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

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Introduction

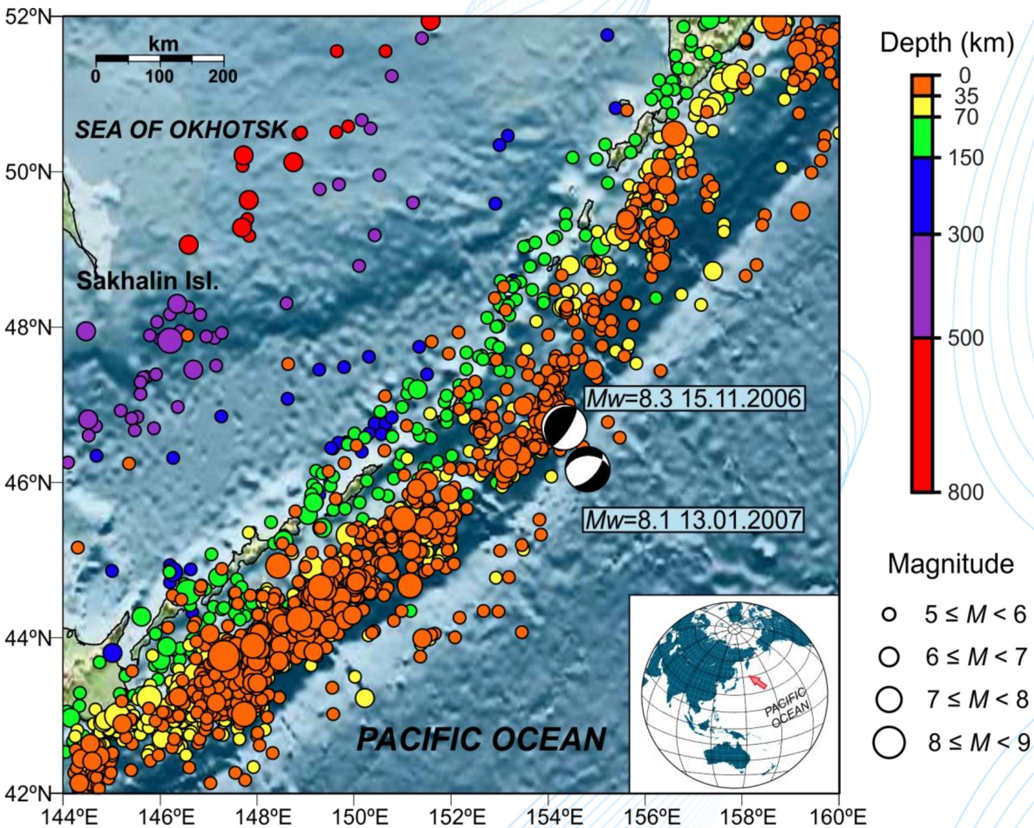
Our motivation:

The strongest subduction earthquakes are quite rare, but lead to the release of colossal elastic stresses accumulated over hundreds or even over a thousand years, and, in turn, to significant socio-economic and environmental damage. Thus, the study of spatio-temporal patterns and features of earthquake cycles in subduction zones is one of the most important and relevant tasks of geophysics.

