

EGU21-305: Two-Element Keyboard-Block Model Of Megathrust Earthquakes Generation For Central Kurils

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Our motivation:

- Prediction of strong subduction earthquakes, causing significant socio-economic and environmental damage, is one of the most important and urgent tasks of geophysics.
- Geological and geophysical data, as well as GNSS observations, indicate block-like structure of the Kuril island arc.
- In this case mechanical keyboard model can be used to explain the features of the seismic deformation cycle in the Kuril islands.

Our goals:

- We want to study the evolution of deformation processes in subduction zones on the basis of geomechanical modeling and GNSS observations of surface displacements.
- We present a generalization (double-element) of the original keyboard model to consider the discontinuity of not only the frontal but also the rear part of the island arc.

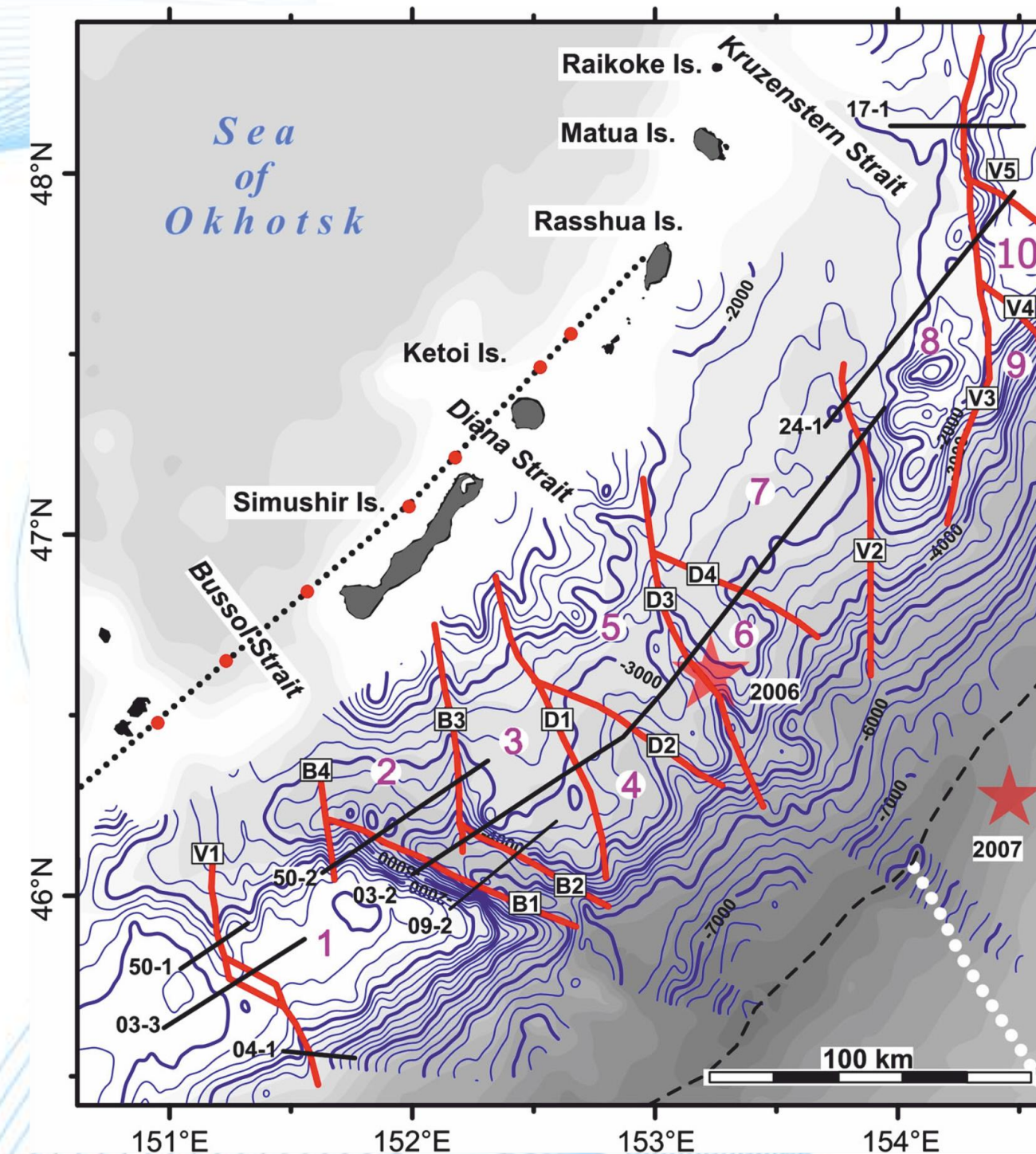


Fig.1 Location of main identified transcurrent faults (red solid lines) in the Central Kuril Islands forearc region based on the data of geophysical surveys [Baranov et al., 2015].

