Shibazaki
Progress in Earth and Planetary Science (2023) 10:43
https://doi.org/10.1186/s40645-023-00575-x

Progress in Earth and Planetary Science

REVIEW

Open Access

Progress in modeling the Tohoku-oki megathrust earthquake cycle and associated crustal deformation processes

Bunichiro Shibazaki[1*]

Abstract

This paper summarizes the results of 10 years of research on models of the megathrust earthquake cycles and crustal deformation associated with the 2011 Tohoku-oki earthquake. Several earthquake cycle models have been proposed for the northeast Japan subduction zone to elucidate why megathrust earthquakes occur at intervals of approximately 600 years and why large slips occurred in the shallow subduction zone. A model that considers a strong asperity in the shallow plate interface, and a hierarchical asperity model that considers the scale dependence of the critical displacement of the rate- and state-dependent friction law have been proposed. Modeling with dynamic weakening of faults has also been proposed. In the model using the shallow friction characteristics obtained by the Japan Trench Fast Drilling Project, rupture from depth can propagate to the trench, resulting in shallow large slips. Submarine crustal deformation has been observed for the first time in addition to dense observations of the inland crustal deformation. The observation of the seafloor deformation near the trench showed that viscoelastic relaxation played an important role in short-term postseismic deformation near the trench. The effects of the low-viscosity region at the oceanic lithosphere and asthenosphere boundary, and the cold forearc mantle wedge (cold nose) have been discussed. Simulations using the nonlinear flow law of rock in the mantle, where a power–law relationship holds between stress and strain rate, and the fault friction law at the plate boundary, show that the Tohoku-oki earthquake caused large stress fluctuations, resulting in a sudden viscosity decrease and rapid flow in the asthenosphere below the oceanic lithosphere. The simulations of the crustal deformation associated with the Tohoku-oki earthquake cycle also indicate that in the later stage of the earthquake cycle, the Pacific coastal region begins to subside due to the increasing slip deficit rate on the deeper parts of the plate interface. These results explain the subsidence of the Pacific coast of northeast Japan observed for about 100 years prior to the Tohoku-oki earthquake. In the future, a model that explains the long-term crust and mantle deformation during the entire Tohoku-oki earthquake cycle must be constructed.

Keywords 2011 Tohoku-oki earthquake, Numerical modeling, Megathrust earthquake cycle, Hierarchical asperity model, Dynamic weakening, Postseismic deformation, Viscoelastic relaxation, Postseismic slip, Long-term vertical deformation

*Correspondence:
Bunichiro Shibazaki
bshiba@kenken.go.jp
[1] International Institute of Seismology and Earthquake Engineering, Building Research Institute, 1 Tatehara, Tsukuba, Ibaraki 305-0802, Japan

1 Introduction

The 2011 off the Pacific coast of Tohoku Earthquake (Mw 9) (hereafter the Tohoku-oki earthquake) occurred on March 11, 2011, at a subduction zone along the Japan Trench, resulting in a large coseismic slip of approximately 50 m near the trench off Miyagi Prefecture (Fujii et al. 2011; Ide et al. 2011; Ito et al. 2011; Lay et al. 2011;

Yagi and Fukahata 2011; Yokota et al. 2011; Fujiwara et al. 2011; Iinuma et al. 2012; Satake et al. 2013). Previously, it was believed that a frictionally stable region exists in the shallow part of the subducting plate boundary, where the frictional strength increases with the increasing slip velocity. In this case, no stress accumulates because no plate coupling occurs during the interseismic period. In addition, the frictional strength increases with the slip velocity; hence, large slips are unlikely to occur. However, in the Tohoku-oki earthquake, large slips occurred in the shallow fault zone, generating huge tsunamis.

There are asperities off Miyagi Prefecture that produced earthquakes of Mw 7.1–7.5 (Yamanaka and Kikuchi 2004). Satake et al. (2008) estimated the magnitude of the 869 Jogan earthquake, which caused a huge tsunami, to be Mw 8.4 based on an analysis of the tsunami deposits in Miyagi Prefecture. Another study published after the Tohoku-oki earthquake (Sawai et al. 2015) identified more tsunami deposits and inferred the recurrence intervals of megathrust earthquakes to be between 500 and 800 years. Thus, in the region off Miyagi Prefecture, Mw 7–8 class earthquakes occur with relatively short periods at specific asperities, and megathrust earthquakes occur at intervals of 500–800 years. These observations raise the questions of how large slips occur in the shallow subduction plate interface, and how large thrust (Mw 7–7.5) and megathrust (Mw 9) earthquakes can overlap within the same subduction zone.

To clarify why the Tohoku-oki earthquake occurred, various models of the megathrust earthquake cycle using a rate- and state-dependent (RS) friction law have been proposed immediately after the earthquake. A model with a strong asperity in the shallow subduction interface off the Tohoku coast (Kato and Yoshida 2011), hierarchical asperity models (M7-class earthquake asperities of velocity weakening with small critical displacements and M9-class earthquake asperity of velocity weakening with large critical displacements) (Hori and Miyazaki 2011; Ohtani et al. 2014; Nakata et al. 2016) have been developed based on the RS friction law. Here, critical displacement defines the sliding displacement required to transition to a new state. Models that account for dynamic weakening (a significant decrease in the frictional strength at high slip rates), which has been confirmed by high-speed friction experiments on rocks (e.g., Di Toro et al. 2011), have also been proposed (e.g., Shibazaki et al. 2011). A possible mechanism of dynamic weakening is the strength reduction caused by the pore pressure increase resulting from frictional heating (thermal pressurization: TP) (Mitsui et al. 2012; Noda and Lapusta 2013; Cubas et al. 2015).

Expeditions 343 and 343T of the Integrated Ocean Drilling Program (IODP), the Japan Trench Fast Drilling Project (JFAST) drilled shallower faults using the Chikyu drilling vessel and directly sampled the fault core displaced during the earthquake (Chester et al. 2013). Thermometers were successfully installed in the fault zone where the coseismic slip occurred to estimate the frictional heat (Fulton et al. 2013). In the shallow part of the plate boundary fault, deformation is localized along the pelagic clay layers containing large amounts of smectite (Chester et al. 2013). The plate boundary fault materials show low friction (Ujiie et al. 2013) and low permeability (Tanikawa et al. 2013). Therefore, a rupture from the deep parts propagating to the shallow parts is difficult to stop, and furthermore, TP can cause significant slips. Slow slip events (SSEs) have also been shown to occur in low-speed friction experiments (Ikari et al. 2015). The megathrust earthquake cycle model that considers the frictional properties of the fault material sampled at JFAST (Sawai et al. 2017) has also been proposed (Noda et al. 2017).

The deformations from the island arc to the trench in the subduction zones are caused by the steady-state subduction of plates and the plate coupling and coseismic slips associated with the megathrust earthquake cycles. These are governed by the viscoelastic structures of the subducting plates and the island arcs (Sato and Matsu'ura 1993). The discussion here focuses on the crustal deformation associated with the megathrust earthquake cycle. The crustal deformation in the interseismic period is reproduced by an interplate coupling model. The crustal deformation caused by a coseismic slip is modeled by considering the elastic response of the media. The complex crustal deformation patterns observed in the postseismic deformation are generated by the elastic response of the postseismic slips (afterslips) and the viscoelastic relaxation processes caused by coseismic and postseismic slips.

During the approximately 600-year earthquake cycle off the northeastern coast of Japan, a large crustal deformation is thought to have occurred from the trench to the interior of the island arc. A high-density crustal deformation observation network exists in the Japanese islands, and the crustal deformations before, during, and after the Tohoku-oki earthquake have been observed with high accuracy. On land, a high-density GNSS network, called GEONET (e.g., Sagiya 2004), has been developed.

Seafloor geodetic observations near the ocean trench have also been obtained during and after the Tohoku-oki earthquake (Sato et al. 2011; Watanabe et al. 2014). This is the first time that coseismic and postseismic crustal deformations have been captured in the vicinity of a trench. Seafloor crustal coseismic deformation observations show uplift and the east-southeastward motion near the trench. As for the postseismic deformation, seafloor crustal deformation observations present subsidence and the west-northwestward motion near the trench caused by viscoelastic relaxation processes (Sun et al. 2014; Watanabe et al. 2014). Viscoelastic relaxation plays an important role in the short-term postseismic deformation near the trench.

Many studies have modeled the postseismic deformation of the Tohoku-oki earthquake (Sun et al. 2014; Sun and Wang 2015; Yamagiwa et al. 2015; Hu et al. 2016; Iinuma et al. 2016; Freed et al. 2017; Suito 2017; Noda et al. 2018; Agata et al. 2019; Muto et al. 2016, 2019; Fukuda and Johnson 2021). Many studies also discuss the effects of the low-viscosity region on the oceanic lithosphere and asthenosphere boundary (LAB) and the cold nose, which is the cold forearc mantle wedge beneath the Pacific coast (Sun et al. 2014). The modeling of the postseismic deformation that considers the realistic rheology of the crust and mantle structures has become necessary in understanding the viscoelastic relaxation processes.

Analyses of the postseismic deformation caused by the Tohoku-oki earthquake indicate the importance of viscoelastic relaxation processes in the mantle. Moreover, the viscoelasticity of the mantle is expected to influence the earthquake cycle. Recently, megathrust earthquake cycle models that take viscoelasticity into account have been developed (Barbot 2020; Shi et al. 2020).

Geodetic observations indicate that the Pacific coast of the Tohoku region had been subsiding at a large rate (3–4 mm/year) for about 100 years prior to the Tohoku-oki earthquake, centered on the Oshika Peninsula and extending 200 km from north to south (Nishimura 2014). The Oshika Peninsula subsided by 1.2 m during the earthquake and rose by 69 cm 10 years after the earthquake (Geospatial Information Authority of Japan 2021). Sasajima et al. (2019) investigated why subsidence occurred along the Pacific coast prior to the Tohoku-oki earthquake, and what mechanism balances vertical deformation along the Pacific coast between the megathrust earthquake cycles. These problems are very important issues in the understanding of the relationship between the strain accumulation and release processes during the megathrust earthquake cycles and the crustal deformation.

Several review papers on the Tohoku-oki earthquake have already been published. Wang et al. (2018) presented fault behavior and mantle rheology revealed by crustal deformation observations associated with the Tohoku-oki earthquake. Uchida and Bürgmann, (2021) reviewed lessons learned from the Tohoku-oki earthquake and discussed insights on the generation processes from various disciplines. Sagiya and Meneses-Gutierrez (2022) summarized the geodetic and geological deformation in the northeastern Japan island arc caused by the Tohoku-oki earthquake. Dhar et al. (2023) reviewed the heterogeneous rheological structure of the northeast Japan subduction zone revealed by analysis of the postseismic deformation of the Tohoku-oki earthquake.

This paper reviews the results obtained during around 10 years following the Tohoku-oki earthquake for the megathrust earthquake cycle modeling and the crustal deformation modeling and highlights their similarities and differences. First, we review the progress of the megathrust earthquake cycle modeling off the northeastern coast of Japan. Then we introduce the modeling of the postseismic crustal deformation after the Tohoku-oki earthquake. We also review the modeling of subsidence at the Pacific coast observed for about 100 years prior to the Tohoku-oki earthquake and discuss the vertical deformation at the Pacific coast during the Tohoku-oki earthquake cycle.

Finally, we discuss future issues in modeling the earthquake cycle and associated deformation processes of the Tohoku-oki earthquake. In previous studies, each process was modeled individually to understand its physical mechanism. However, the earthquake cycle, postseismic deformation (viscoelastic relaxation + postseismic slip), and inter- and pre-seismic deformation are all related to each other. Integrated modeling of these phenomena is a future challenge.

2 Megathrust earthquake cycle models for the Tohoku-oki earthquake

This section presents various megathrust earthquake cycle models with respect to the Tohoku-oki earthquake using the friction law. The Tohoku-oki earthquake caused a large coseismic slip of about 50 m (e.g., Fujii et al. 2011) near the trench off Miyagi Prefecture. The recurrence intervals of megathrust earthquakes have been estimated to be 500 to 800 years (Sawai et al. 2015). However, Mw 7-8 class earthquakes with specific asperities off Miyagi Prefecture have occurred in a relatively short interval (several 10 years) (Yamanaka and Kikuchi 2004). The fundamental questions are as to why the large slip occurred in a shallow subduction zone and how such large thrust (Mw7–7.5) and megathrust (Mw9) earthquakes could occur in the same subduction zone. Furthermore, the Tohoku-oki earthquake was preceded by preparatory decoupling in the zone off Fukushima (Suito et al. 2011). In addition, an Mw 7.3 foreshock occurred 2 days and 3 h before the Tohoku-oki earthquake. Although the average recurrence interval of the off Miyagi Prefecture earthquake is 38 years (Headquarters for Earthquake Research Promotion 2020), plate boundary earthquakes (Mw 7.0 and Mw 6.7) in March 2021 occurred relatively early after the Tohoku-oki earthquake (Yoshida et al. 2022) at a depth of the 1978 off Miyagi Prefecture earthquake fault. SSEs also occurred in the northeast Japan subduction zone prior to the 2011 Tohoku-oki earthquake (Ito et al. 2013). We review the results to date on whether these observed phenomena can be reproduced using the distribution of parameters that define the RS friction law, the dynamic weakening observed in high-speed friction experiments, and the friction law of shallow fault properties obtained by JFAST.

Several earthquake cycle models based on the RS friction law (Dieterich 1981) consider the distribution of the parameters defining the frictional constitutive law and the distribution of effective pressure. In the RS friction laws, the friction coefficient μ depends on the slip rate v and the state variable Θ:

$$\mu = \mu_* + a \ln\left(\frac{v}{v_*}\right) + b \ln\left(\frac{v_*\Theta}{D_c}\right) \quad (1)$$

where μ_* is the reference value for the friction coefficient, a and b are constants; v_* is the reference value for the slip velocity; and D_c is a critical displacement that specifies the sliding displacement required to transition to a new state. The second term in Eq. (1) represents the direct effect, and the third term represents the effect of transitioning to a new state. The RS friction law exists in two forms: aging and slip laws (e.g., Marone 1998). The time evolution of the state variable Θ in the aging law is presented as

$$\frac{d\Theta}{dt} = 1 - \frac{\Theta v}{D_c} \quad (2)$$

The composite law (Kato and Tullis 2001) that incorporates the properties of both the aging and slip laws is also often used. The frictional force τ is proportional to the effective pressure σ_n^{eff}:

$$\tau = \mu\sigma_n^{eff} = \mu(\sigma_n - P_f) \quad (3)$$

The effective pressure σ_n^{eff} is the difference between the normal stress σ_n and the pore pressure P_f. The coefficient of friction at the steady state μ_{ss} is expressed as

$$\mu_{ss} = \mu_* + (a - b)\ln\left(\frac{v}{v_*}\right) \quad (4)$$

For $a - b < 0$, the steady-state friction μ_{ss} decreases with the increasing slip rate [velocity weakening (VW)]. For $a - b > 0$, the steady-state friction μ_{ss} increases with the increasing slip rate [velocity strengthening (VS)]. Postseismic slip can occur at the VS region when a stress perturbation is added (Marone et al. 1991).

Low-slip velocity friction experiments have confirmed the RS friction law. In contrast, high-speed friction experiments on rocks have confirmed that dynamic weakening (a significant decrease in the frictional strength at high slip rates) occurs (Tsutsumi and Shimamoto 1997; Di Toro et al. 2011; Tsutsumi et al. 2011). One possible mechanism of dynamic weakening is the strength decrease caused by the pore pressure increase due to frictional heating (TP) in the fault zone (Noda and Lapusta 2010). In addition, modeling that accounts for the shallow friction characteristics obtained by the JFAST (Sawai et al. 2017) have been performed (Noda et al. 2017).

Modeling is categorized into two types: (1) quasi-dynamic earthquake cycle modeling that considers radiation damping to approximate the effects of inertia during dynamic rupture (Rice 1993); and (2) dynamic earthquake cycle modeling that directly solves the dynamic rupture propagation (Lapusta and Liu 2009).

2.1 Model with a strong asperity in the shallow plate boundary

Kato and Yoshida (2011) constructed a two-dimensional (2D) model of the Tohoku-oki megathrust earthquake cycle using the composite law (Kato and Tullis 2001) in the RS friction law. Their model was based on a strong asperity with a large stress drop and a large critical displacement at the shallow part of the plate boundary and two weak asperities with a small stress drop and a small critical displacement at the deep part off Miyagi Prefecture; hence, it successfully reproduced M7-class earthquakes occurring at intervals of several decades and megathrust earthquakes occurring at intervals of 700 years off Miyagi Prefecture. The strong asperity, which is assumed to exist at depths shallower than 20 km, controlled the occurrence of the megathrust earthquakes at intervals of several hundred years that ruptured the entire seismogenic plate interface. A large postseismic slip occurred at depth after the occurrence of a megathrust earthquake, and an M7-class earthquake occurred early (1 year after the megathrust earthquake) in the asperities off Miyagi Prefecture at depth. A large postseismic slip in the deep extension of the asperity off Miyagi Prefecture increased the stresses on the asperity of the Miyagi Prefecture earthquake, resulting in this early occurrence.

2.2 Hierarchical asperity model

Hori and Miyazaki (2011) proposed a hierarchical asperity model and performed numerical simulations of the megathrust earthquake cycles using the RS law. First, to reproduce the occurrence of the Tohoku-oki earthquake, an M9 earthquake generation zone with VW and a large critical displacement was set up. Then, to reproduce the occurrence of large earthquakes, asperities with VW and a smaller critical displacement were set. In this model, stable sliding occurred due to the large size of the nucleation zone in the M9 earthquake generation zone. The stable sliding gradually narrowed the coupling zone and stressed the M7–8-class earthquake asperities, resulting in large earthquakes at intervals of a few decades. When the coupling zone of the M9 earthquake generation zone narrowed, the rupture of an M7–8-class earthquake was not slowed down but instead grew into an M9-class earthquake. This reproduced large earthquake and megathrust earthquakes occurring at intervals of several decades and hundred years, respectively. The dependence of critical displacements on the rupture scale was discussed in many studies. For example, a multiscale circular patch model in which the rupture energy was proportional to the radius was solved with a slip-weakening friction law to simulate a spontaneous dynamic rupture (Ide and Aochi 2005; Aochi and Ide 2011). Hori and Miyazaki (2011) incorporated the hierarchical nature of rupture into an earthquake cycle model and succeeded in modeling the cycle of M9 megathrust and M7 large earthquakes.

