Great Cascadia megathrust earthquakes: Past, present, and future

Kelin Wang

Pacific Geoscience Centre, Geological Survey of Canada,
Natural Resources Canada

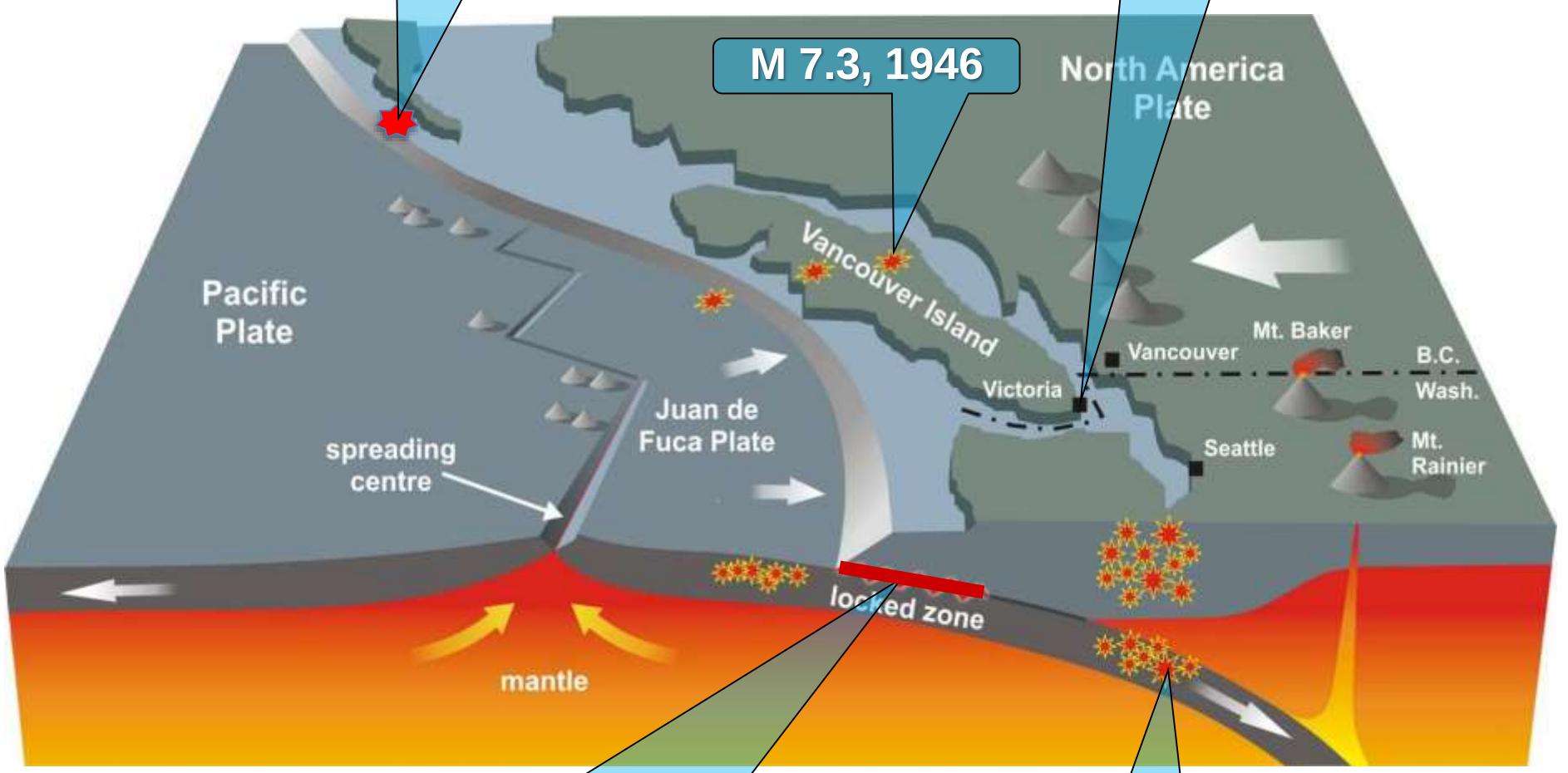
January 26, 2017,
On the 317th anniversary of the AD 1700 great Cascadia earthquake

Megathrust earthquakes and their tsunamis pose threat to communities along much of the west coast of North America. Without an instrumentally recorded great Cascadia earthquake, our knowledge of these events that guides risk mitigation is based on geological observations, geodetic monitoring, geophysical modeling, and global comparison. In this webinar, Kelin Wang will review the state of knowledge of relevant observational and theoretical studies and discuss remaining scientific challenges.

Kelin Wang

Research Scientist
Geological Survey of Canada
Natural Resources Canada

The Cascadia Subduction Zone

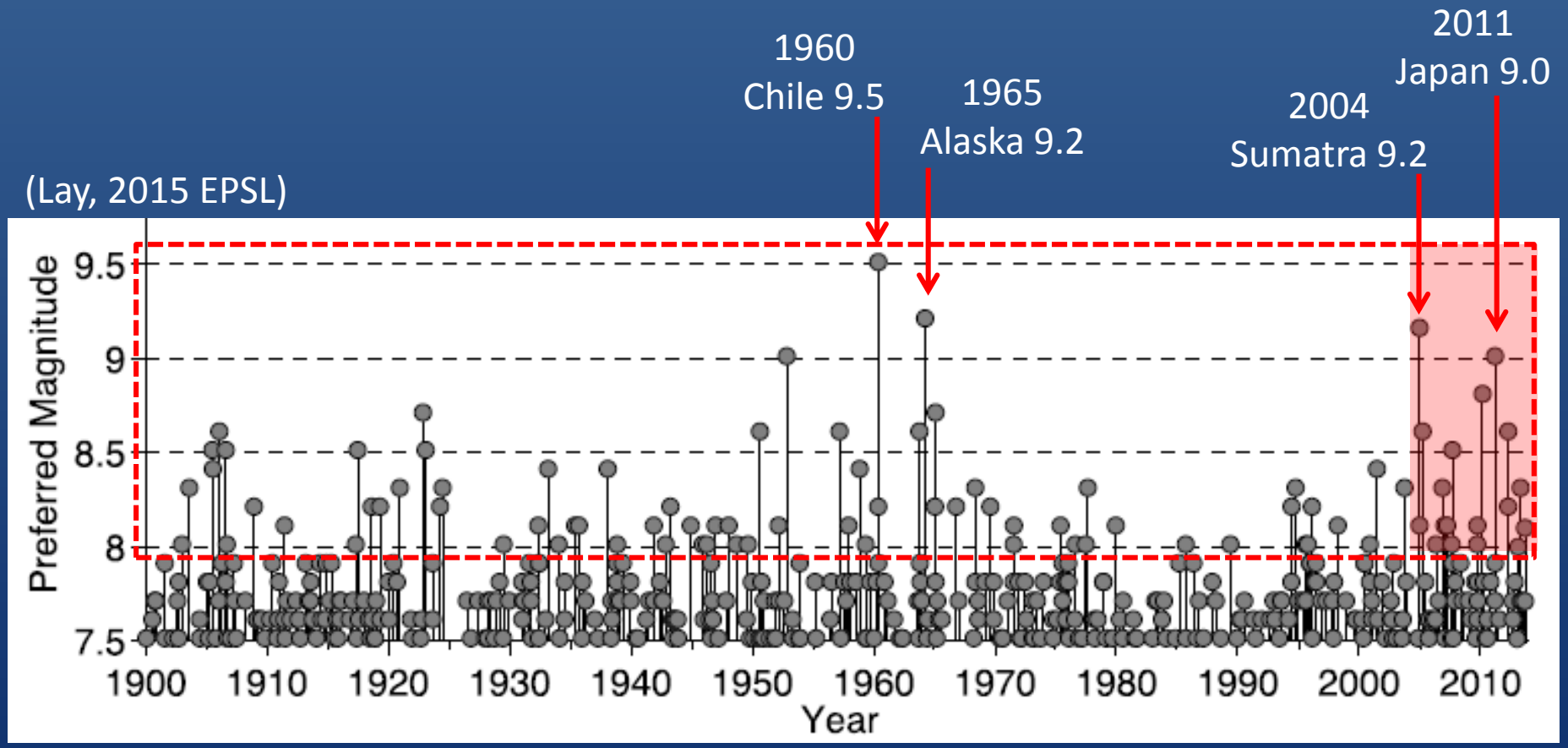


Rupture zone of M ~ 9 Cascadia earthquake, 1700

M 6.8, 2001


2013 Sea of Okhotsk
Mw 8.3
2006/2007 Kuril
Mw 8.4, 8.1
2004, 2005, 2007
Sumatra
Mw 9.2, 8.7, 8.5
2011 Japan
2007 Solomon Is.
Mw 8.2
2013 Santa Cruz Is.
Mw 8.1, 8.0
2012 Indo-
Australia
Mw 8.7, 8.2
2006 Tonga
Mw 8.0
2014 Chile
Mw 8.1
2015
Chile
Mw 8.3
2010 Chile
Mw 8.8
2004 Macquarie
Mw 8.1
Cascadia
in global context

(Lay, 2015 EPSL)

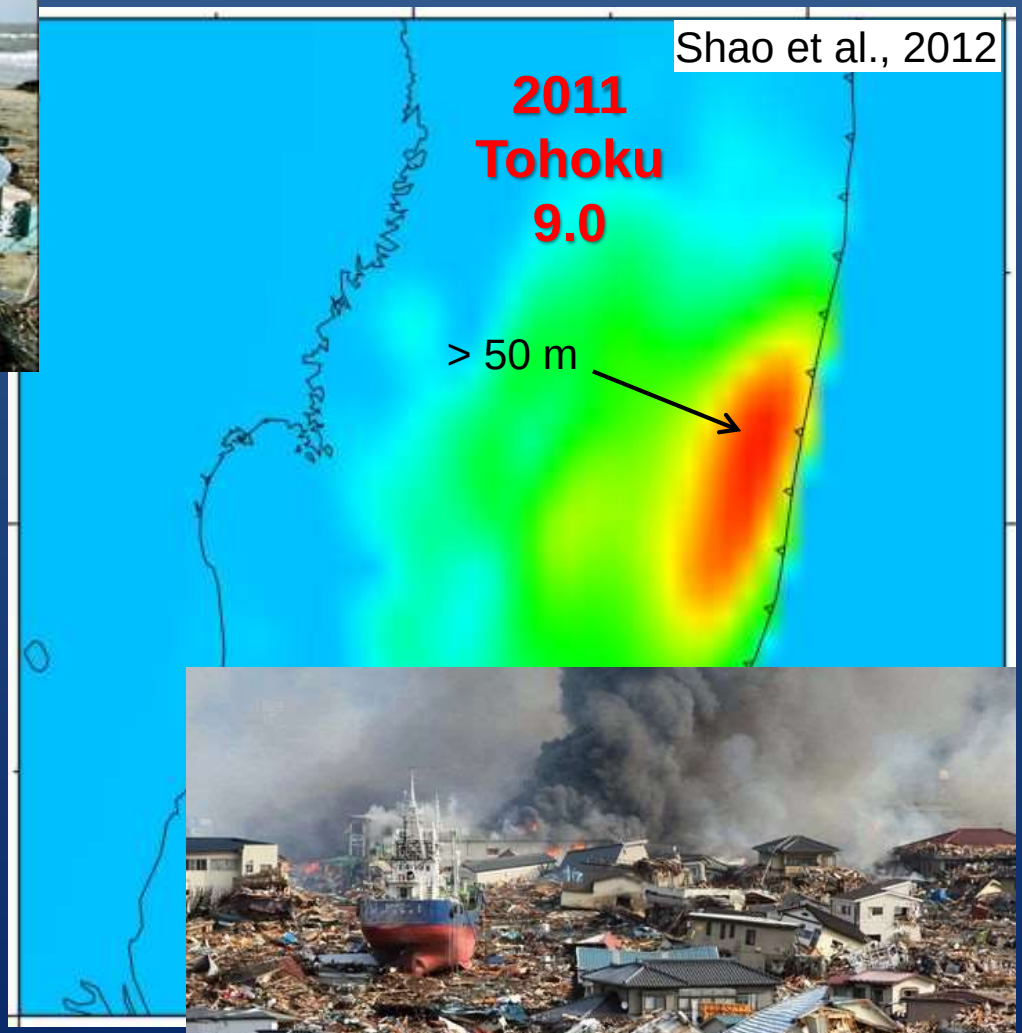


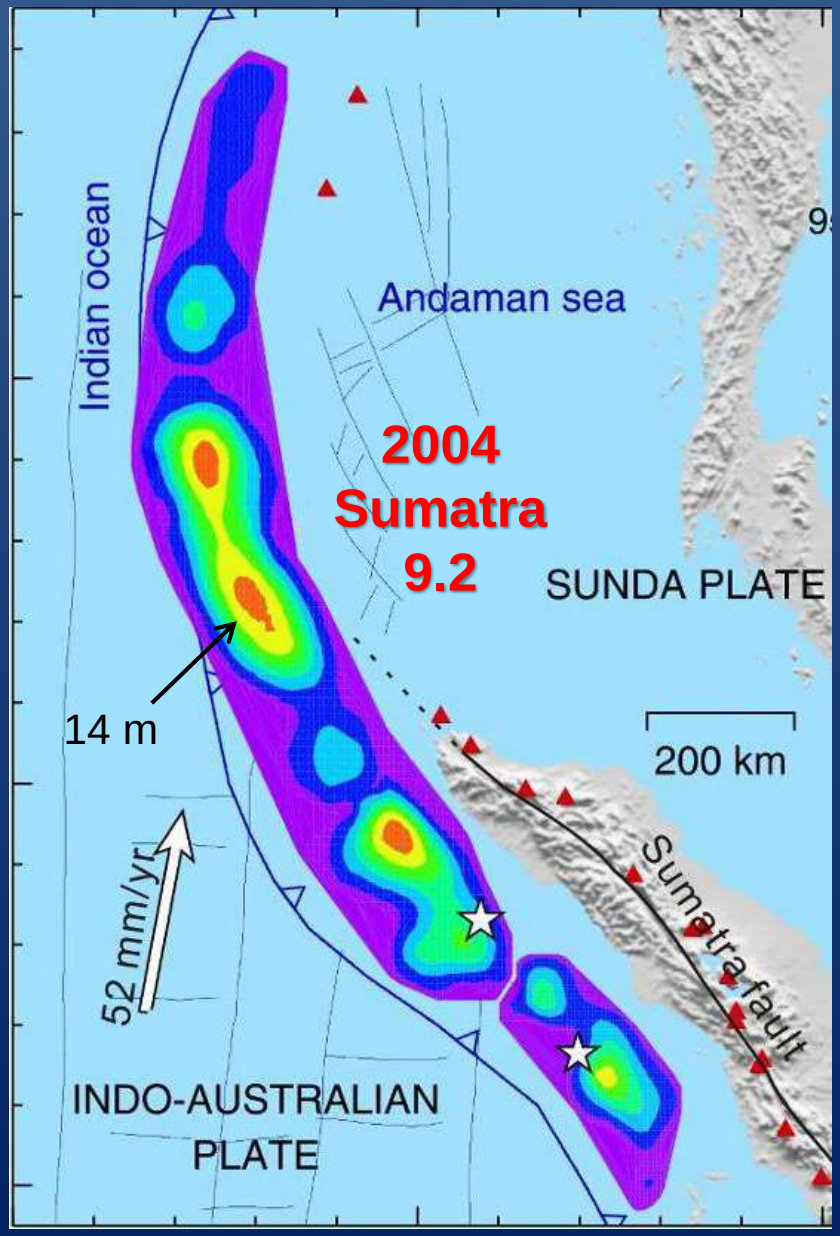
Number of great ($M \geq 8$) earthquakes:

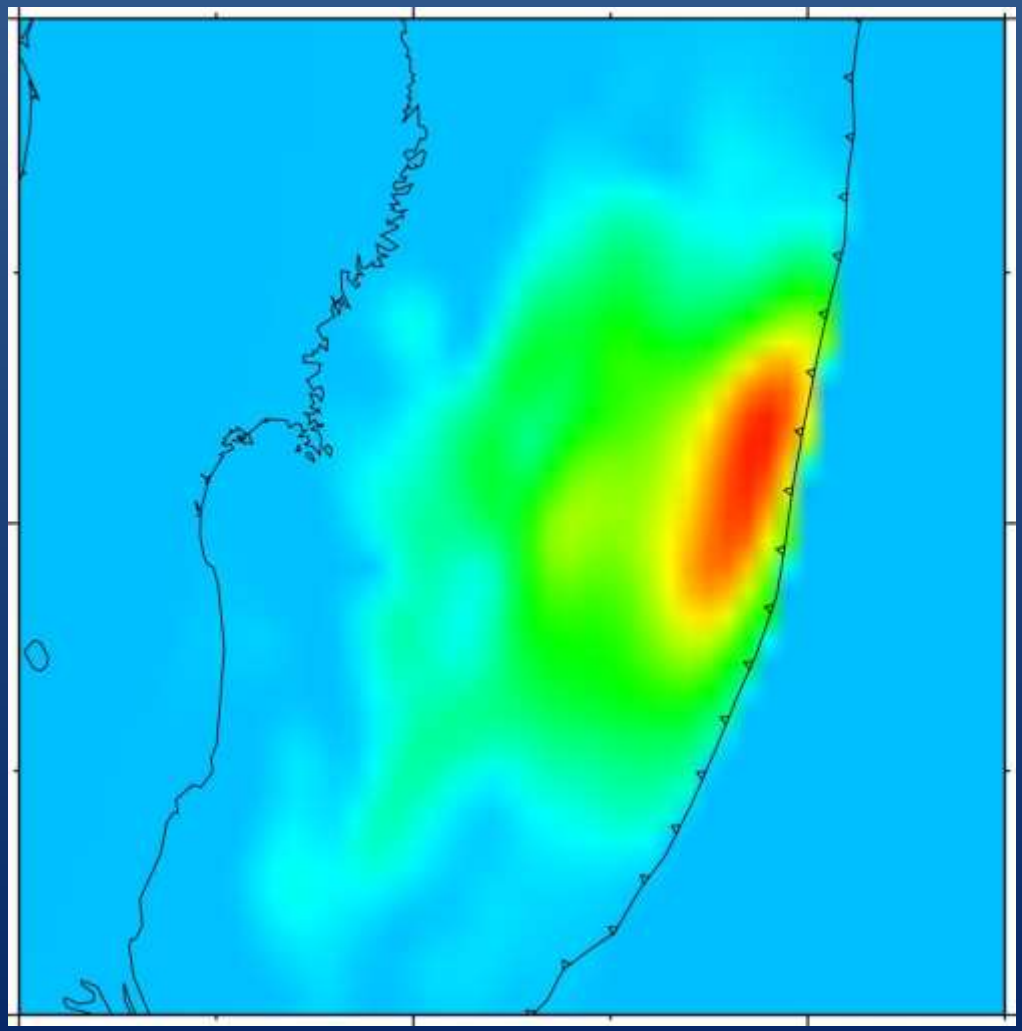
From 1900 – 2004: 71 (Every 18 months)

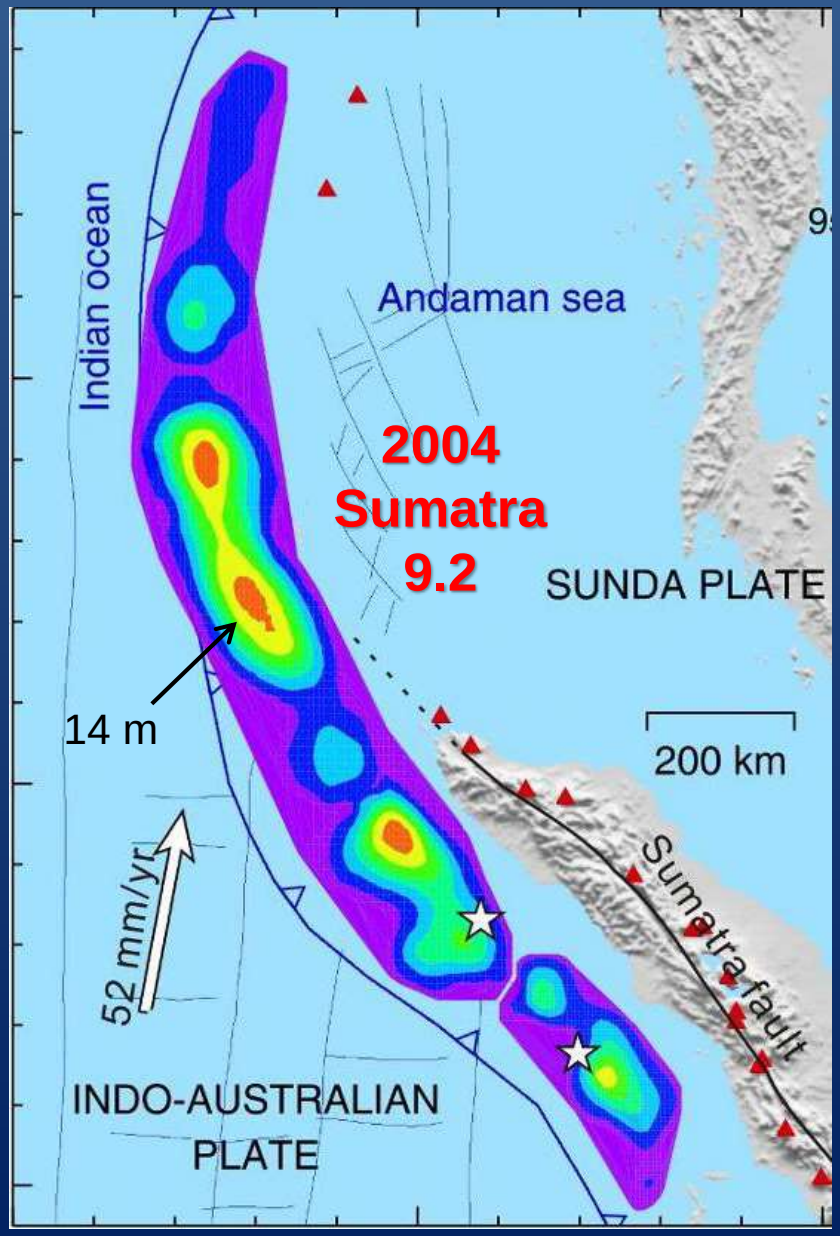
From 2004 – 2015: 19 (Every 7 months)

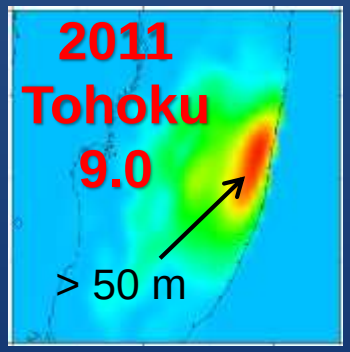
Chlieh et al. (2008)



