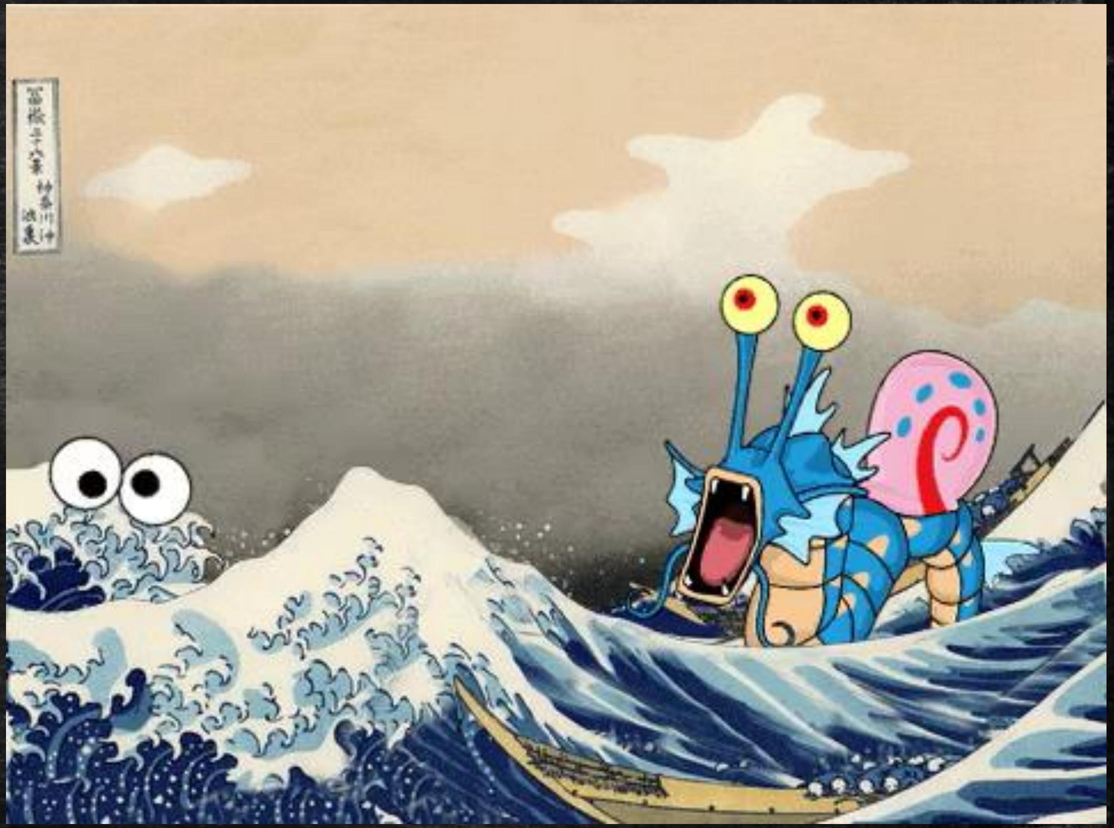
California
Department of
Conservation
California Geological Survey
Seismic Hazards | Tsunami Unit

Cascadia PTHA Updates

- USGS Powell Center Meeting
  - Subject Matter Experts
- CSZ Logic Tree
- CSZ Megathrust Geometry


reddit.com/r/gifs/comments/ftlhkz/this_is_a_gif_i_did_by_myself_inspired_by_an_edit/

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California Department of Conservation
California Geological Survey
Seismic Hazards | Tsunami Unit

USGS Tsunami Sources Powell Center Working Group on Tsunami Sources: Probabilistic Tsunami Hazard Assessment for the Cascadia Subduction Zone

Jason "Jay" R. Patton – California Geological Survey
*Marie C Eble – Physical Oceanographer
Christodoulos Kyriakopoulos – University of Memphis
Patrick J Lynett – University of Southern California
*Dmitry Nicolsky – University of Alaska Fairbanks
*Stephanie Ross – USGS
Kenny J Ryan – Air Force Research Laboratory Albuquerque
Hong Kie Thio – AECOM
*Rick I Wilson – California Geological Survey

* = Principal Investigator

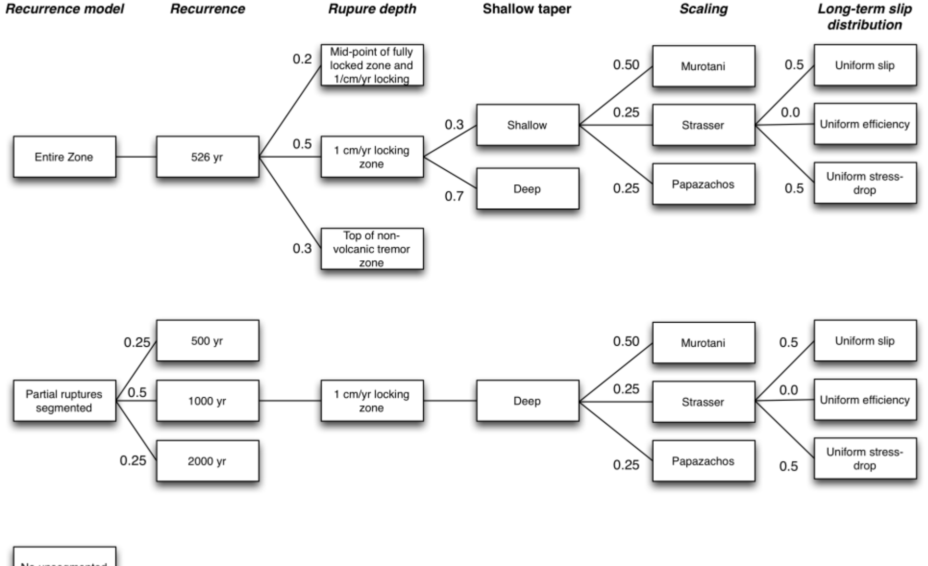
In May 2022 live and remote participants in the photo gathered to discuss peer reviewed literature that has implications for tsunamigenesis along the Cascadia subduction zone (the CSZ).

The presentations and discussion were used to develop a logic tree that will be used as input for Probabilistic Tsunami Hazard Assessment (PTHA) in Cascadia. One major goal is to keep this PTHA consistent with the USGS NSHM 2023 update.

PTHA and Logic Trees

Probabilistic tsunami hazard assessment (PTHA) is a process used to develop a framework to inform tsunami modeling and hazards analyses.

This process uses a logic tree approach to collate the entire suite of possible and probable tsunamigenic behavior of tsunami sources relevant to the area of interest.



From Hong Kie Thio presentation

A logic tree is a way to calculate the relative likelihood for each of all possible scenarios for a given phenomenon.

PTHA and Logic Trees

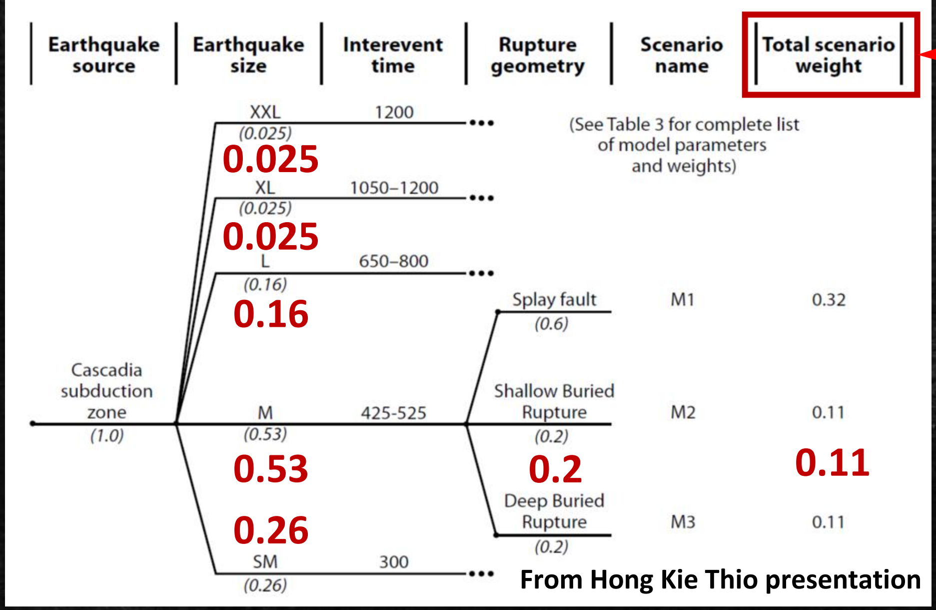
In the logic tree, each possible scenario is organized as a separate branch. Each branch is given a weight, based on expert opinion, that represents the chance that a scenario may happen.

Branch weights, for each splay, are additive vertically & sum to 1:

0.025 + 0.025 + 0.16 + 0.53 + 0.26 = 1 (or 100%)

The weights for each splay are multiplied horizontally to calculate the scenario weight:

0.053 * 0.2 = 0.11 (or 11%)



From Hong Kie Thio presentation

The result is the total weight for each scenario.

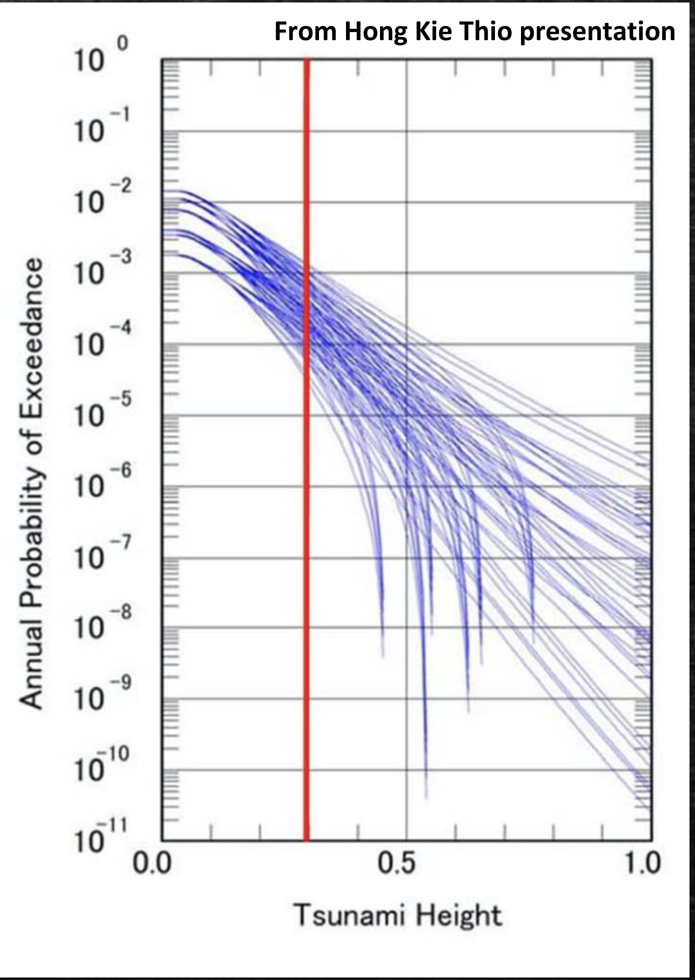
These total weights also add up to 1, vertically (or 100%).

Logic tree results and how to prepare tsunami hazard curves:

- Logic tree weights are used to constrain slip and tsunami source modeling.
- These tsunami models result in a suite of offshore tsunami heights, representing the percent likelihood (chance) for tsunami sizes for given annual probability of exceedance.
- Using this entire suite of model results, we can calculate quantiles that bracket a range of probabilities.
- From these data we can calculate the tsunami size for tsunami with return periods (such as the "975-year tsunami").

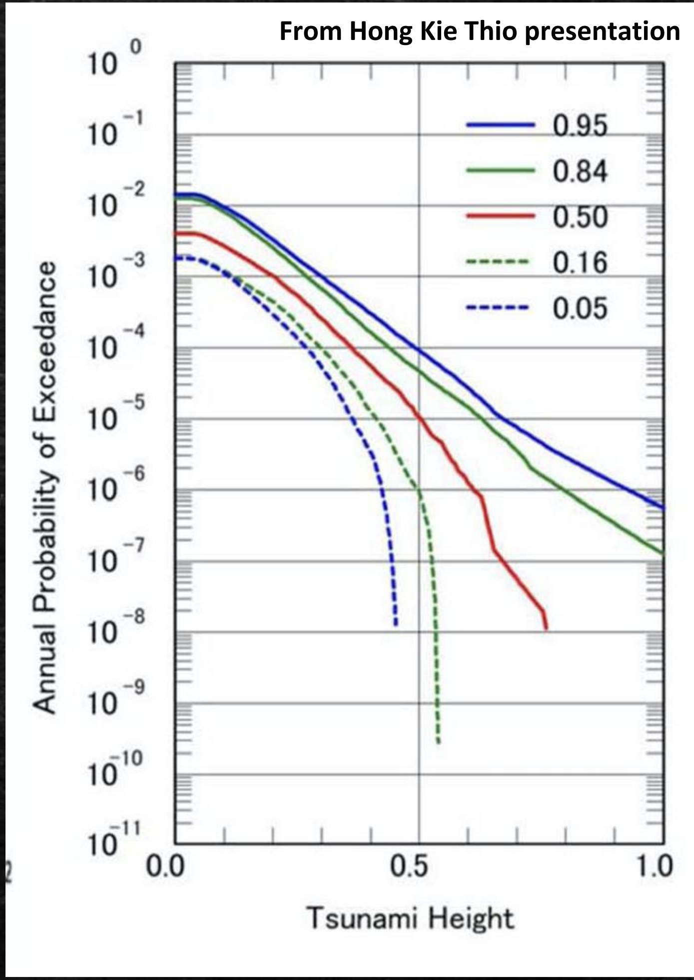
Tsunami Model Results

Each line represents an actualization of a logic tree scenario tsunami, a percent chance (likelihood) for tsunami size with an annual probability of occurrence.



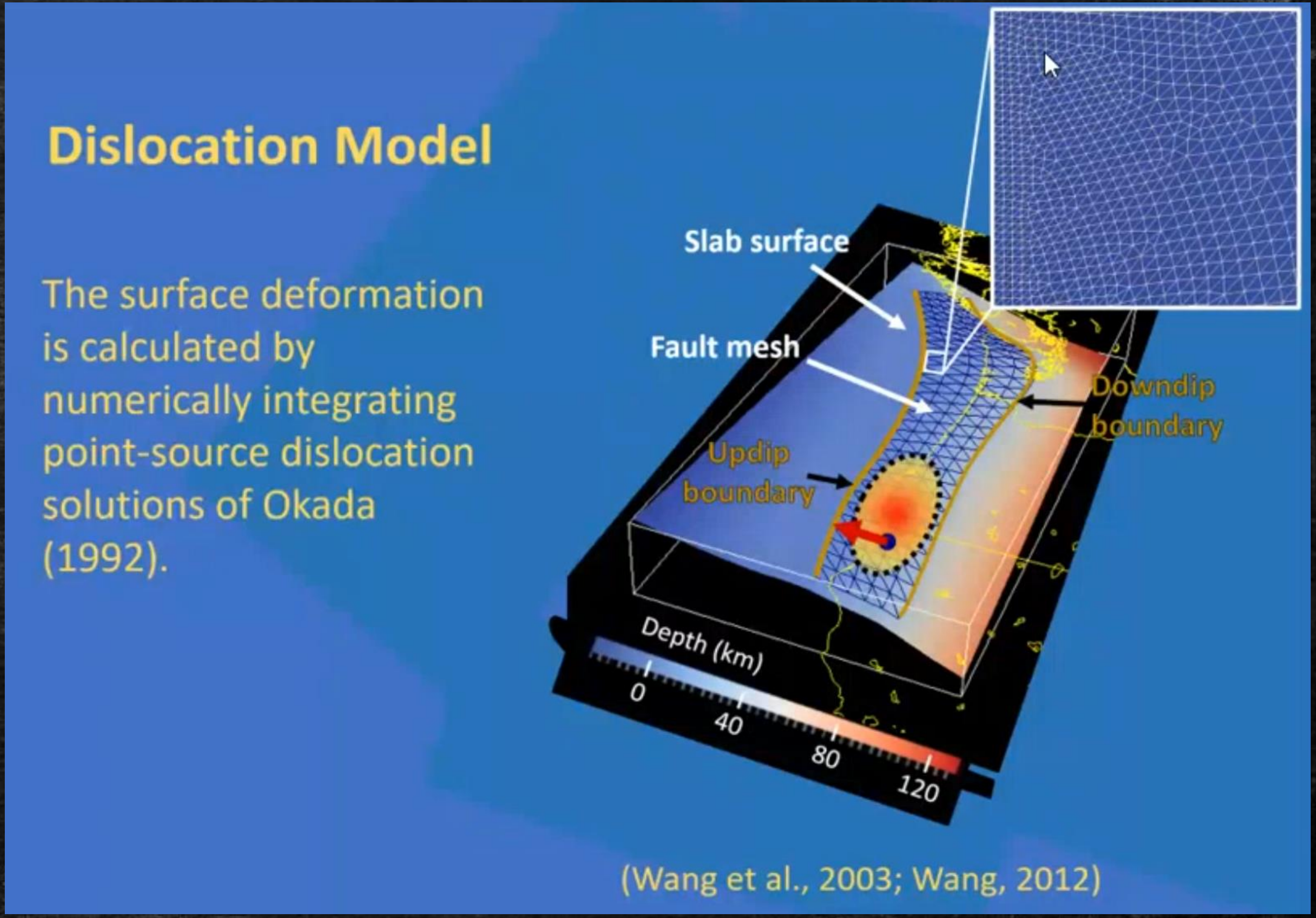
Tsunami Model Quantiles

Each line represents a bracketed summary of the data plotted on the left. E.g., the 0.05 and 0.95 lines bracket 90% of the scenario tsunami plotted on the left.



Cascadia Megathrust Geometry:

- Kelin Wang and Matthew Sypus constructed a CSZ megathrust surface deformation model that is being used for the initial conditions for the tsunami wave simulations.
- We have enlisted the cooperation of Suzanne Carbotte and Harold Tobin who are working with their students and collaborators to establish the fault geometry for the CSZ. For the up-dip region of the fault this work is based on new seismic data collected in 2021 during a margin-wide research cruise called CASIE21. The fault geometry in the down-dip region is based on low frequency earthquake analyses from Michael Bostock and their collaborators.

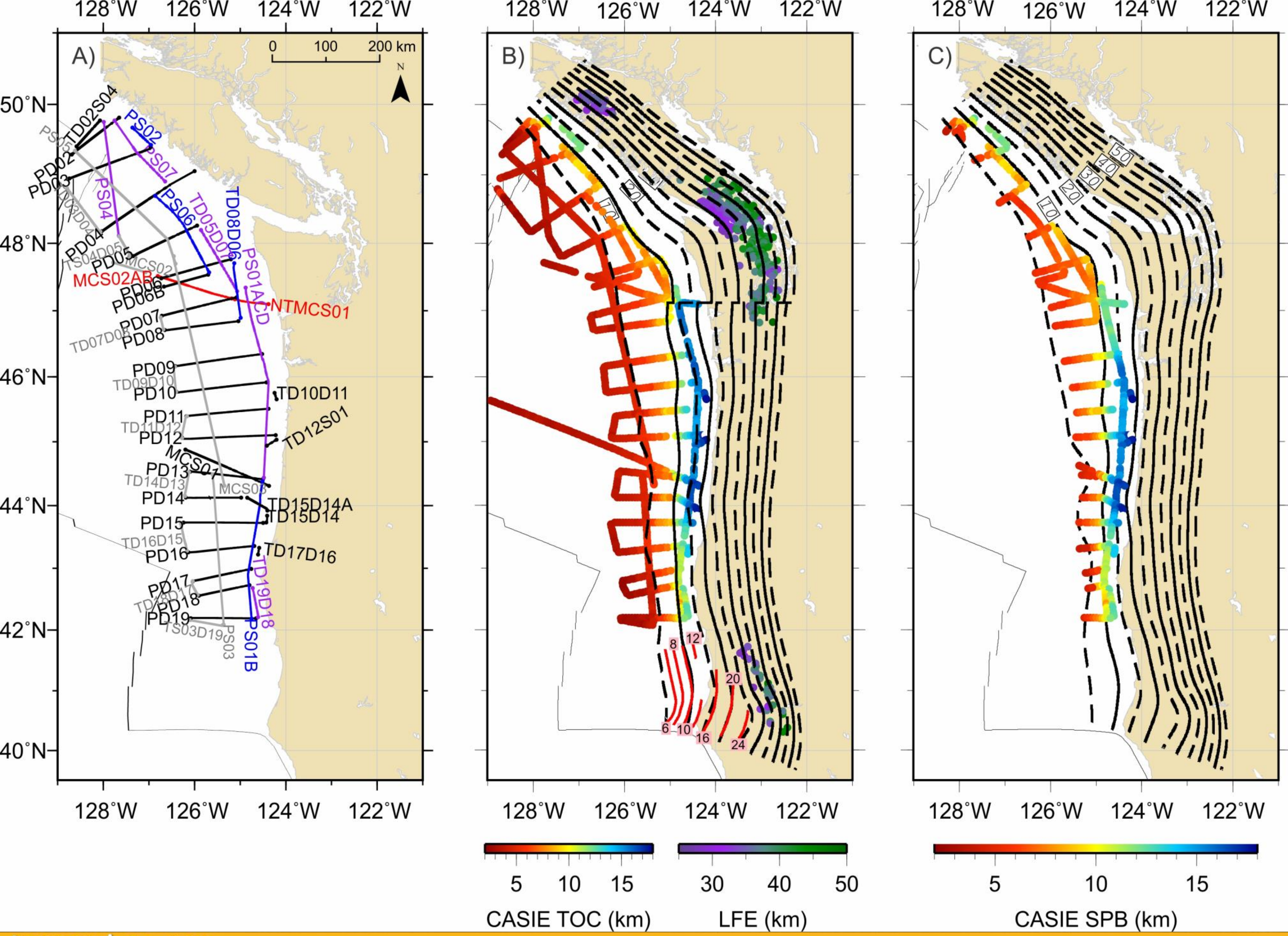


OPEN-FILE REPORT O-24-11

IMPROVED CASCADIA EARTHQUAKE SOURCE MODELS FOR TSUNAMI HAZARD ASSESSMENT

By Matthew Sypus and Kelin Wang[1]

https://www.oregon.gov/dogami/pubs/Pages/ofr/p-O-24-11.aspx

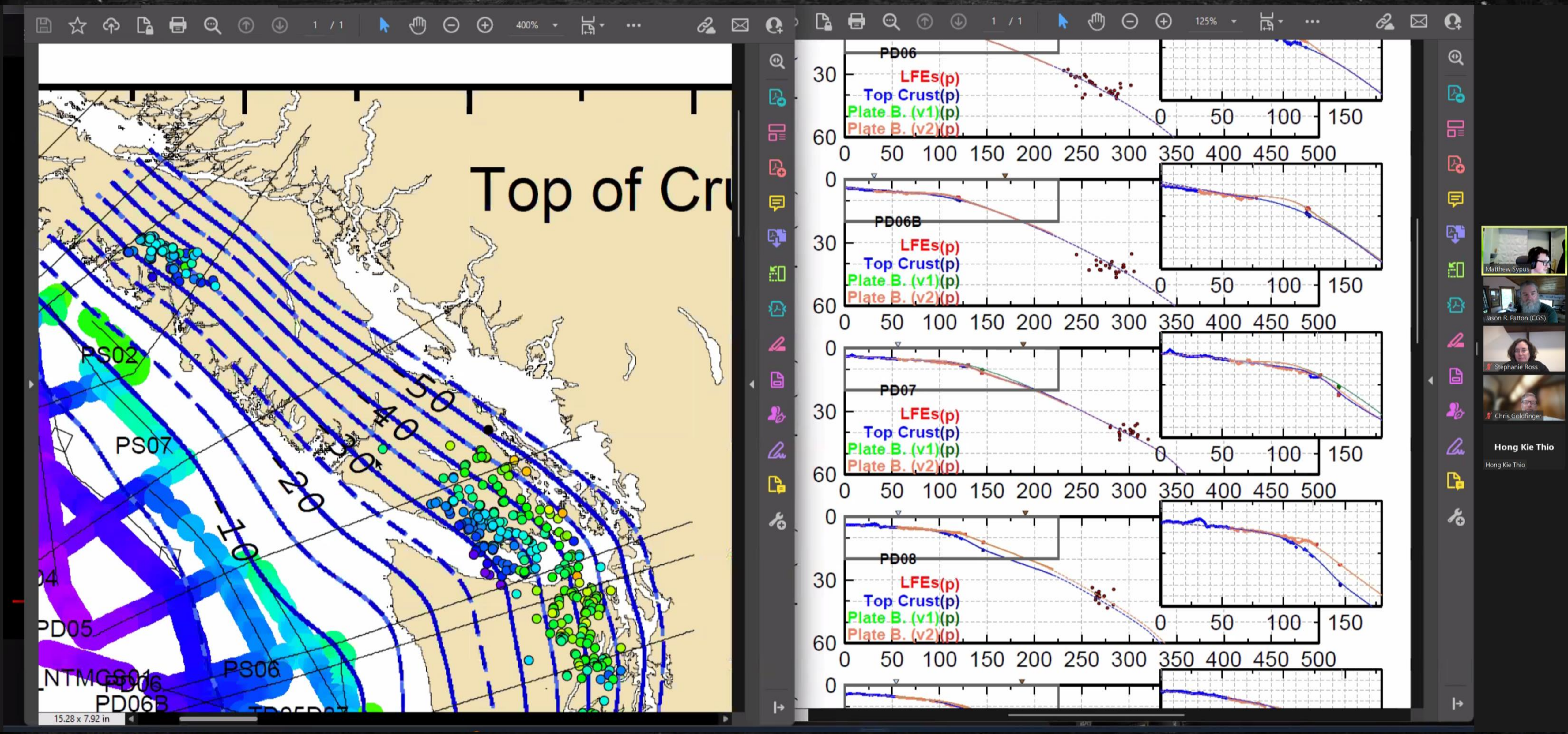


These maps show the spatial extent of the CASIE21 geophysical mapping of the margin, limited to Canada, Washington, and Oregon.

(A) Tracklines
(B) Top of Crust
(C) Slab Contours

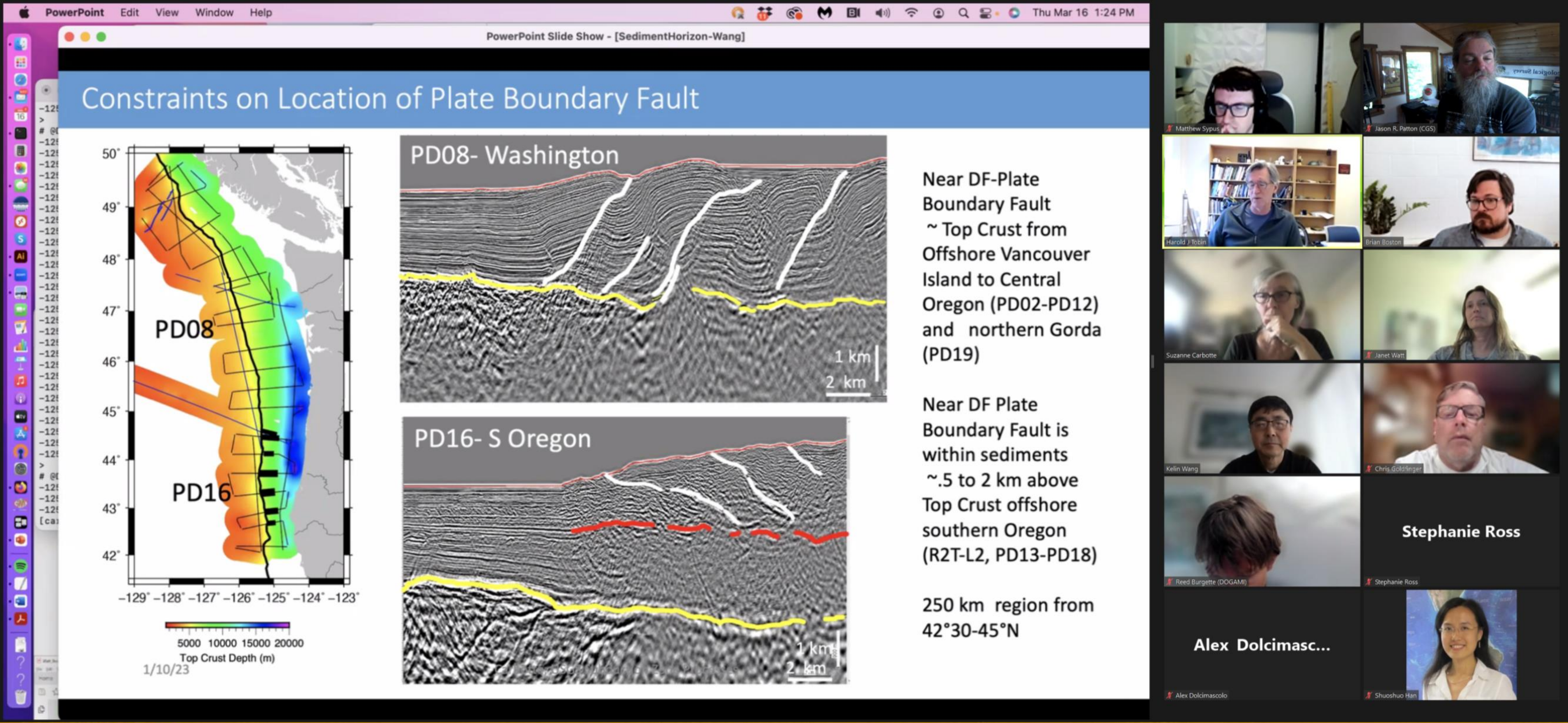
Megathrust Contours

Matt constructed two surfaces: (1) top of crust (blue lines on profiles), (2) décollement (orange lines in profiles).



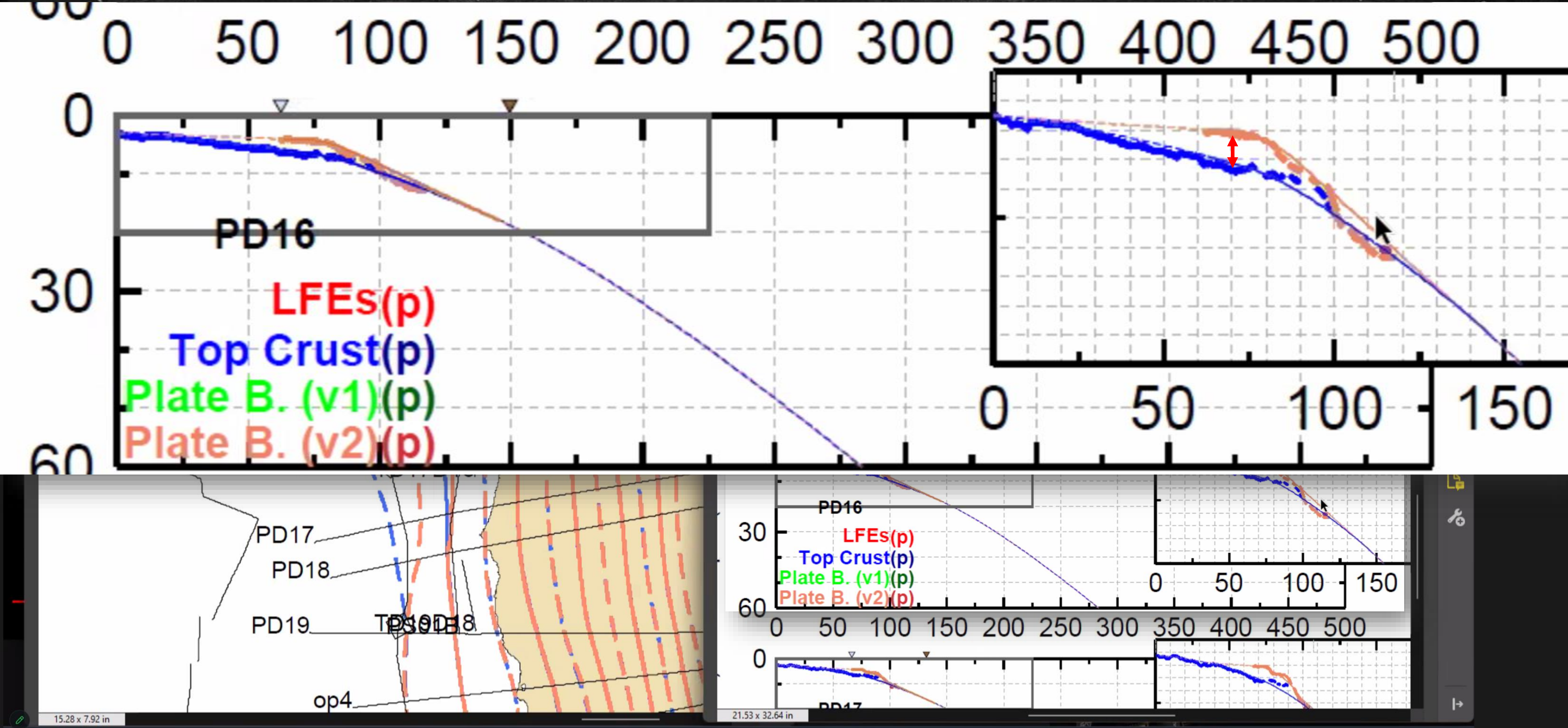
CASIE21: The décollement is in different positions along different parts of the megathrust.

