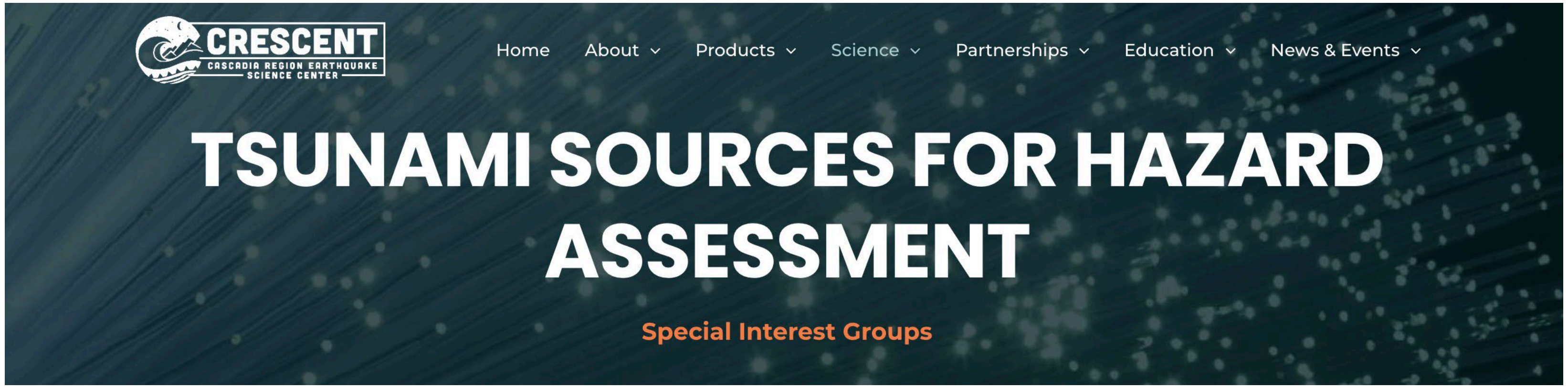
Tsunami Sources for Hazard Assessment

Randy LeVeque
Applied Mathematics
University of Washington

A brief overview based on the work of many people in the room or with us in spirit



TSUNAMI SOURCES FOR HAZARD ASSESSMENT

Special Interest Groups

New SIG!

Scientific Tasks and Community Driven Goals:

Help tsunami modelers and stakeholders understand the relation between these sets of sources and their appropriate use for practical tsunami hazard assessment projects or risk/loss calculations.

Promote transparent reproducibility of source generation methods and foster continued improvements to these models.

Collaborate with other CRESCENT Working Groups to include information on past inundation and land-level changes as context to tsunami sources.

Extend focus to global subduction zones and crustal faults

Collect and catalog sources in open data repositories and develop software and tutorials to facilitate their use.

Are *you* interested in contributing to the tsunami sources special interest group?

Scan here to complete our community **interest survey**

To receive updates, please join **the TSHA community listserv,** here:

Website:

Website: https://cascadiaquakes.org/science/tsunami-sources-for-hazard-assessment/

Some Catalogs of Sources for Numerical Modeling

Designed for Hazard Assessment and/or Other Purposes

Focusing on CSZ

- T-Shirt size events (S, M, L, XL, XXL)
- Powell Center sources
- Fakequakes
- CoPes Hub sources
- Dynamic Rupture models
- Others…

Some uses:

- Inundation maps, evacuation routes
- Maritime studies in ports, marinas
- Estimating forces on structures
- Multihazard studies (EQ + TSU + landslides)
- Probabilistic studies or Scenario modeling

- Understanding paleo evidence (extents, return times)
- Exploring effects of fault properties on tsunamigenesis
- Testing early warning
- Training machine learning algorithms
- Testing numerical methods, fluid dynamics models, grid resolutions, etc.

Probabilistic vs. Scenario Modeling

PTHA requires modeling (many) sources with meaningful probabilities assigned to each.

Goal is often to produce “hazard curves” showing
Annual probability of occurrence vs. magnitude of some Quantity of Interest,
e.g. inundation depth at some point.

Scenario modeling: one or more specific scenarios that are thought to be useful, e.g.,

- ones with a size are likely to occur soon, or
- “worst considered case” or “2500-year” events.

Scenario modeling is sometimes called “deterministic”, but choosing the events to include in the scenario(s) implicitly uses estimates of probabilities.

Sources of Uncertainty

Epistemic Uncertainty:

Lack of knowledge about the correct probability distribution governing the next CSZ earthquake.

Aleatoric Uncertainty:

Even if we knew the probability distribution exactly, which earthquake will occur next will be a random sample from this distribution.

Probability distribution could be:

- Discrete (e.g. a logic tree with finite number of leaves),
- Continuous (e.g. fakequakes specified by random number),
- Hybrid (e.g. logic tree plus random variations)

Modeling Uncertainty:

Choice of parameters such as bottom friction (Manning coefficient).
Choice of numerical model (e.g. shallow water equations or dispersive model).
Choice of resolutions and topography DEMs

Reducing uncertainties

Epistemic uncertainty reduced via more knowledge of the geology and geophysics, (fault structure, return times, etc), e.g.

- Paleoseismic evidence,
- Field work to better understand faults,
- Dynamic rupture simulations.

Aleatoric uncertainty is inherent, but can be made more efficient via techniques from applied mathematics, computational science, e.g.