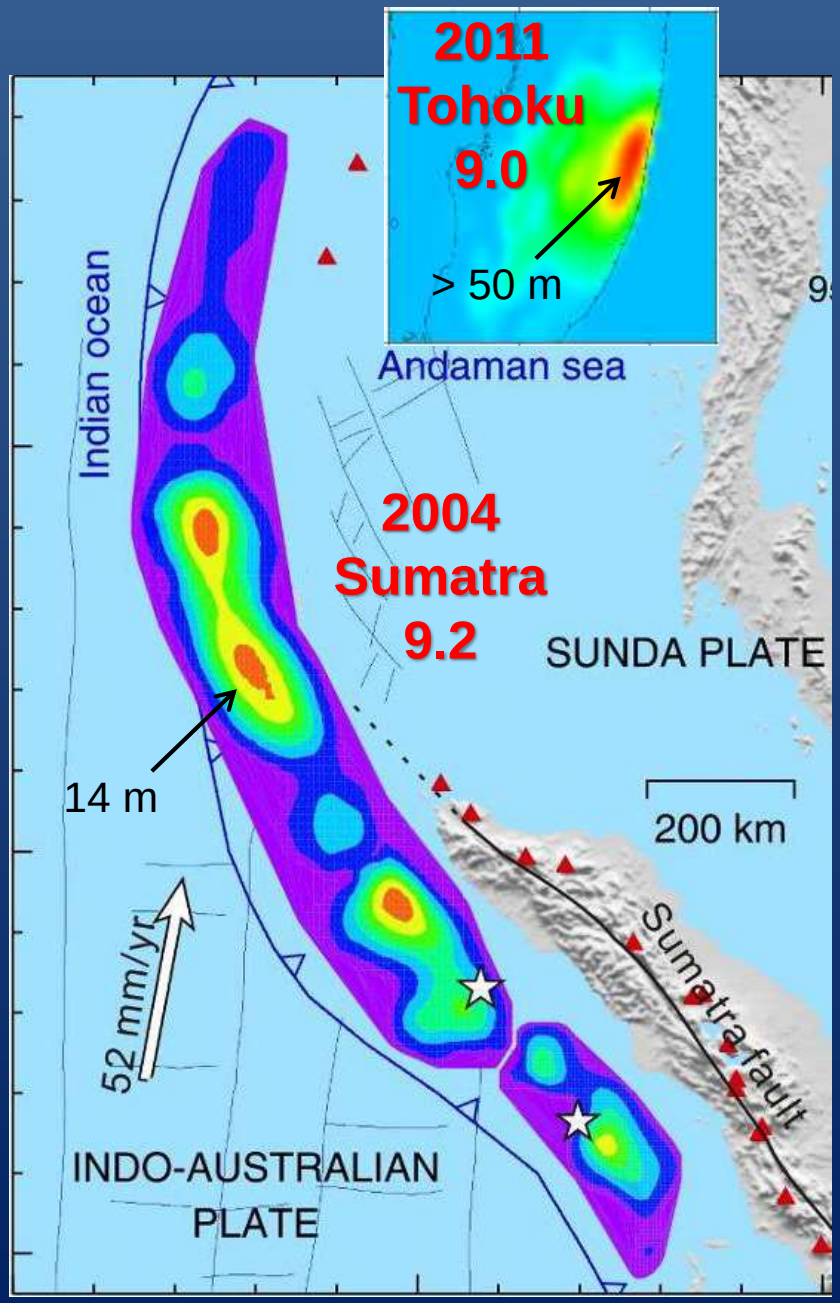

Indian ocean
Andaman sea
2004
Sumatra
9.2
SUNDA PLATE
14 m
200 km
52 mm/yr
Sumatra fault
INDO-AUSTRALIAN
PLATE




Indian ocean
Andaman sea
2004
Sumatra
9.2
SUNDA PLATE
14 m
200 km
52 mm/yr
Sumatra fault
INDO-AUSTRALIAN
PLATE

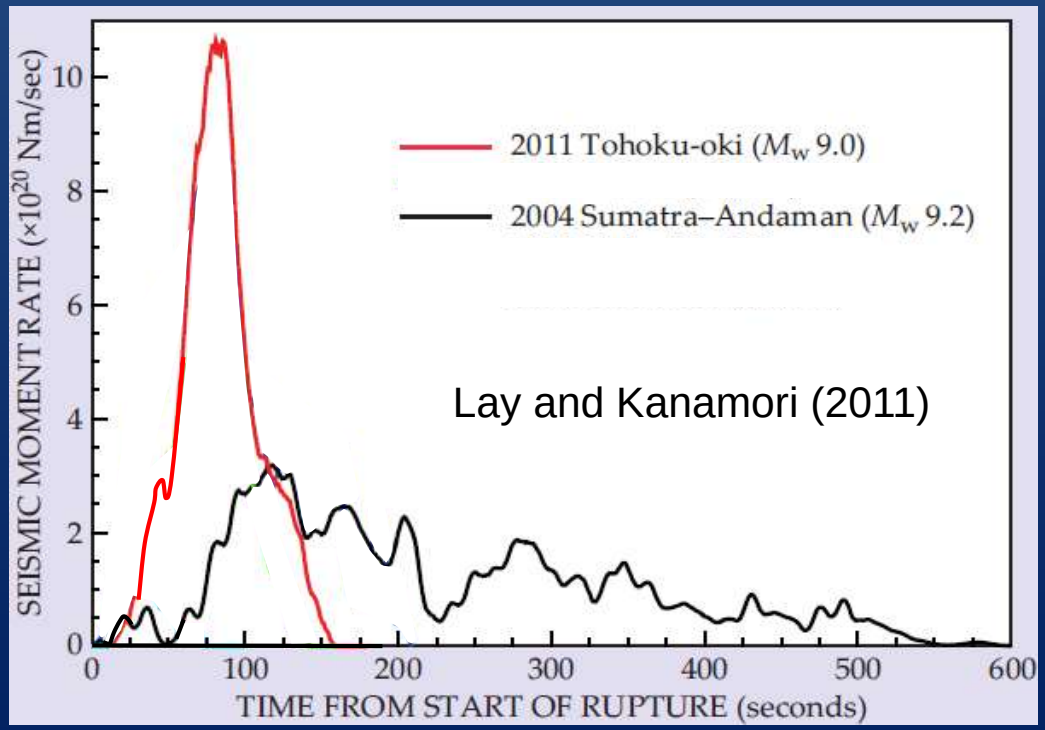

2011
Tohoku
9.0
> 50 m

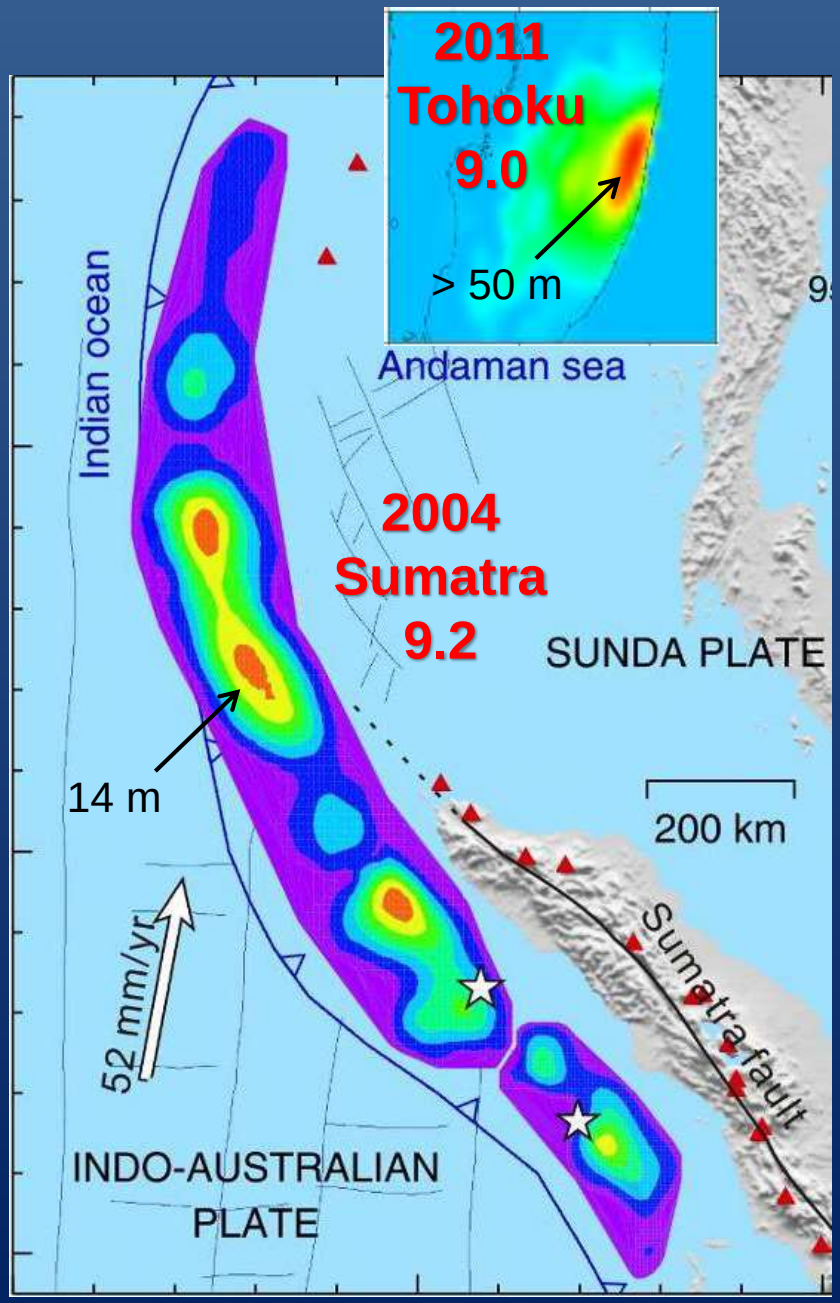
200 km

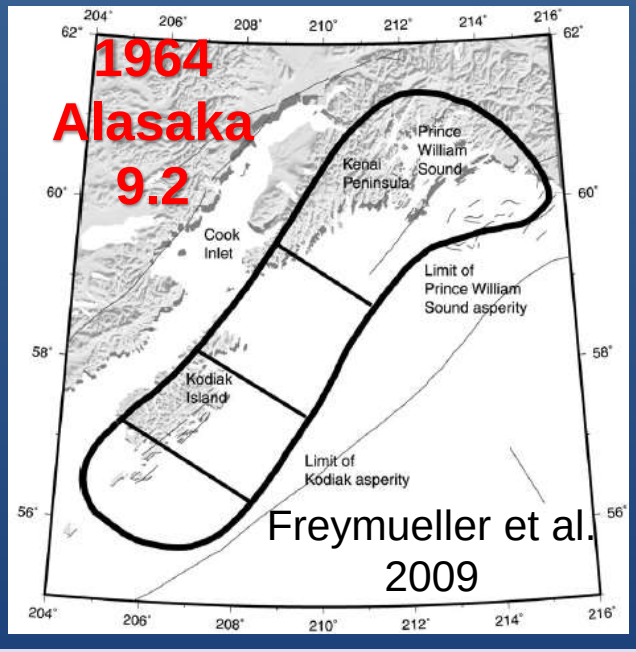


Different types of giant earthquakes

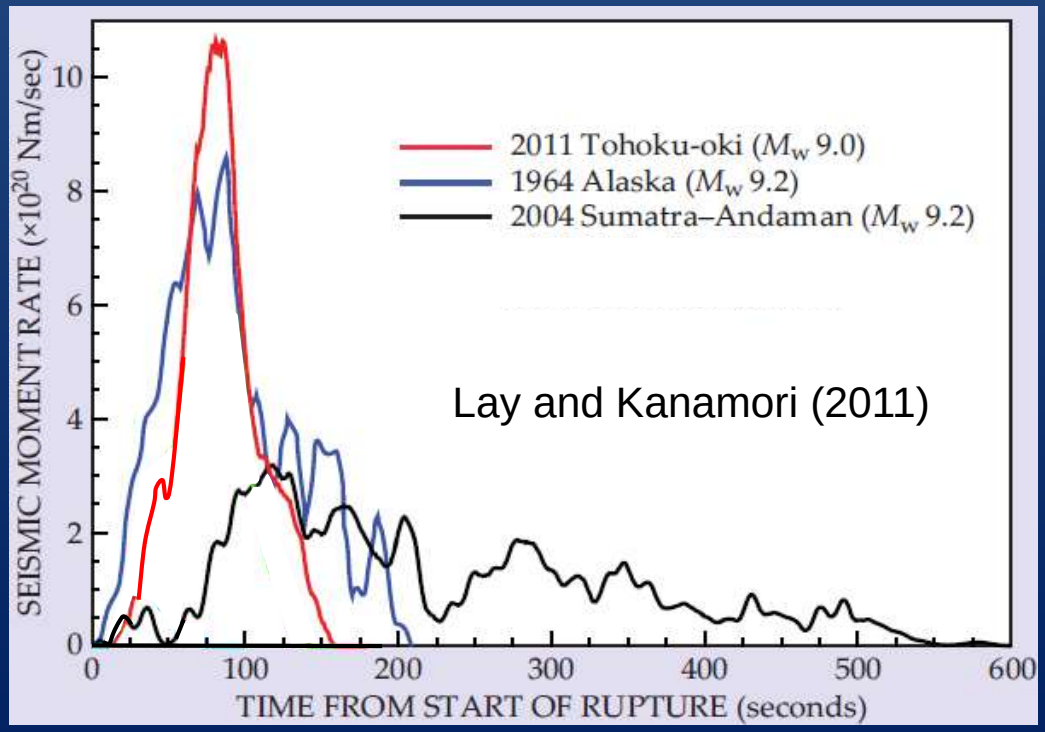
1. Tohoku type (compact):
   small rupture, short duration, huge slip;
   locally strong patch
2. Sumatra type (spread-out):
   long rupture, long duration, smaller slip;
   no locally strong patch

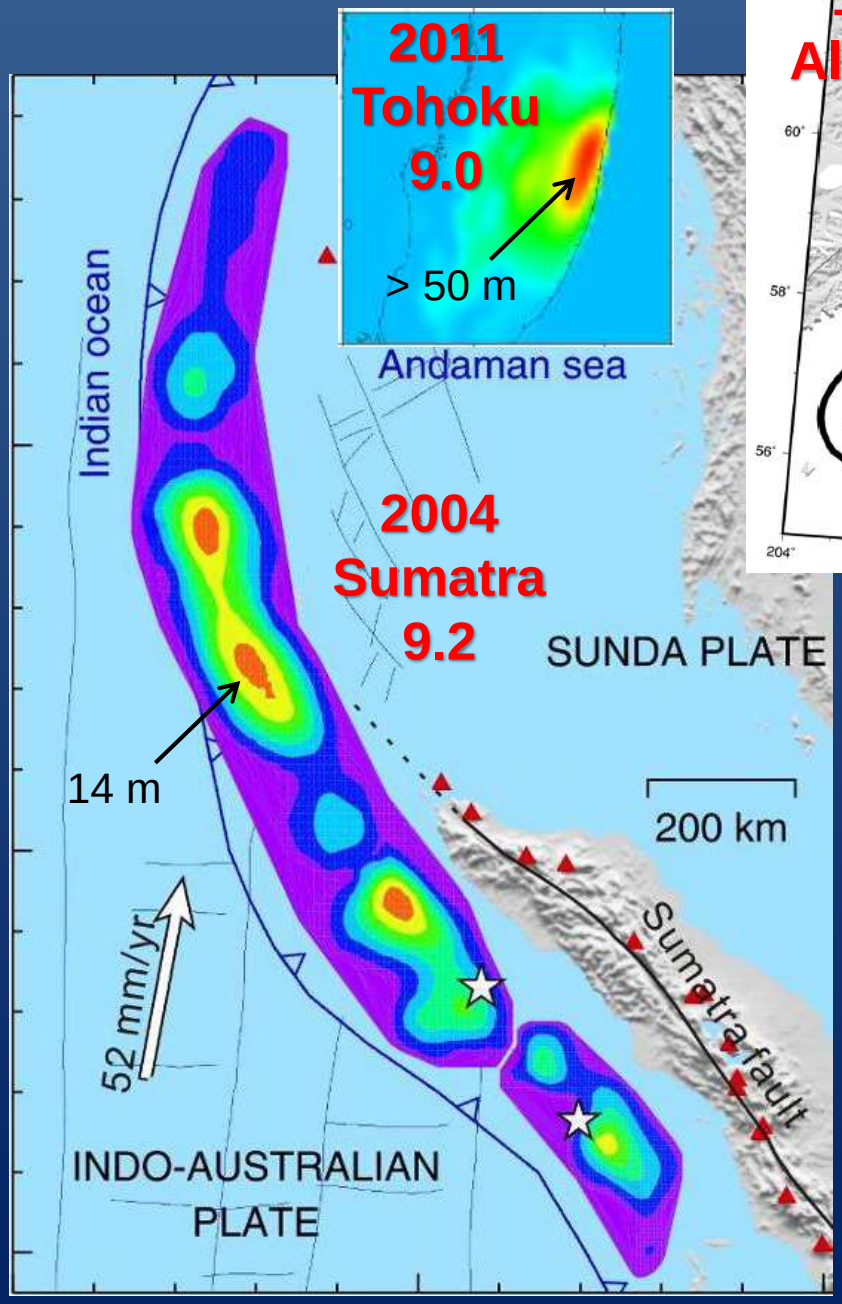


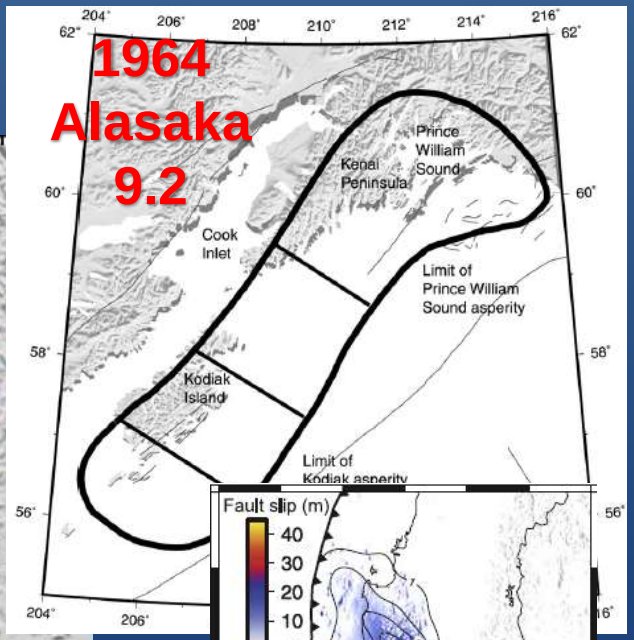

2011
Tohoku
9.0
> 50 m
Andaman sea
Indian ocean
2004
Sumatra
9.2
SUNDA PLATE
14 m
200 km
52 mm/yr
Sumatra fault
INDO-AUSTRALIAN
PLATE

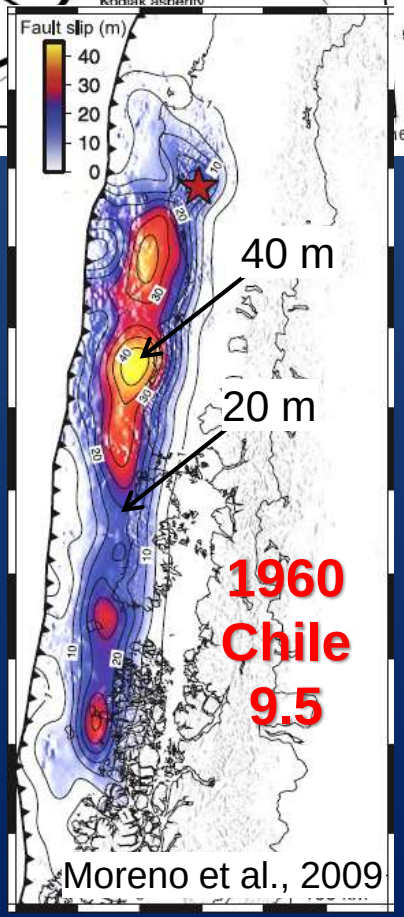

1964
Alasaka
9.2
Prince
William
Sound
Kenai
Peninsula
Cook
Inlet
Limit of
Prince William
Sound asperity
Kodiak
Island
Limit of
Kodiak asperity
Freymueller et al.
2009

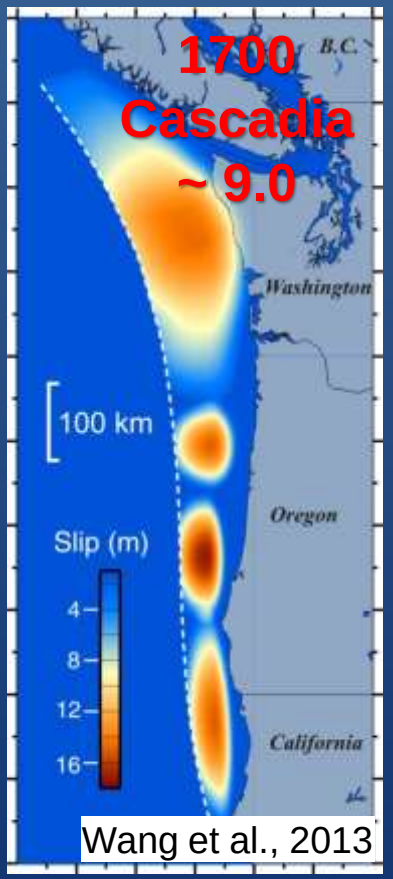
200 km


2011 Tohoku-oki (M_w 9.0)
1964 Alaska (M_w 9.2)
2004 Sumatra–Andaman (M_w 9.2)
SEISMIC MOMENT RATE ($\times 10^{20}$ Nm/sec)
TIME FROM START OF RUPTURE (seconds)
Lay and Kanamori (2011)



