3-D Spherical models for mantle convection, continental drift, and the formation and disintegration of supercontinents

V. P. Trubitsyn and V. V. Rykov

Shcmidt United Institute of Physics of the Earth, Russian Academy of Sciences, B. Gruzinskaya ul. 10, Moscow, 123810 Russia

Abstract. One of the most important problems of geoscience is to explain the drift mechanism of continents uniting periodically to form supercontinents similar to Pangea. This work presents for the first time a numerical model of mantle convection in a 3-D spherical mantle with drifting continents. The mantle is modeled by a viscous fluid developing thermal convection upon heating. When the floating continents are placed into the mantle, they start drifting under the effect of the forces of viscous coupling with mantle convection flows. Subject to numerical solution is the set of mass, heat, and momentum transfer equations for convection in the viscous mantle and the associated set of Euler equations for the movement of each solid continents. The mantle and continents interact with each another mechanically in the course of heat exchange. In order to better understand the mantle-continent interaction processes, we have analyzed two models, one with a single continent and a weak thermal convection with a Rayleigh number of 10^4 and the other with five continents and an intense thermal convection with a Rayleigh number of 10^6. In case of the weak convection, there are formed in the mantle a few ascending and descending flows. The drifting continent is pulled into one of the descending flows. As the size and shape of the continent differ from those of the descending flow zones, its position proves unstable, so that it drifts constantly. In the absence of other continents and any external forces, the continent moves along the descending flow system. At higher Rayleigh numbers, the convection becomes nonstationary, in which case the number, shape, and position of mantle convection flows vary constantly. Besides is more, if there are several continents, the motion of each of them becomes bound and more complex. The continents can collide directly, as well as interact with each other through the intermediary of the mantle and thus change the structure of its convection. The numerical experiments performed demonstrate the possibility of both a partial uniting of several continents and the formation of a single supercontinent like Pangea upon the uniting of all the continents.

1. Introduction

In the 70's, there occurred radical changes in the notions of the processes taking place in the Earth's bowels and their manifestations on the Earth's surface. Being able to study the processes occurring on the bottom of the oceans, American and European scientists discovered that the oceanic lithosphere moves away from the mid-oceanic ridges. In the ridges, the oceanic litho-sphere is being born upon the solidification of the erupting magma, and in the subduction zones, the cooled lithosphere that has grown heavier is being pulled back into the mantle. The entire Earth's lithosphere gets broken down in the process into individual plates some of which bear the continents. These notions were formulated in the form of the concept of the tectonics of oceanic lithospheric plates. The plate tectonics concept is understood not only in this narrow sense, but also in a wider sense wherein it is associated with the formulation of the notions of the principal global processes occurring in the Earth's mantle and manifesting themselves in the motion of the lithospheric plates.

In the same 60-s – 70-s, the first reliable models for the distribution of density, pressure, and temperature in

the Earth were constructed on the basis of measurement data on the seismic wave velocities and experimental and theoretical data on the properties of matter at high pressures.

Density in the mantle grows higher with depth largely not because of changes in its chemical composition, but as a result of changes in its compressibility and the phase transformations consequent upon the rise of pressure. Temperature in the mantle is extremely high, so that the material therein, if exposed to it for a long time, becomes capable of flowing like a highly viscous fluid. The conclusion was drawn on this basis that in the mantle there can occur an intense thermal convection.

The material circulating in the mantle cools down as it rises to the surface and solidifies at a temperature of the order of $T^* = 1300°C$, forming the semirigid oceanic lithosphere. As it moves over the horizontal section of the convection cell, the lithosphere cools still more and grows thicker. In the descending section of the convection cell, the immersed lithosphere stays semirigid for a long time, until it gets heated to a temperature of T^*. Thus, the oceanic lithosphere does not float on the surface of the underlying portion of the mantle, but takes part in the convective circulation of the mantle material in the entire mantle cell and comprises that portion of the mantle which at a given instant is at a temperature below T^*. The horizontal size of convection cells being not more than 20 thousand kilometers and the maximum mantle convection flow velocity, of the order of 10 centimeters per year, the age of the oceanic lithosphere cannot exceed 200 million years.

According to plate tectonics, there are no purely continental plates. The continents are believed to be permanently frozen into oceanic plates, and so can only passively move together with them. Thanks to their buoyancy, the continents cannot sink in the mantle. In contrast to the oceanic lithosphere whose thickness is no more than 80 km, the lithospheric roots of the continents may reach down to a depth of a few hundreds of kilometers. But they do not impede the drift of the continental plates, for the entire mantle, all the way down to the core, behaves like a viscous fluid. It should be noted that the subcrustal lithosphere of the continents, like the oceanic lithosphere, is a region of the mantle that only differs from the rest of the mantle by its rheological properties and can, in principle, also be mixed by convective mantle convection flows.

Numerous numerical experiments have been conducted up to now to investigate thermal convection in the Earth's mantle. 2- and 3-D models in orthogonal and spherical coordinate systems were used to reveal the role of variable, temperature-, pressure-, and stress-dependent viscosity and the effect of phase transformations on the structure of mantle convection flows (see, for example, [*Christensen*, 1983, 1984; *Christensen*

and *Yuen*, 1984; *Glatzmaier*, 1988; *Lenardic and Kaula*, 1994; *Machetel and Weber*, 1991; *Parmentier et al.*, 1994; *Solheim and Peltier*, 1994; *Tackley et al.*, 1994]). It has been demonstrated in these models that the highly viscous oceanic lithosphere can, on the whole, form in a self-consistent manner, considering the fact that the viscosity of the mantle material increases sharply with temperature, especially in the vicinity of the solidification point [*Jacoby and Shmeling*, 1982]. Despite the great success of numerical modeling in the study of mantle convection and oceanic lithosphere as a whole, plate tectonics remains incomplete. The principal problem of plate tectonics is still to be solved. No models that can describe in a self-consistent fashion the breakdown of the oceanic lithosphere into individual plates have as yet been constructed.

Plate tectonics explains the origin and evolution of the oceanic lithosphere alone. As noted earlier, the continental lithosphere possesses substantially different properties in comparison with its oceanic counterpart. It is much thicker, and its age is also much greater. The plate tectonics' suggestion that there exist no purely continental plates only refers to a short interval of time, less than the average age of oceanic plates. In the course of 200 million years, all the oceanic plates get immersed into the mantle. But the continents, though capable of deformation, fragmentation, and uniting, exist for a few billions of years. They cannot therefore be regarded as passive inclusions into oceanic plates. If the continents drifted passively, being frozen into the oceanic plates, it would be impossible to explain also the causes of disintegration of supercontinents [*Trubitsyn and Rykov*, 1995].

Basing on the measurements taken on the ocean floor, it appeared possible to study the properties of the oceanic lithosphere. But the continental lithosphere is hidden beneath the thick continental crust. For this reason, the properties of the continental lithosphere are now being investigated by numerically modeling mantle convection interacting with the drifting continents.

Trubitsyn and Fradkov [1985] have been the first to demonstrate that thermal convection in the upper mantle under the continents is suppressed and the heat flow through the continents is reduced accordingly (by a factor of three). At the same time, the oceanic lithosphere cannot effectively impede the removal of heat from the mantle, because the oceanic lithospheric plates participate in the convective circulation of the mantle material. It has been shown [*Bobrov and Trubitsyn*, 1996; *Lowman and Jarvis*, 1993, 1995, 1996; *Nakakuki et al.*, 1997; *Trubitsyn and Bobrov*, 1994, 1996, 1997; *Trubitsyn et al.*, 1991, 1993a, 1993b, 1994] that a stationary continent first suppresses mantle convection beneath itself and extends the convection cell, and then, a few hundreds of years later when the subcontinental man-

tle gets heated, a hot ascending mantle convection flow develops under the continent.