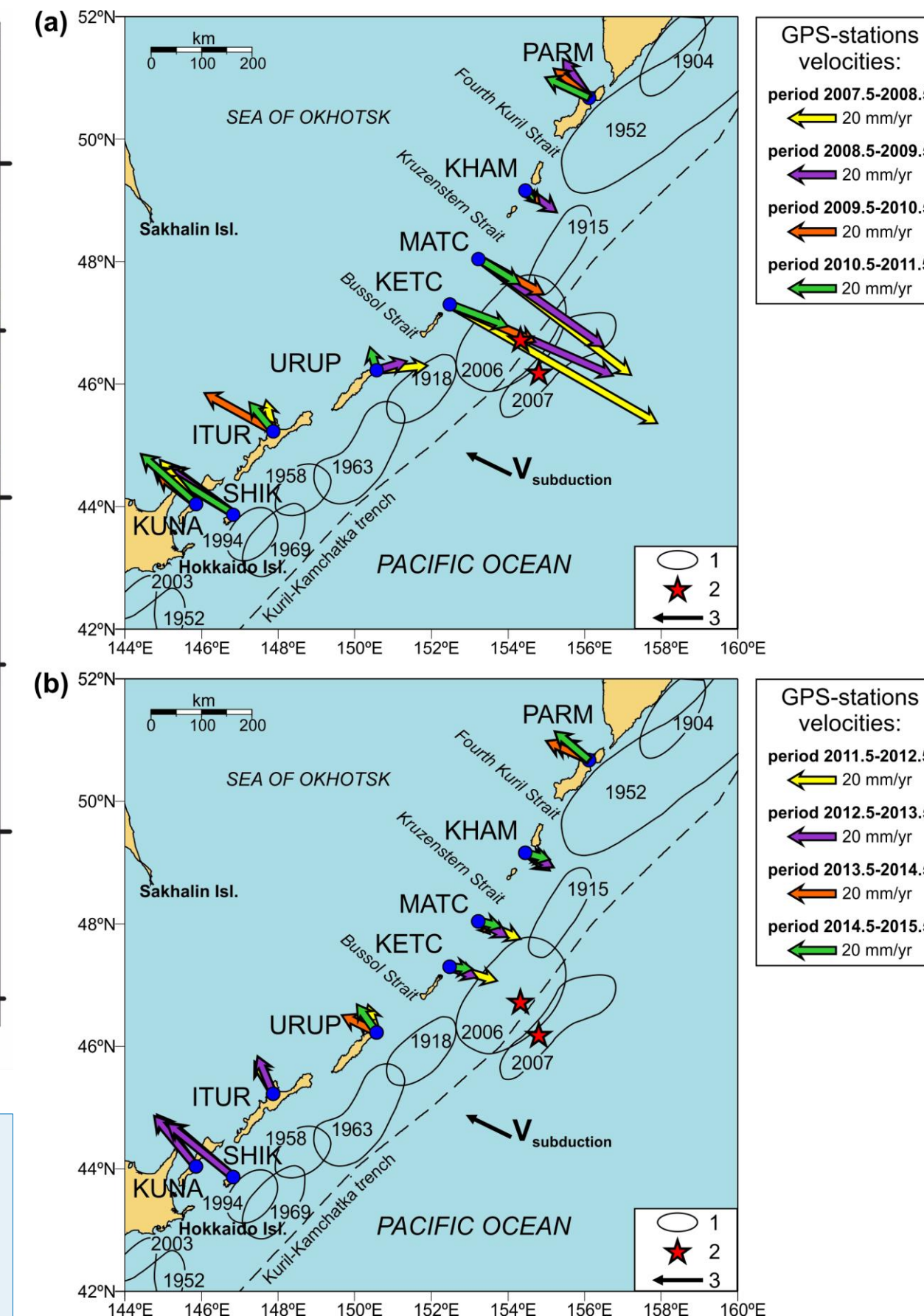


Fig.2 Annual variations of GNSS station velocities over the 8-th year period after M8.3 2006 Simushir earthquake [Vladimirova et al., 2020]

The mechanical keyboard model of subduction deformation cycles 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 [Lobkovsky et al. 1991].

The initial formulation of the model includes only frontal seismogenic block. We want to use GNSS data to verify the constructed models but most of the stations are located on islands far from the trench.

