CRESCENT Topical Workshop | AT THE SHALLOW FRONTIER: FAULTING, DEFORMATION, AND TSUNAMIGENESIS IN CASCADIA
May 28 – 29, 2026 - Eugene, OR

Deciphering Tsunami Records to Understand Subduction Earthquakes

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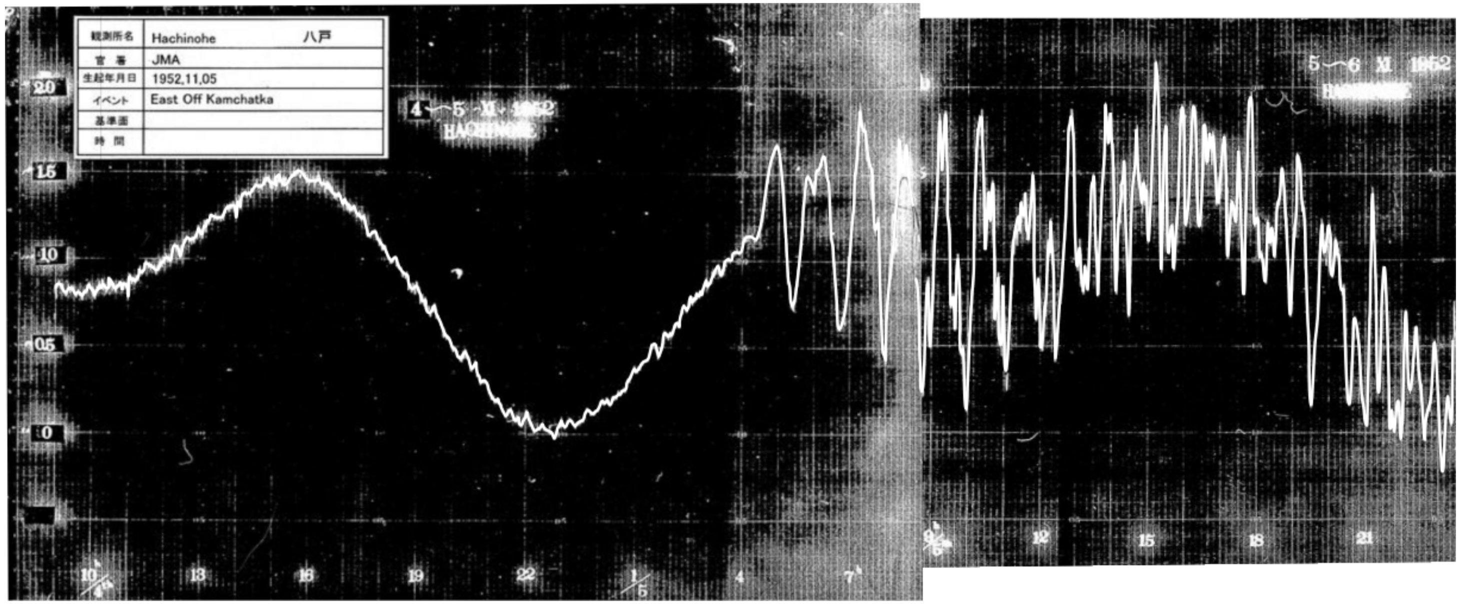
Original marigram of the 1952 tsunami recorded at Hachinohe, Japan



観測所名	Hachinohe　　八戸
官署	JMA
生起年月日	1952,11,05
イベント	East Off Kamchatka
基準面	
時間	

With contributions from

K. Wang, A. Gubler, T. Sun, E. Contreras-Reyes, S. Ruiz, R. Madariaga, G. Davies,
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How do subduction megathrusts rupture in space and time, and what controls this pattern?

How far do rupture zones extend laterally and in depth in large subduction earthquakes?

(e.g., Trench-breaching 2011 Tohoku)

How do rupture zones of successive earthquakes relate in space and time?

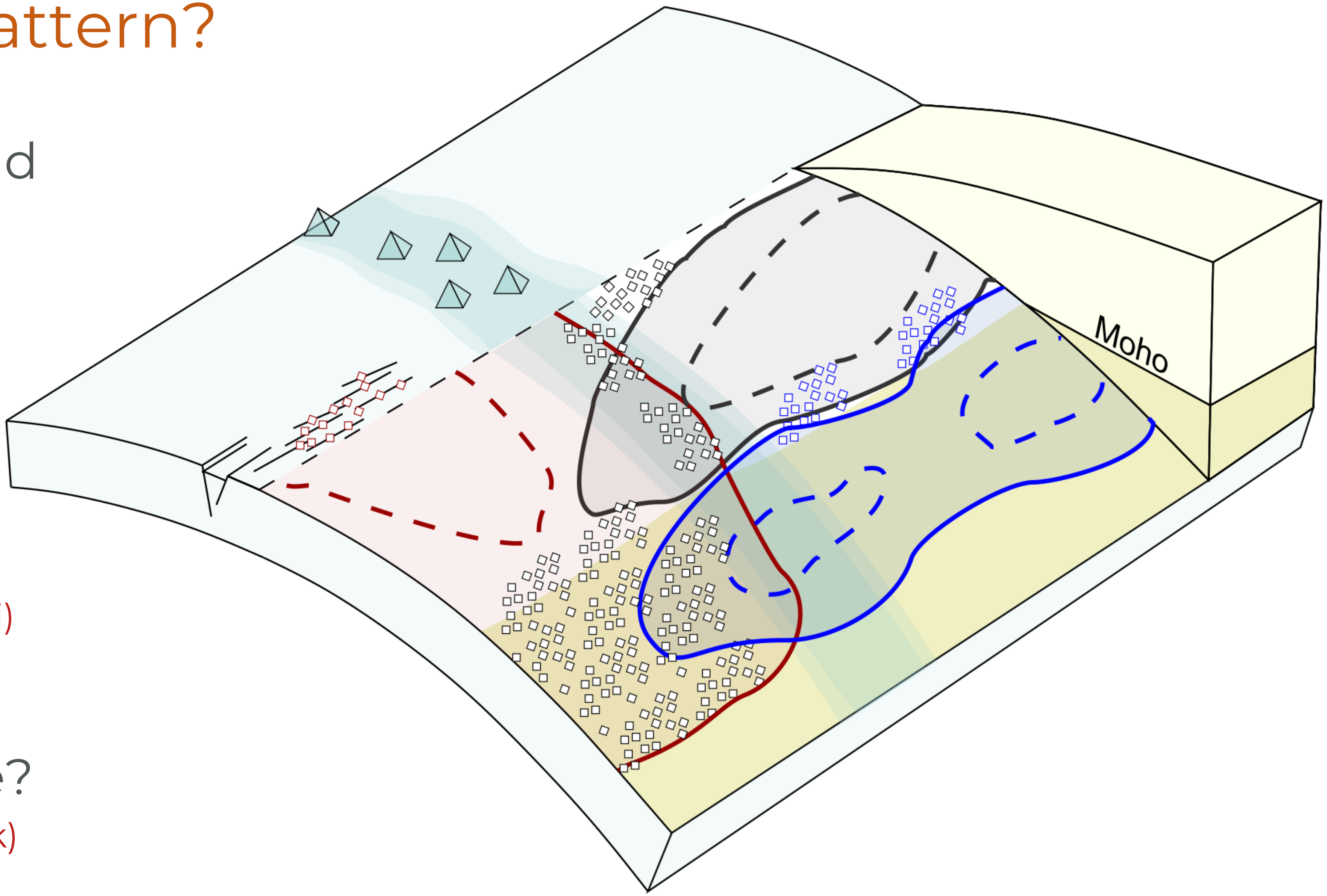
(e.g., Different depths in 2007/2010 Mentawai)

How do seismic and aseismic rupture relate in space and time?

(e.g., updip afterslip/aftershocks in 2021 Chignik)

What tectonic factors control these patterns?

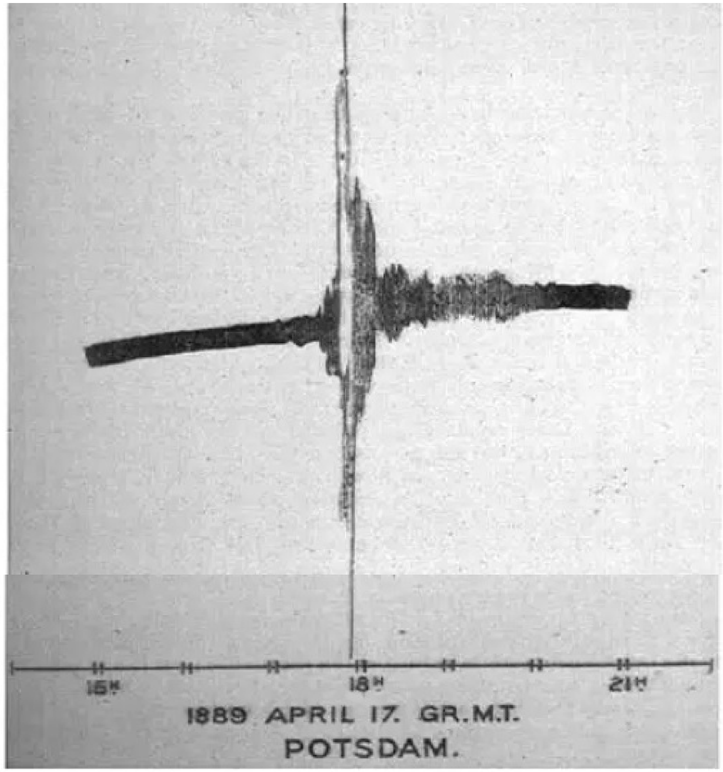
(e.g., Fracture zone barrier in 2001 Peru)



How persistent are megathrust rupture patterns beyond the modern instrumental era?

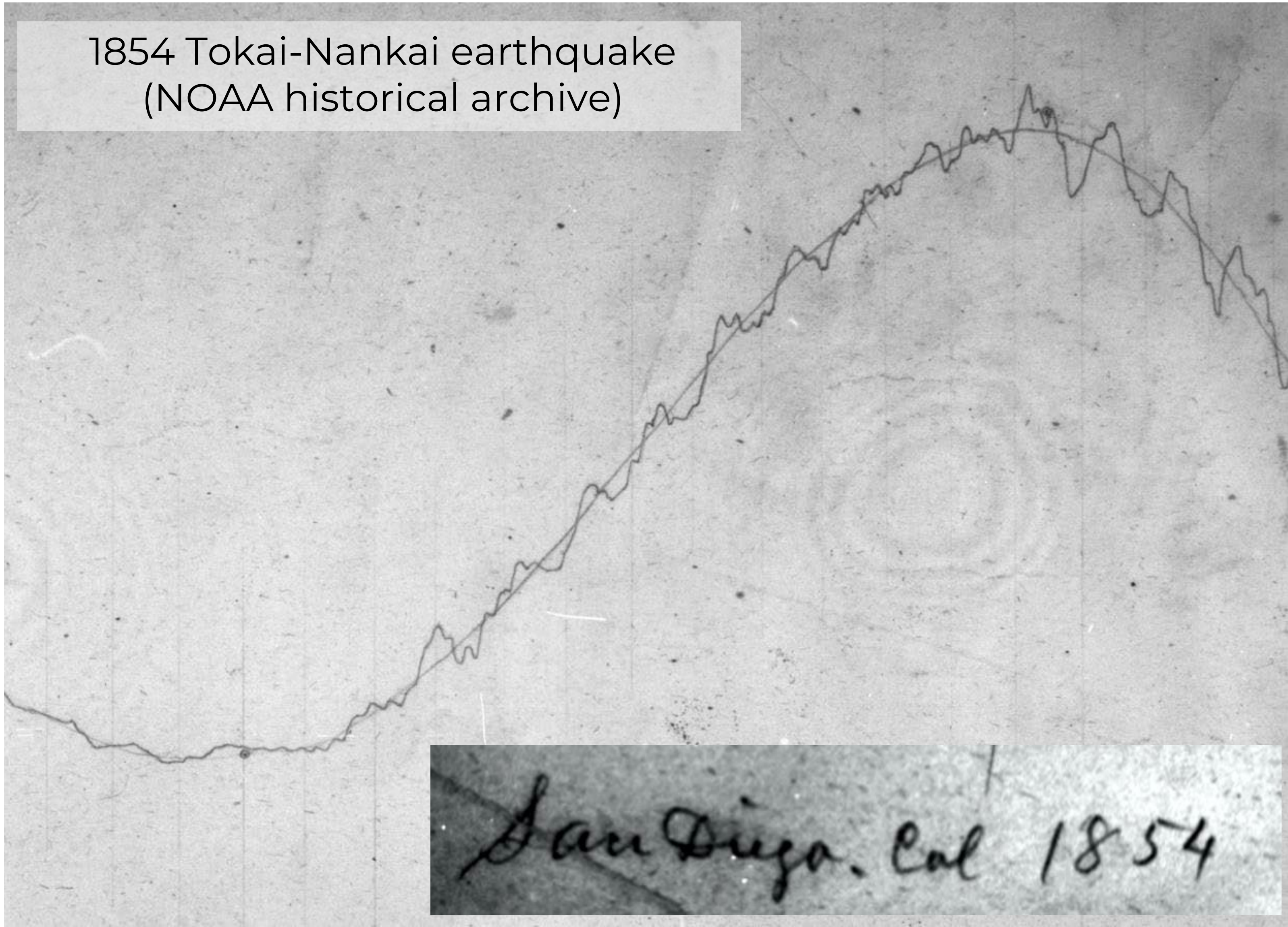
Clues from tsunami records preserved in historical marigrams

First seismogram

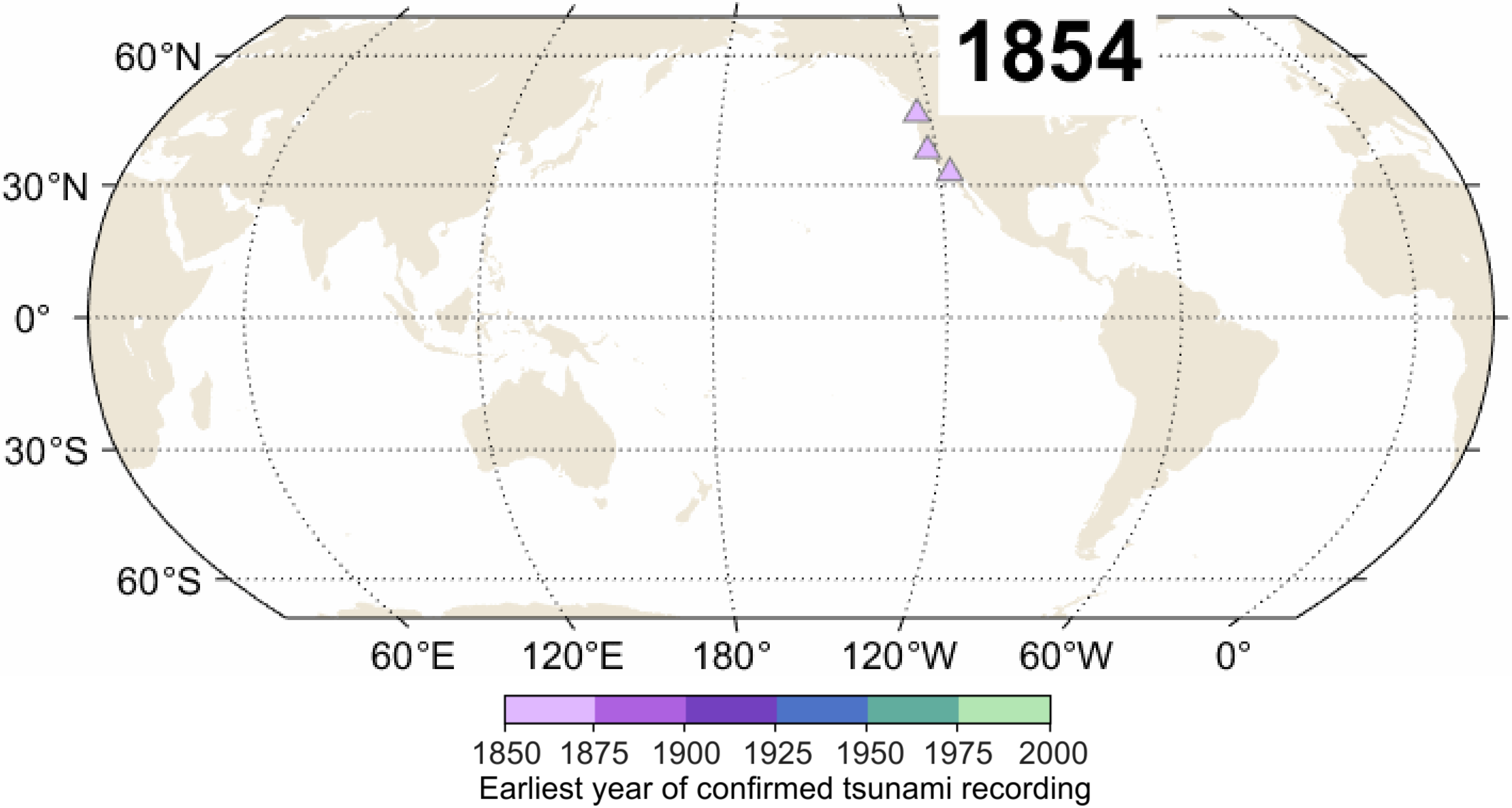


1889 Tokyo earthquake
(von Rebeur-Paschwitz, 1889 NATURE)

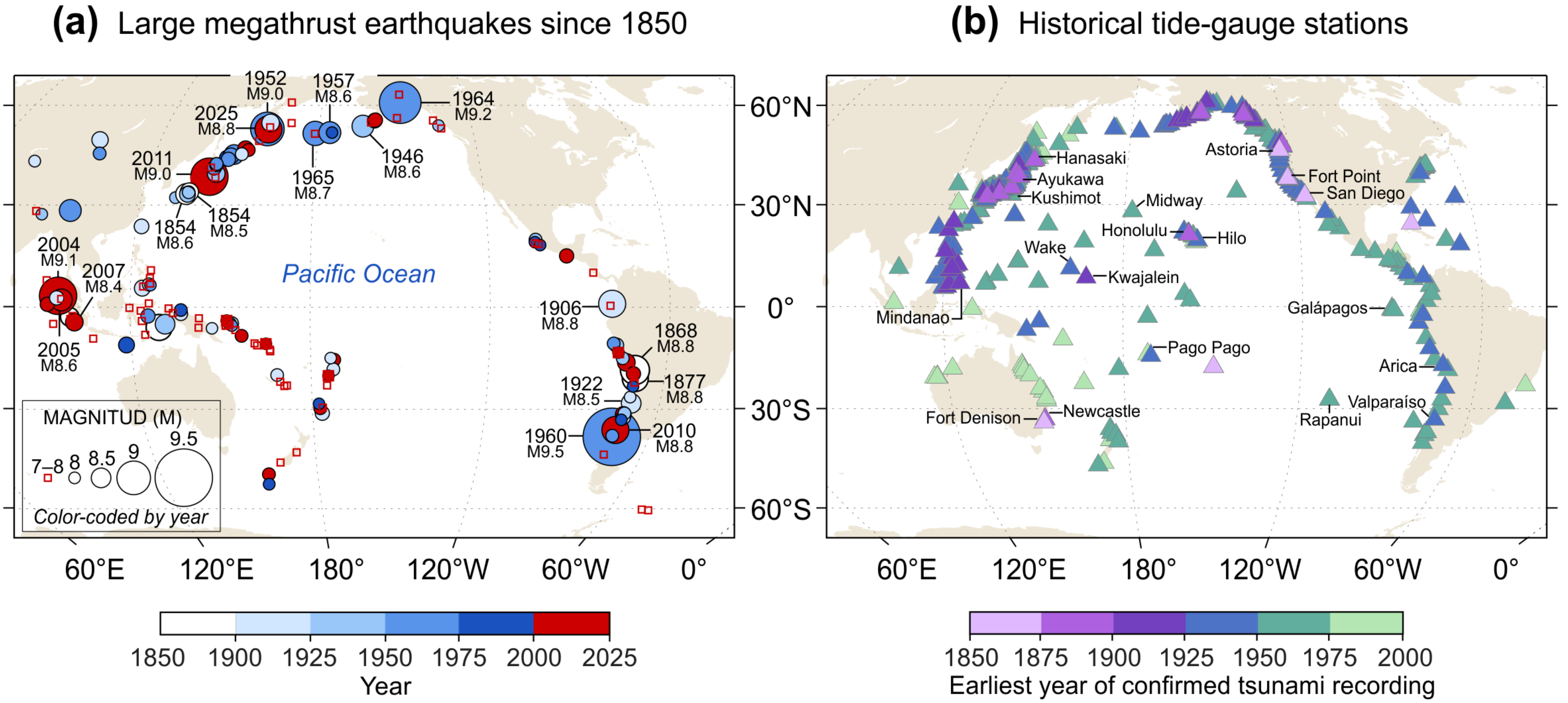
First instrumental record of a tsunami


1854 Tokai-Nankai earthquake
(NOAA historical archive)

Broad spatial and azimuthal coverage of historical tide gauges



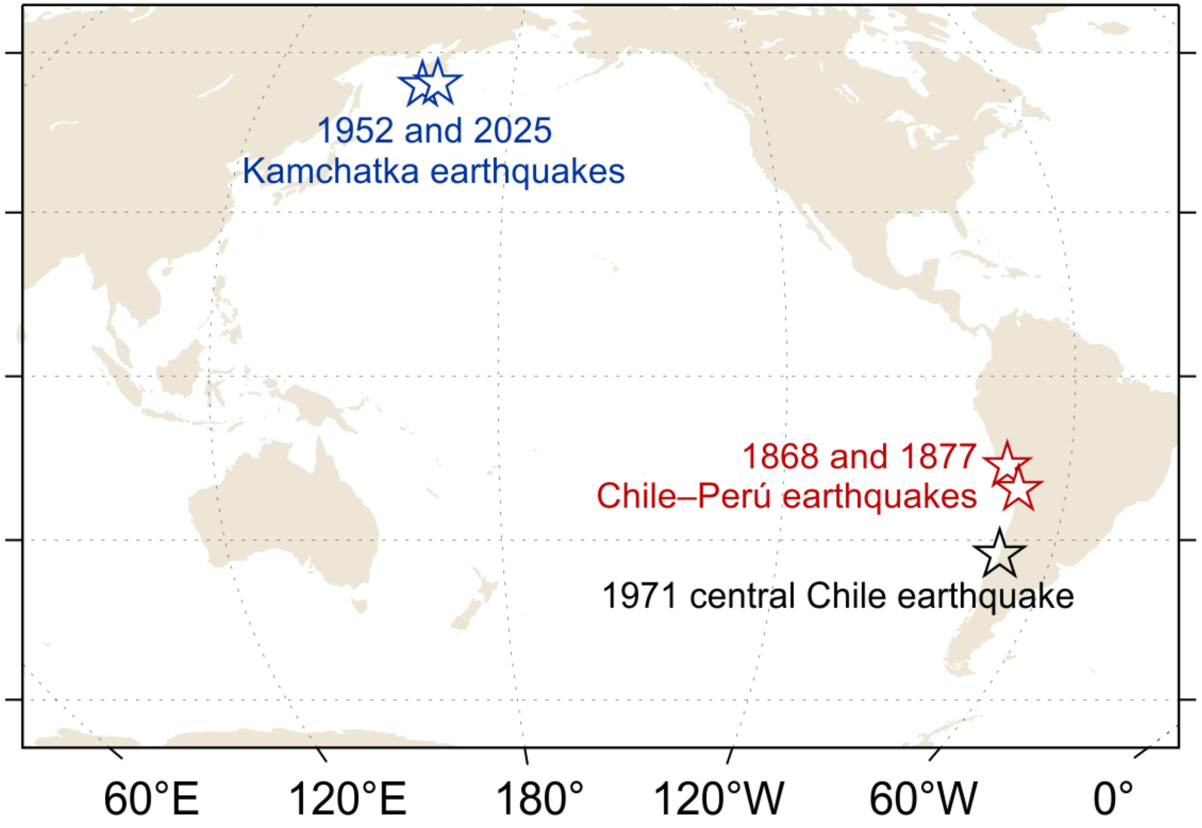
Large earthquakes recorded by historical tide gauges since 1854



(a) Large megathrust earthquakes since 1850

(b) Historical tide-gauge stations

Potential of Historical Tsunami Records: Three Case Studies



Case study 1

Rupture pattern of the Chile–Peru megathrust

Case study 2

1952 and 2025 ruptures: same or complementary areas?