Ohtani et al. (2014) developed a more realistic large-scale quasi-dynamic earthquake cycle model for the Tohoku-oki earthquake. They considered a small asperity with small critical displacements to generate M7-class earthquakes and a strong shallow asperity and surrounding conditionally unstable regions with large critical displacements to generate an M9-class earthquake. The simulation results showed that M7-class earthquakes repeatedly occurred off Ibaraki and Miyagi Prefectures at intervals of several decades and that aseismic slip occurred repeatedly off Fukushima Prefecture in the latter half of the cycle of the megathrust earthquake. Moreover, they reproduced an M7 foreshock that occurred 62 days before the megathrust earthquake.

Nakata et al. (2016) also modeled a large patch with a large critical displacement, leading to an M9 megathrust earthquake, and patches of an M7-class earthquake with a small critical displacement. The time interval between the occurrence of an M9 megathrust earthquake and the occurrence of an M7 off Miyagi Prefecture earthquake was often shorter than half the average recurrence interval of the off Miyagi Prefecture earthquake before the M9 earthquake. The deep postseismic slip may have added stress to the patches of the off Miyagi Prefecture earthquake and caused the earthquake in a short period of time. In fact, plate boundary earthquakes (Mw 7.0 and Mw 6.7) occurred in the deeper part of the 1978 off Miyagi Prefecture earthquake in March 2021 (Yoshida et al. 2022). The model also reproduced the foreshock 13 days before the mainshock. Actually, the Mw7.3 foreshock occurred 2 days and 3 h before the Tohoku-oki earthquake. After the Mw7.3 foreshock, foreshock activity is shown to have propagated with a slow slip from north to south toward the epicenter of the main shock (Kato et al. 2012). The M7-class earthquake and slow slip were considered to occur at a stage when sufficient stress was accumulated in the rupture nucleation zone of the Tohoku-oki earthquake and accelerated its nucleation process.

Nakata et al. (2021) showed that the seismic velocity and density structures differ between the middle (off Miyagi Prefecture) and south segments of the Japan Trench, and that a 1-km-thick channel layer in the south segment can explain the gravity anomalies. The coseismic slip was limited to the middle segment, while postseismic slips occurred in the south segment. They performed numerical simulations assuming large critical displacements in the south segment caused by the existence of the 1-km-thick channel layer. An M9 earthquake occurring only in the central segment was reproduced, followed by clear postseismic slips in the southern segment.

2.3 Modeling with dynamic weakening at high slip velocities

Laboratory experiments using fault zone materials showed that the frictional strength rapidly decreases (dynamic weakening) at high slip velocities (e.g., Di Toro et al. 2011). Shibazaki et al. (2011) performed a three-dimensional (3D) quasi-dynamic simulation of the Tohoku-oki earthquake cycle using the RS friction law with two state variables to represent friction at low slip velocities and the dynamic weakening process at high slip velocities. Based on the experimental results of Tsutsumi et al. (2011), it was assumed that VW or VS occurs at small critical displacements at low to medium slip velocities, while at high slip velocities, strong VW occurs at a large critical displacement. The model set asperities off Miyagi, Fukushima, and Ibaraki Prefectures for M7-class earthquakes, as well as a large asperity in the shallow fault zone off Miyagi Prefecture. This model reproduced the M7-class earthquakes that occurred at intervals of several decades. When the large asperity ruptured in the shallow plate interface off Miyagi Prefecture, dynamic weakening occurred. The VS region at the low slip velocity also became unstable, growing into an M9 megathrust earthquake. The constitutive law used in this model was empirically derived, explaining the experimental results (Tsutsumi et al. 2011).

In particular, a fault slip causes significant strength reduction due to frictional heating and increased pore pressure (TP) (Lachenbruch 1980; Wibberley and Shimamoto 2005). Some authors have developed earthquake cycle models considering TP (Noda and Lapusta 2010, 2013; Mitsui et al. 2012). The fault slip causes a temperature increase due to frictional heating, which

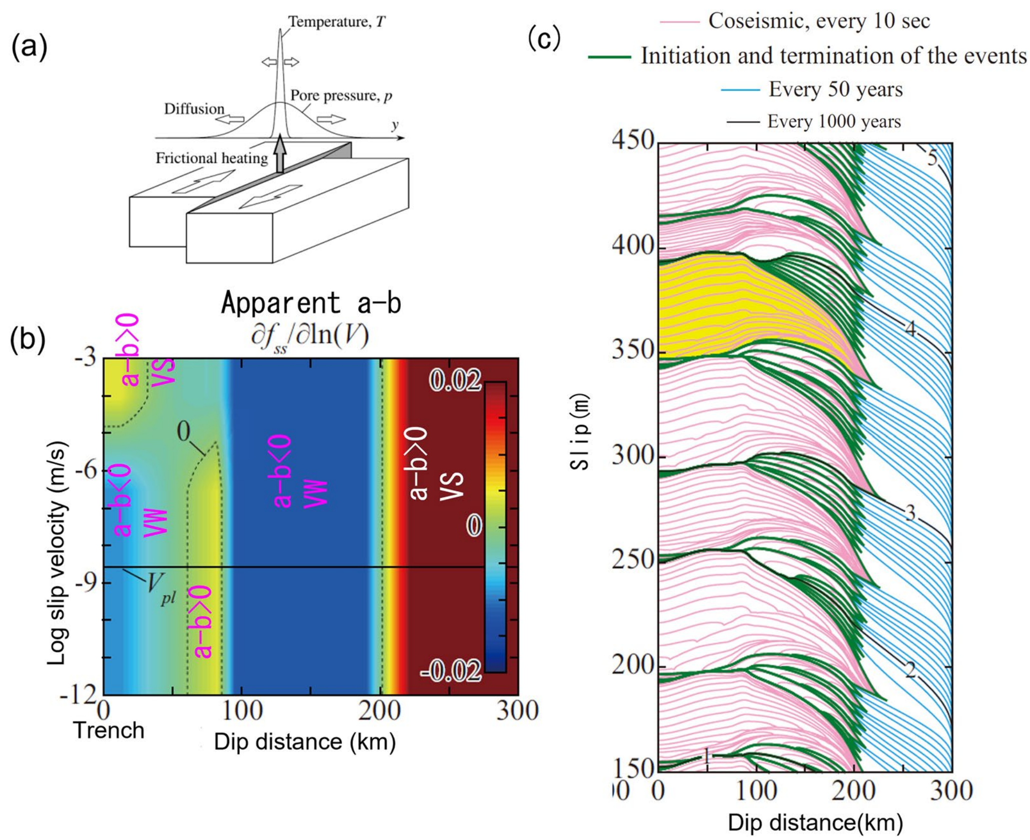

Fig. 1 Megathrust earthquake cycles simulated with the frictional properties of the JFAST shallow-fault zone materials and TP (Noda et al. 2017). **a** TP schematic diagram (Noda and Lapusta 2010). During an earthquake rupture, the frictional shear heating on the fault raises the temperatures and the pore pressure. **b** Slip velocity dependence of the frictional properties of the fault-zone materials collected by the JFAST. The dynamic weakening caused by TP is assumed to occur near the trench. **c** Distribution of the cumulative slip. The pink lines show the slip distribution at 10 s intervals during an earthquake. The green lines show the slip distribution immediately before and after the earthquake. The blue lines show the slip distribution at 50-year intervals. Megathrust earthquakes occur at intervals of about 550 years, whereas large earthquakes occur at intervals of about 50 years. **b** and **c** are after Noda et al. (2017)

consequently causes a pore pressure increase (Fig. 1a). Because the frictional strength is proportional to the effective normal stress (normal stress–pore pressure) according to Eq. (3), the frictional strength decreases as the pore pressure increases. The important parameters governing the pore pressure increase by TP are the thermal diffusivity, hydraulic diffusivity, and width of the fault shear zone as a heat source. The hydraulic diffusivity is proportional to the permeability, and the lower diffusivity leads to a high pore pressure increase.

Mitsui et al. (2012) proposed a quasi-dynamic earthquake cycle model that explains rare (M9-class) and frequent (M7-class) thrust earthquakes by the occurrence of TP near the trench. They modeled the region from the trench to a certain depth (D_{tp}) with low hydraulic diffusivities, such that TP occurs with $a-b=0$. Modeling was performed by setting $D_{tp} > 10$ km, that is, the TP area length was > 30 km along the fault, to reproduce the megathrust earthquakes that occur at intervals of about 600 years. The model reproduced the occurrence of a megathrust earthquake a few days after an M7-class earthquake; however, an M7-class earthquake did not always follow a megathrust earthquake. They showed that when the stress levels in the TP region were sufficiently high, quasi-static slip events near the trench could grow into extremely large coseismic slips due to TP. As noted by Mitsui et al. (2012), it has been confirmed that TP can occur on shallow faults (Tanikawa et al. 2013).

Noda and Lapusta (2013) constructed a dynamic earthquake cycle model that considered TP. Two patches A and B were considered. The friction property of Patch A was assumed to be VW at low slip velocity, and dynamic weakening can occur at high slip velocity due to TP. In contrast, the friction property of Patch B was VS at low slip velocity, and significant dynamic weakening can occur at high slip velocity due to TP. The simulation results reproduced relatively small slips at short intervals in Patch A; however, ruptures from Patch A occasionally propagated to Patch B, leading to large slips due to the dynamic weakening caused by TP. Patch A was locked between earthquakes, but Patch B sometimes crept before the earthquake. This model can be applied to the Tohoku-oki earthquake, where the asperity of the off Miyagi Prefecture earthquake at depth corresponds to Patch A, and the very large slip area at shallow depth corresponds to Patch B.

Cubas et al. (2015) constructed a 2-D dynamic earthquake cycle model of the Tohoku-oki earthquake that considered TP. In particular, they set the hydraulic diffusivity to 3×10^{-3} m^2/s to induce TP in a region 40–80 km from the trench and investigated the cases where low-velocity friction in this region is VS or VW. To account for the frequent occurrence of large earthquakes, they also considered a patch of VW where no TP occurs at a deeper depth. They found that all models were able to reproduce more frequent deeper large earthquakes (Mw 7.5) and less frequent megathrust earthquakes with large slips at shallow depths. However, only the scenario in which the region where TP occurs at shallow depths is the region of VS reproduced millennial earthquake intervals, such as those for the Tohoku-oki earthquake suggested by the historical and geologic records. In this case, seismic and aseismic slips coexisted at shallow depths. Furthermore, the scenario reproduced other features of the Tohoku-oki earthquake, such as large coseismic slip but weak radiation at high frequencies at the shallow fault zone.

2.4 Modeling considering the shallow fault friction characteristics obtained by JFAST

2.4.1 Shallow fault friction characteristics obtained by JFAST

By IODP Expedition 343/343T, JFAST, a shallow source fault with a significant coseismic slip near the trench during the 2011 Tohoku-oki earthquake was drilled to analyze the structure and the composition (Chester et al. 2013). Logging during drilling and observations using core samples revealed that deformation was localized in pelagic clay less than 5 m thick. Chester et al. (2013) indicated that pelagic clay is an important controlling factor in generating the shallow slip of the Tohoku-oki earthquake. Fulton et al. (2013) installed a borehole temperature instrument at a shallow fault near the trench 16 months after the Tohoku-oki earthquake by JFAST. After a 9-month operation, the sensor string was completely recovered, and a temperature anomaly of 0.31 °C was detected at the plate boundary fault. They found an apparent friction coefficient of 0.08, which is considerably smaller than the static value for most rocks.

Ujiie et al. (2013) performed frictional slip experiments at a high slip rate (1.3 m/s) on JFAST samples of shallow plate boundary faults, where deformation was localized (Chester et al. 2013). The results showed that the maximum and steady-state frictional strength are very low, and that the stress drop is small. This extremely low shear strength is caused by the abundance of weak clay (smectite) and TP resulting from frictional heating. This low frictional strength may have caused the huge shallow slip when the rupture propagated to the shallow fault zone.

Tanikawa et al. (2013) measured the hydraulic properties (e.g., permeability and porosity) of sediments of the shallow plate boundary collected by JFAST. They found extremely low permeabilities of the samples from the shallow plate boundary faults, with a hydraulic diffusivity of 10^{-10} m^2/s. The low permeability and the high pore compressibility of the shallow plate boundary faults can lead to TP, in which the fault is dynamically weakened by the fluid pore pressure caused by frictional heat, even when the initial shear stress is low. The experimental results obtained in this study are consistent with the model of Mitsui et al. (2012), who found that accelerated TP at the fault plane caused a major slip in the shallow subduction zone during the Tohoku-oki earthquake. However, the model assumed the hydraulic conductivity of the TP area to be 10^{-2}–10^{-6} m^2/s, which is larger than the experimental value.

Sawai et al. (2014) investigated the frictional properties of the pelagic sediments at the base of the sedimentary layer on the Pacific Plate, which is the input to the northeast Japan subduction zone. These sediments were sampled from the outer rise of the Pacific Plate during Leg 56 of the Deep Sea Drilling Project (DSDP). The experimental results using this clay sediment indicated a low friction coefficient (<0.2) over a broad range of slip velocities from 0.25 mm/s to 1.3 m/s and an extremely low fracture energy (frictional work at the fault plane during slip weakening). Ikari et al. (2015) conducted laboratory shear experiments at low slip rates (<1 mm/s) using the borehole samples collected at JFAST from a plate boundary fault that underwent a significant slip during the Tohoku-oki earthquake. They found that the friction coefficient of the fault is very small (0.2–0.26), while that of the host rock is greater than 0.5, even at low slip velocities. The fault weakness is caused by the high content of smectite clay, which has similar frictional properties to pelagic clay formations of similar composition.

Ito et al. (2013) discovered SSEs in the northeast Japan subduction zone prior to the 2011 Tohoku-oki earthquake. SSEs (Uchida et al. 2016) and various slow earthquake activities (Matsuzawa et al. 2015; Nishikawa et al. 2019, 2023) were also observed in the subduction zone. Ikari et al. (2015) performed laboratory experiments in which rock samples from the Tohoku-oki earthquake fault zone were slowly sheared. They found that a long-term SSE spontaneously occurred when the samples were sheared at about 8.5 cm yr^{-1}, corresponding to the plate's convergence velocity. The maximum slip velocity reached 8×10^{-9} m/s, which reproduces the slip velocity of the long-term SSE observed in several subduction zones around the Pacific Ocean.

Sawai et al. (2017) also conducted friction experiments using the borehole samples taken from the plate boundary fault and the host rock at JFAST to understand how the frictional properties of the plate boundary fault influence the occurrence of slow earthquakes. They found that the frictional properties depend on the slip velocity and the temperature. Under the RS friction law framework, they showed that the plate boundary fault material changed from a VS to a VW behavior at low slip velocities in the temperature range of 50–150 °C. The temperature range of slow earthquake regions in the Japan Trench is between 100 and 150 °C, suggesting that the frictional properties of the plate boundary faults may play an important role in controlling the location of the observed slow earthquakes.

2.4.2 Earthquake generation model incorporating JFAST shallow fault zone frictional properties

Several simulations were performed to verify whether or not the frictional properties obtained from the friction experiments using the core samples collected by JFAST can reproduce the giant coseismic slip at shallow depths. Noda et al. (2017) developed a 2D dynamic earthquake cycle model by using the frictional properties that depend on the temperature and the slip velocity obtained from the experiments of Sawai et al. (2017) (Fig. 1b). Near the trench, VW occurs at low slip velocities; VS occurs at somewhat higher slip velocities; and dynamic weakening caused by TP occurs at even higher slip velocities (Fig. 1a). In the region 60–80 km from the trench, VS occurs at low slip velocities and VW occurs at higher slip velocities. The hydraulic diffusion coefficient in the region up to 80 km from the trench was set to 4.4×10^{-10} m^2/s (Tanikawa et al. 2013) so that dynamic weakening due to TP occurs at higher slip velocities. In the normal seismogenic zone (dip distance of 100–200 km from the trench), the VW friction is at work. The simulation results (Fig. 1c) showed that megathrust earthquakes with a slip of approximately 50 m, which extend the rupture to the trench, occur at intervals of 550 years. The simulation also reproduced the occurrence of large earthquakes at depths (dip distance of 100–200 km from the trench) corresponding to the off Miyagi Prefecture earthquake zone at intervals of 50 years. Furthermore, the results showed that slow earthquakes (maximum slip velocity less than 0.1 m/s) occur at very shallow depths. These events occurred from around 11 km –21 km, but did not propagate downward and remained at a distance of less than 30 km. These complex shallow frictional slip behaviors may be related to the mechanism of tsunami earthquakes and SSEs.

Hirono et al. (2016) analyzed the mineral composition and various physical properties (i.e., friction coefficient, permeability, and thermogravimetric change) of the fault samples obtained by JFAST. They performed a numerical analysis of the slip behavior of the fault during an earthquake to determine the relationship between the amount of slip and shear stress. They found that TP is generated by the low permeability caused by the clayey materials in the shallow fault zone near the Japan Trench, resulting in a large decrease in shear stress, and that TP acts upon in the shallow fault zone of the Nankai Trough subduction zone because of the significant temperature rise associated with the high friction coefficient, resulting in a large decrease in shear stress, although the permeability is high due to sandy materials. Modeling of dynamic rupture propagation using the obtained slip-dependent frictional behavior for the shallow fault zone near the Japan Trench reproduced a large slip of about 80 m, which is almost the same as that observed in the Tohoku-oki earthquake. The results of the analysis of the fault properties from the Nankai Trough using the same analytical method revealed the possibility that the amount of slip near the trench is approximately 30–50 m.

Shibazaki et al. (2019) performed 3D quasi-dynamic earthquake cycle simulations, considering the frictional properties of shallow fault materials and dynamic weakening due to TP (Fig. 2). The frictional properties for several fault zone materials, including those at a shallow plate boundary, obtained by JFAST showed VW or VS at slip velocities of 0.01–0.1 mm/s and VS at slip velocities of 1–100 mm/s (Ikari 2015; Ikari et al. 2015; Ikari and Kopf 2017). Shibazaki et al. (2019) considered the friction characteristics that indicate VW at low slip velocity, VS at intermediate velocity (Shibazaki and Shimamoto 2007), and strong weakening by TP at seismic velocity (Fig. 2b). This friction property was set near the trench, but the region with this shallow friction property was wider in the Sanriku-oki region (Fig. 2a) considering the wide channel-like sediment near the trench (Tsuru et al. 2002). The simulation results (Fig. 3a–h) showed that long-term SSEs occurred regularly in the shallow fault zone although the depths of SSEs are shallower than that of the observed SSEs (Ito et al. 2013). A foreshock occurred 23 days before the M9 earthquake. The simulation reproduced the slow spreading of rupture in the shallow fault zone during the earthquake. In addition, the simulation results of temperature change after the M9 earthquake (Fig. 3i) reproduced a temperature increase of 0.3 K at the drilling site (P2) 2 years after the earthquake. This result is consistent with the observation by JFAST (Fulton et al.

