Digest of PhD Thesis

Crustal Deformation Model of the Southern Kurile Subduction Zone Inferred from Geodetic Observation Data

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1. Introduction

In the southern Kurile subduction zone, many great earthquakes including a tsunamigenic earthquake in the 17th century with magnitude of 9 have occurred along the interplate megathrust fault. Crustal deformation before, during and after the most recent event, i.e. the 2003 M_w 8.0 Tokachi-oki earthquake, has been continuously observed by a dense observation network of Global Navigation Satellite System (GNSS) on land and two offshore Ocean Bottom Pressure Gauges (OBP). These data give us an opportunity to clarify the megathrust fault behavior during interseismic, coseismic and postseismic stages in the earthquake cycle. In this thesis, we model megathrust slip and locking history before, during and after the 2003 event using these geodetic data to understand megathrust fault behavior during the earthquake cycle in this region.

2. Model of Coseismic and Postseismic Deformation Associated with the 2003 M_w 8.0 Tokachi-oki Earthquake

We simultaneously estimate coseismic slip and spatiotemporal postseismic slip including afterslip considering viscoelastic relaxation due to them using the coseismic and postseismic GNSS and OBP data for 7.5 years following the mainshock. Spatial separation of the postseismic slip and coseismic slip of the mainshock and other M 8 earthquakes in neighboring regions is estimated, but postseismic slip occurs in the rupture region of the tsunamigenic event in the 17th century. The kinematically estimated temporal evolution of postseismic slip obeys a logarithmic function, which is consistent with prediction from a rate and state friction law (RSF). Spatial variation of its time constant may reflect frictional heterogeneity of the megathrust fault. Sustained postseismic slip for 7.5 years following the mainshock indicates that megathrust locking has not been fully recovered to the preseismic status.

Postseismic uplifts at the OBP sites provide a constraint on spatial pattern of afterslip distribution to decrease to the trench axis where the tsunamigenic rupture segment of large earthquake in the 17th century has been inferred. Our preferred postseismic slip model explains both the postseismic pressure change recorded at the OBPs and the more stable land GNSS data, which shows that continuous OBPs are capable to capture postseismic pressure change for several years following a great megathrust earthquake.

3. Compliant Volcanic Arc and Backarc Crust in Southern Kurile Suggested by Interseismic Geodetic Deformation

Before constructing a detailed megathrust locking model from GNSS data prior to the 2003 earthquake, we model non-uniform distribution of compliance of the continental elastic plate as well as interseismic viscoelastic relaxation due to megathrust locking using the Finite Element Method. We show that interseismic GNSS velocities require that the elastic upper plate in the volcanic arc and backarc regions is highly and moderately more compliant than that in the forearc region, respectively, which is consistent with observed high heat flow and high attenuation and low velocity of seismic wave in the arc region. From the interseismic GNSS velocities, we cannot distinguish contribution of thinner elastic thickness and lower rigidity to the compliance of the upper plate, but other observations such as coseismic displacements and depth limit of crustal seismicity as well as seismic velocity structure may help distinguish them. The constrained non-uniform compliance suggests viscoelastic lower crust in the arc and backarc regions during the interseismic period, which is consistent with a weak lower crust model.

Previous models of the megathrust locking in this region have included physically problematic features including slip deficit rates exceeding the convergence rate and/or deep locking unexpected from seismological and thermal researches. The simple parameter examination in this Chapter suggests that effects of the non-uniform compliance as well as the interseismic viscoelastic relaxation has been attributed to these problematic features.

4. Megathrust Locking Prior to the 2003 Tokachi-oki Earthquake by Considering Interseismic Viscoelastic Relaxation and Non-uniform Compliance of the Continental Plate

