Origin and formation mechanism of craters, seas and mascons on the Moon

A A Barenbaum\(^1\) and M I Shpekin\(^2\)

\(^1\) Oil and Gas Research Institute of the Russian Academy of Sciences, Gubkin Street 3, Moscow 119991, Russia

\(^2\) Kazan Federal University, Kremlyovskaya 18, Kazan, Tatarstan 420008, Russia

E-mail: MichaelS1@yandex.ru

Abstract. The formation mechanism of craters with diameters \(D \geq 10\) km, as well as seas and mascons on the Moon, caused by the periodic falls of galactic comets, is considered. The basis of this mechanism is the cumulative effect due to the large kinetic energy of galactic comets and the high intensity of their falls. In contrast to craters, formation of seas and mascons occurs with the participation of geodynamic (magmatic) foci, which are formed due to strong heating and melting rocks beneath craters by cometary shock waves. The heating energy needed to create such foci is provided by falls of multiple galactic comets in conditions of high density of their falls. The model has been developed that allows studying cumulative effects at formation of lunar seas and mascons, based on the data of high-precision gravimetric and altimetric studies of the Moon. The model quantitatively explains the differences in the total number of seas and distribution them in size on the visible and reverse side of the Moon.

1. Introduction

In paper [1] the hypothesis is substantiated that large craters, seas and mascons on the Moon [2–4], as well as Mars and Mercury [5, 6] are formed during periods of bombardment of the Solar System by galactic comets. The falls of these comets has the character of intense “comet showers” lasting 2–5 million years, which cyclically repeat in 20–37 million years [7].

The last cometary bombardment, which formed most craters with diameter \(D \geq 10\) km, a seas and mascons on the Moon, took place in time interval from 5 to 1 million years ago. The comets moved relative to the Sun at a speed of \(\approx 450\) km/s, their nuclei consisted mainly of water ice, had a diameter of \(\approx 0.1–3.5\) km, a mass of \(\sim 10^{12}–10^{17}\) g and an energy of \(\sim 10^{20}–10^{25}\) J. The distribution of comets along the diameters was exponential, the density of falls was \(\approx 3–5\) comets on an area of \(100 \times 100\) km\(^2\), and they mostly bombarded the southern hemisphere of the Moon [8].

Calculations show [7] that at the indicated kinetic energy galactic comets on the Moon, as well as on the Mars and Mercury, are able to form craters with a diameter of 10 to 160 km, which like comets are characterized by exponential distribution in size.

In papers [8–11] is noted that at falling on planets at a speed of \(\approx 450\) km/s galactic comets along with the formation of craters cause strong heating of deep-lying rocks, creating in the lithosphere powerful asthenospheric lenses (magmatic chambers). At this a large volume of magmas is formed, which fill crater, and parts of surface exposed to bombardment by comets experience substantial uplift.
It should be taken into account that the fall of one comet can create a crater with a diameter of 10 to 160 km. At the same time, \( \approx 3-5 \) comets can fall during one bombardment on site of 100 \( \times \) 100 km\(^2\). Therefore, the regions of the Moon, Mars and Mercury subjected by bombardment are completely saturated with cometary craters [12]. In this case, the probability of superimposing crater funnels is high, which leads to an increase in the size of the resultant crater, as well as to the heating of rocks from falls of many comets [1]. The physical mechanism for seas and mascons formation as result of multiple falls of galactic comets, we called “cumulative mechanism”. In this mechanism, the formation of seas and mascons is probabilistic process. The size of seas and the magnitude of Bouguer gravitation anomaly over them are determined by number, order and time falling of comets different sizes. All these factors are unknown a priori.

In the paper we propose a model that allows to study cumulative processes associated with the imposition of cometary craters. This model is used by us in the analysis and new interpretation of the empirical data [4, 13, 14].

2. Interpretation model

The model is based on two assumptions.