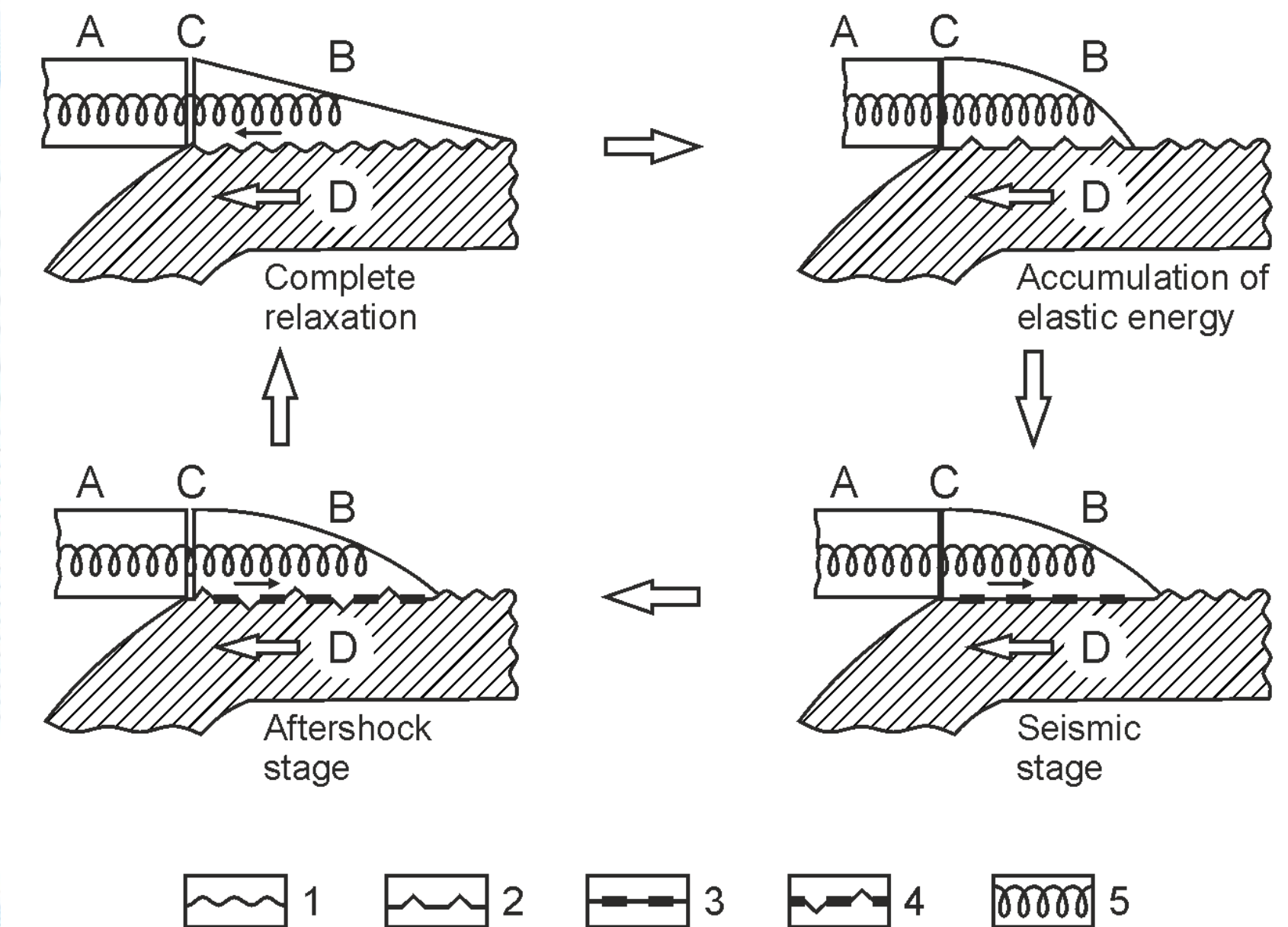


Fig.3 Scheme of successive stages of deformation (loading and relaxation) of the seismogenic blocks and the corresponding stages of the seismic cycle [Lobkovsky et al., 1991]:

- 1 – undisturbed “rough” contact zone structure (CZS) (stable stage);
- 2 – elastic “smoothed” CZS (preseismic stage);
- 3 – strongly fragmented and heterogeneous CZS (seismic stage);
- 4 – partly restored CZS (aftershock stage);
- 5 – spring imitating the elastic interaction between blocks

The equilibrium equation for the i th block:

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

The stresses which occur at the basement and on the lateral planes of the block:

$$\tau_0^{(i)} = -\eta(\dot{\gamma}_i)\dot{\gamma}_i$$

$$= \begin{cases} -\eta(\dot{\gamma}_i) \left(\frac{\partial w_i}{\partial t} - V_i^1 \right) \frac{1}{h} & 0 \leq x \leq l \\ -\tilde{\eta}(\dot{\gamma}_i) \left(\frac{\partial w_i}{\partial t} \right) \frac{1}{h_0} & l \leq x \leq l+r \end{cases}$$

and

$$\begin{cases} \tau_{i-1} = \frac{\mu_{i-1}^{1,2}}{h_g} \left(\frac{\partial w_{i-1}}{\partial t} - \frac{\partial w_i}{\partial t} \right) \\ \tau_{i+1} = \frac{\mu_i^{1,2}}{h_g} \left(\frac{\partial w_{i+1}}{\partial t} - \frac{\partial w_i}{\partial t} \right) \end{cases}$$

where $\dot{\gamma}_i$ is an averaged strain rate of the medium in the contact layer; V_i^1 is the subduction rate of the plate under the i th block; $\eta(\dot{\gamma}_i)$ is the effective viscosity of the contact zone; $\tilde{\eta}(\dot{\gamma}_i)$ is the viscosity of the asthenosphere; h_g is thickness of the gouge zone of interblock faults; $\mu_{i-1}^{1,2}$ and $\mu_i^{1,2}$ are the viscosities of the material between blocks i and $i-1$, or i and $i+1$.

Great earthquakes originate when the critical value of the mean density of the elastic energy in seismic blocks is reached

$$\epsilon_i = \frac{E}{2lH_m} \int_0^l H(x) \left(\frac{\partial w_i}{\partial x} \right)^2 dx = \epsilon_{cr} \quad , H_m = (H_0 + H_l)/2 - \text{mean block thickness}$$