Case study 3

1971 Chile earthquake: rupture–aftershock depth offset

Case study 1

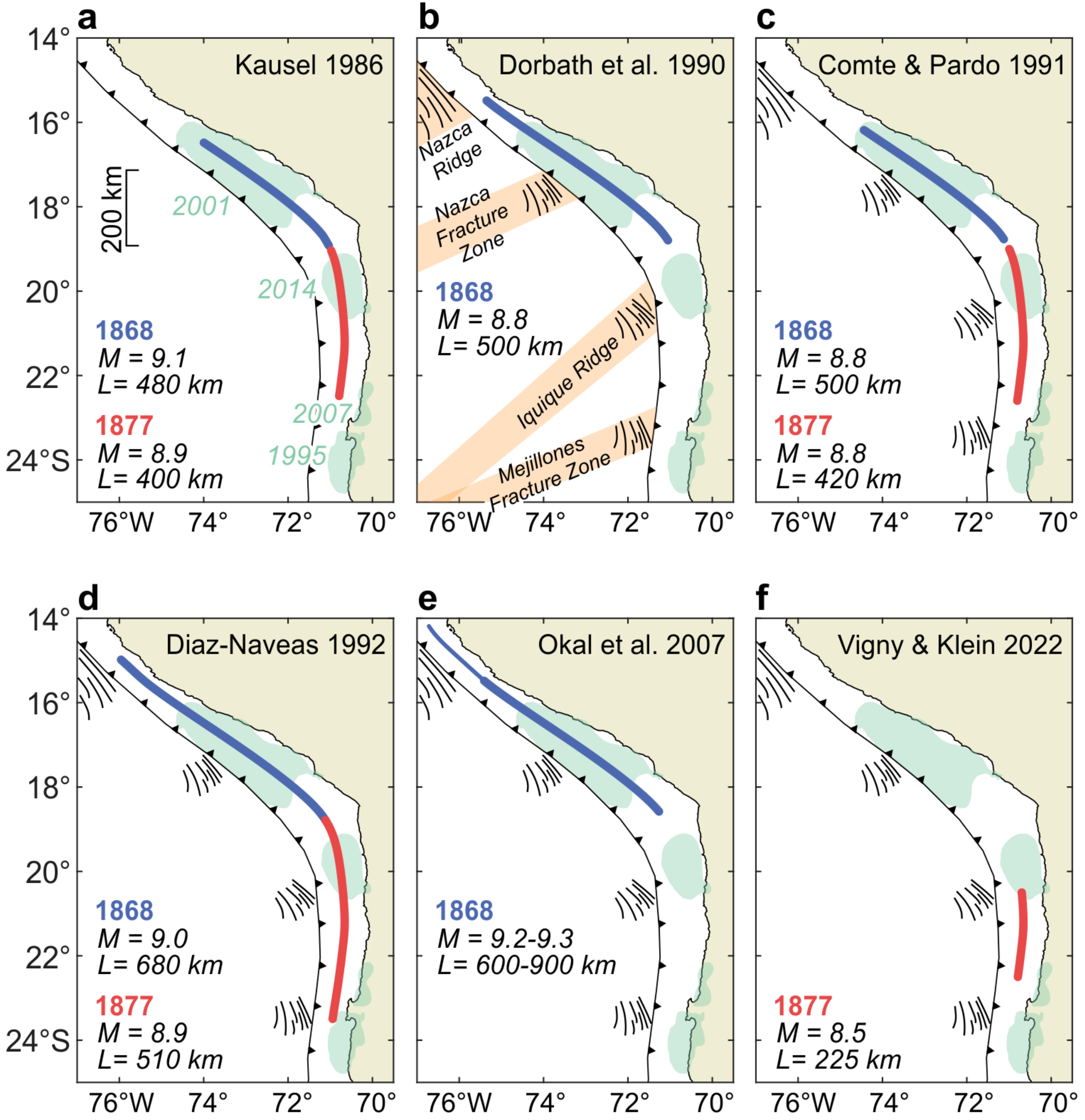
Rupture pattern of the Chile–Peru megathrust

Five M>8 earthquakes in 150 years, including two M 8.8–9 in 1868 and 1877

Published studies infer markedly different rupture lengths for 1868 and 1877

Spatial relation between rupture zones? Complementary or overlapping ruptures?

Spatial relation with subducting seafloor relief?



Case study 1

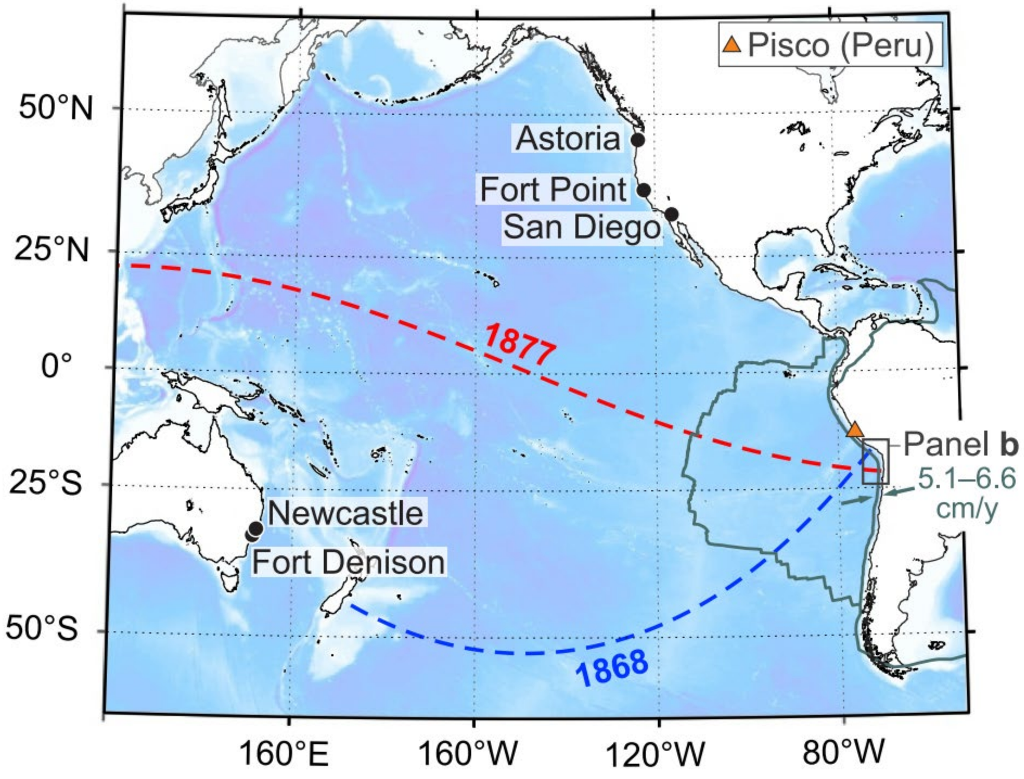
Rupture pattern of the Chile–Peru megathrust

1868 marigrams

- Astoria (USA)
- San Diego (USA)
- Fort Point (San Francisco, USA)
- Fort Denison (Sydney, Australia)

1877 marigrams

- Fort Point (San Francisco, USA)
- Fort Denison (Sydney, Australia)
- Newcastle (Australia)



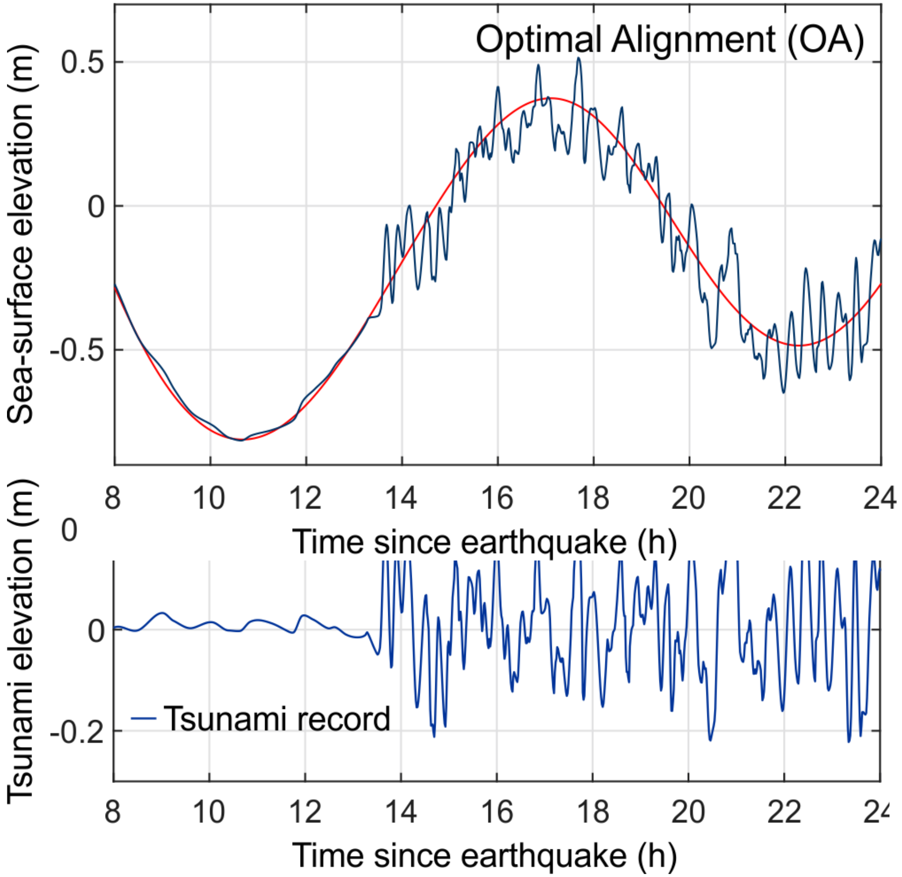
Example: 1877 Marigram recorded at Fort Point (source:NOAA)

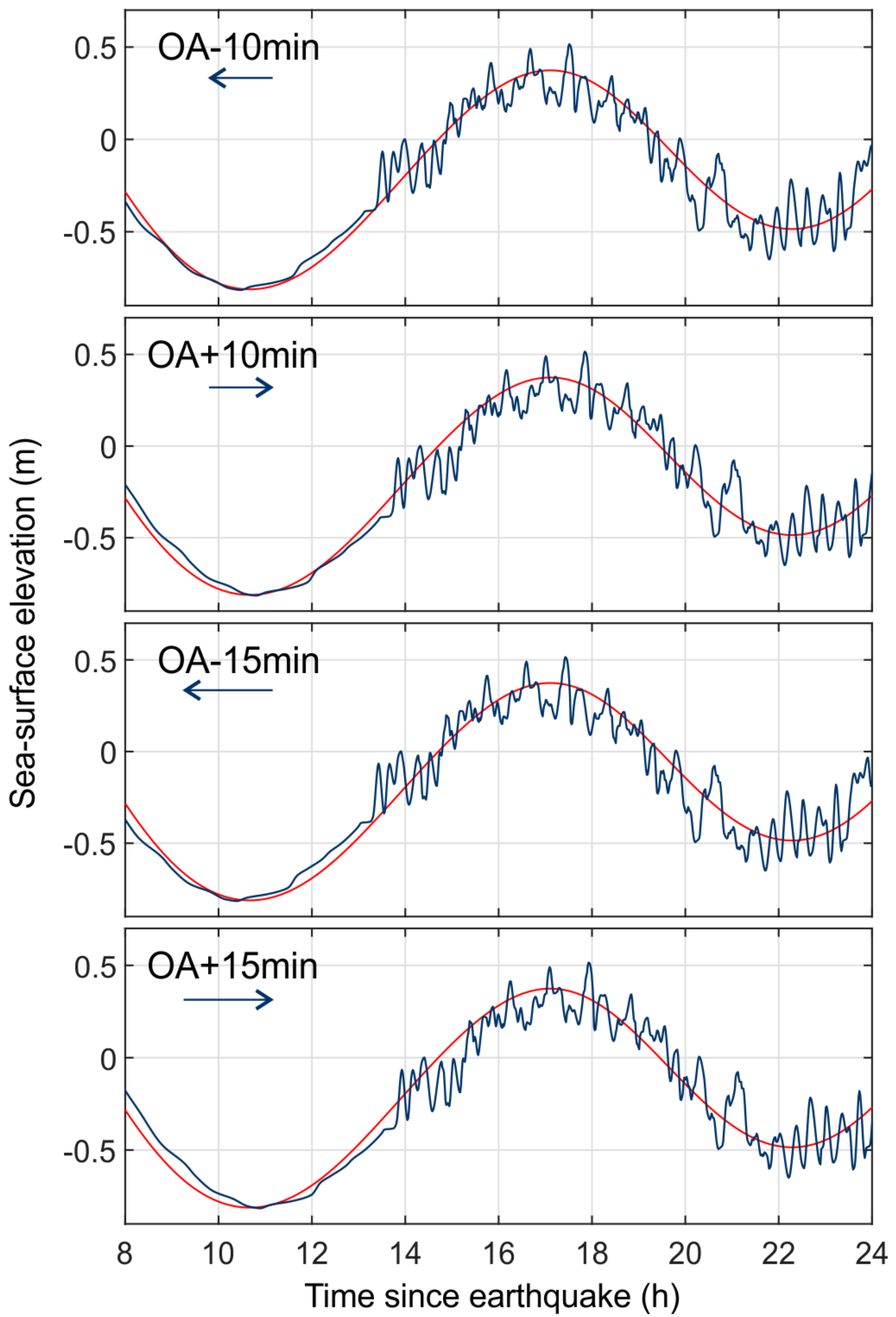
Case study 1

Rupture pattern of the Chile–Peru megathrust

Marigram correction:
We adjust time, trend, offset, and amplitude until optimal alignment with hindcast tide.

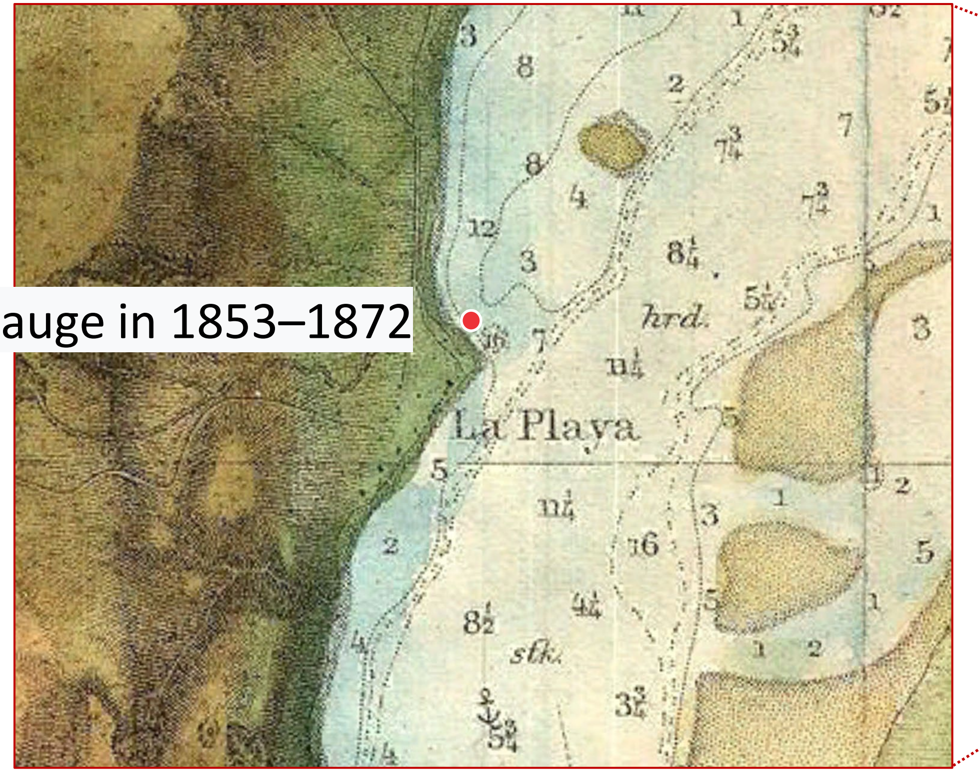
Uncertainties:
Time: < 10–15 min
Amplitude: < 5%





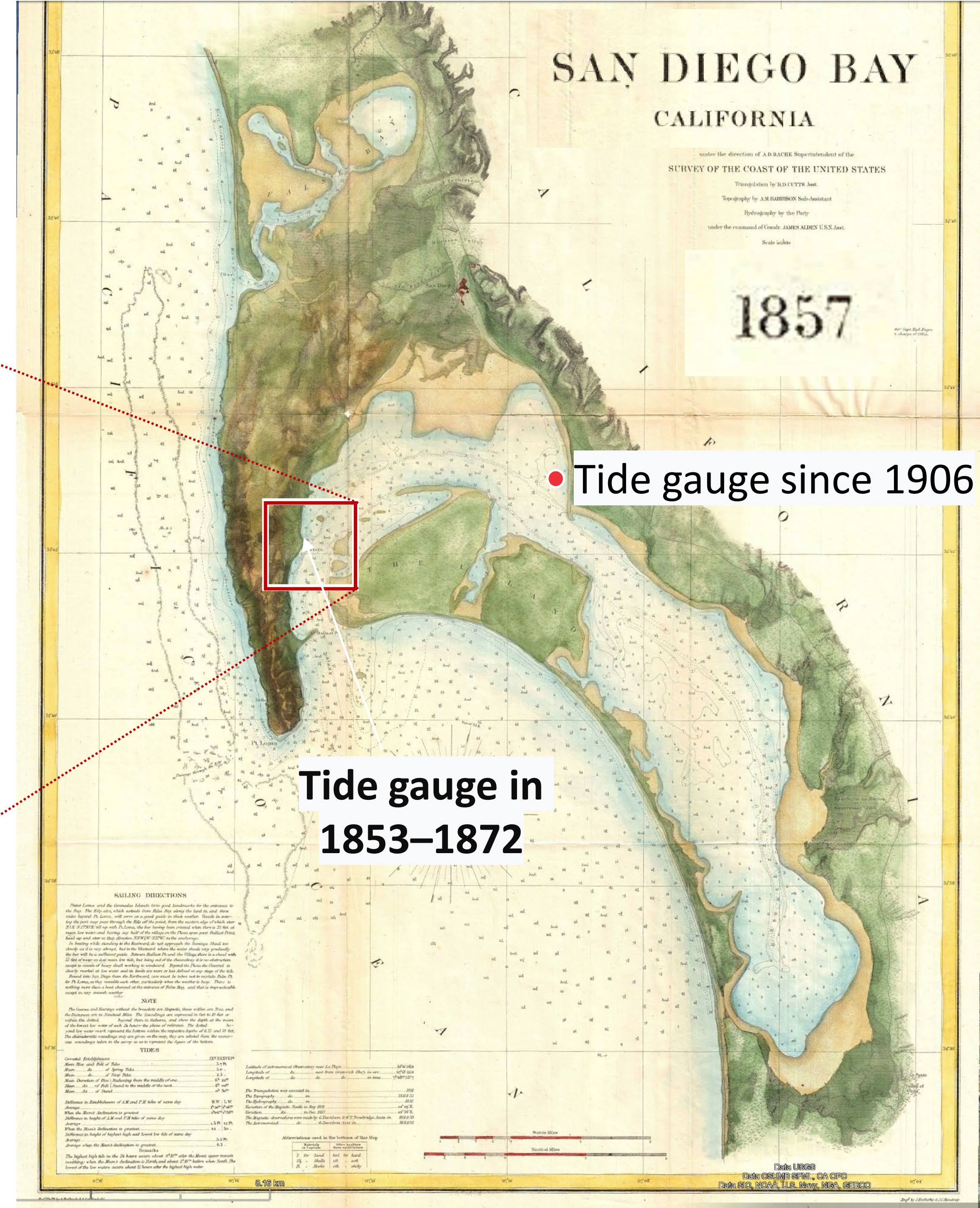
Case study 1

Rupture pattern of the Chile–Peru megathrust



Tide gauge in 1853–1872

Tsunami waveforms are sensitive
to location and bathymetry,
so we reconstruct the historical bathymetry



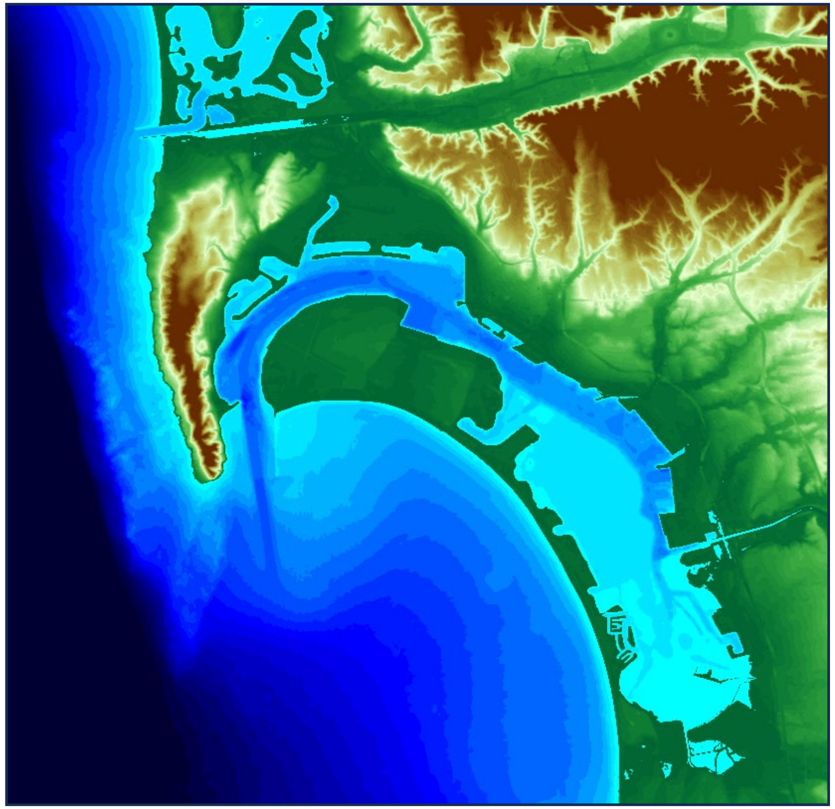
Tide gauge since 1906

Tide gauge in 1853–1872

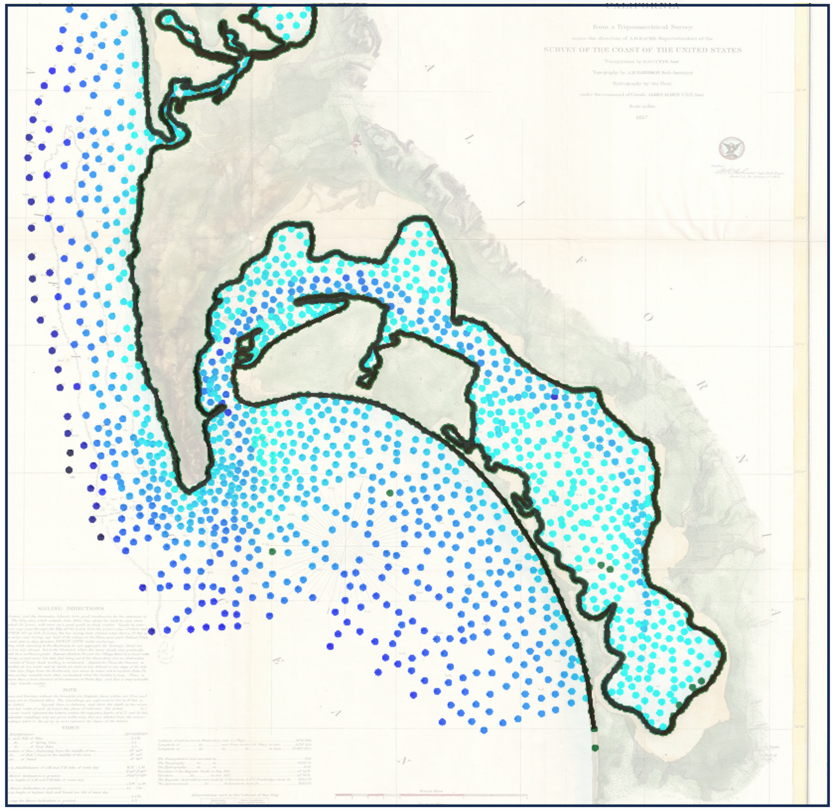
Case study 1

Rupture pattern of the Chile–Peru megathrust

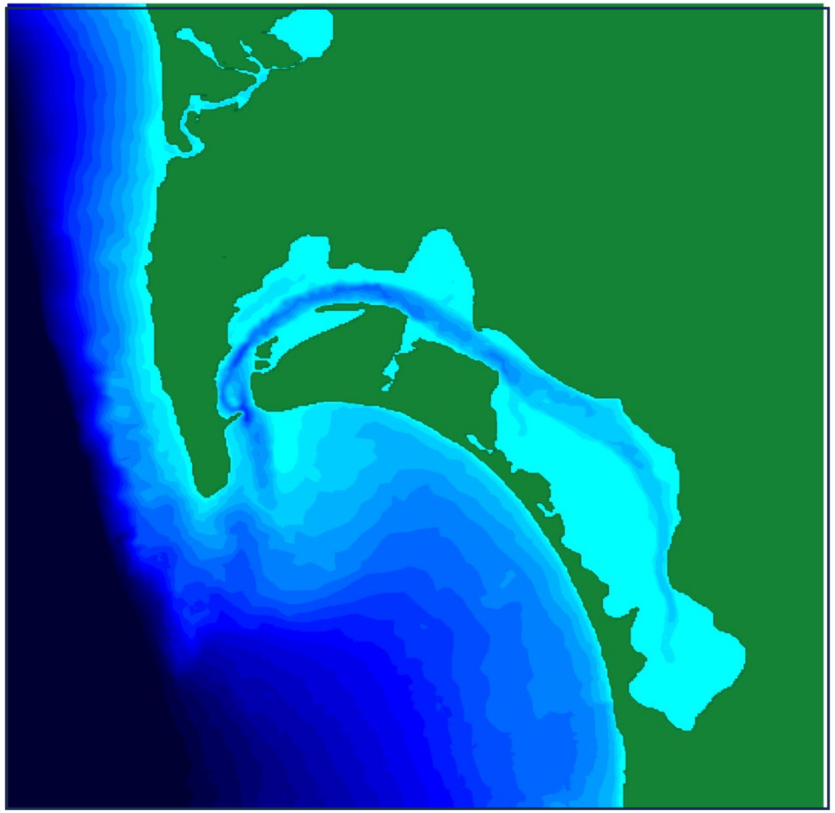
Present-day bathymetry



1857 soundings



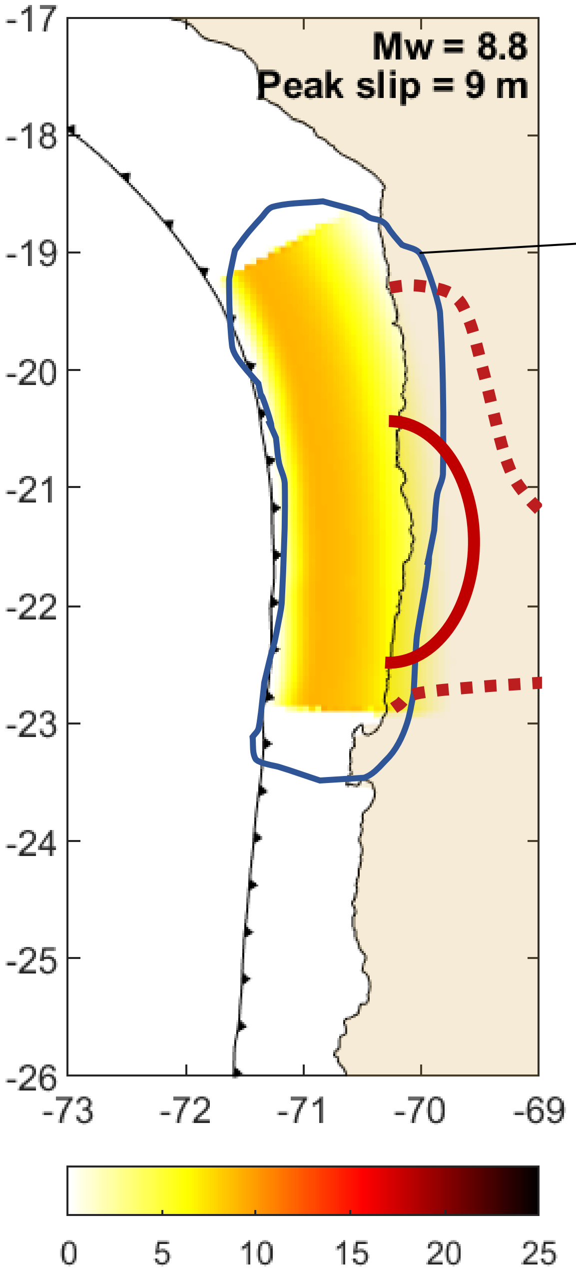
1857 bathymetry



Case study 1

Rupture pattern of the Chile–Peru megathrust

We use simple rupture models to explore what tsunami records from Australia and the United States reveal about the 1868 and 1877 rupture zones.