Assumption 1: Large craters, seas and mascons on the Moon are formed as a result of falls of two different types of bodies:

- asteroids and comets of Solar System;
- galactic comets.

The former have an inversely quadratic distribution in size, and the latter have an exponential distribution. As a result, craters, seas and mascons have size distributions of the same type as cosmic bodies.

The latter circumstance makes it possible to distinguish craters, seas and mascons formed by cosmic bodies of different nature, analyzing their distributions along diameters on two graphs:

- in a double logarithmic coordinate system in the form of R-function [15];
- in a semi logarithmic coordinate system in the form of a cumulative number of \( N(D) \) structures with a diameter greater than \( D \).

The impact structures created by asteroids and Solar System comets on the R-diagram will have distribution in the form of straight line parallel to the abscissa axis. Whereas structures formed by galactic comets will give the distribution \( N(D) \) in semi logarithmic coordinates in the form of oblique line.

Assumption 2: The fall of galactic comets on the Moon is purely random. Therefore, the formation of craters, seas and mascons caused by galactic comets fall is also a random process, to the study of which one can attract the conclusions of a well-developed probability theory.

The probability theory, as it is known, operates with the values of mathematical expectations \( M \), characterizing average values of random variables. Herewith, the summation result of several random variables is also a random variable. In the case of the independence of random variables, the mathematical expectation of their sum is

\[
M_{\Sigma} = \sum_{i=1}^{k} M_i. \tag{1}
\]

Let the random variable will be the diameter of emerging crater \( D \), and the craters themselves are characterized by the exponential distribution of their spectral density over the diameters \( n(D) = n_0 \exp(-\lambda D) \), where \( n_0 \) and \( \lambda \) are constants, the diameters of the craters being within \( \alpha \leq D \leq b \).
Then the process of crater formation can be characterized by mathematical expectation, 
\[ M = \overline{D}, \]
where \( \overline{D} \) is the average crater diameter
\[
\overline{D} = \frac{n_0 \int_a^b D e^{-\lambda D} dD}{n_0 \int_a^b e^{-\lambda D} dD} = \frac{(\alpha + \lambda^{-1})e^{-\lambda \alpha} - (b + \lambda^{-1})e^{-\lambda b}}{e^{-\lambda \alpha} - e^{-\lambda b}}.
\] (2)

In particular, for \( \alpha = 0 \) and \( b = \infty \), the quantity \( M = \overline{D} = 1/\lambda \).

In the case of craters overlap due to accidental fall of several comets, the diameter of a resultant crater increases. The size distribution of such “complex” craters will remain exponential, and their average diameter (mathematical expectation) will be
\[
\overline{D}_\Sigma = \sum_{i=1}^k D_i = k\overline{D} = k/\lambda,
\] (3)
where \( k \) is the number of overlaps. This reasoning is general and therefore applicable to processes that also participate in the formation of seas and mascons. The logic is simple. With increasing \( k \), the thermal energy transferred to the rocks increases, as a result of which the volume of magmatic melts from the craters that form basaltic seas, as well as the depth of occurrence under craters of the magma chambers increases. The increase of the diameter of complex craters leads to increase of the size of sea basins, as well as to the growth of amplitudes Bouguer gravity anomalies over the seas.

3. Actual data and their discussion

Let us now use these conclusions to analyze available evidence separately for craters, seas and mascons on the Moon.

3.1. Craters

It is known that craters with diameter \( D \geq 10 \) km on continents and seas of the Moon, as well as of Mars and Mercury differ morphologically, they are characterized by different size distributions and are unequally located relative to the equator of a planet. Figure 1 shows the differential distribution of craters on diameters in elevated (continental) and depressed (marine) areas of the surface of the Moon, Mars and Mercury [14] in double logarithmic scale with variable pitch (R-graphs). Such R-distribution allows to represent the inverse-quadratic dependence in the form of a straight line parallel to the axis of abscissae. We see that the density of marine craters is 1–2 orders of magnitude lower than that of continental ones. Moreover craters on continents are distributed in diameters differently than on seas.