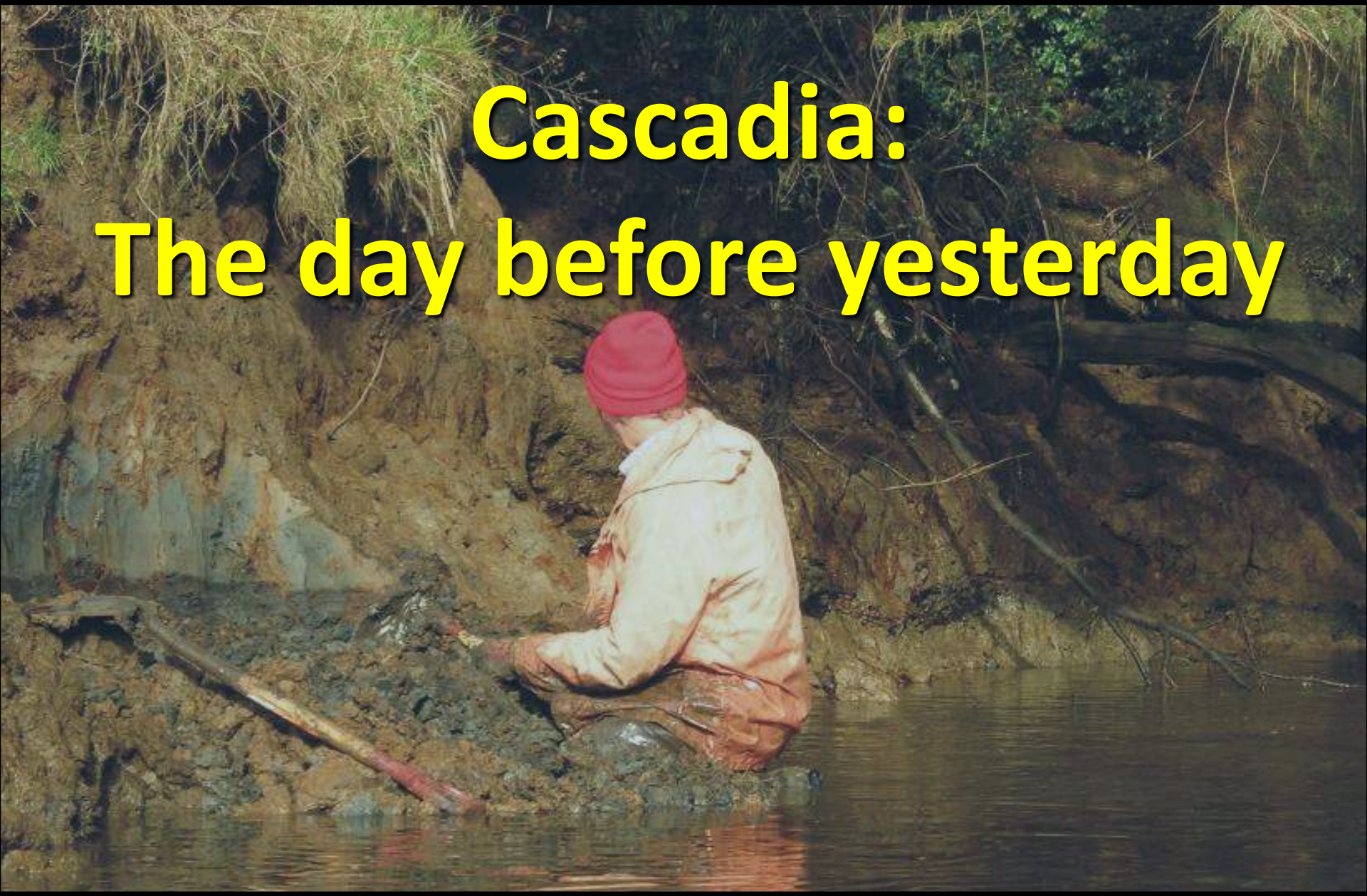




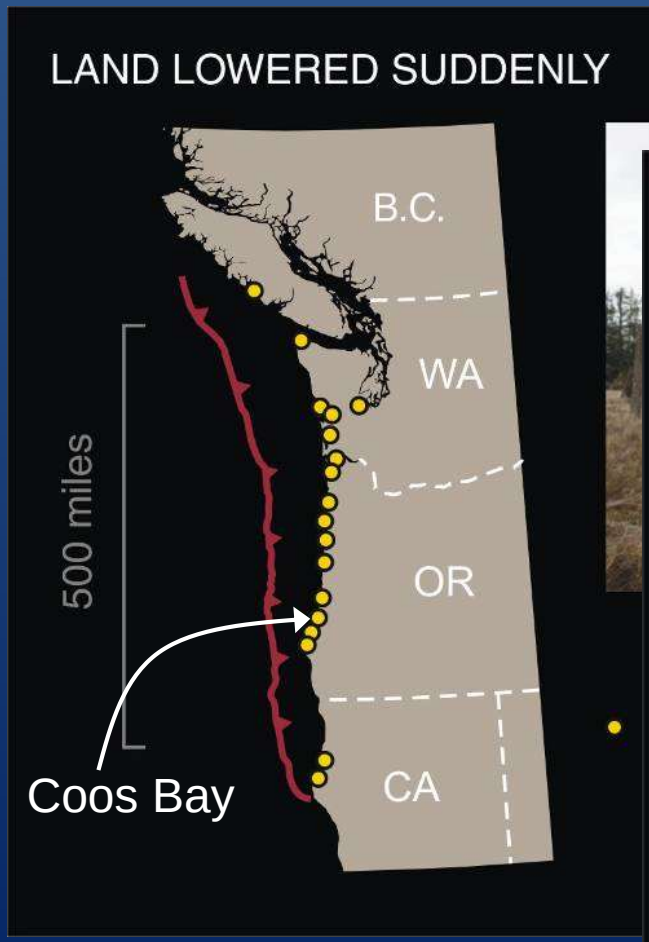


What about Cascadia?

200 km


Cascadia:
The day before yesterday

Great Earthquakes Recorded in Coastal Geology



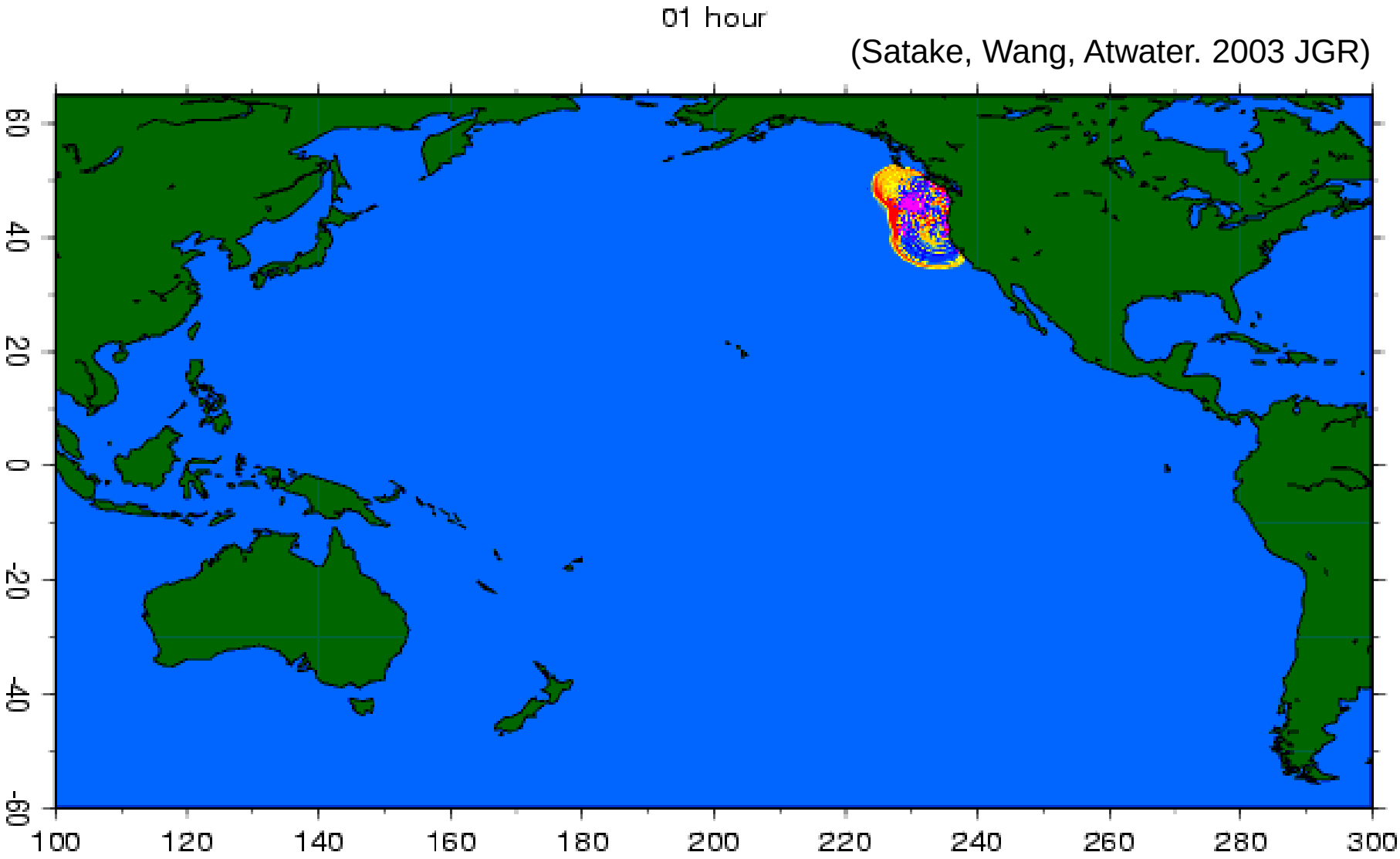
Sand sheet 1680-1720

From Brian Atwater

Great Cascadia earthquake of Jan. 26, 1700, recorded in Japan

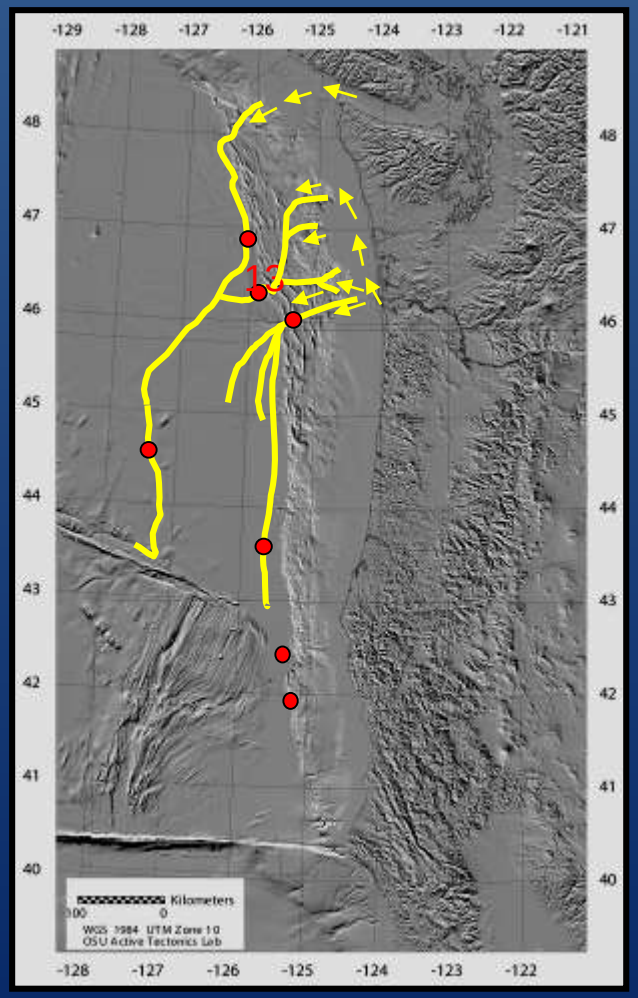
(Atwater et al., 2005)

Great Cascadia earthquake of Jan. 26, 1700, recorded in Japan



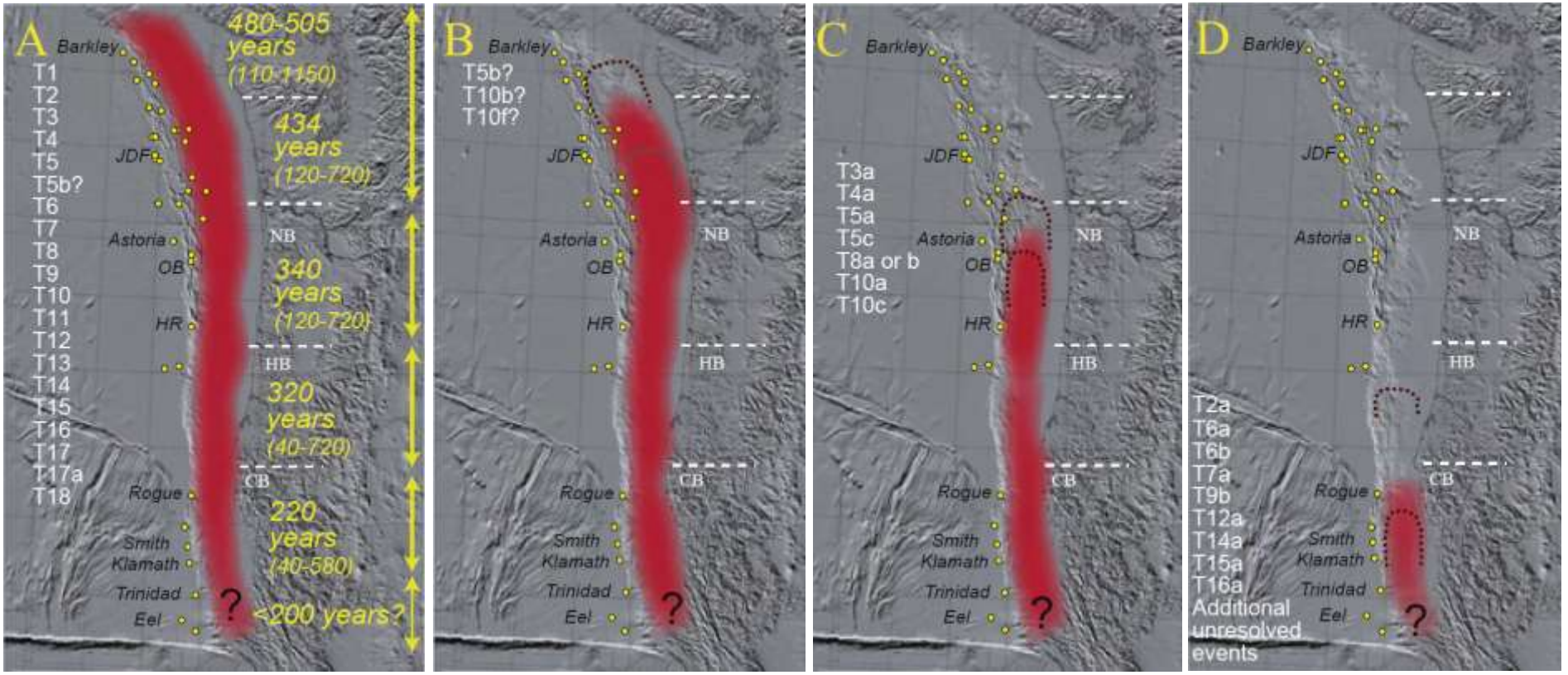
(Satake, Wang, Atwater. 2003 JGR)

Great Earthquakes Recorded in Seafloor Sediment Deposits



(Goldfinger et al., 2005)

Great Cascadia earthquakes recorded in turbidite deposits over the past 10,000 years



M 8.8-9.2
~ 20 events

Many additional events in the south?

Simplified from Goldfinger et al. (2016 Marine Geology)

Cascadia: Today

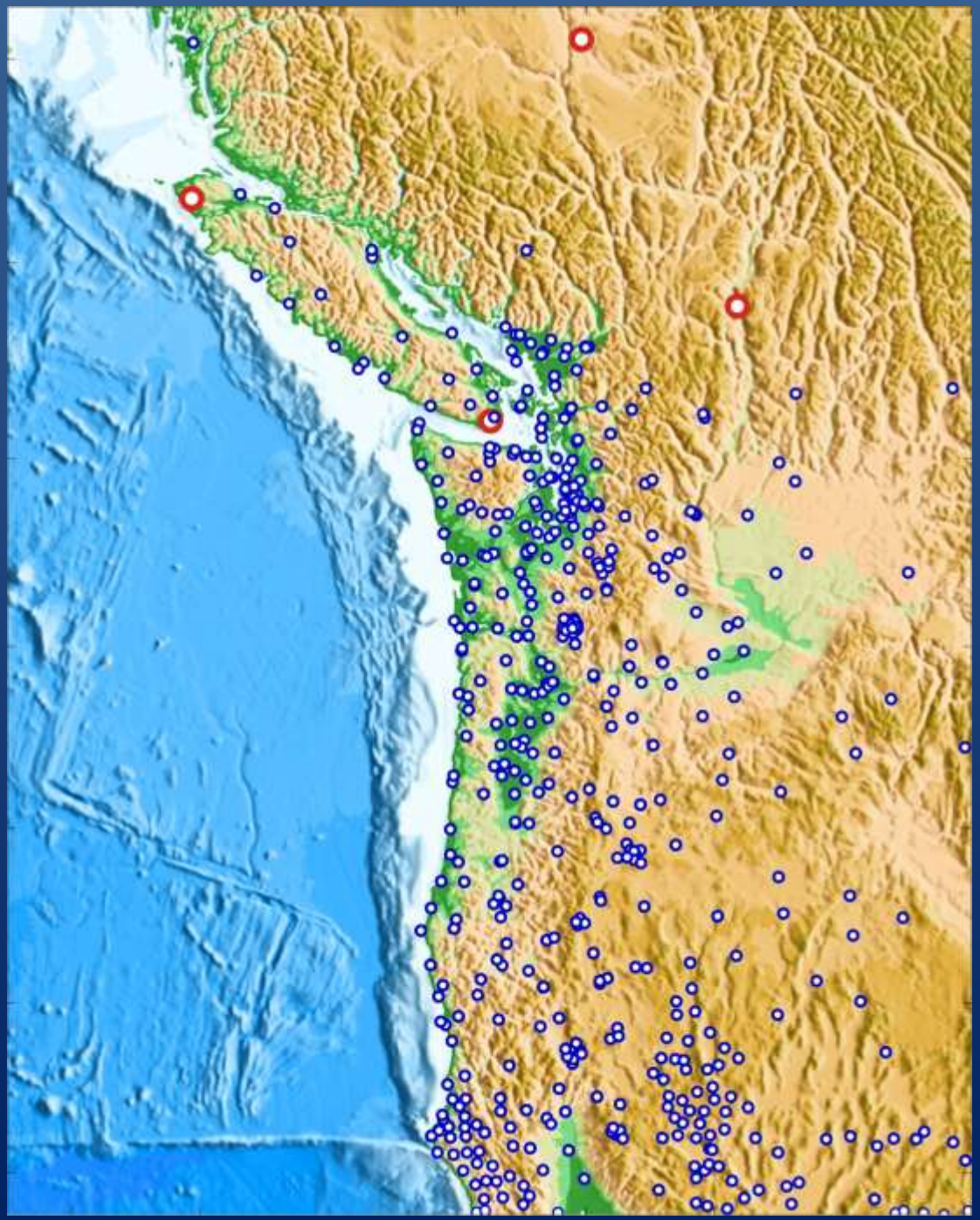
Continuous GPS Stations in 1994:

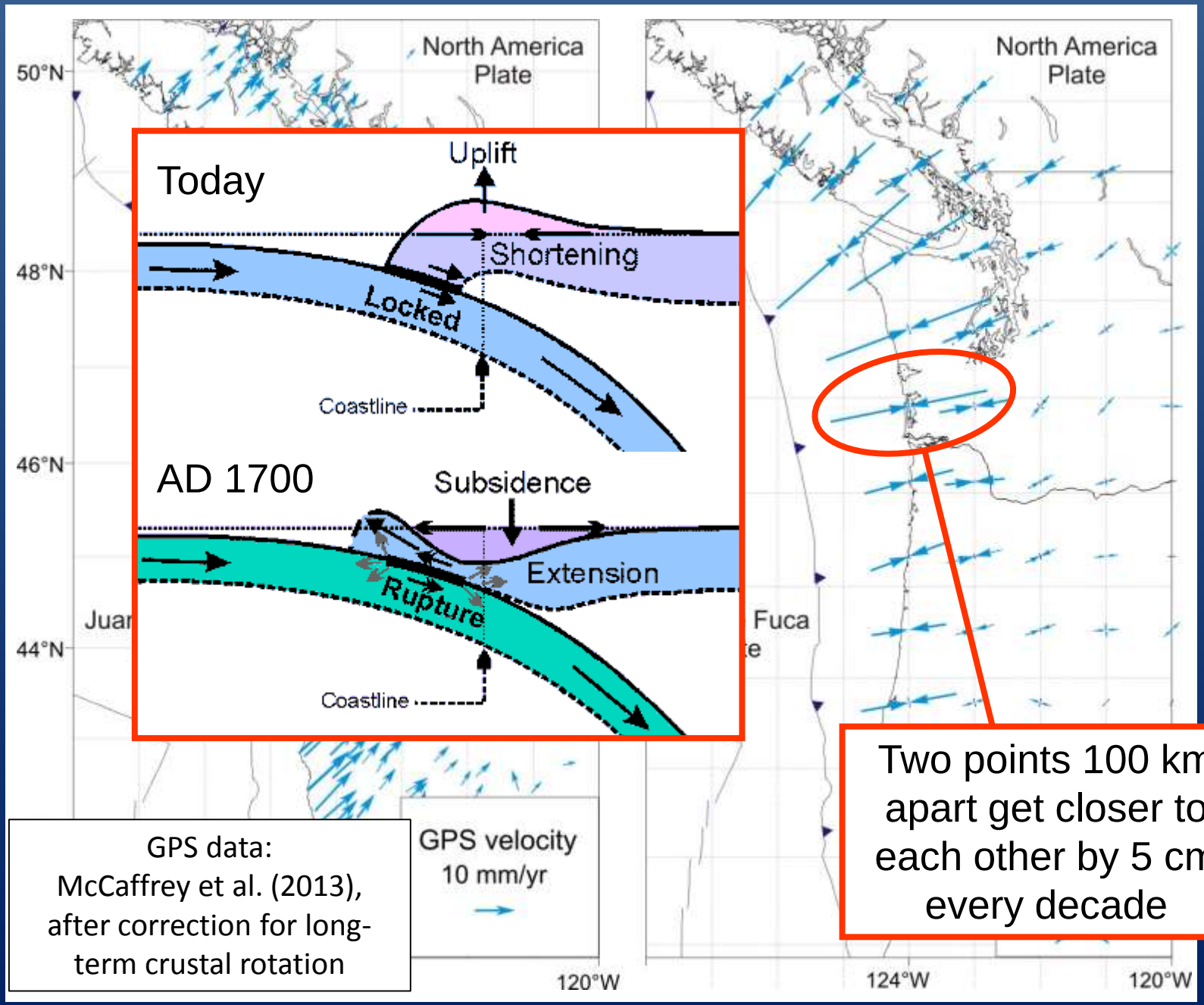
Western Canada Deformation Array began operation

Continuous GPS Stations in 1994:

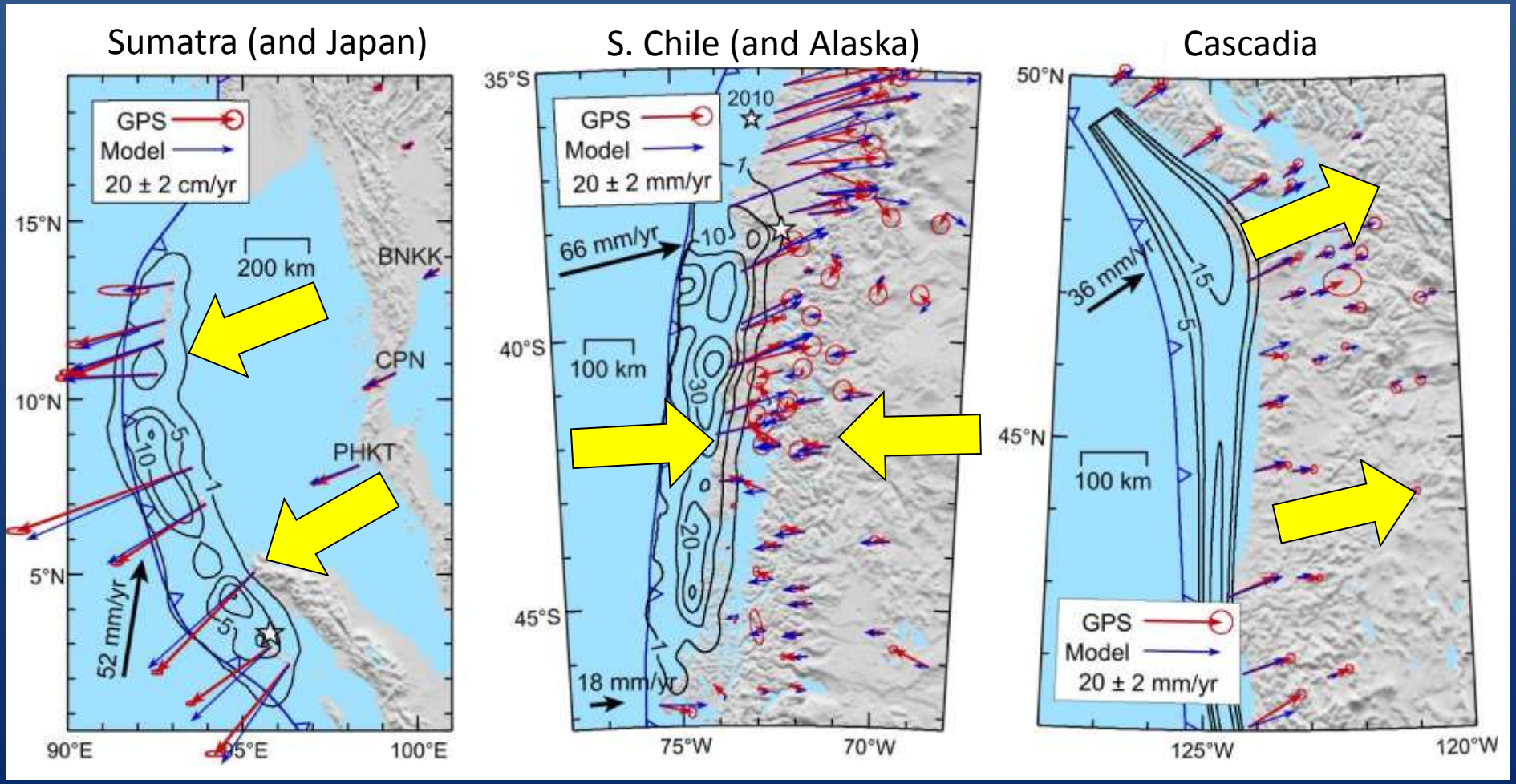
U.S. Plate Boundary Deformation (PBO) and Western Canada Deformation Array

Plus numerous temporary GPS sites and numerous seismic stations




North America Plate
North America Plate
50°N
48°N
46°N
44°N
120°W
124°W
120°W
Today
Uplift
Shortening
Locked
Coastline
AD 1700
Subsidence
Extension
Rupture
Coastline
GPS velocity
10 mm/yr
Two points 100 km apart get closer to each other by 5 cm every decade
GPS data:
McCaffrey et al. (2013), after correction for long-term crustal rotation

Deformation cycles of giant earthquakes in a viscoelastic Earth



A few years | Four decades | Three centuries

Wang, Hu, He (Nature, 2012)

Cascadia since the 1700 earthquake

England and France began to fight in eastern North America (Queen Anne's War).