Insofar as the continents are not fixed in space but drift over the mantle, their effect on the structure of mantle convection becomes even stronger. First investigations accounted only the mechanical interaction between the mantle and mobile plates by formulating an effective boundary condition. At the plate locations, the horizontal drift velocity was specified instead of the free-boundary condition [*Doin et al.*, 1997; *Lux et al.*, 1979; *Trubitsyn and Fradkov*, 1986].

In his paper of 1988, Gurnis presented the results of calculation of a 2-D numerical mantle convection model allowing for both mechanical and thermal interaction with drifting continents. In that case to prevent the spreading of the viscous continents, an implicit technique fixing the extreme points of the continents was used. [*Rykov and Trubitsyn* 1996a, 1996b; *Trubitsyn and Rykov* 1995] constructed the first self-consistent 3-D numerical mantle convection model with two drifting 3-D solid continents, based on the direct solution of a system of interrelated thermal convection equations and equations of motion of the solid continents. This model [*Trubitsyn and Rykov*, 1995] reproduces the general laws governing the formation and disintegration of Pangea. Following the disintegration of Pangea, structures are formed similar to the Atlantic and Pacific Oceans, subduction zones being formed at the oceanic margins of the Pacific, one with an almost vertical subsidence (similar to Kurile–Kamchatka zone) and the other with a very gently sloping subsidence (similar to the South-American zone). In the model with a different initial arrangement of the continents [*Rykov and Trubitsyn*, 1996b], there formed, after the disintegration of the supercontinent, a structure of two coupled continents similar to North and South Americas.

Trubitsyn and Rykov [1997] were the first to explain the causes of the inclined subsidence of the oceanic lithosphere under the overthrusting continent. They carried out a self-consistent numerical modeling of convection in the upper mantle of variable viscosity (at a not very high Rayleigh number of $Ra = 10^4$) interacting with a moving continent. The continent was modeled by a thick solid plate. Cases were analyzed where the plate could drift in the mantle either freely or with a specified velocity. It turned out that as it approached the descending, cold mantle convection flow, the continent deflected the latter, forming structures similar to inclined subduction zones. The inclination angle of the descending mantle convection flow with respect to the horizontal increased with the velocity of the overriding continent.

In their 2-D model, *Trubitsyn and Rykov* [1998b] presented in detail the mathematical formulation of the problem and the method to solve it. They analyzed

a convection model, more like the actual Earth, at a Rayleigh number of $Ra = 10^6$ on a 200 by 80 grid with a thin continent with a thickness of $d = 90$ km and a horizontal dimension of $l = 6$ thous. km. Calculations were made for a long-term evolution of the mantle-continent system. Comparison between the evolution of nonstationary convection in the mantle without and with the continent at the same points in time showed the moving continent to have a drastic effect on the structure of mantle convection.

The same authors presented the results of a series of numerical experiments conducted on 2- and 3-D models [*Trubitsyn and Rykov*, 1998c], which revealed four specific thermal convection features manifesting in the global tectonics of the Earth. Consideration was given to the mechanisms governing the origin and circulation of the oceanic lithosphere, as well as the generation and ascent of plumes, the character of the incomplete mass exchange between the upper and lower mantle, and the effect of drifting continents on mantle convection, causing in particular the difference between the continental and oceanic lithosphere.

They also formulated [*Trubitsyn and Rykov*, 1998a] a new concept of global geodynamic processes, namely, tectonics of drifting continents and oceanic lithospheric plates. Lithospheric plate tectonics explains the processes occurring beneath the oceans and drifting continent tectonics, those taking place beneath the continents. This work presents for the first time a numerical model of convection in a spherical 3-D mantle with drifting continents.

2. Model

As noted in the introduction, over the past few years the authors were publishing the results of modeling mantle convection interacting with drifting continents. It has turned out that it is exactly this interaction that causes global changes in mantle convection. Actually the continents are the regulators of the global geodynamic processes in the Earth [*Trubitsyn and Rykov*, 1998a]. The question may arise as to why nobody has so far published any calculation results for 3-D mantle convection models with drifting continents, though this problem arose ten years ago. The reason is probably that the American and European geodynamics scientists believed the continents to be less viscous than the oceanic lithospheric plates. But in that case, the continents should deform and get crushed faster than the oceanic plates, and this is not the case. The present authors have proceeded from the assumption that the oceanic lithosphere as a whole consists of a set of plates and can deform and sink in the mantle easier than an individual plate. Therefore, as a first approxima-

tion, the authors have taken a model of absolutely rigid continents interacting with a mantle. The viscosity of the mantle being dependent on temperature and pressure, the low-viscosity asthenosphere and high-viscosity oceanic and continental lithosphere are not specified but arise in a self-consistent fashion as a result of solution of equations. Modeling the continents by thick solid slabs and explicitly using natural variables (mantle convection flow and continental drift velocities) have enabled us to describe for the first time not only the translational motion of the continents, but also their rotation in space.

So, the model reduces to the following. A globe is considered as an object whose central part is occupied by a liquid core and the outer shell comprises a viscous silicate mantle. The boundary between the core and the mantle is taken to be undeformable, free from adhesion, and at a fixed temperature. It is assumed for simplicity that the mantle is heated from below and develops thermal convection. Immersed into the mantle are solid drifting continents. Specified on the mantle surface not occupied by the continents are the free-slippage conditions for the velocities and fixed zero temperature. On the entire surface of each continent there are specified the complete adherence condition for mantle convection flows, as well as the temperature and heat flow continuity conditions. Thus, a continent moves under the action of the total force of viscous coupling with the mantle convection flows at the end faces and the foot of the continent. In cases where the continents collide, an effective repelling force is introduced at all the points of contact between them. This force at each instant of time is selected such that the continents neither intersect, nor bounce back off each other to a distance less than the spatial mesh width of the computational grid.

3. Mantle Convection Equations

Thermal convection in a viscous mantle is defined by the convection flow velocity vector distribution $V_i(x, y, z)$, temperature distribution $T(x, y, z)$, and pressure distribution $p(x, y, z)$. In the Boussinesq approximation, these unknown functions are found by solving the set of three equations, namely, the momentum-, heat-, and mass-transfer equations

$$\rho dV_i/dt = -\partial p/\partial x_i + \partial S_{ij}/\partial x_j + \rho g\delta_{i3} \qquad (1)$$

$$dT/dt = \partial(k\partial T/\partial x_i)\partial x_i + Q \qquad (2)$$

$$\partial\rho/\partial t + \partial(V_i\rho)/\partial x_i = 0, \quad i = 1, 2, 3, \qquad (3)$$

where ρ is the density of the mantle, g_i is the acceleration due to gravity, T is the temperature reckoned from the adiabatic distribution, k is the thermal conductivity coefficient, Q is the thermometric density of the heat sources, δ_{ij} is the Kronecker symbol equal to unity at $i = j$ and zero at $i \neq j$, and S_{ij} is the viscous stress deviation tensor [Landau and Lifshits, 1986], given by

$$S_{ij} = \mu(\partial V_i/\partial x_j + \partial V_j/\partial x_i), \qquad (4)$$

where μ is the kinematic viscosity.

The relative magnitude of the inertial terms on the left-hand side of equation (2) for the momentum transfer in a viscous fluid is of the order of $k\rho/\mu \approx 10^{-23}$ with respect to the terms on the right-hand sides of the equations, and so these inertial terms can be disregarded. In the Boussinesq approximation, we put $\rho = \rho_0(1 - \alpha T)$ in the last buoyancy term of equation (1) and $\rho = \rho_0$ in all the remaining terms of equations (1)–(3). We will reckon pressure from its hydrostatic distribution $p(z)$ subject to the condition $\nabla p_0 = -\rho_0 g$. We introduce dimensionless variables, taking the mantle thickness D as a unit of measurement for length, D/k for velocity, D^2/k for time, T_0 for temperature, μ_0 for viscosity, $\mu_0 k/D^2$ for pressure and stress, and kT_0/D^2 for heat source density.

