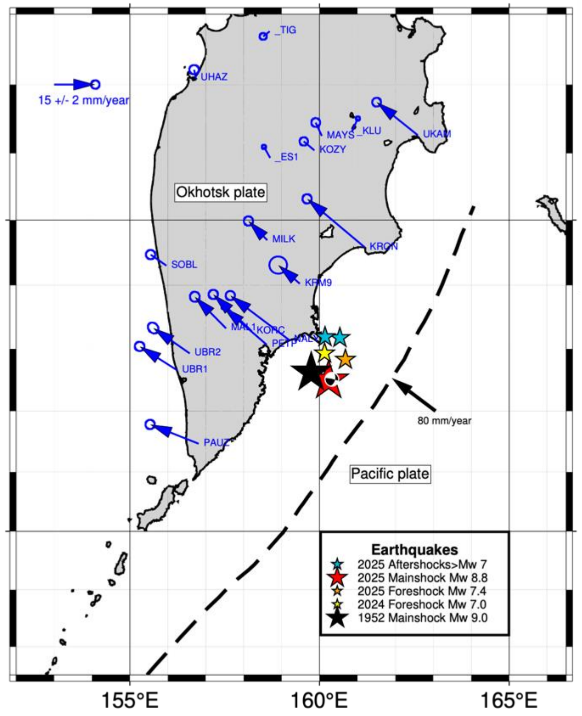
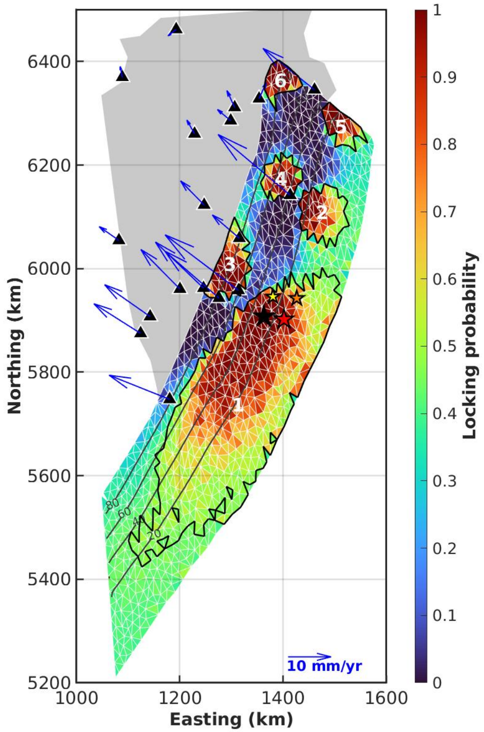
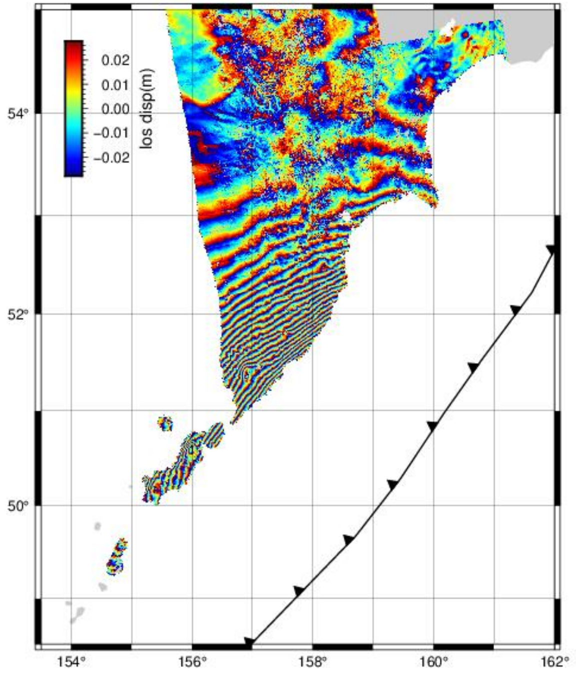
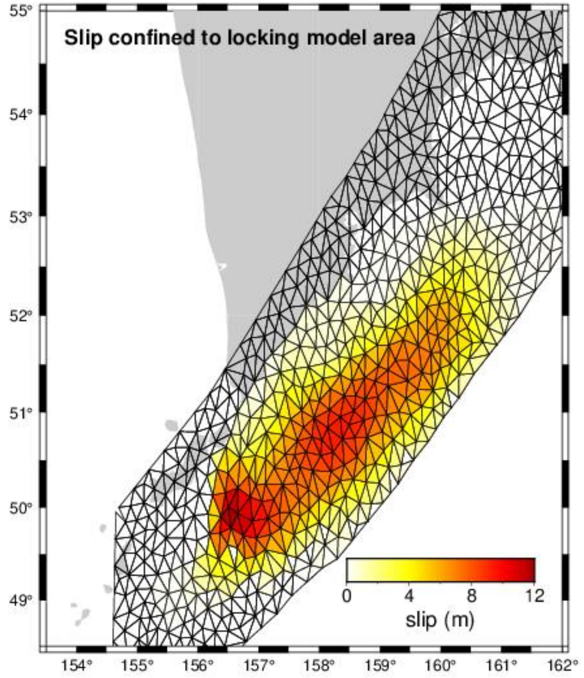
When is a great earthquake not "the big one"?

Insights from modelling of Sentinel-1 InSAR data from the July 2025 M8.8 Kamchatka megathrust earthquake



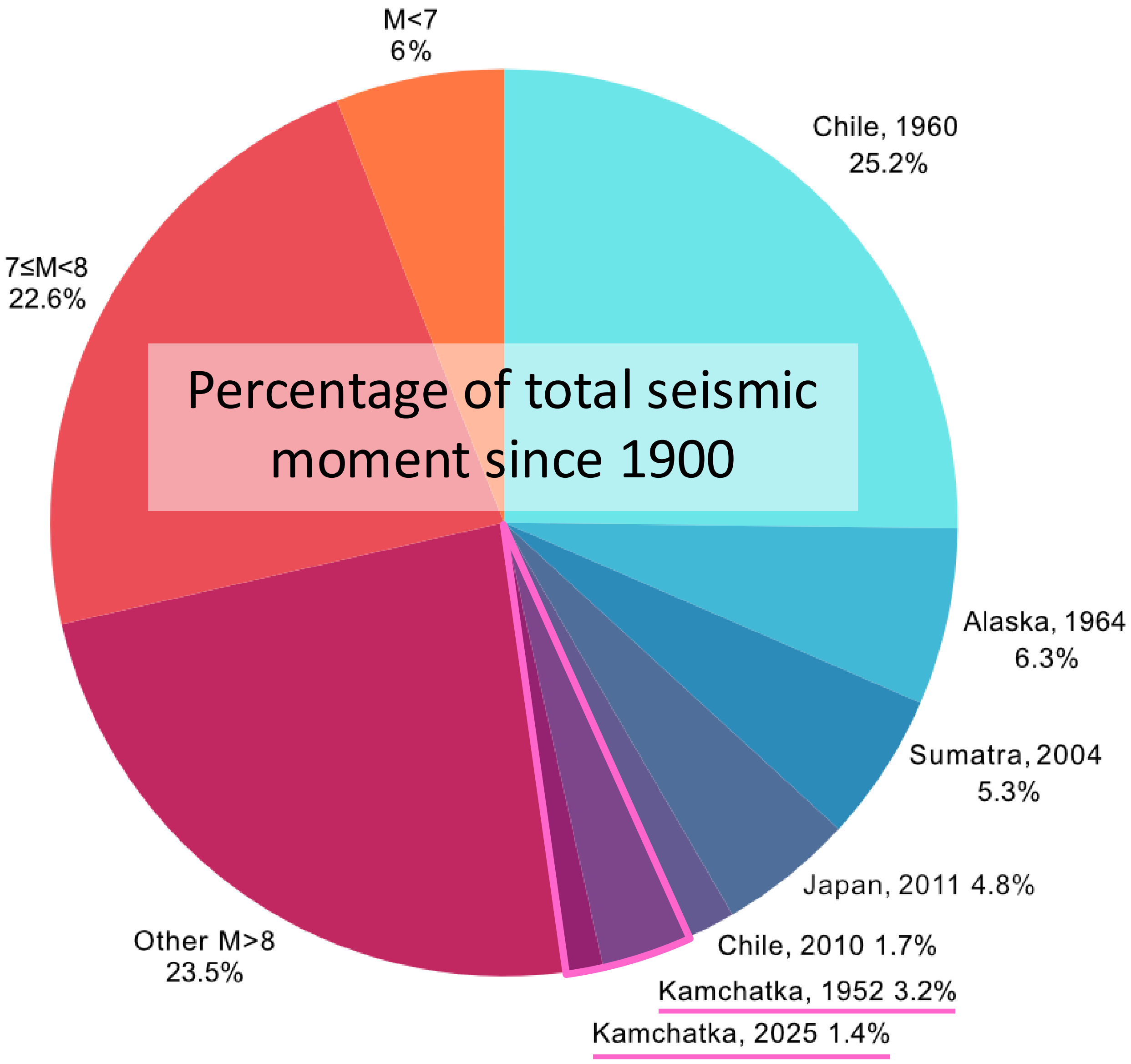


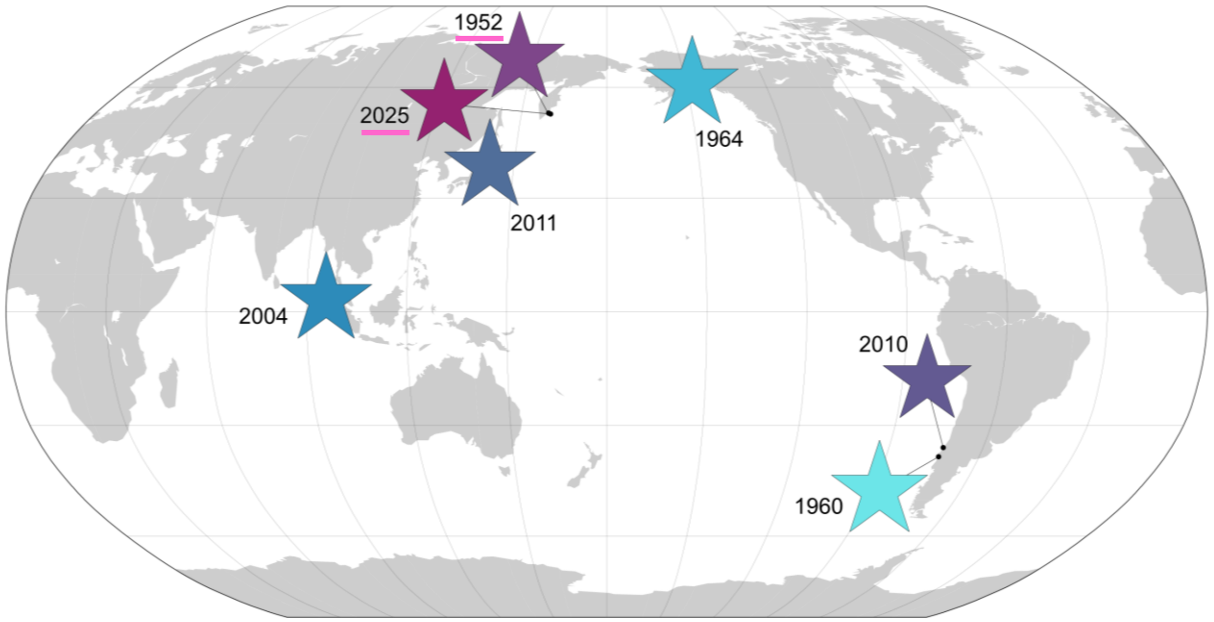




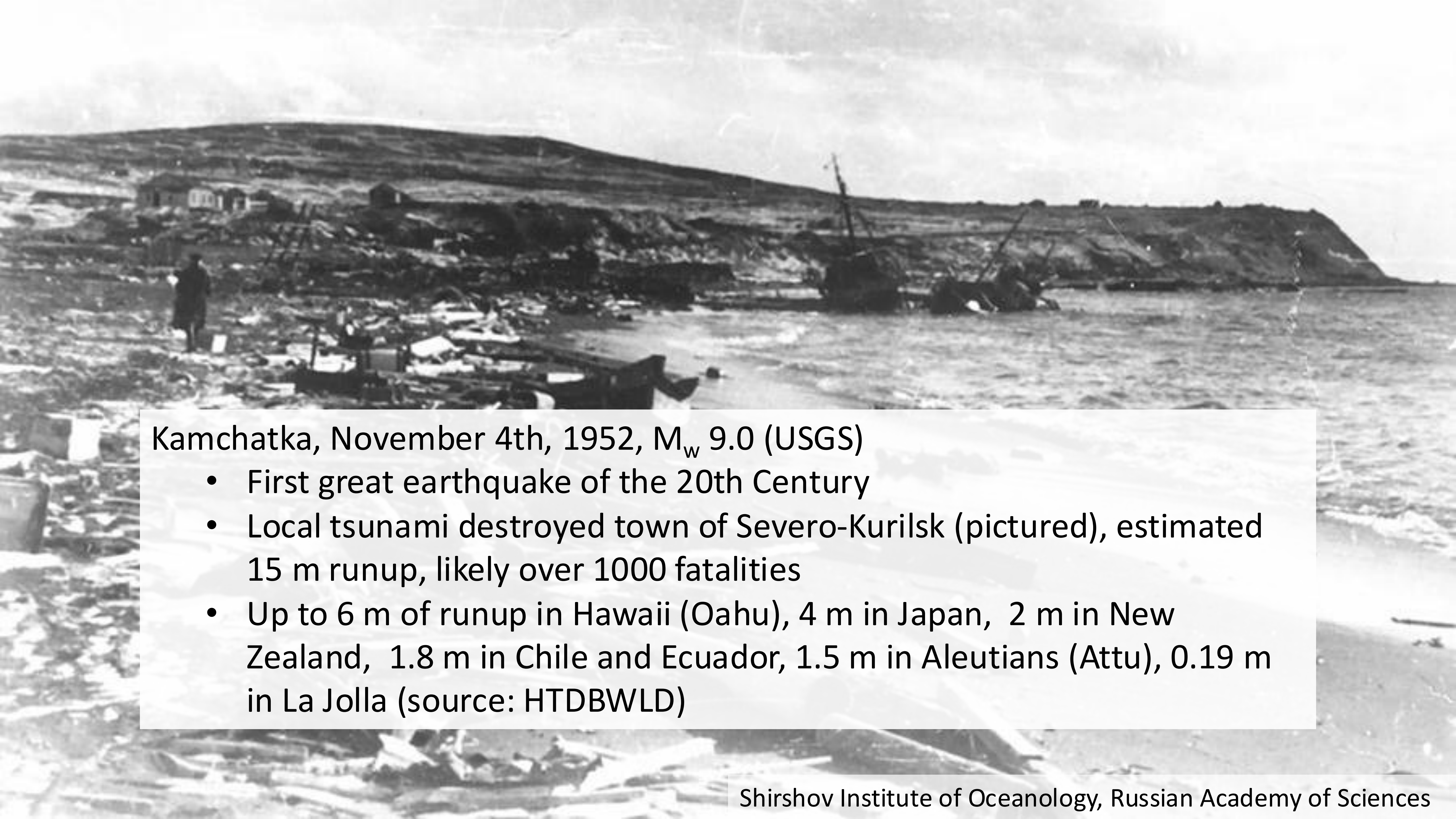
Gareth Funning and Axel Periollat, University of California, Riverside

Global seismic moment release is dominated by megathrust earthquakes





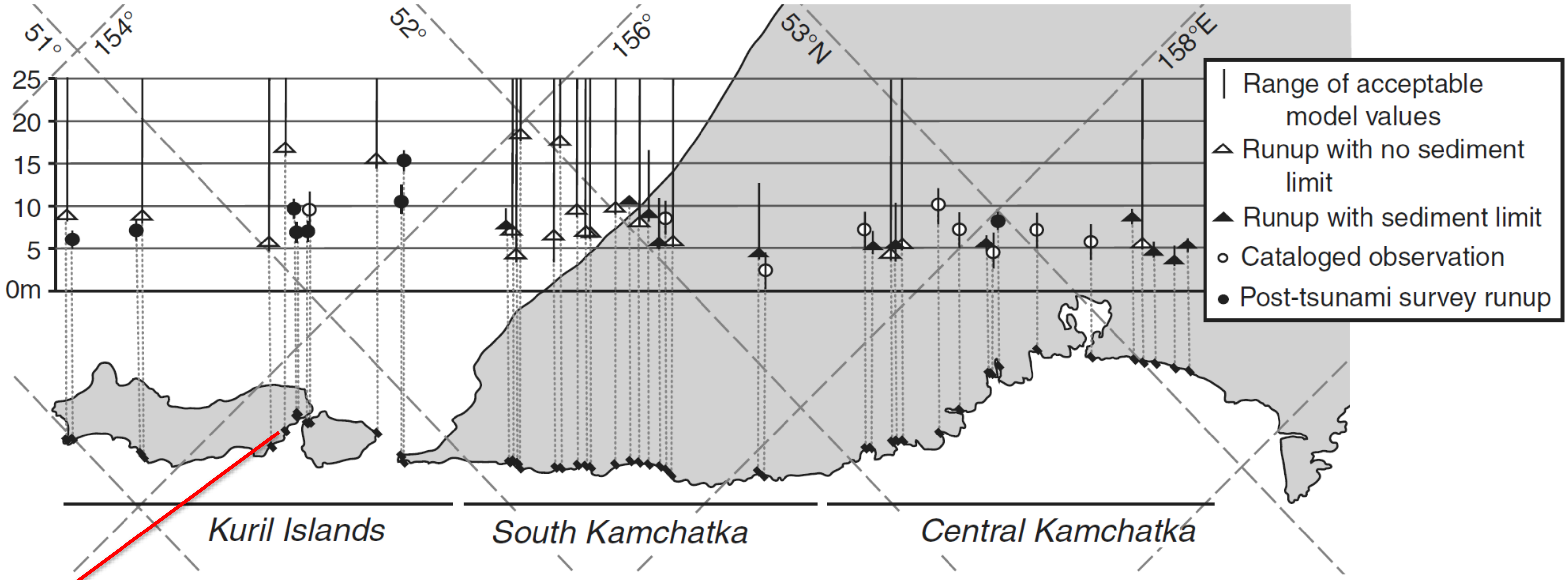
After Ammon et al., 2010; Allen et al., 2009; Duputel et al., 2012; globalcmt.org