1877 rupture zone commonly assumed in the literature

Zone of strongest shaking (VIII isoseismal area)

▬ Soloviev & Go (1975)

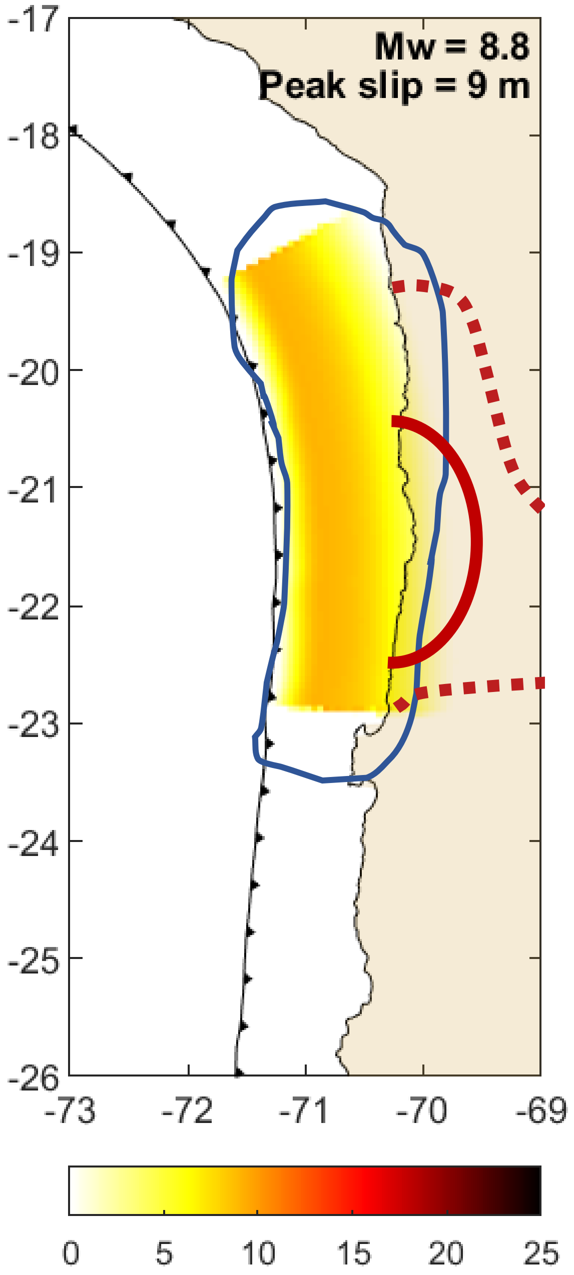
▪▪▪ Kausel (1986)

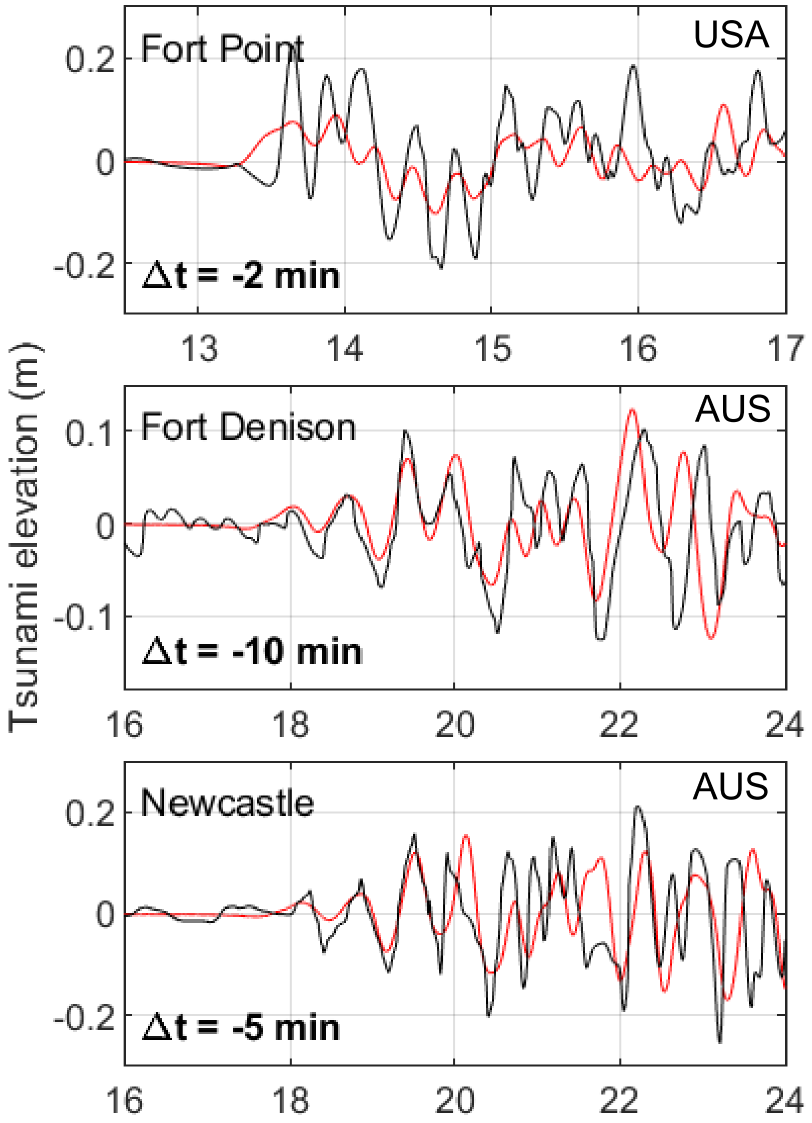
Case study 1

Rupture pattern of the Chile–Peru megathrust

A long rupture, as commonly assumed, can explain the tsunami at AUS quite well

…but cannot explain the three initial impulsive tsunamis at USA



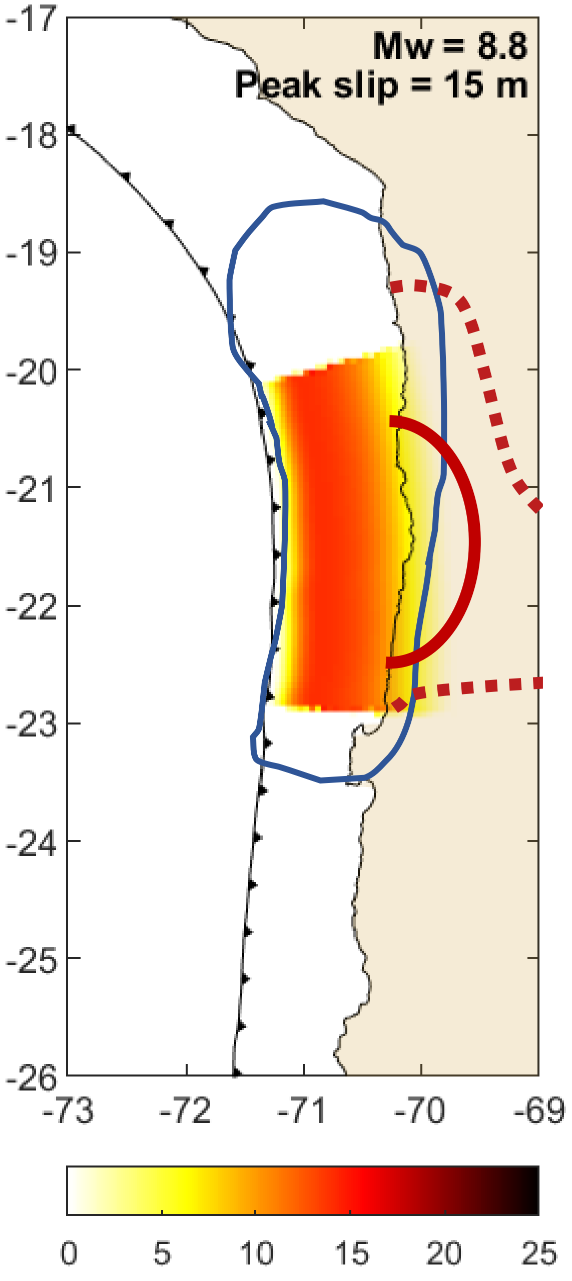


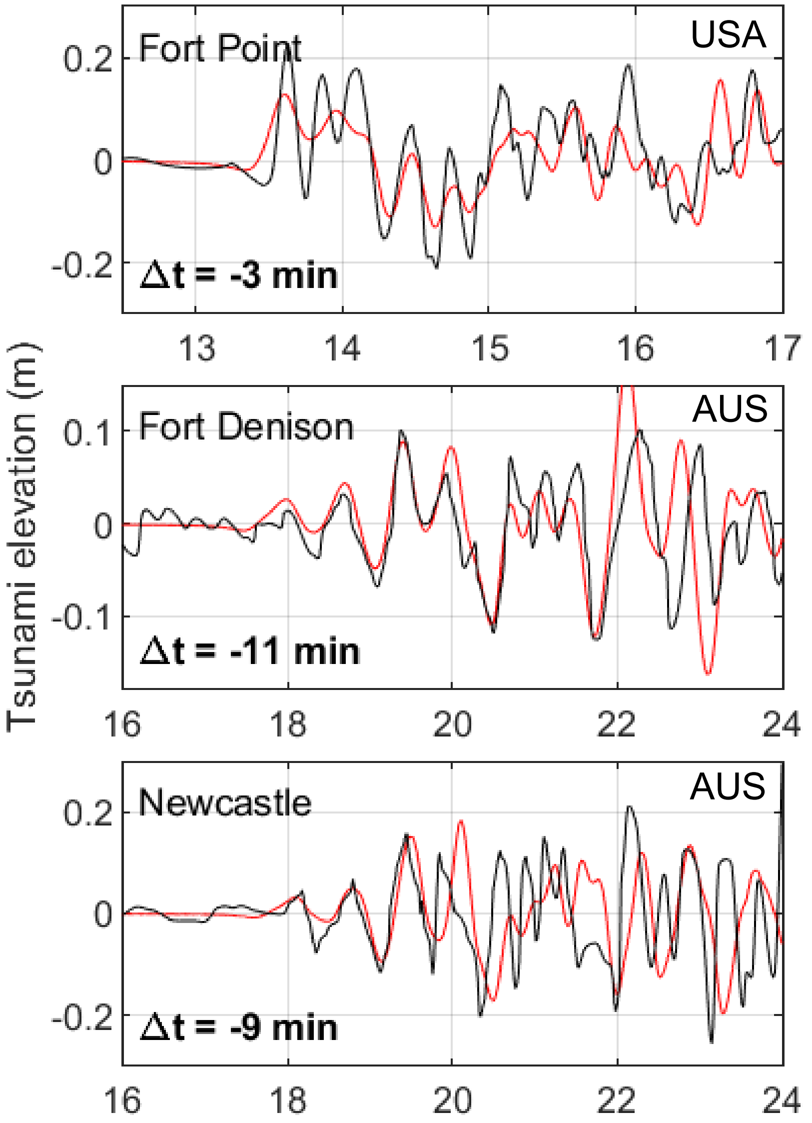
Case study 1

Rupture pattern of the Chile–Peru megathrust

A shorter rupture can explain the AUS tsunami waveforms even better

It can also explain the impulsive character of the leading tsunami at USA much better

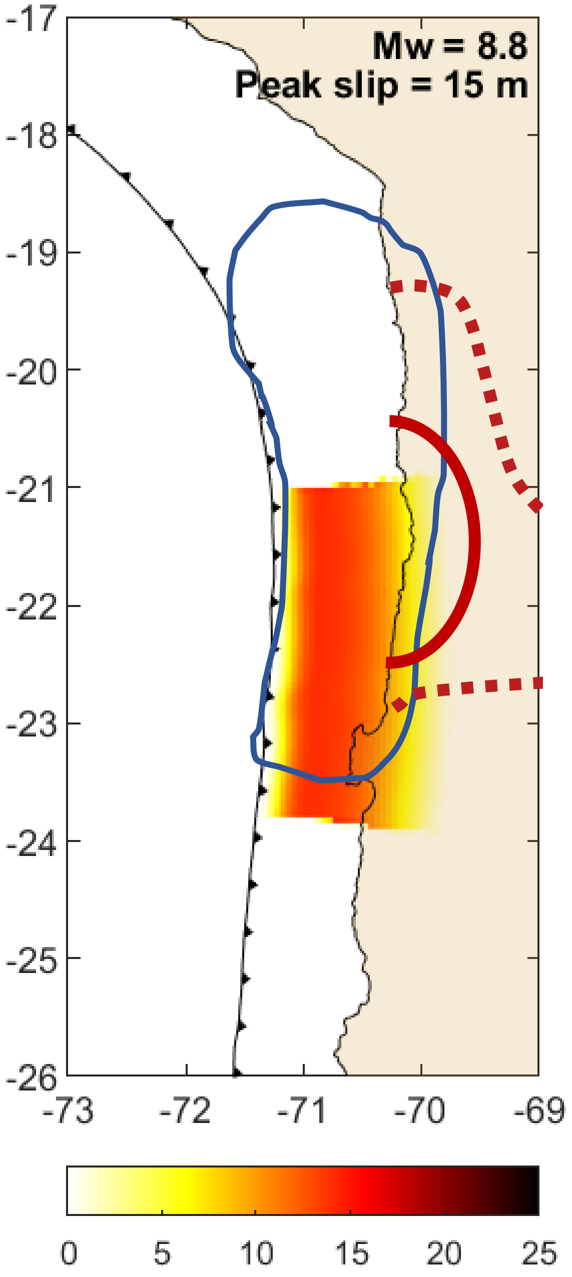


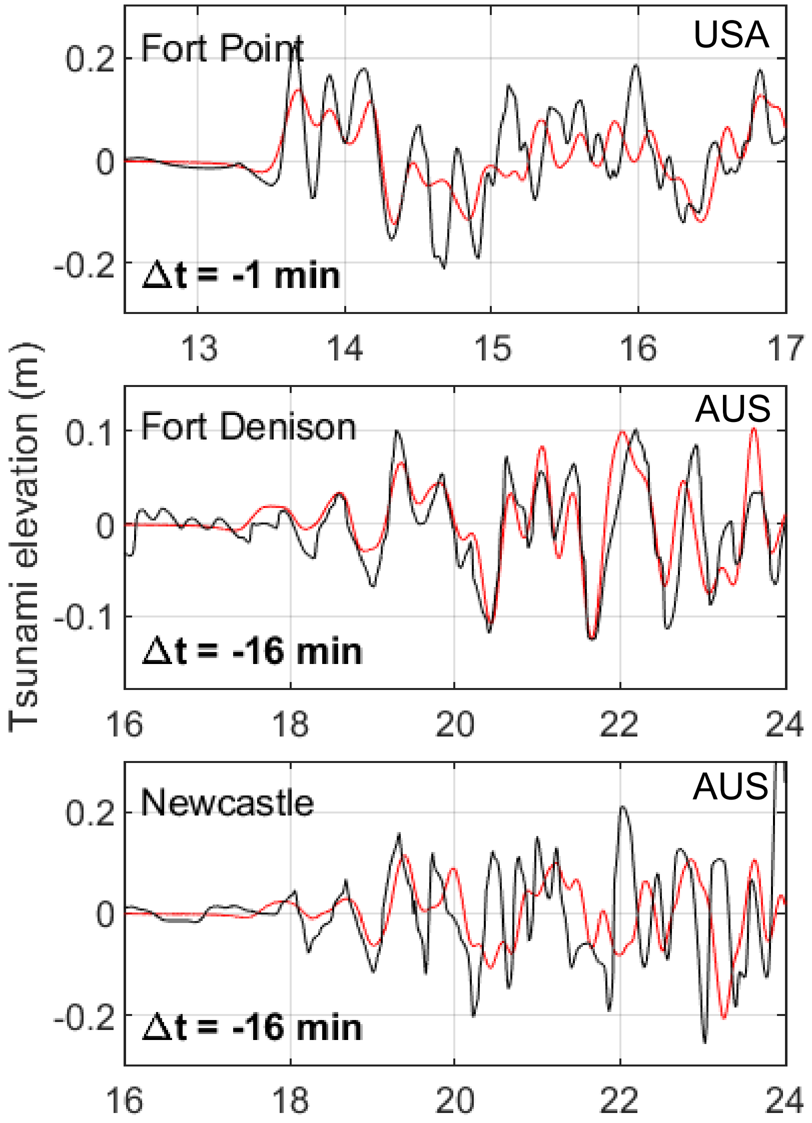


Case study 1

Rupture pattern of the Chile–Peru megathrust

The same shorter rupture shifted southward improves the fit at USA but worsens it at AUS

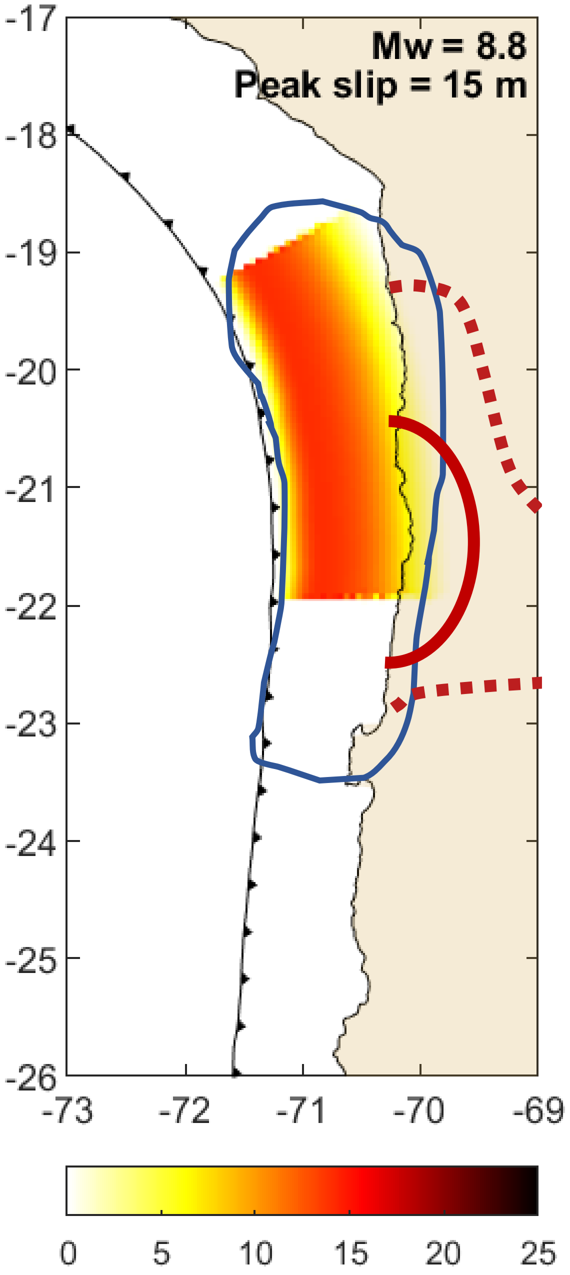


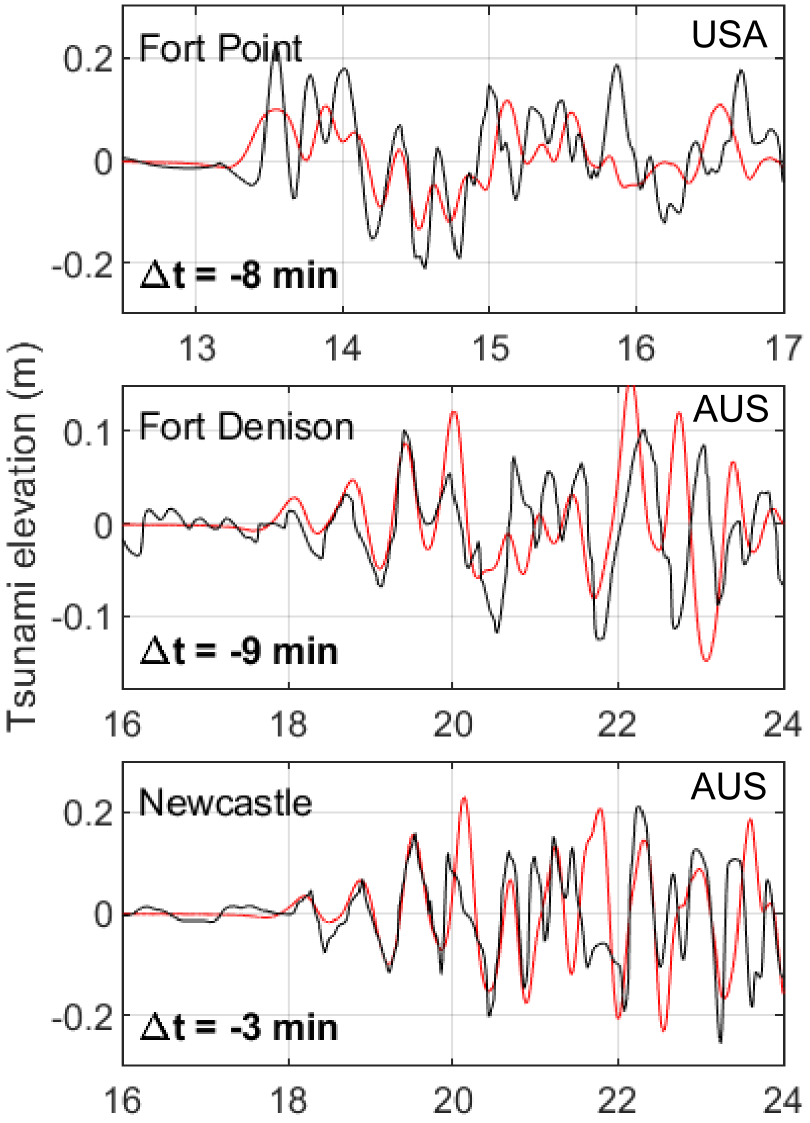


Case study 1

Rupture pattern of the Chile–Peru megathrust

A northward shift improves the fit at AUS but worsens it at USA

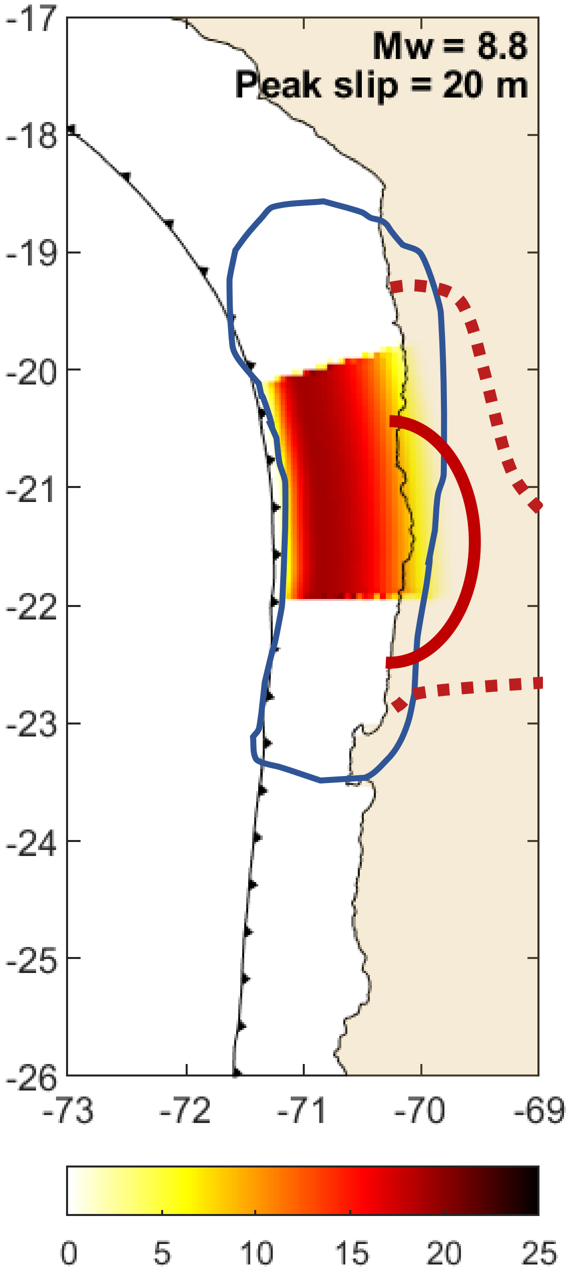


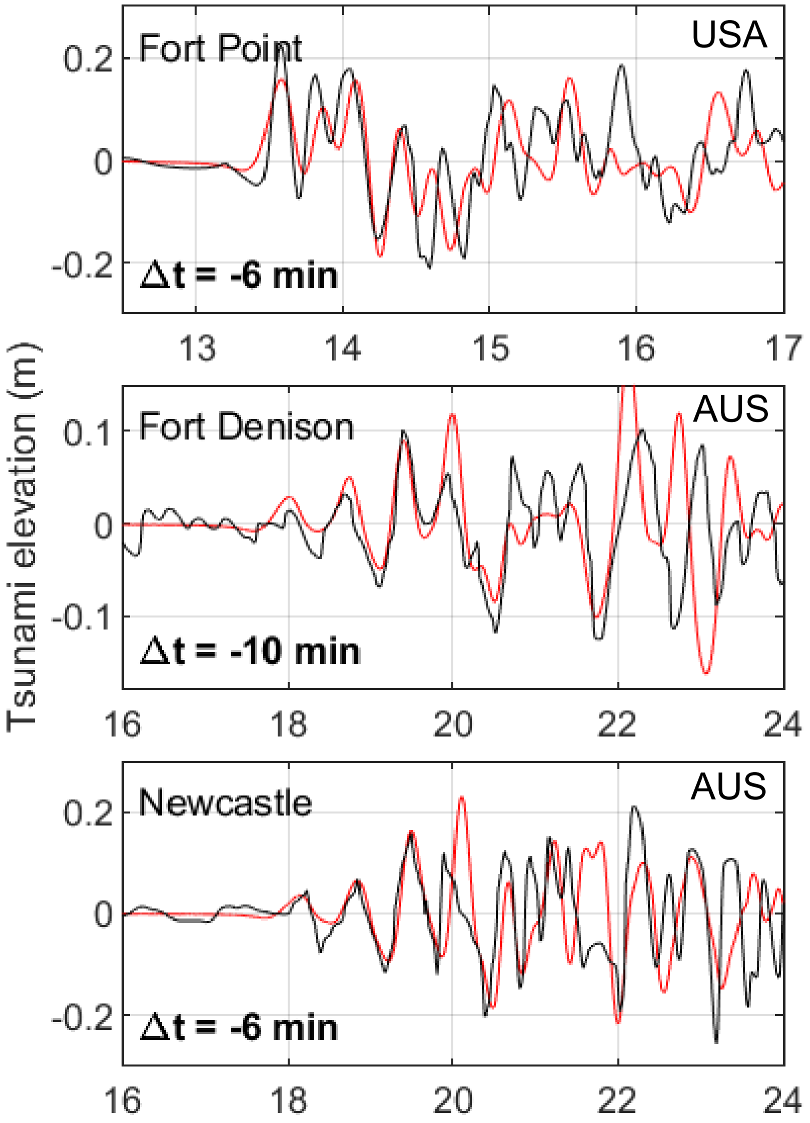


Case study 1

Rupture pattern of the Chile–Peru megathrust

An even shorter rupture can explain the AUS and USA tsunami waveforms much better