In these variables, convection equations (1)–(3) assume the form

$$0 = -\partial p/\partial x_i + \partial S_{ij}/\partial x_j + \mathrm{Ra}\, T\, \delta_{i3} \qquad (5)$$

$$\partial T/\partial t + \mathbf{V}\nabla T = \partial(\partial T/\partial x_i)\partial x_i + Q \qquad (6)$$

$$\partial V_i/\partial x_i = 0, \qquad (7)$$

where Ra is the Rayleigh number given by

$$\mathrm{Ra} = \alpha\rho_0 g T_0 D^3/k\mu_0 \qquad (8)$$

4. Equations of Motion of Freely Drifting Continent

The velocity components $\mathbf{u}(u, v, w)$ of any point of a solid continent may be represented in the form [Landau and Lifshits, 1965]

$$\mathbf{u}_k(x, y, z) = \mathbf{U}_{0k} - \varepsilon_{ijk}\omega_i(x_j - x_{j0}), \qquad (9)$$

where $\mathbf{U}_{0k} = (u_0, v_0, w_0)$ is the instantaneous velocity vector of the center of gravity of the continent, $\omega_i = (\omega_x, \omega_y, \omega_z)$ is the instantaneous angular velocity vector in rotation around this center of gravity, x_i are the coordinates of an arbitrary point of the continent, x_{i0} are the coordinates of the instantaneous center of gravity of the continent, and ε_{ijk} is the Levi-Civita symbol equal to zero when any two of the subscripts

coincide, 1 in the case of even transposition of the subscripts with respect to 123, and -1 in the case of an odd transposition.

$$\mathbf{U}_{0k} = (1/M) \int \rho_c u_k d\tau, \quad M = \int \rho_c d\tau, \qquad (10)$$

where ρ_c is the density distribution in the continent, $d\tau$ is the volume element, and M is the mass of the continent.

In the generals case, the Euler equations for the motion of a solid have the form [*Landau and Lifshits*, 1965]

$$M \partial \mathbf{U}_{0i}/\partial t = \mathbf{F}_i, \qquad (11)$$

$$d\mathbf{M}_i/\mathbf{dt} = \mathbf{K}_i, \qquad (12)$$

where $\mathbf{F}_i$ is the external force and $\mathbf{M}_i$ is the moment of momentum of the solid.

$$\mathbf{M}_i = \mathbf{I}_{il}\omega_l, \qquad (13)$$

where $\mathbf{I}_{ik}$ is the inertia tensor of the solid expressed as

$$\mathbf{I}_{ik} = \int \rho_c [(x_l - x_{lo})^2 \delta_{Ij} - (x_i - x_{io})(x_k - x_{ko})] dv, \quad (14)$$

$\mathbf{K}_i$ is the total force moment made up of the moments $\mathbf{k}_i$ of the forces $\mathbf{f}_j$ acting upon the individual elements of the solid, these moments being given by

$$\mathbf{k}_l = \varepsilon_{ijl}(x_i - x_{io})\mathbf{f}_j \qquad (15)$$

The continent is acted upon by the gravity force applied to its center of gravity and by the forces of interaction with the viscous mantle, applied to the surface elements of the immersed portion of the continent. Under the effect of these forces the continent drifts in the mantle, moving over its surface and rotating around the vertical axis. As the pressure and velocity of the mantle convection flows vary in time and space, both the vertical velocity w_0 of the center of gravity of the continent and its rotation velocities ω_x and ω_y about the instantaneous horizontal axes x and y are in the general case other than zero. Continents can sink (when they are over descending mantle convection flows), together with and relative to the mantle surface, and rise (at ascending flow locations), the subsidence and rise of the opposite ends of the continents being not necessarily equal.

In the subsequent discussion we only consider the horizontal motions of the center of gravity of the continent and the rotation of the latter about its vertical axis, neglecting all the other small effects and putting $w_0 = 0$ and $\omega_x = \omega_y = 0$. In as much as the gravity force is counterbalanced by the buoyant force, the external force acting on the continent is reduced to the force of viscous coupling with the mantle, the pressure p being reckoned from the hydrostatically equilibrium distribution $p_0(z)$:

$$\mathbf{F}_i = \int \int (-p\,\delta_{jk} + S_{jk}) n_k df, \qquad (16)$$

where df is the magnitude of the surface element of the solid continent and n_j is the unit vector of the external normal to the surface of the continent. The integral is taken over the entire surface of the portion of the continent of an arbitrary shape immersed into the mantle.

Thus, the Euler equations for the horizontal motion of a solid continent of an arbitrary shape and its rotation around the instantaneous vertical axis are reduced to the following system of three equations [*Landau and Lifshits*, 1965]:

$$M\,du_0/dt = \int \int (-p\,\delta_{1j} + S_{1j}) n_j df, \qquad (17)$$

$$M\,dv_0/dt = \int \int (-p\,\delta_{2j} + S_{2j}) n_j df, \qquad (18)$$

$$I_{33} d\omega_3/dt = \int \int \varepsilon_{ij3}(x_i - x_{0i})(-p\,\delta_{jk} + S_{jk}) n_k df, \quad (19)$$

$$dx_c/dt = u_0, \quad dy_c/dt = v_0, \quad d\varphi/dt = \omega_3, \qquad (20)$$

where $x_c(t)$ and $y_c(t)$ are the coordinates of the center of gravity of the continent and φ is the angle of rotation of the continent.

In the particular case of horizontal motion of infinitely thin solid continents, the viscous force only acts at the foot of the continent, for which $n_k = (0, 0, -1)$. In that case, the Euler equations are simplified:

$$M\partial u_0/\partial t = -\int \int S_{xz}\; dx\; dy, \qquad (21)$$

$$M\partial v_0/\partial t = -\int \int S_{yz}\; dx\; dy, \qquad (22)$$

$$I\partial\omega/\partial t = \int \int [(y' - y_0')S_{xz} - (x' - x_0')S_{yz}] dx'\; dy', \quad (23)$$

where I is the moment of inertia of the continent about the axis z' passing through its center of gravity and calculated in the moving coordinate system with the axes x' and y' directed along the principal axes of inertia of the continent:

$$I = \int \rho_c [(x - x_0)^2 + (y - y_0)^2] d\tau \qquad (24)$$

It follows from dimensional relations that the magnitude of the inertial terms on the left-hand side of Euler equations (17)–(19) for the motion of continents is, as

in the case of equation (1) for momentum transfer in a viscous fluid, of the order of $k\rho/\mu \approx 10^{-23}$.

With the inertial terms being omitted, The Euler equations for the motion of continents yield the following six relations for finding the coordinates $x_c(t)$ and $y_c(t)$ of the center of gravity of the continent, its angle of rotation φ, and velocities $u_0(t)$, $v_0(t)$, and $\omega_3(t)$:

$$\iint (-p\,\delta_{1j} + S_{1j})n_j\,df = 0, \qquad (25)$$

$$\iint (-p\,\delta_{2j} + S_{2j})n_j\,df = 0, \qquad (26)$$

$$\iint \varepsilon_{ij3}(x_i - x_{0i})(-p\,\delta_{jk} + S_{jk})n_k\,df = 0, \qquad (27)$$

$$dx_c/dt = u_0, \quad dy_c/dt = v_0, \quad d\varphi/dt = \omega_3 \qquad (28)$$

The equation for the distribution of the temperature T_c inside the solid continent in the initial fixed coordinate system reduces to the heat-transfer equation involving advective heat transfer at a rate satisfying relation (9)

$$\partial T_c/\partial t + \mathbf{u}\nabla T_c = \partial(\partial T_c/\partial x_i)\partial x_i + Q_c, \qquad (29)$$

where Q_c is the density of heat sources inside the continent.

