

Evaluating Dynamic Viability of Finite-Fault Slip Models with Ensemble Kalman Inversion

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Key Points:

- Ensemble Kalman Inversion (EKI) efficiently evaluates the dynamic viability of 32 finite-fault slip models of the Tohoku-Oki earthquake
- Using EKI, 26 slip models yield dynamically viable 3D rupture scenarios that match geodetic and teleseismic moment-rate observations.
- Contrasting slip models converge to three dynamic rupture families, suggesting few dominant controls on rupture dynamics.

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Abstract

Finite-fault slip models are widely used to infer earthquake rupture processes, yet they are inherently non-unique and do not guarantee physically consistent rupture evolution. Here, we develop a data-constrained framework that couples Ensemble Kalman Inversion (EKI) with large-scale 3D dynamic rupture simulations to efficiently evaluate the dynamic viability of finite-fault slip models. The framework explores initial shear stress conditions informed by slip models while constraining dynamic rupture scenarios with geodetic observations and the teleseismic moment-rate function. Applying this approach to 32 models of the 2011 Tohoku-Oki earthquake, we identify 26 dynamically viable 3D rupture scenarios using ~ 285 total forward simulations. Across the ensemble, both smooth and highly heterogeneous finite-fault slip models can be reproduced dynamically. Yet these models converge to three dynamic rupture families, characterized by crack-like, single-reactivation, or multiple-reactivation rupture styles. This convergence suggests that apparent finite-fault diversity may reflect a smaller set of dominant controls on rupture dynamics, including the level of prestress heterogeneity. Multiple-reactivation dynamic rupture models best reproduce the observed depth-dependent rupture behavior and moment-rate complexity. By contrast, large tsunamigenic slip near the trench and comparable partitioning of released strain energy between breakdown and radiated energy persist across dynamically viable models, despite differences in initial shear stress conditions and rupture style. These results show that finite-fault slip model heterogeneity can map onto a smaller set of dynamically viable rupture styles, preserving robust first-order features. Our EKI framework provides an efficient pathway for integrating observations with physics-based simulations and identifying dynamically consistent earthquake source models.

Plain Language Summary

Large megathrust earthquakes can rupture faults hundreds of kilometers long over seconds to minutes. To understand these events and their tsunami potential, scientists often reconstruct how slip occurred on the fault using observations. However, different finite-fault slip models for the same earthquake can show different slip patterns, and not every reconstructed pattern is mechanically consistent with how faults actually break. Here, we develop an efficient optimization framework that uses physics-based dynamic rupture simulations and “Ensemble Kalman Inversion” to test which slip models can be realized as spontaneous earthquakes. The method explores stress conditions informed by published slip models and keeps only rupture scenarios that match geodetic observations and the teleseismic moment-rate function. We apply this framework to 32 published slip models of the 2011 Tohoku-Oki earthquake and find 26 dynamically viable rupture scenarios. Although the input slip models differ substantially, the resulting ruptures fall into three main families: crack-like rupture, single reactivation, and multiple reactivation. This suggests that the apparent diversity of finite-fault models may reflect a smaller set of physical controls, especially prestress heterogeneity. Models with multiple reactivation best reproduce the observed depth-dependent rupture behavior. Across the viable models, large near-trench slip and similar overall energy partition persist.

1 Introduction

Characterizing how earthquake ruptures propagate and arrest and identifying the faulting conditions that govern these processes are fundamental to understanding earthquake physics and advancing physics-based seismic hazard assessment. Finite-fault inversions use geodetic, seismic, tsunami, and other observations to infer the spatial distribution of earthquake slip, and for kinematic models, its temporal evolution (e.g., Fan et al., 2014; Ide et al., 2011; Minson et al., 2013; K. Zhang et al., 2023). Combined with elastic or dynamic assumptions, slip models are used to estimate source properties such as stress drop and fracture energy and to relate rupture patterns to the stress and fric-

tional conditions that govern earthquake nucleation, propagation, and arrest (e.g., Causse et al., 2014; Guatteri, 2000; Ide & Takeo, 1997; Melgar & Hayes, 2017; Tinti et al., 2005; Weng & Yang, 2018; Ye et al., 2016). These slip distributions can also be compared with interseismic coupling and afterslip models, as well as seismicity and structural observations, to investigate mechanically distinct fault regions, such as asperities and barriers (e.g., Bassett et al., 2016; Fujie et al., 2020; Johnson et al., 2016; Lay, 2018; Loveless & Meade, 2016; Oryan & Gabriel, 2025; Uchida & Bürgmann, 2021; Yamanaka & Kikuchi, 2004; Zhao et al., 2011).

Despite their widespread use, finite-fault inversions are inherently non-unique. Slip models for the same event may differ substantially, limiting interpretation of rupture processes (e.g., Goda et al., 2014; Lay, 2018; K. Wang et al., 2018). For example, Razafindrakoto et al. (2015) and Wong et al. (2024) revealed pronounced variability in small-scale slip heterogeneity across published finite-fault slip models of the 2011 M_w 9.0 Tohoku-Oki earthquake. Brown et al. (2015) show that this variability can lead to large differences in stress-change estimates and, in turn, to different mechanical interpretations of the Tohoku-Oki earthquake. This variability arises from the ill-conditioned nature of the inverse problem. This ill-conditioning is exacerbated by differences in data types and frequency bandwidths, fault geometry, subfault discretization, Earth-structure parameterization, inversion methodology, and imposed regularization (e.g., Duputel et al., 2014; Gallovič & Ampuero, 2015; Mai et al., 2016; Ragon et al., 2018; K. Wang et al., 2018; Yagi & Fukahata, 2011a; Zahradník & Gallovič, 2010).

In addition, finite-fault slip models are not guaranteed to satisfy the physics of earthquake rupture (e.g., Ide, 2002; Tinti et al., 2021). Static slip models constrain the final coseismic slip distribution but do not contain information about rupture timing, rupture speed, or slip-rate evolution. Kinematic finite-fault models resolve a parameterized spatiotemporal rupture history, but rupture timing and slip-rate evolution are prescribed or inferred within imposed kinematic constraints rather than emerging from fault friction and elastodynamics (Archuleta, 1984; Hartzell & Heaton, 1983; Ide, 2015; Ji et al., 2002). Thus, both static and kinematic finite-fault models may reproduce observations without representing a mechanically self-consistent rupture process.

In contrast, dynamic rupture simulations solve the governing equations for coupled seismic-wave propagation and on-fault frictional evolution and can include off-fault inelastic deformation (e.g., Andrews, 2005; Harris et al., 2018; Ramos et al., 2022). Once rupture is initiated, its subsequent propagation, slip evolution, and arrest emerge from the prescribed initial stress, frictional, and structural conditions, providing a mechanically self-consistent rupture history within the assumed constitutive laws, initial conditions, and geometry. They have been applied across a wide range of tectonic settings, including geometrically complex fault systems (e.g., Ando & Kaneko, 2018; Marschall & Douilly, 2025; Ulrich et al., 2019; Z. Zhang et al., 2019) and large megathrust earthquakes (e.g., Chan et al., 2023; Galvez et al., 2020; Ma, 2023; Prada et al., 2021; Ramos et al., 2021; Ulrich et al., 2022; Wong, Gabriel, & Fan, 2026; Yao & Yang, 2020), to evaluate faulting conditions and mechanisms consistent with interdisciplinary observations.

Dynamic rupture models involve high-dimensional parameter spaces, and their response to initial stress and frictional conditions is strongly nonlinear, making systematic evaluation challenging (e.g., Ampuero & Ben-Zion, 2008; Dunham et al., 2011; Peyrat & Olsen, 2004). High-fidelity 3D simulations are also computationally expensive (Premus et al., 2020; Uphoff et al., 2017). Initial shear traction, effective normal stress, and frictional properties exhibit strong trade-offs (e.g., Di Carli et al., 2010; Goto & Sawada, 2010; Huang et al., 2014; Peyrat et al., 2001; Ruiz & Madariaga, 2011; Schmedes et al., 2010; Vyas et al., 2023) and small changes in prestress relative to frictional strength can produce distinct rupture styles (e.g., Gabriel et al., 2012, 2013; S. B. Nielsen & Carlson, 2000; Zheng & Rice, 1998). Many previous dynamic rupture studies therefore adopted simplified models or prescribed asperities to isolate specific aspects of rupture dynam-

ics (e.g., Huang et al., 2012; Kozdon & Dunham, 2013; Mirwald et al., 2019). Other studies have informed dynamic rupture initial conditions using geodetic coupling models (e.g., Chan et al., 2023; Glehman et al., 2025), static coseismic slip inversions constrained by geodetic observations (**Ulrich2026**; e.g., Hayek et al., 2024; Jia et al., 2023; Yin et al., 2025), or time-dependent kinematic finite-fault models (**Yang et al method 2019**; e.g., Causse et al., 2014; Corish et al., 2007; Day et al., 1998; Tinti et al., 2021; Twardzik et al., 2014; Weng & Yang, 2018). Such studies generally evaluate one selected or representative data-driven model while exploring plausible stress and frictional conditions through grid searches, neighborhood algorithms, or parameter sweeps. (e.g., Ma, 2023; Miyatake, 1992; Olsen et al., 1997; Peyrat et al., 2001; Tanrıcan et al., 2017; Wong, Gabriel, & Fan, 2026; Yao & Yang, 2020).

Recent probabilistic, gradient-based, and scientific machine-learning approaches enable systematic exploration of dynamic rupture parameter spaces. Bayesian dynamic rupture inversion has been used to characterize posterior uncertainty in multi-parameter spaces (e.g., Kostka et al., 2022; Premus & Ampuero, 2026; Schliwa et al., 2024). Such analyses may require on the order of 10^5 forward evaluations (e.g., Gallovič et al., 2019). Multilevel delayed-acceptance sampling with asynchronous pre-fetching provides a more scalable route for Bayesian inversion with high-fidelity 3D dynamic rupture simulations (Kruse et al., 2025; Niu et al., 2026). Fused-ensemble execution can further accelerate concurrent dynamic rupture simulations (Kurapati et al., 2026). Adjoint-based methods provide a complementary way to efficient gradient-based optimization in lower-dimensional dynamic rupture settings (Stiernström et al., 2024). Non-intrusive reduced-order models provide another strategy, e.g., enabling sensitivity analysis of fault-geometry uncertainty (Hobson et al., 2025).

Despite these advances, systematically evaluating the dynamic viability of many alternative finite-fault slip models for the same earthquake remains difficult (Wong, Gabriel, & Fan, 2026). Consequently, it remains unclear which differences among published slip models can be reproduced within a common dynamic parameterization and whether these reflect observational uncertainty, alternative physically plausible faulting conditions, or dynamically inconsistent slip distributions. For the Tohoku-Oki earthquake, this question is important because published slip models imply contrasting levels of heterogeneity that, if interpreted mechanically, would correspond to different faulting conditions and rupture behavior (e.g., K. Wang & Bilek, 2014).

We address this gap using Ensemble Kalman Inversion (EKI, Iglesias et al., 2013). Ensemble Kalman methods provide a derivative-free framework for nonlinear problems in which gradients are unavailable or too costly to compute (Bannister, 2017; Evensen, 2003; Law et al., 2015). They have been widely applied in weather forecasting, reservoir characterization, and solid-Earth applications, including seismic tomography, earthquake-sequence data assimilation, slow-slip cycle modeling, postseismic deformation modeling, and multi-point-source earthquake inversion (**Wong-Preprint-2026**; e.g., Diab-Montero et al., 2023; Evensen, 2009; Fukuda & Barbot, 2025; Hirahara & Nishikiori, 2019; Kaveh et al., 2026; Muir & Tsai, 2020; van Dinther et al., 2019). EKI reformulates inverse problems as a sequence of ensemble updates, using sample covariances between model parameters and predicted observables to guide the ensemble toward data-consistent solutions. In the formulation used here, EKI is an optimization method for identifying data-consistent dynamic rupture parameters, but it does not generate posterior samples or quantify posterior uncertainty. This derivative-free approach is attractive for large-scale 3D dynamic rupture problems, for which parameter-to-observable derivatives are not readily available (Chada et al., 2020; Dunbar et al., 2022).

Here, we develop an EKI framework for dynamic rupture simulations to evaluate the dynamic viability of finite-fault slip models within a common model parameterization and examine the role of slip-informed shear-traction heterogeneity. We apply this approach to 32 finite-fault models of the 2011 M_w 9.0 Tohoku-Oki earthquake (Table 1).

Table 1. Finite-fault slip models of the 2011 M_w 9.0 Tohoku-Oki earthquake used as input to the EKI dynamic rupture framework. The 32 models are taken from the standardized compilation of Wong et al. (2024), in which published finite-fault models were projected onto a common megathrust geometry to enable direct comparison of slip distributions and derived stress-change patterns. Model labels indicate the primary data types used in the original inversions: G denotes geodetic models; S denotes teleseismic and/or geodetic models; R denotes regional seismic and/or geodetic models; T denotes tsunami and/or geodetic models; and J denotes joint inversions that combine geodetic, seismic, and tsunami observations. References listed in the table correspond to the publication of the original finite-fault slip models.