The main reason for the difference between “continental” and “marine” craters is that large craters on continents are created by the fall of galactic comets, and on seas — formed by falls of asteroids and Solar System comets.

This conclusion is illustrated in figure 2, where the distribution of craters on the Moon, Mars and Mercury in the range of diameters \( D = 10–160 \) km [16] is represented as a function
\[
N(D) = \int_a^b n(D)dD
\] (4)
in semi-logarithmic coordinates. Because of the sharp prevalence of craters formed by galactic comets, the integral distribution of all craters in this range of diameters is subject to an exponential dependence \( n(D) = n_0e^{-\lambda D} \) with the exponent \( \lambda = 0.033 \) km\(^{-1}\).
Figure 1. R-distribution of large craters on upland (continental) and lowered (marine) areas of the Moon, Mars and Mercury [14].

Figure 2. Cumulative $N(D)$ distributions of upland craters on the Moon, Mercury and Mars [7].

The data in figure 2 also show that the continental sites of lunar surface are completely saturated with craters created by galactic comets. This conclusion is substantiated as follows [12].

We will proceed from the fact that when a crater is formed, large quantity of rocks is ejected, which forms around crater funnel a continuous covering which smooths out details of the surface in the zone near a crater. At the same time the area of emissions is not small. For craters of Moon in the range of their diameters $D = 1.3–436$ km, radius of outer boundary of continuous cover by emissions is $2.35$ times more than that of crater radius [17]. On Mars the cover by emissions is somewhat less and constitutes $\approx 2$ of crater radius [15].

So, any newly formed crater if not completely eliminates, at least, greatly leveled nearby craters in an area exceeding its own in $\approx 2^2–2.35^2 \approx 4–5$ times. Therefore even for the repeatedly “plowed” lunar surface, completely saturated with craters, the areas under craters and areas not occupied by them, are comparable.

To calculate the value of this relation, let’s suppose that on certain surface of area $S$, the summary area of craters (including the altered by emissions near crater zone) is $s$, where $s < S$. Then the probability that among all craters there are those that have never been “erased”, will be $p_0 = s/S = \sigma$. The probability of existence of craters erased once will be $p_1 = (s/S)^2 = \sigma^2$, twice—$p_2 = \sigma^3$, etc. Assuming that the process of crater formation began a long time ago, and that any point of the surface has experienced a change at least once, we will have

$$
\sum_{n=1}^{\infty} \sigma^n = 1.
$$

On the left-hand side of formula (5) there is a geometric progression its sum is $\sigma/(1-\sigma)$. And, consequently, $\sigma = 0.5$. Thus, we come to the conclusion that in a state of complete saturation of the surface with craters, crater funnels and near-crater emissions will cover $50\%$ of the area of the surface. In this case, craters will occupy $\sigma/5 \approx 10\%$ of all surface.

This conclusion imposes a limitation on lower limit of diameters of galactic comets craters. With complete saturation of surface with cometary craters, crater funnels of diameter $D \leq \alpha$, if
they arise, are not preserved under influence of emissions accompanying the formation of larger craters.

Thus, the lower boundary of the dimensions of the craters $\approx 10$ km in figure 2 is explained by saturation of continents surface with cometary craters with $D \geq 10$ km, which “erase” all smaller craters [7]. The upper limit of range $b$ is explained by the fact that structures with a diameter $D \geq 160$ km on the Moon are qualified not as craters, but as marine basins basalt-filled or, more simply, the “seas”.

We also note that the values of the limiting saturation of the craters of the continents of the Moon, Mercury and Mars are close to $\approx 100$ on an area of 1 million km$^2$ (see figure 2). The distributions of these craters are similar also in size. On the Moon and Mercury, which do not have an atmosphere, the $N(D)$ dependences are practically identical. On Mars, due to the ablation of the nuclei of galactic comets in Martian atmosphere [18], the density of the larger craters is lower. According to formula (1), the average diameter of galactic comets craters on Moon continents is $D_c = 39$ km.