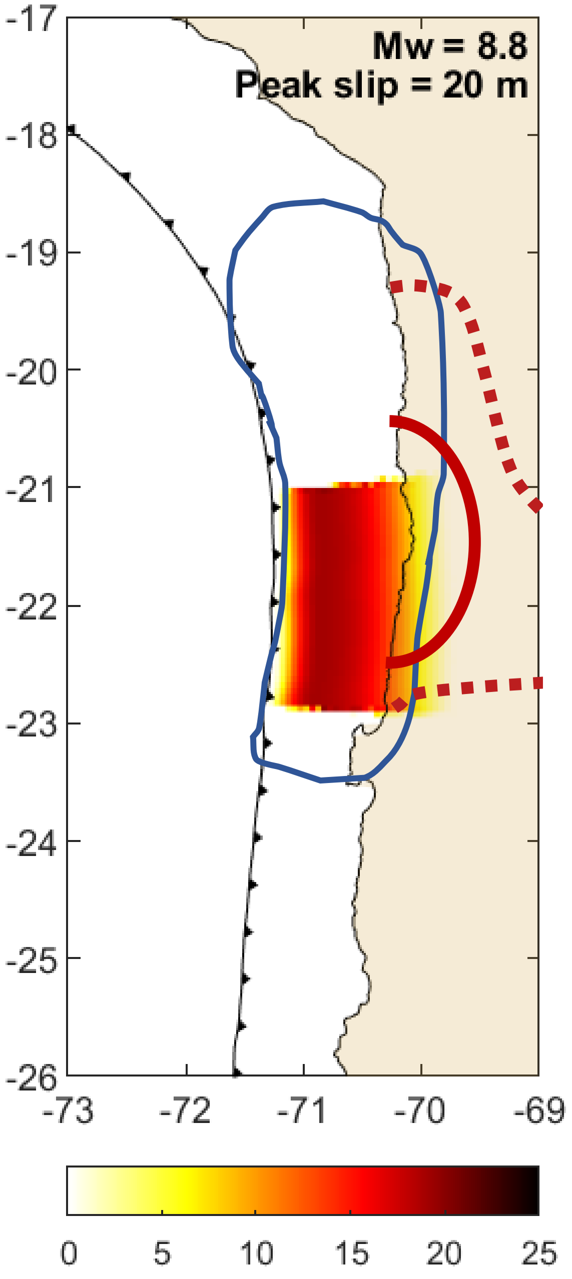


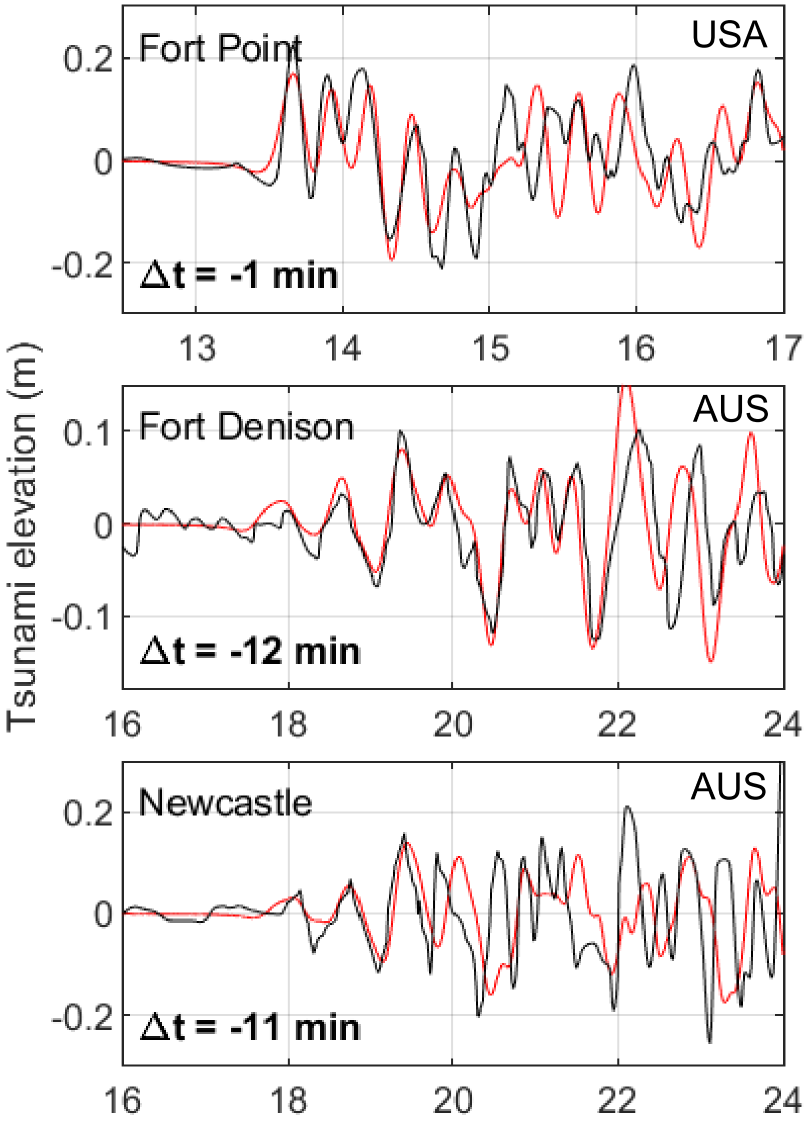


Case study 1

Rupture pattern of the Chile–Peru megathrust

The agreement remains good for slight rupture shifts

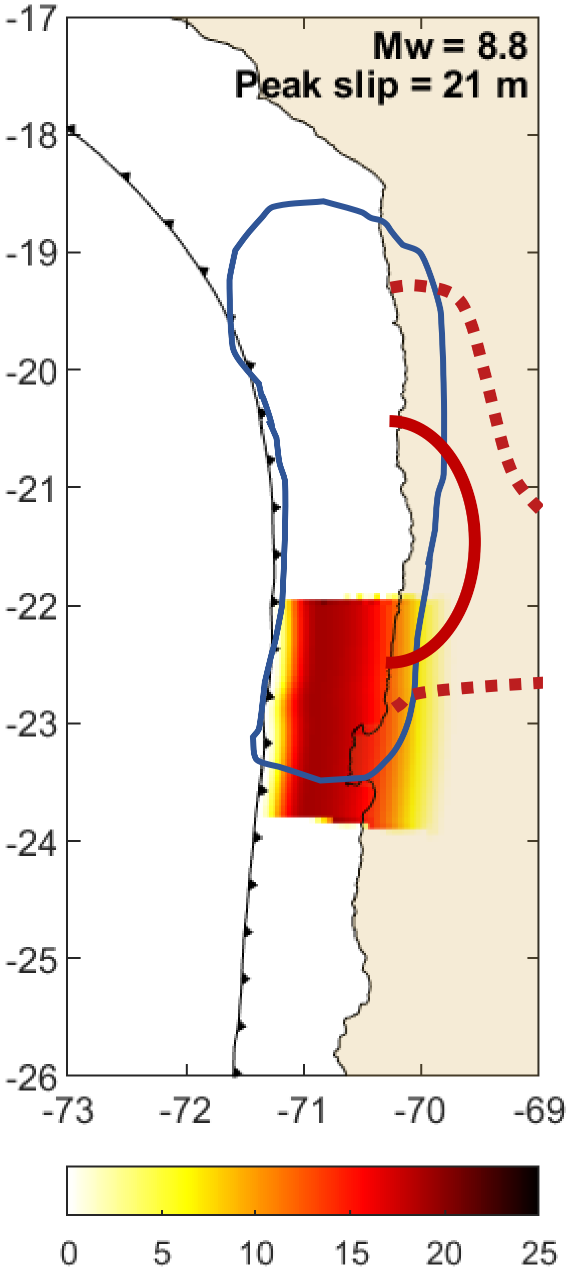


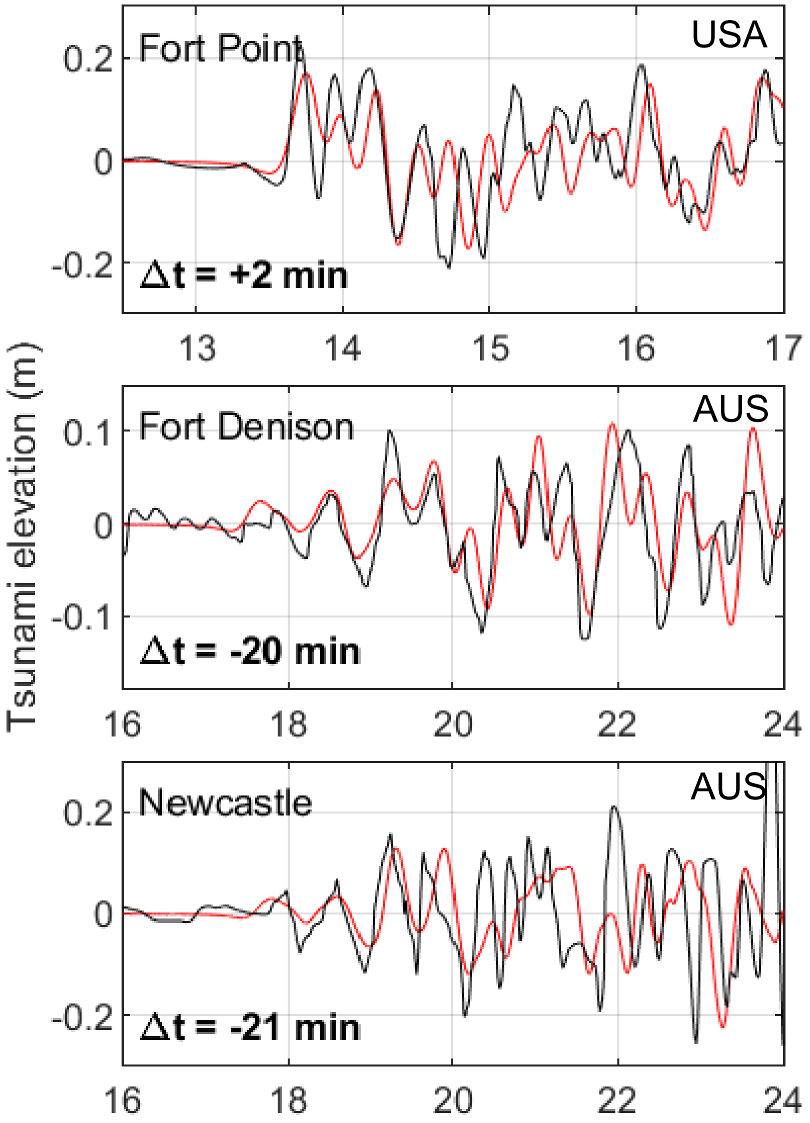


Case study 1

Rupture pattern of the Chile–Peru megathrust

But the fits begin to worsen when the short rupture is shifted too far south

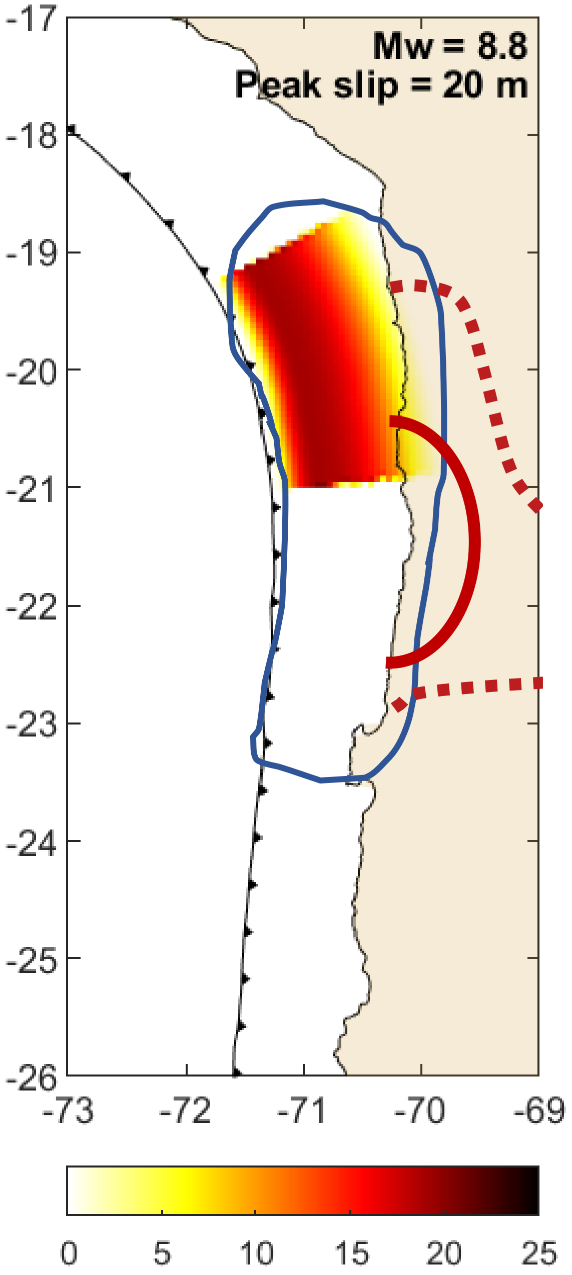


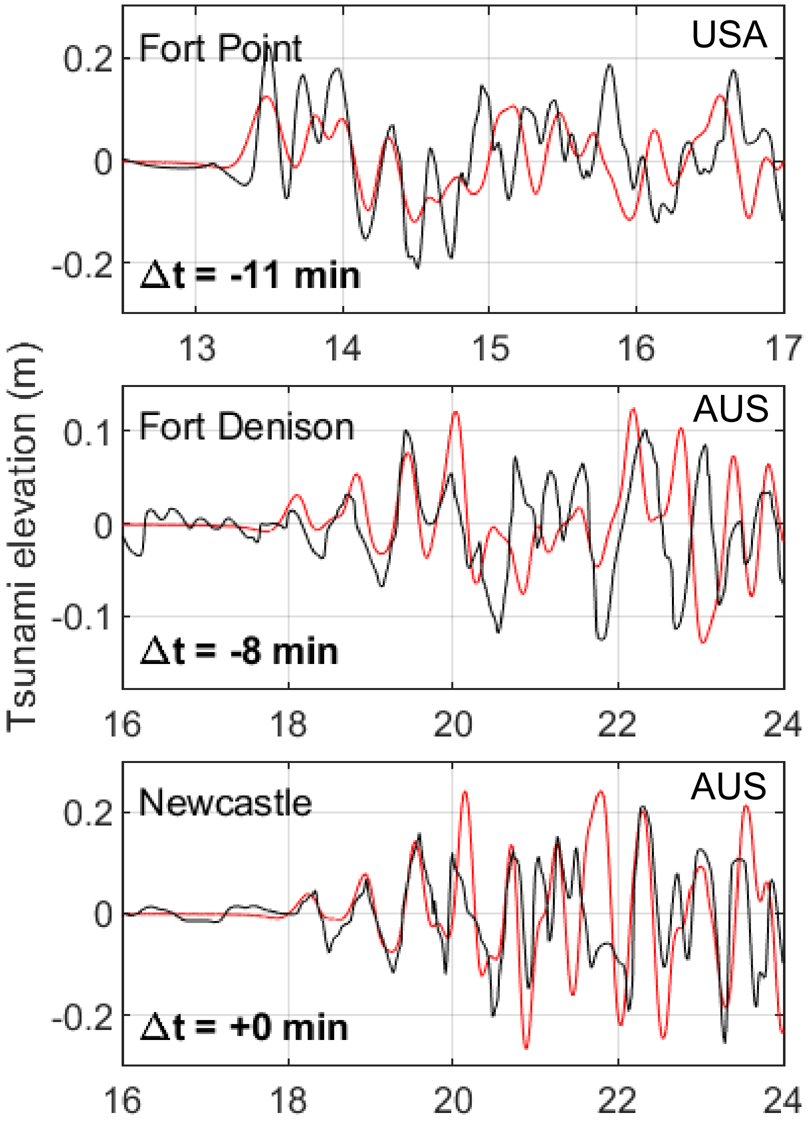


Case study 1

Rupture pattern of the Chile–Peru megathrust

And they worsen more when the rupture is shifted too far north

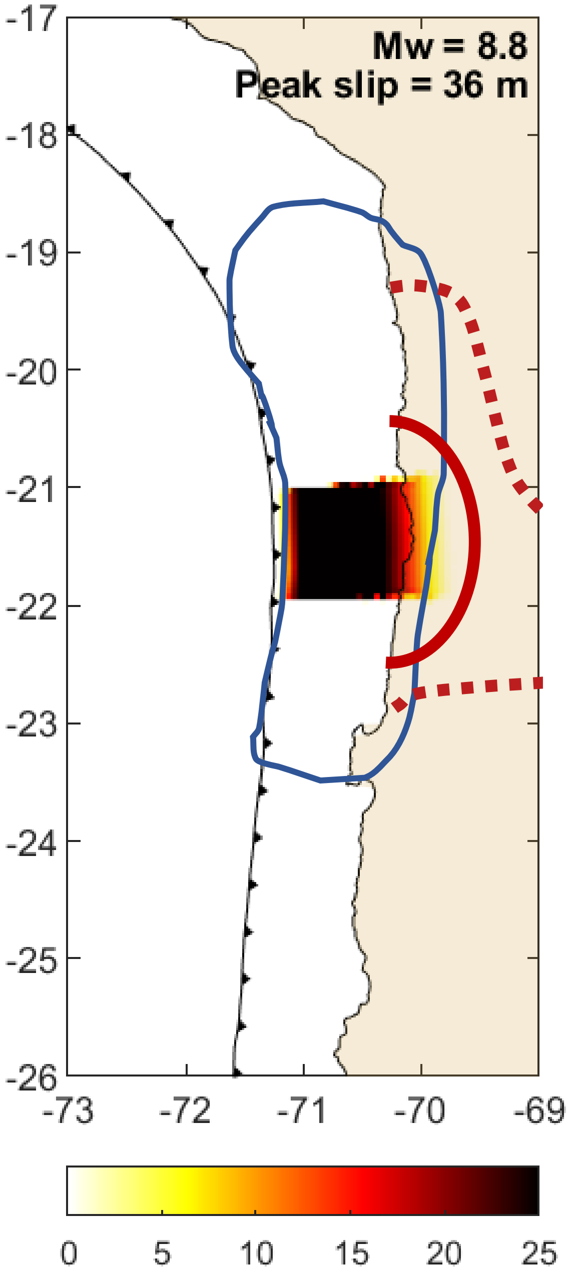


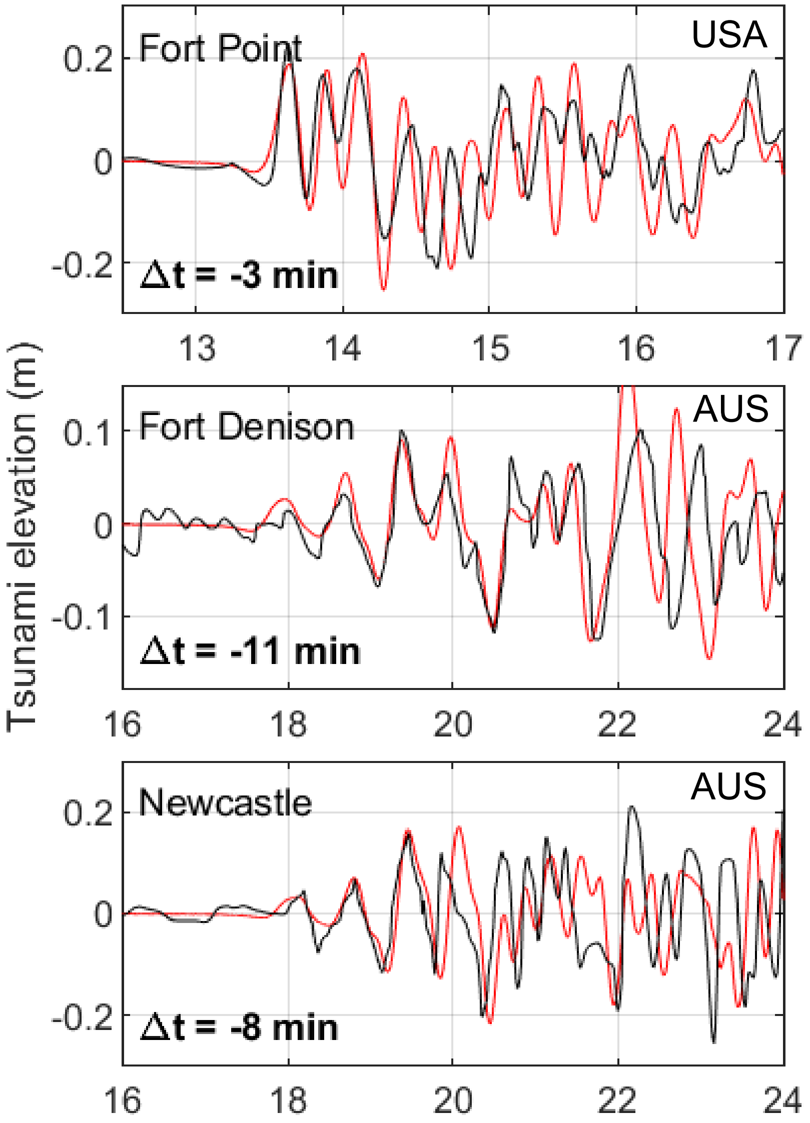


Case study 1

Rupture pattern of the Chile–Peru megathrust

A very short rupture with high slip can explain the AUS and USA tsunami waveforms surprisingly well

