Russ. J. Earth. Sci., Vol. 22, ES1005
https://doi.org/10.2205/2022ES000787

RUSSIAN JOURNAL *of* EARTH SCIENCES

GEODYNAMIC MODEL OF THE INTERACTION BETWEEN THE CONTINENTAL LITHOSPHERE AND THE ACTIVE CONTINENTAL MARGIN IN EAST ASIA

Leopold I. Lobkovsky[1, 2], Yurii V. Gabsatarov[*, 1, 2], Dmitry A. Alekseev[1, 2], Irina S. Vladimirova[1, 2], Mukamay M. Ramazanov[3], and Vyacheslav D. Kotelkin[1, 4]

[1] *P. P. Shirshov Institute of Oceanology, Russian Academy of sciences, Moscow, 117997, Russia*
[2] *Moscow Institute of Physics and Technology (MIPT), Dolgoprudny, 141701, Russia*
[3] *Institute for Geothermal Research and Renewable Energy, Branch of Joint Institute for High Temperatures of the Russian Academy of Sciences, Makhachkala, 367030, Republic of Dagestan, Russia*
[4] *Lomonosov Moscow State University, Moscow, 119991, Russia*

Received 11 March 2022; accepted 25 March 2022; published 6 April 2022.

We propose a concept for a geodynamic model of East Asia, taking into account the mechanism of the interaction between the stable part of the regional continental lithosphere and the active continental margin along the Kuril-Kamchatka and Japan island arcs. The concept involves upper mantle convection combined with keyboard-block mechanism explaining seismic cycle patterns in the active continental margin and provides grounds to resolve the paradoxes of the present-day velocity field observed by satellite geodesy methods. These paradoxes are associated with enormous variation in the velocity field, such as sometimes contradict directions of surface motions in the adjacent portions of the earth's surface. We propose a model that attribute the observed motion pattern to the superposition of the long-term subduction-driven convection regime beneath the continent causing the ocean-ward lithosphere extension and the shorter-term cyclic motion of seismogenic blocks with alternating directions. The model contributes to the development of the physically-based theoretical concepts of modern plate tectonics and eliminates the contradictions between the observed data and classical plate tectonics in East Asia region.

Keywords: East Asia, geodynamics, mantle convection, subduction, seismic cycles, largest earthquakes, satellite geodesy, modern surface displacements

Citation: Leopold I. Lobkovsky, Yurii V. Gabsatarov, Dmitry A. Alekseev, Irina S. Vladimirova, Mukamay M. Ramazanov, and Vyacheslav D. Kotelkin (2022), GEODYNAMIC MODEL OF THE INTERACTION BETWEEN THE CONTINENTAL LITHOSPHERE AND THE ACTIVE CONTINENTAL MARGIN IN EAST ASIA, *RUSS. J. EARTH. SCI.,* Vol. 22, ES1005, 10.2205/2022ES000787.

1 INTRODUCTION

East Asia is a vast, highly tectonically active territory that includes both stable continental areas and active continental margin. Seismic and tectonic activity in East Asia is characterized by significant heterogeneity, which is due to the region's complex geodynamic setting. The developing of a regional-scale structural-dynamic model of East Asia is necessary for solving both fundamental and applied problems of seismology, geophysics and geodynamics, such as earthquake forecasting, seismic hazard assessment and seismic zoning.

The nature of the deformation of the earth crust in tectonically active regions is one of the most controversial issues in geodynamics. The active deployment of regional satellite geodetic networks made it possible to accumulate a large amount of data on modern earth surface's motion in various regions of East Asia. The analysis of these data is currently one of the most widely used methods for studying crustal and lithospheric deformation processes. A key point of this approach, which may be also its weak point, is the choice of a geodynamic model describing the processes that cause deformation of the earth's surface. An incorrect choice of the initial geodynamic model can lead to biased results, even if a mathematically correct and statistically significant solution is obtained.

To develop a structural and dynamical model of East Asia one must consider the three-dimensional distribution of endogenous deformation processes and the coupled deformation of the upper shells of the Earth. Another problem is related to the study of the interaction between the lithosphere of East Asia and the Kuril-Kamchatka and Japanese island arcs, where satellite geodetic measurements

---

[*] Corresponding author: yuryg@gsras.ru

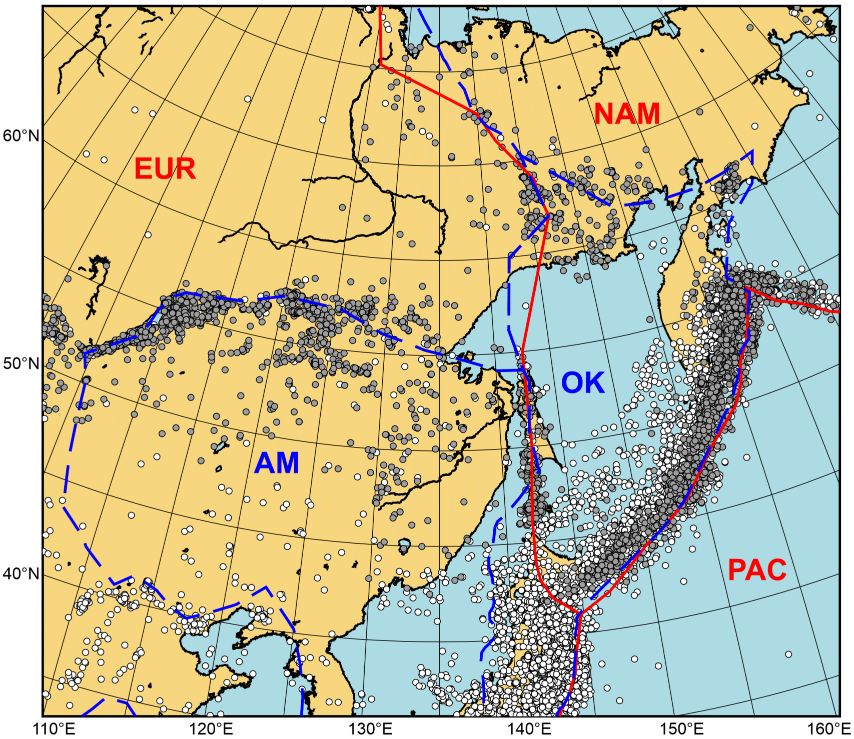

Figure 1: East Asia's regional seismicity provided by Geophysical Survey of the Russian Academy of Sciences (gray circles) [*GS RAS*, 2021] and International Seismological Center (white circles) [*ISC*, 2021]. Red solid lines show lithospheric plate boundaries according to NUVEL-1A model [*DeMets et al.*, 1994], blue dashed lines indicate plate boundaries according to models PB2002 [*Bird*, 2003], and NNR-MORVEL56 [*Argus et al.*, 2011]. PAC – Pacific plate, EUR – Eurasian plate, NAM – North American plate, OK – Okhotsk microplate, AM – Amur microplate.

reveal opposite displacements of neighboring segments of the Earth's surface.

In the framework of the well-known geological model NUVEL-1A [*DeMets et al.*, 1994], the tectonic activity of East Asia is completely determined by the movement of the three largest stable lithospheric plates: Eurasian, North American and Pacific, interacting with each other within narrow deformation belts. At the same time, modern data from structural geology, seismology and space geodesy provide the evidence for a more complex tectonic setting of the region Figure 1 This article is devoted to the development of a conceptual structural-dynamic model of East Asia based on the analysis of GNSS data and existent geomechanical models.

2 Data and methods

2.1 Satellite geodetic data

The first satellite-geodetic observations in East Asia began with the installation in 1992–1993 of two permanent stations of the International GNSS Service (IGS), USUD (Yusuda) and TSKB (Tsukuba) in Honshu island, Japan. Since 1993, the Geospatial Information Authority of Japan (GSI) has been developing a GEONET network of permanent satellite-geodesy stations [*Sagiya et al.*, 2000]. Currently, the GEONET network consists of more than 1400 stations, including seafloor-based ones, uniformly distributed over the territory of Japan with average spacing of 20 km.

In 1997, as a result of joint efforts of the scientific centers of the Russian Academy of Sciences and the Lamont-Doherty Earth Observatory, Columbia University (LDEO), the RUSEG project began aimed at the development of satellite-geodesy network in northeastern Russia, including the deployment of 2 permanent observation stations in Petropavlovsk-Kamchatsky (PETR) and Magadan (MAG0), as well as regional geodynamic networks with campaign stations [*Steblov et al.*, 2003]. The permanent RUSEG stations later became part of the NEDA (North Eurasia Deformation Array) network, being the continental segment of the International GNSS Service (IGS) global network.

In Kamchatka Peninsula, starting from 1997, in order to create a reference points network for regional-scale volcano and deformation studies, a regional geodynamic network was deployed consisting of 9 satellite geodetic stations, which was later extended to 26 stations [*Bürgmann et al.*, 2005].

Satellite-geodetic measurements on Sakhalin Island began in 1995–1997 with installation of three permanent stations in Yuzhno-Sakhalinsk (YUZH, later YSSK), Uglegorsk (UGLE), and Okha (OKHA) [*Takahashi et al.*, 1999]. For a more detailed study of the dynamics of the presumed boundary zone between the Eurasian and North American lithospheric plates on Sakhalin, repeated measurements were also taken at campaign stations [*Kogan et al.*, 2003].

