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GENETIC SOURCES AND TECTONOPHYSICAL REGULARITIES OF DIVISIBILITY OF THE LITHOSPHERE INTO BLOCKS OF VARIOUS RANKS AT DIFFERENT STAGES OF ITS FORMATION: TECTONOPHYSICAL ANALYSIS

S. I. Sherman

Institute of the Earth's Crust, Siberian Branch of RAS, Irkutsk, Russia

Discussion

Abstract: The paper presents the first tectonophysical reconstruction of initial divisibility of the protolithosphere as a result of convection in the cooling primitive mantle. Initial division of the protolithosphere into separate masses, i.e. prototypes of the blocks, and their size are predetermined by the emerging Rayleigh-Benard convection cells. In studies of geology and geodynamics, the Rayleigh-Benard convection cells were first referred to as a factor to explain the formation of initial continental cores. Considering the Rayleigh-Benard cells and their structural relics can help clarify initial divisibility of the protolithosphere and the origin of the major lithospheric plates, i.e. prototypes of continents. In our opinion, the initial mega-scale block structure of the protolithosphere and the emerging lithosphere were predetermined by the Rayleigh-Benard cells as they were preserved in the emerging lithosphere and their lower boundaries corresponded to the core-mantle boundary, i.e. one of the major discontinuities of the planet. Our theoretical estimations are in good agreement with the number and sizes of the Earth's theorized first supercontinents, Vaalbara and Ur.

In our tectonophysical discussion of the formation of the lithospheric block structure, we analyze in detail the map of modern lithospheric plates [*Bird*, *2003*] in combination with the materials from [*Sherman et al., 2000*]. In the hierarchy of the blocks comprising the contemporary lithosphere, which sizes are widely variable, two groups of blocks are clearly distinguished. The first group includes megablocks with the average geometric size above 6500 km. Their formation is related to convection in the Earth mantle at the present stage of the geodynamic evolution of the Earth, as well as at all the previous stages, including the earliest one, when the protolithosphere emerged. The second group includes medium-sized blocks with the average geometric size of less than 4500 km and those with minimum sizes, such as rock lumps. They reflect primarily the degradation of megablocks as a result of their destruction due to high stresses in excess of the tensile strength of the medium. This group may also include blocks which formation is related to convection in the upper mantle layer, asthenosphere. There are grounds to assume that through the vast intermediate interval of geologic time, including supercycles of Kenorlend, Rodin, and and partically Pangea, the formation of the large lithospheric blocks was controlled by convection, and later on, they were 'fragmented' under the physical laws of destruction of solid bodies. However, it is difficult to clearly distinguish between the processes that predetermine the hierarchy of formation of the block structures of various origins – sizes of ancient lithospheric blocks cannot be estimated unambiguously.

Thus, mantle convection is a genetic endogenous source of initial divisibility of the cooling upper cover of the Earth and megablock divisibility of the lithosphere in the subsequent and recent geodynamic development stages. At the present stage, regular patterns of the lithospheric block divisibility of various scales are observed at all the hierarchic levels. The areas of the lithospheric megaplates result from regular changes of convective processes in the mantle, which influenced the formation of plates and plate kinematics. Fragmentation of the megaplates into smaller ones is a result of destruction of the solid lithosphere under the physical laws of destruction of solid bodies under the impact of high stresses.

Key words: lithosphere, tectonic plates, blocks, convection, destruction, tectonophysics, divisibility of the lithosphere, Rayleigh-Benard cells, continents

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Генетические источники и тектонофизические закономерности разноранговой блоковой делимости литосферы на различных этапах ее формирования: тектонофизический анализ

С. И. Шерман

Институт земной коры СО РАН, Иркутск, Россия

Аннотация: Впервые проводится тектонофизическая реконструкция формирования первичной делимости протолитосферы в результате конвекции остывающей примитивной мантии. Формирующиеся в ней конвективные ячеи Рэлея-Бенара предопределяют размеры первичного разделения протолитосферы на отдельные массы – прообразы блоков. Ячеи Рэлея-Бенара не впервые используются в геологии и геодинамике. Первоначально на них ссылались для объяснения формирования первичных континентальных ядер. Обращение к ячеям Рэлея-Бенара и их структурным реликтам способствует пониманию того, как зарождается первичная делимость протолитосферы, которая трансформируется в крупные литосферные плиты – прообразы континентов. Именно консервирующиеся в формирующейся литосфере ячеи Рэлея-Бенара, нижняя граница которых корреспондировала с одним из главных разделов планеты – границей ядра, – предопределили первоначальную мегамасштабную блоковую структуру протолитосферы и формирующейся литосферы. Проведенные теоретические оценки сопоставлены и хорошо согласуются с количеством и размерами площадей первых гипотетических континентальных структур – суперконтинентов Ваальбара и Ура.

Продолжение тектонофизического разбора формирования блоковой структуры литосферы реализовано на детальном анализе карты современных литосферных плит [*Bird, 2003*] с привлечением фактических материалов [*Sherman et al., 2000*]. В широкой по размерам площадей иерархии блоков в современной литосфере Земли отчетливо выделяются две группы. Первая – мегаблоки, среднегеометрический размер которых превышает 6500 км. Их формирование на современном этапе геодинамического развития Земли, а также на всех предшествующих, в том числе и на самом раннем, при зарождении протолитосферы связано с конвекционными процессами в мантии Земли. Вторая группа – блоки со среднегеометрическим размером менее 4500 км, вплоть до минимального, соответствующего кусковатости горных пород, отражают, прежде всего, деструкцию мегаблоков в результате их разрушения под действием высоких внутренних напряжений, превышающих предел прочности среды. В этой же группе могут быть блоки, формирование которых также связано с конвекцией, охватывающей верхний мантийный уровень – астеносферу. Можно предполагать, что в громадном промежуточном интервале геологического времени, охватывающем суперциклы Кенорленд, Родинию и, частично, Пангею, формирование крупных литосферных блоков контролировалось конвекцией, а их дальнейшее «дробление» регулировалось физическими законами разрушения твердых тел. Однако четкую границу между процессами, определяющими иерархию формирования блоковых структур разного генезиса в прошедшие времена, провести трудно из-за неопределенности размеров литосферных блоков далекого прошлого.

Таким образом, конвекция в мантии является генетическим эндогенным источником первичной делимости остывающей верхней оболочки Земли, а также мегаблоковой делимости собственно литосферы в последующие этапы ее геодинамического развития. На современном этапе закономерности разномасштабной блоковой делимости литосферы прослеживаются на всех иерархических уровнях. Площади мегаплит литосферы – результат закономерных изменений конвективных процессов в мантии и их воздействия на формирование и кинематику плит; деструкция мегаплит на меньшие по площади блоки – результат закономерного дробления твердых тел литосферы при высоких напряжениях.

Ключевые слова: литосфера, тектонические плиты, блоки, конвекция, деструкция, тектонофизика, делимость литосферы, ячеи Релея-Бенара, континенты

It is now evident that without understanding the Earth's evolution since the earliest stages when the covers of our planet and its continental crust were formed, it is difficult to determine locations where the major natural resources are accumulated and to reveal how various structural elements and a wide variety of igneous rocks were generated and continue their development.

Academician M.I. Kuz'min [*2014*, p. 626]

1. Introduction

Initial divisibility of the Earth protolithosphere, i.e. the cooling outer hard cover of the planet, and its transformation with time into lithospheric blocks have not been properly studied yet in terms of the geodynamics of faulting, and tectonic regularities in divisibility of the lithospheric blocks of various ranks still need to be clarified. In the outer cover of the Earth, initial divisibility of the protolithosphere was due to cooling of the primitive mantle as a result of heat-gravitational convection manifested by Rayleigh–Bénard cells. In this study, we assess tectonophysical conditions for the generation of such cells and estimate potential sizes of the cells and amounts of primary proto-lithospheric cooling masses as prototypes of the blocks. Our estimations are consistent with the reconstructed first supercontinental cycles of the geodynamic evolution of the Earth. The block divisibility of the recent continental lithosphere is analysed in detail with reference to the map of present tectonic plates and blocks of the lithosphere and the cumulative plate count according to [*Bird, 2003*]. In addition to the data from [*Bird, 2003*] which mainly cover megaplates and blocks of medium sizes, we analyse the parameters specified in [*Sherman et al., 2000*] for medium- and small-size blocks resulting from destruction of megaplates and blocks of the continental lithosphere. We propose regression equations describing divisibility of the continental lithosphere into blocks in a wide scale range, from medium- to small-sized blocks and rock fragments in outcrops. Such fragments result from destruction of medium- and small-sized blocks of the 'solid' lithosphere which takes place when internal stresses exceed the rock breakdown point, as described by exponential functions.

The occurrence of megablocks is related to mantle convection at the early stage of the evolution of the protolithosphere and subsequent stages of its transformation into the lithosphere through the global super-cycles of the geodynamic evolution of the Earth. The scale and organization of mantle convection are factors that predetermine divisibility of the lithosphere into megablocks through all the recent stages of its development, including the present stage.

2. The primary hot cover of the Earth, its composition and thickness

One of the most recent theoretical reviews of the early stages in the evolution of the Solar System and the geological history of the Earth was published by *M.I. Kuz'min* [*2014*] who rightly notes that the global academic geological community is challenged to estimate the time when the first continental crust was formed on the Earth. He develops the concepts co-authored with V.V. Yarmolyuk [*Yarmolyuk, Kuz'min, 2012*] on the formation of the outer and deep covers of the Earth, mantle processes and their impacts on the occurrence of surface structures, igneous rocks and ores.

The review [*Kuz'min*, *2014*] is based on the latest data on the origin of the Solar System and formation of the first continental rocks on the Earth, which contain zircon, the oldest mineral so far dated on the Earth. It is assumed that the Solar System formed from a gas-and-dust nebula 4.568 Ga ago. The continental crust was gradually growing from its recorded peak size (4.25 Ga) till 4.1 Ga, i.e. completion of the first eon in Earth's history, the Hadean. It seems to be a critical milestone in the early geological history of the Earth, followed by the Archaen history [*Kuz'min*, *2014*] – intensive cooling of the outer cover of the Earth commenced in this period. The heat flow was supported by the inner supply of heat generated due to gravitational compression of the planet while its solid body was formed [*Schubert et al., 2001*].

