoic, contrarily to the now largely prevailing hypothesis based on geochemical arguments that the iron core formed very early in the Earth's history and during a geologically short time interval [5] (**Figure 2**).

The fluid core cooled down with time and a solid inner core has been developed by a "freezing" process.

The Earth's magnetic field is generated by convections inside the liquid iron alloy in the outer core. These convections occur because the core is losing heat to the overlying solid mantle. Once the inner core started to freeze, convection inside the fluid core received a strong enhancement in power because light, non-metallic elements remained molten in the outer core and were buoyant relative to the overlying liquid. The process continues today and is thought to be the main source of "fuel" for generating the Earth's magnetic field today [6].

Most estimates for the age of an inner core nucleation (ICN) are during the Proterozoic based on analyses of the palaeointensity variation of the Earth's

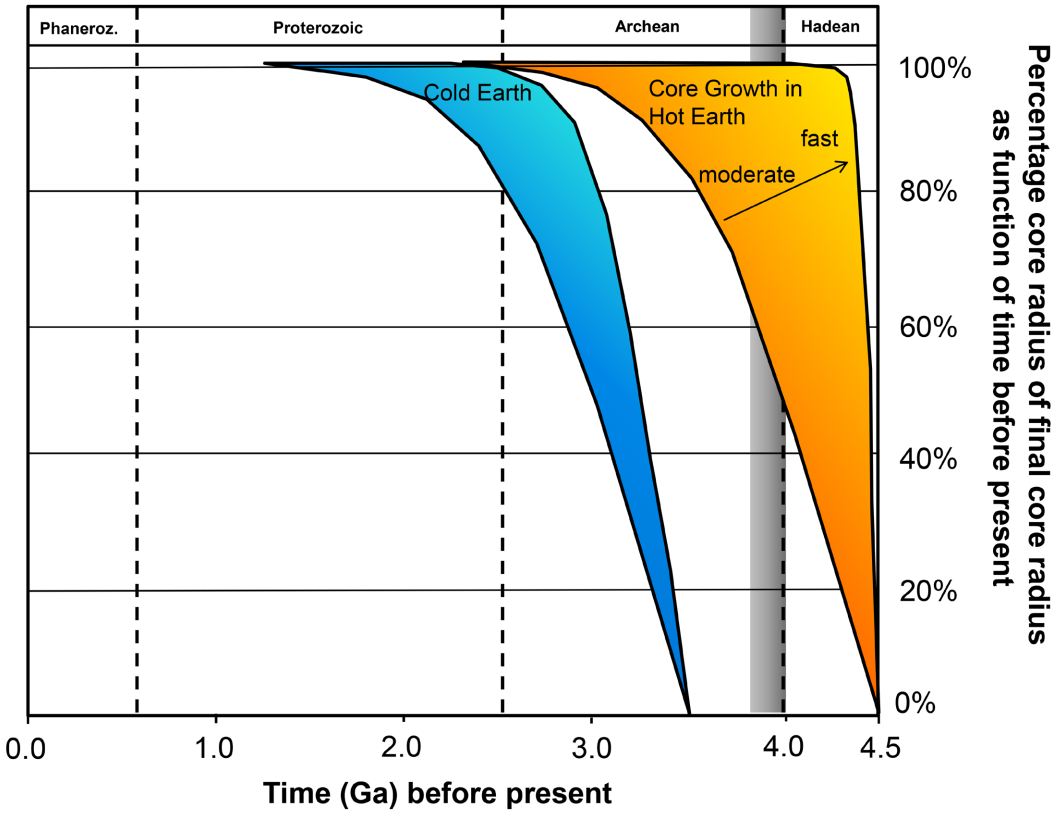

Figure 2. Percentage core radius of the present core radius as function of time. The yellow area represents curves for the core growth of a primary hot Earth with moderate to fast grow rates, the blue area for a cold Earth with a delayed heating of 1 Ga [5]. The Hadean eon is estimated to last roughly until 3.8 (classical)/4.0 (newly defined) Ga ago (greyish zone) as already mentioned above. In case of a fast growth the radius of the Earth's core would have roughly reached its final value already during the Hadean.

magnetic field. The density difference between the inner core and the outer core is small, and the influence of ICN on the rotation of the Earth is estimated to be insignificant. Therefore further segregation of Earth's outer core may still remain a reliable process for the time being, should a late acceleration of the Earth's rotation being real at all as postulated by [7].

According to the work of [7] Earth's core has probably undergone a late rapid growth between 1.9 and 1.4 Ga inferred from an acceleration of the Earth's rotation as derived from paleogeological data. The radius increment is estimated to be up to 1.0×10^6 m for an original core size with a 2500 km radius growing to one with 3500 km.

However, this model of a 1000 km increase of the core's radius during 1.9 - 1.4 Ga contradicts mentioned constraints, and the distribution of Proterozoic and Archean data points should be interpreted differently.