In 2006–2008, as part of the three-stage joint Russian-Japanese-American complex survey on the Kuril Islands, the geodetic team of the Institute of Marine Geology and Geophysics of the Far Eastern Branch of the Russian Academy of Sciences (IMGG FEB RAS) installed 8 permanent and several campaign stations for satellite-geodetic measurements [*Levin et al.*, 2007], with the goal to study of present-day geodynamics in the Sakhalin-Kuril region, and, in particular, to obtain the data to test the hypothesis of the microplate existence in East Asia.

The development of satellite geodetic networks in the south of the vast East Asia mainland began in the 1990s. Initially, the studies involved the deployment of campaign stations as part of geodynamic polygons in North China, Tibet, the Himalayas and along the largest regional fault zones [*Banerjee and Bürgmann*, 2002; *Shen et al.*, 2000, 2001]. Subsequently, as a result of the network growth, regional networks were combined into the Crustal Movement Observation Network of China (CMONOC), which currently has more than 4000 observation stations and covers the entire territory of mainland China [*Wang and Shen*, 2020]. In the last decade, measurements have also been carried out at geodynamic polygons in the Amur, Baikal, and Gorny Altai regions [*Lukhnev et al.*, 2010; *Sankov et al.*, 2014; *Shestakov et al.*, 2011; *Timofeev*, 2014; *Timofeev et al.*, 2019].

In this paper we analyze the Earth surface's displacement data collected at more than 5500 GNSS stations for the period from 1997 to 2016. At the preliminary stage, all published data were converted to the ITRF2014 reference frame using the published transformation parameters and plate motion parameters from the NNR-MORVEL56 model [*Argus et al.*, 2011]. The data on the GNSS displacement rates are considered in the unmodified reference frame ITRF2014 in order to avoid distortions associated with the choice of one or another regional configuration of tectonic blocks. In this case, within the framework of plate tectonics, displacement data contain both a component associated with the displacement of the underlying lithospheric block as a rigid whole-body, and a component associated with the deformation of this block, caused by both marginal and intraplate deformation processes.

The East Asia's satellite geodetic networks, considered in this study, had been deployed for the purpose of regional and global geodynamics studies, ensuring the stable anchoring of the antenna monuments relative to the underlying layers of the Earth's crust. Thus, the obtained satellite-geodetic measurements can be correctly used to study modern tectonic motions.

2.2 Models of regional deformations processes

To explain the intense intraplate tectonic activity observed in East Asia, two fundamentally different approaches have been proposed, the conventional plate tectonics and distributed intraplate strain models.

From the plate tectonics point of view, the observed deformations of the Earth's surface arise due to the existence and interaction of additional regional lithospheric and crustal blocks. In particular, several authors suggested the existence of a wide boundary zone in East Asia, represented by a set of microplates, with Amur and Okhotsk microplates being the largest ones [*Apel et al.*, 2006; *Ashurkov et al.*, 2016; *Savostin et al.*, 1982; *Seno et al.*, 1996]. These predominantly Neogene-Quaternary blocks, were formed as a result of the convergence of the largest plates of the region: Eurasian, North American and Pacific. The spatial dimensions of the Okhotsk and Amur microplates are more than 1000 km, which makes it possible to consider them as «thin» plates (spatial dimensions of the plate are more than ten times larger than its thickness) and determine their kinematics through a standard approach based on the Euler theorem. The identification of the boundaries of the proposed microplates was carried out by mapping the main seismogenic faults in East Asia using data available from geologic, seismologic and satellite geodetic studies [*Hindle et al.*, 2009; *Imaeva et al.*, 2017; *Seno et al.*, 1996; *Shestakov et al.*, 2011]. In a number of studies, satellite geodetic data were analyzed within the plate tectonics approach in order to determine the kinematics of the Okhotsk and Amur microplates [*Apel et al.*, 2006; *Ashurkov et al.*, 2016]. The obtained estimates of the rotation parameters for these microplates and the assumed location of their boundaries are included in the global ensemble of lithospheric plates defined by the modern PB2002 [*Bird*, 2003] and NNR-MORVEL56 [*Argus et al.*, 2011] models.

From another, intraplate strain, point of view, the tectonic activity observed in the region is controlled by macro-scale elastoplastic deformations distributed over a large area that arose as a result of the collision of the Indo-Australian and Eurasian lithospheric plates and subduction of the northwestern part of the Pacific lithosphere. In particular, this tectonic setting is associated with

---

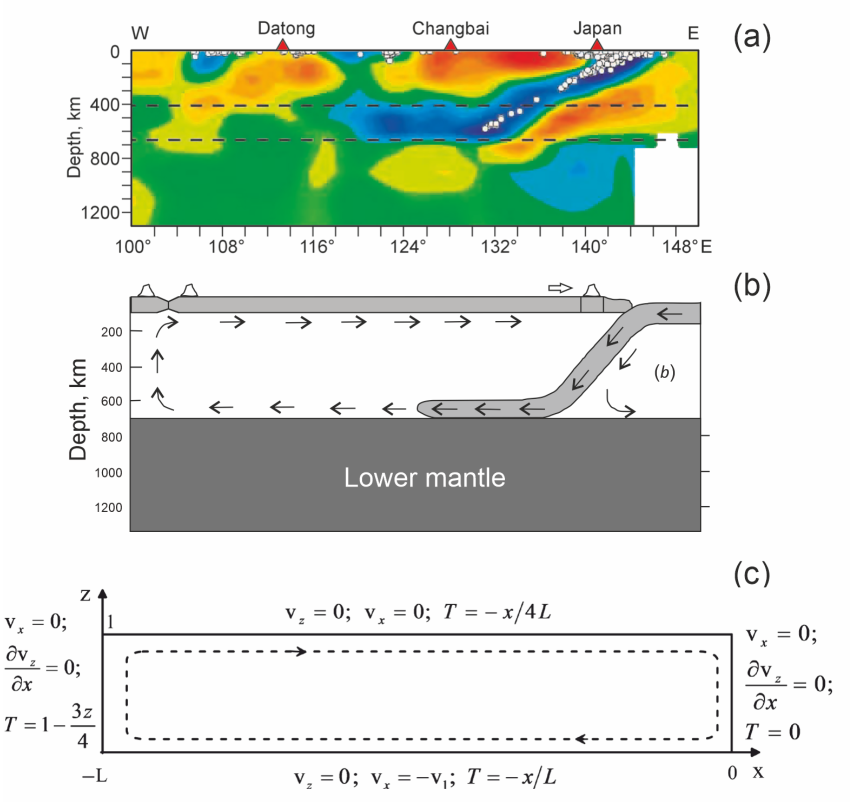

Figure 2: Initial material for constructing a model of a horizontally-expanding convective cell. Upper mantle seismic tomography image (a) [*Zhao et al.*, 2010]; Sketch of a mantle convection cell coupled with a subduction zone (b) [*Lobkovsky*, 2016]; Boundary conditions used for the convective cell model (c) [*Lobkovsky et al.*, 2021a].

the intrusion of a rigid indenter (Indian subcontinent) into a softer elastoplastic structure of the Eurasian lithosphere [*England and Molnar*, 2005; *Molnar and Tapponnier*, 1978] and the regional-scale extension of the East Asian lithosphere caused by the reverse flow of the horizontally-expanding upper mantle convective cell resulted from the subduction of the northwestern Pacific lithosphere [*Lobkovsky*, 2016]. The possibility of the existence of a reverse convective flow in the upper mantle beneath the continental lithosphere is confirmed by seismic tomography data [*Lu et al.*, 2019; *Zhao et al.*, 2010].

A comprehensive geodynamic model of East Asia should provide complete description of the endogenous deformation processes causing modern motions of the Earth's surface. The model should also consider the interaction of the stable part of the continental lithosphere with the active continental margin, which has its own dynamics with a different characteristic time scale.

Analysis of seismic tomography data for the upper mantle in the transition zone from the Pacific Ocean to the Asian continent reveal a uniform-thickness layer having high seismic-wave velocities Figure 2a. This layer is located at the bottom of the upper mantle and can be traced as a continuation of the slab submerging in the subduction zone [*Zhao*, 2009]. This geometry suggests the uniform propagation of this layer towards the continent at a rate comparable to the subduction velocity. From the standpoint of the incompressible fluid hydrodynamics, it is natural to assume that the subducted lithospheric material moving towards the continent along the upper mantle's bottom boundary is involved in a circulating convective cell, in which there is an upper reverse flow moving the mantle material back towards the subduction zone Figure 2b. Such a subduction-associated upper mantle convective cell associated was proposed by L. I. Lobkovsky and his colleagues as a part of geodynamic analysis of the Arctic lithosphere evolution in Upper Cretaceous and Cenozoic [*Laverov et al.*, 2013; *Lobkovsky et al.*, 2013] and was used to explain various structural and geodynamic features of East and North-East Asia [*Lobkovsky*, 2016].