Offshore Washington, the décollement is near the top of the crust. Offshore Oregon, the décollement is within the sedimentary section (there is sediment subduction here).



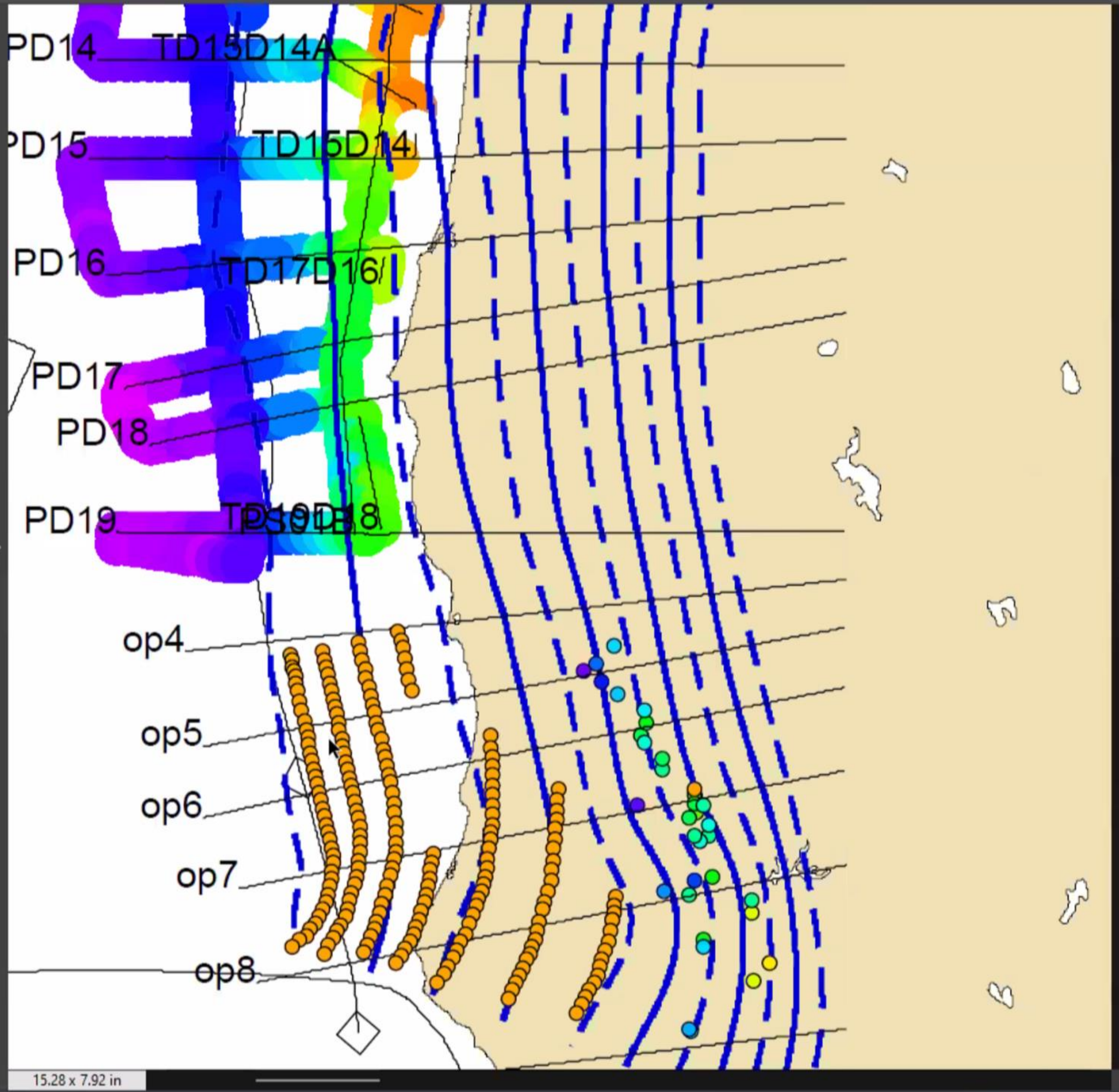
Megathrust Contours

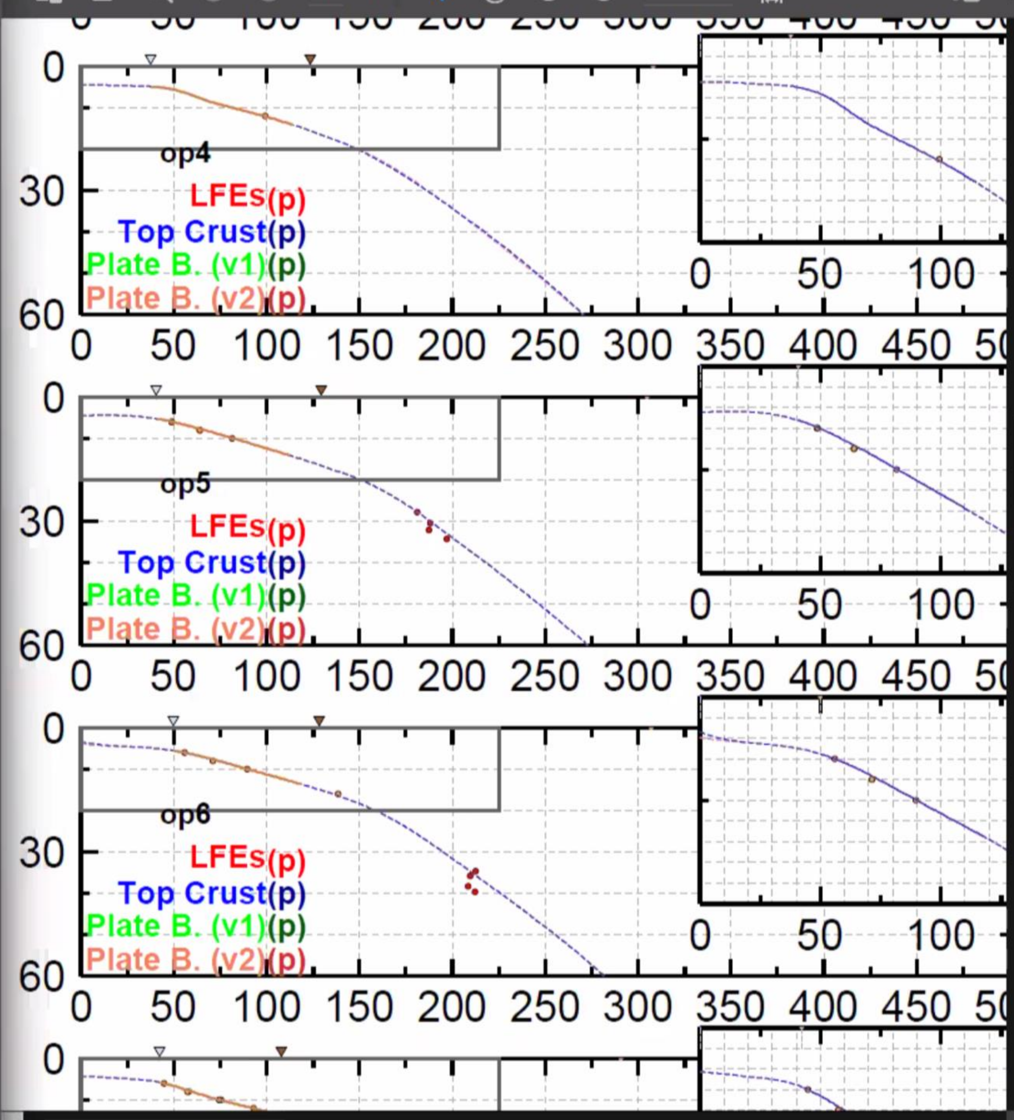
Note the thick sedimentary section offshore of Oregon (difference between orange and blue lines in profiles)



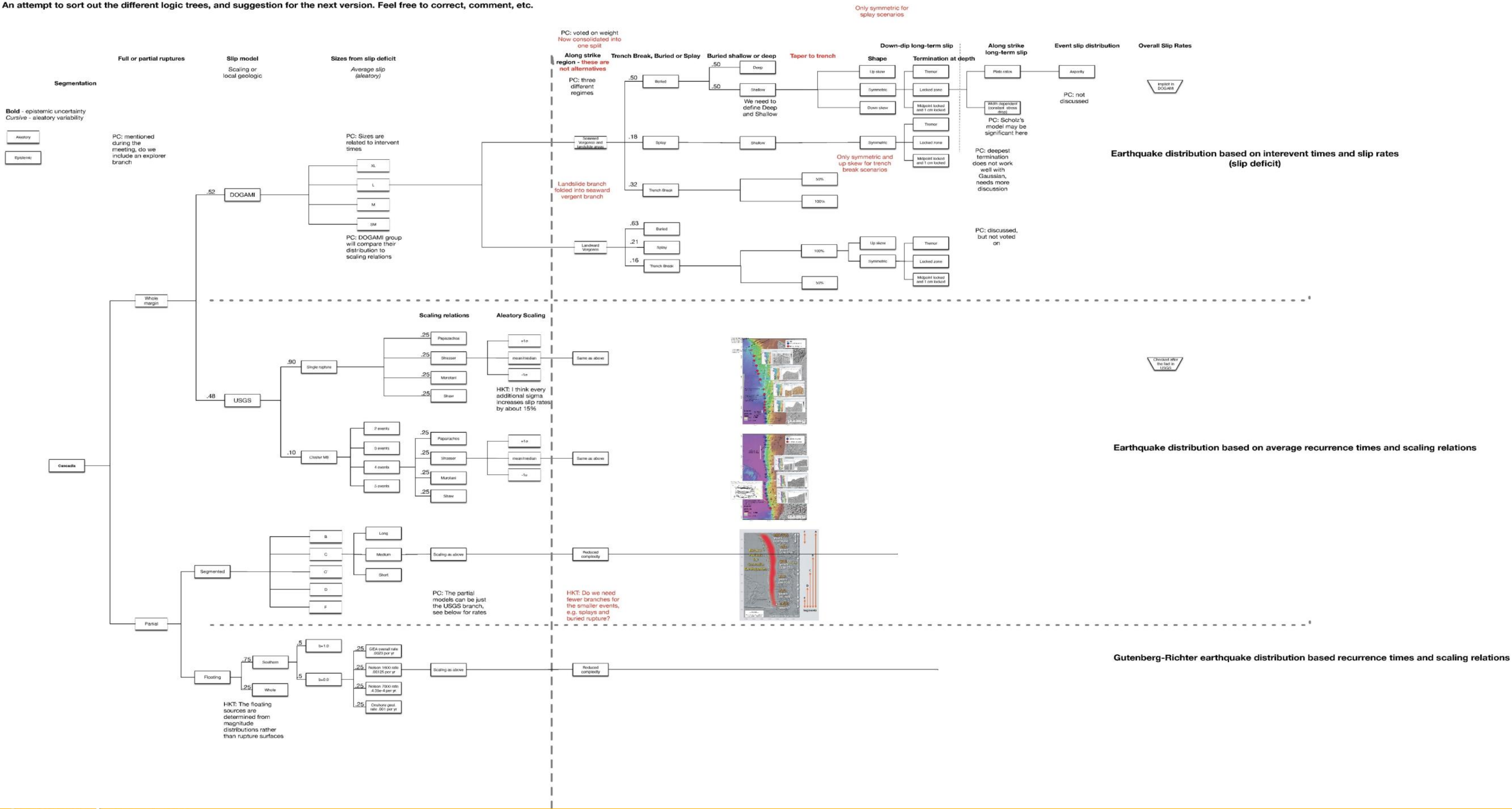
Megathrust Contours

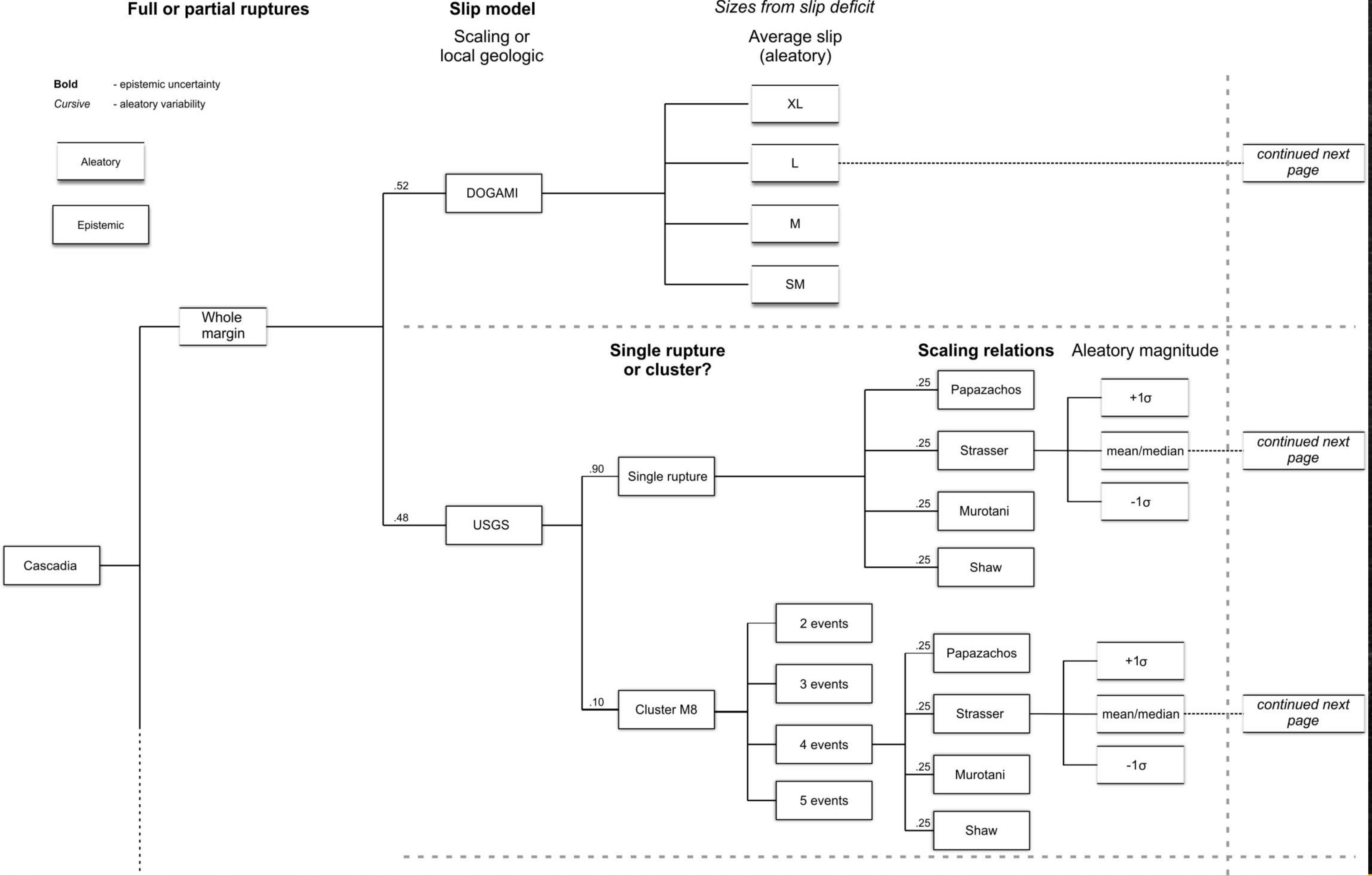
Anne Tréhu provides picks for SCSZ where we lack CASIE21 data.





An attempt to sort out the different logic trees, and suggestion for the next version. Feel free to correct, comment, etc.



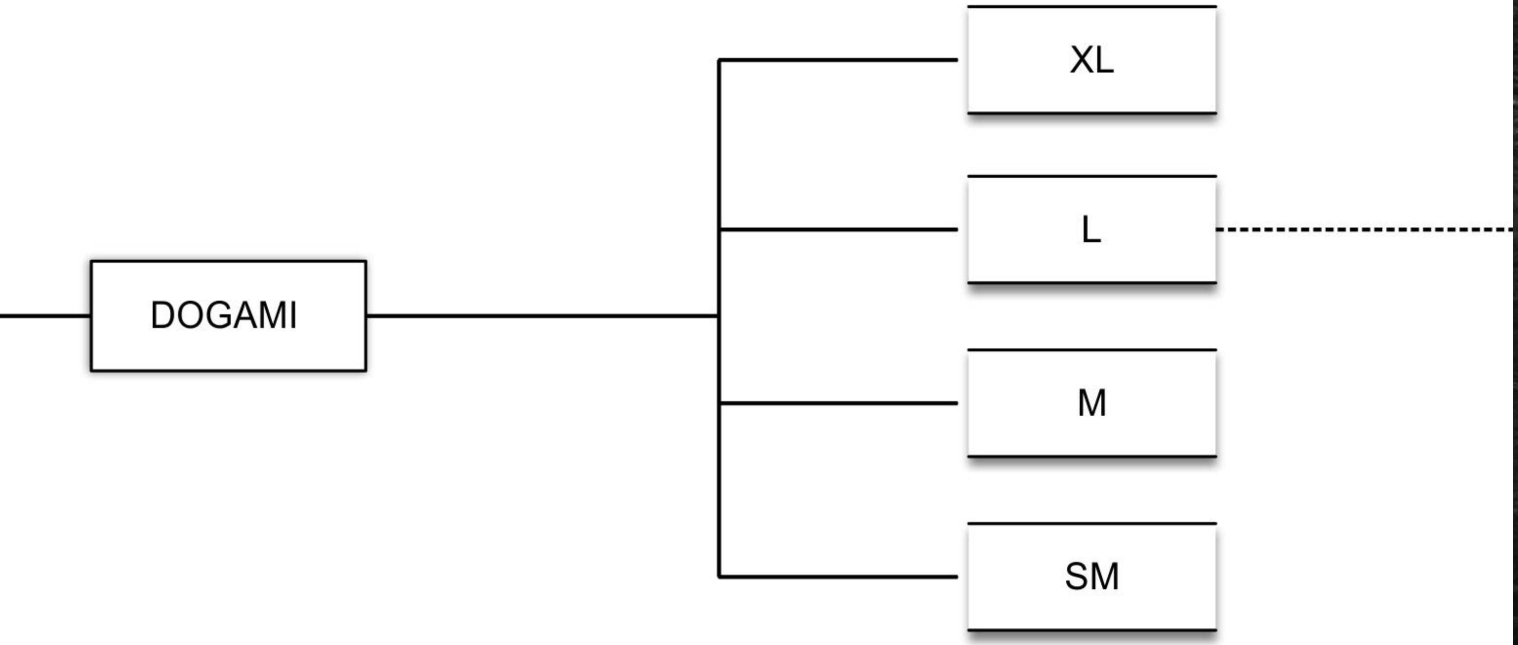

Full or partial ruptures
Slip model
Scaling or local geologic
Sizes from slip deficit
Average slip (aleatory)
Bold - epistemic uncertainty
Cursive - aleatory variability
Aleatory
Epistemic
Cascadia
Whole margin
.52
DOGAMI
XL
L
M
SM
continued next page
.48
USGS
Single rupture or cluster?
.90
Single rupture
.10
Cluster M8
Scaling relations
Aleatory magnitude
.25
Papazachos
.25
Strasser
.25
Murotani
.25
Shaw
+1σ
mean/median
-1σ
continued next page
2 events
3 events
4 events
5 events
.25
Papazachos
.25
Strasser
.25
Murotani
.25
Shaw
+1σ
mean/median
-1σ
continued next page

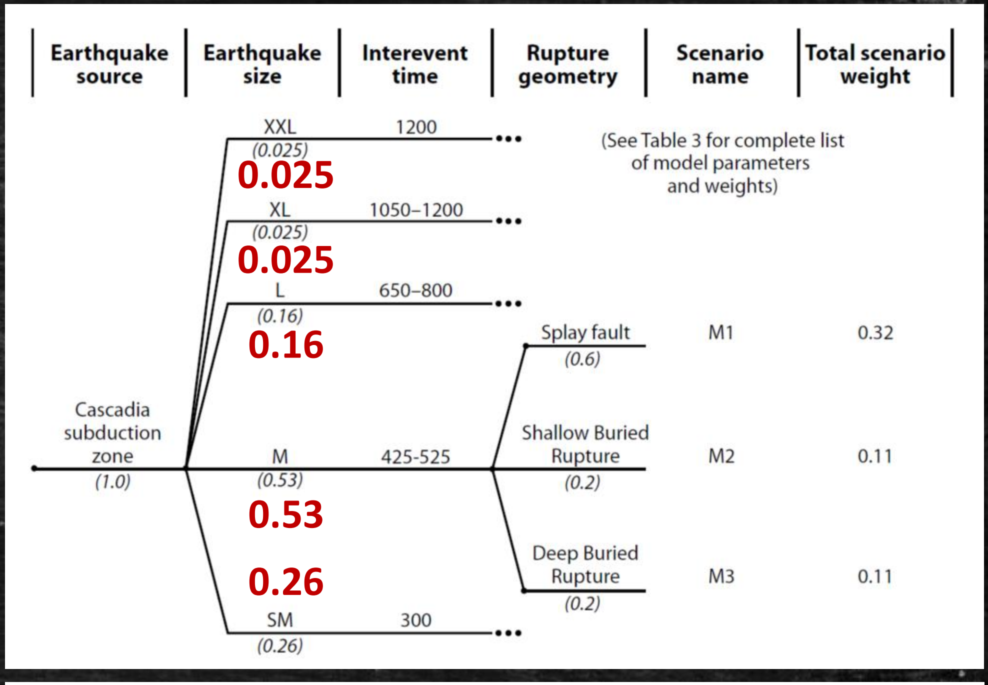
Slip model

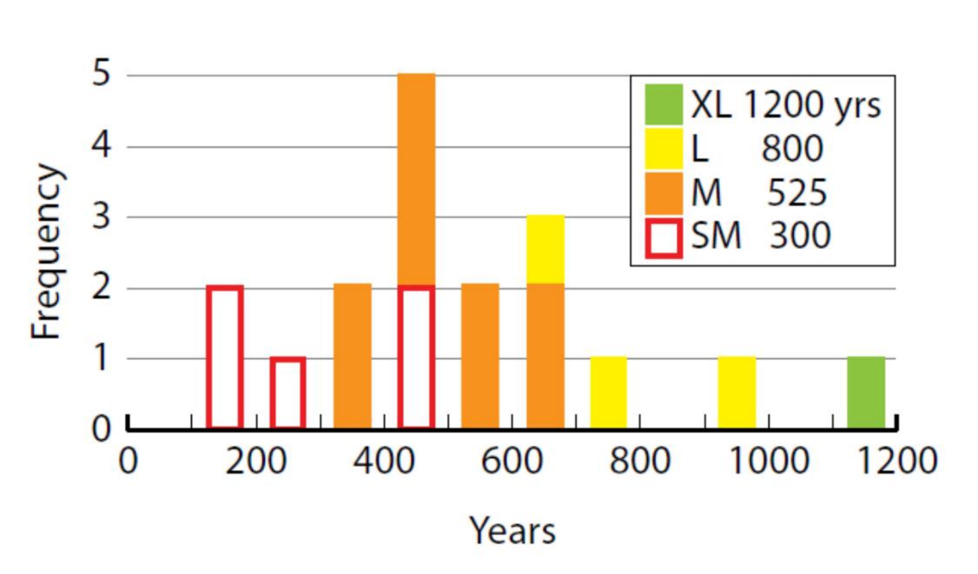
Scaling or local geologic

Sizes from slip deficit

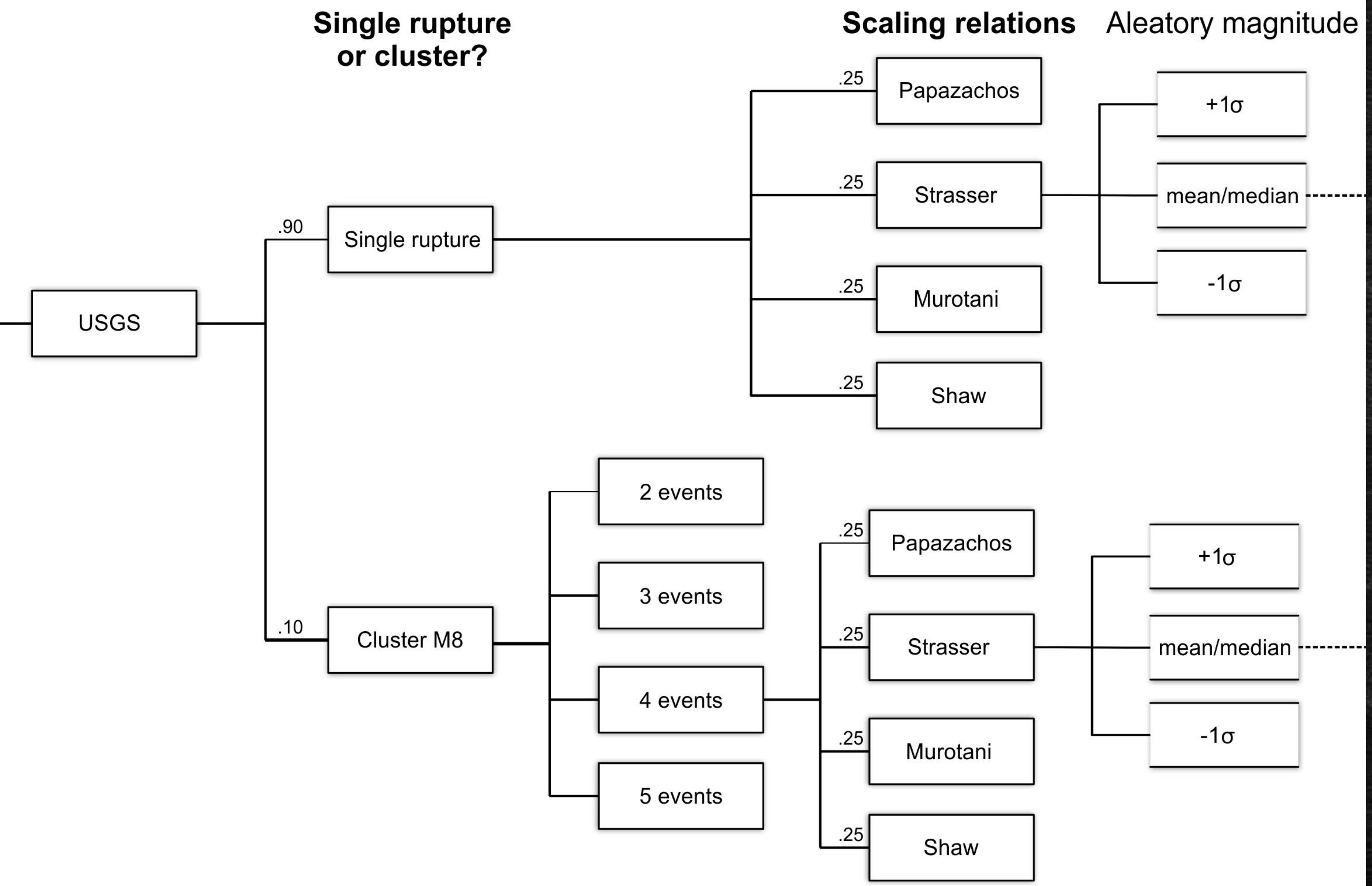
Average slip (aleatory)