Model	Reference	Model	Reference	Model	Reference
G1	Pollitz et al., 2011	R1	Lee et al., 2011	S1	Ide et al., 2011
G2	Ito et al., 2011	R2	Suzuki et al., 2011	S2	Hayes, 2011
G3	Diao et al., 2012	R3	Wei et al., 2012	S3	Hayes, 2017
G4	Iinuma et al., 2012	R4	Yue and Lay, 2013	S4	Ammon et al., 2011
G5	C. Wang et al., 2012			S5	Yagi and Fukahata, 2011b
G6	R. Wang et al., 2013			S6	Kubo and Kakehi, 2013
G7	X. Zhou et al., 2014				
G8	Hashima et al., 2016				
G9	Xie and Cai, 2018				
Model	Reference	Model	Reference		
T1	Simons et al., 2011	J1	Yokota et al., 2011		
T2	Fujii et al., 2011	J2	Minson et al., 2014		
T3	Saito et al., 2011	J3	Bletery et al., 2014		
T4	Gusman et al., 2012	J4	Melgar and Bock, 2015		
T5	Hooper et al., 2013	J5	Yamazaki et al., 2018		
T6	Satake et al., 2013				
T7	Romano et al., 2014				
T8	Kubota et al., 2022				

These models were constrained by different combinations of geodetic, seismic, and/or tsunami observations. For each finite-fault model, we use EKI to search for a best-fitting dynamic rupture scenario by optimizing two parameters that control the amplitude of slip-derived shear-traction heterogeneity and the regional relative prestress ratio (Sec.2). We classify a scenario as dynamically viable if, after prescribed nucleation, rupture propagates and arrests spontaneously and satisfies the specified aggregate geodetic and moment-rate fit criterion. Within this parameterization, 26 of the 32 finite-fault slip models yield dynamically viable rupture scenarios spanning a range of heterogeneity levels and slip distributions. Rather than identifying a single “best” finite-fault model, our approach compares alternative dynamic interpretations under common geodetic, moment-rate, and physical constraints. The 26 viable scenarios fall into three dominant dynamic rupture-style families, suggesting that a smaller set of physical controls may organize the apparent diversity of finite-fault models. By analyzing shared and contrasting features across the ensemble of best-fitting dynamic rupture models, we examine how initial shear-traction heterogeneity relates to rupture style, near-trench slip, and the partitioning of released strain energy.

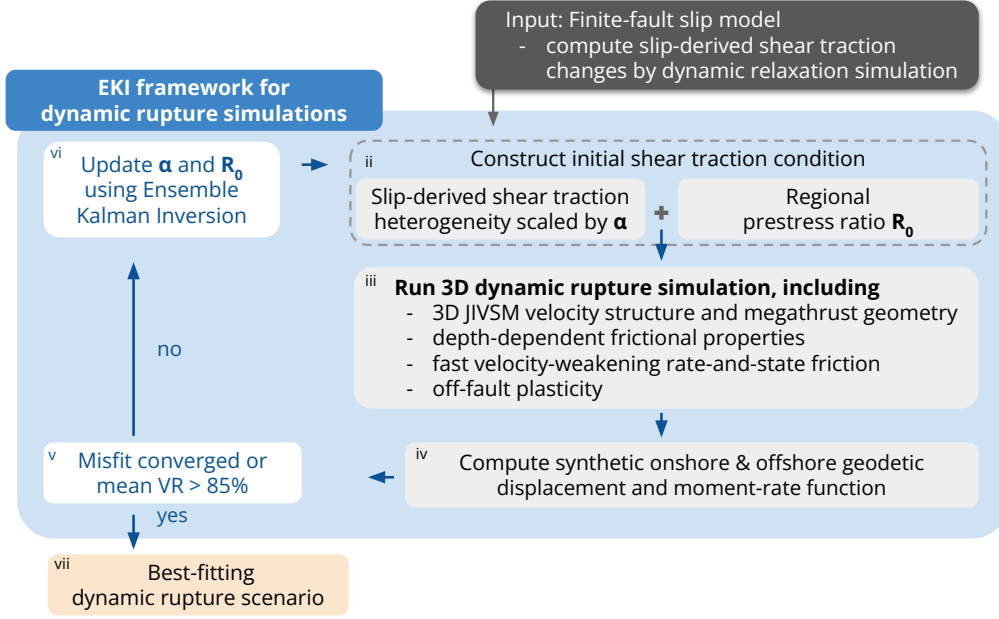


Figure 1. Overview of the Ensemble Kalman Inversion (EKI) dynamic rupture framework. We compute the (pseudo-)static stress change associated with each finite-fault slip model using a dynamic relaxation simulation with SeisSol. The initial shear traction condition combines this heterogeneous prestress-change field, scaled by α , with a smooth regional ambient shear stress field controlled by the relative prestress ratio R_0 (Aochi, 2003). Each pair of (α, R_0) defines one 3D dynamic rupture simulation, which uses the JIVSM velocity structure and megathrust geometry (Koketsu et al., 2009, 2012), depth-dependent frictional properties, fast velocity-weakening rate-and-state friction (Dunham et al., 2011), and off-fault plasticity (Andrews, 2005). Modeled onshore and offshore geodetic displacements and moment-rate function are compared with geodetic and teleseismic observations. If the misfit has not converged or the target variance reduction remains below 85%, EKI updates α and R_0 , and the workflow is repeated. The best-fitting dynamically viable rupture scenario is selected for each corresponding finite-fault slip model.

2 Methods

2.1 Overview of the Ensemble Kalman Inversion (EKI) dynamic rupture framework

For each finite-fault slip model, the EKI optimizes two scalar parameters, $\theta = (\alpha, R_0)$: α scales the amplitude of the slip-model-derived shear-traction heterogeneity, and R_0 sets the level of the smooth regional ambient prestress (Section 2.3). The forward operator $\mathcal{G}(\theta)$ is one 3D dynamic rupture simulation that returns three data-fit metrics: the variance reductions of the onshore geodetic displacements, the offshore geodetic displacements, and the teleseismic moment-rate function. These are reduced data-space measures computed from comparisons with observations, not raw observations. EKI iteratively updates a small ensemble of (α, R_0) pairs to drive the three variance reductions toward their target value of 100% (Section 2.2). The inversion stops when the misfit converges or the mean variance reduction exceeds 85%, and the ensemble member with the highest mean variance reduction is selected as the best-fitting dynamically viable rupture scenario for that slip model.

We develop an Ensemble Kalman Inversion framework for 3D dynamic rupture simulations (EKI-DR) that efficiently evaluates the dynamic viability of varying finite-fault slip models. For each finite-fault slip model, we derive a corresponding heterogeneous initial shear traction distribution (Causse et al., 2014; Olsen et al., 1997; Tinti et al., 2021; Yao & Yang, 2020) and use EKI to identify a best-fitting dynamic rupture scenario that is consistent with geodetic and teleseismic moment-rate observations (Fig. 1). In the following, we first summarize the overall workflow, then describe the EKI algorithm, initial stress parameterization, and dynamic rupture model setup in Sections 2.2, 2.3, and 2.4, respectively.

Fig. 1, step (i), illustrates how to derive the heterogeneous shear-traction change pattern from a given finite-fault slip model. We compute the (pseudo-)static stress change associated with each slip model using a dynamic relaxation simulation with SeisSol (Glehman et al., 2024, e.g.,): the kinematic slip distribution is imposed as a boundary condition on the megathrust, and the simulation is run until the on-fault traction and volumetric stress changes reach a quasi-static state (Section 2.3). This is equivalent to using slip rates from a kinematic finite-fault model to infer initial dynamic parameters (e.g., Causse et al., 2014; Tinti et al., 2005; Tinti et al., 2021; Yang et al., 2019).

In step (ii), we construct the initial shear traction condition for dynamic rupture simulations using the derived shear traction change heterogeneity and regional tectonic observations. Previous studies have proposed to parameterize friction and/or initial shear traction conditions using finite-fault slip models (Guatteri, 2000; Jia et al., 2023; Miyatake, 1992; Olsen et al., 1997; Weng & Yang, 2018; Yao & Yang, 2020). Here, the initial shear traction is defined as a combination of (1) heterogeneous shear traction derived from the given finite-fault slip model and (2) a spatially smooth regional ambient shear stress field based on the principal stress orientation (see details in Method Section 2.3 and Equation 7). Figure 2 illustrates one example of shear traction change distribution informed by finite-fault slip model T5 and the ambient shear stress. The ambient shear stress exhibits limited spatial variability compared to the slip-derived heterogeneity because the regional stress orientation varies gradually and the ambient prestress is resolved along the Japan Trench megathrust interface with limited along-strike variability. We parameterize the initial shear traction with two key parameters: the scaling factor α , which controls the amplitude of slip-informed shear traction heterogeneity, and the regional relative prestress ratio R_0 , which sets the ambient shear traction level.

Using the initial shear traction condition, we perform 3D dynamic rupture simulations with the open-source software SeisSol (Gabriel et al., 2025). The model incorporates a realistic 3D velocity structure and realistic megathrust geometry from the Japan Integrated Velocity Model (Fig. 2d, Koketsu et al., 2009, 2012), and off-fault plastic deformation (Andrews, 2005; Templeton & Rice, 2008). We use the same frictional setup across all models for fair comparison and follow the parameterization in Wong, Gabriel, and Fan (2026). We use a fast velocity-weakening rate-and-state friction law that exhibits strong frictional weakening at coseismic slip rate (~ 0.1 m/s) (Dunham et al., 2011), representing thermal pressurization and flash heating (e.g., Rice, 2006; Viesca & Garagash, 2015). We prescribe a simple depth-dependent rate-and-state frictional parameter ($a - b$) distribution (Fig. 2c). The shallow megathrust is assigned rate-strengthening friction ($a - b > 0$), consistent with laboratory constraints for clay-rich lithified rock and rock gouges at low slip velocities (Saffer & Marone, 2003). The seismogenic zone (10–45 km depth) is assigned rate-weakening friction ($a - b < 0$). Further downdip, between 40–50 km, friction gradually transitions back to rate-strengthening friction, consistent with inferences from repeating earthquakes and slow slip events (Nishikawa et al., 2023). Aside from the depth-dependent variation in $a - b$, we do not prescribe any frictional asperities. All other frictional parameters are spatially uniform and fixed across the ensemble of rupture simulations. Method Section 2.4 provides further details of the dynamic rupture model setup.

For each simulated earthquake, we compute synthetic onshore and offshore geodetic deformation and the moment-rate function (step (iv) in Fig. 1). We compare the synthetics with onshore geodetic observations from the GEONET network, offshore geodetic observations from pressure gauges and acoustic GNSS surveys (Ito et al., 2011; Kido et al., 2011; Yokota et al., 2018), and teleseismic moment-rate estimates from the SCARDEC database (Vallée & Douet, 2016) (step (v) in Fig. 1).

We quantify agreement with each dataset by its variance reduction and define the model prediction as $\mathbf{d} = \mathcal{G}(\theta) = (VR_{\text{onshore}}, VR_{\text{offshore}}, VR_{\text{MR}})$, with target $\mathbf{y} = (100\%, 100\%, 100\%)$. This formulation normalizes across datasets and assigns equal weight. We prescribe $\mathbf{R} = (10\%)^2 \mathbf{I}$, an effective uncertainty in variance-reduction space. This is an effective weighting of reduced data-space metrics rather than a direct observational uncertainty. The $\mathbf{R}$ magnitude is commensurate with the uncertainties of the geodetic data and the variability among published moment-rate estimates (Ito et al., 2011; Kido et al., 2011; Vallée & Douet, 2016), and it controls the step size of the ensemble updates (Equation 6).

We apply the Ensemble Kalman inversion using the calculated misfit to update the ensemble members towards data-consistent solutions. We repeat steps (ii) – (v) of the iterative inversion until the misfit converges or the variance reduction is high (e.g., $\geq 85\%$) to limit computational cost. We select the best-fitting dynamically viable rupture scenario for each corresponding finite-fault slip model.

2.2 Ensemble Kalman Inversion

The EKI algorithm seeks to minimize the cost function

$$\mathcal{L}(\theta) = \|\mathbf{R}_y^{-\frac{1}{2}}(y - \mathcal{G}(\theta))\|^2, \quad (1)$$

where $\mathcal{G}$ maps the model parameters to the data space and η represents observational and modeling errors, assumed Gaussian with zero mean and covariance $\mathbf{R}_y$.

EKI represents the parameter search with an ensemble of N_e model realizations. At iteration i , the ensemble is $\{\theta_i^{(j)}\}_{j=1}^{N_e}$, and each member is propagated through the forward model to produce a synthetic prediction $d_i^{(j)} = \mathcal{G}(\theta_i^{(j)})$. We define the ensemble means as

$$\bar{\theta}_i = \frac{1}{N_e} \sum_{j=1}^{N_e} \theta_i^{(j)}, \quad \bar{d}_i = \frac{1}{N_e} \sum_{j=1}^{N_e} d_i^{(j)}.$$

We then collect the centered ensemble anomalies into matrices

$$\mathbf{\Theta}_i = \frac{1}{\sqrt{N_e - 1}} \begin{bmatrix} \theta_i^{(1)} - \bar{\theta}_i & \theta_i^{(2)} - \bar{\theta}_i & \dots & \theta_i^{(N_e)} - \bar{\theta}_i \\ \vdots & \vdots & & \vdots \end{bmatrix} \in \mathbb{R}^{n_\theta \times N_e}, \quad (2)$$

and

$$\mathbf{D}_i = \frac{1}{\sqrt{N_e - 1}} \begin{bmatrix} d_i^{(1)} - \bar{d}_i & d_i^{(2)} - \bar{d}_i & \dots & d_i^{(N_e)} - \bar{d}_i \\ \vdots & \vdots & & \vdots \end{bmatrix} \in \mathbb{R}^{n_d \times N_e}. \quad (3)$$

The sample cross-covariance between parameters and synthetics and the synthetic covariance are then estimated as

$$\mathbf{C}_{\theta d} = \mathbf{\Theta}_i \mathbf{D}_i^\top, \quad \mathbf{C}_{dd} = \mathbf{D}_i \mathbf{D}_i^\top. \quad (4)$$

The ensemble is updated for the next iteration by

$$\theta_{i+1}^{(j)} = \theta_i^{(j)} + \mathbf{C}_{\theta d} (\mathbf{C}_{dd} + \mathbf{R}_y)^{-1} (y - d_i^{(j)}). \quad (5)$$

The update can be reformulated more compactly with the Kalman Gain

$$\mathbf{K}_i = \mathbf{C}_{\theta d} (\mathbf{C}_{dd} + \mathbf{R}_y)^{-1}, \quad (6)$$

giving $\theta_{i+1}^{(j)} = \theta_i^{(j)} + \mathbf{K}_i (y - d_i^{(j)})$.

