

# **Influence of Regional Tectonic and Rheological Structure on the Seismic Cycle for Northeast Japan**

## **(EGU21–304)**

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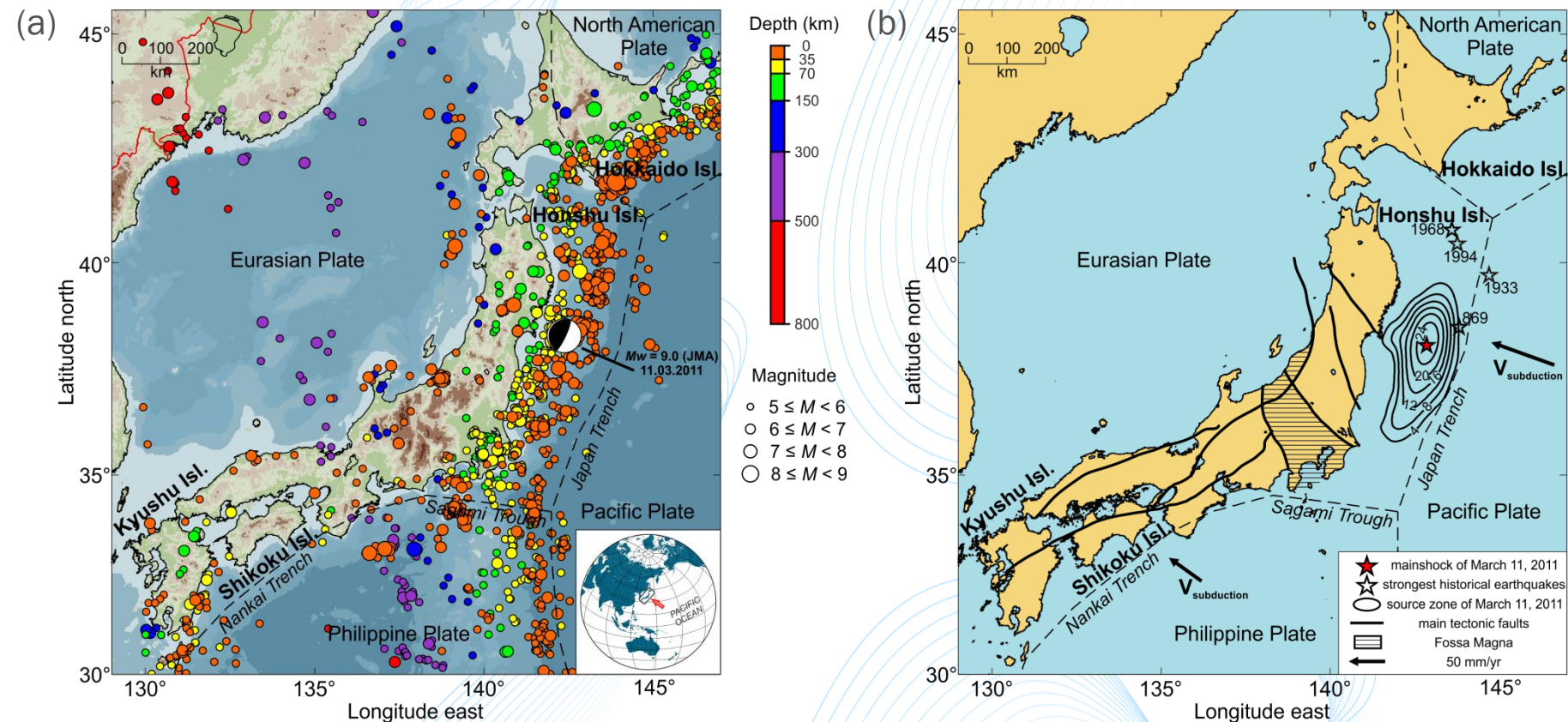
## Our motivation:

The subduction zone is a natural laboratory for studying the seismic cycle. On March 11, 2011, in the central part of the Japan subduction zone, the strongest  $M_w=9.0$  Tohoku-oki earthquake occurred, terminating a seismic cycle that lasted about 1200 years. Understanding the features of seismic cycles associated with such giant earthquakes is a key point to a better assessment of seismic hazards.

## Our goals:

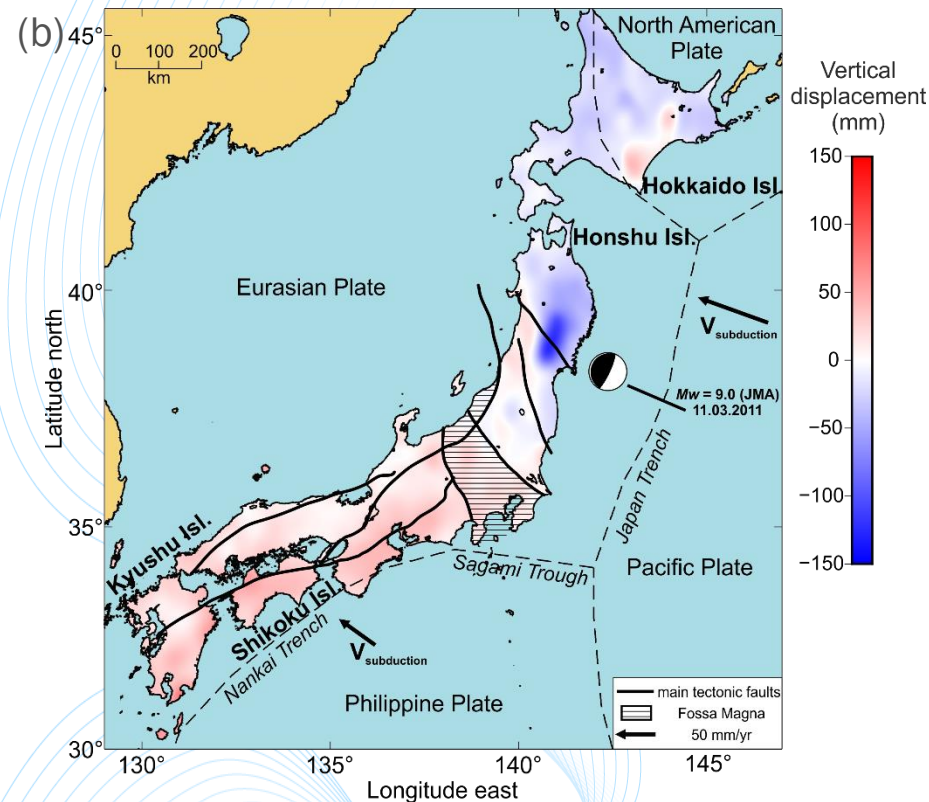
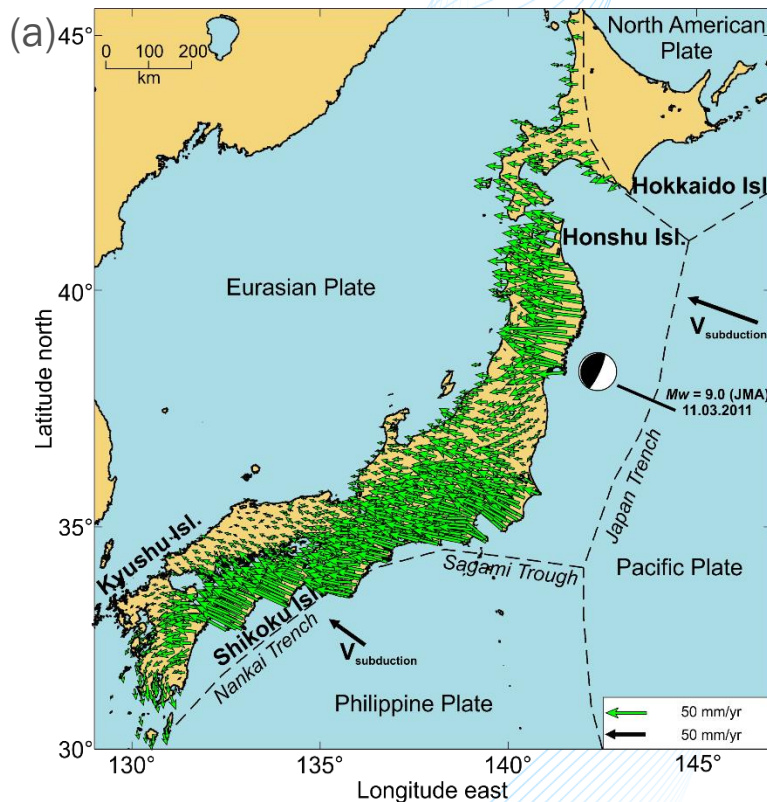
- ✓ We want to study the features of deformation processes that occurred during the seismic cycle associated with the Tohoku-oki earthquake using GNSS data and numerical simulations.
- ✓ We present a generalized approach to the study of seismotectonic deformations, which includes an assessment of the interpolate coupling before an earthquake, the construction of a distributed displacement model in the source zone, and the study of postseismic processes characterizing the relaxation of elastic stresses in the vicinity of the source.