Kamchatka, November 4th, 1952, M_w 9.0 (USGS)

- First great earthquake of the 20th Century
- Local tsunami destroyed town of Severo-Kurilsk (pictured), estimated 15 m runup, likely over 1000 fatalities
- Up to 6 m of runup in Hawaii (Oahu), 4 m in Japan, 2 m in New Zealand, 1.8 m in Chile and Ecuador, 1.5 m in Aleutians (Attu), 0.19 m in La Jolla (source: HTDBWLD)

Shirshov Institute of Oceanology, Russian Academy of Sciences



Severo-Kurilsk

MacInnes et al., 2010

July 29th, 2025

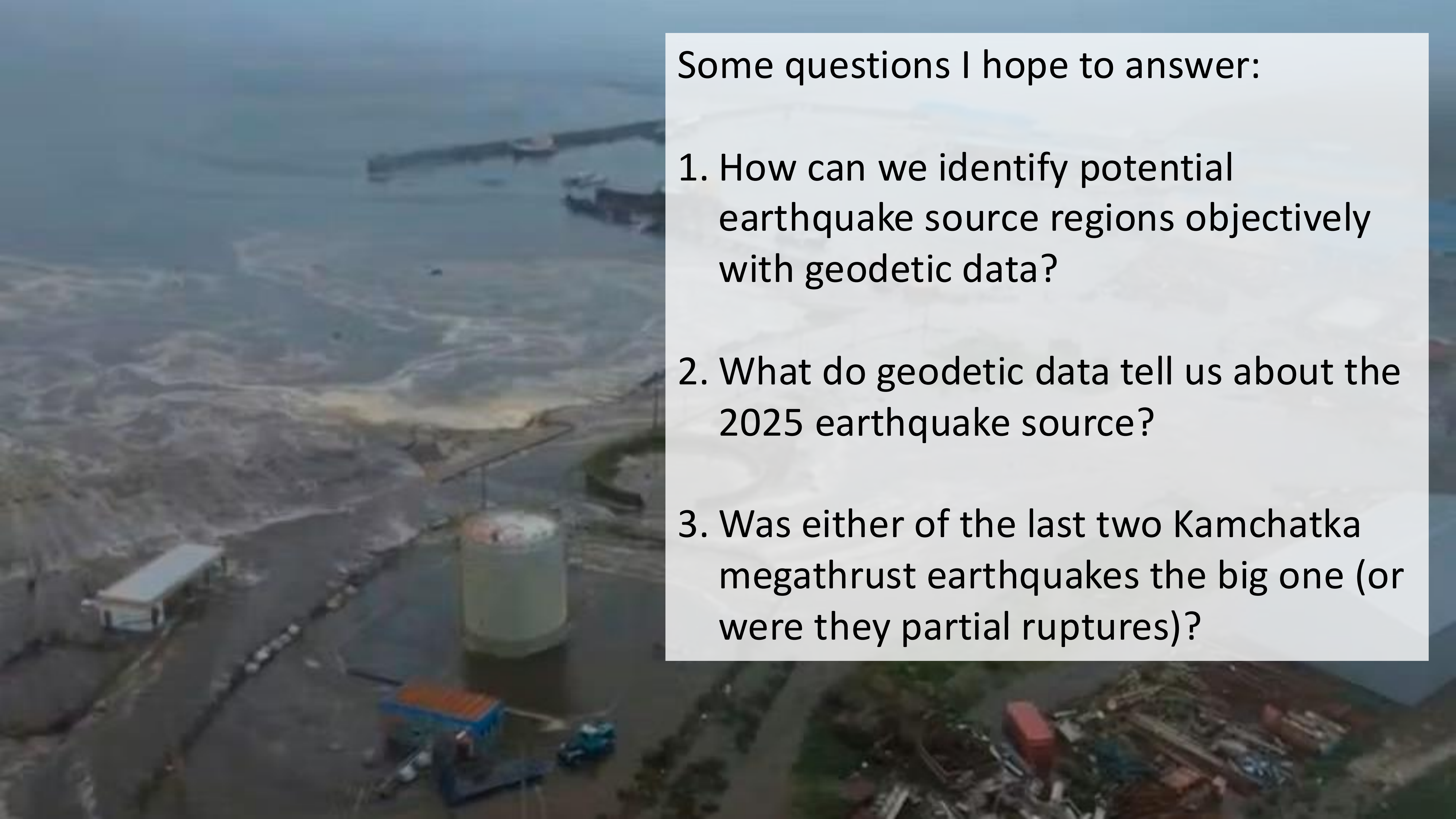
Geophysical Service of the Russian Academy of Sciences


4 m
5 m
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Image © 2026 Airbus
Image © 2026 Maxar Technologies
Google Earth

Kamchatka, July 29th, 2025, M_w 8.8 (USGS)

- Up to 5 m of runup at Severo-Kurilsk (pictured), no fatalities
- Tsunami warning issued across Pacific basin
- Wave heights up to 1.7 m of in Hawaii (Maui), 1.3 m in Japan, 2.5 m in Chile, 0.7 m in Aleutians (Adak), 0.18 m in La Jolla (source: HTDBWLD)

Geophysical Service of the Russian Academy of Sciences

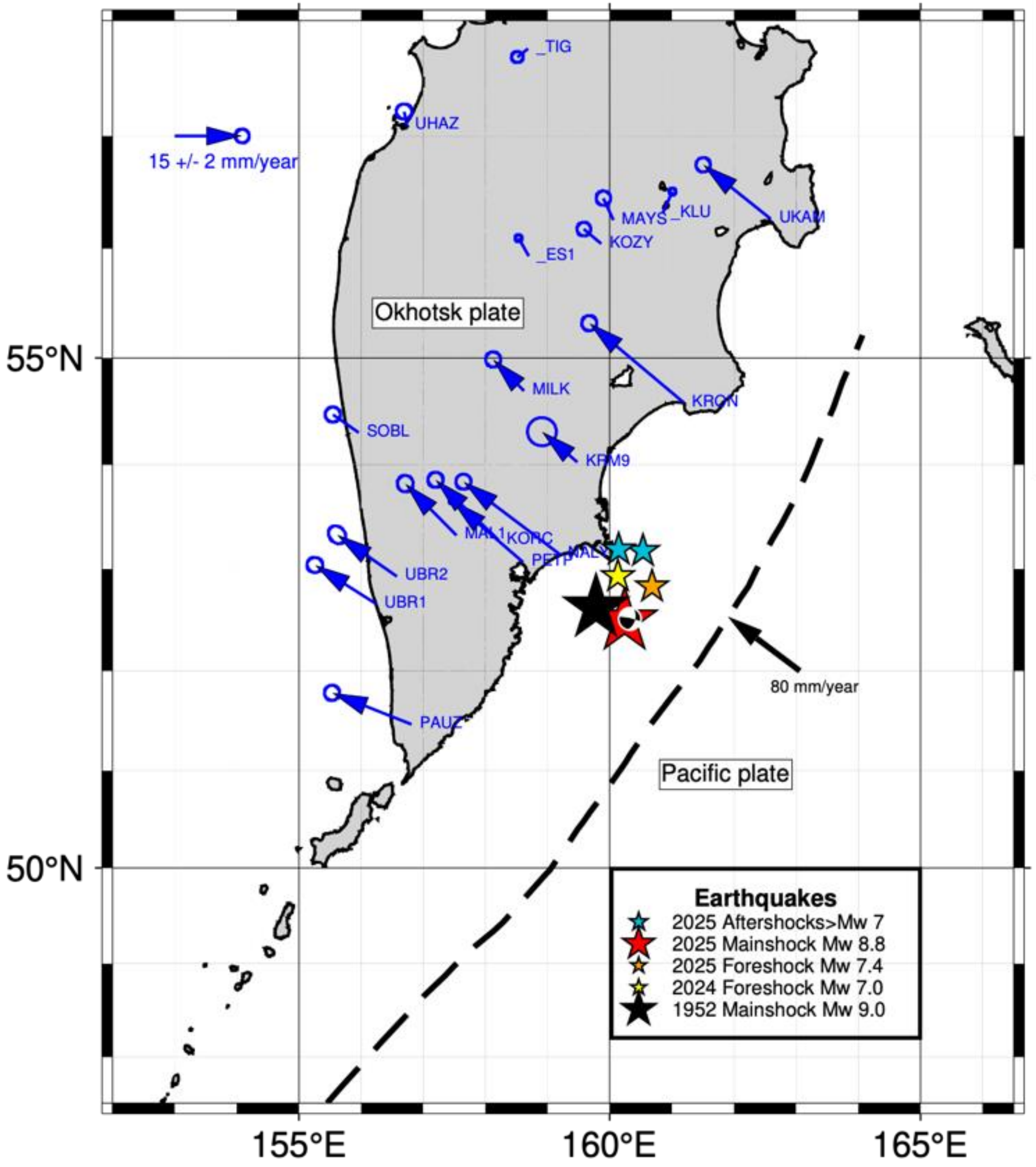


Some questions I hope to answer:

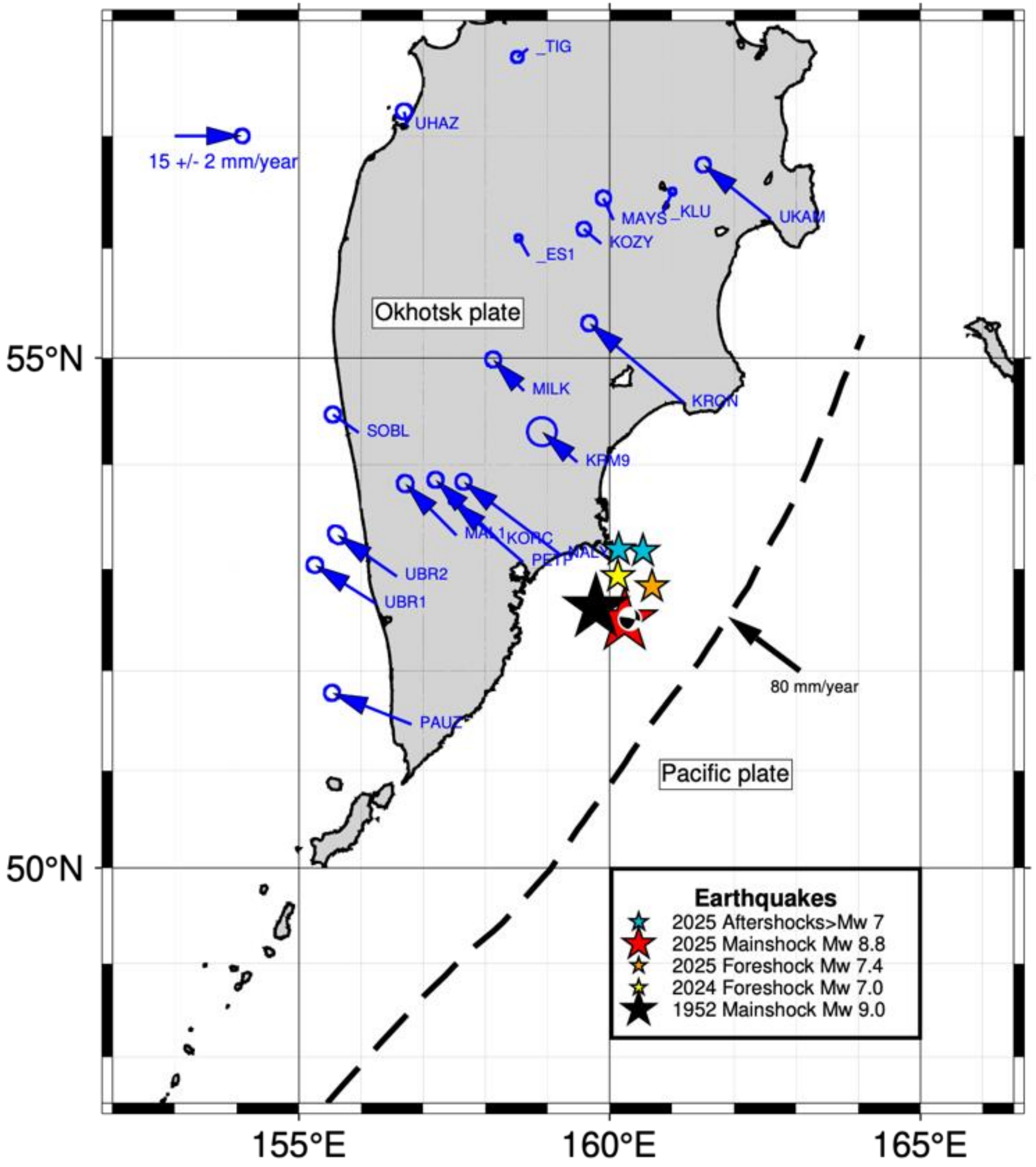
1. How can we identify potential earthquake source regions objectively with geodetic data?

2. What do geodetic data tell us about the 2025 earthquake source?

3. Was either of the last two Kamchatka megathrust earthquakes the big one (or were they partial ruptures)?



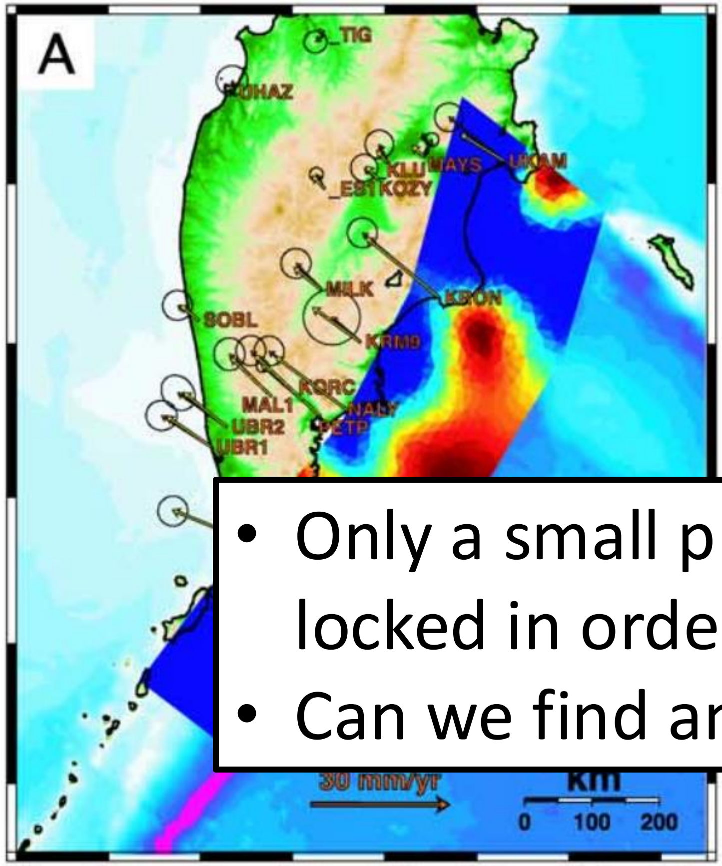
1. How can we identify potential earthquake source regions objectively with geodetic data?



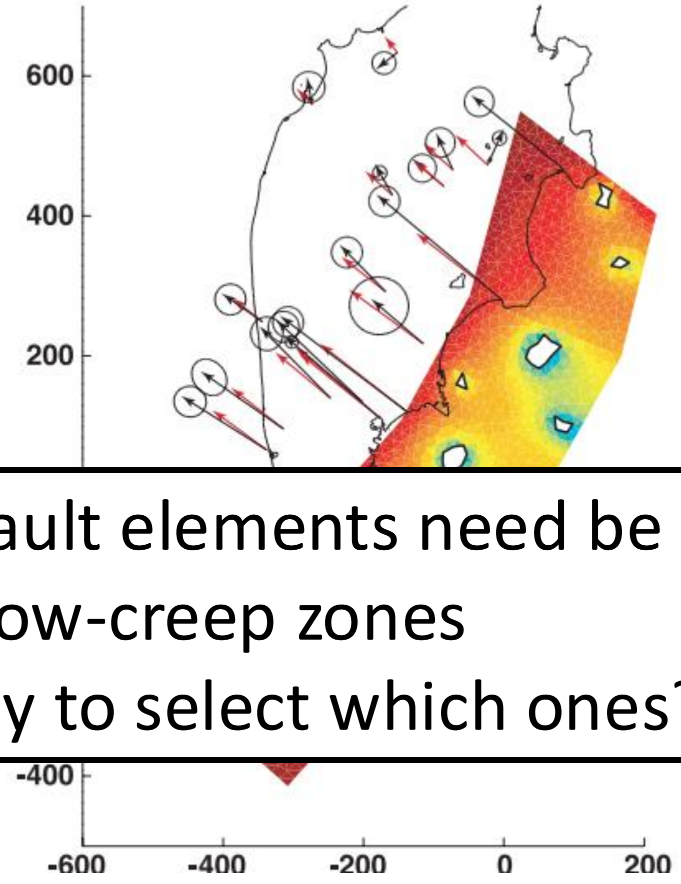
Interseismic campaign GNSS velocities from Steblov et al. (2003) and Burgmann et al. (2005)

How much of a megathrust is frictionally locked?