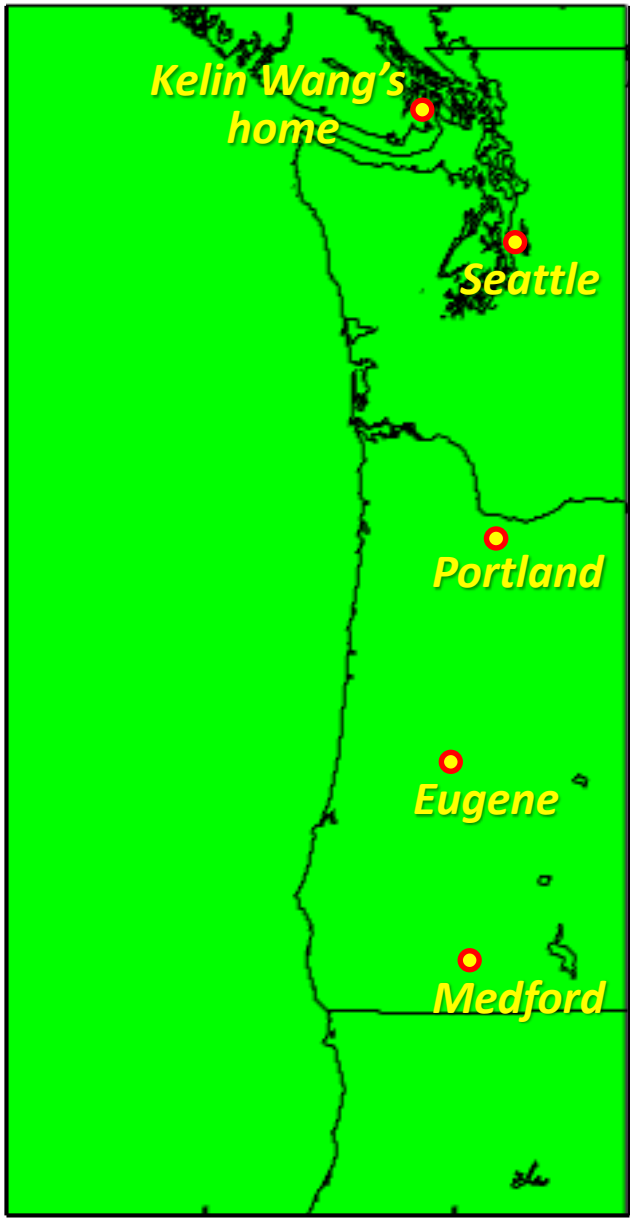
Captain Chirikov (Russia) landed on northwest coast of North America (Prince of Wales Island).

Captain Cook sailed along west coast of North America and stayed at Nootka Sound.

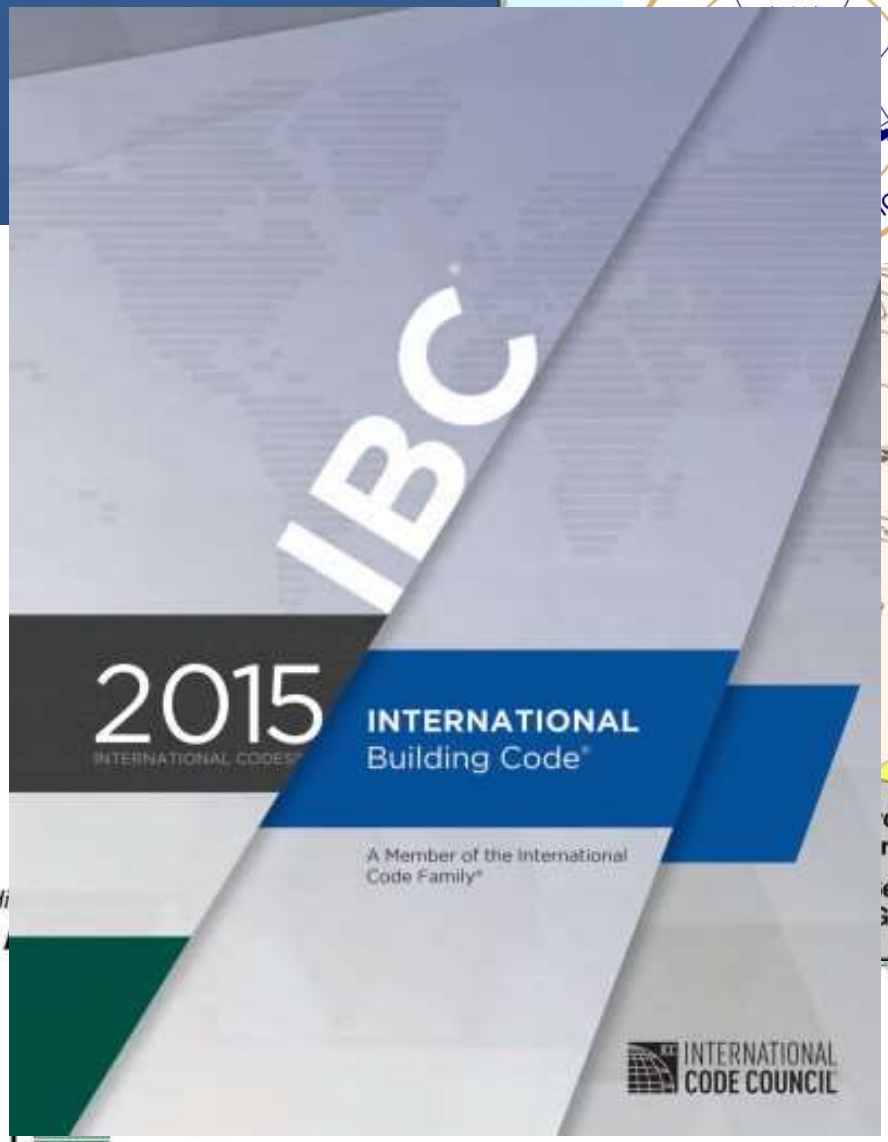
Dr. Wang presents ICLR webinar on 317th anniversary of the earthquake.

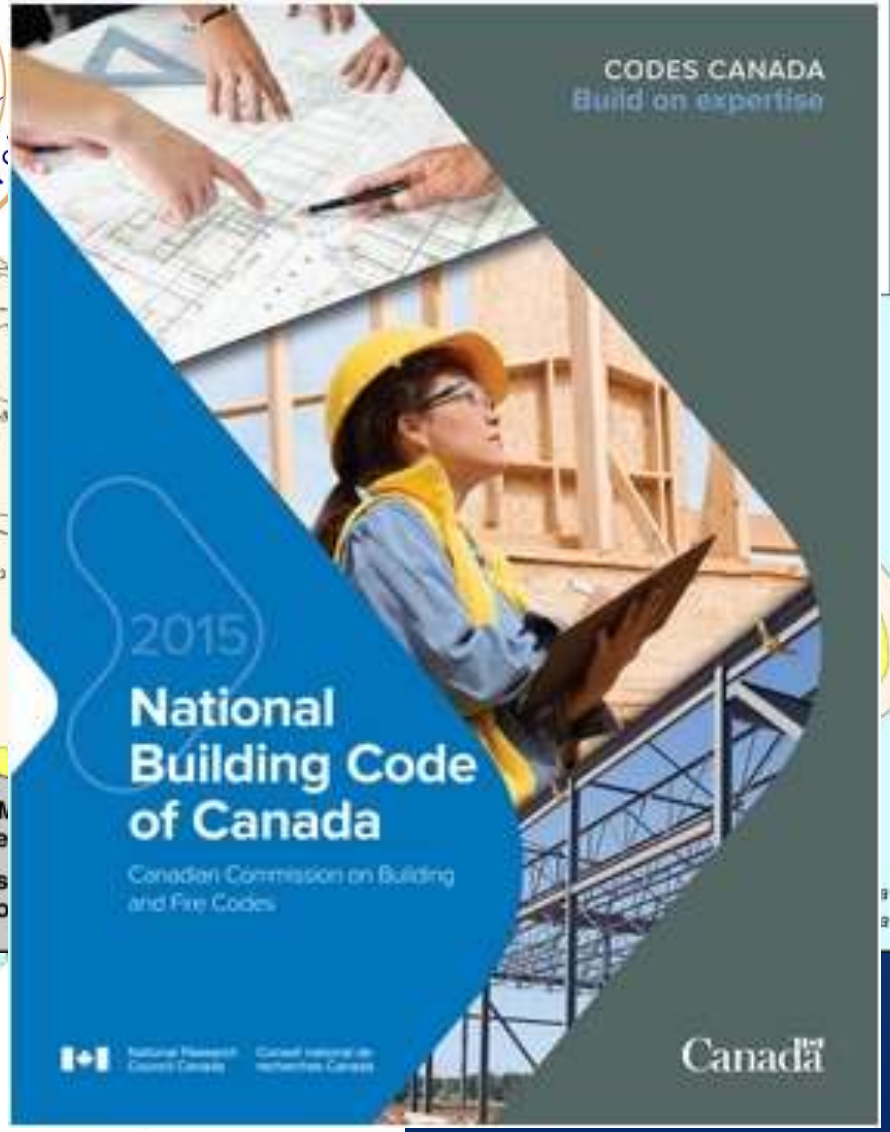
Model by Yan Hu

Cascadia:
The day after tomorrow

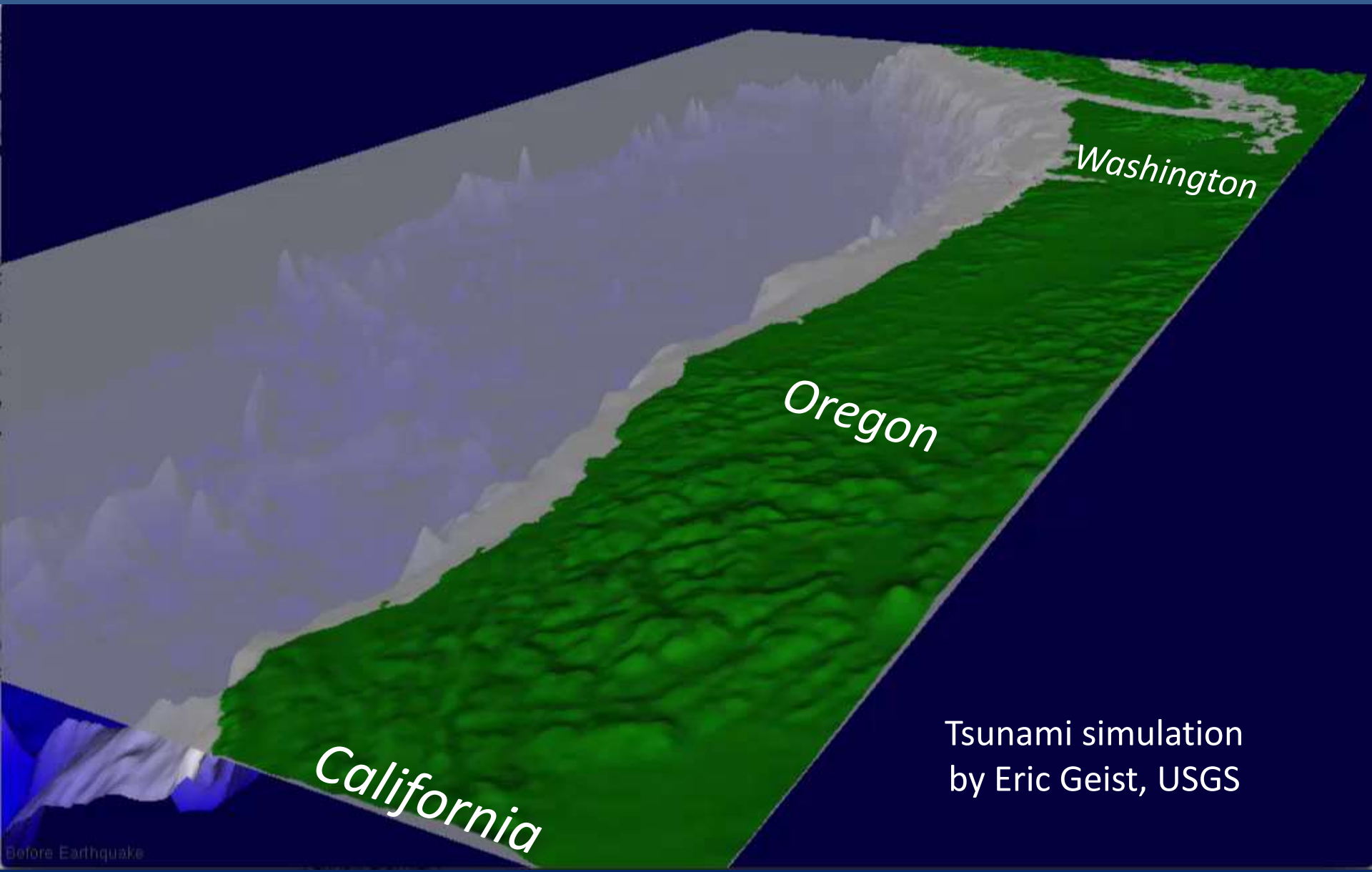


0 1 2 3 minutes

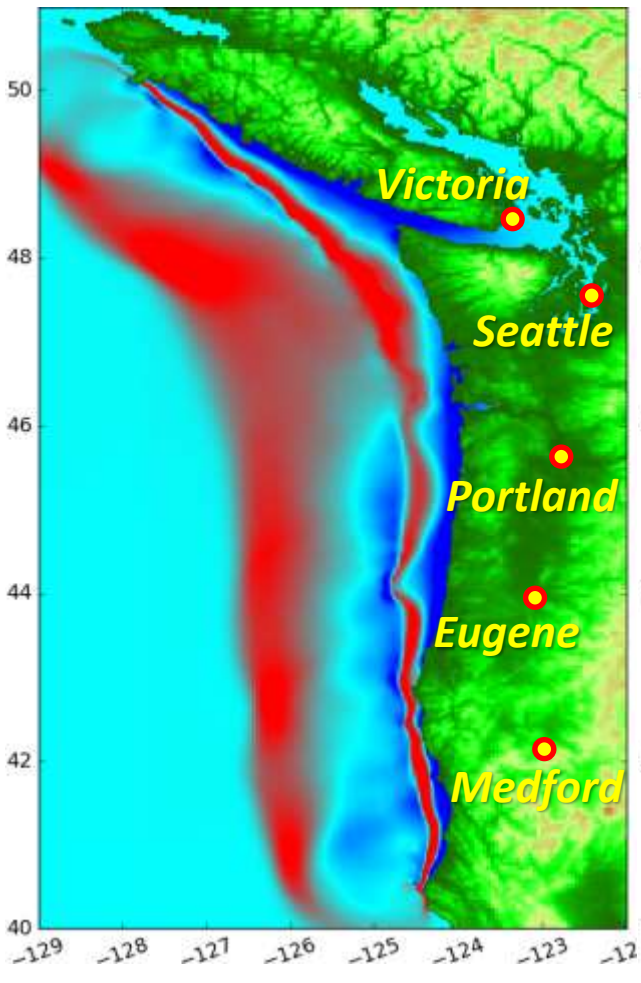




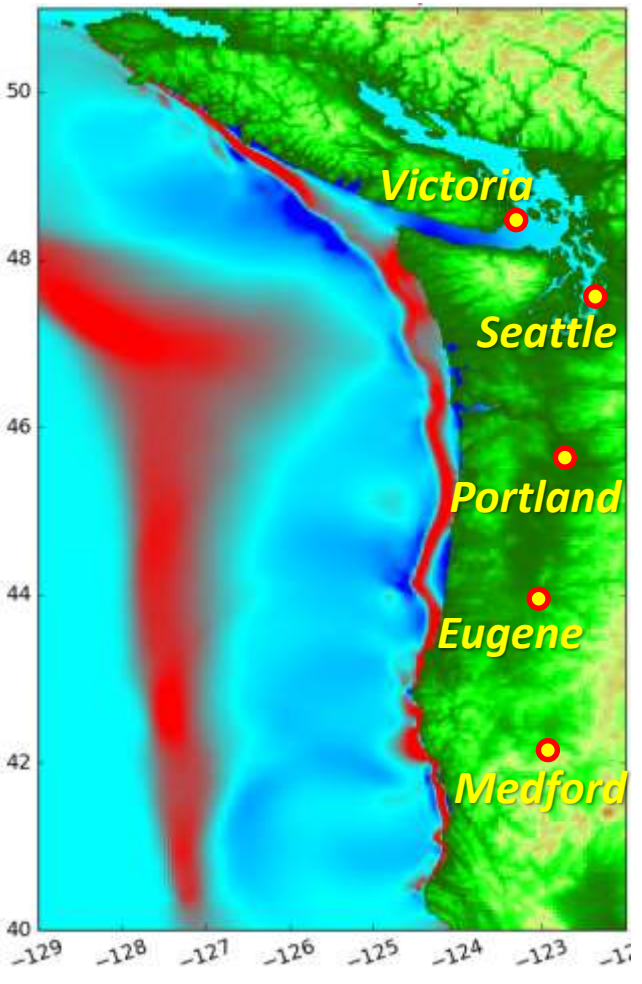
IV
≤ III
Lowest hazard


Washington
Oregon
California
Before Earthquake
Tsunami simulation
by Eric Geist, USGS

