

**Multi-scale constraints resolve the 2025 Kamchatka megathrust
rupture in a 3D heterogeneous Earth**

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This manuscript is a non-peer reviewed preprint submitted to EarthArXiv and it has also been
submitted to Earth and Planetary Science Letters.

Abstract

Great megathrust earthquakes produce deformation over a wide range of spatial scales, yet how near-trench, near-field, and far-field static displacements collectively constrain the same rupture remains poorly understood. Here we analyze the 29 July 2025 Mw 8.8 Kamchatka earthquake using spatially multi-scale observations: tsunami-derived initial uplift models for near-trench offshore deformation, Sentinel-1 InSAR and local GNSS offsets for near-field onshore deformation, and regional-to-far-field GNSS offsets extending to ~ 4000 km. These data are interpreted with a spherical 3D finite-element model that includes trench bathymetry, slab geometry, and first-order elastic heterogeneity. Land-based geodesy constrains the onshore and long-wavelength deformation field but does not uniquely resolve shallow offshore slip. Incorporating two alternative tsunami-derived uplift models produces distinct shallow-rupture scenarios: one with slip mainly at 20–40 km depth and limited trench slip, and another with extensive slip shallower than 20 km. Despite these differences, acceptable slip models predict nearly identical far-field horizontal displacements beyond ~ 1000 km, showing that far-field GNSS offsets provide little direct constraint on detailed slip. Earth-structure tests show that a first-order heterogeneous spherical model reproduces the far-field response of a more detailed LITHO1.0-PREM model to within $\sim 5\%$, whereas a homogeneous elastic model overpredicts regional deformation. Together, these results provide a mechanically consistent, spatially multi-scale analyses of the 2025 Kamchatka rupture, linking near-trench tsunami constraints, near-field geodesy, and far-field static deformation in a heterogeneous spherical Earth.

Key words: 2025 Kamchatka earthquake; coseismic slip; far-field deformation; tsunami constraints; spherical finite-element modeling; Earth structure

1. Introduction

Great megathrust earthquakes are among the most destructive natural hazards, generating intense ground shaking and ocean-wide tsunamis (Lay and Kanamori, 2011; Satake, 2014; Wirth et al., 2022). Beyond their immediate societal impacts, these events provide rare opportunities to investigate how rupture processes and Earth structure control deformation over a broad range of spatial scales (Tregoning et al., 2013; Elliott et al., 2016; Bassett et al., 2025). The static and dynamic effects of giant earthquakes can extend far beyond the near field, exciting Earth's normal modes and producing measurable coseismic deformation thousands of kilometers from the source (Park et al., 2005; Kreemer et al., 2006; Shestakov et al., 2012). Resolving the spatial distribution of slip and the far-field deformation footprint is therefore essential for understanding both earthquake rupture processes and the mechanical response of the Earth (Pollitz et al., 2011).

The Kamchatka Peninsula lies along the Kuril–Kamchatka subduction zone, one of the world's most seismically active convergent margins, where the Pacific plate subducts beneath the Okhotsk microplate at a convergence rate of about 80 mm/yr (DeMets et al., 1990; Seno et al., 1996) (Fig. 1). This margin has repeatedly produced great megathrust earthquakes, most notably the 1952 Mw 9.0 Kamchatka earthquake, the largest instrumentally recorded event along the Kuril–Kamchatka arc (Lay et al., 2009; MacInnes et al., 2010). On 29 July 2025, a Mw 8.8 earthquake ruptured a large portion of the Kamchatka subduction zone, with a rupture area broadly overlapping that of the 1952 event, demonstrating the strong potential of this margin for repeated great megathrust rupture (Fujii and Satake, 2026; Liu et al., 2026; Zhu et al., 2026). As one of the largest earthquakes in recent decades, the 2025 event has attracted broad attention from seismic, geodetic, and tsunami studies, which together provide important constraints on its

61 rupture process (Mikhailov et al., 2025; Li and Jia, 2026; Liu et al., 2026; Sepúlveda et al.,
62 2026).

63 Geodetic observations play a central role in resolving coseismic slip because they directly
64 measure the static deformation field produced by fault rupture (Avouac, 2015; Elliott et al.,
65 2016). Near-field InSAR and GNSS data constrain crustal deformation close to the rupture and
66 are widely used to infer the spatial distribution of coseismic slip, whereas far-field GNSS
67 observations provide complementary constraints on the long-wavelength deformation pattern
68 (Pollitz et al., 2011; Elliott et al., 2016; Ergintav et al., 2024). For the 2025 Kamchatka
69 earthquake, far-field displacements are detectable at distances of thousands of kilometers,
70 particularly with dense modern GNSS networks in Russia, East Asia, and Alaska. This event
71 therefore provides an exceptional opportunity to test how near-field deformation, offshore
72 tsunami constraints, and far-field static offsets constrain different aspects of the same rupture and
73 Earth response.

74 However, land-based geodetic observations have limited sensitivity to shallow slip near the
75 trench, making it difficult to resolve the offshore component of megathrust rupture, which is
76 critical for seafloor vertical uplift and tsunami generation (Lay et al., 2011; Romano et al., 2012).
77 For the 2025 Kamchatka earthquake, tsunami observations from DART records and the SWOT
78 satellite altimetry provide valuable constraints on tsunami-related initial sea-surface uplift and
79 shallow offshore deformation (Ruiz-Angulo et al., 2025; Fujii and Satake, 2026; Sepúlveda et al.,
80 2026). In this study, we do not perform an independent tsunami-source inversion but instead use
81 previously published tsunami-derived uplift models as complementary offshore constraints on
82 the near-trench rupture.

Many source models rely on homogeneous elastic half-space assumptions (Okada, 1985), which neglect key features of subduction zones, including trench bathymetry, spherical geometry, depth-dependent rigidity, and lateral variations in Earth structure. Such simplifications can bias predictions of offshore deformation and the inferred tsunami source, particularly near the trench where bathymetry and elastic-structure contrasts are important (Masterlark, 2003; Dong et al., 2014; Zhu et al., 2025).

Here we investigate the 2025 Mw 8.8 Kamchatka earthquake using a 3D heterogeneous spherical finite-element model that incorporates realistic Earth structure, trench bathymetry, and slab geometry (Dziewonski and Anderson, 1981; Pasyanos et al., 2014; Hayes et al., 2018). We combine near-field InSAR observations, GNSS offsets spanning from the near field to distances of ~4000 km, and previously published tsunami-derived initial uplift models as complementary constraints on shallow offshore deformation (Ruiz-Angulo et al., 2025; Sepúlveda et al., 2026). This multi-scale framework allows us to resolve the preferred slip distribution, evaluate the role of Earth structure in controlling regional to far-field deformation, and examine how the rupture relates to the broader seismogenic environment of the Kamchatka subduction zone.

2. Data and methods

2.1 Coseismic geodetic observations

We use InSAR and GNSS observations to constrain the coseismic displacement field over a broad range of spatial scales. The InSAR data consist of two Sentinel-1 line-of-sight displacement scenes from Liu et al. (2026): ascending track 111 and descending track 60. These scenes cover the southern onshore Kamchatka Peninsula, where the satellite observations record more than 1 m of near-field line-of-sight deformation along the coast.

The GNSS observations combine three data sets with complementary distance ranges. The first consists of 13 published horizontal offsets from near-source stations on the Kamchatka Peninsula (Mikhailov et al., 2025). The second consists of 25 three-component offsets from regional Russian GNSS stations (Table S1), including near-field stations on Kamchatka and intermediate-distance stations in the Russian Far East and Sakhalin region. This data set was newly processed for this study (Text S1). For each station and component, we estimate the coseismic offset from daily position time series by fitting independent lines to the 10 days before and the 10 days after the mainshock, and by taking the difference between the two fitted values at the earthquake epoch.

The third GNSS data set is the Nevada Geodetic Laboratory coseismic-offset compilation for the 2025 Kamchatka earthquake (Blewitt et al., 2018). This compilation contributes more than 1500 stations, mostly at larger epicentral distances in the Russian Far East, East Asia, Alaska, and the Aleutian region. They estimated displacements based on the average positions 10 days before and 10 days after the earthquake, and a median spatial filter was applied to the far-field displacements (they did not specify the definition of “far-field”). It extends the static deformation constraint to distances of about 4000 km from the source. Because far-field vertical offsets from GNSS positions are substantially noisier than the horizontal components, we use all three GNSS components only within 135° – 170° E and 45° – 63° N, and use only horizontal components outside that region. More than 1000 of the >1500 GNSS stations are located in Japan. To prevent this dense regional subset from dominating the objective function, we reduce the weights of Japanese stations by a factor of five. The three GNSS groups are shown in Fig. 1 and together provide a multi-scale geodetic data set for characterizing the regional-to-far-field deformation caused by the earthquake.

2.2 Tsunami-derived offshore constraints

Land geodetic data have limited resolving power for shallow offshore slip near the trench, where vertical seafloor motion is most important for tsunami generation (Lay et al., 2011). We therefore use published tsunami-derived initial sea-surface displacement models as offshore constraints, but we do not perform an independent tsunami waveform inversion in this study. Ruiz-Angulo et al. (2025) inverted the first-arriving waves at three DART stations (21415, 21516, and 21419) for initial sea-surface displacement. Sepúlveda et al. (2026) used five DART stations, including 21414 and 21418, together with InSAR and SWOT observations to infer a finite-fault source and the associated initial sea-surface displacement. The two products differ in their inferred near-trench uplift, likely reflecting differences in data selection, source parameterization, and assumptions about the effective source time (Melgar, 2026). Note that the Ruiz-Angulo et al. (2025) displacements are estimated purely from the DART observations and thus are independent of the land-based data, while the Sepúlveda et al. (2026) displacements are predictions of a slip model (assuming an elastic half space) that also incorporates land-based data.

