# EARLY EVOLUTION OF EARTH AND BEGINNING OF ITS GEOLOGICAL HISTORY: HOW AND WHEN GRANITOID MAGMAS APPEARED

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Earth has a number of differences from the planets of the Solar System, as well as other stellar-planetary systems, which were acquired during its formation and geological history. The early *Chaotian* aeon was marked by Earth's accretion, the differentiation of its primary material into a mantle and a core, as well as the by formation of its satellite (Moon). Earth's geological history began 4500 million years ago in the Hadean aeon. At that time, the endogenous processes on Earth were largely controlled by meteorite and asteroid bombardments, which caused large-scale melting and differentiation of its upper layers. In magmatic chambers, differentiation proceeded until the appearance of granitoid melts. The Hadean continental crust was almost completely destroyed by meteorite bombardments, with the last heavy bombardment occurring at the end of the Hadean aeon (4000–3900 Ma). Conclusions about the geological situation of this aeon can be drawn only from the preserved Hadean zircons. In particular, their geochemical features indicate that Earth had an atmosphere. The Hadean aeon was replaced by the Archaean one, starting from which the processes of self-organisation were predominant on Earth. At that time, a crust composed of komatiite-basalt and tonalite-trondhjemite-granodiorite (TTG) rock series was forming. Its formation was driven by sagduction processes – vertical growth of the crust over rising mantle plumes. Thus, the lower basaltic crust subsided into the mantle, eclogitised and melted, which led to the appearance of sodium TTG rocks series. At the end of the Archaean aeon (3.1–3.0 Ga), lid tectonics, which determined the structure and development of the Archaean crust, was replaced by small-plate tectonics that later evolved into modern plate tectonics combined with mantle plume tectonics.

**Keywords**: *Chaotian and Hadean aeons, Archaean period, lid tectonics, plume tectonics, sagduction, mantle convection*

## INTRODUCTION

Earth is different from other terrestrial planets of the Solar System. What is more, it has no analogues among the planets of 600 stellar-planetary systems that have been discovered in recent decades. It is not a coincidence that the authors of the article "Born from the chaos" [S. Batygin et al., 2016] called Earth a black sheep. An outstanding geologist K. Condy identified a number of characteristics inherent to Earth [Condie, 2011], which allowed it to become the cradle of humankind. The characteristic features of our planet, including its size and mass, a near-circular orbit, existence of a satellite (Moon), were acquired during the birth of the Solar System and then during the Chaotian aeon [Goldblatt et al., 2010]. Earth acquired its other important characteristics, such as the division of Earth's interior into a number of layers, during its subsequent history. The above-mentioned layers include the continental crust containing a significant amount of granitoids, as well as the atmosphere and hydrosphere. The first granites on Earth appeared in the Hadean aeon, while granitoids, well-preserved to our days, were already fairly widespread in the Archaean aeon. The Earth's birth, its formation as a planet, as well as possible mechanisms for the development of the first granitoid rocks in the Hadean and Archaean aeons will be discussed in this work.

Knowing when the tectonics of lithospheric plates got started is of great importance for understanding the geological history of our planet. The mechanisms of endogenous processes stipulated by this theory are well studied. They describe the formation of basic geological structures, such as continents, oceans, orogens. Not coincidentally, in 2008 following a corresponding conference the Geological Society of America published a special issue, which contained articles by a number of prominent geologists covering the onset of plate tectonics on Earth. In his article published in this issue K. Condi writes: "It is unlikely that plate tectonics began on Earth as a single global 'event' at a distinct time, but rather it is probable that it began locally and progressively became more widespread from the early to the late Archaean". However, even today, such well-known Japanese geologists as S. Maruyama and his colleague [Maruyama, Ebisuzaki, 2017], establish the exact start date of plate tectonics (4.37–4.20 Ga) when proposing a new model of the Earth's formation (ABEL). Similar start dates of the plate tectonics on Earth are proposed in the works of other geologists. In the same issue published by the Geological Society of America, R. Stern wrote more cautiously and prudently about the significance of the early tectonic style on Earth saying that we will not be able to understand the current system until we know when the current tectonic style began and what preceded it [Stern, 2008].

## ORIGIN OF THE SOLAR SYSTEM AND EARLY STAGES OF ITS EVOLUTION

The solar system originated 4568 million years ago in a massive dust and gas cloud. The reason for the formation of this protosolar nebula, which must have included a large variety of chemical elements along with various short- and long-lived isotopes, is of the essence here. This cloud (nebula) could have originated from the explosion of a supernova in the vicinity of the future Solar System. Due to nuclear reactions, the explosion of a massive star brought about the synthesis (nucleosynthesis) and, naturally, the appearance of various elements, in particular, radioactive isotopes. This explosion could have induced the condensation of interstellar matter resulting from gravitational compression. Short-lived isotopes and their decay products help to identify a number of features associated the formation of the Solar System and Earth in particular.

The calculations of astronomers and planetary scientists show that a star (proto-Sun) appeared in the centre of the nebula under the influence of gravity in less than 100 thousand years. The proto-Sun was surrounded by a wide disk of gas and dust – a protoplanetary disk [Lin, 2008], which served as the building material for the planets of the Solar System. When moving, particles of dust and gas collided and slowed down, with many of them spiralling onto the proto-Star. Upon collision, solid particles heated, whereas water and other volatiles having a low boiling point evaporated. This resulted in a natural boundary between the areas of the protoplanetary disk, with the predominance of solid particles in one part and volatiles in the other. This boundary (a region between the orbits of Mars and Jupiter) is referred to as the snow line, dividing the Solar System into the inner region, where the terrestrial planets were formed, and the outer one, where the gas giant planets were located [Batygin et al., 2016]. This separation occurred 2 million years after the onset of the Solar System formation (Fig. 1).

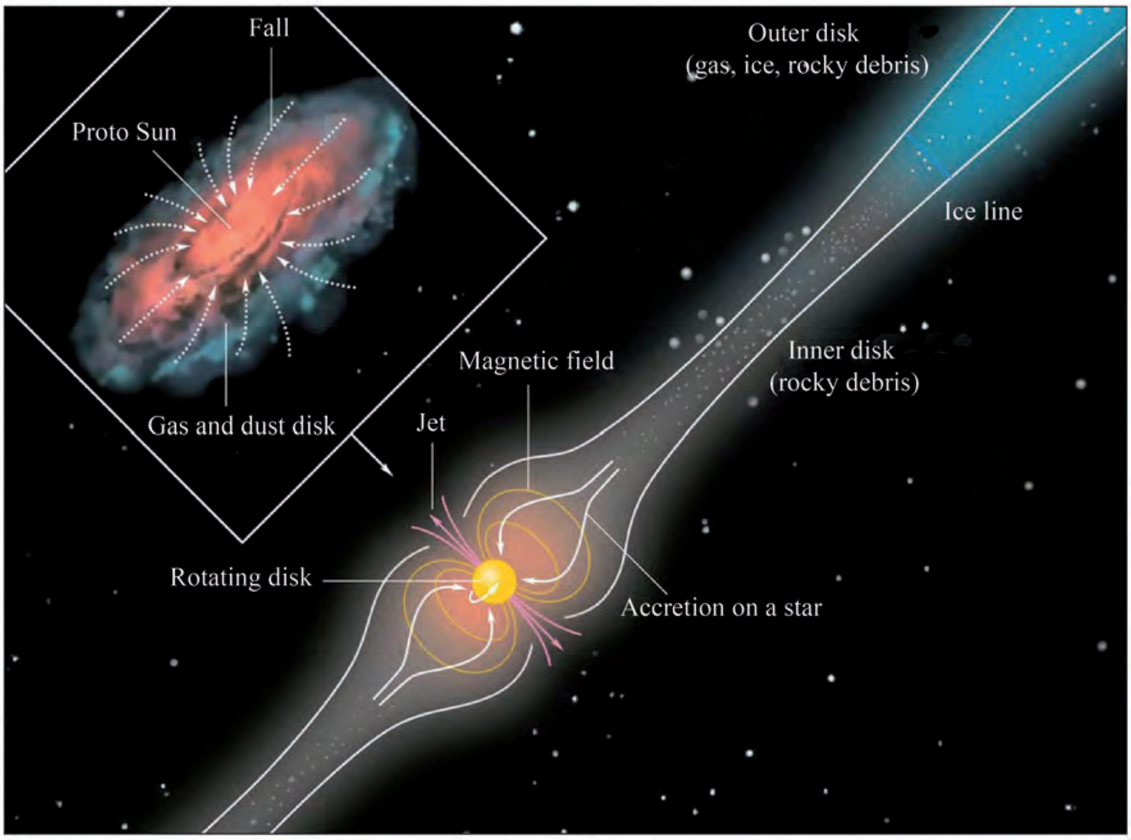


**Fig. 1**. Initial stage of the Solar System's evolution 4568 Ma ago [Batygin et al., 2016].

The beginning of the Chaotian aeon of the Solar System; birth of the proto-Sun; formation of the internal area consisting of stony fragments; snow lines – internal border of the external gas-ice region, where giant planets Saturn and Jupiter were formed 2 million years after the birth of the Solar System.

Thus, in the first 2 million years of the Solar System's history, numerous planetary embryos (planetesimals), as well as giant planets beyond the snow line (Jupiter and Saturn) were formed. In this respect, the Solar System is very different from other planetary systems, where similar giants are located much closer to the sun. According to K. Batygin and his colleagues [2016], such features of the Solar System are products of its youth, which included more drama and chaos. The complex interaction of giant peripheral planets constituted an important part of the primary chaos. For the first time, this was noted in the computer model of F. Masset and M. Snellgrove [Masset, Snellgrove, 2001], who described the simultaneous evolution of Saturn's and Jupiter's orbits in the protoplanetary disk. These studies showed that due to inward migration, the giant planets acquired a certain mutual configuration, due to which they were able to influence the protoplanetary disk. The established balance of forces (gravity, angular momentum, the gravitational influence of the outer belt of comets, etc.) changed the motion of both planets.