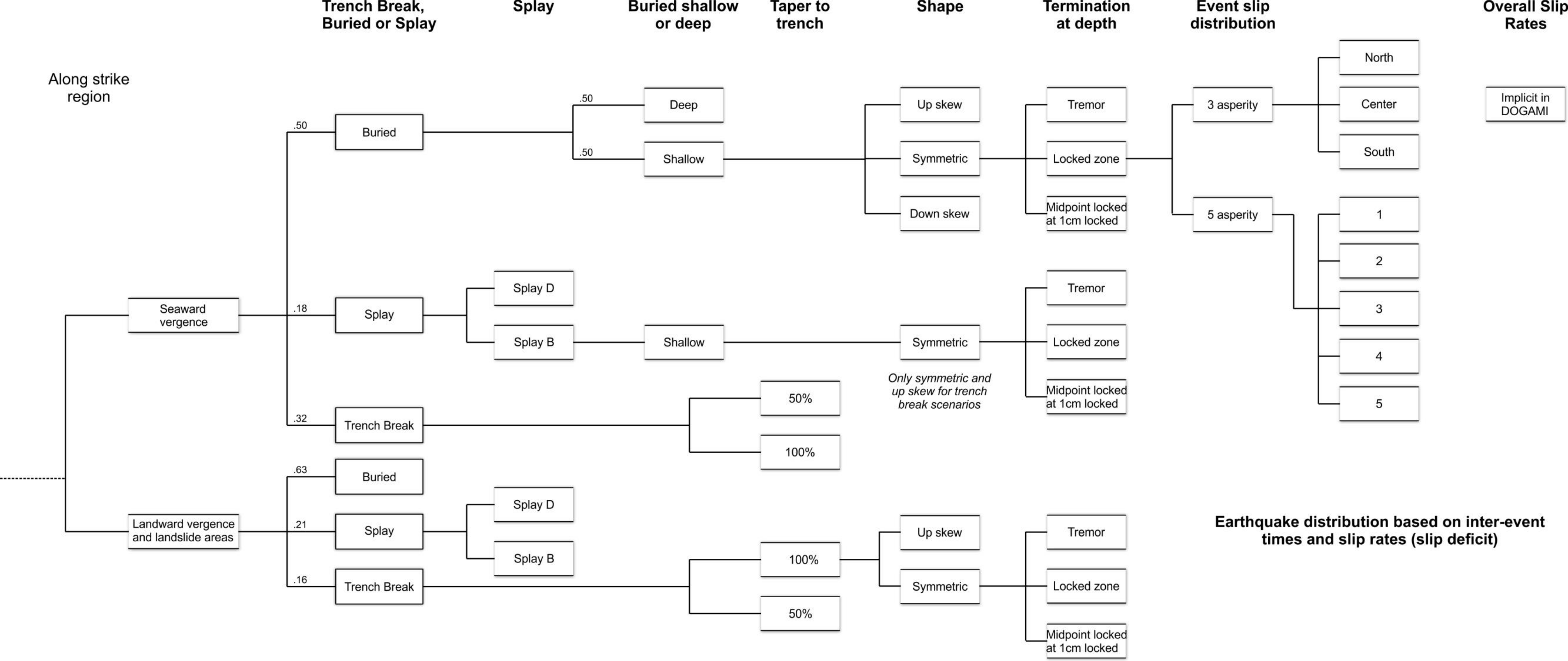


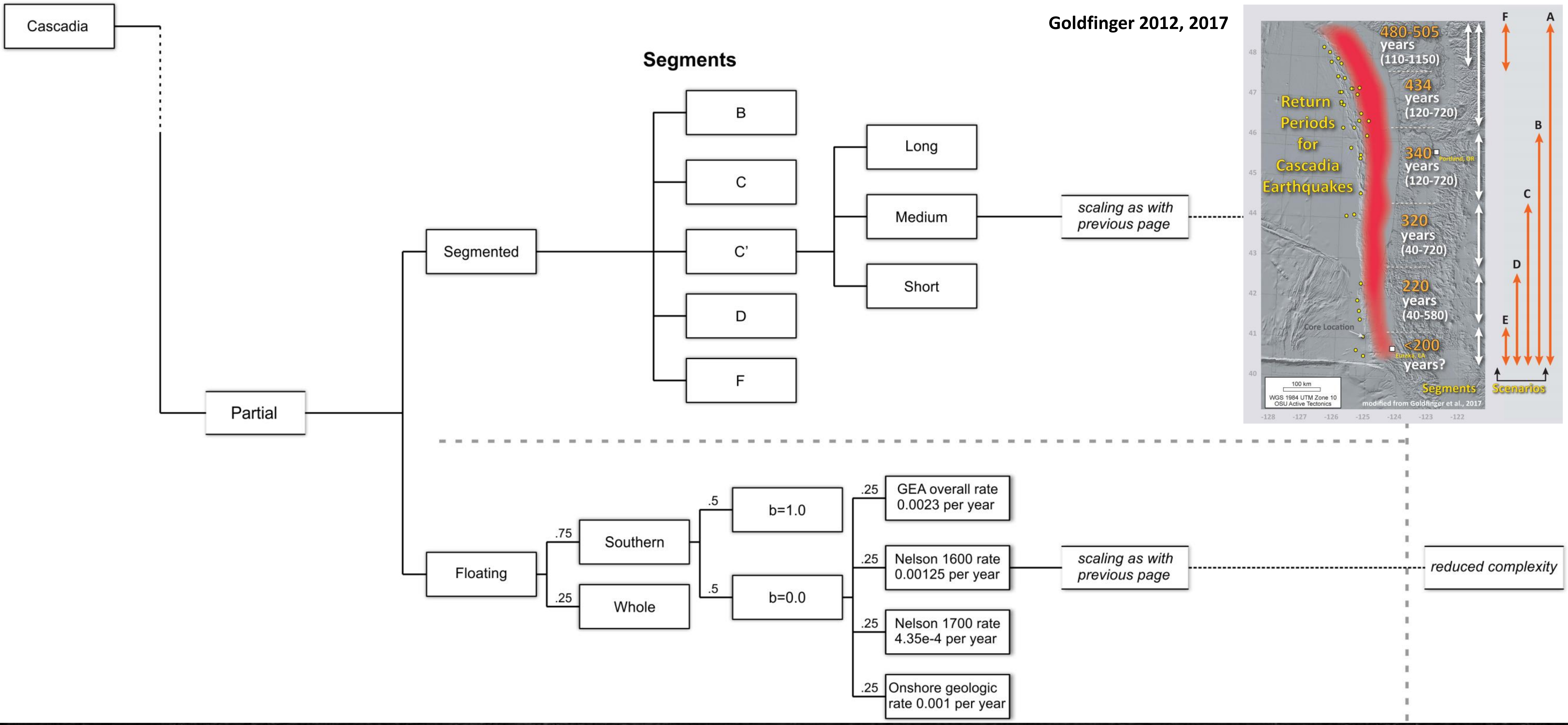


Witter et al., 2013

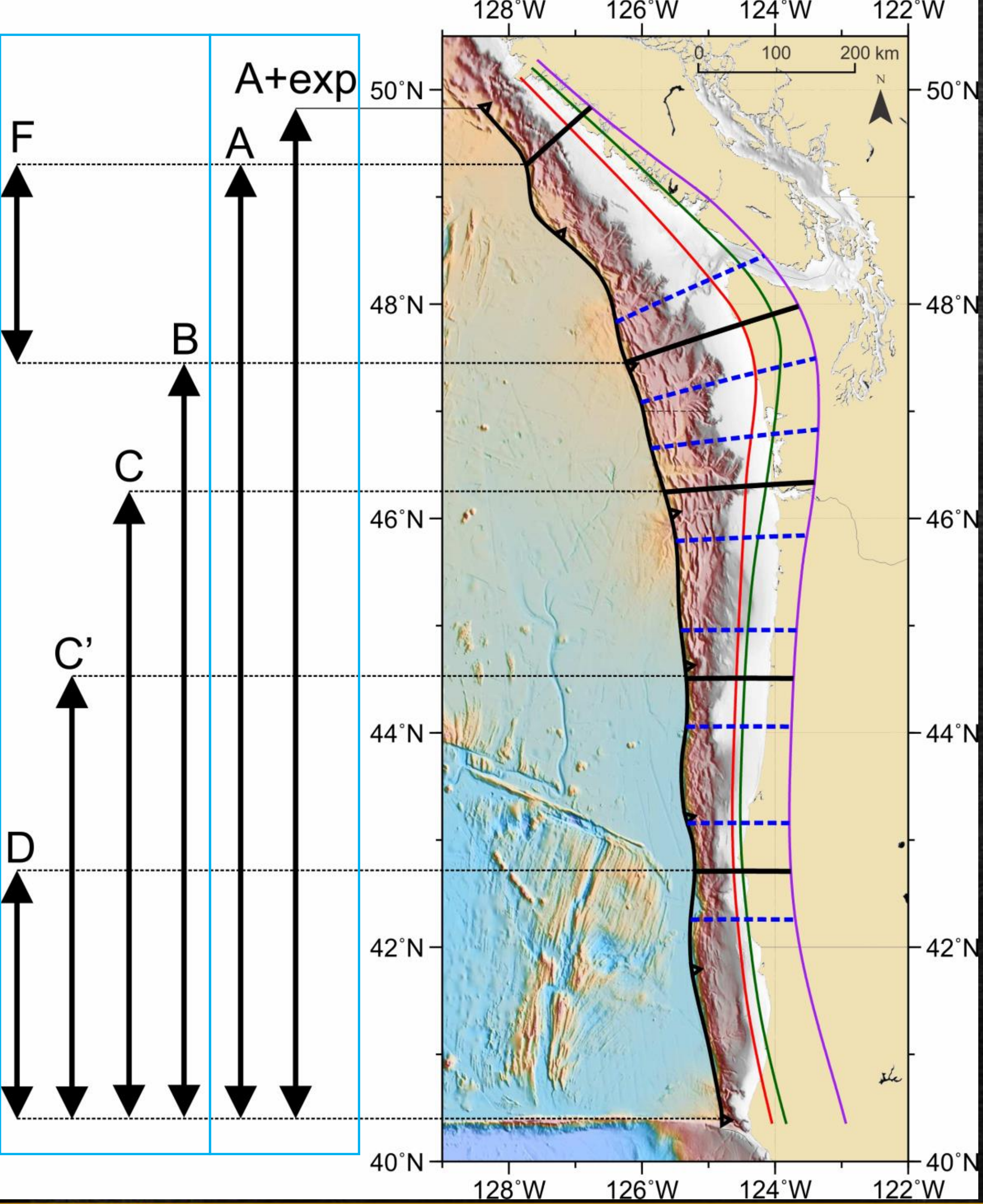


Single rupture or cluster?
Scaling relations
Aleatory magnitude
USGS
.90
Single rupture
.10
Cluster M8
.25
Papazachos
.25
Strasser
.25
Murotani
.25
Shaw
+1σ
mean/median
-1σ
2 events
3 events
4 events
5 events
.25
Papazachos
.25
Strasser
.25
Murotani
.25
Shaw
+1σ
mean/median
-1σ

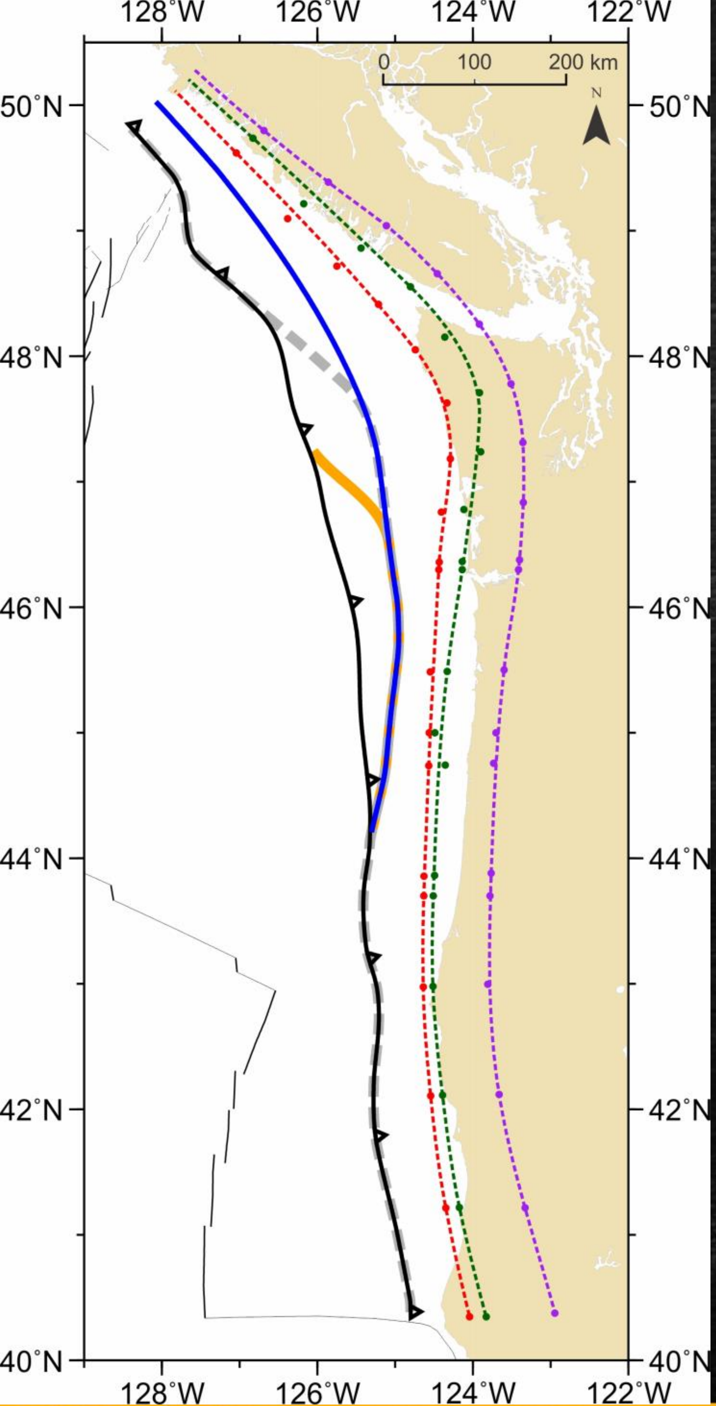

Trench Break, Buried or Splay
Splay
Buried shallow or deep
Taper to trench
Shape
Termination at depth
Event slip distribution
Overall Slip Rates
Along strike region
Seaward vergence
Landward vergence and landslide areas
.50
.18
.32
.63
.21
.16
Buried
Splay
Trench Break
.50
.50
Deep
Shallow
Splay D
Splay B
50%
100%
Up skew
Symmetric
Down skew
Only symmetric and up skew for trench break scenarios
Tremor
Locked zone
Midpoint locked at 1cm locked
3 asperity
5 asperity
North
Center
South
1
2
3
4
5
Implicit in DOGAMI
Earthquake distribution based on inter-event times and slip rates (slip deficit)


Goldfinger 2012, 2017
Segments
Cascadia
Partial
Segmented
B
C
C'
D
F
Long
Medium
Short
scaling as with previous page
Floating
.75
Southern
.25
Whole
.5
b=1.0
.5
b=0.0
.25
GEA overall rate 0.0023 per year
.25
Nelson 1600 rate 0.00125 per year
.25
Nelson 1700 rate 4.35e-4 per year
.25
Onshore geologic rate 0.001 per year
scaling as with previous page
reduced complexity
Return Periods for Cascadia Earthquakes
480-505 years (110-1150)
434 years (120-720)
340 years (120-720)
Portland, OR
320 years (40-720)
220 years (40-580)
<200 years?
Eureka, CA
Core Location
Segments
Scenarios
F
A
B
C
D
E
100 km
WGS 1984 UTM Zone 10
OSU Active Tectonics
modified from Goldfinger et al., 2017

Along Strike Variation in Slip



Map shows the northern and southern limits of the whole-margin (A, A+exp) and segmented ruptures (B–F)



Along Dip Variation in Slip

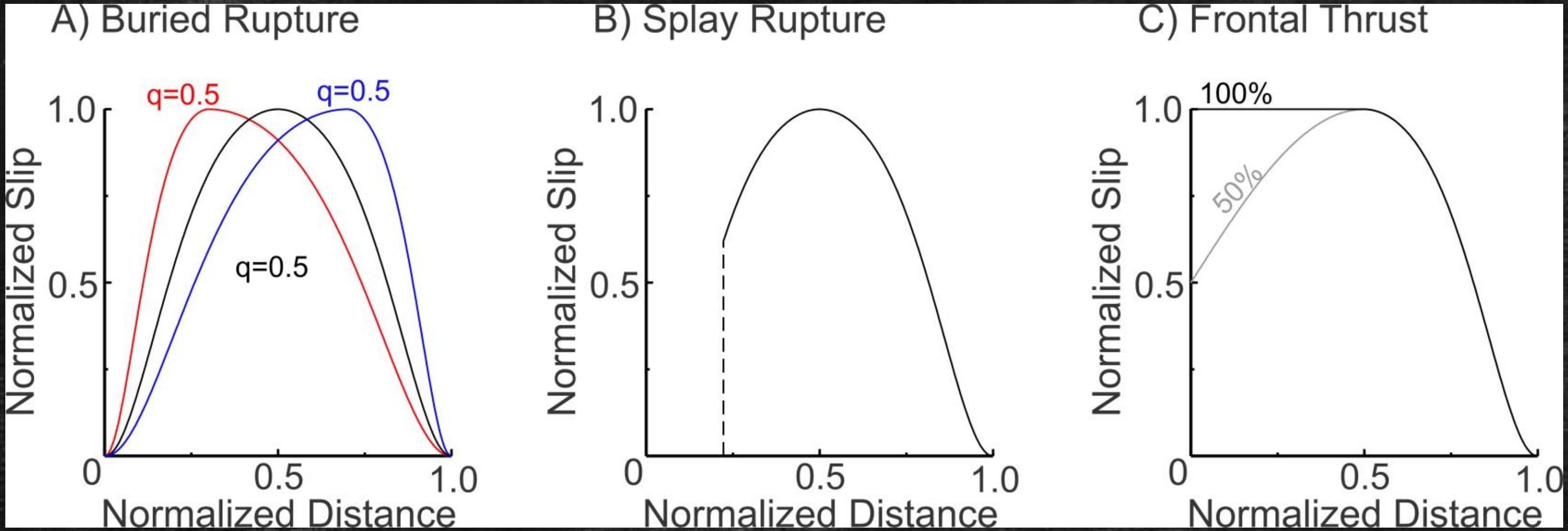
Map shows three downdip slip termination boundaries as adopted by the USGS NSHM:

- Midpoint between fully locked zone and 1 cm/yr locking contour (red)
- The 1 cm/yr locking contour (green)
- The top of the ETS zone (purple)

Map shows updip boundaries of rupture:

- deformation front (black)
- deep buried termination (gray)
- splay B (blue)
- splay D (orange)

Slip in the down-dip direction

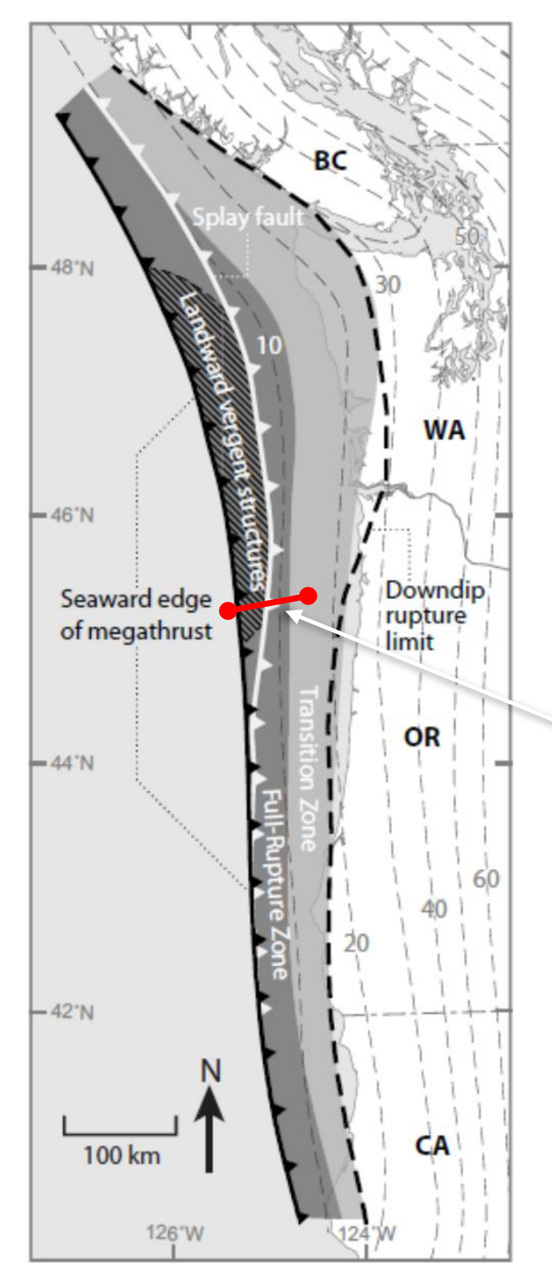


A) Updip skewed (red), symmetric (black), and downdip skewed (blue) bell-shape slip distributions with q= 0.3, 0.5, and 0.7, respectively.
B) For splay-faulting rupture, the bell shape slip profile is cut off at the fault trace.
C) For portions of our trench-breaching rupture, the distribution mirrors the bell shape downdip of the peak slip but tapers updip to the trench to a prescribed percentage of the peak slip.

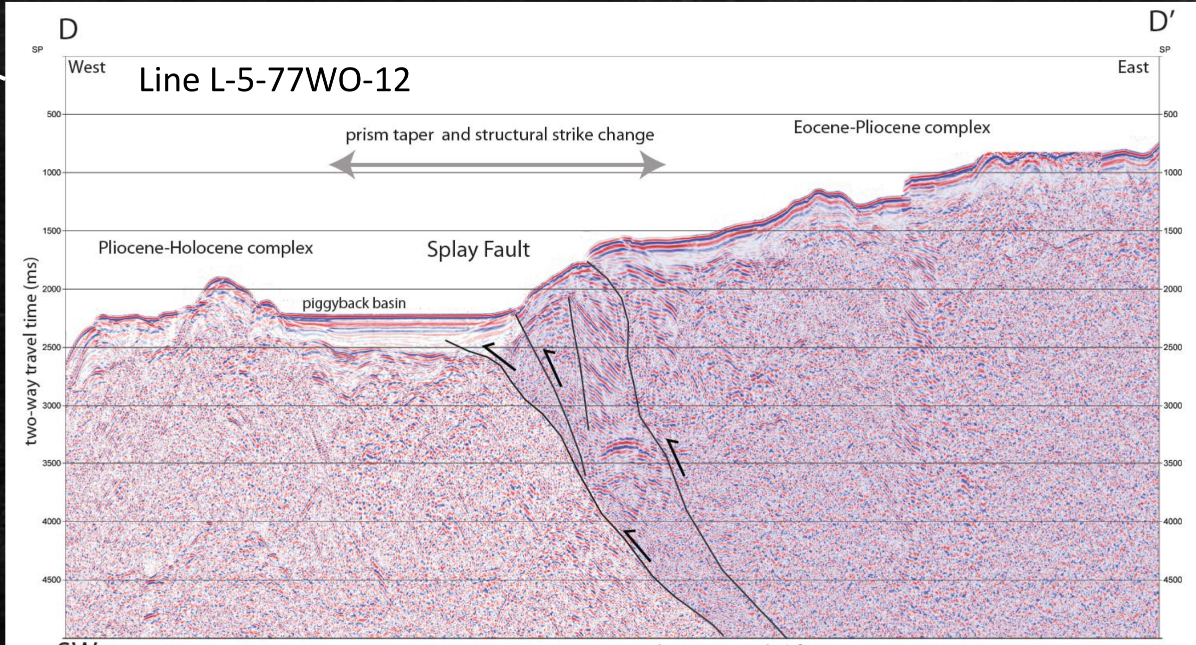
Splay Faulting in Cascadia

There is a splay fault that has been identified in seismic reflection profiles and has been used by some states as a tsunami source. The participants debated the length and activity of this fault system. There are places where the fault does not leave evidence for activity at the surface (so if it is active, the sedimentation rate exceeds the slip rate).

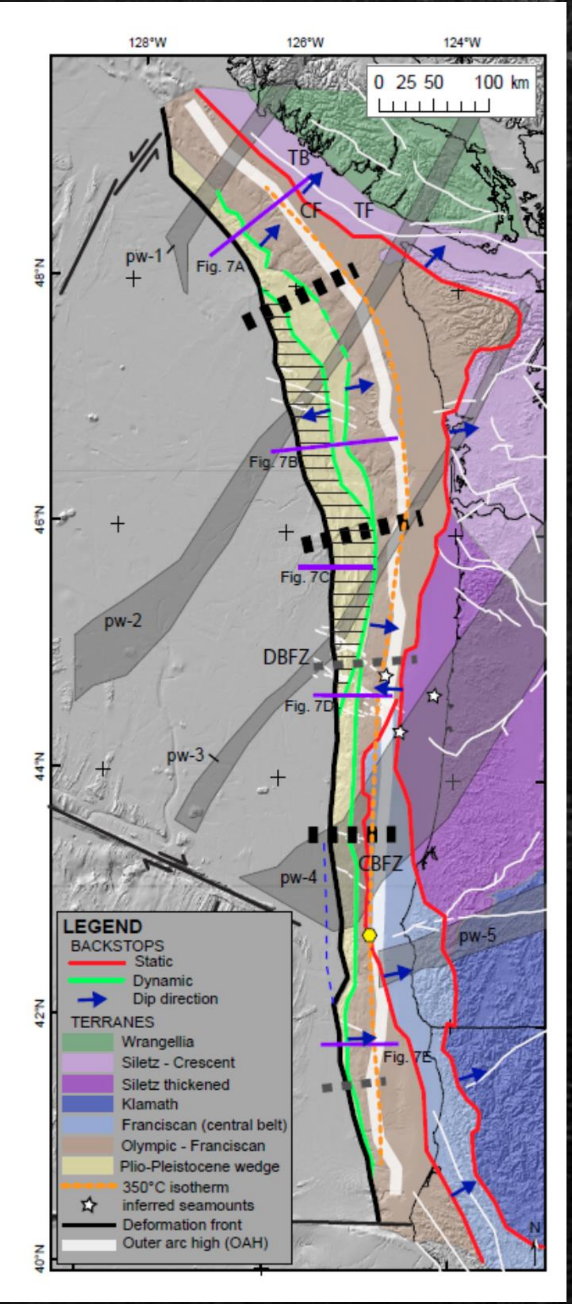
This splay fault (white line at left) is generally at the boundary between the inner (younger) and outer (older) wedges (green line in map on the right).



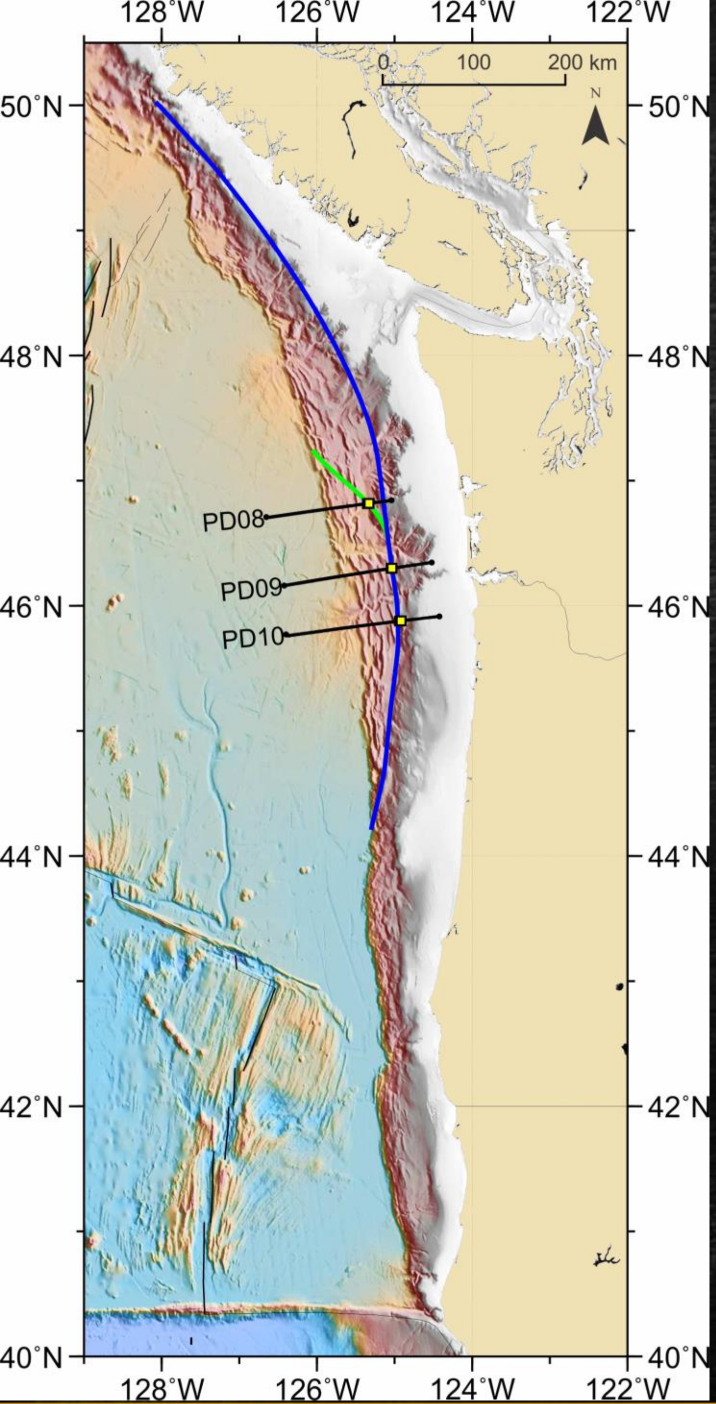
Witter et al., 2013



From Chris Goldfinger presentation



Watt and Brothers, 2021

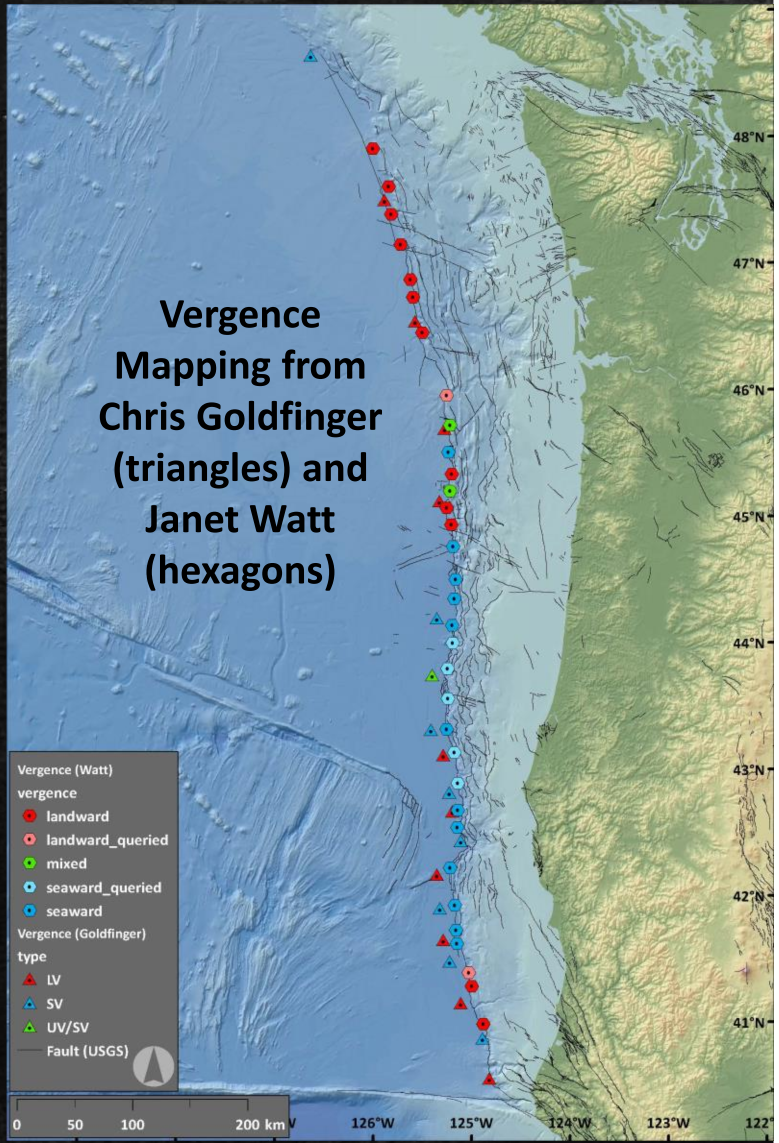


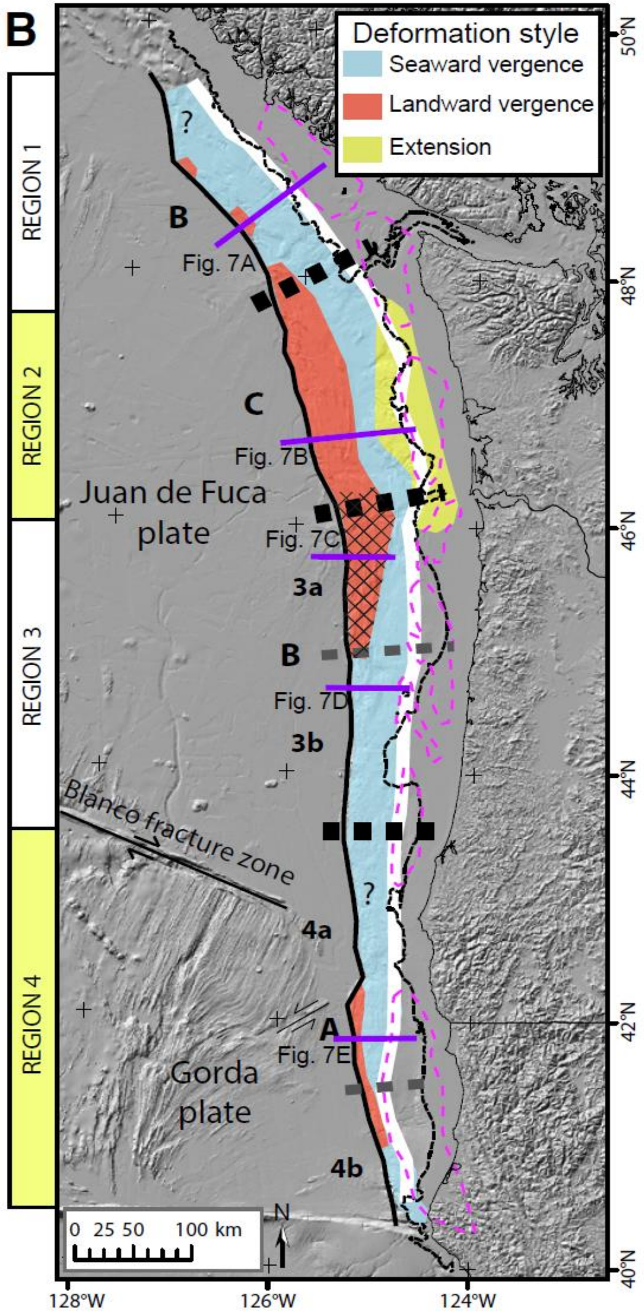
Splay Faults

Traces of the two assumed splay faults used for modelling. Splay B (or "extended L1") is shown in blue and the new Splay D trace is in green. South of 46.5°N, the two traces fully overlap. Yellow squares are the interpreted splay-fault locations from the CASIE21 profiles.