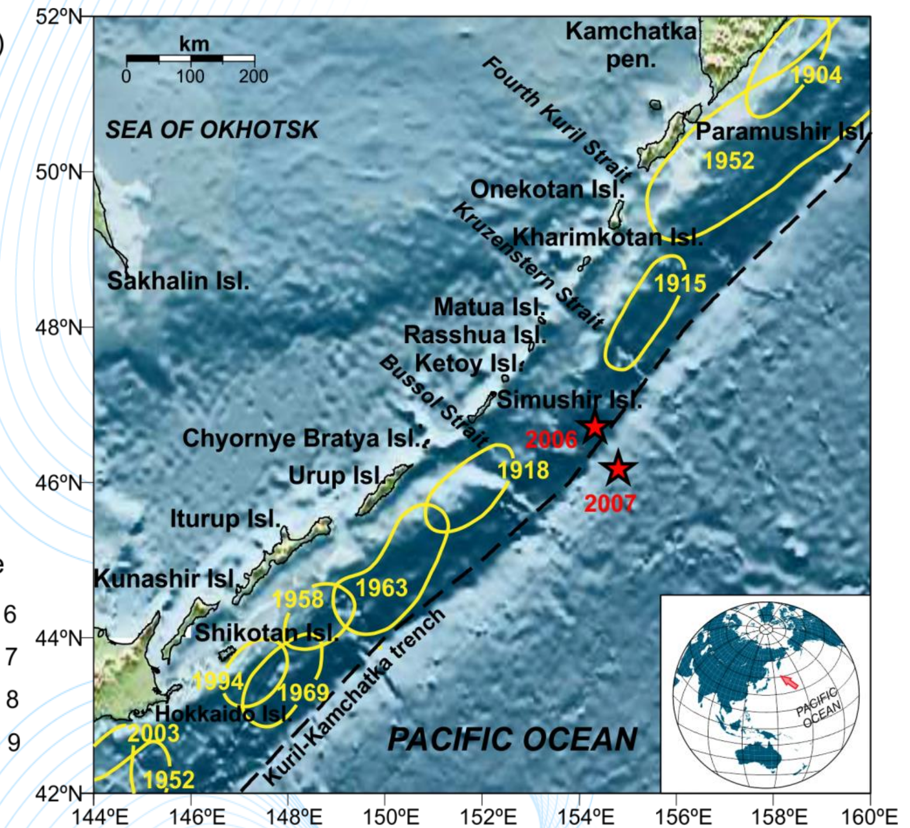
Our goals:

- ✓ We want to study the evolution of deformation processes in subduction zones as one of the most important questions when studying the nature of seismic deformation cycles, which is especially important for understanding the mechanisms of preparing strong earthquakes and, therefore, for assessing seismic hazard.
- ✓ In this study, we want to present a model which is based on verified numerical schemes, which allows us to quantitatively characterize the process of generation of strong earthquakes. 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.

Seismic activity of the Kuril arc region



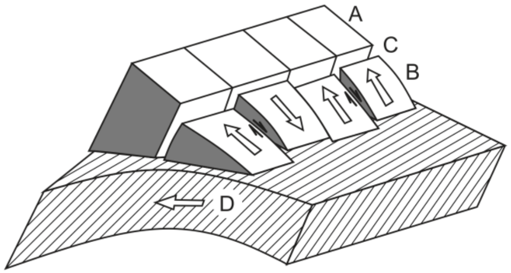
Seismic activity of the Kuril island arc region in the period from 01.01.1976 to 15.11.2006 and the focal mechanisms of the 2006–2007 Simushir earthquakes according to the Global CMT catalog [Ekström et al. 2012]



Source zones of the strongest earthquakes with M ≥ 8, since 1904 [Fedotov and Solomatin, 2015], and the main shocks of the 2006 – 2007 Simushir earthquakes according to the data of the Global CMT catalog

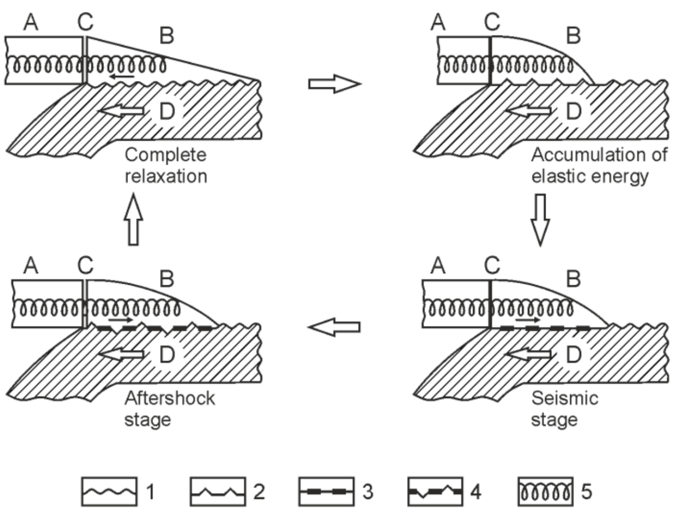
According to historical data, the last catastrophic earthquake in the central part Kuril island arc, from Simushir Island to the Kruzenshtern Strait, occurred in 1780 [Laverov et al. 2006], and for the entire period of instrumental observations, up to 2006, no events were recorded with M > 7.5 [Rogozhin, 2013]. It was established that the average duration of the seismic cycle for the Kuril-Kamchatka arc is 140 ± 60 years [Fedotov, 1968].