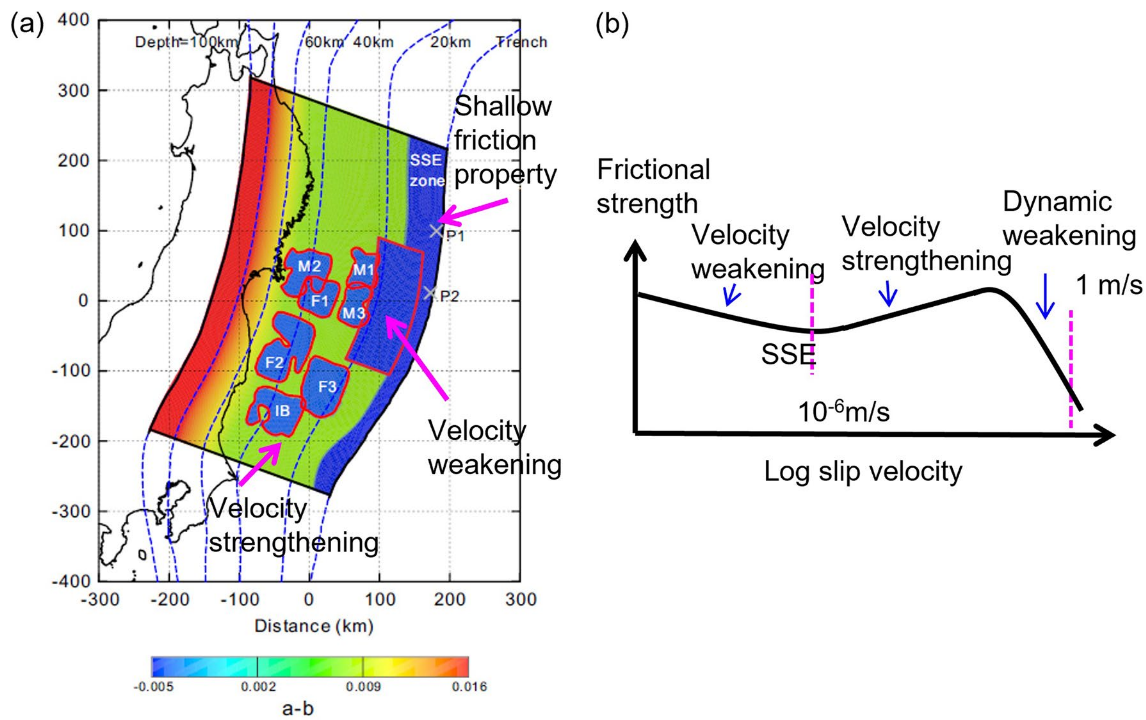

Fig. 2 The setting of the friction parameter for the 3D model of the Tohoku-oki earthquake cycles considering the shallow friction property. After Shibazaki et al. (2019). **a** Distribution of the RS friction parameter a-b on the subduction plate boundary between the Pacific and Okhotsk plates. The largest asperity is located off Miyagi near the trench. The shallow friction property in **b** is considered in the shallow fault zone. **b** Schematic diagram of shallow friction property showing VW at low slip velocities and VS at high slip velocities. In addition, dynamic weakening due to TP occurs at high slip velocities. This friction law can cause SSEs and is considered in the region of the shallow friction property in **a**

2013) that the temperature anomaly that was 0.3 K higher than the surrounding area occurred at the plate boundary fault.

In the model considering TP (e.g., Shibazaki et al. 2019), the first weakening process that depends on the small critical displacement Dc of the RS frictional properties was observed. Weakening with a large displacement due to TP was also observed. In the region where a-b is positive, only the weakening process with a large displacement caused by TP appeared. The model with the RS friction law and TP showed two weakening processes with small and large displacements.

2.5 Discussion on simulation models and results

Several models can produce the Tohoku-oki and M7-class earthquakes. A hierarchical asperity model that considers the scale dependence of the critical displacement of the RS law reproduced the occurrences of an M7-class earthquake with a small critical displacement and that of an M9-class earthquake with a large critical displacement. On the other hand, modeling considering the dynamic weakening (TP) can also reproduce megathrust events. Although physically different, models that consider TP exhibit a strong weakening with an apparently large critical displacement as a second weakening process in addition to the weakening process with a small critical displacement due to the RS frictional properties. Therefore, some similarities exist between the hierarchical asperity model and those that consider TP. Another important factor is that rupture propagation to the trench due to the shallow frictional properties, in which friction strength is very low, and TP can occur.

A foreshock occurred around 2 days before the Tohoku-oki earthquake. Therefore, whether or not such a foreshock can be reproduced in the numerical model is a major issue. Kato and Yoshida (2011) reproduced a foreshock that occurred 2.2 days before the megathrust event, while Ohtani et al. (2014) reproduced a foreshock that occurred 62 days before the megathrust event. In the model by Nakata et al. (2016), the foreshock occurred 13 days before the megathrust event. The models of Shibazaki et al. (2011, 2019) also produced foreshocks that occurred 20 and 13 days, respectively, before the megathrust event. We do not know if foreshocks commonly occur. However, if an M7-class earthquake occurs at a stage when sufficient stress is accumulated in the rupture zone of the Tohoku-oki earthquake, it is likely to accelerate the nucleation of the earthquake.

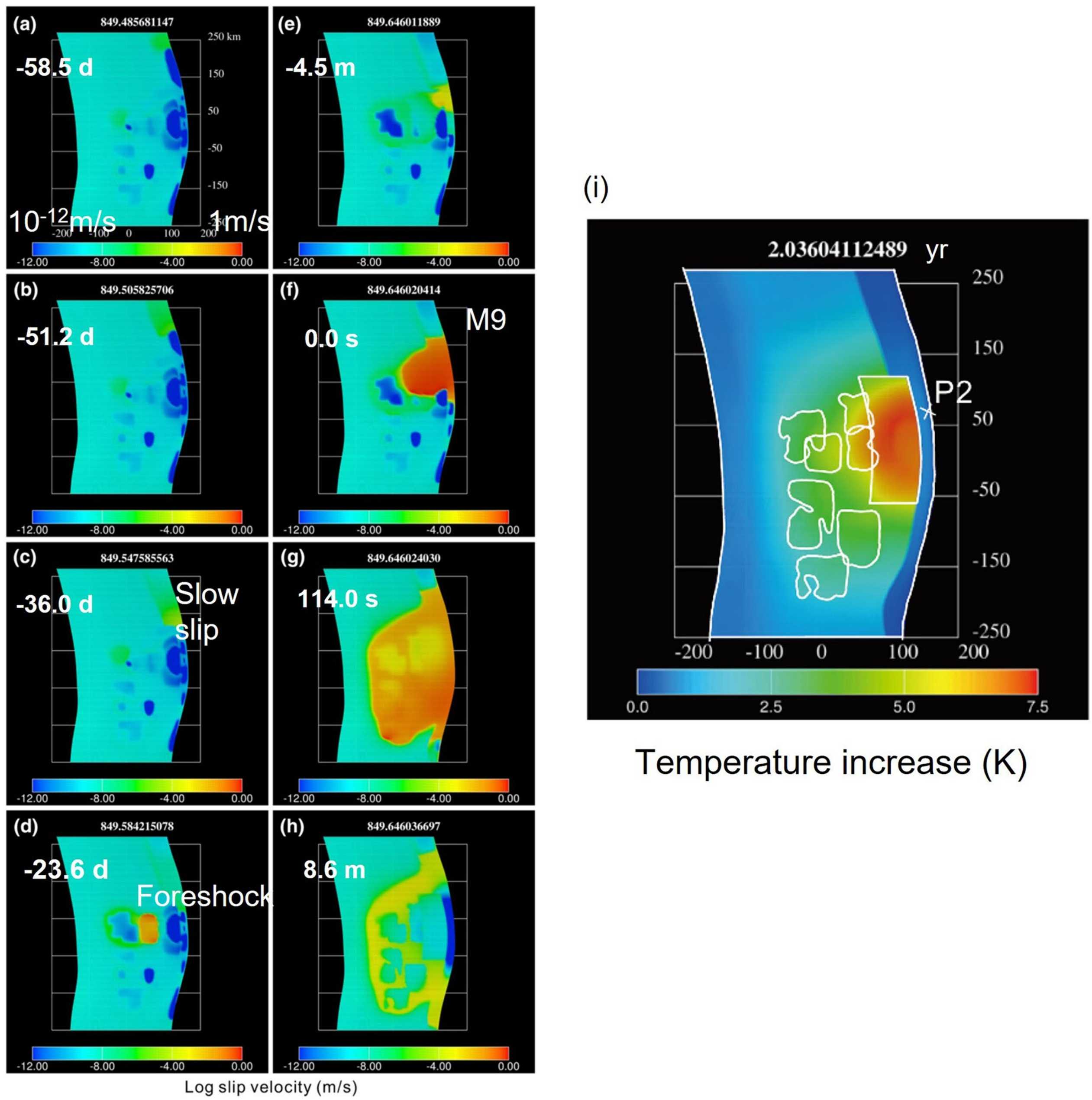

Fig. 3 Numerical results for the 3D model of the Tohoku-oki earthquake cycles. After Shibazaki et al. (2019). **a**–**h** Spatiotemporal development of the slip velocity. Time is shown as a reference to the time of the initiation of a megathrust earthquake. **a**–**c** Spatiotemporal development of the slip velocity for an SSE. **e**–**h** Spatiotemporal development of the slip velocity for the megathrust event. **i** Temperature change 1.983 years after the megathrust earthquake. The white lines indicate the asperities

Mavrommatis et al. (2014) showed increased slip rates and upward migration of deep aseismic slip at the Japan Trench plate boundary in the decades prior to the 2011 Tohoku-Oki earthquake, but modeling on these issues will be the subject of future studies.

The models showed that, after the Tohoku-oki earthquake, stress concentrated in the surrounding area, and postseismic slip occurred. Kato and Yoshida (2011) and Nakata et al. (2016) pointed out that the deep postseismic slip at the plate boundary accelerated the occurrence of the off Miyagi Prefecture earthquake. The rupture of the 2011 Mw 7.0 and Mw 6.7 off Miyagi Prefecture earthquakes occurred at a deep fault area of the 1978 off Miyagi Prefecture earthquake (Yoshida et al. 2022). This observation indicates that a postseismic slip occurred at the deeper extension of the fault of the 1978 off Miyagi Prefecture earthquake and that stress accumulation is progressing at the deeper part of the off Miyagi Prefecture asperity.

How future earthquakes will occur off Miyagi, Fukushima, and Ibaraki Prefectures along the plate boundary is a very important issue that will constrain the frictional properties of the plate boundary. Whether postseismic slip occurred in the deep extension of the off Miyagi Prefecture earthquake fault also requires analysis from crustal deformation data and is discussed in the next section. An earthquake cycle model that includes the effects of viscoelasticity is also presented in the next section.

3 Modeling of the postseismic deformation caused by the Tohoku-oki earthquake

The coseismic crustal deformation resulting from the Tohoku-oki earthquake (Mw 9) was observed over a wide area centered in eastern Japan, including a horizontal crustal movement of over 5 m on the Oshika Peninsula (Ozawa et al. 2011). Significant subsidence was also observed along the Pacific coast of the Tohoku region, and subsidence exceeding 1 m was observed on the Oshika Peninsula (Ozawa et al. 2011). In addition, analysis of data obtained from seafloor geodetic observations showed that large deformations occurred above the hypocenter of the Tohoku-oki earthquake. For example, the seafloor observation station off Miyagi Prefecture (Miyagi-oki 1) located almost directly above the earthquake moved approximately 24 m to the east-southeast and uplifted by approximately 3 m compared to before the earthquake (Sato et al. 2011).

After a megathrust earthquake, complex crustal deformation patterns occur mainly due to postseismic slips, and viscoelastic relaxation processes of the medium caused by coseismic and postseismic slips. In this section, we introduce the postseismic deformation modeling of the Tohoku-oki earthquake. The detailed mechanisms for the postseismic deformation of the Tohoku-oki earthquake are clarified by the dense inland crustal deformation observation network and seafloor crustal deformation observation. While east-southeast oriented motions have occurred in the interior of northeast Japan, subsidence and west-northwest motions have occurred near the Japan Trench off Miyagi (Sun et al. 2014; Watanabe et al. 2014). These motions are caused by the viscoelastic relaxation processes in the mantle (Sun et al. 2014). Modeling of the postseismic deformation considers the transient and rapid viscoelastic deformation immediately after the earthquake and the steady-state viscoelastic deformation that follows, the low viscous LAB, and the cold forearc mantle wedge (cold nose) beneath the Pacific coast (Sun et al. 2014). Decadal seafloor crustal deformation data have been obtained from seafloor observations, and variations in the north–south direction of the postseismic deformation have been discussed (Tomita et al. 2017; Watanabe et al. 2021).

In the analysis of postseismic deformation, it is necessary to properly evaluate the effects of viscoelastic relaxation and postseismic slip. The analysis is roughly categorized into three methods: (1) the effect of the viscoelastic deformation caused by a coseismic slip is calculated, the postseismic slip is analyzed using the data obtained by subtracting the calculated postseismic displacement from the observed data, and the postseismic slip is analyzed; (2) a simultaneous inversion analysis of the coseismic and postseismic slips assuming a viscoelastic structure is performed; and (3) forward modeling is conducted considering the viscoelastic structure and the friction law causing the postseismic slip. Recent models of postseismic deformation by the large-scale finite element method (Agata et al. 2019) and the integral method (Muto et al. 2019; Dhar et al. 2022) are based on experimental laws of rock flow (nonlinear flow law) in the mantle, where a power–law relationship exists between stress and strain rate, and fault friction laws at plate boundaries. This section outlines the progress in modeling of postseismic deformation.

After the 2011 Tohoku-oki earthquake, many researchers consider that the viscoelasticity of the mantle will be important for the earthquake cycle. Barbot (2020) developed an integrated model of the Tohoku-oki earthquake cycle, which can explain both the earthquake cycle and postseismic deformation, based on an experimental nonlinear flow law of rock in the mantle and a fault friction constitutive law. This section also presents the advanced model by Barbot (2020).

3.1 Modeling the postseismic deformation of the Tohoku-oki earthquake

When large stress changes occur in the mantle due to earthquakes, the mantle exhibits transitional viscoelastic behavior. In this case, the viscoelastic properties are represented by Burgers rheology (Maxwell elements + Kelvin elements) (Fig. 4a) (Wang et al. 2012). Sun et al. (2014) modeled the postseismic deformation of the Tohoku-oki earthquake considering a fault slip model modified slightly from Iinuma et al. (2012) and the viscoelastic structure using Burgers rheology (Fig. 4b–d). Based on previous studies on the mechanical decoupling of the oceanic lithosphere and the underlying mantle (Kawakatsu et al. 2009), they considered a low viscosity weak layer at the boundary between the oceanic lithosphere and the asthenosphere

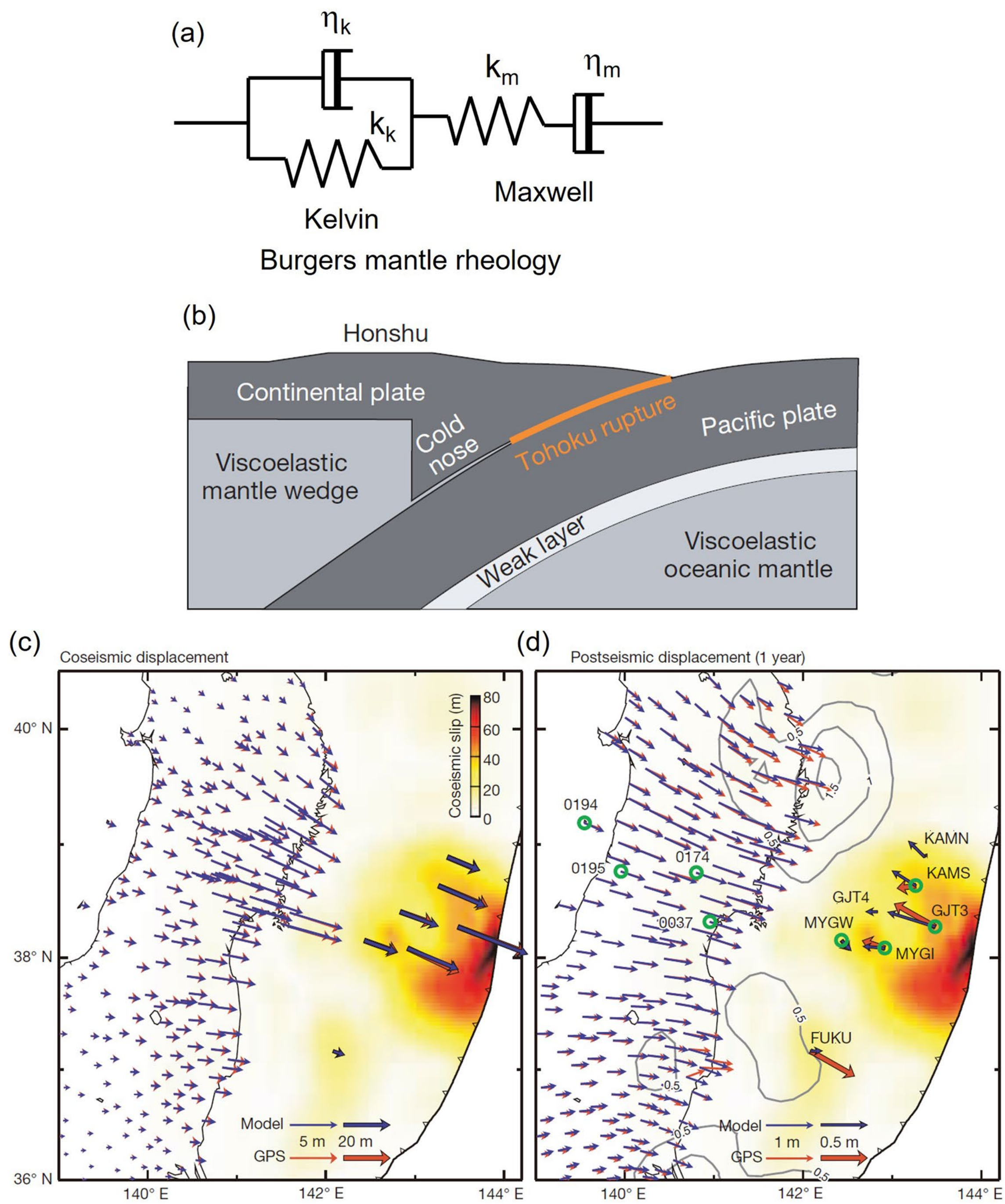

Fig. 4 Model of postseismic deformation by Sun et al. (2014). **a** Burgers rheology model. **b** 2D cross section of the 3D model of the 2011 Tohoku-oki earthquake constructed by Sun et al. (2014). The most seaward part of the wedge covering the slab area shallower than 70 km has an elastic "cold nose." It also includes a weak layer (LAB) beneath the oceanic plate. **c** Coseismic displacement of the 2011 Tohoku-oki earthquake at the GPS sites on land (Ozawa et al. 2011) and ocean floor (Sato et al. 2011; Kido et al. 2011) shown with the displacement predicted by the fault slip model (Iinuma et al. 2012). **d** Postseismic displacement of the 2011 Tohoku-oki earthquake. Displacement on land (Ozawa et al. 2012) and seafloor (Japan Coast Guard and Tohoku University 2013; Watanabe et al. 2014) GPS sites during the first year after the earthquake and model predictions using the viscoelastic finite element method of Sun et al. (2014). Black contours (m) are the postseismic slip distribution used in modeling. **b**–**d** are after Sun et al. (2014)

(LAB) (Fig. 4b). They also considered a cold nose (the presence of a cold elastic forearc mantle wedge) in the most seaward part of the wedge covering the shallower part of the slab (Fig. 4b). The presence of a cold nose was recently confirmed by an analysis of seismic wave anisotropy (Uchida et al. 2020). When analyzing postseismic geodetic observations, it was generally assumed that the short-term (a few years) deformations near the fault zone are mainly caused by a postseismic slip and that viscoelasticity is only important for a longer-term deformation (Hsu et al. 2006). The validity of this assumption is difficult to confirm using conventional geodetic data. However, as shown in Fig. 4d, the observations obtained by the GPS/acoustic seafloor observation for the Tohoku-oki earthquake indicate a rapid landward movement near the trench. This is in contrast to the seaward migration of the GPS sites located inland of the island arc. Using a numerical model of the transient viscoelastic mantle rheology, Sun et al. (2014) showed that this landward movement is the result of the stress relaxation induced by the asymmetric seismic rupture of the thrust earthquake. A large tensile stress on the upper plate during the earthquake causes a west-northwestward motion near the trench and an east-southeastward motion on the landward side as if it were in equilibrium within the viscoelastic relaxation process. Viscoelastic relaxation plays an essential role in short-term postseismic deformation.