Kinematic, inverse model (blue=creeping)

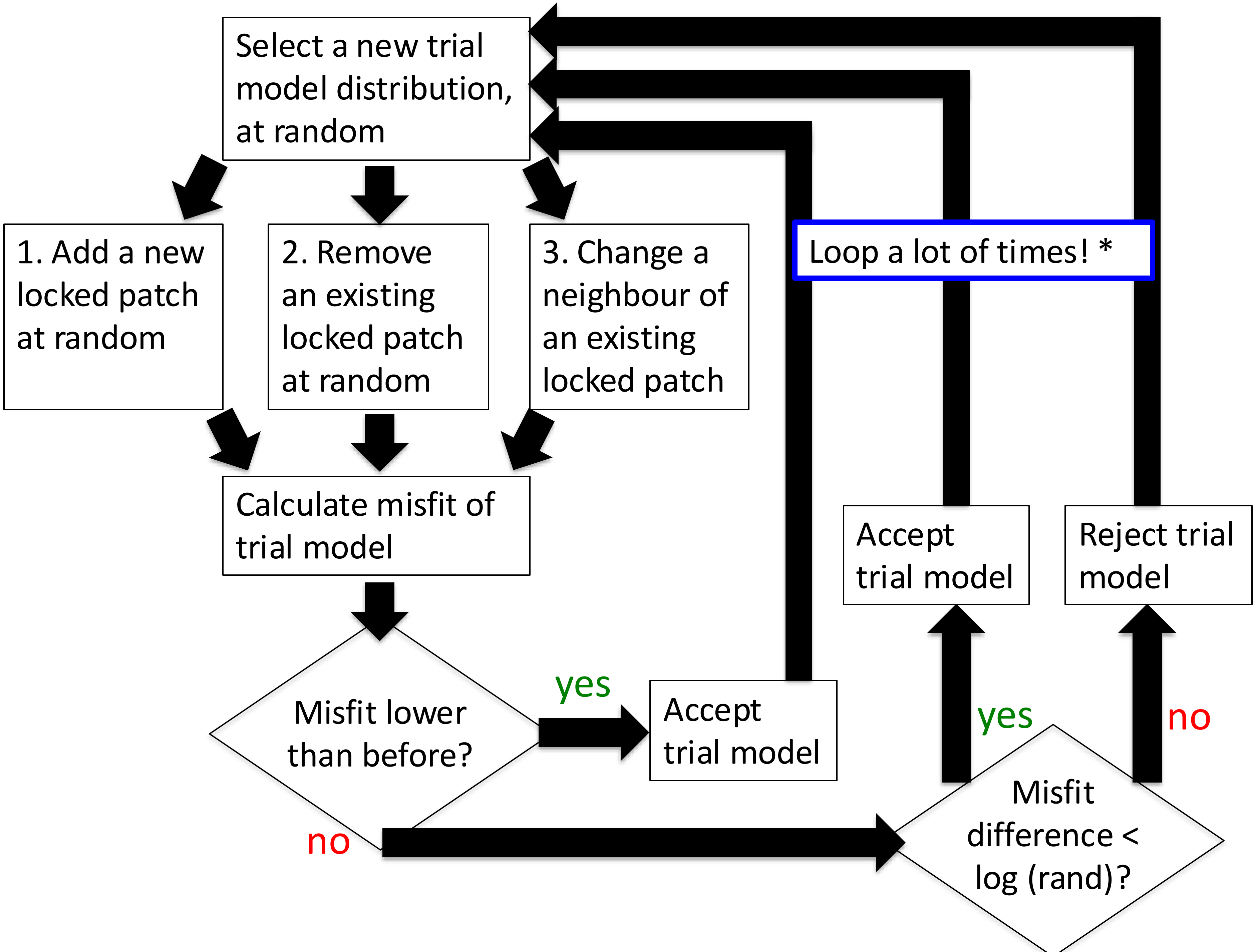


Mechanically coupled, forward model (red=creeping)



- Only a small proportion of fault elements need be fully locked in order to produce low-creep zones
- Can we find an objective way to select which ones?

Bürgmann et al., 2005



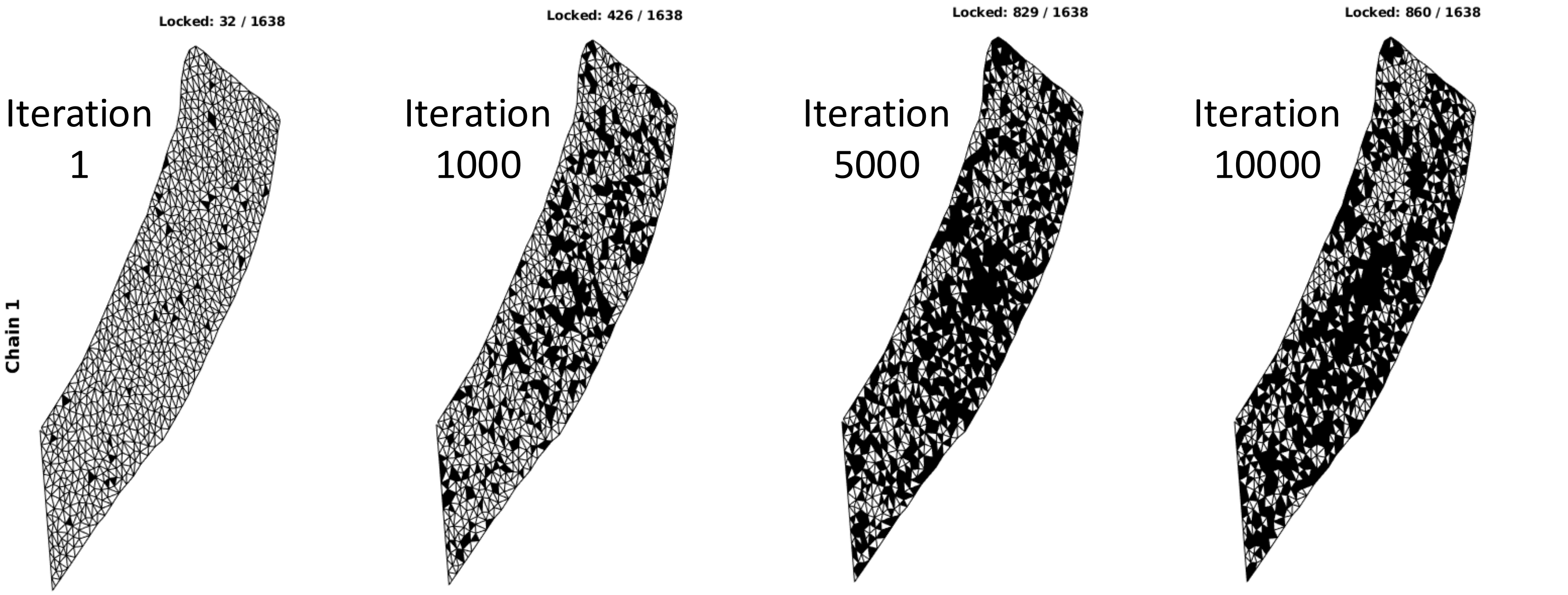
+ Green's functions for estimating surface displacements

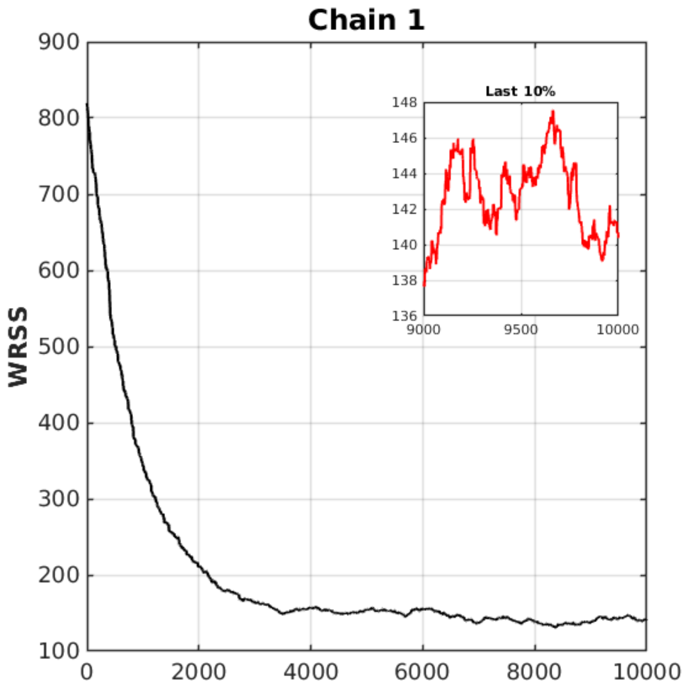
* Can run a few long chains (e.g. 1 million samples each) or many (10^5) short chains

Metropolis et al. (1953)
Hastings (1970)

- tribem boundary element model code (Loveless, 2011) computes slip for a given locking distribution
- ‘locked’ elements backslipped at 80 mm/yr
- Green’s functions (Nikkhoo and Walter, 2015) relate slip to surface velocity

- Mesh of 1638 elements, based on Slab2.0
- Start with 2% of elements locked
- Run 10^6 chains of 10^4 samples each
- Look at the ensemble statistics of all of the chain end-states



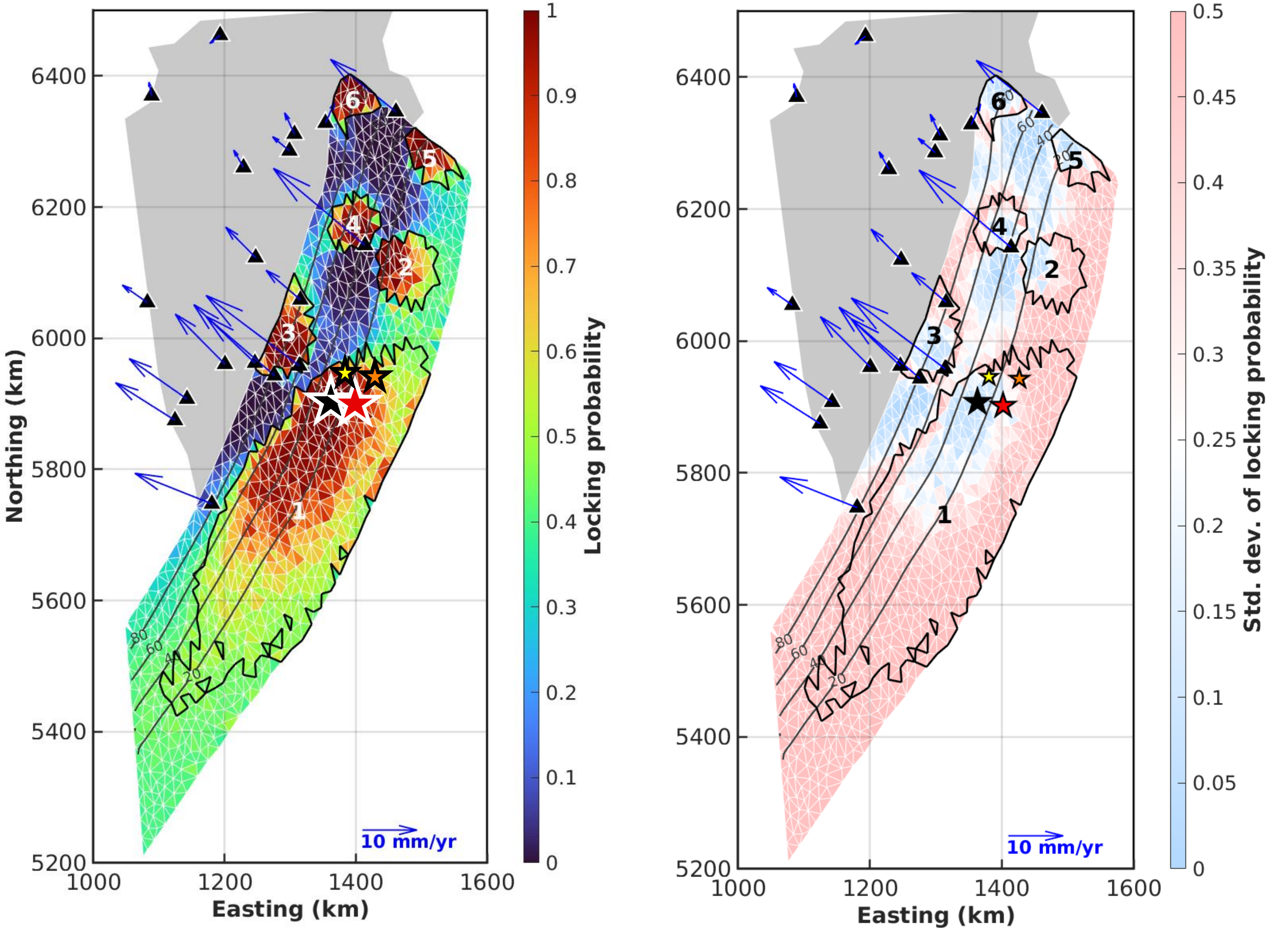


Periollat and Funning, GRL, in press

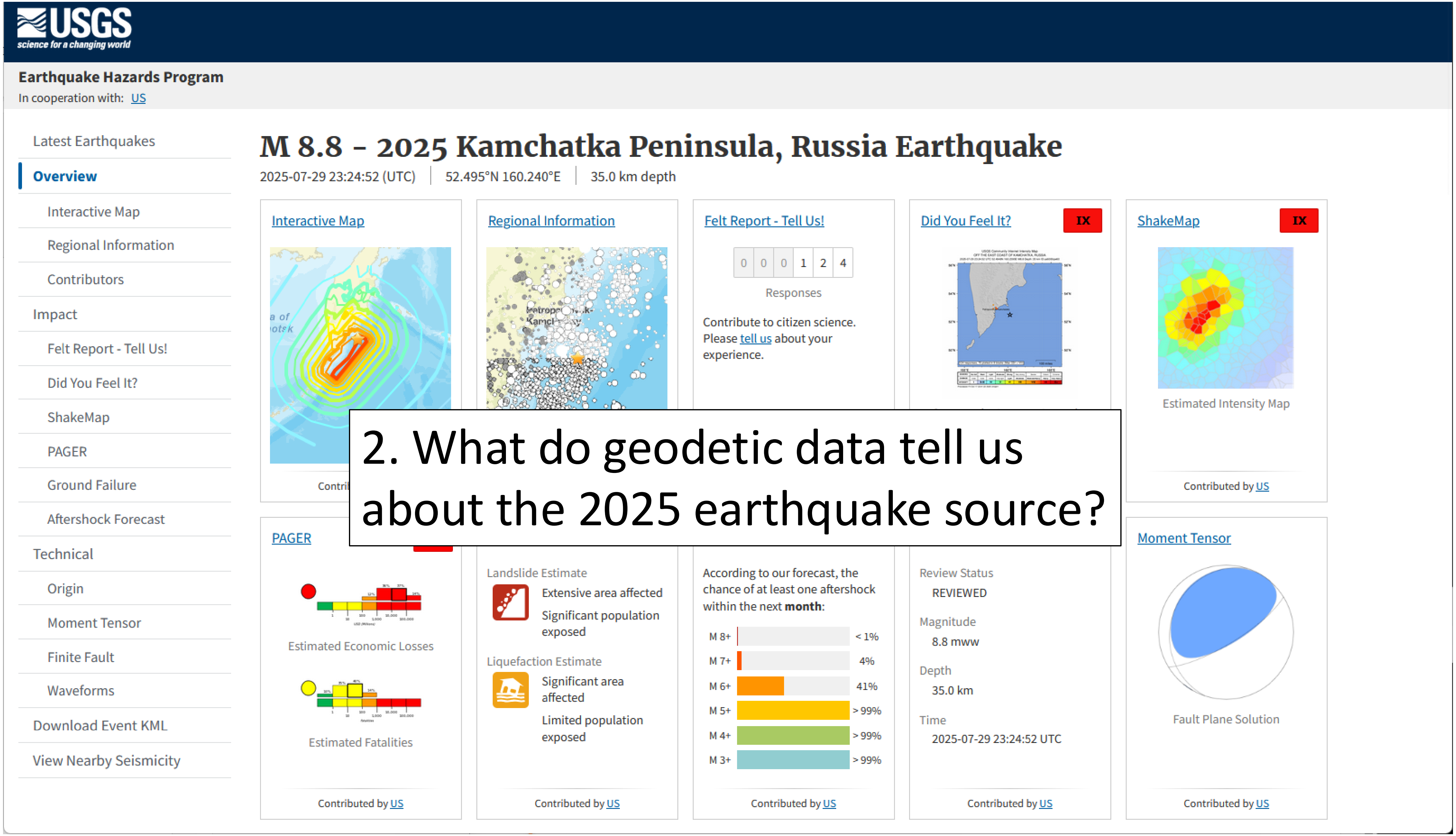
Ensemble results

0.45 threshold (45% or more of models show locking) identifies six candidate locked regions

Cluster 1 is consistent with 1952 and 2025 epicenters



Periollat and Funning, GRL, in press



2. What do geodetic data tell us about the 2025 earthquake source?

USGS science for a changing world

Earthquake Hazards Program

In cooperation with: US

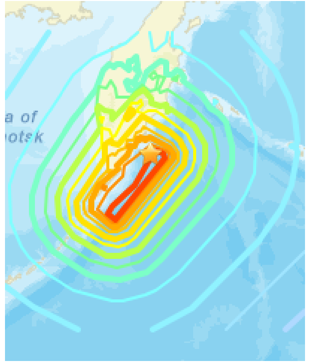
1 day before the AGU abstract deadline!

- Latest Earthquakes
- **Overview**
  - Interactive Map
  - Regional Information
  - Contributors
- Impact
  - Felt Report - Tell Us!
  - Did You Feel It?
  - ShakeMap
  - PAGER
  - Ground Failure
  - Aftershock Forecast
- Technical
  - Origin
  - Moment Tensor
  - Finite Fault
  - Waveforms
- Download Event KML
- View Nearby Seismicity

M 8.8 - 2025 Kamchatka Peninsula, Russia Earthquake

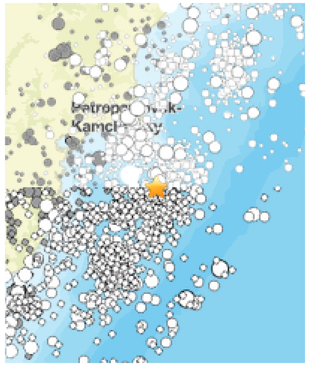
2025-07-29 23:24:52 (UTC) | 52.495°N 160.240°E | 35.0 km depth

Interactive Map



Contributed by US

Regional Information



Contributed by US

Felt Report - Tell Us!