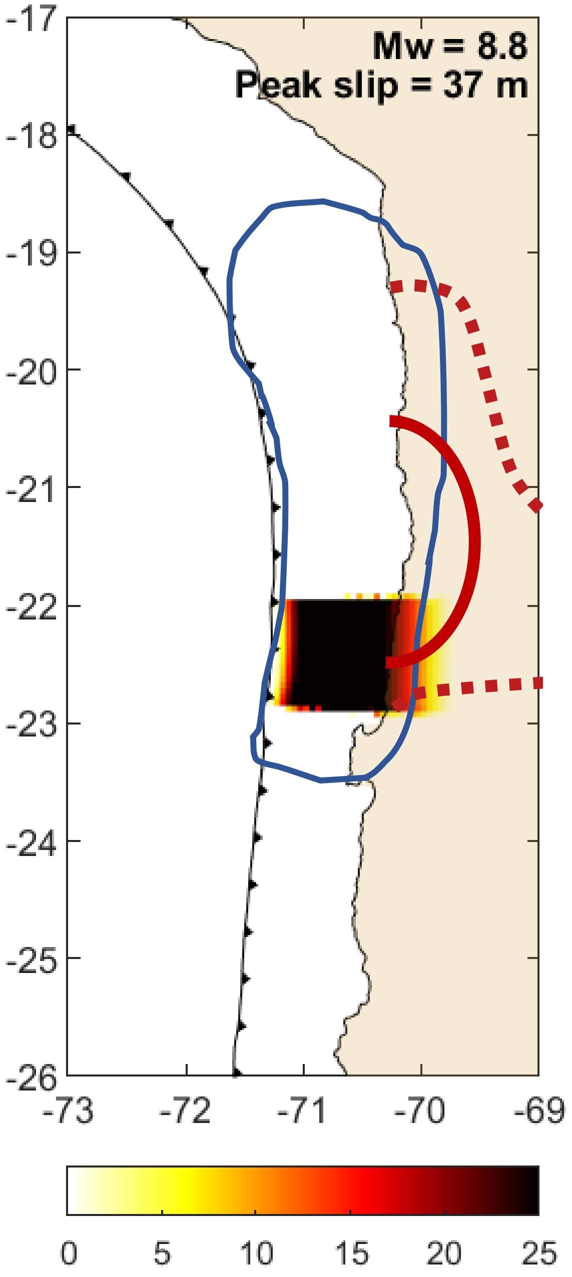


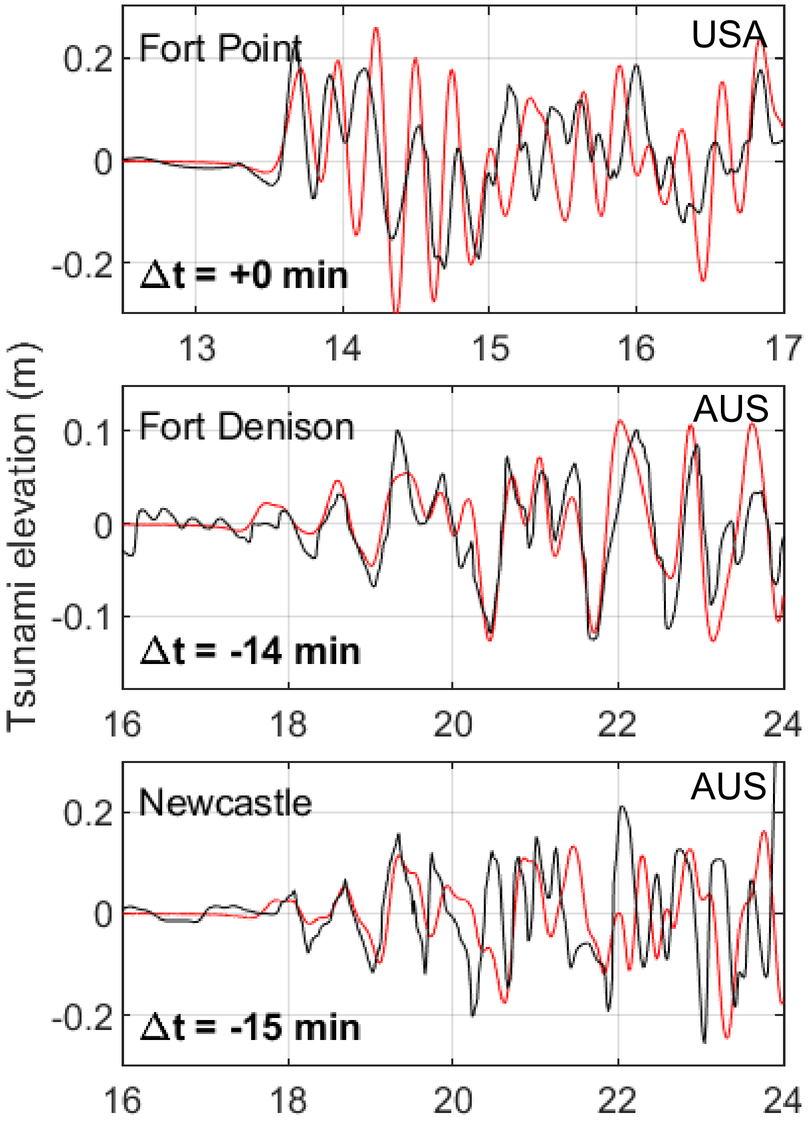


Case study 1

Rupture pattern of the Chile–Peru megathrust

The agreement remains good for slight rupture shifts

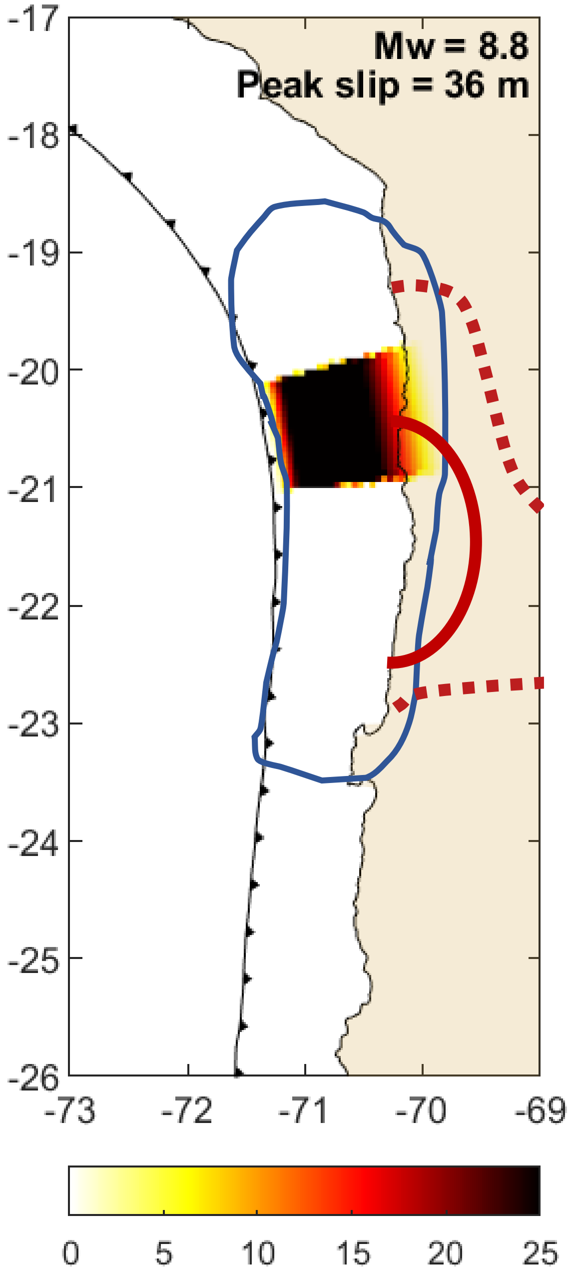


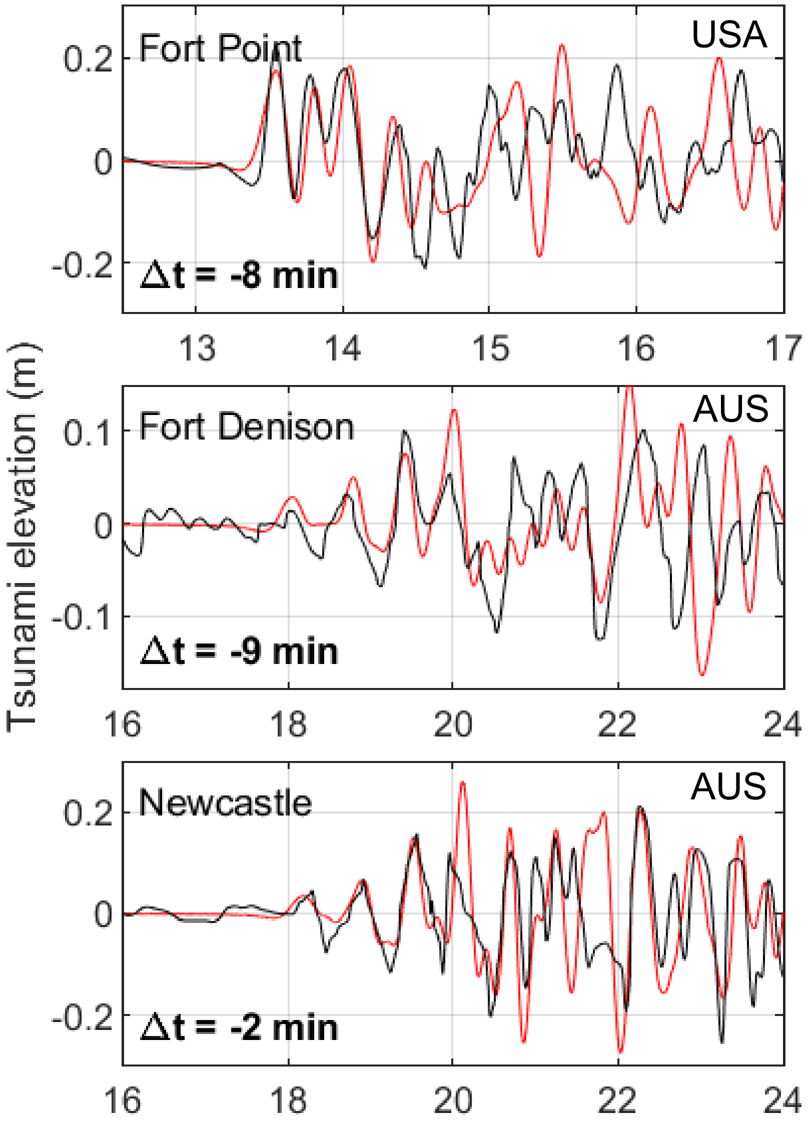


Case study 1

Rupture pattern of the Chile–Peru megathrust

The agreement remains good for slight rupture shifts



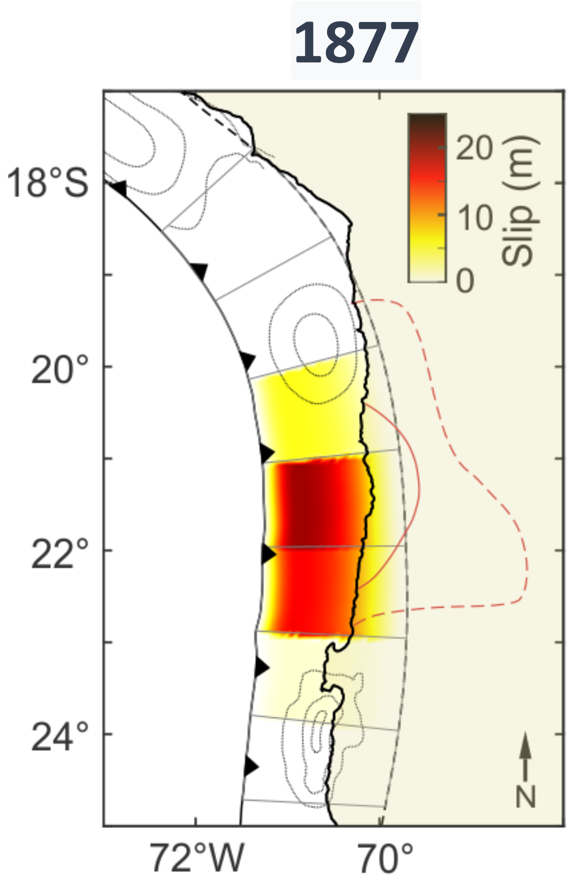


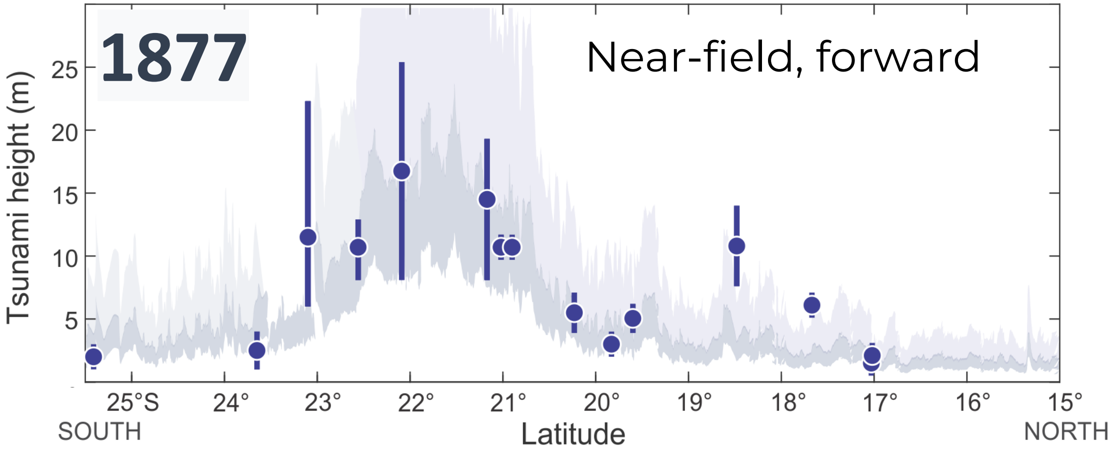
Case study 1

Rupture pattern of the Chile–Peru megathrust

The slip zones inferred from their far-field tsunamis are consistent with near-field reports of shaking and tsunami

The 1868 rupture was longer than 1877 but with lower slip





Formal inversions reveal additional nuances

Case study 1

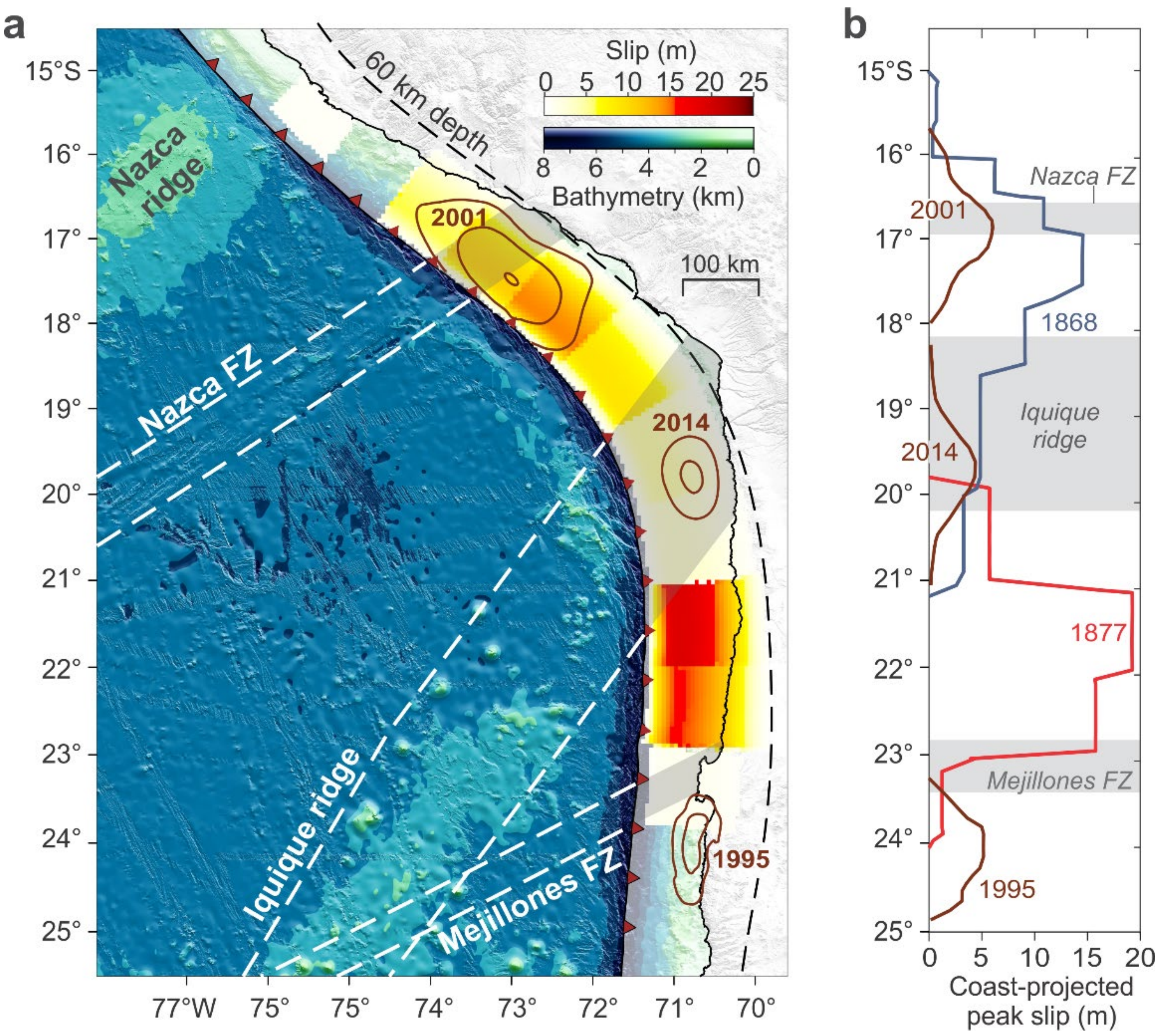
Rupture pattern of the Chile–Peru megathrust

With limited overlap of the peak slip zones, the 1868/1877/1995/2001/2014 sequence ruptured 1,000 km of megathrust

1868 spans the regions later broken in 2001 and 2014, including the gap between them

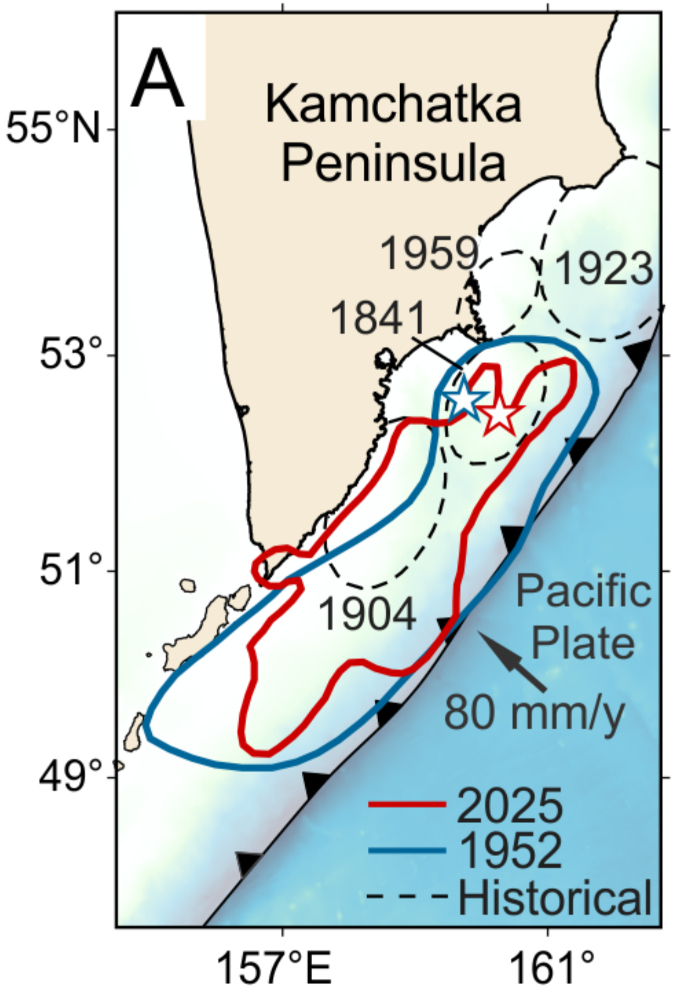
1877 is primarily centered on the gap between 1995 and 2014

M~9 events ruptured between subducted seafloor highs, whereas M~8 events ruptured within them.



Case study 2

1952 and 2025 ruptures:
same or complementary areas?

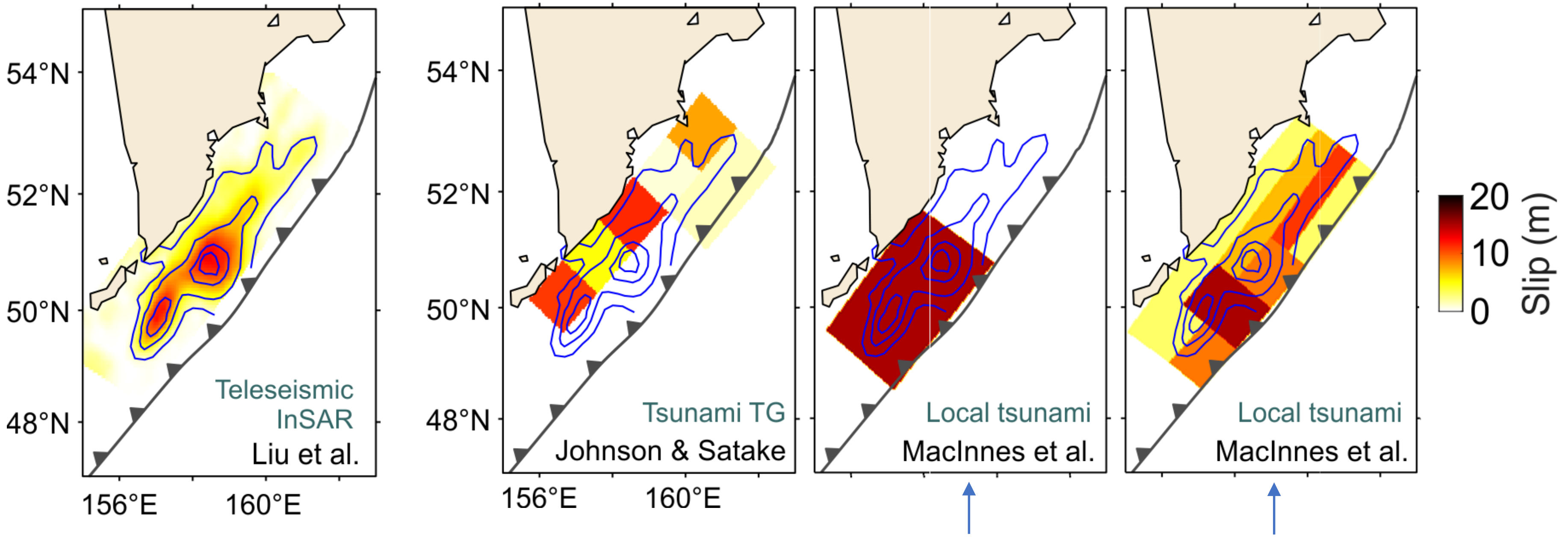


The **poor knowledge of the 1952** rupture zone poses greatest challenge to investigating the overlapping vs. gap-filling relationship

Explain
far-field tsunami

2025

1952



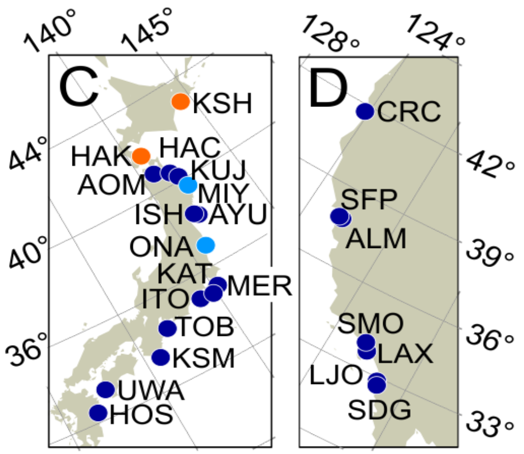
Explain near-field tsunami

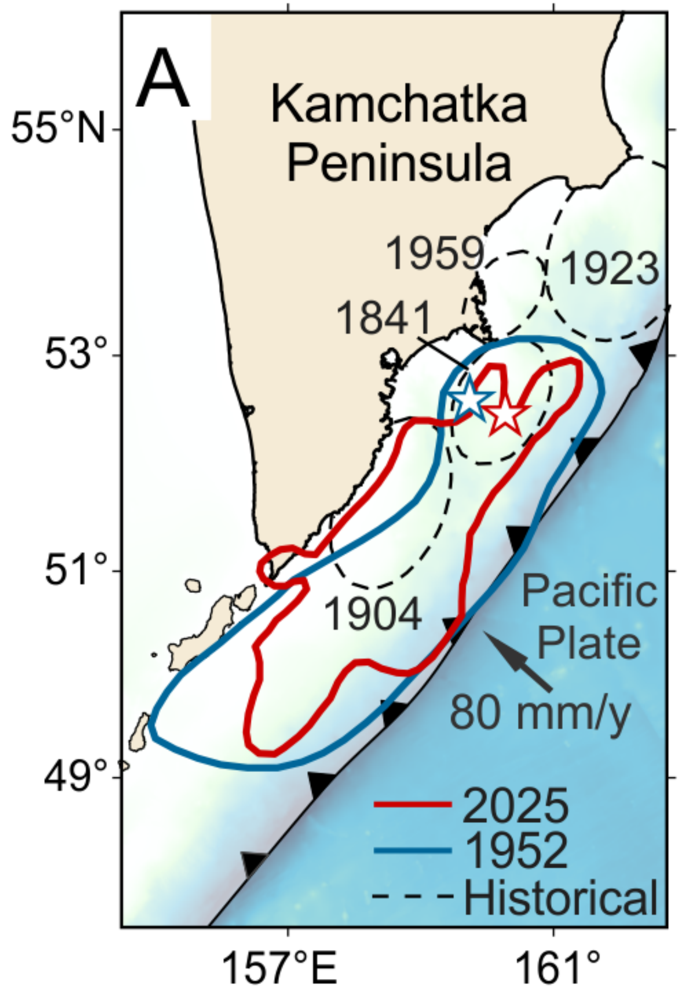
Case study 2

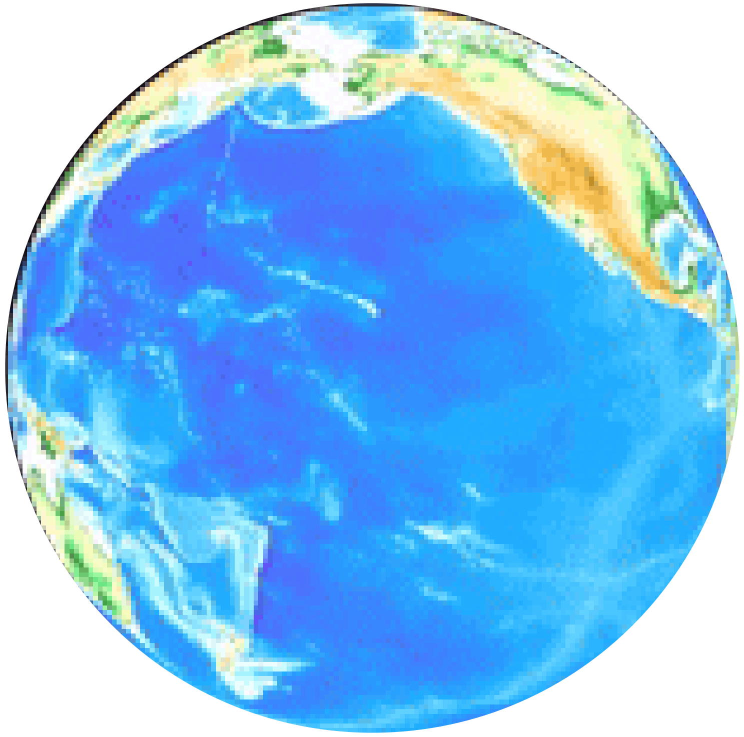
1952 and 2025 ruptures:
same or complementary areas?