The ensemble cross-covariance $\mathbf{C}_{\theta d}$ captures the empirical sensitivity between model parameters and synthetics. Combined with the inverse of the synthetic and observation covariance, the Kalman gain determines both the direction and magnitude of the parameter update. Parameters are adjusted more strongly in directions where the synthetics are sensitive to the data and the observation uncertainty is small, and less strongly where the data are noisy or weakly informative. For nonlinear inversion problems, a single covariance-based update may be insufficient because the empirical parameter-data relationships are nonlocal. EKI therefore applies ensemble Kalman updates iteratively, and each update can be interpreted as a Gauss-Newton optimization step in which the ensemble Kalman gain replaces the forward-model Jacobian (Iglesias et al., 2013; Tong & Morzfeld, 2023).

2.3 Initial shear stress parameterization

We define the initial stress tensor s_{ij} as a linear combination of the slip-derived stress-change tensor b_{ij} scaled by α and the regional ambient stress tensor c_{ij} (Jia et al., 2023; Miyatake, 1992; Olsen et al., 1997).

$$s_{ij} = \alpha b_{ij} + \Omega(z) c_{ij} + (1 - \Omega(z)) \sigma'_n \delta_{ij}. \quad (7)$$

We compute the pseudo-static stress-change tensor b_{ij} using a dynamic relaxation simulation, in which we impose the finite-fault slip distribution as a boundary condition on the megathrust, using the same fault geometry and mesh as in subsequent dynamic rupture simulations (Tinti et al., 2021). This approach is equivalent to using slip rate estimates from finite-fault slip models to infer initial dynamic parameters (e.g., Causse et al., 2014; Miyatake, 1992; Olsen et al., 1997; Tinti et al., 2005).

We use the 32 projected and unified slip models from Wong et al. (2024) (Table 1). These slip models are projected from their original geometries onto the JIVSM megathrust interface while preserving the near-trench slip features and the depth distribution of potency (Supplementary Fig. S1). We resample the projected slip model onto a dense 1 km $\times$ 1 km subfault grid while preserving the moment-potency distribution. We run each dynamic relaxation simulation for 250 s to allow seismic waves to exit the major rupture area and the shear traction-change field to reach a quasi-steady state. Shear-stress change artifacts may arise from sharp edges and different geometric projections in finite-fault slip models. We apply a Gaussian filter to the stress-change field with $\sigma = 2$ km to reduce the artifacts. This 2 km length scale is shorter than the typical 15–30 km subfault size used in finite-fault slip models.

The heterogeneous stress-change tensor b_{ij} is scaled by α , whereas the regional ambient stress tensor c_{ij} is modulated by a depth-dependent taper function $\Omega(z)$ that smoothly tapers deviatoric stress below the seismogenic zone (> 45 km depth). The seismogenic zone is defined based on the seismicity patterns in the Japan Subduction Zone (Nishikawa et al., 2023). σ'_n is the effective normal stress. We assume an elevated pore pressure reaching 90% of the lithostatic stress, as evident from drilling observations and seismic reflection studies (Jamali Hondori & Park, 2022; Saffer & Tobin, 2011), as well as principal stress orientation analysis (Hardebeck & Loveless, 2018).

The amplitude of the ambient stress tensor c_{ij} is parameterized by the regional relative prestress ratio R_0 , which is defined as $R_0 = 1/(1 + S)$ (Andrews, 1976; Aochi, 2003; Das & Aki, 1977) with S as the seismic ratio, and describes the ratio of the maximum possible stress drop to frictional strength drop. In the rate-and-state friction formulation, peak shear strength is not prescribed. We approximate the peak shear strength

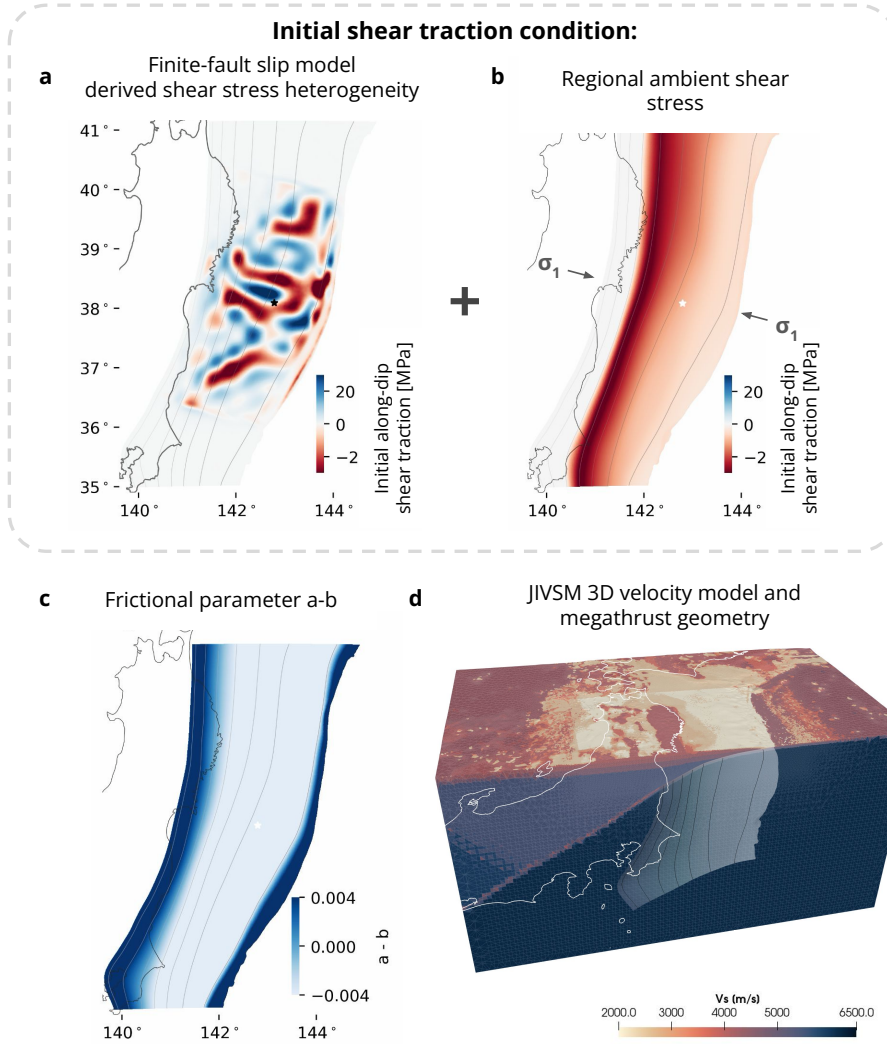


Figure 2. 3D dynamic rupture model setup of initial shear traction condition, frictional properties, and 3D velocity model and fault geometry. (a) Finite-fault slip model-derived shear traction change pattern. The shear traction heterogeneity is derived using the slip model from Model T5 (Hooper et al., 2013) using the dynamic relaxation simulation. (b) Regional ambient shear traction informed by principal stress orientation, as denoted by the arrows with σ_1 (Heidbach et al., 2018). The initial shear traction condition is a combination of (a) and (b) using Equation 7. (c) Along-dip frictional parameters $a - b$ distribution. Rate-strengthening friction with $a - b > 0$ (rate-strengthening) is prescribed above ~ 10 km and gradually transitions from rate-weakening at 40 km to rate-strengthening at 50 km depth, representing the shallow accretionary wedge frictional rheology and downdip limit of seismicity. (d) JIVSM megathrust geometry and 3D velocity structure model used in the study (Koketsu et al., 2009, 2012). The mesh resolution is refined around the megathrust interface and velocity structure to resolve the seismic wavefield up to 0.5 Hz. Plastic cohesion C_0 is defined based on a constant ratio between the shear modulus (Equation 11). Contour lines on the megathrust interface in both map view (a-c) and 3D view (d) delineate depth at 10 km intervals.

as $f_0\sigma'_n$ and the fully weakened shear strength as $f_w\sigma'_n$, where f_0 is the reference friction coefficient and f_w is the fully weakened friction coefficient. Hence,

$$R_0 = \frac{\tau_0 - f_w\sigma'_n}{(f_0 - f_w)\sigma'_n}, \quad (8)$$

where τ_0 is the initial shear traction. Higher values of R_0 therefore indicate that the megathrust is, on average, closer to failure. The regional ambient stress tensor is constructed following Ulrich et al. (2019) using the principal stress orientation inferred for the Japan Subduction zone from the World Stress Map database (Heidbach et al., 2018), with maximum principal stress azimuth of 100° , plunge of 8° , and principal stress ratio $(s_1 - s_2)/(s_1 - s_3) = 0.25$.

2.4 Dynamic rupture simulation

We use the open-source software SeisSol (Gabriel et al., 2025) to conduct the 3D dynamic rupture simulations. SeisSol solves earthquake rupture and seismic wave propagation on unstructured tetrahedral meshes using the ADER-DG method (Dumbser & Käser, 2006; Käser & Dumbser, 2006; Pelties et al., 2014; Wollherr et al., 2018).

We adopt a fast velocity-weakening rate-and-state friction law that produces substantial weakening once slip rate reaches coseismic speed, thereby approximating strong coseismic weakening processes such as thermal pressurization and flash heating (Rice, 2006; Viesca & Garagash, 2015). We follow the friction formulation by Dunham et al. (2011). The steady-state friction coefficient f_{ss} is given by

$$f_{ss}(V) = f_w + \frac{f_{LV,ss}(V) - f_w}{(1 + (V/V_w)^4)^{1/4}}, \quad (9)$$

where V_w is the onset of the weakening velocity, f_w is the fully weakened friction coefficient, and the steady-state low-velocity friction coefficient is:

$$f_{LV,ss} = f_0 - (b - a) \ln(V/V_0), \quad (10)$$

with b as the state-evolution parameter, and f_0 as the reference friction coefficient. The steady-state friction behavior is asymptotic, such that $f_{ss}(V) \approx f_{LV,ss}(V)$ for $V \ll V_w$ and $f_{ss}(V) \approx f_w$ for $V \gg V_w$. This behavior aligns with laboratory observations in various rock types and drilling samples in the Japan Subduction Zone (Beeler et al., 2008; Goldsby & Tullis, 2011; Ujiie et al., 2013), capturing classic rate-and-state frictional behavior at low sliding velocities and pronounced frictional weakening at high sliding velocities. A depth-dependent distribution of $(a - b)$ is used to represent the velocity-weakening seismogenic zone (10–45 km) and shallow velocity-strengthening materials in the accretionary wedge (above 10 km depth; Fig. 2c). The remaining frictional parameters are uniform and held fixed across the ensemble of rupture simulations, as listed in Table 2.

Our dynamic rupture models incorporate realistic megathrust geometry, high-resolution topobathymetry, and a 3D velocity model with an adaptive refined mesh to accurately capture rupture processes and seismic wave propagation up to 0.5 Hz (Breuer & Heinecke, 2022) (Figure 2d). The Japan Integrated Velocity Structure Model (JIVSM) includes layered continental and oceanic crust, an accretionary wedge, and mantle material (Koketsu et al., 2009, 2012). Our model uses a minimum shear wave velocity of 1700 m/s to limit the computational resources to resolve wavefields in low-velocity structures. The megathrust geometry follows the upper surface of the subducting oceanic crust and is smoothly extrapolated to shallow depths to connect to the trench in the 3D bathymetry. We use realistic topobathymetry from the GEBCO dataset at 15 arc-s (~ 380 m) resolution (GEBCO, 2024).

Our model also accounts for off-fault inelastic energy dissipation using a Drucker-Prager visco-elasto-plastic rheology (Andrews, 2005; Drucker & Prager, 1952; Templeton & Rice, 2008; Wollherr et al., 2018). We employ a material- and depth-dependent

377 cohesion model motivated by laboratory-inferred low cohesion at shallow depths. The
 378 bulk cohesion $C(z, \mu)$ varies linearly with confining pressure at different depths and varies
 379 with the 3D velocity structure:

$$C(z, \mu) = C_0(\mu) + C_1(z)\sigma'_c, \quad (11)$$

380 where $C_0 = \mu \times 10^{-3}$ represents the intrinsic cohesion based on rock shear modulus μ
 381 (Roten et al., 2014), $C_1(z)$ represents rock hardening with depth and $\sigma'_c = \sigma_{litho} - P_f$
 382 is the effective confining stress. Hence, the cohesive strength follows the 3D velocity struc-
 383 ture, with weak strength in the shallow accretionary wedge.