We construct detailed megathrust locking models using the GNSS velocities prior to the 2003 earthquake. By incorporating the non-uniform compliance constrained in Chapter 3, the interseismic viscoelastic relaxation and postseismic one caused by previous M 8 events in the southern Kurile subduction zone, a full locking depth is shallower than rupture dimensions of M 8 or larger megathrust events in this region including the 2003 mainshock. This result suggests shrinking of the locked area prior to the 2003 mainshock and/or invasion of dynamic rupture into the low locking degree area. However, another forward model in which most of the 1973 M_w 7.8 Nemuro-oki and the 2003 rupture dimensions is fully locked can fit the horizontal GNSS reasonably, so the shallowing of full locking depth needs careful interpretation. Most of the rupture region of the tsunamigenic event in the 17th century is locked before the 2003 event and the coseismic and postseismic slip of the 2003 event does not invade into Nemuro-oki and near-trench segments of the source fault model of the tsunamigenic event. Therefore, the accumulated slip deficit in the Nemuro-oki region is not released associated with the 2003 event. Even after incorporating the interseismic viscoelastic relaxation and the non-uniform compliance, fault kinematics near the trench axis cannot be resolved from the land GNSS data. With the postseismic viscoelastic relaxation caused by previous M 8 events subtracted, overall fitting to the interseismic GNSS velocities is improved, which suggests certain contribution of them to the observed 'interseismic' velocities.

5. Implications to Earthquake Cycle Behavior in the Southern Kurile Subduction Zone

Characteristics of the obtained kinematic slip and locking history is consistent with predictions from numerical simulations employing the RSF. By comparing the obtained slip and locking history with numerical simulations, we infer that, as a first order approximation, possibly big isolated rate-weakening patches are located in the Nemuro-oki and Tokachi-oki regions, between which a region capable to host both afterslip and dynamic rupture lies, but there still remain big ambiguities of frictional parameters predicting such diverse slip modes.

6. Conclusions and Future Studies

In this thesis, we have presented new models of crustal deformation in the southern Kurile subduction zone based on the GNSS and OBP data before, during and after the 2003 M_w 8.0 Tokachi-oki earthquake. Following points are key findings of this thesis.

(1) Afterslip does not overlap with rupture dimensions of M 8 earthquakes in neighboring regions for 7.5 years following the mainshock, but occurs in the rupture area of the tsunamigenic event in the 17th century.

(2) Temporal evolution of the estimated afterslip obeys a logarithmic function expected from the RSF, with a spatially variable time constant. It may reflect the heterogeneity of frictional properties of interplate faults.

(3) The decadal Kurile OBP data has successfully captured transient postseismic seafloor pressure changes following the 2003 events.

(4) The interseismic velocities require the elastic upper plate in the volcanic arc and backarc regions is highly and moderately more compliant than that in the forearc region, respectively, suggesting a weak lower crust along the volcanic arc region.

(5) Full locking depth prior to the 2003 event is shallower to some extent than the rupture dimensions of M 8 megathrust earthquakes, including the 2003 mainshock, suggesting spatiotemporal change of locking during the interseismic period.

Built on the key findings listed above, following issues would be necessary to be addressed in the future to achieve comprehensive understanding of the earthquake cycle in the southern Kurile subduction zone.

(1) We need to model longer slip and locking history using longer geodetic data to investigate spatiotemporal change of megathrust locking suggested in Chapter 4. Geodetic observations have been carried out in Hokkaido since around 1900, from which we can retrieve megathrust signals and model slip and locking.

(2) With increase of spatiotemporal resolution of available geodetic data, many studies including

Chapter 3 of our thesis have shown importance of higher order heterogeneity of viscosity and rigidity to evaluate crustal deformation due to slip and locking appropriately.

(3) It is important to construct a physical model based on a fault friction law to understand what mechanisms are responsible for megathrust fault slip and locking inferred from observations.

Citations for Published Works

Results in Chapter 2 have been published as follows:

Itoh, Y., Nishimura, T., Ariyoshi, K., & Matsumoto, H. (2019). Interplate Slip Following the 2003 Tokachi-oki Earthquake From Ocean Bottom Pressure Gauge and Land GNSS Data. *Journal of Geophysical Research: Solid Earth*, 124, 4205-4230. doi:10.1029/2018JB016328

Results in Chapter 3 have been published as follows:

Itoh, Y., Wang, K., Nishimura, T., & He, J. (2019). Compliant Volcanic Arc and Backarc Crust in Southern Kurile Suggested by Interseismic Geodetic Deformation. *Geophysical Research Letters*, 46, 11790-11798. doi:10.1029/2019GL084656