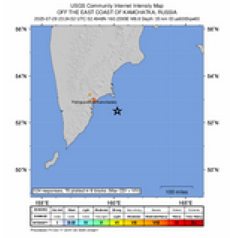
0 0 0 1 2 4

Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

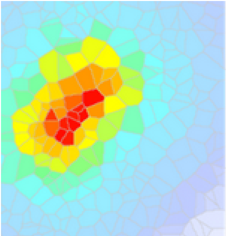
Did You Feel It? IX



Community Internet Intensity Map

Contributed by US

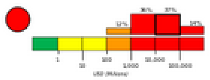
ShakeMap IX



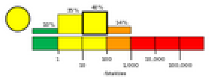
Estimated Intensity Map

Contributed by US

PAGER RED



Estimated Economic Losses



Estimated Fatalities

Contributed by US

Ground Failure

Landslide Estimate

Extensive area affected

Significant population exposed

Liquefaction Estimate

Significant area affected

Limited population exposed

Contributed by US

Aftershock Forecast

According to our forecast, the chance of at least one aftershock within the next **month**:

M 8+	< 1%
M 7+	4%
M 6+	41%
M 5+	> 99%
M 4+	> 99%
M 3+	> 99%

Contributed by US

Origin

Review Status

REVIEWED

Magnitude

8.8 mww

Depth

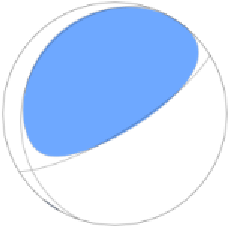
35.0 km

Time

2025-07-29 23:24:52 UTC

Contributed by US

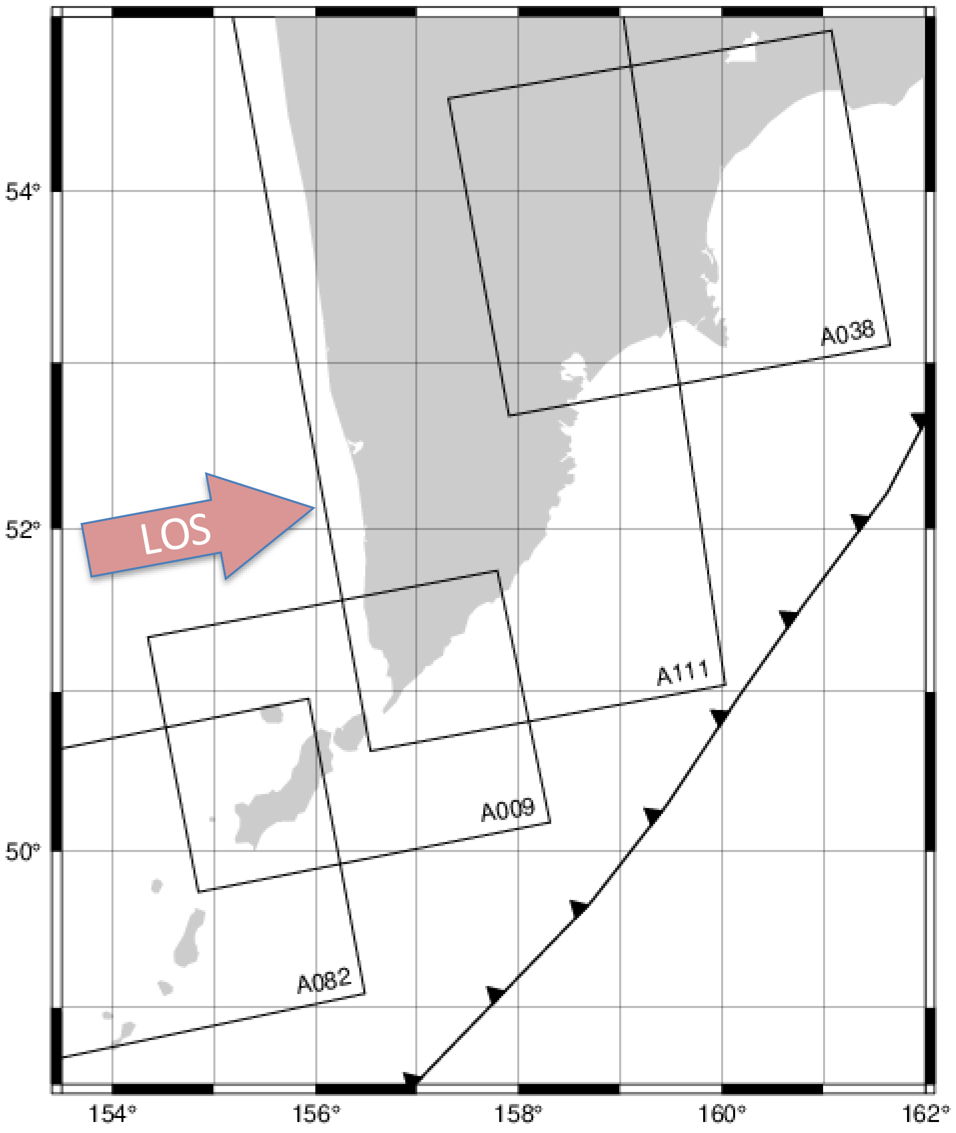
Moment Tensor



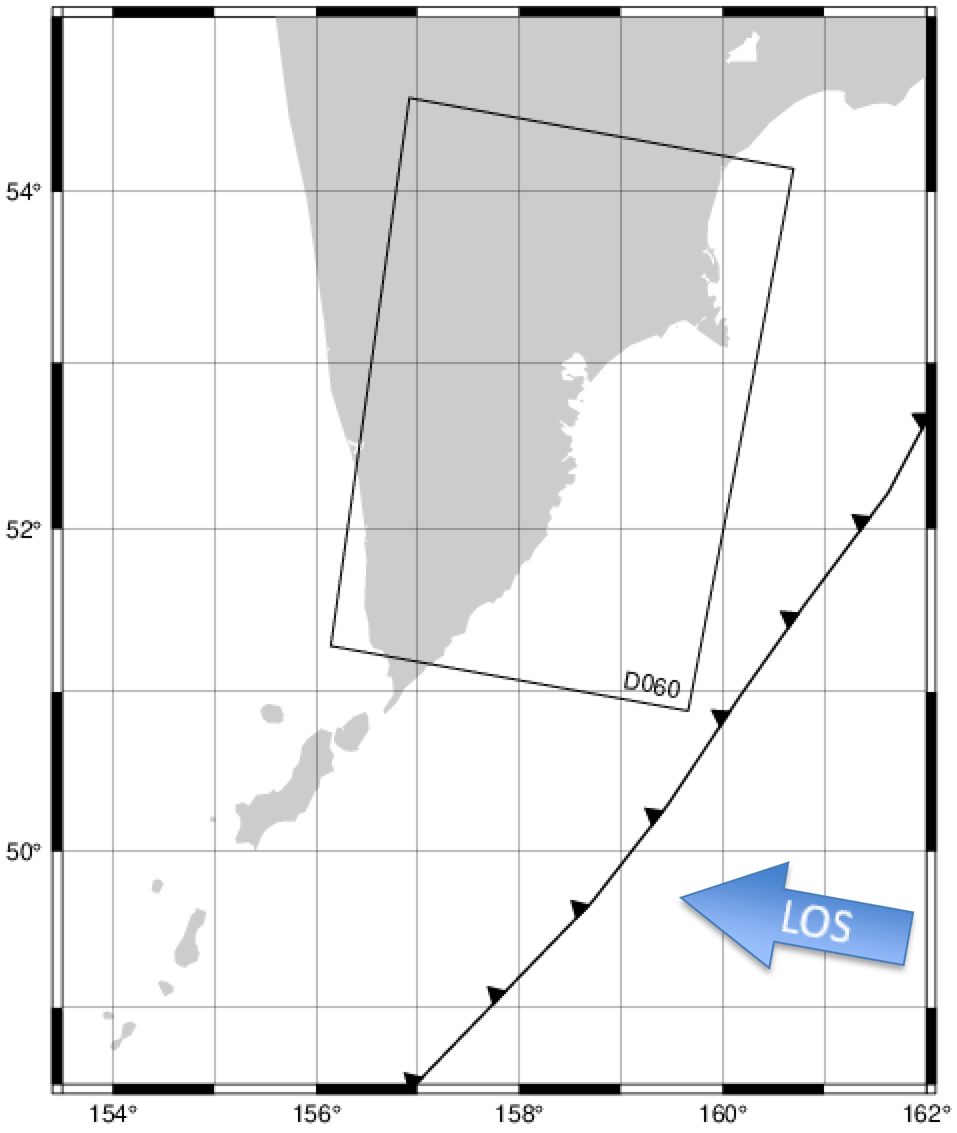
Fault Plane Solution

Contributed by US

Ascending

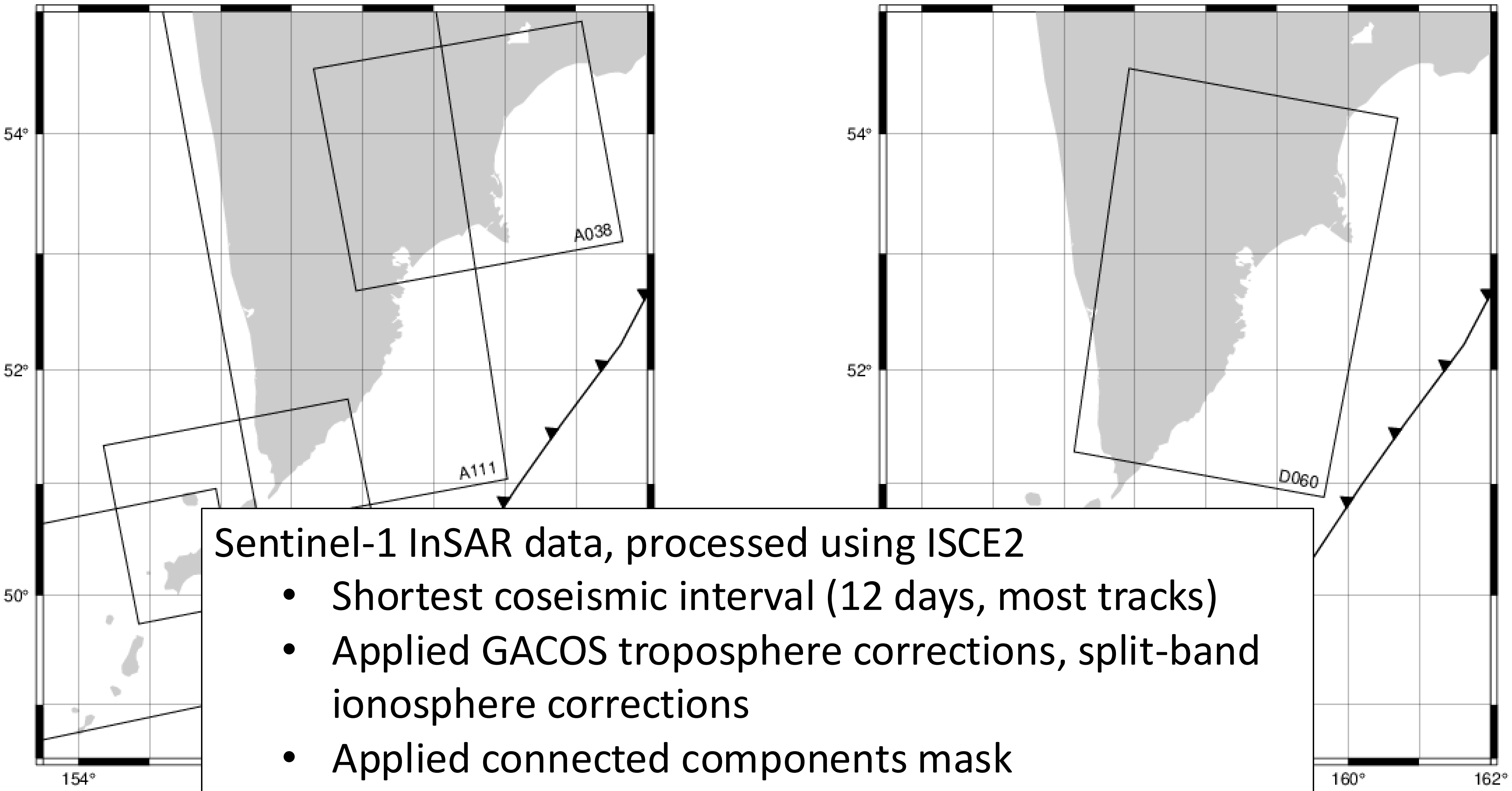


Descending



Ascending

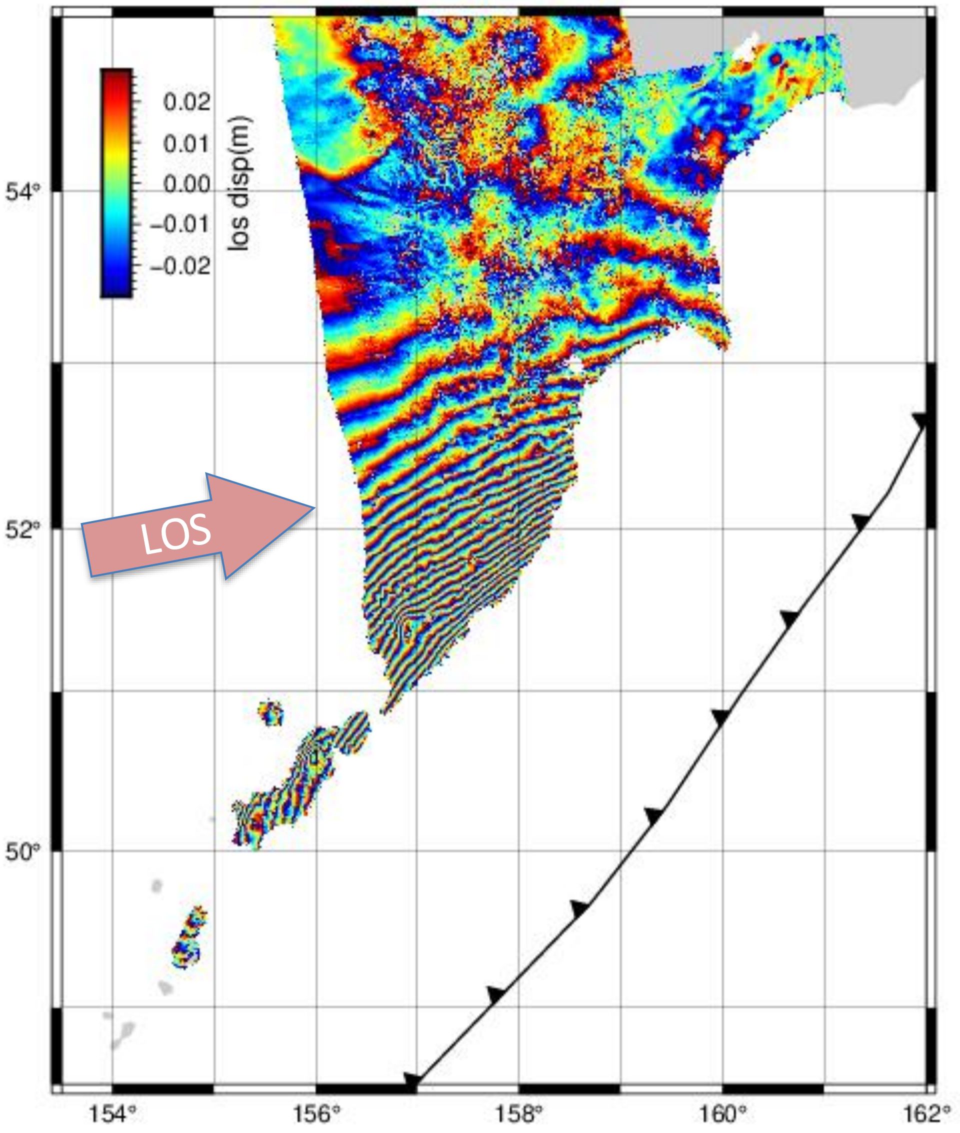
Descending



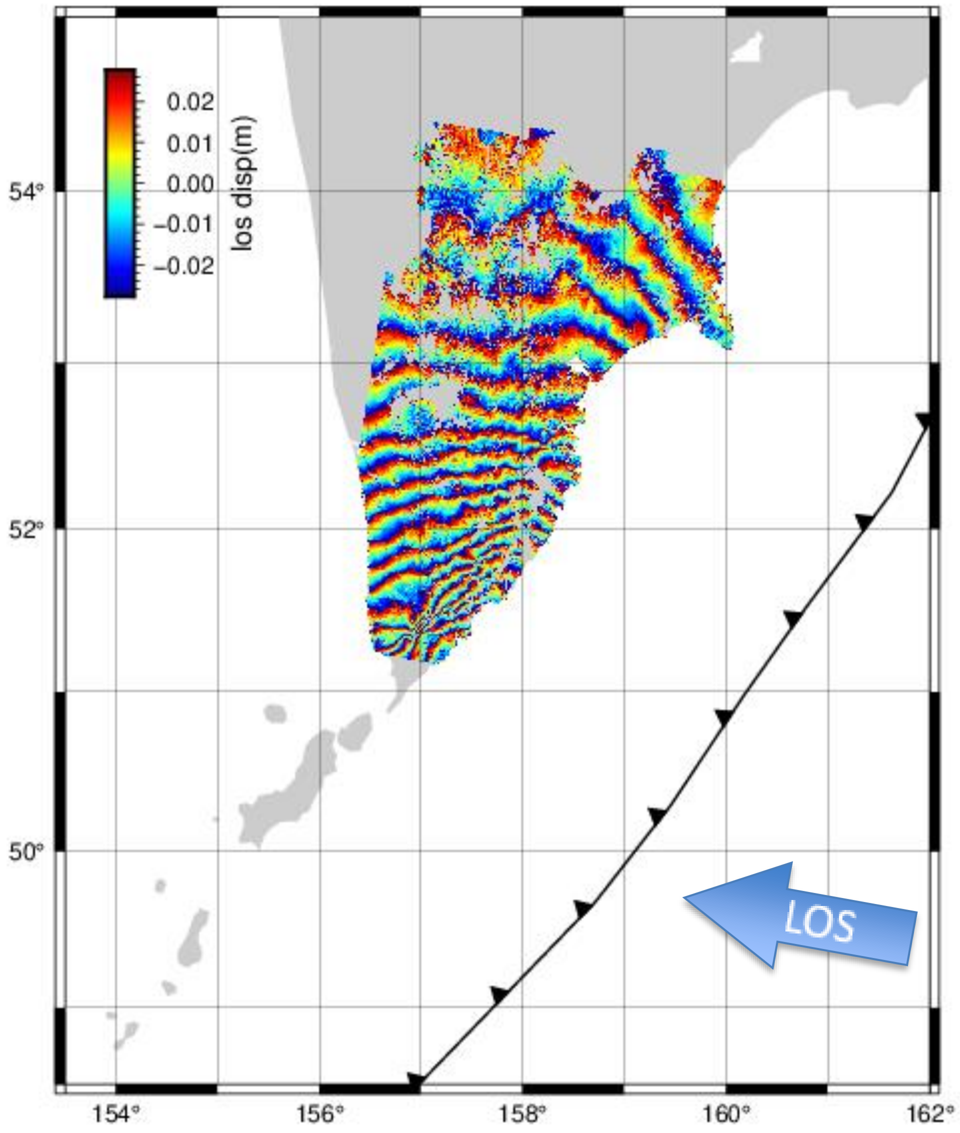
Sentinel-1 InSAR data, processed using ISCE2