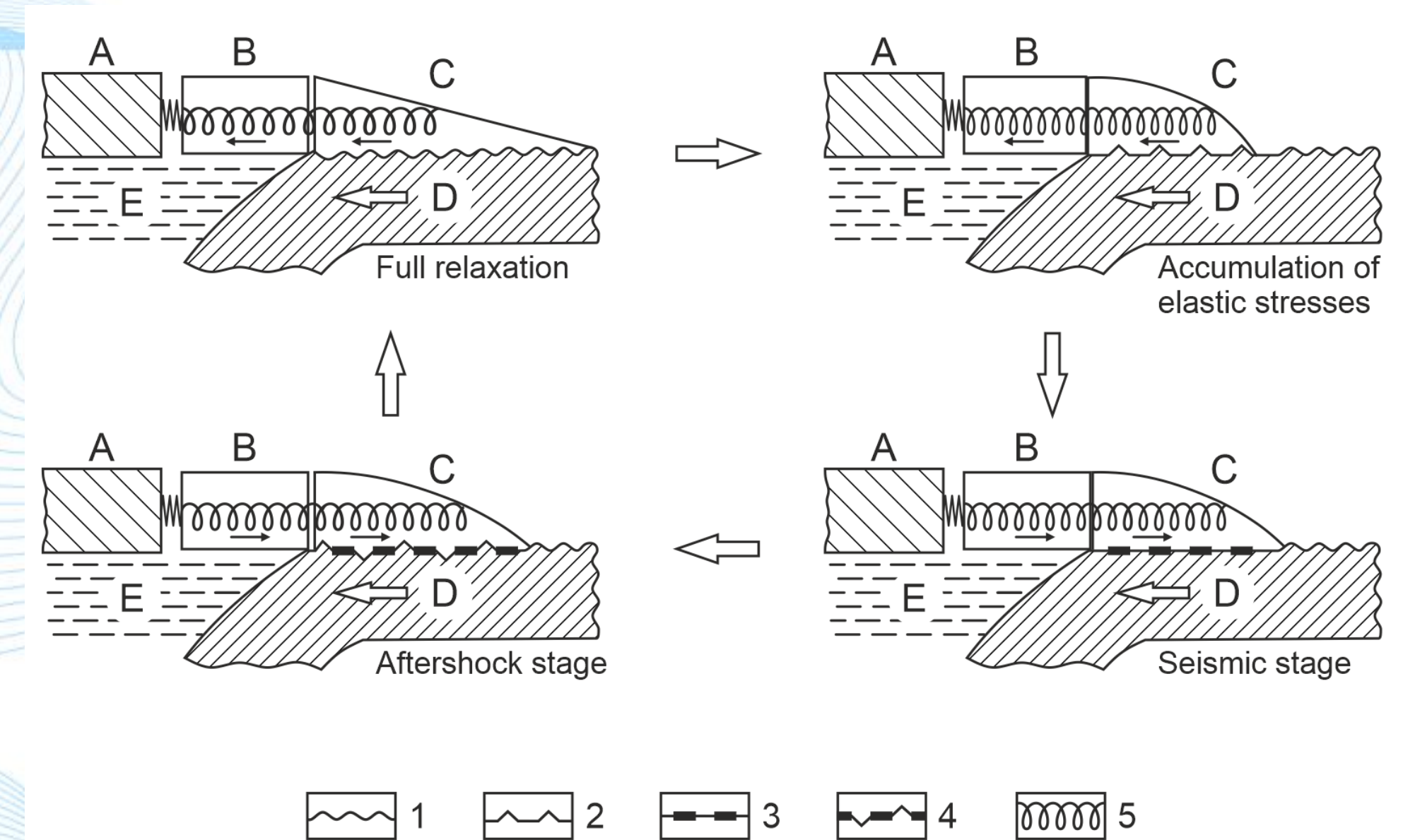


Fig.4 Scheme of successive stages of deformation (loading and relaxation) for 2 frontal blocks and the corresponding stages of the seismic cycle [Lobkovsky et al., 2020]:

- 1 – undisturbed “rough” contact zone structure (CZS) (stable stage);
- 2 – elastic “smoothed” CZS (preseismic stage);
- 3 – strongly fragmented and heterogeneous CZS (seismic stage);
- 4 – partly restored CZS (aftershock stage);
- 5 – spring imitating the elastic interaction between blocks

- spatial dimensions of blocks (width of blocks, length of blocks, thickness profile of blocks)
- initial stresses and strains in blocks
- widths of interplate and interblock gouge zones
- rheological parameters (Young modules for blocks, stiffnesses of springs, effective viscosities of the gouge zones and asthenosphere)
- amounts of critical accumulated energy in blocks
- amounts of accumulated energy released during earthquakes
- rates of stress accumulation in blocks
- other parameters governing postseismic processes (recovery time for effective viscosity, healing time for contact zones)