Developing these ideas, K. Batygin and his colleagues [2016] demonstrated that a change in the motion direction of the giant planets (tacking) mainly resulted in the attack of Jupiter and Saturn on the 'population' of the primary inner planets of the Solar System, i.e. terrestrial planets. Even when migrating towards the Sun, the giants affected the motion of small bodies, which shattering in collisions formed swarms of debris., The mass of debris that could fall on the Sun over hundreds of thousands of years is comparable to any super-Earth (planet exceeding the Earth in mass). As the former super-Earths were driven into the Sun, they had to leave behind a gap in a protoplanetary nebula. It is assumed that, before changing the tack, Jupiter migrated towards the Sun to the current position of Mars. In doing so, Jupiter pushed accumulations of ice, evidently along with solid material, having a mass of more than 10 Earth's masses towards the inner region of the Solar System, thus enriching it with water and other volatile substances. The proto-planets forwarded to the inner parts of the Solar System changed the orbital angular momentum of both Jupiter and Saturn, which resulted in their outward migration. The building material brought by the giant planets ensured a fairly large mass of Earth and Venus.

Gradually, the migrating planets stabilised their orbits, which was facilitated by their interaction with other giant planets (Neptune and Uranus), as well as the outer Kuiper Belt. It is assumed that the stabilisation of their orbits resulted in sending another swarm of debris into the inner region of the Solar System, thus causing powerful asteroid bombardments of the inner planets. The asteroid bombardments left their mark in the form of craters on the surface of the Moon, Mercury and Mars, whereas on Earth they led to the almost complete destruction of the Hadean continental crust – the first crust in the geological history of our planet. Approximately 3.9 billion years ago, the giant planets settled down. Thus, the Solar System acquired its current structure [Batygin et al., 2016].

Astronomers distinguish a chaotic period in the Solar System's development (beginning of Earth's formation to 4.0–3.9 billion years). In the geological literature, this period is divided into two aeons: Chaotian (4568–4500 Ma) and Hadean (4500–4000 / 3900 Ma) [Goldblatt et al., 2010].

## EARLY STAGES OF EARTH'S FORMATION AND EVOLUTION

### Chaotian Eon (4568–4500 Ma)

The accretion of Earth took place in this period. As little as 11 million years after the onset of its formation, Earth acquired 63% of its current mass, in 30 million years amounting to 93% [Wood, 2011]. During this period, accreted Earth underwent differentiation into a liquid iron-nickel core and a silicate mantle, accompanied by the formation of the Earth's satellite (Moon) resulting from the collision of a large space body with proto-Earth.

Data on the composition of the protosolar nebula, from which the Sun and the planets of the Solar System were formed, are of great importance for calculating the composition of the Earth's layers. It has been established that the composition of the Sun is similar to that of the nebula from which this whole system originated [Kuzmin, 2014]. Carbonaceous chondrites correspond to this composition. With the exception of hydrogen and helium, they have the same composition as the Sun, which can be observed from the diagram (Fig. 2) comparing the relative abundances of elements on the Sun's surface and in carbonaceous chondrites [Wood, 2011]. The composition of carbonaceous chondrites differs from that of the Sun in the content of lithium that is destroyed by thermonuclear reactions in the Sun. In addition, meteorites are characterised by reduced content of three volatile components – N, C, O. This is quite understandable, as in the initial period of the Solar System's formation (first 2 million years) these gases were driven into its outer part, where they were used, among other things, to form gas giant planets. As can be seen from this diagram, Fe, O, Mg, Si and Ni account for 95% of the Solar System's mass (that is not H and He) and, naturally, the terrestrial planets, with 9 more elements – Cu, Al, S, Cr, Ni, Mn, P, Ti and Co – bringing the total to over 99% [Lauretta, 2011].

Considering the geochemical properties of the elements, as well as the composition of the Earth's silicate mantle, data on the composition of the material (carbonaceous chondrites) from which Earth was formed allows us to estimate the composition of Earth's core [Allègre et al., 1995; McDonough, Sun, 1995]. In this

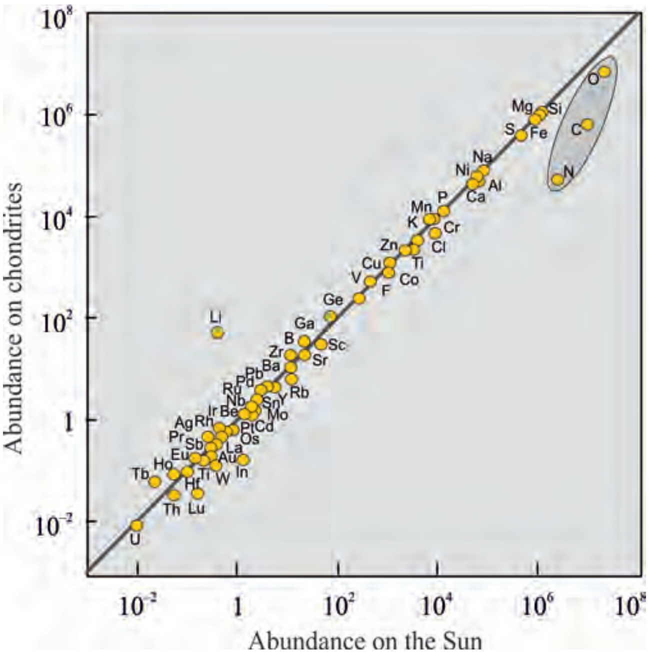


**Fig. 2**. Comparison of elemental abundances in carbonaceous chondrites (CI) and on the Sun's surface according to [Wood, 2011].

The general content of the petrogenic and rare elements in the Sun and carbonaceous meteorites (CI) is the same with the exception of Li which is destroyed on the Sun in the course of nuclear reactions. The content of volatile components (N, C, O) in meteorites is less than in the Sun, since in the first 1–2 Ma most of these volatile elements were involved in the formation of gas giant planets in the outer part of the Solar System.

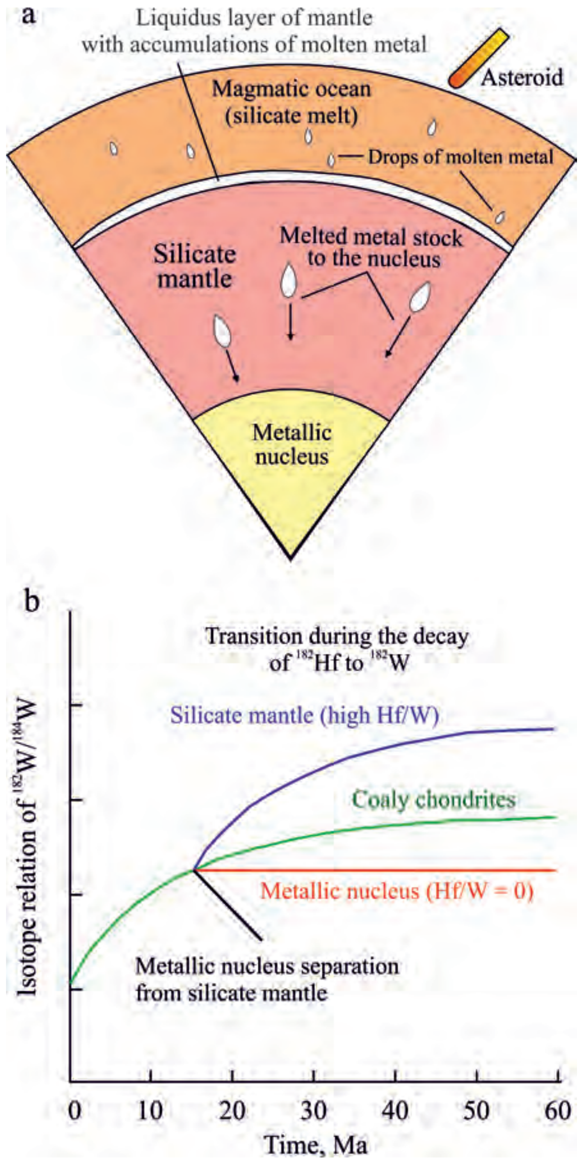


**Fig. 3**. Model of Earth's differentiation in the course of accretion according to [Wood, 2011].

a. *Formation of the mantle and the core under the asteroid and meteorite bombardments of proto-Earth.* The energy produced by asteroids colliding with Earth led to the formation of large magmatic basins reaching a depth of 400–700 km. Drops of siderophile elements formed during the melting of the iron-stone material of asteroids (meteorites) and were submerged to the bottom of the magmatic basin, where they formed accumulations of molten metal, which plunged through the lower mantle, thus increasing the core. b. *Time of the core's formation determined using* $^{182}Hf \rightarrow$ $^{182}W$ *system;* $T_{1/2} = 8.9$. The diagram shows *changes in the* $^{182}W/^{184}W$ ratio depending on the system (iron core, carbonaceous chondrites, silicate mantle) according to [Wood, 2011]. They indicate that the core was mostly formed in about 20 Ma, with almost the entire core being formed in 50 Ma.

connection, knowing the properties of individual elements in terms of their affinity with iron, silicate and volatile elements is of great importance [Allègre et al., 1995; Kuzmin, 2014]. According to the analysis, silicate Earth (i.e. mantle) contains the same amount of refractory lithophile elements (Zr, Al, Sc, rare-earth elements, Ti, Ca, Mg) as carbonaceous chondrites, whereas the content of siderophile elements in the mantle is low as compared to chondrites, as they accumulate in the core. Silicate Earth has the lowest content of highly-siderophile elements (Pd, Pt, Re, Os, etc.), whose concentration is maximum in the core. However, judging by the mantle xenoliths found in kimberlites, a slightly higher content of these elements in the mantle is occasionally observed, which may have been caused by the meteorite shower that hit the Earth after most of the core had already been formed [Wood, Halliday, 2010].

The time of the Earth's core formation can be estimated using the data on the distribution of products of short-lived isotope systems (Fig. 3), whose parent and daughter isotopes could have different geochemical properties, in the silicate layer of Earth. As a result, they behaved differently in the course of the Earth's differentiation into layers. In this respect, the most interesting results were produced by the $^{182}Hf \rightarrow {}^{182}W$ system. Its parent isotope $^{82}Hf$ having a half-life of about 9 million years almost disappeared during the first 50 million years of the Earth's history. Unlike the siderophile daughter isotope $^{182}W$, hafnium is a lithophile element. In the course of the planet's differentiation into the iron core and the silicate mantle, $^{182}W$ headed towards the core, whereas $^{182}Hf$ remained in the mantle (see Fig. 3). If the core had formed immediately following accretion, the daughter isotope would have remained with the parent isotope in the mantle and would have corresponded to the composition of chondrites. As compared to chondrites, the mantle is depleted of tungsten (Hf / W = 19 and 1.1, respectively), which indicates that the core formed at a certain interval of geological time during which tungsten along with iron was partially redistributed to the nucleus. Judging by the tungsten isotopic composition of the Earth's mantle, the minimum time (following the onset of Earth's accretion) required for the core to form is estimated at 34 ± 7 Ma [Kostitsyn, 2012].