5. Boundary Conditions

Mantle convection equations (1)–(3) and equations (17)–(19) for the motion of the continent and equation (29) for heat transfer therein are interrelated through the intermediary of boundary conditions.

As noted, zero flow and zero slippage conditions (i.e., zero normal fluid velocity component and zero tangential viscous force components) are specified at the bottom and side boundaries of the computational region:

$$V_k n_k = 0, \quad S_{ki}\tau_i = 0, \quad i = 1, 2, \qquad (30)$$

where n_k is the unit vector normal to the given surface and τ_i are the unit vectors tangent to it.

Specified at the boundaries of the solid mobile continent, all over its portion immersed into the mantle, is the zero flow and adherence condition, i.e., the equality between the mantle convection flow and continent drift velocities,

$$V_i = u_i \qquad (31)$$

The temperature at the lower boundary of the region is fixed at $T = 1$. At the side boundaries there is specified the zero heat flow condition

$$\partial T/\partial n_k = 0, \qquad (32)$$

where n_k is the unit vector normal to the lateral surface of the region.

The temperature of the mantle on the top, free surface is equal to zero ($T = 0$) but only in the oceanic region outside the continent.

On the surface of the immersed portion of the continent there are specified the mantle-continent temperature and heat flow continuity conditions

$$T = T_c, \quad \partial T/\partial n = \partial T_c/\partial n \qquad (33)$$

The temperature on the top surface of the continent is taken to be zero:

$$T_c = 0 \qquad (34)$$

Thus, the mathematical problem reduces to the following. There are three unknown functions of coordinates and time for mantle convection, namely, the mantle convection flow velocity vector distribution $V_i(x, y, z, t)$, temperature distribution $T(x, y, z, t)$, and pressure distribution $p(x, y, z, t)$, and also four unknown functions of time for the motion of continents as a whole, namely, the two components of the instantaneous translational velocity of the center of gravity, i.e., $u_0(t)$ and $v_0(t)$, one component of the instantaneous angular velocity of the continent around its center of gravity, $\omega(t)$, and the temperature distribution in the continent, $T_c(x, y, z, t)$. To find these unknowns, there is a system of connected equations, namely, three differential convection equations (1)–(3), three integral relations (25)–(27) whereto the Euler equations of motion have reduced, and continental heat-transfer equation (29). Given the position of the continent and its velocities $u_0(t)$, $v_0(t)$, and $\omega(t)$, one can find its position at the next instant of time. Boundary conditions (30)–(34) serve to find the integration constants for the differential equations.

The difference between the present problem with a freely drifting continent and the well-known problem with a fixed continent is that the boundary conditions for the convection flow velocities and temperature at the mantle-continent boundary are specified at each given instant of time at the location of the drifting continent whose velocity and position are not known beforehand, but are determined by solving a set of connected differential equations.

If there is a number of continents, equations of motion (25)–(27) and temperature equation (29) are written down for each continent. Besides, in the case where solid continents collide, the condition is specified for the impossibility of their penetration into each other. To this end, at an instant when the colliding continents come into contact at some point a repelling force is applied at this point to each continent, in addition to the

forces of viscous coupling with the mantle, the force being directed opposite to the relative velocity of the continents. The algorithm for computing these forces is described below.

6. Numerical Technique

6.1. Method of Joining Two Regions and Through Computation Method

To numerically solve the set of thermal convection equations in the case of drifting continents, one can use two principally different methods. In the method of two regions, heat- and mass-transfer equations are solved at each time step separately for the mantle outside of the continent and for the continent, and the solutions obtained are then joined together so that to satisfy the boundary conditions on the continent's portion immersed into the mantle. In the through computation method, analyzed at each time-step at the given position of the continent is its own unified computational region, the jump of the parameters characterizing the different properties of the materials of the mantle and continents being explicitly allowed for on the surface of the latter. The numerical algorithm procedure in the through computation method is simpler, but it is necessary in that case to smooth out the jumps of the functions by replacing at each time step the solid continent by a high-viscosity region.

6.2. Algorithm for Computing Forces of Interaction Between Thermal Convection and a Drifting Continent

In the general case, the algorithm for the numerical solution of the set of thermal convection equations in the case of drifting continent reduces to the following. Let there be given at the instant t_1 the convective flow velocities, the field of the temperatures $T(t_1)$ and pressures $p(t_1)$ in the mantle, as well as the position $x_1(t_1)$, $y_1(t_1)$ of the continent and its velocities $u_0(t_1)$, $v_0(t_1)$, and $\omega(t_1)$. We need to find the solution of the set of equations (1)–(5), (25)–(27), and (29) at the next instant of time, $t_2 = t_1 + \Delta t$. The new position of the continent, $x_1(t_2)$, $y_1(t_2)$, at the instant t_2 can simply be found from equation (28): $x_1(t_2) = x_1(t_1) + u_0(t_1)\Delta t$, $y_1(t_2) = y_1(t_1) + v_0(t_1)\Delta t$. If the new velocities $u_0(t_2)$, $v_0(t_2)$, and $\omega(t_2)$ of the continent in this position were also known, it would then be possible again to solve thermal convection equations (1)–(5) subject to boundary conditions (32)–(34) for temperature and (30)–(31) for velocities, corresponding to the new position of the continent, and find the mantle convection flow velocities $V_x(t_2)$, $V_y(t_2)$, and $V_z(t_2)$, the temperature $T(t_2)$, and pressure $p(t_2)$. But the difficulty of the problem is precisely the fact that it is exactly these velocities of the continent, $u_0(t_2)$, $v_0(t_2)$, and $\omega(t_2)$, that are unknown. They must be such as to make the newly found mantle convection flow velocities $V_x(t_2)$, $V_y(t_2)$, and $V_z(t_2)$ corresponding to these new velocities $u_0(t_2)$, $v_0(t_2)$, and $\omega(t_2)$ satisfy equations of motion (25)–(27) of the continent as well. It is therefore necessary to use some iteration technique to find these velocities of the continent. One can, in principle, use a certain scheme to search for the continent velocity values, computing convection flow velocity fields and evaluating integrals (25)–(27), until such values of the velocities $u_0(t_2)$, $v_0(t_2)$, and $\omega(t_2)$ are found as make the right-hand sides of relations (25)–(27) differ from zero by an amount less than the preset number ε corresponding to the prescribed accuracy of computation. Since the right-hand side of relations (25)–(27) corresponds, in a physical sense, to the forces and moment of force acting on the continent, then $\varepsilon > 0$ if the selected continent velocities $u_0(t_2)$, $v_0(t_2)$, and $\omega(t_2)$ are underestimated and $\varepsilon < 0$ if they are overestimated.