Nevertheless, the Earth's inner core grows by the freezing of liquid iron at its surface. The point in history at which this process initiated marks a step-change in the thermal evolution of the planet. Recent computational and experimental studies have presented radically differing estimates of the thermal conductivity of the Earth's core, resulting in estimates of the timing of inner-core nucleation ranging from less than half a billion to nearly two billion years ago, which includes the a.m. timespan of 1.9 - 1.4 Ga. Recent inner-core nucleation (high thermal conductivity) requires high outer-core temperatures in the early Earth that complicate models of thermal evolution. The nucleation of the core leads to a different convective regime and potentially different magnetic field structures that produce an observable signal in the palaeomagnetic record and allow the date of inner-core nucleation to be estimated directly. According to the examination of results from an expanded Precambrian database of palaeomagnetic intensity measurements is an increase in both average field strength and variability that is observed to occur between a billion and 1.5 billion years ago. Combining both mentioned timespans 1.4 - 1.5 Ga would be the most likely point of history of the inner-core nucleation. The timing would tend to favor a modest value of core thermal conductivity and supports a simple thermal evolution model for the Earth [6].

4. Phanerozoic Eon and Geodynamic Cycles

The Phanerozoic eon is characterized by roughly two 300 million yearlong geodynamic cycles of different geological, geophysical, and biological processes, which are modulated by roughly four 150 million yearlong periodicities. These processes are linked together in one way or the other, which conceptually leads to the definition of a geodynamic feedback system. Sea level variations, variations in magmatic/volcanic activity, deposition cycles of oil and gas source rocks, changes in the magnetic field, and global climate changes testify to this development. The variations in shelf areas, which are linked to the variations in sea level, the tidal dissipation, which is influenced by these, the Moon's recession and rotational history of the Earth bring the Moon into the system as an active participant. In case no other forces are available the Moon as an external force may have caused a feedback between the geodynamic processes and force these into cyclic dependencies. If the shelf areas on the Earth increase or decrease due to proceeding geological processes the tidal dissipation increases or decreases depending on the distance between the Earth and the Moon and the Earth's rotation is decelerated to a greater or smaller extent [8]. However, since the Earth rotates differently modulated around the sun and the solar system itself wanders on a complex path around the center of the Milky Way galaxy, subsequent cyclic changes in the geological record might consequently occur. These changes encompass astronomically enforced processes as well as terrestrially induced intrinsic ones. Examples are the observed geodynamic periodicities of about 300 and 150 Million years of global sea level fluctuations, magmatism, orogeny, sedimentation (e.g. of organic carbon) and climate [9] [10] as well as periodicities with shorter repetition times [11]-[16]. The 150 Million year cycle appears to be related to the configuration of the Milky Way galaxy with its four spiral arms containing higher concentration of dust and acting as preferred birth places also of later exploding stars. Whether the exploding stars, either as planetary nebulae or as specific supernovae, have contributed directly to the geodynamic processes on Earth via dust, cosmic rays or neutrinos, may be debatable [17]. The encounters of the four spiral arms lead to an orbit time of about 600 Ma around the slower rotating Milky Way structure. Climate changes on Earth with a 150 Million year periodicity point to a possible strong influence of spiral arm encounters (**Figure 3**). An astronomical input seems obvious [7]. The 300 Million year cycle reflects also the internal structure of the Milky Way galaxy with two strong and two weak spiral arms. Therefore the path of the solar system may finally lead to a forced periodicity of the intrinsically lunar affected Phanerozoic geodynamic feedback system.

Our Milky Way galaxy appears to be the master and the geodynamic processes on Earth represent the slaves, in a system-theoretical view. Within Earth, a subsequent master-slave system of geodynamic cycles [8] has been established as a follow-up at least during Phanerozoic times. The ruling forces coming from space do not support the Gaia hypothesis [18] that Earth and the life on it are effectively controlling their own destiny through intrinsic processes.

Taking into account the evolution of the shallow seas during the Phanerozoic, the continental growth back to the beginning of the Archean, conditions for the filling of the Earth's oceans in the Hadean as derived from zircon crystals, and the widely accepted theory on the origin of the Moon, the Moon's recession rates back in time as well as the early rotation history of the Earth can be estimated.