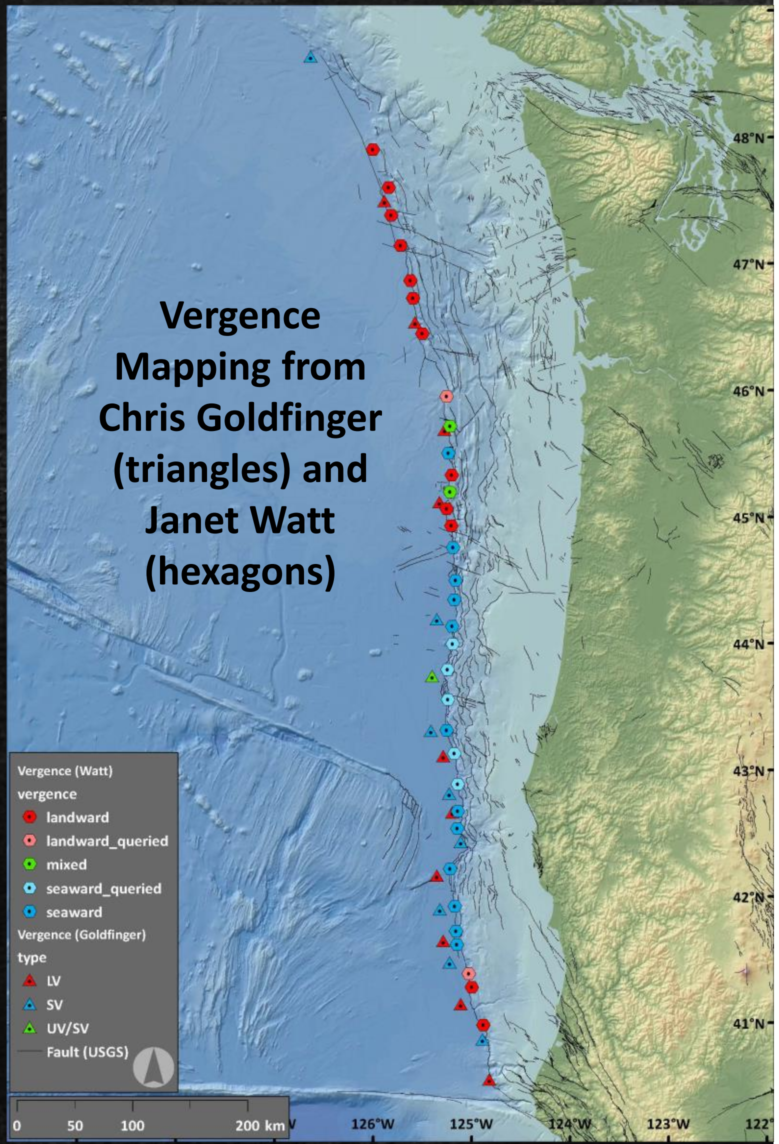
Fault Vergence

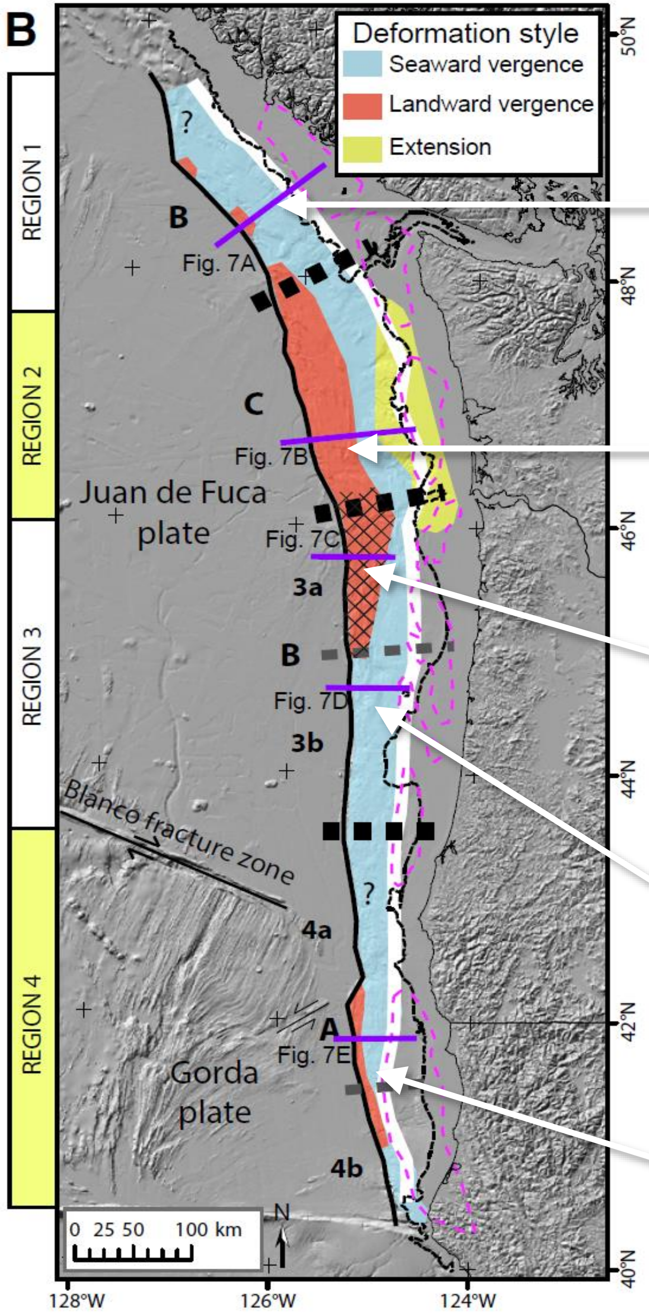
- Fault vergence in the outer wedge can also have influence on fault slip and tsunamigenesis.
- Watt & Brothers (2021) remind us that landward vergent regions may be more favorable to strain accumulation and more prone to trench breaking rupture (e.g., Han et al., 2017; Beeson et al., 2017).
- Watt and Brothers (2021) present an overview of fault vergence
- Following the workshop, we compared their observations with those of others, like from Chris Goldfinger and results from CASIE21.

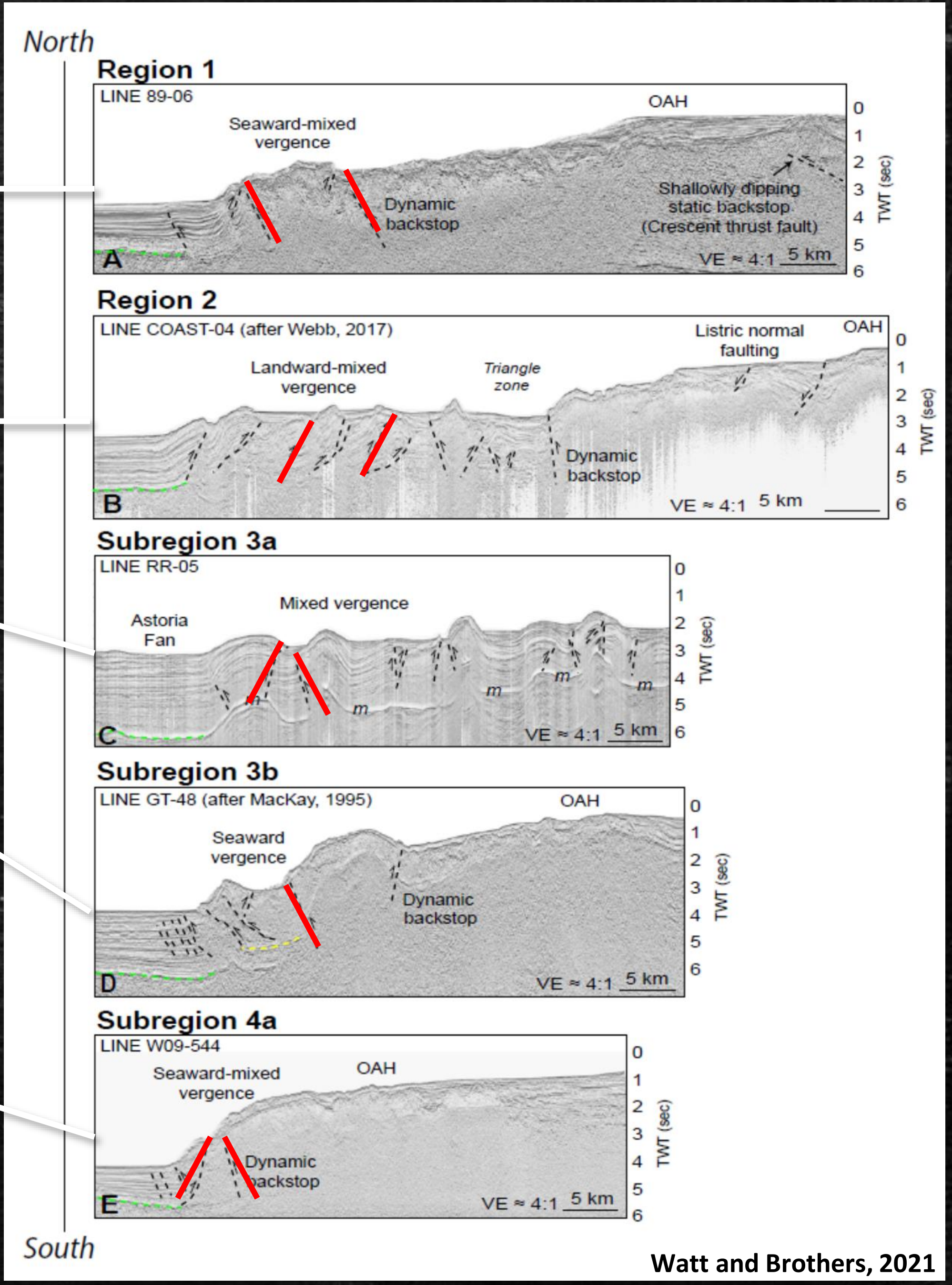




Watt and Brothers, 2021


Vergence Mapping from Chris Goldfinger (triangles) and Janet Watt (hexagons)
Vergence (Watt)
vergence
landward
landward_queried
mixed
seaward_queried
seaward
Vergence (Goldfinger)
type
LV
SV
UV/SV
Fault (USGS)
0
50
100
200 km
126°W
125°W
124°W
123°W
48°N
47°N
46°N
45°N
44°N
43°N
42°N
41°N


B
Deformation style
Seaward vergence
Landward vergence
Extension
REGION 1
REGION 2
REGION 3
REGION 4
B
Fig. 7A
C
Fig. 7B
Juan de Fuca plate
Fig. 7C
3a
B
Fig. 7D
3b
Blanco fracture zone
4a
A
Fig. 7E
Gorda plate
4b
0 25 50 100 km
N
128°W
126°W
124°W
50°N
48°N
46°N
44°N
42°N
40°N


North
Region 1
LINE 89-06
Seaward-mixed vergence
OAH
Dynamic backstop
Shallowly dipping static backstop (Crescent thrust fault)
VE ≈ 4:1 5 km
TWT (sec)
Region 2
LINE COAST-04 (after Webb, 2017)
Landward-mixed vergence
Triangle zone
Listric normal faulting
OAH
Dynamic backstop
VE ≈ 4:1 5 km
Subregion 3a
LINE RR-05
Astoria Fan
Mixed vergence
VE ≈ 4:1 5 km
Subregion 3b
LINE GT-48 (after MacKay, 1995)
Seaward vergence
OAH
Dynamic backstop
VE ≈ 4:1 5 km
Subregion 4a
LINE W09-544
Seaward-mixed vergence
OAH
Dynamic backstop
VE ≈ 4:1 5 km
South
Watt and Brothers, 2021

Frontal Thrust Geometry

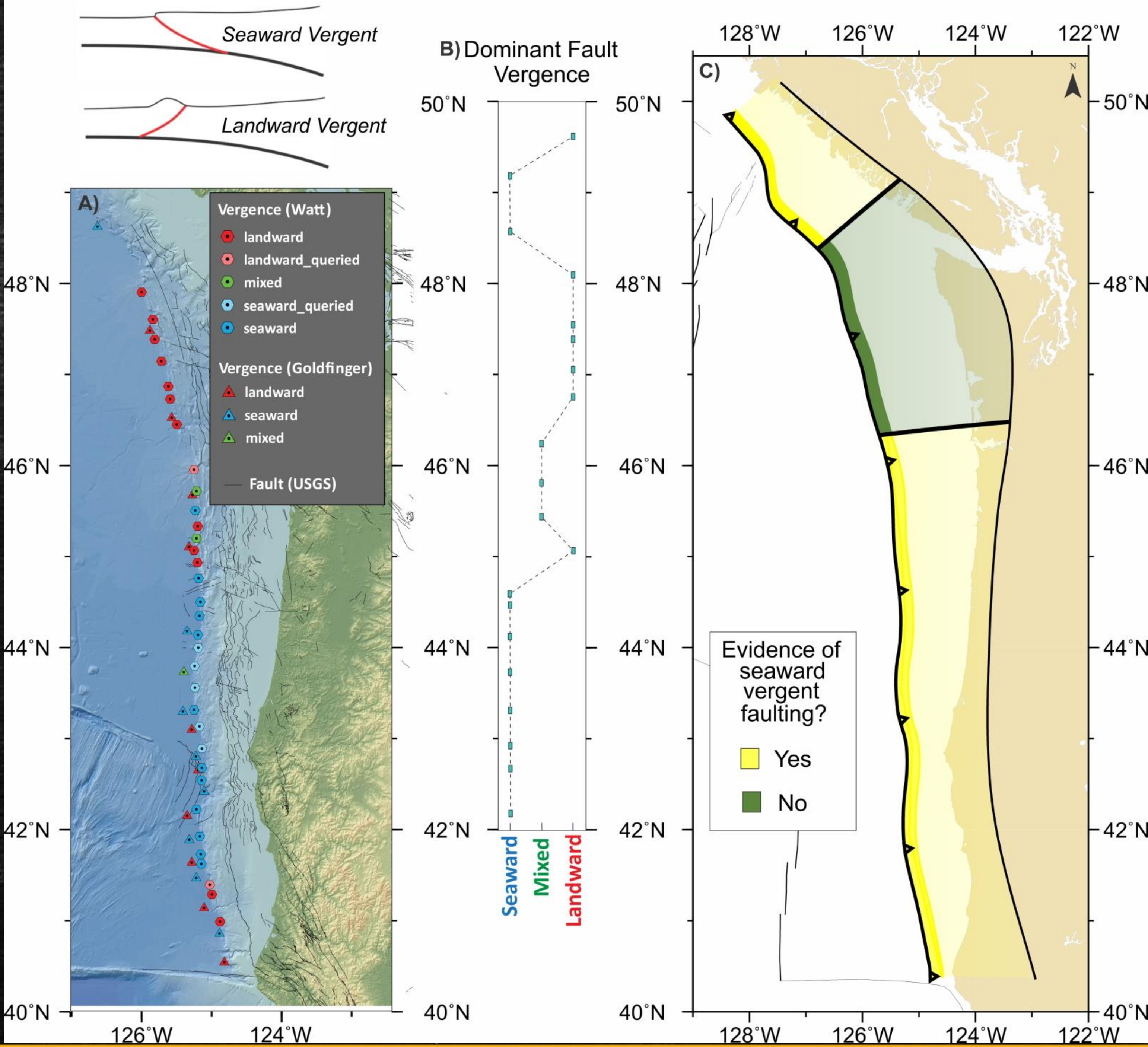
The top left: hypothetical seaward and landward vergence faulting in cross section view.

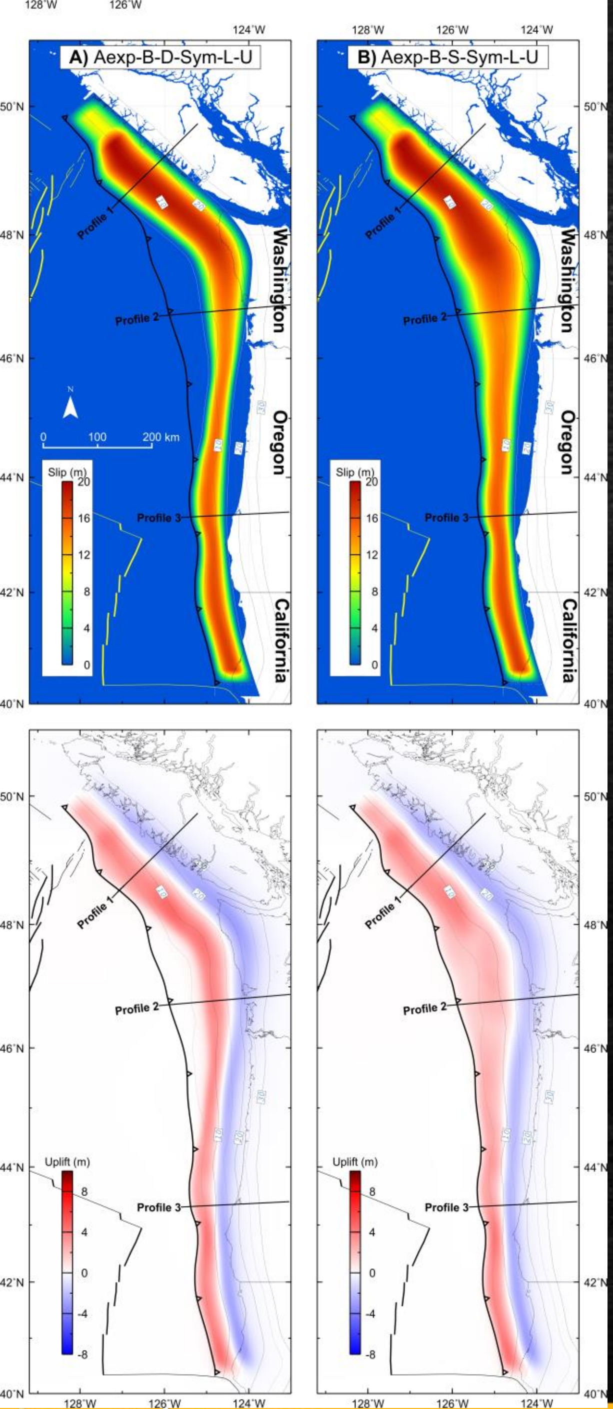
A) Vergence directions in the frontal accretionary prism compiled by CSWG members Janet Watt and Chris Goldfinger.

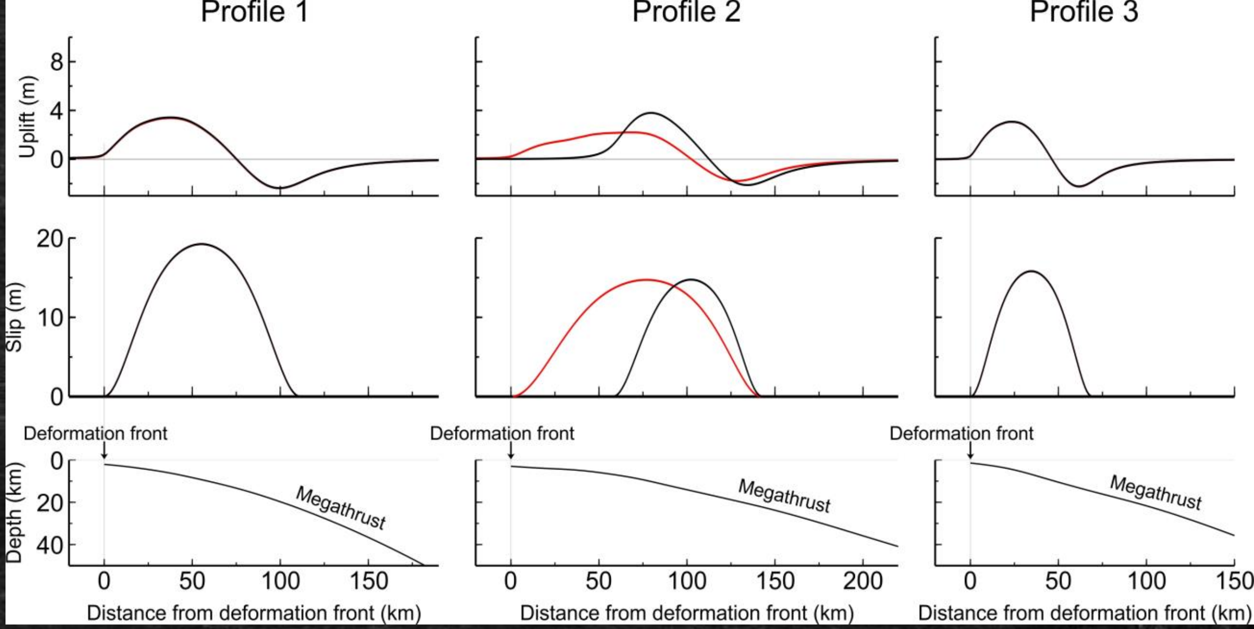
B) Vergence directions compiled by CASIE21 member Shuoshuo Han.

C) Simplification for modeling trench-breaching rupture scenarios.

Where there is any evidence for seaward-vergent thrust faulting (yellow), a single frontal thrust is used. Where there is no such evidence (green), highly up-skewed buried slip is assumed.







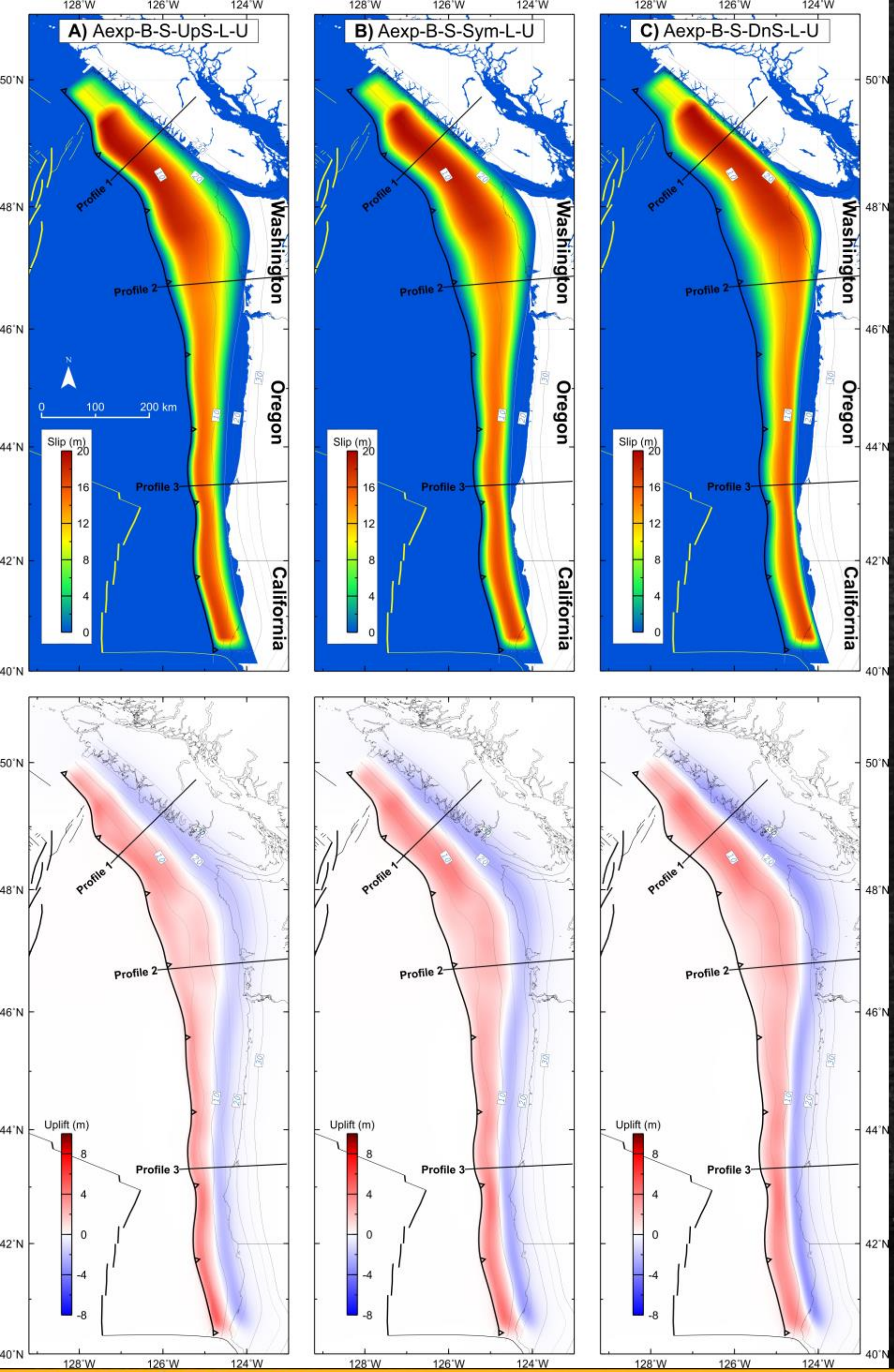
Examples for Whole Margin (A) Deep and (B) Shallow Buried Rupture

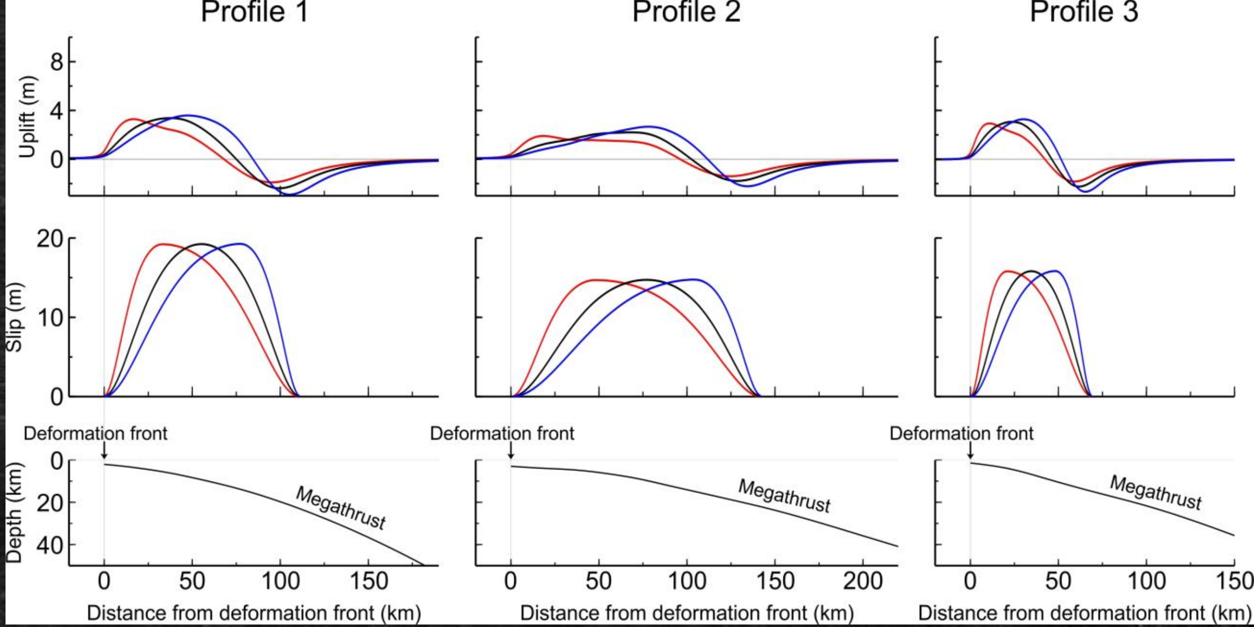
Maps

- **Slip Distribution**
- **Vertical Deformation**

Along Dip Profiles

- **Vertical Deformation**
- **Slip Distribution**
- **Megathrust Geometry**





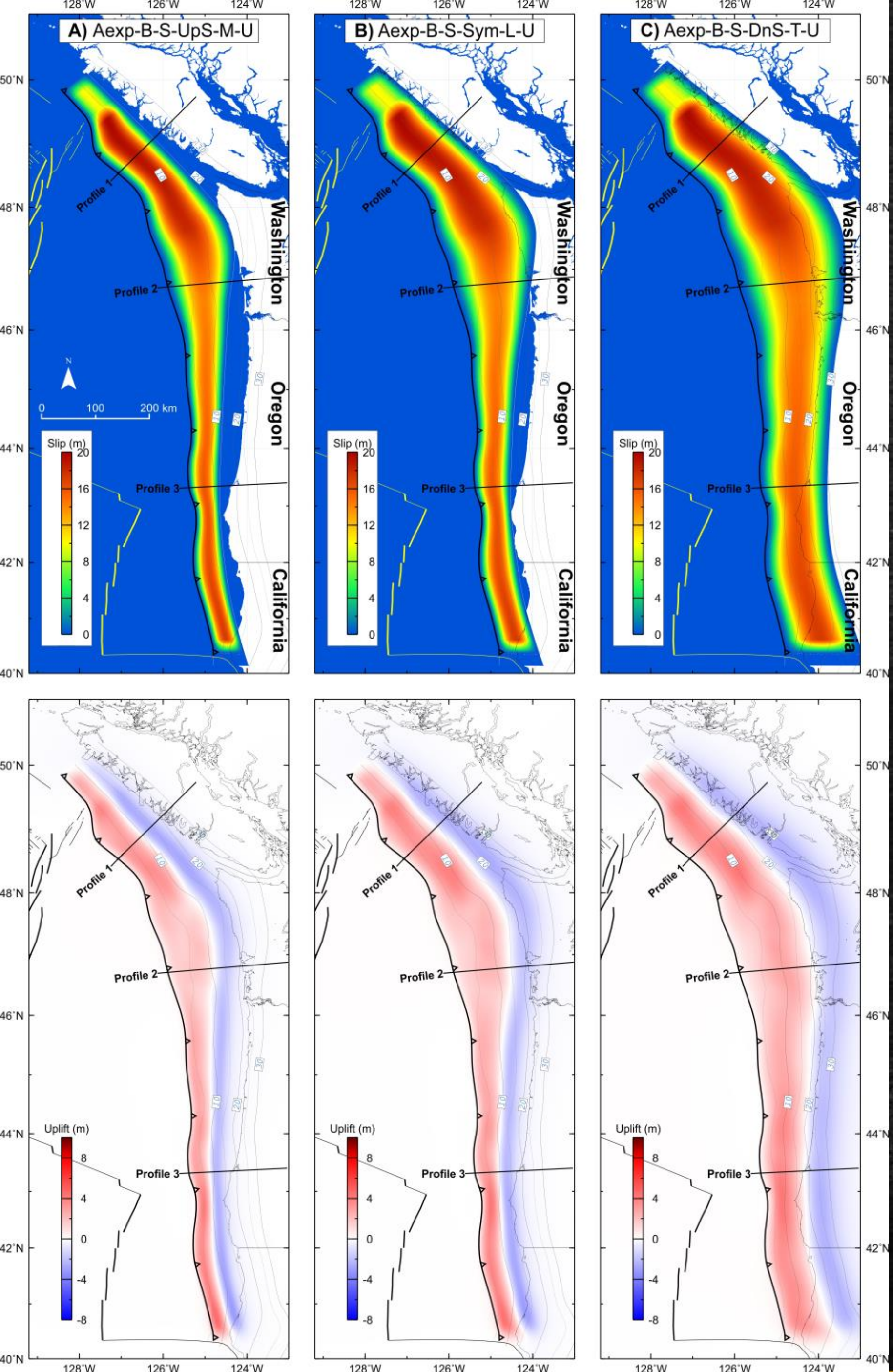
Examples for Whole Margin (A) up-skew (B) symmetric (C) down skew buried rupture

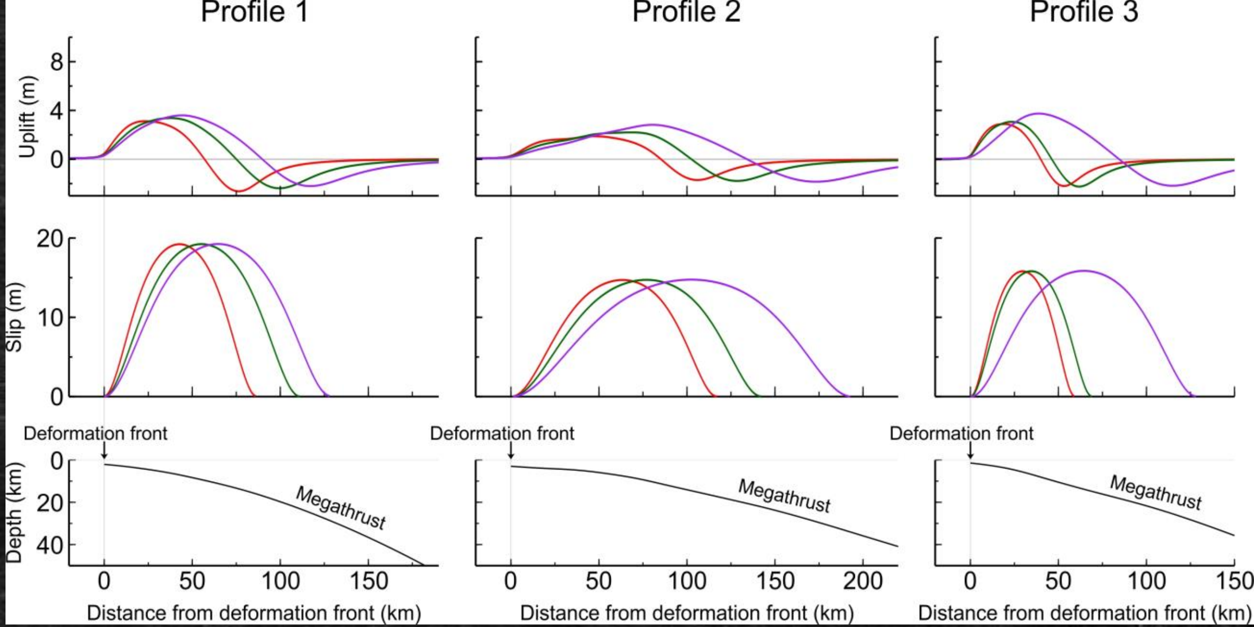
Maps

- Slip Distribution
- Vertical Deformation

Along Dip Profiles

- Vertical Deformation
- Slip Distribution
- Megathrust Geometry





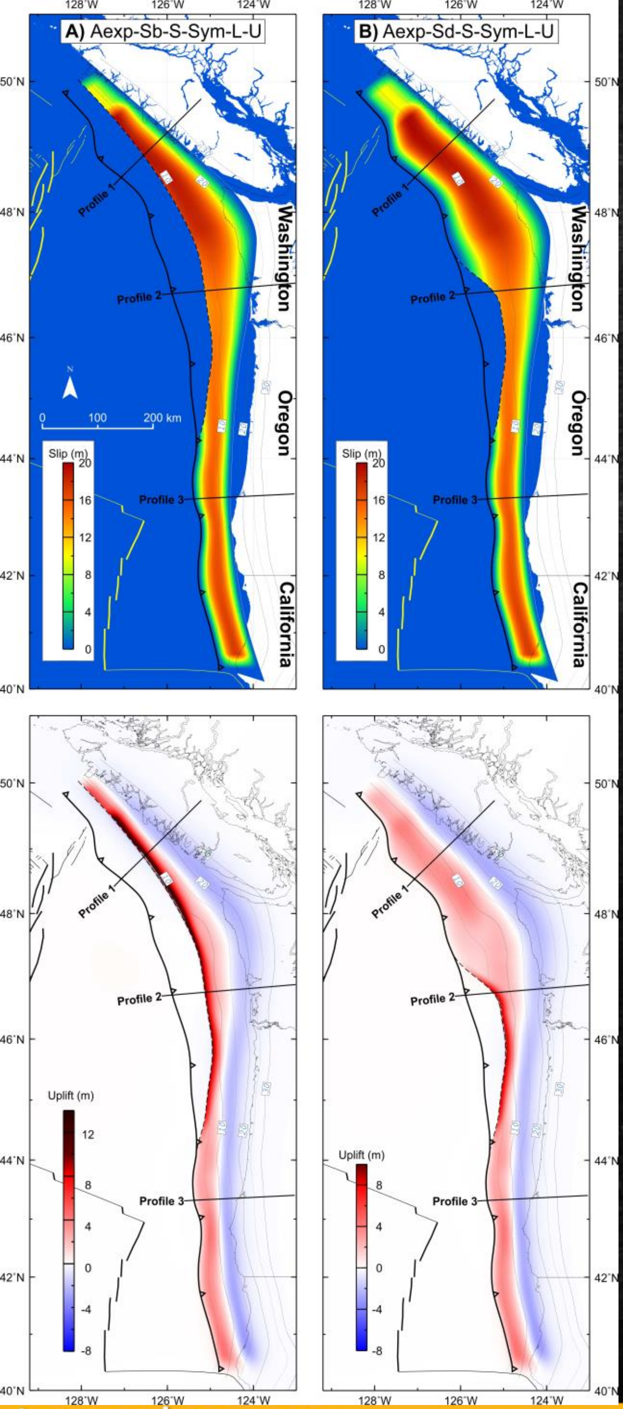
Examples for Whole Margin (A) Midpoint locked & 1 cm locked, (B) Locked zone and (C) ETS downdip limits