Seismological records provide insufficient constraints, but…

Both events produced trans-Pacific **tsunamis** that were recorded by **50+ tide gauges**







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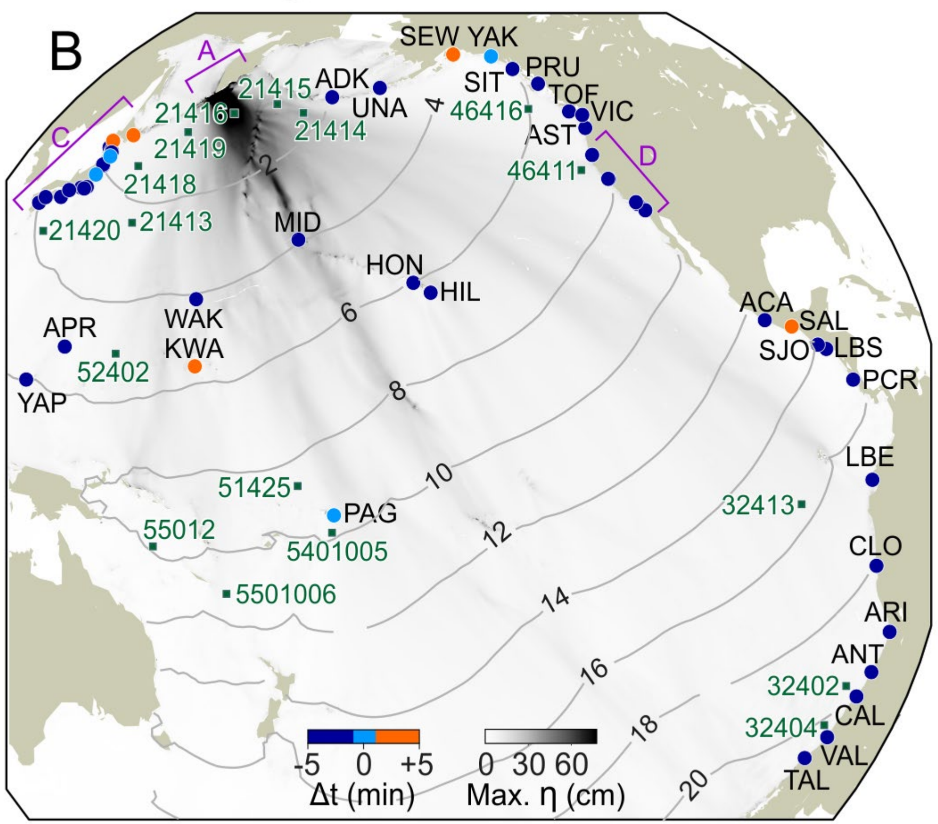
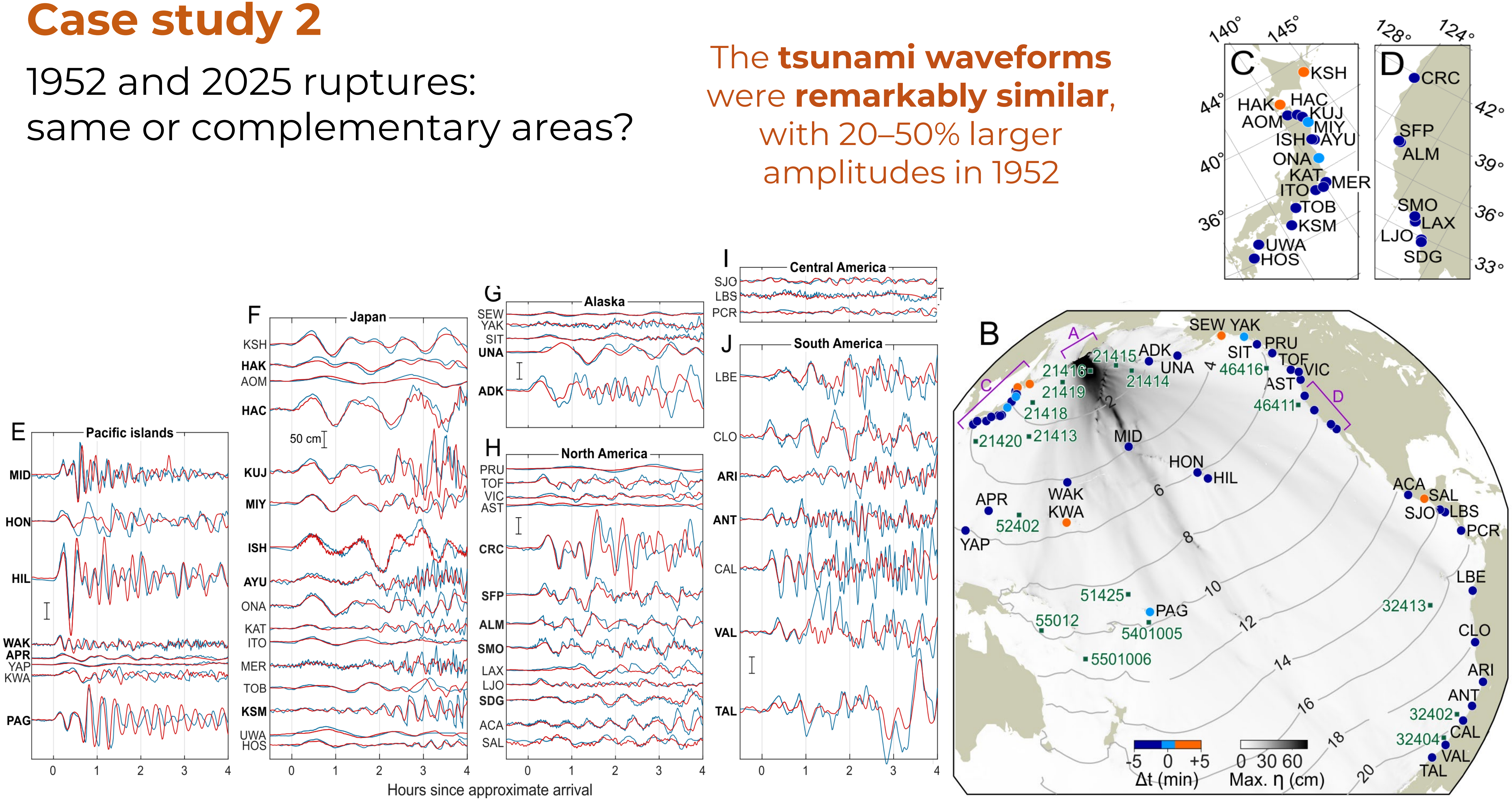


Case study 2

1952 and 2025 ruptures:
same or complementary areas?

The **tsunami waveforms** were **remarkably similar**, with 20–50% larger amplitudes in 1952

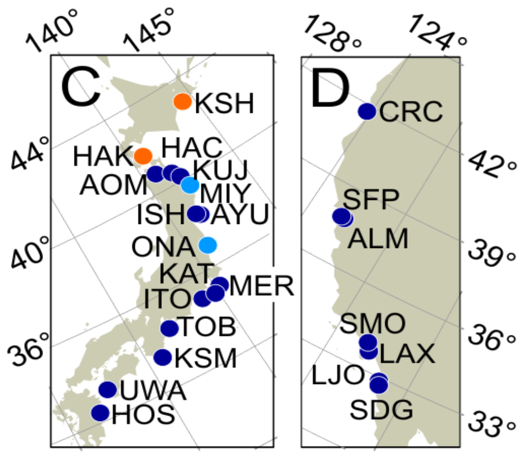


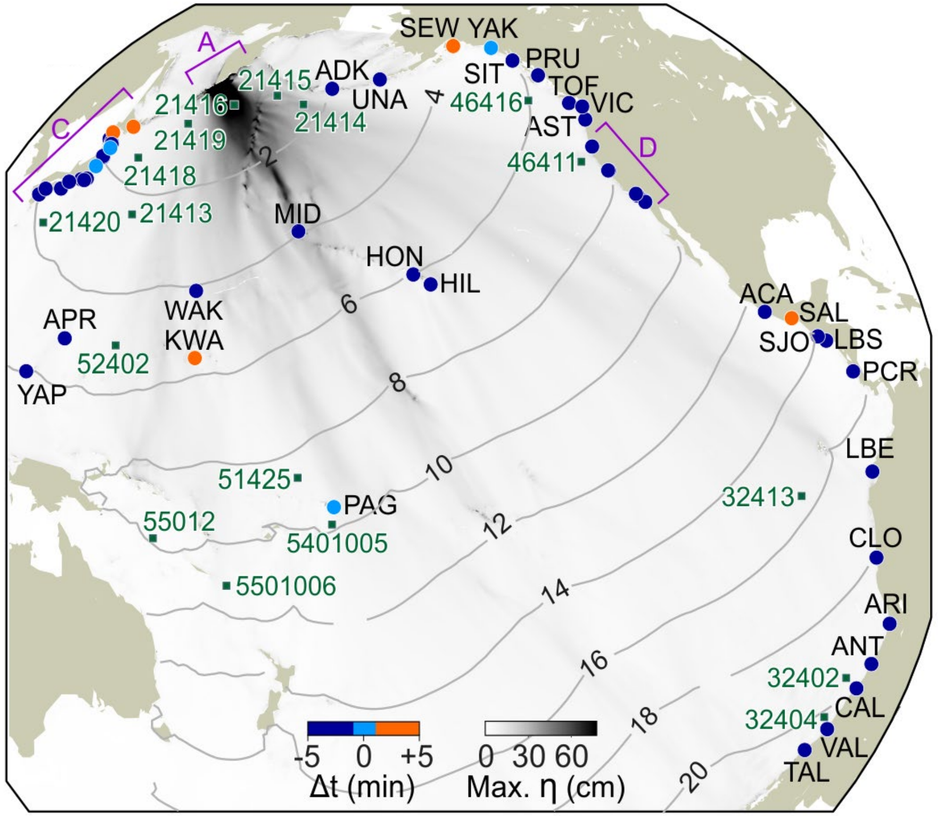
Case study 2

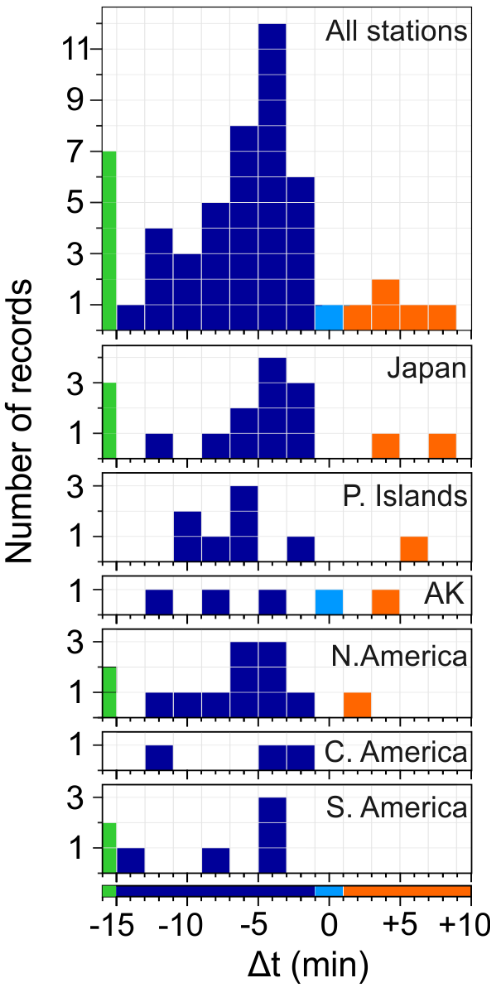
1952 and 2025 ruptures:
same or complementary areas?

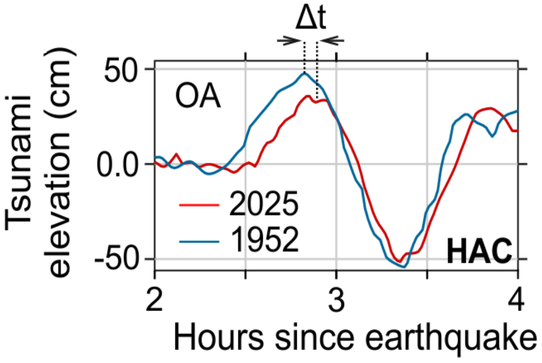
Tendency for Δt ≤ 0

→ The 1952 rupture zone is at a similar distance, or slightly closer, to the tide gauge stations







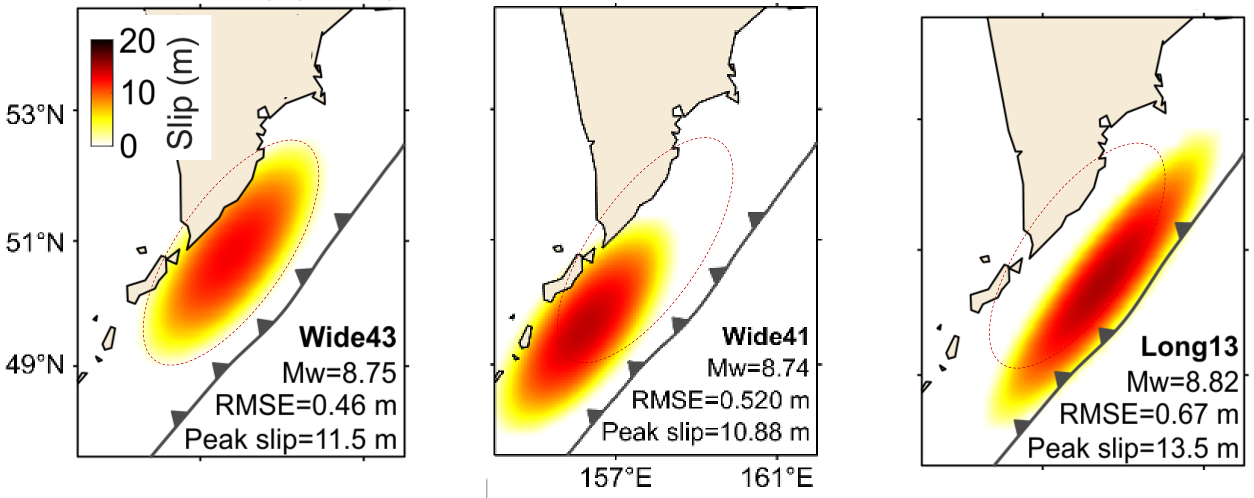


$$\Delta t = Travel\ Time_{1952} - Travel\ Time_{2025}$$

Shorter travel times in 1952
(i.e., Δt ≤ 0)

Case study 2

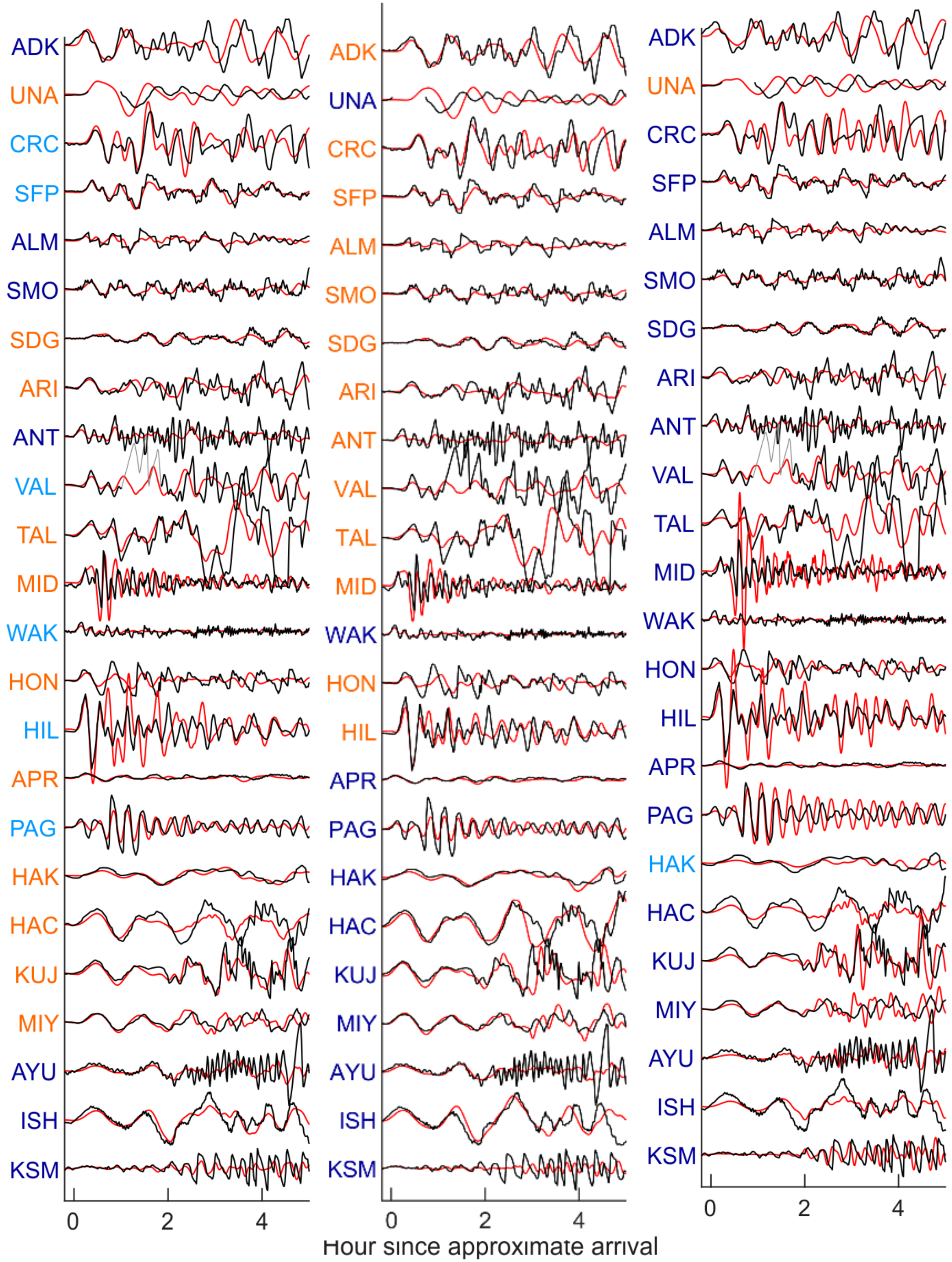
1952 and 2025 ruptures:
same or complementary areas?



Deep ruptures at different locations fit waveforms well but fail to explain **Δt ≤ 0**

A shallow, longer rupture explains **Δt ≤ 0** but fits waveforms less well

Waveform fit alone cannot constrain 1952 rupture location; **Δt provides necessary constraints**



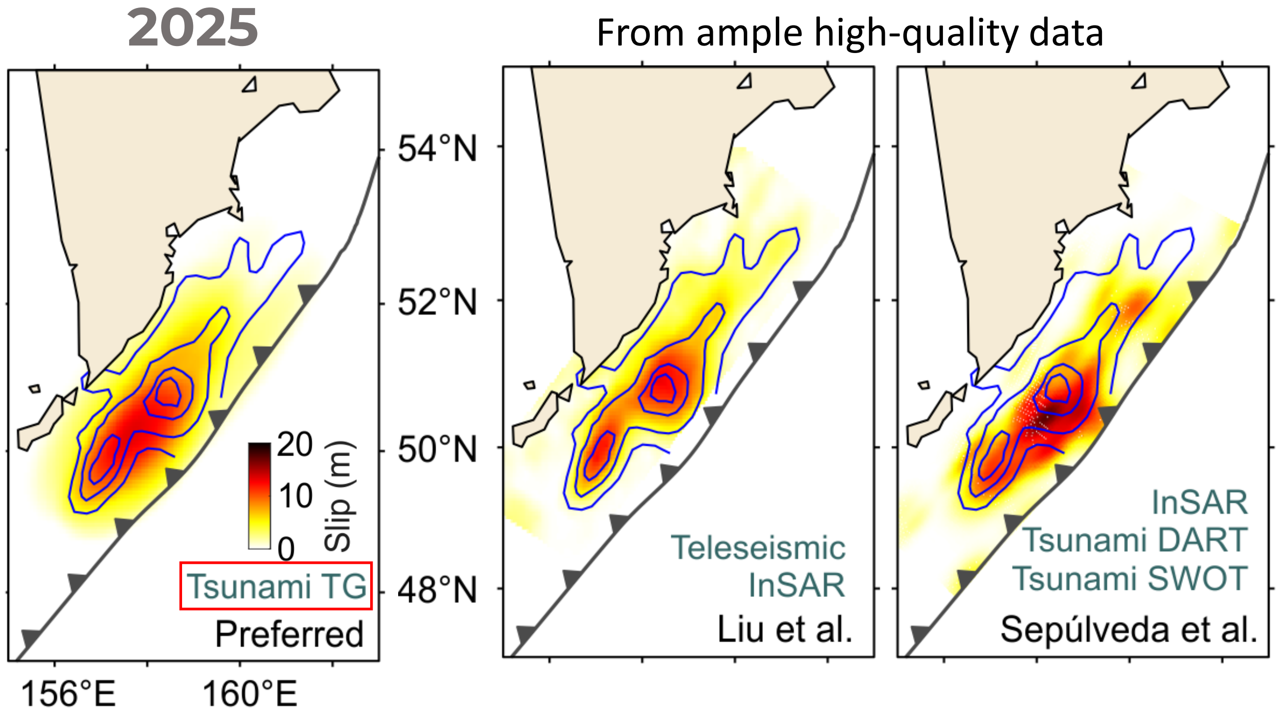
Case study 2

1952 and 2025 ruptures:
same or complementary areas?

The 2025 slip model from tide-gauge data is similar to those from high-quality data

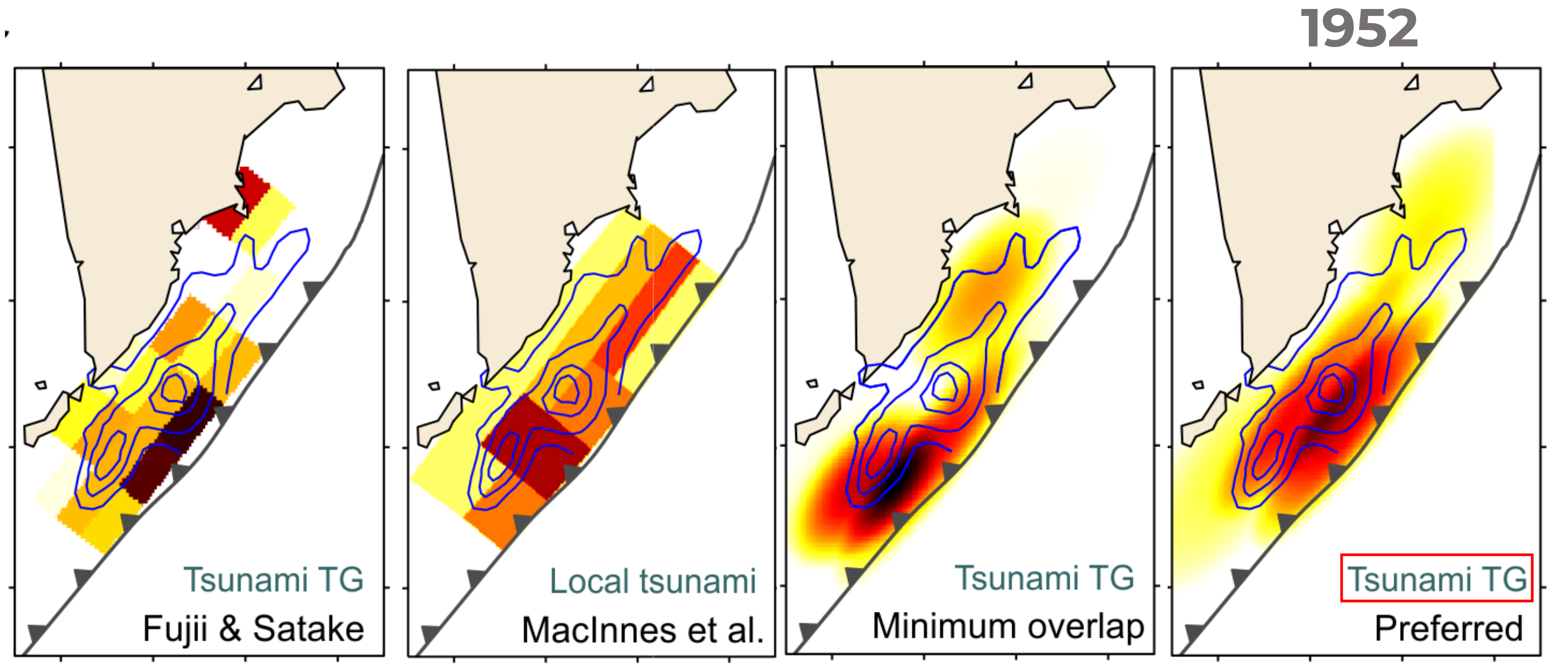
→ Highlights key constraints provided by tide-gauge data

→ Gives us confidence in the 1952 slip model derived using the same data



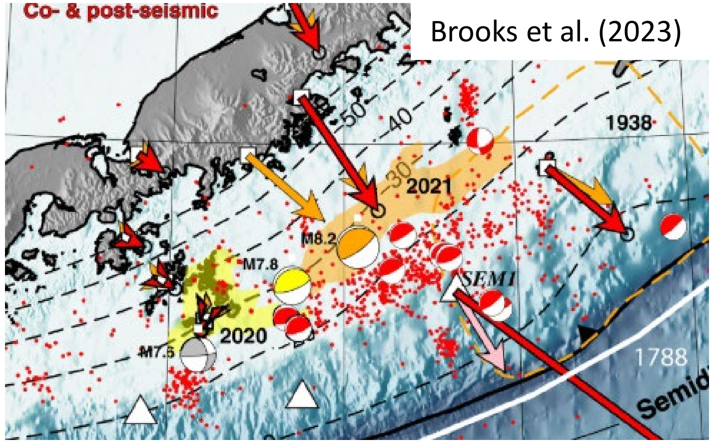
The **substantial overlap** of 2025 and 1952 can be **explained by fast energy buildup in a viscoelastic Earth**

(*sensu* Wang et al., 2021 GRL)



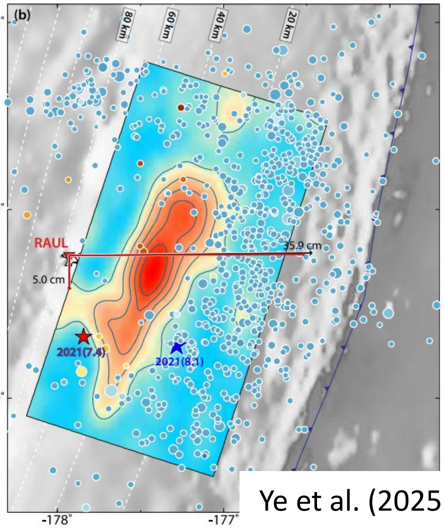
Case study 3 1971 Chile earthquake: rupture–aftershock depth offset

A Mw 8.2 2021 Alaska



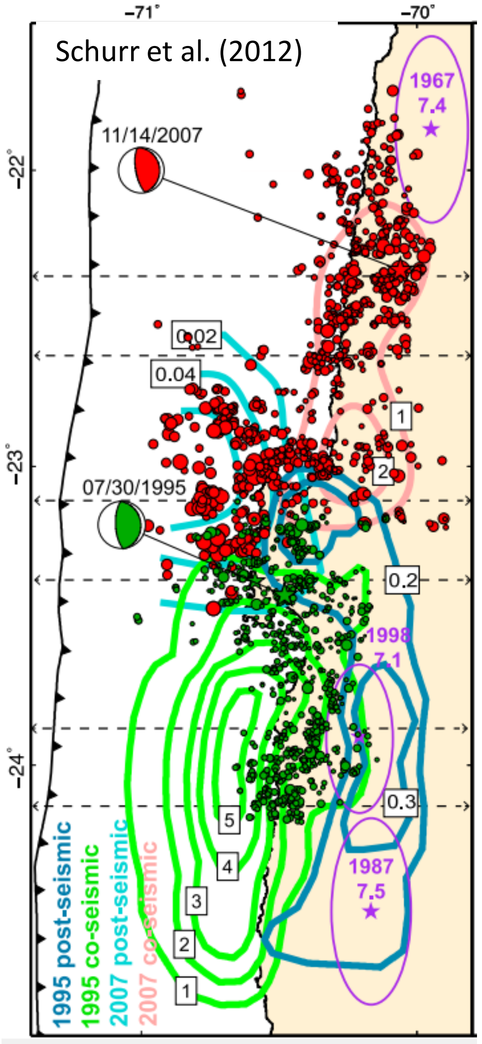
Brooks et al. (2023)