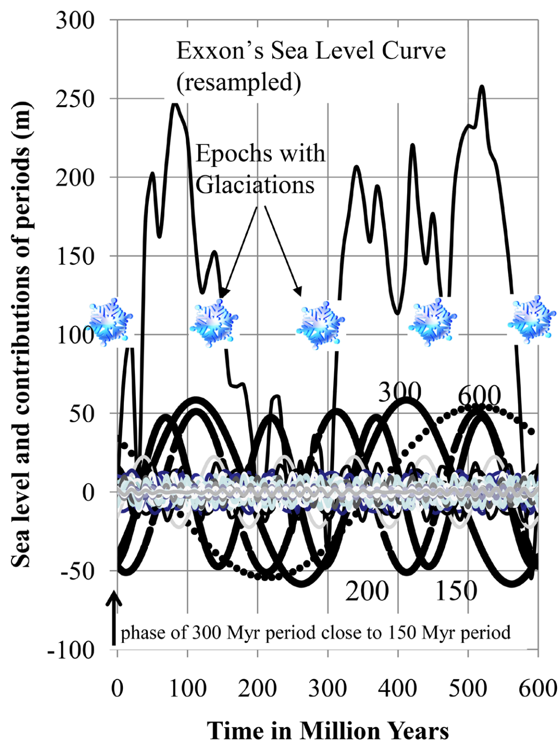

Figure 3. Analysis of Exxon's sea level [19] curve by applying Fast Fourier Transformation (FFT), resulting in the resolution of contributing periods, their amplitudes and phases. Epochs with glaciations after references [20] and [21] in [15].

5. Proterozoic and Archean Eons and Tidal Dissipation

The progressive loss of rotational energy within the Earth-system is caused by tidal interaction [8], counteracting the acceleration of Earth's rotation during the growth of the core. The minor effect of the Sun is neglected here. Derived from astronomical observations over the last 200 years the total energy loss due to tidal dissipation is today about 2.7×10^{19} ergs/sec [22] [23]. Observations and records of several eclipses of the Moon and the Sun between 0 and 1000 B.C. are a second data source to estimate the secular acceleration of the Moon [24]. Perturbations in satellite movements likewise contain information about the effect of tides on the Earth [25]. The tidal friction processes on the ocean floors and in the shallow seas (shelf areas) of the Earth and in the body of the solid Earth are considered to be sinks for the rotational energy loss of the Earth. The dissipation of tidal energy is proportional to the effective surface area of the sea bottom and depends on the third power of the tidal current velocity [23]. As the tidal forces vary with the third power of the distance between two bodies [26], the constantly receding Moon continuously and moderately loses its influence on the Earth. The rotational energy of the Earth is mainly lost due to friction processes in connection with erosion and material transport at the sea bottom as well as heat dissipation.

The area of the shallow seas has varied periodically within Phanerozoic time. Variations of the shelf areas can be derived by referring to global plate tectonic history [27] [28] and the history of marine clastic sedimentation [29] [30]. As expected, the variations of the shelf areas and the deposition of marine sediments show behavior similar to the sea level variations, as they are interdependent.

Present-day tidal current velocities range from 1 cm/sec in the deep ocean [23] to more than 1 m/sec in the shallow seas [31]. This is a ratio of 1:100. As the third power of the current velocity is effective the contribution of the deep ocean to tidal dissipation is probably negligibly small.

Applying the physical laws for current velocities, pressure differences, and tidal forces in an appropriate manner, a formula can be derived, which will describe the tidal dissipation as function of the distance between Earth and Moon and of the shelf area of the Earth. According to Bernoulli's law, current velocities between two points within a fluid are proportional to the square root of the pressure difference between the points. For the tidally influenced seas the pressure difference can roughly be expressed as a function of the differences in the tidal heights. The amplitude of the tidal height is a reverse function of the distance between the Earth and the Moon and varies with its 3rd power. These laws immediately result in the following formula for the tidal dissipation D, where $A(t)$ = shelf area, $U(t)$ = average current velocity, $H(t)$ = tidal height, $R(t)$ = distance between Earth and Moon, β, c_1 & c_2 = intermediate constants and t = time:

$$D = \beta \times A(t) \times U(t)^3 \quad [23]$$

$$= \beta \times A(t) \times \left(SQRT\left(c_1 \times H(t)\right)\right)^3 \quad \text{(Bernoulli's law)}$$

$$= \beta \times A(t) \times \left(c_2 \times R(t)^{-3}\right)^{3/2} \quad \text{(see [26])}$$
$$= \beta^* \times A(t) \times R(t)^{-4.5}$$

where β^* = final constant value.

Taking today's value for the tidal dissipation of shallow seas of about 1.7×10^{19} ergs/sec [23], represented by a shelf area of 27 million km^2, and today's average distance between the Earth and the Moon of 384,401 km, the following equation results as a function of time:

$$D = \left(1.7 \times 10^{19} \times 10^{-6} / 27 \times 384,401^{4.5}\right) \times A(t) \times R(t)^{-4.5} \text{ ergs/sec}$$
$$= 0.85234 \times 10^{37} \times A(t) \times R(t)^{-4.5} \text{ ergs/sec with } A(t) \text{ in km}^2 \text{ and } R(t) \text{ in km}$$

By applying this formula tidal dissipation in shelf areas would account for the bulk of the dissipated rotational energy of the Earth, as already indicated above [8].