- Monte Carlo sampling,
- Extreme event simulation,
- Source filtering,
- Surrogate or reduced-order models.
- Uncertainty quantification

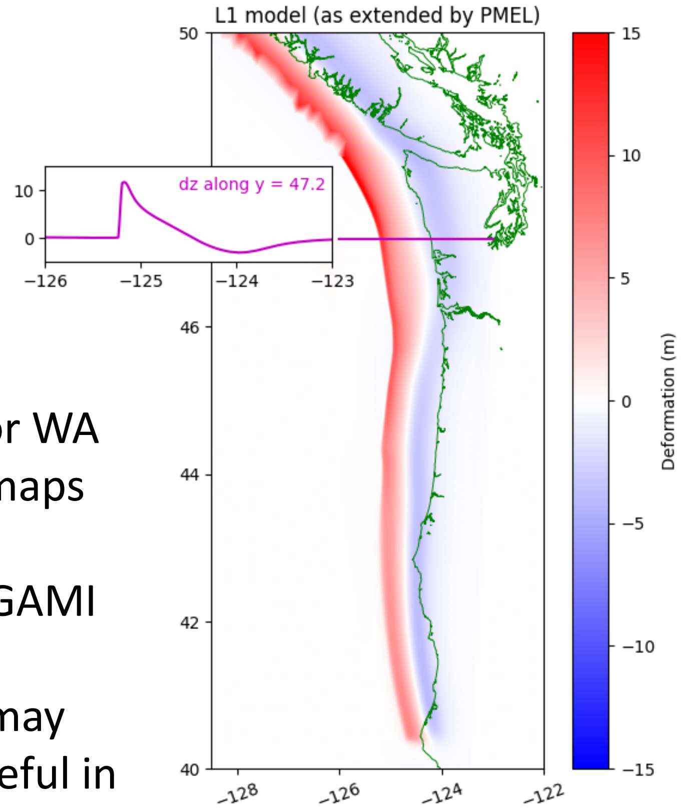
Modeling uncertainty can be reduced by e.g.

- Careful selection of grid resolutions
- More study of different model equations,
- Exploration of parameter spaces, e.g. bottom friction

T-shirt events

Witter et al. DOGAMI SP 43, 2011.

Set of 15 events with weights based on evidence from last 10K year.



L1 event has been used for WA State inundation/hazard maps

L1, XL1, XXL1 used by DOGAMI

Includes MegaSplay that may not be realistic but still useful in providing single source that can be used for multiple sites.

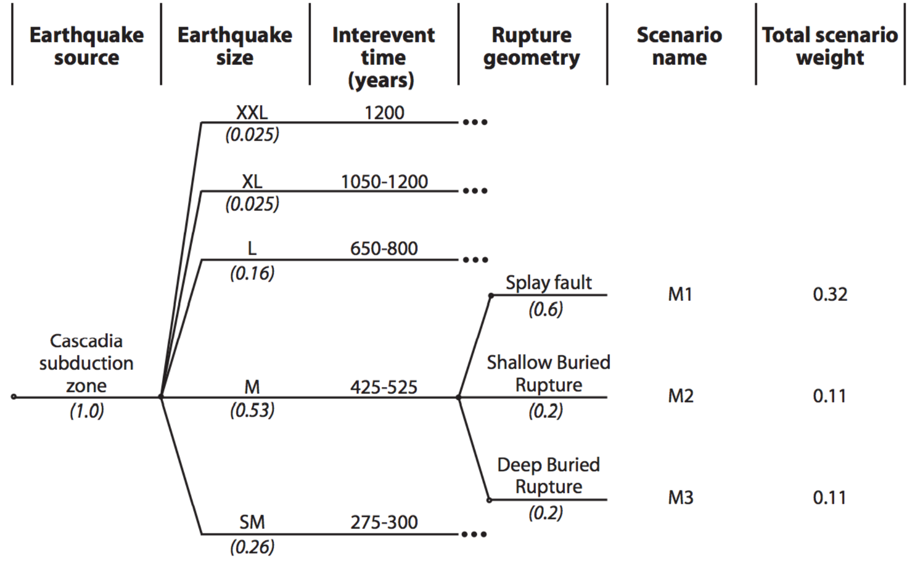


Table 3. Cascadia earthquake source parameters used to define 15 rupture scenarios. Logic tree branch weights shown in parentheses. Total scenario weight listed in right column.

Earthquake Size	Interevent Time (yrs)	Fault Geometry	Slip Range (m)		M_w	Scenario Name	Total Weight
			Maximum	Average			
Extra Extra Large (0.025)	1,200	Splay fault (0.8)	36–44	18–22	~9.1	**XXL 1**	0.02
		Shallow buried rupture (0.1)	36–44	18–22	~9.2	**XXL 2**	0.0025
		Deep buried rupture (0.1)	36–44	18–22	~9.1	**XXL 3**	0.0025
Extra Large (0.025)	1,050–1,200	Splay fault (0.8)	35–44	17–22	~9.1	**XL 1**	0.02
		Shallow buried rupture (0.1)	35–44	17–22	~9.2	**XL 2**	0.0025
		Deep buried rupture (0.1)	35–44	17–22	~9.1	**XL 3**	0.0025
Large (0.16)	650–800	Splay fault (0.8)	22–30	11–15	~9.0	**L 1**	0.128
		Shallow buried rupture (0.1)	22–30	11–15	~9.1	**L 2**	0.016
		Deep buried rupture (0.1)	22–30	11–15	~9.0	**L 3**	0.016
Medium (0.53)	425–525	Splay fault (0.6)	14–19	7–9	~8.9	**M 1**	0.318*
		Shallow buried rupture (0.2)	14–19	7–9	~9.0	**M 2**	0.106
		Deep buried rupture (0.2)	14–19	7–9	~8.9	**M 3**	0.106
Small (0.26)	275–300	Splay fault (0.4)	9–11	4–5	~8.7	**SM 1**	0.104
		Shallow buried rupture (0.3)	9–11	4–5	~8.8	**SM 2**	0.078
		Deep buried rupture (0.3)	9–11	4–5	~8.7	**SM 3**	0.078

*Scenario M1 carries the highest weight and represents the "most likely" event in our analysis.