We use these two published uplift products as alternative offshore pseudo-observation sets. The gridded initial sea-surface displacement fields are downsampled and entered the inversion as vertical displacement constraints at their geographic sample points. In the long-wavelength limit relevant to deep-ocean tsunami generation, initial sea-surface displacement approximately follows vertical seafloor displacement. More generally, the linear hydrostatic filter gives

$$\hat{\eta}(\mathbf{k}) = \frac{\hat{u}_z(\mathbf{k})}{\cosh(|\mathbf{k}|H)},$$

where $\hat{\eta}$ is the Fourier transform of the sea-surface displacement, $\hat{u}_z$ is the Fourier transform of the vertical seafloor displacement, H is water depth, and $\mathbf{k}$ is horizontal wavenumber. Because the dominant source wavelengths are much longer than the water depth, $\cosh(|\mathbf{k}|H)$ is close to one for most of the retained signal. We therefore use the published initial sea-surface displacement directly as a proxy for vertical seafloor deformation.

The predicted offshore vertical signal also includes the effect of horizontal seafloor motion across bathymetric slopes (Tanioka and Satake, 1996). For the tsunami pseudo-observations, we compute

$$\eta_{\text{pred}} = U - \left(E \frac{\partial Z}{\partial E} + N \frac{\partial Z}{\partial N} \right),$$

where E , N , and U are the predicted east, north, and vertical seafloor displacements and Z is seafloor elevation. This correction is evaluated from the finite-element surface topography, with gridded bathymetry used in sensitivity tests. Because the Ruiz-Angulo et al. (2025) product is independent of our InSAR data, whereas the Sepúlveda et al. (2026) product partly reflects a joint DART-InSAR-SWOT inversion, we treat the two tsunami-derived constraints as alternative tests rather than as a single definitive offshore data set.

2.3 Spherical finite-element forward model

We compute elastic Green's functions with a spherical finite-element model that includes Earth curvature, trench bathymetry, slab geometry, and first-order lateral and radial variations in elastic structure (Fig. 2). The model extends from the Earth's surface to the core-mantle boundary. The subducting Pacific slab follows the Slab2 geometry (Hayes et al., 2018) and is represented with a 70 km thickness (Fig. S1). Trench bathymetry is approximated with piecewise planar slopes,

with a trench depth of 7.4 km and an incoming oceanic-plate depth of 5.5 km. To remove rigid-body motion without imposing an artificial fixed base beneath the source region, we fix six displacement degrees of freedom at three nodes on the far side of the core-mantle boundary, leaving the rest of the core-mantle boundary traction-free.

Our preferred elastic structure is a first-order laterally and radially heterogeneous reference model designed to capture the dominant mechanical contrasts in the subduction system and basic Earth layering (Fig. 2c). It includes a 70 km thick slab with shear modulus 64 GPa, a 35 km thick overriding continental plate with shear modulus 48 GPa, an upper mantle to 660 km depth with shear modulus 80 GPa, and a lower mantle to 2900 km depth with shear modulus 230 GPa. Poisson's ratio is fixed at 0.25 throughout.

Green's functions are calculated with PyLith 4.2.0 for unit left-lateral and reverse slip at each fault vertex (Aagaard et al., 2013). The two PyLith slip components are linearly combined so that the inversion parameters represent along-strike slip and up-dip thrust slip in the local fault geometry. The PyLith displacement fields at Earth surface are rotated from the model Cartesian frame into geographic east, north, and up components. For GNSS and tsunami pseudo-observations, the three-component Green's functions are interpolated from the finite-element surface to each observation point. For InSAR, the interpolated east, north, and up displacements are projected into the satellite line of sight using the local look-vector components.

2.4 Slip inversion

We solve for the coseismic slip distribution with a weighted least-squares inversion for left-lateral strike slip and thrust slip. Each InSAR scene contains one planar ramp estimation to reduce long-wavelength misfit. The matrix equation to be inverted is

$$\begin{bmatrix}
 \mathbf{W}_{\text{ins}} \mathbf{G}_{\text{ins}}^{ss} & \mathbf{W}_{\text{ins}} \mathbf{G}_{\text{ins}}^{ds} & \mathbf{W}_{\text{ins}} w_r \mathbf{R} \\
 \mathbf{W}_g \mathbf{G}_{g,h}^{ss} & \mathbf{W}_g \mathbf{G}_{g,h}^{ds} & 0 \\
 \mathbf{W}_g \mathbf{G}_{g,v}^{ss} & \mathbf{W}_g \mathbf{G}_{g,v}^{ds} & 0 \\
 \mathbf{W}_{\text{tsu}} \mathbf{G}_{\text{tsu}}^{ss} & \mathbf{W}_{\text{tsu}} \mathbf{G}_{\text{tsu}}^{ds} & 0 \\
 \sqrt{\lambda} \mathbf{L}_{ss} & 0 & 0 \\
 0 & \sqrt{\lambda} \mathbf{L}_{ds} & 0 \\
 \sqrt{\eta} \sin \psi_0 \mathbf{I} & -\sqrt{\eta} \cos \psi_0 \mathbf{I} & 0
 \end{bmatrix}
 \begin{bmatrix}
 \mathbf{m}_{ss} \\
 \mathbf{m}_{ds} \\
 \mathbf{m}_r
 \end{bmatrix}
 =
 \begin{bmatrix}
 \mathbf{W}_{\text{ins}} \mathbf{d}_{\text{ins}} \\
 \mathbf{W}_{g,h} \mathbf{d}_{g,h} \\
 \mathbf{W}_{g,v} \mathbf{d}_{g,v} \\
 \mathbf{W}_{\text{tsu}} \mathbf{d}_{\text{tsu}} \\
 0 \\
 0 \\
 0
 \end{bmatrix}.$$

Here $\mathbf{m}_{ss}$ and $\mathbf{m}_{ds}$ are the strike and dip slip, and $\mathbf{m}_r$ contains the InSAR ramp parameters. The data blocks correspond to InSAR, horizontal GNSS, vertical GNSS, and tsunami pseudo-observations. The matrices $\mathbf{L}_{ss}$ and $\mathbf{L}_{ds}$ impose L2 smoothing on neighboring fault nodes, and the last row imposes a soft rake prior with target thrust rake ψ_0 and weight η . GNSS components are weighted by their reported uncertainties. Relative weights for InSAR and tsunami data are selected from fit-reduction tests (Xu et al., 2016), to be 0.1 and 0.4 respectively, and the smoothing factor λ is selected at 0.2 from an L-curve analysis (Fig. S2). Slip bounds, including near-zero bounds on selected fault-edge nodes, are imposed in the solution. We perform separate inversions with no tsunami constraint and with each tsunami-derived uplift model.

3. Results

3.1 Slip models with different offshore constraints

We compare three coseismic slip models: an inversion using land-based geodetic data only, and two inversions that additionally include the alternative tsunami-derived offshore uplift constraints (Fig. 3a-c). The two tsunami-constrained models produce substantially different shallow-slip patterns (Fig. 3d, e). When the Ruiz-Angulo et al. (2025) model (Tsunami model 1) is used as the offshore constraint, the preferred rupture has a maximum slip of 14.8 m and Mw 8.849. Most of the slip is concentrated at 20-40 km depth, with little resolvable slip near the

trench (Fig. 3a). In contrast, the model constrained by the Sepúlveda et al. (2026) offshore vertical displacement field (Tsunami model 2) has a maximum slip of 17.4 m and Mw 8.936, with most of the slip shallower than 20 km depth and a broad shallow region with slip exceeding 15 m (Fig. 3b). The land-only model has a lower maximum slip of 8.2 m and Mw 8.897, and produces a much smoother slip distribution extending from ~40 km depth toward the trench (Fig. 3c).

These contrasts demonstrate that the shallow offshore component is controlled primarily by the tsunami-derived constraints rather than by the land geodetic data. The land-only inversion can match the onshore displacement field, but its shallow slip is largely governed by smoothing and therefore should not be interpreted as a well-resolved near-trench rupture. The two tsunami-derived uplift models imply different end-member shallow-rupture scenarios, one with limited trench slip and one with substantial near-trench slip. The slip distributions from the two tsunami-constrained models are consistent with the corresponding offshore uplift fields, with similar dominant wavelengths and spatial positions (Fig. 3f).

This discrepancy may arise from the different assumptions and data selections used in the published tsunami-source models, including their treatment of the static source. In particular, these two studies make different assumptions about the timing of tsunami generation, which likely impacts the east-west location of the inferred seafloor uplift. Despite this difference, both offshore constraints can be incorporated without strongly degrading the fit to GNSS or InSAR data (Fig. S3). Fit-reduction tests show that the Ruiz-Angulo et al. (2025) uplift field is slightly more compatible with the land geodetic data, but both products are broadly consistent with the observed deformation within the adopted weighting scheme. The slightly higher mismatch with

the Sepúlveda et al. (2026) displacements might result from differences in the Greens functions (half space vs 3D elastic) or from assumptions in their inversion that are incompatible with ours.

3.2 Model predictions

All three coseismic models reproduce the principal features of the near- and far-field GNSS offsets, the InSAR line-of-sight displacements, and the corresponding offshore pseudo-observations (Figs. 4, S4 and S5). For the following results and discussion, we use the model constrained by Sepúlveda et al. (2026) as a representative model, because its shallow-slip component is consistent with recent studies that favor substantial near-trench slip during the 2025 Kamchatka earthquake (Sepúlveda et al., 2026; Zhu et al., 2026). However, the land-geodetic fits of the three models are nearly identical, and the detailed slip distribution remains dependent on the tsunami-derived offshore constraint used. The tsunami-constrained model with shallow slip provides a representative fit to the multi-scale GNSS field: it captures the large near-field offsets on the Kamchatka Peninsula, the regional displacements across the Russian Far East and Sakhalin, and the first-order amplitudes and orientations observed in Alaska and the Aleutian Islands (Fig. 4). In the Japan–Korea direction, some stations at distances greater than ~2000 km appear to show horizontal offsets of ~2–3 mm, whereas both the model predictions and the observed offsets at comparable distances in Alaska are generally at the ~1 mm level. This regional mismatch may reflect reference-frame differences, processing differences among GNSS products, residual plate-motion effects, and uncertainty in small far-field coseismic offsets, rather than source complexity alone.