# Seismic activity of the Japanese island arc



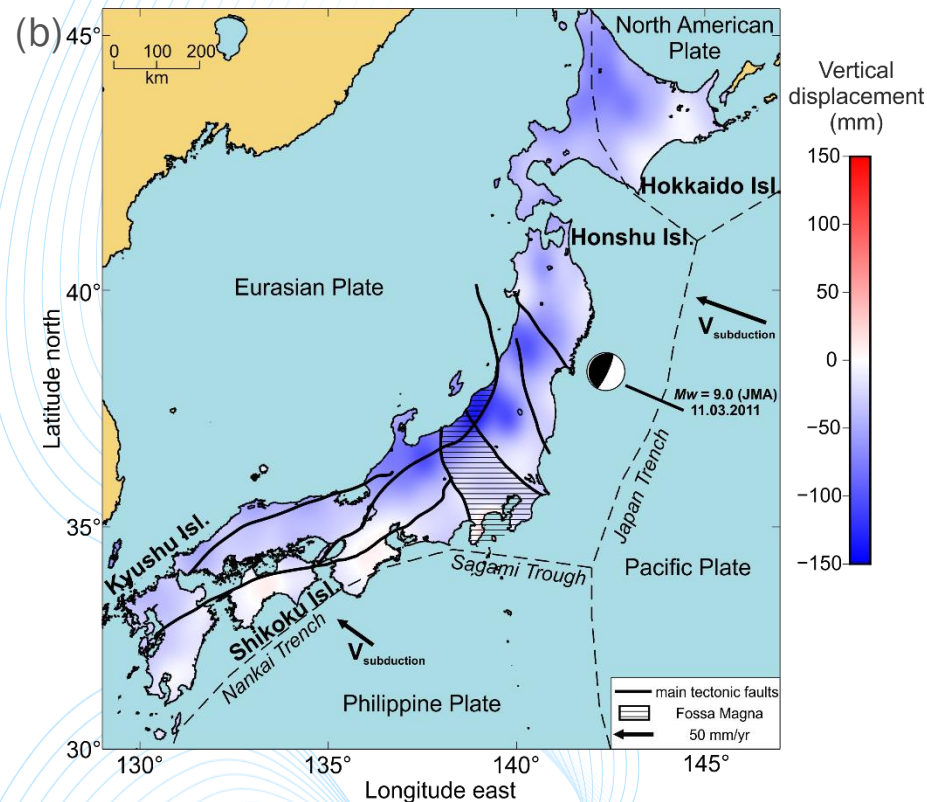
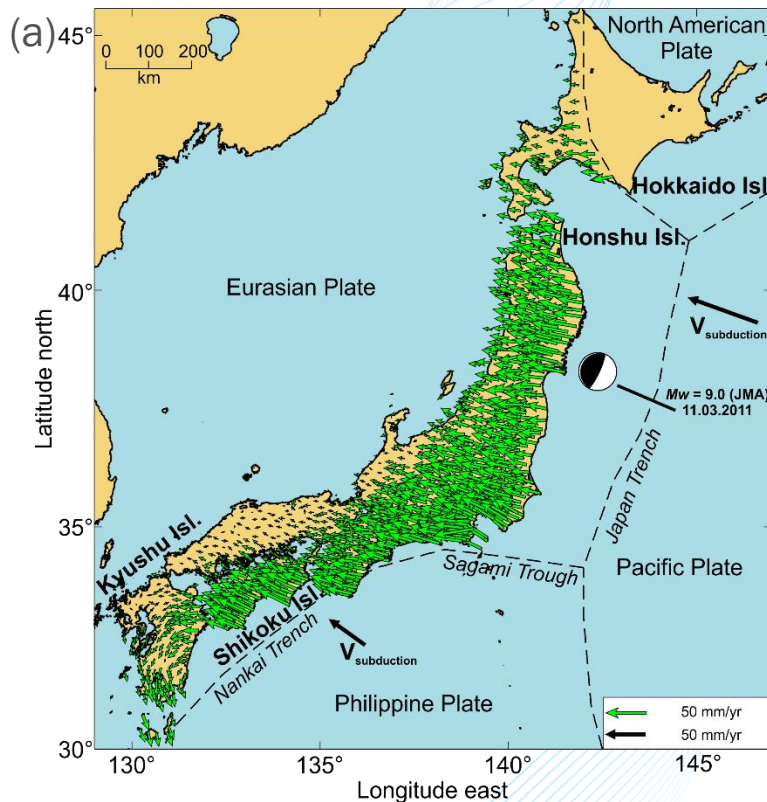
The last catastrophic interplate earthquake, Dzeigan-Sanriku, occurred in the northeastern part of Japan in 869. The magnitude of this earthquake, according to different estimates, varies from 8.4 to 9.0.

The seismic cycle in the northeastern part of the Japanese seismic focus zone is approximately 800–1100 years (Minoura et al., 2001). According to other estimates, the time required for the accumulation of elastic seismogenic potential, which corresponds to the Tohoku earthquake, is about 350–700 years (Ozawa et al., 2011).



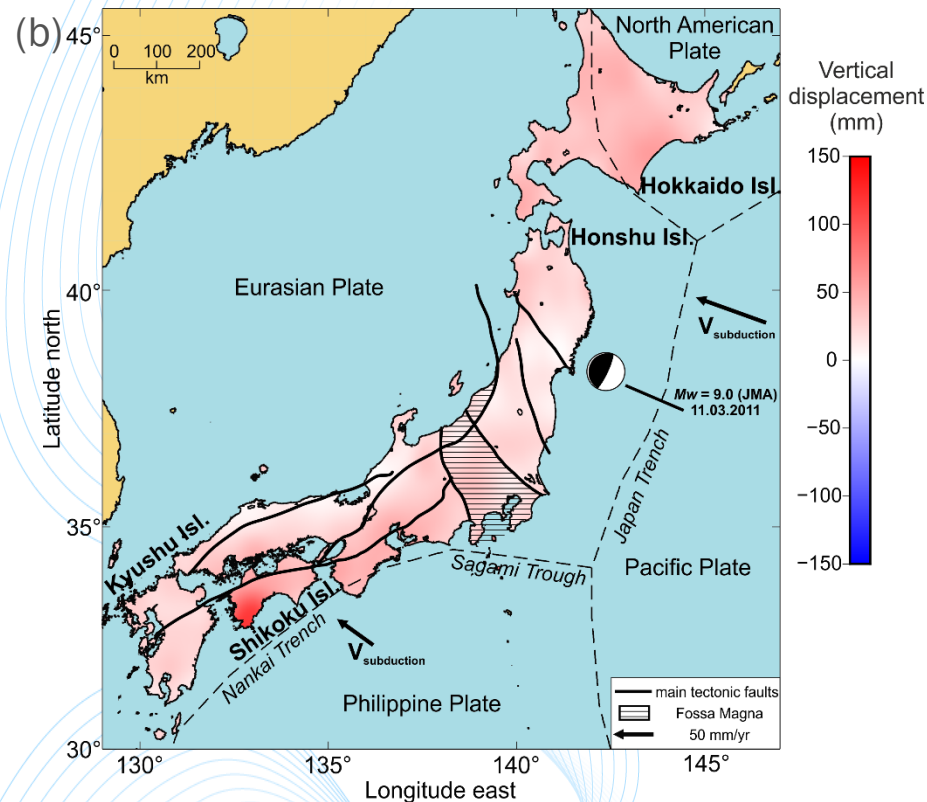
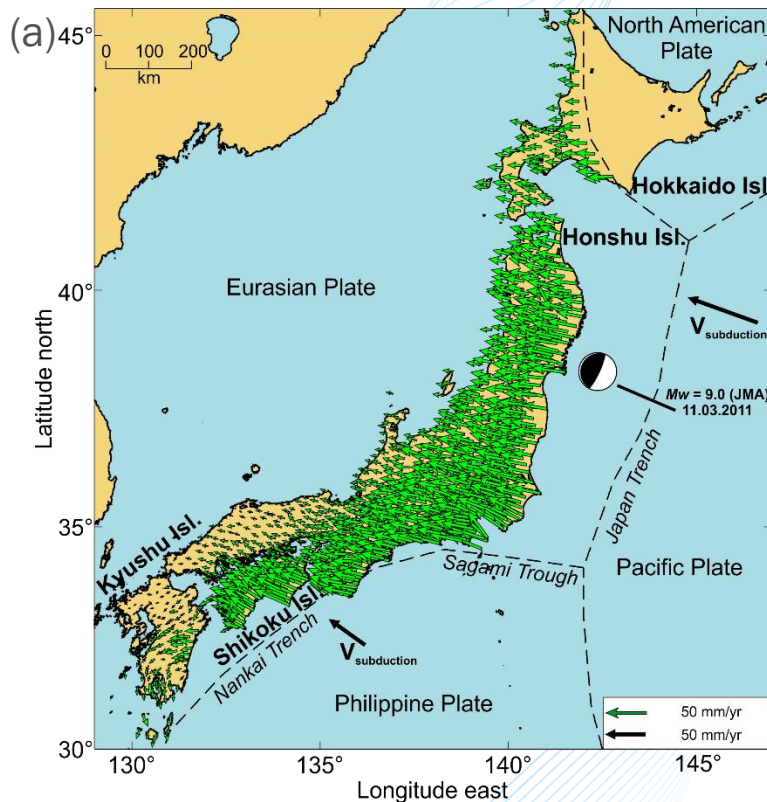
To identify the spatiotemporal variations of surface deformations following the 2011 earthquake we analyzed long-term timeseries of GPS observations from over 1400 stations that covers the entire territory of Japanese islands. Analysis of temporal variations was performed on the basis of 1-year displacement fields. All displacements are relative to the Eurasian plate.