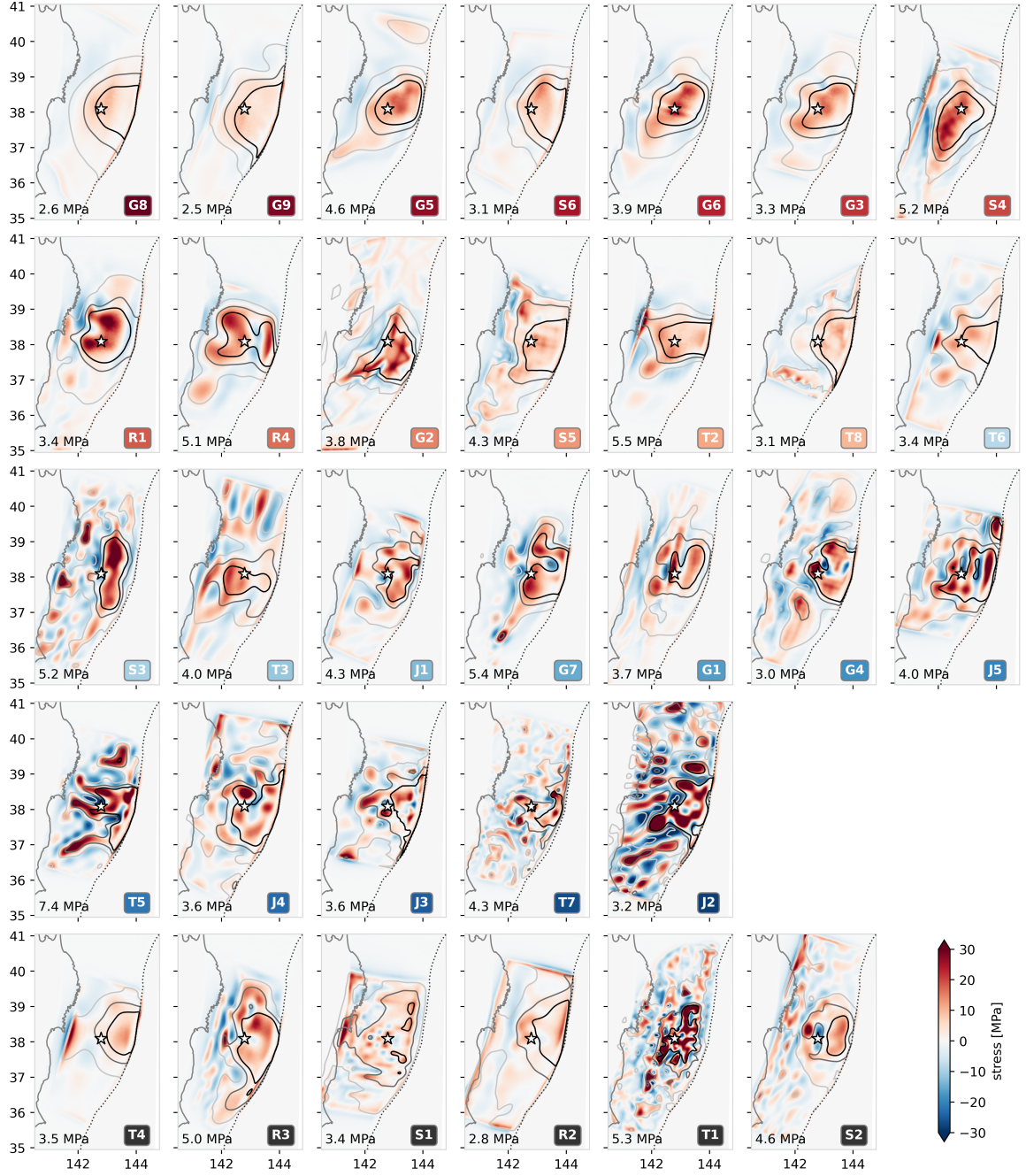


Figure 3. Coseismic shear traction change patterns derived from the 32 finite-fault slip models of the M_w 9.0 Tohoku-Oki earthquake. Red and blue colors represent regions with positive and negative stress drop, respectively. Stress drop equals the negative change in shear traction. The models are sorted by increasing heterogeneity using power spectral density estimates (Mai & Beroza, 2002; Wong et al., 2024), with red model tags indicating less heterogeneity and blue tags indicating more heterogeneity (Supplementary Material ??, Fig. ??). The first three rows show the 26 traction-change patterns that successfully produce a spontaneous rupture model in our framework. The bottom row shows the six shear traction-change patterns that failed to obtain a realistic rupture model within our framework. White star denotes the hypocenter location. Black contour lines delineate the finite-fault slip distribution at amplitudes of 5, 15, and 25 m. Dotted line indicates the trench location. The average stress drop value within 5 km slip contour is listed in the bottom left of each subplot. Table 1 lists the references of the 32 finite-fault slip models used.

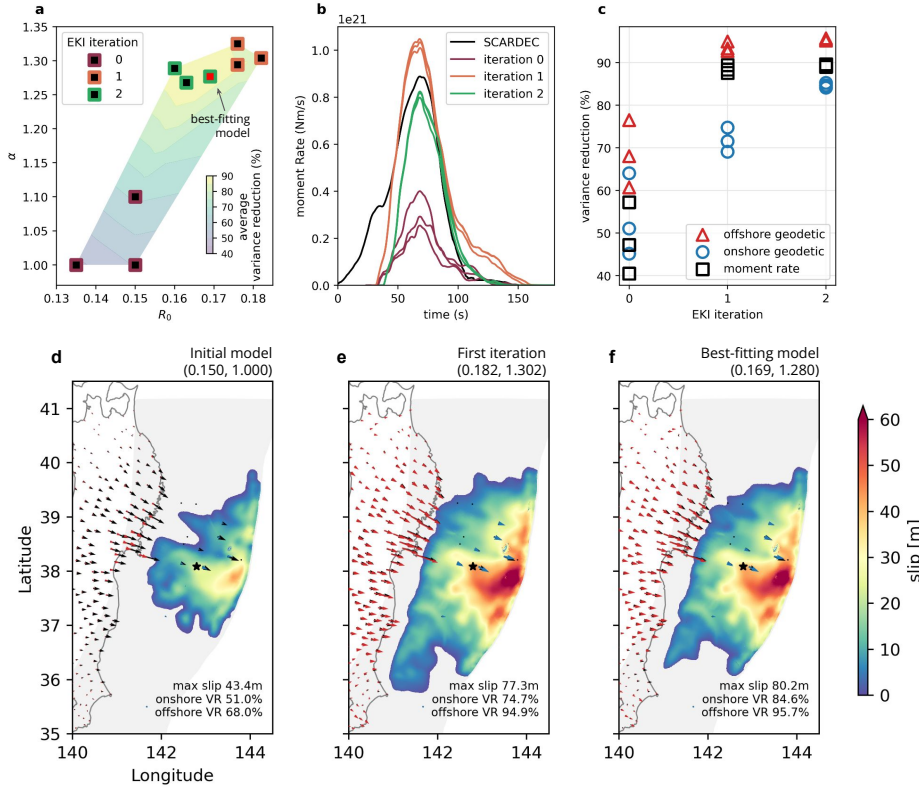


Figure 4. Data-informed dynamic rupture models using Ensemble Kalman inversion for finite-fault slip model T7. (a) Iterative exploration of the initial shear traction parameters (R_0, α). Each marker represents an ensemble member, colored by iteration. Background shading shows interpolated contours of the mean variance reduction, illustrating the iterative ensemble convergence toward a region of improved data fit. The best-fitting model is highlighted by the arrow. (b) Time-shifted moment rate functions of the ensembles in the iterative inversion. The black line represents the teleseismic SCARDEC moment rate function. The colored lines show the moment rate of the ensemble simulations. The simulated moment rates are time shifted with maximum cross-correlation coefficient. (c) Evolution of variance reduction across EKI iterations. Red triangles, blue circles, and black squares denote variance reduction for offshore geodetic data, onshore geodetic data, and the moment-rate function, respectively. (d–f) Dynamic rupture models at each EKI iteration. Color shading shows coseismic slip. Red and blue arrows represent synthetic onshore and offshore surface displacements, respectively, while black arrows represent observations. The initial model (d) underestimates both rupture extent, slip amplitude, and moment release, resulting in significant misfit. The first iteration (e) substantially increases rupture extent and slip amplitude, improving agreement with observations. The best-fitting model (f), obtained after two iterations, shows high agreement with observations, with mean variance reductions of up to 90%.

3 Results

We apply the Ensemble Kalman Inversion framework to evaluate the dynamic viability of 32 finite-fault slip models of the Tohoku-Oki earthquake (Fig.1). Figure 3 shows the shear stress change patterns derived from each finite-fault slip model, sorted by increasing degree of heterogeneity. Shear stress changes depend strongly on the spatial gradients of coseismic slip and therefore exhibit even greater spatial variability than the corresponding slip distributions (Brown et al., 2015). Most geodetic inversion models with smooth slip distributions produce relatively smooth shear stress change patterns, with peak amplitudes of about 5-10 MPa (e.g., Models G8, G9, and G5). In contrast, models derived from joint geodetic, seismic, and tsunami datasets, or from tsunami data alone (Model J and T groups), exhibit the most heterogeneous distributions of shear stress change. These models exhibit alternating positive and negative stress drop within the major rupture area, with amplitudes reaching 20–30 MPa (e.g., Models J3, T7, and J2). Despite this substantial variability, the average stress drop remains relatively consistent across models (2.5–7.4 MPa, values shown in each subplot of Fig. 3), in agreement with previous estimates (Brown et al., 2015).

We apply the EKI-DR framework to each finite-fault slip model to identify the best-fitting dynamic rupture scenario, using the corresponding shear-traction-change heterogeneity to construct initial shear-traction conditions (Fig. 2; Equation 7). Fig. 4 illustrates the iterative inversion process using shear traction change heterogeneity inferred from Model T7. The inversion is initialized with an ensemble of three forward simulations centered around $(R_0, \alpha) = (0.15, 1.0)$. We use an ensemble size of three, the minimum required to span the two-dimensional parameter space. We select the initial value of R_0 so that the maximum available stress drop, $\tau_0 - f_w \sigma'$, is comparable to that inferred from the finite-fault slip models. The initial rupture models substantially underestimate the rupture extent, geodetic deformation, and moment release (Fig. 4b,d), resulting in variance reductions below 70% for the onshore and offshore geodetic and teleseismic moment-rate observations.

In subsequent iterations, the ensemble is updated using the Kalman gain computed from the cross-covariance between the ensemble parameters and the data misfit (Equation 5). The first update shifts the ensemble to $(R_0, \alpha) = (0.182, 1.302)$ and substantially increases rupture extent and slip amplitude (Fig. 4e). The variance reduction increases from 68.0% to 94.9% for the offshore geodetic data, from 51.0% to 71.7% for the onshore data, and from 49.0% to 88.2% for the time-shifted moment-rate function. Models from this intermediate iteration slightly overestimate the rupture area and moment-rate function (Fig. 4b,e). The final update reduces the regional relative prestress ratio, yielding the best-fitting dynamically viable rupture scenario at $(R_0, \alpha) = (0.169, 1.280)$ with variance reductions of 84.6% (onshore), 95.7% (offshore), and 89.2% (moment rate; Fig. 4c,f). The average variance reduction reaches 89.8%, exceeding the target threshold of 85%. We therefore select this best-fitting model as the dynamic rupture model associated with finite-fault Model T7.

Among the 32 initial shear stress patterns informed by finite-fault slip models, the EKI-DR framework successfully identifies 26 dynamically viable rupture scenarios, each requiring three or fewer iterations. Each simulation requires ~ 1550 CPU-hours (or ~ 400 GPU-hours), resulting in a total computational cost of $\sim 450,000$ CPU-hours (or $\sim 114,000$ GPU-hours) across 285 simulations.

For the remaining six models (bottom row of Fig. 3), our EKI-DR framework produces either premature arrest near the hypocenter with limited moment release ($M_w < 7.5$) or runaway rupture without spontaneous arrest ($M_w > 9.3$). These cases are associated with low initial shear traction in the hypocentral area. Consequently, rupture either arrests prematurely because of insufficient available strain energy, or the iterative update increases the initial shear traction conditions sufficiently to sustain rupture through

the hypocentral region but simultaneously promote runaway rupture elsewhere. We therefore cannot exclude that alternative initial-stress parameterizations beyond our two-parameter family (e.g., spatially variable α , different ambient-stress tapers, alternative nucleation positions, or frictional heterogeneity) could yield viable scenarios for these six models.

3.1 Slip distribution and geodetic deformation of the 26 best-fitting dynamic rupture scenarios

The ensemble of 26 best-fitting dynamically viable rupture scenarios reproduce both smooth and heterogeneous slip distributions. Figure 5 shows the simulated slip distributions and corresponding surface deformation, ordered by increasing initial shear stress heterogeneity.

Models with smoother initial shear stress conditions produce relatively simple slip patterns, typically characterized by a dominant slip asperity updip of the hypocenter (e.g., Models G8 and G9). In contrast, more heterogeneous initial shear stress conditions give rise to more complex slip features, including extended slip towards the south (e.g., Models S4 and S3) and north (e.g., Models T6 and J5). The most heterogeneous initial shear stress patterns produce highly variable slip patterns, with localized high-slip regions (e.g., Models T5, T7, and J2).

Despite this diversity, most simulations reproduce both the slip features of their corresponding finite-fault slip models and the observed geodetic deformation. Figure 6 quantifies this agreement using spatial correlation between the simulated and finite-fault model slip distributions. Correlations between each dynamic rupture model and its corresponding finite-fault model are consistently high (mean: 0.93; minimum: 0.88), substantially higher than the pairwise correlations among the finite-fault slip models (mean: 0.79; (Wong et al., 2024)).

Importantly, this agreement does not systematically depend on the degree of initial shear stress heterogeneity. Both smooth and highly heterogeneous initial shear stress conditions can reproduce their respective target slip distributions. As a result, the dynamic rupture simulations can reproduce contrasting slip features proposed in previous studies (Lay, 2018; Wong et al., 2024), including southern slip extensions (e.g., Models T5 and S5) and northern shallow slip extensions (e.g., Models J5 and J2).

However, a systematic difference remains between dynamic rupture models and finite-fault inversion. In all simulations, slip develops through a spatially connected rupture, whereas finite-fault slip models can produce isolated slip patches. For example, finite-fault slip model T5 includes an isolated slip patch in the northern region (Fig. S1), while the corresponding dynamic rupture model produces a connected slip distribution despite alternating positive and negative initial shear stress conditions. This discrepancy likely reflects physical constraints imposed by dynamic rupture propagation that are absent from kinematic finite-fault inversions.

