Resolving Near-Trench Interseismic Deformation: Evaluating GNSS-Acoustic Capabilities along the Aleutian Arc

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A quick background

The Aleutian-Alaska megathrust has hosted devastating earthquakes and tsunamis, including the 1946 Unimak Island event. Despite its estimated magnitude of 7.4, it generated a tsunami typically associated with magnitude 9.0 earthquakes. Such "tsunami earthquakes" (TsE) are marked by long rupture durations, slow stress release, low-frequency energy, and significant vertical water displacement. These characteristics result in low ground shaking, complicating timely warnings for coastal populations. Understanding the coupling state of the Aleutian-Alaska Trench is essential for advancing

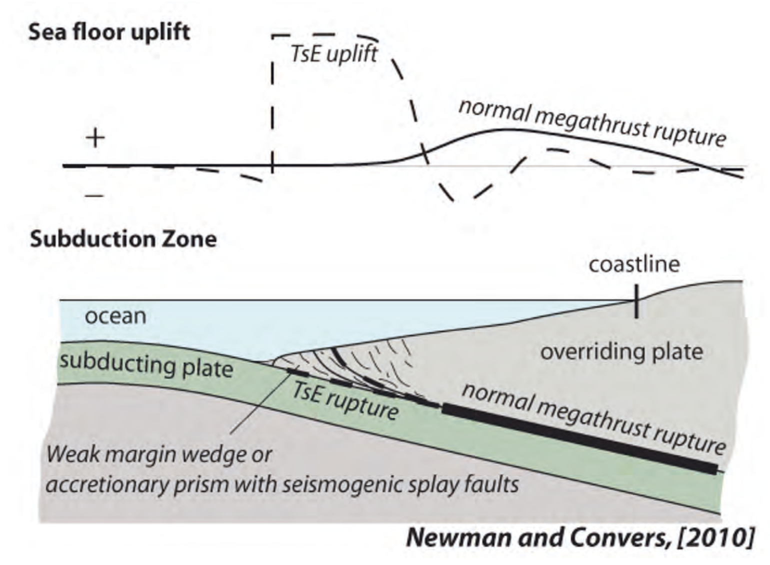

Figure 1. Diagram of TsE uplift vs normal megathrust rupture.

Figure 2. 1946 Aleutian Islands earthquake. In Wikipedia. https://en.wikipedia.org/wiki/1946_Aleutian_Islands_earthquake

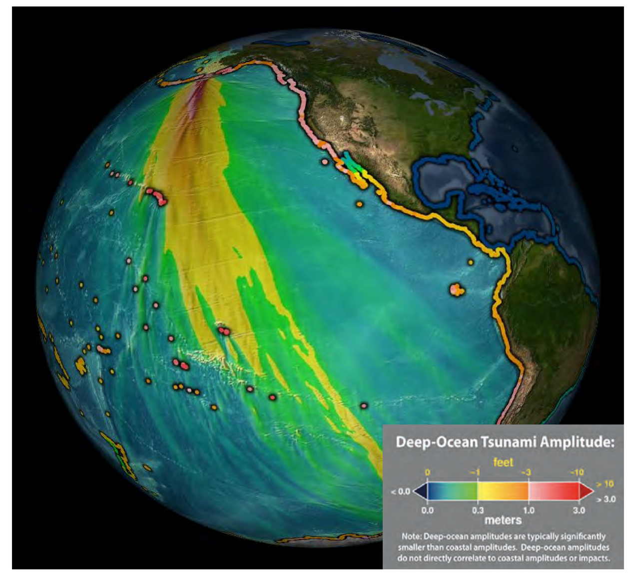

Figure 3. NOAA (2016): Energy map showing maximum sea-level rise caused by the tsunami in open ocean.

About the project

Modeling coupling behavior in subduction zones is challenging, especially near the trench, where tsunami earthquakes often originate. Land-based geodetic stations have limited reach, but GNSS-Acoustic (GNSS-A) technology addresses this gap by combining GNSS signals with underwater acoustic communication to monitor seafloor deformation closer to the trench. This is particularly valuable in shallow subduction zones, where fault slip behavior is poorly understood. In summer 2024, GNSS-A stations were deployed near the Aleutian-Alaska megathrust trench to study coupling behavior in these critical regions.