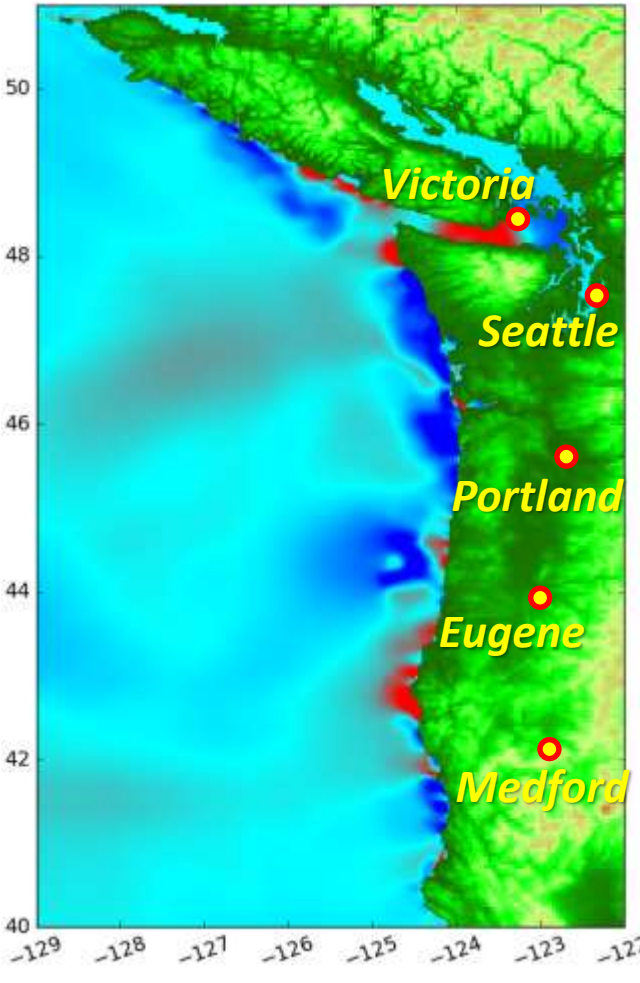
10 minutes



20 minutes



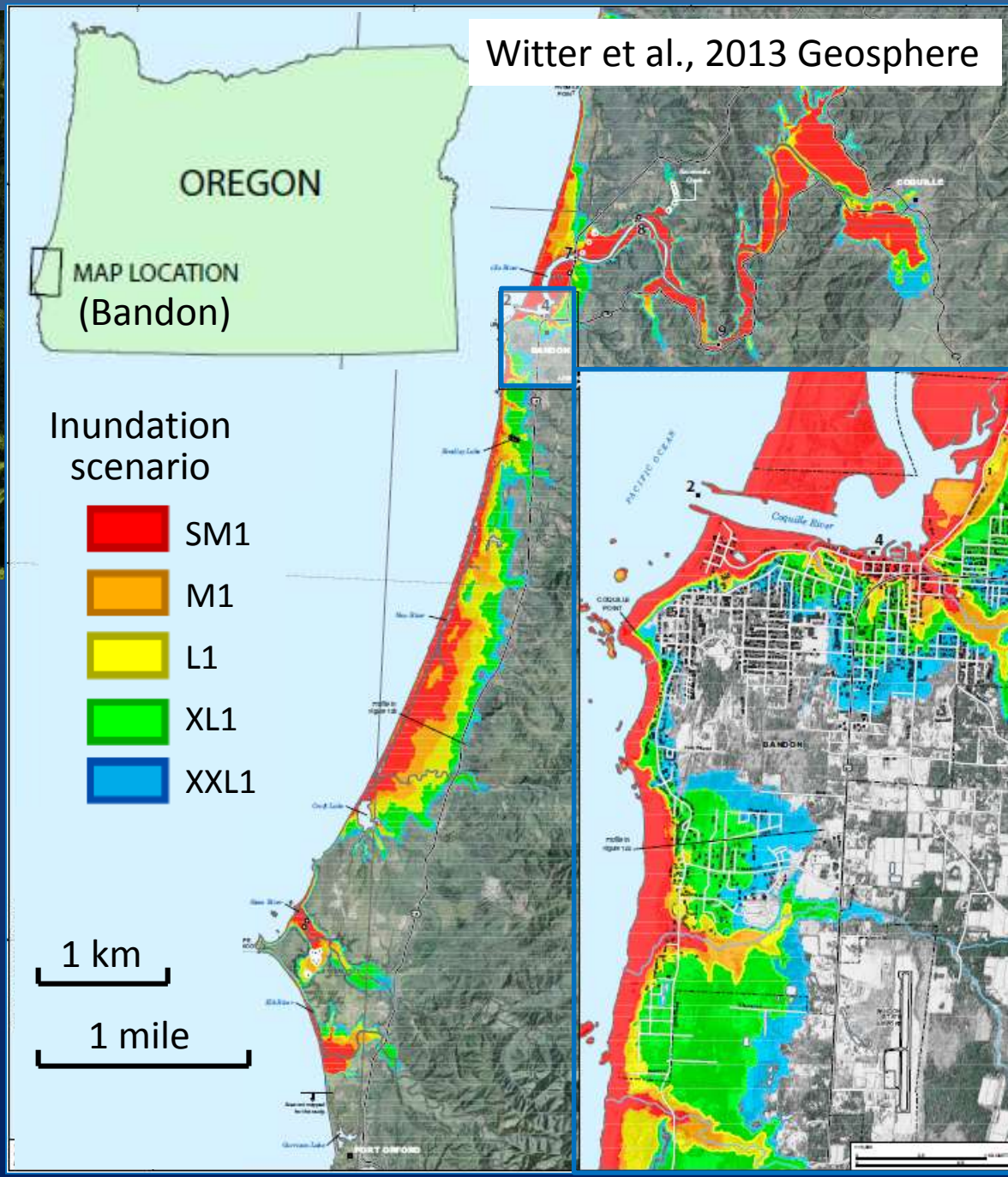
80 minutes



Tsunami simulation by Randall LeVeque, Universityu of Washington


Charleston to Bandon
Scenic Tour Route
TSUNAMI
EVACUATION
ROUTE

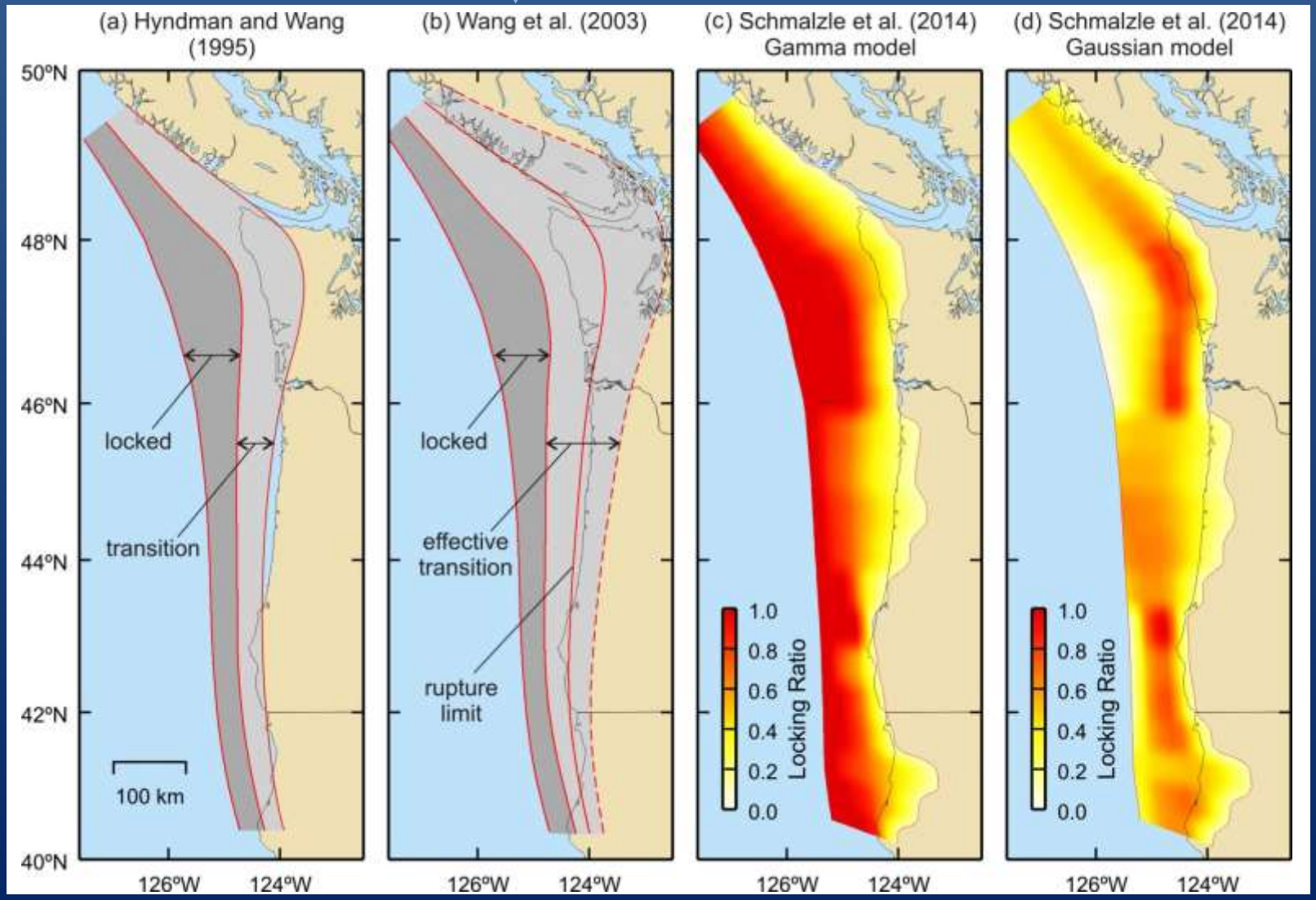
Witter et al., 2013 Geosphere



Cascadia: Scientific challenges

Is the seismogenic zone fully locked?

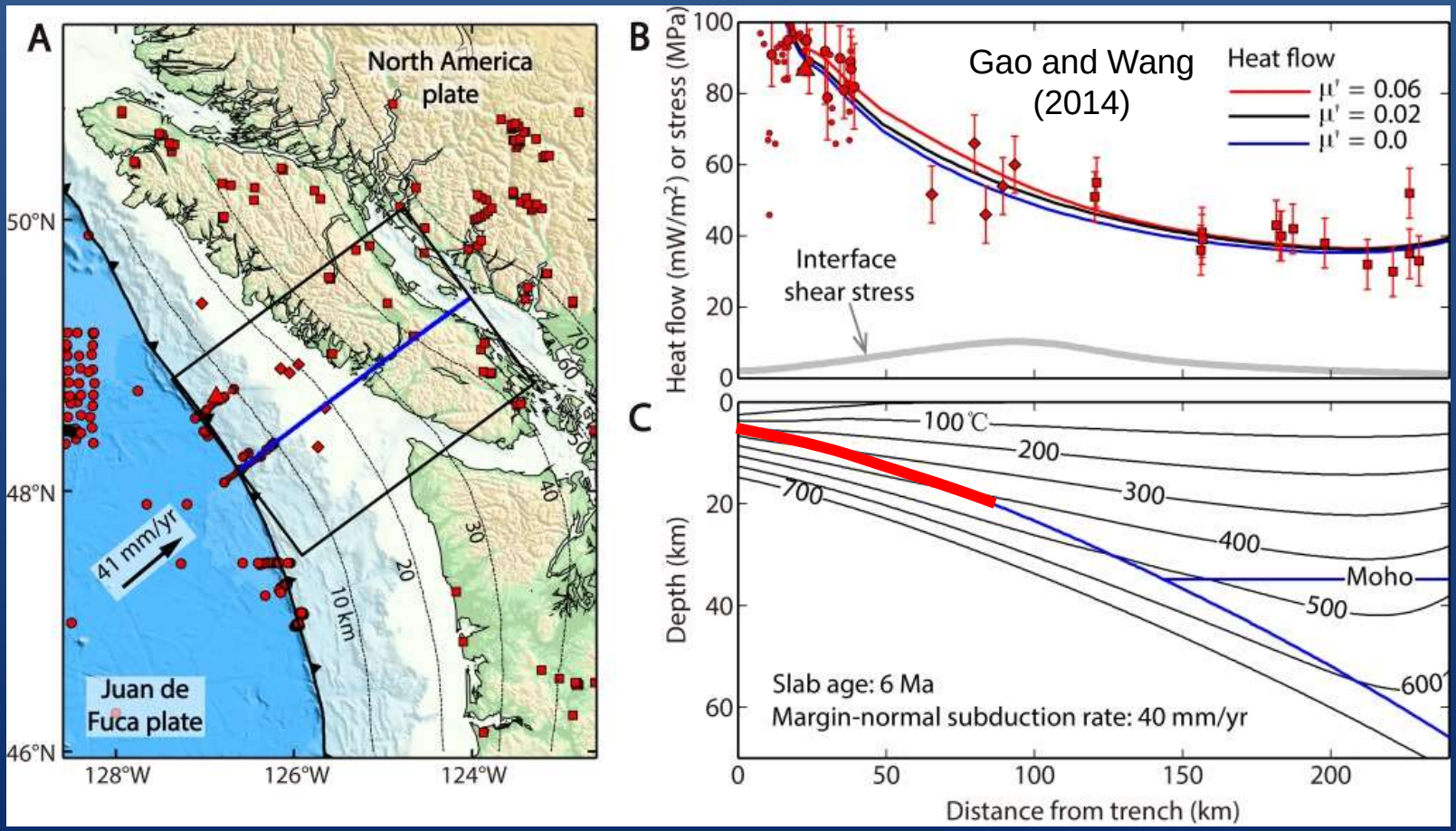
Used in Canadian and U.S. seismic zoning



With thermal constraints

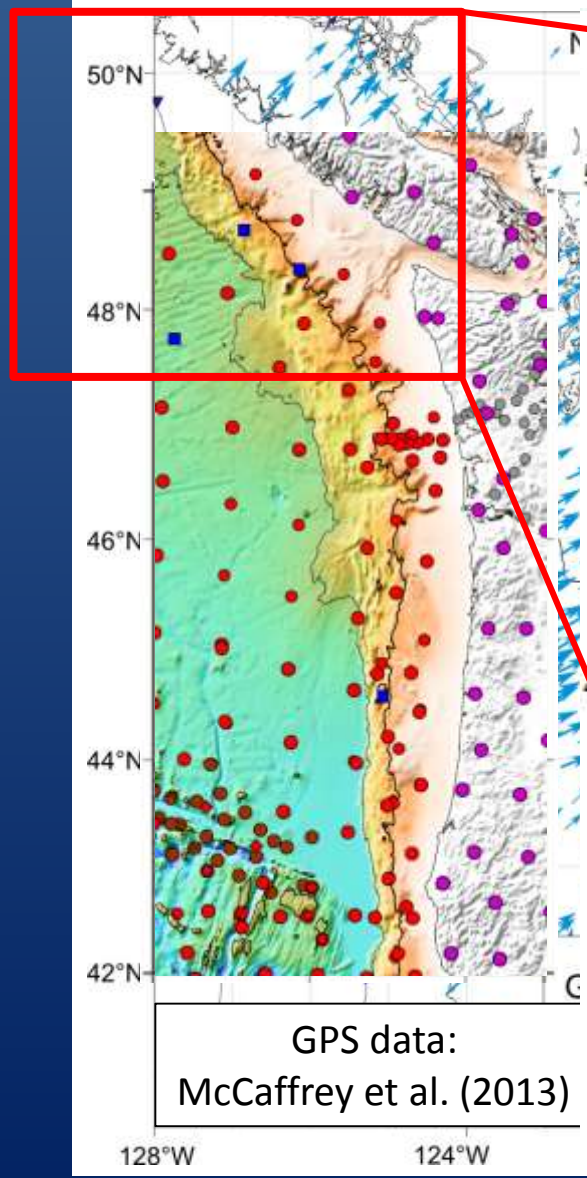
Geodetic inversion only

Why do we assume “shallow and narrow”? — Very warm megathrust

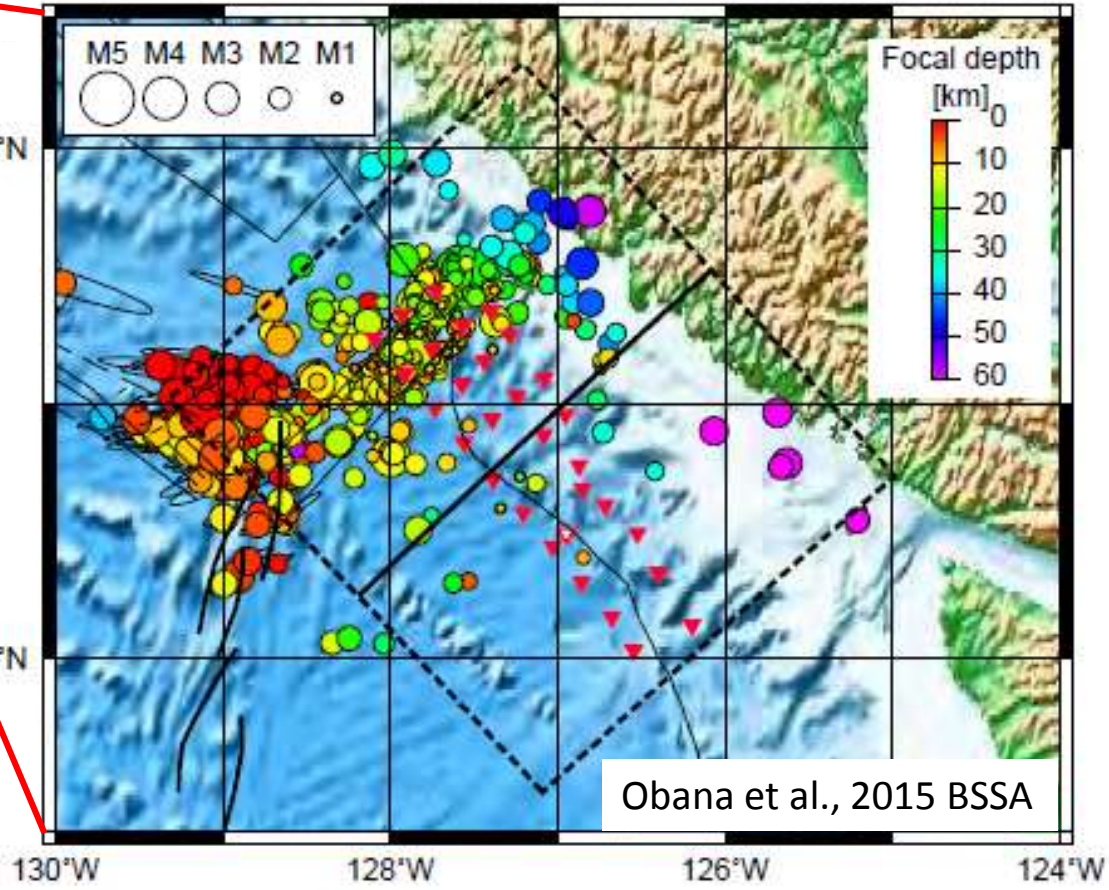


Because of young slab and thick sediment cover, megathrust temperature > 400°C at 20 km depth, too warm for seismic rupture if fault-zone material is quartz-rich.

Why do we assume full locking? — Eerily quiet megathrust

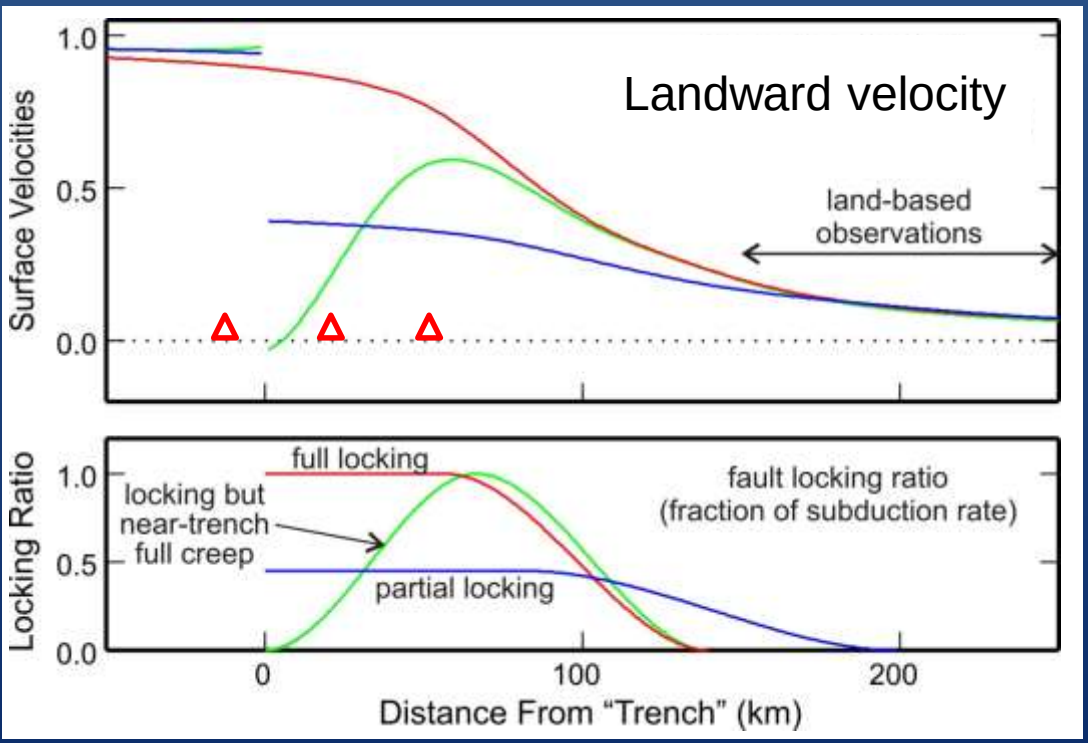


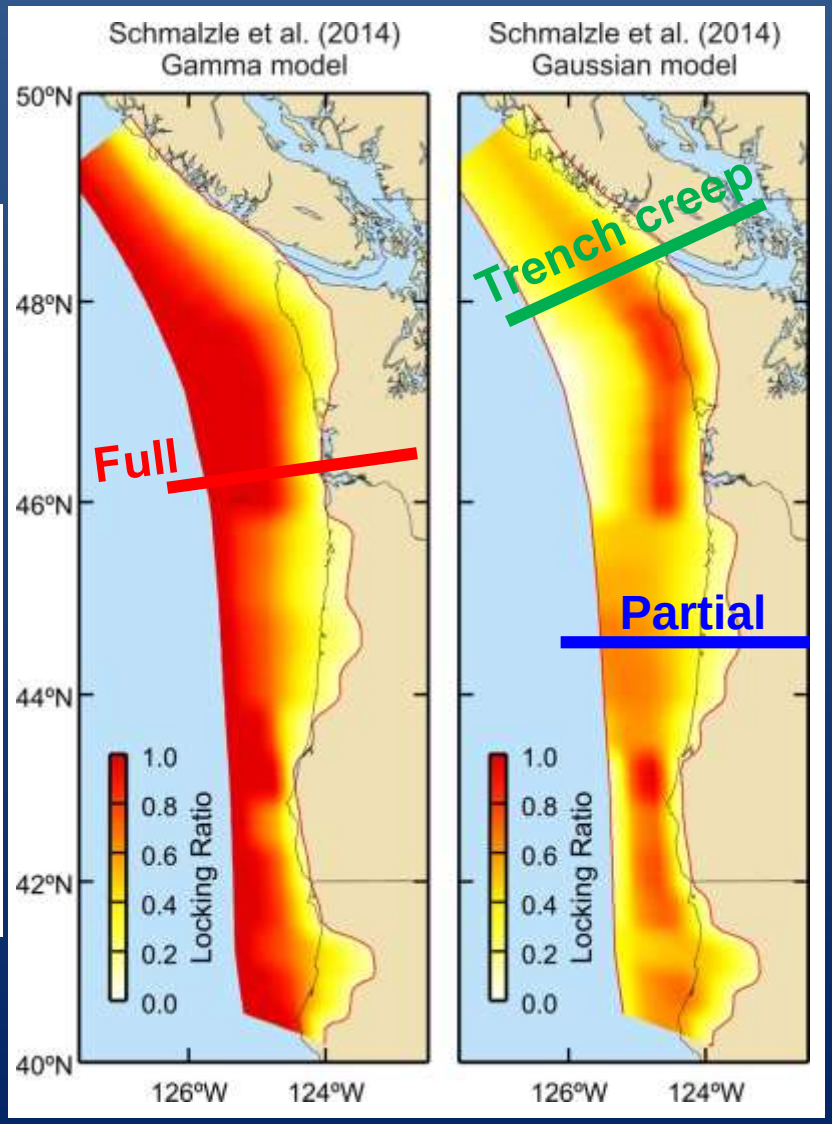
GPS data:
McCaffrey et al. (2013)