Thus, the Earth's differentiation began almost from the moment of its formation. Collisions of the emerging planet with large asteroids, as well as the heat of radioactive decay (primarily of short-lived isotopes) resulted in the melting of its silicate layer to the extent that magma oceans were formed. At a high temperature and pressures of 20–23 hPa, magma was divided into silicate and iron melts [Wood, 2011]. After the first 5–8 Ma, the volume of Earth was already half of its present size. Collisions with large asteroids could result in the formation of magma basins reaching up to 400 km in depth. Iron melts, as the heavier ones, accumulated at the bottom and then fell through it, thus increasing the core [Wood, 2011].

The Moon's formation (Fig. 4) – which took place approximately 30 million years after the birth of the Solar System – is of great importance for Earth. Different scenarios for its formation were proposed: fission of proto-Earth; joint formation of Earth and Moon; capture of an independent space body by Earth. The available facts are most consistent with the impact origin of the Moon. The Moon was formed as a result a Mars-sized body Theia (about 0.14% of Earth's mass) colliding with Earth at a velocity of about 5 km/s [Condie, 2011]. By that time, the Earth's core was largely formed and separated from the mantle; Earth had an atmosphere similar to that of Venus (this example shows what the Earth's atmosphere would have been like if it had not been affected by such a large collision).

In the course of discussing the first models of the impact Moon formation, some questions were raised [Cameron, 1986; Hartmann, 1986] which prevented the proposed model to be conclusively accepted. The above-mentioned questions were primarily related to the composition of the cosmic body with which proto-Earth had collided. The determination of the lunar soil composition solved this issue. Lunar rocks have the same isotopic composition of oxygen as those of Earth. They are also characterised by a deficiency of siderophile elements. This fact suggests that the cosmic body called Theia was formed in the inner part of the Solar System along with other terrestrial planets. Hence, like proto-Earth, Theia had a formed core and mantle. A computer simulation carried out in 1989 [Newsom, Taylor, 1989] revealed that, as a result of the impact, the silicate (mantle) part of this cosmic body, together with the Earth's mantle, turned into the impact-generated melt and dust cloud, whereas the iron core of this cosmic body sank into the core of proto-Earth merging with it. Figure 4a shows some modelled images of Earth's collision with Theia. According to H. Newsom and S. Taylor [1989], the formation of the Moon was completed in no more than first hundreds of years.

Figure 4b shows a scheme of Theia colliding with proto-Earth and the resulting formation of the Moon from the melt and dust cloud generated by the impact. This cloud consisted of molten mantle silicates from the colliding bodies, silicate dust particles, and, possibly, the gases of proto-Earth's atmosphere. Most likely, this cloud was stretching in the direction of the Earth's collision with the cosmic body. The core of Theia penetrated into that of Earth, increasing it. On the periphery of the cloud, the Moon began to accrete from its molten part. A comparative geochemical analysis of the silicate parts of Earth and the Moon [Condie, 2011] reveals that lunar rocks are enriched in refractory oxides (according to K. Condie's classification) (Ca, Sc, Ti, Th). In addition, volatile lithophile (Na, K, Rb, Sr) and especially siderophile (Co, Ni) elements are shown to be depleted in the lunar mantle, as compared to that of Earth. Such geochemical characteristics are quite explicable. The Moon crystallised from the inner part of the molten silicate disc of the impact cloud; therefore, it was slightly enriched with refractory elements, whereas Earth's rocks were enriched with lithophile (volatile, according to [Condie, 2011]) elements having lower condensation temperatures. As for siderophile elements, they were concentrated in the cores of two planetary bodies during accretion and initial differentiation. Volatile components (proto-Earth's atmosphere) appeared into the Earth's atmosphere after it cooled down, which is confirmed by the presence of oxygen in the Earth's atmosphere at the beginning of the Hadean aeon.

Considering the crystallisation of the Moon's and Earth's magma oceans (on Earth it reached about 700 km in depth and maybe more), all these events ended by 4520–4505 Ma, given that 4,500 Ma ago the Moon and Earth were already solid, which is evidenced by the traces of meteorite bombardments on the Moon's surface.

## Hadean aeon

The Hadean aeon was proposed in the 1980s when zircons dated at 4376 Ma were found in metamorphosed sedimentary rocks outcropping in the Jack

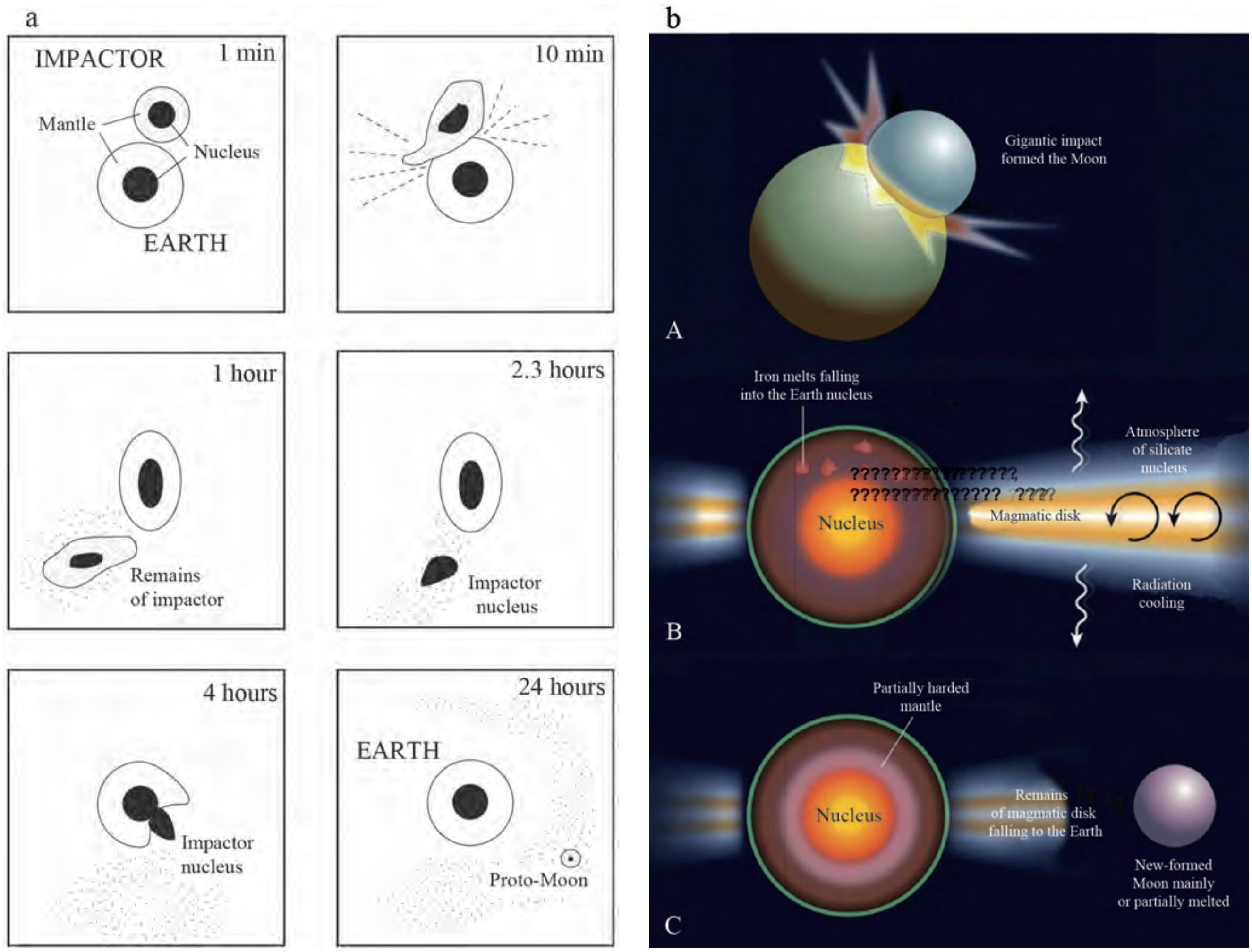


**Fig. 4**. Formation of the Moon as a result of the cosmic body (Theia) colliding with Earth.

a. *Computer simulation of Theia colliding with Earth and the resulting formation of the Moon according to [Newsom, Taylor, 1989].*
According to the model, the birth of the moon took 24 h. The authors of the model believe that the Moon's formation took no more than hundreds of years following the collision.
b. *Model of the Moon's formation [Condie, 2011].*
A. A planetary embryo (Theia) colliding with almost formed Earth.
B. Following the collision, a melt-dust disc was formed stretching in the direction of the location where the Moon was formed.
C. The Moon formed on the periphery of the disc; the mantle crystallised around the Earth's core.

Hills of Western Australia [Myers, 1988]. This period marks the beginning of the Earth's geological history. At first, there were great doubts whether it was possible to uncover the conditions for the formation of the first rocks on Earth, relying on such scarce materials as accessory minerals preserved from those rocks. However, due to the development of modern analytical research methods, tangible results were obtained in as early as the 21st century, which allow us to understand the geological situation on Earth in the Hadean aeon.

The results of detailed studies on Hadean zircons are given in [Nebel et al., 2014]. In addition, recent data on the geological situation in the Hadean aeon are presented in [Kuzmin, 2014; Kuzmin, Yarmolyuk, 2016; and etc.]. The first results on the content of rare elements in Hadean zircons were obtained by R. Maas and his colleagues [Maas et al., 1992]. The results showed that the content of Hf in these zircons reached 0.86–1.30 wt %, with Zr / Hf = 30–57. In addition, fractional distribution of REE (high ratio of HREE / LREE), exhibited both positive Ce and negative Eu anomalies. The same researchers discovered inclusions of potassium feldspar, quartz, plagioclase, monocyte and apatite in zircons, which allowed the authors to conclude the granite composition of the Hadean zircon source.

Studies on the oxygen isotopic composition of zircons were of great importance for uncovering the conditions for their crystallisation in the Hadean aeon. It should be pointed out that oxygen isotopes can fractionate during magmatic differentiation. The isotopic composition of primary rocks can be significantly changed in the course of weathering when weathering products are enriched with a heavy oxygen isotope. Respective changes in the oxygen isotopic composition were detected in the Hadean zircons, which led to the following conclusions: 1) weathering processes, similar to modern ones, were active during the Hadean aeon; 2) granitoid melts were formed under near-surface conditions [Nebel et al., 2014].