The estimated average temperatures of the mantle range from 1250–1350 °C to 1400 °C, and a roughly estimated temperature of the cooling Earth is 0 °C. In the present stage, the maximum temperature of the asthenosphere top is about 1350–1400 °C, and this temperature level is supported by various endogenous heat sources of the Earth and compensates heat losses caused by cooling. At the early stage of the Earth evolution, temperatures range from 0°C (or slightly above 0°C) at the Earth's surface to ~1350–1400 °C at the depth levels whereat temperature changes in the period of cooling are less significant due to heat influx. Under this assumption, the cover can be viewed as a gradually cooling low-viscous fluid body comprising the lower and upper layers which temperatures are significantly different. At the first stage when the outer cover of the Earth was formed, convection was the major mechanism of heat energy dissipation. It can be assumed that convection commenced in the pre-Katarchean eon and is underway until now, while the volumes and forms of convective flows have significantly changed with time. This time period agrees with the maximum age of about 4.1 Ga determined in [*Kuz'min, 2014*] for the start of the development of the protolithosphere that converted with time into the lithosphere which development is continued.

By its initial composition, the cooling upper cover of the Earth corresponds to the so-called primitive mantle, as evidenced by the composition of chondrites, i.e. stony (non-metallic) meteorites. The bulk composition of the primitive mantle is similar to the silicate cover of the Earth which was formed of the protoplanet material after the core had separated [*Hofmann*, *1997*]. It is noteworthy that variaitons in the composition of the primitive mantle do not influence estimations of temperatures at the lower boundaries of the primary mantle masses at the cooling surface of the Earth.

Physical parameters and the composition of the primitive mantle changed in the post-Archean period [*Vrevsky et al., 2010*] including several large cycles of the geodynamic development of the Earth, which were also related to mantle convection. By the Archean period, the Earth's crust was completely formed, and the upper boundary of the mantle convection processes went down into the Earth interior by dozens of kilometres [*Artemieva*, *2011*]. Responses of the upper solid part of the lithosphere as a rheological body to external impacts, especially external loading at different velocities, became different. In the former convective medium, convection in the cooling upper layer of the quasi-fluid was replaced by heat conduction/diffusion in the solid body. Studies of destruction of solid bodies and rank-variable fracturing and faulting are reported in many papers, including [*Peive*, *1990*; *Sherman et al.*, *1991, 1992, 1994*; *Seminsky*, *2003*; *Sherman*, *2002*, *2012*, *2014a*, *2014b;* and others], and it is established that physical laws of deformation and destruction of solid bodies are applicable.

A major challenge is to analyse, in a retrospective, the origin and initial formation of structures in the cooling protolithosphere which physical properties are assumed similar to those of the cooling low-viscous quasi-liquid mass. In such a medium, the maximum dissipation of energy was ensured by convection of various types, from structurally organized (Rayleigh–Bénard cells) to chaotic. This long-term process in the upper cover of the Earth had its regular features due to convective flows of the mega mass that was cooling it. The total thickness of the cooling mass of the primitive mantle can be assumed at 2900 km as the outer core boundary is located at this depth. Below we review hydrodynamic regularities in convection of cooling low-viscous materials and relic structures which are important for reconstructing the paleogeodynamic settings of the distant past and estimating probable dimensions of the primary blocks.

3. Key regularities in the formation of convective cells in cooling low-viscous materials and relic structures

It is most reasonable to believe that energy in the cooling low-viscous medium is dissipated by mantle convection that is most common manifested by Rayleigh–Bénard cells. The cooling surface of the Earth is assumed to behave as the cooling low-viscous medium much time before the Katarchean. Convection is generally reviewed below as a prerequisite for an assessment of conditions for initial divisibility of the outer cover of the protolithosphere.

General convection equation. The onset of convection occurs when the Rayleigh number reaches some critical value. The Rayleigh number, *Ra* is a dimensionless number predetermining the behaviour of gas, fluid or mass of a very low viscosity at a specified temperature gradient. When the Rayleigh number exceeds its critical value, the equilibrium of the cooling fluid is disturbed, which leads to the occurrence of convection flows and bifurcation. The bifurcation point is the critical value of the Rayleigh number:

$$\mathrm{Ra} = \frac{g\beta\Delta T L^3}{\upsilon\chi}, \quad (1)$$

where g is the gravity acceleration; L is the size of the fluid area; ΔT is the difference of temperatures at the surface and the lower layer of the fluid; υ is the kinematic viscosity of the fluid; χ is the heat conductivity of the fluid; β is the coefficient of thermal expansion of the fluid.

If the *Ra* value is small, convection does not start. If values of *Ra* are average, conditions are favourable for heat convection. Chaos occurs at high values of *Ra*. Values of *Ra* depend on combinations of all other parameters in equation 1. However, considering cooling of the primitive mantle in the model discussed here, the difference of temperatures and thickness of the cooling layer are the main parameters. It should be noted that patterns of convective cells are significantly dependent on dimensions of the cooling area. In such cases, an additional parameter needs to be introduced – aspect ratio, *G* [*Getling*, *1998*]:

$$G=L/h, \quad (2)$$

where L is horizontal size of an area (for a circular section, it corresponds to a radius); h is vertical size of the area.

The Grashof (*Gr*) and Prandtl (*Pr*) numbers are also widely used in studies of Rayleigh–Bénard cells, but not in this review.

In the below discussion of the natural conditions, we refer to cases with large values of *G*. Horizontal projections of cells are called planforms. The planforms may significantly vary depending on parameters of the medium. Planforms of the cells which are typical observed in the experimental and natural settings are reviewed below.

Planforms of convective cells, and physical conditions for their formation and stability. Three types of cell planforms are typically observed in the experiments [*Getling, 1998*]: two-dimensional bars, hexagonal cells and square/rectangular cells (Fig. 1).

As shown in Fig. 1a, 2D bars are oriented along axis X and parallel to axis *Y (x-bars)* or *vice versa,* and a cell is formed by a pair of neighbouring bars that occupy the entire spatial interval. In the bars, fluid circulates in vertical plane *X, Z* as well as in the opposite directions.

Hexagonal cells (Fig. 1, *b*) are composed by the superposition of three systems of bars which are located at angles 2π/3 to each other. Such cells are characterised by periodicity in directions of axes *X* and *Y* and invariant in case of rotation by an angle of 60°. A hexagonal cell is classified in l-type in liquid convection cases (Fig. 1, *b–l*) or g-type in gas convection cases (Fig. 1, *b–g*) with regard to a velocity vector, i.e. depending on whether the liquid is ascending in the central part of

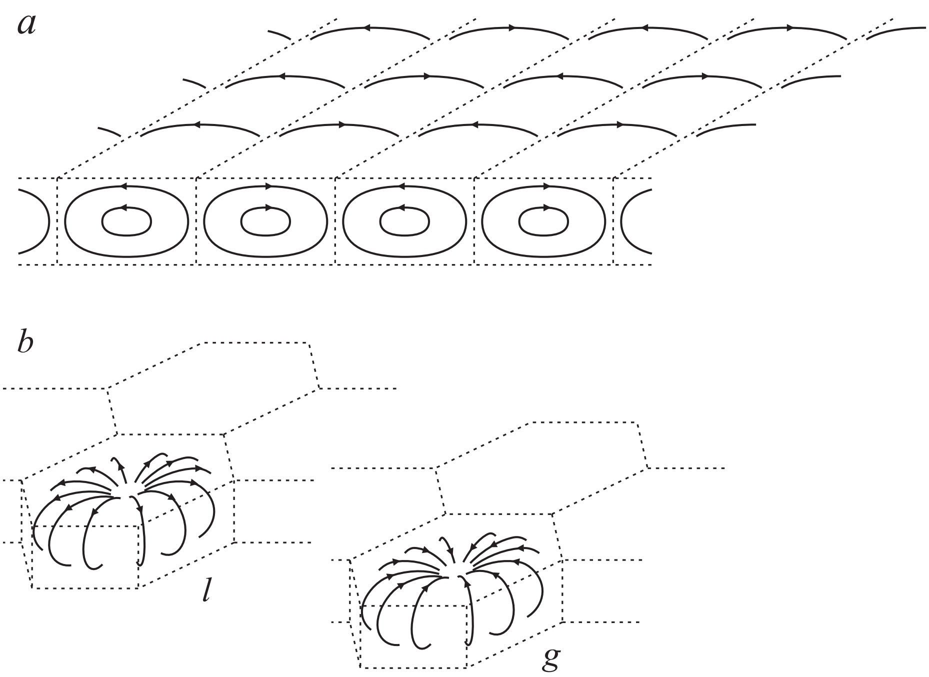

Fig. 1. Schematics of convective cells: *a* – 2D bars; *b* – hexagonal cells of l- and g-types (according to [*Getling, 1998*]).

Рис. 1. Схематическое изображение конвективных ячеек: *a* – двумерные валы; *b* – шестиугольные ячейки l- и g-типа (по [*Getling, 1998*]).

the cell or gas is descending, which, in its turn, is related to the temperature dependence from the viscosity of the medium. As known, with higher temperatures, viscosity of fluids decreases, while viscosity of gases increases. A velocity vector depends on a sign of derivative $d\gamma/dT$ which is negative for liquids and positive for gases. In the ascending convective flow, the material is always warmer than in the descending flow. Respectively, the liquid viscosity in the central parts of l-cells is lower, while the gas viscosity in the central parts of g-cells is higher. Circulation tends to follow the direction where the viscosity is lower in the centre of the cell. The stability of circulation trends, as well as the unchangeability of stationary flows of bars in relation to variations of defining parameters are estimated in a wide range of Rayleigh and Prandtl numbers, taking into account $k=2\pi/\lambda$, i.e. the number of waves of length λ per 2π radians, or the number of spatial intervals of waves per on 2π radians.

Square cells form systems which directions are rotated by a $\pi/4$ angle with respect to the coordinate system (*X*, *Y*).

Cell planforms are significantly influenced by even minor changes in the physical conditions of the medium and variations of its parameters included in the general equation of convection (see Equation 1). Two-dimensional bars are the main form of stationary convective structures produced by thermal-gravitational or thermocapillary convection mechanisms. In case of thermal-gravitational convection, the scale of flow can increase depending on ΔT and G (see Equations 1 and 2).

For the geological interpretation of the significance of cellular structures developing in cooling masses of the primitive mantle material, two facts are of importance: (1) relic structures, such as boundaries of cellular structures in the cooling protolithosphere, and subsequently, in the upper part of the lithosphere, and (2) relic masses of the deep mantle material, which were delivered into the Earth's upper horizons and cooled in zones of inter-cell boundaries, i.e. relic structures at the boundaries of the primary cellular formations. Specialists in the laws of Rayleigh–Bénard convection believe that two groups of boundaries in the Earth's upper horizons are of importance: boundaries between convective cells and border lines between orderly fragment-textures with different orientations of the bars, which comprise a more complex pattern (Fig. 2).