- Shortest coseismic interval (12 days, most tracks)
- Applied GACOS troposphere corrections, split-band ionosphere corrections
- Applied connected components mask
- Downsampled with a quadtree decomposition

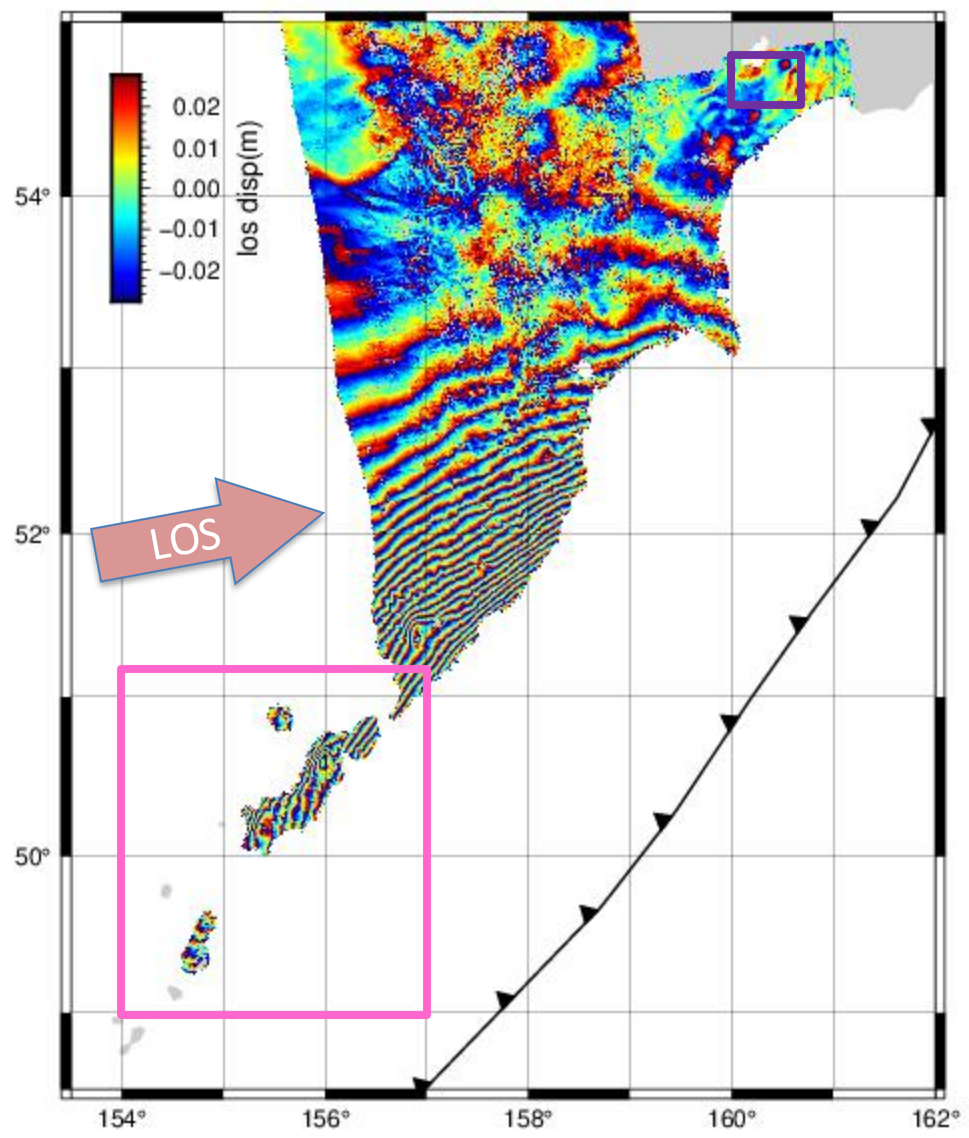
Ascending

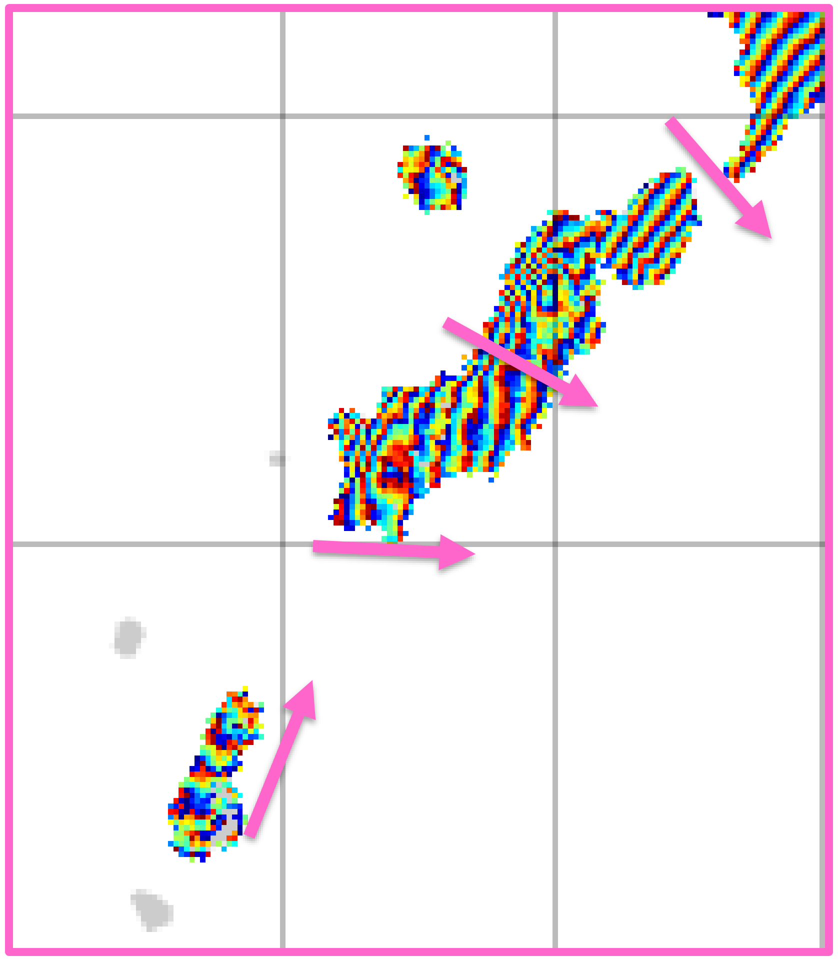


Descending

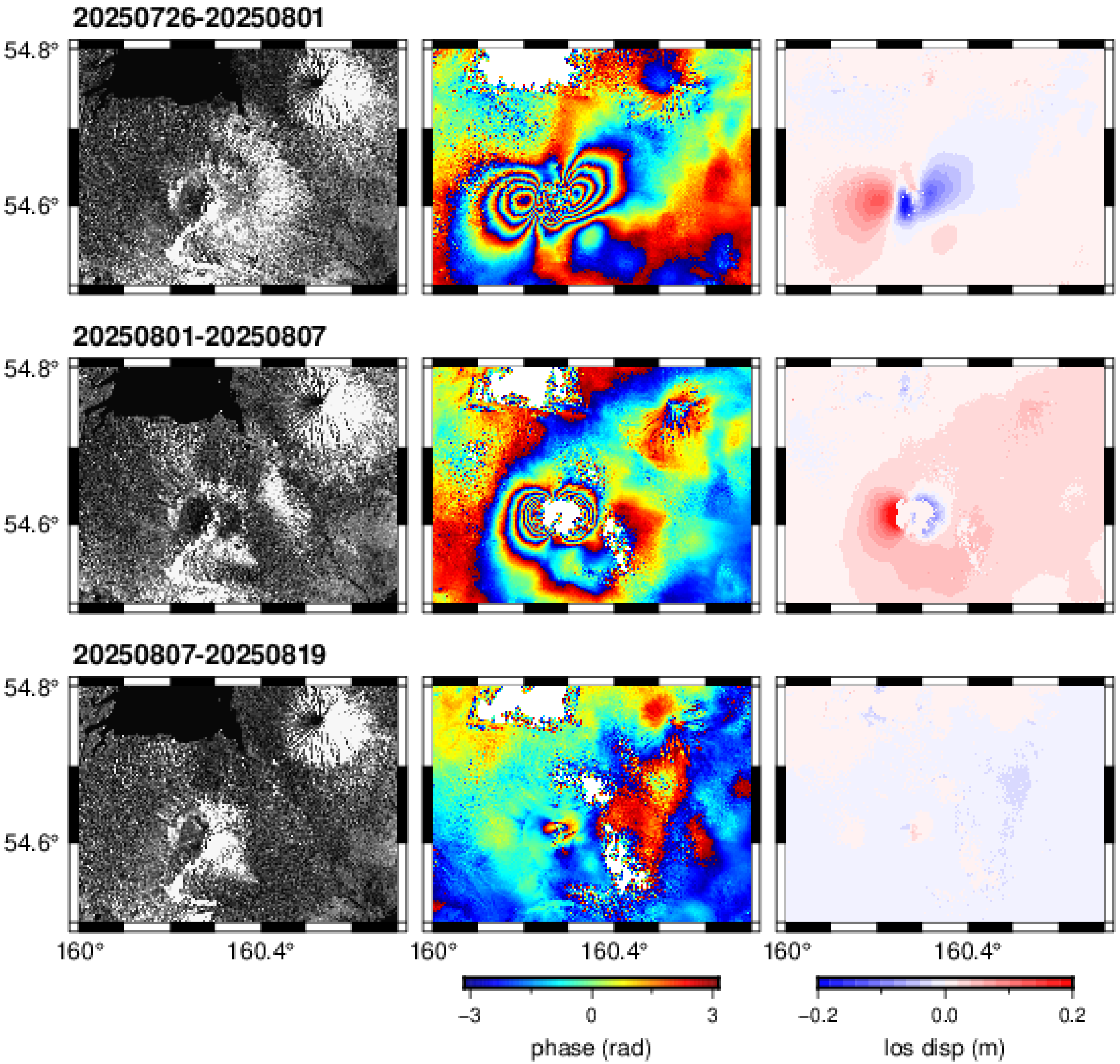


Ascending





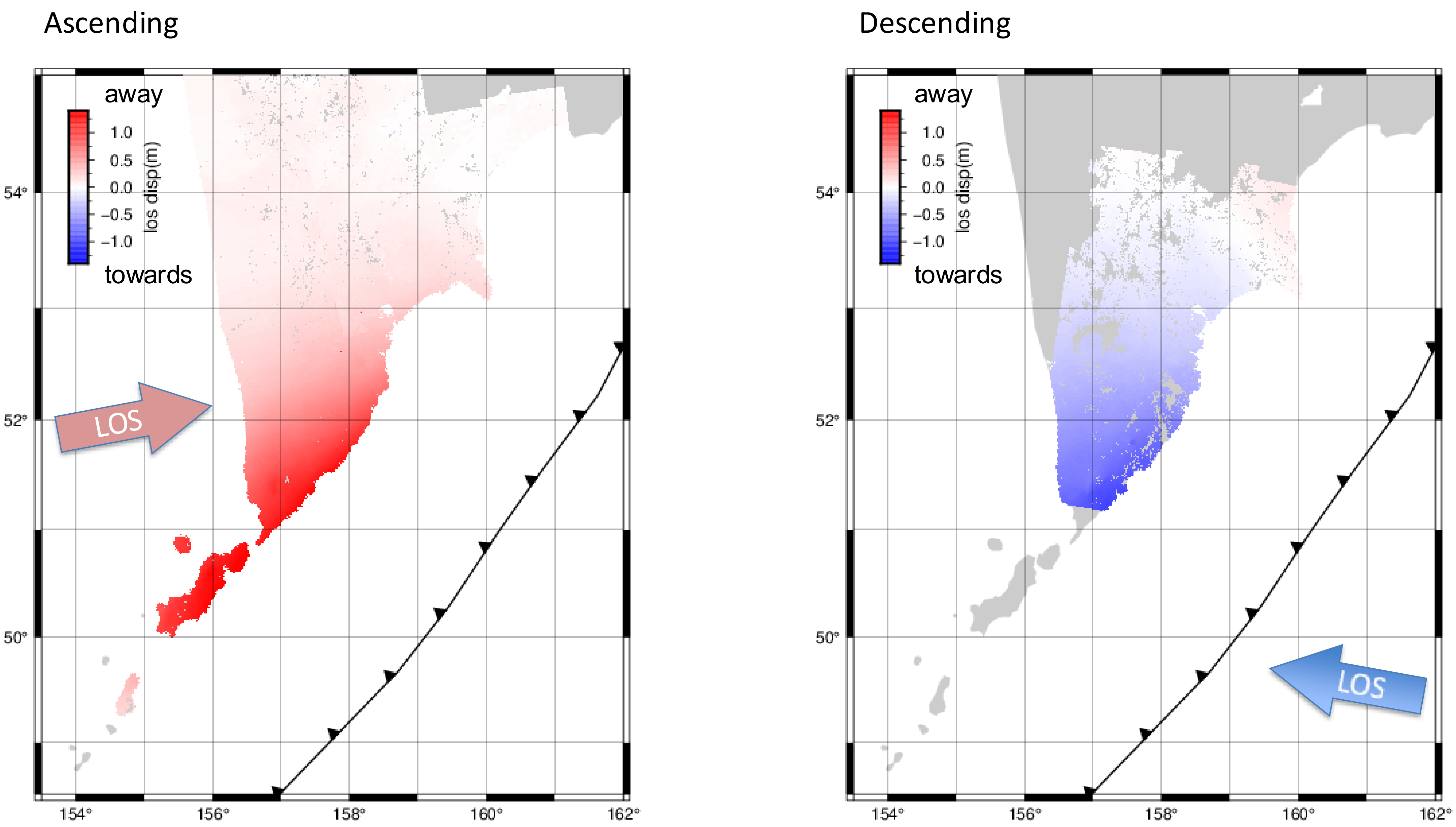
Direction of maximum phase gradient rotates counter-clockwise to the SW



Sentinel-1 D162

Coseismic interferogram shows dyke intrusion at Krasheninnikov Volcano up to 1 day before eruption was observed!

See poster by Weber et al. today!


Ascending
Descending
away
towards
los disp(m)
1.0
0.5
0.0
−0.5
−1.0
LOS
54°
52°
50°
154°
156°
158°
160°
162°

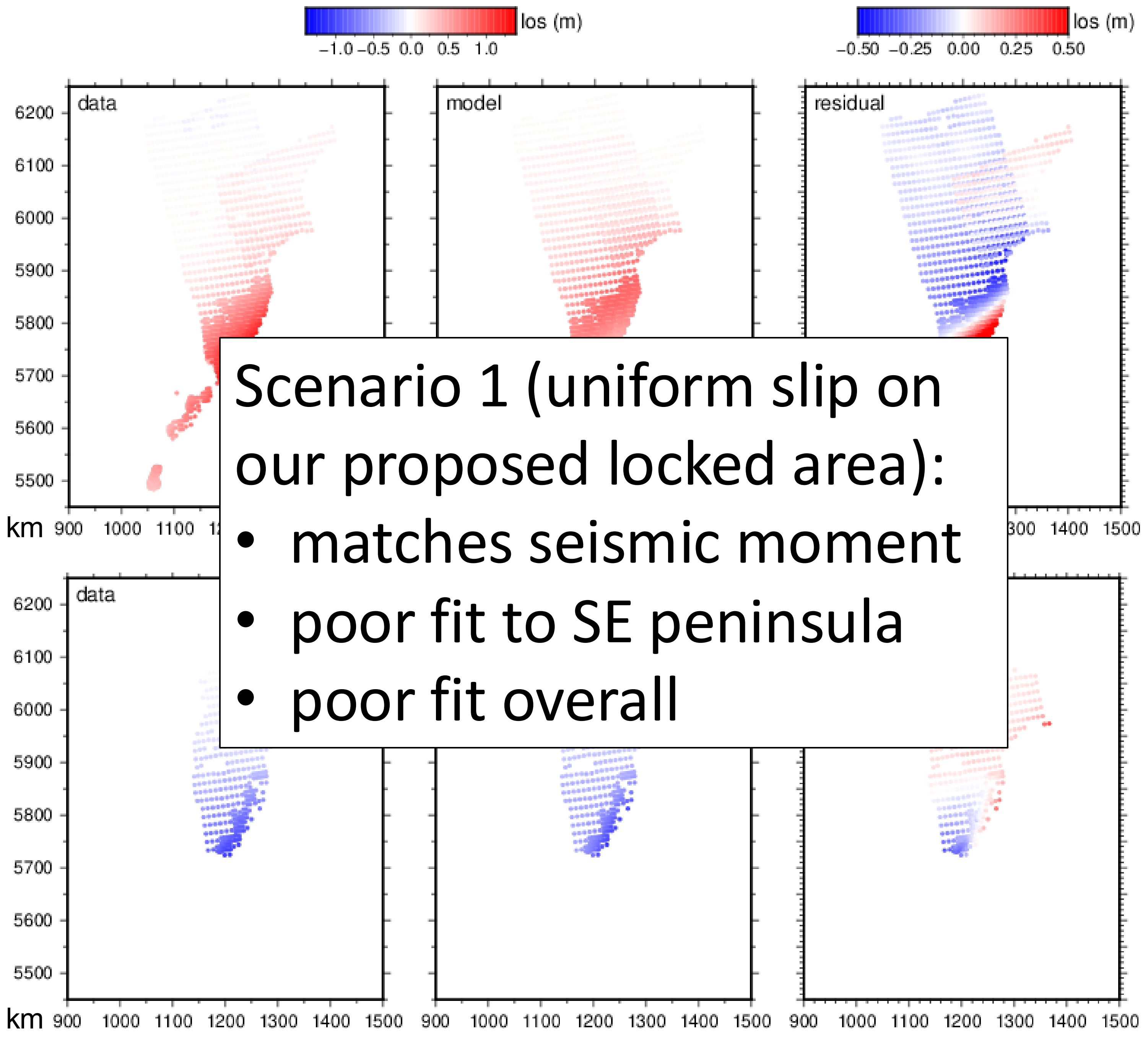
Modeling the 2025 earthquake

- Same triangular element mesh (based on Slab2.0)
- Displacement Green's functions computed using code of Nikkhoo and Walter
- (where appropriate) Laplacian smoothing constraint, selected using L-curve method
- Least squares inversion, no positivity constraints
- Rake fixed to plate motion direction