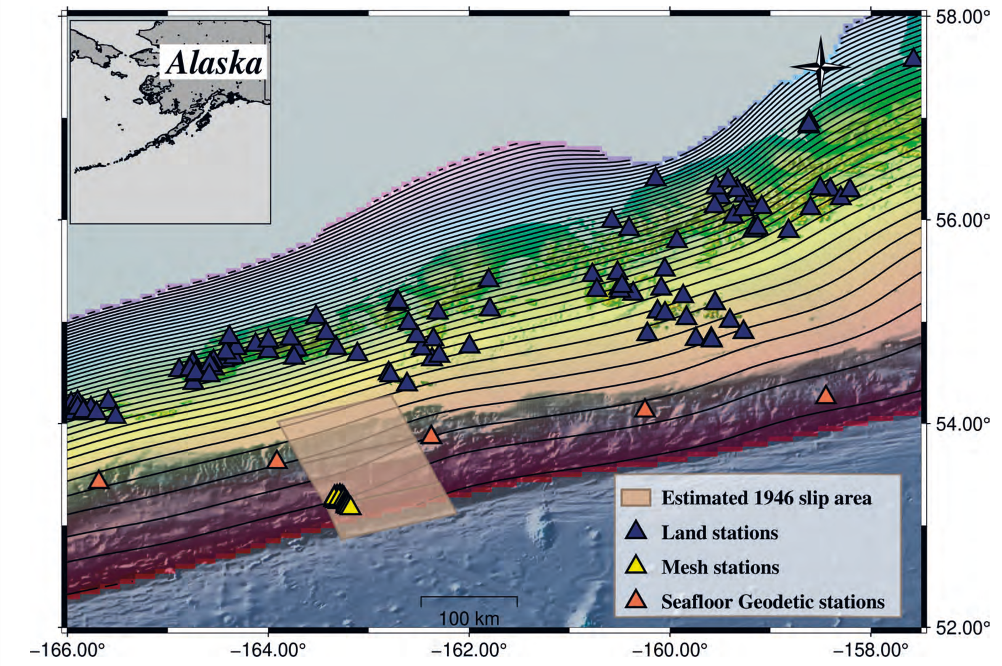

Figure 4. Geodetic station distribution for current inland stations (blue), deployed community stations (orange) and mesh station distribution (yellow). The orange rectangular area corresponds with the rupture area proposed by Johnson & Satake (1997). The colored contour represents the Slab 2.0 (Hayes, 2018).

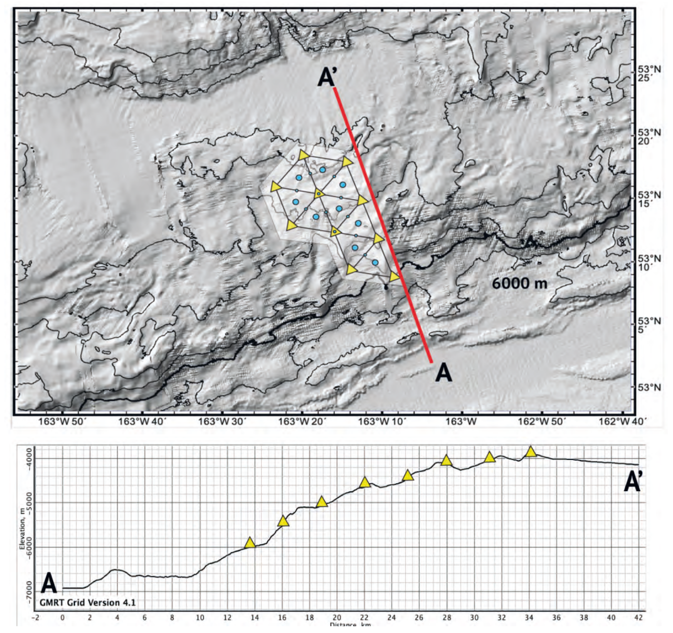

Figure 5. Planned mesh station distribution, installed during Summer of 2024 with the respective profile.