B Mw 8.1 2021 Kermadek



Ye et al. (2025)

C Mw 7.7 2007 and Mw 8.1 1995 Chile

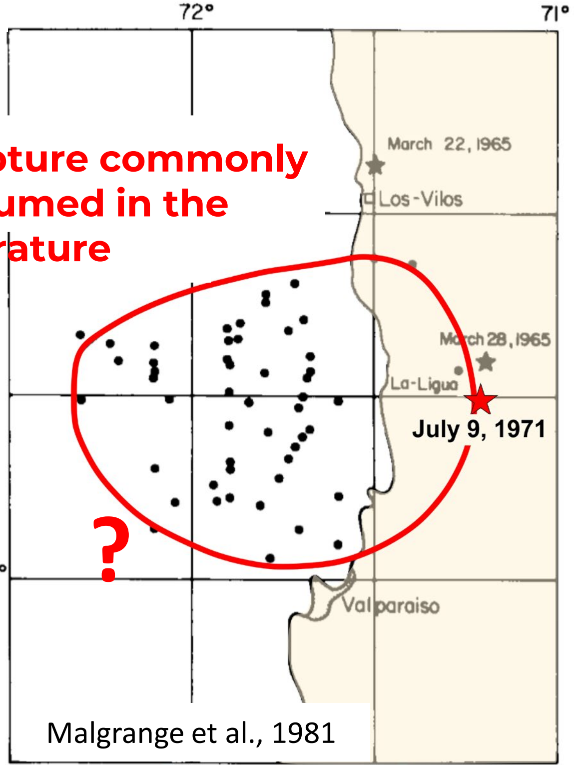


Schurr et al. (2012)

Depth offset observed in recent rupture-aftershok sequences

... challenges historical rupture zones derived from aftershocks

D Mw 7.8 1971 Chile



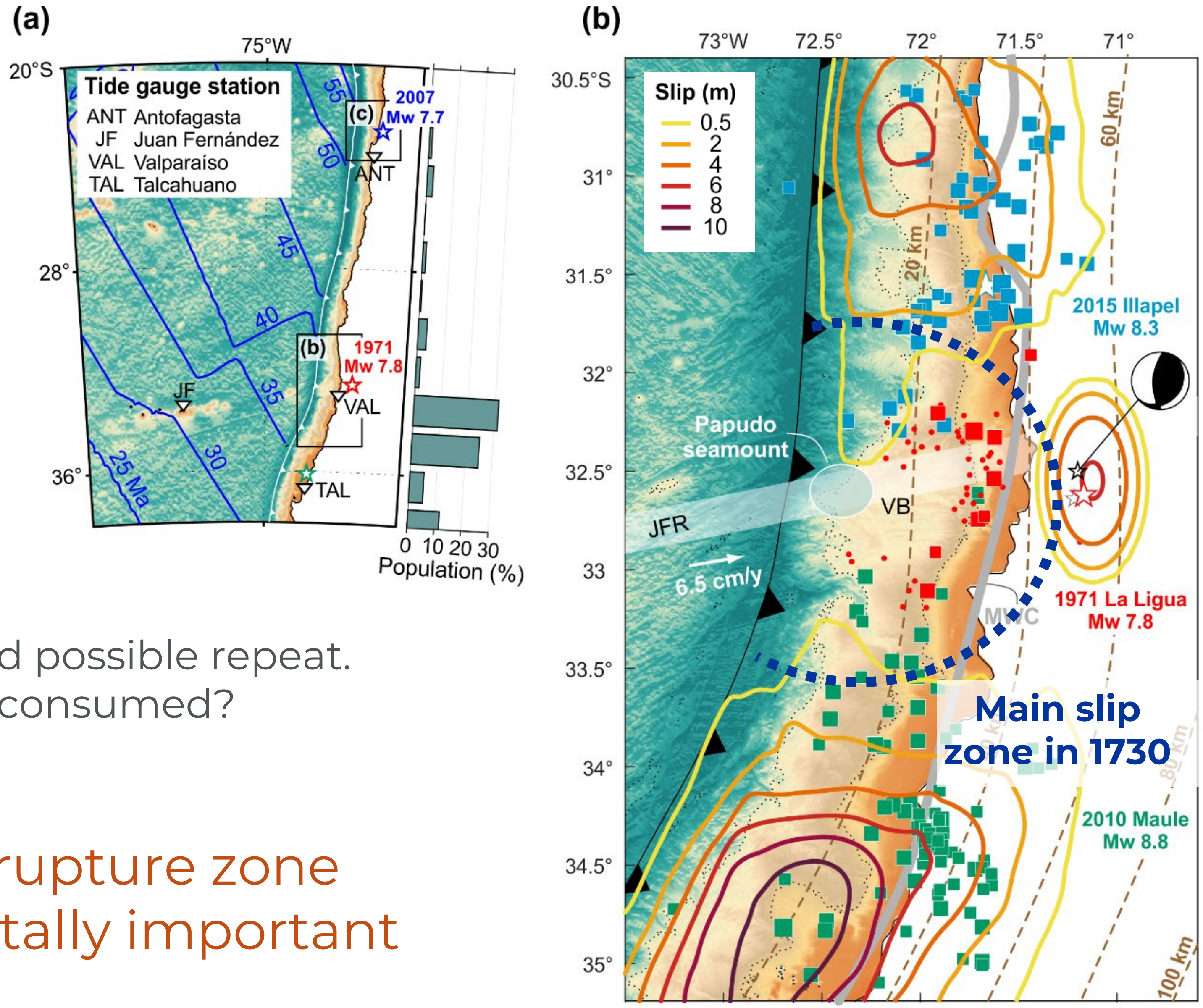
Malgrange et al., 1981

Case study 3 1971 Chile earthquake: rupture–aftershock depth offset

The 1971 earthquake (M7.8) ruptured between 2010 M8.8 and 2015 M8.3, where Chile’s population concentrates

Aftershocks occurred offshore despite hypocenter ~60 km beneath land

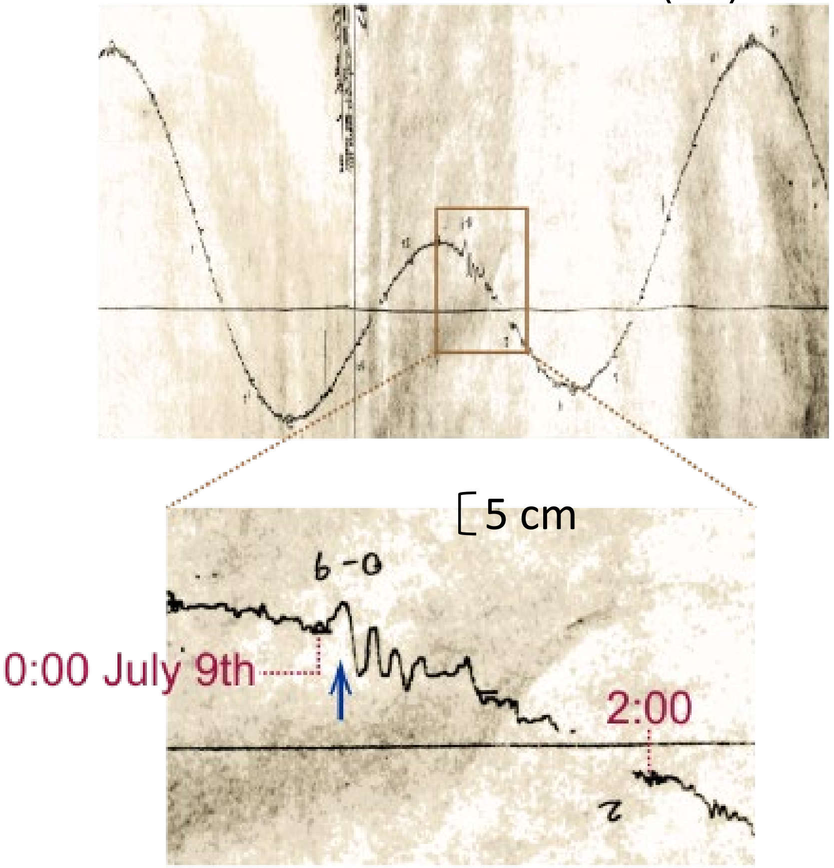
Offshore tsunamigenic rupture in 1730, and possible repeat. How much offshore slip did the 1971 consumed?

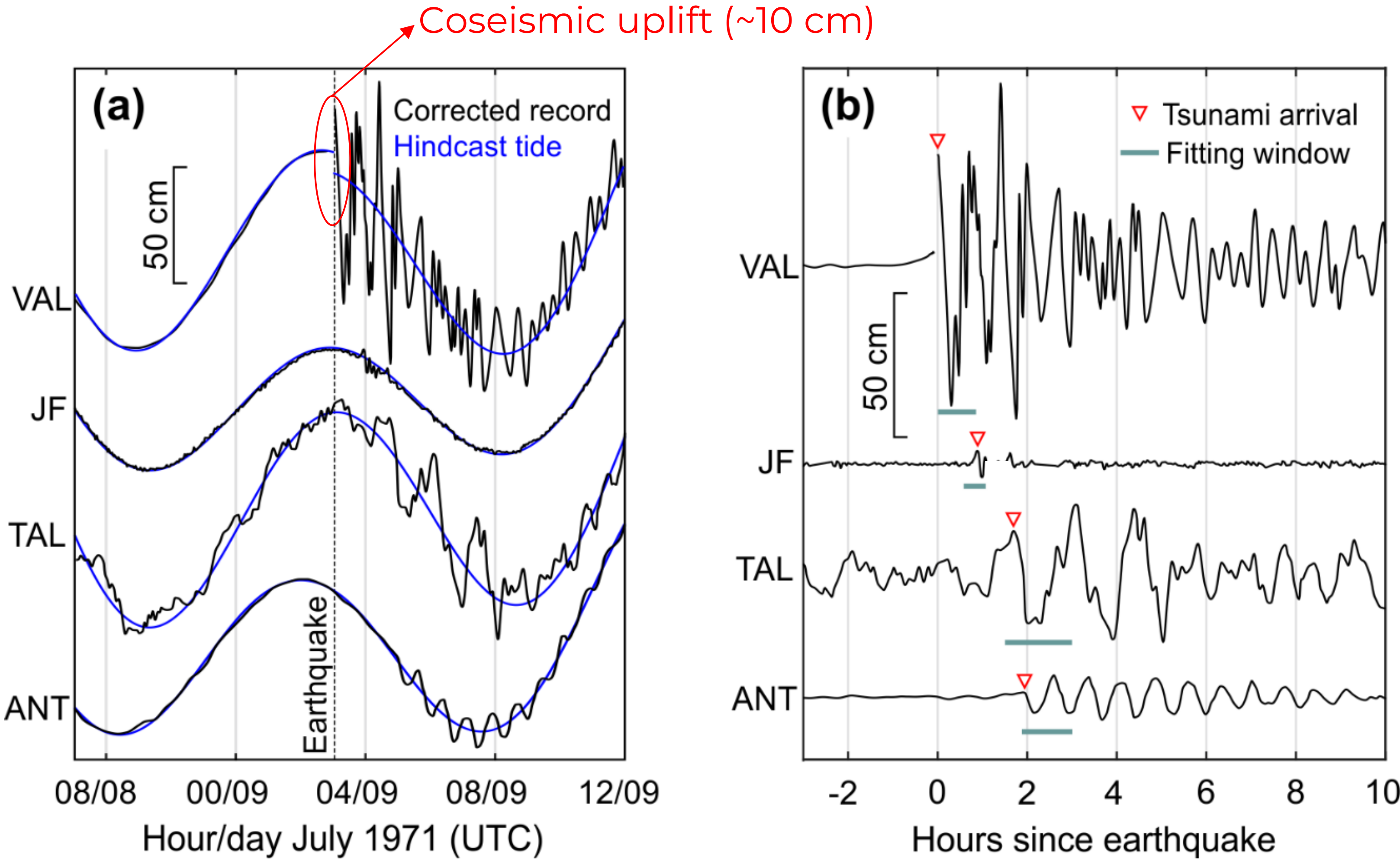


Constraining the 1971 rupture zone is scientifically and societally important

Case study 3 1971 Chile earthquake: rupture–aftershock depth offset

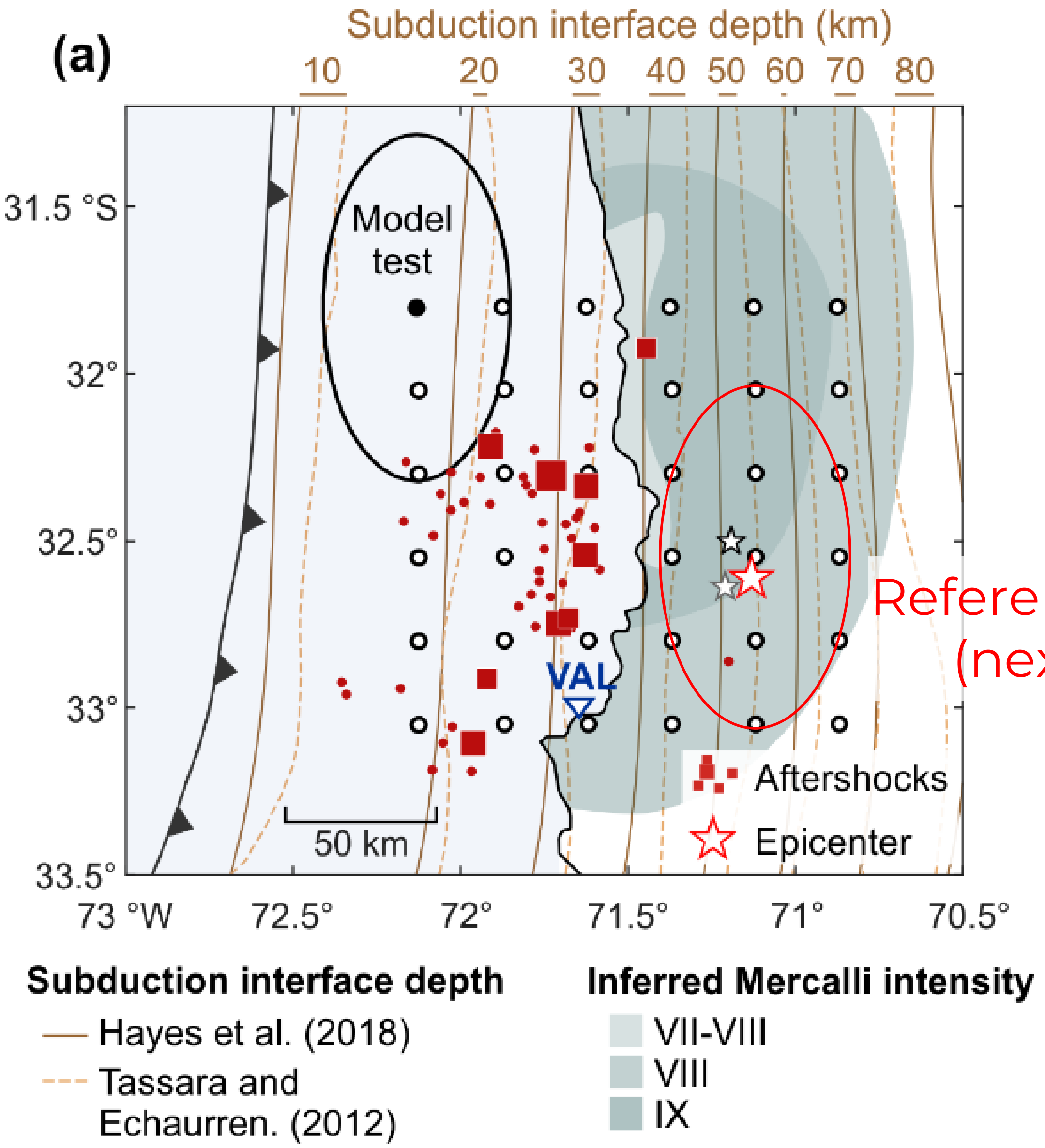
Juan Fernández (JF)



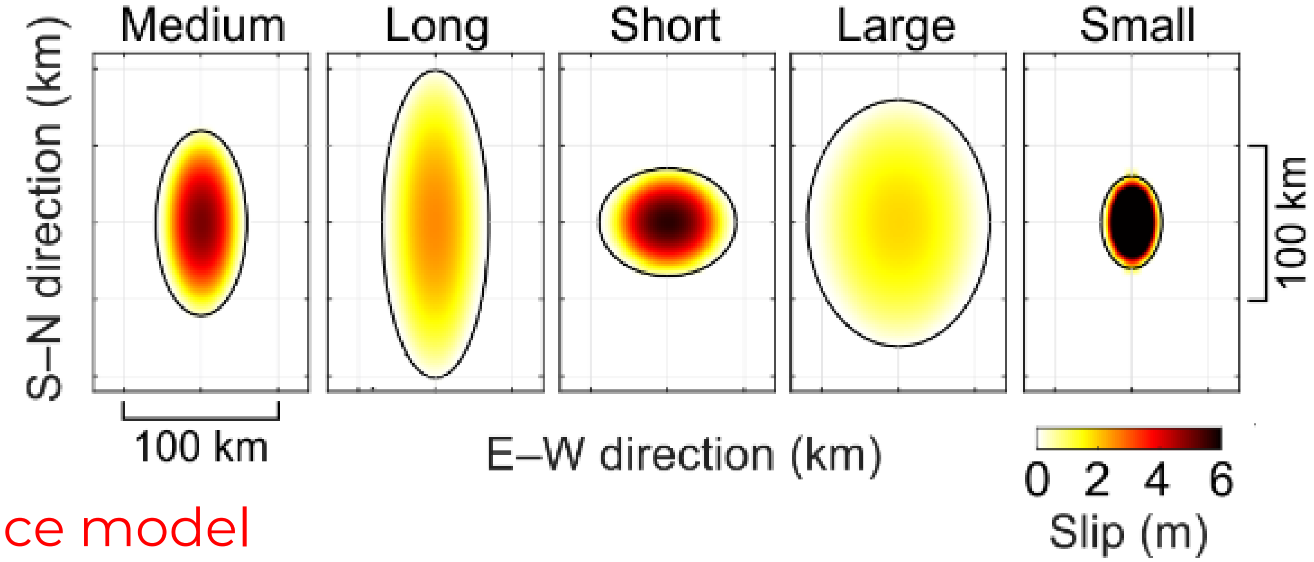


Case study 3

1971 Chile earthquake: rupture–aftershock depth offset



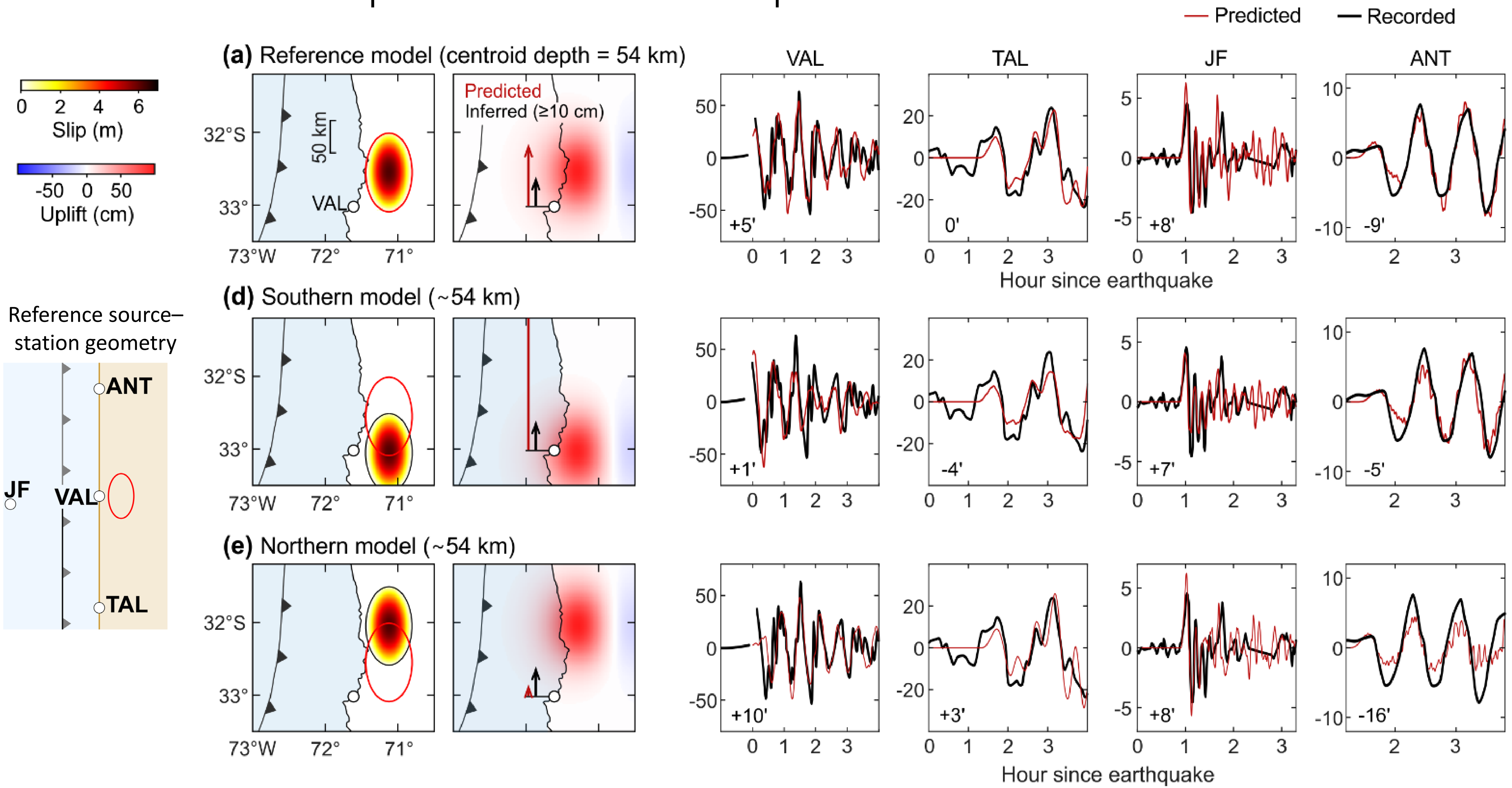
Reference model (next slide)



Simple rupture models to explore what tsunami records reveal about the 1971 rupture zone

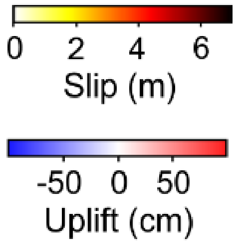
Case study 3

1971 Chile earthquake: rupture–aftershock depth offset

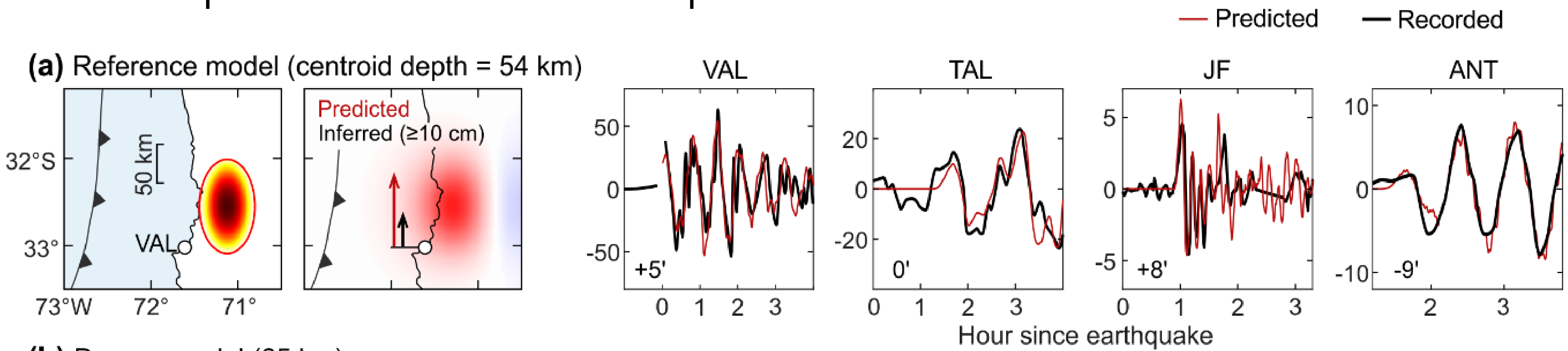

Reference source–station geometry

Case study 3

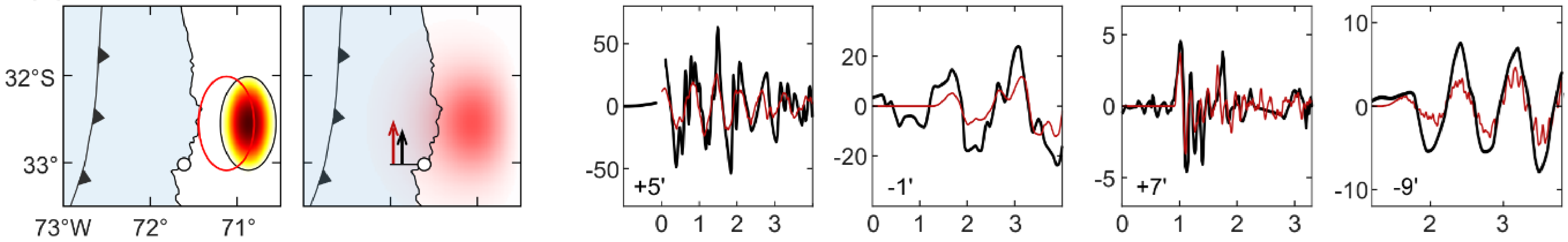
1971 Chile earthquake: rupture–aftershock depth offset