The available seismic tomography data imaging the structure of the mantle in the transition zone between the Pacific Ocean and East and North-east Asia, as well as theoretical models of the upper mantle expanding convective cells beneath

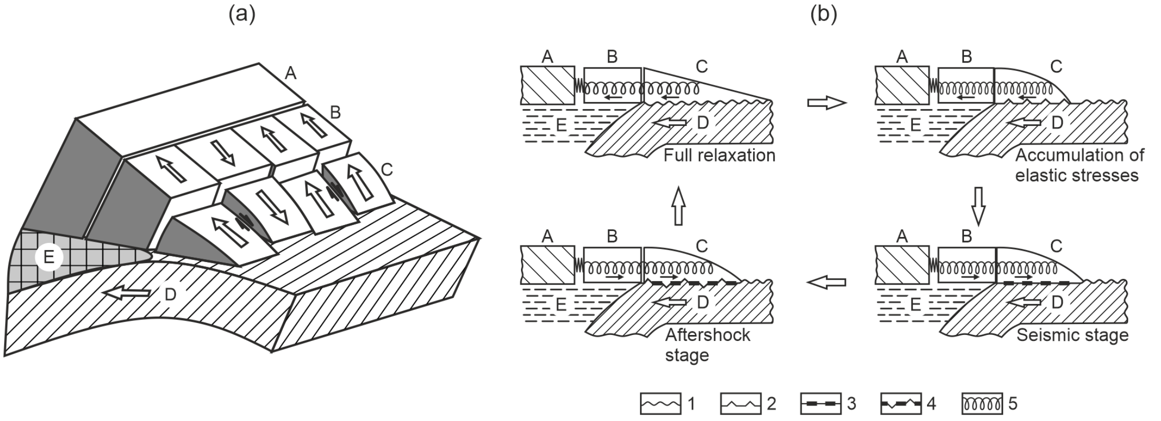

Figure 3: Three-dimensional geometry of the two-element keyboard-block model (a), and seismic deformation cycle phases, showing block loading-unloading sequence (b). A is the fixed undeformable continental margin; B is the rear-segment block; C is the frontal-segment block; D is the subducting plate; E is the asthenospheric wedge. 1 – intact "rough" contact zone structure (CZS) (stable stage of the cycle); 2 – plastically smoothed CZS (preseismic stage of the cycle); 3 – highly fragmented and heterogeneous CZS (seismic rupturing stage); 4 – partially recovered CZS (aftershock stage of the cycle); 5 – spring simulating the elastic interaction of blocks and an undeformed part of the continental plate.

the continental margin adjacent to the subduction zone, allows us to propose a mathematical formulation for the subduction-driven mantle convection problem in the East Asia region [*Lobkovsky et al.*, 2021a]. Applying the Stokes and Boussinesq approximations to the considered problem of the flow of a liquid with constant velocity in the upper mantle, we have the following system of equations:

$$-\nabla p + \mu \Delta v + \rho_0 \left[1 - \beta (T - T_0)\right] g = 0,$$

$$\nabla v = 0, \; \rho_0 = const, \tag{1}$$

$$v \nabla T = \chi \Delta T, \; \chi = \frac{\lambda}{\rho_0 C_p}.$$

Here v is velocity field, T is temperature, μ is dynamic viscosity, β is thermal expansion coefficient, g is gravitational constant, λ is thermal conductivity, C_p is isobaric heat capacity, and χ is thermal diffusivity.

Introducing the stream function ψ and expressing the velocity as $\lambda / \rho_0 C_p h$ and time as $\rho_0 C_p h^2 / \lambda$, where h is upper mantle thickness, ρ_0 is the density, and ΔT is the temperature gradient over the left-hand boundary, the system (1) can be scaled and reformulated in dimensionless form:

$$\Delta^2 \psi = Ra \frac{\partial T}{\partial x}, \qquad v_x \frac{\partial T}{\partial x} + v_z \frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2},$$

$$v_x = \frac{\partial \psi}{\partial z}, \; v_z = -\frac{\partial \psi}{\partial x}, \tag{2}$$

$$Ra = \frac{\rho_0^2 C_p g \beta \Delta T h^3}{\lambda \mu}.$$

Here Ra is the Rayleigh number. The boundary conditions are written as follows:

$$\begin{aligned}
x = 0: &\quad \psi = 0, \; \frac{\partial^2 \psi}{\partial x^2} = 0, \; T = 0; \\
x = -L: &\quad \psi = 0, \; \frac{\partial^2 \psi}{\partial x^2} = 0, \; T = 1 - \frac{3z}{4}; \\
z = 0: &\quad \psi = 0, \; \frac{\partial \psi}{\partial z} = -v_1, \; T = -\frac{x}{L}; \\
z = 1: &\quad \psi = 0, \; \frac{\partial \psi}{\partial z} = 0, \; T = -\frac{x}{4L}.
\end{aligned} \tag{3}$$

The numerical solution of system (2) with boundary conditions (3) shown on Figure 2c was obtained and presented earlier in [*Lobkovsky and Ramazanov*, 2021; *Lobkovsky et al.*, 2021a].

As a model, capable to explain the dynamics of the continental margin of East Asia, we consider the keyboard model of the generation of the megathrust earthquakes [*Lobkovsky et al.*, 1991]. Within the framework of the keyboard model, the frontal parts of island arcs and active continental margins are divided by transverse vertical faults into separate wedge-shaped blocks, with characteristic size of ~100 km. From the outer (frontal) side, the blocks are bounded by oceanic trench, while from the inner (rear) side, by the longitudinal faults separating them from the massive domains of the island arc or active continental margin Figure 3 These seismogenic blocks are located on the sub-horizontal portion of the subducting slab.

The seismogenic blocks experience loads mainly due to their compression across the strike of the arc. The load is due to the strong coupling of blocks' bottom parts to the subducting plate surface via a relatively thin highly plastic contact layer formed by the sediments of the oceanic plate filling of the negative blocks' bottom landforms [*Sorokhtin and Lobkovsky*, 1976]. At their rear edges, the blocks interact with the main domain of the arc, which prevents their further displacement towards the continent. In addition, the block-to-block interaction due to friction along their lateral surfaces is taken into account, which makes it possible to describe the deformation of both a single isolated block and a system of seismogenic blocks [*Kerchman and Lobkovsky*, 1988].

A megathrust earthquake occurs when a critical value of elastic energy is accumulated in a seismogenic block or several blocks. At that instant, the contact zone material is assumed to experience destruction, accompanied by a drop in shear stresses, and the partly unloaded seismogenic blocks are almost instantly displaced towards the ocean.

During the aftershock stage of the seismic cycle, the displaced block continues moving towards the ocean along the softened contact surface being pushed by the remaining part of the elastic energy stored in it. At the end of the aftershock stage, under the action of increased viscous friction forces at the bottom, the block goes into compression and starts moving towards the continent, gradually accumulating energy [*Kerchman and Lobkovsky*, 1988].

In [*Lobkovsky et al.*, 1991], a numerical scheme was proposed for modeling the displacements of frontal seismogenic blocks at different stages of the seismic cycle. In that study the rear part of the island arc was considered as a single structural element not subjected to its own horizontal displacements. According to modern satellite geodetic data [*Lobkovsky et al.*, 2017a,b, 2018; *Vladimirova et al.*, 2020] during the seismic events both rear and frontal blocks experience almost instantaneous jump-like displacements. In the post-seismic period, a slow straightening of the rear blocks occurs, controlled by the resistance of the underlying asthenospheric layer under conditions of viscous friction at the block's bottom.

The resulting numerical scheme for modeling the continental margin blocks' displacements during the seismic cycle is based on solving the stress equilibrium equation, which is assumed for each block of either frontal or rear segment:

$$\frac{\partial (H\sigma_i)}{\partial x} = \left[\tau_0^{(i)} + \frac{H}{d_i}\left(\tau_{i-1} + \tau_{i+1}\right)\right], \tag{4}$$

where $\tau_0^{(i)}$ is tangential stress acting on the bottom surface of the i-th block due to the viscous contact layer, τ_{i-1} and τ_{i+1} are the stresses due to the friction with neighboring blocks, d_i is the block size along strike direction, parallel to the trench, and H is the block thickness. The shear stresses applied to the bottom and lateral surfaces of each block can be expressed as following:

$$\begin{gathered}
\tau_0^{(i)} = -\eta\left(\dot{\gamma}_i\right)\dot{\gamma}_i = \begin{cases} -\eta\left(\dot{\gamma}_i\right)\left(\frac{\partial w_i}{\partial t} - V_i^1\right)\frac{1}{h} & 0 \le x \le l \\ -\eta_c\left(\frac{\partial w_i}{\partial t}\right)\frac{1}{h_0} & l \le x \le r \end{cases} \\
\tau_{i-1} = \frac{\mu_{i-1}^{1,2}}{h_g}\left(\frac{\partial w_{i-1}}{\partial t} - \frac{\partial w_i}{\partial t}\right) \\
\tau_{i+1} = \frac{\mu_i^{1,2}}{h_g}\left(\frac{\partial w_{i+1}}{\partial t} - \frac{\partial w_i}{\partial t}\right)
\end{gathered} \tag{5}$$

Here $\dot{\gamma}_i = \left(\frac{\partial w_i}{\partial t} - V_i^0\right)\frac{1}{h}$ is the mean strain rate in the contact layer with thickness h, V_i^1 is the subduction rate, $h_0 \approx 15$ km is the thickness of the asthenospheric layer, $\eta\left(\dot{\gamma}_i, x\right)$ is the effective viscosity of the contact layer, η_c is the constant viscosity of the crustal asthenosphere, h_g is the thickness of the viscous material filling the interblock faults, while $\mu_{i-1}^{1,2}$ and $\mu_i^{1,2}$ are the viscosities of that material between blocks number i and $i-1$, as well as i and $i+1$ both in the frontal and rear segments of the model, l and r denotes the lengths of the frontal and rear blocks respectively.