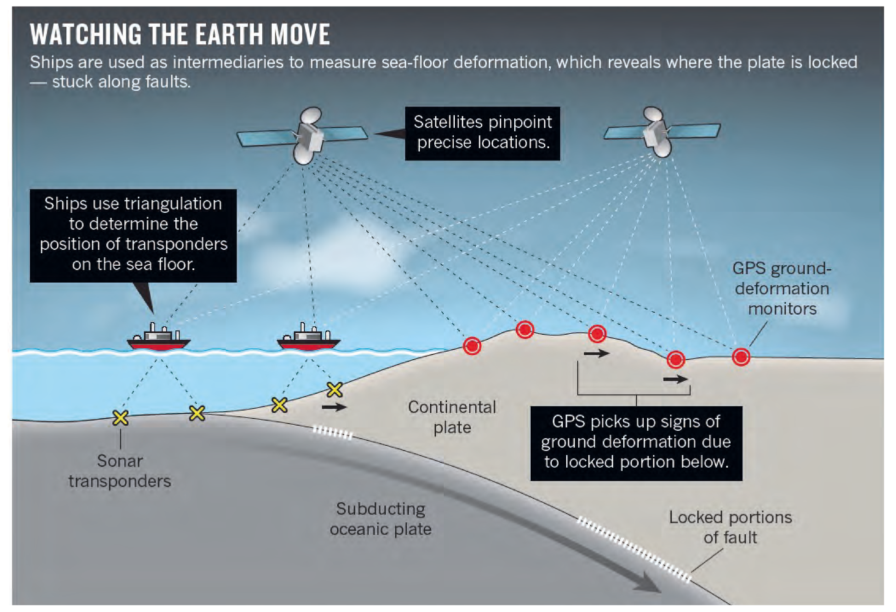

Figure 6. GNSS system set up using acoustic transmission (A.V. Newman, Nature 2011)

Figure 7. Wave glider, operating on the surface to transmit the position to the satellites

Figure 8. Deployment of the Wave Glider, near Aleutian Islands.

Figure 9. Transponder Acoustic GNSS station

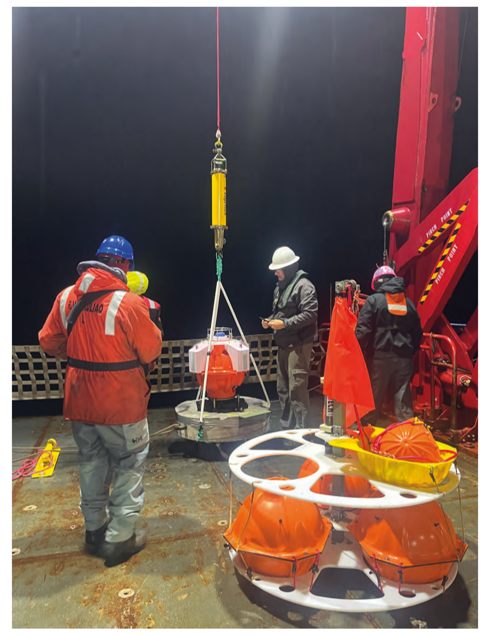

Figure 10. Deployment of the transponder

Methods and Results

To test the station geometry's resolution, we invert synthetic forward models for the planned network using GTDef, which predicts displacements from rectangular dislocations (Okada, 1985). FA linear least squares inversion relates the data (d) to the model (m) using the Green's functions (G):

$$\mathbf{d} = \mathbf{Gm}$$

We generate synthetics using a forward thrust model, adding Gaussian noise to simulate data errors: **3 mm** and **6 mm** for **land-based GNSS** horizontal and vertical data, respectively, and **2.5 cm** for horizontal **GNSS-Acoustic data**. The data is then inverted to evaluate model recovery, applying error-based weighting (w) and regularization based by model smoothness (Laplacian of slip and Kappa coefficient):

$$\mathbf{d} = \mathbf{Gm} \;\Rightarrow\; \begin{bmatrix} w_{ii}d \\ 0 \end{bmatrix} = \begin{bmatrix} w_{ii}\mathbf{G} \\ K\nabla^2 s \end{bmatrix}\mathbf{m}$$