Most best-fitting dynamic rupture scenarios also reproduce realistic onshore and offshore surface deformation. Approximately two-thirds of the models achieve variance reduction exceeding 80% for both onshore and offshore geodetic observations (Figure 6), comparable to the finite-fault inversions. Notably, models with stronger initial shear stress heterogeneity (T and J groups) perform as well as with smoother geodetic-only models (G group), indicating that the geodetic observations available during the Tohoku-Oki earthquake cannot discern the level of heterogeneity. This is consistent with previous results showing the limited sensitivity of both onshore and offshore geodetic observations to the small-scale slip features among the slip models (Wong et al., 2024).

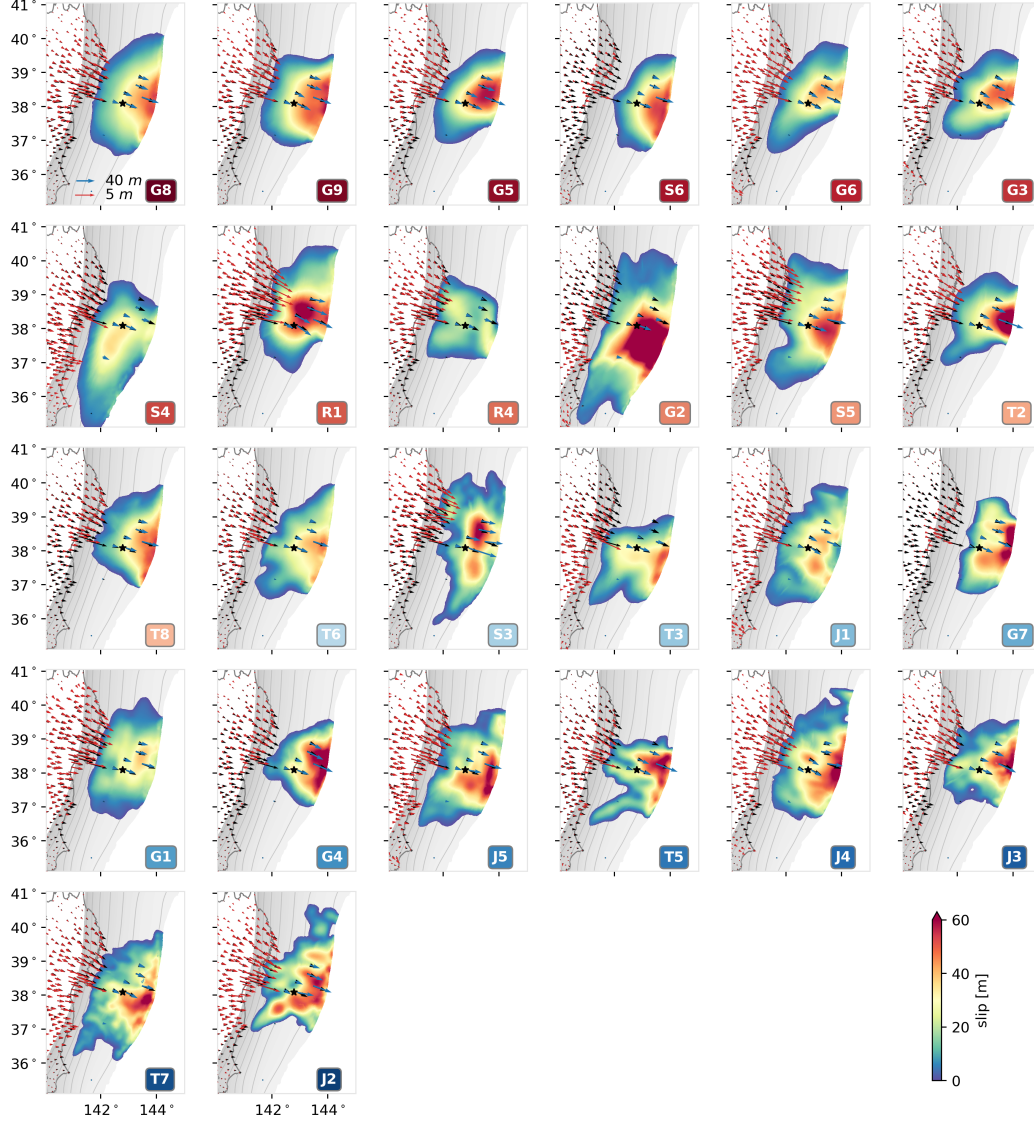


Figure 5. Slip distribution of 26 best-fitting dynamic rupture scenarios and corresponding geodetic deformation. Blue and red arrows represent offshore and onshore geodetic deformation synthetics, while black arrows represent observations. The top-left panel shows the two different scaled onshore and offshore displacement vectors, with a 40 m offshore displacement and a 5 m onshore displacement reference vector. The black star represents the hypocenter location. The light gray lines along the fault interface indicate depth at 10 km intervals.

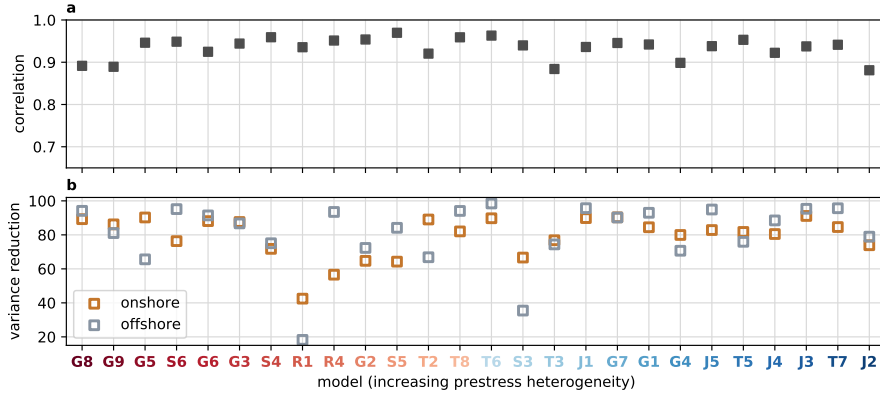


Figure 6. Dynamic viability of the best-fitting dynamic rupture scenarios on slip distribution and surface deformation. (a) Correlation between the dynamic rupture model slip distribution and finite-fault slip models. (b) Variance reduction between model predictions and onshore and offshore geodetic observations. The models are sorted in increasing order of stress-change heterogeneity.

3.2 Rupture evolution and moment-rate function

Despite dynamic rupture simulations reproducing the diverse slip distributions and observed geodetic deformation, rupture evolution varies substantially across the ensemble. Three dominant styles emerge, each systematically associated with the degree of initial shear stress heterogeneity. Fig. 7 highlights the three rupture styles, with the top row showing the moment-rate functions of the models with similar styles and the bottom row showing the slip-rate evolution across the hypocentral along-dip profile of each representative model.

3.2.1 Crack-like rupture

Models with relatively low initial shear stress heterogeneity predominantly exhibit crack-like rupture behavior (Fig. 7a,d). Crack-like rupture is characterized by prolonged local slip durations (rise times) comparable to the total event duration, whereas pulse-like rupture is characterized by transient and short rise times followed by a healing front (Heaton, 1990). Figure 8a shows the rupture evolution of Model G6 as an example of crack-like rupture. The rupture expands radially after the prescribed nucleation for the first 40 s. Continuous slip behind the rupture fronts leads to a prolonged local slip duration (rise time) up to 40 s near the hypocenter, consistent with crack-like rupture characteristics. At 40 s, the expanding rupture front reaches both the updip and downdip limits of the seismogenic zone, creating a stopping phase. The rupture subsequently transitions to a bilateral rupture that propagates along-strike. The bilateral rupture gradually decays and arrests in low-initial-shear-stress regions (around 80-90 s).

This simple crack-like rupture leads to a characteristic moment release rate (Fig. 7a). Continuous slip behind the rupture front during the first half of the crack-like rupture leads to significant moment release. The moment rate peaks at about 40 s when the rupture saturates the seismogenic zone. The formation of the stopping phase and the transition to bilateral rupture lead to a rapid decay in the moment-release rate and result in a relatively symmetric triangular moment-rate, as shown in Figure 7a. The early peak and limited duration are in contrast with the observed gradual moment-rate release at

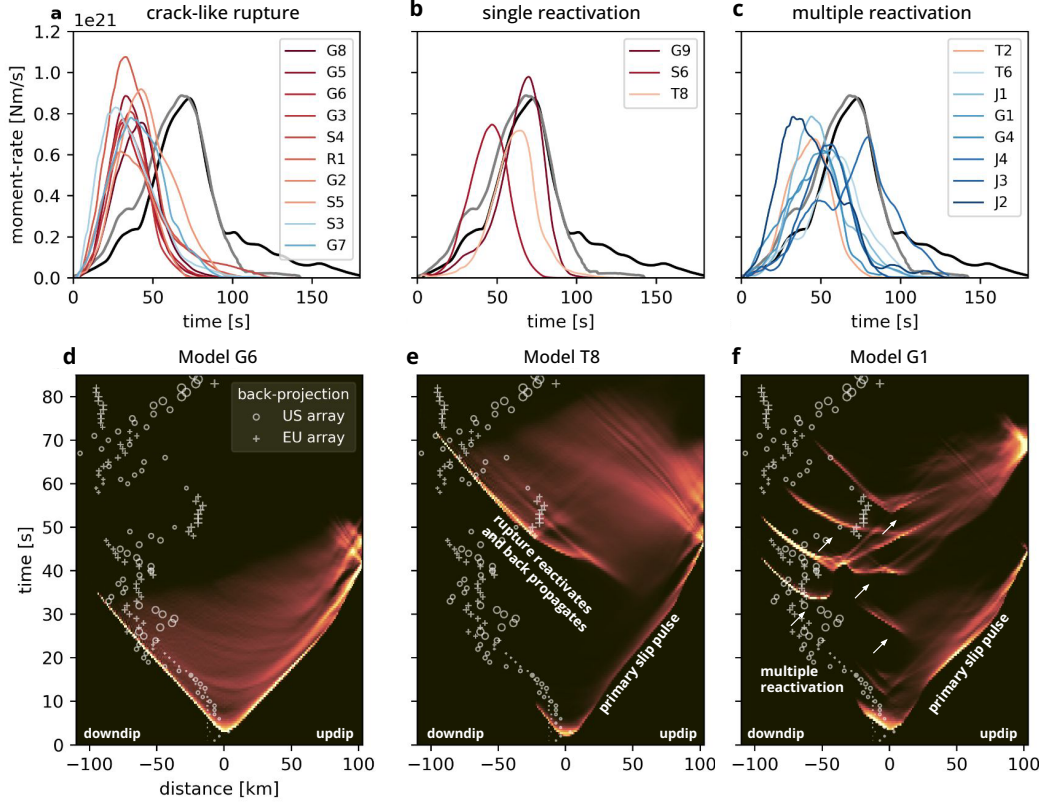


Figure 7. Three major rupture styles of the dynamic rupture simulations and their moment-rate functions. (a–c) Moment-rate functions of models exhibiting (a) crack-like rupture, (b) single-reactivation (pulse–crack transition) rupture, and (c) multiple-reactivation rupture. Grey and black lines show the SCARDEC (Vallée & Douet, 2016) and USGS (<empty citation>) moment-rate functions. (d–f) Along-dip slip-rate evolution of one representative model per style; white crosses and circles mark high-frequency back-projection radiators (Meng et al., 2011) for the US and EU arrays. (d) Model G6 (crack-like) produces an early moment-rate peak and overestimates early moment release. (e) Model T8 (single reactivation) first propagates updip as a slip pulse, then reactivates at about 35 s and back-propagates as a crack-like rupture. (f) Model G1 (multiple reactivation) exhibits five reactivation episodes and two major updip ruptures with longer rise times than the sharp downdip pulses.

the first 30 s and peak moment-rate at about 60–70 s of the Tohoku-Oki earthquake inferred from the seismic observations (Hayes, 2011; Vallée & Douet, 2016).

3.2.2 *Single reactivation pulse-crack transition rupture*

A second rupture style emerges with a single reactivation pulse-crack transition rupture style. Compared to the pure crack-like model, this rupture style first initiates as a pulse-like rupture propagating updip of the hypocenter. Figure 8b shows the rupture evolution of Model S6, representing this rupture style. The rupture initiates as a single slip pulse propagating updip for the first 15 s. During 15–20 s, the primary slip pulse spirals and the rupture reactivates at the hypocentral region, forming a secondary reactivated rupture behind the primary rupture front. In contrast to the primary slip pulse, the reactivated rupture front expands radially in a crack-like rupture and coalesces with the primary pulse-like rupture front at about 30 s. The combined rupture forms a simple circular crack-like rupture that follows the same rupture behavior as the pure-crack-like rupture. The circular crack saturates the seismogenic zone at about 40 s and forms the stopping phase at 40 s as the rupture propagates into the downdip region of low initial shear stress. The stopping front propagates updip, and the crack-like rupture transitions into a bilateral rupture (55 s in Fig 8b). The bilateral rupture propagates along strike and gradually arrests.

This pulse-crack rupture style has a distinct moment-rate function with two-slope moment-release acceleration (Fig 7b). The first 15–25 s are characterized by a gradual moment release due to the initial pulse-like rupture with limited rise time. The moment release rate increases and forms a steeper slope as the rupture reactivates, coalesces with the primary front, and transforms into a crack-like rupture. The moment rate peaks when crack-like rupture saturates the seismogenic zone, then decays rapidly as the stopping phase forms and the rupture transitions to bilateral rupture. This moment rate has a longer duration than the pure crack-like rupture and a distinct two-slope moment rate in the first half of the earthquake, more consistent with the observation inferred moment-rate function (Fig 7b).