Watanabe et al. (2014) detected a significant motion directly above the epicenter of the 2011 Tohoku-oki earthquake using GPS/acoustic seafloor positioning. While the coastal GNSS sites reported a trench-ward and upward motion, the repeated observations over a period of about 3 years at an offshore site above the main slip zone in the northern part of the epicenter area showed several tens of centimeters of landward displacement and significant subsidence. This offshore crustal deformation is consistent with the predicted consequences of viscoelastic relaxation of the upper mantle. In contrast, the results for the southern section of the epicenter region show a combination of viscoelastic relaxation and postseismic slip effects.

Iinuma et al. (2016) used seafloor and land-based geodetic data to estimate the postseismic slip distribution. They first subtracted the theoretical postseismic displacements calculated by the finite element method by Sun et al. (2014) from the observed postseismic displacements. Using the corrected data, which must be caused by postseismic slips, they then estimated the postseismic slips and found that the coseismic and postseismic slip distributions were spatially separated. The regions of postseismic slip were also consistent with the repeating earthquake activity. During the analysis period of about 8 months, they found the three regions, where large postseismic slip occurred at the plate interface: (1) the mid-depth area off Iwate Prefecture (25–55 km depth); (2) the mid-depth area off southern Miyagi and northern Fukushima (30–40 km depth); and (3) the shallow area off southern Fukushima and Ibaraki (< 20 km depth). These three areas are located outside the coseismic slip areas of the Tohoku-oki earthquake (Iinuma et al. 2012).

Analyses have also been performed using viscoelastic Green's functions for models with an upper elastic layer and a lower viscoelastic substrate (Yamagiwa et al. 2015; Noda et al. 2018). Yamagiwa et al. (2015) performed an inversion analysis of displacements of GPS inland stations and GPS/acoustic stations at the seafloor to obtain 2.5 years of postseismic slip, and coseismic slip for the 2011 Tohoku-oki earthquake, simultaneously. The results show that the postseismic slip zone is separated from the rupture zone of the Tohoku-oki earthquake and that the postseismic slip had almost decayed by September 10, 2013, 2.5 years after the main shock. The inversion results also suggest that the postseismic landward displacement observed at the seafloor GPS/acoustic station is due to viscoelastic relaxation, whereas the trench-ward displacement observed at the inland station is mainly an elastic response due to postseismic slip. The model does not account for the effects of elastic subducting plates. Stratified viscoelastic structures are considered to have greater landward motion near the trench.

Hu et al. (2016) integrated geodetic observations and postseismic constraints from small repeating earthquakes on the megathrust to more clearly distinguish between the viscoelastic relaxation processes and the postseismic slip contributions. They modeled the postseismic slip as a concentrated shear deformation that spontaneously occurs in a 2-km-thick low-viscosity shear zone in a region away from the coseismic zone of the Tohoku-oki earthquake. The transient Burgers rheology was used to simulate both the viscoelastic relaxation of the upper mantle and the deformation of the shear zone. The transient Kelvin viscosity was set as one order of magnitude less than the Maxwell viscosity. The postseismic slip on the fault leads to uplift and mostly seaward movement above the postseismic slip zone. The seafloor geodetic observations of subsidence and landward motion over the large coseismic slip region provide evidence for the presence of a low-viscosity LAB. The Maxwellian viscosity of 10^{17} Pa s for the low-viscosity shear zones below 50 km depth is optimal and is constrained by the estimates of the postseismic slip from the repeating earthquakes.

Freed et al. (2017) developed a 3D viscoelastic finite element model for the postseimic deformation of the

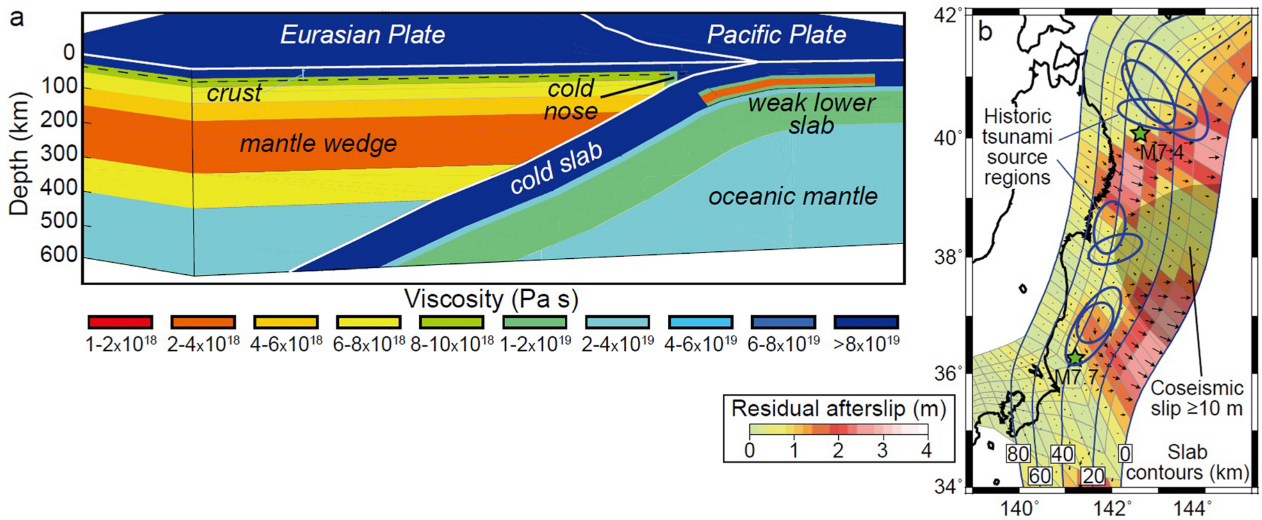

Fig. 5 Model of postseismic deformation by Freed et al. (2017). **a** Viscoelastic structure model used in the analysis by Freed et al. (2017). **b** Postseismic slip distribution explaining the 3-year postseismic displacements observed after the 2011 Tohoku-oki earthquake. The green stars are the epicenters of two large interplate aftershocks that occurred after the earthquake. The tsunami source area indicated by blue ovals is from Hashimoto et al. (2009). After Freed et al. (2017)

Tohoku-oki earthquake, considering the slab geometry associated with the Pacific and Philippine Sea plates, cold nose, depth-dependent viscous structure in the mantle wedge, and the low-viscosity region under the subducting slab, which is a region where stress is thought to be high due to plate bending (Fig. 5a). They estimated the postseismic slip (Fig. 5b) based on the residual surface displacement (i.e., observed GPS displacements minus predictions from the viscoelastic relaxation) and developed a combined viscoelastic relaxation and postseismic slip model that explains all observed horizontal and vertical postseismic displacements of the land and the seafloor. They also found that the pattern of crustal deformation caused by viscoelastic relaxation and postseismic slip is spatially distinct. The accurate prediction of horizontal and vertical postseismic displacement requires a depth-dependent viscous structure of the mantle wedge. The westward postseismic seafloor displacement is likely caused by the flow resulting from the low-temperature creep in the lower half of the Pacific lithosphere, which has been weakened by plate bending. The dominant mechanism of postseismic deformation immediately after the earthquake is both the postseismic slip and the viscoelastic relaxation caused by the Tohoku-oki earthquake.

Suito (2017) used a finite element method to construct a 3D viscoelastic model to investigate how each part of the viscoelastic medium affects the postseismic surface deformation. The viscoelasticity of the mantle wedge causes eastward propagation, uplift along the Pacific coast and offshore, and extensive expansion on the landward side. The viscoelasticity of the oceanic mantle, conversely, causes primarily westward motion offshore, widespread subsidence, slight uplift in marginal areas, and contraction offshore. As presented by Sun et al. (2014), a model with a thin low-viscosity layer (LAB) beneath the subducting oceanic plate may largely explain the near-field observations on land and at the seafloor, but not the far-field data. A model that considered the depth-dependent viscosity of the mantle wedge in the former model can explain the far-field observations as well as the near-field data. In modeling the viscoelastic relaxation process, it is particularly important to consider the difference in the viscosities of the mantle wedge and the oceanic mantle and to include the thin low-viscosity layer (LAB), which dramatically affects seafloor deformation.

Wang et al. (2018) reviewed what we have learned about the fault behavior and the rheology of the Earth from observations and modeling of the crustal deformation before, during, and after the Tohoku-oki earthquake. The postseismic geodetic measurements of the seafloor clearly indicate that viscoelastic relaxation is the dominant factor in short-term postseismic deformation. They also pointed out that the postseismic slip at the depth of the main rupture, deep off Miyagi Prefecture, differed depending on the model. For example, the results of Iinuma et al. (2016) indicate postseismic slip in the deep offshore Miyagi Prefecture is small, while the model of Yamagiwa et al. (2015) depicts the occurrence of large postseismic slips.

Previous thermopetrological models predicted a thermal contrast between the cold forearc and the hot backarc (e.g., Abers et al. 2006; Wada and Wang 2009). Analysis of seismic anisotropy also showed the existence of a cold, non-flowing forearc mantle wedge (cold nose) beneath the Pacific coast of northeast Japan (Uchida et al. 2020). Luo and Wang (2021) considered the sharp thermal contrast between the cold forearc and the hot backarc, which produces rheological contrasts in the mantle wedge: elastic in the forearc (cold nose) and viscoelastic in the backarc. Luo and Wang (2021) showed that the postseismic deformation associated with large subduction earthquakes gives independent evidence that rheological contrast is thermally controlled. Specifically, such a rheological contrast generates the upward deflection of seaward postseismic motion near the edge of the cold nose, resulting in an uplift in the forearc. They suggested that an uplift in the forearc after the Tohoku-oki earthquake was also attributed to the presence of the cold nose.

It has been argued that the vertical and horizontal variations of the postseismic deformation in inland northeast Japan are influenced by the volcanic front (Muto et al. 2016). By the postseismic deformation of the Tohoku-oki earthquake, the Pacific coast was uplifted; however, the Ou Backbone Range subsided. Muto et al. (2016) reported that this is due to the rheological structure of the crust and mantle structure, especially the existence of low-viscosity regions beneath the volcanic front.

3.2 Modeling of the postseismic deformation considering viscoelastic properties and friction law

Agata et al. (2019) performed large-scale numerical simulations of the postseismic deformation after the Tohoku-oki earthquake. They solved the postseismic slip driven by the stress changes caused by coseismic slip using the RS friction law. The rheological property was assumed to be a nonlinear flow law that follows the power–law relationship between strain rate and stress, which has been confirmed by laboratory experiments. The postseismic slip and the viscoelastic relaxation processes driven by stress changes were modeled using the coseismic slip (Fig. 6a) obtained from the model of earthquake cycles by Nakata et al. (2016).

In the nonlinear flow law, the effective viscous coefficient is proportional to the $-(n-1)$ power of the stress: $\sigma^{-(n-1)}$. Therefore, for $n=3$, the effective viscosity decreases when subjected to large stress variations. Figure 6b shows the distribution of the viscosity coefficient and the total displacement vector 2.8 years after the Tohoku-oki earthquake in the cross section of Miyagi Prefecture. Figure 6c shows the effects of the postseismic slip and the viscoelastic relaxation processes, separately. The simulation results indicated the possibility that the Tohoku-oki earthquake caused a large stress fluctuation, resulting in a sudden decrease in viscosity in the asthenosphere below the oceanic lithosphere due to nonlinear flow characteristics, and a rapid flow occurred there.

A linear viscoelastic model of the postseismic deformation of the Tohoku-oki earthquake assumed a thin low-viscosity layer along the boundary of the oceanic lithospheric asthenosphere (LAB) (Sun et al. 2014). This study suggests that it may be caused by nonlinear flow properties. The crustal deformation by the postseismic slip (Fig. 6c) showed that an eastward upward motion is occurring in the MYGW station off Miyagi Prefecture. As for the viscoelastic effect, a westward uplift motion occurs near the trench and a downward motion occurs at the MYGW. An eastward motion is observed east of the MYGW.

Muto et al. (2019) performed 2D modeling of the postseismic deformation using the integral method developed by Barbot et al. (2017), considering the nonlinear rheological properties of a rock reported from laboratory deformation experiments and the frictional properties of VS. In addition to the GEONET, Tohoku University has its own GNSS continuous observation network in this area, and high-density observations were conducted. They showed that the presently observed uplift of the Pacific coast is caused by postseismic slips in the deeper part of the fault zone, where coseismic slip occurred significantly during the earthquake. They modeled using the integral method, where the elastic constants are uniform, and the effect of gravity is not taken into account, but the heterogeneous viscous structure and friction law are taken into account. To investigate the along-arc variability in the cold forearc mantle wedge (cold nose), Dhar et al. (2022) performed a 3D modeling of the postseismic deformation using the integral method with constitutive laws from laboratory deformation experiments. The results suggest the heterogeneity in the forearc mantle rheology along the arc. A narrow cold nose was found to exist in the Miyagi Prefecture forearc region, and a wide cold nose in the Fukushima Prefecture forearc region.

Fukuda and Johnson (2021) developed a Bayesian inversion method that uses postseismic geodetic data to estimate the parameters for a stress-driven postseismic deformation model that integrates the postseismic slip produced by the VS friction property and the viscoelastic mantle relaxation. They used the 2.5D spectral element code VISCO2.5D developed by Pollitz (2014). The postseismic slip and the viscoelastic relaxation were assumed to occur due to coseismic stress changes resulting from the Tohoku-oki earthquake and to interact mechanically. The distribution of coseismic slip that drives the postseismic process and the parameters of fault friction and

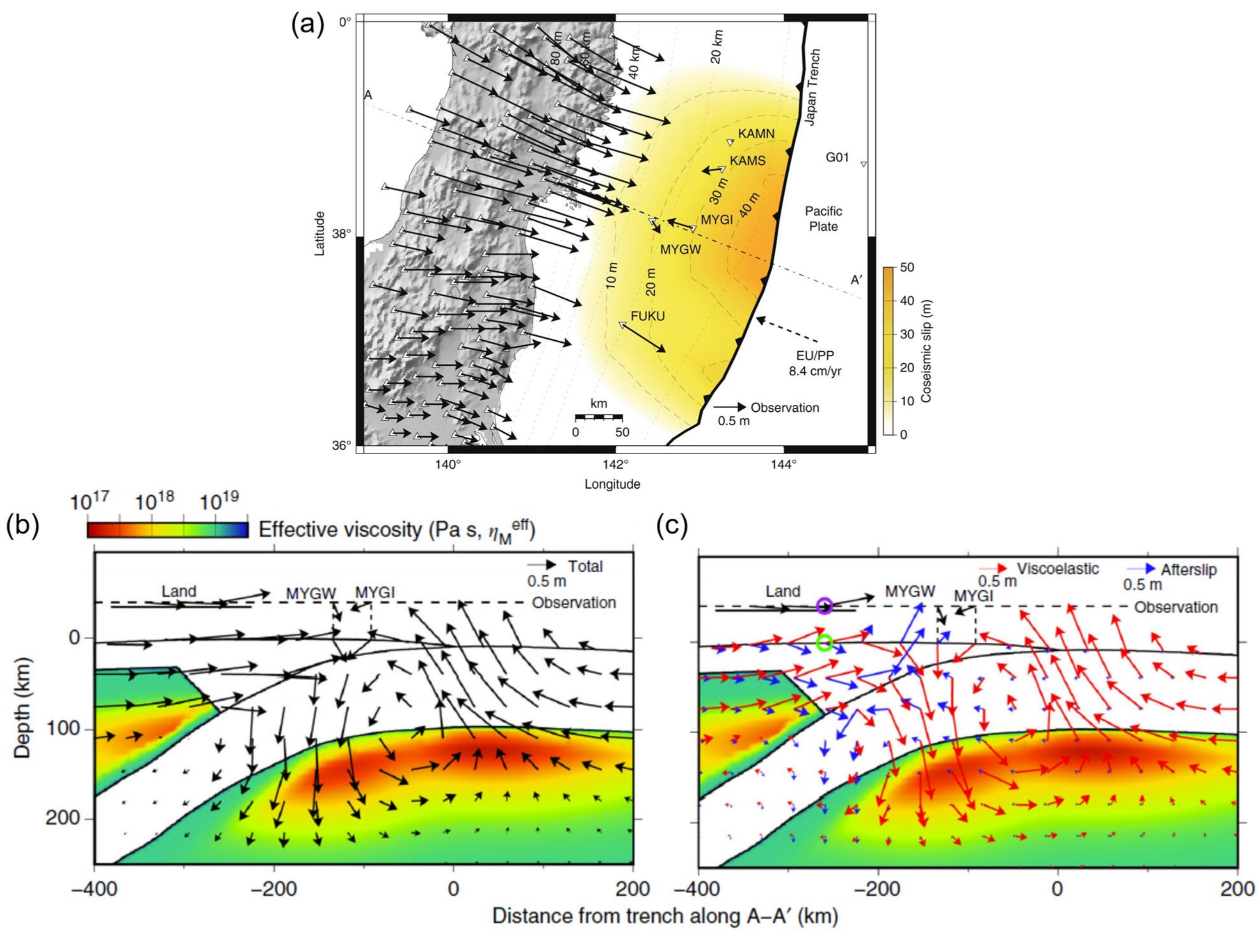

Fig. 6 Model of the postseismic deformation after the Tohoku-oki earthquake (Agata et al. 2019). **a** Observed displacement of the land and seafloor stations shown by triangles and inverted triangles, respectively. The dashed-dotted line (A–A′) indicates the location of the vertical cross section. The dotted lines show the depth counter lines of the plate boundary. Coseismic slip is used from the simulation results of the megathrust earthquake cycle in the Tohoku region (Nakata et al. 2016). **b** Total displacement and viscosity of the viscoelastic medium 2.8 years after the Tohoku-oki earthquake. The distribution of effective viscosity in non-linear Maxwell elements immediately after the earthquake is shown with color. The observed displacements in A–A′ profiles, including stations MYGW and MYGI, are represented by the black arrows on the horizontal dashed lines. **c** Decomposed into viscoelastic relaxation and postseismic slip contribution. Elastic deformation caused by the postseismic slip and the contribution of viscoelastic deformation after 2.8 years. The observed displacement at the location of the purple circle shows an uplift. The uplift caused by the viscoelastic deformation at the location of the green circle is counteracted by the subsidence caused by postseismic slip

mantle viscosity are unknown parameters for estimation. They used this method to analyze the time series of the coseismic and postseismic displacements of the 2011 Tohoku-oki earthquake. The first-order spatial and temporal patterns for the postseismic horizontal and vertical deformation were well reproduced by the estimated model. Postseismic slip and viscoelastic relaxation have spatially distinct contributions to the horizontal and vertical deformations following the Tohoku-oki earthquake. The findings of Fukuda and Johnson (2021) indicate that postseismic slip occurred at the lower extension of the coseismic slip, which is consistent with earlier models, including the stress-driven postseismic slip (Agata et al. 2019; Hu et al. 2016; Muto et al. 2019).