Scenario 1: Uniform slip within the interseismic locked zone we identified

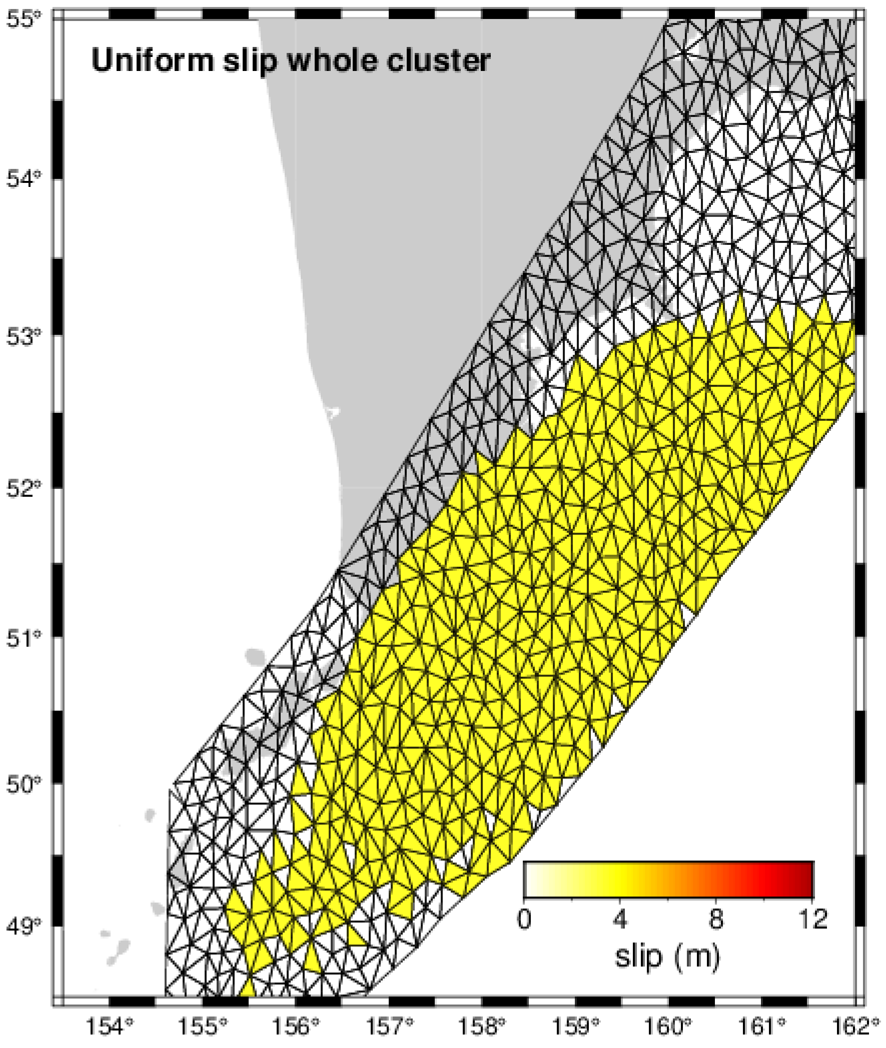
Scenario 2: Variable slip within the interseismic locked zone we identified

Scenario 3: Model slip on the whole megathrust ("unconfined")

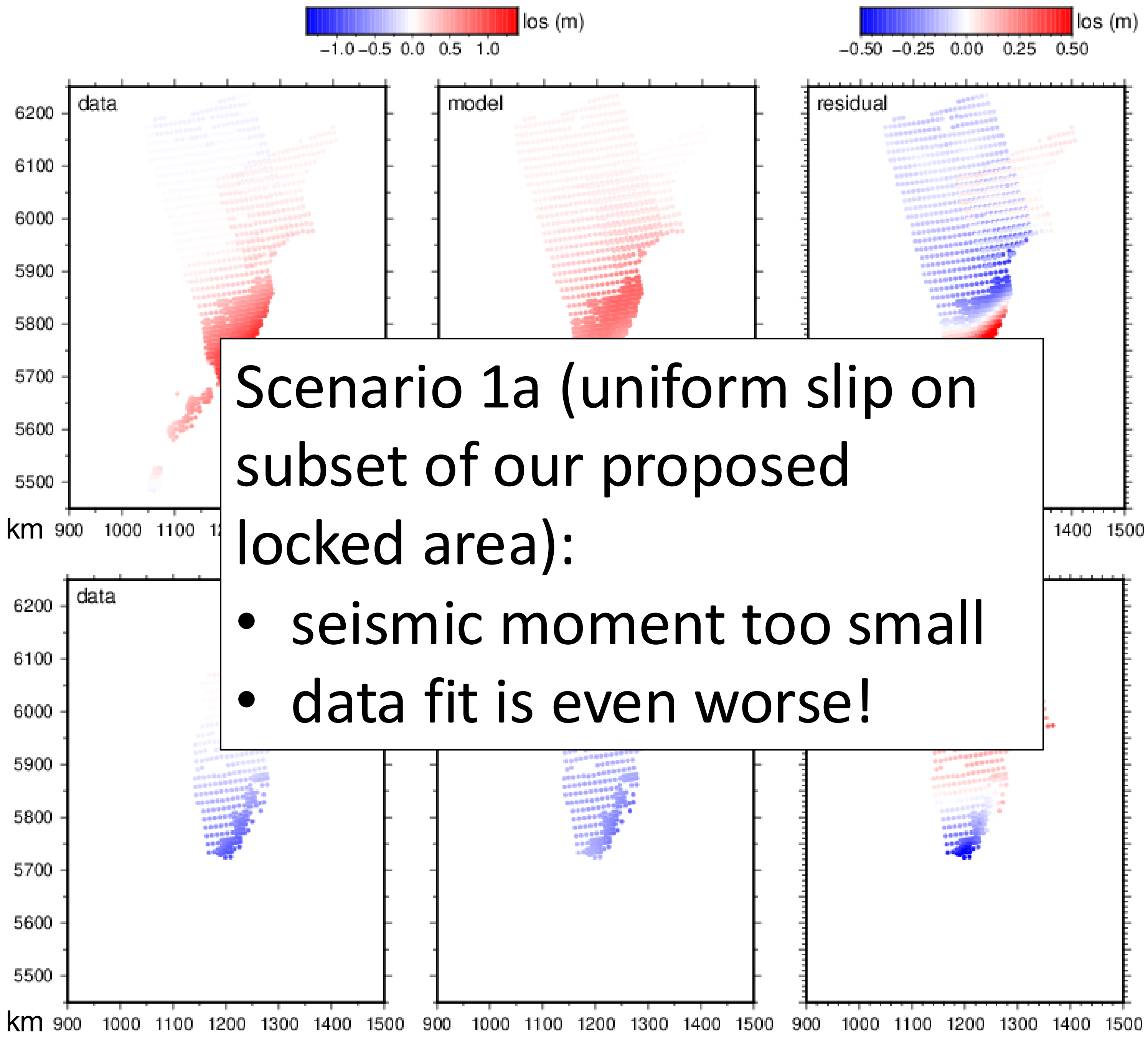


Scenario 1 (uniform slip on our proposed locked area):

- matches seismic moment
- poor fit to SE peninsula
- poor fit overall

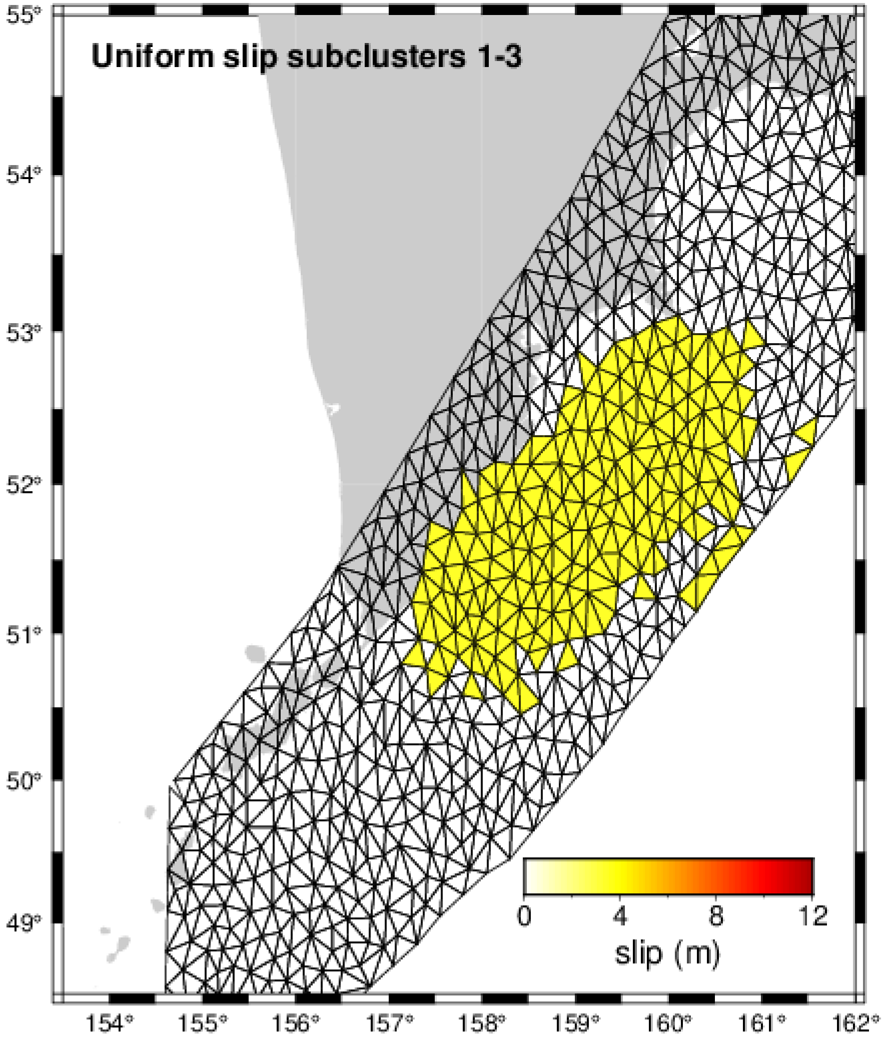


$M_0 = 1.76 \times 10^{22}$ Nm (M_w 8.80)
max slip = 3.4 m, rms = 0.23 m



Scenario 1a (uniform slip on subset of our proposed locked area):

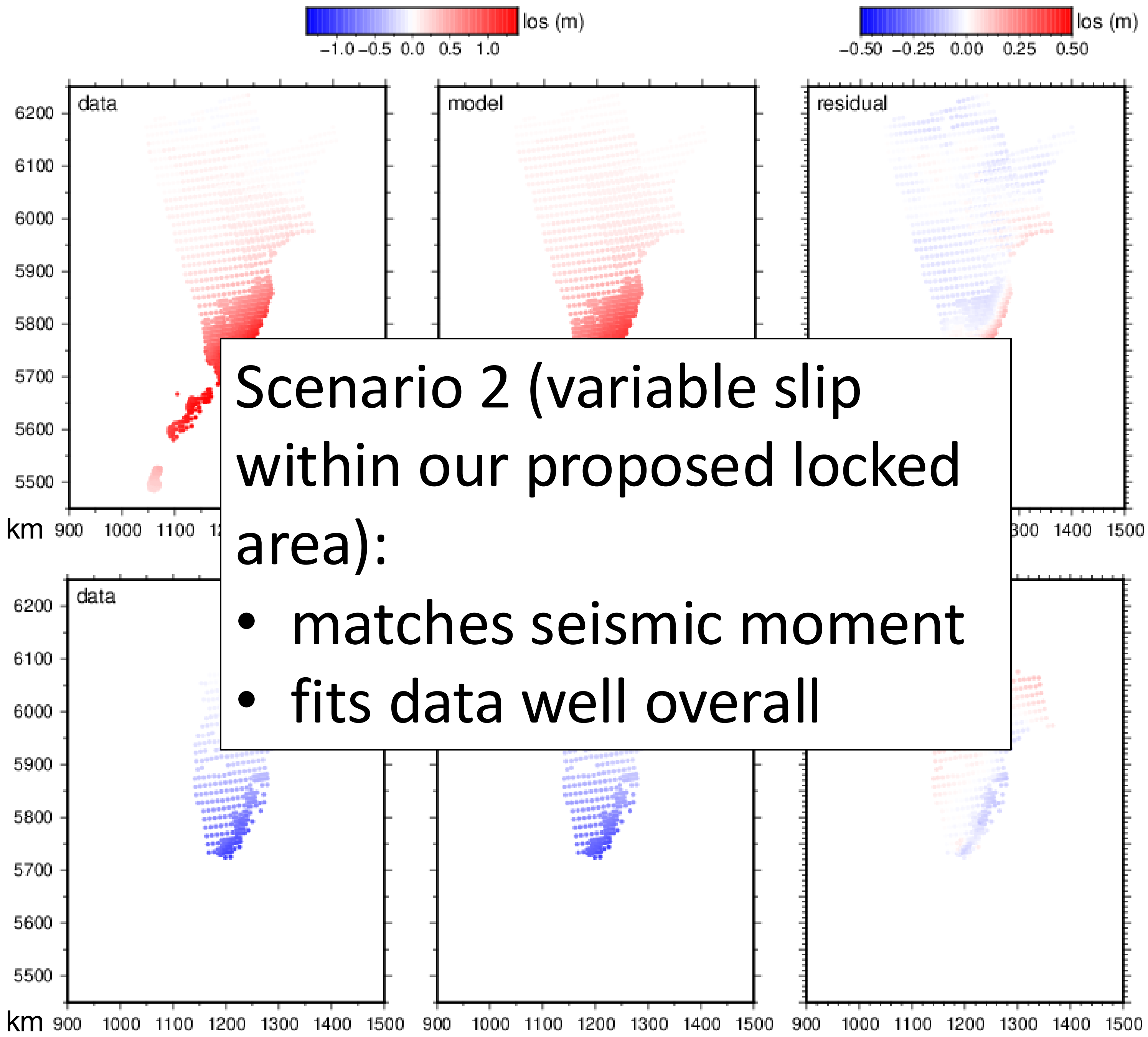
- seismic moment too small
- data fit is even worse!

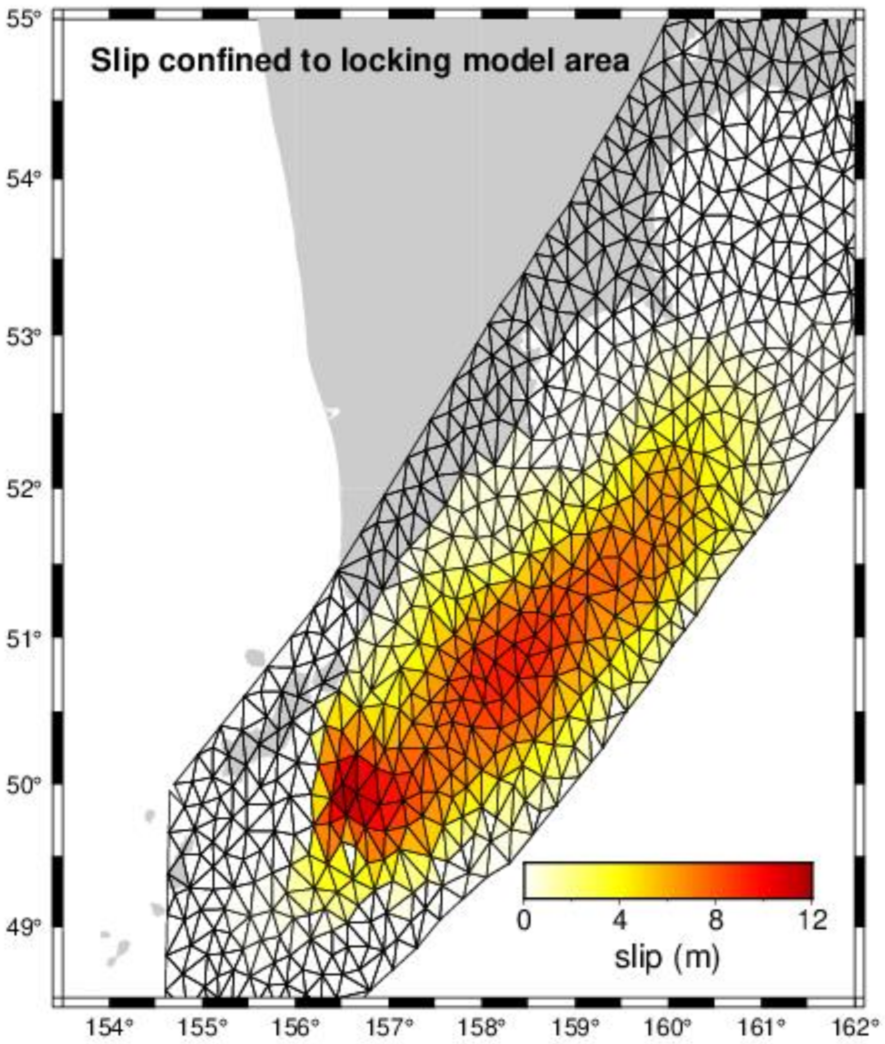


$M_0 = 7.42 \times 10^{21}$ Nm (M_w 8.55)
max slip = 3.4 m, rms = 0.24 m

Scenario 2 (variable slip within our proposed locked area):