In addition to equations (5), the following conditions are applied at the model boundaries:

$$c\,\frac{\partial w_i}{\partial x}\bigg|_{x=0} = 0 \tag{6}$$

$$c\left(\frac{\partial w_i}{\partial x} + k_i^r\,w_i\right)\bigg|_{x=r} = 0 \tag{7}$$

Condition (6) indicates that the outer edges of the frontal blocks are free, while (7) defines an elastic interaction of the rear blocks with the fixed margin controlled by the stiffness coefficient k_i^r. The condition applied at the segment boundary is variable, depending on the current state of the seismic cycle. During the stress accumulation phase (interseismic stage), the frontal block motion is fully transferred to the rear segment:

$$c\,\frac{\partial w_i}{\partial x}\bigg|_{x=l} = 0 \tag{8}$$

During the postseismic (aftershock) phase of the cycle, the segments are considered to be separated by a "gap" due to different rates of elastic straightening in the frontal and rear blocks, accompanied by pronounced motion of the blocks towards the ocean. In this case, the motion of the frontal edge of the rear segment satisfies the free boundary condition:

$$c\,\frac{\partial w_i}{\partial x}\bigg|_{x=l^-} = 0 \tag{9}$$

The above models of deformation of the continental and marginal parts of East Asia's lithosphere have a common energy source – the process of subduction of the Pacific plate, which provides basis for their further combination into a single geodynamic model of East Asia.

3 Results

To reveal the features of the regional deformation field and to check the applicability of the methods presented above to describe the regional deformation processes we perform the analysis of modern surface motions provided by satellite geodesy data and construct the comprehensive geodynamic model of East Asia which can explain the observed surface displacements.

3.1 Analysis of the present-day movements of the Earth's surface in East Asia

Satellite geodesy allows one to make direct measurements of the modern motions of tectonic blocks and to estimate the intensity of deformation processes, both at plate boundaries and in their central stable regions. The satellite measurements analyzed in this study cover the entire territory of East Asia, both the mainland and the active continental margin. This enables one to see the significant heterogeneity of the displacement field caused by the action of various deformation processes. Figure 4 shows the downsampled distribution of horizontal component of the displacement rate vectors, and its prominent variations. The downsampling was done in a way preserving the main patterns of the velocity field. Studying the presented velocity field variations is important due to the occurrence of the largest subduction earthquakes at the continental margin of East Asia: the 2006–2007 Simushir earthquakes ($\mathrm{Mw} = 8.1 - 8.3$) and the 2011 Tohoku earthquake with $\mathrm{Mw} = 9.0$ [*Dziewonski et al.*, 1981; *Ekström et al.*, 2012], that have seriously affected the regional deformation field. Earlier, we have carried out a detailed investigation of the seismic cycles of these earthquakes and their impact on the velocity field at the East Asia's continental margin [*Lobkovsky et al.*, 2017b, 2018; *Vladimirova et al.*, 2020].

Analysis of the horizontal velocities of the Earth's surface in East Asia Figure 4 revealed a number of its specific features. Throughout the continental part of East Asia, including the territory of mainland China, as well as the Far Eastern and Arctic regions of Russia, including Sakhalin Island, a well-correlated motion of observation stations to the southeast (towards Pacific Ocean) is observed, while the displacement vectors tend to have not only similar directions but also their magnitudes. At the same time, on the active continental margin of East Asia, the displacement field is extremely heterogeneous both along the oceanic trench strike and towards the inland. These inhomogeneities are especially noticeable in the satellite-measured data in Kamchatka Peninsula: the western coast and the central part of the peninsula are displaced to the southeast in accordance with the predominant direction of the regional displacement field, while the east coast shows a significant reversal of displacement vectors to the south-west. In addition, there is a general gradual decrease in the magnitudes of the displacement vectors in the west-east direction across Kamchatka. Such a displacement pattern is well explained if the observed displacements are presented as the vector sum of the regional displacement trend (pointing to the southeast) and the deformation vector associated with the compression of the overhanging continental edge due to the subduction of the Pacific plate. The deformation vectors' magnitudes rapidly decrease towards the continent interior and their orientations are obviously aligned with the plate convergence vector, which in Kamchatka is directed to the northwest, perpendicular to the oceanic trench Figure 4. Thus, the satellite measurements in Kamchatka Peninsula indicate the stationary interseismic stage of elastic stress accumulation in the subduction zone. If a continuum model is assumed, such a deformation regime should cause significant gradients in the quantities characterizing the stress-strain state of the region's lithosphere.

The GNSS data in Kuril and Japan Islands differ significantly from the displacement pattern typical for the entire region and allow us to study the continental margin's response to the process of elastic stresses release occurring in the source of the largest subduction earthquake. Most of the stations of the Kuril network were installed only about six months prior to Simushir events, while the other part, especially near the earthquakes' epicenters, were deployed about six months later [*Vladimirova et al.*, 2020], which made it difficult to estimate the stationary interseismic displacement velocity in the Kuril Islands. Figure 4 show the variations in displacement velocities along the Kuril and Japan Islands (estimated at one-year intervals): prior to Simushir earthquakes Figure 4a one year after the Simushir earthquakes Figure 4b and one year after the Tohoku earthquake Figure 4c. Before the Simushir earthquakes, the northern flank of the Kuril island arc was experiencing drift consistent with the predominant direction of the Kamchatka's east coast, which suggests that the region was at a stable interseismic stage. At the same time, the displacements at the southern flank of the Kuril arc are extremely het-

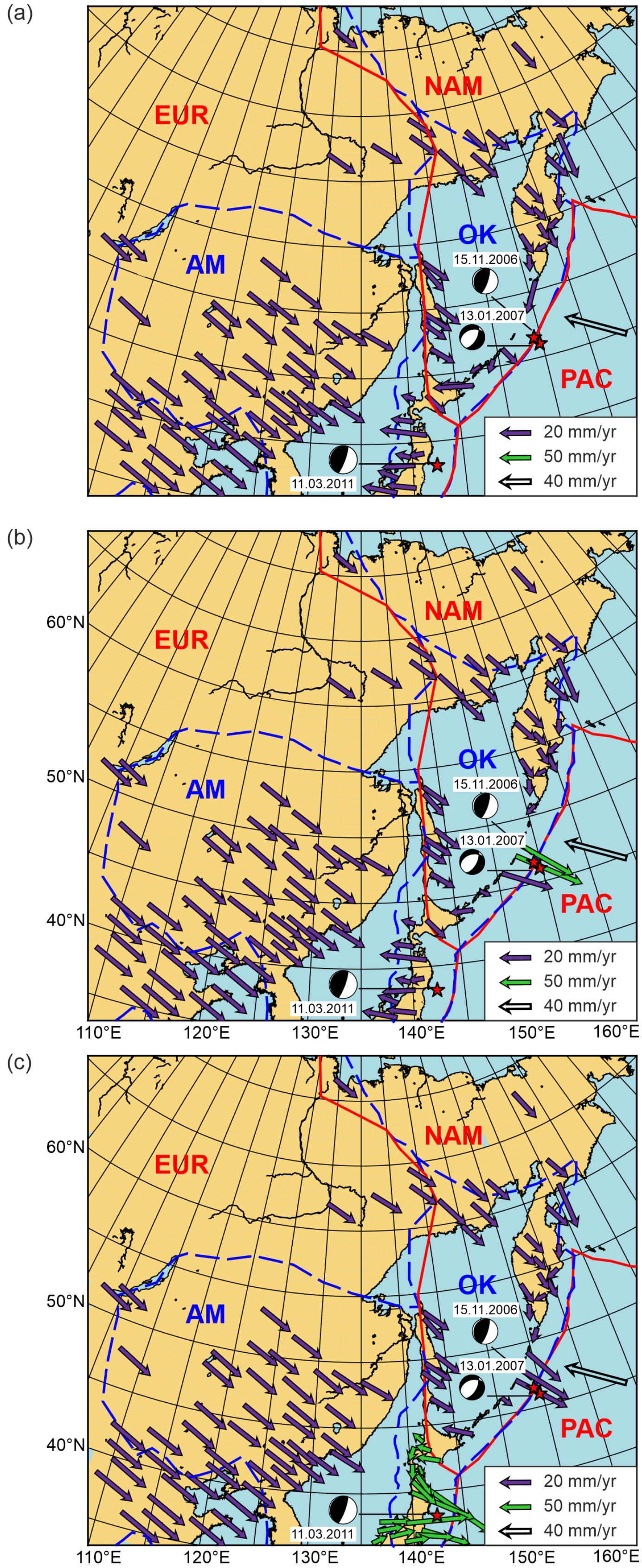

Figure 4: Time variations in the horizontal velocity components of GNSS stations in East Asia. The velocities for active continental margin were estimated (a) – prior to the 11/15/2006 Simushir earthquake; (b) – in the first year after the 2006 Simushir earthquake; (c) – in the first year after the 03/11/2011 Tohoku earthquake. White arrow shows the direction and magnitude of the convergence vector of the Pacific and North American plates according to the NNR-MORVEL56 model [*Argus et al.*, 2011]. Plate boundaries are following the notation of Figure 1.

erogeneous along the trench and gradually change from the southeast to the west, while increasing in magnitude. Unfortunately, these velocities were estimated over very short time intervals (up to six months), which does not allow us to rule out local-scale variations and the effects of seasonal bias. A similar displacement pattern is observed in this region several years after the Simushir earthquakes Figure 4, which proves that this trend is characteristic of the interseismic stage. Differences in the displacements' direction can be caused both by the peculiarities of the deformation process (variations in the mechanical coupling in the interplate interface), and by the process of the future Simushir earthquakes preparation.