The present recession rate of the Moon is about 3.47 cm/year [32] and thus about twice as high as the average rate of 1.78 cm/year during the last 10 million years. This point to a recent acceleration phase of the Moon's recession, whose cause is possibly different from tidal dissipation in shallow seas due to the difference compared with the total energy loss.

Tracing the Moon's recession rate far back towards early times of the Earth history by deriving an average decrease in the shelf areas in the course of time (**Figure 4**) from the growth curve of the continents taken from [33], the distance between the Moon and the Earth can be determined at least to the beginning of the Archean time about 3800 (classical)/4000 (newly defined) Million years ago. At the time break between the Hadean and Archean, the filling of the oceans was already completed. According to this calculation there are no indications that the Moon was ever closer than 325,000 km from the Earth and that the Earth rotated much faster than 13 h/day since then. Supporting this idea, it has been observed [34] that the general dynamics of tidal sedimentation have hardly changed at all since Archean and that—for this reason—changes in the Earth-Moon system have been rather moderate as well (see also [35]). During the Hadean, the time before with no significant geological record, the Earth's oceans evolved, and the interaction between Moon and Earth was certainly very different from the time after.

Asteroids, comets, and early Earth contributed to Earth's water inventory as determined by [36]. At the beginning of the filling, the entire surface of the Earth probably acted like a "shelf", resulting in an effective sink of dissipation energy of maximal 511 Million km^2, limited only by the available amount of liquid water. At the end of the filling, about 4000 m of hydrosphere covered the more or less shelfless Hadean Earth and no effective dissipation sink may have existed. Taking these early filling conditions into account, the above derived formula can be applied accordingly. Restrictions are the condition of the Earth-Moon system 3800 Million years ago as derived above and the condition of the origin of Earth

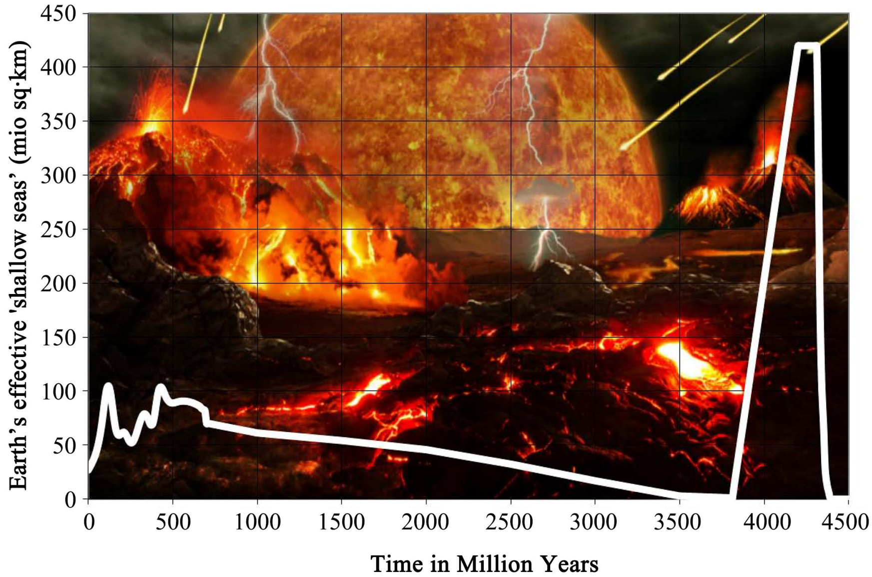

Figure 4. Model curve of the Earth's shallow seas (white line) by applying the more or less known distribution of Phanerozoic shelf areas, an assumed continental growth during the Archean and Proterozoic and the water cover of the early Earth during the filling process of the ocean. The background image is taken from Tim Bertelink, 2016, Artist's impression of the Hadean Eon (Wikipedia Creative-Commons-License 4.0 international). The Proterozoic to Archean part is estimated by taking 35% of the continental areas, derived by the continental growth curve as proposed by [33].

and Moon. According to [37], the Moon is generally believed to have formed from debris ejected by a large off-centre collision with the early Earth. The impact orientation and size are constrained by the angular momentum contained in both the Earth's spin and the Moon's orbit, a quantity that has been nearly conserved over the past 4500 Million years. The planetary body, which hit the about 50 million-year-old Earth with roughly the mass of Mars about 4450 Million years ago, had formed nearby with an orbit that had, by chance, placed it on a collision course with Earth. The early giant collision destroyed the planetary body, likely vaporized the upper layers of Earth's mantle, and ejected large amounts of debris into Earth orbit. From this pre-lunar debris swarm the Moon coalesced most likely just outside of the Roche limit of 3 - 5 Earth radii (about 20,000 - 30,000 km), possibly on a time scale as short as one to 100 years.