During the inversion, we calculate a generalized Green's function, to recover the model resolution matrix, R. If all model parameters are independent, R becomes an identity matrix (diagonal elements are 1, others 0). The diagonals can describe the model's resolution and its interdependence with neighboring patches. Then, the resolution spread, r is :

$$r_j = {L_j}/{\sqrt{R_{jj}}}$$

We used the **Slab 2.0** methodology (Hayes, 2018) to construct a **3D model**, incorporating mesh stations, previous and current sea-floor stations, and land stations. A checkerboard test with patch sizes of 700 km, 300 km, and 150 km was applied to estimate the minimum resolvable slip area given the station geometry, with all setups showing good reliability.

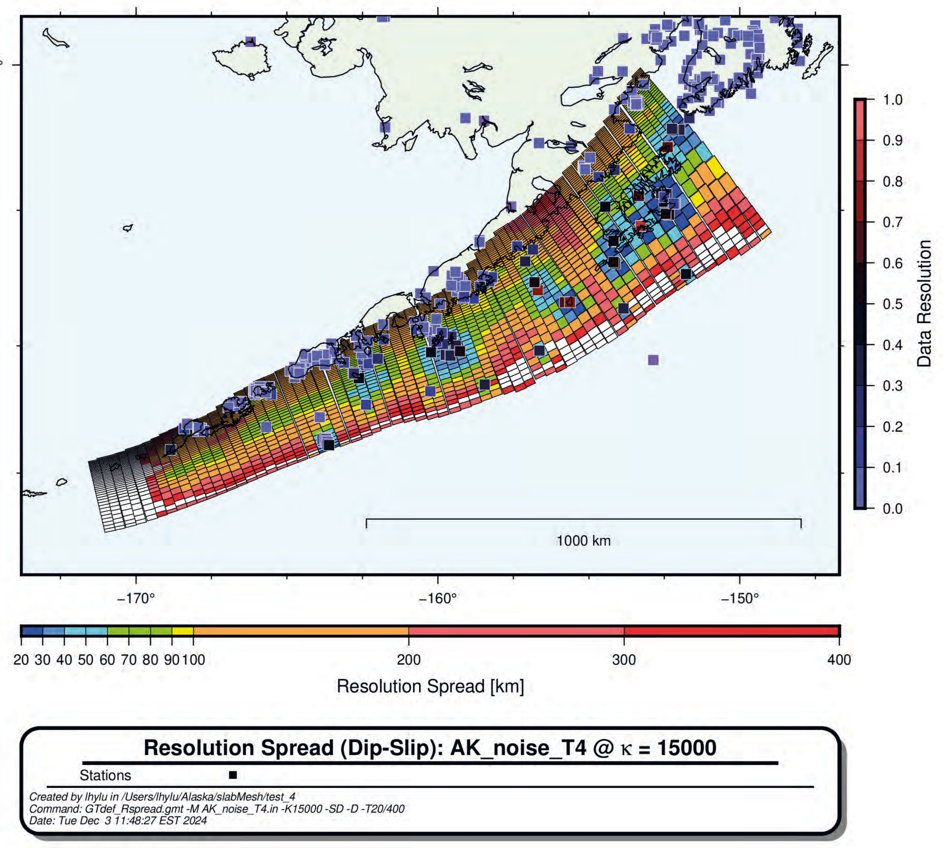

Figure 11. Resolution Spread for the Slab 2.0 model at the Aleutians island, using the current land and sea-floor stations distribution.