An important feature of the geodetic predictions is that the three slip models produce nearly identical far-field GNSS displacements as a function of epicentral distance, even though their

slip details and scalar moments differ substantially (Fig. 5b, c). This similarity indicates that, for the range of acceptable models considered here, the far-field GNSS data have limited resolving power for rupture details. Instead, these observations are most useful for evaluating the large-scale static deformation predicted by the source model and elastic Earth structure. In Alaska, our model successfully predicts the pattern of observed displacements. In Japan, displacements are well predicted as far south as the south end of Hokkaido island, but the model underpredicts the displacements further away. Displacements on the Asian mainland are predicted well, except the displacements in Korea are systematically underpredicted.

We also test the tsunami implications of the slip models with GeoClaw forward simulations (Text S2), using the predicted vertical displacement as the tsunami source. Models that include an offshore tsunami-derived constraint reproduce the DART waveforms more successfully than the land-only model (Fig. 5a). The land-only prediction underestimates the tsunami amplitude and does not reproduce the arrival timing as well, although it captures the broad waveform trend. We further compare simulations that treat the vertical model prediction either as seafloor motion or directly as initial sea-surface uplift (Fig. S5). The differences are small for the retained wavelengths, supporting our approximation that the published initial uplift fields can be used as vertical offshore pseudo-observations in the coseismic inversion.

4. Earth-structure controls on regional and far-field static deformation

Near-field coseismic deformation from GNSS, InSAR, and optical imagery is commonly used to study earthquake source processes, because these observations directly measure the static surface deformation produced by fault rupture and can be inverted for slip at depth (Avouac, 2015; Elliott et al., 2016). In contrast, far-field static deformation has received less attention in most

source studies, even though giant earthquakes can generate measurable permanent displacements over continental-scale distances. The 2004 Sumatra-Andaman earthquake produced static GPS offsets greater than 1 mm at distances up to ~7800 km from the rupture, and the 2011 Tohoku-Oki earthquake was modeled using onshore GPS data extending to ~4000 km from the source, together with offshore GPS observations near the high-slip region (Kreemer et al., 2006; Pollitz et al., 2011). Far-field coseismic deformation from great earthquakes can also influence regional velocity fields and reference-frame interpretations if it is not explicitly accounted for (Tregoning et al., 2013). More recently, the 2023 Kahramanmaraş earthquake sequence produced unexpectedly large far-field offsets at distances greater than 700 km, exceeding predictions from conventional elastic dislocation models (Ergintav et al., 2024). These studies show that far-field static deformation is not merely a small residual signal, but a useful observable for testing how large earthquakes deform the lithosphere and mantle over regional to continental scales.

The 2025 Kamchatka earthquake provides a useful case for evaluating how far-field GNSS should be interpreted for great subduction earthquakes, because it is constrained by observations spanning near-field deformation to far-field GNSS offsets extending to ~4000 km. Because the three acceptable coseismic models produce similar far-field predictions despite different slip distributions, far-field residuals should not be interpreted solely as evidence for errors in the slip model. They also depend on the elastic Earth structure, reference frame, and other long-wavelength signals in the GNSS field.

Among these factors, elastic structure is a major source of uncertainty in predicting regional and far-field static deformation. Previous studies have shown that homogeneous half-space assumptions can bias subduction-zone deformation predictions, and that Earth layering and curvature can affect coseismic displacement fields (Masterlark, 2003; Dong et al., 2014). To

evaluate this sensitivity, we compare Green's functions and slip inversions for three structural models: the preferred first-order heterogeneous spherical model used throughout this study, a more detailed LITHO1.0-PREM model (Fig. S6), and a homogeneous elastic model. The preferred model represents a simplified first-order approximation that captures the dominant rigidity contrasts among the overriding plate, subducting slab, upper mantle, and lower mantle. The LITHO1.0-PREM model provides a more complex structural assumption, with detailed lithospheric heterogeneity from LITHO1.0 and a PREM layered mantle (Dziewonski and Anderson, 1981; Pasyanos et al., 2014), whereas the homogeneous model provides the simplest end-member assumption of uniform elastic properties with Poisson's ratio fixed at 0.25.

The preferred model and the LITHO1.0-PREM model predict similar regional-to-far-field displacement fields, with differences mostly less than 5%. In contrast, the homogeneous model generally overpredicts the displacement field, except at the most distant Asian stations beyond ~2000 km, where the residual pattern is dominated by the Japan mismatch discussed above (Fig. 6a, b). This indicates that the far-field response is controlled mainly by first-order radial stiffening and large-scale rigidity contrasts, rather than by the full details of lithospheric heterogeneity. The homogeneous model performs worse because it lacks the increase in rigidity with depth and therefore transmits unrealistically large, long-wavelength displacements.

Structural effects are more evident in the near field and offshore than in the overall far-field pattern. In inversions using the same land geodetic data and offshore constraints, the preferred block model and the LITHO1.0-PREM model produce similar slip distributions. The homogeneous model, however, reduces slip by about 1 m within ~80 km of the trench (Fig. 6c). This difference likely reflects how slab and overriding-plate rigidity contrasts map shallow slip into coastal and seafloor deformation. Because near-trench vertical seafloor motion is directly

relevant to tsunami generation, simplified elastic structure can bias both the inferred geodetic slip model and the predicted offshore deformation used as a tsunami source.

5. Interseismic coupling controlling rupture extent

We also use the same finite-element framework to invert interseismic coupling from published GNSS velocities (Bürgmann et al., 2005). The model indicates strong locking to ~80 km depth across the main rupture area of the 1952 and 2025 earthquakes. To the north, near the 2025 mainshock initiation region, the inferred locking depth decreases to ~20 km, consistent with reduced overriding-plate shortening in the available GNSS velocities (Fig. 7). A broadly similar along-strike reduction in coupling is present in previous work, although the absolute coupling amplitude and locking depth are sensitive to the reference-frame realization and block-motion correction used to define the interseismic velocity field (Bürgmann et al., 2005; Xiao et al., 2026).

The key feature is therefore not the exact coupling amplitude, but the location of the along-strike transition. This transition lies near the northern side of the 2025 rupture, where the mainshock initiated, and within the zone that hosted dense pre-earthquake seismicity, including the largest foreshock and two $M_w > 7$ aftershocks. Recent seismic analyses suggest that foreshocks migrated toward the 2025 mainshock epicenter before rupture initiation (Zhang et al., 2026). The spatial association among reduced locking depth, foreshock migration, large foreshock-aftershock activity, and mainshock initiation suggests that the northern edge of the locked segment may represent a mechanically complex transition zone between a strongly coupled asperity and a shallower or more creeping part of the megathrust.

Nevertheless, the first-order along-strike change in coupling provides useful context for the coseismic rupture: the 2025 earthquake initiated near a transition in the inferred interseismic locking pattern and in the distribution of foreshock-aftershock activity, coinciding with the northern boundary of the 1952 rupture. This spatial correspondence suggests that along-strike variations in coupling may have helped define both the segmentation and nucleation environment of the Kamchatka megathrust.

6. Conclusions

We resolve the 2025 Mw 8.8 Kamchatka earthquake with a multi-scale data set and a 3D heterogeneous spherical finite-element model. The main conclusions are:

1. Land-based InSAR and GNSS observations robustly constrain the onshore and long-wavelength deformation field, but they do not uniquely resolve shallow offshore slip near the trench. Inversions using land geodesy alone produce smooth shallow slip that mainly reflects regularization.
2. Published tsunami-derived uplift models provide essential offshore information but lead to different shallow-slip scenarios. Both are compatible with the land geodetic data under reasonable weighting, highlighting the remaining uncertainty in the near-trench rupture.
3. Far-field GNSS displacements, observed to distances of ~ 4000 km, are remarkably insensitive to the detailed slip distribution. Models with different near-trench behavior and different scalar moments produce similar far-field static offsets, indicating that these observations primarily constrain the long-wavelength deformation field and Earth structure.

4. Earth structure strongly affects regional and far-field static deformation. A first-order heterogeneous spherical model gives predictions close to those from a more detailed LITHO1.0-PREM structure, whereas a homogeneous elastic model overpredicts much of the displacement field. Depth-dependent rigidity is especially important for suppressing unrealistically large long-wavelength deformation.

5. Interseismic coupling appears strong to ~80 km depth within the 1952 and 2025 rupture area, but decreases sharply to the north. The coincidence of this coupling transition with the rupture boundary, foreshock activity, large aftershocks, and the 2025 epicentral region suggests that along-strike variations in locking helped control both rupture extent and nucleation behavior.

Together, these results show that interpreting great megathrust rupture requires spatially multi-scale observations and a physically realistic Earth model capable of reproducing regional-to-far-field static deformation. For the 2025 Kamchatka earthquake, the deep and intermediate-depth rupture is well constrained by land geodesy, whereas the shallowest offshore slip remains dependent on tsunami-source assumptions. The regional and far-field deformation, however, provides a robust constraint on the long-wavelength coseismic response of a heterogeneous spherical Earth.

Acknowledgements

This work was funded by the Geology of Solid Earth endowment at Michigan State University. Y.H. was supported by Jianghuai Talent Development Program 2024 Outstanding Project in Innovation Fields of Research Institutes. We thank the Nevada Geodetic Laboratory team for

providing the coseismic GNSS offset compilation and for helpful correspondence regarding the processing strategy.

Data Availability Statement

The earthquake catalog used in this study was obtained from the U.S. Geological Survey ANSS Comprehensive Earthquake Catalog (ComCat; <https://earthquake.usgs.gov>). The Nevada Geodetic Laboratory coseismic GNSS offset compilation for the 2025 Kamchatka earthquake is available at https://geodesy.unr.edu/news_items/20250907/us6000qw60_24hr_06-Sep-2025_msf.txt. The local GNSS coseismic offsets processed in this study are provided in Supplementary Table S1. The coseismic slip models derived in this study are provided in the Supplementary Material. PyLith version 4.2.0, used for finite-element modeling, is available at <https://zenodo.org/records/14635926>. GeoClaw, used for tsunami forward modeling, is available at <https://github.com/clawpack/geoclaw>.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used OpenAI ChatGPT and Anthropic Claude for assistance with language editing and drafting utility scripts. The authors reviewed and edited the output as needed and take full responsibility for the content of the published article.