The discovery of zircons on the Moon played a great role in understanding the geological processes in the Hadean aeon as well. Hadean zircons [Nebel et al., 2014], as well as the ones found on the Moon [Taylor et al., 2009], are dated at 4.0–4.4 Ga; however, their formation temperatures differ: the Hadean zircons crystallised at ≈700°C [Harrison et al., 2008], whereas the lunar ones did at 975–1150 °C [Taylor et al., 2009]. Normalised graphs showing REE distribution in the lunar (Fig. 5a) and Hadean (Fig. 5b) zircons are similar and characterised by the predominance of HREE over LREE. At the same time, lunar zircons differ from the Hadean ones in the absence of a positive Ce anomaly; hence, they were formed in a reducing environment. An important conclusion on the crystals of lunar zircon was made when studying the zircon microstructure [Grange et al., 2013]. The study of the zircon microstructure revealed local areas of recrystallisation, localised amorphous areas, plastic crystal deformations and faults, cracks, i.e. typical traces of impact structures.

Considering the proximity between the Moon and Earth on a cosmic scale, it is clear that these two bodies were simultaneously subjected to meteorite and asteroid bombardments. While on the Moon, these bombardments resulted in numerous meteorite craters; on Earth, these bombardments continuously destroyed the continental crust being created, plunging into the mantle where it melted. Nonetheless, refractory zircon crystals were preserved and as a result of mantle plumes poured onto the surface together with the new portions of the primary mantle magma. On the surface,

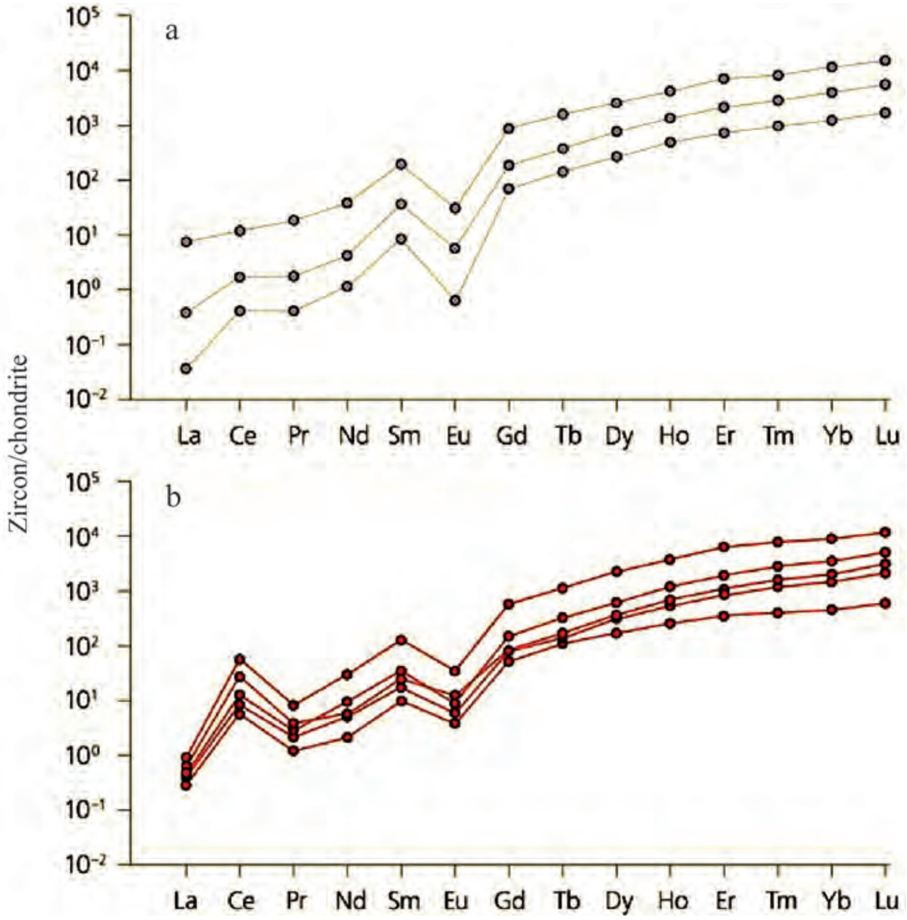


**Fig. 5**. Chondrite-normalised graphs showing the content of rare-earth elements in the lunar (a; according to [Taylor et al., 2009]) and Hadean (b; according to [Maas et al., 1992]) zircons.

Age of the lunar and Hadean zircon is estimated at 4.0–4.4 Ga. Lunar and Hadean zircons formed at 975–1150°C [Taylor et al., 2009] and ≈ 700°C [Harrison et al., 2008], respectively.

they underwent differentiation, while zonal zircons crystallised from small volumes of granitoid melts. This served as a sort of recycling for the Hadean continental crust, as evidenced by the zonal Hadean zircons [Nebel et al., 2014].

Despite the heavy bombardment of the terrestrial planets, which was caused, as mentioned above, by the stabilisation of the giant planets' orbits (Saturn and Jupiter), a small part of the Hadean primary crust was preserved, discovered and described in detail in [O'Neil et al., 2012]. These most ancient rocks of Earth were recently discovered in the Nuvvuagittuq Greenstone Belt on the northeast coast of the Hudson Bay (Canada). Its central part (Ujaraaluk unit) is composed of basic and ultrabasic volcanic and intrusive rocks. The age of rocks was estimated by the ratio of decay products of short-lived ($^{146}Sm \rightarrow {}^{142}Nd$; T1/2 = 68 Ma) and long-lived ($^{147}Sm \rightarrow {}^{143}Nd$, T1/2 = 106 Ga) isotope systems, amounting to about 4,400 Ma. The obtained results indicate that these rocks belong to the oldest crust of Earth, which developed following the Moon's formation. Age determination of the Hadean rocks is shown in Fig. 6 [O'Neil et al., 2012].

A small rock unit (Idiwhaa) outcropping 4.03 Ga Hadean granitoids was recently discovered among the rocks of the Nuvvuagittuq Greenstone Belt [Reimink et al., 2014]. These granitoids occur among typical Archaean TTG (tonalite-trondhjemite-granodiorite) rocks in the Acasta Gneiss Complex (Canada). The identified granitoids from the Idiwhaa unit form thin interlayers in amphibolites and gneisses with a thickness ranging from several centimetres to a decimetre. The constituent minerals of tonalites include plagioclase, quartz, hornblende and biotite. Their composition comprises 57.9–66.9 wt % of $SiO_2$ with a low content of $Al_2O_3$ (13.8–14.1 wt %), high content of total iron ∑FeO (8.6–15.2 wt %) and a low magnesian coefficient Mg# (13–18 wt %). Unlike Archaean TTG rocks, the Hadean tonalites have a completely different distribution of normalised REEs (Fig. 7). While Archaean TTG rocks are enriched with LREEs, which indicates their formation during the partial melting of the mantle substance in the presence of garnet, the Hadean tonalites originated at shallower depths during the partial melting of the hydrous basalt crust in the presence of plagioclase, which contributed to the development of a negative Eu anomaly.

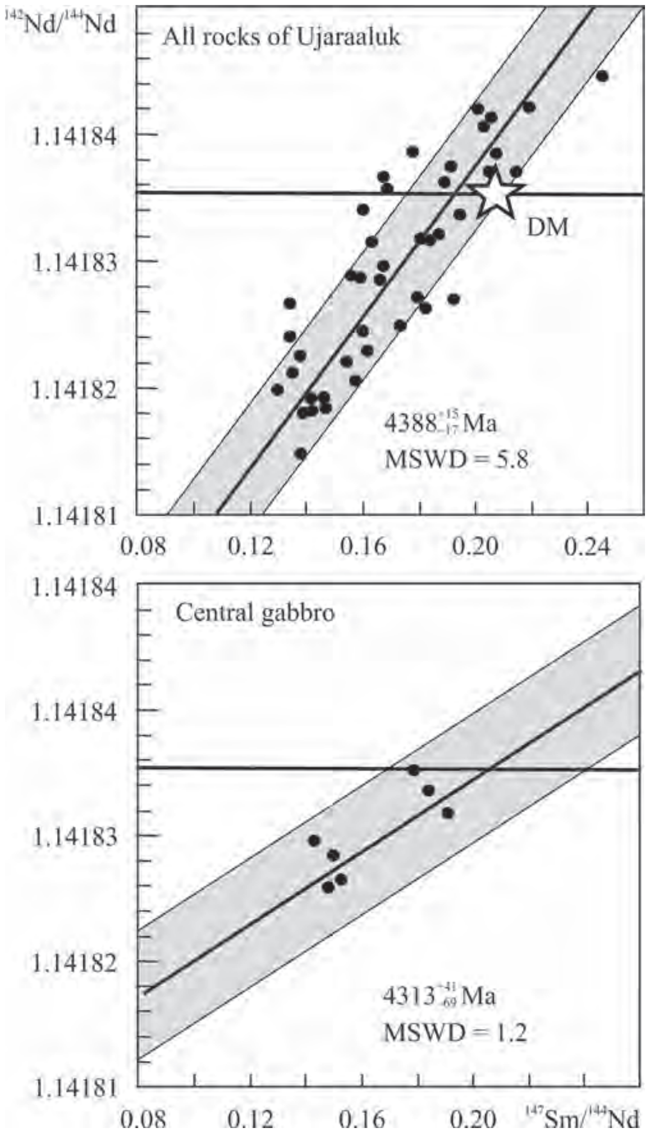


**Fig. 6**. Age of the Ujaraaluk series obtained using two isotopic pairs $^{147}Sm \rightarrow {}^{143}Nd$ ($T_{1/2}$ = 106 Ga) and $^{146}Sm \rightarrow {}^{142}Nd$ ($T_{1/2}$ = 68 Ma) according to [O'Neil et al., 2012].

Perhaps this is the only part of the Hadean crust left after the giant impact that formed the Moon. The site was preserved after the last heavy bombardment of Earth, which destroyed the Hadean crust.

Hadean granitoid rocks of such genesis were obviously formed at various points in time. 4.2 Ga zircon xenocrystals were found in Archaean TTG rocks dated at 3.9 Ga [Iizuka et al., 2006]. An example of such xenocrystal, located in the centre of a magmatic zircon dated at approximately 3.9 Ga, is shown in Fig. 8a. In this case, magma that generated Archaean TTG rocks must have been smelted from the residual magmatic reservoir of the Hadean time. It could have been a partially melted remnant of the Hadean crust which was immersed in the mantle as a result of a meteorite bombardment. Figure 8b shows the distribution of normalised REEs in Hadean zircons dated at approximately 4.2 Ga. In terms of the REE distribution, these zircons are comparable to Hadean zircons found in Austria. It should be pointed out that zircon xenocrystals of the Hadean time were found in various cratons, which indicates a wide distribution of the Hadean continental crust on Earth.