The most significant structural boundaries are lines bordering fragments-textures with different orientations of the bars [*Getling, 1998*]. The duration of their existence predetermines the stability of stationary convection flows and the geological significance of convection. According to [*Clever, Busse, 1996*], the hexagonal cells can be stable at $Pr \geq 1.2$ and $Ra \geq 3000$. If $Pr \leq 10$, the stability area of the hexagon cells looks like a band stretching from smaller to larger Ra values. If the

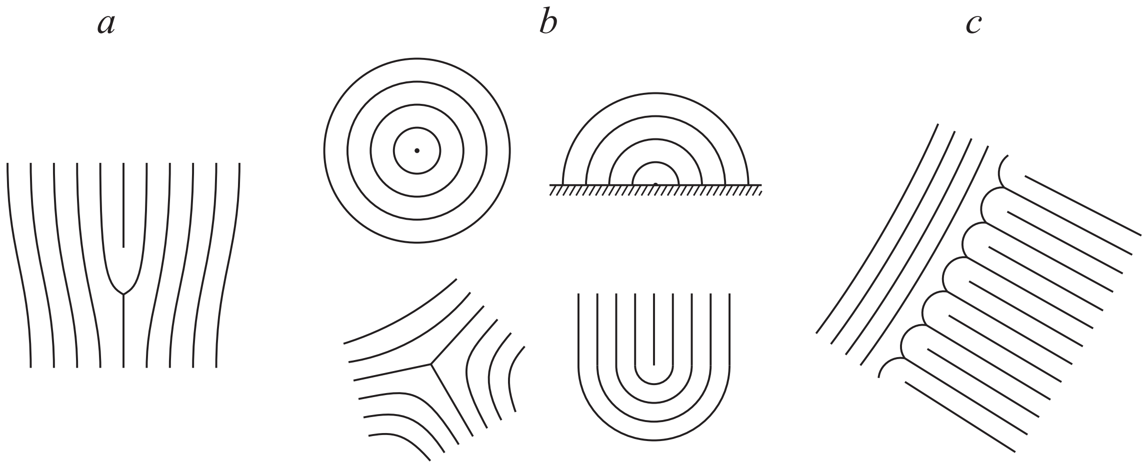

Fig. 2. Defects of bar structures (lines show boundaries of bars): *a* – dislocation; *b* – disclination (singularities of the focus type are below); *c* – structural boundary (according to [*Getling, 1998*]).

Рис. 2. Дефекты валиковых структур (линии соответствуют границам валов): *a* – дислокация; *b* – дисклинации (внизу сингулярности типа фокуса); *c* – структурная граница (по [*Getling, 1998*]).

Prandtl numbers are larger than 10, the area of stable hexagon cells is disturbed. In the experiments with *Ra* <3000, no stable hexagons are recorded.

The area of stable square cells is wider and covers the range of *Ra* from 4000 to 50000 with *Pr* varying from 2.5 to 16. When approaching the specified minimum value, the stability area narrows and becomes undetectable when *Pr*=2.5 [*Busse, Clever*, *1998*].

The material conveyed by the convective flows is hardening in places where the flows begin to move downward due to lower temperatures. Solidification takes place at the walls of thermal convection cells. Thus, when the vertical walls of the cells (i.e. surfaces of basalt prisms) are solidified, thermal convection continues inside the prisms until complete solidification of all the lava components. A photo in Fig. 3 shows the tops of basalt pillars with sagging centres of the columns which were the last to cool and solidify.

Based on the brief review of convective planforms and conditions of their formation, it is possible to reveal a common pattern of convection processes taking place during cooling of the homogeneous medium. In space and time, convection is manifested by a highly ordered flow of cooling quasi-liquid masses. The stability area is wide. As the area occupied by the flow is narrowing, stability is reduced as the characteristic scale of inhomogeneity of the structure is reducing [*Getling*, *1998*].

In standard experimental conditions, Rayleigh–Bénard convection cells occupy the entire thickness of the cooling layer, and their typical horizontal size is comparable to the vertical size or slightly exceeds it. In the majority of problems solved by geodynamics, it is assumed that convection cells occupy the entire mantle or partially occupy the layer or occur between the layers [*Kirdyashkin, Dobretsov*, *1991*; *Dobretsov et al.*, *2001*; *Trubitsyn V.P., Trubitsyn A.P.*, *2014*]. In such conditions, the main factor predetermining convection is viscosity of the medium, which is included in equations of interrelated Rayleigh, Grashof and Prandtl numbers. It can significantly increase or decrease their values and change the stability of convection accordingly. When viscosity varies by two or three orders (which may take place in the cooling upper part of the protolithosphere), the main viscosity gradient is in the topmost layer, wherein viscosity is increasing relatively faster than in the lower layers, and a hard cover is thus formed. Convection goes downward. Moreover, in the discussed cases of ascending convection, the cooling masses drift towards borders of the cells and subside due to gravity, which leads to simultaneous thickening of the emerging vertical border zone (i.e. a plane), which substance is more viscous. As the process develops further, such planes create favourable conditions for initial faulting of the lithosphere, and the lithospheric plates and large blocks are thus bordered by faults that are stable in time.

As a result of gradual cooling, a protective cap is formed over the cooling mass. As the process develops, the solid cap becomes thicker. The merger of the two descending cooling flows leads to further thickening of the emerging cap, and the partition between emerging blocks of the lithosphere is thus fixed.

Fig. 3. Solidified convection flows of basalt lava with 'sagging' surfaces in the centres of cells [*Shumilov, 2009*].

Рис. 3. Застывшие конвекционные потоки базальтовой лавы с «проседанием» поверхностей в центрах ячей [*Shumilov, 2009*].

Over time, the cap thickens and evolves into the brittle part of the lithosphere, while convection flows continue to function in the mantle and gradually drift to the lower hypsometric levels. The above-mentioned processes take place as the equilibrium of the convection system under the cap is disturbed due to changes of temperature and viscosity gradients. Conditions that are favourable for convection are now found at larger depths, and heat energy dissipation is facilitated. In this time period, the dominating convection occupying the entire mantle may be either replaced by convection in two layers or occur in a more complicated pattern.

Regardless of their planforms, the Rayleigh–Bénard cells give evidence that convection non-equilibrium can be a source of order. In comparison with the homogeneous hot mass, convective cells (regardless of their forms) can be regarded as highly organized structures facilitating the dissipation of energy and the formation of other, more stable forms in the cooling mantle. In this regard, the system remains open and continues to give the entropy.

Based on the above, cooling of the pre-Katarchean Earth's surface can be analysed with an assumption that the energy of the hot low-viscous body dissipated by thermal-gravitational convection. In this case, the Rayleigh–Bénard cells can be viewed as initial structures in the cooling mantle of the Earth, and boundaries between the cells were the first to get solidified and thus predetermined the contours of the future huge masses/blocks of the protolithosphere, which were the basis of Vaalbara and, may be, other theorized first supercontinents of the Earth.

4. The origin of the first largest local structures in the protolithosphere as viewed under the concept of convection in the cooling primitive mantle: a tectonophysical approach to paleogeodynamic reconstructions

In this study, a tectonophysical approach is proposed to analyse initial divisibility of the protolithosphere. The origin of the primary local structures / blocks is related to cooling of the Earth's surface layer composed by hot low-viscous masses of the primitive mantle. In such a medium, a relatively efficient way of heat dissipation is convection that is structurally arranged in Rayleigh–Bénard cells. Their relics, i.e. protocontinents, can be regarded as residual structures giving evidence of intitial atectonic divisibility of the protolithosphere. In this assumption, laws of their formation are determined by the laws of convection.

The cooling upper layer covered the entire primary surface of our planet. Its thickness was limited by the outer boundary of the almost completely formed core which was located at a depth of about 2900 km. It is known that the evolution of convection and its patterns are significantly influenced by dimensions (diameter and depth) of the area involved in convection (see Equation 2). For circular cross-sections in the experiments, the horizontal size of convection cells corresponds to the depth of the layer wherein convection takes place. Original convection experiments are described in the book by *N.L. Dobretsov et al.* [*2001*] who estimated the minimum horizontal size of convection cells in the lower mantle: "As follows from results of the experiments and the classical laws of convection, a cell can be stable if its transverse size is only by a factor of 1.8 times (or less) larger than its thickness" (p. 161).

Therefore, when convection takes place in a rather thick layer, a pattern of convection cells is compatible with the thickness of the layer. In our study of the mega-scale case, the horizontal size of the layer subject to convection is much larger than its vertical size, and the layer can thus be considered as a cooling flat body. The radius of the first round-shaped convective cells can amount to 2900–3000 km, and the distance between the emerging cooling boundaries of areas with descending masses (i.e. cell diameter) can be about 6000 km. In this case, the cell diameter can be numerically similar to the radius of the cooling Earth, and the cell area can be determined as the area of a spherical segment ($S_s=2\pi Rh$, where R is the Earth radius, and h is the thickness of the cooling layer, i.e. $R/2$). It amounts to πR^2 or about 3 steradians[1]. The total area of the Earth surface is $4\pi R^2$ (or $4\pi\ \Omega$). Under ideal conditions,

[1] Steradian, sr (Ω) a solid angle at the centre of a sphere subtending a section on the surface equal in area to the square of the radius of the sphere.

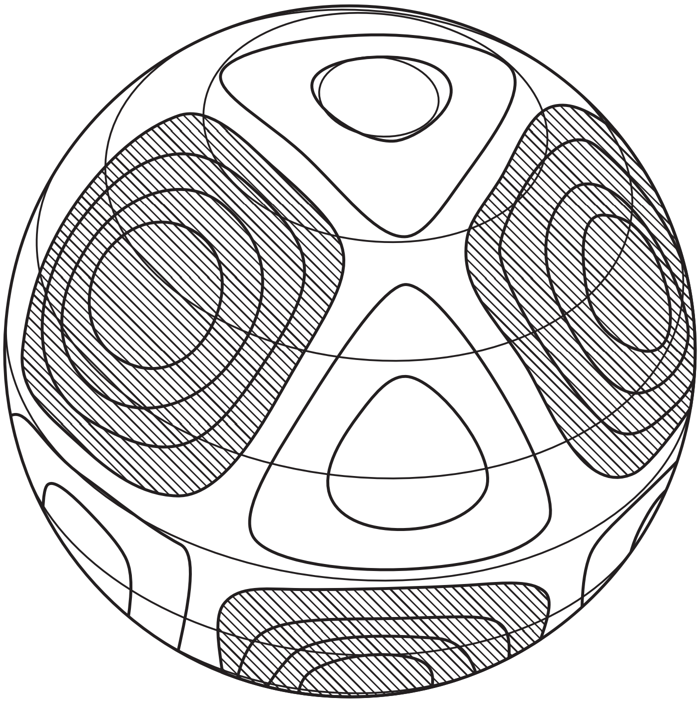

Fig. 4. Principal scheme of Rayleigh-Benard cells on the spherical surface.