Analysis of GPS data prior to Tohoku earthquake revealed a notable anomaly – a subsidence of coastal region directly opposite the future source zone of 2011 earthquake. This can be an evidence for the termination of elastic stresses accumulation and the transition of corresponding part of the seismogenic zone to the preseismic stage of the seismic cycle.



Horizontal displacements observed before the Tohoku earthquake and the vectors of plate convergence have the same direction.

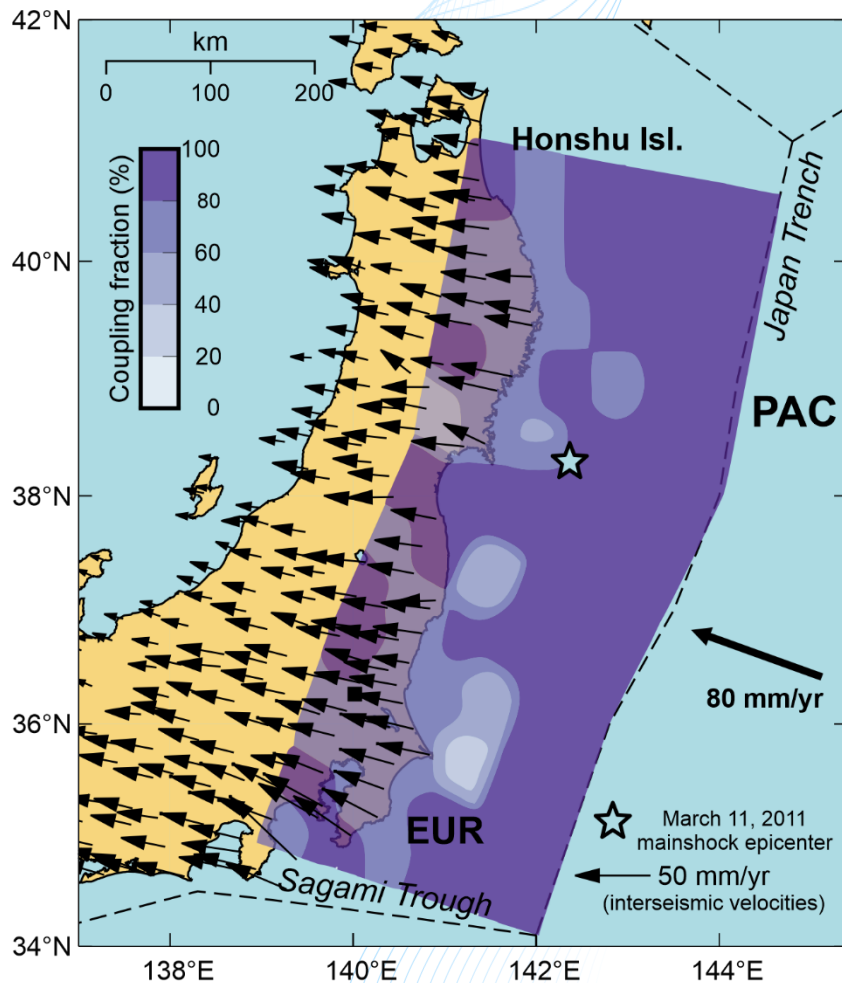
At the same time, magnitudes of displacement vectors gradually decreases from 4 cm/yr on the eastern coast to 2 cm/yr on the western coast.



Displacement fields observed prior to Tohoku earthquake significantly differ year to year. It can be an evidence of nonstationary behavior of seismogenic zone.

We can see the 30-percent increase in magnitudes of displacements just before the Tohoku earthquake.

# Preseismic coupling distribution



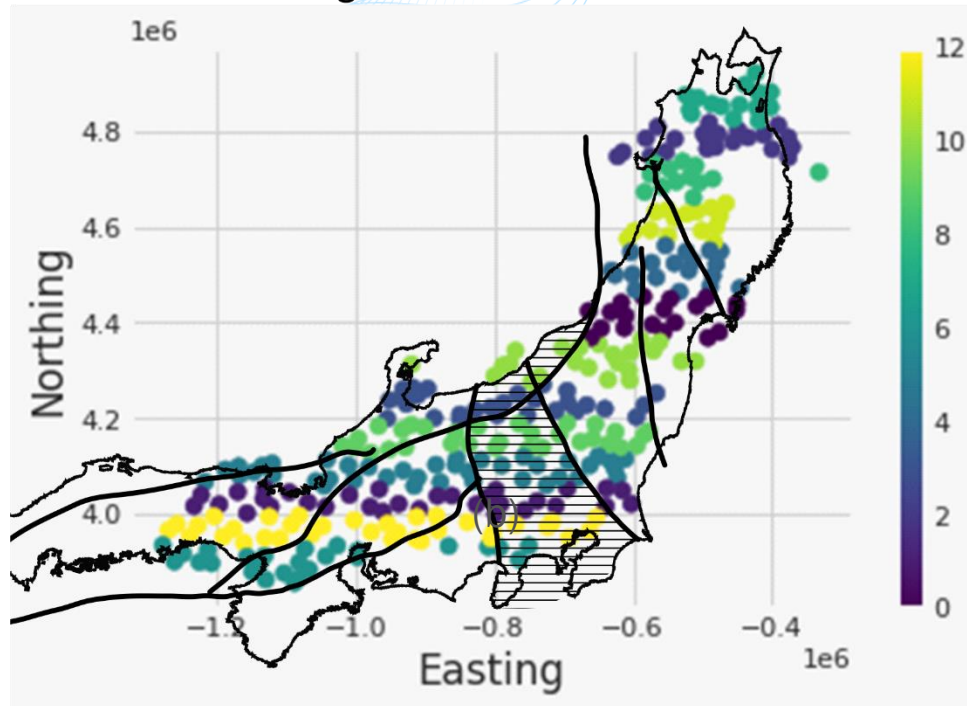
We investigated the spatial distribution of interplate coupling in the area of the March 11, 2011 Tohoku-oki earthquake on the basis of preseismic GPS velocities estimated over last 3 years before the earthquake. Figure shows distribution of interplate coupling over a period 11.03.2010–10.03.2011.

We found that the degree of coupling immediately prior to the earthquake was relatively high. The coupling coefficient reaches its maximum values near the trench. This coupling configuration could be a factor contributing to the occurrence of such a devastating tsunami as after the Tohoku earthquake.

Directly down dip of the main rupture we can see the areas of substantially lower coupling that likely prevented further propagation of the mainshock rupture.

Our preferred model of interseismic coupling is in good agreement with the similar model based on small repeating earthquake data (Uchida and Matsuzawa, 2011).

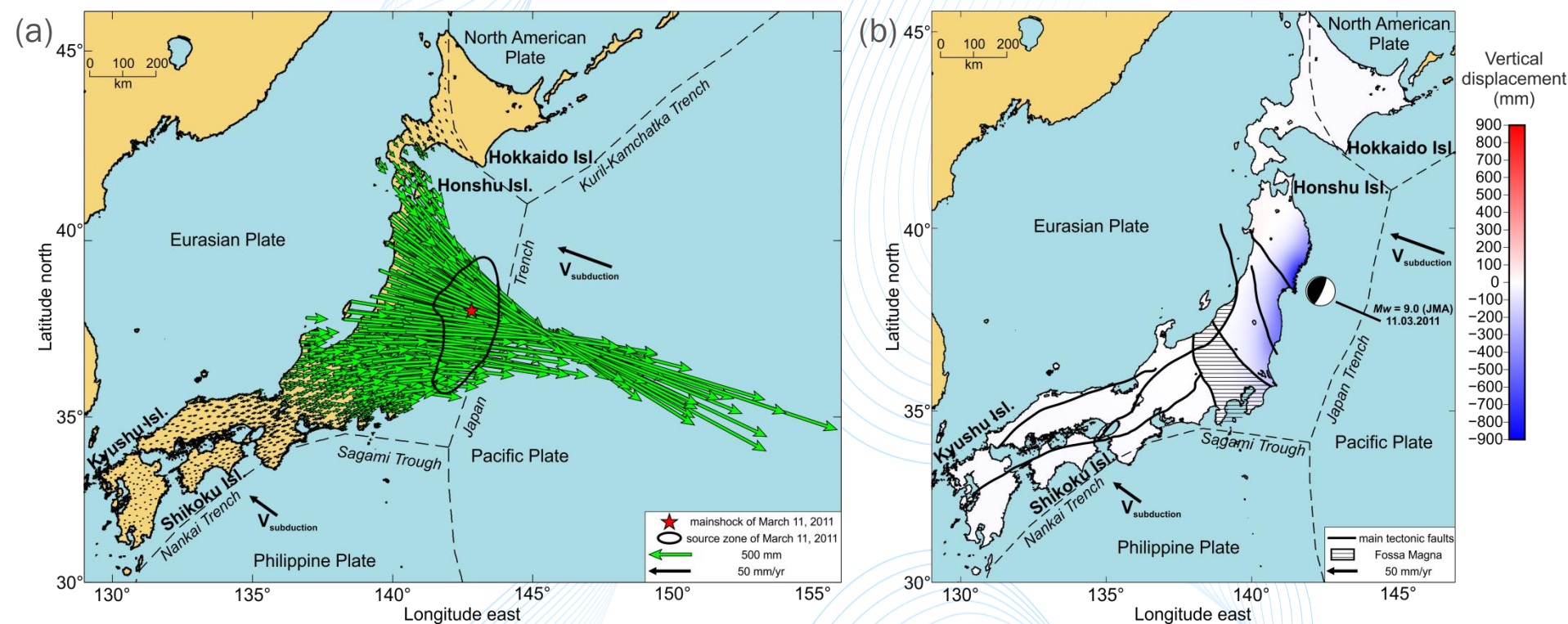
## Clustering of interseismic velocities



