The role of the fault-block structure of the continental margin in the generation of the strongest subduction earthquakes

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INTRODUCTION

- Large subduction earthquakes are often characterized by very long source zones and complex long-term postseismic processes, following the coseismic release of accumulated elastic stresses.
- Modern seismotectonic studies are aimed at obtaining a self-consistent explanation of fault zone heterogeneity, the rupture process, recurrence times and rupture mode of large earthquake sequences. A set of mechanical models was already proposed to describe the generation of largest earthquakes based on the idea of the synchronous failure of several adjacent asperities [Ruff, 1992; Kaneko et al., 2010; Rosenau et al., 2019].
- In this study, we propose a model that is based on verified numerical schemes, which allows us to quantitatively characterize the process of generation of strong earthquakes [Lobkovsky et al., 1991]. The model takes into account the fault-block structure of the continental margin and combined the ideas of a possible synchronous destruction of several adjacent asperities, mutual sliding along a fault plane with a variable coefficient of friction and subsequent healing of medium defects under high pressure conditions.

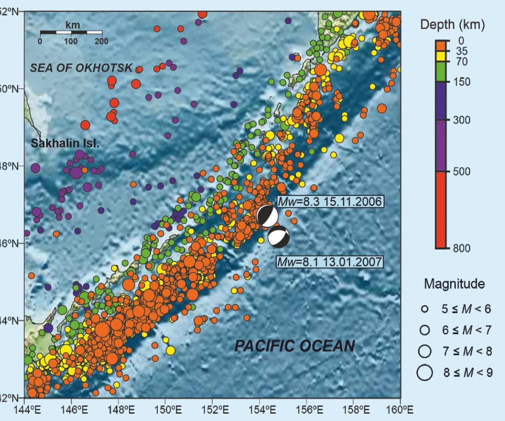

Figure 1. Seismic activity of the Kuril island arc region in the period from 01.01.1976 to 15.11.2006 and the focal mechanisms of the 2006–2007 Simushir earthquakes according to the Global CMT catalog [Ekström et al. 2012]

- The applicability of the proposed model is shown on the basis of the recent seismic history of the Kuril subduction zone. Kuril island arc is one of the most tectonically active regions of the world (Fig. 1) due to very high plate convergence rate. Heterogeneities in the mechanical coupling of the interplate interface in this region lead to the formation of the block structure of the continental margin (Fig. 2).
- Keyboard structure of the central part of the island arc is confirmed by the data obtained during the complex oceanographic expeditions carried out in this region in 2005–2006. According to these data the central part of the Kuril island arc is divided into 10 blocks with the characteristic sizes from 30 to 100 km [Baranov et al., 2015].
- The First Simushir earthquakes 15.11.2006 Mw = 8.3 (according to the Global CMT catalog [Ekström et al. 2012]) started the new episode in the history of the Kuril-Kamchatka seismically active zone.
- According to historical data, the last catastrophic earthquake in the central part Kuril island arc, from Simushir Island to the Kruzenshtern Strait, occurred in 1780 [Laverov et al. 2006], and for the entire period of instrumental observations, up to 2006, no events were recorded with M > 7.5 [Rogozhin, 2013]. It was established that the average duration of the seismic cycle for the Kuril-Kamchatka arc is 140 ± 60 years [Fedotov, 1968].

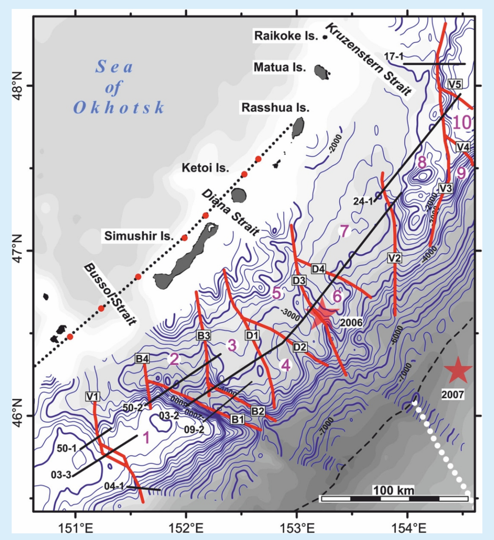

Figure 2. Location of the main identified transcurrent faults (red solid lines) in the Central Kurils region based on the data of geophysical and oceanographical surveys [Baranov et al., 2015]. Seismogenic blocks are denoted by numbers