The contribution of viscoelasticity and postseismic slip to the vertical deformation of the forearc seems to be unresolved. It may depend on the modeling approach. Previous analyses considering the kinematic postseismic slip and the effects of the viscoelastic mantle relaxation and elastic subducting slab showed that the postseismic slip in the lower extension of coseismic slip zone in Miyagi Prefecture was small (Iinuma et al. 2016; Sun et al. 2014; Wang et al. 2018). The upward deflection of postseismic seaward motion near the edge of the cold nose causes uplifts of the forearc (Luo and Wang 2021).

In the stress-driven model, stress concentrates, and postseismic slip occurs in the deep extension of the coseismic slip zone. It is possible that the postseismic slip in the deep extension of the off Miyagi Prefecture earthquake occurred due to the stress increase caused by the Tohoku-oki earthquake. As explained in Section 2.6, the 2021 M_w7.0 and M_w6.7 off Miyagi Prefecture earthquake occurred in the deep part of the 1978 off Miyagi Prefecture earthquake fault (Yoshida et al. 2022), indicating that postseismic slip occurred in the deep part of the earthquake fault and that stresses were accumulated at the source region of the 2021 off Miyagi Prefecture earthquake.

3.3 Modeling of earthquake cycles considering viscoelastic properties and friction laws

Applying the integral method (Barbot 2018), Barbot (2020) developed a model of the Tohoku-oki earthquake cycle that accounts for the 2D rheological structure and the segmental structure of the frictional properties of the plate boundary (Fig. 7a). Although this model adopts homogeneous elastic constants, it can consider viscoelastic structures in the mantle wedge and the oceanic asthenosphere. To model the off Miyagi Prefecture earthquake, a patch of VW is set at the mantle-wedge corner. Above this patch is a region of VS, which is structurally controlled. Therefore, off Miyagi prefecture earthquakes occur regularly at the mantle-wedge corner. In the forearc basement and shallow sections, where the unstable zone is much larger than the nucleation size, the rupture sequence becomes complex because the fault-slip dynamics are inherently nonlinear. Under these conditions, partial and full rupture of the VW regions occurs. This characteristic of the earthquake cycle causes aperiodicity in the sequence (Fig. 7b–d). For full rupture, the rupture reaches the trench. This model reproduces the occurrence of megathrust earthquakes with millennial intervals and earthquakes with multidecadal intervals off Miyagi Prefecture. The model also reproduces the coseismic crustal deformation during the Tohoku-oki earthquake and the postseismic deformation observed from 21 to 265 days after the Tohoku-oki earthquake. How viscoelastic flow affects the cycles of megathrust and off Miyagi Prefecture earthquakes is an important issue for future studies. Shi et al. (2020) developed a model of large earthquake cycles and long-term and short-term SSEs in the Nankai trough subduction zone, which accounts for viscoelastic structures. They found that viscoelastic flow in the upper mantle gradually changes the earthquake cycle and the occurrence of SSEs. More details are given in Shi et al. (2020).

4 Long-term vertical deformation along the Pacific coast before and after the Tohoku-oki earthquake

4.1 Observation of long-term vertical deformation along the Pacific coast

The vertical crustal deformation rates for about 100 years before the Tohoku-oki earthquake were investigated by level survey observations (Kunimi et al. 2001; Nishimura 2014). Figure 8 shows the distribution of the vertical crustal deformation rates for about 93 years before the Tohoku-oki earthquake (Sasajima et al. 2019). On the Pacific coast, large subsidence rates (3–4 mm/yr) were observed over an area of about 200 km from north to south, centered on the Oshika Peninsula. In addition, uplifting at a rate of 1–4 mm/yr occurred from the volcanic front to the Japan Sea coast. These uplift and subsidence rates were almost constant over 100 years.

On the other hand, geomorphological and geological studies have shown that the Pacific coast had been uplifting at a rate of 0.1–0.5 mm/yr over a long-term time scale of 100,000 years (Koike and Machida 2001). This suggested that the subsidence that occurred before the earthquake would be resolved and uplifted by the occurrence of a megathrust earthquake (Ikeda 2014). In reality, however, a huge slip of up to 50 m occurred at the shallow part of the plate boundary during the Tohoku-oki earthquake, resulting in significant uplift off Miyagi Prefecture and significant subsidence along the Pacific coast, west of the large slip area (Fig. 9 left) (Geospatial

(See figure on next page.)

Fig. 7 Simulation model of earthquake cycles and viscoelastic flow in the Japan Trench subduction zone (Barbot 2020). **a** 2D cross sections of the parameters of the segmental structure of the subduction plate boundary and the viscoelastic structure of the medium. The VW and VS segments at the plate boundary are shown in yellow and gray, respectively; the two plates adhere deep in the brittle-plastic region. The background colors indicate the temperatures in the oceanic and mantle-wedge asthenosphere. The viscoelastic region is divided by a triangular mesh. Steady-state viscosity contours are shown in yellow, green, and blue profiles for 10^{20} Pa s, 10^{21} Pa s, and 10^{22} Pa s, respectively. The small numbers in the corners of the fault segments indicate the starting depths in the model. **b** and **c** Slip-velocity changes in the dip direction of the Megaspray and Megathrust faults over 1000 years. The dashed horizontal lines delineate the segment boundaries. The stars indicate the earthquake locations. They are color-coded by the peak slip velocity reached during the earthquake. Partial rupture is restricted to the forearc base. In megathrust earthquakes, the slip propagates to the trench and megasplay faults. All earthquakes are followed by postseismic slips. The event groups before and after the megathrust rupture correspond to foreshocks and aftershocks, respectively. **d** Change in slip velocity at the center of the VW segment and the peak velocity at all locations along the megathrust/megaspray system

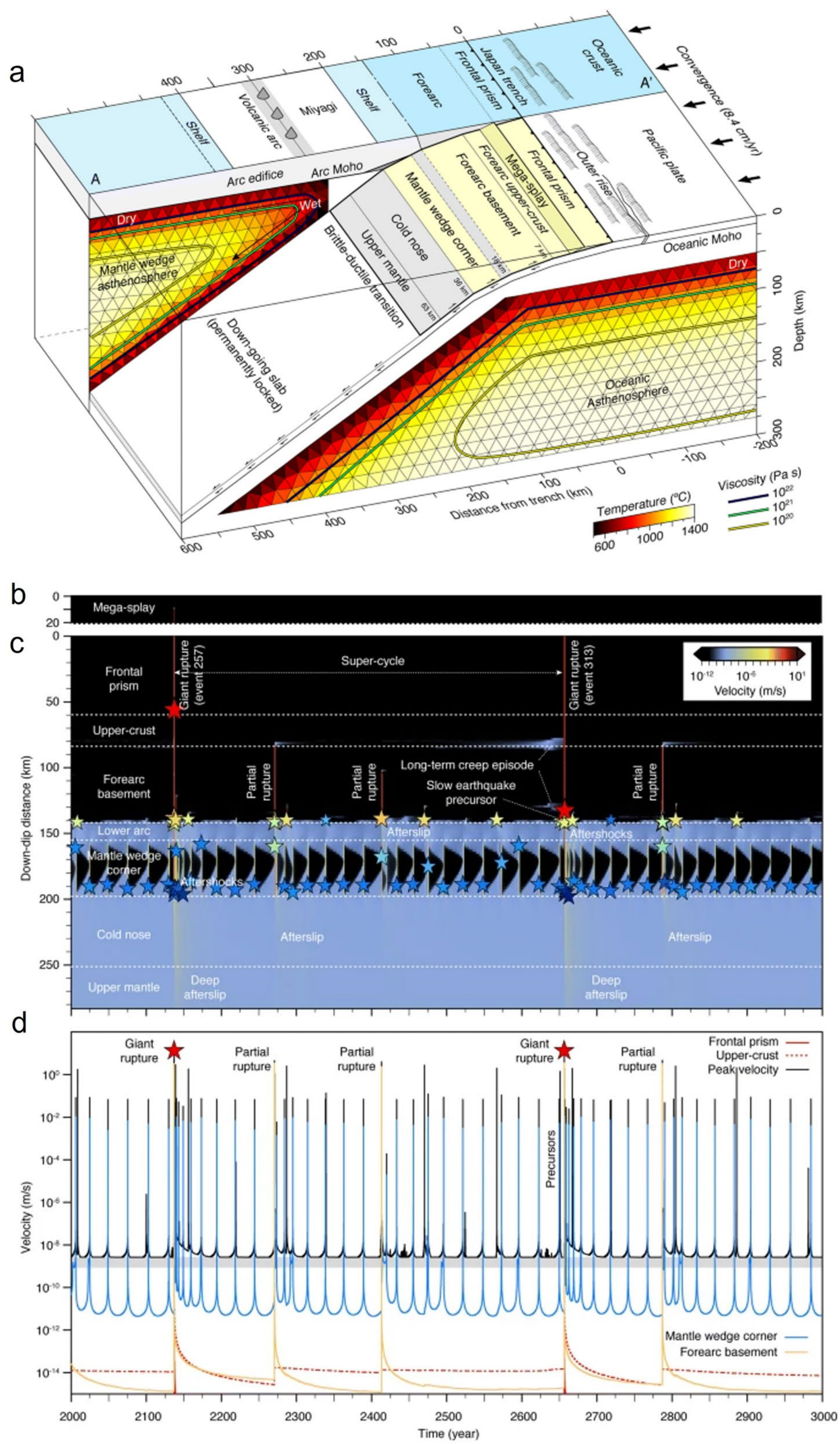

Fig. 7 (See legend on previous page.)

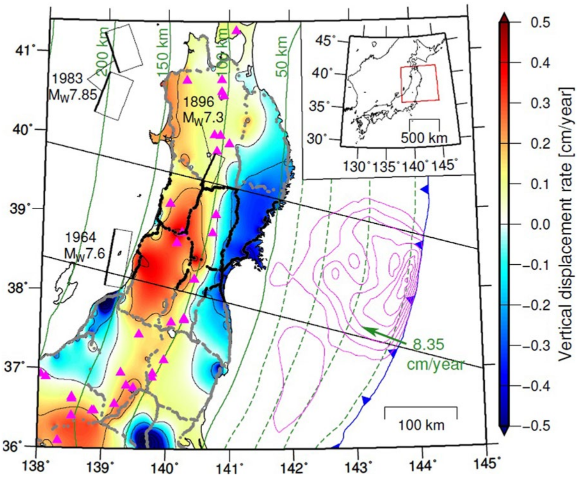

Fig. 8 Vertical land-surface deformation rates in the Tohoku region for about 100 years before the Tohoku-oki earthquake. Leveling measurements were taken from 1892–1906 to 1986–1999 (original data from Kunimi et al. 2001). The effects of coseismic and postseismic deformation of the three major earthquakes (the inland earthquake and the two earthquakes in the Sea of Japan) are excluded in the figure. The contours are at 0.2 cm/yr intervals, and the thick line represents 0 cm/yr. The gray dots on land represent points of leveling measurements. The model results (Fig. 8) are compared with the data for the area enclosed by the two black lines. The pink lines off Miyagi Prefecture show the distribution of estimated slip during the 2011 Tohoku-oki earthquake (Iinuma et al. 2012) (shown at 10 m intervals). The green contours represent the depth of the upper surface of the subducting Pacific plate. Modified from the figure in Sasajima et al. (2019)

Information Authority of Japan 2021). A GPS crustal movement station on the Oshika Peninsula experienced 1.2 m of subsidence.

After the Tohoku-oki earthquake, the uplift has been progressing mainly along the Pacific coast of northeast Japan due to the postseismic deformation (Fig. 9 right) (Geospatial Information Authority of Japan 2021). On the Oshika Peninsula, approximately 69 cm of uplift was observed 10 years after the Tohoku-oki earthquake, which is about 60% of the 1.2 m subsidence that occurred during the earthquake. A further uplift is expected to occur in the future to explain the uplift on a long-term geological time scale.

This section presents the model by Sasajima et al. (2019), which explains why subsidence occurred along the Pacific coast before the Tohoku-oki earthquake. We then also discuss how vertical deformation of the Pacific coast proceeds over megathrust earthquake cycles and even over geologic timescales, including recent observations of postseismic deformation. The crustal deformation between earthquake cycles will be a critical issue in monitoring the strain accumulation and release processes of megathrust earthquakes.

4.2 Mechanism of vertical deformation of the Pacific coast before the Tohoku-oki earthquake

The subsidence rates observed along the Pacific coast of northeast Japan during the 100 years prior to the Tohoku-oki earthquake have been attempted to be reproduced by kinematic models of earthquake cycles of interplate coupling and sliding. Nishimura (2014) used a model that assumes an elastic half-space to reproduce the observed interseismic subsidence. This model showed that very deep interplate coupling is required with a coupling ratio of 50–30% at depths of 50–100 km (Nishimura 2014; Suwa et al. 2006). The coupling ratio is defined as $(v_{pl} - v)/v_{pl}$, where v_{pl} and v denote the long-term plate convergence and interseismic fault slip rates, respectively. Models that assume layered elastic and viscoelastic structures produced different results and required a shallow (< 40 km depth (Sagiya 2015) or < 25 km depth (Hashima and Sato 2017)) interplate coupling to yield the observed interseismic subsidence rates. However, there is a subducting slab that behaves elastically and needs to be evaluated.

Sasajima et al. (2019) estimated the 2D distribution of crustal and mantle viscosity coefficients based on the thermal structure and water content distributions and the results of rock flow experiments (Fig. 10a). The thermal structure and water-content distribution were determined based on the simulation results of the mantle wedge convection and dehydration reported in a previous study (Horiuchi and Iwamori 2016). Sasajima et al. (2019) approximated the frictionally stable part of the crust and the upper mantle as a thin viscous layer in a manner similar to Hu et al. (2016). At the deep plate boundary, frictional slip on the fault plane changes to volumetric and ductile deformation in the shear zone (e.g., Angiboust, et al. 2015). Based on the depth of the early postseismic slip that occurred approximately nine months after the 2011 Tohoku-oki earthquake, the transition depth from a brittle zone (frictional slip on the fault plane) to a ductile zone (volumetric ductile deformation in the shear zone) is estimated to be 70 km (Fig. 10a, c). However, the viscosity, width, and shape of the shear zone are not well known. Therefore, Sasajima et al. (2019) tested various scenarios with respect to the shear zone and selected the scenario that best explained the observed vertical deformation of the crust. At depths below 70 km, the width and viscosity of the shear zone increased from 3 to 10 km and from 2×10^{17} to 2×10^{19} Pa s, respectively, representing a transition from local to distributed deformation. They simulated the crustal deformation associated with the Tohoku-oki earthquake cycle, reproduced the vertical crustal deformation along the coast, and clarified why subsidence occurred along the Pacific coast prior to earthquakes. In particular, in volcanic fronts,

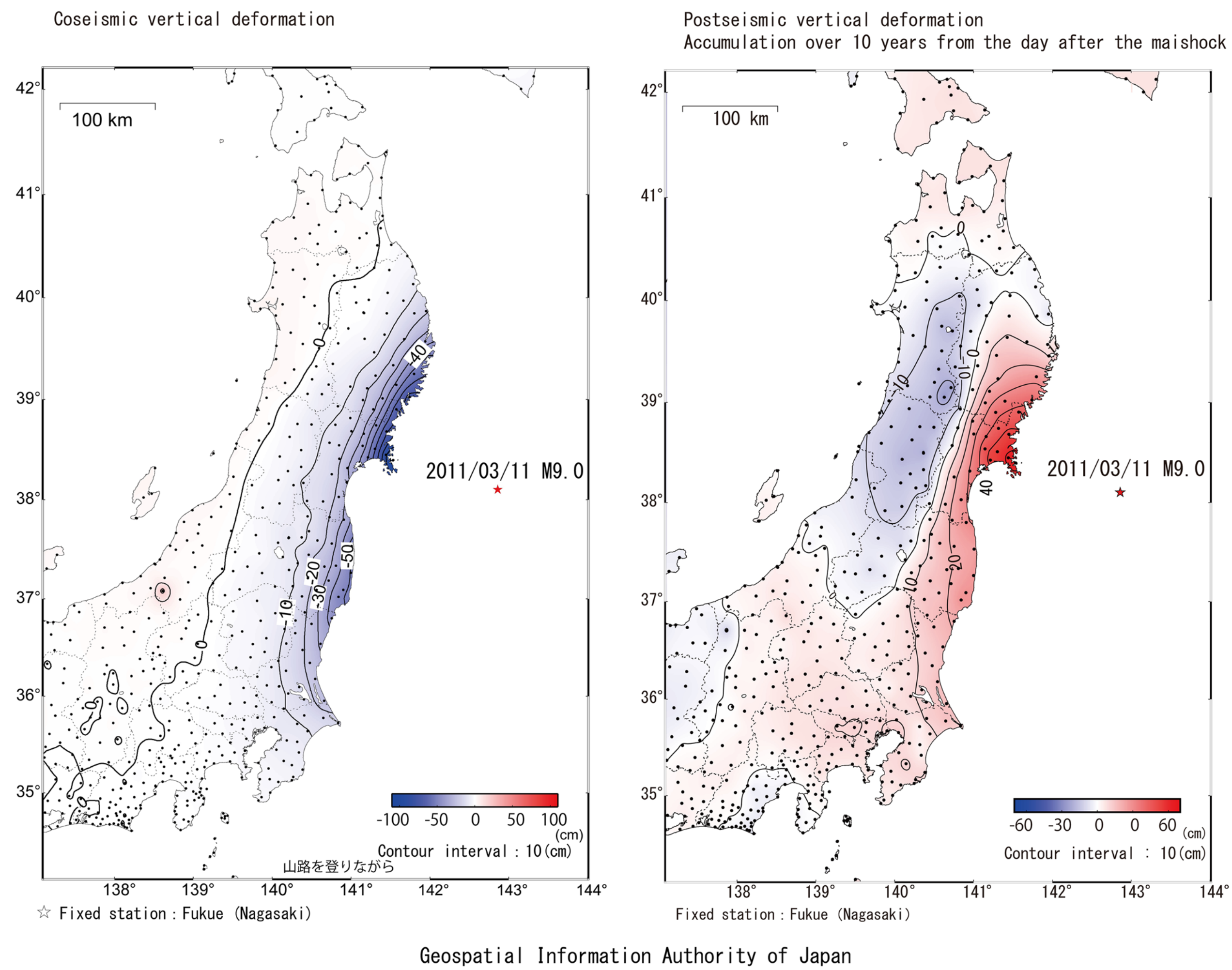

Fig. 9 Coseismic and postseismic displacement of the Tohoku-oki earthquake. (Right) Coseismic vertical displacement of the Tohoku-oki earthquake. (Left) Postseismic vertical deformation (accumulated for 10 years from the day after the Tohoku-oki earthquake). The black dots indicate the GPS sites. Modified from the GSI website (Geospatial Information Authority of Japan 2021)

low-viscosity regions are thought to exist in the shallow crust.