6.3. Algorithm for Computing Repelling Forces for Colliding Continents

As noted earlier, when computing the motion of continents, the condition is specified for the impossibility of their mutual penetration. This condition is implemented by the following algorithm. In computing the motion of the continents, the condition for preventing their overlapping is being constantly checked. If at some instant t_1^* some point of one continent falls in the region of another continent, the computational procedure goes back to the previous instant of time, $t_2^* = t_1^* - \Delta t$, and the computation starts again at that instant with a continent repelling force being added to the right-hand side of equations of motion (27)–(29). The direction, magnitude, and point of application of this force are chosen as follows. The first to be found are the average velocities U_1 and U_2 of the points of each continent that have found themselves in the continent overlapping region. Next the difference between these velocities is found. The point of application of the repelling forces to each continent is taken to be the center of the overlapping region. The direction of the continent repelling forces is taken to be opposite to that of the relative velocity of one continent with respect to the other. The magnitude of the forces is selected in an iterative manner. At first, some value of the repelling force is taken, and next the systems of heat convection equations (1)–(5), heat-transfer equations (29), and equations of motion (25)–(27) are solved with due regard for this additional force. If in the course of the time interval Δt the continents part to a distance greater than the mesh width of the computational grid, the magnitude of the repelling force selected is reduced. While the continents stay in contact their translational and rotational velocities change sub-
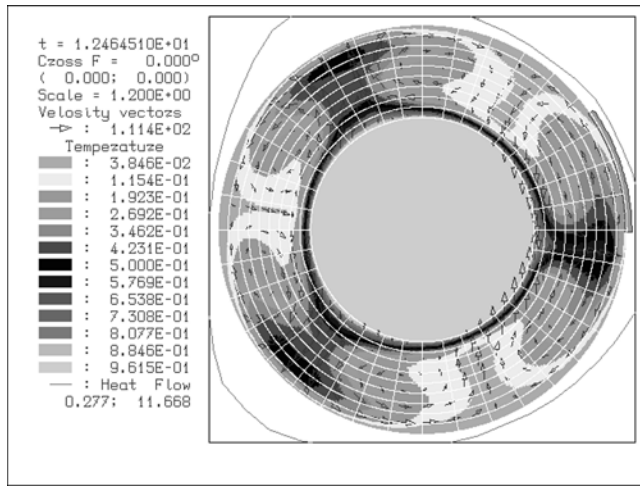
Figure 1. Radial distribution of dimensionless temperature and dimensionless heat flow (Nusselt number) for the mantle convection model with Ra $= 10^4$.

stantially in comparison with freely drifting continents.

6.4. Numerical Solution of Convection Differential Equations

The system of thermal convection equations with drifting continents were solved by the finite-difference technique [*Rykov and Trubitsyn*, 1996b]. When numerically solving heat-transfer equations (6), (29), use was made of the Zalesak flux-corrected transport technique [*Zalesak*, 1979]. Velocity and pressure equations (5), (7), (25)–(28) were reduced to elliptic equations with variable coefficients (generalized Poisson equations). These equations were solved by means of the alternating triangular technique in the three-layer modification, the iterative parameters being chosen by the conjugate gradient method [*Samarskii and Nikolaev*, 1978].

7. Computation Results

Computations were carried out on 3-D spherical models. Therefore, the general equations discussed above were converted to a spherical coordinate system for the mantle convection flow velocities $V_r(r, \theta, \phi, t)$, $V_\theta(r, \theta, \phi, t)$, and $V_\phi(r, \theta, \phi, t)$, temperature $T(r, \theta, \phi, t)$, the velocities of the centers of gravity of the continents, $u_\theta(r, \theta, \phi, t)$ and $u_\phi(r, \theta, \phi, t)$, and their solid-body rotation with the angular velocities $d\varphi/dt$ in the local instantaneous coordinate system.

To analyze the interaction between drifting continents and mantle convection flows, two models were considered: Model 1 with a single freely drifting continent and a weak thermal convection in the mantle at a Rayleigh number of Ra $= 10^4$ and Model 2 with five drifting continents and an intense thermal convection at a Rayleigh

number of Ra $= 10^6$. A fixed temperature at the mantle-core boundary and zero temperature at the surface were taken as the boundary conditions for both models. The initial state was taken to be a viscous convection-free mantle with its temperature distribution corresponding to a steady-state conductive heat flow. A small arbitrary temperature perturbation was then introduced, and the temperature and convection flow velocity evolution was calculated by the mantle convection equations. With time a quasistationary thermal convection was established in the mantle, its structure being almost independent of the initial perturbation. Thereupon continents were placed into the mantle, and the subsequent evolution of the mantle-continent system was computed by solving the system of connected mantle convection equations and equations of motion of the continents.

As noted earlier, the mantle convection structure in dimensionless variables at a constant viscosity depends on a single parameter – the Rayleigh number Ra. For the spherical Earth, the Rayleigh number is estimated by various authors at around 10^6. At a lower intensity, convection in the mantle is less chaotic, and the motion of continents is more regular. To reveal the drift specifics of the continents, we first computed Model 1. Figure 1 presents the radial distributions of the above-adiabatic temperature, $T(r)$, and the Nusselt number Nu $=$ Nu(r) of the dimensionless heat flow, established in the course of convection in the mantle at a Rayleigh number of Ra $= 10^4$. Shown in Figure 2 is the temperature distribution $T(r, \theta)$ in the zero-longitude cross section. The dimensionless temperature values are in the interval from zero (on the surface) to unity (at the mantle-core boundary). The correspondence between
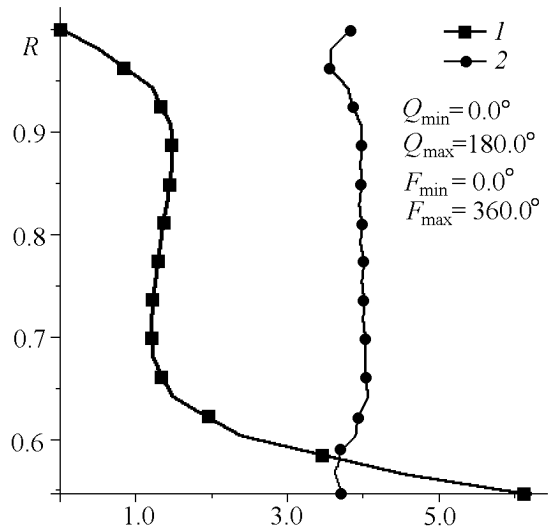

Figure 2. Temperature distribution $T(r, \theta)$ (1) and heat flow (2) in the zero-longitude cross section.

the temperature values and the color scale is indicated at the left of the Figure 2 . The liquid core of the Earth is colored dark-red. The arrows indicate the direction and relative magnitude of mantle convection flows. The dimensionless velocity scale is also given at the left of the figure. Indicated at the upper left of the figure is the dimensionless instant of time at which convection reached the steady state. The continent, colored red on the right- hand side of the sphere, is placed into the mantle at that instant.

Figure 3 (7 frames) presents the computation results for the evolution of the mantle-continent system. For the sake of definiteness, the shape of the continent and its position are chosen to be similar to modern Africa. But the structure of mantle convection cannot correspond to the modern Earth, because the state of mantle convection at the moment the continent is placed into the mantle is selected arbitrarily. Thus, the model under consideration only serves to reveal the principal possibility of and the laws governing the drift of the continent. The distribution of the computed dimensionless heat flow (the Nusselt number) over the Earth's surface is depicted in color. Recall that the temperature at the surface of the continent and the surface of the free portion of the mantle is the same and equals zero in the dimensionless units adopted. The entire surface of the Earth in these figures is shown in developed projection.

A more detailed continental drift evolution in Model 1 is given in the online version of this paper in the form of a film (**anim01**). This film contains 55 frames. As one can see from these pictures, when convection is weak, there are formed but a few ascending and descending convection flows in the mantle, the descending flows being practically united into a single system. The continent at first is pulled into the site of one of the descending flows. But since the shape and size of the continent fail to coincide with those of the descending flow spot on the Earth's surface, this position of the continent proves unstable. As the constant-viscosity model under consideration disregards the oceanic lithosphere and contains but a single continent, the motion of the latter turns out to be free. The continent starts drifting along the system of united descending mantle convection flows. Because the continent impedes the outflow of heat from the mantle, the mantle starts heating, provided the continent is stationary and large enough, so that in 200–400 million years there develops an ascending, hot convection flow [*Trubitsyn and Bobrov,* 1996]. If the continent drifts rapidly, no hot ascending mantle convection flow has enough time to develop beneath it. But one can see from the film, when the drift is slowed down, an ascending flow can partially arise behind the continent.