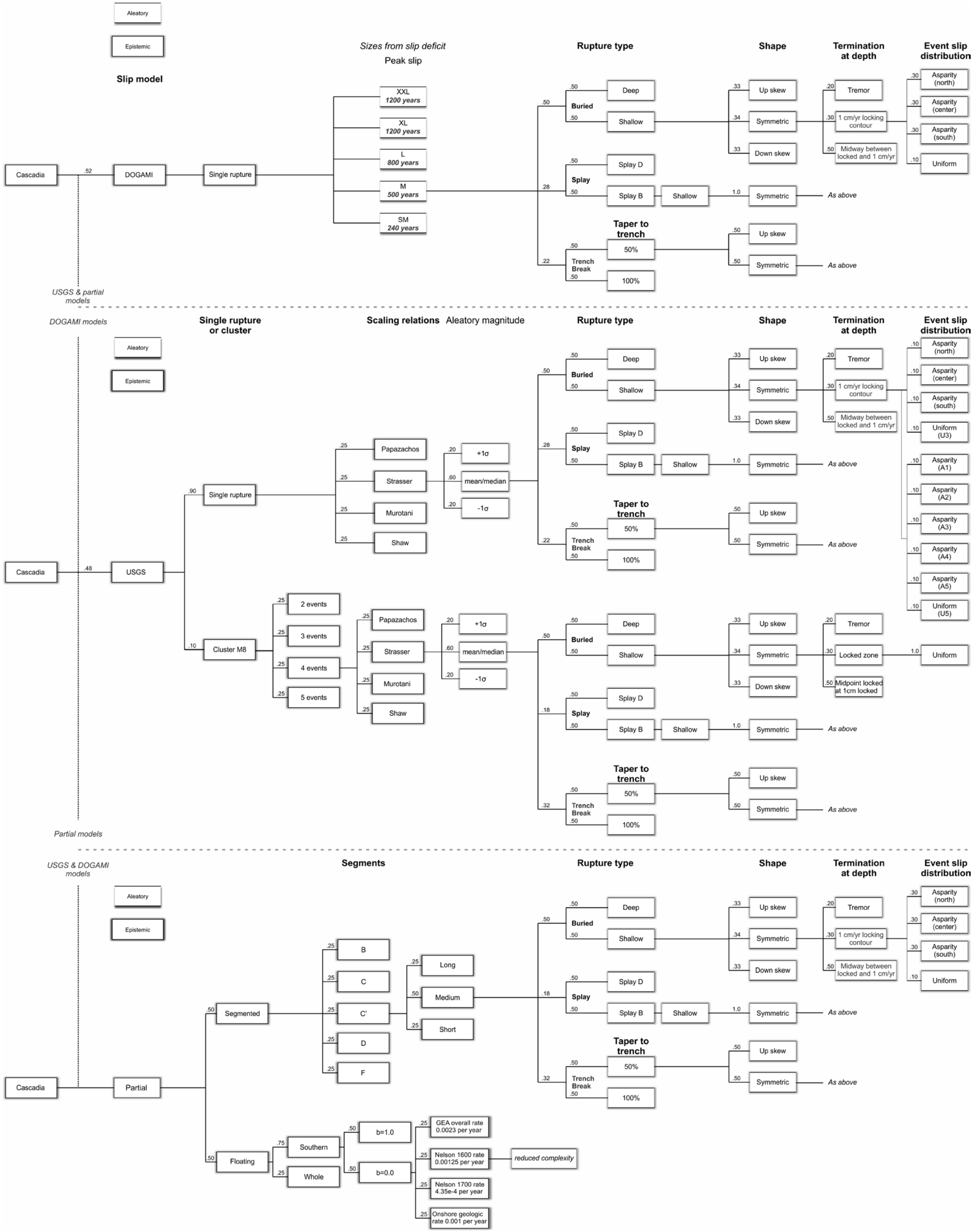
Powell Center / Cascadia Source Working Group

Many branches in logic tree.

Scaled in size based on four different global scaling relations.

Results in 11,744 distinct sources.

ASCE: Construct hazard curves at Offshore gauges (100 m depth)
To be used in design of critical structures in inundation zones.