Because a large slip occurred in a shallow subduction interface during the Tohoku-oki earthquake (Iinuma et al. 2012), Sasajima et al. (2019) modeled the crustal deformation by assuming that the shallow large slip area (asperity) is completely coupled, and that a slip deficit $v_{pl}t$ occurs during the interseismic period (Fig. 10d). The simulation results show that when the coupling at the asperity continues for several hundred years, the viscous nature of the mantle wedge makes the overlying landward plate more easily dragged. The slip deficit rate at depth (Fig. 10d) increases as the landward plate is dragged down to the deeper part of the plate boundary (about 100 km depth), and the Pacific coastal region begins to subside (Fig. 10b). Figure 10b shows that the Pacific coast exhibits uplift in the first half of the megathrust earthquake cycle but turns to subsidence in the second half. In addition, the distribution of the vertical displacement rate 600 years after the occurrence of the megathrust earthquake shows subsidence along the Pacific coast and uplift from the volcanic front to the Sea of Japan coast. This result is consistent with the observations obtained by level surveying. The subsidence of the Pacific coast observed for about 100 years prior to the Tohoku-oki earthquake is thought to have occurred as a result of the asperities of the large slip zone of the 2011 Tohoku-oki earthquake remaining locked for 500–600 years.

Figure 11 shows the modeled cross sections of the velocity vectors in the continental crust and mantle at 100, 250 and 600 years after a megathrust earthquake. After 100 years, the trench-oriented motion occurs in the island arc, but westward motion gradually becomes dominant (at $t' = 250$ years). At $t' = 600$ years, the predicted

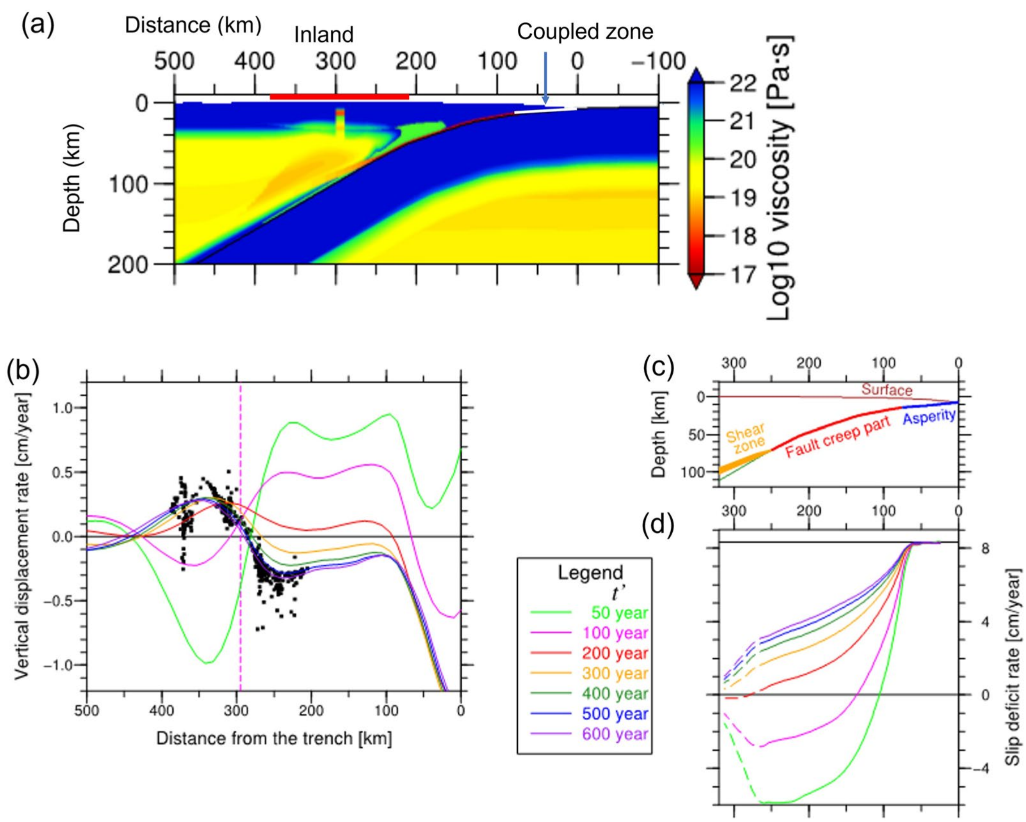

Fig. 10. 2D Model and numerical results of the vertical deformation during the Tohoku-oki earthquake cycle. After Sasajima et al. (2019). **a** Rheological structure (viscosity distribution) in a finite element model. The white line indicates the complete coupled zone, providing the backslip between earthquakes. The plate boundary at the deep extension of the coupled zone comprises a thin (~ 3 km) viscoelastic layer (red zone) with a low viscosity that almost freely creeps during the interseismic period. The viscosity distribution is established based on pressure, water fugacity, assumed strain rate, and mineral flow laws. **b** Modeling results of the interplate coupling in the megathrust earthquakes. The vertical displacement rates are obtained from the observations and simulations. The black dots indicate the surface vertical displacement rates for approximately 100 years before the Tohoku-oki earthquake based on the level survey observations in the area between the two black lines in Fig. 8. Each colored line illustrates the vertical displacement rates at the elapsed time *t'* after the asperities of the megathrust earthquakes have been coupled. The location of the volcanic front is indicated by the pink vertical dashed line. The simulation results show that the subsidence rate in the Pacific coastal region increases toward the latter half of the megathrust earthquake cycle, and the results after 500–600 years are roughly in good agreement with the level survey observations. **c** Cross section of the 2D model with the plate boundary conditions. The green line is the plate boundary. **d** The slip deficit velocities at the plate boundary and the ductile shear zone obtained by the model are represented by the solid and dashed lines. The horizontal solid line shows the slip deficit velocity (8.35 cm/yr) under complete coupling

horizontal displacement velocity in the forearc region (3.0–3.7 cm/yr) is compatible with the interseismic horizontal displacement velocity (~ 3–4 cm/yr) in the forearc region (38°–39° N) recorded by the GNSS in 1997–2000 (Nishimura 2014).

4.3 Mechanism of vertical deformation of the Pacific coast over Tohoku-oki earthquake cycle and geological time scale

Nishimura (2014) proposed a model of vertical crustal deformation along the Pacific coast associated with the Tohoku-oki earthquake cycle. In this model, the coast subsides at a rate of about 3–4 mm/yr starting in the latter half of the earthquake cycle, subsides significantly during the earthquake, and then uplifts over a period of several decades. In the long-term geological time scale, the Pacific coast is uplifting at a rate of 0.1 mm/yr.

A subsidence of 1.2 m occurred at the Oshika Peninsula along the Pacific coast during the 2011 Tohoku-oki earthquake, and an uplift of about 69 cm occurred there due to the postseismic deformation over 10 years (Geospatial Information Authority of Japan 2021). As explained in the previous section, analyses of postseismic deformation indicate that the uplift along the Pacific coast in the years after the earthquake was caused by the postseismic slip in the deeper extension of the large slip zone, although a contribution from postseismic deformation caused by the cold,

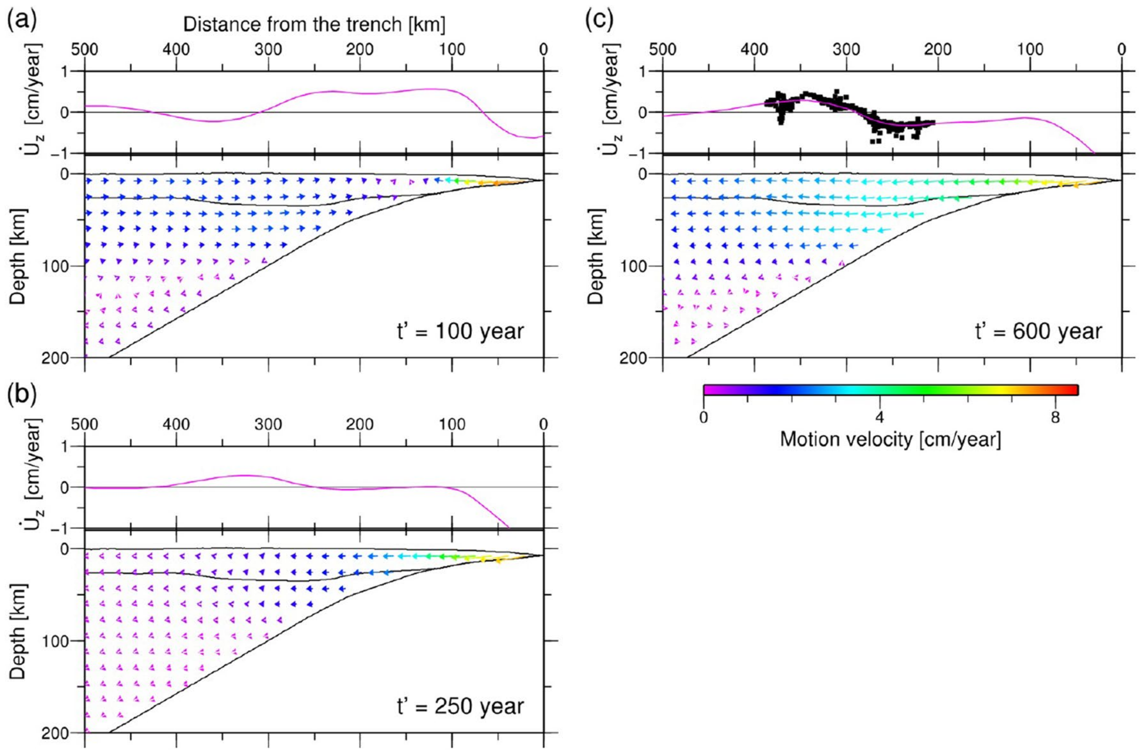

Fig. 11 Cross sections of the modeled velocity vectors and surface vertical displacement velocities in the continental crust and mantle. **a**–**c** The pink lines at the top of each image show the modeled vertical surface displacement rates ($\dot{U}_Z$) at **a** $t'=100$ years, **b** $t'=250$ years, and **c** $t'=600$ years (t' is the time since the fifth earthquake in the model). The black dots in **c** show the observed $\dot{U}_Z$ for the northeast Japan island arc for approximately 100 years before the 2011 Tohoku-oki earthquake (see Fig. 8). The colored arrows at the bottom of each image indicate the modeled velocity vector for the continental crust and mantle at each t'. The magnitude of the velocity is indicated by the arrow length and color. The black lines in each image indicate the top surface of the land or ocean floor, the continental Moho, and the subducting ocean lithosphere. After Sasajima et al. (2019)

flow-resistant mantle wedge (cold nose) beneath the Pacific coast of northeast Japan, was also proposed.

There should be enough uplift to counteract the pre-seismic and coseismic subsidence to explain the uplift on a geologic scale (0.1 mm/yr). Therefore, it is expected that it will take several more decades for this uplift to compensate for interseismic and coseismic subsidence. The model of Sasajima et al. (2019) predicted that slow shear deformation occurs in the ductile shear zone at depth and reproduces uplift over several decades on the Oshika Peninsula. Furthermore, the area turns to subsidence a few hundred years after the earthquake because of the interplate coupling at the asperity of the megathrust earthquakes.

The model developed by Sasajima et al. (2019) is useful for estimating the long-term deformation associated with one cycle of the 2011 Tohoku-oki earthquake, but did not model crustal deformation that occurred one decade after the Tohoku-oki earthquake. Sasajima et al. (2019) approximated the frictionally stable part of the crust and the upper mantle as a thin viscous layer but did not adjust the parameters to account for the initial postseismic slip. Moreover, Sasajima et al. (2019) assumed Newtonian viscoelasticity without considering transient deformation immediately after the earthquake. Hence, future numerical modeling attempts must incorporate the fault friction law at the deeper extension of the asperity and transient rheology to model postseismic deformation and deformation associated with one cycle of the Tohoku-oki earthquake.

Hu et al. (2016) also discussed whether the long-term coastal uplift is caused by deformation due to earthquake cycles. They examined the coastal uplift and subsidence in one earthquake cycle caused by interseismic relocking of faults, coseismic rupture (≤ 1.0 m subsidence), postseismic viscoelastic deformation (≤ 2 m uplift), and glacial isostatic adjustment (~ 0.1 m) since the last glacial maximum. To obtain the vertical deformation during the interseismic period of one earthquake cycle, they estimated mean velocities derived from GPS time series data from 1998 to 2002. The total net coastal deformation was ~ 3 mm/year of subsidence, the opposite of the observed long-term coastal uplift. Hu et al. (2016) also developed a viscoelastic model of interseismic relocking of the fault, in which the strain released by the 2011 Tohoku-oki earthquake accumulates linearly over 600 years. The net coastal vertical deformation estimated using this result instead of using preseismic mean velocities is 2 mm/year of uplift, which is more consistent with geologic terrace uplift.

Furthermore, models of long-term crustal deformation must consider various factors, including gravity, heterogeneous viscoelastic structures, transient viscoelasticity, interseismic coupling, coseismic slip, and postseismic slip. The deformation caused by steady plate subduction must also be considered. Although long-term deformation processes considering the earthquake cycles and steady plate subduction have been modeled with layered elastic and viscoelastic structures (Sagiya 2015; Hashima and Sato 2017), the effects of the slab also need to be considered.

Like the Pacific coast of northeast Japan, the Pacific coast of Hokkaido has also been subsiding over the past 50 years. Studies on tsunami deposits (Nanayama et al. 2003) revealed that a megathrust earthquake occurred in the Chishima Trench subduction zone in the seventeenth century, and that the megathrust earthquakes occur there at intervals of about 400 years. Furthermore, the Pacific coast was uplifted by 1.5 m over about 60 years after the last earthquake, which is thought to be due to the postseismic changes after a megathrust earthquake (Sawai et al. 2004). The subsequent subsidence is likely to have occurred along the Pacific coast of Hokkaido as a result of the 400-year coupling of the megathrust asperity. If seismic coupling continues at the asperity, the slip deficit will be at least 30 m, which could result in a megathrust earthquake that would recover the slip deficit.

5 Future issues

We summarize the future challenges in modeling earthquake cycles and associated crustal deformation. The earthquake cycle models developed by Noda and Lapusta (2013), Cubas et al. (2015) and Noda et al. (2017) consider dynamic effects by assuming planar or linear faulting in an elastic medium. However, the other models considering the 3D plate boundary considered dynamic effects approximately. In the future, earthquake cycle models considering 3D subduction interface geometry and dynamic effects should be constructed. It is also noted that dynamic effects due to low-velocity regions such as the accretionary wedge and free surfaces are important for shallow rupture processes (Kozdon and Dunham 2013).

Shibazaki et al. (2019) proposed a model that considers the frictional properties of shallow faults, demonstrating that SSEs can occur on shallow faults. SSEs occurred in the shallow part of the Japan Trench (an approximate depth of 10–20 km) before the Tohoku-oki earthquake (Ito et al. 2013). However, SSEs at these depths were not reproduced in the study by Shibazaki et al. (2019). Nishikawa et al. (2023) showed that various types of SSEs and low-frequency tremors occur in the northeast Japan subduction zone. The mechanisms of these SSEs and low-frequency tremors must be studied in the future.

Other important considerations based on the Tohoku-oki earthquake cycle are seismic activities at the plate boundaries deep off Miyagi Prefecture, off Fukushima Prefecture, and off Ibaraki Prefecture around the large postseismic slip regions. It has been suggested that postseismic slip in the deeper extension of the coseismic slip zone of the Tohoku-oki earthquake results in the early occurrence of the off Miyagi Prefecture earthquake (Nakata et al. 2016). The effect of such postseismic slips on the earthquake cycle off Fukushima and Ibaraki Prefectures must also be resolved. The amount of postseismic slip at the deeper extension of the off Miyagi Prefecture earthquake should also be estimated by the analysis of postseismic deformation.

As for the uplift in the last 10 years along the coast of northeastern Japan (Miyagi Prefecture), the extent to which viscoelastic deformation and postseismic slip contribute to the uplift, respectively, when the cold nose is considered is still unclear. The 2021 M_w7.0 and M_w6.7 off Miyagi Prefecture earthquakes occurred at the deeper part of the 1978 off Miyagi earthquake zone (Yoshida et al. 2022), indicating that some postseismic slip occurred at depth and that stress accumulated on the asperity of the off Miyagi Prefecture earthquake.

The effects considered in postseismic deformation models depend on the analysis method. For example, the integral method accounts for heterogeneous viscoelastic structures and postseismic slip but excludes differences in elastic constants and density. In contrast, some finite element modeling accounts for heterogeneity in the elastic constants and density, viscoelastic structures, and postseismic slip. The dependence of the results on the modeling method should be further evaluated in future research.