We also used spatially-distributed GNSS observations of GEONET stations to check the possible influence of fault-block structure of Japan islands on the process of elastic stress accumulation.

Using linear spline approximation we obtained estimates of yearly velocities of all stations over last 3 years before the earthquake. These velocity fields together with UTM coordinates of stations served as input data to k-means clusterization algorithm which allowed us to distinguish 13 clusters. The clusters were consistently traced all 3 years before the Tohoku earthquake.

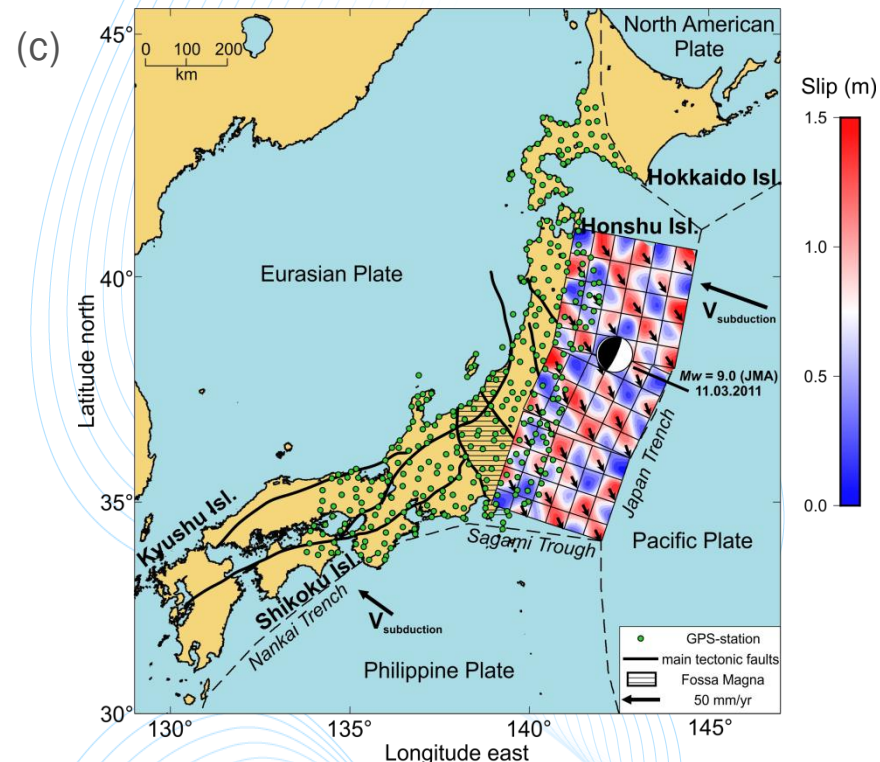
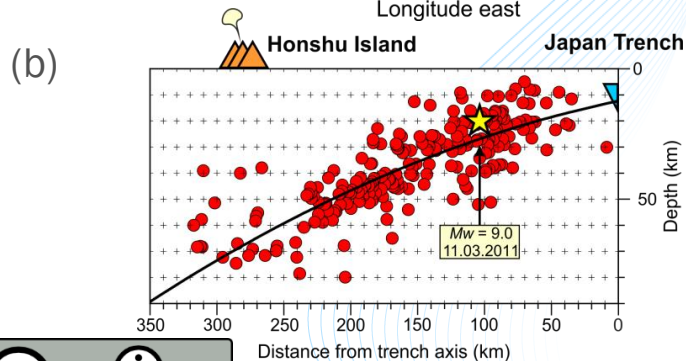
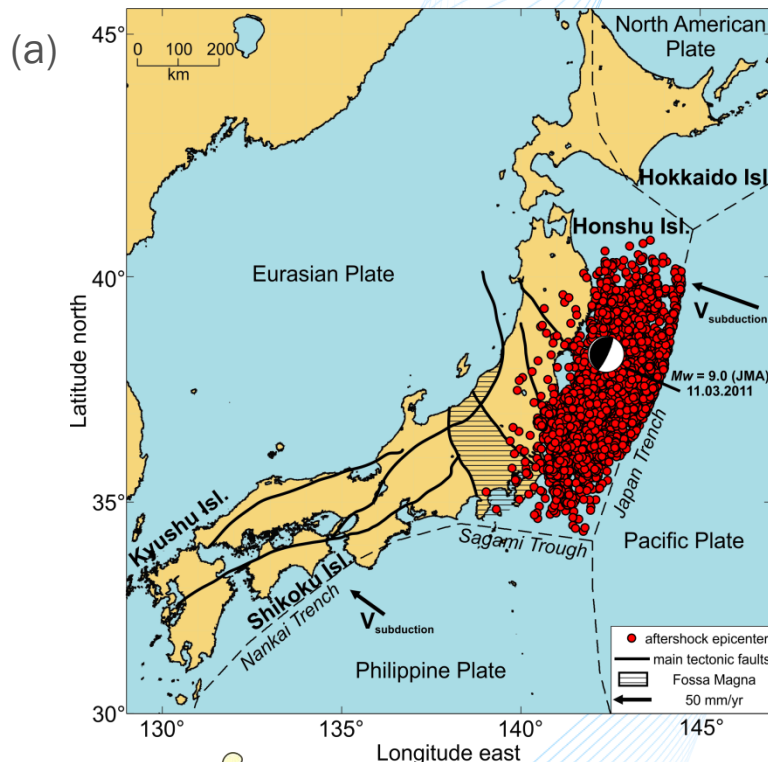
We found little to no agreement in the orientation of the identified clusters and the main fault structures in the northern part of Honshu.



The magnitudes of the coseismic displacements recorded during the Tohoku earthquake varied from 2-5 meters for stations located near the source zone to 3-5 centimeters at stations remote from the source (a).

Moreover, the observed data reveal prominent effect of Fossa Magna Graben on the coseismic deformations pattern.

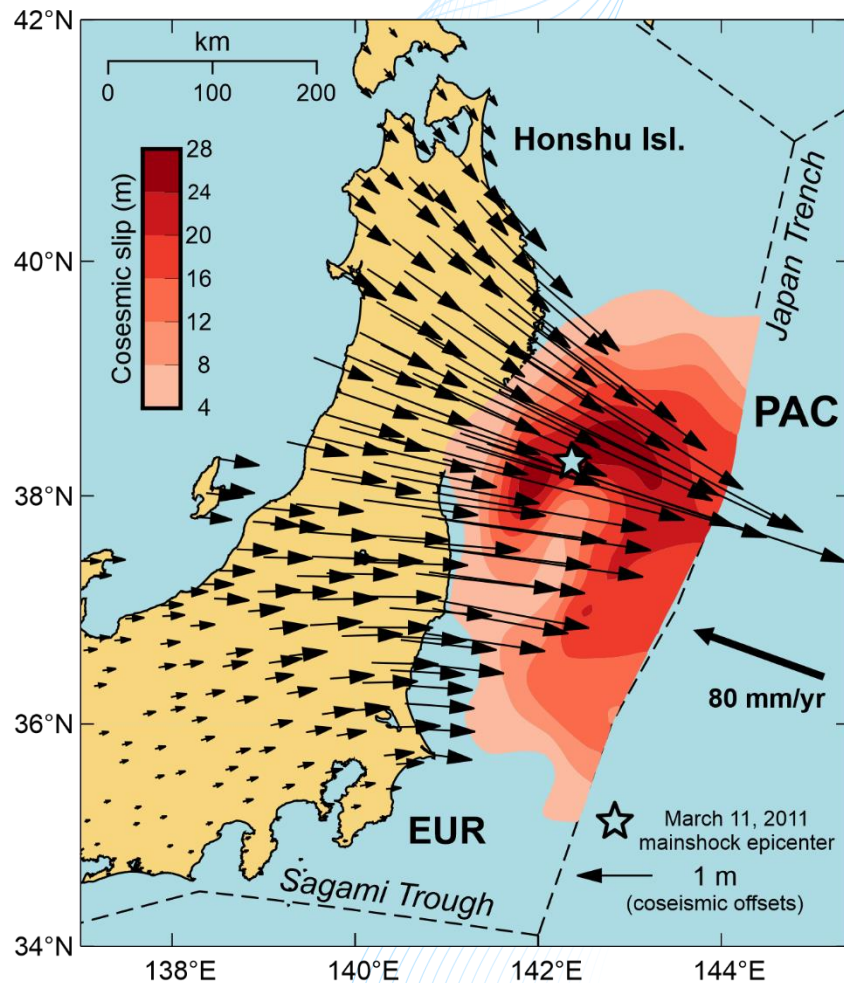
Vertical coseismic motion indicates significant subsidence of the coastal area opposite the source zone (b).