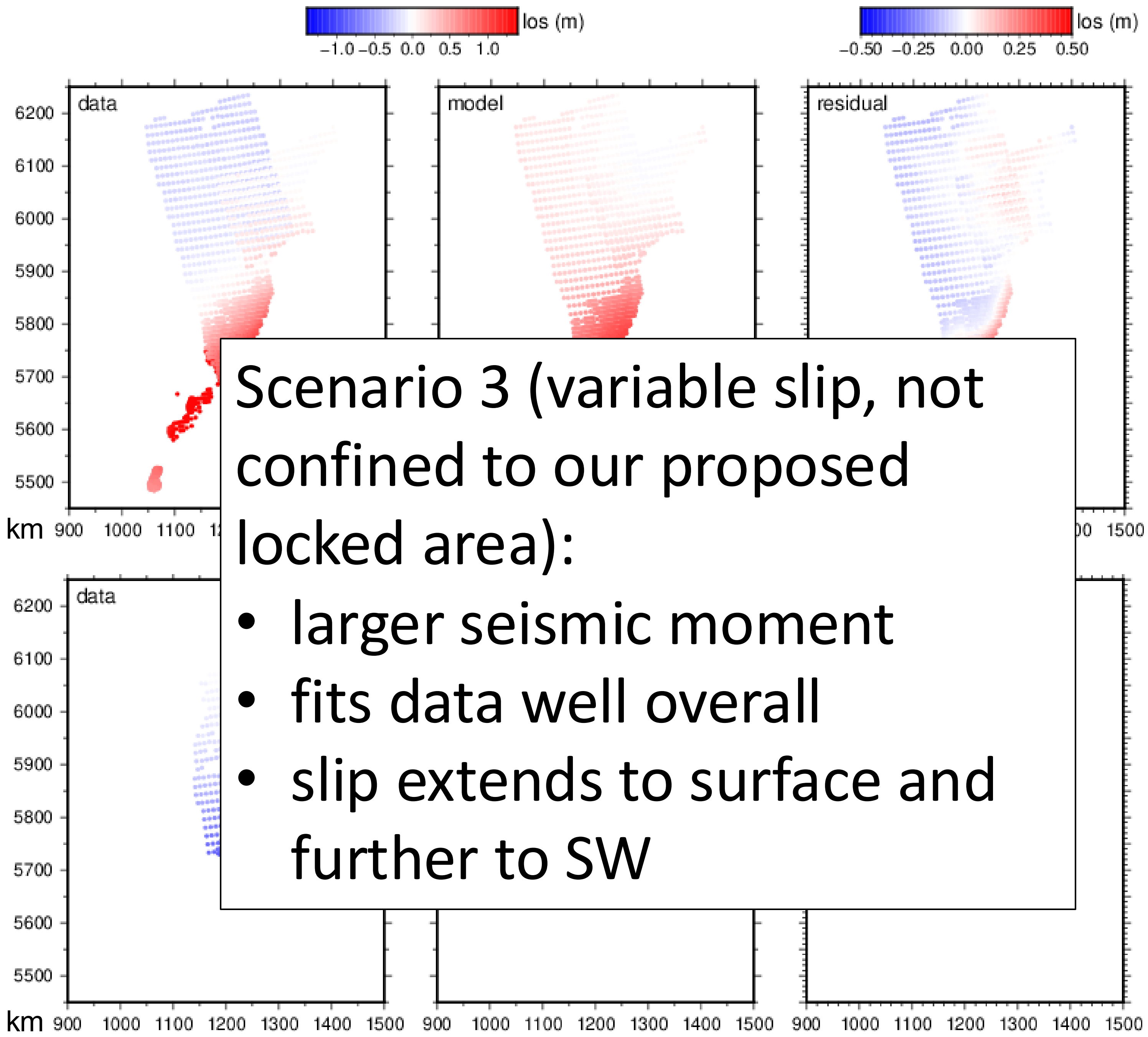
- matches seismic moment
- fits data well overall





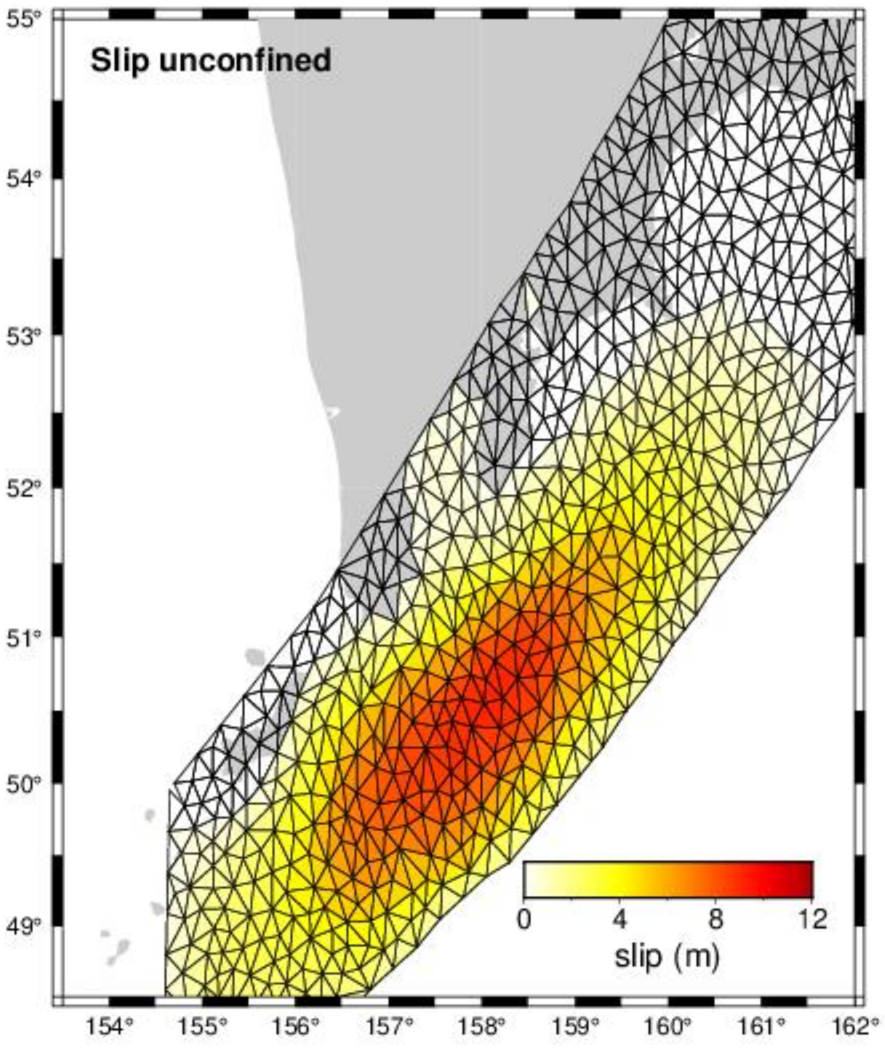
$M_0 = 1.85 \times 10^{22}$ Nm (M_w 8.82)

max slip = 11.9 m, rms = 0.027 m



Scenario 3 (variable slip, not confined to our proposed locked area):

- larger seismic moment
- fits data well overall
- slip extends to surface and further to SW

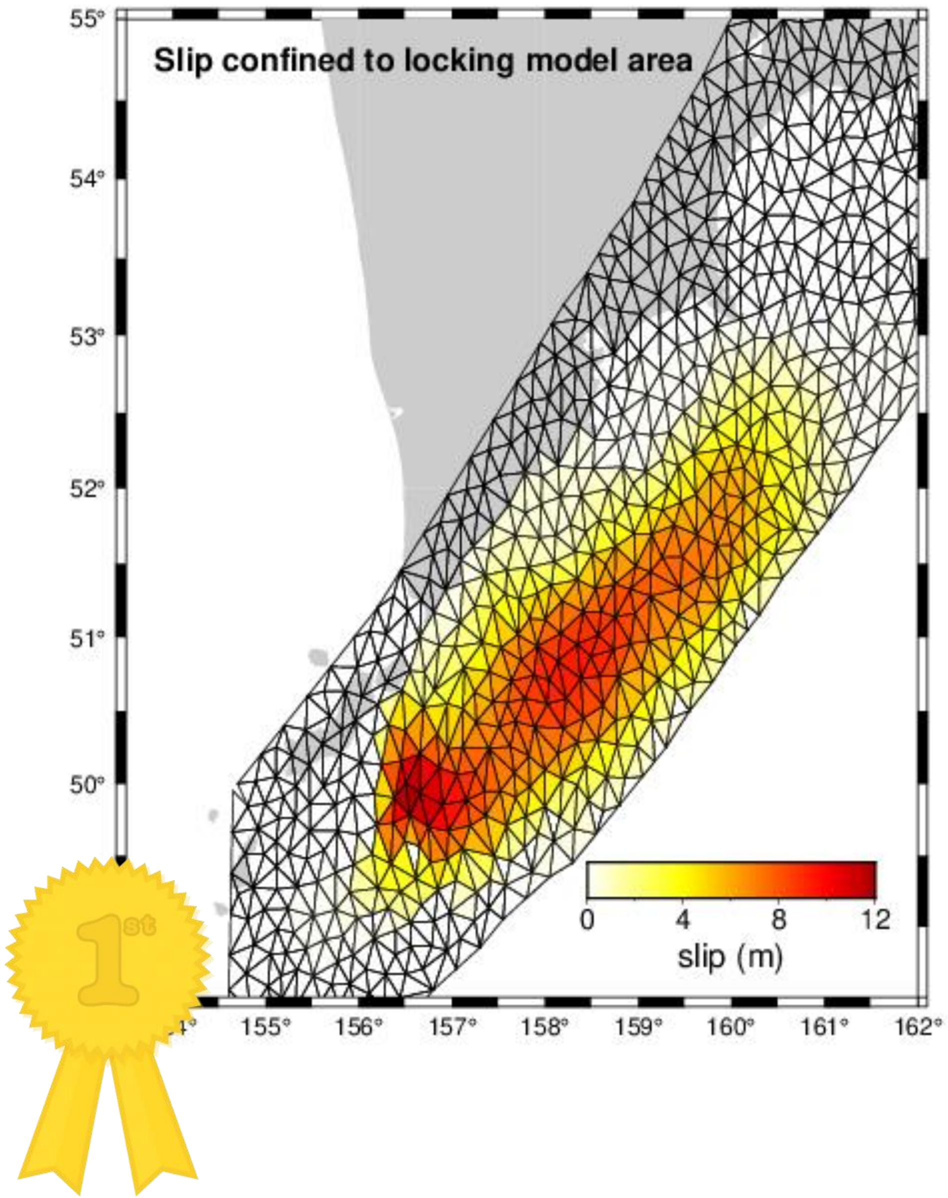


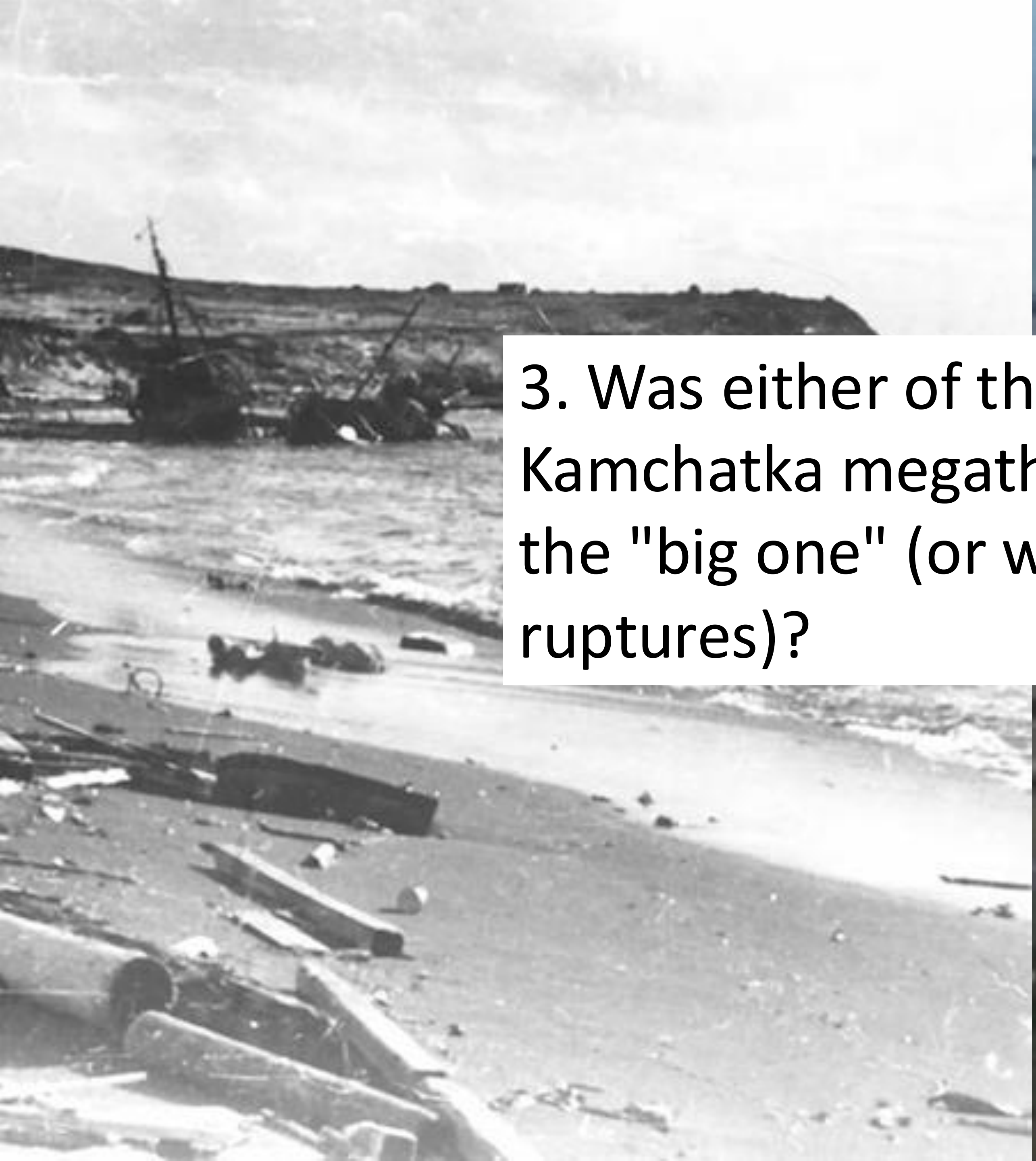
M_0 = 2.32 × 10^{22} Nm (M_w 8.88)
max slip = 9.1 m, rms = 0.023 m

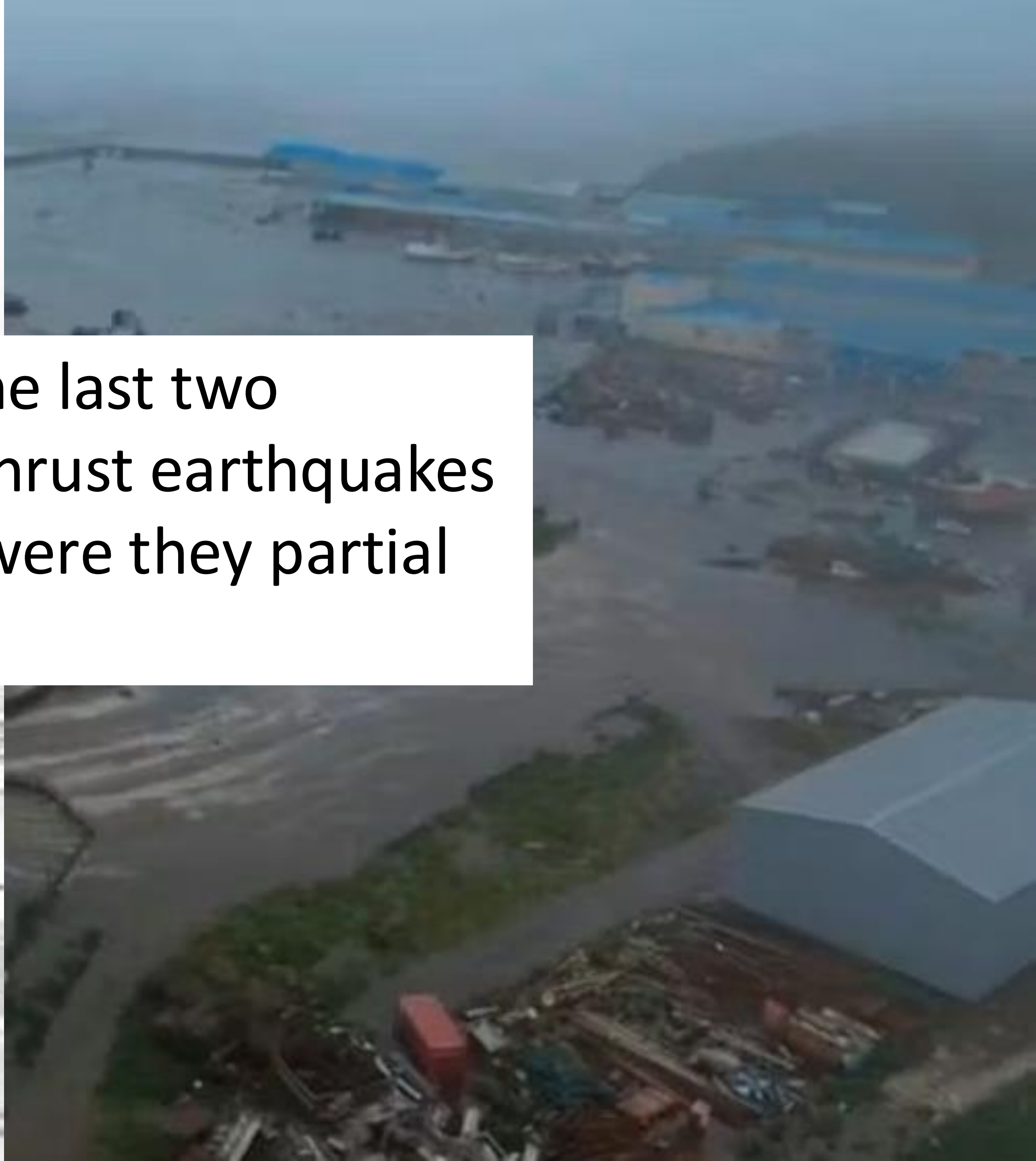
Which model do I prefer?