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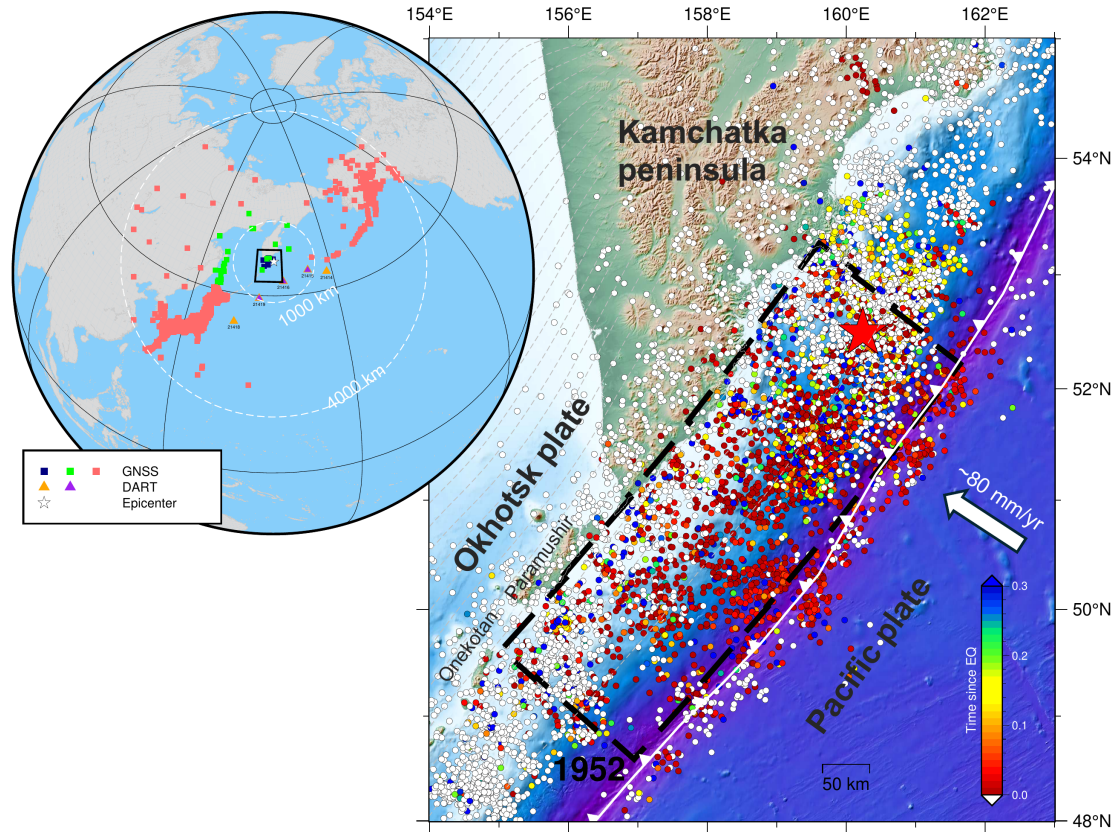
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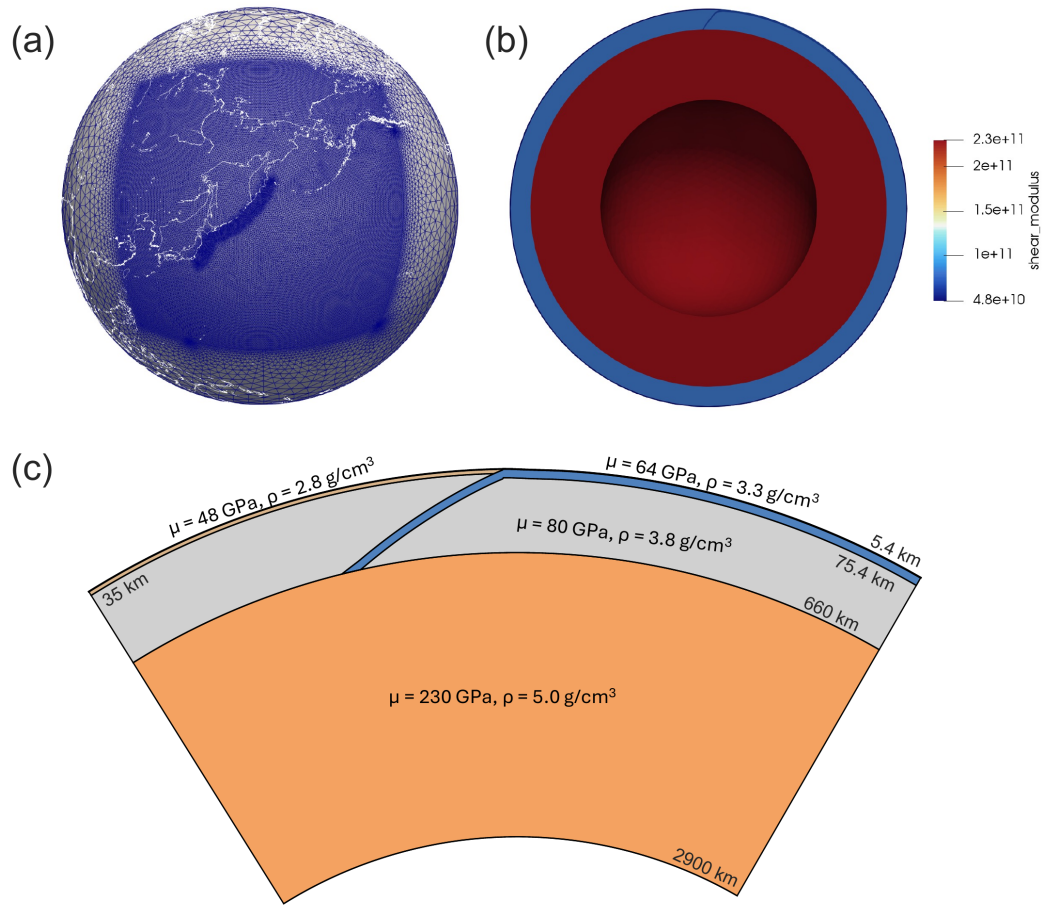
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529

530 Fig. 1. Tectonic setting, seismicity, and geophysical stations used in this study. Seismicity is
 531 from the USGS earthquake catalog for the period from 1 January 2000 to 1 January 2026.
 532 Tsunami model 1 (Ruiz-Angulo et al., 2025) is constrained by the DART stations shown in
 533 purple, whereas tsunami model 2 (Sepúlveda et al., 2026) is constrained by the stations shown in
 534 orange. The blue, green and red squares denote GNSS stations with coseismic offsets from
 535 Mikhailov et al., (2025), this study and the Nevada Geodetic Laboratory coseismic-offset
 536 solution, respectively. The black dashed line denotes the rupture area of the 1952 earthquake
 537 (MacInnes et al., 2010). The red star marks the epicenter of the 2025 Kamchatka earthquake.



538

539 Fig. 2. (a) Finite-element mesh developed in this study. (b) Cross section and (c) physical
 540 properties used in the block-structured Earth model. The Poisson's ratio is fixed at 0.25.

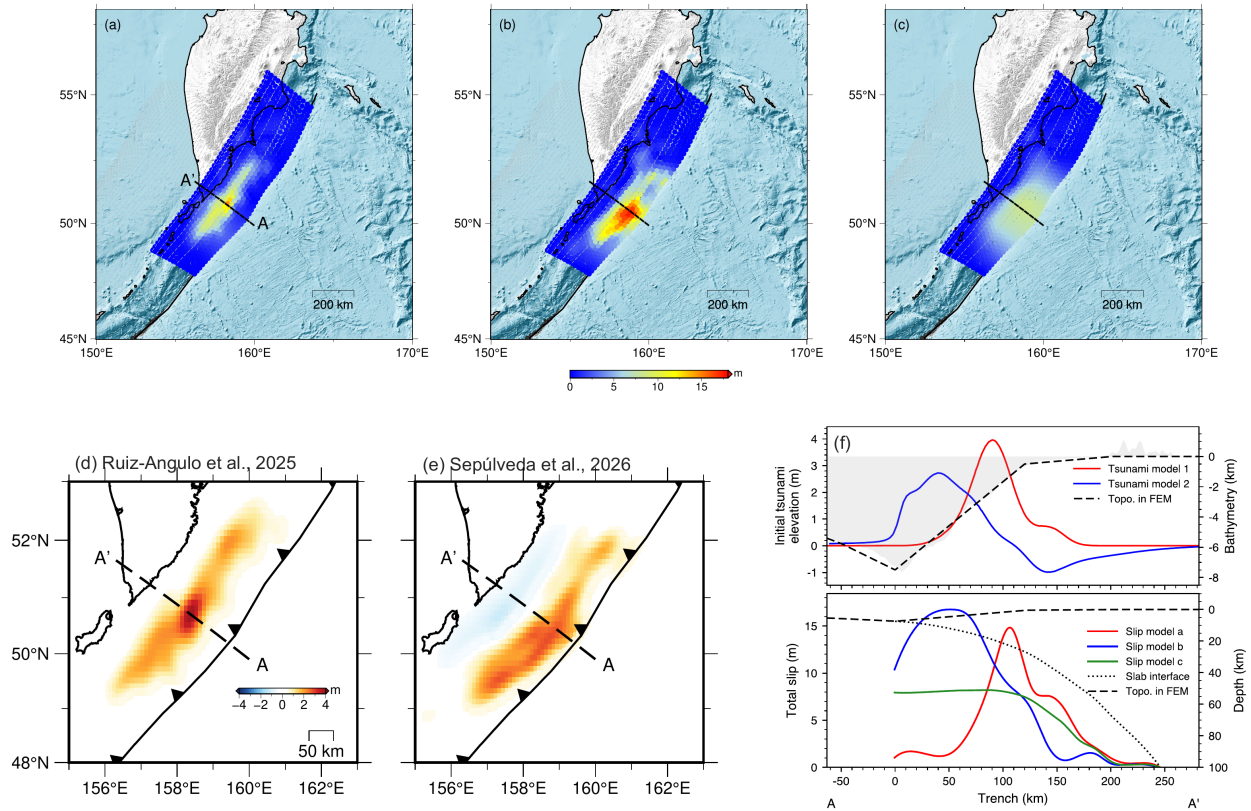


Fig. 3. Coseismic slip models and tsunami-derived offshore constraints. (a) to (c) Slip distributions inverted from GNSS, InSAR, and different offshore constraints: (a) slip model A, constrained with tsunami model 1; (b) slip model B, constrained with tsunami model 2; and (c) slip model C, constrained only by land-based geodetic observations. (d) and (e) Tsunami model 1 and tsunami model 2, respectively. The colored background shows the downsampled initial tsunami elevation. (f) Initial tsunami elevation (top panel) and slip from the three models (bottom panel) along profile AA'. The gray background in the top panel shows topography and bathymetry.