3.2.3 *Multiple reactivation rupture*

A third rupture style emerges as the complex depth-dependent rupture evolution with multiple reactivation. Models with more heterogeneity, including G1, J3, and J2, exhibit this complex rupture style. Figure 9 shows the map view rupture evolution of two exemplary models, G1 and J3. Model G1 initiates as a primary slip pulse for the first 20 s. The slip pulse propagates updip and along strike, forming three separate slip pulses modulated by regions of high initial shear stress. At about 28 s, the bilateral slip pulses spiral and re-nucleate second rupture fronts near the hypocentral and downdip region. The downdip reactivated rupture fronts propagate as slip pulses, collide at about 46 s, and reactivate new rupture fronts. In contrast to the downdip slip pulses, the updip reactivated rupture fronts propagate as crack-like ruptures and expand and coalesce with the downdip rupture. The crack-like rupture transforms into bilateral slip pulses propagating along-strike when saturating the seismogenic zone width at 65 s. The bilateral slip pulses gradually propagate and arrest spontaneously.

Model J3 rupture evolves similarly, with multiple reactivations at the hypocentral and downdip region, while reactivated fronts coalesce into an updip crack-like rupture (Fig. 9b). Model J3 initiates as a primary slip pulse in the first 20 s. Between 25–30 s, the updip primary slip pulses spiral and re-nucleate multiple times behind the primary fronts. Between 30–45 s, the reactivated fronts coalesce into an updip crack-like rupture while continuously re-nucleating at the downdip and hypocentral region. At 55 s, a last episode of rupture reactivates, and the updip crack-like rupture transitions to bilateral

rupture as it saturates the seismogenic zone width. The bilateral rupture propagates along-strike and spontaneously arrests.

As shown by models G1 and J3, both involving multiple rupture reactivations, each rupture is strongly modulated by the initial shear-stress heterogeneity and evolves differently. Variability in rupture evolution leads to greater variability in the corresponding moment-rate functions of these multiple-reactivation models, compared to those of simple crack-like rupture or the single-reactivation model. Figure 7c shows that episodic rupture reactivation modulates the slope of the moment rate. The first 20 s of the simulations also shows a gentle moment release characterized by the initial slip pulses. Despite the complex evolution of the rupture, the overall shape of the moment rate function is triangular, consistent with observations.

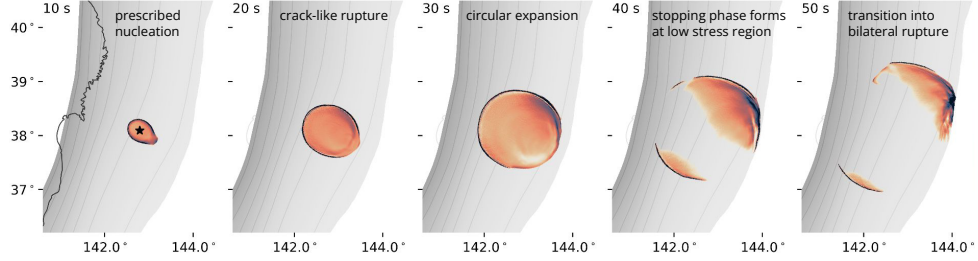
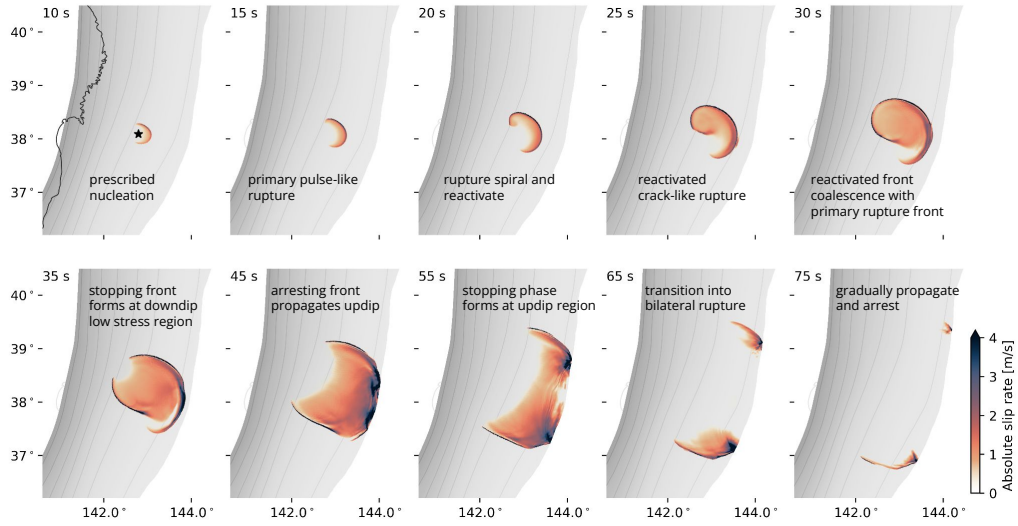
a Model G6 - crack-like rupture**b Model S6 - simple pulse-crack transition**

Figure 8. Rupture evolution of (a) Model G6 with crack-like rupture and (b) Model S6 with pulse-crack transition rupture style. (a) Map-view snapshots of absolute slip rate, showing the circular expansion of crack-like rupture from 10–40s and transition to bilateral rupture subsequently. (b) The rupture first initiates as an updip propagating slip pulse. The rupture spirals and reactivates at 20 s, with reactivation in the hypocentral region. The reactivated crack-like rupture coalesces with the primary pulse-like rupture. A stopping phase forms at the downdip region of low shear stress and propagates updip. The rupture transitions to bilateral rupture at 65 s and then gradually arrests. The black star indicates the hypocenter. Dotted contour lines delineate 10 km depth intervals.

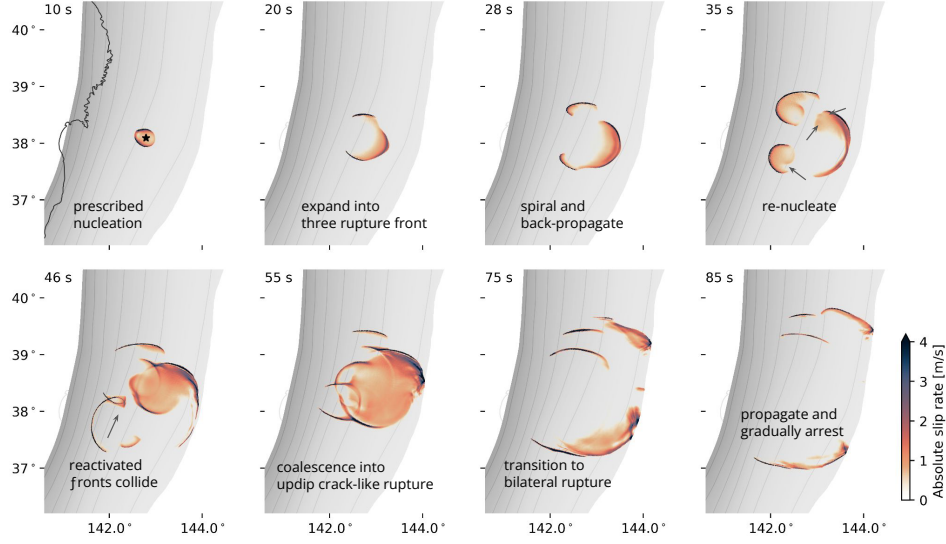
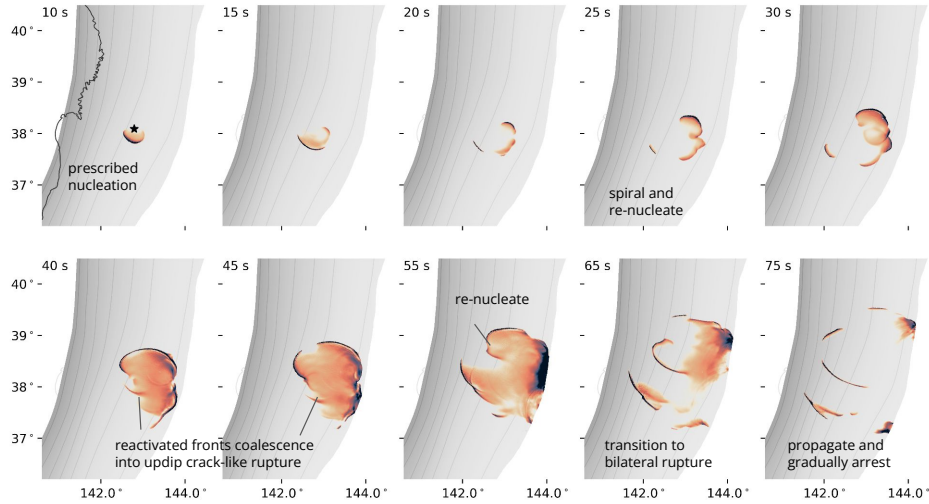
a Model G1 - multiple rupture reactivation**b Model J3 - multiple rupture reactivation**

Figure 9. Rupture evolution of the model G1 and J3 with multiple rupture reactivation. Both models rupture first by propagating an expanding slip pulse. Between 25 and 30 seconds, the rupture spirals and re-nucleates behind the primary rupture front. The reactivated rupture propagates updip and coalesces with the primary rupture to form an updip crack-like rupture between 30 and 60 s. Reactivation repeats at the downdip region, leading to multiple slip pulses at depth. After 65 s, rupture transitions to bilateral rupture and propagates along-strike. The rupture gradually arrests subsequently. Black star denotes the hypocenter, and the contours denote 10 km depth intervals.

4 Discussion

4.1 Efficient EKI-dynamic rupture modeling framework to examine finite-fault slip models with physics constraints

Our EKI-DR framework (Fig. 1) provides an efficient, physics-based approach for evaluating the dynamic viability of finite-fault-slip-model-informed rupture scenarios within a common model parameterization constrained by observations. The derivative-free ensemble optimization efficiently explores the nonlinear parameter space while simultaneously enforcing the physical constraints of spontaneous dynamic rupture. Although the inversion considered here involves only two parameters, previous dynamic rupture studies commonly relied on grid searches requiring more than 30 simulations to identify a preferred model (Wong, Gabriel, & Fan, 2026). More generally, an exhaustive grid search over d parameters requires $\mathcal{O}(k^d)$ forward simulations for k trial values per parameter, making systematic exploration increasingly expensive as the parameter dimension grows. In contrast, EKI uses an ensemble whose size needs to scale at least with the effective dimension of the parameter space to resolve the span of the parameter–data covariances, requiring $\mathcal{O}(k^d)$ forward simulations.

This computational efficiency enables us to systematically evaluate a large ensemble of alternative rupture scenarios. We examine 32 finite-fault slip models of the 2011 Tohoku-Oki earthquake and identify 26 dynamically viable, observation-consistent 3D dynamic rupture models using only 285 forward simulations in total. Rather than selecting a single preferred finite-fault representation, this ensemble of dynamically viable models allows us to quantify which inferred rupture characteristics are robust to uncertainties among finite-fault inversions and to examine how data-informed variations in initial traction level and heterogeneity influence earthquake rupture dynamics.

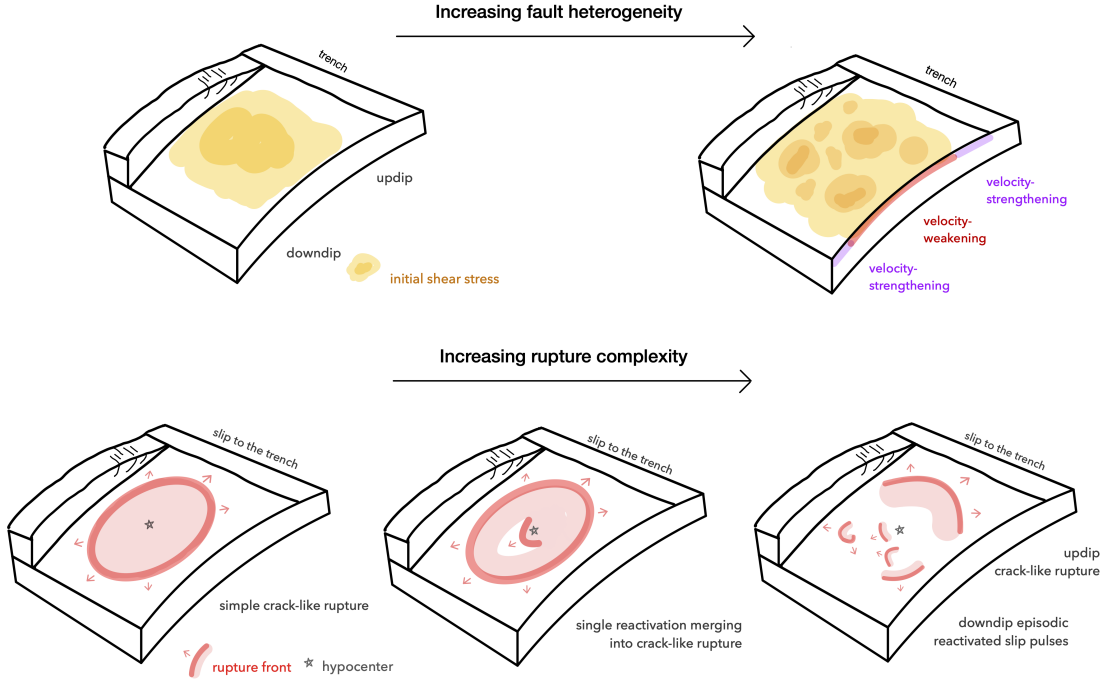


Figure 10. Illustration of the role of fault heterogeneity on rupture behavior. The top row indicates the faulting condition as heterogeneity increases. The bottom row illustrates the rupture behavior as complexity increases, corresponding to the faulting conditions. A smooth initial shear stress field without much frictional heterogeneity would lead to a simple circular rupture. Relatively smooth faulting conditions can also lead to rupture behavior of a single reactivation merging into crack-like rupture. A heterogeneous faulting condition with localized regions of high shear stress leads to complex depth-dependent rupture behavior with updip crack-like rupture and downdip episodic reactivated slip pulses. These reactivated slip pulses may spiral, back-propagate, collide, and coalesce with the primary rupture fronts.