Keyboard model of the seismic cycle



Keyboard model of the frontal part of island arc:

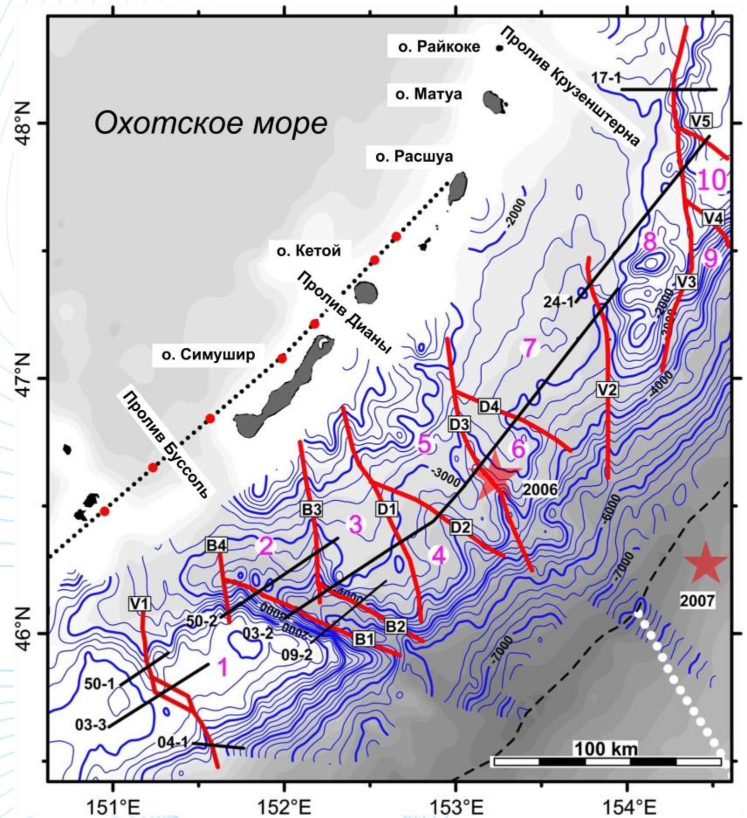
A – rear block of the arc;
B – frontal seismogenic block;
C – longitudinal fault;
D – subducting plate.



Scheme of successive stages of deformation (loading and relaxation) of the seismogenic blocks and the corresponding stages of the seismic cycle:

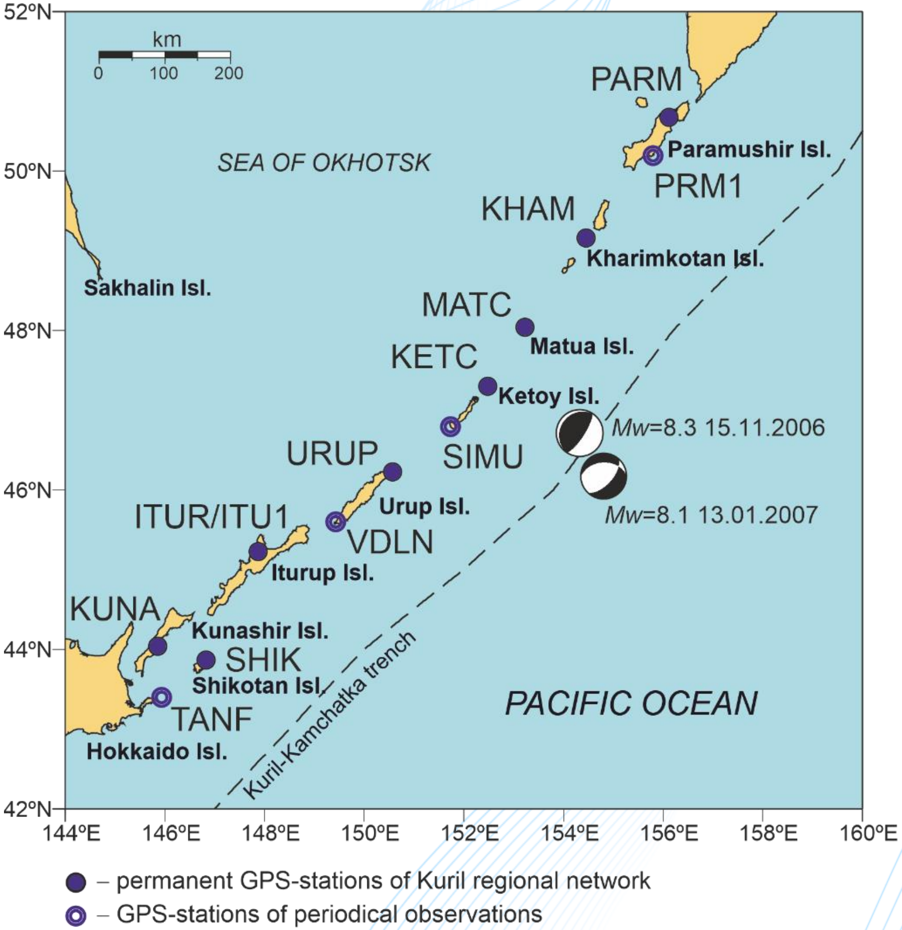
1 – undisturbed "rough" contact zone structure (CZS) (stable stage of the cycle);
2 – elastic "smoothed" CZS (preseismic stage of the cycle);
3 – strongly fragmented and heterogeneous CZS (seismic stage of the cycle);
4 – partly restored CZS (aftershock stage of the cycle);
5 – spring imitating the elastic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