KEYBOARD MODEL OF THE SEISMIC DEFORMATION CYCLE (SDC)

- The mechanical keyboard model (MKM) of subduction deformation cycles [Lobkovsky et al. 1991] was proposed to explain the patterns of seismic activity distribution taking into account the block-like structure of the continental margin. This model combines the ideas of possible synchronous failure of several adjacent asperities and slip-dependent friction and stress-dependent healing along the subduction interface to describe the generation of megathrust earthquakes.
- According to the keyboard model the frontal part of the island arc is divided on wedge-shaped blocks (keys – B), which are separated from each other by transcurrent vertical faults (C) that reach the surface of a subducting plate (D) (Fig. 3). The blocks are bounded from the ocean-side by deep-sea trench, and from the island arc side by a longitudinal fracture zone, which separates them from the main arc massif (A).
- Due to interaction between the oceanic and continental lithospheric plates, the blocks accumulate stresses, which are released during the megathrust earthquakes. The stage of elastic energy accumulation within each block occupies the principal part of the periods between consequent great earthquakes (Fig. 3).
- The block projection on the surface during the seismic stage is identified with a seismic gap. The release of the seismic energy of the whole seismogenic block occurs when a critical value of the tangential stress is achieved along the greater part of the interplate contact surface.

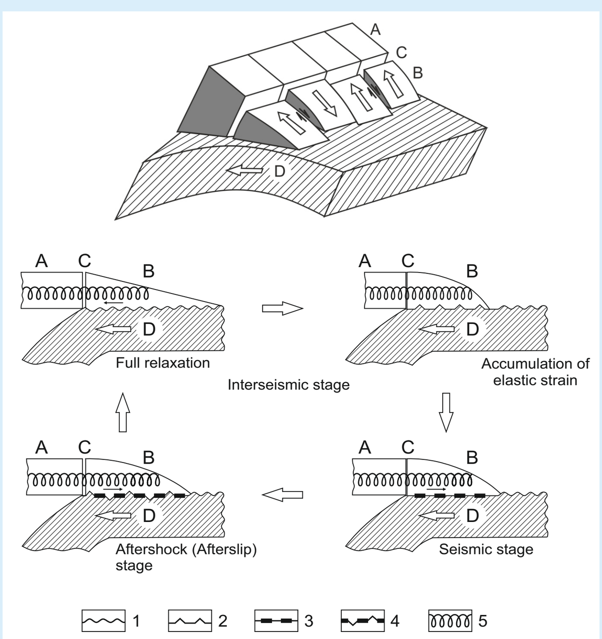

Figure 3. Scheme of successive stages of deformation (loading and relaxation) of the seismogenic blocks and the corresponding stages of the seismic cycle:
1 – Undisturbed "rough" contact zone structure (CZS) (stable stage of the cycle); 2 – elastic "smoothed" CZS (preseismic stage of the cycle); 3 – strongly fragmented and heterogeneous CZS (seismic stage of the cycle); 4 – partly restored CZS (aftershock stage of the cycle); 5 – spring imitating the elastic interaction between blocks [Lobkovsky et al., 1991]

- During a fast seismic stage, only a partial relaxation of accumulated stress occurs. The release of the remaining part of the elastic energy stored in the blocks takes place at the aftershock stage of the seismic cycle during the final "straightening" of the system. During the main shock the material of the contact zone is destroyed, that leads to significant decrease in its effective viscosity from interseismic 10^{19} Pas down to 10^{18} Pas.
- The aftershock stage can last up to several years and its termination marks the beginning of a new seismic deformation cycle (SDC), when the seismogenic blocks are at a maximum distance from the islands.

KURILNET DATA AND EARTH SURFACE DEFORMATIONS

- Analysis of spatiotemporal distribution of deformations related to the great 2006–2007 Simushir earthquakes became possible after installation of the regional network of continuous GPS stations (Fig. 4). This regional geodynamic network (KurilNet) was arranged in the period from 2006 to 2008 along the entire Kuril island arc from Japan to Kamchatka by joint efforts of the Institute of Marine Geology and Geophysics of the Far East Branch of the Russian Academy of Sciences (RAS), Ioffe Institute of RAS and Geophysical Survey of RAS. The final configuration of the Kuril network consisted of four survey-mode sites and eight continuously tracking permanent sites: PARM (Paramushir Isl.), SHIK (Shikotan Isl.), KUNA (Kunashir Isl.), ITUR (Iturup Isl.), URUP (Urup Isl.), KETC (Ketoy Isl.), MATC (Matua Isl.), and KHAM (Kharimkotan Isl.), which provided unique data to study the seismic cycle deformation.