Among all else, available data on a possible mechanism for the formation of Hadean zircon melt suggest that granitoid melts could have been formed in the

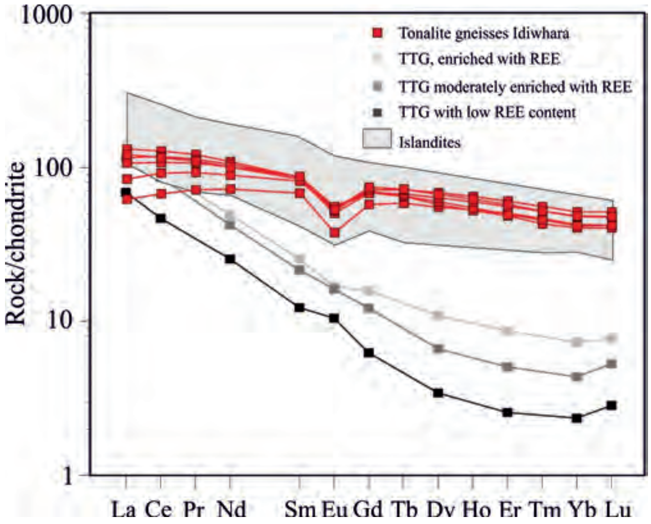


**Fig. 7**. Normalised distribution of rare-earth elements in the tonalite gneisses of the Idiwhaa site (4.03 Ga) and in Archaean TTG rock series according to [Reimink et al., 2014].

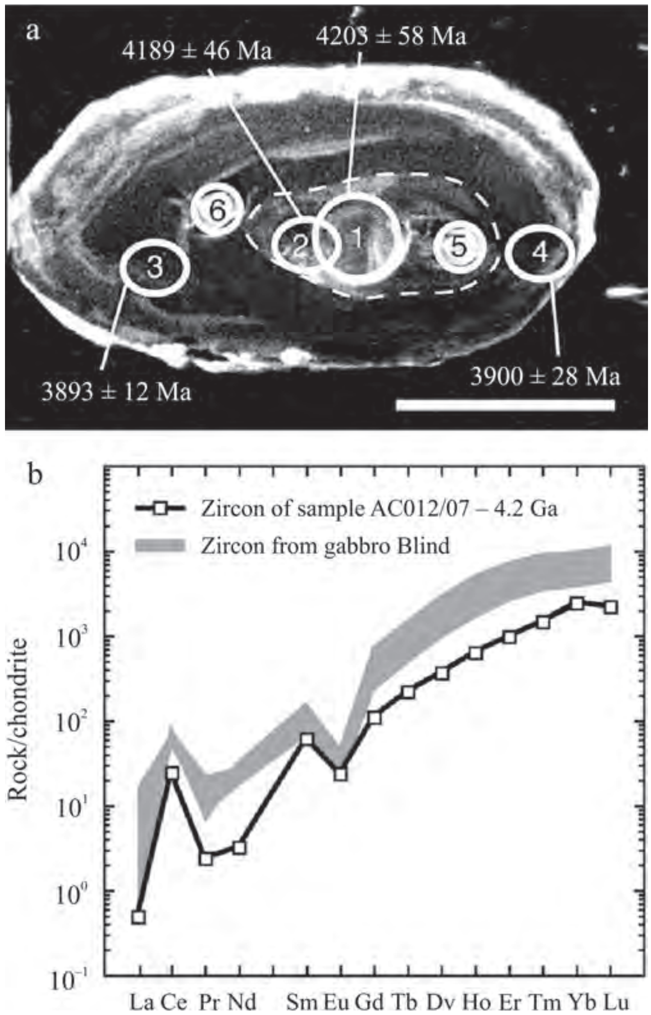


**Fig. 8**. Comparison of Hadean xenocrystals with Archaean zircon from the rocks of the Acasta Gneiss Complex (Canada) according to [Iizuka et al., 2012].

a. Position of xenocrystals in the zircon host and their age characteristics.
b. Normalised distribution of chondrite-normalised contents of rare-earth elements in zircon xenocrysts. The distribution of REE in gabbro is given for comparison.

Hadean aeon in various ways, but in shallow chambers and usually in an oxidising environment when the hydrous basalt crust was melting.

In concluding the analysis of the Hadean geological history, we consider it necessary to draw attention to one important factor observed in [Jackson et al., 2017]. The authors of this work noted high values of the $^3He/^4He$ ratio in some basalts, which was shown to be related to hot plumes, namely Hawaiian and Icelandic. In these basalts, the value of the $^3He/^4He$ ratio was 30–50 times higher than its atmospheric values. It was suggested that this could be due to the presence of non-degassed reservoirs in the mantle, which have survived to the present. It is likely, that such reservoirs had high density, so they were not mixed in the course of mantle convection. The authors of this article refer to the Oligocene basalts (Baffin Island, West Greenland) associated with the proto-Iceland plume, which are plotted between the 4.55 Ga and 4.45 Ga geochrons in lead isotope diagrams, as shown in [Jackson et al., 2010]. However, basalts from a number of hot spots not having high $^3He/^4He$ ratios, as well as basalts from mid-oceanic ridges, are plotted in the same area of this diagram (in terms of the lead isotope ratio), which does not allow basalts having a high $^3He/^4He$ ratio to be clearly identified as the products of ancient non-degassed mantle reservoirs. At the same time, it is known that volatiles, in particular He and H, can form compounds with metals (He – metal of high density). It is likely, that some of them got into the core in the course of the Earth's accretion and the formation of its core [Gilat, Vol, 2012]. Subsequently, these elements (or compounds) concentrated in the outer core, whose density is lower than that of the inner core; then they could get into the D'' layer, which according to geophysicists, comprises ultrahigh velocity zones [Garnero, McNamara, 2008], probably, represented by magmatic chambers feeding mantle plumes. Obviously, research in this direction should be continued, since it will help solve a number of issues related to the early evolution of Earth.

## ARCHAEAN TTG ROCKS: PRESERVED PRIMORDIAL CONTINENTAL CRUST OF EARTH

The Archaean aeon was marked by the preservation of the continental crust represented by the tonalite-trondhjemite-granodiorite (TTG) rock association. There are marked petrochemical and geochemical differences between early Archaean TTG rocks (grey gneisses) and Phanerozoic granitoids [Condie, 2011].

TTG rocks are notably different (petrochemically and geochemically) from the late Archaean, Proterozoic and Phanerozoic rocks. It can be seen in Figure 9a that TTGs are typical sodic rocks plotted at the Na-apex of the ternary Na–K–Ca diagram. It is quite clear that the ancient mantle of Earth – which has not yet parted with most of the lithospheric elements used in the formation of the Earth's continental crust – served as the parent material for TTG rocks [Kuzmin, Yarmolyuk, 2017]. Post-Archaean calc-alkaline rocks, usually confined to subduction zones, exhibit a significantly higher potassium content, since the lithosphere together with the continental crust served as the basis for their genesis. The rocks are even more contrasted in terms of the rare element content (Fig. 9b). Firstly, TTG rocks are strongly enriched with LREEs. This is obviously due to the considerable depth at which partial melting of the Archaean basaltic crust immersed in the mantle took place. The Archaean basaltic crust must have been enriched with lithophile elements, as compared to the Phanerozoic MORB (mid-ocean ridge basalts), whose ancient basic rocks represented by proto-ophiolites were identified in 1977 [Glukhovskii et al., 1977]. A distinct prevalence of

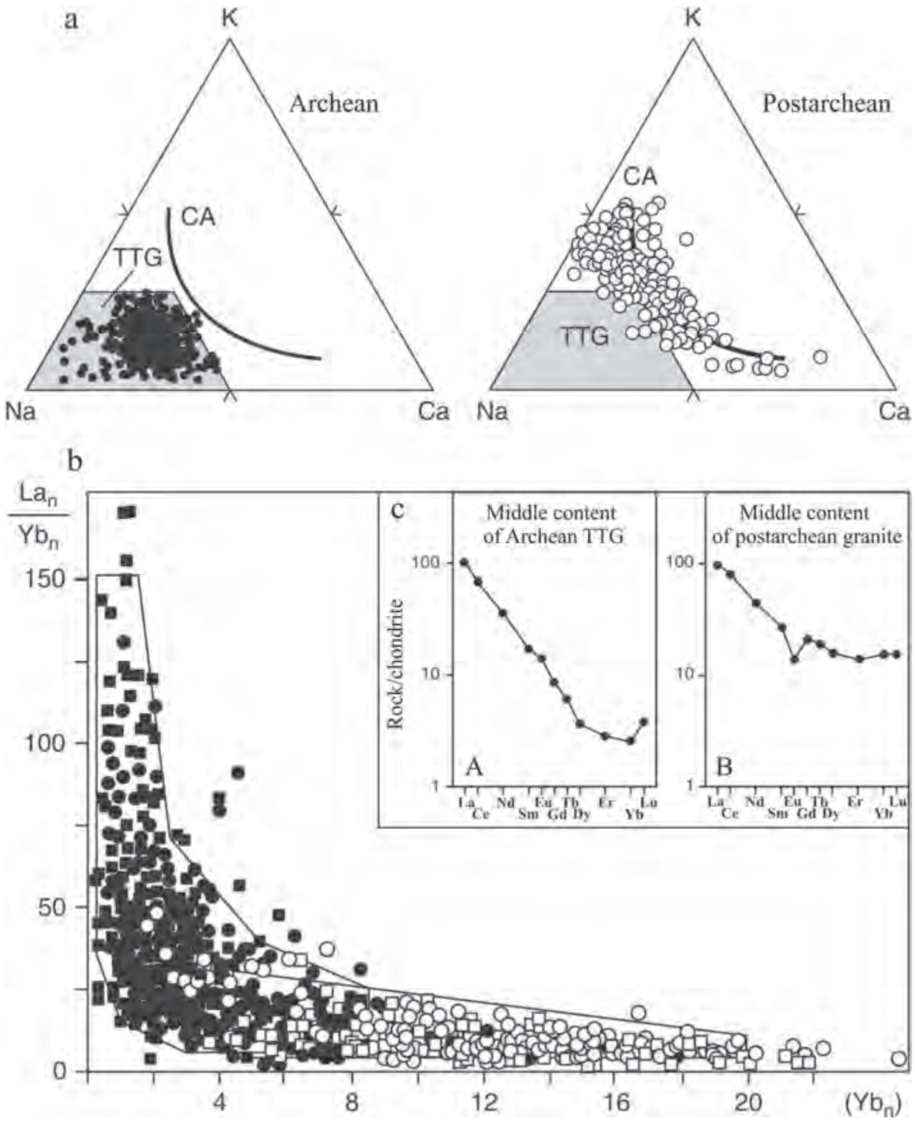


**Fig. 9**. Comparison of the rock formations of the Archaean tonalite-trondhjemite-granodiorite series (A) and the post-Archaean granites (B) according to [Condie, 2011]).

a. K–Na–Ca diagrams show differences determined mainly by the sodium composition of TTG series and by the calc-alkaline composition of the post-Archaean volcanites and granites, according to [Condie, 2011].
b. Distribution of normalised REE contents, as well as the La/Yb ratio on the La/Yb–$Yb_{norm}$ plot in the TTG and post-Archaean rocks. The TTG rocks are enriched with light REE, as compared to heavy REE.