[Lobkovsky et al, 1991]



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].

Kuril regional satellite geodetic network



The final configuration of the Kuril network consisted of four survey-mode sites and eight continuously tracking permanent sites

- ✓ Kuril 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 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.

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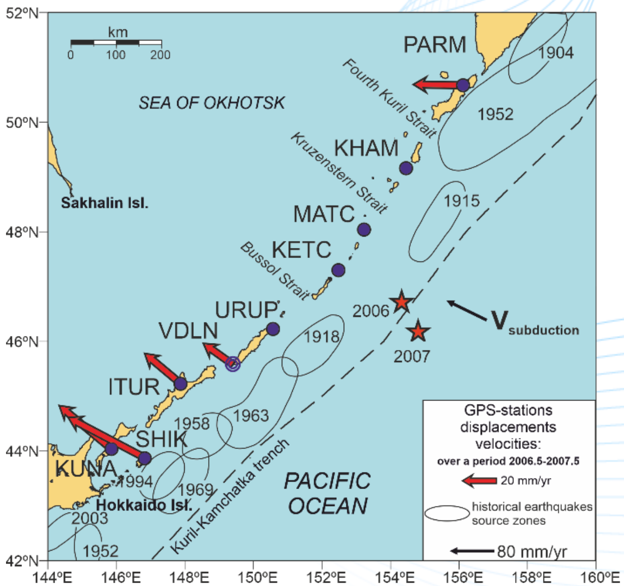
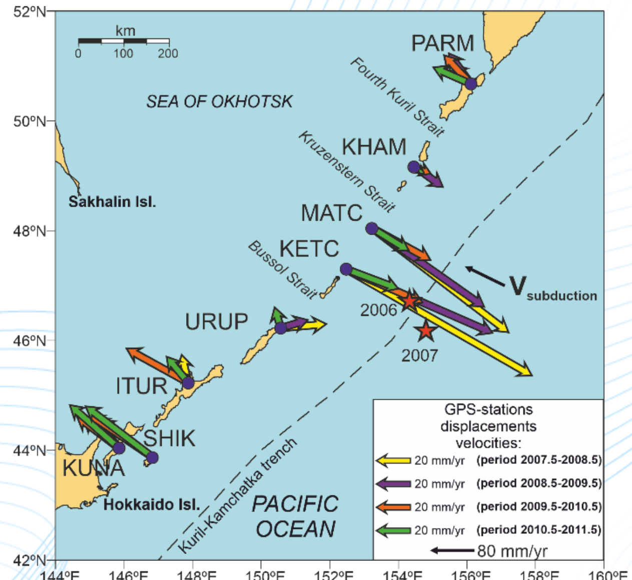
Earth surface deformations