The depth of cometary craters is also important. According to [19], in the range of diameters $11 \leq D \leq 400$ km, depth of continental craters is related to their diameter by the relation $H = 1.044D^{0.301}$. With that, under the action of galactic comets, rocks from depths of $\approx 3$–7 km can be ejected to the Moon surface. Obviously, at this the surface rocks on Moon are mixed approximately to these depths.

Let us also pay attention to the fact that although all rocks on the Moon are represented by basalts, the continents of Moon are composed of basalts of a different type than basalts of marine basins. If the continental rocks are represented by a brecciated anorthosite consisting of plagioclase, olivine, pyroxene and magnetite, then in marine basalts there are more olivines and pyroxenes and less plagioclase. Herewith they are enriched with iron and titanium.

Note rocks of continents and oceans are different in composition also on our planet. We explain these differences by different conditions of the formation of continents and oceans in the Earth history [20, 21]. Some conclusions from these works, perhaps, can be carried over to the Moon.

The available facts suggest that [1, 22], that most of the “continental” craters on the Moon arose as the result of the last cometary bombardment on Neogene and Quarter boundary (5–1 million years ago), and in a smaller amount in the two or three previous bombings on boundaries of Oligocene–Miocene, Paleocene–Eocene, and Cretaceous and Paleogene. Therefore, lunar landscape presented by craters and seas, probably has age of the Cenozoic, i.e. not older than 65 million years.

Valuable information on the process of crater formation can be obtained from the analysis of craters on the seas (see figure 1). As in craters on continents (see figure 2), the diameter of marine craters does not exceed 160 km. In this case, a significant number of marine craters have an asteroid origin, since within the errors their R-graph is parallel to the abscissa axis. A weak raise of marine craters in the R-graph with the increase of their $D$, however, indicates the presence in seas of some fraction of galactic comets craters.

The data in figure 1 also lead to the conclusion [23] that the seas on the Moon and Mars arose either at the end of the last cometary bombardment, or immediately after its termination. Since otherwise density of large craters in the seas would not be so much lower than on the continents.

3.2. Sea basins

There is no doubt that a craters with diameter $D \geq 160$ km, which we qualified as sea basins also are formed by galactic comets, since their size distribution (see figure 1) is a consequence of representation of exponential dependence in coordinates of R-graph. In [4] a size distribution of a large sample of marine basins was constructed. In figure 3(a), we present these data in a
Figure 3. (a) Integral distributions of the sea basins by diameter [4] in a semi-logarithmic coordinate system. Black rhombuses and red squares refer to basins on the near and far sides of Moon, respectively. Range of possible errors in the averaging is shaded. (b) Amplitude of central gravitational Bouguer anomaly (BA) over continental craters of the Moon. Orange line shows model results [13].

semi-logarithmic coordinate system, approximating $N(D)$-distribution of seas by exponentials (dashed lines). The solid line shows averaged dependence.

The authors of [4] found that on the near side of the Moon there are more large basins ($D \geq 350$ km), whereas on the back side there are smaller basins. The authors explain the differences in sizes of basins on the visible and opposite Moon sides by the different thicknesses of the crust on both sides of Moon, as well as by differences in porosity and temperature of lunar rocks.

According to our interpretation of the data, figure 3(a), marine basins arise when crater funnels are applied from several fallen comets, and very large comets, which leads to a much larger volume of basaltic lavas.

The mathematical expectation of this random process, calculated from formula (2), gives mean diameter of seas on the near and the far sides of Moon of $\approx 520$ km and $\approx 350$ km, respectively. And for the Moon as a whole, the average value is equal to $D_s = 426$ km.