So far, researchers have developed relatively simple models to clarify the physical mechanisms of the elementary processes of earthquake cycles and postseismic deformation. In future work, the modeling of the stress accumulation processes, nucleation, dynamic rupture, and postseismic and interseismic deformation should be integrated. Earthquake cycle models that consider viscoelasticity, such as the one constructed by Barbot (2020), are pioneering studies, but the effects of viscoelasticity on the earthquake cycle must be clarified.

In the future, we will obtain long-term crustal deformation observation data. Based on the data, it will be necessary to construct a model that can explain the long-term postseismic deformation caused by the Tohoku-oki earthquake. Such a model should consider the viscoelastic relaxation processes, postseismic slip, and interplate coupling, along with heterogeneous elastic constants, density structures, and viscosity coefficients. It is necessary to elucidate how vertical variations evolve in time along the Pacific coast over the several decades following the Tohoku-oki earthquake and what mechanisms are responsible for these variations.

Comparative studies in other subduction zones are needed. For example, in the Kuril Trench, as well as in the northeast Japan subduction zone, megathrust earthquakes are known to occur once every several hundred years. In addition, as mentioned in Sect. 4, subsidence along the Pacific coast is progressing. The findings obtained by studying the occurrence of the Tohoku-oki earthquake might be applicable to these studies.

Another important issue, which has not been discussed in this paper, is the modeling of the stress field from the subducting Pacific Plate to the island arc associated with a megathrust earthquake cycle. There have already been several observations on the coseismic rotation of the stress field in most of the offshore forearc after the Tohoku-oki earthquake (e.g., Hasegawa et al. 2011, 2012). The mechanisms of this stress reversal in offshore forearc due to the Tohoku-oki earthquake were discussed by Wang et al. (2019). Modeling the absolute stress field and stress changes associated with the Tohoku-oki earthquake cycle from the subduction zone to the island arc is also a future task.

6 Conclusion

This paper summarized the results of 10 years of research on earthquake cycle modeling and crustal deformation modeling associated with the Tohoku-oki earthquake. Several earthquake cycle models have been proposed to elucidate why megathrust earthquakes occur at intervals of about 600 years and M7-class earthquakes occur at intervals of several decades in the northeast Japan subduction zone, and why giant slips occur in the shallow subduction zone. A model that considers strong asperities by setting a region of high effective stress in the shallow plate interface off the Tohoku coast, and a hierarchical asperity model that considers the scale dependency of the critical displacements of the RS friction law: a small critical displacement for M7-class earthquakes, a large critical displacement for M9-class earthquakes, have been proposed.

Based on high-speed friction experiments on rocks, modeling that accounts for dynamic weakening (a significant decrease in frictional strength at high slip velocities) has also been proposed. In the model considering TP, a second weakening process with an apparently large critical displacement appears in addition to the response caused by the properties of the RS friction law. Although the physical mechanism is different, the large value of critical displacement is also taken into account, as in the hierarchical asperity model. The shallow friction and the hydraulic characteristics obtained by JFAST indicate that the friction strength at shallow depths is small, but TP can still occur. The frictional properties also indicate that SSEs can occur. Rupture from depth can easily propagate to the trench, resulting in significant coseismic slip in the shallow plate interface.

Regarding the postseismic deformation of the Tohoku-oki earthquake, crustal deformation near the trench has been observed, for the first time, through seafloor geodetic observations in addition to a detailed crustal deformation observed by the dense GNSS network on land. The detailed mechanism of the postseismic deformation has been clarified. While east-southeast motions had been occurring in the land region, subsidence, and west-northwest motions had been occurring near the Japan Trench, off Miyagi. These motions were shown to be caused by the viscoelastic relaxation processes in the mantle. Viscoelastic relaxation was found to play an important role in short-term deformation after the earthquake. The transient and rapid viscoelastic deformation immediately after the earthquake and the steady-state viscoelastic deformation thereafter, the low viscosity zone (LAB) between the oceanic plate and the asthenosphere beneath it, and the cold flow-impeding forearc mantle wedge (cold nose) have been discussed.

In the analysis of postseismic deformation, it is necessary to properly evaluate the effects of the viscoelastic relaxation of the oceanic mantle and mantle wedge, and the postseismic slip along the plate boundary. The simulation using the experimental law of rock flow in the mantle, in which strain rate depends on the power of stress, and the fault friction law at the plate boundary, showed that the Tohoku-oki earthquake caused large stress fluctuations and a sudden decrease in viscosity in the asthenosphere beneath the oceanic lithosphere due to the nonlinear flow properties, resulting in the occurrence of fast flow in the asthenosphere.

Furthermore, the deformation of the landward plate associated with the megathrust Tohoku-oki earthquake cycle over a period of about 600 years has been simulated. The results showed that when the coupling at the asperity continues for several hundred years, the viscous nature of the high-temperature part of the mantle wedge makes the overlying landward plate more easily dragged. The inter-plate coupling was shown to extend to a depth of about 100 km and to cause subsidence in the Pacific coastal region. Therefore, the subsidence of the Pacific coast of northeast Japan, which was observed for about 100 years prior to the 2011 Tohoku-oki earthquake, is likely to have been caused by the continuous tectonic plate interplate coupling at the asperity for more than several hundred years. This could have been the cause of the 2011 Tohoku-oki earthquake.

In the future, integrated modeling of strain accumulation processes (deformation before the earthquake), earthquake rupture, and postseismic deformation, considering viscoelastic structures and a fault friction law, is needed. We will obtain long-term crustal deformation observation data. Based on these data, it is necessary to construct a model that can explain the long-term postseismic and interseismic deformation caused by the Tohoku-oki earthquake.

Abbreviations

RS	Rate and state
VW	Velocity weakening
VS	Velocity strengthening
SSEs	Slow slip events
JFAST	Japan Trench Fast Drilling Project
IODP	Integrated Ocean Drilling Program
LAB	Lithosphere and asthenosphere boundary
TP	Thermal pressurization
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GEONET	GNSS Earth Observation Network System
GSI	Geospatial Information Authority of Japan

Acknowledgements
Many thanks to Takeshi Iinuma, the editor of this special issue. I would like to thank Jun Muto and Roland Bürgmann for their very helpful comments. I also would like to thank Ryohei Sasajima for the useful discussions. The discussion in Specific Research Project (B) (ERI JURP 2020-B-07) was useful.

Author contributions
BS designed the structure of the review and drafted the manuscript.

Funding
This review was supported by JSPS KAKENHI 0H01987. This was also supported by a Grant-in-Aid for Scientific Research on Innovative Areas, "Crustal Dynamics -Unified Understanding of the Inland Earthquake after the Tohoku-oki Earthquake" (Project numbers: 26109007 and 26109006). This study was supported by ERI JURP 2020-B-07 in Earthquake Research Institute, the University of Tokyo. This study was also supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under the Second Earthquake and Volcano Hazards Observation and Research Program (Earthquake and Volcano Hazard Reduction Research).

Availability of data and materials
Since this manuscript does not contain any data, data are not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 13 December 2022 Accepted: 19 July 2023
Published online: 31 July 2023

References
Abers GA, van Keken PE, Kneller EA, Ferris A, Stachnik JC (2006) The thermal structure of subduction zones constrained by seismic imaging: Implications for slab dehydration and wedge flow. Earth Planet Sci Lett 241(3–4):387–397. https://doi.org/10.1016/j.epsl.2005.11.055

Agata R, Barbot SD, Fujita K, Hyodo M, Iinuma T, Nakata R, Ichimura T, Hori T (2019) Rapid mantle flow with power-law creep explains deformation after the 2011 Tohoku mega-quake. Nat Commun 10(1):1385. https://doi.org/10.1038/s41467-019-08984-7

Angiboust S, Kirsch J, Oncken O, Glodny J, Monié P, Rybacki E (2015) Probing the transition between seismically coupled and decoupled segments along an ancient subduction interface. Geochem Geophys Geosyst 16(6):1905–1922. https://doi.org/10.1002/2015GC005776

Aochi H, Ide S (2011) Conceptual multi-scale dynamic rupture model for the 2011 off the Pacific coast of Tohoku Earthquake. Earth Planets Space 63(7):761–765. https://doi.org/10.5047/eps.2011.05.008

Barbot S (2018) Asthenosphere flow modulated by megathrust earthquake cycles. Geophys Res Lett 45:6018–6031. https://doi.org/10.1029/2018GL078197

Barbot S (2020) Frictional and structural controls of seismic super-cycles at the Japan trench. Earth Planets Space 72(1):63. https://doi.org/10.1186/s40623-020-01185-3

Barbot S, Moore JD, Lambert V (2017) Displacement and stress associated with distributed anelastic deformation in a half-space. Bull Seismol Soc Am 107(2):821–855. https://doi.org/10.1785/0120160237

Chester FM, Rowe C, Ujiie K, Kirkpatrick J, Regalla C, Remitti F, Moore JC, Toy V, Wolfson-schwehr M, Bose S, Kameda J, Mori JJ, Brodsky EE, Eguchi N, Toczko S, Expedition 343 and 343T Scientists (2013) Structure and composition of the plate-boundary slip zone for the 2011 Tohoku-Oki earthquake. Science 342:1208–1211. https://doi.org/10.1126/science.1243719

Cubas N, Lapusta N, Avouac JP, Perfettini H (2015) Numerical modeling of long-term earthquake sequences on the NE Japan megathrust: comparison with observations and implications for fault friction. Earth Planet Sci Lett 419:187–198. https://doi.org/10.1016/j.epsl.2015.03.002

Dhar S, Muto J, Ito Y, Miura S, Moore JD, Ohta Y, Iinuma T (2022) Along-arc heterogeneous rheology inferred from post-seismic deformation of the 2011 Tohoku-oki earthquake. Geophys J Int 230(1):202–215. https://doi.org/10.1093/gji/ggac063

Dhar S, Muto J, Ohta Y, Iinuma T (2023) Heterogeneous rheology of Japan subduction zone revealed by postseismic deformation of the 2011 Tohoku-oki earthquake. Prog Earth Planet Sci 10(1):9. https://doi.org/10.1186/s40645-023-00539-1

Dieterich JH (1981) Constitutive properties of rock with simulated gouge, Chap. 8. In: Carter NL et al (eds) Mechanical behavior of crustal rocks: the handing volume, Geophysical Monograph Series 24. American Geophysical Union, Washington, DC, pp 103–120. https://doi.org/10.1029/GM024p0103

Freed AM, Hashima A, Becker TW, Okaya DA, Sato H, Hatanaka Y (2017) Resolving depth-dependent subduction zone viscosity and afterslip from postseismic displacements following the 2011 Tohoku-oki, Japan earthquake. Earth Planet Sci Lett 459:279–290. https://doi.org/10.1016/j.epsl.2016.11.040

Fujii Y, Satake K, Sakai SI, Shinohara M, Kanazawa T (2011) Tsunami source of the 2011 off the Pacific coast of Tohoku Earthquake. Earth Planets Space 63(7):815–820. https://doi.org/10.5047/eps.2011.06.010

Fujiwara T, Kodaira S, No T, Kaiho Y, Takahashi N, Kaneda Y (2011) The 2011 Tohoku-Oki earthquake: displacement reaching the trench axis. Science 334(6060):1240–1240. https://doi.org/10.1126/science.1211554

Fukuda J, Johnson KM (2021) Bayesian inversion for a stress-driven model of afterslip and viscoelastic relaxation: method and application to Postseismic deformation following the 2011 Mw 9.0 Tohoku-Oki earthquake. J Geophys Res Solid Earth 126(5):e2020JB021620. https://doi.org/10.1029/2020jb021620

Fulton PM, Brodsky EE, Kano Y, Mori J, Chester F, Ishikawa T, Harris RN, Lin W, Eguchi N, Toczko S, Expedition 343, 343T, and KR13-08 Scientists (2013) Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements. Science 342:1214–1217. https://doi.org/10.1126/science.1243641

Geospatial Information Authority of Japan (2021) Crustal deformation for ten years since the 2011 off the Pacific coast of Tohoku Earthquake. https://www.gsi.go.jp/kanshi/h23touhoku_10years.html. Accessed 1 Dec 2022
Hasegawa A, Yoshida K, Asano Y, Okada T, Iinuma T, Ito Y (2012) Change in stress field after the 2011 great Tohoku-Oki earthquake. Earth Planet Sci Lett 355–356:231–243. https://doi.org/10.1016/j.epsl.2012.08.042
Hasegawa A, Yoshida K, Okada T (2011) Nearly complete stress drop in the 2011 Mw 9.0 off the Pacific coast of Tohoku Earthquake. Earth Planets Space 63(7):703–707. https://doi.org/10.5047/eps.2011.06.007
Hashima A, Sato T (2017) A megathrust earthquake cycle model for Northeast Japan: bridging the mismatch between geological uplift and geodetic subsidence. Earth Planets Space 69(1):1–10. https://doi.org/10.1186/s40623-017-0606-6
Hashimoto C, Noda A, Sagiya T, Matsu'ura M (2009) Interplate seismogenic zones along the Kuril-Japan trench inferred from GPS data inversion. Nat Geosci 2(2):141–144. https://doi.org/10.1038/ngeo421
Headquarters for Earthquake Research Promotion (2020) The catalogue of long-term foracast of active faults and subduction zone earthquakes. https://www.jishin.go.jp/main/choukihyoka/ichiran.pdf
Hirono T, Tsuda K, Tanikawa W, Ampuero JP, Shibazaki B, Kinoshita M, Mori JJ (2016) Near-trench slip potential of megaquakes evaluated from fault properties and conditions. Sci Rep 6(1):1–13. https://doi.org/10.1038/srep28184
Hori T, Miyazaki SI (2011) A possible mechanism of M 9 earthquake generation cycles in the area of repeating M 7–8 earthquakes surrounded by aseismic sliding. Earth Planets Space 63(7):773–777. https://doi.org/10.5047/eps.2011.06.022
Horiuchi S, Iwamori H (2016) A consistent model for fluid distribution, viscosity distribution, and flow-thermal structure in subduction zone. J Geophys Res Solid Earth 121(5):3238–3260. https://doi.org/10.1002/2015jb012384
Hsu YJ, Simons M, Avouac JP, Galetzka J, Sieh K, Chlieh M, Natawidjaja D, Prawirodirdjo L, Bock Y (2006) Frictional afterslip following the 2005 Nias-Simeulue earthquake. Sumatra Sci 312(5782):1921–1926. https://doi.org/10.1126/science.1126960
Hu Y, Bürgmann R, Uchida N, Banerjee P, Freymueller JT (2016) Stress-driven relaxation of heterogeneous upper mantle and time-dependent after slip following the 2011 Tohoku earthquake. J Geophys Res Solid Earth 121(1):385–411. https://doi.org/10.1002/2015jb012508
Ide S, Aochi H (2005) Earthquakes as multiscale dynamic ruptures with heterogeneous fracture surface energy. J Geophys Res Solid Earth. https://doi.org/10.1029/2004jb003591
Ide S, Baltay A, Beroza GC (2011) Shallow dynamic overshoot and energetic deep rupture in the 2011 Mw 9.0 Tohoku-Oki earthquake. Science 332:1426–1429. https://doi.org/10.1126/science.1207020
Iinuma T, Hino R, Kido M, Inazu D, Osada Y, Ito Y, Ohzono M, Tsushima H, Suzuki S, Fujimoto H, Miura S (2012) Coseismic slip distribution of the 2011 off the Pacific Coast of Tohoku Earthquake (M9.0) refined by means of seafloor geodetic data. J Geophys Res Solid Earth 117:B07409. https://doi.org/10.1029/2012JB009186
Iinuma T, Hino R, Uchida N, Nakamura W, Kido M, Osada Y, Miura S (2016) Seafloor observations indicate spatial separation of coseismic and postseismic slips in the 2011 Tohoku earthquake. Nat Commun 7(1):13506. https://doi.org/10.1038/ncomms13506
Ikari MJ, Ito Y, Ujiie K, Kopf AJ (2015) Spectrum of slip behaviour in Tohoku fault zone samples at plate tectonic slip rates. Nat Geosci 8(11):870–874. https://doi.org/10.1038/ngeo2547
Ikari MJ, Kopf AJ (2017) Seismic potential of weak, near-surface faults revealed at plate tectonic slip rates. Sci Adv 3:e1701269. https://doi.org/10.1126/sciadv.1701269
Ikari MJ (2015) Data report: rate- and state-dependent friction parameters of core samples from Site C0019, IODP Expedition 343 (JFAST). In: Chester FM, Mori J, Eguchi N, Toczko S (eds) The Expedition 343/343T Scientists, Proc. IODP, 343/343T: Tokyo (Integrated Ocean Drilling Program Management International, Inc). https://doi.org/10.2204/iodp.proc.343343t.203.2015
Ikeda Y (2014) Strain buildup in the Northeast Japan orogen with implications for gigantic subduction. J Int Geosci 37(4):234–245. https://doi.org/10.18814/epiiugs/2014/v37i4/003
Ito Y, Hino R, Kido M, Fujimoto H, Osada Y, Inazu D, Ohta Y, Iinuma T, Ohzono M, Miura S, Mishina M, Suzuki K, Tsuji T, Ashi J (2013) Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake. Tectonophysics 600:14–26. https://doi.org/10.1016/j.tecto.2012.08.022
Ito Y, Tsuji T, Osada Y, Kido M, Inazu D, Hayashi Y, Tsushima H, Hino R, Fujimoto H (2011) Frontal wedge deformation near the source region of the 2011 Tohoku-Oki earthquake. Geophys Res Lett. https://doi.org/10.1029/2011GL048355
Japan Coast Guard, Tohoku University (2013) Seafloor movements observed by seafloor geodetic observations after the 2011 off the Pacific coast of Tohoku Earthquake. Comm Earthq Predict 90:139–144
Kato A, Obara K, Igarashi T, Tsuruoka H, Nakagawa S, Hirata N (2012) Propagation of slow slip leading up to the 2011 Mw 9.0 Tohoku-Oki earthquake. Science 335(6069):705–708. https://doi.org/10.1126/science.1215141
Kato N, Tullis TE (2001) A composite rate-and state-dependent law for rock friction. Geophys Res Lett 28(6):1103–1106. https://doi.org/10.1029/2000gl012060
Kato N, Yoshida S (2011) A shallow strong patch model for the 2011 great Tohoku-oki earthquake: a numerical simulation. Geophys Res Lett 38(7):L00G04. https://doi.org/10.1029/2011GL048565
Kawakatsu H, Kumar P, Takei Y, Shinohara M, Kanazawa T, Araki E, Suyehiro K (2009) Seismic evidence for sharp lithosphere-asthenosphere boundaries of oceanic plates. Science 324(5926):499–502. https://doi.org/10.1126/science.1169499
Kido M, Osada Y, Fujimoto H, Hino R, Ito Y (2011) Trench-normal variation in observed seafloor displacements associated with the 2011 Tohoku-oki earthquake. Geophys Res Lett 38(24):7. https://doi.org/10.1029/2011gl050057
Koike K, Machida H (2001) Atlas of quaternary marine terraces in the Japanese Islands. University of Tokyo Press, Tokyo
Kozdon JE, Dunham EM (2013) Rupture to the trench: dynamic rupture simulations of the 11 March 2011 Tohoku earthquake. Bull Seismol Soc Am 103(2B):1275–1289. https://doi.org/10.1785/0120120136
Kunimi T, Takano Y, Suzuki M, Saitou T, Narita T, Okamura S (2001) Vertical crustal movements in Japan estimated from the leveling observations data for the past 100 years. J Geospatial Inf Auth Jpn 96:14
Lachenbruch AH (1980) Frictional heating, fluid pressure, and the resistance to fault motion. J Geophys Res Solid Earth 85(B11):6097–6112. https://doi.org/10.1029/jb085ib11p06097
Lapusta N, Liu Y (2009) Three-dimensional boundary integral modeling of spontaneous earthquake sequences and aseismic slip. J Geophys Res 114:B09303. https://doi.org/10.1029/2008JB005934
Lay T, Ammon CJ, Kanamori H, Xue L, Kim MJ (2011) Possible large near trench slip during the 2011 M w 9.0 the Pacific coast of Tohoku Earthquake. Earth Planets Space 63:687–692. https://doi.org/10.5047/eps.2011.05.006
Luo H, Wang K (2021) Postseismic geodetic signature of cold forearc mantle in subduction zones. Nat Geosci 14(2):104–109. https://doi.org/10.1038/s41561-020-00679-9
Marone C (1998) Laboratory-derived friction laws and their application to seismic faulting. Annu Rev Earth Planet Sci 26(1):643–696. https://doi.org/10.1146/annurev.earth.26.1.643
Marone CJ, Scholz CH, Bilham R (1991) On the mechanics of earthquake afterslip. J Geophys Res Solid Earth 96(B5):8441–8452. https://doi.org/10.1029/91JB00275
Matsuzawa T, Asano Y, Obara K (2015) Very low frequency earthquakes off the Pacific coast of Tohoku. Jpn Geophys Res Lett 42(11):4318–4325. https://doi.org/10.1002/2015GL063959
Mavrommatis AP, Segall P, Johnson KM (2014) A decadal-scale deformation transient prior to the 2011 Mw 9.0 Tohoku-oki earthquake. Geophys Res Lett 41:4486–4494. https://doi.org/10.1002/2014GL060139
Mitsui Y, Kato N, Fukahata Y, Hirahara K (2012) Megaquake cycle at the Tohoku subduction zone with thermal fluid pressurization near the surface. Earth Planet Sci Lett 325–326:21–26. https://doi.org/10.1016/j.epsl.2012.01.026
Muto J, Moore JDP, Barbot S, Iinuma T, Ohta Y, Iwamori H (2019) Coupled afterslip and transient mantle flow after the 2011 Tohoku earthquake. Sci Adv. https://doi.org/10.1126/sciadv.aaw1164
Muto J, Shibazaki B, Iinuma T, Ito Y, Ohta Y, Miura S, Nakai Y (2016) Heterogeneous rheology controlled postseismic deformation of the 2011