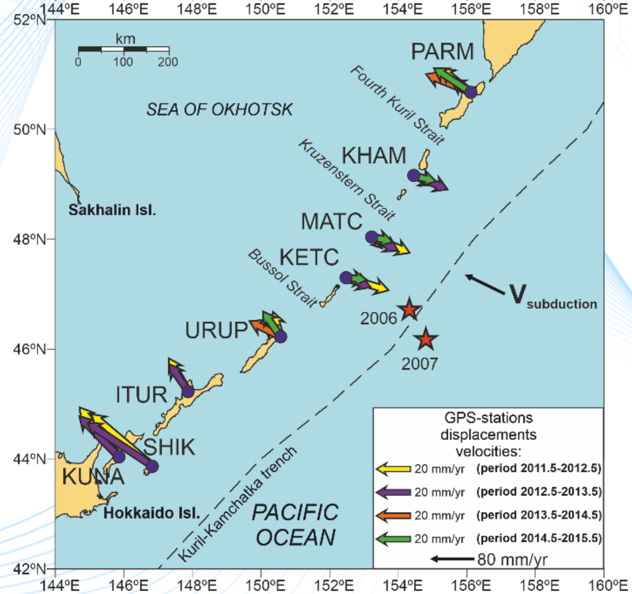
Preseismic displacements (2006.5–2007.5)



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. According to the keyboard model, it reflects the compression of the main massif of the island arc during the interseismic stage of the seismic deformation cycle.

Postseismic displacements (2007.5–2015.5)





At the same time, the sites 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 keyboard 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.

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

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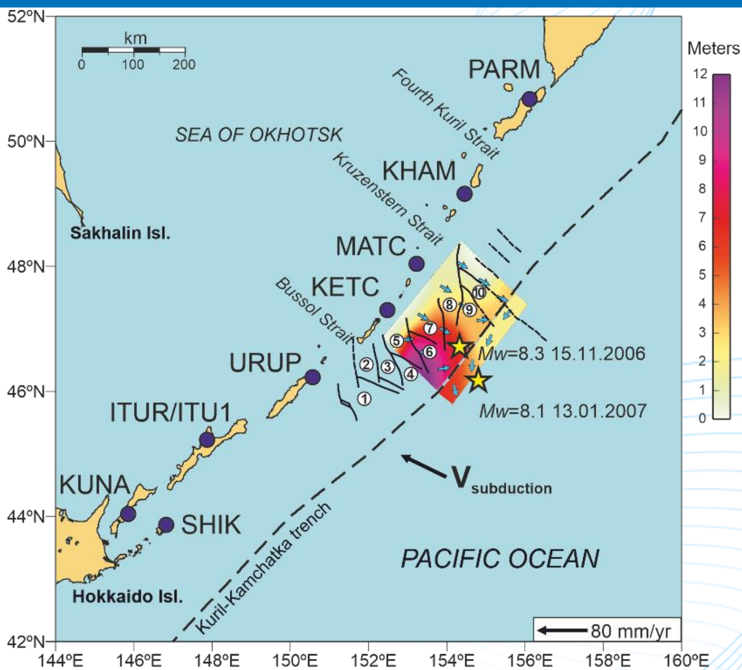
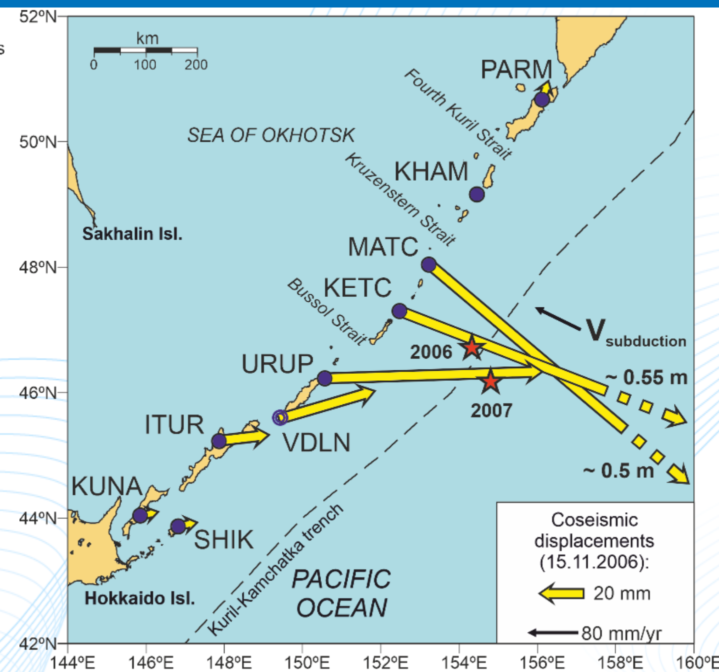
Numerical modeling: Simushir earthquakes