According to these data, the number of overlapping cometary craters forming the seas is $k = D_s/D_c = 11 \pm 2$. On the near side of the Moon, the number $k$ is greater due to the smaller thickness of the crust. The reduction of thickness of refractory anorthosite crust, other things being equal, leads to formation of larger sea basins. The obtained value of number $k$ is probably overestimated, since, in contrast to falls of comets, growth of diameters of craters and sea basins, strictly speaking, is not accidental, since it depends on their size and the degree of rock heating.

The value $k$ can be estimated in another way, based on a joint analysis of the data in figures 2 and 3(a). From these data it follows that, as diameter increases, the transition from craters to sea basins is not monotonous. So, if the number of craters with $D \geq 160$ km is $N_c(160) \approx 0.7$ per million km$^2$ (see figure 2), then the number of basins of the same diameter is $N_s(160) = 2 \pm 0.5$ per million km$^2$, see figure 3(a). From this we find the number $k \approx 3$.

We explain the excess $N_s(160)$ according to $N_c(160)$ by the specificity of the mechanism of the formation of craters and seas by galactic comets. Taking into account the study of these
processes on Earth [9, 20, 24], it should be assumed that craters are formed in the “dense” continental lithosphere from the fall of individual comets. While, seas arise in conditions of “thin” oceanic lithosphere, where they are created by magma which pours out to the surface from asthenospheric lenses, formed at high frequency of cometary falls.

In our model, large sea basins are formed mainly by imposition of craters from falls of many galactic comets. Therefore, within a single basin, several centers may arise, which are capable of forming a system of non-aligned topographic rings of different diameters. Such ring structures are really observed in large sea basins [4].

3.3. Mascons

The above representations are fully applicable to mascons, with the difference that mantle diapirs require more energy for heating rocks than craters and basaltic seas. Therefore, mascons are present only in fairly large marine basins [4, 13].

According to [13], reliable positive Bouguer anomalies indicating the presence of a mascon under the pool bottom are observed in structures with a diameter $D \geq 200$ km, figure 3(b). Although in figure 3(b) all such structures are called craters, starting from $D \geq 160$ km, they should be qualified as marine basins. As the size of the basin increases, the magnitude of Bouguer anomaly also increases.

However, the term “size of sea basin” needs to be clarified. The size of not very large basins is determined by the diameter of their inner topographic ring, which coincides with the diameter of the mascon [4, figure 4]. In large sea basins the diameter of the main, most clearly topographically expressed ring is implied under their size. This definition, in particular, is resorted to when analyzing the relationship between the size of the Bouguer anomaly and the size of seas in the whole range of their diameters [4, figure 3].

The authors [4] provide a catalog of mascons on the Moon, containing a total of 181 structures, which are subdivided into several groups according to morphology. These are “complex” craters of diameters of 160–200 km, some of which have elevated values of Bouguer anomaly, and some are not (37 objects); sea basins with one topographic ring without internal structure (29); sea basins of the “peak-ring” type (16); “multi-ring” basins (11), heavily degraded basins without clear topographic signs of impact impacts (17). The largest group of mascons (71) is represented by strongly modified structures that cannot be classified. These mascons are mostly located on the continents and do not show an obvious connection with continental craters.

Here are two conclusions that we draw on the basis of data [4]. The first is that the processes of formation of the seas and mascons on the Moon, in contrast to the formation of craters, have an energy threshold. Hereafter the energy of mascons formation is higher than that of sea basins. So if energy required for sea basins is greater than for craters with $D = 160$ km (see figure 2), then for mascons, see figure 3(b) this energy should exceed formation energy of sea basins with a diameter $D = 218 \pm 17$ km [13]. On visible and opposite sides of the Moon the energy of formation of sea basins the same size is different, see figure 3(a).

The second conclusion concerns the possibility of the evolution of marine basins with time. We proceed from the assumption that sea basins on the Moon arise when rocks of lunar lithosphere are sufficiently strong heated by cometary shock waves, which leads to the formation of large asthenospheric lenses under the craters. We believe that this process is also taking place on Earth, where it participates in creation of magmatic chambers in “thin” oceanic lithosphere. Subsequently these magmatic chambers float to surface, which allows us to explain some features of intraplate magmatism in oceans [7].