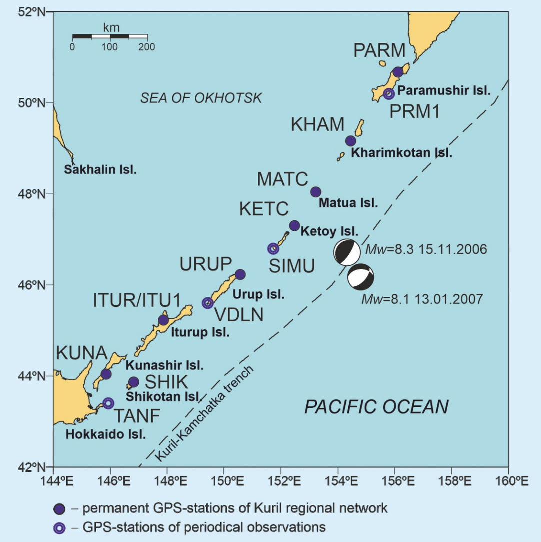

Figure 4. Final configuration of the Kuril geodetic network. Continuous GPS-stations are denoted by filled circles, campaign-mode stations are denoted by open circles

- The KurilNet is located along the margin of the Sea of Okhotsk on the hanging wall of the Kuril megathrust, which in our study is considered as a part of the North American lithospheric plate (NAM) due to very small relative motion (less than 2–3mm/a relative to NAM) of the Sea of Okhotsk region.
- High-quality long-term geodetic observations provided a "snapshot" of the evolution of the seismic deformation cycle in the Kuril subduction zone. The obtained data allowed us to determine interseismic velocities, coseismic displacements during both Simushir earthquakes and postseismic deformations developing near the source zone of the 2006 event for the next eight years.
- To investigate patterns of postseismic surface deformations caused by 2006–2007 Simushir earthquakes we fit the time series (from mid-2007 to mid-2015) of GPS displacements with piecewise linear functions constructed using linear spline approximation. This approach allowed us to assess station velocities over 1-year intervals and mitigate the biases in these estimates. The obtained velocities allowed us to study the spatio-temporal variations of rates and directions of surface motions after the 2006–2007 Simushir earthquakes along the Kuril island arc (Fig. 6,7). Analysis of these variations revealed a multidirectional movement of the earth surface observed along the Kuril island arc. Such a pattern of displacements indicates that different segments of the Kuril arc are at different stages of the SDC [Lobkovsky et al., 2017].