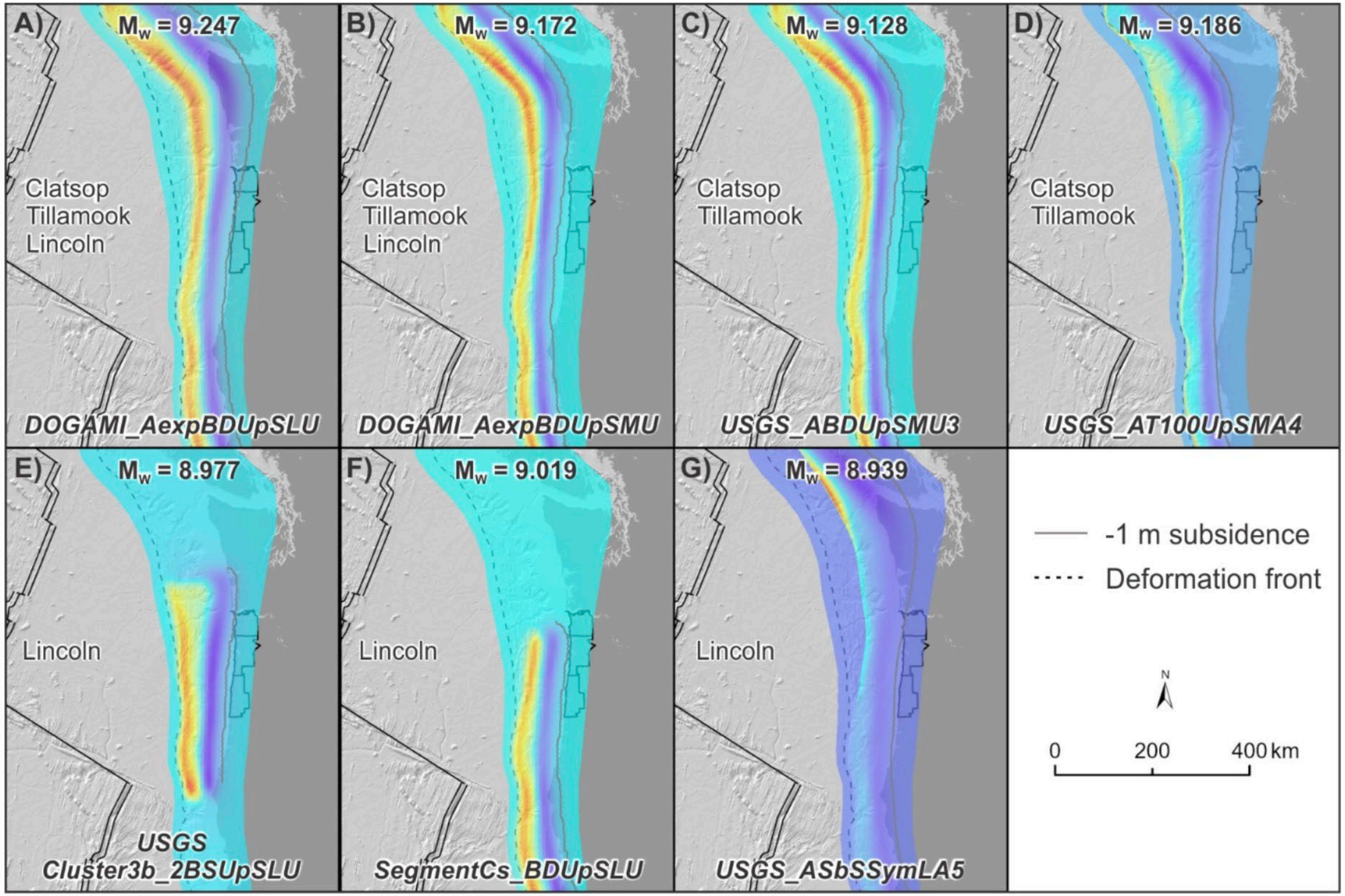
Disaggregation:

Find sources that give values at 100m isobath that are similar to 2475-year values on hazard curves.

Different source required for different coastal locations.

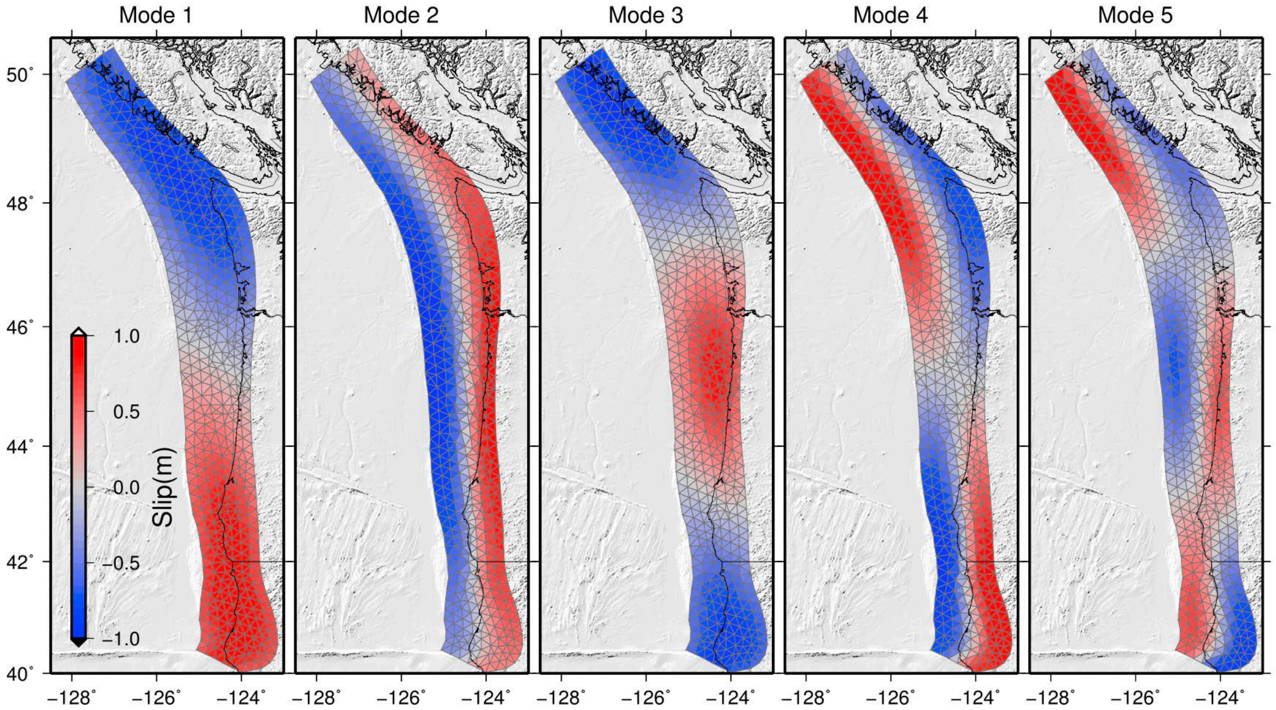
Figure from DRAFT DOGAMI report on modeling for Oregon.