Figures 4, 5, and 6 present the computation results for the evolution of mantle convection with five continents at a Rayleigh number of $Ra = 10^6$. Shown in Figure 4 is the computed radial distribution of temperature (violet curve) and heat flow (red curve) in the mantle. Figure 5 (4 frames) presents the computation results for the evolution of the mantle-continent system in Model 2. As distinct from Model 1, these figures show the Earth's hemisphere as seen from the observation point with a latitude of $90°$ and longitude of $0°$. The initial position and shape of the continents are taken to be similar to Africa, North and South Americas, Australia, and Eurasia. The shape of each continent is described approximately on the basis of 12 angular points of the contour. The structure of convection at the moment the continents are placed into the mantle being arbitrary, the model computed does not aim to trace the drift of the continents on the actual Earth, but merely reveals the principal specifics of the drift of the continents, particularly the possibility of their uniting into supercontinents and subsequent parting.

As seen from Figure 5, three continents (Africa, Eurasia, and North America) start drifting northwards. The other two continents (Australia and South America) drift southwards.

Figure 6 (11 frames) illustrates the further evolution of the mantle-continent system. Insofar as the continents by that instant have gone to the other Earth's hemisphere, these figures show the view of the globe as seen from the point with the coordinates $45°S$ and $210°E$. It can be seen that at the instant of dimensionless time $t = 14.0298$ three continents (South America, Eurasia, and Australia) unite into a supercontinent. At the instant $t = 14.03296$ all the five continents unite into a single supercontinent – Pangea. As heat is accumulated beneath Pangea, the mantle material at that spot becomes lighter in weight. The descending convection flow changes to an ascending one which splits Pangea apart by the instant of dimensionless time $t = 14.0355$. Following the breakup of Pangea, there remains for a long time at its location a system of hot ascending mantle convection flows similar to the giant hot anomaly beneath the Pacific Ocean.

A more detailed drift evolution of the five continents in Model 2 in the online version of this paper in the form of a film (**anim02**). This film contains 16 frames for the initial stage of evolution viewed from one side and 85 frames for the evolution stage involving the uniting of three and five continents.

8. Conclusion

As stated at the 1998 International Gordon Conference (Gordon Research Conference – Interior of the Earth, June 28 – July 3, 1998, Boston, USA), the two most important problems of geoscience still to be solved
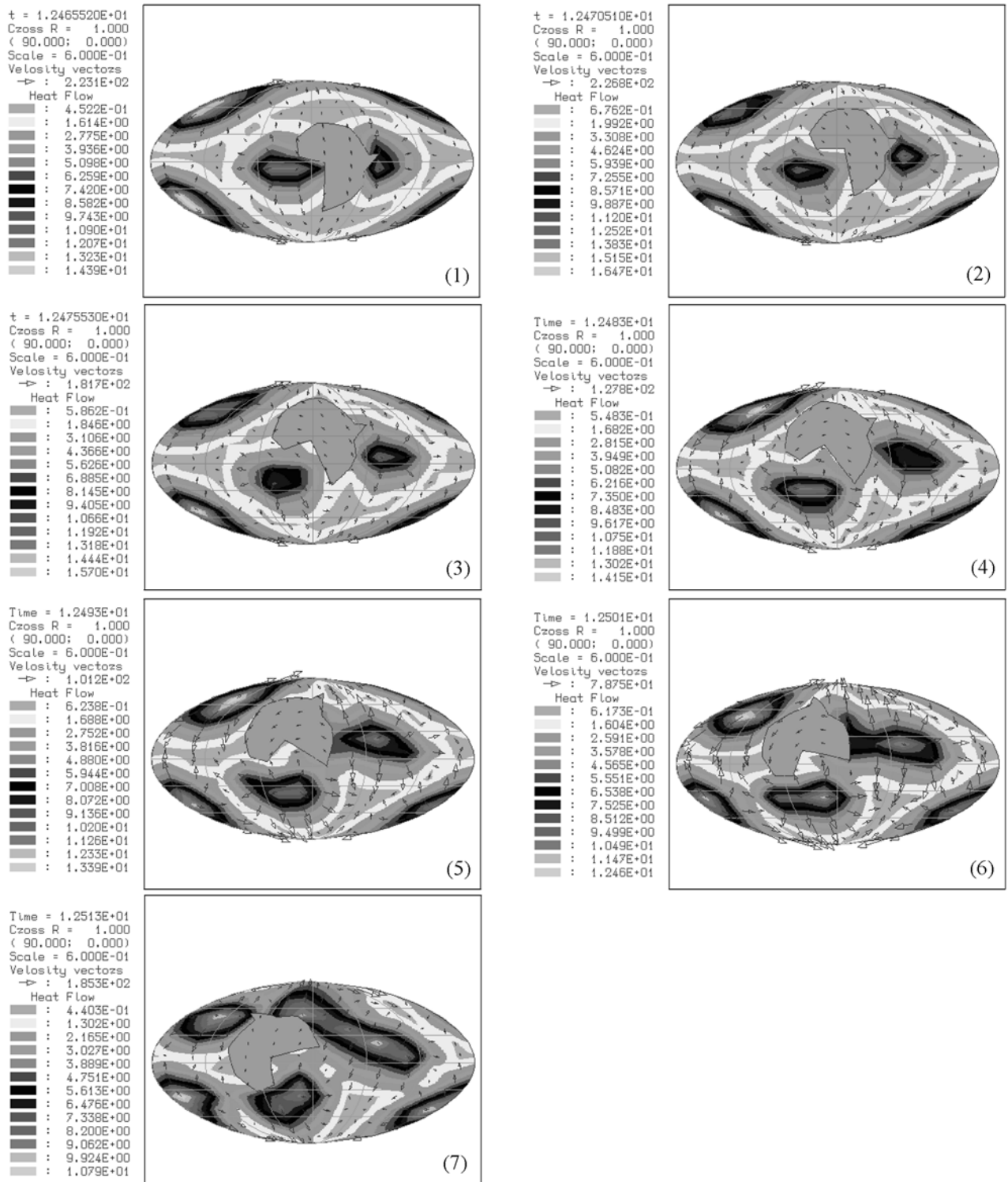
Figure 3. Computed evolution of the mantle-continent system in Model 1. The entire Earth's surface is shown in a developed projection. Shown at the left of the figures is the correspondence between colors and computed values of the dimensionless heat flow over the Earth's surface, as well as the velocity scale.
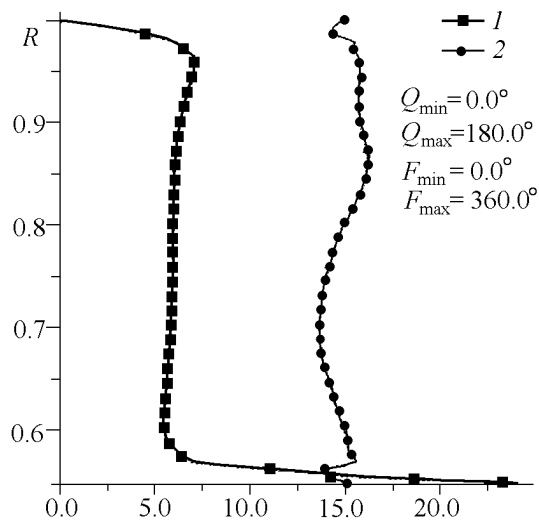
Figure 4. Radial distribution of dimensionless temperature and dimensionless heat flow (Nusselt number) for the mantle convection model with Ra = 10^6.

are the explanation of the continent uniting and parting events that took place repeatedly in the Earth's history and the explanation of the nature of the continental lithosphere, its formation and evolution.