Determination of the aftershock sequence (a) was carried out on the basis of the algorithm from (Molchan and Dmitrieva, 1992) implemented in the program code by B.V. Smirnov (Smirnov, 2009).

Approximation of the subduction zone profile (b) was performed on the basis of data from The Centennial Catalog (Engdahl and Villaseñor, 2002).

The checkerboard test (c) was carried out on the basis of data of 355 GPS-stations evenly distributed throughout Japan.

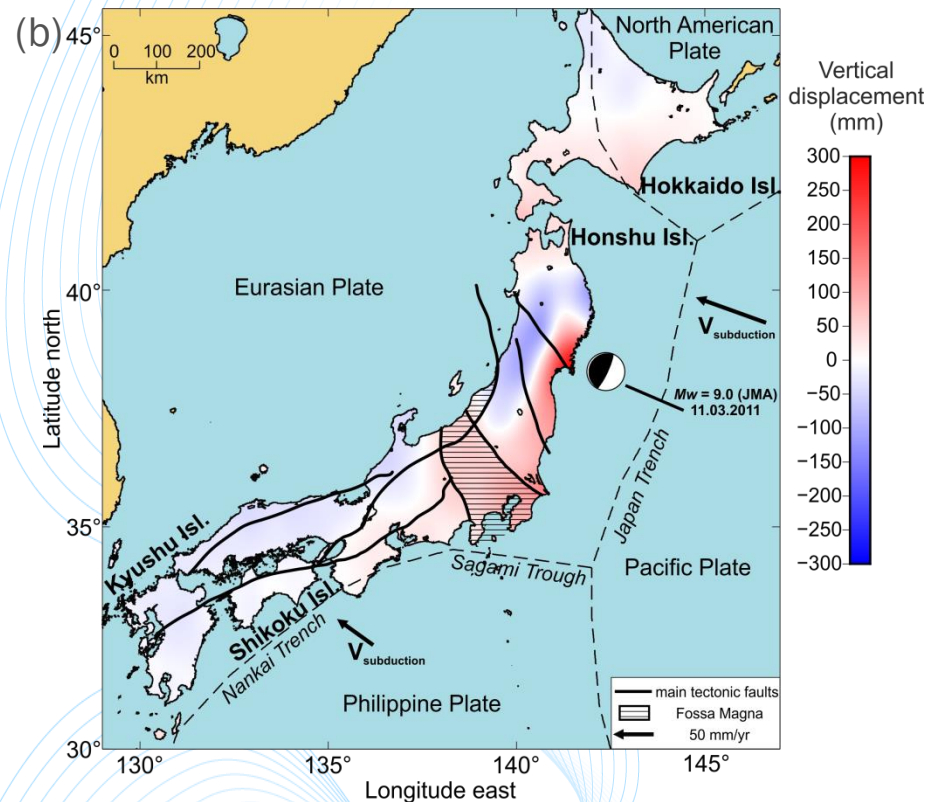
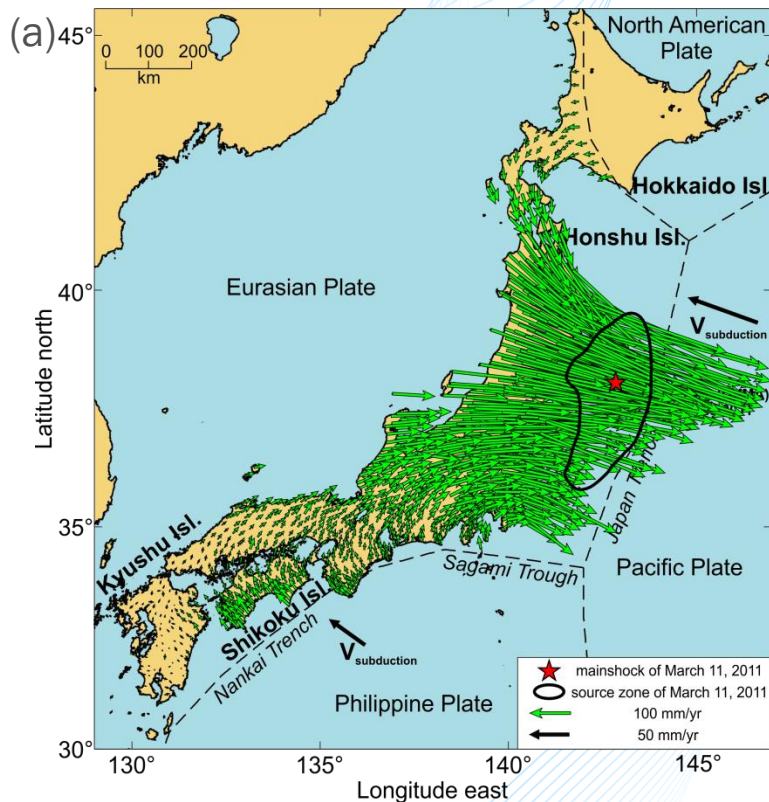


Horizontal coseismic displacements recorded by the GPS-stations during the Tohoku earthquake were used to construct a model of distributed slip in the source zone of this earthquake using code STATIC1D by F. Pollitz (Pollitz, 1996).

Source zone of the Tohoku earthquake affected all possible seismogenic blocks, limited by geological margins, such as Fossa Magna, which resulted in reestablishing of seismic cycle for the whole northeastern part of Japan subduction zone.

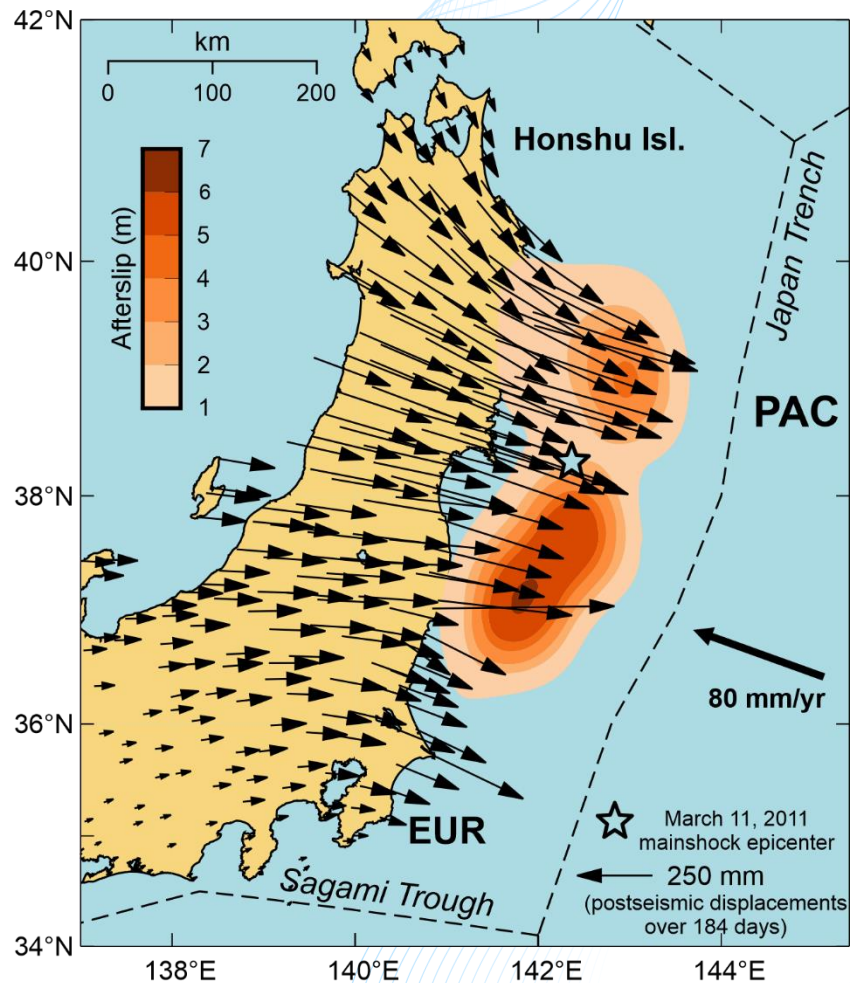
Maximal slip in the source zone reaches 28 meters and the moment magnitude calculated on the basis of obtained slip distribution is equal to 9.0. This value is exactly corresponds to JMA estimate.