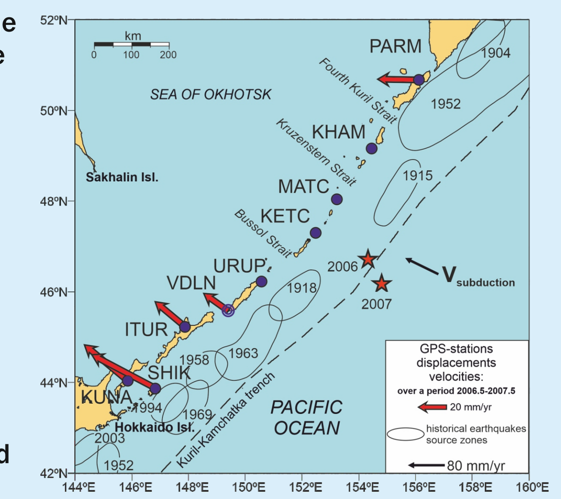

Figure 5. Interseismic velocities registered on KurilNet stations

- The northwestern direction of the displacement vectors of the sites KUNA, SHIK, ITUR and PARM located on the southwestern and northeastern flanks of the Kuril arc is close to the direction of plate convergence and is consistent with the direction of the displacements recorded at these stations before the Simushir earthquakes (Fig. 4). According to the keyboard model, it reflects the compression of the main massif of the island arc during the interseismic stage of the SDC and indicates the ongoing process of accumulation of elastic stresses in these parts of the subduction zone.
- At the same time, the sites KETC and MATC located in the central part of the island arc, between the Kruzenshtern and Bussol Straits, are sliding towards the ocean during the entire observation period. Their initially high velocities (up to 90 mm/yr) decrease with time (by about 30% per year), and gradually rotate to the stationary interseismic state. The nature and duration of these displacements can be explained using the MKM model assuming ongoing retreat of released seismogenic blocks toward the ocean at the aftershock stage. On the other side, this can indicate the presence of transient postseismic process in the region surrounding the source zone of the 2006 Simushir earthquake, most likely caused by the viscous response of the asthenosphere. The possibility of appearance of asthenospheric flow after penetration of coseismic deformations to sufficient depth is confirmed by the results of numerical simulations [Lobkovsky et al. 2017]. Thus, it is likely that the high rates of the observed postseismic deformations of the earth surface within the island arc are associated with significantly lower effective viscosity of the underlying asthenospheric wedge [Vladimirova et al., 2020] due to the local loosening of its material by fluid transport from the subducting slab. The velocity of the site URUP located south-west of the source zone of the 2006 Simushir earthquake demonstrates similar behavior, which can be explained by possible evolution of the initial seismic rupture in the corresponding direction in the first months after the earthquake during the aftershock stage [Vladimirova et al., 2020].

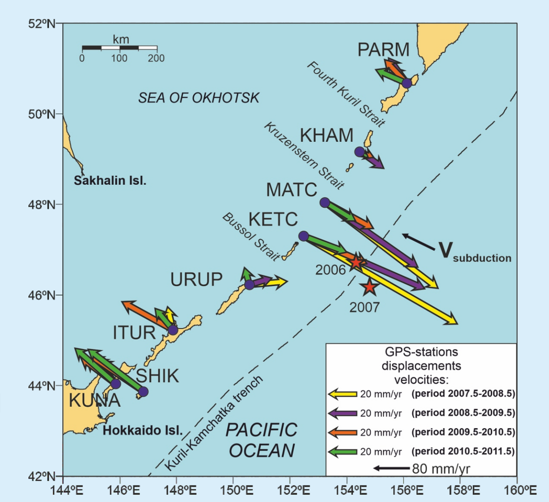

Figure 6. Velocities of horizontal postseismic displacements of KurilNet stations estimated over 1-year intervals from 2007.5 to 2011.5

- GPS data provide clear evidence of abrupt changes in directions and rates of station consistent with the block-like motion hypothesis.

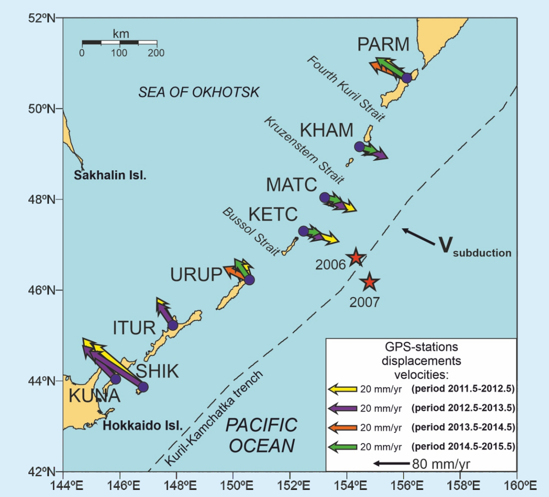

Figure 7. Velocities of horizontal postseismic displacements of KurilNet stations estimated over 1-year intervals from 2011.5 to 2015.5

NUMERICAL MODELING

- We model the deformation processes providing the relaxation of accumulated elastic stresses in the vicinity of the sources of the 2006–2007 Simushir earthquakes using the classical dislocation approach for spherical layered earth to analyze deformation fields occurring at the different stages of the SDC [Vladimirova et al., 2020].
- We invert our coseismic displacements to make an estimation of the slip distribution in the sources of these events (Fig. 8). We estimated spatial dimensions of the source zones of the 2006–2007 Simushir earthquakes based on aftershock distributions recorded in the first 2 months after 2006-2007 earthquakes according to GCMT catalog [Ekström et al., 2012]. The fault plane of the 2006 earthquake consists of three 230 km-long and 50 km-width rectangles dipping 9, 16, and 22°, each of which was divided into 4 subplanes. The fault plane of the 2007 earthquake consists of one 230 km-long and 50 km-width rectangles dipping 59°, which was divided into 4 subplanes. We calculated the seismic moments for our distributions, which were 5.93×10^{21} N·m for the 2006 earthquake and 2.98×10^{21} N·m for the 2007 earthquake. The obtained values are consistent with those obtained in [Steblov et al., 2008] within 15% and are about 1.5 times higher than those provided by GCMT [Ekström et al., 2012]. The maximum slip in the source of the 2006 Simushir earthquake reaches 12 m. Overall, the area of maximum coseismic displacement in the source (with slip ranging from 6 to 12 m) affected three seismogenic blocks from 5 to 7 (Fig. 8). Coseismic displacement of several adjacent seismogenic blocks caused the source extension. This situation is possible in conditions of local compression of seismogenic blocks due to oblique subduction. The modeling provides us with additional information about the tectonic and rheological structure of the studied area, in particular, the duration of postseismic stage (which exceeds 10 years), mean effective viscosity of underlying asthenosphere, which is as low as 3×10^{17} Pas [Vladimirova et al., 2020].