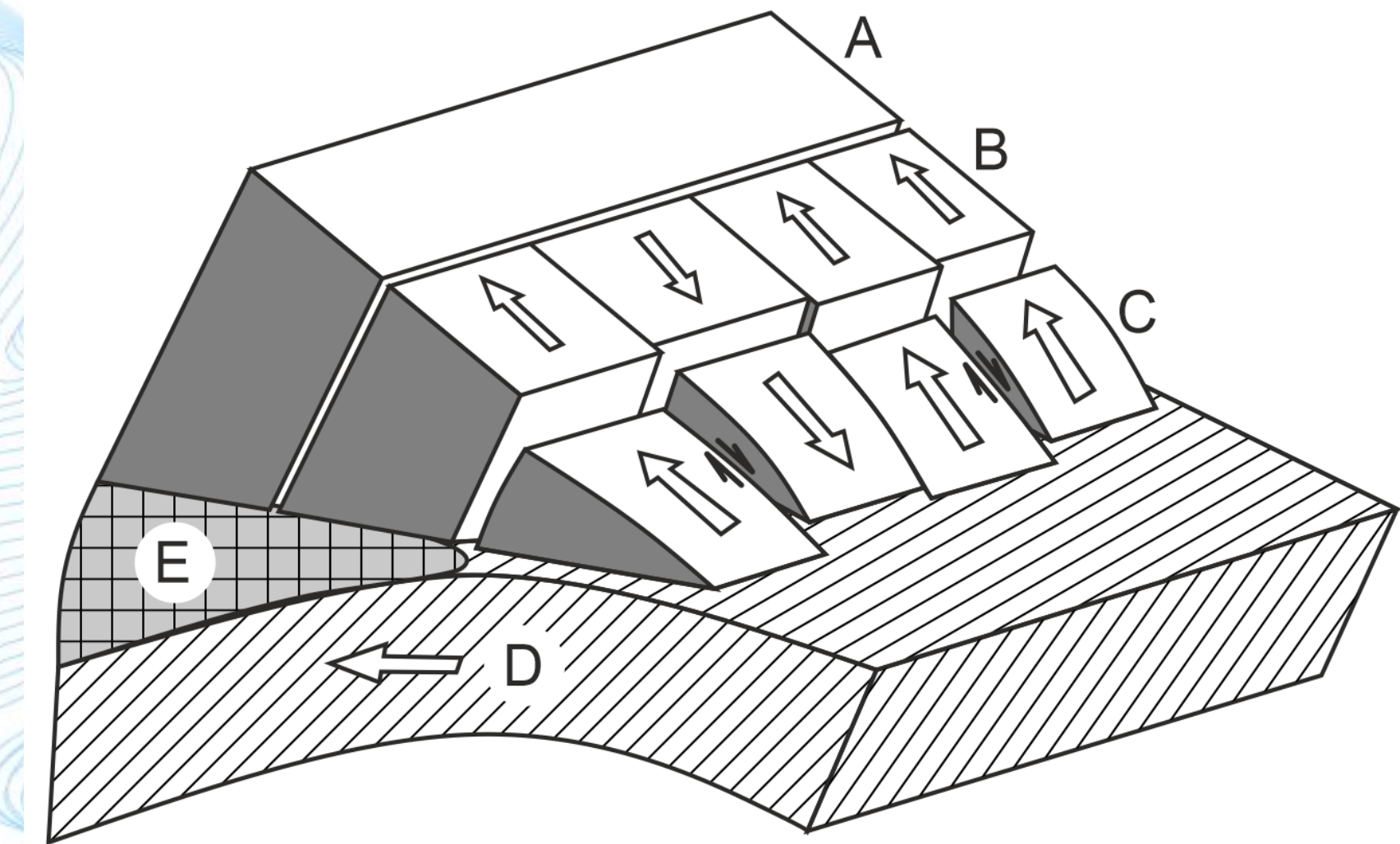


Fig.5 Keyboard model of the frontal part of the island arc
A - undeformed part of the lithospheric plate;
B - rear block;
C - frontal block;
D - movable plate;
E - asthenosphere.

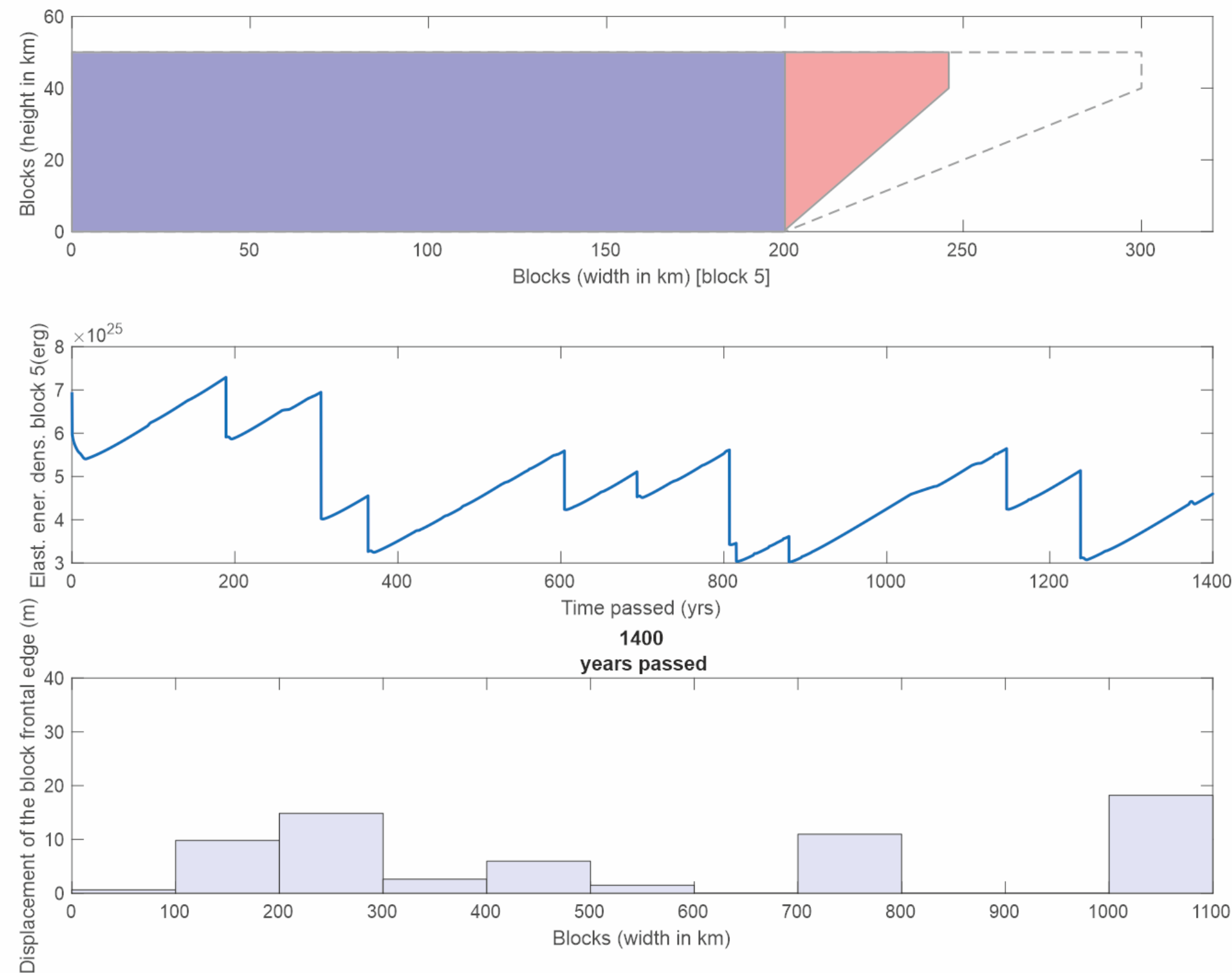


Fig.6 Simulation of several seismic deformation cycles in Kuril subduction zone for initial formulation of keyboard model. Stochastic condition for amount of relaxed and accumulated elastic energy