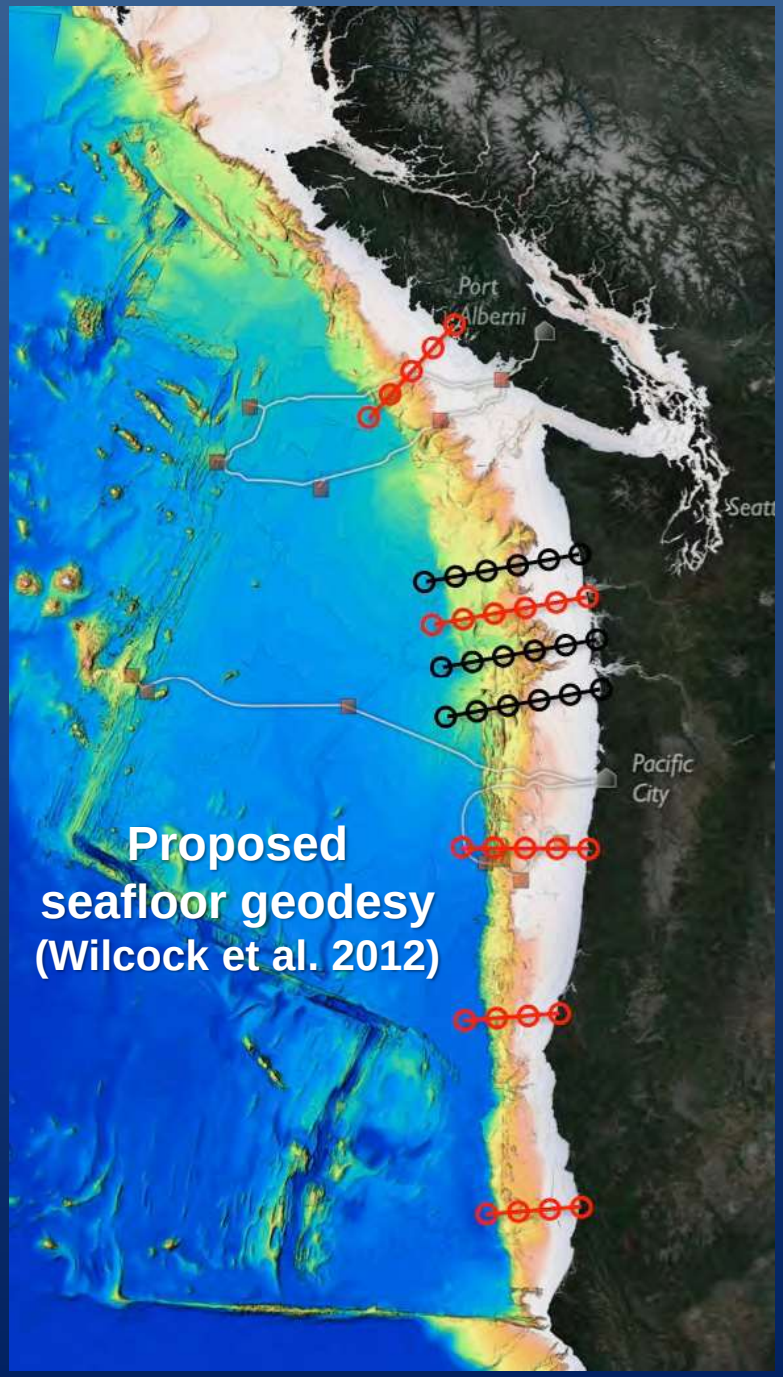


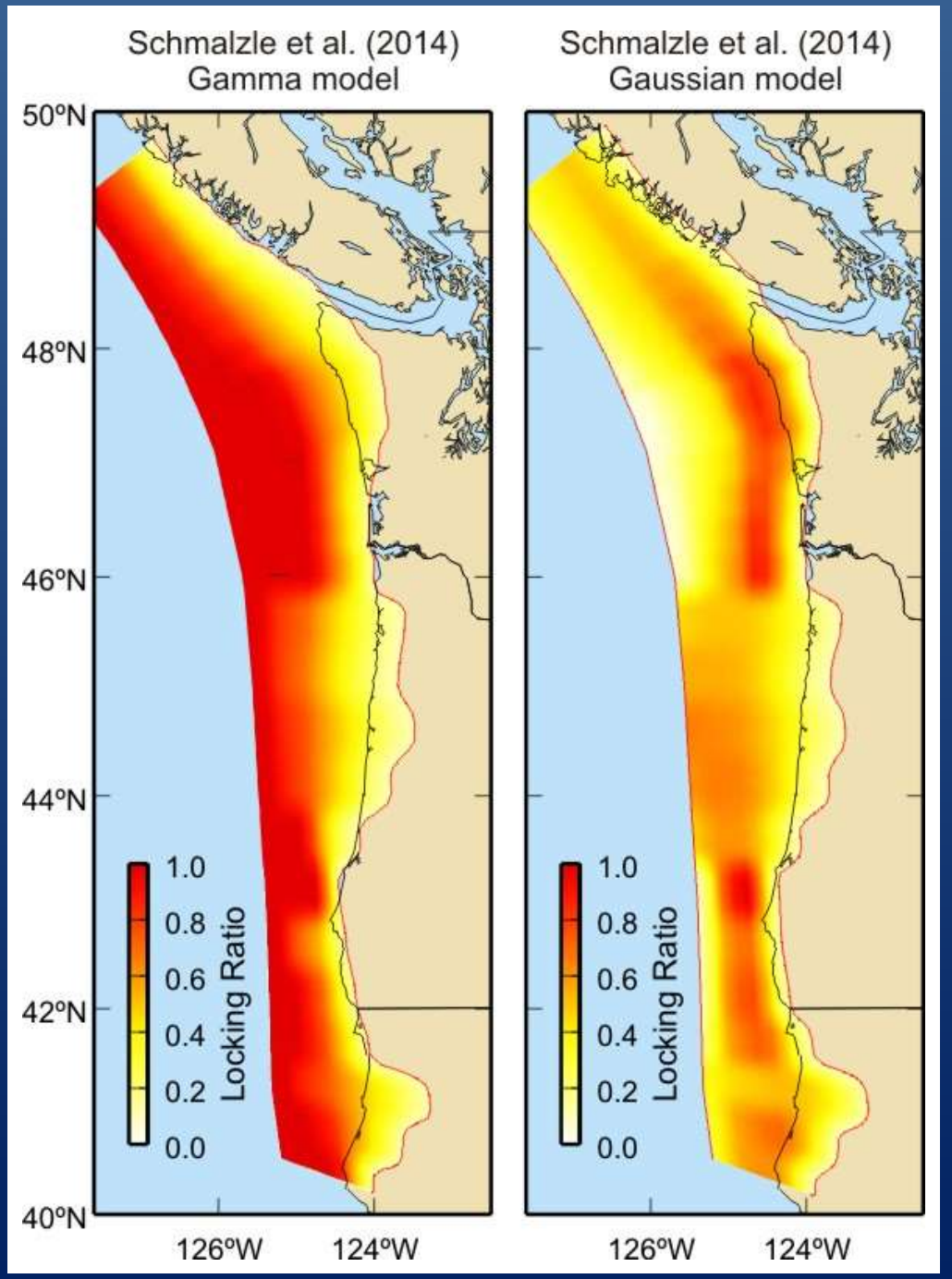
Obana et al., 2015 BSSA

SeaJade OBS monitoring:
Three months in 2010 and nine months in 2012 detected almost no earthquakes on megathrust.


Surface Velocities
1.0
0.5
0.0
Landward velocity
land-based
observations
Locking Ratio
1.0
0.5
0.0
full locking
locking but
near-trench
full creep
partial locking
fault locking ratio
(fraction of subduction rate)
0
100
200
Distance From "Trench" (km)


Schmalzle et al. (2014)
Gamma model
Schmalzle et al. (2014)
Gaussian model
50°N
48°N
46°N
44°N
42°N
40°N
Full
Trench creep
Partial
1.0
0.8
0.6
0.4
0.2
0.0
Locking Ratio
126°W
124°W

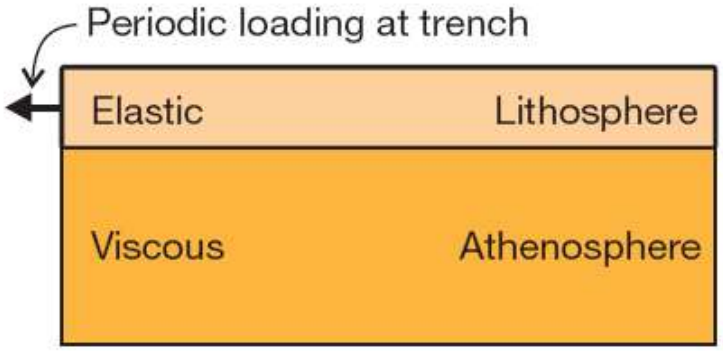

Port Alberni
Seatt
Pacific City
Proposed seafloor geodesy (Wilcock et al. 2012)


Schmalzle et al. (2014) Gamma model
Schmalzle et al. (2014) Gaussian model
50°N
48°N
46°N
44°N
42°N
40°N
126°W
124°W
1.0
0.8
0.6
0.4
0.2
0.0
Locking Ratio

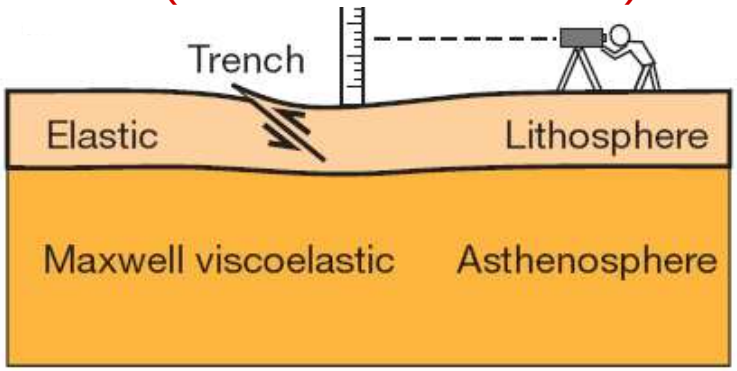
Interseismic stress relaxation

The Earth's mantle exhibits a viscoelastic behaviour

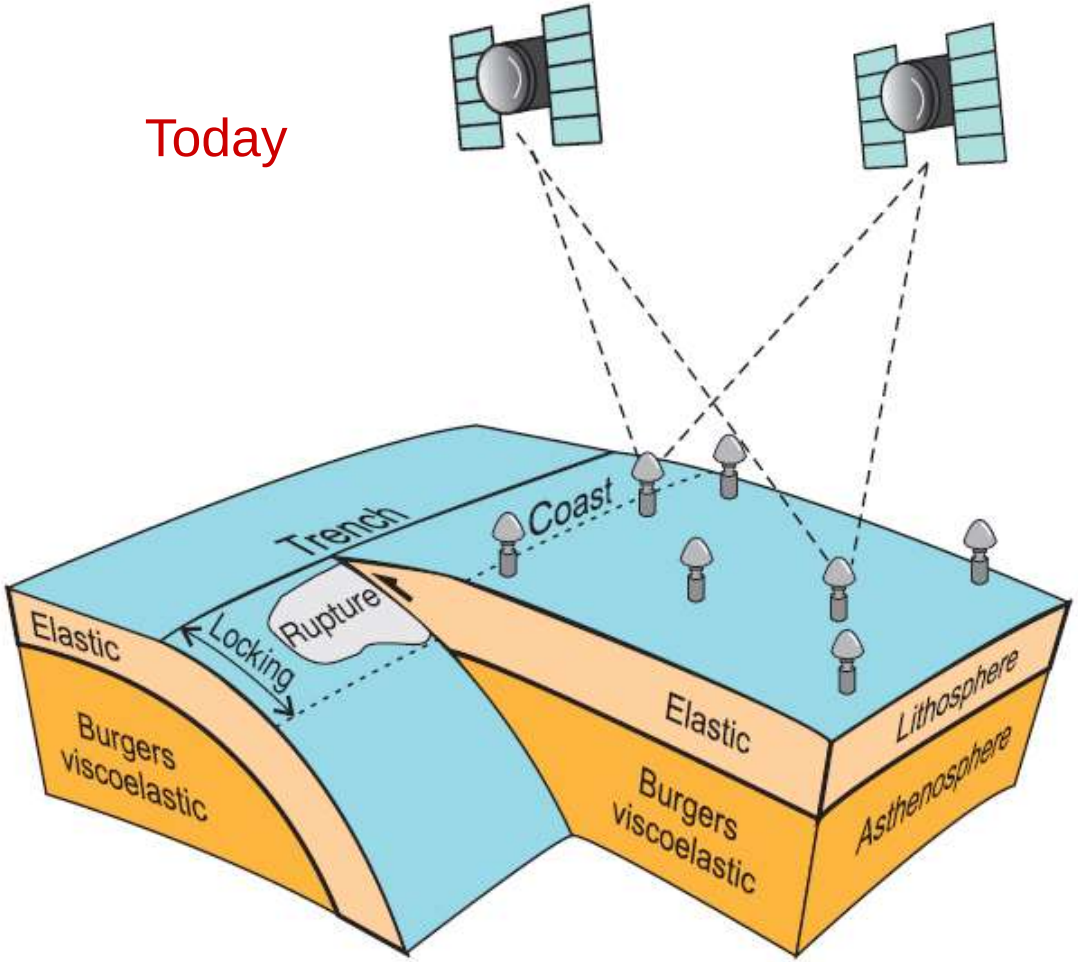
1973 (Bott and Dean)



1984 (Thatcher and Rundle)

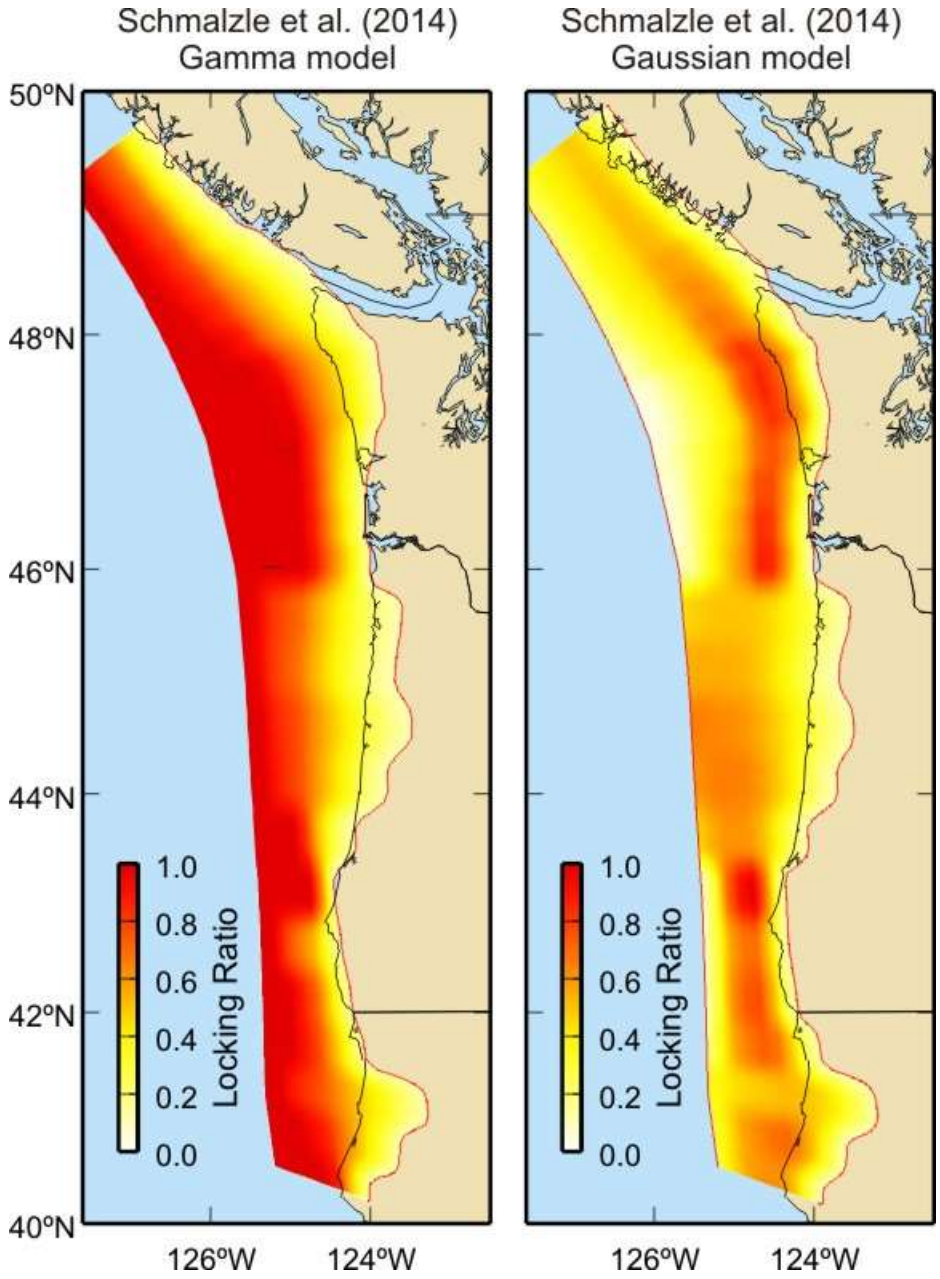


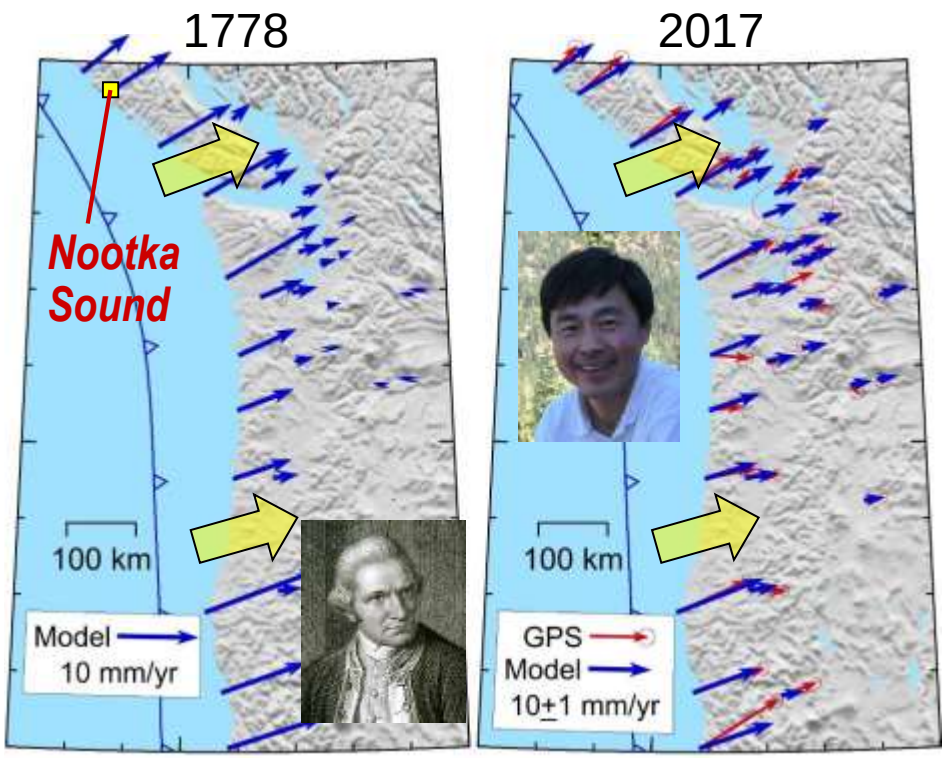
Today



Wang, Hu, He (Nature, 2012)

1700 earthquake



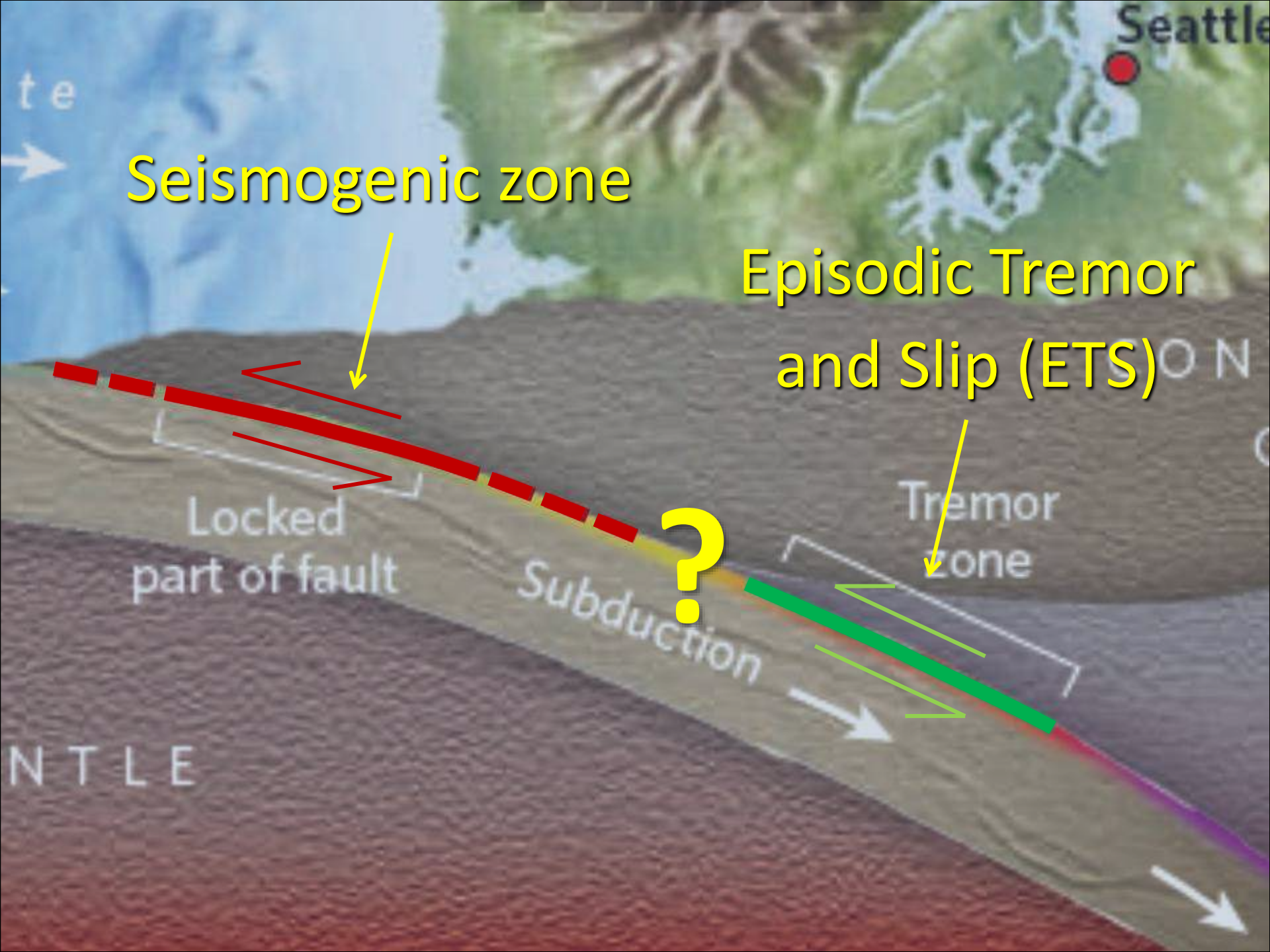


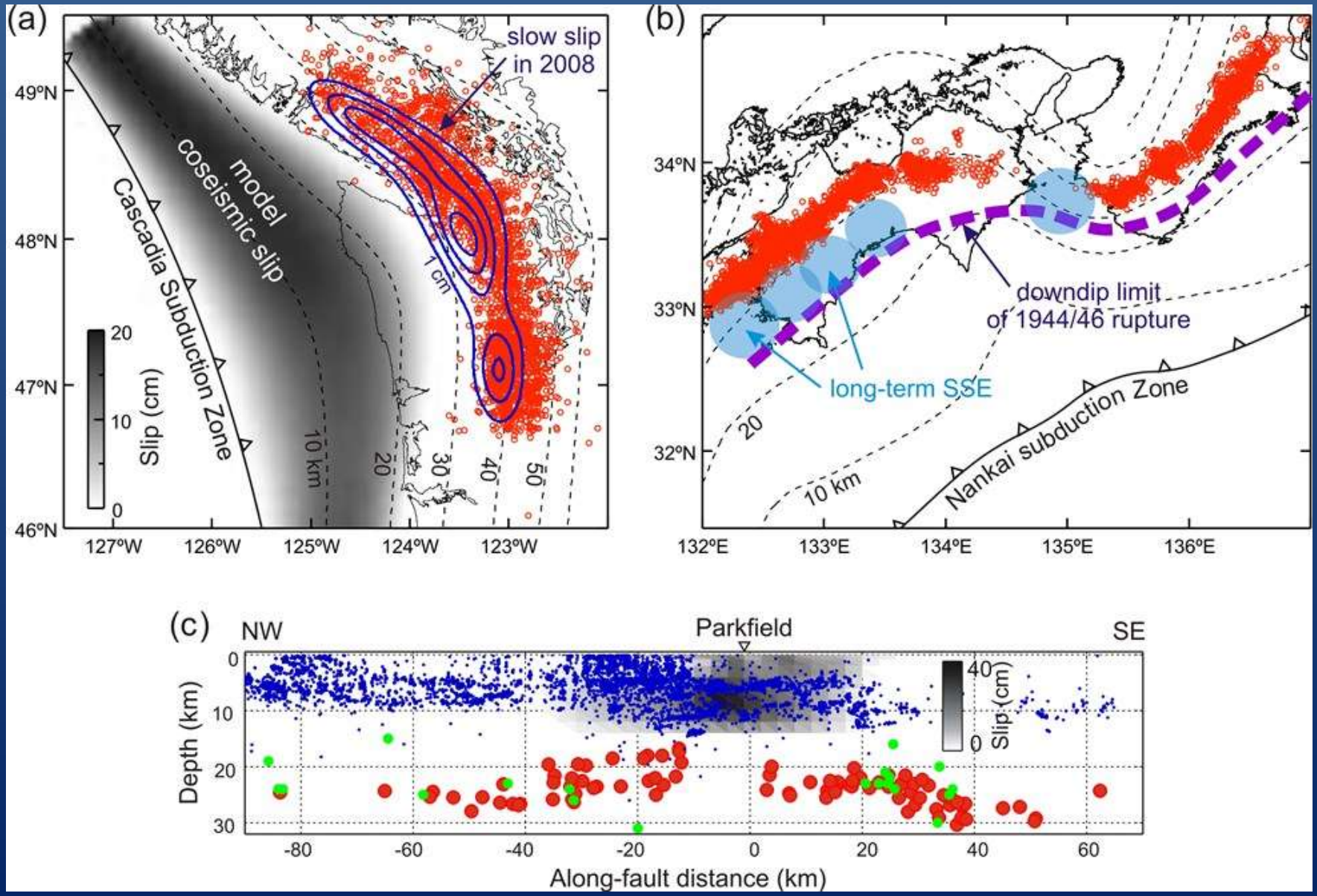
Captain Cook sailed along west coast of North America and stayed at Nootka Sound.