Already about 50 Million years later, very early crust evolved and liquid water filled the first topographic lows. This is supported by a Zircon crystal with an age as old as 4404 ± 8 Million years, found in the Jack Hills in the Narryer Gneiss Terrane, Yilgarn Craton, Western Australia [38]. Magmatic oxygen isotope ratios point toward the involvement of supracrustal material that has undergone low-temperature interaction with a liquid hydrosphere. This zircon thus represents the earliest evidence for continental crust and oceans on the Earth.

At this time, 4400 Million years ago, the filling of the oceans could have been started, when the Moon was approximately 30,000 km away from Earth. Within a period of 600 Million years the Moon escaped from an orbit in about 30,000 km to an orbit in about 300,000 km distance. Assuming that tidal forces within the evolving ocean were the only driving mechanism, an active "shelf area" as given in **Figure 4**, in which the previously outlined conditions have been included, will yield to the Hadean escape rate of the Moon as well as to the evolution of the Earth's rotation. The escape rate is very sensitive to the initial phase of the filling, which had to be modelled in the way, that coming from the younger times the Roche limit had to be hit exactly. After many trials a model with an effective acting surface of the Earth of about 420 Million km^2 (roughly 80% of the entire surface), a rapid filling within 60 Million years(?) until the total Earth was covered with oceanic water, a plateau phase of about 100 Million years, in which the effective surface was more or less constant, and a linear decrease of the acting surface due to the rise of the sea level and the subsequent reduction of the shallow seas until the end of the Hadean 3800 Million years ago, could be established. Since the theory about the origin of the Moon and the dissipation model, derived via the study of the Phanerozoic cycles as described above, can be merged without any obvious conflict, the presented ideas may at least contain some truth.

6. Length of the Day (LOD)

During the last 20 years a set of new data on LOD has been gathered for the Precambrian (Proterozoic and Archean) and compiled by [7]. These data do not fit the theoretical model proposed by [39] with an offset of more than 2 h around 2 to 2.5 Ga. The observed decrease of LOD is interpreted by [7] as a result of interior geodynamic processes, probably either inner core nucleation or the further segregation of Earth's (outer) core. The assumed rapid growth of the core took place around 1.9 - 1.4 Ga ago. This offset has also been discussed differently by [5] [40] [41] [42]. Only [5] supported the idea that a late and slow growing core could be the cause of the observation. Based on a statistical analysis the day length stalled at about 19 h for about 1 billion years during the mid-Proterozoic [40]. It is proposed that the accelerative torque of atmospheric thermal tides from solar energy balanced the slowing down torque of lunar oceanic tides, temporarily stabilizing Earth's rotation. This stalling coincides with a period of relatively limited biological evolution known as the boring billion. This assumption is contradicted by [41], since new analytical models for the thermal atmospheric tides suggest that the atmospheric tidal resonance, which is the crucial ingredient for the LOD locking in the Precambrian, was never of sufficiently large amplitude to allow for this tidal LOD lock. According to [42], 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. However, the new Precambrian data can be easily merged with the Phanerozoic data as presented here by applying a power law fit (**Figure 5**). This fit has to be extended into the Hadean by an independent approach. Since the data undulate