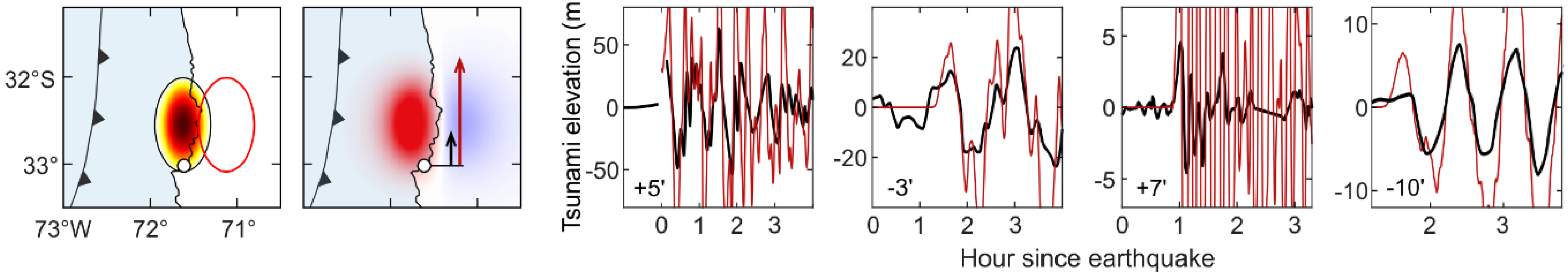
(a) Reference model (centroid depth = 54 km)



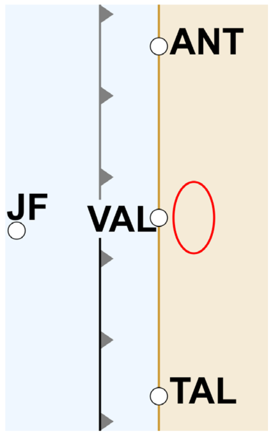
(b) Deeper model (65 km)



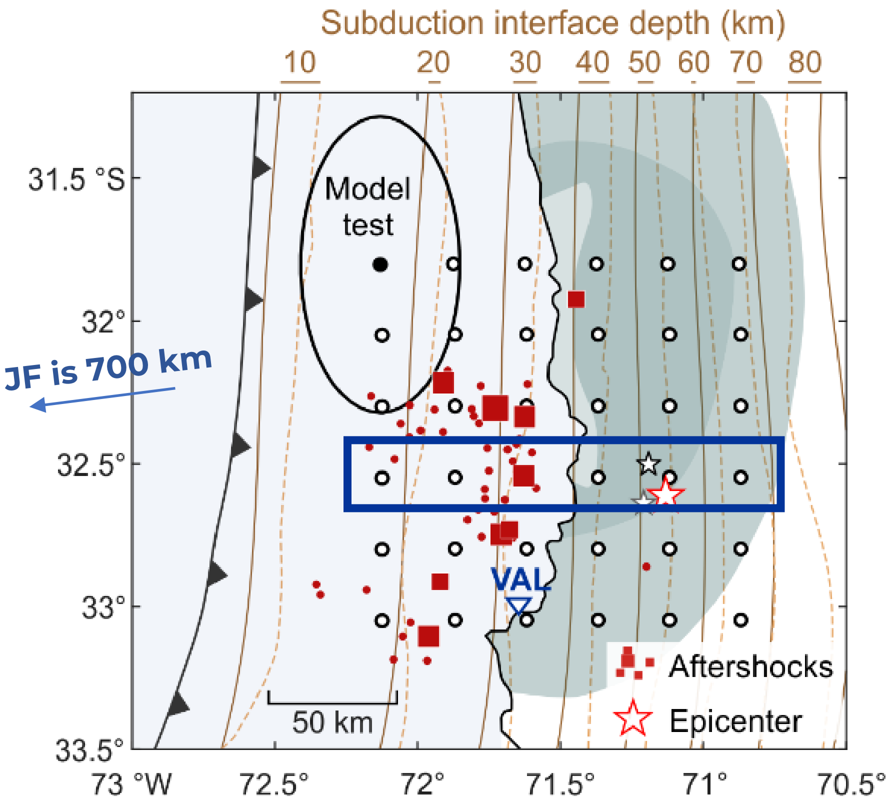
(c) Shallower model (33 km)

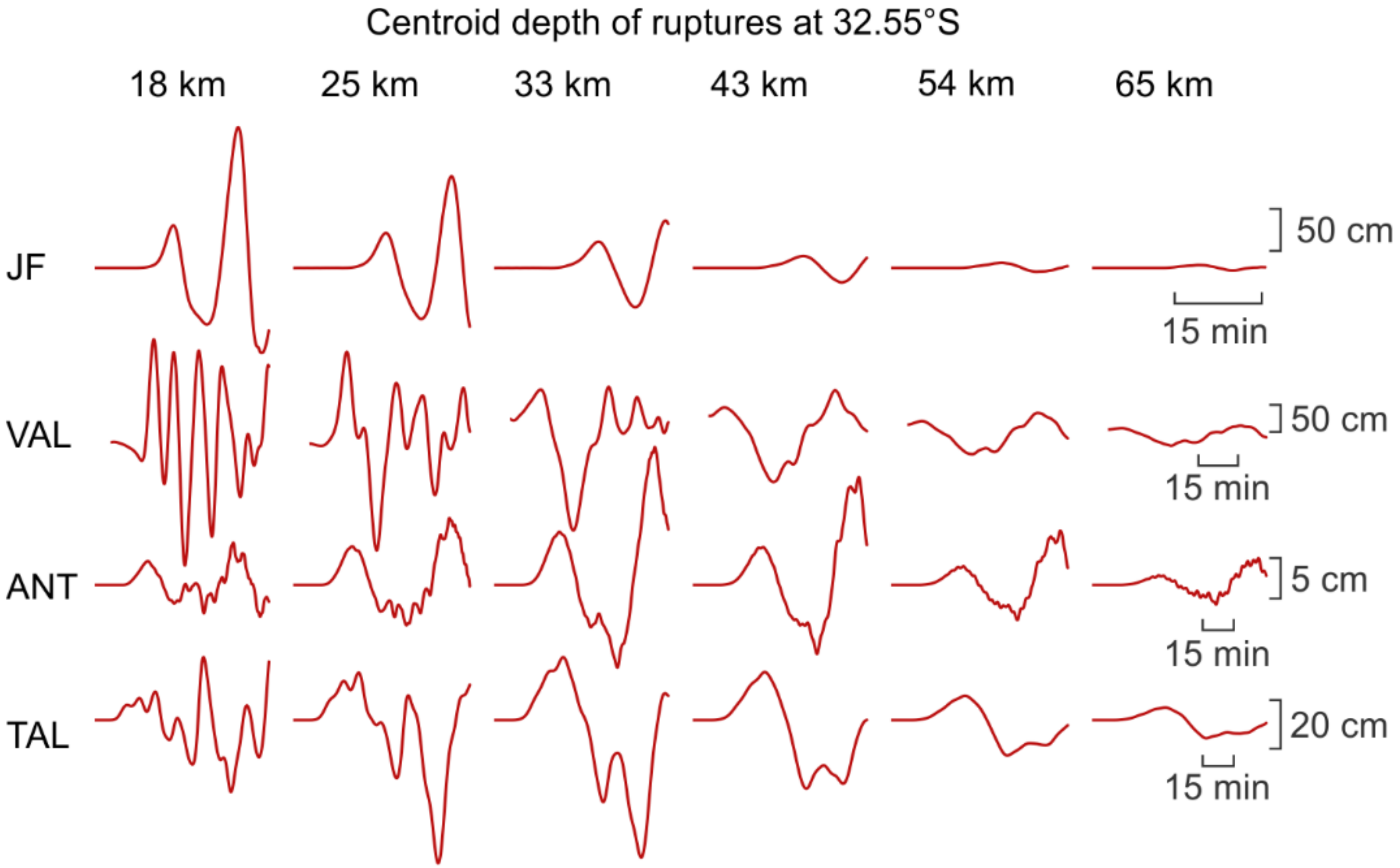


Reference source–station geometry

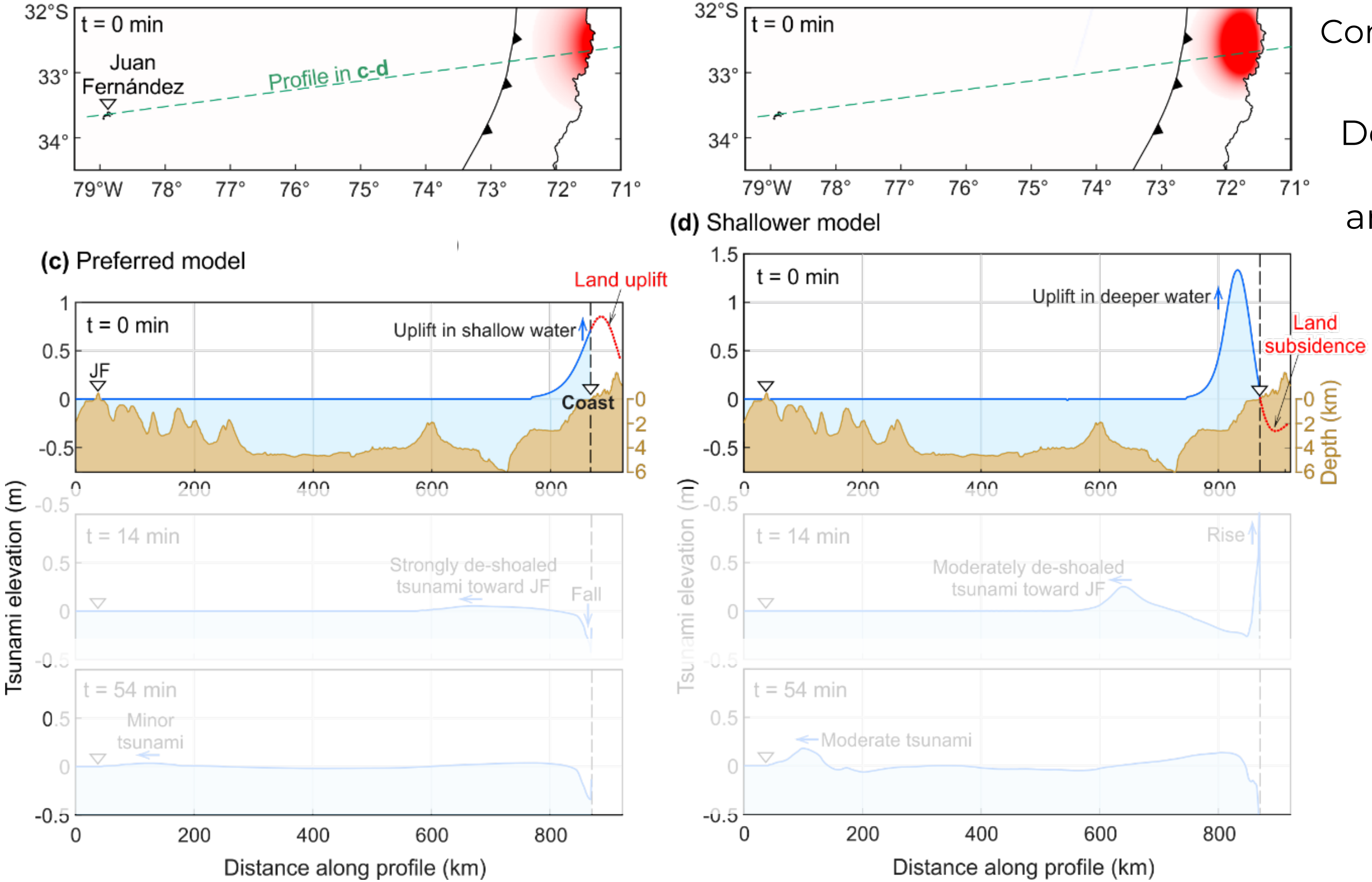


Case study 3 1971 Chile earthquake: rupture–aftershock depth offset





Case study 3 1971 Chile earthquake: rupture–aftershock depth offset

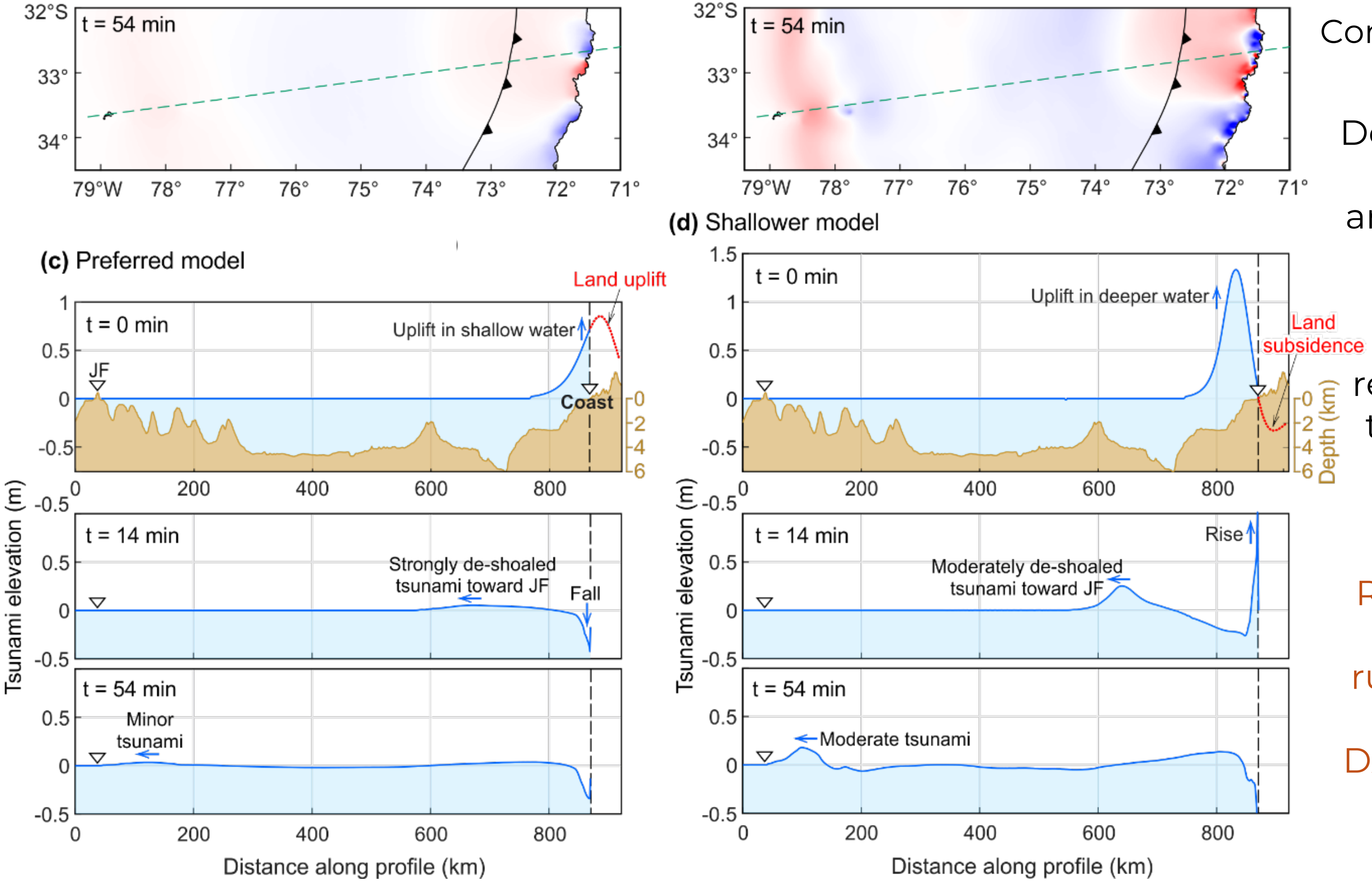

(c) Preferred model

(d) Shallower model

Compared to offshore rupture

Deep rupture beneath land causes land uplift and uplift in shallow water.

Case study 3 1971 Chile earthquake: rupture–aftershock depth offset



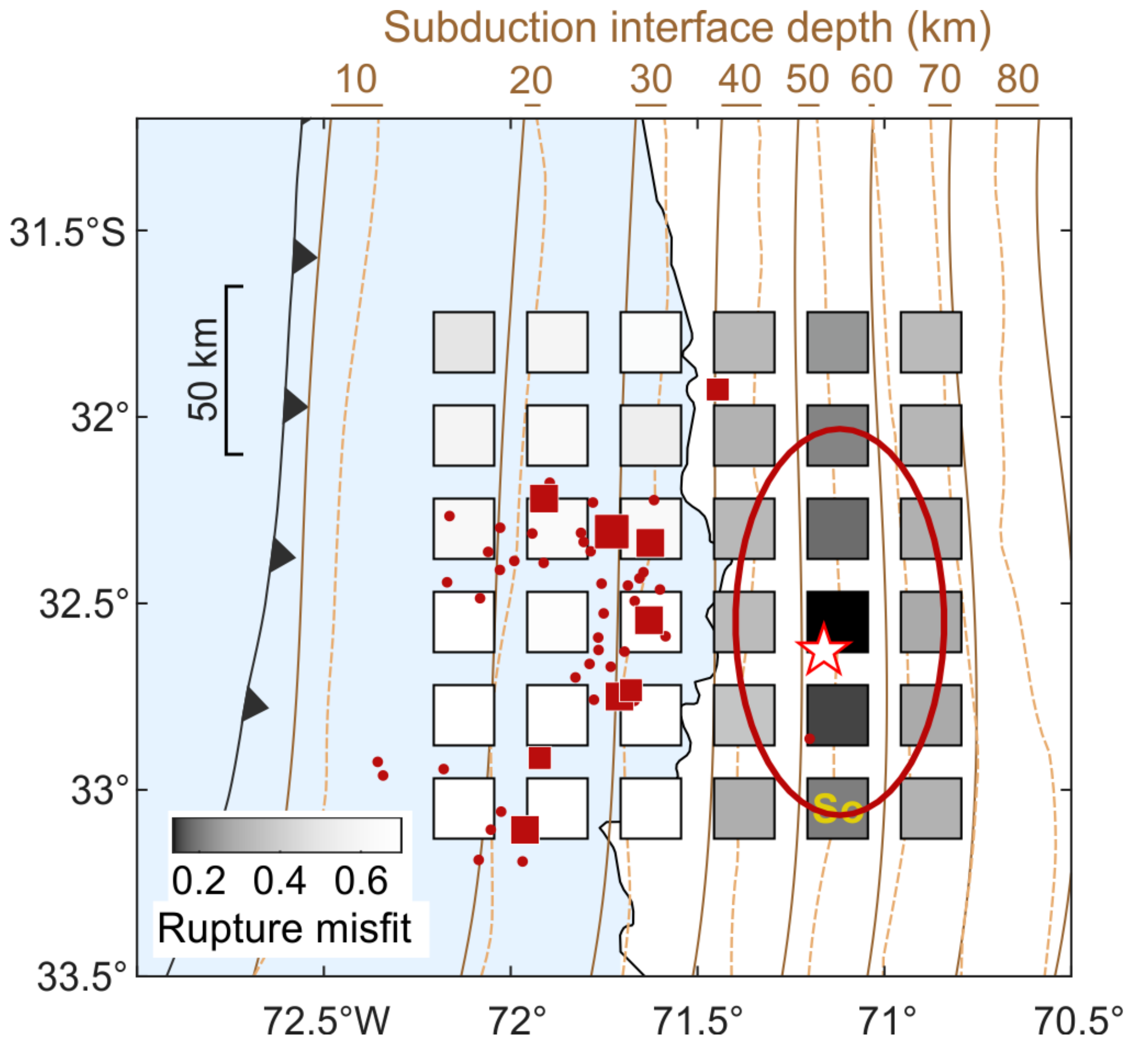
Compared to offshore rupture

Deep rupture beneath land
causes land uplift
and uplift in shallow water.

Uplift in shallow water
results in small-amplitude
tsunamis in deep waters
(due to de-shoaling)

Records at JF can provide
strong constraints on
rupture depth in historical
earthquakes, much like
DART buoys do for modern
earthquakes

Case study 3 1971 Chile earthquake: rupture–aftershock depth offset



The tsunami records favor a rupture centered around the epicenter, at 50 km beneath land

All rupture models that explain tsunami data are centered downdip of the aftershock zone.

The 1971 earthquake consumed little, if any, of the potentially accumulated offshore slip since 1730

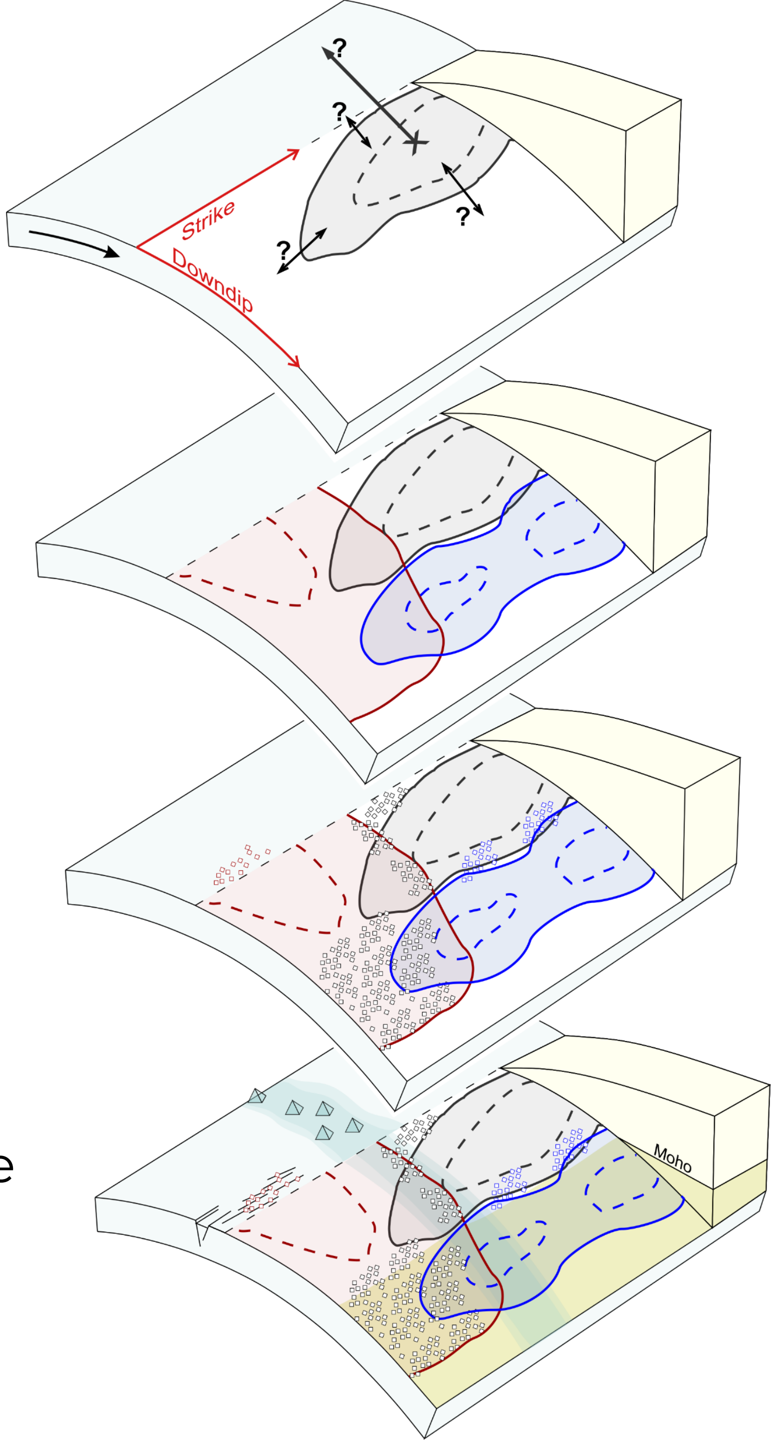
Conclusions

Historical tsunami records have the potential to extend our view of megathrust behavior beyond the instrumental era.

Revised historical rupture zones reinforce the role of subducted seafloor relief in rupture segmentation
(e.g., Chile–Peru earthquakes).

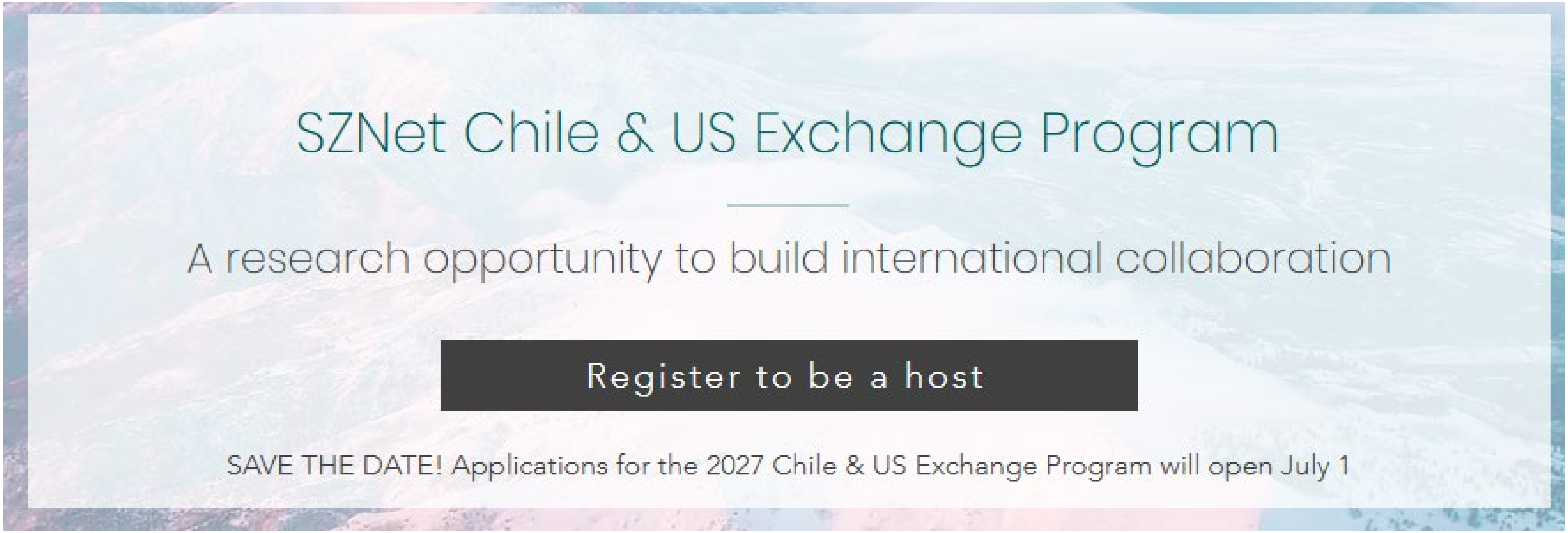
Great earthquakes may repeatedly rupture the same segment within only half of the average recurrence interval
(e.g., 1952 and 2025 Kamchatka earthquakes).

Aftershock zones may not accurately represent megathrust rupture zones, and some historical ruptures should be revisited
(e.g., 1971 central Chile earthquake).



Visit us in Chile and let’s decipher together tsunami records to learn about historical earthquakes

matias.carvajal@pucv.cl



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