LREE in TTG rocks can be observed in Figure 9c. Post-Archaean granitoids and calc-alkaline volcanites also exhibit high contents of LREEs, as compared to HREEs; however, they are not as predominant, which may indicate that Phanerozoic volcanites were formed at shallower depths.

Summarising the data on the TTG composition, it is clear that these preserved Archaean continental rocks are of mantle genesis considering the published data on the isotopic composition of TTG rocks, obtained from the U–Th–Pb, Sm–Nd, Rb – Sr and Re–Os systems, many of which are given in the monograph [Condie, 2011]. It has been established that TTG rocks were formed during the melting of highly hydrolysed basalts at sufficiently high pressures, at which the garnet remained stable in refractory residue [Reimink et al., 2014], which indicates eclogite paragenesis. At the same time, the increased values of incoherent elements in the source basalts indicate that the composition of TTG rocks is comparable with the island-arc rocks of the Phanerozoic time. However, no traces of subductions occurring in the course of TTG formation were detected. It can be assumed that basic and ultrabasic mantle magmas derived from Archaean plumes were responsible for the formation of a thick basaltoid crust. Having been formed from these magmas, Archaean basaltoids were enriched with lithophile elements, as compared to Phanerozoic MORBs.

The upper mantle derived from rising plumes was saturated with fluids, whereas crustal basalts were saturated with incoherent elements. Under the weight of a massive basaltoid crust, basaltoids sagged, being immersed into the mantle. This process involving vertical motions [Hain, 2003] is called sagduction.

The most ancient (3.9–3.8 Ga) TTG rocks originated from protoliths or the Hadean crustal matter during the formation of primary magmas for Archaean TTG rocks. Drawing on the study of Lu–Hf and U–Pb isotopes in gneisses, the work of A. Bauer and his colleagues [Bauer et al., 2017] provides detailed evidence of the Hadean mantle source (age > 4.0 Ga) being involved in the formation of Archaean gneissic TTG rocks (Canada). Figure 10 shows the distribution of isotopic characteristics exhibited by the tonalites (TTG) of the Acasta Gneiss Complex (Canada) for the two above-mentioned isotopic series. In terms of the subchondritic $^{177}$Lu /$^{177}$Hf ratio, they are connected by two ratio values 0.015 and 0.022; whereas in terms of age, five rock groups are distinguished: 3.96–3.94 Ga (group A), 3.74–3.72 Ga (B), 3.66– 3.58 Ga (C), ≈3.4 Ga (D) and 2.9 Ga (E). As shown in [Bauer et al., 2017], these TTG rocks are obviously derived from two Hadean igneous protoliths originating at different times. The rocks of groups A, B and partly C (the lower part of this group in Fig. 10) are linked to the subchondritic $^{177}$Lu/$^{177}$Hf isotope ratio of 0.015, whereas groups D and E, as well as the upper part of group C, are linked to the subchondritic ratio of the same isotopes equal to 0.022. As rightly noted in [Bauer et al., 2017], this is due to the different depths to which the remnants of the Hadean crust originating at different times sank into the mantle as a result of meteorite bombardments. This Hadean crust was melted and mixed with the mantle material. Subsequently, this material served as a protolith for magmas that gave rise to Archaean TTG rocks. The protolith (source of younger rocks) could have formed at great depths; thus later it was involved in magma formation.

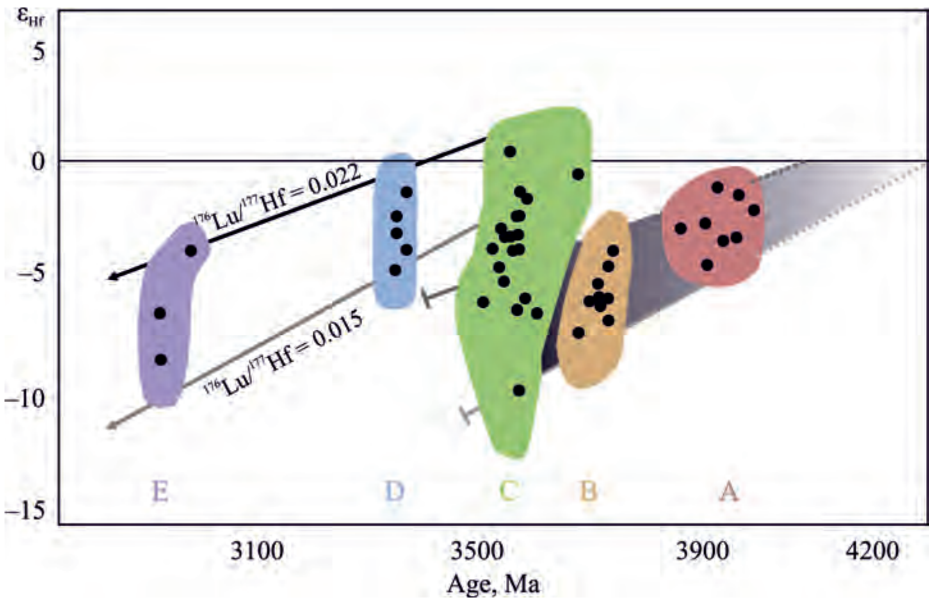


**Fig. 10**. Model Lu/Hf age of TTG sources from the Acasta Gneiss (Canada) according to [Bauer et al., 2017].

Judging by the presented data, the gneiss source of groups A and B is less radioactive than the magma source of younger gneisses.

In [Bauer et al., 2017], the authors also studied Archaean rocks from Greenland and Central Africa using a similar method: they established close age groups having slightly different subchondritic Lu/Hf isotope ratios. These observations indicate a wide distribution of the Hadean crust on Earth.

In his work [Bédard, 2006], J. Bédard gives a detailed consideration of a sagduction model drawing from a detailed petrological and geochemical study of a greenstone belt (Superior Province, Canada). The greenstone belt in question comprises volcanites of basalt-komatiite composition, which are associated with the rocks of the tonalite-trondhjemite series (Fig. 11). The model is as follows: bazaltoid volcanic series of high-thickness crust are intruded by magmas generated by a rising plume. As a result, the volcanites are partially melted and restites subside, whereas granitoid (tholeiitic) magmas rise from the lower crust to its upper levels. The formation of TTG series consists of multiple stages. In the proposed model, it includes at least 3-4 stages. To some extent, this model can be applied to the formation of oceanic plateaus. It is evident that the drilling of modern oceanic plateaus, which, like Archaean TTG series, occur above mantle plumes, will give a better understanding of this process. The formation of granitoid rocks is in many ways similar to the formation of calc-alkaline series of subduction-related volcanites and granitoids. Unlike subduction, the sagduction process involves vertical subsidence of basaltoid rocks into the depths of the mantle.

In 2011–2016, an international program aimed at studying the Archaean magmatism of Earth was carried out. The results of these studies were published as a collective work [Halla et al., 2017]. In the course of work, Archaean granitoid formations in North Atlantic, Fennoscandian, Indian and Ukrainian shields were studied.

The researches working on the program came to the following conclusions.

The formation of tonalite-trondhjemite-granodiorite rock associations (called grey gneisses in Russia) from the studied cratons is dated at 3.9–3.6–3.4–3.1 Ga. Granitoid massifs – including batholiths – younger than 3.1 Ga were replaced by potassium calc-alkaline granitoids (sanukitoids, monzogranites enriched with rare elements and quartz monzonites).

According to the authors of [Halla et al., 2017], a change in the Earth's dynamics triggered plate tectonics.

It is assumed [Halla et al., 2017] that during the formation of K granitoids dated at 3.1–2.5 Ga, some Precambrian cratons, which previously constituted a single supercontinent, were divided into a series of smaller ones separated by oceanic basins.

Thus, lid tectonics, the tectonics of mantle overturns and deep mantle plumes of ultrabasic-basic composition lasted until 3.1 Ga.