Dr. Wang presents ICLR webinar on 317th anniversary of the earthquake.

Model by Yan Hu

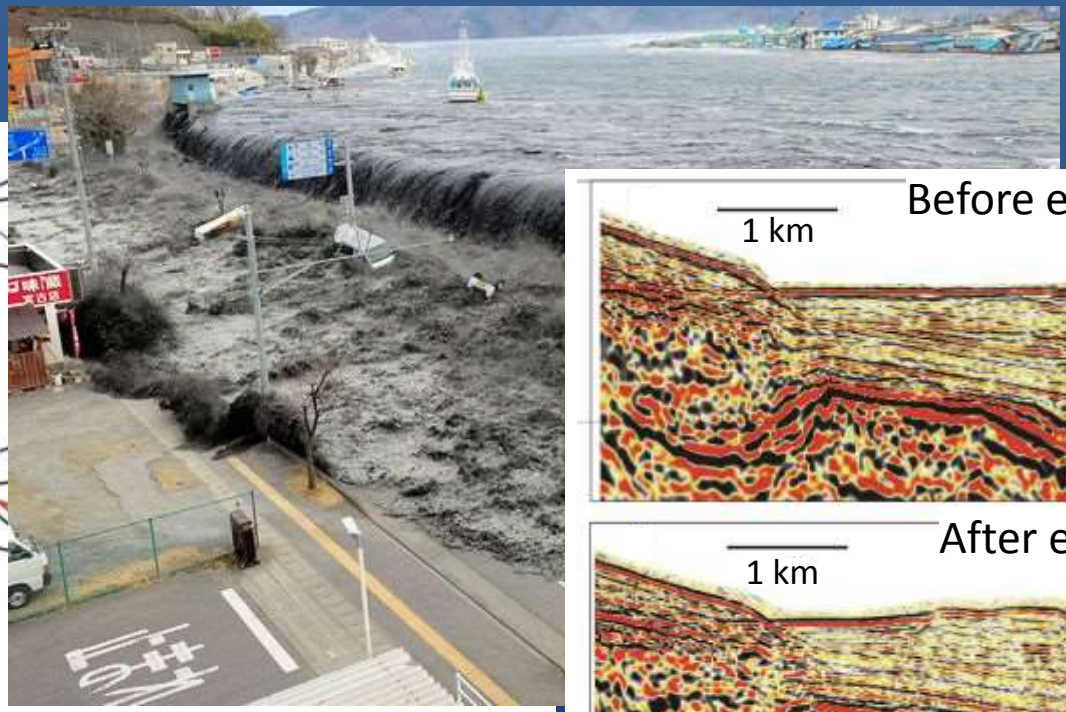
ETS and the seismogenic zone

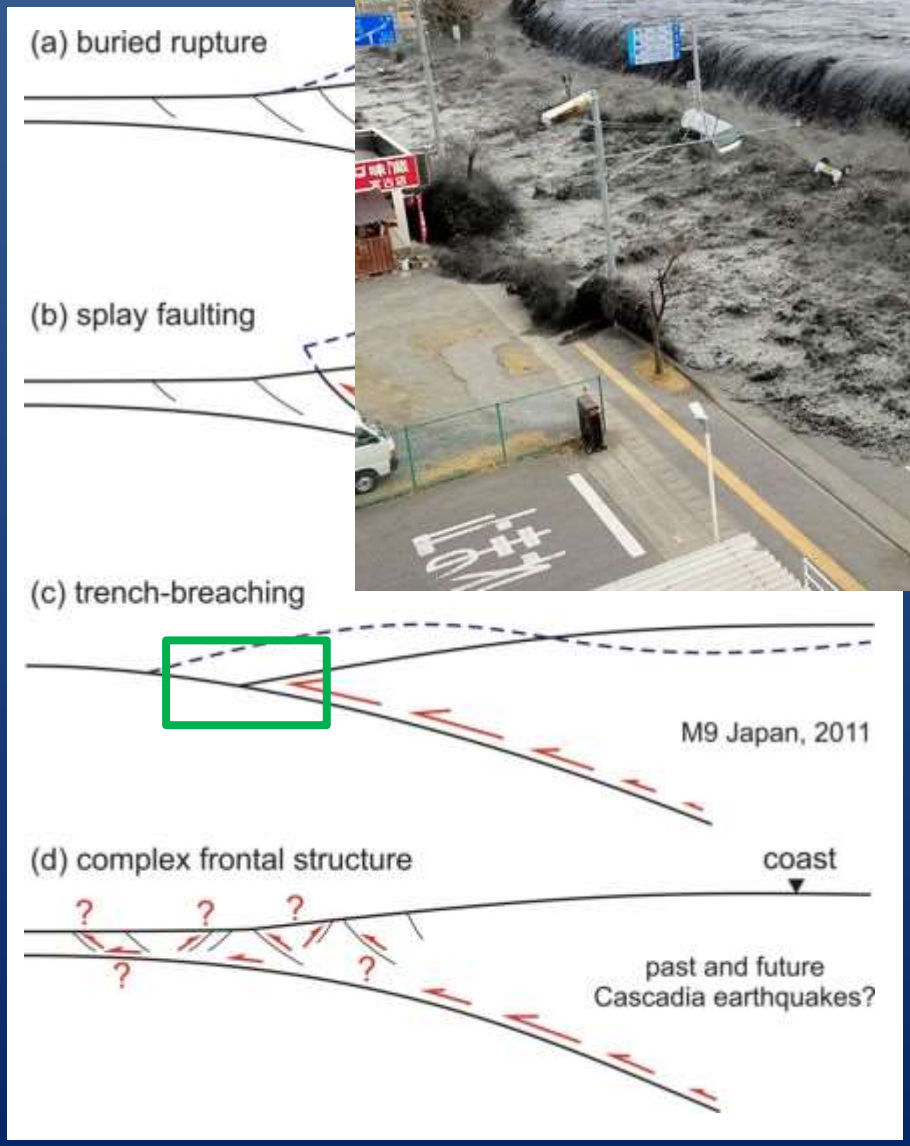

Seismogenic zone
Episodic Tremor
and Slip (ETS)
Locked
part of fault
?
Subduction
Tremor
zone
Seattle



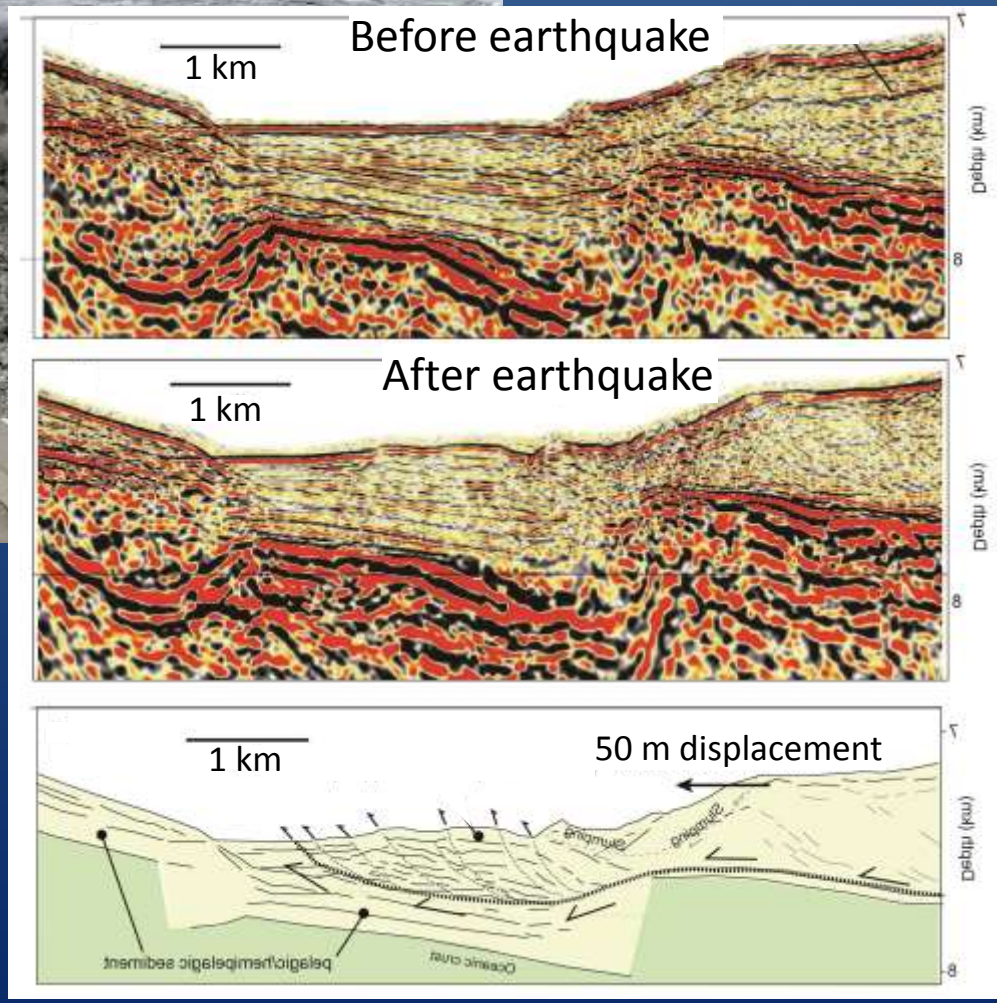
Wang and Trehu (2016 J. Geodyn.)

Tsunamigeneic seafloor deformation

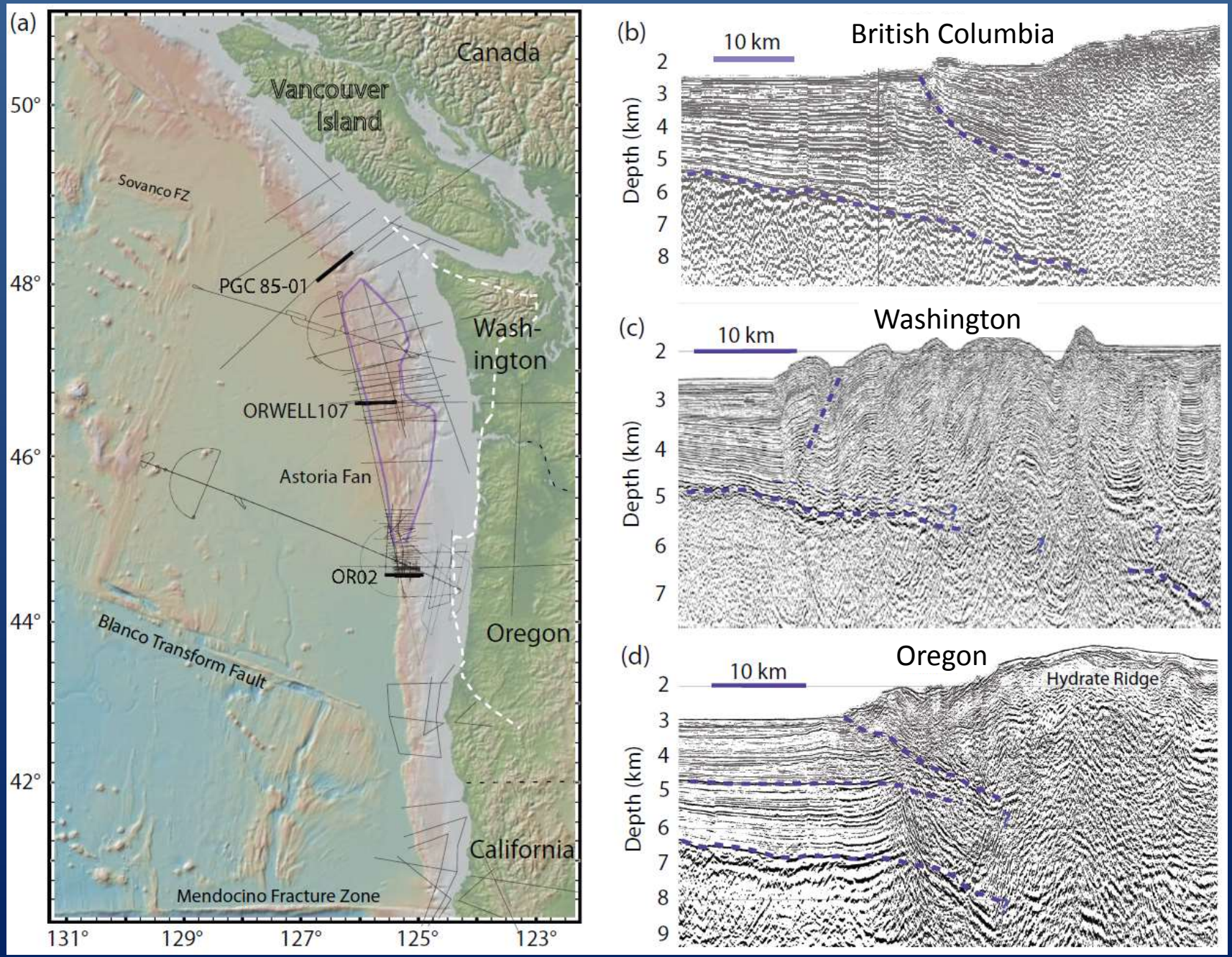




Wang and Trehu (2016 J. Geodyn)

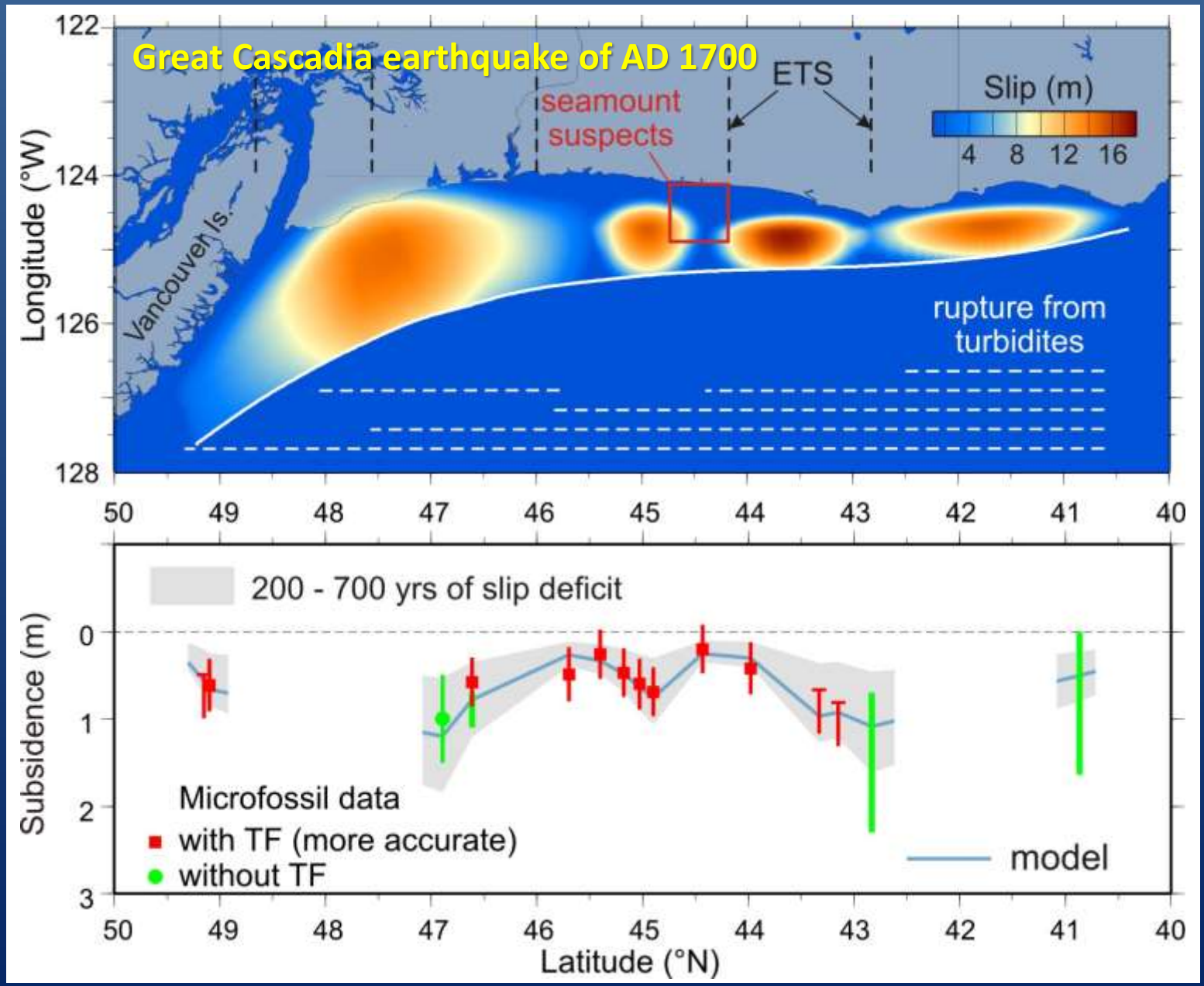


Kodaira et al. (2012 Nature Geoscience)



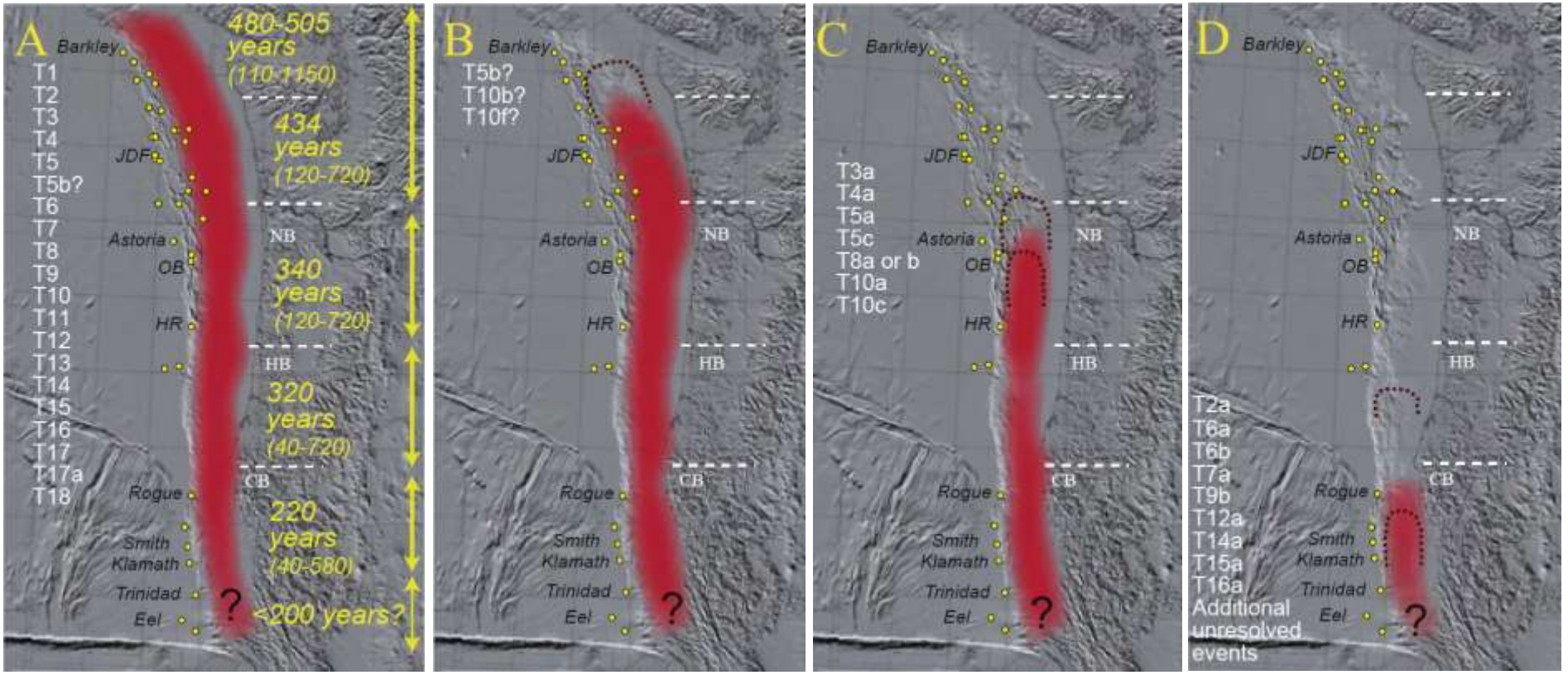
Wang and Trehu (2016 J. Geodyn.)