Рис. 4. Принципиальная схема конвективных ячей Рэлея-Бенара на сфере.

as a maximum, four mega-large convective cells with an average area of about three steradians can form in the cooling upper cover of the Earth. It should be noted that the boundary of the bottom surfaces of the cells is the outer core of the Earth, which square area is four times smaller than that of the Earth surface. As the area of the bottom surfaces of the cells is restricted, the cells cannot achieve their potential maximum area on the surface. If a minimum surface area of a cell is one steradian, 12 cells as a maximum can form at the Earth surface. Therefore, the total number of the primary cells predetermining the initial divisibility of the emerging protolithosphere can range between 3–4 (minimum) to 12 (maximum) (Fig. 4).

Paleogeodynamic reconstructions shows that the first supercontinent Vaalbara (2.8–3.6 Ga) consisted of two major structures, i.e. protocontinents/cratons Kaapval and Pilbara [*Hazen, 2012*], which reflect the divisibility of the already solid protolithosphere and, may be, the divisibility of the emerging lithosphere. The concept that convection took place in the primitive mantle at the very early stages of the protolithosphere is not denied, although not widely discussed in the press [*Nebel et al., 2014*]. An acceptable argument is proposed by *I. Artemieva* and *B. Mooney* [*2001*] who consider the 'thermal' age of the Archean formations of the Earth.

There are grounds to state that convective processes in the Earth's mantle played the major role and were the basic criterion for the formation of the first largest block structures of the protolithosphere and also for subsequent transformations of such blocks into the lithospheric structures. According to the reconstructions, after Vaalbara supercontinent reconstructted Ura (about 3 Ga) and younger Kenorland (2100–2700 Ma), Columbia (1500–1800 Ma), Rodinia (750–1050 Ma) and Pangea (200–300 Ma) supercontinents [*Li et al., 2008*; *Lubnina, 2011*; *Hazen, 2012*]. About 200 mln years ago, Pangea broke apart to form Laurasia and Gondwana, i.e. groups of the southern and northern continents, respectively. The lithospheric megablocks have not been completely formed and destructed yet, and these processes are still ongoing at the present stage that is transitional to the formation of a new supercontinent. In the long-term geological history of the Earth, the number and dimensions of the lithospheric plates, which were actively involved in super cycles, were variable, but the blocks and plates *per se* have never disappeared completely (!). Since the Archean, these integral large bodies have been subject to many geodynamic catastrophes and reconstructions [*Li et al., 2008*], and their initial masses were partially 'lost' in some of the geodynamic cycles, regained in the others, converted into the six major lithospheric plates and survived! Strongly metamorphosed rocks of the Archaean age are observed in huge areas of the six continental lithospheric plates (Africa, Antarctica, North America, Eurasia, Australia and South America).

It is challenging to conduct a proper mathematical analysis of changes in the number of the lithospheric plates and their areas from one super cycle to another. The major cycles in the geodynamic evolution of the Earth and corresponding lithospheric plates of different shapes and kinematics are revealed by paleogeodynamic reconstructions. The lithospheric plates can provide for stable mantle convection at $Ra \leq 10^6$, but it becomes unsteady at $Ra \geq 10^7$ [*Getling, 1998*]. In response to changes in the convection pattern, the system of interacting lithospheric plates has to readjust itself. Numerical solutions of equations of energy, mass and momentum transfer suggest that mantle convection takes place while a set of plates is self-generated. According to [*Trubitsyn V.P., Trubitsyn A.P., 2014*], “the set of plates is inevitably generated, without requiring any additional boundary and initial conditions” (p. 146). The foregoing explains why the Earth has been subject to numerous transformations, including the catastrophic ones, in the natural course of its geodynamic evolution. Is this not a proof of the law of self-organized criticality which is discussed in [*Bak, 1996*]?

Obviously, mantle convection has been the major long-term genetic source providing for the cyclic geodynamic development of the entire lithosphere and its mega-block pattern.

In this regard, results of studies by P. Bird and co-authors [*Bird, 1988, 1998, 2003; Bird, Rosenstock, 1984; Bird et al., 2002*] are noteworthy – the hierarchy of the lithospheric plates and blocks is mathematically analyzed and the cumulative-number/area distribution is established. In our study, their results are complemented by experimental data published in [*Sherman et al., 2000*] (Table) and compared with other quantified information on the formation of plates and the fault-block structure of the lithosphere which vary in ranks at the present stage of development. We apply tectonophysical methods to analyse the hierarchy of the lithospheric plates and blocks with regard to their square areas at the present stage of the geodynamic evolution of the lithosphere. The analysis is aimed at identification of genetic sources and patterns of the lithosphere block divisibility at various hierarchical levels in different stages of the lithosphere evolution.

5. Recent hierarchic divisibility of the fault-block structure of the lithosphere: tectonophysical analysis

The subject of our analysis and the basis of further reconstructions is the map of lithospheric blocks of the Earth which is published in [*Bird, 2003*] (Fig. 5). Its main original features are (1) the pattern of the plates on the present surface of the Earth, and (2) calculations of plate areas in steradians (Table). To analyse ratios between areas and boundaries of the lithospheric plates, P. Bird showed them on the map close to each other in an arbitrary reconstruction (no more! – S. Sh.) of the 'intact' surface of the Earth. His map shows 52 plates of various ranks, including 'Manus microplate' which area is the smallest (0.0002 sr, see Table). Another specific feature of the map is the use of steradian, a dimensionless unit to estimate areas of plates and blocks, thus avoiding some skewing in quantitative comparisons of plates and blocks located at different latitudes of the sphere. Using this method, P. Bird presented in digital form a global set of boundaries of the present lithospheric plates and blocks of various sizes and ranks and estimated plate sizes. He established a mathematical regularity in the abrupt, non-uniform decrease of plate areas on the present Earth's sphere (columns 2 and 3 in Table). In Figure 6, the cumulative plate count as a function of plate areas in steradians is shown in the bilogarithmetic scale.

Based on Table (Nos. 1–52, column 3) supplemented by data from [*Bird, 1988, 1998, 2003; Bird, Rosenstock, 1984; Bird et al., 2002*], regression equations show that areas of the plates and blocks are decreasing with increasing numbers in the hierarchy, i.e. with transition from mega structures to regional and local ones (Fig. 6). The detailed interpretation of the plot is given in [*Bird, 2003*], and a brief is given in the figure caption (Fig. 6). The main regression line based on the data from Table has two bends.

According to *P. Bird* [*2003*], when plotted with logarithmic scales, the plates of areas between 0.002 and 1 steradian (from the relatively small Jian Fernandes plate, JZ to the large South America plate, SA) occur in numbers that roughly obey a power law:

$$\text{(cumulative count) } N\sim 7 \text{ (steradians)}^{-1/3} \text{ or } N\approx 7\Omega^{-1/3}. \qquad (3)$$

This equation clearly reflects the scale relationship between the increase in the number of plates and a proportional reduction in their areas. This is characteristic of plates which areas are smaller than one steradian, i.e. plates with an average lateral size of about 4000 km (see Table).

For a more detailed tectonophysical analysis of the relationships between sizes of the lithospheric plates and blocks, the data published by P. Bird are supplemented by results of similar studies focused on intracontinental areas [*Sherman et al., 2000*]. The consolidated database provides for analyses of tectonophysical regularities in the block divisibility of the present 'solid' lithosphere. For now, seven major lithospheric plates (Nos. 1 to 7 in Table) are outside the scope of analysis and considered below in the closing statements. These major plates are viewed as original indicators of the initial and subsequent stages of lithosphere divisibility, and it seems more reasonable to consider them after reviewing and 'excluding' quantitative data on plates dominating in number in other hierarchic levels.

Table consolidates three data sets – [*Bird, 2003*] (Nos. 1 to 52, columns 1, 2 and 3), [*Cheremnykh, 1998*] and [*Sherman et al., 2000*] (Nos. 53 to 225) and thus provides for a more detailed consideration of the ratios of areas of medium- and small-sized lithospheric plates from [*Bird, 2003*] and the ratios of areas of continental lithospheric blocks from other publications. For an adequate comparison of plate areas in different hierarchical levels, the areas calculated in steradians are converted to measurement system SI and given in square kilometres and corresponding characteristic linear dimensions (columns 4 and 5, Table). In the recalculations, it is assumed that the Earth's radius is R=6371 km, and the equation from [*Sadovsky et al., 1987; Sadovsky, Pisarenko, 1991*] is used to calculate linear dimensions L_b and plate/block areas, S_b:

$$L_\text{b} = \sqrt{S_\text{b}}. \qquad (4)$$

Regression equations are calculated for comparative analyses of the three above-mentioned data sets:

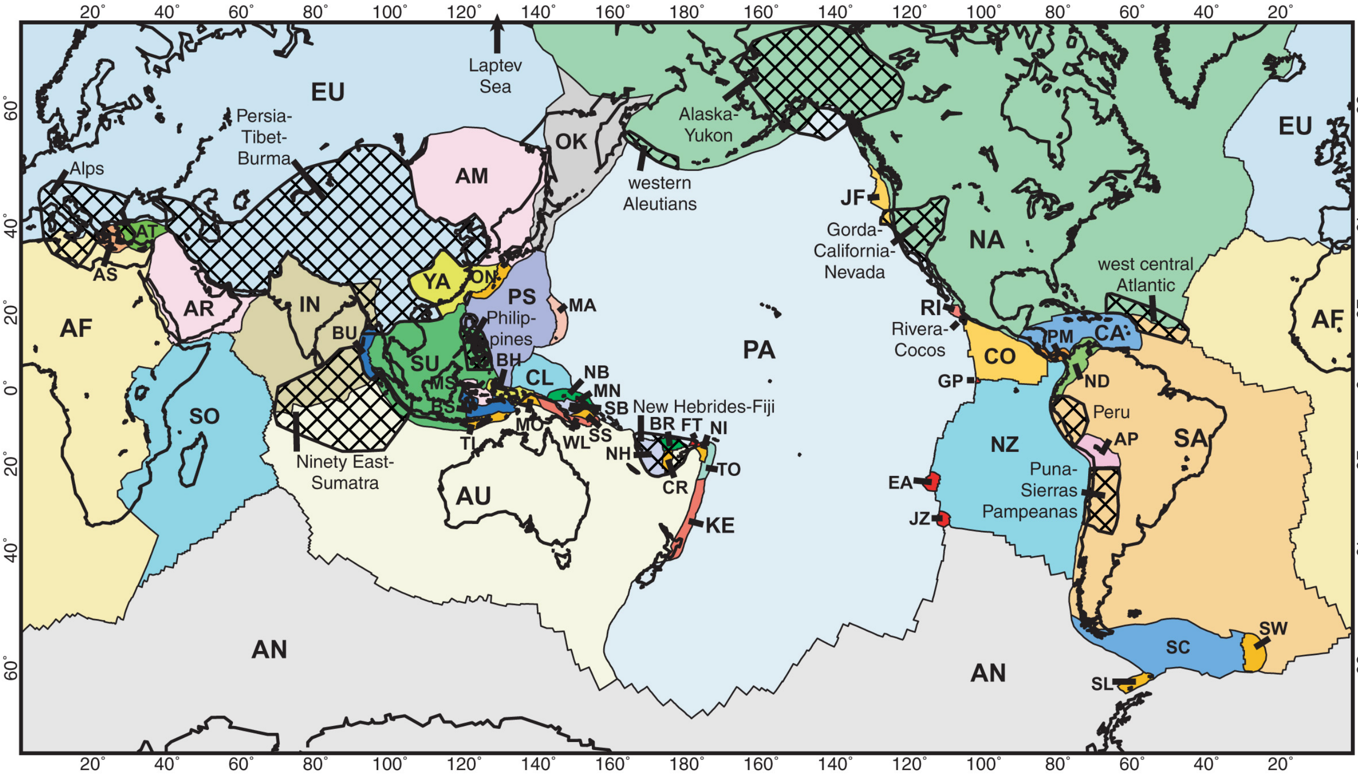

Fig. 5. Lithospheric plates mapped by P. Bird [*Bird, 2003*].