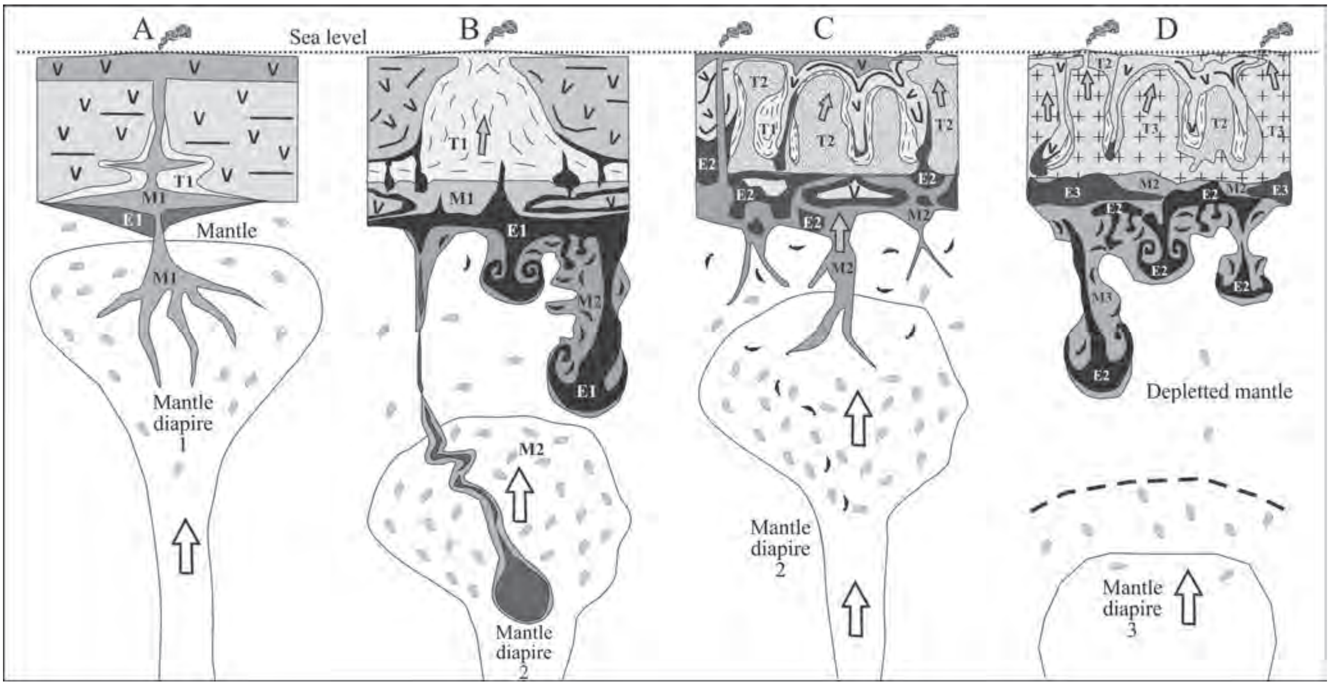


**Fig. 11**. Model of sagduction describing the generation of 3.9–3.1 Ga TTG rocks [Bédard, 2006].

The Archaean crust of high thickness subsides into the mantle to a depth at which garnet remains in restite after melting. Under the influence of high mantle temperatures, the TTG rocks are melted from the eclogitised Archaean basaltoid, which intrude into the main Archaean crust, forming the preserved first continental crust. J.H. Bédard noted that there could be 3–4 such stages.

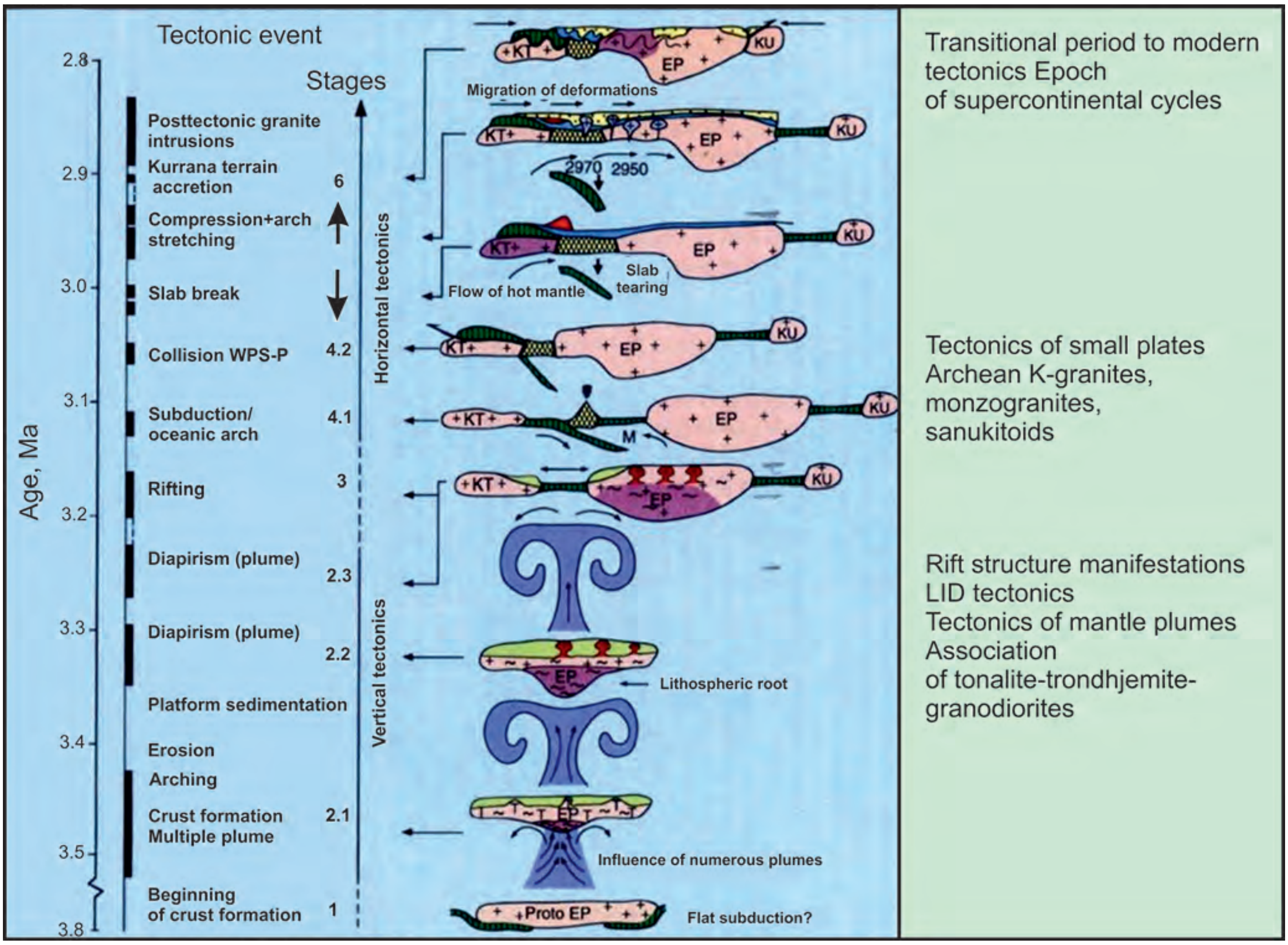


**Fig. 12**. Diagram showing tectonic-magmatic events involved in the formation of the geological structure of Pilbara Craton (Australia) according to [Pease et al., 2008] with additions.

We believe that the time interval of 3.1–2.7 Ga included a period of small-plate tectonics, whereas the interval of 2.7–2.0 Ga constituted a transitional period from the small-plate tectonics to modern-style tectonics. At that time, all the Earth's inner layers were formed [Kuzmin, Yarmolyuk, 2016, 2017]. The changes of tectonic movements, as well as the types of tectonic structures, that took place from the beginning of the Archaean aeon to the onset of plate tectonics, can be illustrated by a diagram (Fig. 12) containing the authors' additions.

## CONCLUSION

Studying the early stages of the Earth's evolution constitutes the basis for understanding its further geological history. The Chaotian aeon was marked by cosmic events that determined the initial development of our planet. At that time (4568–4500 Ga), the Earth formed as a result of planetesimal accretion and cosmic factors determined all the processes occurring on Earth: differentiation into the core and the mantle, formation of the Earth's satellite – the Moon. At the same time, the evolution of the Solar System itself determined its division into rocky inner and gas-water outer parts, in which the terrestrial planets were located closer to the Sun, whereas its outer part was occupied by giant gas-ice planets. The early history of the giant planets, as well as the intensity with which the terrestrial planets were bombarded by meteorites, greatly contributed to the delivery of building material to the inner part of the system.

Heavy meteorite bombardments of the Earth continued in the Hadean aeon as well. At the time, the first crust of the Earth began to form; however it was practically destroyed at the end of the Hadean aeon when the giant planets settled in their orbits and the main meteorite material was accreted by the terrestrial planets, with a significant part of it being absorbed by the Sun. Despite the fact that the Hadean aeon is seen as the beginning of the Earth's geological history, it was dominated by cosmic events. In particular, Earth, like other planets of the terrestrial group, was constantly subjected to meteorite and asteroid bombardments. Figure 13

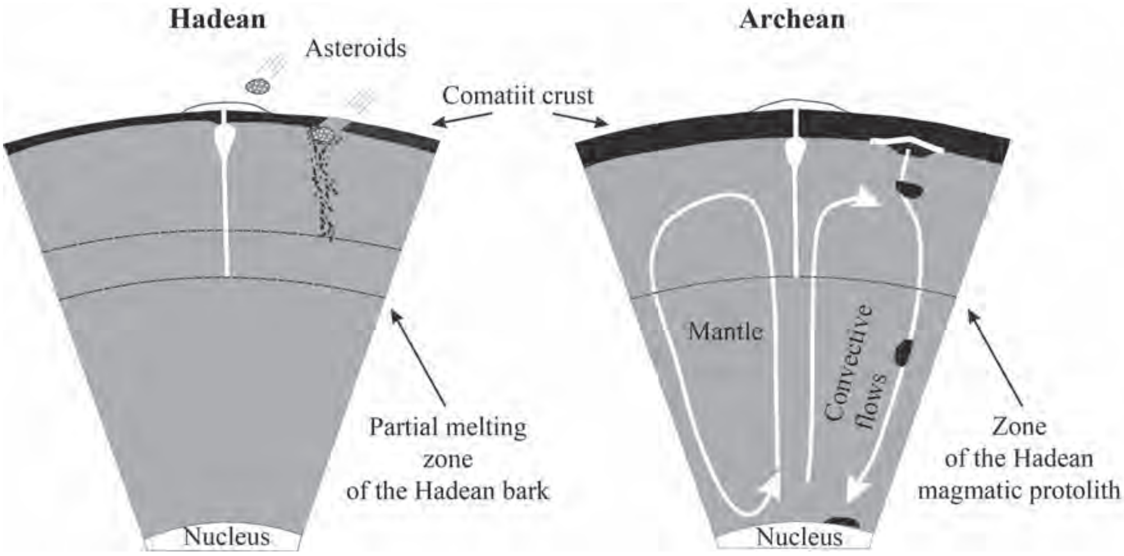


**Fig. 13**. Models of possible endogenous processes in the Hadean aeon and the Eoarchaean era.

In the Hadean aeon, a thin crust was formed by mantle magmas, whose eruptions were induced by asteroid bombardments. The bombardments destroyed the crust that subsided into the upper part of the mantle forming the Hadean protolith for subsequent magma generation. Whole-mantle convection began in the Archaean aeon, which also involved the Hadean protolith in melting. The melting of the lower crust under the influence of mantle magmas caused the appearance of melts forming TTG complexes. The restite of the lower crust descended into the lower mantle (see the text for explanation).

shows a model of the manifested endogenous processes characteristic of the Hadean time. A high temperature of the Hadean mantle, on the one hand, resulted from recently crystallised hot mantle ocean produced by the Moon-forming impact and, on the other, from the presence of a great number of short-lived isotope systems releasing a large amount of energy during the radioactive decay of parent isotopes. In this connection, whole-mantle convection most likely did not exist in the Hadean aeon. A flat stagnated surface of Earth was hit by cosmic asteroids or large meteorites destroying the planet's surface represented by rocks formed during the outpouring and differentiation of basic mantle magmas. The fragments of surface rocks subsided into the mantle, melting and mixing with the mantle material. This material subsequently formed the protoliths of the late-Hadean and Archaean magmas, which could contain refractory zircon crystals. New portions of the basic and komatiitic mantle magmas poured into the destroyed parts of the Hadean Earth's surface, which were restored by the subsequent crystallisation of magma and damaged again during the next bombardment. Thus, the Earth's endogenous activity in the Hadean aeon was completely affected by space processes.