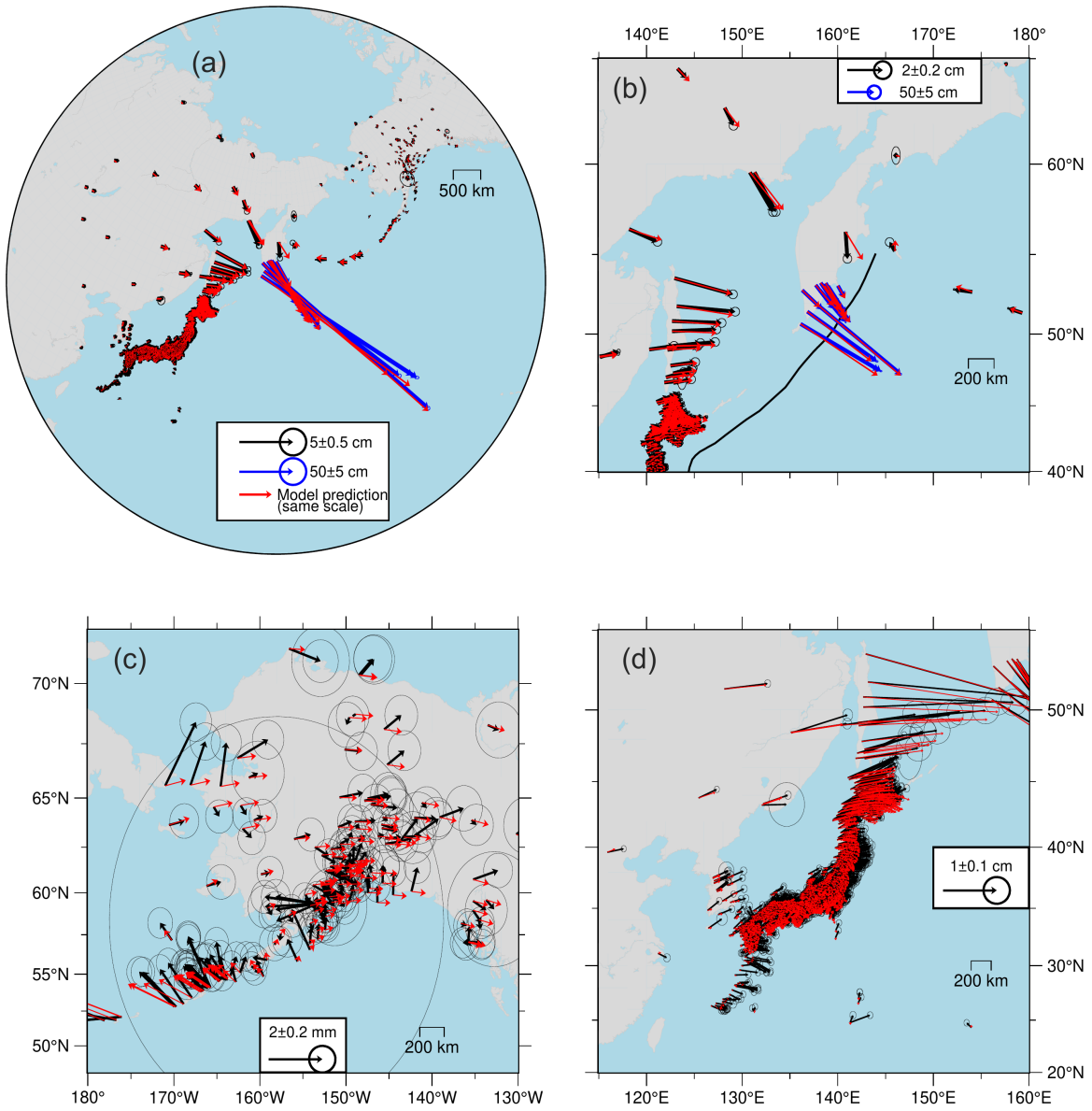


Fig. 4. Comparison between GNSS observations and predictions from slip model B. Black and blue arrows represent GNSS observations. Red arrows represent model predictions.

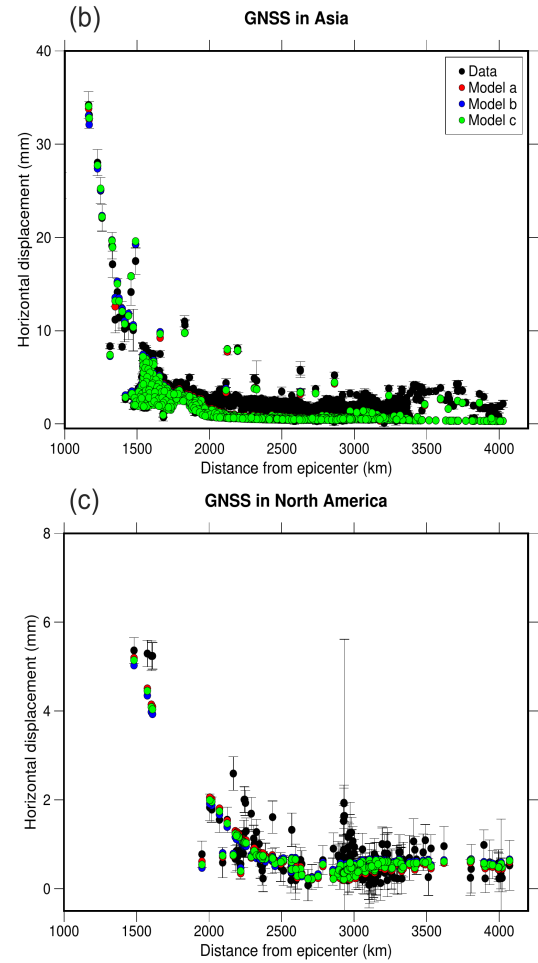
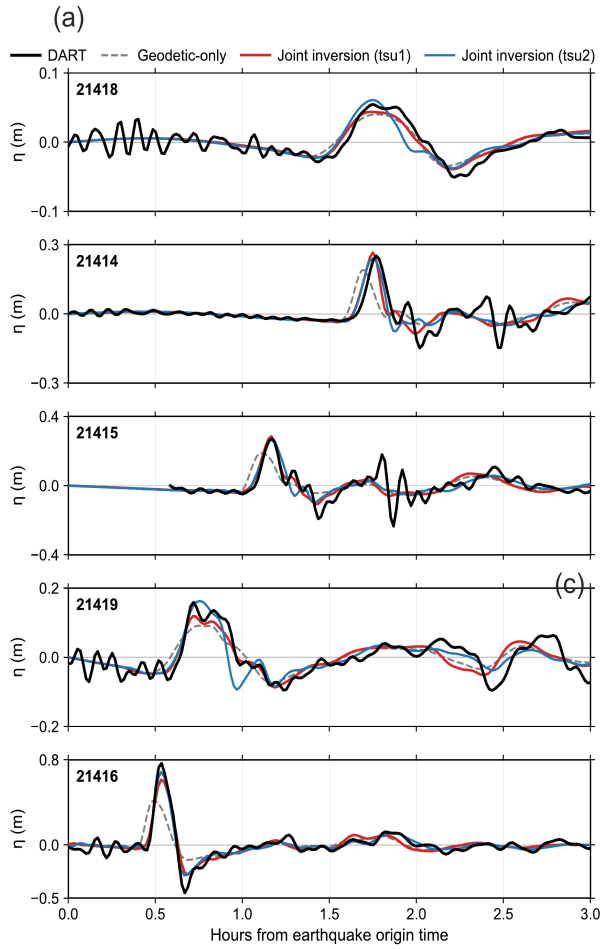
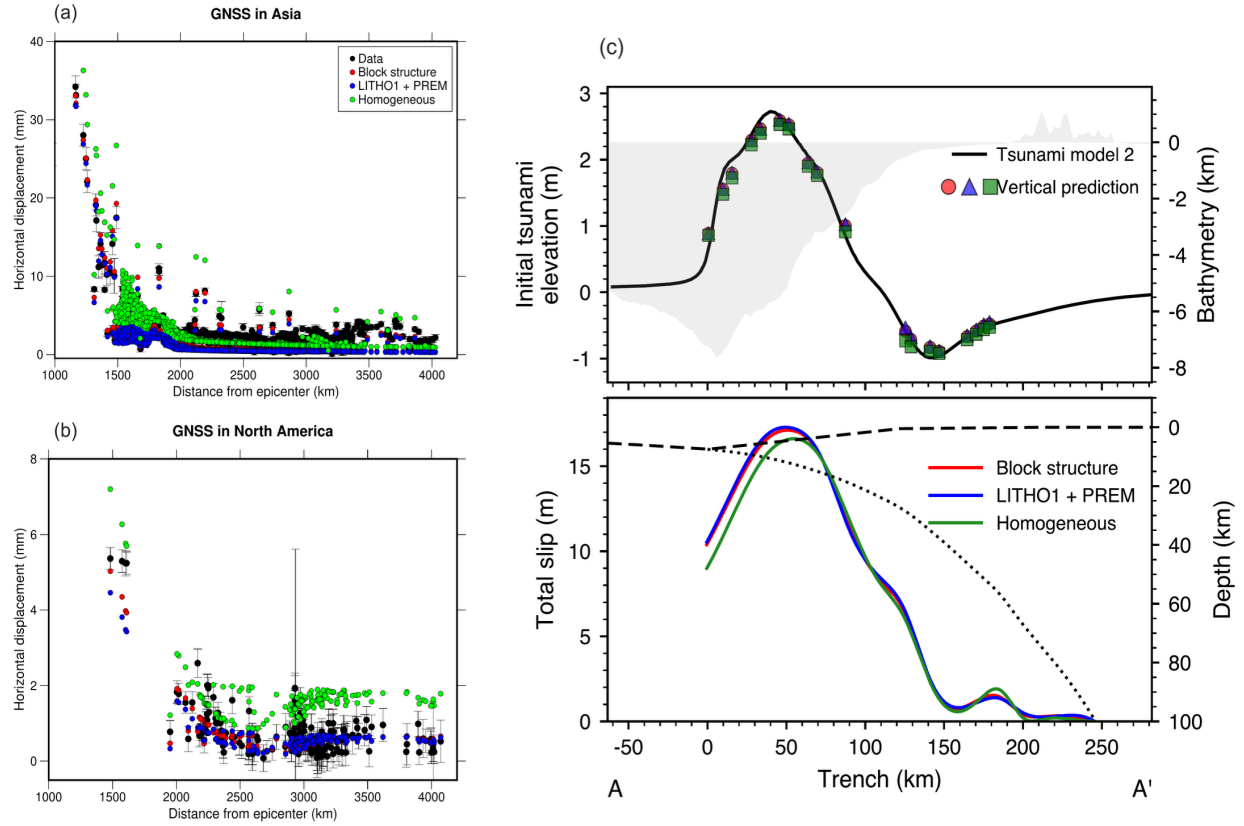