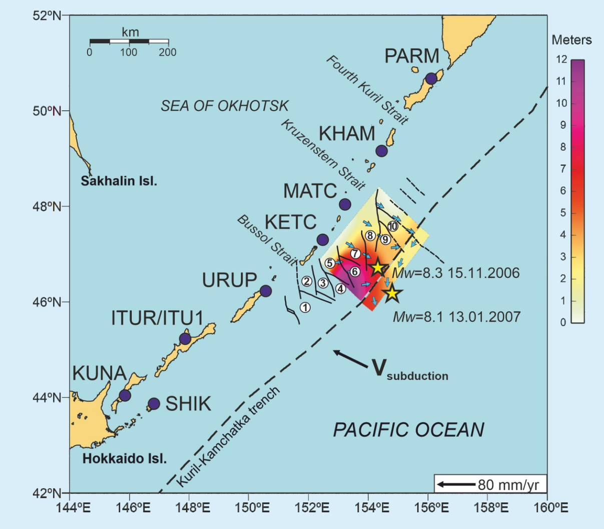

Figure 8. Slip models for the 2006–2007 Simushir earthquakes constructed on the basis of coseismic displacements observed at Kuril GPS stations during these events

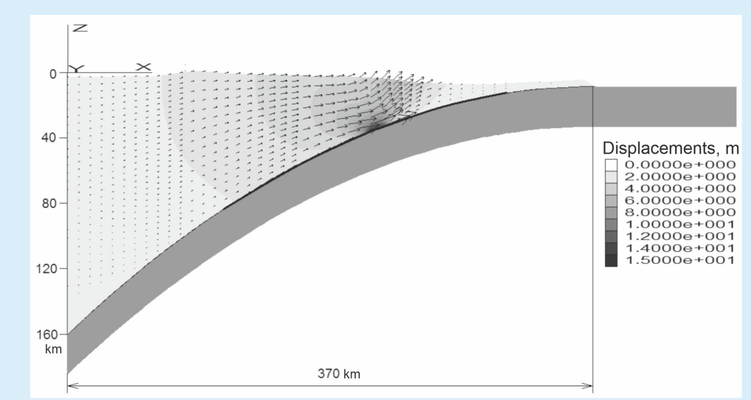

Figure 9. Result of modeling of coseismic displacements distribution during the 2006 Simushir earthquake. The black line at the plate interface shows a region of decreased dry friction forces [Lobkovsky et al., 2017]

- In order to check the applicability of GPS data for studying of spatial patterns of the propagation of deformations caused by the first Simushir earthquake, we perform mathematical modeling of the distribution of coseismic displacements in a section crossing the Kuril-Kamchatka subduction zone through the earthquake source. In our model we use the density and lithostratigraphic model characterizing the current state of the transition zone. For the Earth's crust and lithosphere, a model of unassociated plastic flow with the Coulomb-Mohr yield condition has been selected. It is assumed that sliding on the contact surface of the plates occurs under conditions of dry friction. For mathematical modeling, we use FLAC3D software, which implements an explicit finite-difference scheme for solving three-dimensional problems of continuum mechanics.
- As a result, we constructed the distribution of displacements in the section and on the earth surface (Fig.9). The maximum slip in the source at the interplate contact reaches 7 m, and the vertical and horizontal displacements in the medium were about three meters. At a distance of 200 km from the source, horizontal displacements are no more than half a meter, which is in good agreement with the observational data (Fig. 10).