During the postseismic stage of the seismic cycle associated with the Simushir earthquakes, the displacements on the southern and northern flanks of the Kuril island arc do not change their direction, but decrease in magnitude in the first year after the event Figure 4b, and nearly getting back to their original values 6 years after the earthquake Figure 4c. At the same time, measurements in the central part of the arc, near the epicenter, demonstrate long-term and intense displacements of this part of the subduction zone towards the ocean, gradually decreasing with time Figure 4b–Figure 4c. On the whole, this kind of displacement pattern sharply contrasts with the displacements' behavior in the neighboring parts of the island arc and shows that the release of accumulated elastic stresses occurred only in a local region near the earthquake epicenter. Under the assumption of a continuum-based model for the Kuril island arc region, the observed displacement pattern should have led to the accumulation of significant shear stresses.

Satellite measurements recorded in Japan demonstrate a surface's displacement pattern similar to that of the other parts of the active continental margin. At the interseismic stage Figure 4a–Figure 4b, the displacement vectors are pointing to the west, which is consistent with the plate convergence vector direction, and decrease in magnitude across the Japan Islands from east to west. Thus, the observed displacements are in good agreement with the idea that the dominant displacement component is the one associated with the continental margin deformation due to the subduction of the Pacific plate. In the first year after the Tohoku earthquake, the displacement vectors abruptly change their direction to the southeast, opposite to the interseismic orientation, and retain this direction near the epicenter for at least 4 years, gradually decreasing in magnitude [*Lobkovsky et al.*, 2018].

The divergent orientation of the present-day velocities along the Kuril-Kamchatka trench, revealed by satellite geodesy data, is associated both with the fact that different segments of the island arc are subjected to the different stages of the seismic cycle [*Lobkovsky et al.*, 2017b], and with a substantial inhomogeneity of the mechanical coupling both along the dip, and along the strike of the subduction surface between the Pacific and North American lithospheric plates [*Steblov et al.*, 2010].

In general, the analysis of the present-day horizontal movements of the Earth's surface shows that for most of the seismic cycle, which in the study region can have duration of hundred years or more [*Fedotov*, 1968], the displacement directions at the active continental margin are inconsistent with the direction of modern surface motions in most of East Asia, and is sometimes reverse. Such a displacement pattern creates a paradox, where enormously large strain values would have expected within the back-arc basins, which are not confirmed by the regional seismicity data and the features of the tectonic structure of the region.

The modern motions of the Earth's surface in the mainland East Asia, recorded by satellite geodesy methods Figure 4, have velocity magnitudes of 3–4 cm per year and are directed towards the ocean, which turns out to be in good agreement both in magnitude and direction with the displacements associated with the lithosphere extension caused by return convection flow in the upper mantle [*Lobkovsky et al.*, 2021a]. The overview of the GNSS-measured displacements recorded along the Kuril-Kamchatka and Japan trenches suggests that the characteristic changes in the direction and magnitude of the displacement vectors can be explained in terms of decomposition of the total displacement into individual components caused by the action of long-term motion towards the ocean and more rapid deformation process, periodically changing its direction and intensity. Thus, the resulting geodynamic model of East Asia can be obtained as a superposition of the deformation models of the continental part of the region and the deformation model of the active continental margin, which have a common energy source.

3.2 East Asia's geodynamic model

In [*Lobkovsky et al.*, 2021a] it was shown that considering the interaction of the lithosphere and the upper mantle in the active continental margin within the framework of the nonstationary convective cell model allows one to explain the modern displacements of the Earth's surface and seismic tomography data observed over a distance of up to 2000 km continent-ward without involving any additional lithospheric blocks. Figure 5 shows the calculated streamline patterns in the upper mantle for various Rayleigh number values.

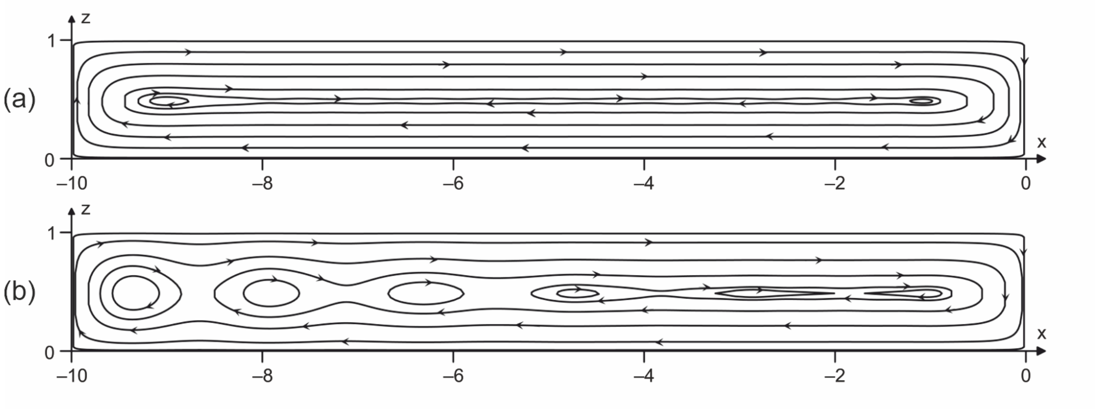

Figure 5: Upper mantle convection flow assuming no plate motion motion (v_1=0) calculated for Rayleigh number Ra=10^3 (a) and $Ra = 5 \times 10^3$ (b) [*Lobkovsky et al.*, 2021a].

From Figure 5a, it can be seen that at $Ra = 10^3$, the outer streamlines fill the entire modeling region and this pattern corresponds to a single-cell structure. However, inside the region there are inner cells circulating in the same direction as the outer cell. Figure 5b, shows the behavior for $Ra = 5 \times 10^3$, where the outer streamlines still represent a single-cell structure. This agrees with the experimental data [*Kirdyashkin et al.*, 2002], showing that only one asthenosphere convection cell is formed at $Ra = 6.3 \times 10^3$. However, in this case, in the central part of the modeling region, the flow appears to have a complex structure as a series of horizontally-aligned inner cells having the same circulation direction as an outer one. This structure is more complex than that for the smaller Rayleigh number values Figure 5a.

The 3D modeling results [*Lobkovsky et al.*, 2021a] indicate that the cold region at the bottom of the modeling domain (the submerged slab of the Pacific Plate) is steadily moving to the left and travelling over 2000 km. The obtained velocity distribution shows that the lateral size of the convective cell increases synchronously with the motion of the cooled Pacific lithosphere towards left under the continent.

Numerical modeling of the deformation process of East Asia's continental margin, taking into account its two-element structure, has shown good agreement of the model displacements with geological-geophysical evidence and satellite geodetic data [*Lobkovsky et al.*, 2021b,c]. This approach provides natural explanation for the observed anomalies of the present-day displacement field along the subduction margin of East Asia. According to the two-element keyboard model, the significant lateral inhomogeneities of the displacement velocity field along the strike of the oceanic trenches are associated with the fact that different segments of the island arc are currently under the different stages of the seismic cycle. Particularly, the rapid reversals of the displacement velocity vectors near the fault zones of large subduction earthquakes are caused by the significant slide of seismogenic blocks towards the ocean during the seismic and postseismic stages. Over the seismic cycle, elastic stresses accumulate locally within the seismogenic blocks of the continental margin, which are then unloaded when the large subduction earthquake occurs. Figure 6 shows that over a series of seismic cycles there is no substantial displacement of the continental margin towards the continent. Continent-directed displacement phases last for about 80–100 years or more, and each one is followed by a rapid ocean-ward motion occurring during the seismic and postseismic stages of the seismic cycle.

At the same time, according to the upper mantle convection cell model, the long-term displacement of the entire active continental margin takes place, causing its movement towards the ocean. The presented model resolves the paradoxes related to the observation of anomalously large modern velocity field gradients between neighboring segments of island arcs, as well as between the mainland and the continental margin of East Asia. Thus, the geodynamic model of East Asia proposed in this study Figure 7 makes it possible to explain the observed dynamics of the Earth's surface, which has manifestations at different time scales, by taking into account the dominant regional geodynamic processes.

The process of the continental lithosphere extension continues for millions of years and can be considered stationary when interpreting satellite geodesy data. Within the framework of the proposed two-element keyboard-block deformation model, the continental margin can behave like a continuum structure or deform segmentally, due to the fault-block structure and the dominance of the viscous friction regime between the blocks and at the subduction interface.