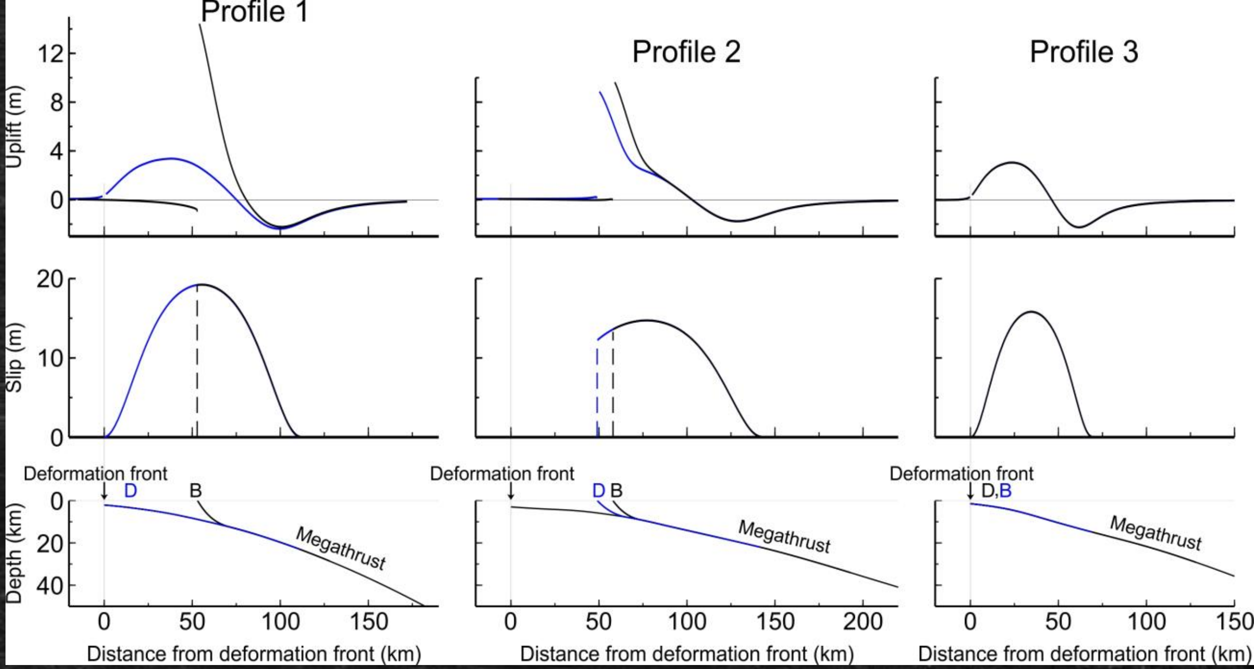
Maps

- Slip Distribution
- Vertical Deformation

Along Dip Profiles

- Vertical Deformation
- Slip Distribution
- Megathrust Geometry





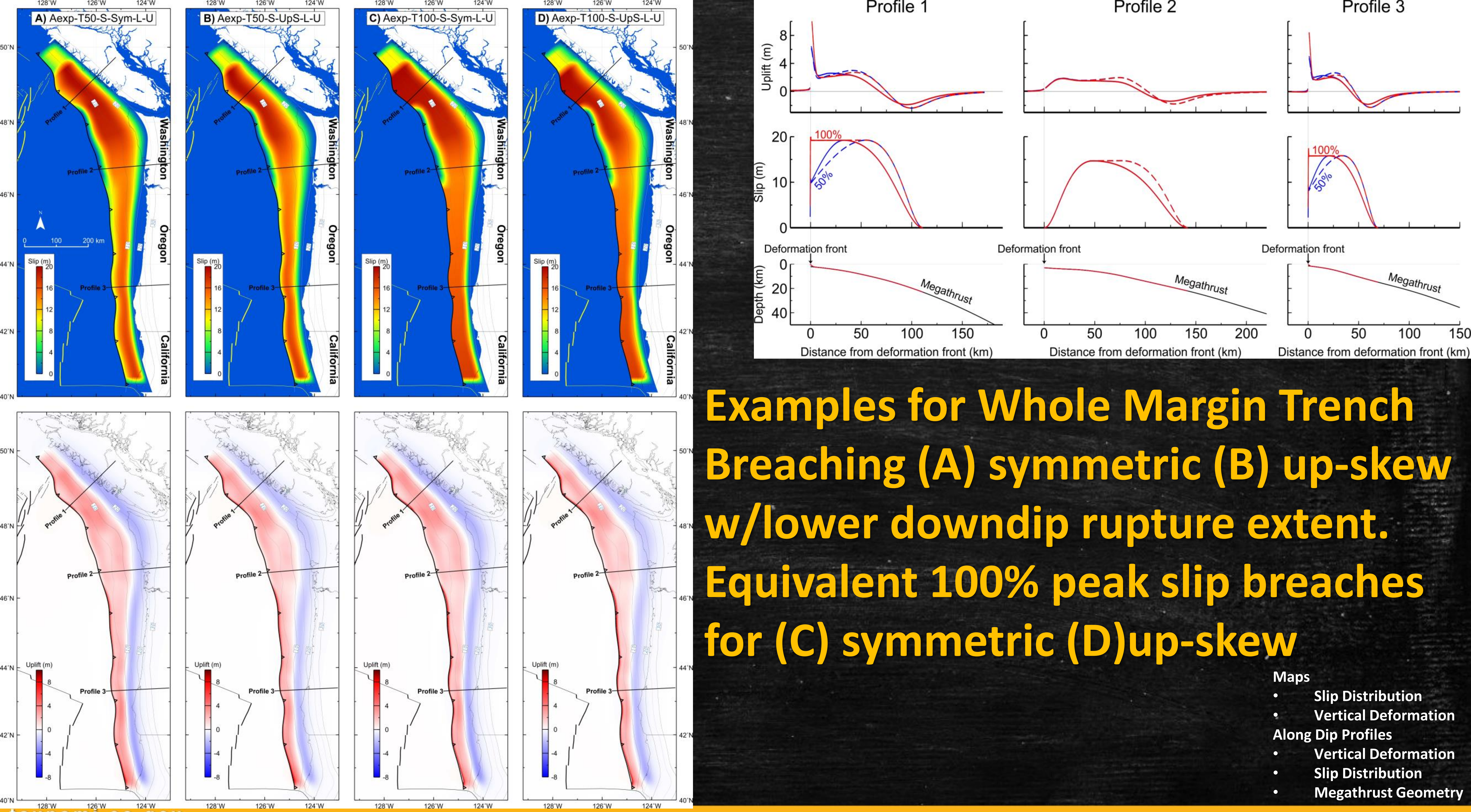
Examples for Whole Margin for (A) Splay B and (B) Splay D

Maps

- **Slip Distribution**
- **Vertical Deformation**

Along Dip Profiles

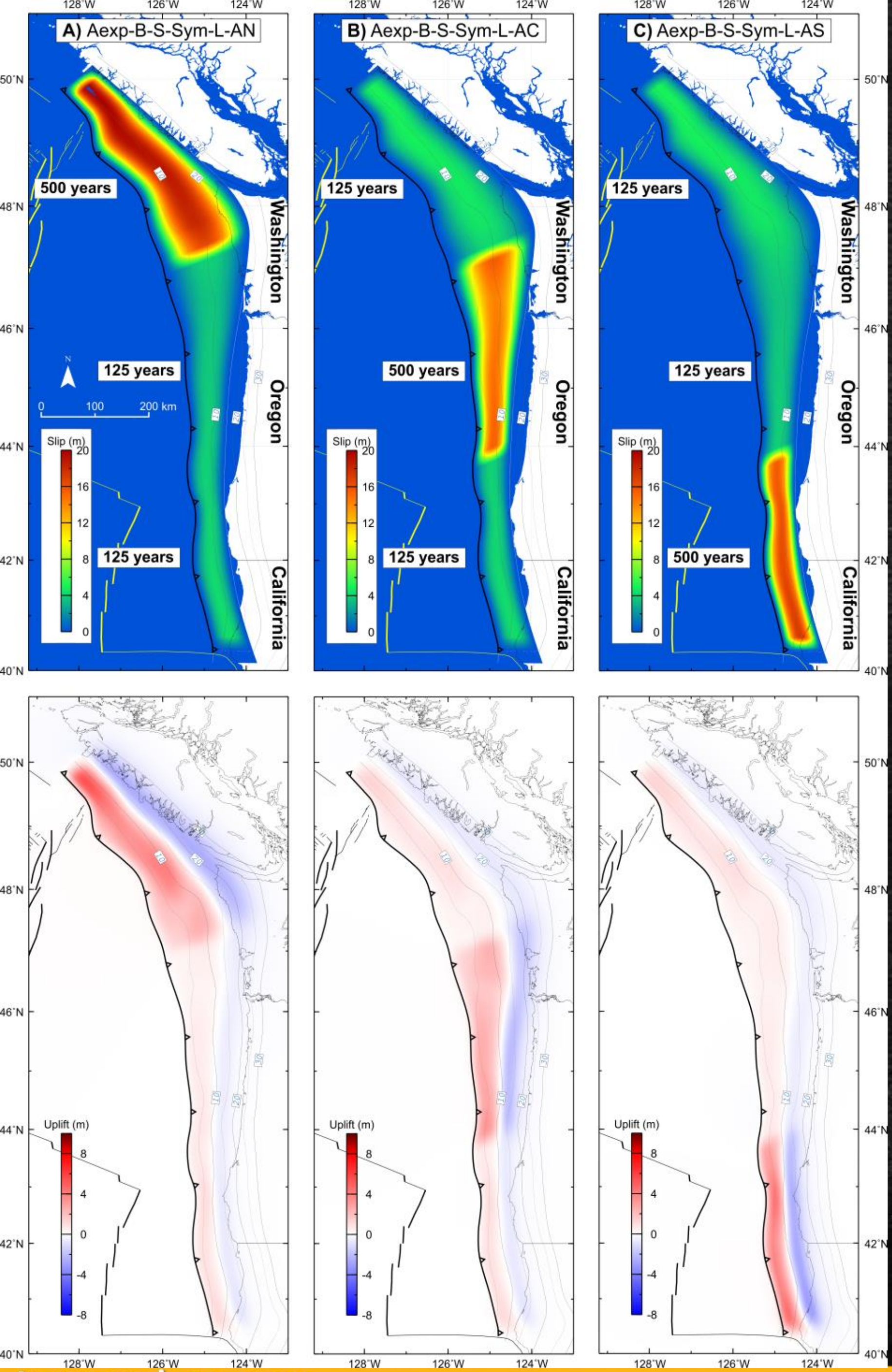
- **Vertical Deformation**
- **Slip Distribution**
- **Megathrust Geometry**



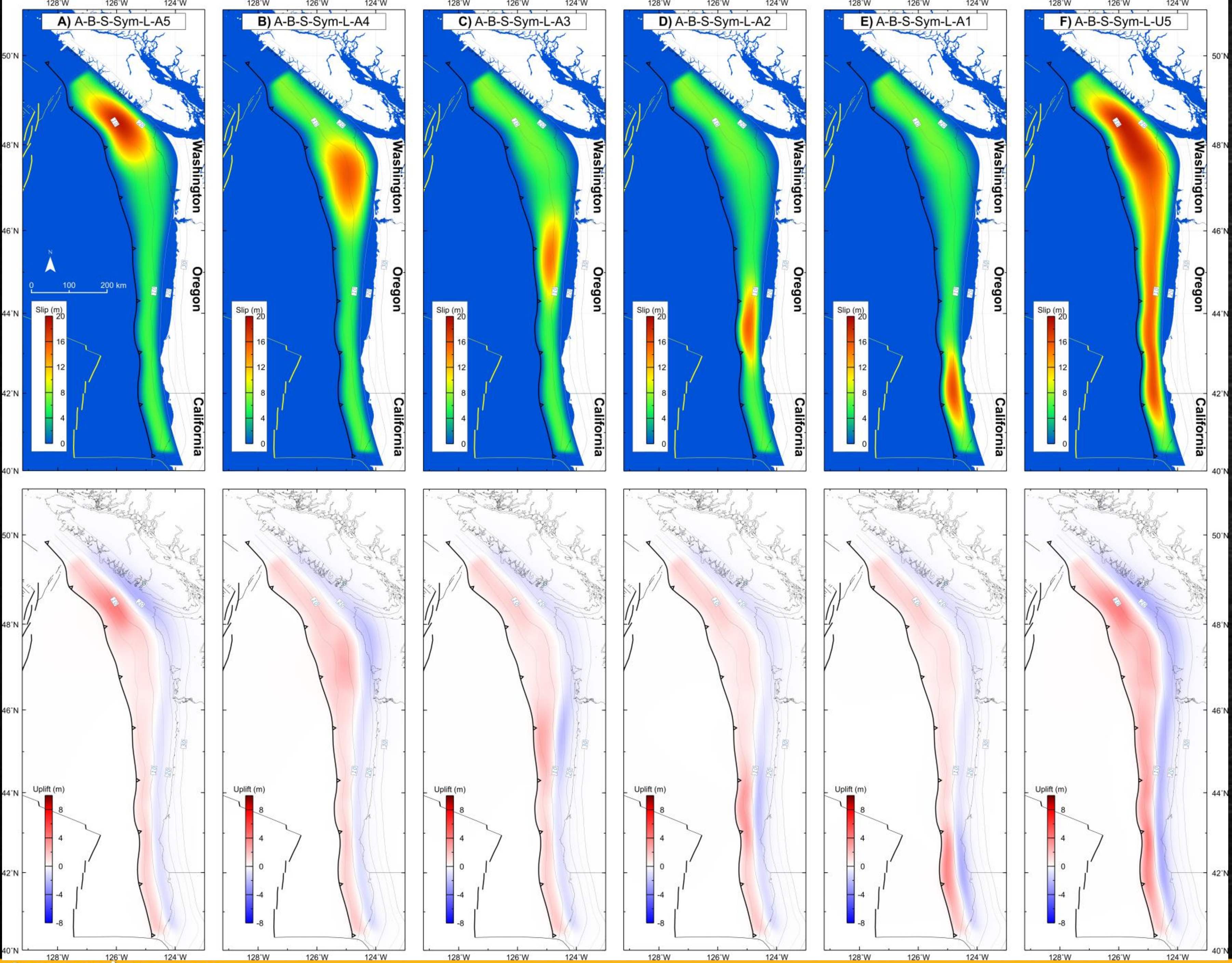
Examples for Whole Margin Trench Breaching (A) symmetric (B) up-skew w/lower downdip rupture extent. Equivalent 100% peak slip breaches for (C) symmetric (D)up-skew

Maps
- **Slip Distribution**
- **Vertical Deformation**

Along Dip Profiles
- **Vertical Deformation**
- **Slip Distribution**
- **Megathrust Geometry**

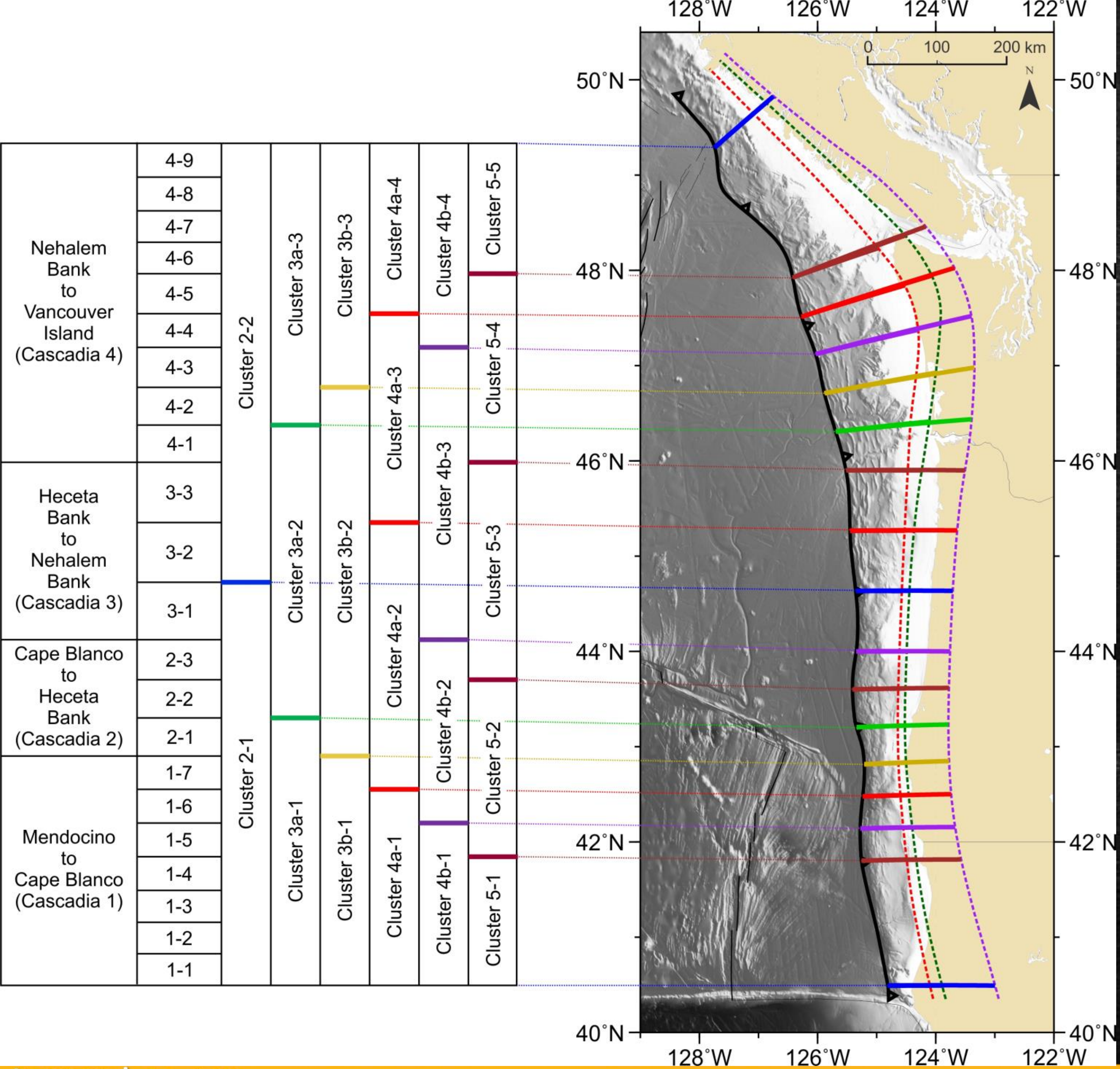


Examples for DOGAMI Whole Margin asperity models (A) northern (B) center (C) southern asperities. These use symmetric shallow buried rupture.

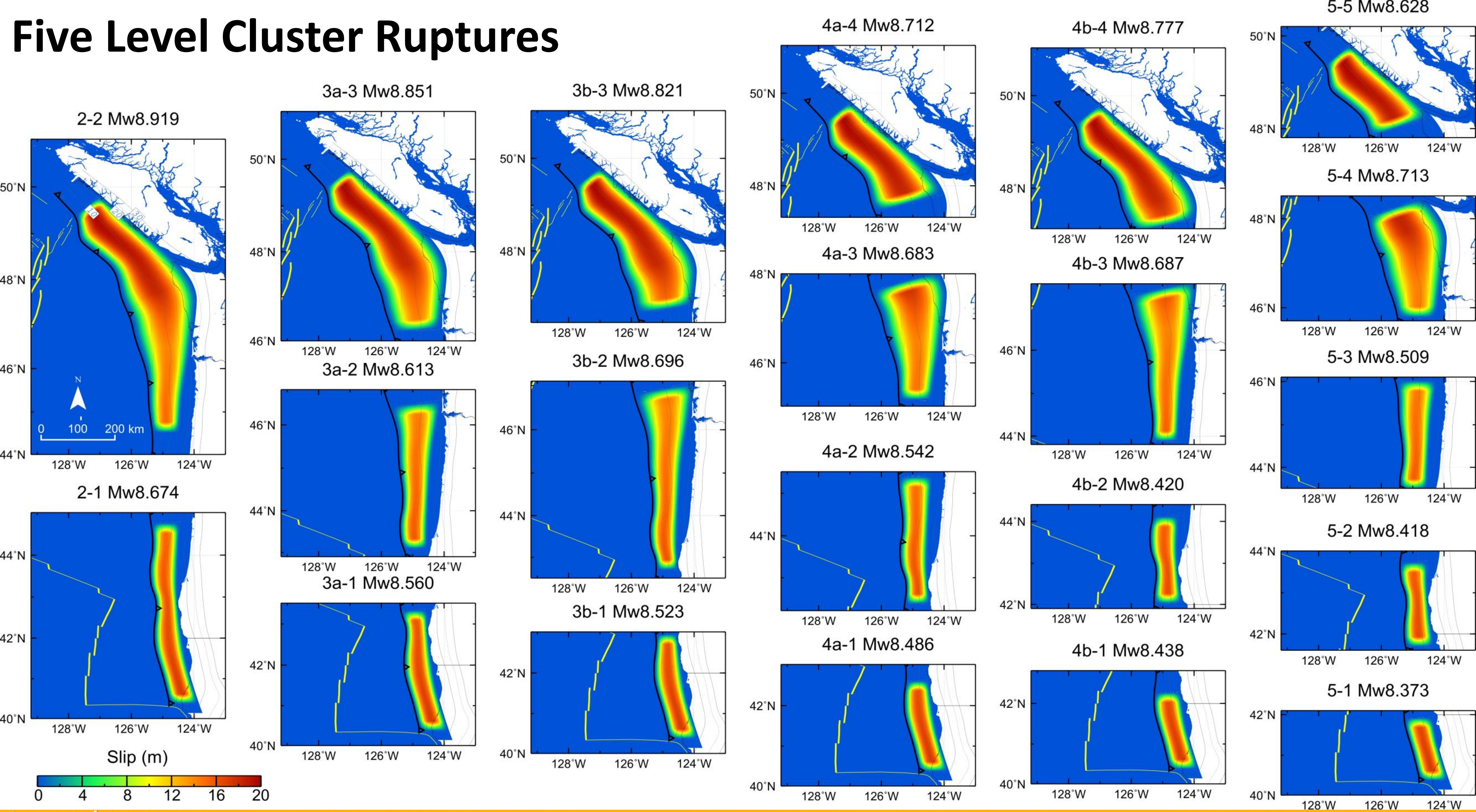


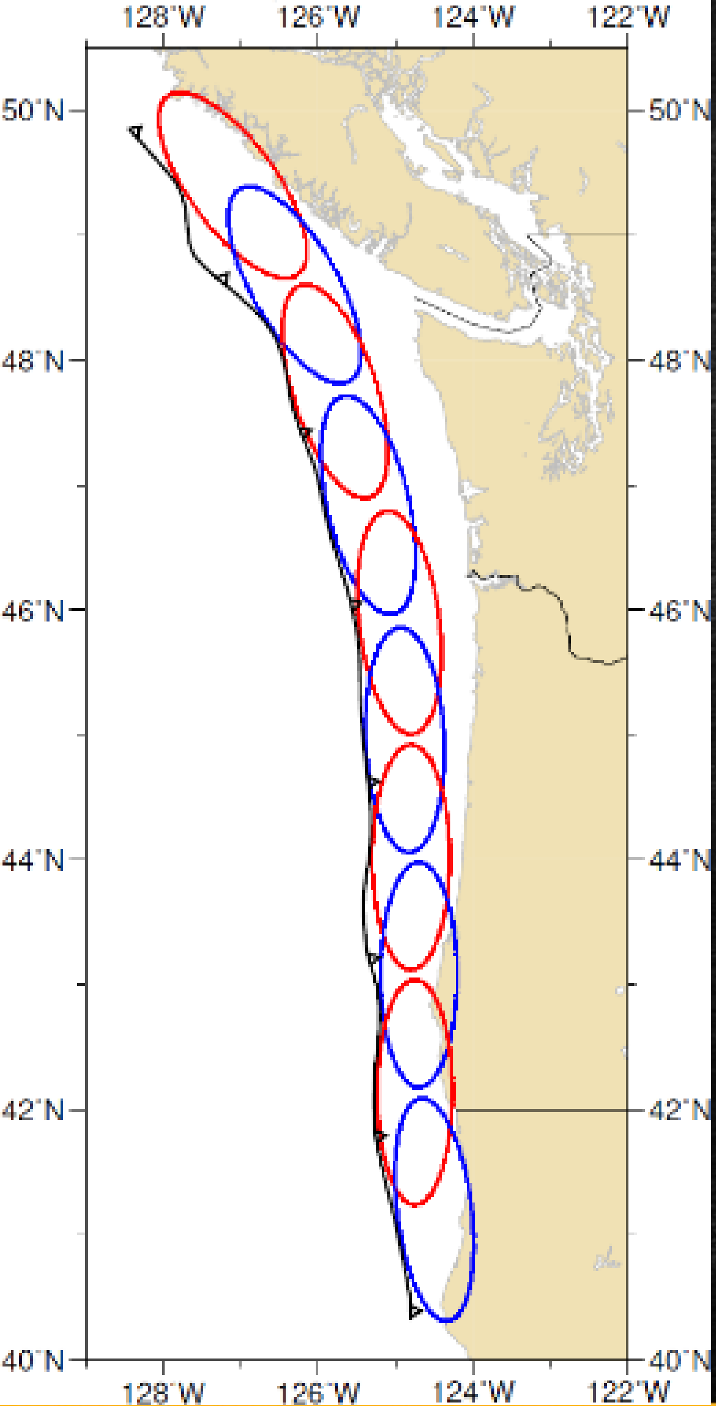
Examples for Whole Margin asperity models. These use symmetric shallow buried rupture with 1 cm/yr locking downdip limit.

Definition of the five-level cluster ruptures based on the cluster setup in the USGS NSHM.



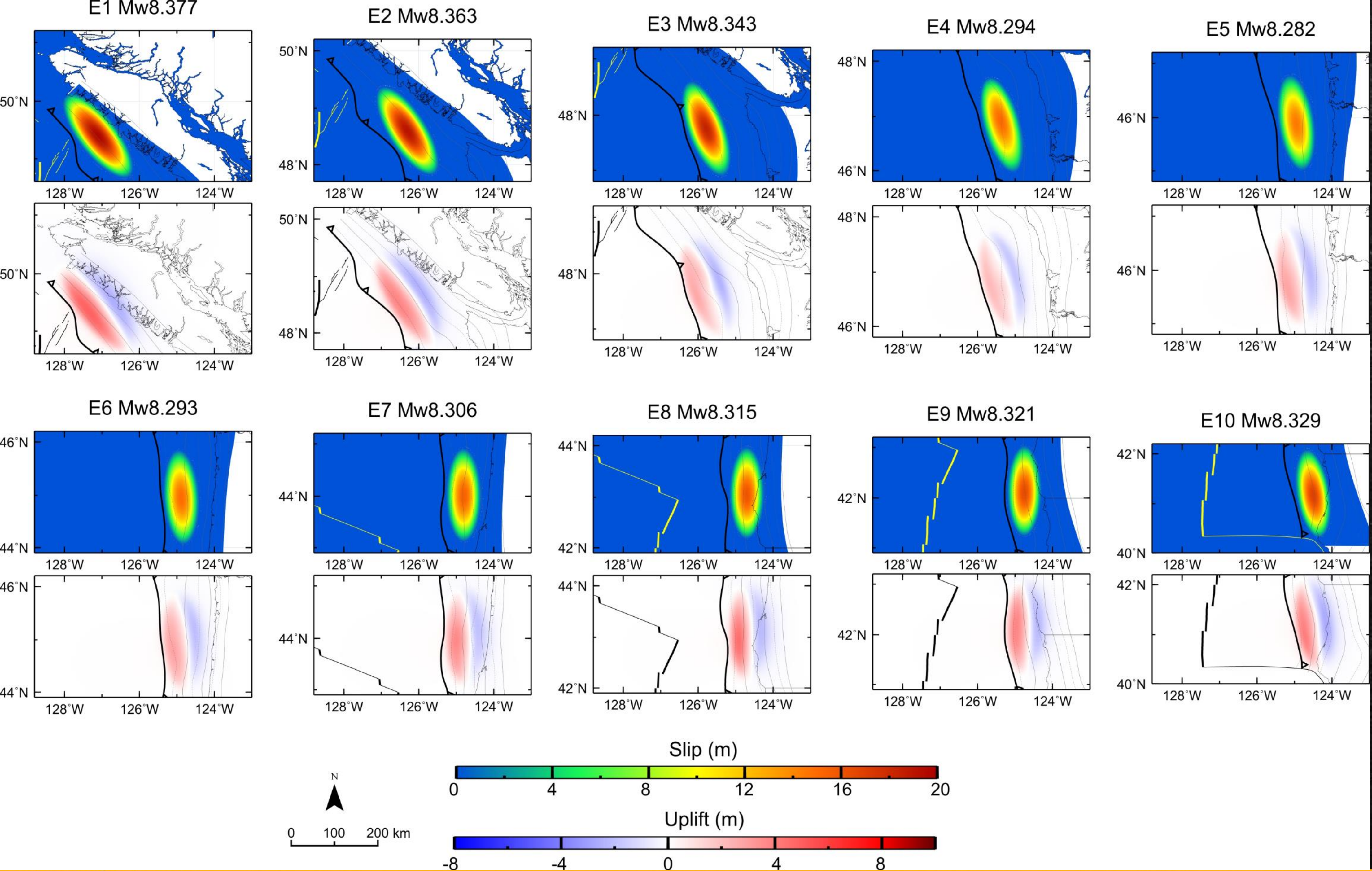
Five Level Cluster Ruptures





Floating rupture boundaries

The use of red and blue colors is only for display clarity with no other significance.
All the ruptures are elliptical and of the same size in map view.



Slip distribution (upper) and surface vertical deformation (lower) for all ten elliptical floating-rupture patch scenarios

Thank You!