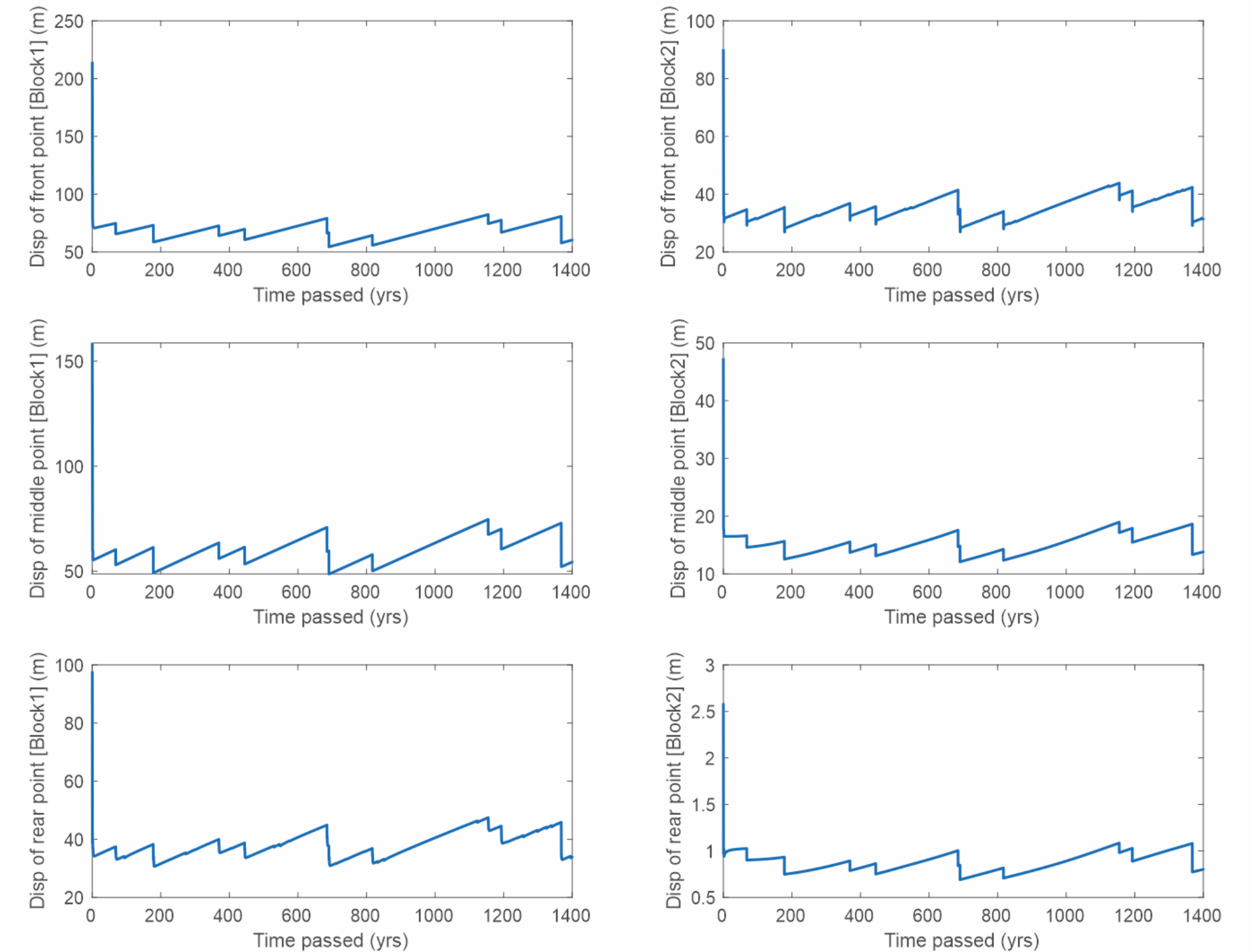


Fig.7 Simulation of several seismic deformation cycles in Kuril subduction zone for generalized keyboard model. Left column of images shows the displacements of frontal block, right column shows the displacements of rear block. Stochastic condition for amount of relaxed and accumulated elastic energy

We made a numerical simulation of series of seismic cycles using initial and generalized formulations of keyboard model with stochastic behavior of parameters governing the critical amount of accumulated elastic energy and the amount of relaxed energy. During the simulations the model parameters were constrained to values that are typical for the Kuril subduction system ($E_1 = 29$ GPa , $E_2 = 80$ Gpa, block width_i = 200 km, frontal block length = 100 km, rear block length = 200 km, effective viscosity of the contact layer and the asthenosphere = $1 \cdot 10^{19}$ Pa*s) We also performed a comparison of obtained model parameters with calculated earlier using continuum medium model [Pollitz, 1996] and geophysical data.