Figure 3.4. Seven 2,475-yr CSZ deformation models evaluated in this study and the counties where the models were found to apply. Calculated moment magnitudes are included in the figure. Model scenarios are described in more detail in Table 3.1, Table 3.2, and Table 3.3.



Fakequakes

Random Slip Patterns Generated using Karhunen-Loève Expansion



http://dx.doi.org/10.1002/2016JB013314

Generalization of 2D Fourier series to non-rectangular faults.

Covariance matrix for slips has:

- Eigenvectors that become more and more oscillatory,
- Eigenvalues that decay rapidly if correlation distance is large.

Karhunen-Loève expansion:

$$d = \mu + \sum_{k=1}^{m} z_k \sqrt{\lambda_k}\, v_k$$

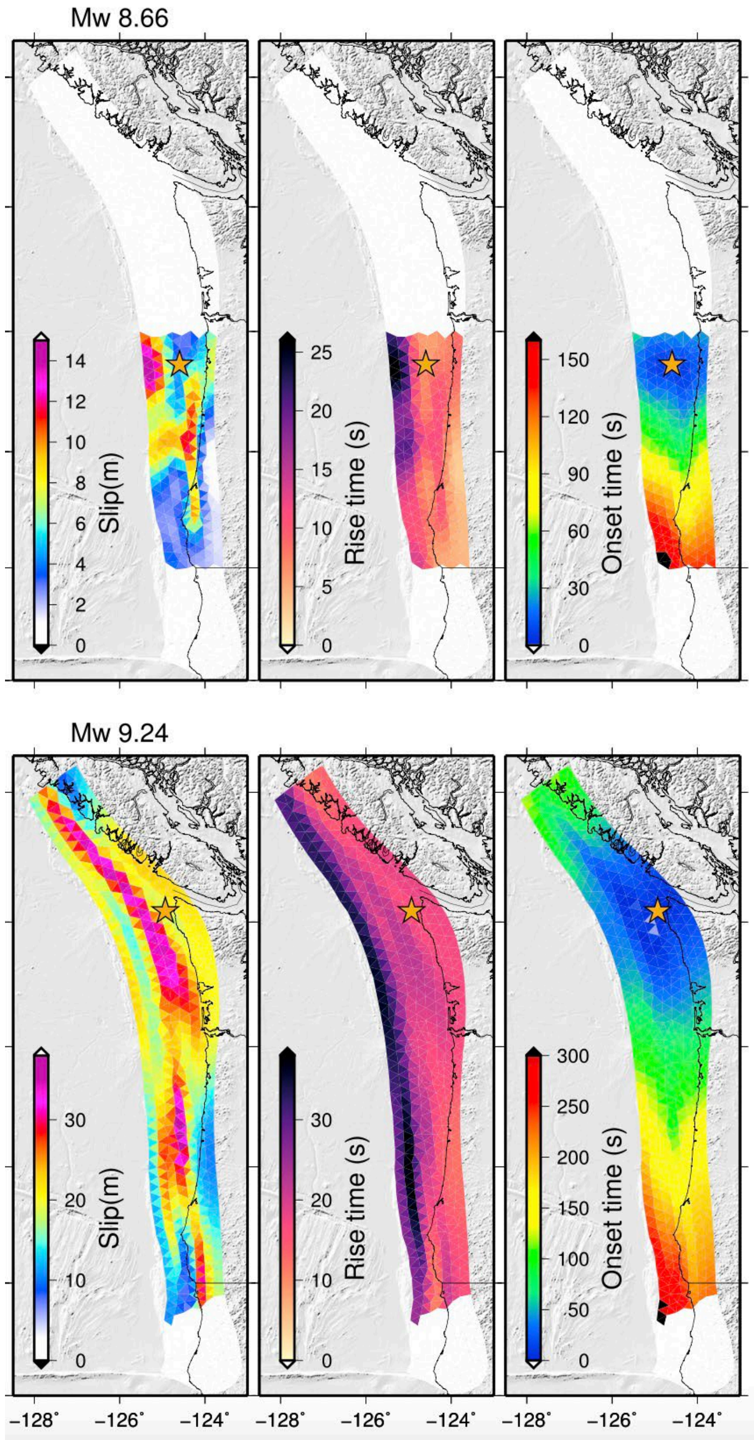
where the z_k are chosen to be independent random numbers, normally distributed with mean 0 and variance 1.

(Exponentiate to get lognormal distribution.)

Very easy to generate thousands of random earthquakes from the same probability distribution. (MudPy Software on Github)

Some uses:

- Developing and testing PTHA methodology
- Generating test data for early warning systems
- Exploring the effect of different assumptions, e.g. downdip extent, locked regions, etc.
- Generating data for machine learning algorithms for tsunami early warning



Time-Dependent Ruptures

- Time-Dependent ruptures may have effect how tsunami waves combine.
- Can have strong effect in far field, wave directed differently.
- Useful for multihazard studies of earthquake plus tsunami.