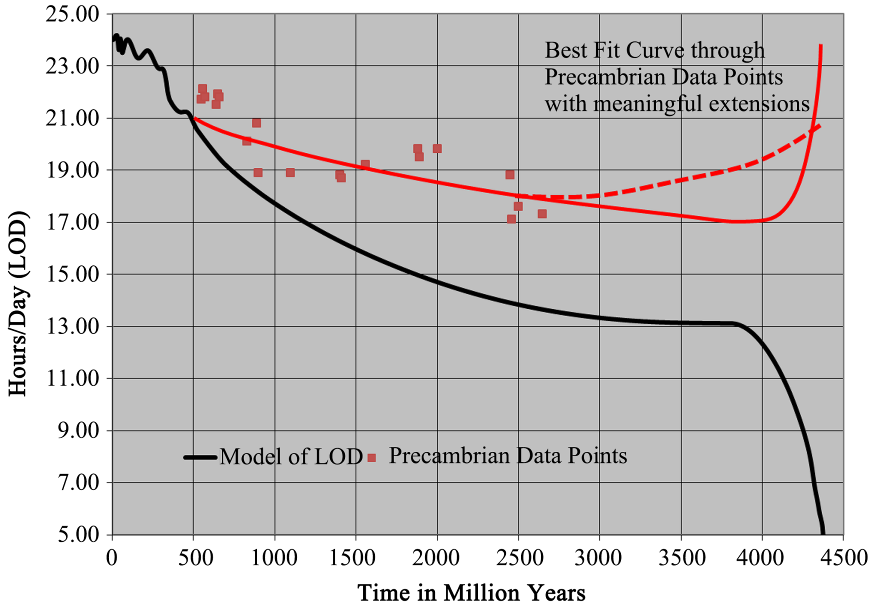

Figure 5. The length of the day (LOD) in hours/day since the Hadean Eon about 4.4 Ga ago. The black curve represents the presented Tidal Dissipation Model based on the presence of shallow seas either as growing continental shelf areas or as the entire Earth during the filling process of the ocean. The red curve is a fit through the Precambrian Proterozoic and Archean LOD data points as compiled by [7] (Mean values only) and reflects the sum of the effects of core growth and tidal dissipation, extrapolated towards the Hadean in two different ways by ignoring the very early tidal dissipation. The red solid line is based on the assumption that the core grows very fast very early, which would lead to a decrease of the LOD by about 6.57 h/day [5] and therefore for an acceleration of Earth's rotation. The interrupted line characterizes a moderate growth rate and a longer growth phase extending into the Archean. The LOD would then have been decreased by 2.5 - 3 hours only. In the first case the growth of the core and the tidal dissipation during the ocean filling process could have been more or less balanced and might have been dependent from each other. In the second case the Hadean tidal dissipation would have been dominant and only a weak dependency may have existed. In both cases the rotation of the Earth in very early times started with about 24 or 20 hours per day, accelerated up to 17 - 18 hours per day, and followed the data point supported curve with a quite similar behavior like the tidal dissipation model but with a dipping LOD plateau about 1 - 4 hours per day higher. This would indicate that the LOD was never shorter than about 17 h/day since the end of the Hadean, which is very similar to the assumption of [42] with values between 19.5 and 17.5 h as a realistic estimation. The situation for the time before remains unknown and may have been chaotic through the conflict between the growing core and the simultaneous water release into the developing ocean.

significantly around the best fit curve, some geological information may has been archived in the observed data distribution as well and would require further investigations. However, data uncertainties could be the cause of these undulations, too.

The Phanerozoic data set encompasses tidally controlled growth patterns exhibited by Phanerozoic stromatolites and fossil mollusks, complemented by Precambrian 650 - 900 million year-old sandstone varves. They show luni-solar periodicities and allow estimates of the number of days in the month (lunar) and in the year (solar) respectively.

The Proterozoic and Archean data points are based on the obliquity and precession periods derived from the Nanfen Fm. The Earth–Moon distance and LOD at about 1.1 Ga are constrained at $3.43 \pm 0.04 \times 10^8$ m and 18.94 ± 0.39 h, respectively. Furthermore, the cyclostratigraphic results from the rhythmites of the Xiamaling Fm in the China yield a LOD of 18.68 ± 0.25 h at about 1.4 Ga and the coeval strata of the Roper Group in Australia yield similar results. The cyclostratigraphic datum at about 2.65 Ga is from carbonate cycles of the Cheshire Fm in Zimbabwe with a LOD of 17.3 h. Tidalites data points at about 2.5 Ga are from laminae sequences of the banded iron formation (BIF) in the WeeliWolli Fm of Australia and the cyclostratigraphic data point at about 2.5 Ga is from BIF of the Dales Gorge Member of the Brockman Iron Fm in Australia. The stromatolite data points of about 2.0 Ga and about 1.88 Ga are from the Great Slave Supergroup, Gunflint Fm of Canada and the Biwabik Fm of America [7].

The length of the day (LOD) in hours/day since about 4.4 Ga ago in the Hadean Eon is presented in **Figure 5**. The black curve represents the presented Tidal Dissipation Model based on the presence of shallow seas either as growing continental shelf areas or as the entire surface of the Earth during the filling process of the ocean. The red curve is a fit through the Precambrian Proterozoic and Archean LOD data points as compiled by [7] and reflects the sum of the effects of core growth and tidal dissipation [8], extrapolated towards the Hadean in two different ways by ignoring the very early tidal dissipation. The red solid line is based on the assumption that the core grows very fast very early, which would lead to a decrease of the LOD by about 6.57 h/day [5] and therefore for an acceleration of Earth's rotation. The interrupted line characterizes a moderate growth rate and a longer growth phase extending into the Archean. The LOD would have been decreased then by 2.5 - 3 hours only. In the first case the growth of the core and the tidal dissipation during the ocean filling process could have been more or less balanced and might have been dependent from each other. In the second case the Hadean tidal dissipation would have been dominant and only a weak dependency with the growth of the core may have existed. In both cases the rotation of the Earth in very early times started either with about 24 or 20 hours per day, accelerated up to 17 - 18 hours per day due to the core growth, and followed then the data point supported curve with a quite similar behavior like the tidal dissipation model but with a dipping LOD plateau about 1 - 4 hours per day higher. This would indicate that the LOD was never shorter than about 17 h/day since the end of the Hadean, which is very similar to the assumption of [42] with values between 19.5 and 17.5 h as a realistic estimation. The situation for the time before remains unknown and may have been chaotic through the conflict between the growing core and the simultaneous water release to the developing ocean.