The geodynamic model of East Asia proposed in this study allows one to interpret the observed dis-

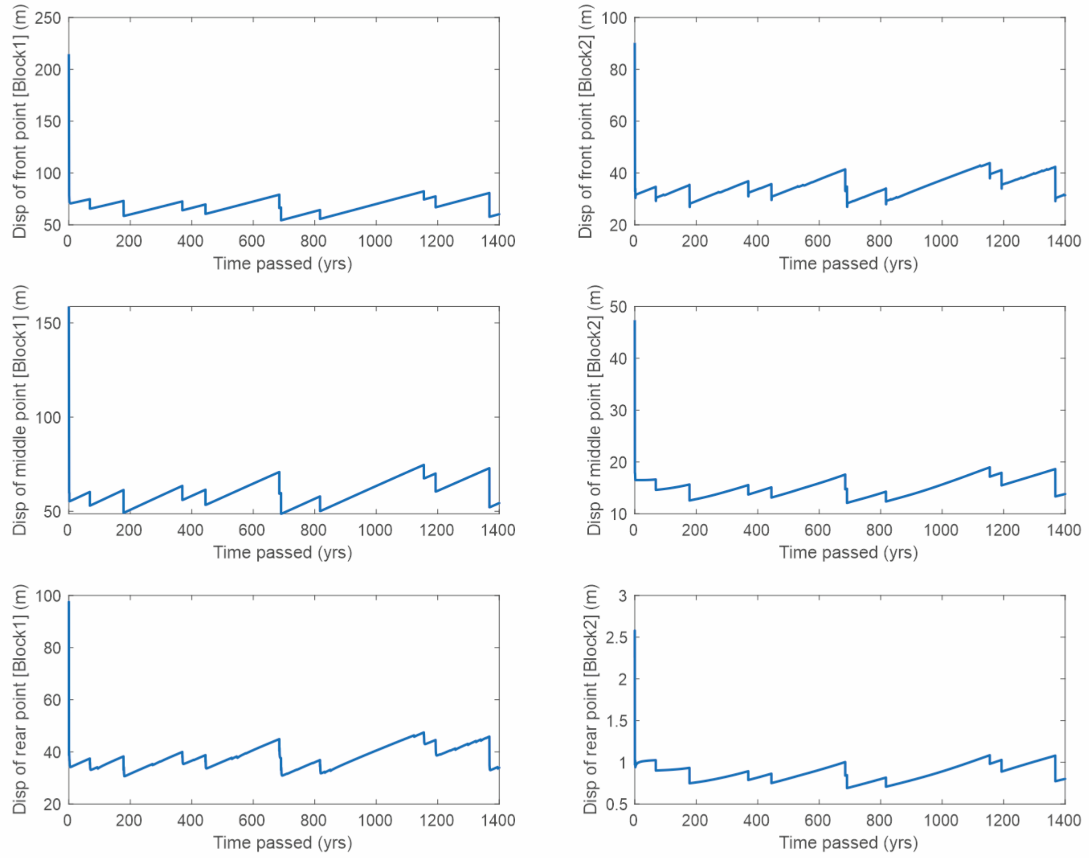

Figure 6: Simulation of several seismic deformation cycles in Kuril subduction zone for two-element keyboard model. Left column of images shows the displacements of frontal block, right column shows the displacements of rear block. Stochastic condition for amount of relaxated and accumulated elastic energy was applied [*Lobkovsky et al.*, 2021c].

placements of the Earth's surface within the framework of a single physical process that causes both long-term deformation of the continental lithosphere and short-term cycles of elastic stress accumulation and release along the continental margin.

4 Discussion and conclusions

The classical plate tectonic approach using Euler's theorem to describe the kinematics of lithospheric and crustal blocks has proven itself well in the early stages of plate tectonics development and revealed good agreement between present-day movements of the Earth's surface and similar estimates averaged over the past several million years for large portions of the Earth's surface [*Sella et al.*, 2002]. An attempt to extend this convenient and simple mathematical approach, which does not require taking into account the dynamics of the underlying mantle, has been repeatedly taken to describe regions that are more complex in tectonic structure, including East Asia [*Apel et al.*, 2006; *Ashurkov et al.*, 2016; *Calais et al.*, 2006; *Cook et al.*, 1986; *Kreemer et al.*, 2003; *Loveless and Meade*, 2010; *Sella et al.*, 2002; *Seno et al.*, 1996; *Wang and Shen*, 2020]. The kinematic models of the Okhotsk and Amur plates, as well as smaller blocks, proposed in these studies, differ greatly in terms of plate boundaries' geometry and plate kinematics parameters for each of these blocks. In addition, the presence of scattered seismicity belts in East Asia, reaching 600 km in width Figure 1, and the absence of aseismic regions surrounded by seismicity belts, do not allow to accurately determine the location and confirm the presence of closure of the boundaries of the presumed lithospheric blocks. Further deformation analysis of a large amount of satellite geodetic measurements in China and on the Japan Islands revealed a large tectonic fragmentation of the presumed Okhotsk and Amur microplates with the identification of additional tectonic domains [*Loveless and Meade*, 2010; *Wang and Shen*, 2020].

At the same time, modern seismic tomography data clearly image three-dimensional deformation structure of the East Asia region and a significant correlation between the Earth's surface dynamics and convective flow in the asthenosphere and upper mantle [*Zhao*, 2004, 2009; *Zhao et al.*, 2010]. Several studies prove the possible segmentation of

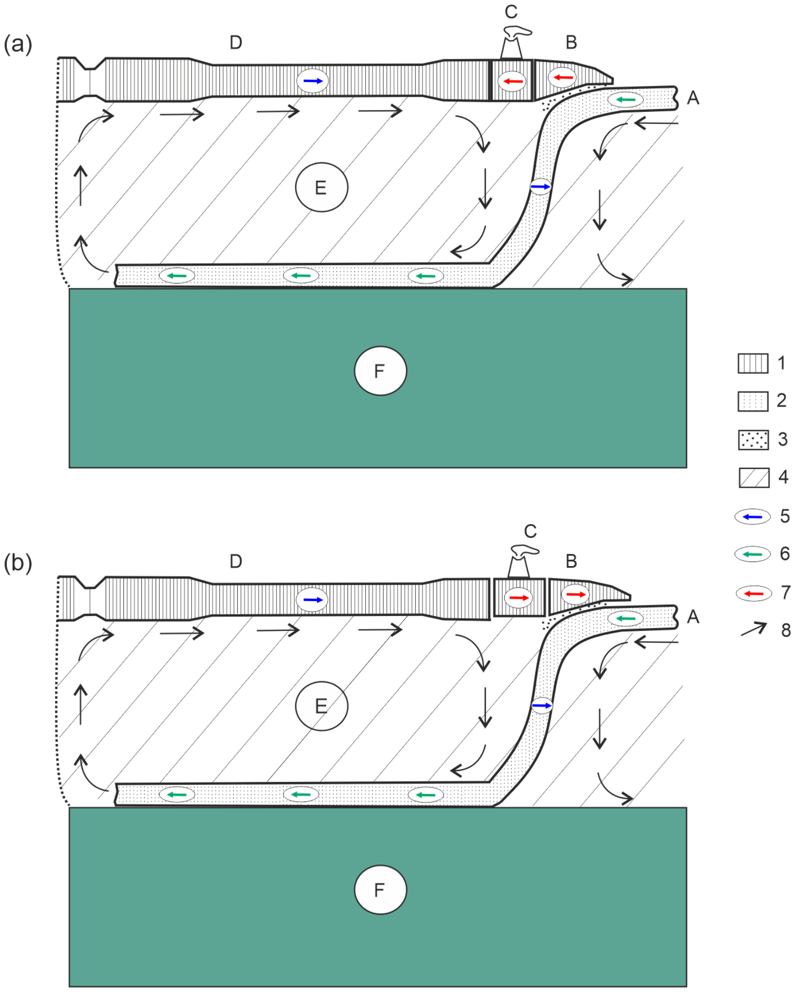

Figure 7: Sketch of the geodynamic model of East Asia featuring the emergence of a horizontally expanding convective cell in the asthenosphere and upper mantle. (a) – long interseismic stage of elastic stress accumulation in the subduction zone, (b) – postseismic stage, accompanied by relaxation of accumulated elastic stresses. A – subducting oceanic plate, B – frontal seismogenic block, C – island-arc (rear) block, D – continental plate, E – horizontally expanding convective cell in the upper mantle, F – lower mantle. 1 – continental lithosphere, 2 – oceanic lithosphere, 3 – viscous interplate contact layer, 4 – viscoelastic asthenosphere and upper mantle, 5 – direction of the continental lithosphere stretching and subduction zone drift, 6 – direction of the oceanic plate subduction, 7 – directions of the continental marginal blocks' displacements, 8 – convection flow directions. Displacement rates and sizes of major structural elements are not to scale.

the active continental margins in subduction regions including existence of trench-parallel and transverse strike-slip faults [*Baranov et al.*, 2015; *DeMets*, 1992; *Kogan et al.*, 2017; *La Femina et al.*, 2002]. Another issue arising from the application of the plate tectonic approach in the analysis of present-day movements is the revealed discrepancy between the deformation regime in the Arctic region established from geological and geophysical data and that predicted by the global models of the tectonic structure and evolution [*Lobkovsky*, 2016]. This fact suggests the existence of some sort of mechanical coupling between the Eurasian and North American lithospheric plates in the region between the Gakkel ridge and the Aleutian subduction zone.

In this regard, in order to construct a comprehensive geodynamic model of East Asia region, and solve the problems relevant to the geodynamic regime study and seismic hazard prediction, the classical plate-tectonic approach, which requires identification of all existing lithospheric blocks (plates) and determination of their kinematics, turns out to be incomplete.

The model of the geodynamic structure of East Asia proposed in this study links the dynamics of the active continental margin, which is characterized by seismic-induced direction-alternating movements of the continental margin with a period from several tens to several hundred years, and a long-term process of oceanic slab subduction with the formation of a return convective cell in the mantle. Within the framework of this model, the dynamics of the Earth's surface of the entire East Asia region is governed by the interaction of the subduction slab with upper mantle material and, through convection, with the continental lithosphere, leading to its ocean-ward extension. The present-day displacements of the Earth's surface observed by satellite geodesy methods are in good agreement with the directions of movements predicted assuming this model, both near the oceanic trench and at a distance of up to 2000 km inland.