Fig. 5. (a) Comparison between DART observations and predictions from the inverted models in this study. (b) and (c) Far-field GNSS observations and predictions from the three inverted slip models. The horizontal axis shows distance relative to the epicenter.



559

560 Fig. 6. (a) and (b) Far-field GNSS observations and predictions based on inversions using
 561 different Earth structures. (c) Slip and corresponding predicted initial tsunami elevation along
 562 profile AA' for different Earth-structure assumptions. Lines and markers with the same color
 563 correspond to the same model. The black line in the top panel shows the original initial elevation,
 564 whereas the colored markers show model predictions at the downsampled locations.

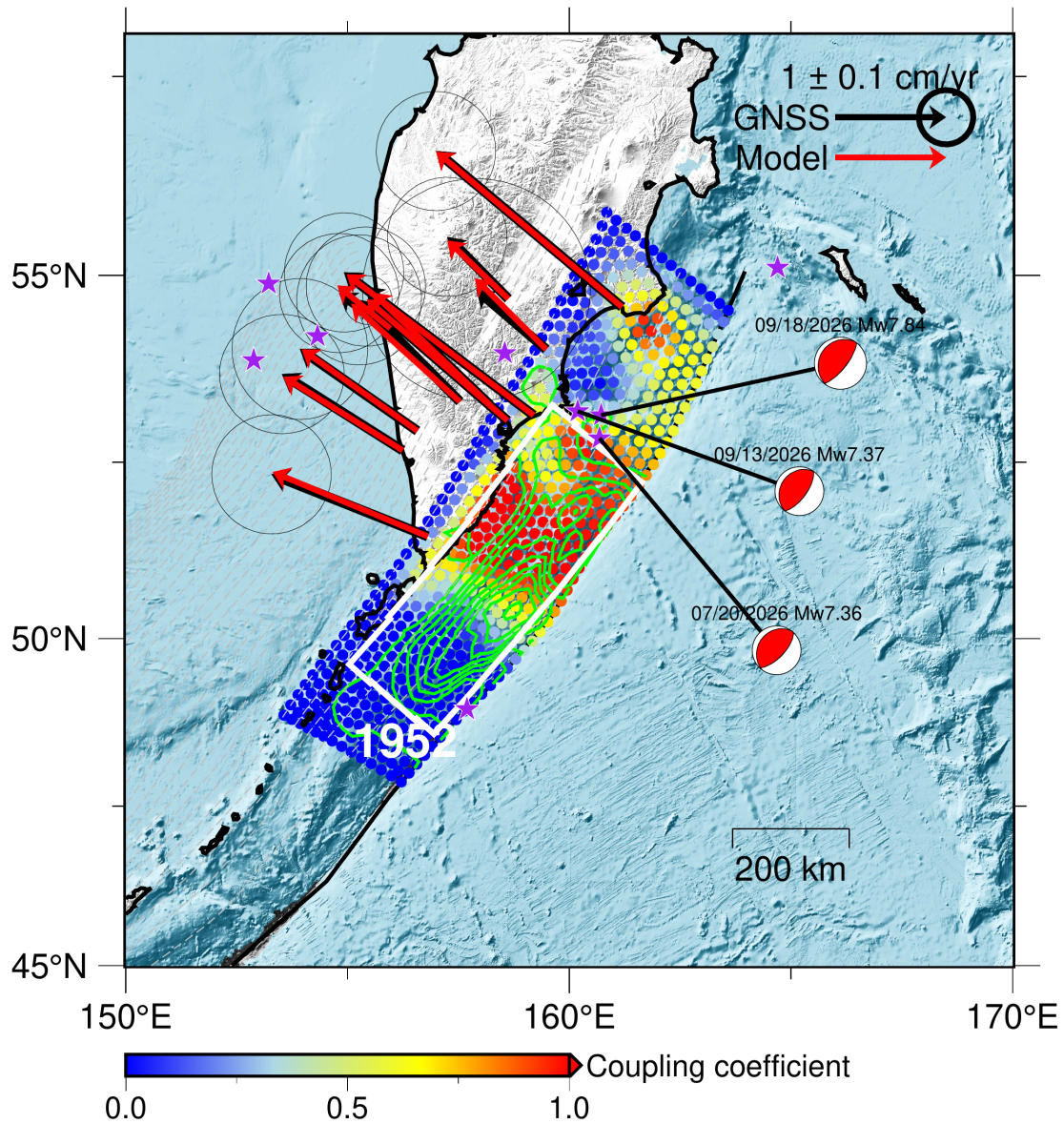


Fig. 7. Inverted interseismic coupling based on global spherical FEM and GNSS data from Bürgmann et al. (2005). Purple stars denote earthquakes with $M_w > 7$ since 1 January 2000 from the USGS catalog. Green contours show slip from model B, with a contour interval of 2 m. The white box indicates the rupture area of the 1952 earthquake (MacInnes et al., 2010).

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Supplementary Information for

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“Multi-scale constraints resolve the 2025 Kamchatka megathrust

575

rupture in a 3D heterogeneous Earth”

576

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Table S1

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Figures S1 to S6

593 Text S1 GNSS data processing

594 For the regional Russian data set, multi-system GNSS observations (GPS, GLONASS, and
595 Galileo) with a 30-s sampling interval were processed for the period 19 July–8 August 2025
596 (DOY 200–220) using BERNese GNSS Software version 5.4 (Dach et al., 2015) in relative
597 mode. Data for the period 23:24–24:00 UTC on 29 July 2025 were excluded from the analysis.
598 The final CODE products, including precise satellite orbits and clocks, ionosphere, ERP, and
599 DCB files, were used together with corrections for ocean tidal loading from the FES2014 model
600 (Lyard et al., 2021) and atmospheric tidal loading based on ECMWF operational analyses (Ray
601 and Ponte, 2003). For tropospheric modeling VMF3 data were used (Landskron, D. and J. Böhm,
602 2018). A standard regional data processing scheme was used following the BERNese tutorial
603 (see <https://www.bernese.unibe.ch/docs/TERMINAL.pdf>).

604 Solutions were aligned to the IGB20 realization of ITRF2020, implemented using a set of 18 IGS
605 stations (AIRA, BJFS, CHAN, CHUM, DAEJ, FAIR, GLSV, GUAM, HYDE, IRKJ, KIT3,
606 MCIL, SHAO, STK2, SUWN, TNML, ULAB, URUM) by applying the minimum (no net
607 translation) condition to the barycenter of the reference sites coordinates. Coseismic offsets in
608 the local topocentric coordinate system (NEU) were estimated for each site independently as the
609 difference between the positions obtained using a linear regression fit to the time series within 10
610 days after and 10 days before the mainshock. The RMS of the coseismic offset in each
611 coordinate component was calculated as $\sqrt{\sigma_{before}^2 + \sigma_{after}^2}$, where σ_{before} and σ_{after} are the
612 RMS values obtained from linear approximation of the time series before and after the
613 mainshock, accordingly.

614 The Nevada Geodetic Lab estimated displacements from their 5-minute sampling high-rate time
615 series (Blewitt et al., 2018). The models used in their data analysis strategy are provided on their
616 website (<https://geodesy.unr.edu/gps/ngl.acn.IGS20.txt>). They estimated positions every 5
617 minutes using the JPL orbit and clock products, with the global solution aligned to the IGS20
618 realization of ITRF2020 using transformation parameters estimated by JPL and provide with the
619 orbits. Aside from the use of GipsyX 2.3 rather than Bernese, the models used are similar to
620 those used in the analysis of the Russian data. Displacements were computed by differencing the
621 median pre- and post-earthquake positions, defined over a 10-day interval. NGL applied a medial

spatial filter to the far-field data, but did not specify how far-field was defined. For some publicly available stations in Korea, we independently analyzed the data and found the same average displacement as NGL did.

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Text S2 Tsunami forward model

We use pressure-gauge records from five NOAA DART buoys (the same ones used by Sepúlveda et al., 2026.): 21418, 21414, 21415, 21416, and 21419. Raw bottom-pressure time series were de-tided and bandpass-filtered to isolate the tsunami signal. For each buoy, we fit the waveform within a window spanning the tsunami arrival, selected from a 180-minute interval beginning at the earthquake origin time, and compare them to synthetic waveforms computed with GeoClaw (Berger et al., 2011).