As the tidally controlled growth patterns exhibited by Phanerozoic stromatolites, fossil mollusks and Precambrian 650 - 900 million year-old sandstone varves show luni-solar periodicities. They allow estimates of the number of days in the month (lunar) and in the year (solar) respectively. The number of months per year can be calculated from these data. Figures for days/month or days/year can be calculated in a subsequent step. The figures thus determined represent the most probable data sequences despite the error range of the initial data. As there are no indications that the solar year changed during the Phanerozoic, the number of hours per day can be determined using given, interpolated and calculated data. Applying Keppler's 3rd planetary law to the month/year data makes it possible to estimate the changes in the distance between the Moon and the Earth. The number of days per month has decreased from about 31.5 to about 29.5, the number of months per year from about 13.4 to 12.4 and the number of days per year from about 420 to about 365 during the Phanerozoic eon. Synchronously, the Moon has distanced itself from the Earth by 24,000 km from about 360,000 km to about 384,000 km in the last 510 million years. None of these data shows a simple linear relationship [8].

7. Moon's Recession

The history of the Earth–Moon system as reconstructed from the geological record remains indistinct when only based on the analysis of fossil growth patterns and tidal laminations. Tidally controlled growth patterns are exhibited by Phanerozoic stromatolites and fossil mollusks and Precambrian sandstone varves show luni-solar periodicities and allow estimates of the number of days in the month (lunar) and in the year (solar) respectively. A further important method is provided by the sedimentary record of Milankovitch cycles (climatic precession, obliquity, and orbital eccentricity), whose relative ratios in periodicity change over time as a function of a decreasing Earth spin rate and increasing lunar distance. With a robust cyclostratigraphic approach, a reliable datum for the lunar recession history by more than 1 Ga could be provided [43].

Due to tidal interactions in the Earth-Moon system, the spin of the Earth slows down and the Moon drifts away [44]. This current recession of the Moon can be measured with great precision, but the extrapolation of the recorded value back in time leads to an age of the Moon that is largely inconsistent with geochronological, geochemical and astronomical evidences. However, many of these models have not been able to fit both the estimated lunar age and the present rate of lunar recession simultaneously. In the presented work this problem might have been solved. This solution fits the available geological proxies for the history of the Earth-Moon system well and it strengthens the presented tidal dissipation model.

The study of tides from the sedimentary record of tidal rhythmites contributes as well to the understanding of the evolution of our dynamic planet, and of the astronomical cycles that influenced the ancient tidal systems. The lunar retreat calculated at different stages of the Earth's history identifies three possible time-spans of extremely high recession rates: Archean-Paleoproterozoic (6.93 cm/year), Neoproterozoic-Ediacaran (7.01 cm/year) and Ediacaran-early Cambrian (6.48 cm/year). Older comparable recession rates are difficult to recognize because of the lack of tidal rhythmic sequences [45].

Quite recently published data on the evolution of the Earth-Moon distance have been made available for further investigations. These include firstly the evaluation of the sedimentary record of Milankovitch cycles in the Proterozoic eon. Cyclostratigraphic analysis and high-precision U-Pb zircon dating of the lower Paleoproterozoic Joffre Member of the Brockman Iron Formation, NW Australia, providing evidence for Milankovitch forcing of regular lithological alternations related to Earth's climatic precession and orbital eccentricity cycles were the driver of the investigation. An Earth–Moon distance of 321,800 ± 6500 km and a daylength of 16.9 ± 0.2 h at 2.46 Ga have been estimated [43]. Secondly, an examination of the oldest tidal record of Archean time from the Moodies Group, South Africa, with an age of 3.22 Ga has been carried out [45] [46]. The Earth-Moon distance at this age was about 300,000 km. This value fits to the modelled trend. It has been calculated by applying the integration of the sequence of time dependent recession rates as mentioned above. The value should be treated with some caution, since the calculation needs a further review. No LOD data has been provided. However, a recent reexamination leads to a value of roughly 270,000 km [47]) and a LOD of 13 h. But it will require an abrupt jump of the Earth-Moon distance around 3 Ga ago and should be treated therefore with caution as well. This extreme value will be neglected here. Together with the data from [32] [48] [49] these four data points fit quite well the theoretically derived history of Moon's recession (**Figure 6**). Compared to the course of LOD (**Figure 5**), which is certainly affected by the growth of the Earth's core and tidal dissipation, Moon's recession appears predominantly governed by tidal dissipation alone.