Input

Output

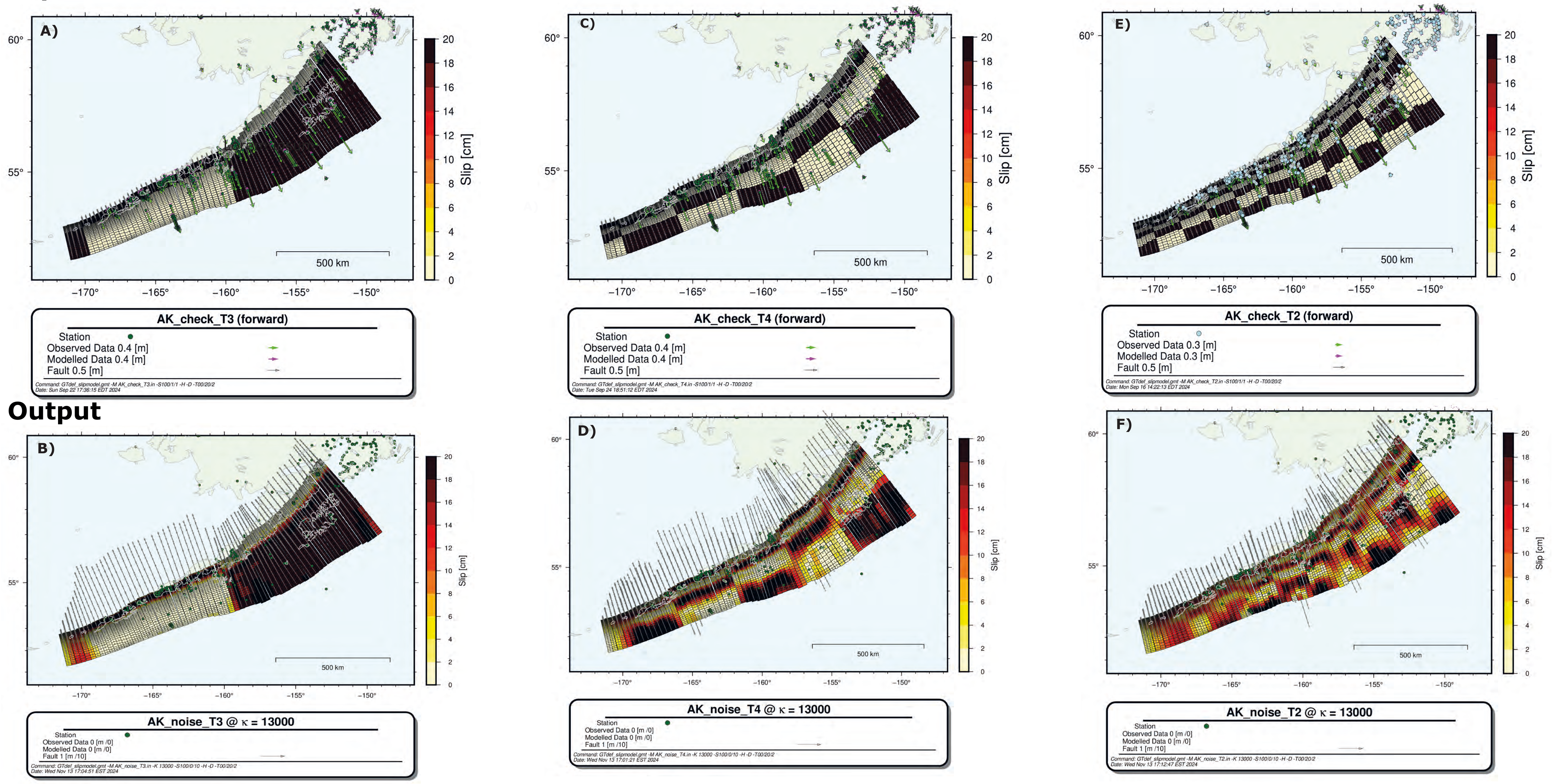

Figure 12. A) and B) Checkboard forward model using patches of 700 km, and the resulting inversion after adding noise. C) and D) Checkboard forward model using patches of 300 km, and the resulting inversion after adding noise. E) and F) Checkboard forward model using patches of over 150 km, and the resulting inversion after adding noise.

Summary

The Aleutian-Alaska megathrust, including the 1946 Unimak tsunami earthquake, highlights the need to understand coupling near subduction zone trenches. GNSS-Acoustic (GNSS-A) technology addresses land-based station limitations by measuring seafloor deformation in shallow zones. In 2024, GNSS-A deployments near the Aleutian trench advanced studies of fault slip behavior and coupling, critical for earthquake research and tsunami hazard mitigation.

References

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