I prefer scenario 2! Why?

- Consistent with interseismic locking and coseismic deformation
- Fit to data is good (not the best, but more than acceptable)
- Limited slip towards the trench, could explain modest tsunami



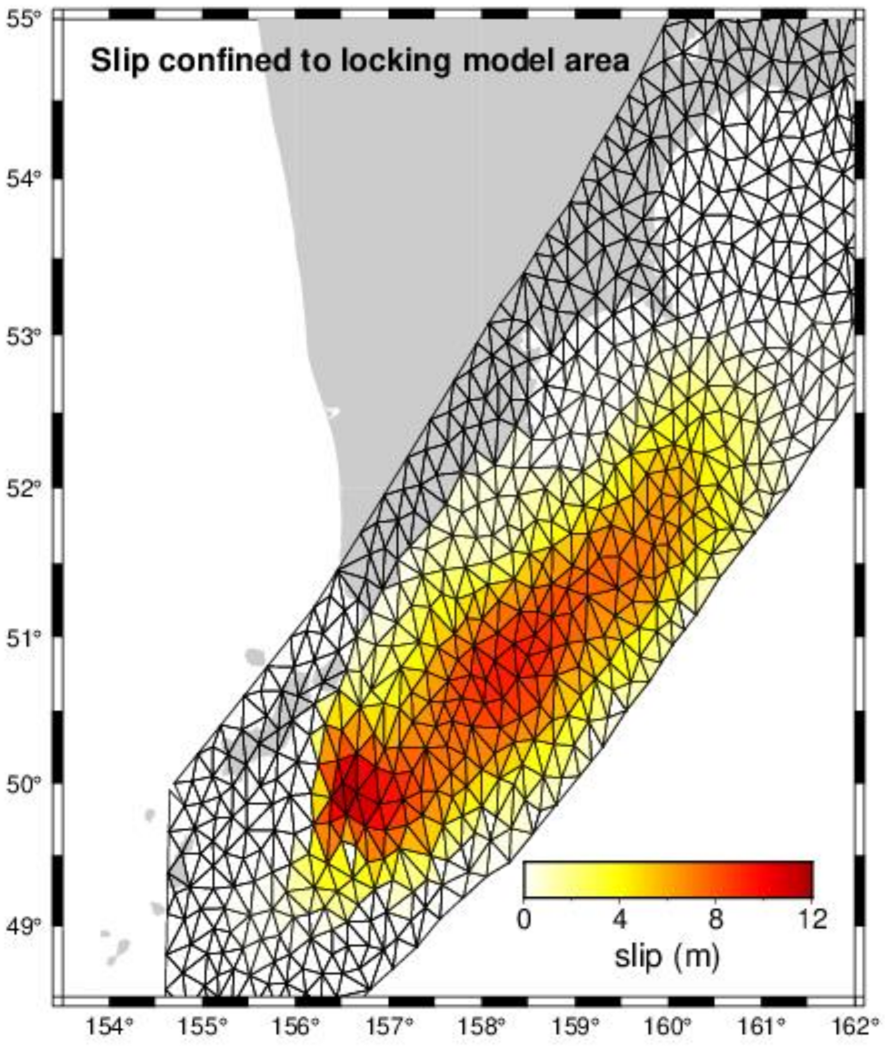




3. Was either of the last two Kamchatka megathrust earthquakes the "big one" (or were they partial ruptures)?

InSAR-based models imply larger slip than the slip deficit!

~12 m of peak slip in our preferred model is more than double the expected slip deficit that would have accumulated between 1952 and 2025 (~5.8 m)

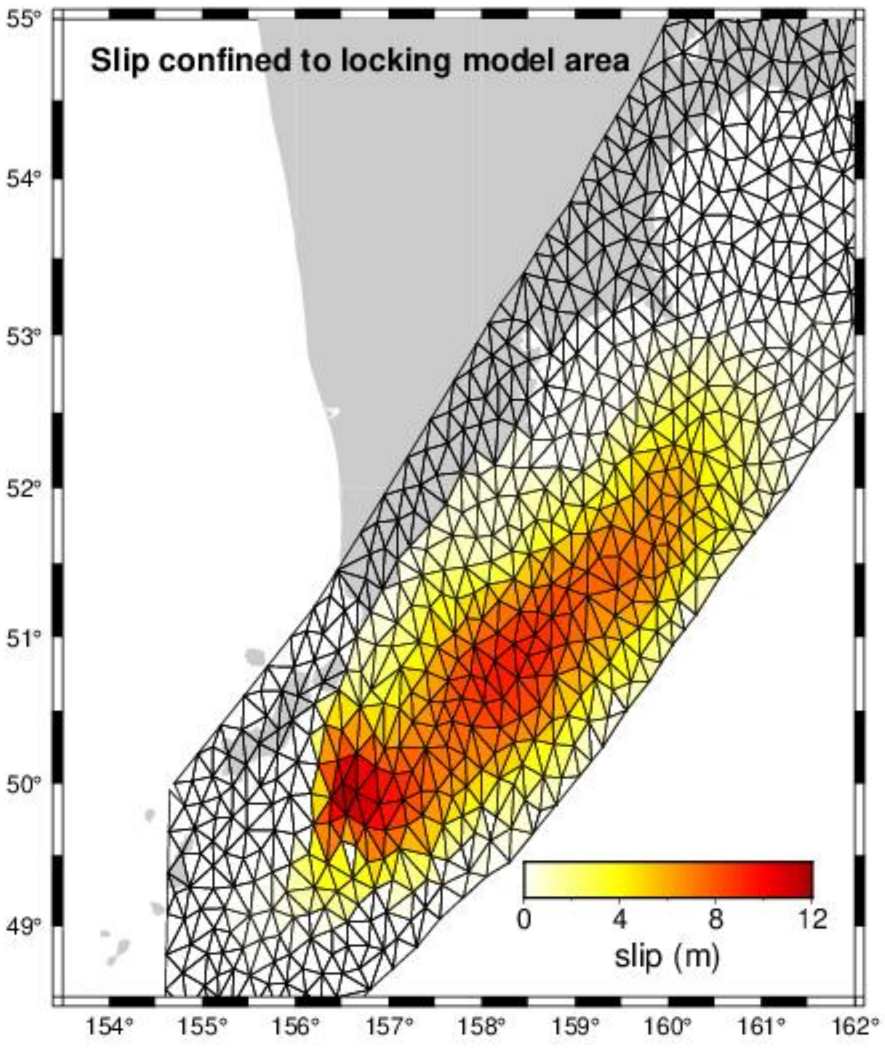


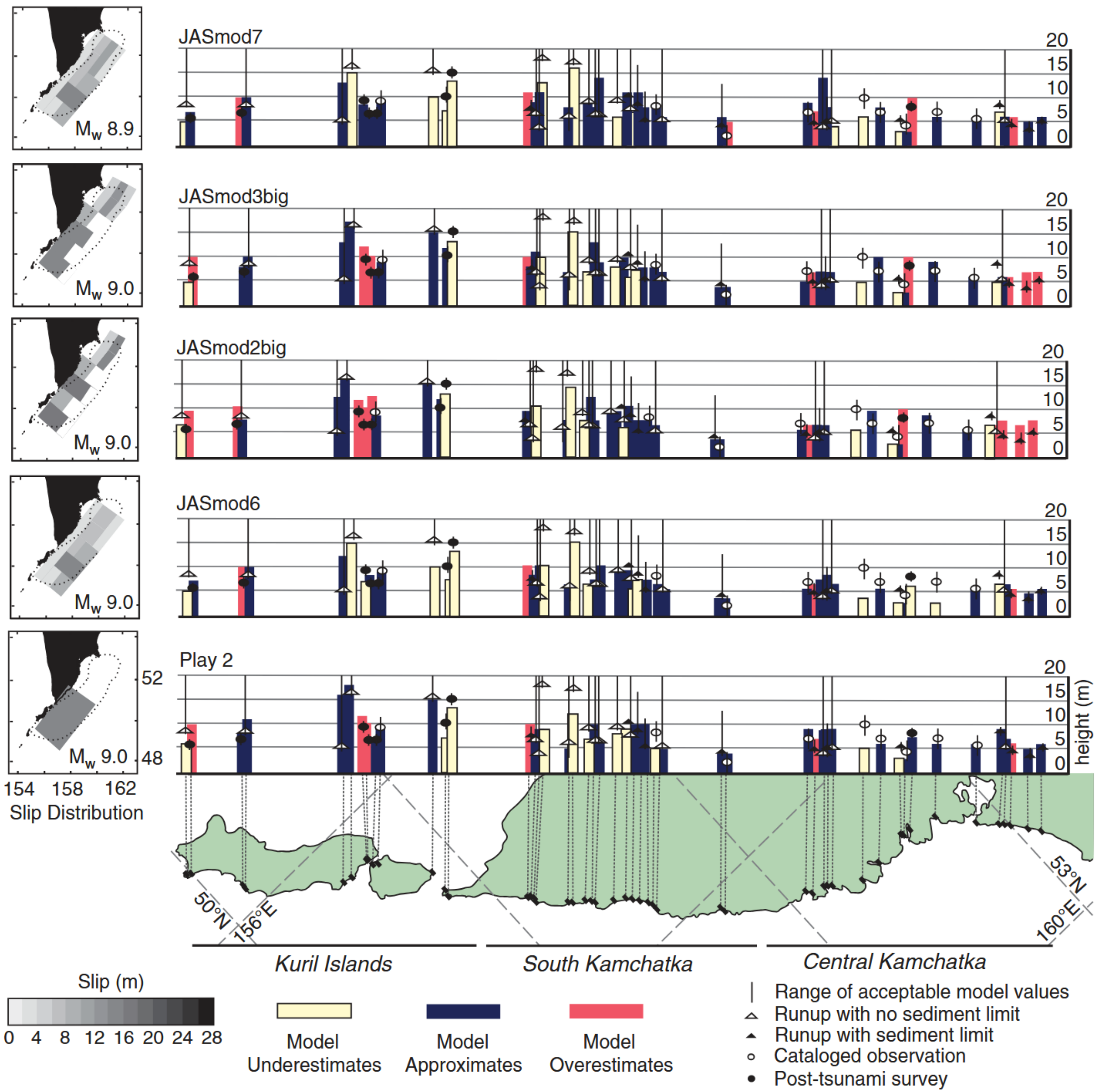
InSAR-based models imply larger slip than the slip deficit!

~12 m of peak slip in our preferred model is more than double the expected slip deficit that would have accumulated between 1952 and 2025 (~5.8 m)

What could potentially explain that?

- Rapid postseismic relocking (it would have to be very rapid, potentially observable post-2025)
- Unreleased slip deficit from before the 1952 event released in 2025



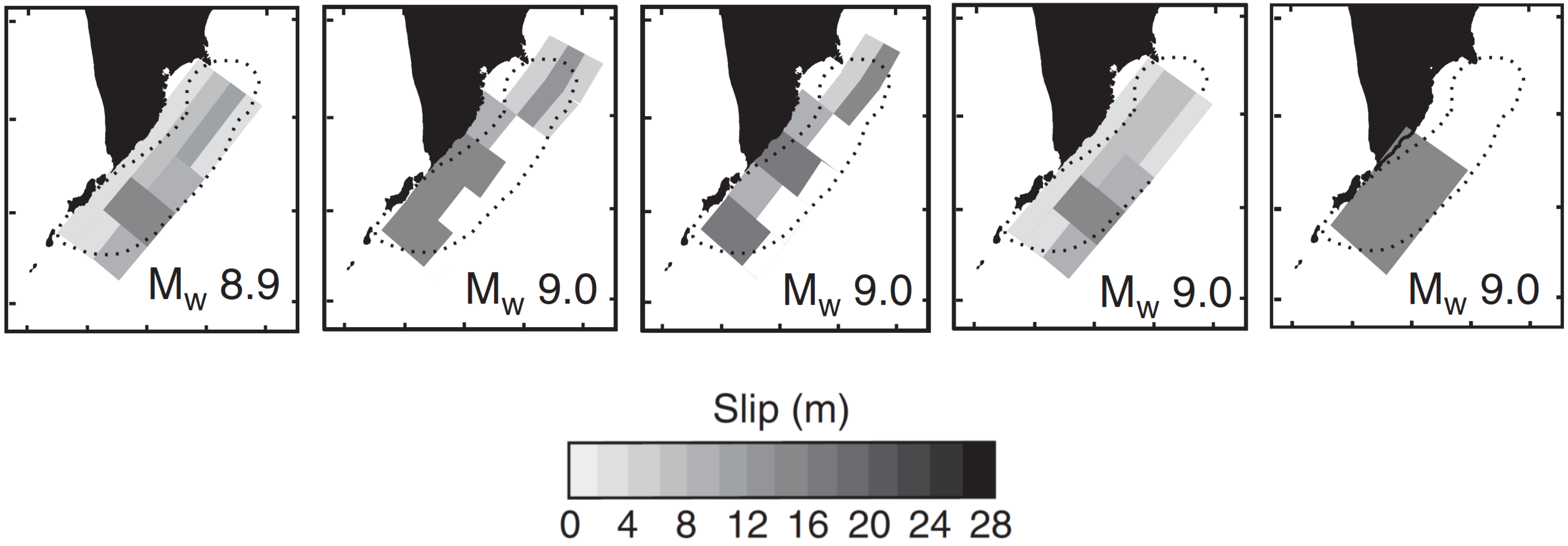


MacInnes et al. (2010) identified five slip scenarios that fit tsunami runup data somewhat well

MacInnes et al., 2010

Well-fitting models for 1952 tsunami have similar features:

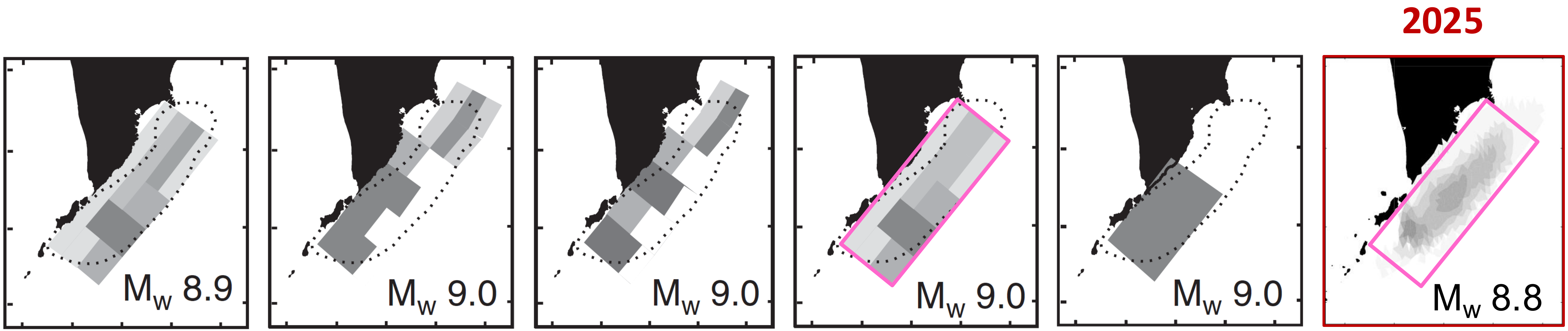
- Large shallow slip
- Slip extends SW of peninsula
- M_w at higher end of possible range (≥ 8.9)



MacInnes et al., 2010

Well-fitting models for 1952 tsunami have similar features:

- Large shallow slip – ruptured further updip than 2025?
- Slip extends SW of peninsula – ruptured further SW than 2025?
- M_w at higher end of possible range (≥ 8.9) – 1.5–2 times bigger than 2025?



- 1952 earthquake probably slipped different portions of the megathrust to the 2025 earthquake
- 2025 earthquake probably released strain that was not released in 1952
- It is probable that neither event was a full rupture of the megathrust

If 1952 wasn't the "big one", what was?

1737, October 16 GMT (October 6, Julian date, in Kamchatka). A great earthquake and tsunami occurred in the Kuril Islands and Kamchatka at 3 A.M. The tsunami had heights of 20 m in the Northern Kuril Islands and 30 m at Avacha on Kamchatka. Natives were killed, buildings destroyed, and the topography changed.

G.V. Steller, a scientist traveling with the Bering Expedition in 1740, stopped at the island now known as Bering Island, Komandorskiye Islands, Russia. He noted in his journal that "Great changes on the island [Bering] may have resulted from earthquakes and high sea tides." He found driftwood, and sea mammal bones high up on the shore. He also found trees washed up on a bluff to a height of 30 *sazhens* [230 feet], and trees buried upright in new sand dunes which he attributed to the 1737 Kuril earthquake (Soloviev and Ferchev, 1961).

Tikhmenev (1978, p. 403 and 498) quotes Teben'kov (1825) as follows: "Half-rotten drift-wood is piled up on the shore of Amchitka Island in some places forty and fifty feet above the water mark." Footnote 11 continues: "The circumstances and the large quantity of driftwood on the shores of Alaska and Norton Sound, is attributed by natives to the terrible earthquake of 1737, which shook Kamchatka and the Kuril Islands."

"Half-rotten driftwood is piled up on the shore of Amchitka Island in some places forty and fifty feet above the water mark… [this observation] is attributed by natives to the terrible earthquake of 1737, which shook Kamchatka and the Kuril Islands." (Teben'kov, 1825)

From Lander, 1996, *Tsunamis Affecting Alaska*

Conclusions

- The 2025 Kamchatka earthquake had a smaller tsunami and probably a smaller magnitude than the 1952 earthquake
- Our data-driven locking model scheme identifies a locked area that agrees broadly with the source region of both events using GNSS data
- We can produce a model that agrees with both the interseismic locking and coseismic InSAR data…
- …but we estimate double the slip that would have accumulated between the events. Was there unreleased slip deficit from 1952?

Thanks: Roland Burgmann and Kaj Johnson for discussions, support from NASA award 80NSSC23K0736