T-shirts and Powell Center sources are instantaneous.

Dynamic rupture approach gives time-dependent seafloor motion.

Kinematic rupture: time-dependent but with slips, rupture time, rise time specified by some simpler model. Still very expensive if surface deformation is computed using 3D seismic code.

Kinematic Okada (KinOkada) approach:

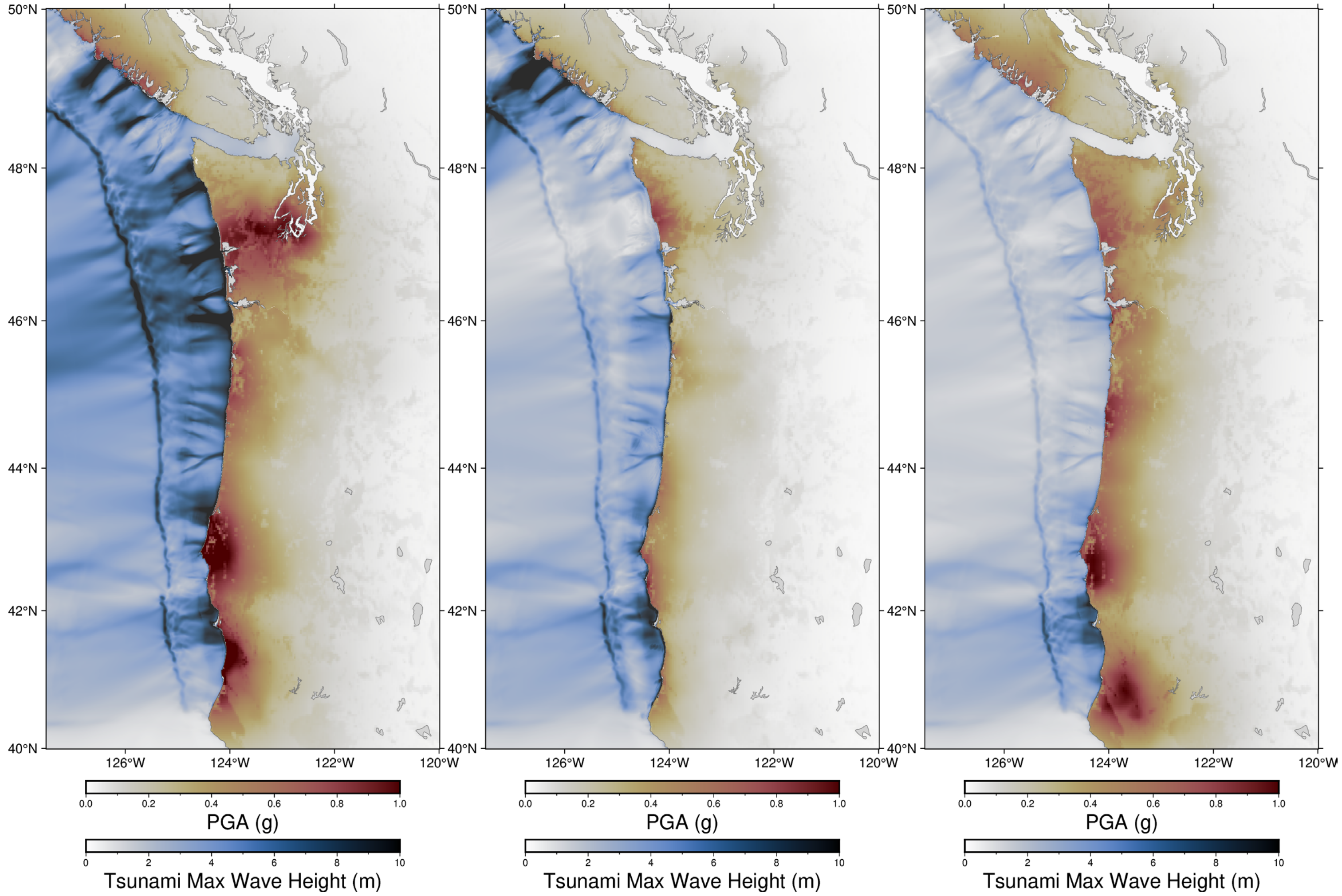
High frequency seismic waves less important for tsunami generation.

Okada model gives eventual static surface deformation from slip on each subfault.

Add these up over all subfaults that have ruptured before time t[j] to compute deformation at this time (for a sequence of times t[0], t[1], t[2], …)