Tohoku-oki earthquake. Geophys Res Lett 43(10):4971–4978. https://doi.org/10.1002/2016gl068113
Nakata R, Hori T, Hyodo M, Ariyoshi K (2016) Possible scenarios for occurrence of M ~ 7 interplate earthquakes prior to and following the 2011 Tohoku-oki earthquake based on numerical simulation. Sci Rep 6(1):25704. https://doi.org/10.1038/srep25704
Nakata R, Hori T, Miura S, Hino R (2021) Presence of interplate channel layer controls of slip during and after the 2011 Tohoku-oki earthquake through the frictional characteristics. Sci Rep 11(1):1–11. https://doi.org/10.1038/s41598-021-86020-9
Nanayama F, Satake K, Furukawa R, Shimokawa K, Atwater BF, Shigeno K, Yamaki S (2003) Unusually large earthquakes inferred from tsunami deposits along the Kuril trench. Nature 424(6949):660–663. https://doi.org/10.1038/nature01864
Nishikawa T, Ide S, Nishimura T (2023) A review on slow earthquakes in the Japan Trench. Prog Earth Planet Sci 10(1):1. https://doi.org/10.1186/s40645-022-00528-w
Nishikawa T, Matsuzawa T, Ohta K, Uchida N, Nishimura T, Ide S (2019) The slow earthquake spectrum in the Japan Trench illuminated by the S-net seafloor observatories. Science 365(6455):808–813. https://doi.org/10.1126/science.aax5618
Nishimura T (2014) Pre-, co-, and post-seismic deformation of the 2011 Tohoku-oki earthquake and its implication to a paradox in short-term and long-term deformation. J Disaster Res 9(3):9. https://doi.org/10.20965/jdr.2014.p0294
Noda H, Lapusta N (2010) Three-dimensional earthquake sequence simulations with evolving temperature and pore pressure due to shear heating: effect of heterogeneous hydraulic diffusivity. J Geophys Res 115:B12314. https://doi.org/10.1029/2010JB007780
Noda H, Lapusta N (2013) Stable creeping fault segments can become destructive as a result of dynamic weakening. Nature 493:518–521. https://doi.org/10.1038/nature11703
Noda H, Sawai M, Shibazaki B (2017) Earthquake sequence simulations with measured properties for JFAST core samples. Philos Trans R Soc A Math Phys Eng Sci 375(2103):20160003. https://doi.org/10.1098/rsta.2016.0003
Noda A, Takahama T, Kawasato T, Matsu'ura M (2018) Interpretation of offshore crustal movements following the 2011 Tohoku-oki earthquake by the combined effect of afterslip and viscoelastic stress relaxation. Pure Appl Geophys 175(2):559–572. https://doi.org/10.1007/s00024-017-1682-z
Ohtani M, Hirahara K, Hori T, Hyodo M (2014) Observed change in plate coupling close to the rupture initiation area before the occurrence of the 2011 Tohoku earthquake: Implications from an earthquake cycle model. Geophys Res Lett 41(6):1899–1906. https://doi.org/10.1002/2013GL058751
Ozawa S, Nishimura T, Munekane H, Suito H, Kobayashi T, Tobita M, Imakiire T (2012) Preceding, coseismic, and postseismic slips of the 2011 Tohoku earthquake, Japan. J Geophys Res Solid Earth 117:B07404. https://doi.org/10.1029/2011JB009120
Ozawa S, Nishimura T, Suito H, Kobayashi T, Tobita M, Imakiire T (2011) Coseismic and postseismic slip of the 2011 magnitude-nine Tohoku-oki earthquake. Nature 475:373–376. https://doi.org/10.1038/nature10227
Pollitz FF (2014) Post-earthquake relaxation using a spectral element method: 2.5-D case. Geophys J Int 198:308–326. https://doi.org/10.1093/gji/ggu114
Rice JR (1993) Spatio-temporal complexity of slip on a fault. J Geophys Res Solid Earth 98(B6):9885–9907. https://doi.org/10.1029/93JB00191
Sagiya T (2004) A decade of GEONET: 1994–2003 The continuous GPS observation in Japan and its impact on earthquake studies. Earth Planets Space 56(8):29–41. https://doi.org/10.1186/bf03353077
Sagiya T (2015) Paradoxical vertical crustal movement along the Pacific coast of northeast Japan. Int Assoc Geod Symp 145:73–78. https://doi.org/10.1007/1345_2015_189
Sagiya T, Meneses-Gutierrez A (2022) Geodetic and geological deformation of the Island arc in Northeast Japan revealed by the 2011 Tohoku earthquake. Annu Rev Earth Planet Sci 50:345–368. https://doi.org/10.1146/annurev-earth-032320-074429
Sasajima R, Shibazaki B, Iwamori H, Nishimura T, Nakai Y (2019) Mechanism of subsidence of the Northeast Japan forearc during the late period of a gigantic earthquake cycle. Sci Rep 9(1):1–13. https://doi.org/10.1038/s41598-019-42169-y
Satake K, Fujii Y, Harada T, Namegaya Y (2013) Time and space distribution of coseismic slip of the 2011 Tohoku earthquake as inferred from tsunami waveform data. Bull Seismol Soc Am 103(2B):1473–1492. https://doi.org/10.1785/0120120122
Satake K, Namegaya Y, Yamamoto S (2008) Numerical simulation of the AD 869 Jogan tsunami in Ishinomaki and Sendai plains. Annu Rep Act Fault Paleoearthq Res 8:71–89
Sato M, Ishikawa T, Ujihara N, Yoshida S, Fujita M, Mochizuki M, Asada A (2011) Displacement above the hypocenter of the 2011 Tohoku-oki earthquake. Science 332(6036):1395–1395. https://doi.org/10.1126/science.1207401
Sato T, Matsu'ura M (1993) A kinematic model for evolution of island arc-trench systems. Geophys J Int 114(3):512–530. https://doi.org/10.1111/j.1365-246X.1993.tb06984.x
Sawai M, Hirose T, Kameda J (2014) Frictional properties of incoming pelagic sediments at the Japan Trench: implications for large slip at a shallow plate boundary during the 2011 Tohoku earthquake. Earth Planets Space 66(1):65. https://doi.org/10.1186/1880-5981-66-65
Sawai Y, Namegaya Y, Tamura T, Nakashima R, Tanigawa K (2015) Shorter intervals between great earthquakes near Sendai: Scour ponds and a sand layer attributable to A.D. 1454 overwash. Geophys Res Lett 42(12):4795–4800. https://doi.org/10.1002/2015GL064167
Sawai M, Niemeijer AR, Hirose T, Spiers CJ (2017) Frictional properties of JFAST core samples and implications for slow earthquakes at the Tohoku subduction zone. Geophys Res Lett 44(17):8822–8831. https://doi.org/10.1002/2017GL073460
Sawai Y, Satake K, Kamataki T, Nasu H, Shishikura M, Atwater BF, Horton BP, Kelsey HM, Nagumo T, Yamaguchi M (2004) Transient uplift after a 17th-century earthquake along the Kuril subduction zone. Science 306(5703):1918–1920. https://doi.org/10.1126/science.1104895
Shi Q, Barbot S, Wei S, Tapponnier P, Matsuzawa T, Shibazaki B (2020) Structural control and system-level behavior of the seismic cycle at the Nankai Trough. Earth Planets Space 72(1):27. https://doi.org/10.1186/s40623-020-1145-0
Shibazaki B, Matsuzawa T, Tsutsumi A, Ujiie K, Hasegawa A, Ito Y (2011) 3D modeling of the cycle of a great Tohoku-oki earthquake, considering frictional behavior at low to high slip velocities. Geophys Res Lett 38(21):L21305. https://doi.org/10.1029/2011GL049308
Shibazaki B, Noda H, Ikari MJ (2019) Quasi-dynamic 3D modeling of the generation and afterslip of a Tohoku-oki earthquake considering thermal pressurization and frictional properties of the shallow plate boundary. Pure Appl Geophys 176(9):3951–3973. https://doi.org/10.1007/s00024-018-02089-w
Shibazaki B, Shimamoto T (2007) Modelling of short-interval silent slip events in deeper subduction interfaces considering the frictional properties at the unstable–stable transition regime. Geophys J Int 171:191–205. https://doi.org/10.1111/j.1365-246X.2007.03434.x
Suito H (2017) Importance of rheological heterogeneity for interpreting viscoelastic relaxation caused by the 2011 Tohoku-Oki earthquake. Earth Planets Space 69(1):1–12. https://doi.org/10.1186/s40623-017-0611-9
Suito H, Nishimura T, Tobita M, Imakiire T, Ozawa S (2011) Interplate fault slip along the Japan trench before the occurrence of the 2011 off the Pacific coast of Tohoku earthquake as inferred from GPS data. Earth Planet Space 63:615–619. https://doi.org/10.5047/eps.2011.06.053
Sun T, Wang K (2015) Viscoelastic relaxation following subduction earthquakes and its effects on afterslip determination. J Geophys Res Solid Earth 120(2):1329–1344. https://doi.org/10.1002/2014JB011707
Sun T, Wang K, Iinuma T, Hino R, He J, Fujimoto H, Kido M, Osada Y, Miura S, Ohta Y, Hu Y (2014) Prevalence of viscoelastic relaxation after the 2011 Tohoku-oki earthquake. Nature 514(7520):84–87. https://doi.org/10.1038/nature13778
Suwa Y, Miura S, Hasegawa A, Sato T, Tachibana K (2006) Interplate coupling beneath NE Japan inferred from three-dimensional displacement field. J Geophys Res. https://doi.org/10.1029/2004jb003203
Tanikawa W, Hirose T, Mukoyoshi H, Tadai O, Lin W (2013) Fluid transport properties in sediments and their role in large slip near the surface of the plate boundary fault in the Japan Trench. Earth Planet Sci Lett 382:150–160. https://doi.org/10.1016/j.epsl.2013.08.052
Tomita F, Kido M, Ohta Y, Iinuma T, Hino R (2017) Along-trench variation in seafloor displacements after the 2011 Tohoku earthquake. Sci Adv 3(7):e1700113. https://doi.org/10.1126/sciadv.1700113

Di Toro G, Han R, Hirose T, De Paola N, Nielsen S, Mizoguchi K, Ferri F, Cocco M, Shimamoto T (2011) Fault lubrication during earthquakes. Nature 471:494–498. https://doi.org/10.1038/nature09838
Tsuru T, Park J-O, Miura S, Kodaira S, Kido Y, Hayashi T (2002) Along-arc structural variation of the plate boundary at the Japan Trench margin: implication of interplate coupling. J Geophys Res Solid Earth 107(B12):2357. https://doi.org/10.1029/2001JB001664
Tsutsumi A, Fabbri O, Karpoff AM, Ujiie K, Tsujimoto A (2011) Friction velocity dependence of clay-rich fault material along a megasplay fault in the Nankai subduction zone at intermediate to high velocities. Geophys Res Lett 38(19):L19301. https://doi.org/10.1029/2011GL049314
Tsutsumi A, Shimamoto T (1997) High-velocity frictional properties of gabbro. Geophys Res Lett 24(6):699–702. https://doi.org/10.1029/97GL00503
Uchida N, Bürgmann R (2021) A decade of lessons learned from the 2011 Tohoku-oki earthquake. Rev Geophys. https://doi.org/10.1029/2020rg000713
Uchida N, Iinuma T, Nadeau RM, Bürgmann R, Hino R (2016) Periodic slow slip triggers megathrust zone earthquakes in northeastern Japan. Science 351(6272):488–492. https://doi.org/10.1126/science.aad3108
Uchida N, Nakajima J, Wang K, Takagi R, Yoshida K, Nakayama T, Hino R, Okada T, Asano Y (2020) Stagnant forearc mantle wedge inferred from mapping of shear-wave anisotropy using S-net seafloor seismometers. Nat Commun 11(1):1–8. https://doi.org/10.1038/s41467-020-19541-y
Ujiie K, Tanaka H, Saito T, Tsutsumi A, Mori JJ, Kameda, J, Brodsky EE, Chester FM, Eguchi N, Toczko S, Expedition 343 and 343T Scientists (2013) Low coseismic shear stress on the Tohoku-oki megathrust determined from laboratory experiments. Science 342:1211–1214. https://doi.org/10.1126/science.1243485
Wada I, Wang K (2009) Common depth of slab-mantle decoupling: reconciling diversity and uniformity of subduction zones. Geochem Geophys Geosyst 10:Q10009. https://doi.org/10.1029/2009GC002570
Wang K, Brown L, Hu Y, Yoshida K, He J, Sun T (2019) Stable forearc stressed by a weak megathrust: mechanical and geodynamic implications of stress changes caused by the M = 9 Tohoku-oki earthquake. J Geophys Res Solid Earth 124:6179–6194. https://doi.org/10.1029/2018JB017043
Wang K, Hu Y, He J (2012) Deformation cycles of subduction earthquakes in a viscoelastic Earth. Nature 484(7394):327–332. https://doi.org/10.1038/nature11032
Wang K, Sun T, Brown L, Hino R, Tomita F, Kido M, Iinuma T, Kodaira S, Fujiwara T (2018) Learning from crustal deformation associated with the M9 2011 Tohoku-oki earthquake. Geosphere 14(2):552–571. https://doi.org/10.1130/ges01531.1
Watanabe SI, Ishikawa T, Nakamura Y, Yokota Y (2021) Co- and postseismic slip behaviors extracted from decadal seafloor geodesy after the 2011 Tohoku-oki earthquake. Earth Planets Space 73:162. https://doi.org/10.1186/s40623-021-01487-0
Watanabe S, Sato M, Fujita M, Ishikawa T, Yokota Y, Ujihara N, Asada A (2014) Evidence of viscoelastic deformation following the 2011 Tohoku-Oki earthquake revealed from seafloor geodetic observation. Geophys Res Lett 41(16):5789–5796. https://doi.org/10.1002/2014GL061134
Wibberley CA, Shimamoto T (2005) Earthquake slip weakening and asperities explained by thermal pressurization. Nature 436:689–692. https://doi.org/10.1038/nature03901
Yagi Y, Fukahata Y (2011) Rupture process of the 2011 Tohoku-oki earthquake and absolute elastic strain release. Geophys Res Lett 38(19):L19307. https://doi.org/10.1029/2011GL048701
Yamagiwa S, Miyazaki SI, Hirahara K, Fukahata Y (2015) Afterslip and viscoelastic relaxation following the 2011 Tohoku-oki earthquake (Mw9.0) inferred from inland GPS and seafloor GPS/Acoustic data. Geophys Res Lett 42(1):66–73. https://doi.org/10.1002/2014GL061735
Yamanaka Y, Kikuchi M (2004) Asperity map along the subduction zone in northeastern Japan inferred from regional seismic data. J Geophys Res Solid Earth 109:B07307. https://doi.org/10.1029/2003JB002683
Yokota Y, Koketsu K, Fujii Y, Satake K, Sakai S, Shinohara M, Kanazawa T (2011) Joint inversion of strong motion, teleseismic, geodetic, and tsunami datasets for the rupture process of the 2011 Tohoku earthquake. Geophys Res Lett 38:L00G21. https://doi.org/10.1029/2011GL050098
Yoshida K, Matsuzawa T, Uchida N (2022) The 2021 Mw7.0 and Mw6.7 Miyagi-oki earthquakes nucleated in a deep seismic/aseismic transition zone: possible effects of transient instability due to the 2011 Tohoku earthquake. J Geophys Res Solid Earth 127(8):2022024887. https://doi.org/10.1029/2022JB024887

Publisher's Note