The presented model is capable to resolve the paradoxes of the regional modern velocity field observed by satellite geodesy, associated with a significant variation in the velocities along the continental margin and sharp changes in their directions during the seismic cycle, as well as significant gradients of the velocity field in the back-arc basins. The model makes it possible to extend the physically-based theoretical concepts of modern plate tectonics and eliminate the contradictions between the observed data and classical plate tectonics in East Asia region. The model presented in the study is currently in the conceptual stage of its development, while we have already quantitatively implemented all of its components in a series of recent publications. The next stage in the development of the geodynamic model of East Asia will be the analysis of the mutual effect of the model's individual components, as well as the refinement of the resulting model parameters based on the available satellite geodetic, geological and geophysical data.

Acknowledgment

This study was funded by the Russian Science Foundation, grant number 20-17-00140.

Conflicts of Interest

The author declares no conflict of interest.

References

Apel, E. V., R. Burgmann, G. Steblov, N. Vasilenko, R. King, and A. Prytkov, Independent Active Microplate Tectonics of Northeast Asia From GPS Velocities and Block Modeling, *Geophys. Res. Lett.*, *33*, L11,303, doi:10.1029/2006GL026077, 2006.

Argus, D. F., R. G. Gordon, and C. DeMets, Geologically Current Motion of 56 Plates Relative to the No-Net-Rotation Reference Frame, *Geochem. Geophys. Geosyst.*, *12*, Q11,001, doi:10.1029/2011GC003751, 2011.

Ashurkov, S. V., V. A. Sankov, M. A. Serov, P. Y. Lukyanov, G. S. Bordonskii, N. N. Grib, and M. G. Dembelov, Evaluation of Present-Day Deformations in the Amurian Plate and its Surroundings, Based on GPS Data, *Russian Geology and Geophysics*, *57*(11), 1626–1634, 2016.

Banerjee, P., and R. Bürgmann, Convergence Across the Northwest Himalaya from GPS Measurements, *Geophysical Research Letters*, *29*(13), 1652, 2002.

Baranov, B. V., A. I. Ivanchenko, and K. A. Dozorova, The Great 2006 and 2007 Kuril Earthquakes, Forearc Segmentation and Seismic Activity of the Central Kuril Islands Region, *Pure appl. geophys.*, *172*(12), 3509–3535, 2015.

Bird, P., An Updated Digital Model of Plate BSoundaries, *Geochem. Geophys. Geosyst.*, *4*(3), 1–52, 2003.

Bürgmann, R., M. G. Kogan, G. M. Steblov, G. Hilley, V. E. Levin, and E. Apel, Interseismic Coupling and Asperity Distribution Along Kamchatka Subduction Zone, *J. Geophys. Res.*, *110(B7)*, 1–17, doi:10.1029/2005JB003648, 2005.

Calais, E., L. Dong, M. Wang, Z. Shen, and M. Vergnolle, Continental Deformation in Asia from a Combined GPS Solution, *Geophysical Research Letters*, *33*, L24,319, 2006.

Cook, D., K. Fujita, and C. Mcmullen, Present-Day Plate Interactions in Northeast Asia–North-American, Eurasian, and Okhotsk Plates, *Journal of Geodynamics*, *6*, 33–51,, doi:10.1016/0264-3707(86)90031-1., 1986.

DeMets, C., Oblique Convergence and Deformation Along the Kuril and Japan Trenches, *J. Geophys. Res.*, *97 (B12)*, 17,615–17,625, doi:10.1029/92JB01306, 1992.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of Recent Revisions to the Geomagnetic Reversal Time Scale on Estimates of Current Plate Motions, *Geophys Res. Lett.*, *21*(20), 2191–2194, doi:10.1029/94GL02118, 1994.

Dziewonski, A., T.-A. Chou, and J. Woodhouse, Determination of Earthquake Source Parameters from Waveform Data for Studies of Gobal and Regional Seismicity, *Journal of Geophysical Research*, *86*, 2825–2852, doi:10.1029/JB086iB04p02825, 1981.

Ekström, G., M. Nettles, and A. Dziewonski, The Global CMT Project 2004–2010: Centroid-Moment Tensors for 13,017 Earthquakes, *Physics of the Earth and Planetary Interiors*, *200–201*, 1–9,, doi:10.1016/j.pepi.2012.04.002., 2012.

England, P., and P. Molnar, Late Quaternary to Decadal Velocity Fields in Asia, *J. Geophys. Res.*, *110*, B12,401, doi:10.1029/2004JB003541, 2005.

Fedotov, S. A., The Seismic Cycle, Possibility of the Quantitative Seismic Zoning, and Long-Term Seismic Forecasting, in *Seismic Zoning in the USSR*, edited by S. V. Medvedev, pp. 133–166, Moscow, (in Russian), Nauka, 1968.

GS RAS, *On-line Catalog "Earthquakes of Russia"*, Geophysical Survey of the Russian Academy of Sciences, 2021.

Hindle, D., K. Fujita, and K. Mackey, Deformation of the Northwestern Okhotsk Plate: How it is Happening?, *Stephan Mueller Spec. Publ. Ser.*, *4*, 147–156, doi:10.5194/SMSPS-4-147-2009, 2009.

Imaeva, L. P., G. S. Gusev, V. S. Imaev, S. V. Ashurkov, V. I. Melnikova, and A. I. Seredkina, Geodynamic Activity of Modern Structures and Tectonic Stress Fields in Northeast Asia, *Geodynamics & Tectonophysics*, *8*(4), 737–768, doi:10.5800/GT-2017-8-4-0315, 2017.

ISC, On-line Bulletin, International Seismological Centre, doi:10.31905/D808B830, 2021.

Kerchman, V. I., and L. I. Lobkovsky, Numerical Simulation of the Seismotectonic Process in Island Arcs and at Active Continental Margins, *Izvestiya Physics of the Solid Earth*, *3*, 13–27, 1988.

Kirdyashkin, A. A., N. L. Dobretsov, and A. G. Kirdyashkin, Experimental Modeling of the Effect of Subduction on the Spatial Structure of Convective Flows in the Asthenosphere under the Continent, *Doklady Earth Sciences*, *384*(5), 682–686 (in Russian), 2002.

Kogan, M. G., R. Burgmann, N. F. Vasilenko, C. H. Scholz, R. W. King, A. I. Ivashchenko, D. I. Frolov, G. M. Steblov, C. Kim, and S. G. Egorov, The 2000 Mw 6.8 Uglegorsk Earthquake and Regional Plate Boundary Deformation of Sakhalin from Geodetic Data, *Geophys. Res. Lett.*, *30*(3), 1102, doi:10.1029/2002GL016399, 2003.

Kogan, M. G., D. I. Frolov, N. F. Vasilenko, J. T. Freymueller, G. M. Steblov, G. Ekström, N. N. Titkov, and A. S. Prytkov, Plate Coupling and Strain in the Far Western Aleutian Arc Modeled from GPS Data, *Geophys. Res. Lett.*, *44*, 3176–3183, doi:10.1002/2017GL072735, 2017.

Kreemer, C., W. Holt, and A. Haines, An integrated global model of present-day plate motions and plate boundary deformation, *Geophysical Journal International*, *154*(1), 8–34,, doi:10.1046/j.1365-246X.2003.01917.x, 2003.

La Femina, P. C., T. Dixon, and W. Strauch, Bookshelf Faulting in Nicaragua, *Geology*, *30*(8), 751–754, doi:10.1130/0091-7613(2002)030<0751:BFIN>2.0.CO;2, 2002.

Laverov, N. P., L. I. Lobkovsky, M. V. Kononov, N. L. Dobretsov, V. A. Vernikovsky, S. D. Sokolov, and E. V. Shipilov, A Geodynamic Model of the Evolution of the Arctic Basin and Adjacent Territories in the Mesozoic and Cenozoic and the Outer Limit of the Russian Continental Shelf, *Geotectonics*, *1*, 1–30, doi:10.1134/S0016852113010044, 2013.

Levin, B. W., B. Fitzhugh, J. Bourgeois, A. V. Rybin, N. G. Razzhigaeva, A. B. Belousov, N. F. Vasilenko, A. S. Prytkov, D. I. Frolov, T. I. Nushko, A. A. Kharlamov, and I. G. Koroteev, A Complex Expedition to the Kuril Islands in 2006. (1 Stage), *Vestnik of Far Eastern Branch of Russian Academy of Sciences*, *1*, 14400,148 (in Russian), 2007.

Lobkovsky, L. I., Deformable Plate Tectonics and Regional Geodynamic Model of the Arctic Region and Northeastern Asia, *Russian Geology and Geophysics*, *57*(3), 371–386, 2016.

Lobkovsky, L. I., and M. M. Ramazanov, Investigation of Upper Mantle Convection Thermomechanically Related to a Subduction Zone, and its Geodynamic Applications for the Arctic and Northeast Asia, *Fluid Dynamics*, *3*, 139–150, (in Russian), doi:10.1134/S001546282103006X, 2021.

Lobkovsky, L. I., V. I. Kerchman, B. V. Baranov, and E. I. Pristavakina, Analysis of Seismotectonic Processes in Subduction Zones from the Standpoint of a Keyboard Model of Great Earthquakes, *Tectonophysics*, *199*, 211–236, doi:10.1016/0040-1951(91)90173-P, 1991.