The same may occur on the Moon and reverberate on magnitude of Bouguer anomaly and morphology of a sea basin. From this point of view, basins with one topographic ring without an internal structure are an earlier stage in the evolution of marine basins than structures of the “peak-ring” type. Other types of marine basins are older. First of all, this refers to unclassified
mascons, many of which are located on the continents and do not show an obvious connection with continental craters.

The origin of “continental” mascons should be discussed separately. The fact is that due to inclination of ecliptic to Galaxy’s plane by angle of $62^\circ$, at orbital motion of the Sun in Galaxy galactic comets alternately in 150 million years bombard southern and northern hemisphere of all planets. Therefore, when for example in the southern hemisphere craters are formed, the relaxation processes in northern hemisphere level out the unevennesses of surface that arose earlier. And vice versa.

It was found that during the last 65 million years (in Cenozoic), comets predominantly bombard the southern hemisphere of the Earth and Mars, while 200–150 million years ago they (in Jurassic) bombarded the northern hemisphere [12]. This conclusion, obviously, is also true for the Moon. Therefore, it should be expected that in the southern hemisphere of the Moon there are more “young” Cenozoic basins, whereas in the northern hemisphere “old” mascons predominate, like modern oceans on Earth, in the Jurassic time. We believe that mascons on the continents of the Moon are the mantle diapirs that were previously in sea basins. However, at present these basins have already ceased to exist. Transformed by bombards of galactic comets these seas today have turned into continents.

Figure 4 shows the latitudinal distributions of 29 marine basins with one topographic ring without an internal structure, which we consider “young”, and 71 mascons with unclassified structure, which we consider “old”. It is clear that the young basins dominate the southern hemisphere of Moon, while the number of older structures is greater in the northern hemisphere.

4. Conclusions

The following results and conclusions are obtained in the article:

- The formation mechanism of large craters ($D \geq 10$ km), seas and mascons, caused by the periodic fall of galactic comets to the Moon, is considered. The basis of this mechanism is the cumulative effect due to the large kinetic energy of galactic comets and the high intensity of their falls.
• Sea basins and mascons require more energy for their formation than craters. They arise in result of superimposition of falls several large galactic comets. At this craters formed by single comets have $D = 10–160$ km, marine basins $D \geq 160$ km, and structures with mascons $D \geq 218 \pm 17$ km. In the case of mascons, the heating of rocks extends to the mantle depths.

• In contrast to the craters, the sea basins and mascons are arisen with the participation of geodynamic (magmatic) foci, which are formed by heating and melting rocks by cometary shock waves. Only large number of galactic comets can provide the energy necessary to create magmatic foci in conditions of high density of their falls.

• Distribution of the seas in size and their average diameter on the near and far sides of the Moon is explained by the thickness of the lunar crust. According to our preliminary estimates, on the near side of the Moon the average diameter of the seas is determined by $\approx 13$ comet falls, whereas on the far side of the Moon, the mean diameter of the seas is determined by $\approx 9$ comet falls.

• Sea basins and most craters on the continents of the Moon arose in the Cenozoic under the influence of 2–3 last bombardments by galactic comets. The continental mascons of the Moon are older, but their age hardly exceeds Mesozoic (the last 180 million years).