We carry out the tsunami propagation simulation at 5 dart stations using the open-source code GeoClaw. Bathymetry is represented by a 1 arcmin grid obtained from GEBCO 2026, and are used with adaptive mesh refinement (AMR) levels ranging from 3 arcmin to 1 arcmin. For the geodetic-only inversion result and the joint inversion result with the seafloor uplift provided Ruiz-Angulo et al. (2025) (tsu1), we assume an instantaneous tsunami triggering right at the earthquake origin time, as indicated by Ruiz-Angulo et al. (2025). For the joint inversion result with the seafloor uplift provided by Sepúlveda et al., (2026) (tsu2), we set a 3 minute delay between the tsunami initiation and the rupture, as described by the supplementary text of Sepúlveda et al., (2026). Because the arrival time of the tsunami at the DART buoys is determined by the data, the assumed tsunami initiation time will trade off with the location of slip. If an earlier tsunami origin time is assumed, the slip will be estimated to be located further to the west, and more down dip. If a later tsunami origin time is assumed, the slip will be estimated to be located further to the east, and at shallower depth.

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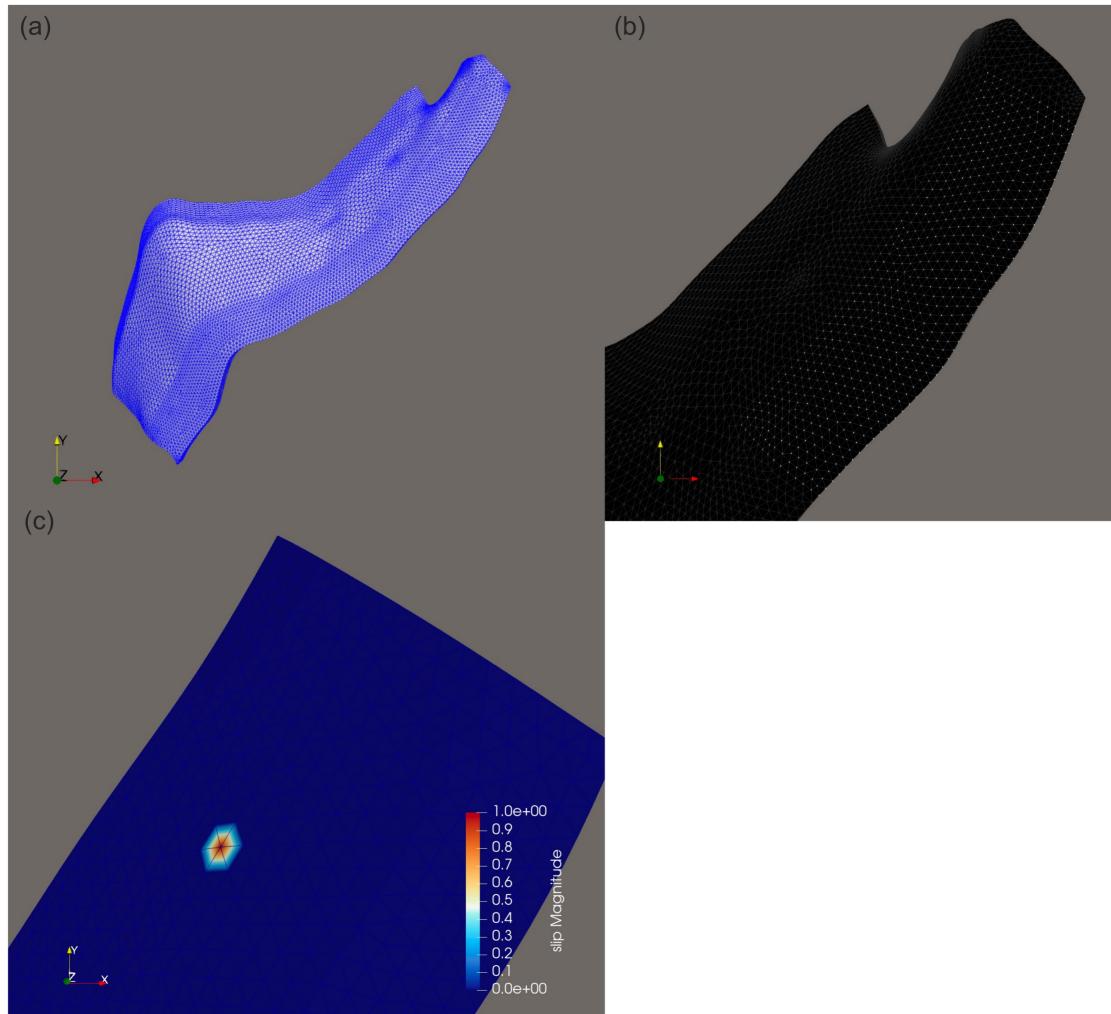
665 Sepúlveda, I., Nilsson, B., Yu, Y., Carvajal, M., Brandin, M., Gabriel, A.A., Sandwell, D., 2026.
666 SWOT detects dispersive tsunami tied to a near-trench source in the 2025 Kamchatka
667 earthquake. *Science* 391, 1368-1372. <https://doi.org/10.1126/science.aeb8634>

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669 **Table S1 GNSS offsets processed in this study**

Site	Lat.	Lon.	dN	RMS_dN	dE	RMS_dE	dU	RMS_dU
	deg	deg	mm	mm	mm	mm	mm	mm
SKUR	50.668	156.114	-864	5	1493	8	-190	3
PEMK	53.083	158.591	-538	6	365	5	-64	2
ELIZ	53.180	158.387	-480	6	322	4	-39	3
SKCH	53.152	157.691	-438	5	340	4	-26	2
KLUC	56.318	160.826	-15	1	1	1	-5	2
TILI	60.439	166.089	0	2	0	1	-2	2
NIKL	55.193	165.984	5	1	-3	1	-6	2
MGDN	59.566	150.814	-22	1	13	1	-2	2
SUSU	62.779	148.168	-10	1	5	1	0	2
OLAM	59.573	151.294	-22	1	12	1	-1	3
AYAN	56.466	138.176	-7	1	16	1	-1	2
OHAA	53.570	142.923	-9	1	33	1	0	3
NGLK	51.811	143.156	-3	1	33	1	-1	2
TMVS	50.855	142.662	-1	1	28	1	-2	2
ONOR	50.187	142.669	1	1	25	1	-1	2
PONK	49.224	143.095	2	1	22	1	-3	2
SAKH	49.157	142.112	2	1	19	1	-2	2

Site	Lat.	Lon.	dN	RMS_dN	dE	RMS_dE	dU	RMS_dU
KRNL	48.947	142.189	2	1	17	1	-1	2
VZMO	47.856	142.504	2	1	14	1	-1	2
DLNS	47.314	142.790	3	1	11	1	-4	2
HLSK	47.033	142.033	3	1	10	1	-3	2
NESK	46.677	141.855	1	2	10	1	1	6
RDLN	46.646	142.810	2	1	10	1	-1	2
USKH	47.035	142.716	4	1	11	1	-1	2
SOGN	48.964	140.282	2	1	14	1	0	2



671

672 Figure S1. Finite-element fault mesh and inversion parameterization. (a) Mesh of the subducting
 673 Pacific slab. (b) Vertices of the fault domain used in the slip inversion. (c) Unit-slip basis
 674 functions assigned to each fault vertex in the inversion.

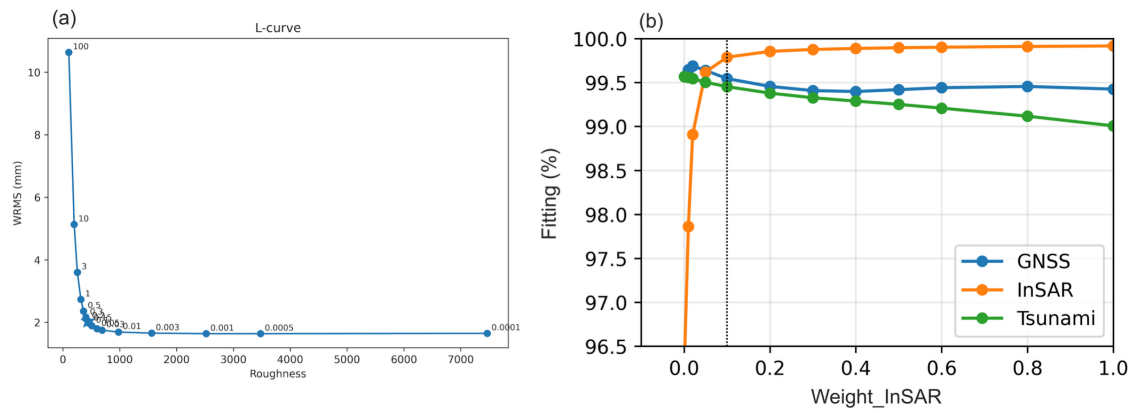
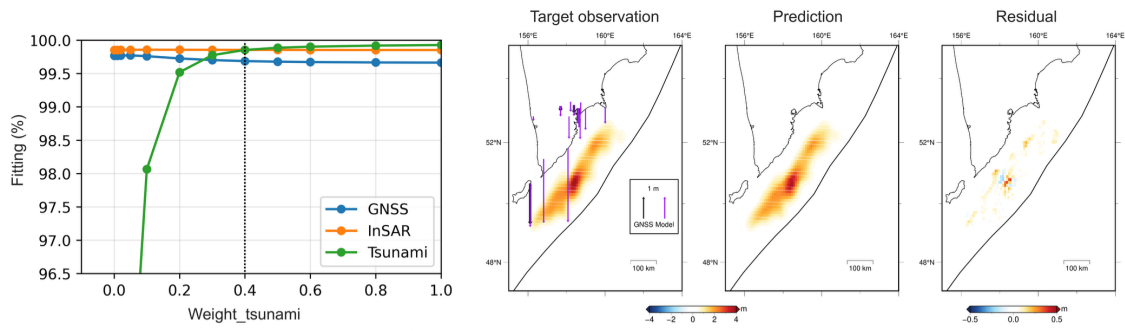
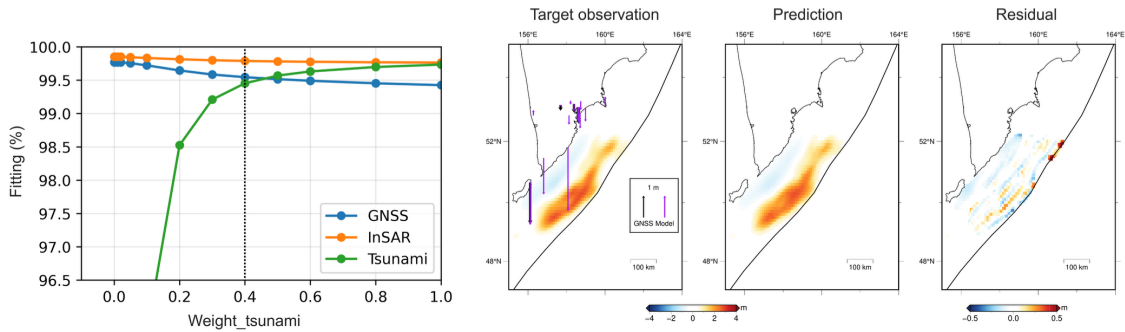


Figure S2. Inversion-parameter tests. (a) L-curve used to select the smoothing factor. (b) Fitting percentage as a function of increasing InSAR weight. Tsunami constraint is based on Sepúlveda et al., 2026.