At the end of the Hadean aeon, the mantle temperature was lowered due to the loss of a large amount of endogenous energy following the last heavy meteorite bombardment, as well as to the cessation of the radioactive decay of short-lived isotopes, which marked the beginning of the Archaean period of the Earth's geological history.

It can be assumed that due to the beginning of the whole-mantle convection (see Fig. 13), a decrease in mantle temperature did not affect the thermal state of the Earth's core. Consequently, Earth became a self-organised unit, which led to the manifestation of deep tectonic processes, i.e. endogenous activity of the planet itself, whereas cosmic impact on Earth decreased significantly. The Earth's surface remained flat and stagnated, i.e. the operation of lid tectonics continued; however it was torn apart by rising deep plumes carrying magmas of ultrabasic-basic composition, which formed a thick crust of the basic (basaltoid) composition at the exit points. The surface layer of Earth could not withstand the load of the upper layer, which, undergoing sagduction, subsided forming granitoid magmas, subsequently producing rocks of the TTG series. Pouring onto the surface, magmas formed the Archaean granitoid continental crust that has been preserved to date.

With its thickness gradually increasing, the continental crust started to break and sink into the mantle: marking the onset of small-plate tectonics, which due to the formation of the Earth's inner layers [Condie, 2011; Kuzmin, Yarmolyuk, 2017] further evolved into the modern-style tectonics combining plate tectonics and plume tectonics.

Surely, this general view of our planet's evolution is largely speculative and needs to be further revised, which in turn requires detailed comprehensive geological studies.

## REFERENCES


Allègre C.J., Poirier J.P., Humler E., Hofmann A.W. (1995) The Chemical-Composition of the Earth. *Earth Planet., Sci. Lett.*, **134**(3-4), 515-526. http://dx.doi.org/10.1016/0012-821X(95)00123-T

Batygin K., Laflin G., Morbidelli A. (2016) Born from the chaos. *V mire nauki*, (7), 16-27. (In Russian)

Bauer A.M., Fisher C.M., Vervoort J.D., Bowring S.A. (2017) Coupled zircon Lu-Hf and U-Pb isotopic analyses of the oldest terrestrial crust, the >4.03Ga Acasta Gneiss Complex. *Earth Planet. Sci. Lett.*, **458**, 37-48.

Bédard J.H. (2006) A catalytic delamination-driven model for coupled genesis of Archaean crust and sub-continental lithospheric mantle. *Geochim. Cosmochim. Acta*, **79**, 1188-1214.

Cameron A.G.W. (1986) The impact theory for origin of the Moon. *Origin of the Moon* (Eds W.K. Hartmann, R.J. Phillips, G.J. Taylor). Houston, TX: Lunar & Planetary Institute, 609-616.

Condie K.C. (2011) Earth as an evolving Planetary System. Elsevier, 574 p.

Garnero E.J., McNamara A.K. (2008) Structure and Dynamics of Earth's Lower Mantle. *Science*, **320**, 626-628

Gilat A., Vol A. (2012) Degassing of primordial hydrogen and helium as the major energy source for internal terrestrial processes. *Geosci. Front.*, **1**, 911-921. doi:10.1016/j.gsf.2012.03.009

Glukhovskii M.Z., Moralev V.M., Kuzmin M.I. (1977) Tectonics and petrogenesis of the Katarchean complex of the Aldan Shield in connection with the problem of protophyolites. *Geotektonika*, (6), 103-117. (In Russian)

Goldblatt C., Zahnle K.J., Sleep N.H., Nisbet E.G. (2010) The eons of chaos and hades. *Solid Earth*, **1**, 1-3. http://dx.doi.org/10.5194/se-1-1-2010

Grange M.L., Pidgeon R.T., Nemchin A.A., Timms N.E., Meyer C. (2013) Interpreting the U-Pb data from primary and secondary features in lunar zircon. *Geochim. Cosmochim. Acta*, **101**, 112-132. http://dx.doi.org/10.1016/j.gca.2012.10.013

Hain V.E. (2003) *Osnovnye problemy sovremennoi geologii* [The main problems of modern geology]. Moscow, Nauch. mir Publ., 348 p. (In Russian)

Halla J., Whitehouse M.J., Ahmad T., Bagai Z. (2017) Archaean granitoids: an overview and significance from a tectonic perspective. http://sp.lyellcollection.org/bu guest on February 3

Harrison T.M., Schmitt A.K., McCulloch M.T., Lovera O.M. (2008) Early (N = 4.5 Ga) formation of terrestrial crust: Lu–Hf, $\delta^{18}O$ and Ti thermometry results for Hadean zircons. *Earth Planet. Sci. Lett.*, **268**(3-4), 476-486.

Hartmann W.K. (1986) Moon origin: the impact-trigger hypothesis. *Origin of the Moon* (Eds W.K. Hartmann, R.J. Phillips, G.J. Taylor). Houston, TX: Lunar & Planetary Institute, 579-608. http://dx.doi.org/10.1016/j.epsl.2008.02.011.

Iizuka T., Horie K., Komiya T., Maruyama S., Hirata T., Hidaka H., Windley B.F. (2006) 4.2 Ga zircon xenocryst in an Acasta gneiss from northwestern Canada: Evidence for early continental crust. *Geology*, **34**(4), 245-248.

Jackson M.G., Carlson R.W., Kurz M.D., Kempton P.D., Don Francis, Blusztajn J. (2010) Evidence for the survival of the oldest terrestrial mantle reservoir. *Nature*, **466**, 853-856.

Jackson M.G., Konter J.G., Becker T.W. (2017) Primordial helium entrained by the hottest mantle plumes. *Nature*, **542**, 340-343.

Kostitsyn Yu.A. (2012) Age of the Earth's core by isotopic data: matching of Hf-W and U-Pb systems. *Geokhimiya*, (6), 531-554. (In Russian)

Kuzmin M.I. (2014) Precambrian history of the origin and evolution of the solar system and the Earth. Article I. *Geodynam. Tectonophys.*, 5(3), 625-640. (In Russian)

Kuzmin M.I., Yarmolyuk V.V. (2017) Biography of the Earth: the main stages of geological history. *Priroda*, (6), 12-25. (In Russian)

Kuzmin M.I., Yarmolyuk V.V. (2016) Change in the style of tectonic movements in the evolution of the Earth. *Dokl. Akad. Nauk*, **469**(6), 706-710. (In Russian)

Lauretta D. (2011) A cosmochemical view of the Solar System. *Elements*, **7**(1), 11-16. http://dx.doi.org/10.2113/gselements.7.1.11

Lin D. (2008) Origin of the planets. *V mire nauki*, (8), 22-31. (In Russian)

Maas R., Kinny P.D., Williams I.S., Froude D.O., Compston W. (1992) The Earths oldest known crust – a geochronological and geochemical study of 3900–4200 Ma old detrital zircons from Mt. Narryer and Jack Hills, Western Australia. *Geochim. Cosmochim. Acta*, **56**(3), 1281-1300. http://dx.doi.org/10.1016/0016-7037(92)90062-N

Maruyama S., Ebisuzaki T. (2017) Origin of the Earth: A proposal of new model called ABEL. *Geosci. Front.*, **8**, 253-274.

Masset F., Snellgrove M. (2001) Reversing type II migration: resonance trapping of a lighter giant protoplanet. *Mon. Not. R. Astron. Soc.*, **320**(4), L55-L59.

McDonough W.G., Sun S.S. (1995) The composition of the Earth. *Chem. Geol.*, **120**(3-4), 223-253. http://dx.doi.org/10.1016/0009-2541(94)00140-4

Myers J.S. (1988) Early Archean Narryer gneiss complex, Yilgarn Craton, Western-Australia. *Precambr. Res.*, **38**(4), 297-307. http://dx.doi.org/10.1016/0301-9268(88)90029-0

Nebel O., Rapp R.P., Yaxley G.M. (2014) The role of detrital zircons in Hadean crustal research. *Lithos*, **190-191**, 313-327.

Newsom H.E., Taylor S.R. (1989) Geochemical implications of the formation of the Moon by a single giant impact. *Nature*, **338**, 29-34.

O'Neil J., Carlsona R.W., Paquetteb J.L., Francisc D. (2012) Formation age and metamorphic history of the Nuvvuagittuq Greenstone Belt. *Precambr. Res.*, **220-221**, 23-44.

Pease V., Percival J., Smitbies J., Stevens G., Kranendank M. (2008) When did plate tectonics begin? Evidence from the orogenic record. *Geol. Soc. Amer., Spec. Paper*, **440**, 199-228.

Reimink J.R., Chacko T., Stern R.A., Heaman L.M. (2014) Earth's earliest evolved crust generated in an Iceland-like setting. *Nat. Geosci.*, **7**, 529-533.

Roth A.S.G., Bourdon B., Mojzsis S.J., Touboul M., Sprung P., Guitreau M., Blichert-Toft J. (2013) Inherited $^{142}$Nd anomalies in Eoarchean protoliths. *Earth Planet. Sci. Lett.*, **361**, 50-57.

Stern R.J. (2008) Modern-style plate tectonics began in Neoproterozoic time: An alternative interpretation of Earth's tectonic history. *Geol. Soc. Amer., Spec. Paper*, **440**, 265-280.

Taylor D.J., McKeegan K.D., Harrison T.M. (2009) Lu-Hf zircon evidence for rapid lunar differentiation. *Earth Planet. Sci. Lett.*, **279**(3-4), 157-164. http://dx.doi.org/10.1016/j.epsl.2008.12.030

Wood B. (2011) The formation and differentiation of Earth. *Physics Today*, **64**(12), 40-45. http://dx.doi.org/10.1063/PT.3.1362

Wood B.J., Halliday A.N. (2010) The lead isotopic age of the Earth can be explained by core formation alone. Nature, **465**(7299), 767-771. http://dx.doi.org/10.1038/nature09072