The 52 plates of his model PB2002 are shown with contrasting colours. Two-letter plate identifiers are explained in Table. The 13 cross-hatched areas are 'orogens' in which an Eulerian plate model is not expected to be accurate. Labels of small plates and orogens are offset (with leader lines) for clarity. Mercator projection.

Рис. 5. Карта литосферных плит по П. Бёрду [*Bird, 2003*].

Цветом выделены 52 плиты по модели PB2002. Наименование плит дано двойными буквами в соответствии с таблицей. Заштрихованные квадратной сеткой площади 13 районов соответствуют «орогенам», для которых модель вращения вокруг Эйлеровых полюсов не совсем точна. Двухбуквенное наименование мелких плит вынесено за их границы. Карта дана в проекции Меркатора.

(1) Regression by P. Bird, in its middle part showing areas from Jian Fernandes plate (JZ) to South America plate (SA), i.e. from mega- to medium-sized plates and blocks (Nos. 8 to 52, Table; equation 3 (in sr), and N_c=2259.3$L^{-0.67}$ (5) (symbol 1 in Fig. 7);

(2) Regression for the additional data on medium- and small-sized blocks (Nos. 53 to 225, Table; N_c=7049.1$L^{-0.91}$ (6) (symbol 2 in Fig. 7). An important indicator is an inclination angle of the regression curve. Equation 6 differs from Equation 5 by an increase of the inclination angle. Taking into account that Equation 6 is based on numerous data from geological and structural maps of continents in various scales, it can be noted that 'small-sized' blocks are more numerous that 'large' ones. This is a logical consequence following the ratio of data obtained by direct field observations that always record more small blocks on sites than large ones. The same is valid for even rock outcrops and evidenced by the plot from [*Bird*, *2003*] (see Fig. 6) at the second bend of the regression line;

(3) Regression for the consolidated data on plates and blocks of different characteristic sizes (No. 8 to 225, Table; N_c=3080.8$L^{-0.72}$ (7) (symbol 3 in Fig. 7). Regression (7) shows a significantly smoothed transition from small-sized lithospheric blocks to intra-continental blocks divisibility.

In general, equations 3, 5, 6 and 7 are similar, which suggests that the fragmentation of 'solid' rocks follows a physically uniform pattern, and, in more general terms, there is a tectonophysical law of the fault-block divisibility of the lithosphere which is valid for lithospheric blocks of a wide range of areas, from blocks which size is compatible with North and South America continents, i.e. nearly as big as lithospheric plates, to lump of rocks observed on small outcropped sites.

With account of our detailed studies of fault-block continental lithosphere structures of different ranks and in view of the identity of the physics of the process and the similarity of mathematical equations 5, 6 and 7, we construct a continuation of the regression curve

Areas and dimensions of lithospheric plates and blocks

Параметры площадей и размеров литосферных плит и блоков литосферы

#	Names of plates and blocks	Identifiers	Area, steradian	Area, km^2	Average geometric size, km
1	**Pacific**	**PA**	2.57685	104593416	10227.09
2	**Africa**	**AF**	1.44065	58475466	7646.925
3	**Antarctica**	**AN**	1.43268	58151967	7625.744
4	**North America**	**NA**	1.36559	55428808	7445.053
5	**Eurasia**	**EU**	1.1963	48557388	6968.313
6	**Australia**	**AU**	1.13294	45985628	6781.27
7	**South America**	**SA**	1.03045	41825596	6467.271
8	Somalia	SO	0.47192	19155063	4376.65
9	Nazca	NC	0.39669	16101505	4012.668
10	India	IN	0.30637	12435448	3526.393
11	Sunda	SU	0.21967	8916326	2986.022
12	Philippine Sea	PS	0.13409	5442665	2332.952
13	Amur	AM	0.13066	5303442	2302.92
14	Arabia	AR	0.12082	4904040	2214.507
15	Okhotsk	OK	0.07482	3036917	1742.675
16	Caribbean	CA	0.07304	2964667	1721.821
17	Cocos	CO	0.07223	2931790	1712.247
18	Yangtze	YA	0.05425	2201988	1483.91
19	Scotia	SC	0.0419	1700706	1304.111
20	Caroline	CL	0.03765	1528200	1236.204
21	North Andes	ND	0.02394	971716	985.7566
22	Altiplano	AP	0.0205	832087.6	912.1884
23	Banda Sea	BS	0.01715	696112.3	834.3335
24	New Hebrides	NH	0.01585	643345.8	802.0884
25	Anatolia	AT	0.01418	575561.1	758.6574
26	Birds Head	BH	0.01295	525635.9	725.0075
27	Burma	BU	0.0127	515488.4	717.9752
28	Kermadec	KE	0.01245	505341	710.8734
29	Woodlark	WL	0.01116	452980.4	673.0382
30	Mariana	MA	0.01037	420914.6	648.7793
31	Molucca Sea	MS	0.0103	418073.3	646.5859
32	North Bismarck	NB	0.00956	388037	622.9261
33	Timor	TI	0.0087	353129.9	594.2473
34	Okinawa	ON	0.00802	325528.9	570.5514
35	Aegean Sea	AS	0.00793	321875.9	567.341
36	South Bismarck	SB	0.00762	309293.1	556.1412
37	Panama	PM	0.00674	273574.2	523.0432
38	Juan de Fuca	JF	0.00632	256526.5	506.4845
39	Tonga	TO	0.00625	253685.3	503.6718
40	Balmoral Reef	BR	0.00481	195236.2	441.8554
41	Sandwich	SW	0.00454	184277	429.2749
42	Easter	EA	0.00411	166823.4	408.4402
43	Conway Reef	CR	0.00356	144499.1	380.1304
44	Solomon Sea	SS	0.00317	128669.2	358.7048
45	Niuafo'ou	NI	0.00306	124204.3	352.4263
46	Maoke	MO	0.00284	115274.6	339.5211
47	Rivera	RI	0.00249	101068.2	317.9123
48	Juan Fernandez	JZ	0.00241	97821.03	312.7635
49	Shetland	SL	0.00178	72249.56	268.7928
50	Futuna	FT	0.00079	32065.82	179.0693
51	Galapagos	GP	0.00036	14612.27	120.8812
52	Manus	MN	0.0002	8117.928	90.09955
53	Angara-Ilim-9	IA_9		47520	218
54	Angara-Ilim-13	IA_{13}		34120	185
55	Angara-Ilim-3	IA_3		33620	183
56	Angara-Ilim-12	IA_{12}		31430	177
57	Prisayan-Enisei-2	IPE_2		28100	168
58	Baikal-Patom-3	$IIIBP_3$		27450	166
59	Angara-Ilim	IA_7		27380	165
60	Mirny	IM_1		25113	158
61	Stanovoy	IV_1		24000	155

Continuation of Table

Продолжение таблицы

#	Names of plates and blocks	Identifiers	Area, steradian	Area, km^2	Average geometric size, km
62	Angara-Ilim	IA_{11}		23790	154
63	Angara-Ilim	IA_{5}		21770	148
64	Prisayan-Enisei	IPE_{1}		20700	144
65	Aldan	II_{1}		20680	144
66	Angara-Ilim	IA_{10}		18940	138
67	Selenga-Yablonovy	$IIISYa_{18}$		17730	133
68	Mirny	IM_{21}		17480	132
69	Mirny	IM_{25}		17300	131
70	Barguzin	$IIIB_{3}$		17060	131
71	Selenga-Yablonovy	$IIISYa_{15}$		16780	129
72	Angara-Ilim	IA_{15}		16380	128
73	Aldan	II_{2}		16370	128
74	Baikal-Patom	$IIIBP_{1}$		15700	125
75	Mirny	IM_{11}		15340	124
76	East Sayan	$IIIES_{2}$		15500	124
77	Selenga-Yablonovy	$IIISYa_{5}$		15200	123
78	Mirny	IM_{7}		14820	122
79	Selenga-Yablonovy	$IIISya_{21}$		14810	122
80	Stanovoy	IV_{2}		14580	121
81	Aldan	II_{6}		14360	119
82	Tunguska	IT_{1}		13900	118
83	Barguzin (IIIБ$_2$)	$IIIB_{2}$		13875	118
84	Mirny	IM_{5}		13800	117
85	Mirny	IM_{23}		13460	116
86	Aldan	II_{5}		13400	116
87	Selenga-Yablonovy	$IIISYa_{19}$		13470	116
88	Angara-Ilim	IA_{1}		13280	115
89	Aldan	II_{16}		13150	115
90	Baikal-Patom	$IIIBP_{6}$		13320	115
91	Selenga-Yablonovy	$IIISYa_{13}$		13200	115
92	Khentei-Dauria	$VKhD_{2}$		13260	115
93	Mirny	IM_{2}		13053	114
94	Barguzin	$IIIB_{13}$		12700	113
95	Angara-Ilim	IA_{4}		12470	112
96	East Sayan	$IIIES_{10}$		12400	111
97	East Transbaikalie	VET_{3}		12100	110
98	Barguzin	$IIIB_{5}$		11700	108
99	Selenga-Yablonovy	$IIISYa_{4}$		11600	108
100	Stanovoy	IV_{10}		11450	107
101	Mirny	IM_{9}		11170	106
102	Selenga-Yablonovy	$IIISYa_{20}$		11220	106
103	Angara-Ilim	IA_{16}		11020	105
104	Angara-Ilim	IA_{8}		10570	103
105	Sayan-Altai	$IIISA_{3}$		10320	101
106	Selenga-Yablonovy	$IIISYa_{16}$		10260	101
107	Stanovoy	IV_{7}		10300	101
108	Mirny	IM_{3}		9800	99
109	Mirny	IM_{14}		9730	99
110	Baikal-Patom	$IIIBP_{4}$		9800	99
111	Selenga-Yablonovy	$IIISYa_{23}$		9420	97
112	East Sayan	$IIIES_{9}$		9190	96
113	Selenga-Yablonovy	$IIISYa_{14}$		9200	96
114	Baikal-Patom	$IIIBP_{11}$		8900	94
115	Sayan-Altai	$IIISA_{2}$		8530	92
116	Barguzin	$IIIB_{1}$		8490	92
117	Barguzin	$IIIB_{11}$		8550	92
118	Baikal-Patom	$IIIBP_{12}$		8500	92
119	Stanovoy	IV_{8}		8530	92
120	East Transbaikalie	VET_{1}		8600	92
121	Mirny	IM_{6}		8250	91
122	Barguzin	$IIIB_{19}$		8100	90
123	Baikal-Patom	$IIIBP_{2}$		8100	90