Acknowledgments
The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

References
[1] Barenbaum A A and Shpekin M I 2018 J. Phys.: Conf. Ser. 946 012079
[2] Akim E L 1966 Dokl. Akad. Nauk SSSR 170 799
[3] Paul M and Sjogren W 1968 Science 161 680
[4] Neumann G A, Zuber M T, Wieczorek M A, Head J W, Baker D M H, Solomon S C, Smith D E, Lemoine F G, Mazarico E, Sabaka T J et al 2015 Sci. Adv. 1 e1500852
[5] Smith D E, Lerch F J, Nemer R S, Zuber M T, Patel G B, Fricker S K and Lemoine F G 1993 J. Geophys. Res. 98 871
[6] Smith D E, Zuber M T, Phillips R J, Solomon S C, Hauck S A, Lemoine F G, Mazarico E, Neumann G A, Peale S J, Margot J L, Johnson C L, Torrence M H, Perry M E, Rowlands D D, Goossens S, Head J W and Taylor A H 2012 Science 336 214
[7] Barenbaum A A 2010 Galaxycentric Paradigm in Geology and Astronomy (Moscow: Librokom)
[8] Barenbaum A A 2012 Uralian Geological Journal (6) 3
[9] Barenbaum A A 2013 Uralian Geological Journal (1) 21
[10] Barenbaum A A 2015 J. Phys.: Conf. Ser. 653 012073
[11] Barenbaum A A and Shpekin M I 2016 J. Phys.: Conf. Ser. 774 012096
[12] Barenbaum A A 2002 Galaxy, Solar System, Earth. Subordinated Processes and Evolution (Moscow: GEOS)
[13] Soderblom J M, Evans A J, Johnson B C, Melosh H J, Mlijkovic K, Phillips R J, Andrews-Hanna J C, Biersen C J, Head J W, Milbury C, Neumann G A, Nimmo F, Smith D E, Solomon S C, Sori M M, Wieczorek M A and Zuber M T 2015 Geophys. Res. Lett. 42 6939
[14] Woronov A, Strom R G and Garkis M 1986 Interpretation of the crater chronicle: from Mercury to Ganymede and Callisto Satellites of Jupiter vol 2 ed Morrison D (Moscow: Mir) pp 5–48
[15] Melosh H J 1989 Impact Cratering. A Geological Process (New York: Oxford University Press Inc.)
[16] Kazimirov D A, Rodionova Z F, Sitnikov B D and Poroshkivka G A 1980 Density distribution of craters on Moon, Mercury and Mars Preprint (Moscow: Geological Institute RAS & Sternberg Astronomical Institute of Moscow State University)
[17] Chapman C R and McKinnon W B 1986 Cratering of planetary satellites Satellites ed Burns J A and Matthews M S (Tucson: University of Arizona Press) pp 492–580
[18] Barenbaum A A 2006 The study of the interaction of galactic comets with the gas shells of planets on the basis of the application of the theory of ablation and models of impact cratering Physics of Extreme States for Matter—2006 ed Fortov V E et al (Chernogolovka: IPCP RAN) pp 154–5
[19] Pike R J 1977 Size-depend in the shape of fresh impact craters on the Moon *Impact and Explosion Cratering* ed Roddy D J, Pepin R O and Merrill R B (New York: Pergamon Press) pp 489–509

[20] Barenbaum A A 2015 On the mechanism of formation of the basaltic layer of the crust of the oceans *Geology of Seas and Oceans: Proc. XXI Int. Conf. on Mariner Geology* vol 5 (Moscow: GEOS) pp 24–8

[21] Barenbaum A A 2015 On the origin of continents crust: A new approach to solving the problem *Geology of Seas and Oceans: Proc. XXI Int. Conf. on Mariner Geology* vol 5 (Moscow: GEOS) pp 29–33

[22] Barenbaum A A 2011 Tectonomagmatic processes in oceans and on continents as indicators of falls of galactic comets *Proc. Int. Conf. Dedicated to Memory of V.E. Khain: Current State of Earth Sciences* (Moscow: Moscow State University) pp 166–71

[23] Barenbaum A A and Shpekin M I 2011 *Vestnik Otdelenia Nauk o Zemle RAN* 3 NZ6011

[24] Barenbaum A A 2016 The formation of the asthenosphere by galactic comets as a new trend in tectonophyscs *Tectonophysics and Topical Issues of Earth sciences. Conf. Proc.* vol 2(5) (Moscow: Institute for Earth Physics RAN) pp 430–8