The solution of these problems will actually be the next important stage in the development of the concept of the structure of the Earth and of the processes occurring therein. Plate tectonics has only explained the nature of the oceanic lithosphere, the continents being merely regarded as passively drifting inhomogeneities frozen into oceanic plates. As the oceanic lithospheric plates have existed for no more than 200 million years, plate tectonics cannot in principle explain global geological processes lasting for billions of years, particularly the causes of formation and breakup of supercontinents. Obviously the continental lithosphere which is older than the oceanic plates could not arise but for the continents. The properties and evolution of the continental lithosphere must be governed by the long-lasting mobile continents.

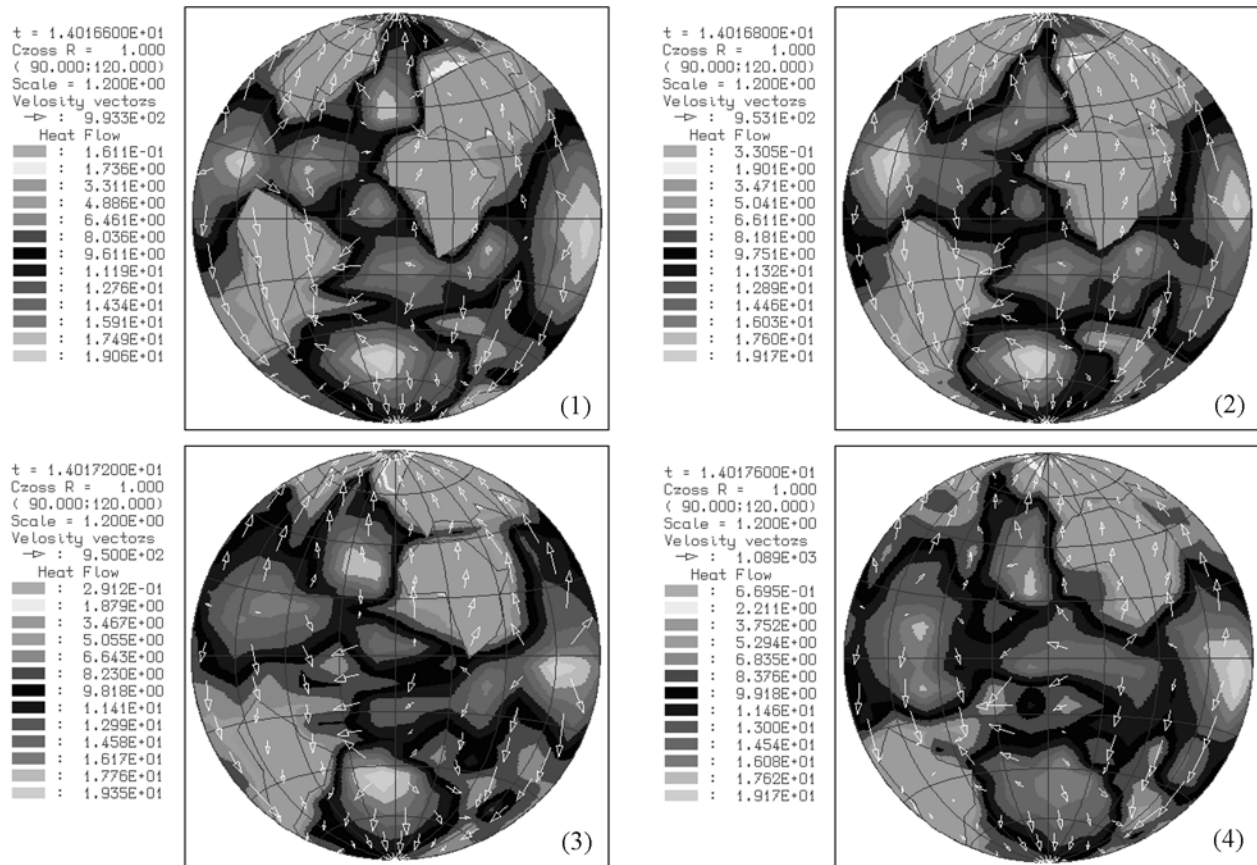A new approach to global tectonics was advanced

Figure 5. Computed evolution of the mantle-continent system for Model 2. The view of the globe as seen from the observation point with a latitude of 90° and a longitude of 0°.
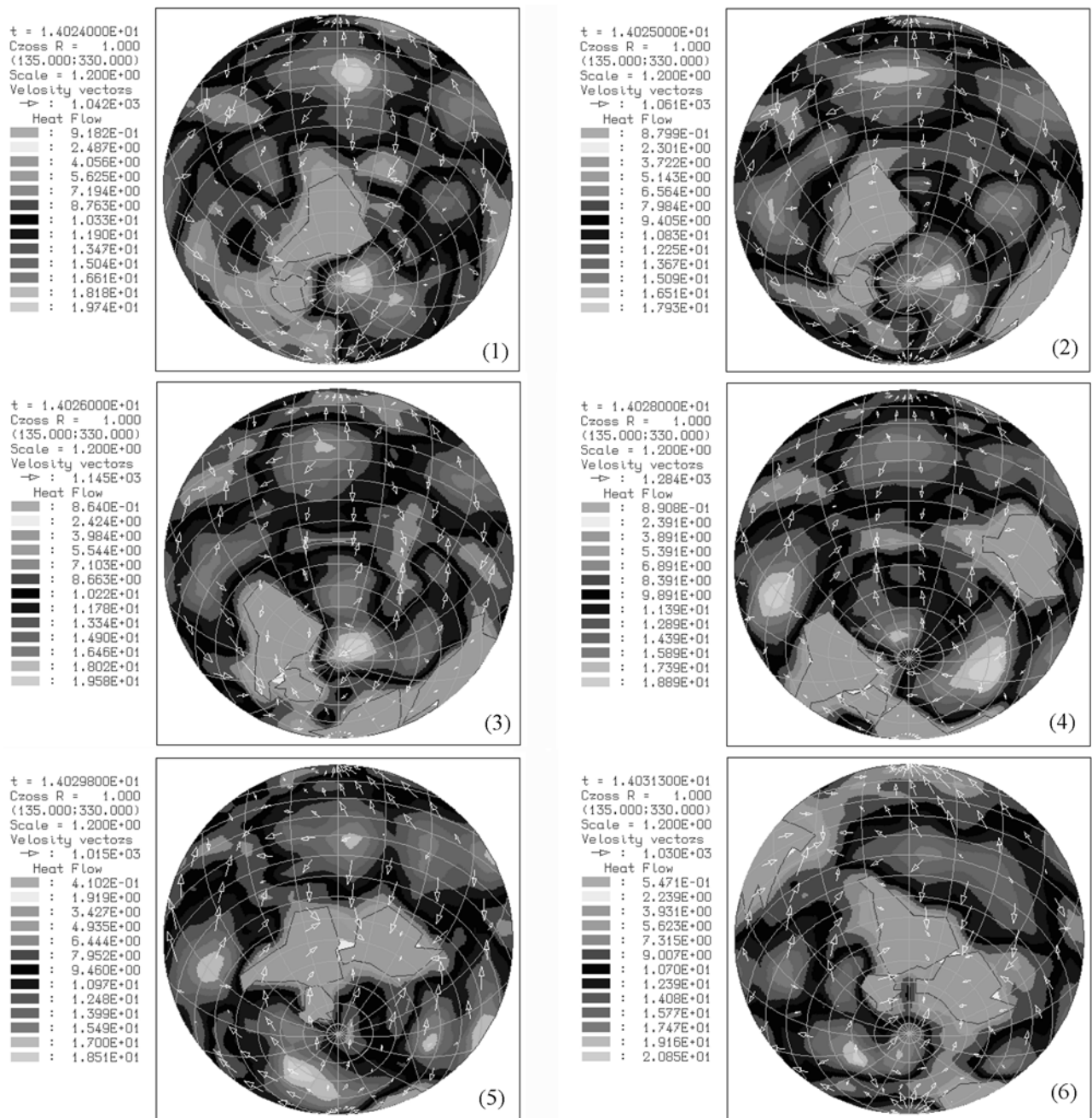
Figure 6. Further evolution of the mantle-continent system in Model 2. The view of the globe as seen from the observation point with coordinates 45°S and 210°E, At the instant of dimensionless time $t = 14.0298$ (Figures 2–10) a supercontinent if formed from three continents. At the instant of dimensionless time $t = 14.03296$ all the five continents unite into a single supercontinent – Pangea. By the instant of dimensionless time $t = 14.0355$ (Figures 2–16) there remains, following the breakup of Pangea, a system of hot ascending mantle convection flows similar to the giant hot anomaly beneath the Pacific Ocean. Frames 1–6.