Continuation of Table

Продолжение таблицы

#	Names of plates and blocks	Identifiers	Area, steradian	Area, km^2	Average geometric size, km
124	Selenga-Yablonovy	$IIISYa_{24}$		8080	90
125	Selenga-Yablonovy	$IIISYa_{7}$		8000	89
126	Barguzin	$IIIB_{7}$		7700	88
127	Baikal-Patom	$IIIBP_{5}$		7600	87
128	Aldan	II_{9}		7315	86
129	Aldan	II_{18}		7400	86
130	Angara-Ilim	IA_{14}		7180	85
131	Barguzin	$IIIB_{21}$		7200	85
132	Baikal-Patom	$IIIBP_{15}$		7200	85
133	Selenga-Yablonovy	$IIISYa_{9}$		7300	85
134	Barguzin	$IIIB_{23}$		6850	83
135	East Sayan	$IIIES_{12}$		6750	82
136	Barguzin	$IIIB_{15}$		6750	82
137	Baikal-Patom	$IIIBP_{7}$		6700	82
138	East Transbaikalie	VET_{20}		6800	82
139	Dzhida	($IIID_{1}$)		6600	81
140	Khentei-Dauria	($VKhD_{1}$)		6500	81
141	East Transbaikalie	(VET_{16})		6500	81
142	East Transbaikalie	(VET_{17})		6500	81
143	Angara-Ilim	(IA_{2})		6400	80
144	Mirny	(IM_{24})		6400	80
145	Aldan	(II_{13})		6075	78
146	Barguzin	($IIIB_{10}$)		6000	77
147	Mirny	(IM_{4})		5800	76
148	Barguzin	($IIIB_{14}$)		5800	76
149	Baikal-Patom	($IIIBP_{8}$)		5850	76
150	Selenga-Yablonovy	($IIISYa_{11}$)		5800	76
151	Selenga-Yablonovy	($IIISYa_{12}$)		5800	76
152	Baikal-Patom	($IIIBP_{9}$)		5625	75
153	Dzhida	($IIID_{2}$)		5600	75
154	Mirny	(IM_{22})		5300	73
155	Stanovoy	(IV_{13})		5380	73
156	Stanovoy	(IV_{14})		5140	72
157	Barguzin	($IIIB_{12}$)		5100	71
158	Barguzin	($IIIB_{22}$)		5000	71
159	Stanovoy	(IV_{5})		5000	71
160	Angara-Ilim	(IA_{18})		4900	70
161	Aldan	(II_{8})		4855	69
162	Aldan	(II_{17})		4700	69
163	Stanovoy	(IV_{6})		4700	69
164	Mirny	(IM_{16})		4490	67
165	Pribaikalsky fault zone			4500	67
166	Stanovoy			4500	67
167	East Transbaikalie	VET_{8}		4500	67
168	Angara-Ilim	IA_{6}		4350	66
169	East Sayan	$IIIES_{8}$		4400	66
170	Baikal-Patom	$IIIBP_{13}$		4275	65
171	Mirny	IM_{13}		4040	64
172	Aldan	II_{12}		4050	64
173	Barguzin	$IIIB_{20}$		4150	64
174	Mirny	IM_{26}		4040	63
175	Baikal-Patom	$IIIBP_{10}$		4000	63
176	Selenga-Yablonovy	$IIISYa_{8}$		4000	63
177	East Transbaikalie	VET_{12}		4000	63
178	East Transbaikalie	VET_{15}		4000	63
179	Barguzin	$IIIB_{8}$		3800	62
180	Stanovoy	IV_{4}		3800	62
181	East Transbaikalie	VET_{13}		3800	62
182	Aldan	II_{10}		3740	61
183	Barguzin	$IIIB_{24}$		3600	60
184	Stanovoy	IV_{12}		3590	60
185	East Transbaikalie	VET_{7}		3590	60

E n d o f T a b l e

О к о н ч а н и е т а б л и ц ы

#	Names of plates and blocks	Identifiers	Area, steradian	Area, km^2	Average geometric size, km
186	Aldan (II_{11})	II_{11}		3350	58
187	Baikal-Patom	$IIIBP_{14}$		3350	58
188	Aldan	II_{15}		3200	57
189	East Transbaikalie	VET_4		3300	57
190	East Transbaikalie	VET_{21}		3230	57
191	Aldan	II_{14}		3100	56
192	East Sayan	$IIIES_{11}$		3000	55
193	East Sayan	$IIIES_6$		2900	54
194	Barguzin	$IIIB_{16}$		2900	54
195	Stanovoy	IV_{11}		2900	54
196	Angara-Ilim	IA_{17}		2680	52
197	Mirny	IM_{10}		2690	52
198	Mirny	IM_{15}		2690	52
199	East Sayan	$IIIES_7$		2700	52
200	East Sayan	$IIIES_{13}$		2700	52
201	Barguzin	$IIIB_4$		2700	52
202	Selenga-Yablonovy	$IIISYa_{17}$		2700	52
203	Khentei-Dauria	$VKhD_4$		2690	52
204	East Transbaikalie	VET_9		2690	52
205	Mirny	IM_{17}		2470	50
206	East Sayan	$IIIES_3$		2475	50
207	Selenga-Yablonovy	$IIISYa_1$		2400	49
208	Khentei-Dauria	$VKhD_3$		2400	49
209	East Sayan	$IIIES_4$		2250	47
210	Selenga-Yablonovy	$IIISYa_{22}$		2240	47
211	Selenga-Yablonovy	$IIISYa_3$		2100	46
212	Mirny	IM_{18}		2000	45
213	Barguzin	$IIIB_9$		1800	42
214	East Sayan	$IIIES_5$		1700	41
215	Barguzin	$IIIB_{17}$		1600	40
216	Mirny	IM_{27}		1570	39
217	Selenga-Yablonovy	$IIISYa_{10}$		1500	39
218	Mirny	IM_8		1390	37
219	Barguzin	$IIIB_6$		1300	36
220	Barguzin	$IIIB_{18}$		1200	35
221	East Transbaikalie	VET_5		1100	33
222	East Transbaikalie	VET_{11}		1100	33
223	Mirny	IM_{19}		898	30
224	Mirny	IM_{12}		540	23
225	East Transbaikalie	VET_{10}		494	22

N o t e s. The table consolidates the following data: Nos. 1 to 52 – from [*Bird*, *2003*] with recalculation for area and linear sizes; Nos. 53 to 225 – according to [*Cheremnykh, 1998; Sherman et al., 2000*]. Names of the largest plates are bold printed; the general laws of destruction of solid bodies do not apply to such plates. Names and two-letter identifiers of megablocks correspond to [*Bird, 2003*]. Names of regional blocks are from the catalogue by A.V. Cheremnykh.

П р и м е ч а н и е. Данные с № 1 по 52 – по [*Bird, 2003*] с пересчетом на площадные и линейные меры; с № 53–225 – по [*Cheremnykh, 1998; Sherman et al., 2000*]. Жирным шрифтом выделены самые крупные литосферные плиты, не вписывающиеся в общие закономерности деструкции твердого тела. Названия мегаблоков соответствуют карте [*Bird, 2003*], названия региональных блоков даны по авторскому каталогу А.В. Черемных.

derived from equation 3 (Fig. 7) in the direction that has been substantiated by P. Bird (see Fig. 6). The two regression lines based on equations 3 and 7 have the same physical meaning in bilogarithmical scales, and their middle parts are identical in Figure 6 and generally similar in Figure 7. The regression lines and the equations reflect destruction patterns of the 'solid' lithosphere in a wide variety of scales.

The area estimations obtained by different methods provide for well-reasoned general conclusions concerning regular patterns of the block destruction of the Earth's lithosphere at specified hierarchical levels. The reviewed results complement each other and extend our knowledge of destruction of the lithosphere as the solid cover of the Earth. It is now reasonable to briefly review the known laws of destruction of solid bodies, i.e. rocks.

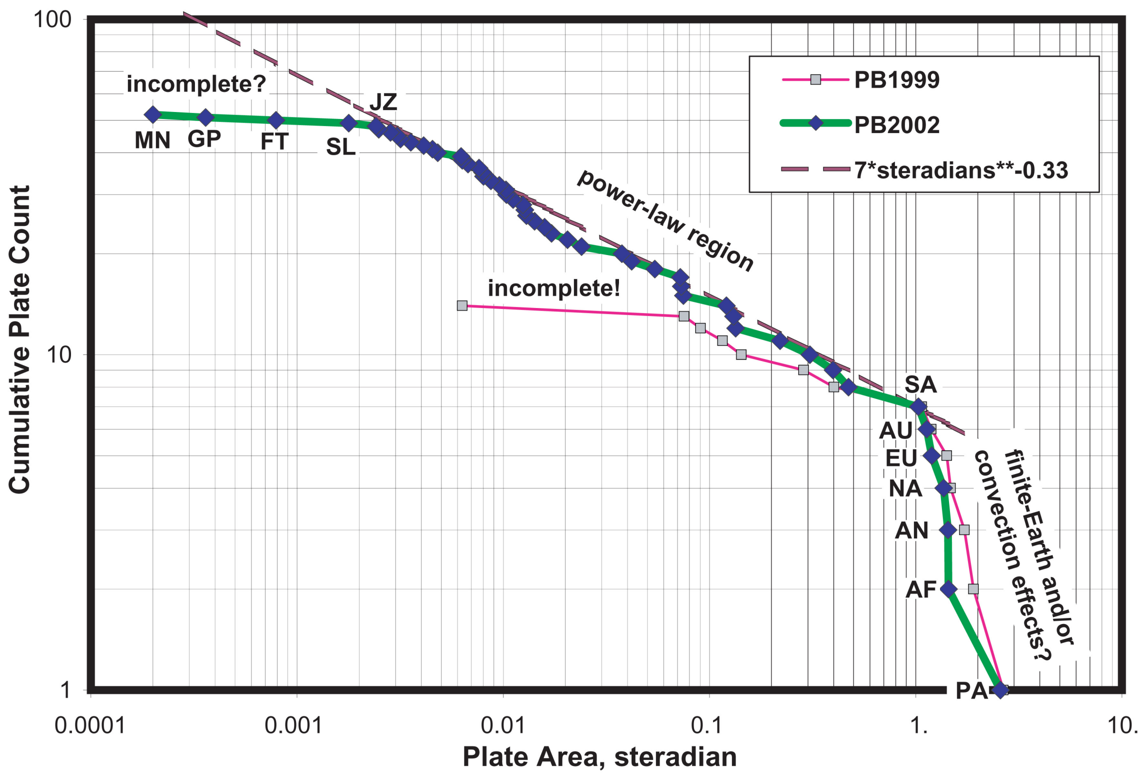

Fig. 6. Number of plates plotted as a function of area [*Bird, 2003*, fig. 19].