However, due to the Moon's increasing and irregular orbit combined with irregularities of the Earth's rotation (LODs) their time dependent effect on motion in the core is unstable and can cause fluctuations in the geodynamo [50]. This process could produce changes of the thermal history of the Earth through heat pulses in the outer core and at its boundary with the Earth's mantle. Deep mantle melting and possibly major volcanic events at the Earth's surface may have been the consequences over the course of time. This model demonstrates that the Moon's effect on the Earth goes well beyond causing tides alone. The Earth's magnetic field as maintained by the geodynamo with a rapid motion of huge quantities of liquid iron alloy in the outer core requires in the classical model that the Earth's core has cooled from around 6800˚C to 3800˚C today by around 3000˚C over the past 4.3 billion years. Now it has been suggested that, on the contrary, its temperature has fallen by only 300˚C. Recent modeling of the thermal history of the planet, together with geochemical studies of the composition of the oldest carbonatites and basalts, do not support such cooling. The action of the Moon is assumed to have counterbalanced for this difference and kept the geodynamo active. The effect of gravitational forces on a planet's magnetic field

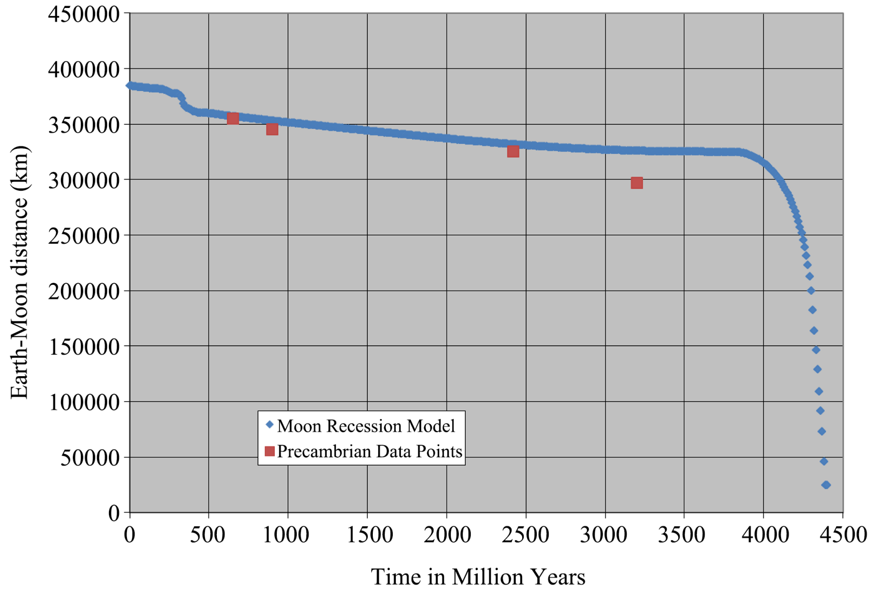

Figure 6. The Earth-Moon distance as function of time for the presented lunar recession model from the Hadean to the Phanerozoic (blue line) and four published Precambrian data points (red rectangles) [32] [40] [43] [46] [48] [49] Data points and model coincide quite well, which supports the assumption that the lunar recession is predominantly affected by the tidal dissipation in shallow seas. The growth of the core does not have any significant influence like it has for the LOD.

has already been documented for two of Jupiter's moons, Io and Europa, and for a number of exoplanets. During the Hadean eon with its exorbitant tidal processes on Earth [8] and very high recession rates of the Moon the development of the Earth's core and the geodynamo therein were certainly significantly affected. During the Proterozoic eon the evolution of the inner core may have interacted with the tidal processes as well, should the geodynamo model [50] being applicable at all.

Additionally to its tidal influence on the Earth the Moon had an extensive magnetosphere for several hundred million years soon after it was formed and when it was within 20 Earth Radii from the Earth. The early lunar magnetosphere may have affected the magnetospheric dynamics within the coupled Earth-Moon magnetospheres over time, and may have played an unforeseen and substantial role in shielding the Earth's atmosphere from the destructions of the young Sun's intense space weather [51].

8. Conclusion

The presented Earth-Moon model, which incorporates tidal dissipation via shallow sea areas as affected by continental growth together with the filling of the ocean since Hadean times and the growth of the Earth's core during the early Earth, is an update of an older work with a simple approach, complemented by additional new data. The recession rate of the Moon and the development of the LOD back to the early time of the Earth have been determined, leaving no conflict between the merged theories behind. These theories encompass global Phanerozoic cycles, continental growth, filling of the ocean, growth of Earth's core, and the conditions of the Moon's origin. The original rotation rate of the Earth was probably not far away from the present value. The Moon's recession is assumingly affected by tidal dissipation only, whereas the rotation of the Earth is influenced by the sum of tidal dissipation and core growth. In Hadean times tidal dissipation and the growth of the Earth's core may have been strongly interacted and yet unknown geodynamic processes may have taken place inside the body of the Earth. Possibly these include the magnetospheric dynamics between Earth and Moon, too.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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