by *Trubitsyn and Rykov* [1995, 1997, 1998a, 1998b, 1998c]. Based on detailed numerical experiments on 2- and 3-D models in orthogonal coordinates, they have demonstrated that the continents are not passive inclu-sions in lithospheric plates, but, on the contrary, are the chief regulators of the entire global tectonics of the Earth. It were precisely the continents that came into existence more than three billion years ago that formed
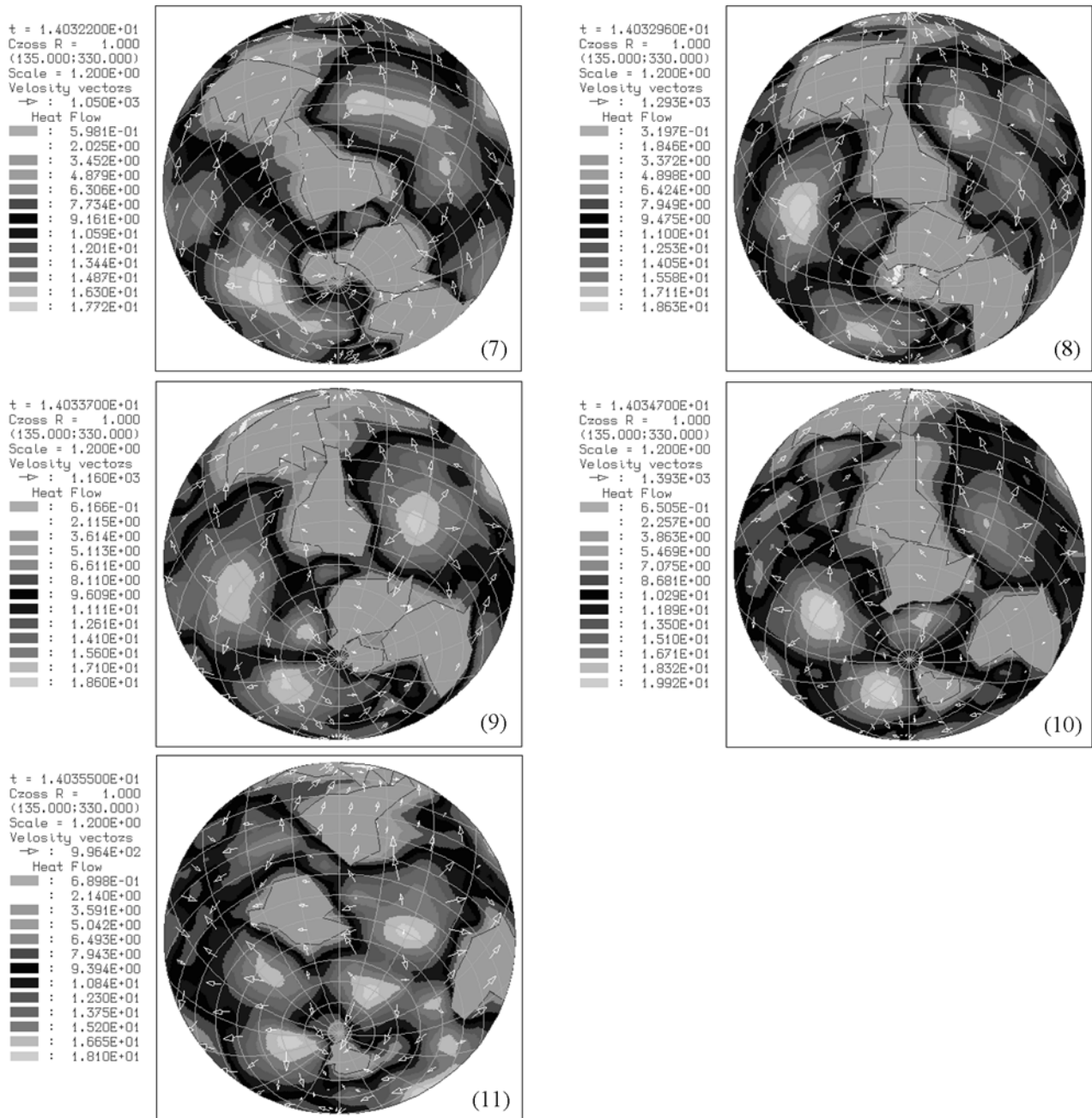
Figure 6. Continuation. Frames 7–11.

the continental lithosphere and determined its properties different from those of the oceanic lithosphere.

Presented for the first time in this work is a 3-D spherical model of mantle convection interacting with several drifting continents. The adherence condition on the surface of the mantle-immersed portion of the continents introduces the mechanical interaction between the mantle and continents. The temperature and heat flow continuity conditions on the mantle-continent bound-

aries introduces the thermal mantle-continent interaction. The continents interact with one another upon direct collision and through the intermediary of the mantle, thus changing its structure. The solution of the system of connected mass-, heat-, and momentum-transfer equations for the viscous mantle and Euler equations for the solid continents has for the first time allowed the evolution of the mantle-continent system to be described in a self-consistent fashion on a 3-D model.

Thanks to the sphericity of the model (devoid of side boundaries), it has proved possible to trace a very long drift evolution of the continents and describe for the first time both the formation and breakup of supercontinents.

It should be noted that the present model only proves the principal possibility of formation and breakup of supercontinents without any direct relation to the actual Earth. This is due to the fact that the structure of mantle convection at the instant the continents were placed into the mantle was taken on the basis of model computations for the establishment of convection, whereas the actual mantle convection structure resulted from a great number of complicating processes, such as the differentiation of matter, redistribution of heat sources, substantial changes in viscosity, and so on.

However, the solution of the problem proves possible if use is made of seismic tomography data. Converting the distribution of seismic wave velocities yields the modern instantaneous temperature distribution in the Earth. Solving the system of convection equations with drifting continents will therefore provide the possibility of determining the mantle convection flow velocities which materially depend on adherence to the solid continents. More than that the mathematical apparatus developed by the authors makes it possible to compute the drift velocities of the continents themselves, heat flow distribution, relief, gravity field, and stress distribution over the entire Earth. With the model parameters being optimized so that to make the computation results agree with the entire mass of observation data available, it will be possible to construct a complete geodynamic model of the Earth. This model will enable one to observe on the computer the processes occurring in the Earth's interior, specifically those giving rise to mineral deposits and altering the general stress field.

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