The constructed model is in good agreement with the same models based on teleseismic and other geodetic data (Lay et al., 2011; Ozawa et al., 2011; Kyriakopoulos et al., 2013; Hashima et al., 2016).



Continuous GPS observations allows us to study postseismic displacement following the Tohoku earthquake.

In the first year, the displacements in the northeastern part of Honshu Island retain their direction toward the ocean. This process is accompanied by further release of accumulated elastic stresses in the seismogenic zone.

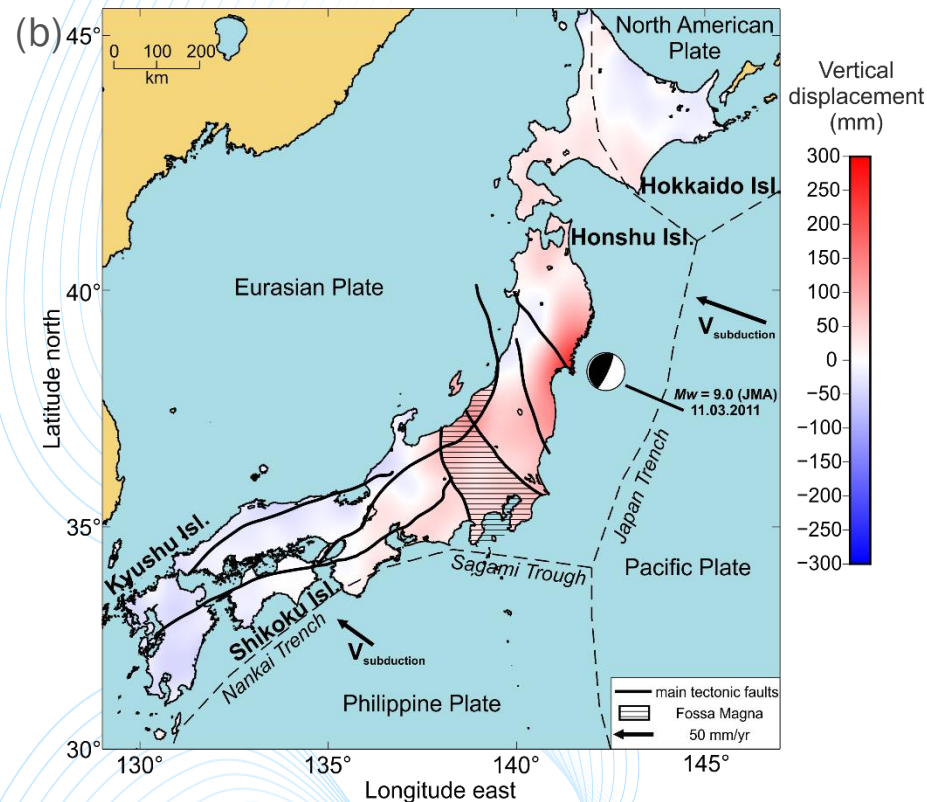
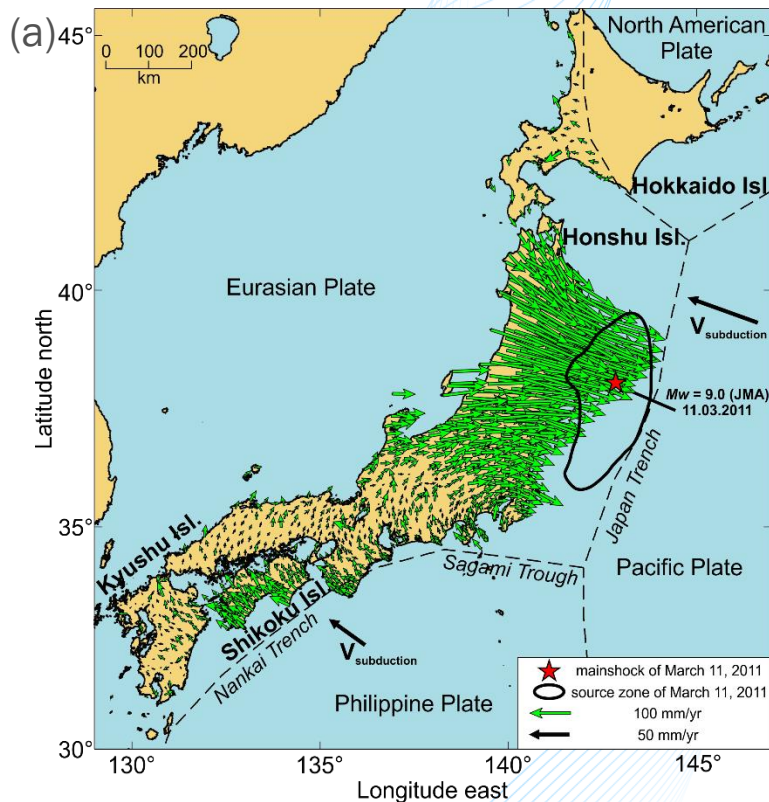


Surface deformations observed in the first months after strong subduction earthquakes are primarily caused by afterslip and viscoelastic relaxation processes, and to a lesser extent by the process of patches relocking in the rupture zone. The relative contributions of the afterslip and viscoelastic relaxation to postseismic deformations observed in the first months after the earthquake remains unclear. Correct assessment of the duration, intensity, spatial scales and energy characteristics of these processes contributes to the understanding of the mechanics of fault formation and the refinement of regional rheological parameters.

We simulated the process of short-term viscoelastic relaxation after the March 11, 2011 Tohoku-oki earthquake and took into account the resulting displacements when constructing the cumulative afterslip model.

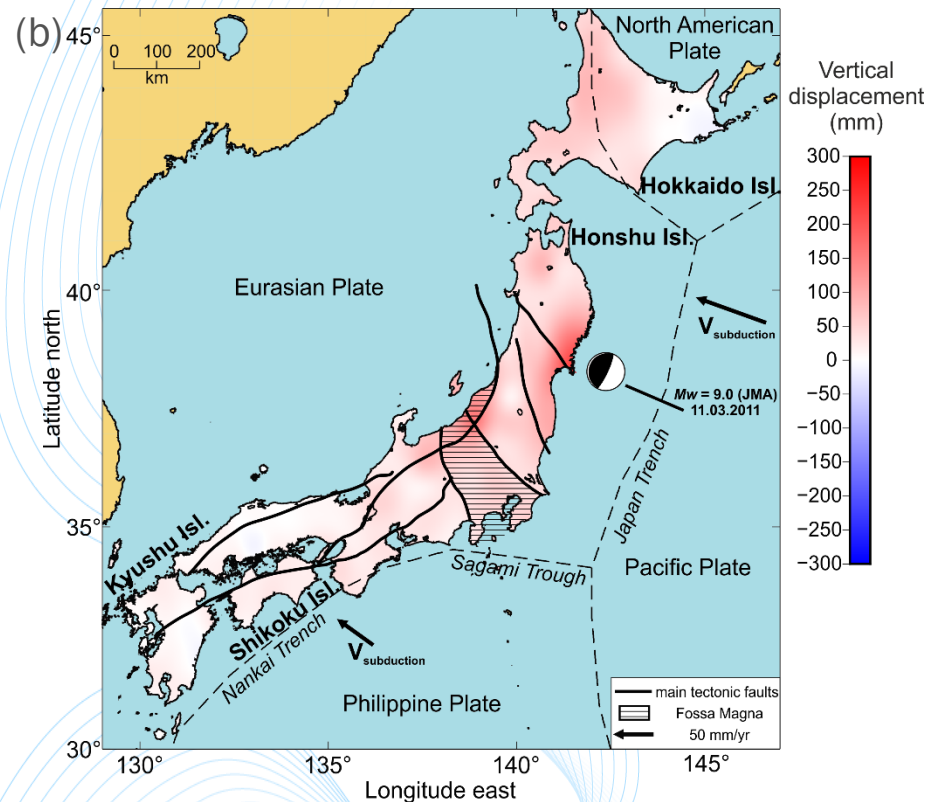
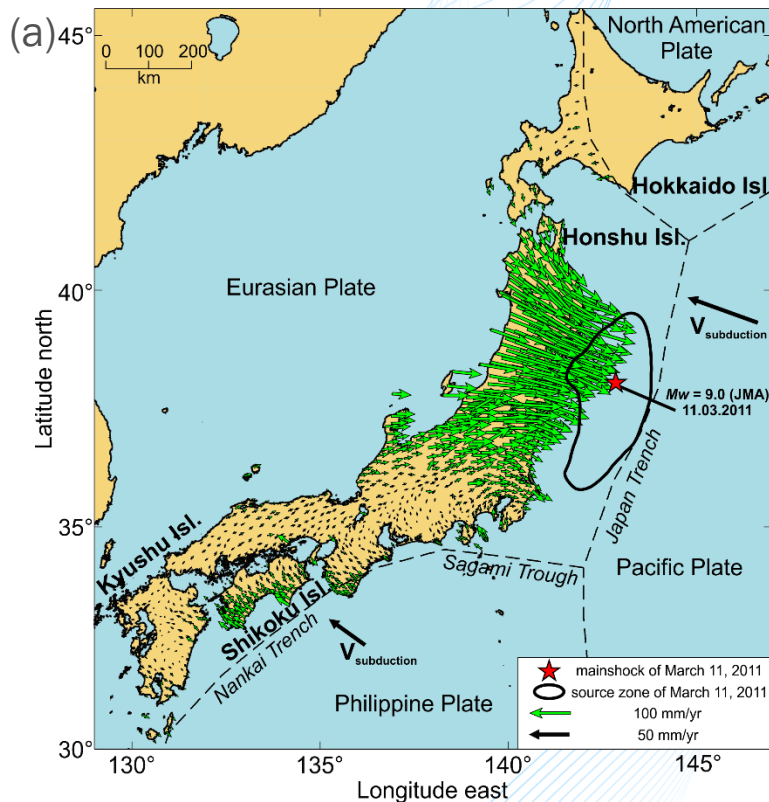
Recent observations of postseismic motions of seafloor GPS stations after the Tohoku earthquake on March 11, 2011 (Sun et al., 2014; Sun and Wang, 2015) showed that neglecting the short-term viscoelastic relaxation for events with  $M_w \geq 8.0$  leads to an incorrect estimation of the amplitude of the displacements caused by the afterslip. This reflects in the underestimation of the displacement values at shallow depths and their overestimation at depths exceeding the lower edge of the rupture.