Lobkovsky, L. I., E. V. Shipilov, and M. V. Kononov, Geodynamic Model of Upper Mantle Convection and Transformations of the Arctic Lithosphere in the Mesozoic and Cenozoic, *Izvestiya of the Physics of the Solid Earth*, *49*, 767–785, doi:10.1134/S1069351313060104, 2013.

Lobkovsky, L. I., I. S. Vladimirova, Y. V. Gabsatarov, B. V. Baranov, I. A. Garagash, and G. M. Steblov, Seismotectonic Deformations Associated with the 2010 Maule Earthquake at Different Stages of the Seismic Cycle According to Satellite Geodetic Observations, *Dokl. Earth Sci.*, *477*, 716–721, doi:10.1134/S1028334X17120261, 2017a.

Lobkovsky, L. I., I. S. Vladimirova, Y. V. Gabsatarov, I. A. Garagash, B. V. Baranov, and G. M. Steblov, Post-Seismic Motions After the 2006–2007 Simushir Earthquakes at Different Stages of the Seismic Cycle, *Dokl. Earth Sci.*, *473*, 375–379, doi:10.1134/S1028334X17030266, 2017b.

Lobkovsky, L. I., I. S. Vladimirova, Y. V. Gabsatarov, and G. M. Steblov, Seismotectonic Deformations Related to the 2011 Tohoku Earthquake at Different Stages of the Seismic Cycle on the Basis of Satellite Geodetic Observations, *Dokl. Earth Sci.*, *481*, 1060–1065, 2018.

Lobkovsky, L. I., M. M. Ramazanov, and V. D. Kotelkin, Convection Related to Subduction Zone and Application of the Model to Investigate the Cretaceous-Cenozoic Geodynamics of Central East Asia and the Arctic, *Geodynamics & Tectonophysics*, *12*(3), 455–470, (in Russian), doi:10.5800/GT-2021-12-3-0533, 2021a.

Lobkovsky, L. I., I. S. Vladimirova, D. A. Alekseev, and Y. Gabsatarov, Two-Element Keyboard Model of Strongest Subduction Earthquakes Generation, *Dokl. Earth Sci.*, *496*, 72–75, doi:10.1134/S1028334X2101013X, 2021b.

Lobkovsky, L. I., I. S. Vladimirova, Y. V. Gabsatarov, and D. A. Alekseev, Keyboard Model of Seismic Cycle of Great Earthquakes in Subduction Zones: Simulation Results and Further Generalization, *Appl. Sci.*, *11*, 9350, doi:10.3390/app11199350, 2021c.

Loveless, J. P., and B. J. Meade, Geodetic Imaging of Plate Motions, Slip Rates, and Partitioning of Deformation in Japan, *J. Geophys. Res.*, *115*, B02,410, doi:10.1029/2008JB006248, 2010.

Lu, Y., J. Li, L. Liu, and L. Zhao, Complex Uppermost Mantle Structure and Deformation Beneath the Northwest Pacific Region, *J. Geophys. Res.*, *124*(7), 6866–6879, doi:10.1029/2019JB017356, 2019.

Lukhnev, A. V., V. A. San'kov, A. I. Miroshnichenko, S. V. Ashurkov, and E. Calais, GPS Rotation and Strain Rates in the Baikal-Mongolia Region, *Russian Geology and Geophysics*, *51*(7), 785–793, doi:10.1016/J.RGG.2010.06.006, 2010.

Molnar, P., and P. Tapponnier, Active Tectonics of Tibet, *J. Geophys. Res.*, *83*(B11), 5361–5375, doi:10.1029/JB083IB11P05361, 1978.

Sagiya, T., S. Miyazaki, and T. Tada, Continuous GPS Array and Present-Day Crustal Deformation of Japan, *Pure appl. geophys.*, *157*, 2303–2322, doi:10.1007/PL00022507, 2000.

Sankov, V. A., A. V. Lukhnev, A. I. Miroshnitchenko, A. A. Dobrynina, S. V. Ashurkov, L. M. Byzov, M. G. Dembelov, E. Calais, and J. Déverchère, Contemporary Horizontal Movements and Seismicity of the South Baikal Basin (Baikal Rift System), *Izvestiya Physics of the Solid Earth*, *50*(6), 785–794, doi:10.1134/S106935131406007X, 2014.

Savostin, L. A., A. I. Verzhbitskaya, and B. V. Baranov, Modern Tectonics of the Okhotsk Sea Region, *Doklady AN SSSR*, *266*(4), 961–965 (in Russian), 1982.

Sella, G. F., T. H. Dixon, and A. Mao, REVEL: A Model for Recent Plate Velocities from Space Geodesy, *J. Geophys. Res.*, *107*(B4), doi:10.1029/2000JB000033, 2002.

Seno, T., T. Sakurai, and S. Stein, Can the Okhotsk Plate be Discriminated from the North American Plate?, *J. Geophys. Res.*, *101*(B5), 11,305–11,315, 1996.

Shen, Z. K., C. Zhao, A. Yin, Y. Li, D. D. Jackson, P. Fang, and D. Dong, Contemporary Crustal Deformation in East Asia Constrained by Global Positioning System Measurements, *J. Geophys. Res.*, *105*(B3), 5721–5734, doi:10.1029/1999JB900391, 2000.

Shen, Z. K., M. Wang, Y. Li, D. D. Jackson, A. Yin, D. Dong, and P. Fang, Crustal Deformation Along the Altyn Tagh Fault System, Western China, from GPS, *J. Geophys. Res.*, *106*(12), 30,607–30,621, doi:10.1029/2001JB000349, 2001.

Shestakov, N. V., M. D. Gerasimenko, A. G. Kolomiets, G. N. Gerasimov, H. Takahashi, M. Kasahara, V. A. Bormotov, V. G. Bykov, N. F. Vasilenko, A. S. Prytkov, V. Y. Timofeev, D. G. Ardyukov, and T. Kato, Present Tectonics of the Southeast of Russia as seen From GPS Observations, *Geophysical Journal International*, *184*(2), 529–540, doi:10.1111/J.1365-246X.2010.04871.X, 2011.

Sorokhtin, O. G., and L. I. Lobkovsky, Mechanism for Pulling of Sediments in Subduction Zone of Lithospheric Plates, *Izvestiya Physics of the Solid Earth*, *12*(5), 3–10, 1976.

Steblov, G. M., M. G. Kogan, R. W. King, C. H. Scholz, R. Burgmann, and D. I. Frolov, Imprint of the North American Plate in Siberia Revealed by GPS, *Geophys. Res. Lett.*, *30*(18), 1–4, doi:10.1029/2003GL017805, 2003.

Steblov, G. M., T. A. Grekova, N. F. Vasilenko, A. S. Prytkov, and D. I. Frolov, Dynamics of the Kuril-Kamchatka Subduction Zone from GPS, *Izvestiya Physics of the Solid Earth*, *46*(5), 440–445, doi:10.1134/S1069351310050095, 2010.

Takahashi, N., M. Kasahara, F. Kimata, S. Miura, K. Heki, T. Seno, T. Kato, N. Vasilenko, A. Ivashchenko, V. Bahtiarov, V. Levin, E. Gordeev, F. Korchagin, and M. Gerasimenko, Velocity Field of Around the Sea of Okhotsk and Sea of Japan Regions Determined from a New Continuous GPS Network Data, *Geophys. Res. Lett.*, *26*(16), 2533–2536, doi:10.1029/1999GL900565, 1999.

Timofeev, V. Y., Generalization of the Results of Long-Term Strainmeter and GPS Observations for Intraplate Regions, *Izvestiya Physics of the Solid Earth*, *50*(6), 752–769, doi:10.1134/S1069351314060093, 2014.

Timofeev, V. Y., D. G. Ardyukov, A. V. Timofeev, and E. V. Boiko, Modern Movements of the Crust Surface in Gorny Altai from GPS Data, *Geodynamics & Tectonophysics*, *10*(1), 123–146, doi:10.5800/GT-2019-10-1-0407, (in Russian), 2019.

Vladimirova, I., L. Lobkovsky, Y. Gabsatarov, G. Steblov, N. Vasilenko, A. Prytkov, and D. Frolov, Patterns of the Seismic Cycle in the Kuril Island Arc from GPS Observations, *Pure and Applied Geophysics*, *177*(8), 3599–3617, doi:10.1007/s00024-020-02495-z, 2020.

Wang, M., and Z. Shen, Present-day crustal deformation of continental China derived from GPS and its tectonic implications, *J. Geophys. Res.*, *125*, e2019JB018,774, 2020.

Zhao, D., Global Tomographic Images of Mantle Plumes and Subducting Slabs: Insight into Deep Earth Dynamics, *Physics of the Earth and Planetary Interiors*, *146*(1), 3–34, doi:10.1016/J.PEPI.2003.07.032, 2004.

Zhao, D., Multiscale Seismic Tomography and Mantle Dynamics, *Gondwana Research*, *15*(3), 297–323, doi:10.1016/J.GR.2008.07.003, 2009.

Zhao, D., F. Pirajno, N. L. Dobretsov, and L. Liu, Mantle structure and dynamics under east russia and adjacent regions, *Russian Geology and Geophysics*, *51*, 925–938, doi:10.1016/J.RGG.2010.08.003, 2010.