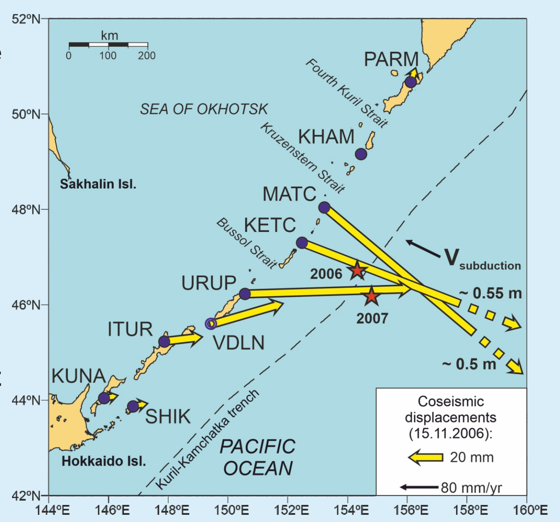

Figure 10. Coseismic displacements observed on KurilNet stations during the 2006 Simushir earthquake

- The possibility of direct high-precision satellite geodesy observations of earth surface displacements in subduction regions provides new opportunities for constructing a quantitative keyboard model taking into account discontinuities in the rear massif, as well as spatiotemporal heterogeneities of the rheological characteristics of the contact "lubricating" layer and of the asthenospheric wedge at different stages of the SDC. The construction of such a model allows us to assess the times of transition of structural elements of the subduction system from one state to another. In particular, realistic estimates of the time of the end of healing of the contact layer (i.e., the moment of restoration of mechanical coupling between the seismogenic block and the subducting plate), the time of the termination of the displacement of the rear array by the viscoelastic asthenospheric flow (i.e., the end of the postseismic stage), as well as the moment of the beginning of the stage of elastic compression of the system, accompanied by the accumulation of stresses are very important in solving problems of long-term and medium-term forecast.
- The geometric characteristics of the blocks are set using available geological and geophysical information, including seismic tomography and seismic data (to take into account the geometry of blocks in the section) and available materials on fault tectonics of the studied region.
- Since the blocks were considered identical, the limiting condition for the occurrence of strong earthquakes can be formulated in terms of the critical elastic energy UC of the entire block. UC values were assumed uniformly distributed over the interval (2-8) x 10^{25} erg. The decrease in the amount of accumulated elastic stresses as a result of the earthquake was supposed to be uniformly distributed over the interval [0.8, 0.95]. These values were reevaluated for each new seismic cycle to maintain stochastic conditions.

- The computational scheme that was used to build the keyboard model is described by a system of equilibrium equations connecting the stresses in the seismogenic block under consideration and the corresponding block of the rear massif, as well as neighboring blocks, expressed through the displacement rates and viscosity of the material of the contact layer, the asthenosphere under the rear block and fault zones separating blocks (Fig. 11). In this case, the outer edges of the blocks from the side of the trench are free. Additional conditions include an abrupt coseismic change of stresses, which leads to synchronous displacements of the points of the seismogenic block. Calculation of elastic energy density on the basis of model displacements of block points and its comparison with the critical value allows us to obtain the condition for triggering a seismic event. The system of equations constructed in the manner described above is characterized by significant non-linearity, and we solve it using an explicit finite-difference scheme, which allows to obtain the increment of displacement of the nodal points (taking into account the location of the observation stations) within each block for a set of times specified with a certain step.

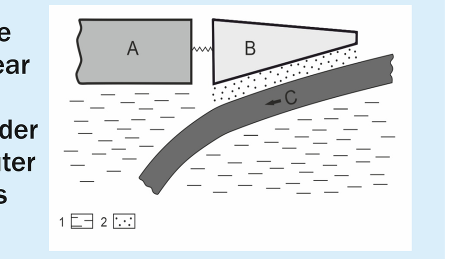

Figure 11. Keyboard elastic deformation system.
A - island arc massif,
B - seismogenic block,
C - subducting lithosphere,
1 - underlying asthenosphere,
2 - viscous contact layer

- Here we present the modeling results of the seismogenic blocks dynamic in the middle part of the Kuril island arc for 1400 years (10 times the mean duration of SDC for Kuril-Kamchatka subduction zone [Fedotov, 1968]). To simplify the model, the block sizes are assumed to be the same (100x100 km). According to earthquake catalog data, large subduction earthquakes of the Kuril Islands are characterized by a focal length of 120 to 250 km (Fig. 12). The rheological properties of medium are selected according to the results of modeling of geodynamic processes associated with the SDC related to the First Simushir earthquake.
- As a result of the simulation, we estimated the total duration of the seismic cycle, which lies in the interval of [113, 330] years with an average value of 196 years and the duration of the postseismic stage, which corresponds to a range of [11, 19] years with an average value of ~ 15 years (Fig. 13). These estimates are in good agreement with the real values of the seismic cycle associated with the 2006 Simushir earthquake, which is 224 years and more than 10 years, respectively.