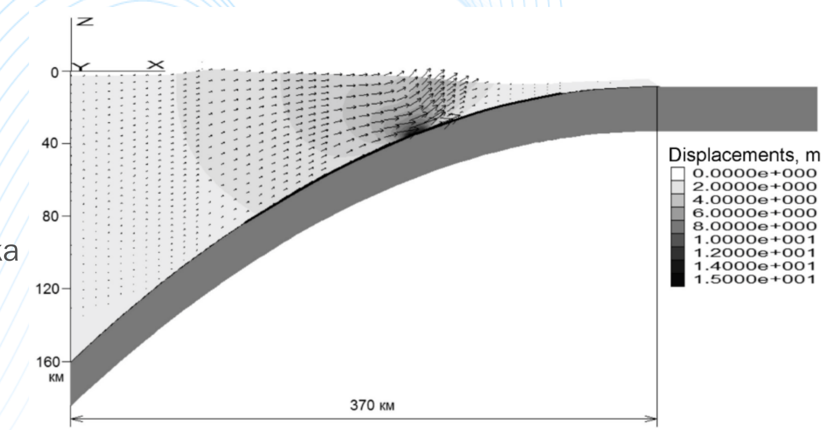
Slip models for the 2006–2007 Simushir earthquakes constructed on the basis of cosesmic displacements observed at Kuril GPS stations during these events



Coseismic displacements observed on KurilNet stations during the 2006 Simushir earthquake

Coseismic displacement of several adjacent seismogenic blocks caused the source extension. This situation is possible in conditions of lateral 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 $3x10^{17}$ Pa·s [Vladimirova et al., 2020].

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.
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.



Numerical modeling: seismic cycle

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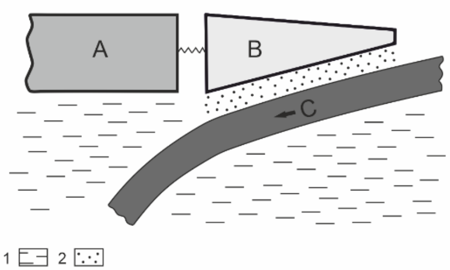
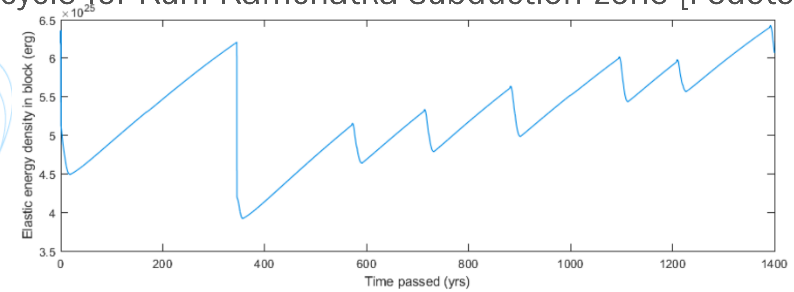
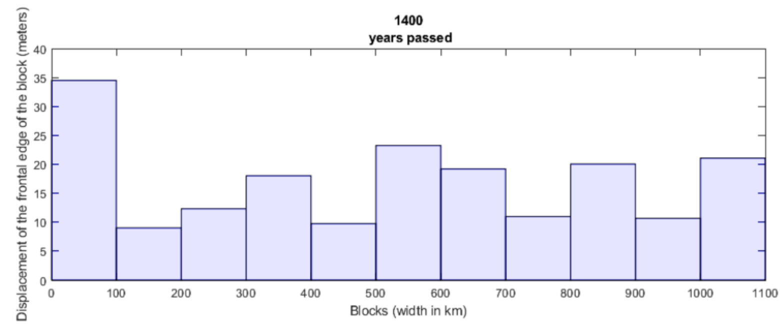
The possibility of direct high-precision satellite geodesy observations of earth surface displacements in subduction regions provides new opportunuties for constructing a quantitative keyboard model taking into account discontinuities in the rear massif, as well as spatiotemporal heterogeneities of the rheological characteristics of the contact “lubricating” layer and of the asthenospheric wedge at different stages of the seismic deformation cycle.

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 seismic cycle for Kuril-Kamchatka subduction zone [Fedotov, 1968]).



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





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 post-seismic stage, which corresponds to a range of [11, 19] years with an average value of ~ 15 years. 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.

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Conclusions

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- ✓ 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.

The full version of the poster with detailed comments will be available at
https://doi.org/10.1002/essoar.10502997.1
(must be approved within a few days from now).

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