Are there any questions?

giphy.com/gifs/starwars-3ornk03njkdi5mNKJG

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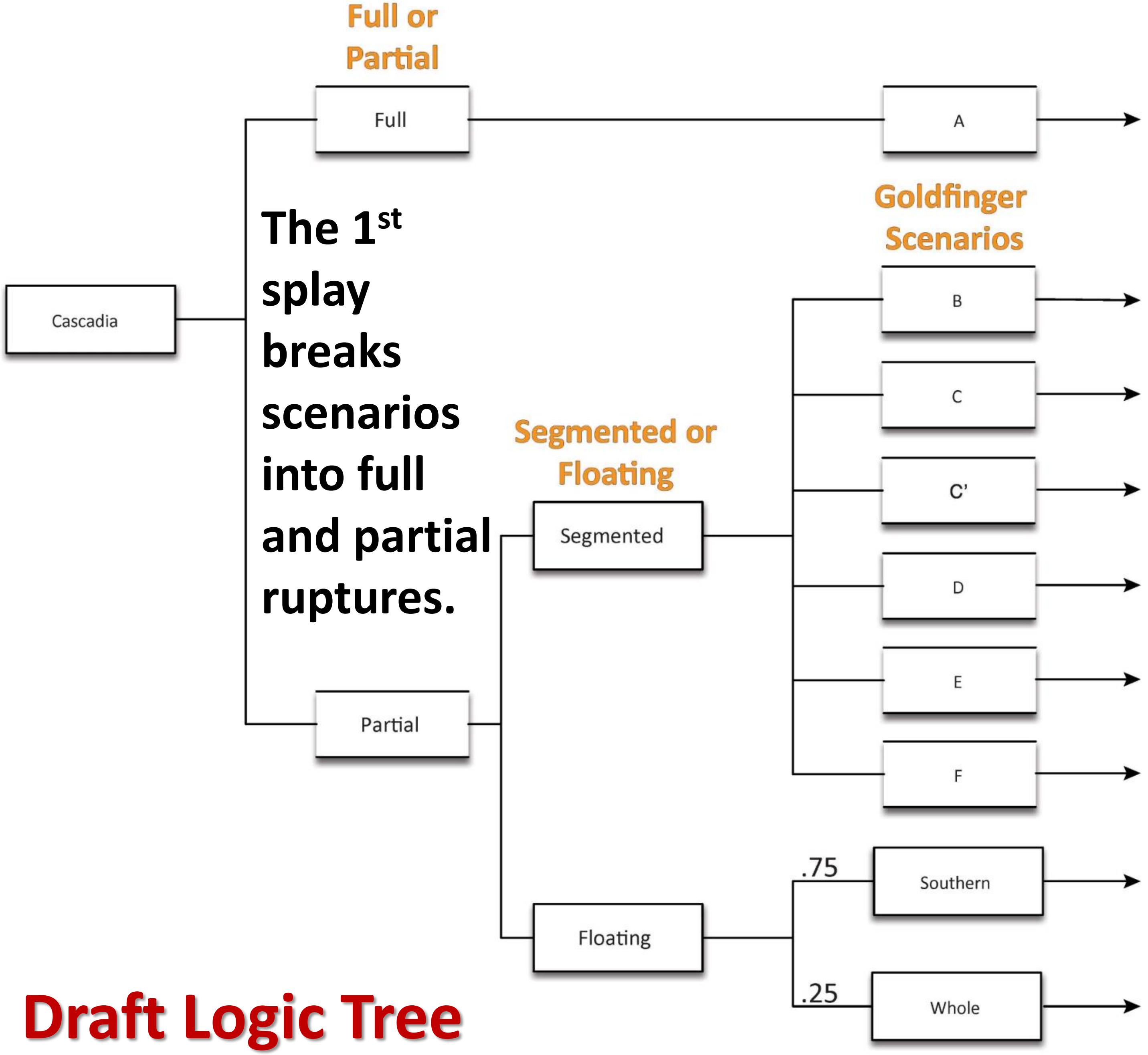
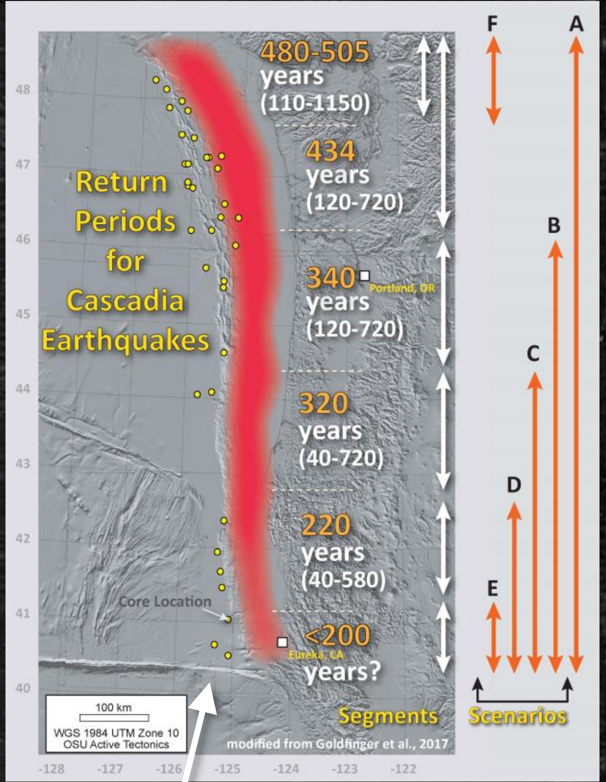


The 1st splay breaks scenarios into full and partial ruptures.

Draft Logic Tree

Goldfinger 2012, 2017

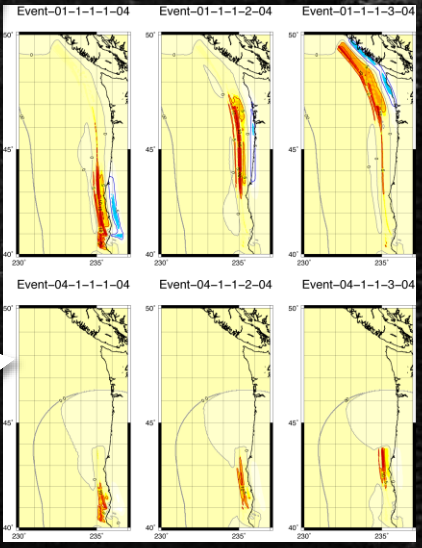
- The full rupture branch presumes a margin-wide earthquake (e.g., A from Goldfinger et al., 2012, 2017).
- The partial rupture branch represents earthquakes that do not span the entire margin.



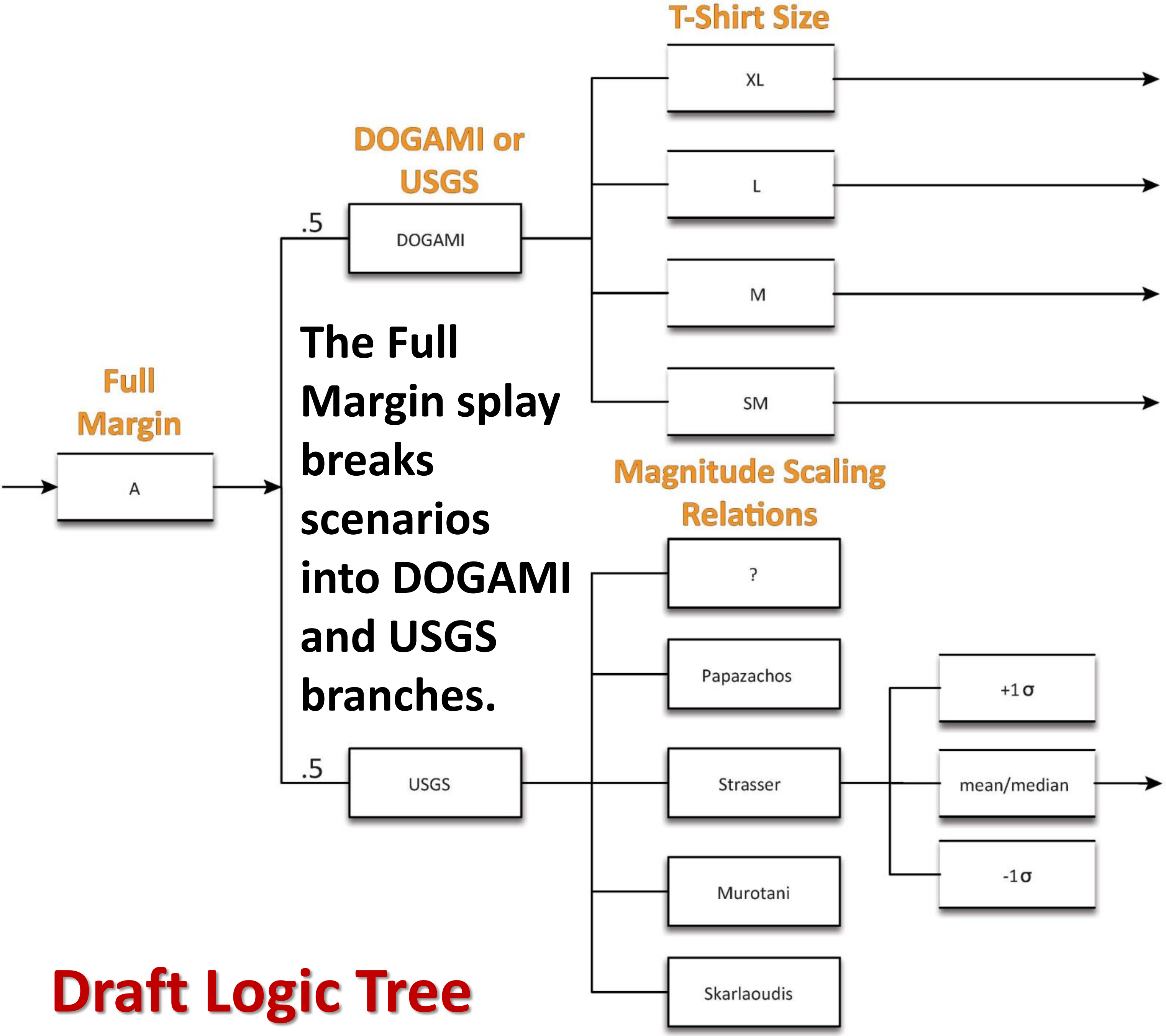
The two partial branches are segmented and floating:

(1) based on the Goldfinger et al. (2012, 2017) paleoseismic scenarios

(2) based on floating ruptures

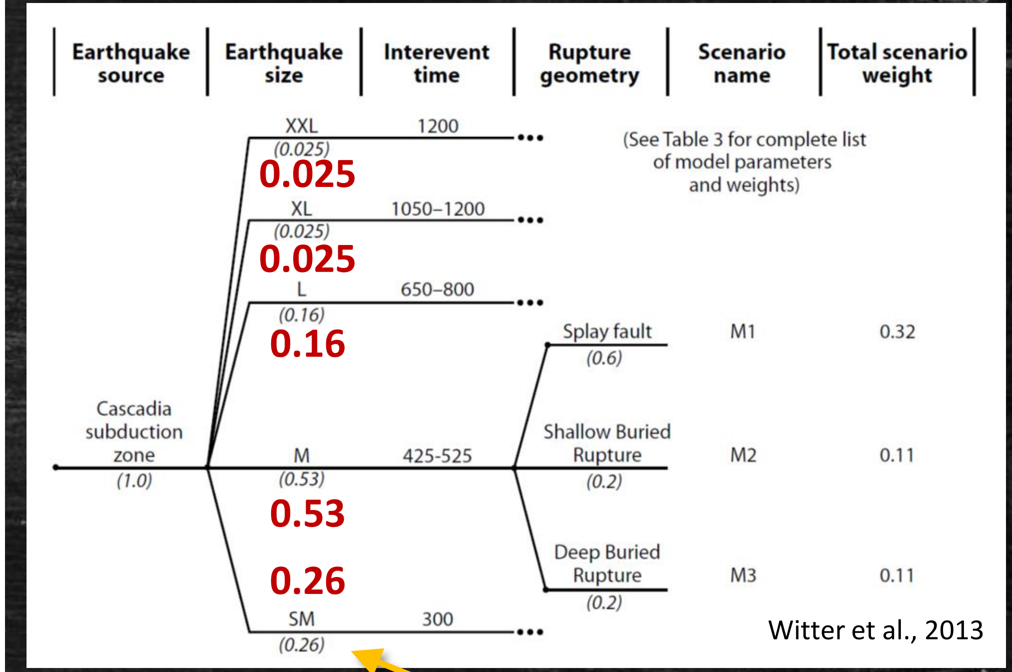


Thio, 2020

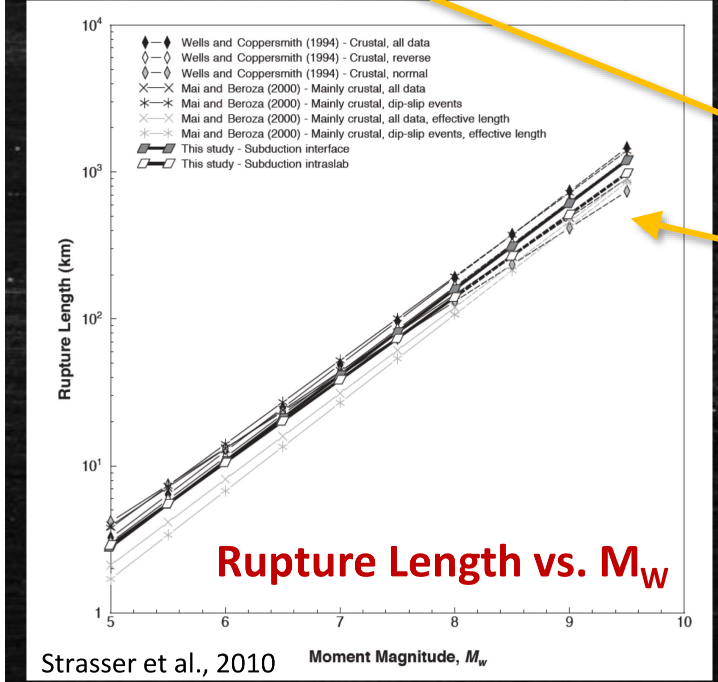


The Full Margin splay breaks scenarios into DOGAMI and USGS branches.

Draft Logic Tree



Witter et al., 2013



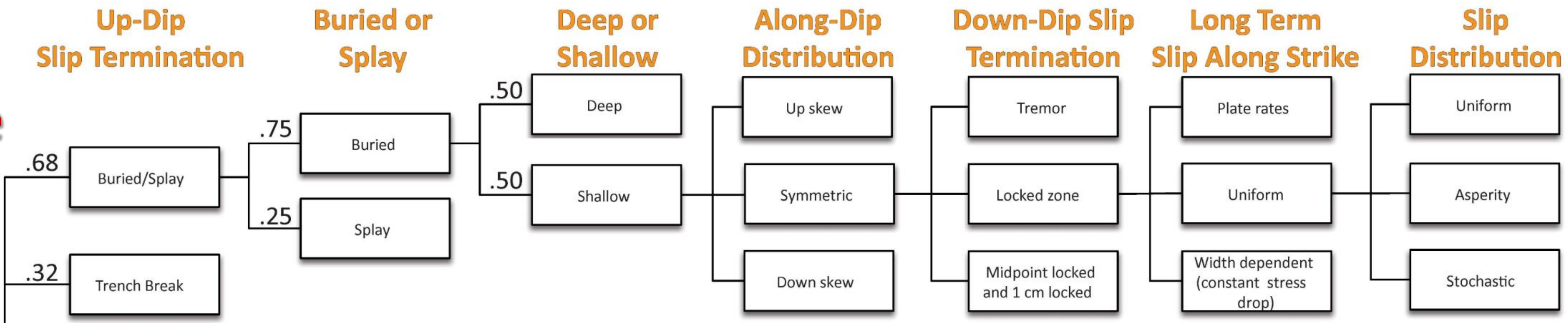
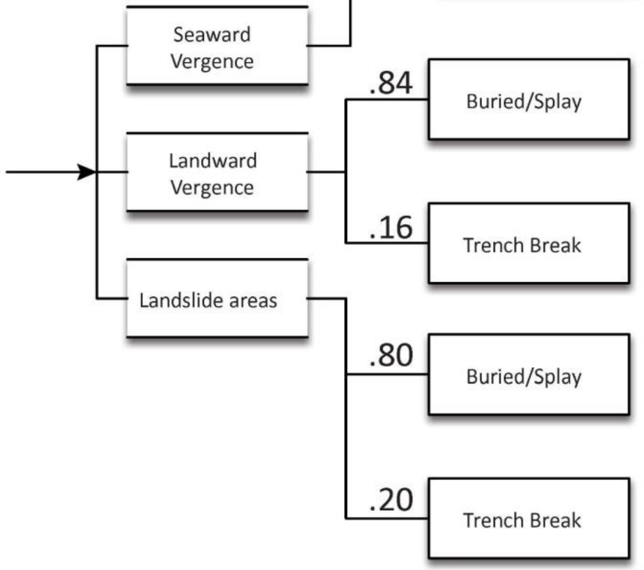
Strasser et al., 2010

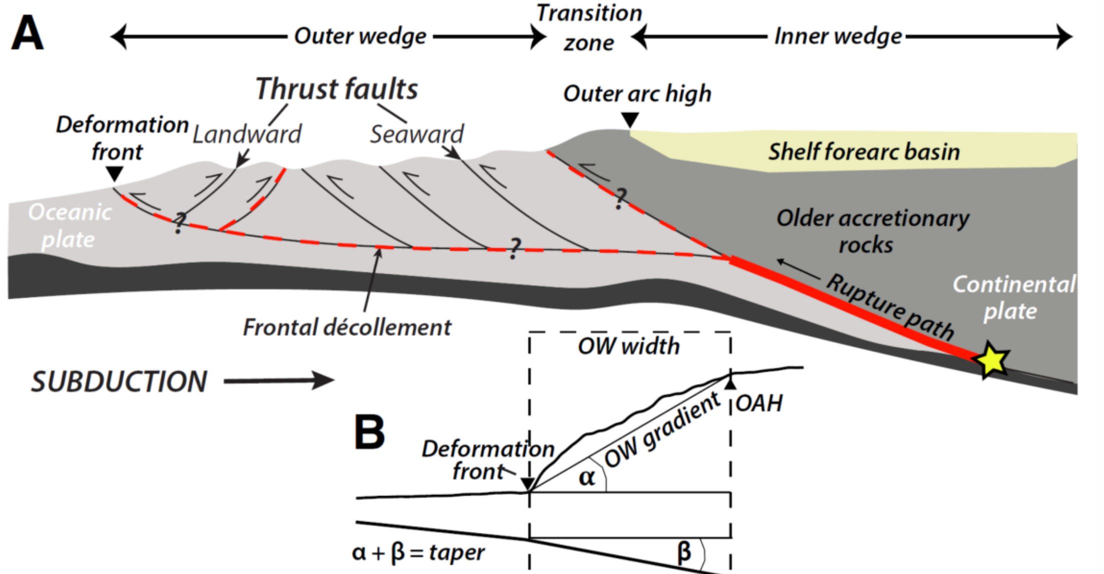
Rupture Size

(1) t-shirt size (DOGAMI)

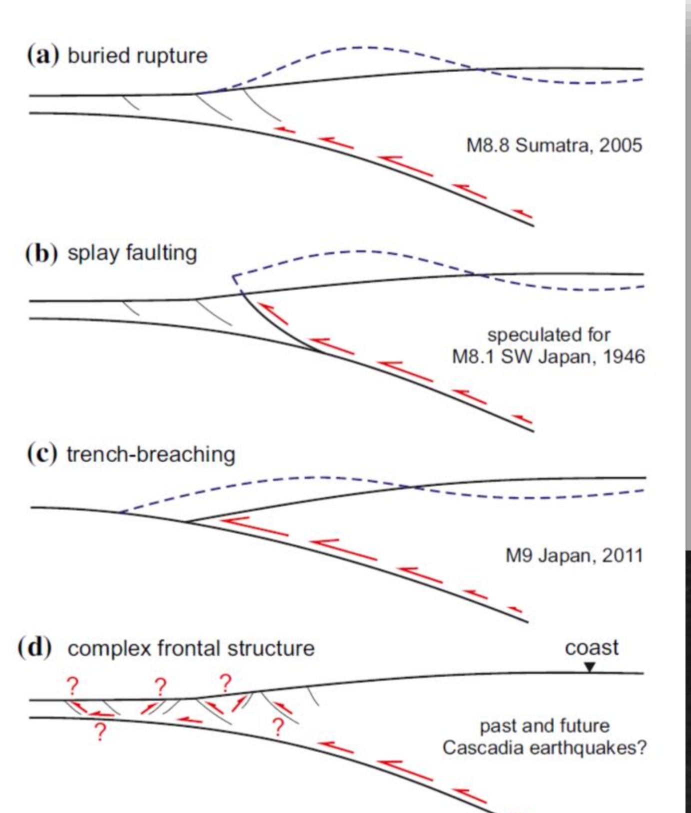
(2) magnitude scaling relations (USGS)

Draft Logic Tree



Watt and Brothers, 2021



Gao et al., 2018

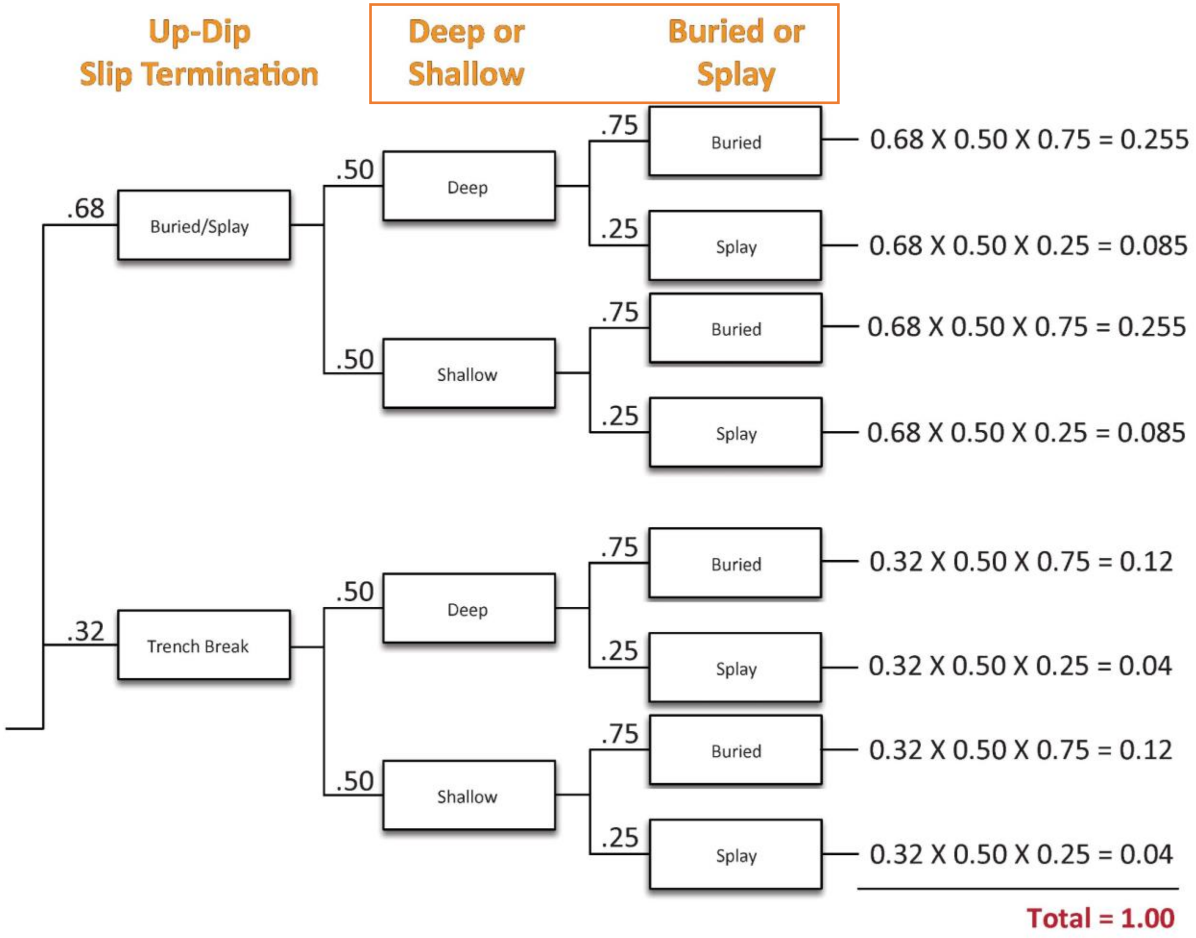
Fault geometry can influence both slip and tsunami source models. Trench breaking slip can generate larger tsunami.

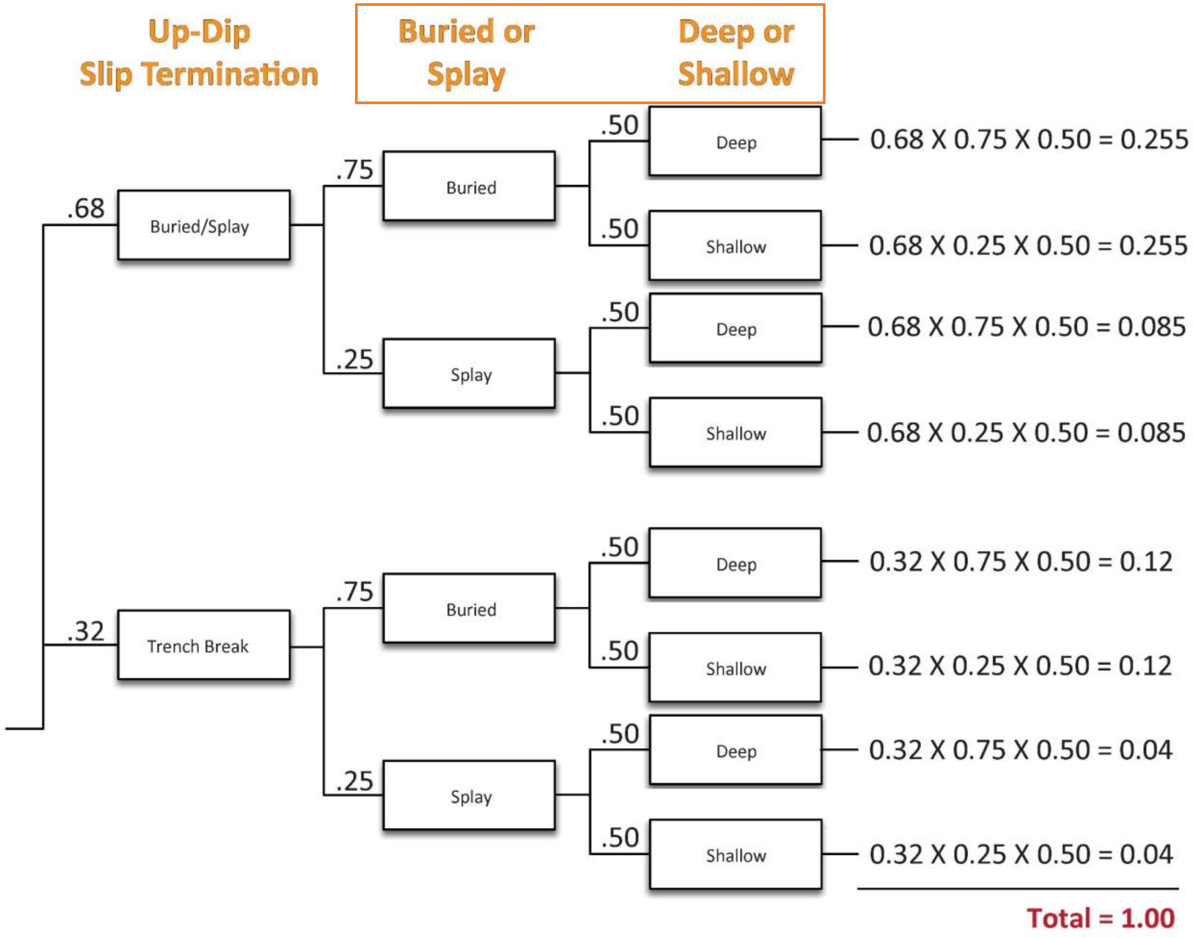
Illustrations shows hypothetical slip scenarios (and seafloor uplift) for a range of fault geometry.

PTHA and Logic Trees

In the logic tree, the order of the branches does not matter.

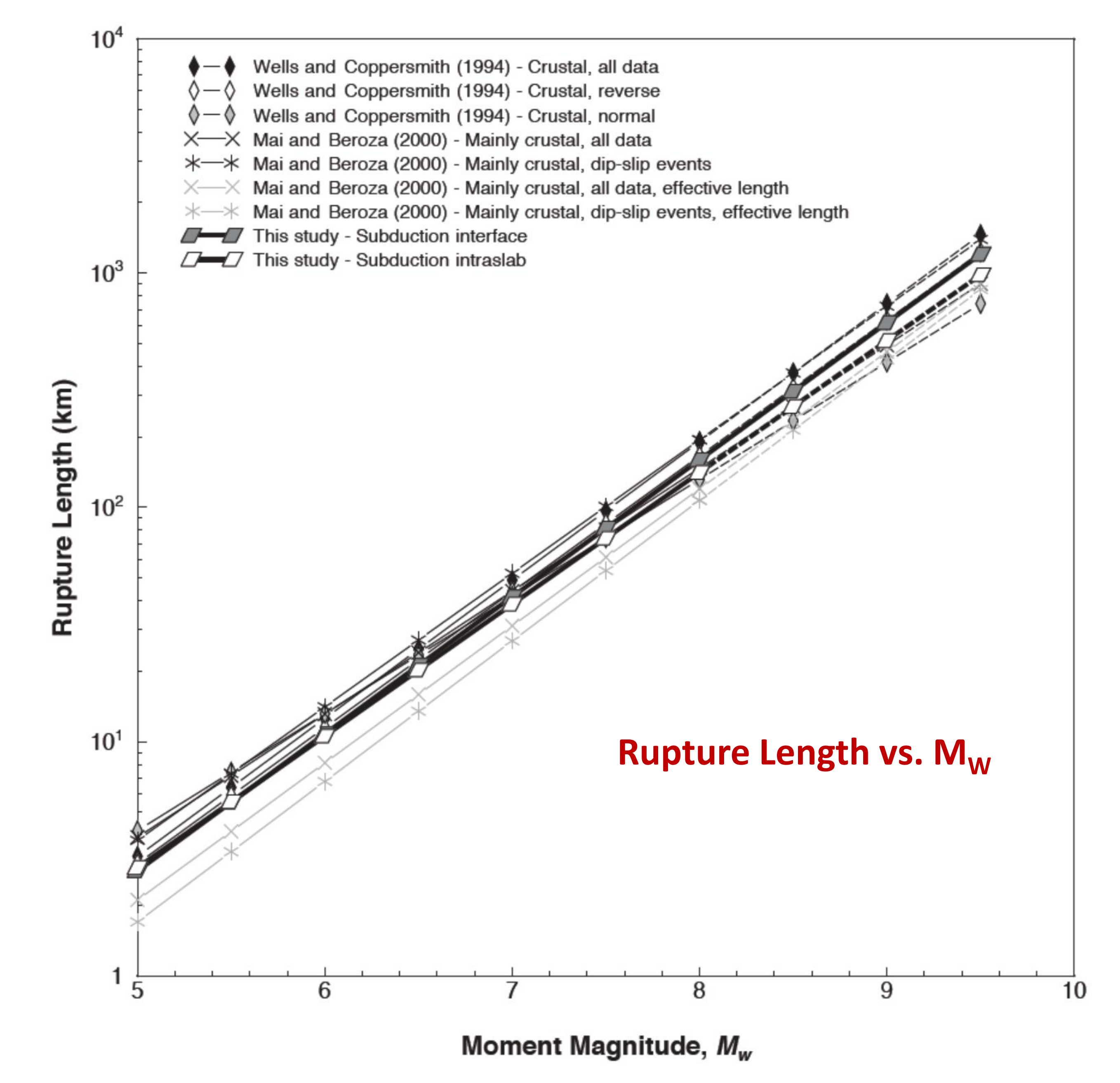
Example on the left has the deep/shallow branch before buried/splay branch. The example on the right has the buried/splay branch before the deep/shallow branch. Note how the probabilities for each option sum to 1.00.