(a) Ruiz-Angulo et al., 2025

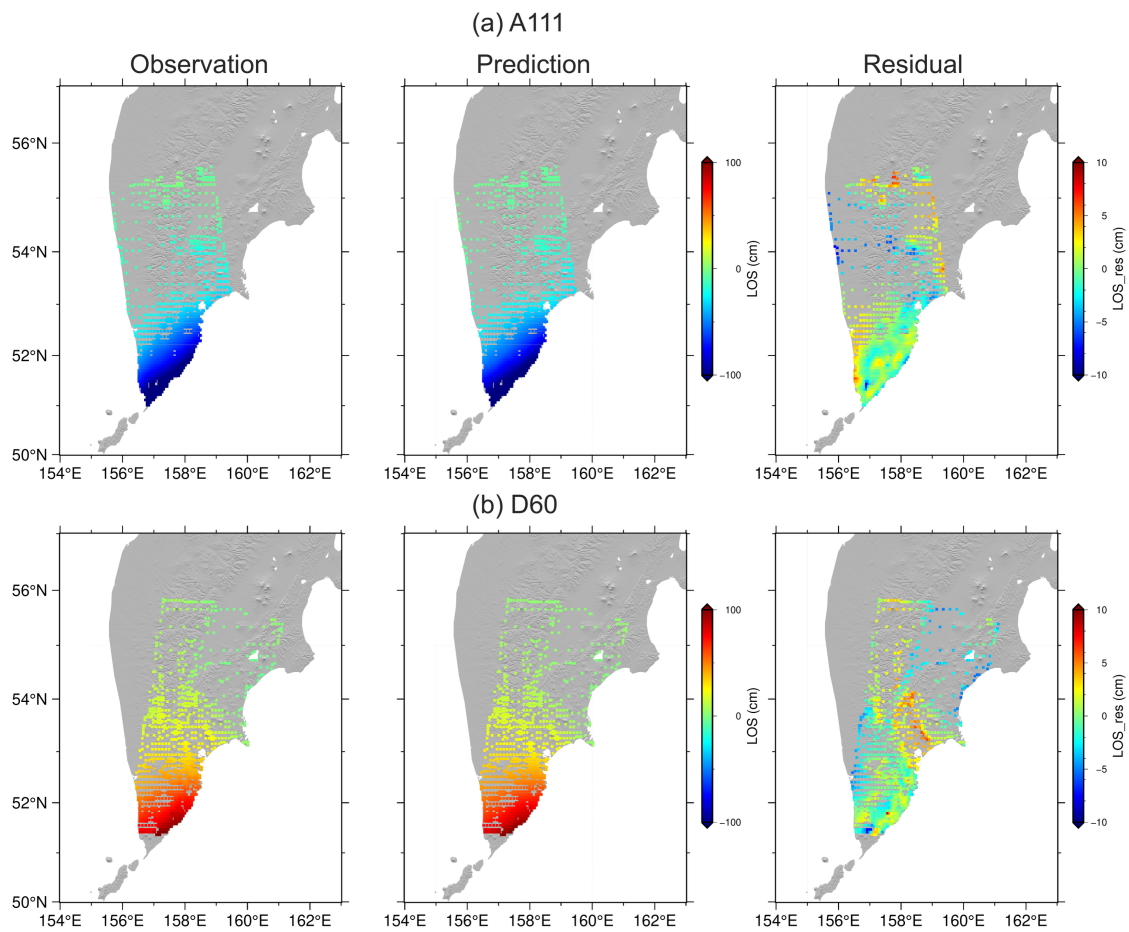


(b) Sepúlveda et al., 2026



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681 Figure S3. Sensitivity of model fit to the tsunami-data weight. The figure shows changes in
682 fitting percentage with increasing tsunami weight, together with comparisons between the
683 offshore vertical constraints and model predictions for the two tsunami-derived uplift models.



684

685 Figure S4. Comparison between observed and predicted InSAR line-of-sight displacements from
 686 model b.

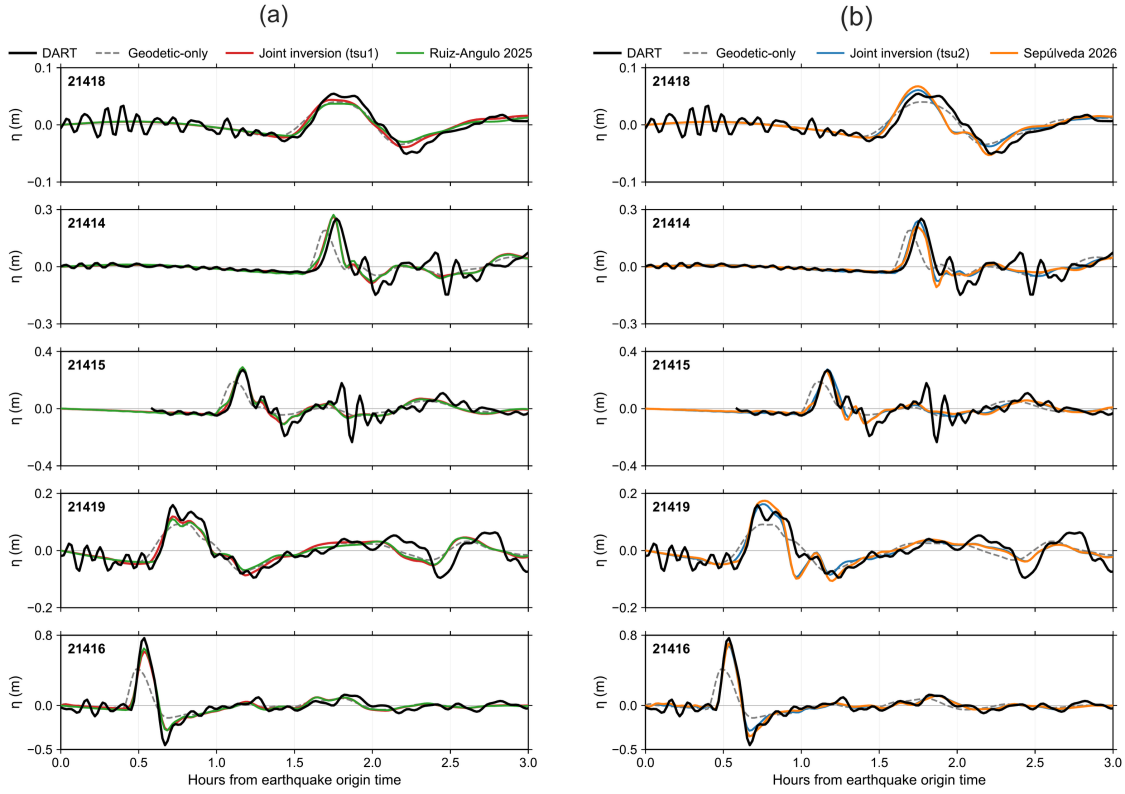
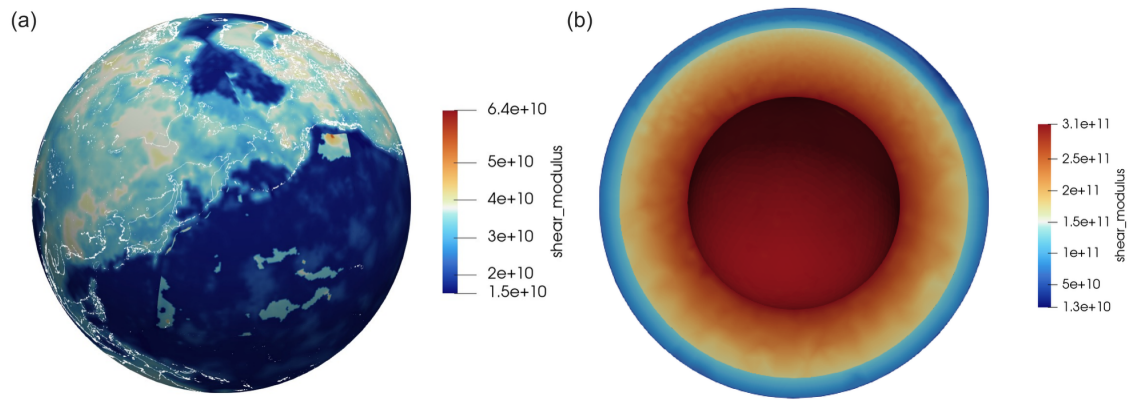


Figure S5. Comparison between DART observations and forward tsunami simulations. The red and blue curves show simulations using our predicted vertical seafloor deformation from the joint inversions as the tsunami source. The green and orange curves show simulations using the original initial tsunami-elevation models of Ruiz-Angulo et al. and Sepúlveda et al., respectively, as the source input.



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695 Figure S6. Material properties for Earth surface and cross view with the LITHO1.0-PREM

696 structural model used in finite element model.

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