Curve PB2002 (green) refers to the model in Fig. 7. A relatively steady slope of the curve for plate areas between 0.002 and 1 steradian suggests a power law relationship between the number of plates and their minimum size. Flattening in the left segment of the curve is due to the model incompleteness, i.e. there are many plates of smaller sizes which are not included in model PB2002. An abrupt variation of the slope in the right segment of the curve suggests that very large plates are limited in their area because of the finite area of the Earth, and perhaps also by mantle convection tractions.

Рис. 6. График взаимосвязи количества плит как функции их площади (по [*Bird, 2003,* fig. 19]).

Кривая PB2002 (зеленый цвет) отражает ситуацию по данным рисунка 7. Относительно постоянный наклон кривой между границами площадей 0.002 и 1.000 стерадиан отражает взаимоотношения между числом плит и их минимальным размером. Изменение угла наклона в левой части графика отражает недостаточное число наблюдений, то есть имеются еще более мелкие, не учтенные в авторской модели блоки. Резкое изменение угла наклона в правой части графика показывает, что крупные плиты ограничены в своих размерах конечной площадью Земли, а также, возможно, конвекционными мантийными потоками.

6. Genetic sources of the lithosphere divisibility of various ranks

It can be stated that Equation 7 and its specific variants (see Fig. 7) are sufficient to fully describe relatively small lithospheric plates and intraplate blocks of the 'solid' lithosphere up to rock lumps. The experimental methods have yielded similar equations that mathematically reflect the physics of destruction of solid bodies in a wide range of scales (from a medium-size block which size amounts to a few thousand kilometres, to a rock fragment which diameter is a dozen centimetres), and there are ground to state that the block divisibility of the lithosphere follows laws of self-similarity. In the physics of destruction of solid and viscoelastic bodies, self-similarity patterns have been noted long ago at different scale levels. However, self-similarity in a very wide spectrum of hierarchical levels, from centimetres to mega sizes, has not been considered yet, and this paper is the first attempt in this respect.

Based on results of independent studies, *A.N. Kolmogorov* [*1941*] and *A.F. Filippov* [*1962*] established that rocks are subject to fragmentation according to the law of destruction of solid bodies, and the following exponential expression is linear in coordinates *lgN* and *lgL*:

$$lgN=f(lgL), \quad (8),$$

where *L* is the sample's arbitrary size, and *N* is the number of samples.

This conclusion includes the above-described empirical relationships that refer to large-size objects, such as lithosphere blocks of various ranks and, partly,

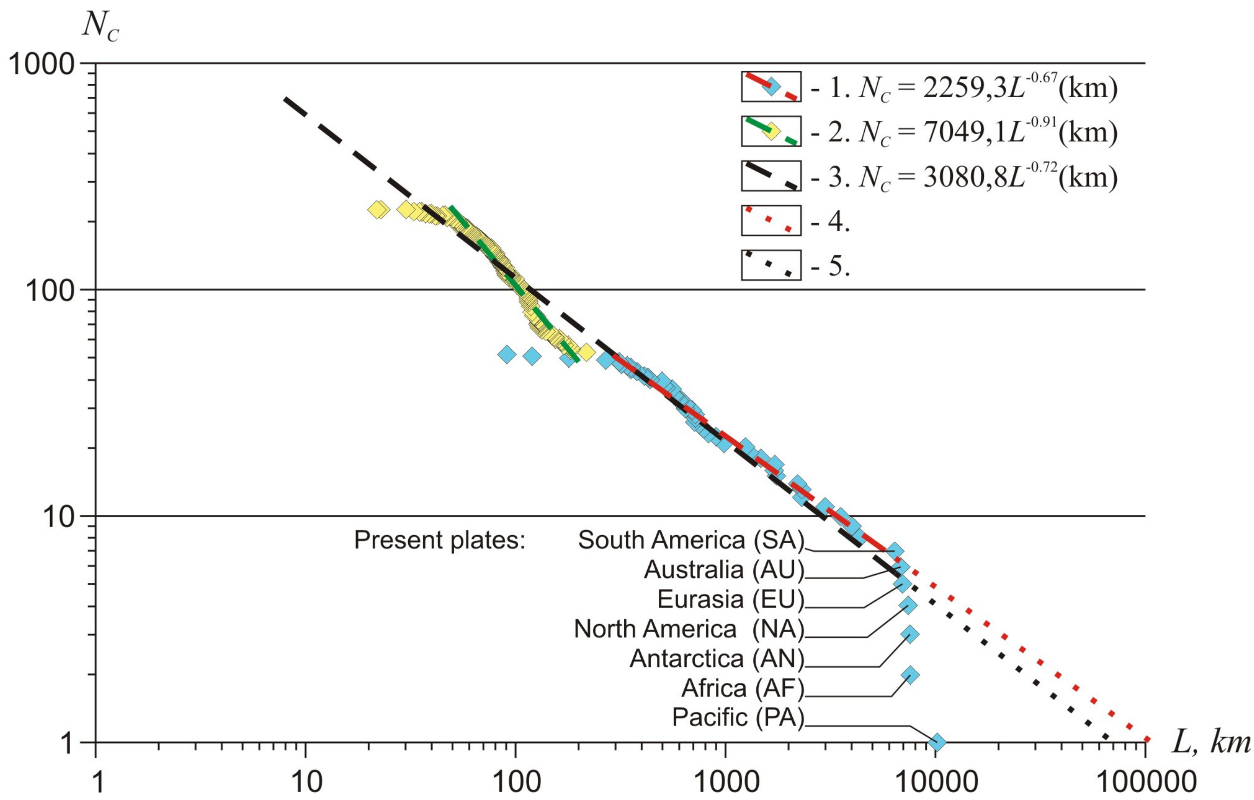

Fig. 7. Curves of relationships between medium lateral dimensions of lithospheric plates and blocks: 1 – according to [*Bird, 2003*]; 2 – according to [*Cheremnykh, 1998*; *Sherman et al., 2000*]; 3 – integrated regression line based on data (1) and (2); 4 – extrapolated regression line according to equation 1; 5 – extrapolated regression line according to equation 3. 3. N_c – row of lithospheric plates and blocks by average characteristic sizes L, km (analogues to reconstructions by P. Bird in steradians).

Рис. 7. Графики взаимосвязи средних поперечных размеров плит и блоков литосферы по: 1 – по данным [*Bird, 2003*]; 2 – по данным [*Cheremnykh, 1998*; *Sherman et al., 2000*]; 3 – совмещенная линия регрессии по данным [1 и 2]; 4 – экстраполяция линии регрессии по данным уравнения (1); 5 – экстраполяция линии регрессии по данным уравнения (3). N_c – последовательность литосферных плит и блоков в порядке увеличения усредненных характерных размеров L, км (по аналогии с построениями П. Бёрда в стерадианах).

faults in the upper brittle layer of the lithosphere, which cross each other to form the corresponding hierarchic group of the fault-block structures of the solid cover of the Earth [*Sherman*, *1977*; *Sherman et al., 2000, 2004; Seminsky, 2001, 2003*; and many others]. Obviously, this property mitigates issues related to 'buckling' of the regression lines at the boundaries of Juan Fernandez (JZ) and Shetland (SL) plates (0.00241 and 0.00178 sr, respectively). Buckling occurs due to the lack of quantitative data. In our study, this issue is completely eliminated after the additional data are supplemented (Table).

It can thus be stated that deformation and destruction of the Earth's solid cover under the influence of external loads take place according to a regular pattern. From certain hierarchical levels, residual destruction (in the form of blocks varying in ranks) is distributed in accordance with the characteristic sizes of the blocks and their number, as described by Equation 7. The regression is buckling at the transition from medium-sized plates to large ones (see Fig. 6 and 7) due to other reasons.

In terms of physics, buckling of the regression line showing the hierarchy of plate sizes versus plate areas (see Fig. 6 and 7) is related to sources of rank-variable destruction of the lithosphere as a solid body. The buckle occurs abruptly at the transition from a few very large lithospheric plates to medium-sized plates and small blocks that are statistically abundant. The regression curve is buckled from a very steep angle to a more gentle one at the boundary between South America (area of 1.03 sr) and Somali plates (area of 0.47 sr). A jump occurs when the square area is doubled. For six large plates (Africa, Antarctica, North America, Eurasia, Australia and South America; data on Pacific plate are not taken into account), the regression curve is a steep, almost vertical line. Their areas are nearly similar and almost unchangeable. Naturally, they are governed by another law of formation of solid lithospheric masses, which is not consistent with the laws of destruction of solid bodies. In this respect, *P. Bird* [*2003*] also notes that the fact that large plates are clearly established is indicative of a very weak dependence of plate areas from any quantitative parameters, except for the Earth radius. When the Earth radius is used as a natural independent unit to measure solid angles in steradians, it is clearly revealed that very large areas of the above-mentioned six plates (Pacific plate is an exception) are almost similar. According to *P. Bird* [*2003*], typical areas of the large lithospheric plates correlate with mantle convection: "....this characteristic size seems more consistent with whole mantle convection than with layered convection". Indeed, the formation of the largest blocks (i.e. primary lithospheric plates originating at the stage when the protolithosphere was formed and later periods) is more in line with mantle convection than destruction of the solid body. The author fully shares these assumptions by P. Bird as they are supported by all the above discussed data, arguments and tectonophysical calculations.