Along-strike heterogeneity and earthquake recurrence behaviour



Model by Wang et al. (2013 JGR)
Microfossil data: A. Hawkes, S. Engelhart, B. Horton, etc.

Great Cascadia earthquakes recorded in turbidite deposits over the past 10,000 years



M 8.8-9.2
~ 20 events

Many additional events in the south?

Simplified from Goldfinger et al. (2016 Marine Geology)

Some points to emphasize

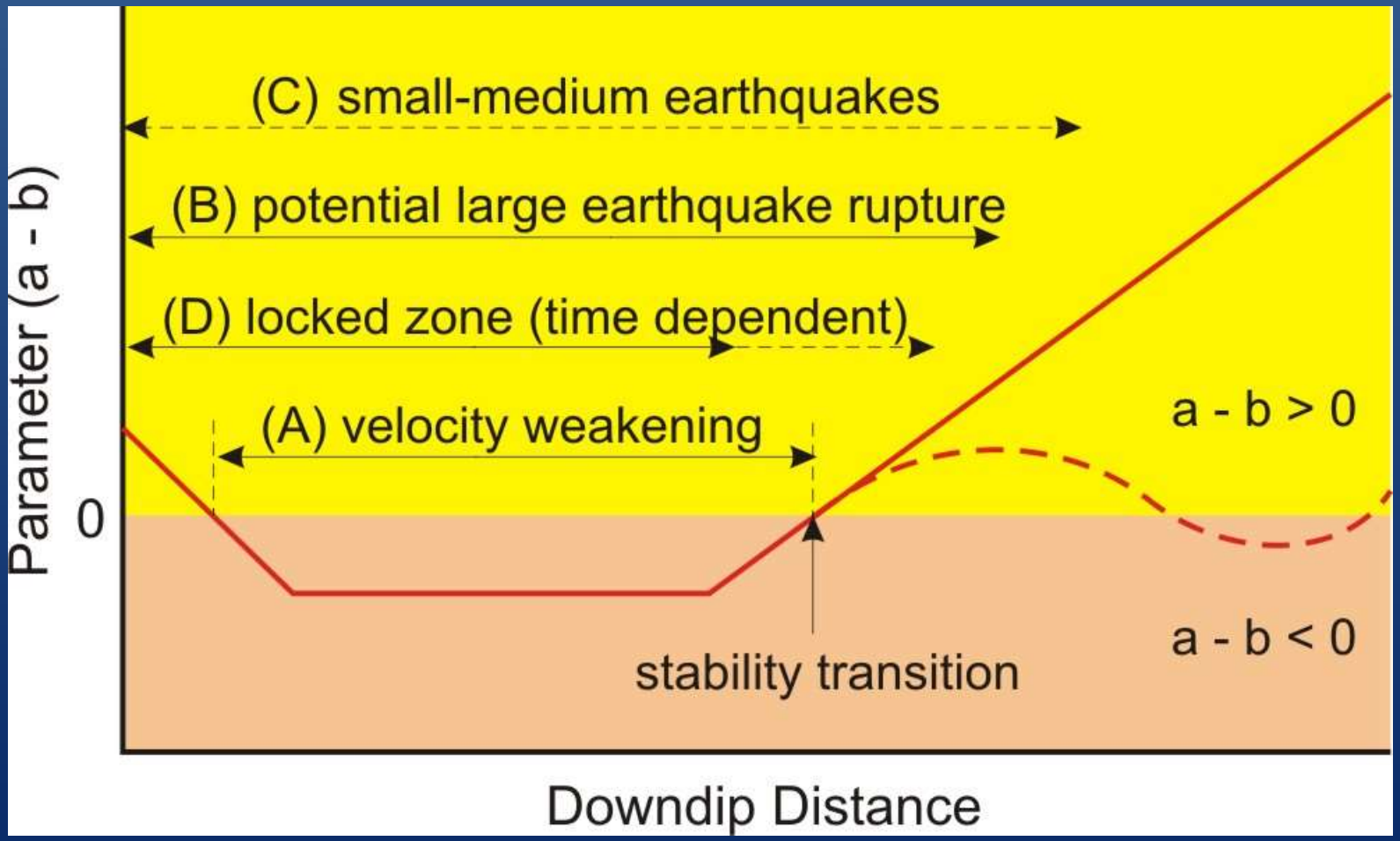
- Cascadia likely has a Sumatra-type megathrust featuring spread-out ruptures (large strike length, moderate slip).
- No doubt, the Cascadia megathrust is presently locked to some degree.
- Narrow and shallow locking is assumed because of high temperature.
- Full locking is assumed because of paucity of interface seismicity.
- Seafloor geodesy and seismometry are needed to define the true locking state.
- Multidisciplinary research is needed to understand the relation between ETS and the seismogenic zone.
- Geophysical imaging and geological studies are needed to investigate whether Tohoku-like trench-breaching rupture occurs at Cascadia.
- Structural and paleoseismic research needs to examine possibly persistent, geologically controlled along-strike heterogeneity in seismogenic behaviour.
- Local-scale research is needed to study site conditions pertaining to shaking amplification, tsunami inundation, and secondary hazards.

- Cascadia likely has a Sumatra-type megathrust featuring spread-out ruptures (large strike length, moderate slip).
- No doubt, the Cascadia megathrust is presently locked to some degree.
- Narrow and shallow locking is assumed because of high temperature.
- Full locking is assumed because of paucity of interface seismicity.
- Seafloor geodesy and seismometry are needed to define the true locking state.
- Multidisciplinary research is needed to understand the relation between ETS and the seismogenic zone.
- Geophysical imaging and geological studies are needed to investigate whether Tohoku-like trench-breaching rupture occurs at Cascadia.
- Structural and paleoseismic research needs to examine possibly persistent, geologically controlled along-strike heterogeneity in seismogenic behaviour.
- Local-scale research is needed to study site conditions pertaining to shaking amplification, tsunami inundation, and secondary hazards.

- Cascadia likely has a Sumatra-type megathrust featuring spread-out ruptures (large strike length, moderate slip).
- No doubt, the Cascadia megathrust is presently locked to some degree.
- Narrow and shallow locking is assumed because of high temperature.
- Full locking is assumed because of paucity of interface seismicity.
- Seafloor geodesy and seismometry are needed to define the true locking state.
- Multidisciplinary research is needed to understand the relation between ETS and the seismogenic zone.
- Geophysical imaging and geological studies are needed to investigate whether Tohoku-like trench-breaching rupture occurs at Cascadia.
- Structural and paleoseismic research needs to examine possibly persistent, geologically controlled along-strike heterogeneity in seismogenic behaviour.
- Local-scale research is needed to study site conditions pertaining to shaking amplification, tsunami inundation, and secondary hazards.

Questions welcome

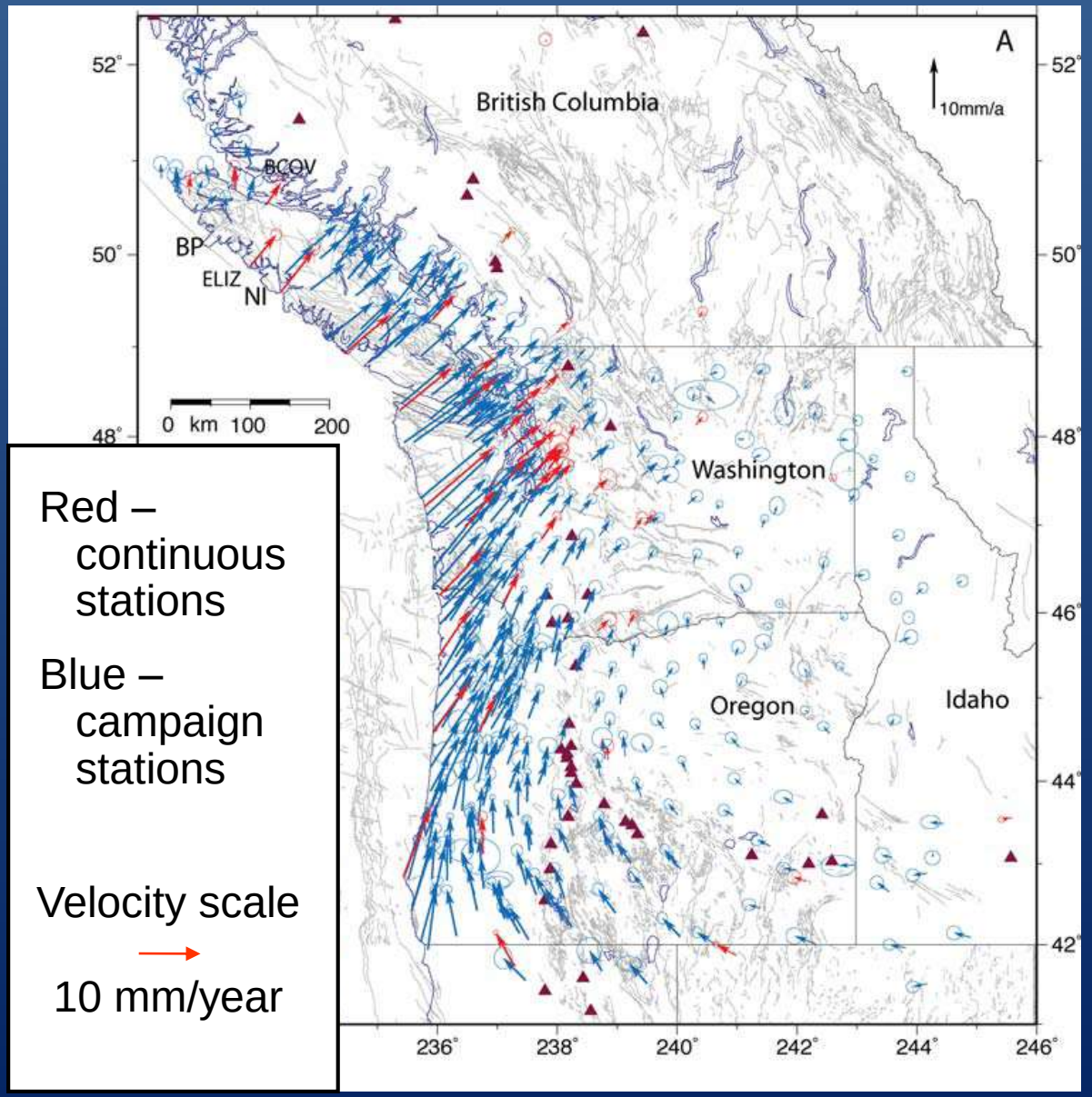
www.earthquakescanada.nrcan.gc.ca


(C) small-medium earthquakes
(B) potential large earthquake rupture
(D) locked zone (time dependent)
(A) velocity weakening
a - b > 0
a - b < 0
stability transition
Parameter (a - b)
0
Downdip Distance

GPS Observations (1991-2004)

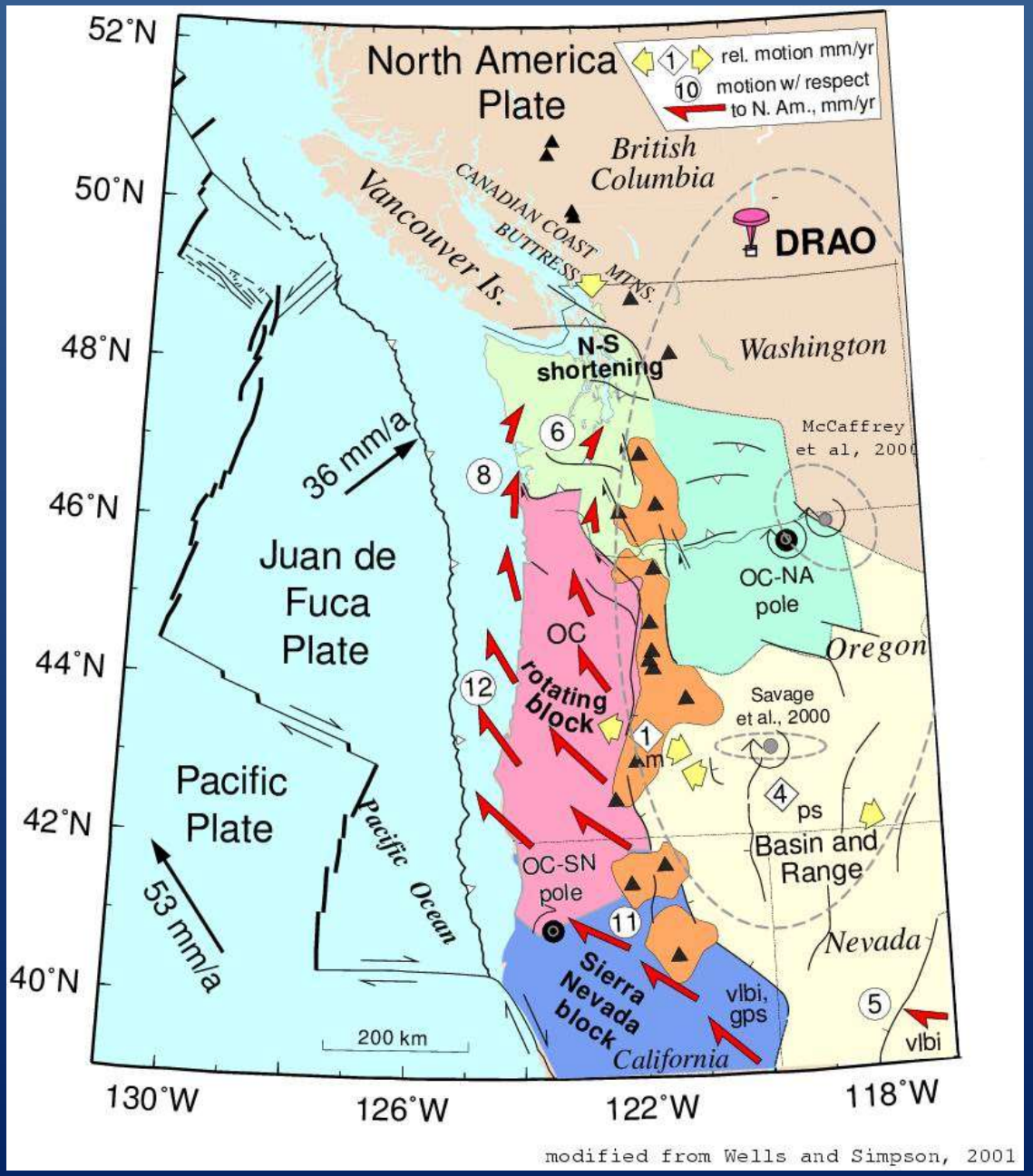
Station velocities with respect to stable North America

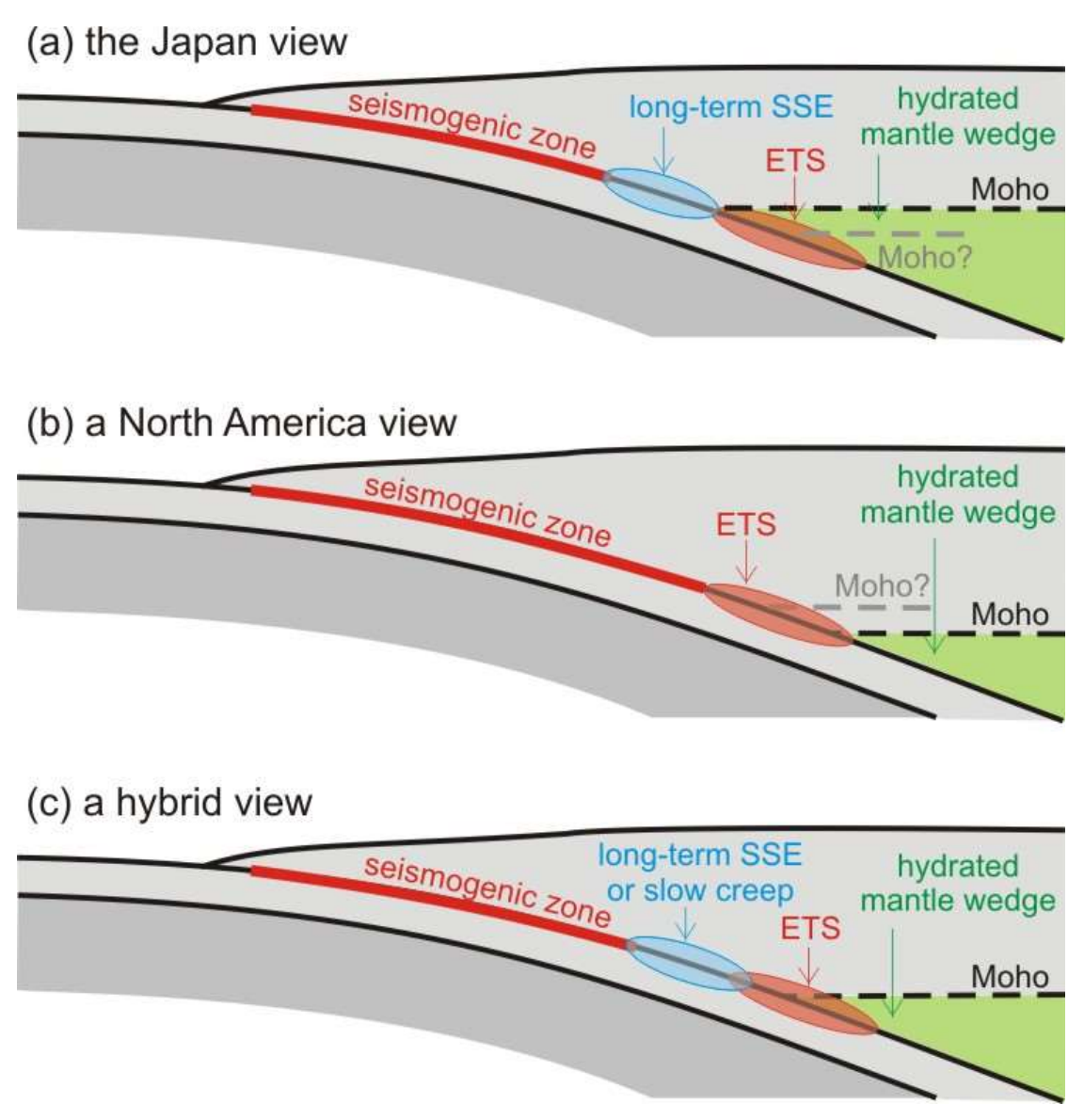
(Compiled by McCaffrey et al., 2007)



Secular motion of coastal region

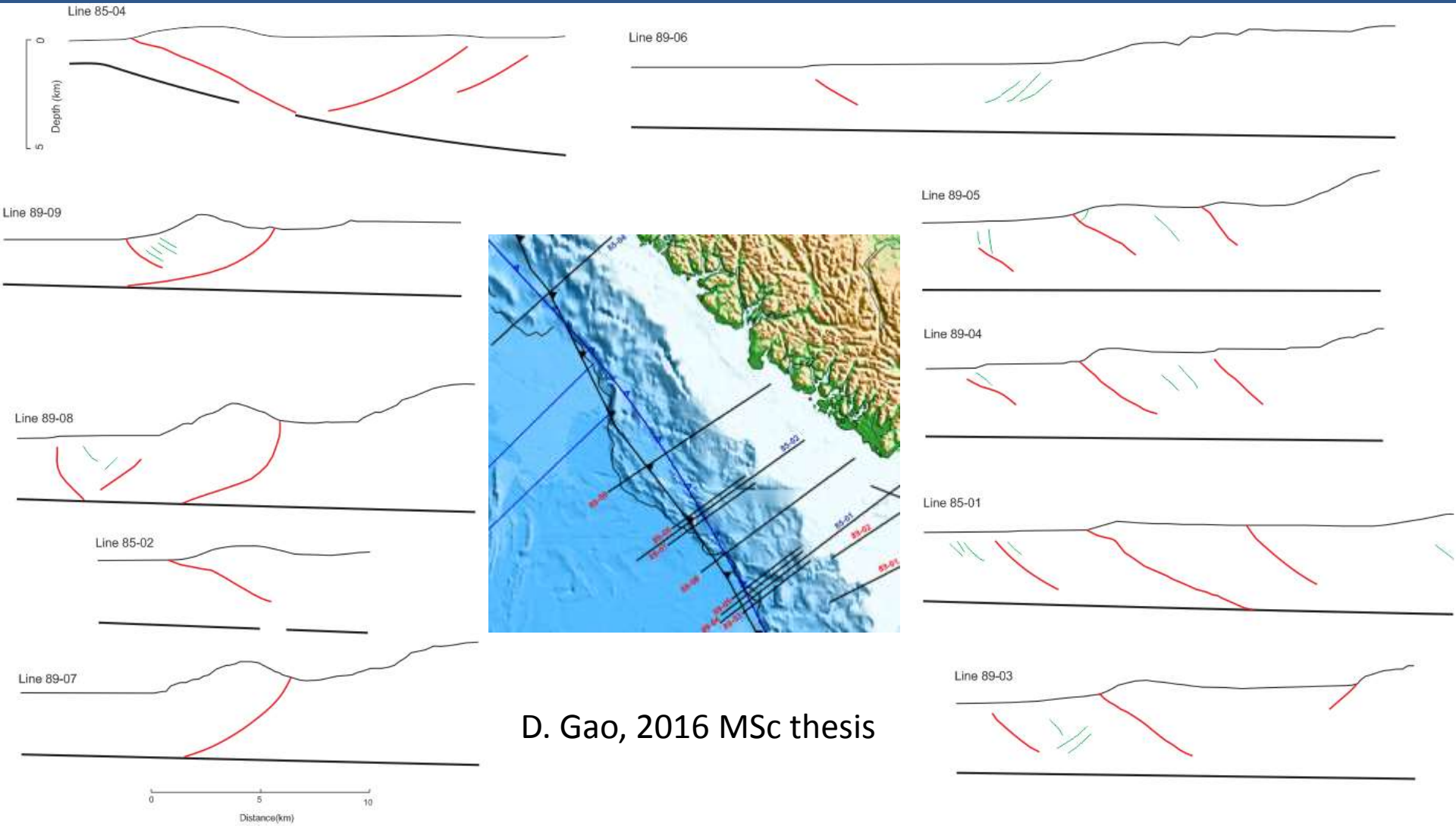
(*Model of Wells et al., 1998, based on Earth's magnetic field recorded in rocks and other geological data*).





Wang and Trehu (2016 J. Geodyn.)

Frontal thrusts off Vancouver Island identified from seismic survey profiles



D. Gao, 2016 MSc thesis