Our preferred model of cumulative afterslip (see Fig.) demonstrates bilateral development of the source zone, predominantly near the lower edge of the rupture.



In the second year after the Tohoku earthquake, the displacements retain their oceanward direction, but their maximal magnitudes rapidly decrease from 50 cm/yr in the first year to 20-23 cm/yr.

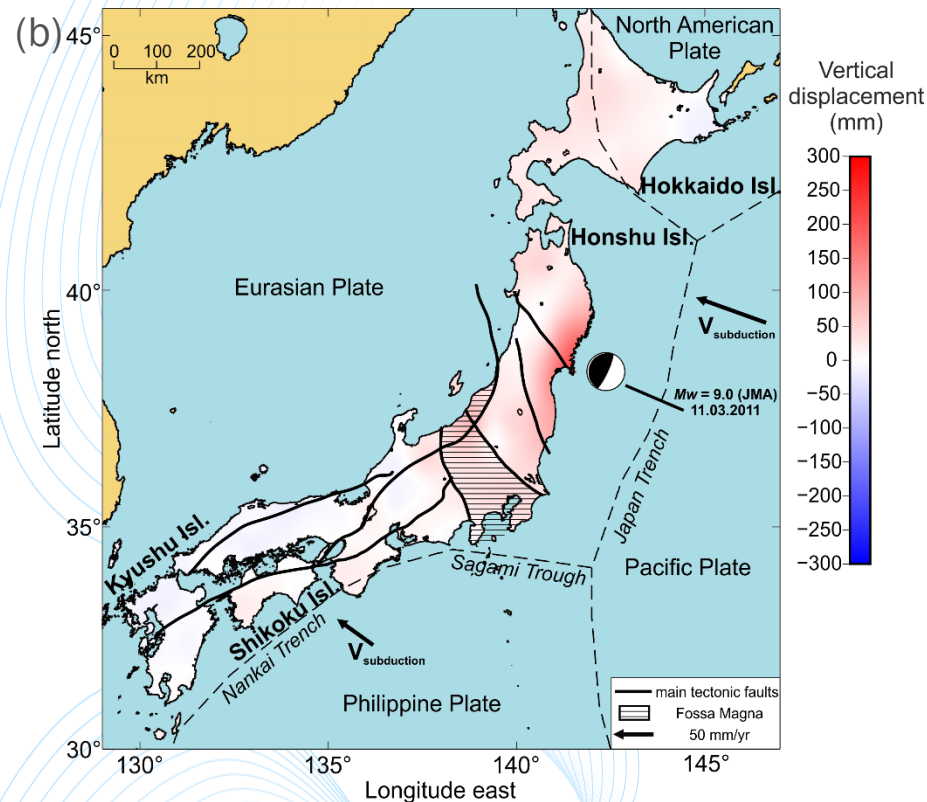
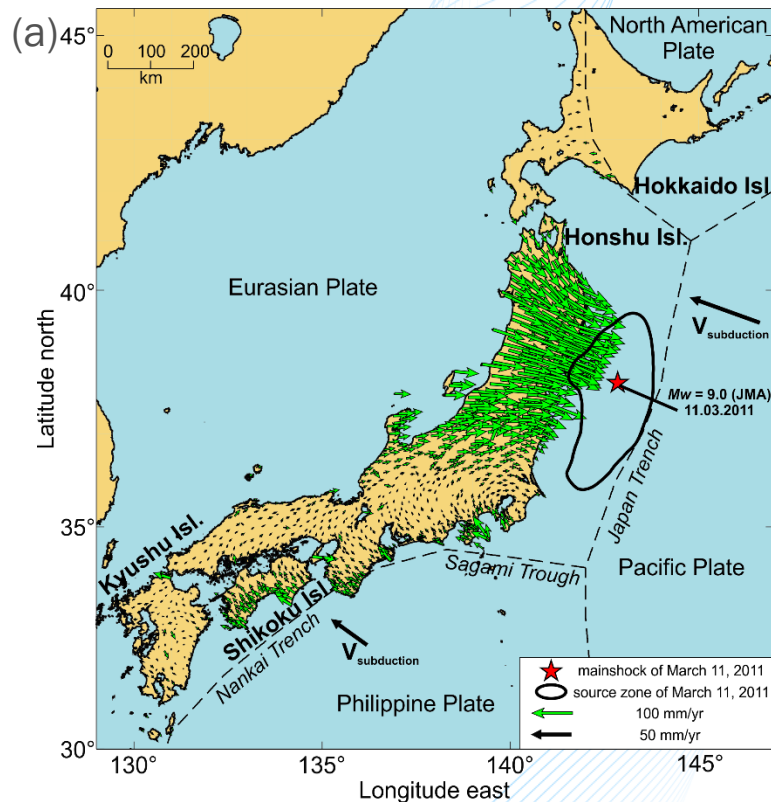
Decrease of displacements and their oceanward direction suggest an existence of transient postseismic process near the source zone of Tohoku earthquake.



The directions and magnitudes of displacement vectors to the southwest of the Fossa Magna remain unchanged relative to the interseismic stage of the seismic cycle.