Cascadia CoPes Hub Ground motions

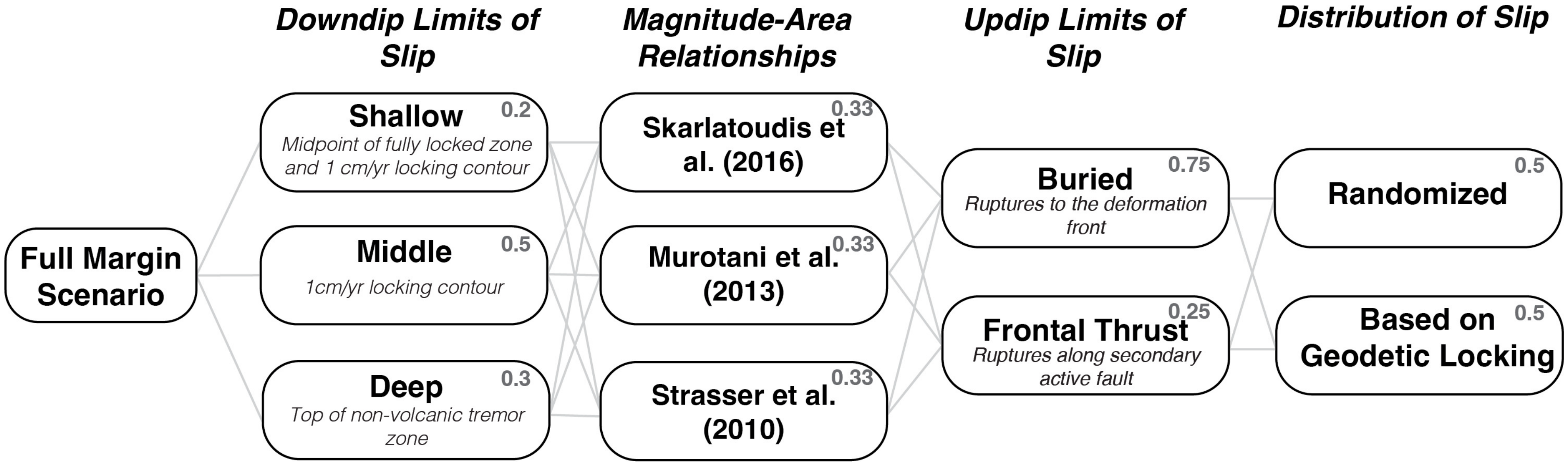
Set of 36 kinematic ground motions from 3D seismic modeling (SPECFEM3D)



Onshore Shakemap combined with offshore tsunami amplitudes for 3 events

Cascadia CoPes Hub Sources Logic Tree

36 events



Full Margin Scenario

Downdip Limits of Slip

Shallow 0.2
Midpoint of fully locked zone and 1 cm/yr locking contour

Middle 0.5
1cm/yr locking contour

Deep 0.3
Top of non-volcanic tremor zone

Magnitude-Area Relationships

Skarlatoudis et al. (2016) 0.33

Murotani et al. (2013) 0.33

Strasser et al. (2010) 0.33

Updip Limits of Slip

Buried 0.75
Ruptures to the deformation front

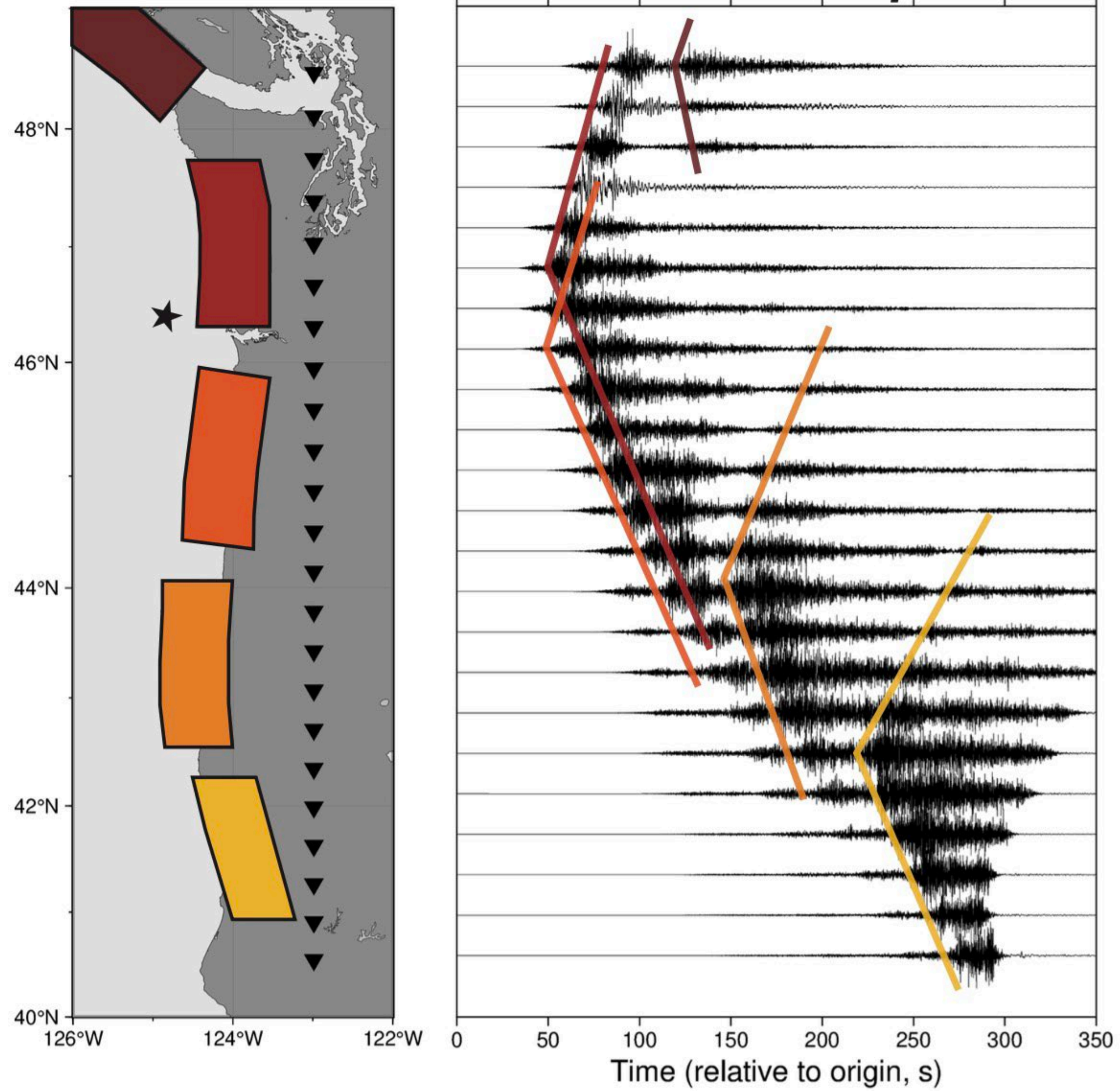
Frontal Thrust 0.25
Ruptures along secondary active fault