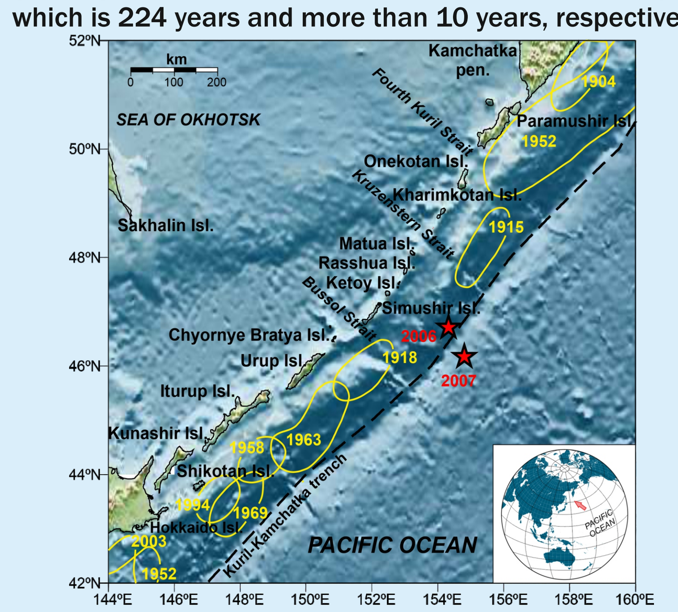

Figure 12. Source zones of the strongest megathrust earthquakes with M ≥ 8, since 1904, and the main shocks of the 2006–2007 Simushir earthquakes

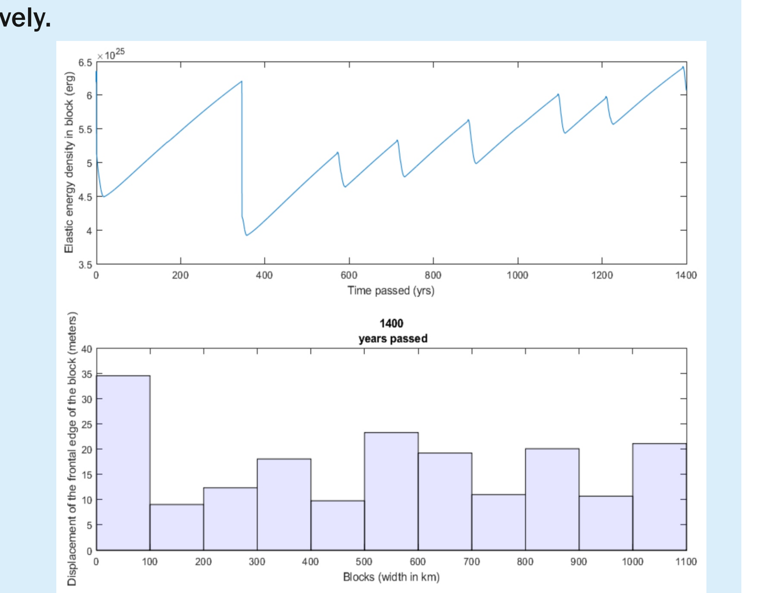

Figure 13. An example of simulation a series of seismic cycles governed by block-like structure of the continental margin

CONCLUSIONS

- GPS observations recorded at different stages of seismic cycle related to the 2006–2007 Simushir earthquakes allow us to model geodynamic processes of slow strain accumulation and its rapid release during the earthquake and the subsequent postseismic process. We use parameters describing the regional tectonic structure and rheology obtained from the inversion of geodetic data to construct a model of generation of large earthquakes in central Kurils. Analysis of paleoseismic data on dates and rupture characteristics of previous major earthquakes shows a good agreement between the modeled and observed seismic cycle features. The predicted horizontal displacements of the seismogenic block at the coseismic stage are consistent with satellite geodetic data recorded during the 2006 Simushir earthquake.
- The proposed model provides new insights into the geodynamic processes controlling the occurrence of strong subduction earthquakes.

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TS5.2 (GD9/NH4/SM4) Advances in understanding earthquake sequences and (a)seismic slip across scales

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