4.2 Role of heterogeneity on megathrust rupture behavior

Using the efficient EKI-DR framework, we analyze heterogeneity patterns derived from 32 finite-fault slip models and assess their effects on rupture dynamics. These models span a broad range of heterogeneity distributions, characterized by contrasting spatial scales and amplitudes (Fig. 3). Despite this diversity, our suites of dynamic rupture models indicate that the overall level of heterogeneity exerts primary control on rupture dynamics, whereas the specific spatial realization of the heterogeneity plays a secondary role (Fig 10).

Across the 26 preferred models, a wide range of slip distributions and geodetic deformation patterns can be reproduced. This result indicates that multiple realizations of heterogeneity can dynamically reproduce geodetic observations and the variability ob-

served in published slip models. However, rupture behavior varies systematically with the degree of heterogeneity, directly influencing the evolution of moment rate and seismic radiation patterns. Models with smoother initial shear stress distributions tend to produce more coherent, circular, crack-like rupture propagation, whereas stronger heterogeneity promotes complex rupture evolution, including episodic rupture reactivation and depth-varying seismic radiation patterns.

Smooth and elevated initial shear stress distributions favor simple crack-like rupture behavior. Crack-like rupture occurs when the relative prestress ratio (defined as stress drop over strength drop) exceeds a critical threshold (Zheng & Rice, 1998). Models such as G8 exhibit elevated and spatially smooth initial stress conditions that sustain crack-like rupture. Other smooth initial shear stress models, such as G9, display an initial slip pulse followed by a single reactivation. In these cases, the initial shear stress in the hypocentral region may be insufficient to sustain crack-like rupture. However, the healing front formed at the tail of the slip pulse restores fault friction and allows the shear stress to rebuild (Perrin et al., 1995; Wong, Gabriel, & Fan, 2026). The resulting broad region of reloaded shear stress facilitates a subsequent reactivated crack-like rupture (Figure 7).

In contrast, models with strong heterogeneity, characterized by concentrated shear stress asperities separated by low-stress regions, promote multiple reactivation and depth-varying rupture styles. Pulse-like rupture emerges when rupture propagates into areas of reduced initial shear stress or encounters frictional or geometric barriers (S. Nielsen & Madariaga, 2003; Paglialonga et al., 2026). At the tail of the slip pulse, the healing front recovers fault strength, allowing stress re-accumulation from the propagating rupture front. When the re-accumulated stress exceeds the local yield strength over the nucleation size, rupture re-nucleates and generates secondary fronts. All reactivated ruptures are pulse-like down-dip for heterogeneous models, due to the locally heterogeneous nature of the slip left behind by the primary rupture front, which correlates with the distribution of the primary residual stresses (Gabriel et al., 2012). This process may repeat multiple times as successive slip pulses restrengthen the fault and rebuild shear stress behind the rupture front. The downdip reactivated front may coalesce with the primary rupture and the free-surface reflected rupture, leading to a prolonged crack-like rupture updip while multiple slip pulses occur downdip (Wong, Gabriel, & Fan, 2026). This process is not specific to a single pattern of heterogeneity or to depth-dependent heterogeneity; it consistently arises across all heterogeneous models.

The observed moment-rate function provides an additional constraint on rupture style. Compared with the abrupt moment release predicted by simple crack-like rupture models, the observed moment-rate function suggests a more gradual release, consistent with an initial pulse-like rupture followed by reactivation. Models with single or multiple reactivations better reproduce the overall source duration, whereas smooth and elevated initial stress models tend to produce an early moment-rate peak and often overestimate the early portion of the observed moment-rate function.

Previous work on heterogeneity has focused on frictional parameters and their effects on nucleation and arrest (e.g., Ide & Aochi, 2005, 2013). Our study shows that heterogeneity is fundamental in governing characteristic rupture dynamics common in many megathrust earthquakes. While heterogeneous fault conditions are expected with the broad spectrum of faulting behavior observed along the Japan subduction zone (Nishikawa et al., 2023), the nature of heterogeneity remains unresolved. The stress heterogeneity explored in our study can arise from variations in frictional properties, structural complexity, stress conditions, fault geometry, or a combination of these factors (Bassett et al., 2016; Nishikawa et al., 2023). Dynamic rupture models often exhibit a strong trade-off between frictional strength and dynamic stress drop (e.g., Tinti et al., 2021; Wong, Gabriel, & Fan, 2026), limiting the ability to resolve coseismic stress alone. Observations across multiple spatial and temporal scales would help distinguish between stress-, friction-, structure-

, and geometry-controlled sources of rupture complexity (e.g., Premus et al., 2022; Schliwa et al., 2024).

In addition to the nature of heterogeneity, the constraints on its distribution are equally important. This highlights that, in addition to resolving the large-scale slip deficit from interseismic coupling inversion, which provides insights into large-scale stress and frictional conditions, characterizing the shorter-scale heterogeneity is fundamental for accounting for dynamic effects and thus forecasting rupture behavior and seismic hazards.

4.3 Large tsunamigenic trench slip despite contrasting near-trench initial stress conditions

We examine near-trench slip behavior that governs the seafloor displacement and tsunami generation of the 2011 Tohoku-Oki earthquake. Finite-fault slip models exhibit substantial variability in shallow slip towards the trench (Sun 2017). Approximately half of these models taper near the trench, whereas others indicate peak slip towards the trench, depending on the datasets used and the imposed no-slip or free-slip boundary. The stress change patterns inferred from this wide range of slip behaviors imply contrasting shallow prestress conditions prior to the Tohoku-Oki earthquake (Fig. 11). For example, Models G7 and G8 suggest available initial shear stress at shallow depths prior to the Tohoku-Oki earthquake. In contrast, Models R1 and J1 suggest limited to negative initial shear stress, while more heterogeneous models, including Models J5 and J2, represent possible alternating initial shear stress conditions. Tectonic loading conditions at shallow depths prior to the earthquake remain poorly constrained due to limited offshore near-trench measurements. Existing coupling models (e.g., Lindsey et al., 2021; Loveless & Meade, 2016) suggest a wide possible range of coupling ratios, implying either accumulated or limited stress along the shallow megathrust prior to the 2011 Tohoku-Oki earthquake.

Our suite of dynamic rupture models examines this range of possible initial shear stress conditions (Fig. 11). Despite these variations in shallow initial shear stress conditions, imposed velocity-strengthening friction ($a - b > 0$) at shallow depths, and off-fault inelastic deformation, the simulations consistently produce large near-trench slip (Fig. 12a). Twenty-four out of 26 rupture models exhibit trench slip exceeding 25 m, with a median along-dip profile indicating ~ 40 m of slip at the trench and only a 20% shallow slip deficit from the 50 m peak slip 20 km horizontal distance from the trench. In comparison, only five finite-fault slip models suggest more than 40 m slip at the trench, and the median slip of all 32 finite-fault models has a trench slip less than 20 m with a ~ 50 % shallow slip deficit.

These results highlight the large tsunamigenic potential of megathrust earthquakes, even under unfavorable shallow prestress conditions, with velocity-strengthening friction and off-fault plastic deformation. Strong dynamic weakening at depth and the momentum carried by propagating rupture promote large slip into the shallow region (Kozdon & Dunham, 2013; Wong, Gabriel, & Fan, 2026). The resulting shallow slip is consistent with differential bathymetry survey (Kodaira et al., 2020; Sun et al., 2017) and agrees with prior numerical studies that reproduce large near-trench slip under comparable shallow fault and wedge rheology (Kozdon & Dunham, 2013; Ulrich et al., 2022; Wong, Gabriel, & Fan, 2026).

4.4 Stress drop, radiated energy, and breakdown energy

The long-standing debate over whether earthquake rupture propagates predominantly in a crack-like or pulse-like mode has direct implications for inferred frictional behavior and energy partition (Cocco et al., 2023; Kammer et al., 2024; Lambert et al., 2021).

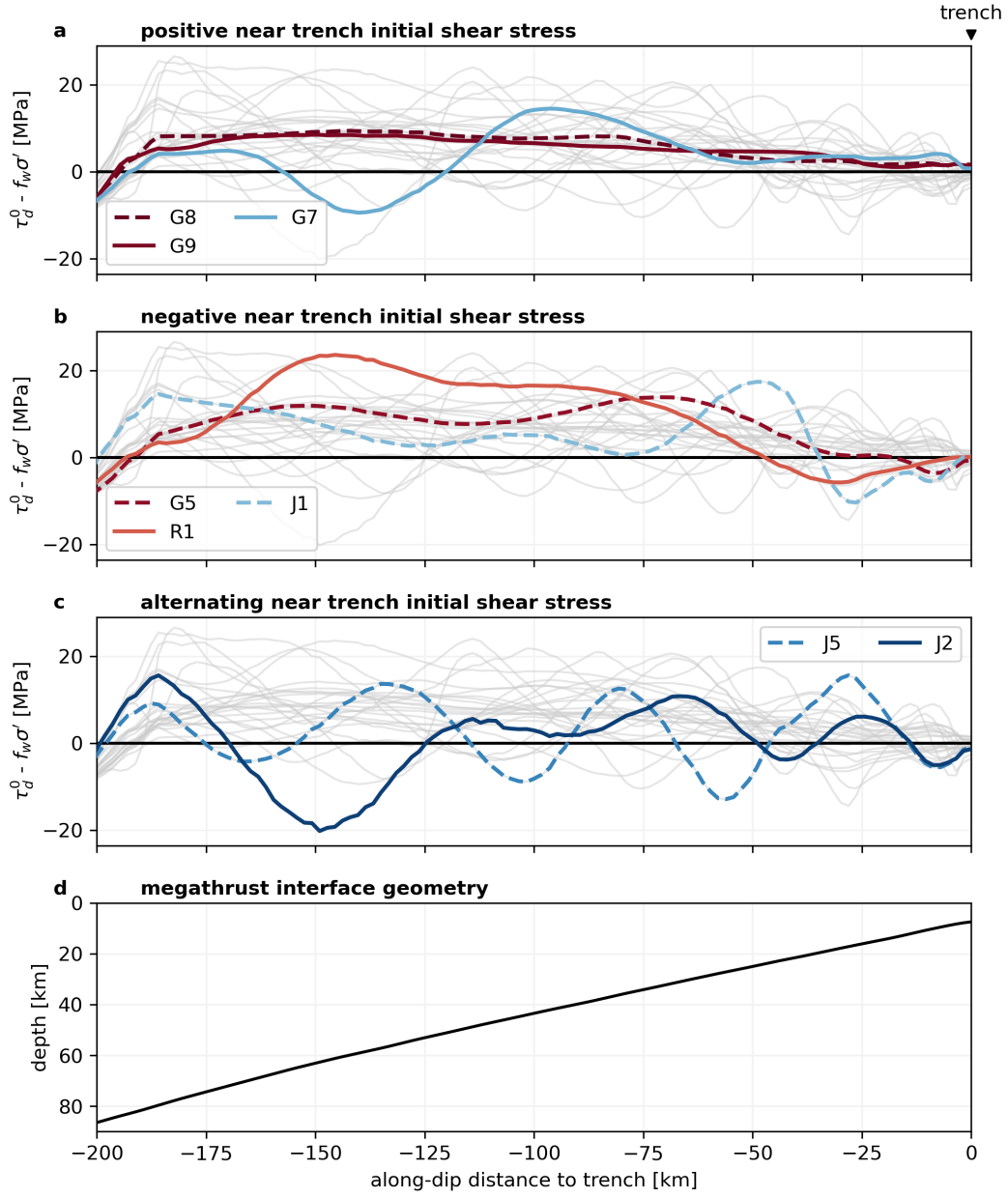


Figure 11. Along-dip variations in initial shear stress for the 26 preferred rupture models. Panels (a–c) show the initial shear stress along the megathrust interface for the 26 preferred rupture models. Gray curves indicate all preferred models, and colored curves highlight representative cases. The example models are grouped by their near-trench initial shear stress patterns: (a) positive, (b) negative, and (c) alternating initial shear stress. Panel (d) shows the corresponding megathrust interface geometry.