As shown by the analysis of areas of the rank-variable present lithospheric plates (see Table), the total area of the seven largest plates (less than 14 % of the total number of plates) is about 10.15 steradians, and they occupy almost 81 % of the entire surface of the Earth. The area of the six continental plates (Africa, Antarctica, North America, Eurasia, Australia and South America) is more than 60 % of the planet's surface area. They are well traced in the history of Pangea and less evidently in the more distant past. Through the history of the Earth, these huge integral bodies were subject to numerous geodynamic catastrophes and transformations. Some of them lost much of the initial mass, others completely 'disappeared' in the mantle, while some of the plates have grown in size. Therefore, from one super-continental cycle to another, the lithospheric blocks differ in number and kinematics. Based on the available data, it is impossible to state for sure which of them were formed before the Archaean and are still in place, and which of them were more or less transformed. It is challenging to restore the genesis of structural relics in the cooling medium of the protolithosphere and those in the lithosphere medium with reference to the very distant past. It is an inverse problem with unambiguous solutions. As a definite and indisputable conclusion cannot be drawn, one can only assume that convection is the most probable and better argumented physical process that took place when the low-viscous medium of the protolithosphere was cooling down to form large masses in the first hypothetical (?) supercycles of Vaalbara and Ur, and, finally, convection can be viewed as a mechanism predetermining the present shape of the Earth's continents. It is most probable that the megablocks were fragmented in the similar pattern in Kenorlend and later supercycles. However, based on the available materials, it is possible only to justify the block structure of the present stage.

It is reasonable here to quote the book by *N.L. Dobretsov et al.* [*2001*]: "In the history of the Earth, convection in two layers was replaced by convection in the entire mantle and vice versa, and this might have taken place several times... Therefore, it is most likely that in the Earth's history, convection in the entire mantle was replaced by two-layer convection. Another possible scenario is more complicated: about 2.5 Ga ago, two-layer convection was replaced by convection in the entire mantle [*Maruyama*, *1994*]; after a period of one billion years, two-layer convection occurred again [*Honda*, *1995*], and, finally, a transition back to convection in the entire mantle took place in the past 150-100 Ma [*Trubitsyn, Rykov, 2000*]" (p. 111). Convection predetermines the major cycles in the geodynamics of the Earth and fragmentation of the lithosphere into megablocks. The latter are destructed under the physical laws of destruction of solid rocks. Currently, destruction of the lithosphere is actively continued in seismic zones of the continental lithosphere and zones of subduction and spreading at the margins of the lithospheric blocks.

7. Discussion

Publications on convection in the Earth's mantle and its role in global geodynamic processes are quite numerous. In the majority of papers, recent geodynamic processes are considered with an assumption that the evolution of convection in the mantle and asthenosphere took place in two- or three-layer or more complicated patterns [*Lobkovsky, 1988; Lobkovsky, Kotelkin, 2000; Lobkovsky et al., 2004; Rykov, Trubitsyn, 1994a, 1994b; Trompert, Hansen, 1988; Trubitsyn, Rykov, 2002; Trubitsyn V.P., Trubitsyn A.P., 2014*]. Mantle convection was discussed in a number of publications many years ago, the most famous of which are [*Pekeris*, *1935*; *Molnar et al.*, *1979*].

According to [*Molnar et al.*, *1979*], large sizes of continental plates are related to convection in the entire mantle, and horizontal dimensions of the plate depend on the depth of the convective process. Their analysis is based on the proportional change in the length of the subduction zone on the surface and the velocity of its sinking which depends on heat assimilation in the absence of a barrier at the border with the lower mantle.

The two-layer convection in the Earth mantle is described by *L.P. Zonenshain* and *M.I. Kuz'min* [*1993*] and reconstructed in a world-known scheme by *S. Maruyama* [*1994*].

To sum up this very brief information on the two-layer models of convection in the Earth mantle, it is worthy to refer again to the book by *N.L. Dobretsov et al.* [*2001*] who give much attention to convection as an important component of geodynamic processes. In their book, prior to the geodynamic analysis of processes in the mantle, asthenosphere and lithosphere, they provide a comprehensive description of the two main models of thermal-gravitational convection which provide the basis for a variety of geodynamic reconstructions. In the first model, convection take place in the entire mantle, from boundaries of the lithosphere base (30 to 100km) to the upper limit of the core (about 2900 km). The second model shows convection in the upper and lower mantle without any significant mass transfer between the two layers. In [*Dobretsov et al*., 2001], the authors focus on the complexity of geodynamic processes in the mantle and discuss their evolution up to the present stage of the Earth development. The concept of two-layer mantle convection is convincingly proved by results of many original experiments conducted by the authors with the use of specially designed installations [*Kirdyashkin, Dobretsov, 1991; Dobretsov, Kirdyashkin, 1993*]. Besides, they estimated parameters of convection. Specifically, based on the video records, they revealed flow lines in the two-layer fluid convection system and estimated horizontal and vertical velocities of the flows. Their very important observation is that convection flows above and below the interface go in different directions, and this is an evidence that vector directions of horizontal convection flows in the layers located one upon another are not interrelated. According to [*Dobretsov et al., 2001*], vectors of the vertical flows are similar, and this fact emphasises the major role of convection in the mantle which provides for dissipation of heat energy. Important are the digital parameters and vectors of flow velocities and cell sizes. In the bottom layer (which is thicker), cell sizes are proportional to the layer's thickness, and flow velocities are lower. In [*Dobretsov et al*., *2001*], the concept of the two-layer convection in the Earth's mantle is well established by the experimental and actual observation data. Nonetheless, the authors note: "In the majority of cases, the geochemical data support the two-layer convection model, while much geophysical data may be interpreted in favour of convection in the entire mantle" (p. 108).

In [*Trubitsyn V.P., Trubitsyn A.P., 2014*], a digital model is described in detail to show that the present set of the lithospheric plates is a result of the evolution of convection. It provides an insight into the possible mode of flows in the entire mantle, movements of the masses between the upper and lower mantle, as well as between the central and lateral limits of the convection cells. Using equations, V.P. Trubitsyn and A.P. Trubitsyn calculated temperature, viscosity and velocity of mantle convection flows generated by effective diffusion-dislocation creeping in the absence of pseudo-plastic deformation and in case of the very hard lithosphere. In particular, their temperature distribution pattern shows that small cold descending flows, i.e. small-scale convection, occur under the lithosphere. The estimated scheme of convection in the entire mantle in [*Trubitsyn V.P., Trubitsyn A.P., 2014*] is consistent with our ideas of the primary genetically emerging block divisibility of the protolithosphere. In the initial state, the protolithosphere remains uniform at the surface, has a roughly constant thickness and increased quasi-strength at the primary inter-cell boundaries whereat the viscosity of the medium is increasing due to cooling of the protolithosphere.

Regretfully, initial divisibility of the emerging upper solid cover of the Earth is taken into account by few researchers in their estimations, while such divisibility is one of the most likely results of convection in the cooling protolithosphere. This is obviously due to the absence of direct geological materials and the lack of appropriate paleo-reconstruction methods that can integrate geological, geophysical and geochemical databases. As shown by our study, computational methods are helpful, to a certain extent, in solving ill-conditioned inverse problems to reconstruct processes and structures of the distant past.

The concept of the single-layer convection, assuming that convection took place through the ½-radius depth at the initial stage when the Earth lithosphere was formed, is acceptable and seems quite realistic, even though the literature is still insufficient on this subject. This justifies the author's efforts to clarify the origin of divisibility of the primary non-solid, almost continuous cover of the Earth which evolution history includes periods of the Phanerozoic and contemporary faulting in the lithosphere and its fragmentation under the laws of destruction of solid bodies. It can be noted in general that the upper cover of the Earth is subject to destruction in a regular pattern, from larger to smaller masses.

8. Conclusion

This study is pioneering in tectonophysical reconstruction of initial divisibility of the protolithosphere as a result of convection in the cooling primitive mantle. Initial division of the protolithosphere into separate masses, i.e. prototypes of the blocks, and their size was predetermined by the emerging Rayleigh–Bénard convection cells. In studies of geology and geodynamics, the Rayleigh–Bénard convection cells were first referred to as a factor to explain the formation of initial continental cores. Considering the Rayleigh–Bénard cells and their structural relics can help clarify initial divisibility of the protolithosphere and the origin of the major lithospheric plates, i.e. prototypes of continents.

In our opinion, the initial mega-scale block structure of the protolithosphere and the emerging lithosphere were predetermined by the Rayleigh–Bénard cells as they were preserved in the emerging lithosphere and their lower boundaries corresponded to the core-mantle boundary, i.e. one of the major discontinuities of the planet. Our theoretical estimations are in good agreement with the number and sizes of the Earth's theorized first supercontinents, Vaalbara and Ur.

In our tectonophysical discussion of the formation of the lithospheric block structure, we analyse in detail the map of modern lithospheric plates [*Bird*, *2003*] in combination with the materials from [*Sherman et al., 2000*]. In the hierarchy of the blocks comprising the present lithosphere, which sizes are widely variable, two groups of blocks are clearly distinguished. The first group includes megablocks with the average geometric size above 6500 km. Their formation is related to convection in the Earth mantle at the present stage of the geodynamic evolution of the Earth, as well as at all the previous stages, including the earliest one, when the protolithosphere emerged. The second group includes medium-sized blocks with the average geometric size of less than 4500 km and those with minimum sizes, such as rock lumps. They reflect primarily the degradation of the megablocks as a result of their destruction due to high internal stresses in excess of the tensile strength of the medium. This group may also include blocks which formation is related to convection in the upper mantle layer, asthenosphere. There are grounds to assume that through the vast intermediate interval of geologic time, including supercycles of Kenorlend, Rodin, and Pangea, the formation of the large lithospheric blocks was controlled by convection, and later on, they were 'fragmented' under the physical laws of destruction of solid bodies. However, it is difficult to clearly distinguish between the processes that predetermine the hierarchy of formation of the block structures of various origins – sizes of ancient lithospheric blocks cannot be estimated unambiguously.

Thus, mantle convection is a genetic endogenous source of initial divisibility of the cooling upper cover of the Earth and megablock divisibility of the lithosphere in the subsequent and recent geodynamic development stages. In the present stage, regular patterns of the lithospheric block divisibility of various scales are observed at all the hierarchic levels. The areas of the lithospheric megaplates result from regular changes of convection processes in the mantle, which influenced the formation of plates and plate kinematics. Fragmentation of the megaplates into smaller ones is primarily a result of destruction of the solid lithosphere under the physical laws of destruction of solid bodies under the impact of high stresses.

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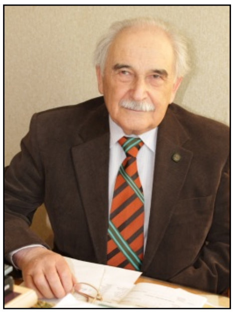

Sherman, Semen I., Academician of the Russian Academy of Natural Sciences,
Doctor of Geology and Mineralogy, Professor, Chief Researcher
Institute of the Earth's Crust, Siberian Branch of RAS
128 Lermontov street, Irkutsk 664033, Russia
Tel.: (3952)428261; ✉ e-mail: ssherman@crust.irk.ru

Шерман Семен Ийонович, академик Российской академии естественных наук,
докт. геол.-мин. наук, профессор, г.н.с.
Институт земной коры СО РАН
664033, Иркутск, ул. Лермонтова, 128, Россия
Тел.: (3952)428261; ✉ e-mail: ssherman@crust.irk.ru