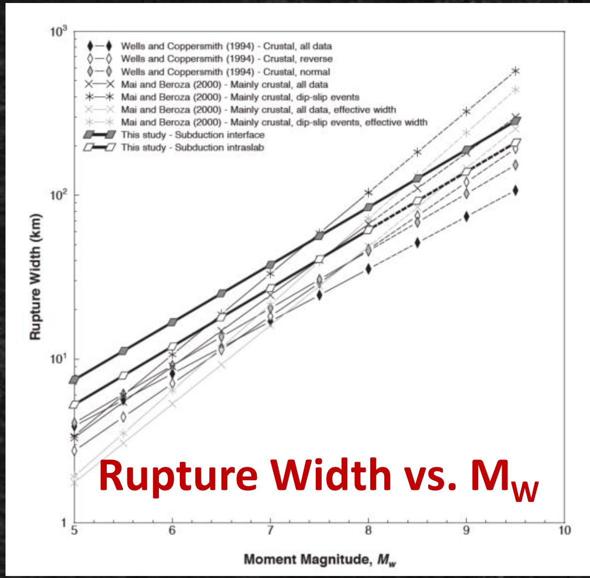


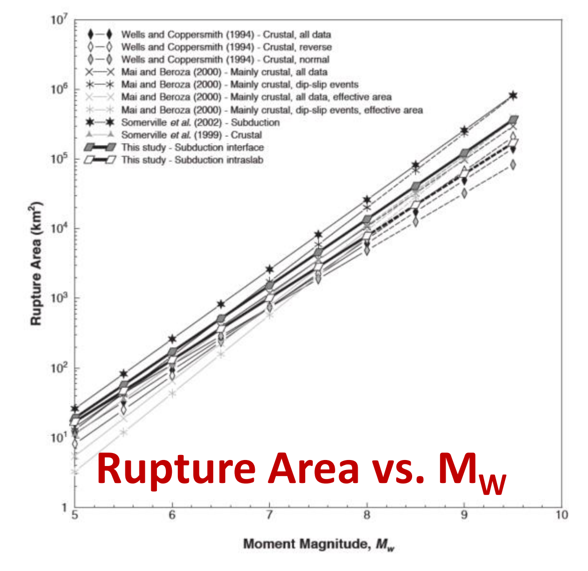


Rupture Size – Magnitude Scaling Relations

- These empirical scaling relations allow us to take rupture dimensions and estimate a magnitude for that sized rupture.
- Example scaling relations from Strasser et al., 2010 show magnitude vs. rupture length, rupture width, and rupture area.

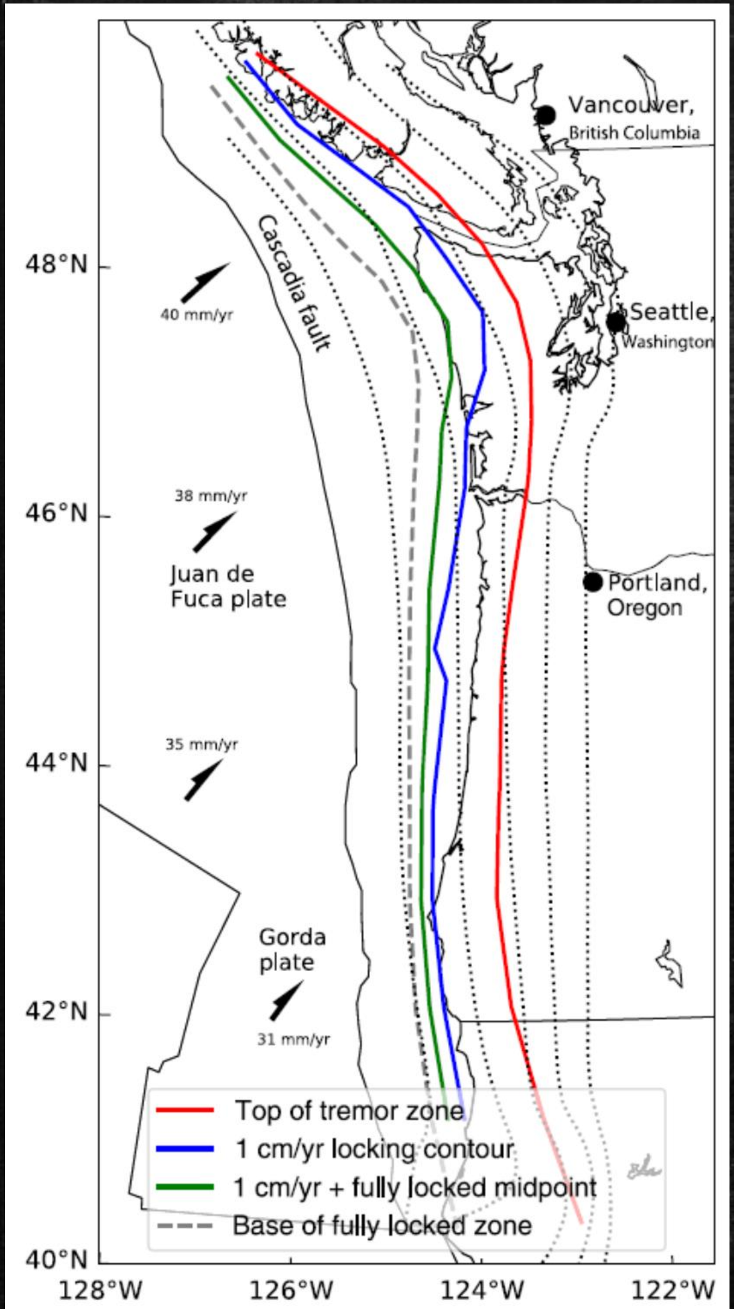






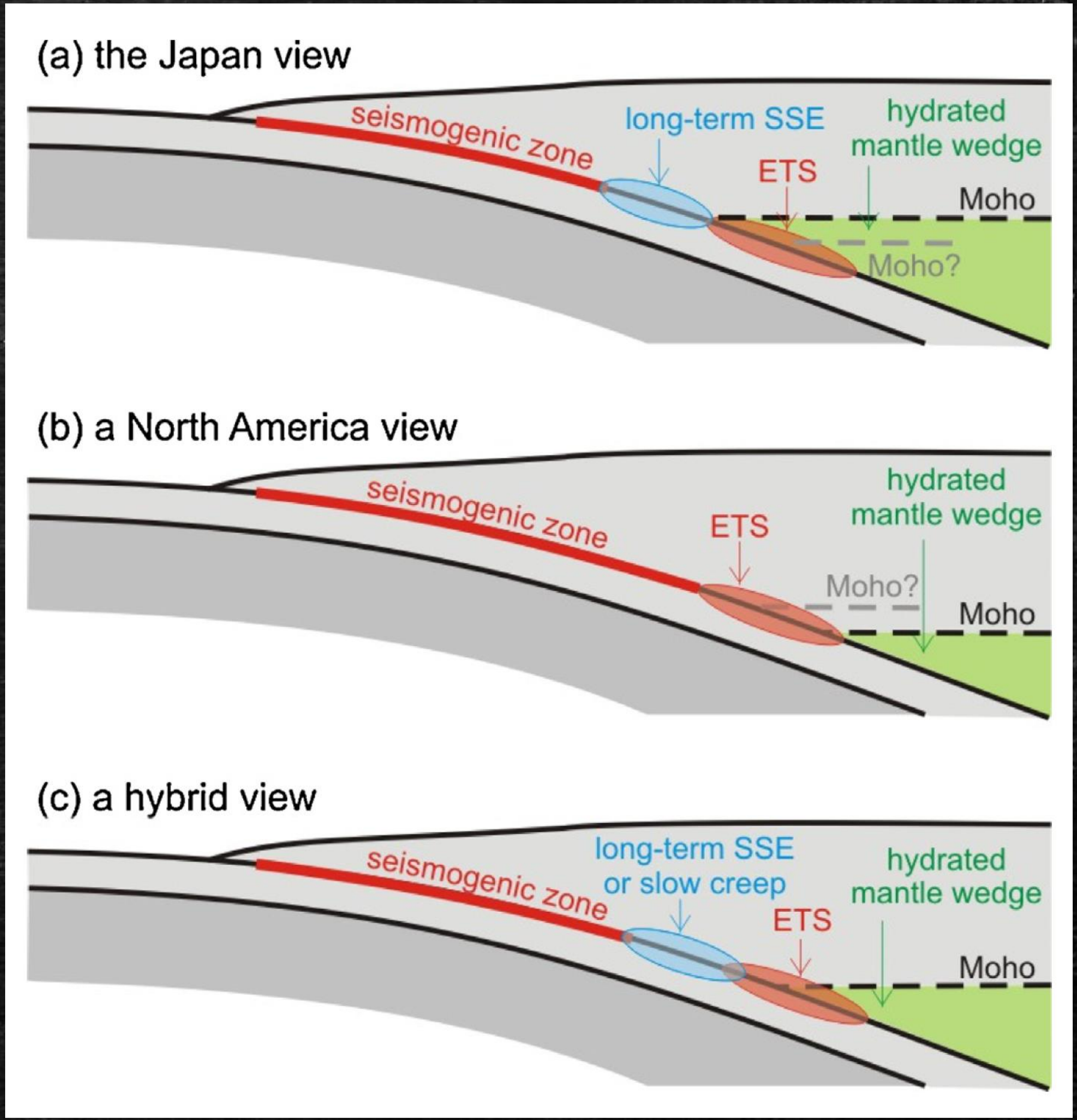
Strasser et al., 2010

Down-Dip Limit of Rupture



Wirth and Frankel, 2019

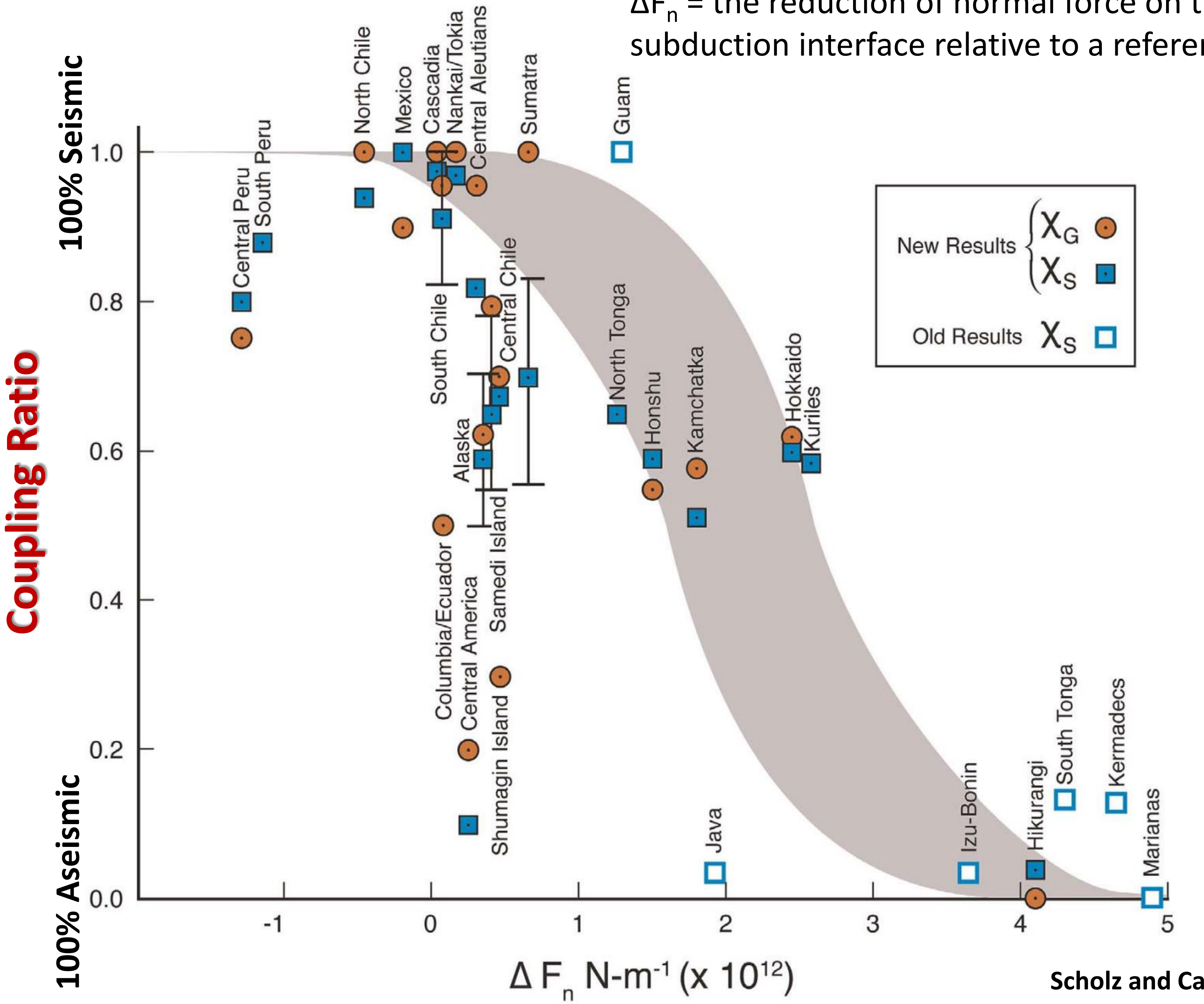
The slip distribution at the down dip limit of rupture may have little influence on tsunamigenesis, unlike for ground motions used in the USGS NSHM. This highlights some ways in which these logic trees must be slightly different.



Wang and Trehu, 2014

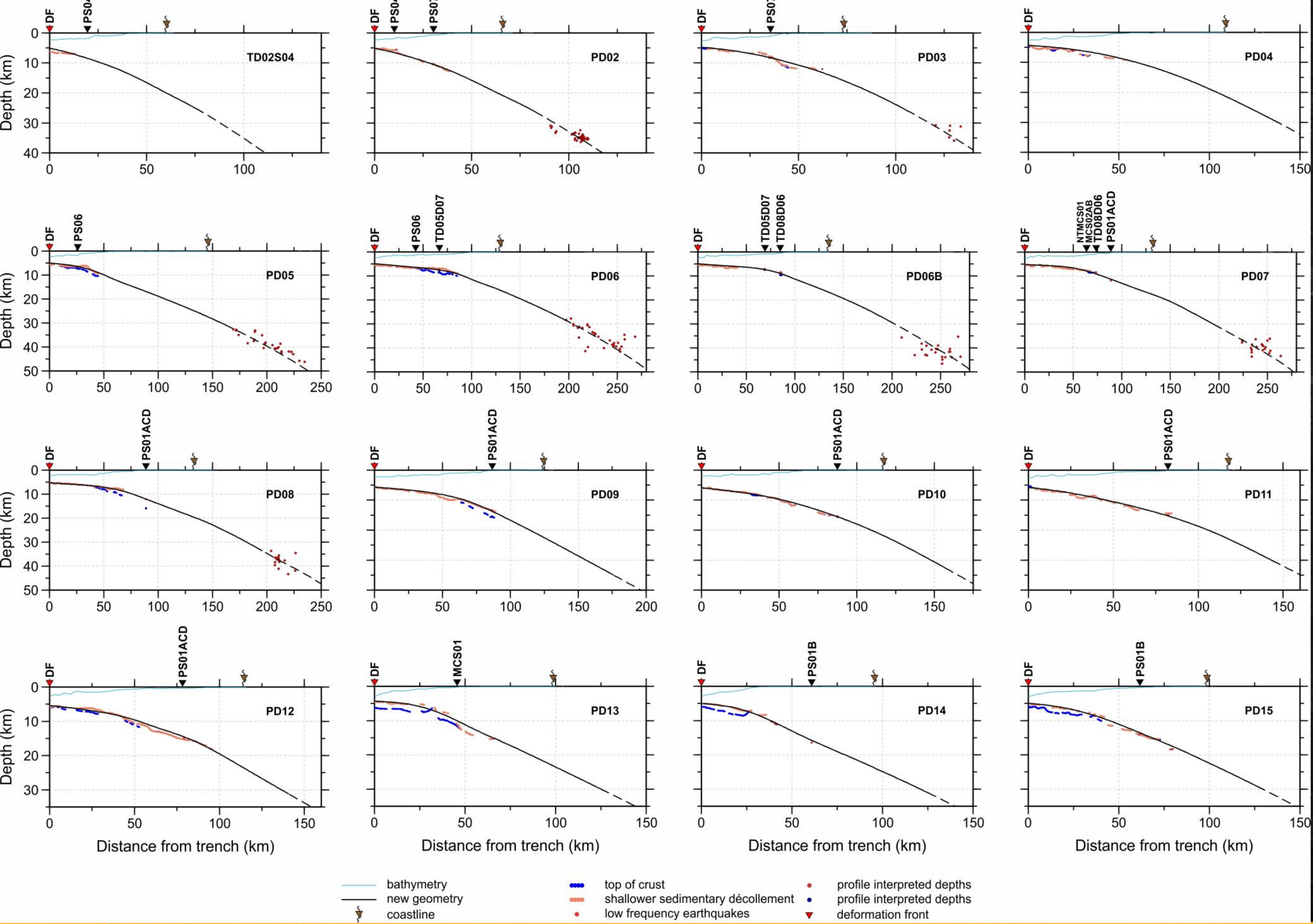
Long Term Slip Rate: Coupling Ratio

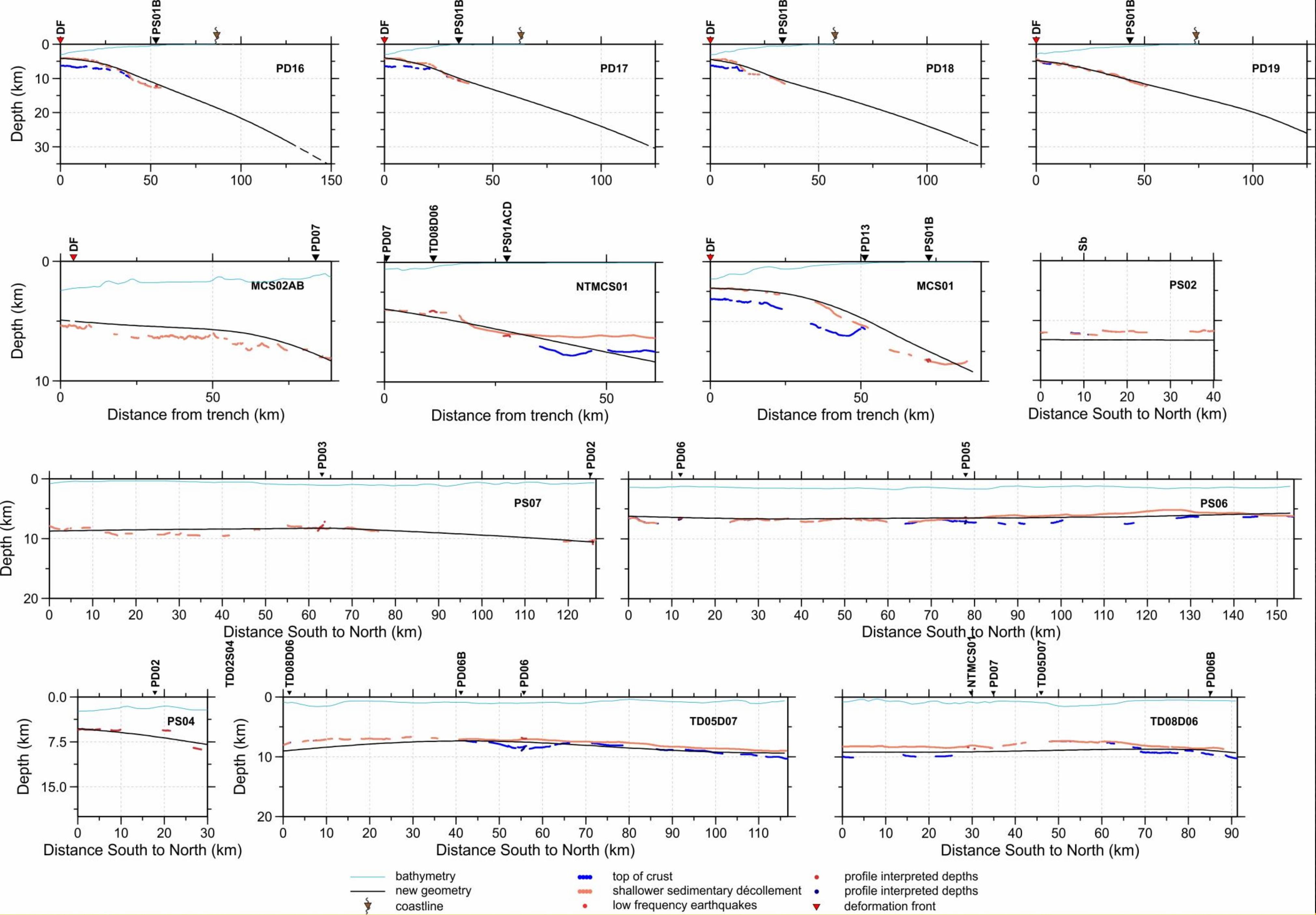
ΔF_n = the reduction of normal force on the subduction interface relative to a reference state



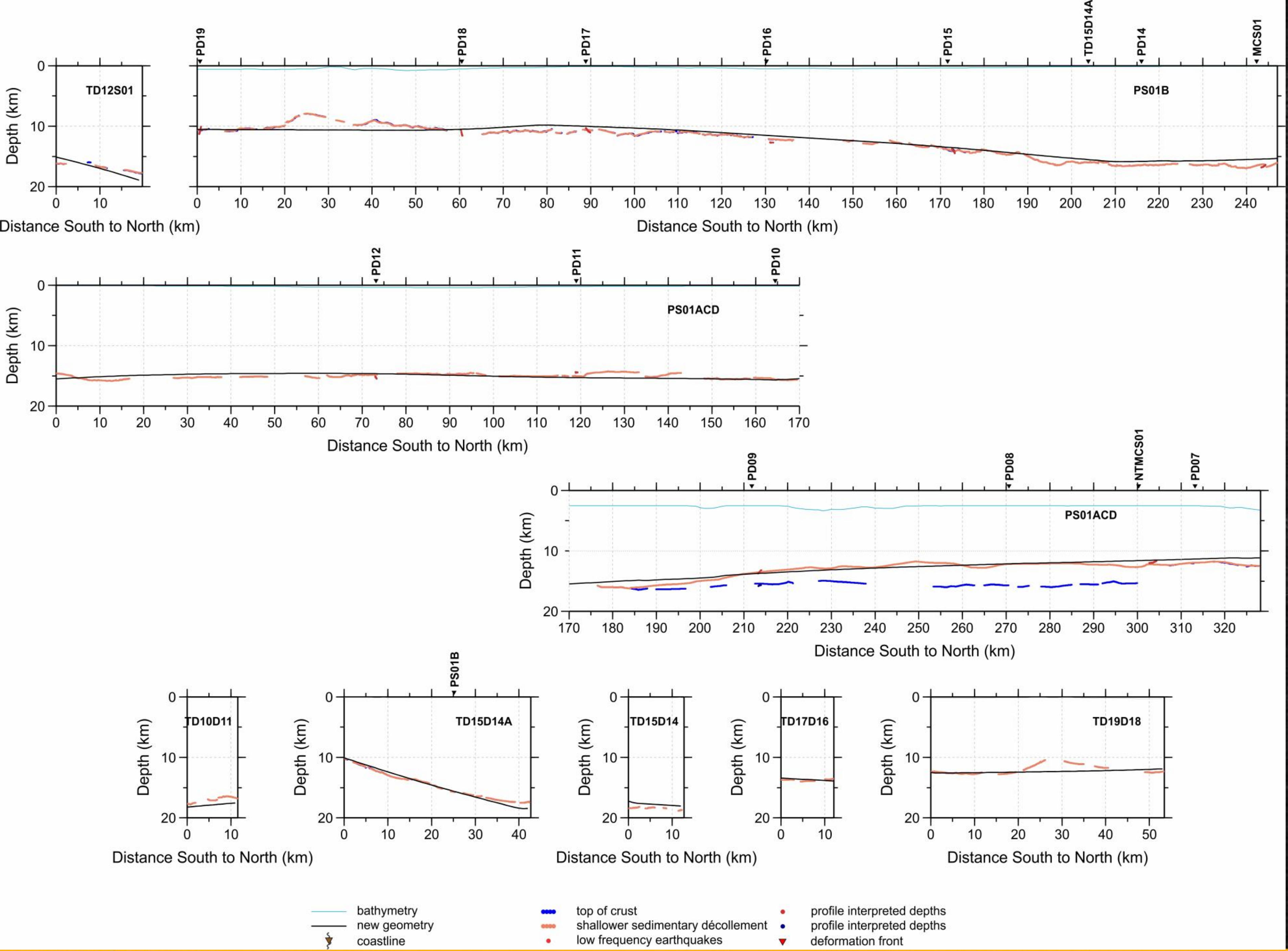
Scholz and Campos, 2012

- Participants agreed that long term slip needs to be balanced by plate motion rate in some way.
- The coupling ratio is amount of plate motion rate that is accumulated as tectonic strain (i.e., the ratio of seismic vs. aseismic slip).
- If the coupling ratio is less than 1, then the entire plate rate that contributes to long term slip is less than the plate convergence rate.

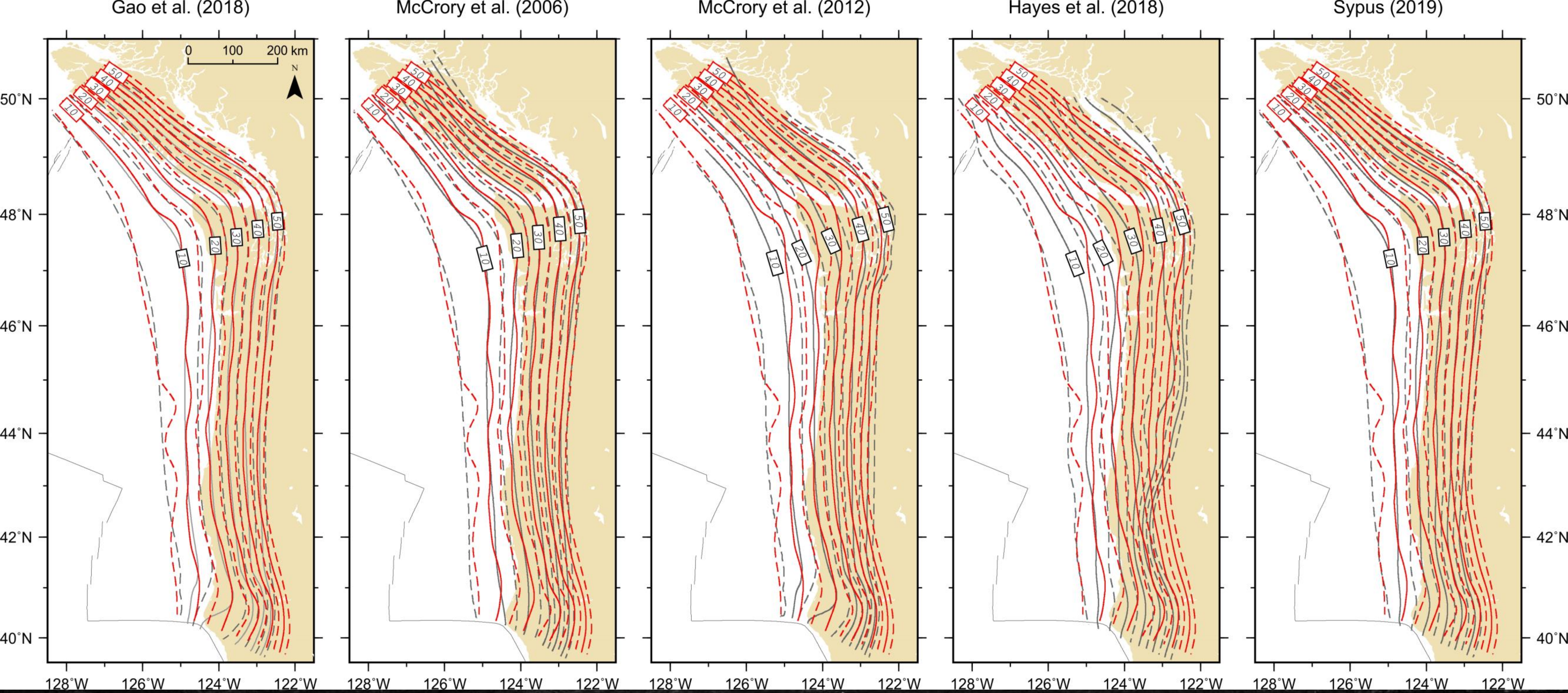

TD02S04
PD02
PD03
PD04
PD05
PD06
PD06B
PD07
PD08
PD09
PD10
PD11
PD12
PD13
PD14
PD15
DF
PS06
TD05D07
TD08D06
NTMCS01
MCS02AB
PS01ACD
MCS01
PS01B
Depth (km)
Distance from trench (km)
bathymetry
new geometry
coastline
top of crust
shallower sedimentary décollement
low frequency earthquakes
profile interpreted depths
profile interpreted depths
deformation front

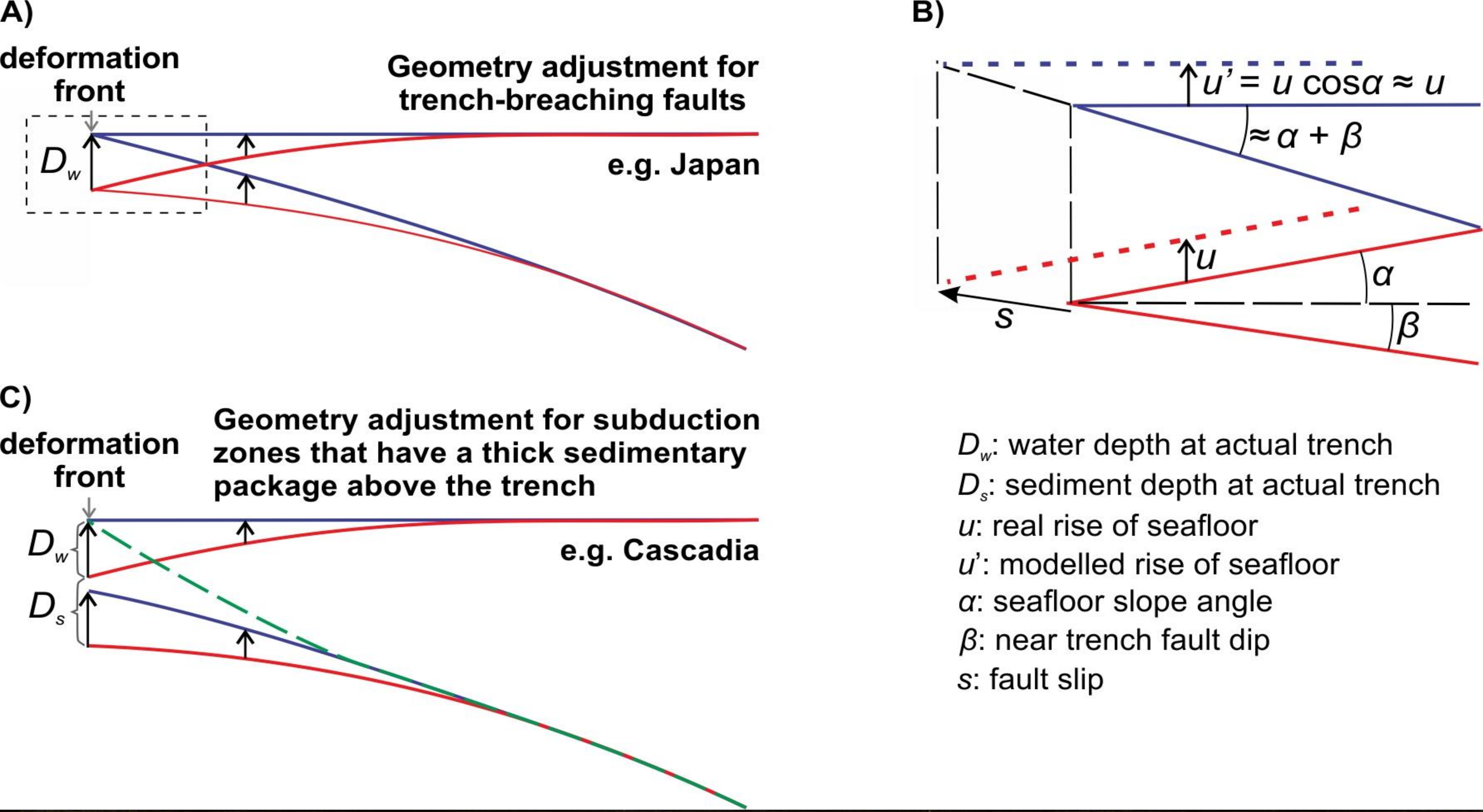


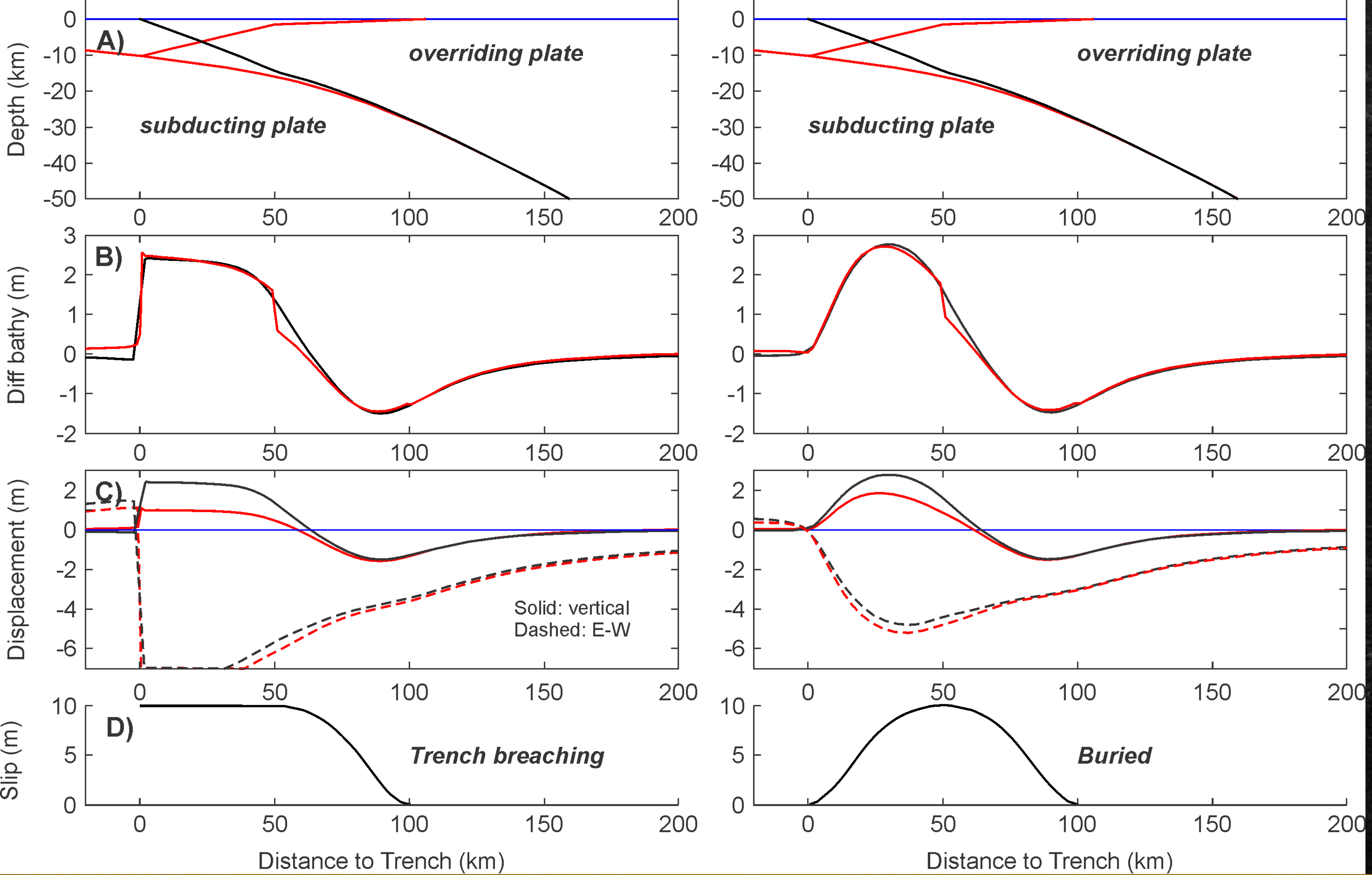
PD16
PD17
PD18
PD19
MCS02AB
NTMCS01
MCS01
PS02
PS07
PS06
PS04
TD05D07
TD08D06
DF
PS01B
PD07
TD08D06
PS01ACD
PD13
Sb
PD03
PD02
PD06
PD05
TD02S04
PD06B
NTMCS01
TD05D07
Depth (km)
Distance from trench (km)
Distance South to North (km)
bathymetry
new geometry
coastline
top of crust
shallower sedimentary décollement
low frequency earthquakes
profile interpreted depths
profile interpreted depths
deformation front