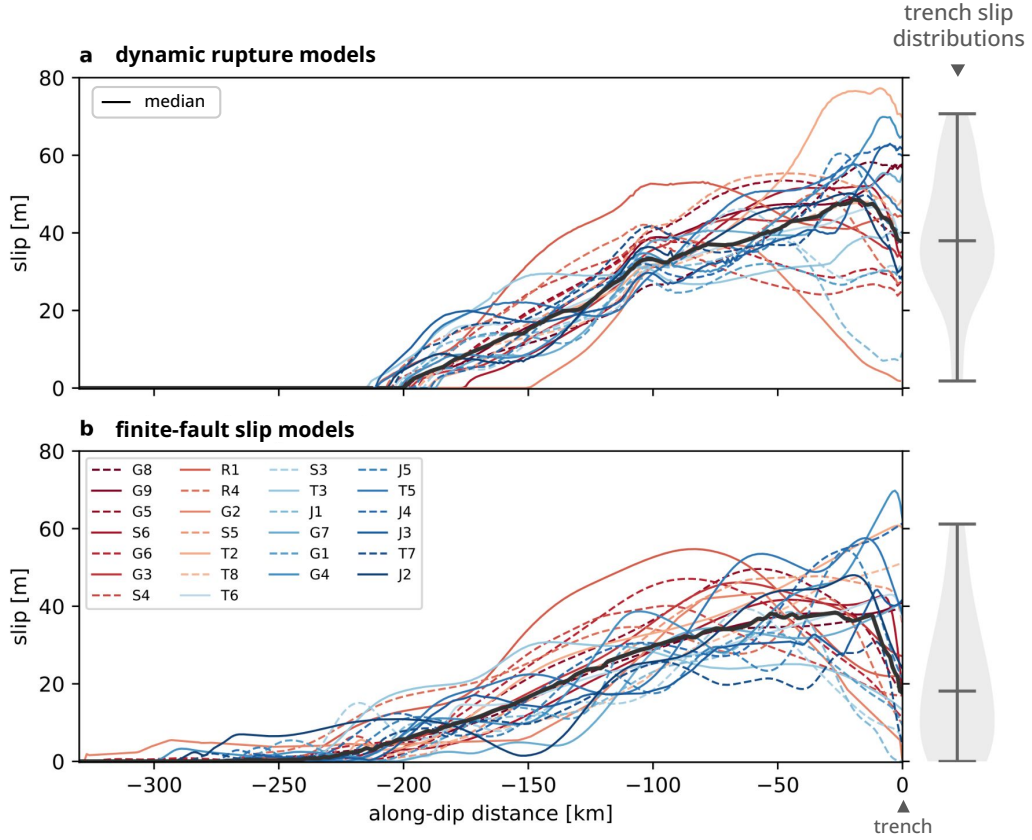


Figure 12. Along-dip cross-section of slip distribution across the hypocenter region. (a) Dynamic rupture models. (b) Finite-fault slip models. The color lines correspond to the slip models, and the solid black line represents the median slip distribution. The median slip distribution based on dynamic rupture models shows about 20 % slip deficit at the trench, while the finite-fault models show about 50 % slip deficit. The violin plot in the right panel shows the corresponding trench slip distribution, with most finite-fault models suggesting trench slip less than 30 m while most dynamic rupture models suggest trench slip more than 30 m. The grey bars represent the minimum, maximum, and median values.

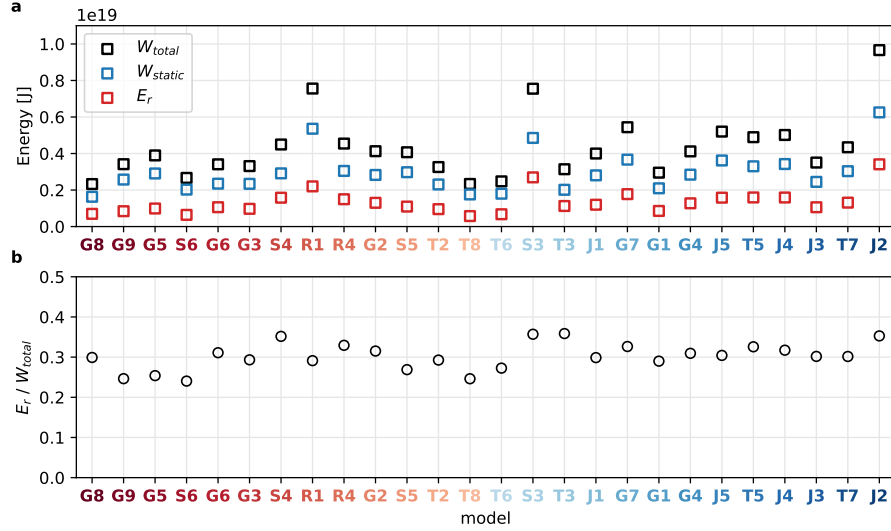


Figure 13. Comparison of the energy partition and seismic efficiency among 26 dynamic rupture models. (a) Total strain energy release W_{total} , breakdown energy W_{static} , radiated energy E_r . (b) Seismic efficiency E_r/W_{total} .

Under classical rate-and-state friction, crack-like ruptures are often associated with relatively large breakdown energy, enhanced by dynamic overshoot, and comparatively lower radiated energy (Abercrombie & Rice, 2005). In contrast, pulse-like ruptures are commonly expected to radiate a large fraction of the available strain energy. Finite-fault slip models often indicate short rise times for many earthquakes, which has been interpreted as evidence for pulse-like rupture behavior (Heaton, 1990).

Our ensemble of dynamic rupture models spans a wide range of rupture styles, including crack-like rupture, pulse-crack transitions, and complex rupture with multiple reactivation and episodic slip pulses. Figure 13 compares the energy budget across the 26 preferred rupture models, including total strain energy release (W_{total}), breakdown energy (W_{static}), radiated energy (E_r), and seismic efficiency (E_r/W_{total}). Despite substantial variability in rupture evolution and slip pattern, most models exhibit comparable total energy partition and similar seismic efficiency. This indicates that differences in rupture styles, driven by initial stress heterogeneity and contrasting spatial distribution of breakdown energy, do not necessarily translate into large variations in the integrated energy budget. The overall similarity of energetics across contrasting rupture styles is consistent with recent theoretical analysis, which suggests that both pulse-like and crack-like ruptures can produce comparable breakdown energy and scaling behavior under the strong dynamic weakening frictional behavior (Gabriel et al., 2024). This relatively constant energy partition provides an important implication for estimating future earthquake rupture based on available strain energy and fracture energy estimates (<empty citation>).

4.5 Role of the velocity model on rupture behavior

We account for 3D velocity structure using the Japan Integrated Velocity Structure Model from Koketsu et al., 2009, 2012, which incorporates layered crustal and mantle structure. The rupture style differs from the simulations using a 1D layered velocity model with the same fault geometry and frictional setup (Wong, Gabriel, & Fan, 2026). In particular, the simulation incorporating initial traction heterogeneity informed by Model

T7 in Wong, Gabriel, and Fan, 2026 exhibits multiple rupture reactivation with the 1D velocity model, whereas the same model here develops a pulse-crack transition with the 3D velocity structure. In contrast, Models J4 and J5, which have stronger initial shear stress heterogeneity, exhibit multiple reactivation in both the 1D and 3D velocity models.

These results suggest that the 3D velocity structure primarily affects rupture behavior by modifying shear modulus and subsequent dynamic shear stress transfer. At depth, the 1D velocity model has higher shear modulus and seismic velocities than the 3D velocity model. The higher-shear-modulus material carries stronger stress concentration behind the slip pulse (S. Nielsen & Madariaga, 2003; S. B. Nielsen & Carlson, 2000). Consequently, secondary rupture pulses can nucleate more readily in the 1D model. In the 3D model, the lower shear modulus reduces the shear stress concentration behind the primary pulse, favoring a transition toward more sustained crack-like rupture. The persistence of multiple reactivation in Models J4 and J5 further indicates that sufficiently strong initial fault heterogeneity can dominate over velocity-model effects.

4.6 Spiraling rupture in reactivated rupture fronts

Our models with multiple rupture reactivation exhibit an intricate spiraling circular rupture expansion. The reactivated front often re-nucleates locally within the previously slipped region and then expands outward in a circular pattern (Figure 9). During this expansion, the apparent transverse propagation speed of the rupture front can exceed the local shear wave velocity, while the radial expansion speed remains subshear (Schliwa et al., 2024; Wong, Gabriel, & Fan, 2026). Despite this radial expansion of the rupture front, the slip vector remains predominantly aligned with the thrusting direction.

This behavior is analogous to recent laboratory observations of rapidly expanding fluid-injection-induced cracks (Cochard et al., 2024). In the experiments, high-speed imaging captures the detailed evolution of cracks driven by increasing fluid pressure. The cracks initiated from a localized region and expanded rapidly in either bilateral or unilateral directions, producing transversely supershear yet radially subshear crack growth.

In our model, the primary propagating slip pulse concentrates shear stress within the previously slipped region (S. Nielsen & Madariaga, 2003). This produces a broad zone of elevated shear stress in the wake of the slip pulse. In addition, the irregular rupture front generates streaks of high shear stress, leading to a heterogeneous shear stress field behind the propagating front. These stress concentrations create favorable conditions for secondary rupture nucleation. Once a local patch is reloaded above its rapidly restrengthened frictional strength, a secondary rupture can initiate and expand outward from that patch. The resulting spiraling and reactivation rupture patterns therefore reflect the combined effects of dynamic stress concentration, frictional restrengthening, and the stress heterogeneity imprinted by irregular pulses.

4.7 Limitations and future work

While our EKI-DR framework provides an efficient framework to evaluate the finite-fault slip models using dynamic rupture simulations, the current setup focuses only on initial stress heterogeneity informed by finite-fault slip models, without accounting for rupture complexities arising from frictional or geometric variations. Previous studies have shown that friction and initial stress can exhibit strong trade-offs in controlling rupture dynamics, as both govern the available strain energy and the breakdown energy required for fracture growth (Tinti et al., 2021; Wong, Gabriel, & Fan, 2026). Future extensions of this framework could incorporate full-scale heterogeneity in frictional properties, initial stress distributions, effective normal stress, and fault geometry, all of which have been

proposed as key factors controlling the rupture characteristics of megathrust earthquakes (Bassett et al., 2016; Lay et al., 2012; Noda & Lapusta, 2013; K. Wang & Tréhu, 2016).

While Ensemble Kalman Inversion can handle nonlinear inversion, it assumes parameter spaces are continuous. Dynamic rupture behavior can change abruptly across distinct rupture-style transitions (Gabriel et al., 2012; S. Nielsen & Madariaga, 2003; Wong, Gabriel, & Fan, 2026). The six finite-fault slip models that we failed to reproduce also exhibit sharp changes in the initial stress parameters as the rupture transitions from premature arrest to no spontaneous arrest, rupturing the entire megathrust. Recent studies that transform a nonlinear space into a linear space using explicit or machine-learning methods have significantly improved Ensemble Kalman methods for nonlinear and discontinuous problems (e.g., X.-H. Zhou et al., 2026).

Our framework identifies initial conditions that yield reasonable dynamic rupture models with only a limited number of simulations. While we limit our inversion to two parameters for this study, Ensemble Kalman methods are also well-suited for high-dimensional problems, with multiple techniques, including covariance inflation, localization, and regularization, developed to efficiently construct the Kalman gain in the presence of noisy observations and limited ensemble members (e.g., Chada et al., 2020; Emerick & Reynolds, 2013; Tong & Morzfeld, 2023; Vishny et al., 2024). A natural extension is a full inversion for the spatial distributions of initial stress and frictional strength (e.g., Wong, Fan, Gabriel, & Morzfeld, 2026).

5 Conclusions

We develop a new ensemble optimization framework to systematically evaluate suites of data-driven finite-fault slip models using physics-based constraints from 3D dynamic rupture simulations. Using an Ensemble Kalman inversion approach, we efficiently optimize initial stress conditions for each finite-fault informed heterogeneity pattern and identify dynamically viable rupture scenarios that satisfy geodetic and moment-rate observational constraints. We apply the framework to 32 published finite-fault slip models of the 2011 M_w 9.0 Tohoku-Oki earthquake. Rather than focusing on a single deterministic model, the framework yields an ensemble of 26 plausible dynamic rupture models of the Tohoku-Oki earthquake.

Across the ensemble, the dynamic rupture models reproduce diverse slip features, ranging from smooth, single-patch distributions to highly heterogeneous patterns, demonstrating that multiple kinematic interpretations can be dynamically viable under contrasting initial stress conditions. At the same time, initial stress heterogeneity governs the evolution of rupture. We identify three major families of rupture behavior. Smooth initial stress distribution favors predominantly crack-like rupture, whereas increasing heterogeneity promotes rupture reactivation and episodic slip pulses, including mixed pulse-crack behavior. Our study demonstrates that physics-based dynamic rupture simulations can serve as quantitative constraints to assess the dynamic viability of finite-fault slip models and to examine dynamic viability over plausible ranges of fault conditions and rupture processes. The proposed ensemble framework provides a computationally efficient pathway to evaluate alternative rupture scenarios for other large earthquakes and to examine robust rupture features across largely unconstrained fault conditions, thereby elucidating the underlying physical mechanisms that govern earthquake rupture.

Table 2. Fault frictional parameters assumed in this study. VW: velocity-weakening, VS: velocity-strengthening.

Parameter	Symbol	Values	Unit
Direct-effect parameter	a	VW: 0.01 VS: 0.018	
Evolution-effect parameter	b	0.014	
Reference slip rate	V_0	10^{-6}	m/s
Reference friction coefficient	f_0	0.5	
Weakened slip rate	V_W	0.1	m/s
State evolution distance [†]	L	0.6	m
Fully weakened friction coefficient	f_w	0.1	
Initial slip velocity	V_i	10^{-16}	m/s

6 Open Research

All the model outputs are available in the GEO-INQUIRE data simulation lake. The model parameters and the Ensemble Kalman Inversion algorithm are available in the Zenodo repository (<https://doi.org/10.5281/zenodo.20262697>). The 32 projected and unified finite-fault slip models are available from Wong et al. (2024). The model parameter files and the Ensemble Kalman Inversion workflow are available on Zenodo (<https://doi.org/10.5281/zenodo.20262697>). Simulation outputs are available in the Geo-INQUIRE simulation data lake (data available upon publication). Dynamic rupture simulations were performed with SeisSol v1.3.0 (Gabriel et al., 2025), <https://seissol.org>. GEONET GNSS displacements are provided by the Geospatial Information Authority of Japan Geospatial Information Authority of Japan, 2026; offshore geodetic data are from Ito et al. (2011), Kido et al. (2011), and Yokota et al. (2018); the SCARDEC moment-rate function is from Vallée and Douet (2016); the JIVSM velocity model is from Koketsu et al. (2009, 2012); topobathymetry is from GEBCO (2024).

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