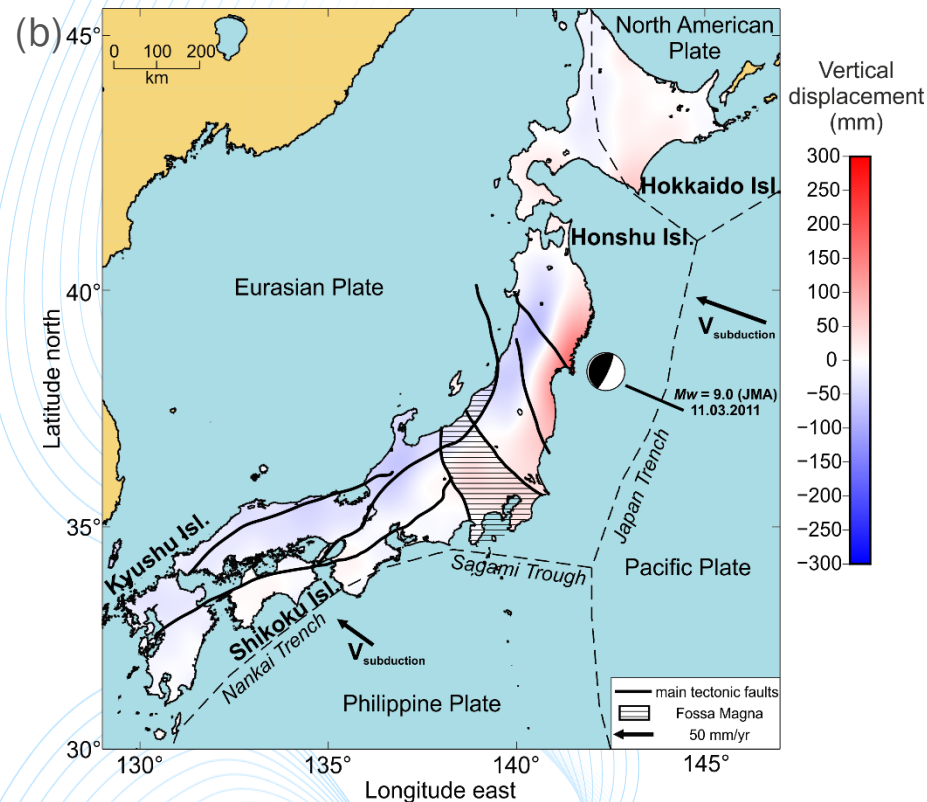
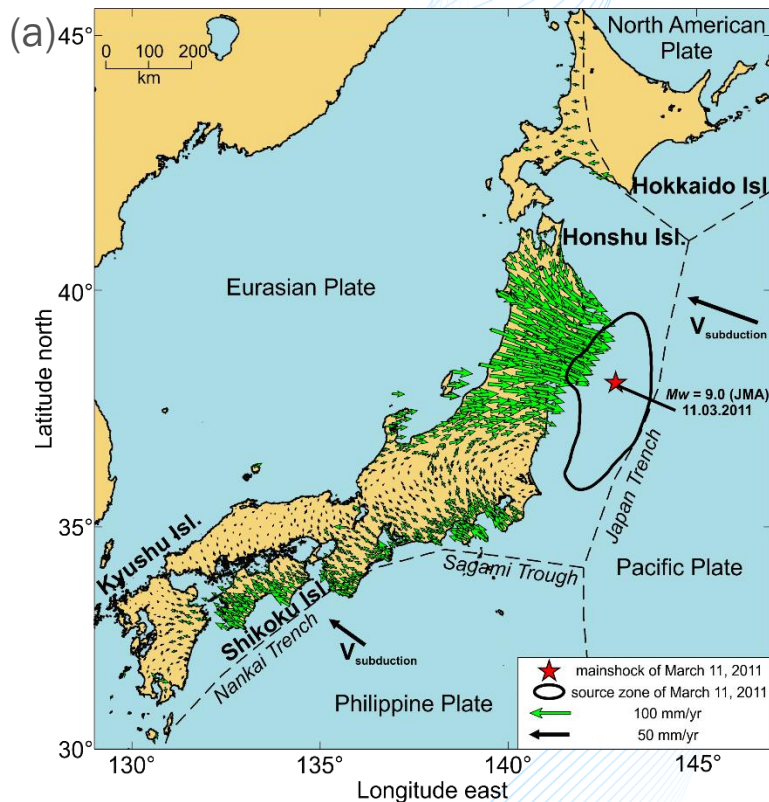
Another notable feature of postseismic displacements field is a significant difference between the magnitudes and directions of vectors to the north and to the south of Fossa Magna Graben. This also reveals the geological margins of the affected segment of seismogenic zone.

At the same time, displacements of the rear massifs from over all Japanese islands retain their direction toward the source zone, which reflects the spatial scale of postseismic processes.



Vertical displacements fields after the Tohoku earthquake reveal the restoring of coastal uplift along the trench. In terms of the keyboard model, it may be caused by the reestablishing of interplate coupling and further energy accumulation.

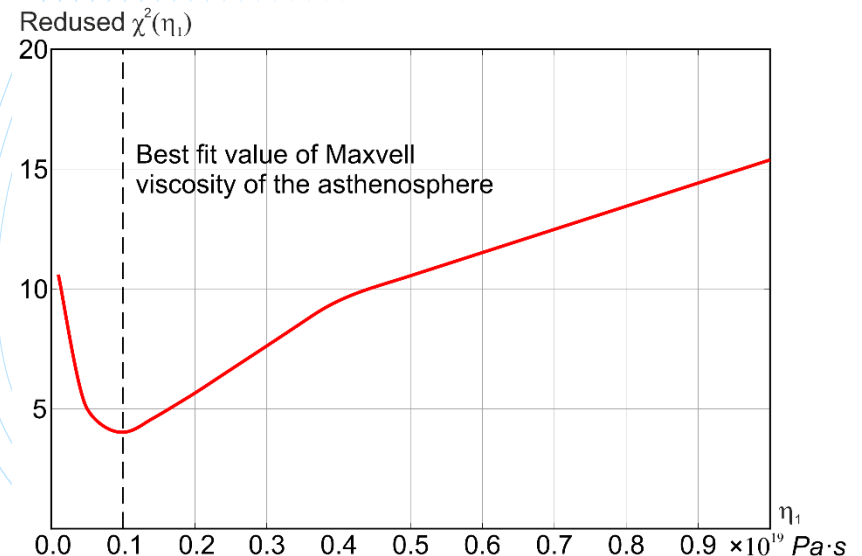
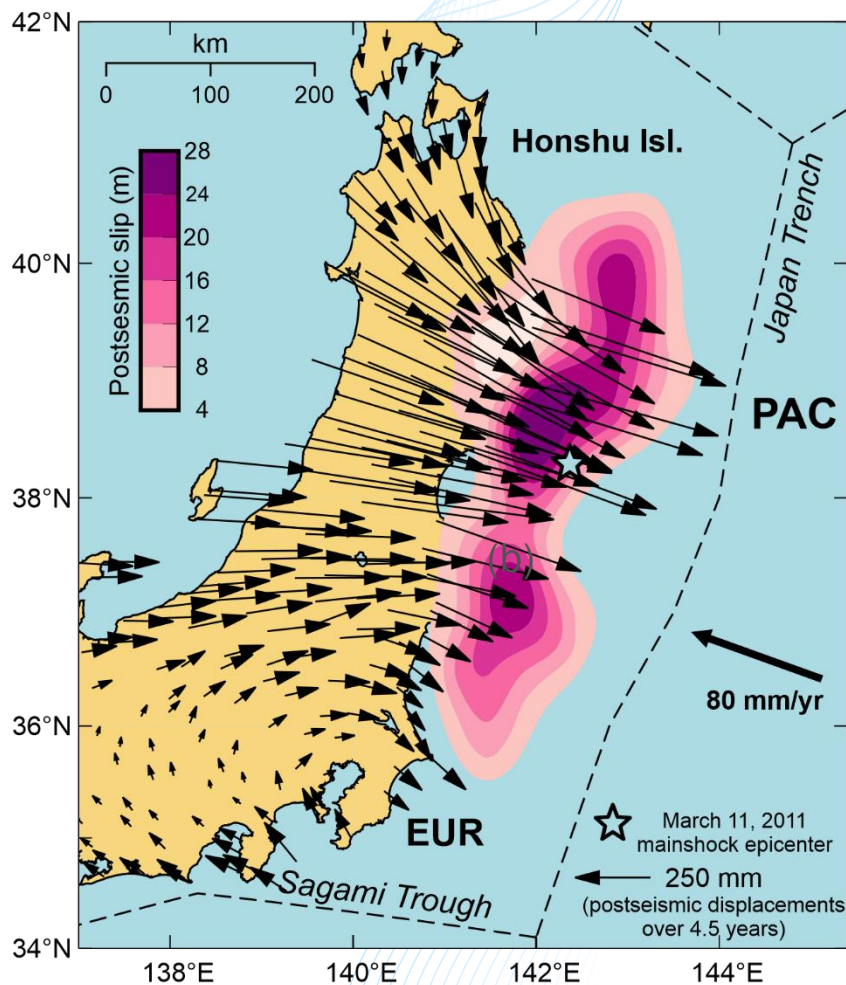
However, joint analysis of horizontal and vertical displacements suggest that the observed uplift may be caused by long-term postseismic processes, rather than interseismic compression.



The observation data 5 years after the Tohoku earthquake definitely reflect the continuation of the postseismic stage of the seismic cycle.

Among possible mechanisms responsible for such a long nonstationary oceanward displacements can be considered frictional afterslip and/or viscoelastic relaxation in the asthenospheric wedge underlying rear massif.

# Effective postseismic slip distribution



We construct a model of viscoelastic relaxation in the asthenosphere using the program code VISCO1D (Pollitz, 1997). Rheology of the asthenosphere was represented by biviscous Burgers body, comprising both Maxwell and Kelvin viscosities. The slip distribution retains a bilateral pattern but covers a much larger area. This indicates the wider spatial scales of the viscoelastic relaxation process.

The rheological properties of the asthenosphere remains debatable but postseismic deformations caused by such strong earthquakes can impose some restrictions on the mechanical characteristics of rocks.

The obtained value of the effective Maxwell viscosity of the asthenosphere is ten times lower than the standard value.

According to the forecast based on this model, the viscoelastic relaxation in the asthenosphere will decay in about 30 years.

- ✓ Significant differences were found both in magnitudes and in the orientation of the displacement vectors of the Earth surface on the territory of the Japanese islands at all stages of the seismic cycle. The observed differences can be explained by the presence of large fault structures, rooted in the contact zone of interacting lithospheric plates, and dividing the islands into separate blocks. Moreover, due to the relatively weak interaction between neighboring blocks, each of them can be deformed independently of adjacent structural segments.
- ✓ A long-term postseismic stage, which can last after Tohoku-oki earthquake more than 30 years, can significantly affect the passage of the seismic cycle in the northeastern part of the Japan subduction zone. It can provide one of possible explanations for such a long duration of the entire cycle.
- ✓ Models of geodynamic processes at all stages of the seismic cycle were constructed and the rheological parameters of the Japanese subduction zone were refined.

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