	Geological+ Geophysical data [Fedotov, 1968]	Continuous medium model [Vladimirova et al., 2020]	Mechanical keyboard model	Generalized mechanical keyboard model
Seismic cycle duration	140 +- 60 years	159 years	60-267 years av. 136 years	40-338 years av. 162 years
Postseismic stage duration	Up to 35-50 years	0.5 years [afterslip], up to 10 years [viscoelastic relaxation]	2-7 years	1-5 years
Coseismic hotizontal surface displacements	—	$55 \cdot 10^{-2}$ meters [GNSS observations]	—	$10 \cdot 10^{-2} - 1.8$ meters [depends on range]

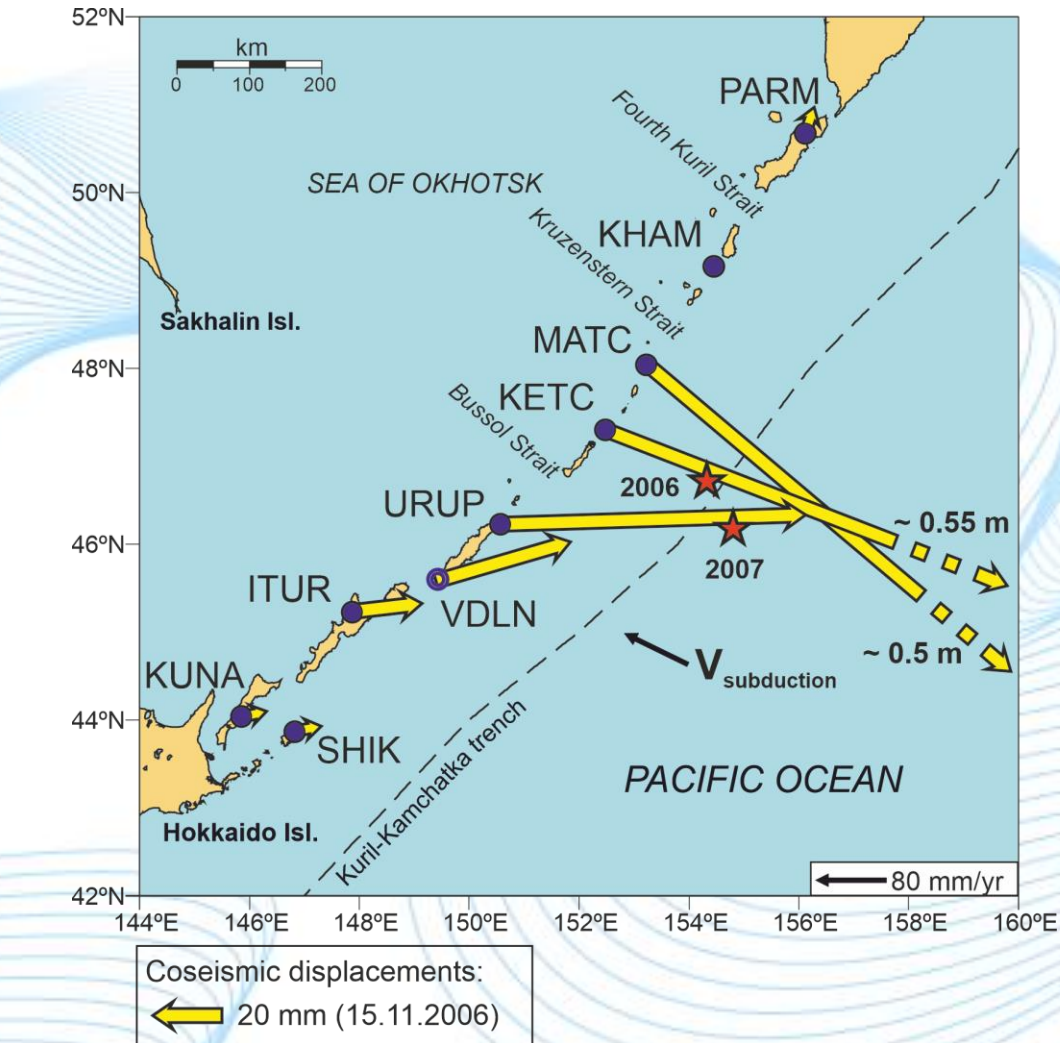


Fig.8 Coseismic offsets during the 2006 Simushir earthquake.