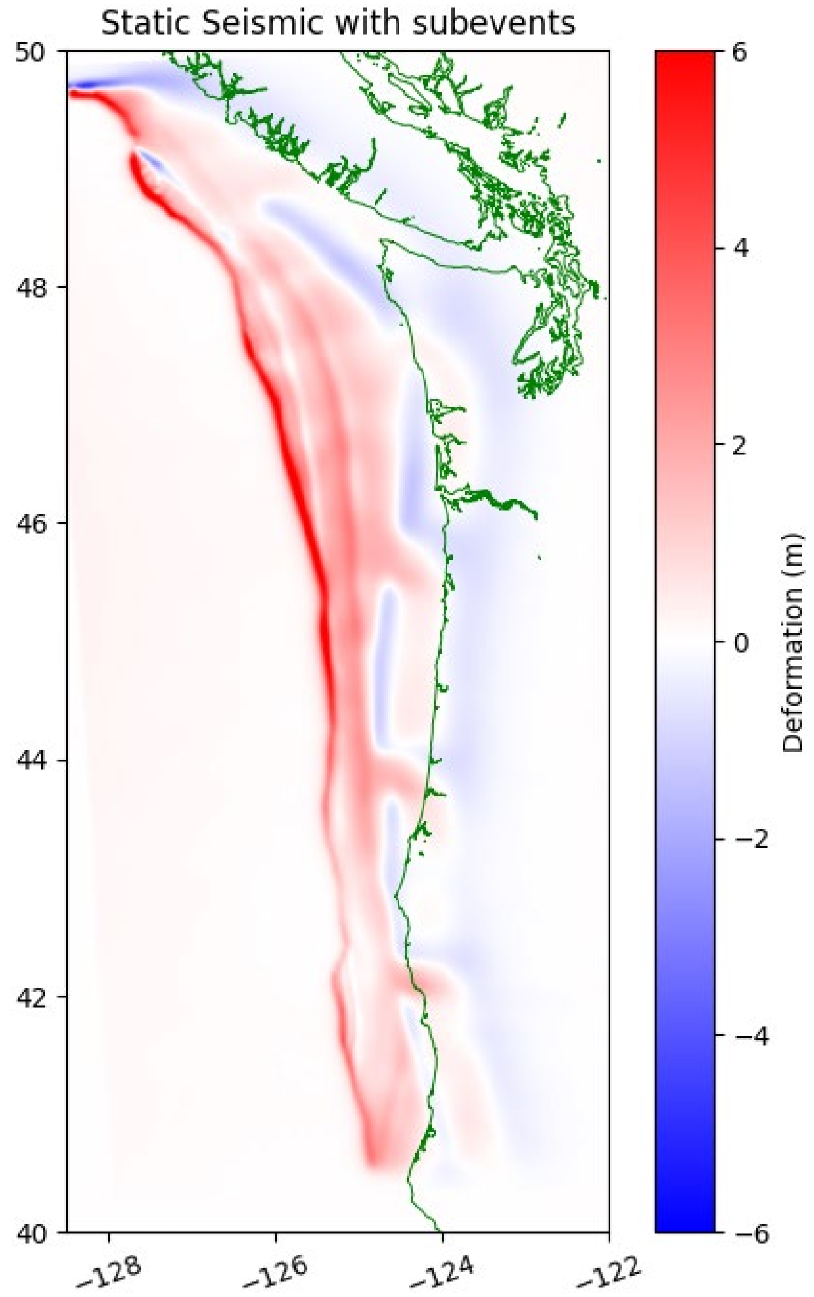
Distribution of Slip

Randomized 0.5

Based on Geodetic Locking 0.5

M9.05 Cascadia Scenario Earthquake





New Set of Slips Developed without Subevents

- With same magnitude, same tim
  evolution as originals
- On a coarsened triangulation of
  (8000 subfaults instead of 350-3
- KinOkada rather than full 3D sei
  simulations

For more information:

Dynamic Ruptures

Physics-based simulations that couple fracture mechanics
to wave propagation to generate slips dynamically.

Some possible uses related to tsunami modeling:

- Better understanding of "tsunami earthquakes", slow slip events, shallow slip amplification
- Modeling coupling in complex fault systems, activation of splay faults, etc.
- Better understanding of the epistemic uncertainties in developing PTHA models

As direct tsunami sources:

3D Seismic model output at sea floor can be used as time-dependent tsunami source
(as with kinematic ruptures)

Coupled seismic / ocean acoustics can model tsunami generation dynamically.
Can lead to better understanding of how acoustic waves can be used in tsunami early warning

Summary

What set of sources you should use depends on your needs!

- You *might* need a probabilistic set of sources with well understood uncertainties.
- You *might* need a single source / small set with particular characteristics.
- You *might* need a time-dependent source.
- You *might* need coupled seismic/tsunami output.
- You *might* need low modeling uncertainty (e.g. very fine grid resolution).

To learn more about sources for hazard assessment, or to contribute to the discussion, join the TSHA SIG mailing list.

Primary goal: Reducing uncertainty among users and practitioners of how best to develop and use tsunami sources for hazard assessment.