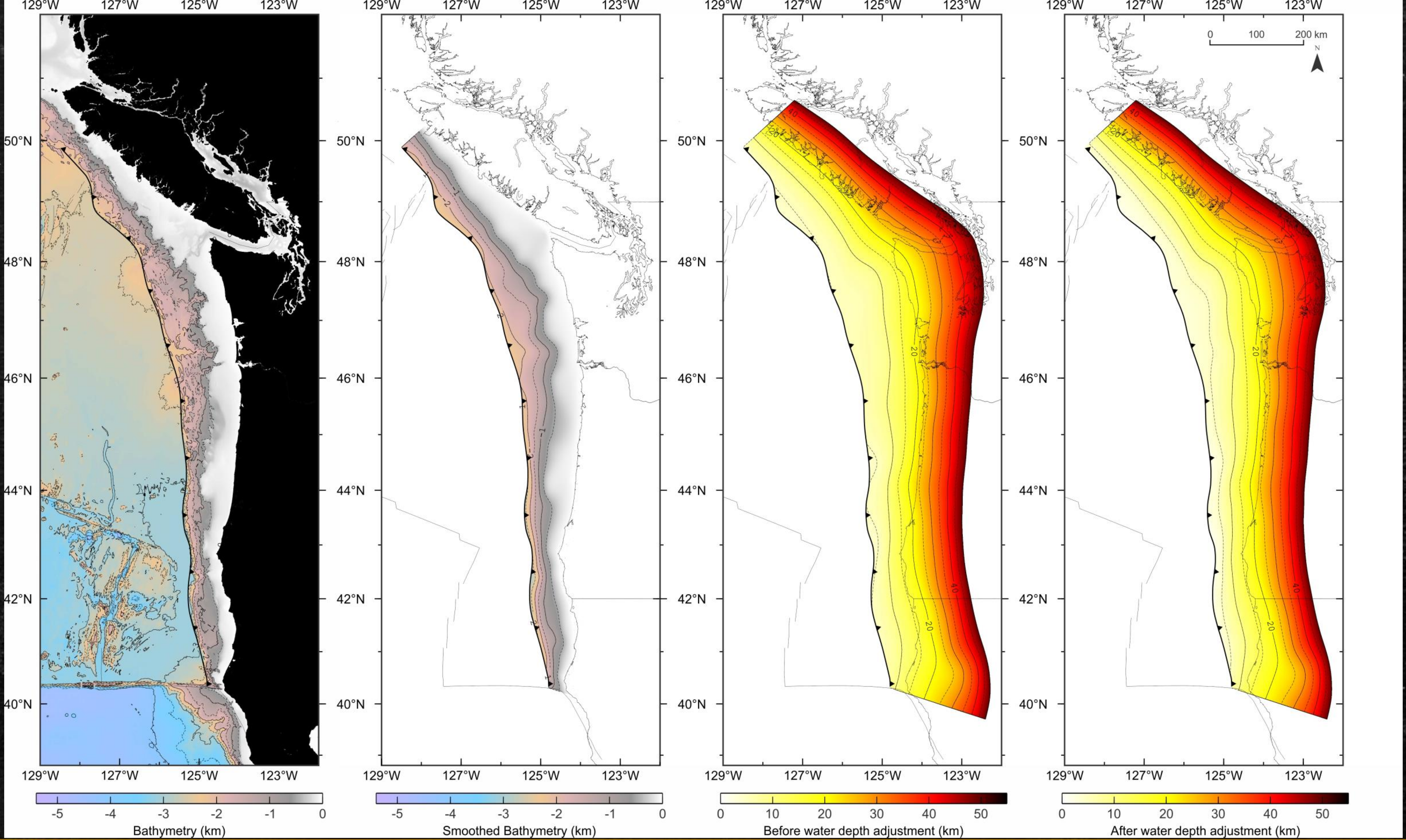
TD12S01
PS01B
PS01ACD
PS01ACD
TD10D11
TD15D14A
TD15D14
TD17D16
TD19D18
PD19
PD18
PD17
PD16
PD15
TD15D14A
PD14
MCS01
PD12
PD11
PD10
PD09
PD08
NTMCS01
PD07
PS01B
Depth (km)
Distance South to North (km)
bathymetry
new geometry
coastline
top of crust
shallower sedimentary décollement
low frequency earthquakes
profile interpreted depths
profile interpreted depths
deformation front


Gao et al. (2018)
McCrory et al. (2006)
McCrory et al. (2012)
Hayes et al. (2018)
Sypus (2019)
0 100 200 km
N
10
20
30
40
50
40°N
42°N
44°N
46°N
48°N
50°N
128°W
126°W
124°W
122°W

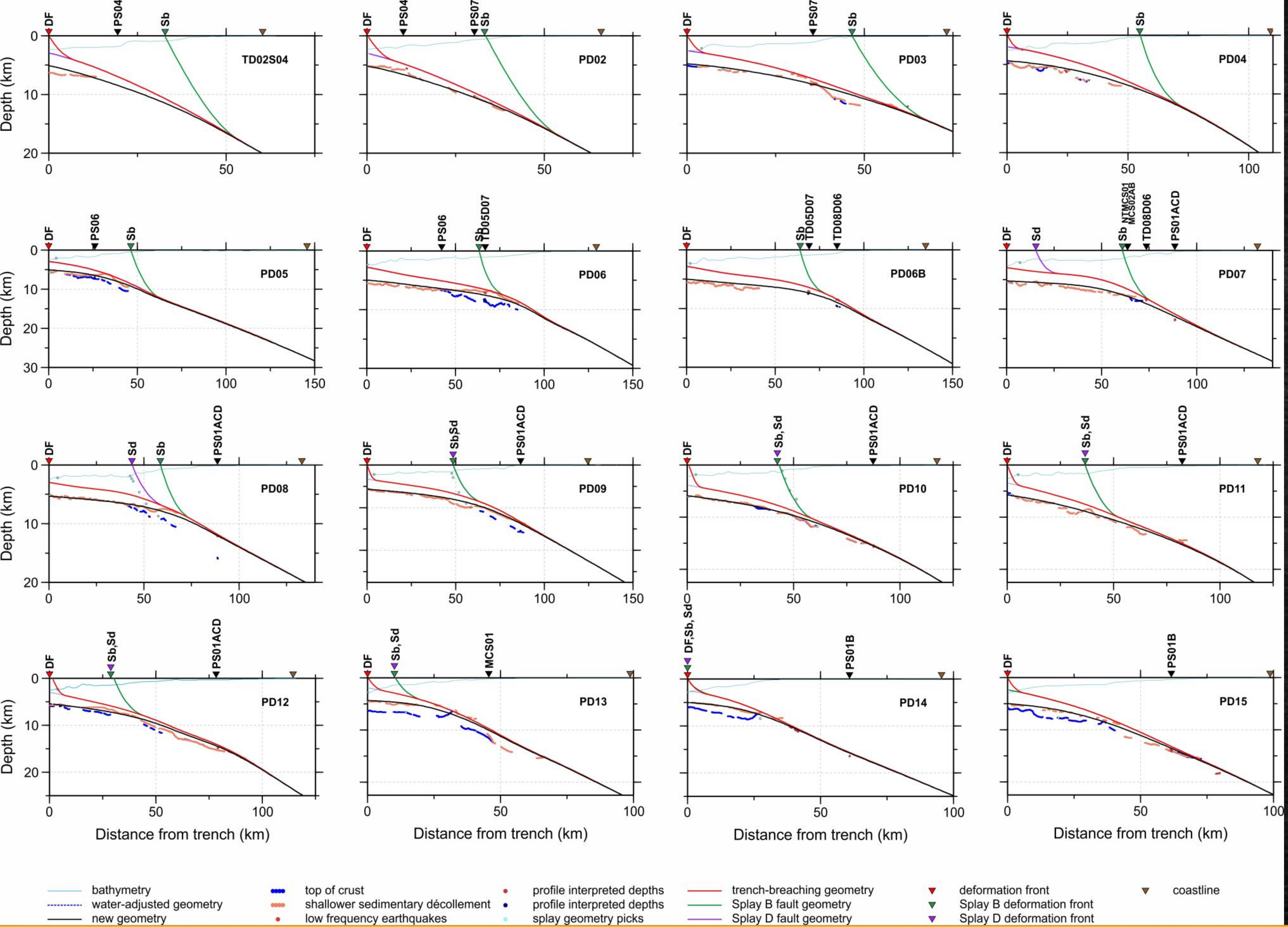

A)
deformation front
Geometry adjustment for trench-breaching faults
D_w
e.g. Japan
B)
$u' = u \cos\alpha \approx u$
$\approx \alpha + \beta$
u
α
β
s
C)
deformation front
Geometry adjustment for subduction zones that have a thick sedimentary package above the trench
D_w
D_s
e.g. Cascadia
D_w: water depth at actual trench
D_s: sediment depth at actual trench
u: real rise of seafloor
u': modelled rise of seafloor
α: seafloor slope angle
β: near trench fault dip
s: fault slip

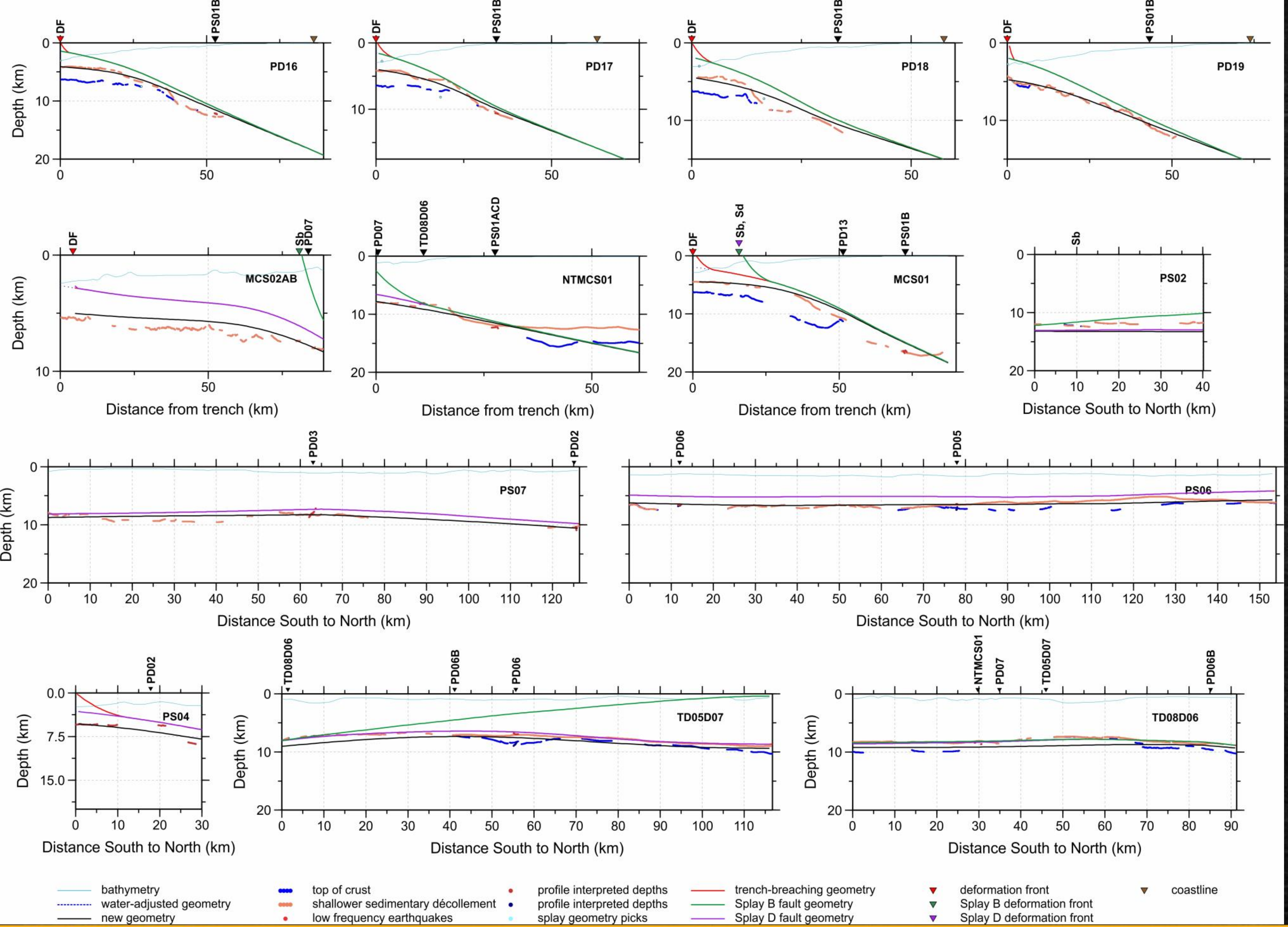


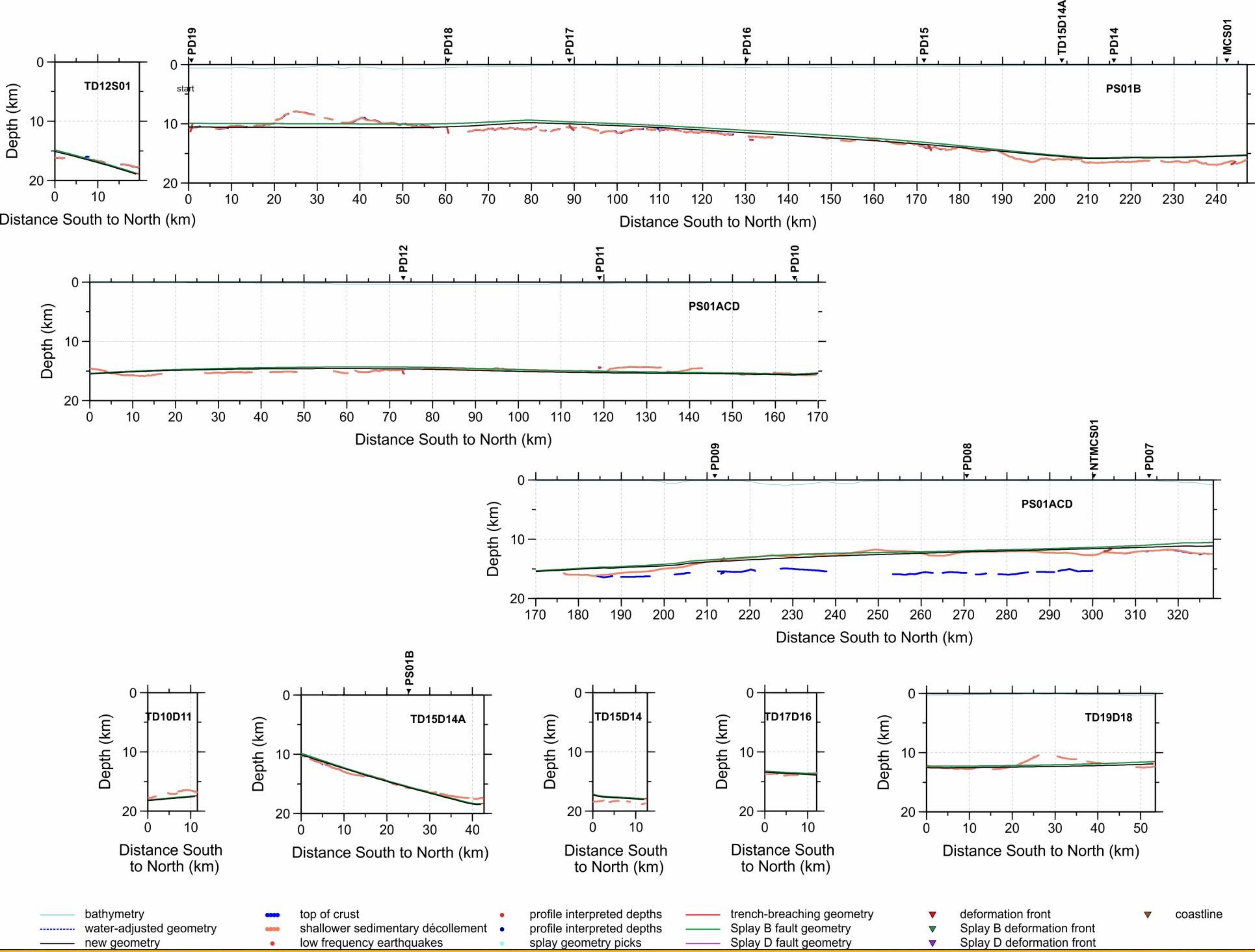
A)
overriding plate
subducting plate
Depth (km)
B)
Diff bathy (m)
C)
Displacement (m)
Solid: vertical
Dashed: E-W
D)
Slip (m)
Trench breaching
Buried
Distance to Trench (km)
Distance to Trench (km)



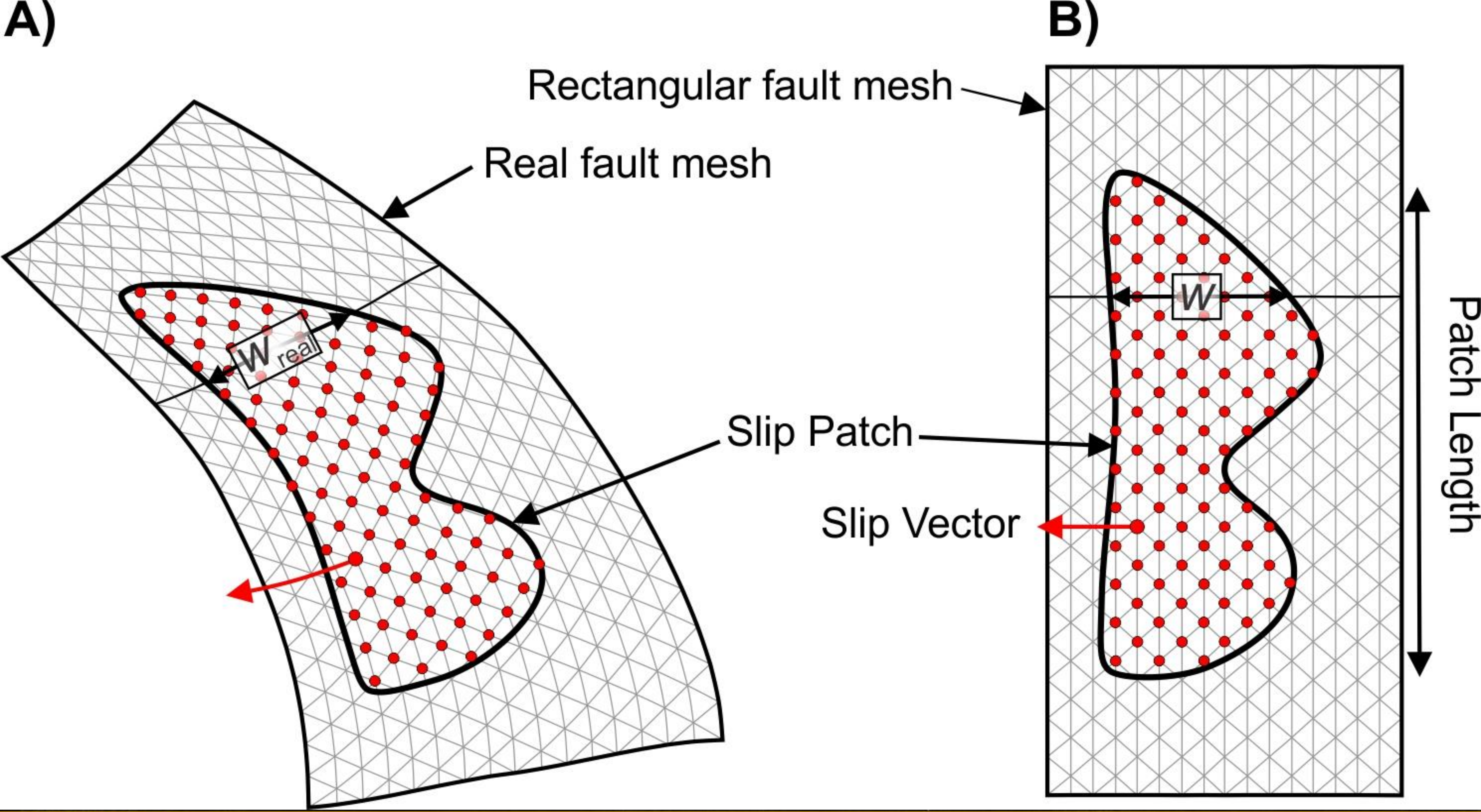
Bathymetry (km)
Smoothed Bathymetry (km)
Before water depth adjustment (km)
After water depth adjustment (km)
0 100 200 km

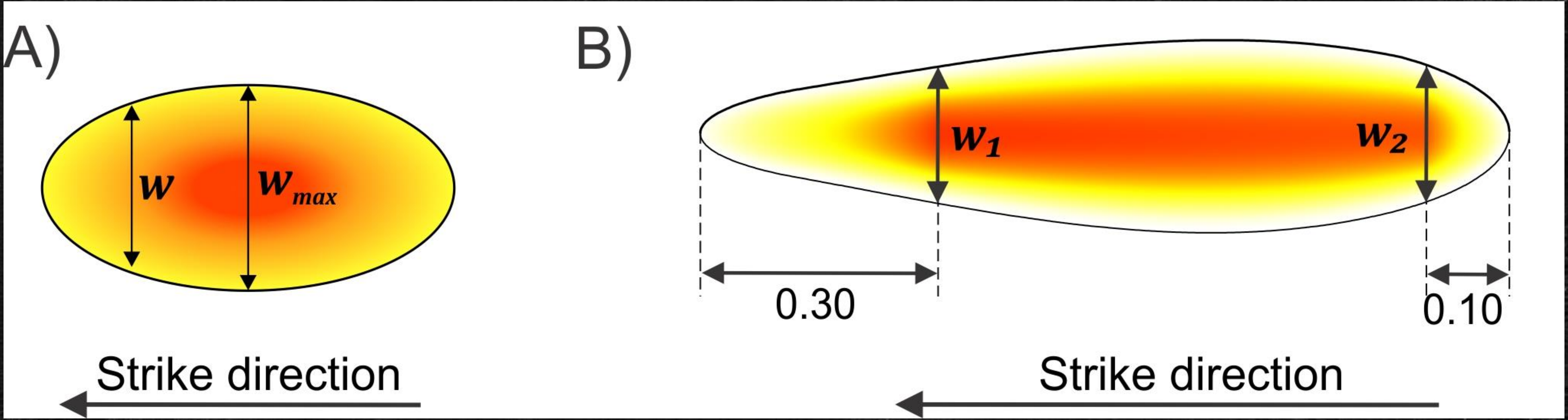

TD02S04
PD02
PD03
PD04
PD05
PD06
PD06B
PD07
PD08
PD09
PD10
PD11
PD12
PD13
PD14
PD15
DF
Sb
Sd
Sb,Sd
DF,Sb,Sd
PS04
PS07
PS06
TD05D07
TD08D06
NTMCS01
MCS02AB
PS01ACD
MCS01
PS01B
Depth (km)
Distance from trench (km)
bathymetry
water-adjusted geometry
new geometry
top of crust
shallower sedimentary décollement
low frequency earthquakes
profile interpreted depths
profile interpreted depths
splay geometry picks
trench-breaching geometry
Splay B fault geometry
Splay D fault geometry
deformation front
Splay B deformation front
Splay D deformation front
coastline

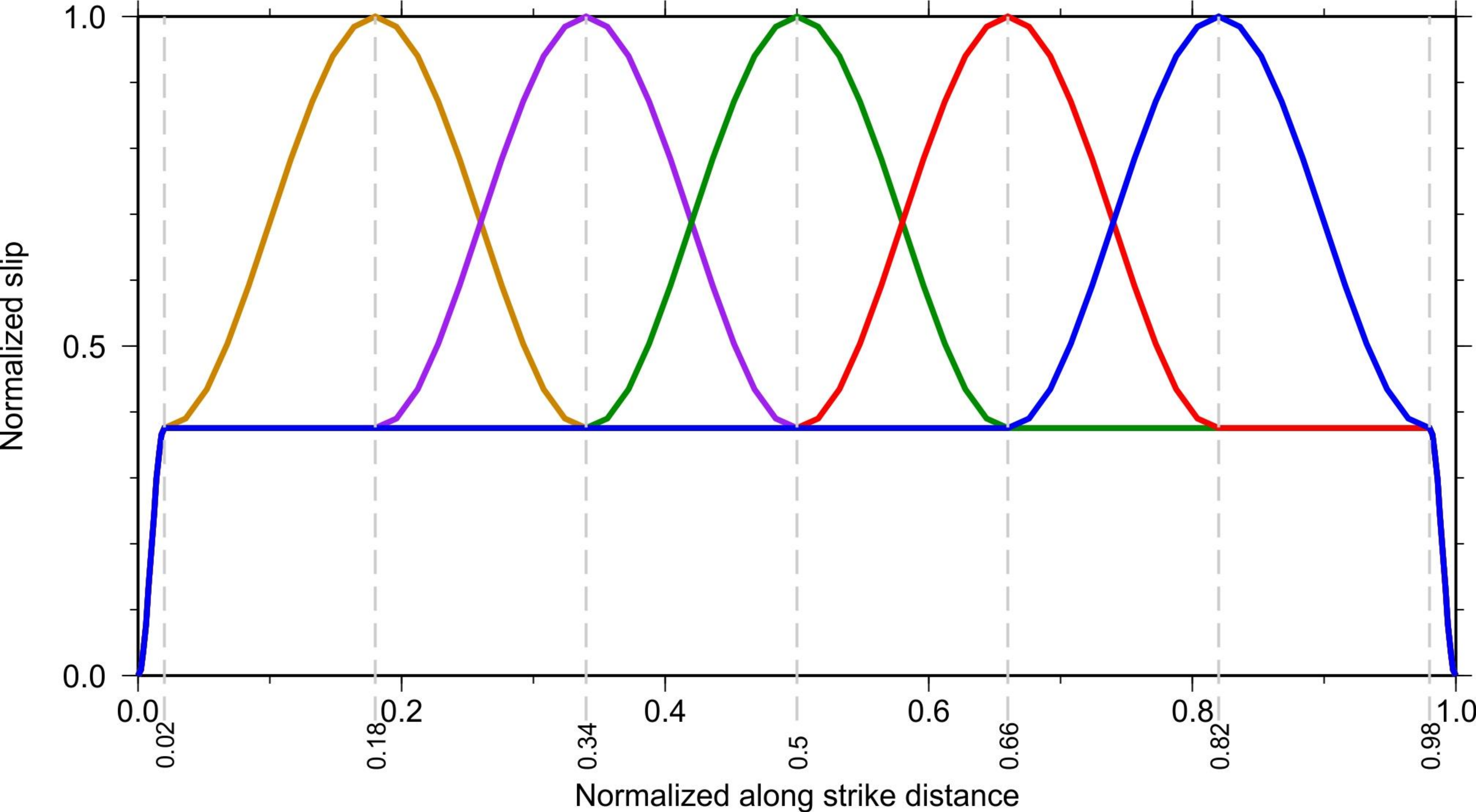

PD16
PD17
PD18
PD19
MCS02AB
NTMCS01
MCS01
PS02
PS07
PS06
PS04
TD05D07
TD08D06
DF
PS01B
Sb
PD07
TD08D06
PS01ACD
Sb, Sd
PD13
PD03
PD02
PD06
PD05
PD06B
NTMCS01
TD05D07
Depth (km)
Distance from trench (km)
Distance South to North (km)
bathymetry
water-adjusted geometry
new geometry
top of crust
shallower sedimentary décollement
low frequency earthquakes
profile interpreted depths
profile interpreted depths
splay geometry picks
trench-breaching geometry
Splay B fault geometry
Splay D fault geometry
deformation front
Splay B deformation front
Splay D deformation front
coastline



TD12S01
PS01B
PS01ACD
PS01ACD
TD10D11
TD15D14A
TD15D14
TD17D16
TD19D18
PD19
PD18
PD17
PD16
PD15
TD15D14A
PD14
MCS01
PD12
PD11
PD10
PD09
PD08
NTMCS01
PD07
PS01B
start
Depth (km)
Distance South to North (km)
bathymetry
water-adjusted geometry
new geometry
top of crust
shallower sedimentary décollement
low frequency earthquakes
profile interpreted depths
profile interpreted depths
splay geometry picks
trench-breaching geometry
Splay B fault geometry
Splay D fault geometry
deformation front
Splay B deformation front
Splay D deformation front
coastline


A)
B)
Rectangular fault mesh
Real fault mesh
W real
W
Slip Patch
Slip Vector
Patch Length


A)
w
w_{max}
Strike direction
B)
w_1
w_2
0.30
0.10
Strike direction


1.0
0.5
0.0
Normalized slip
0.0
0.2
0.4
0.6
0.8
1.0
0.02
0.18
0.34
0.5
0.66
0.82
0.98
Normalized along strike distance

California
Department of Conservation
California Geological Survey
Seismic Hazards | Tsunami Unit

Thank you

Any Questions?

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- **Yvette LaDuke** – California Governor's Office of Emergency Services
- **Nick A. Graehl, M.S.** – California Geological Survey, Tsunami Unit
- **Rick I. Wilson, M.S.** – California Geological Survey, Tsunami Unit

https://dribbble.com/shots/696822-Surfing-Tsunami-Animated