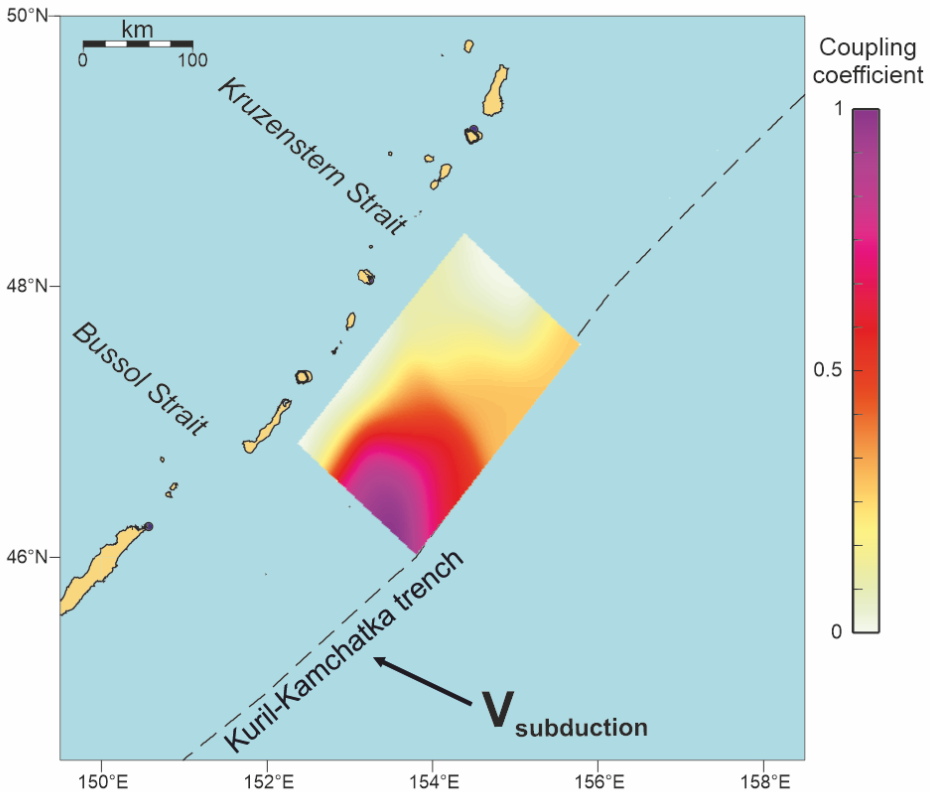


Fig.10 Mechanical coupling model used in continuous medium model [Vladimirova et al., 2020]

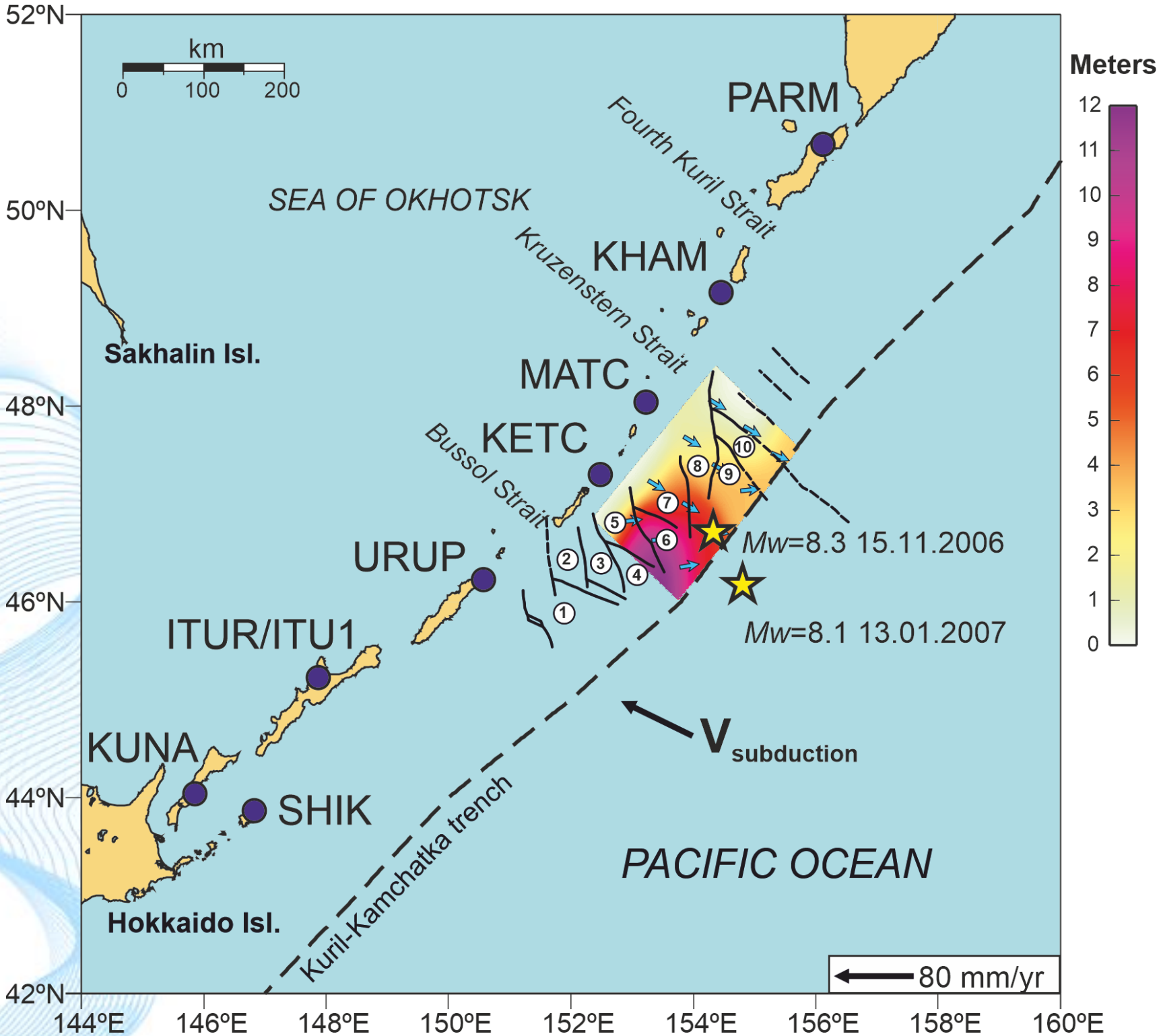


Fig.9 Model of slip distribution in the source of the 2006 Simushir obtained on the basis of coseismic displacements [Vladimirova et al., 2020]. Dashed lines indicate faults that outlined seismogenic blocks [Baranov et al., 2015].

Our results	Future plans
• An analytical solution and a numerical scheme for calculating the parameters of the generalized keyboard model have been developed. Numerical scheme was implemented using MATLAB. • The analysis of the model showed that for the rheological and spatial parameters typical for the Kuril subduction zone, the results of the generalized model are quite close to the results of the original keyboard model and the results of previous studies. At the same time, the generalized model allowed us to compare the model displacements with the GNSS data.	• Development of an inversion technique and refinement of model parameters through GNSS data inversion. • Development of a three-dimensional generalized keyboard model for modeling seismotectonic deformations in various subduction zones.

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