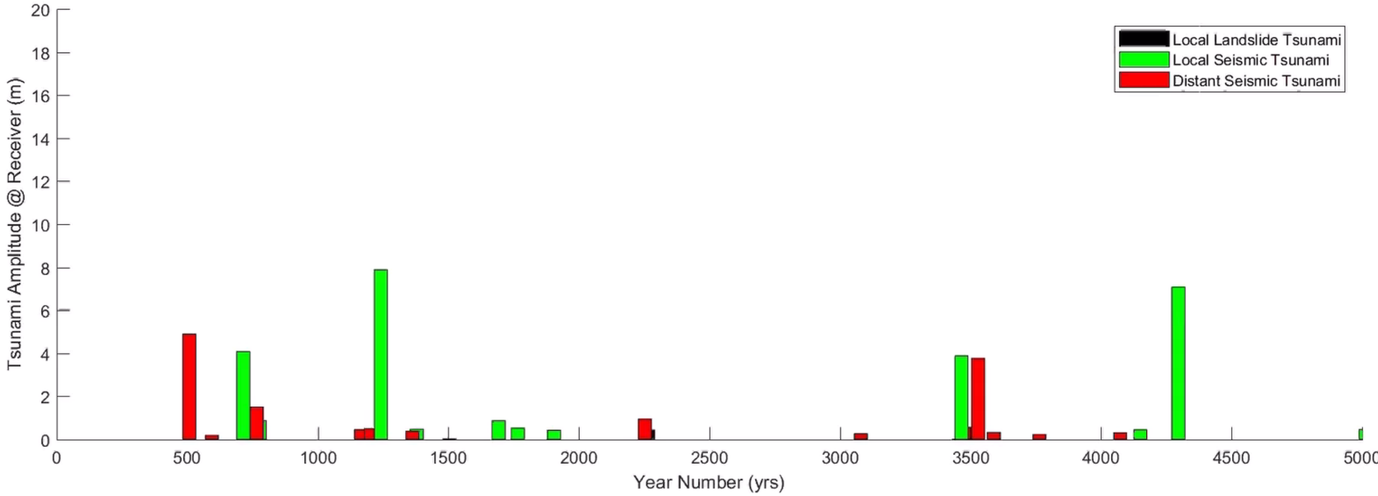
Hazard from Landslide-Generated Tsunamis: Progress and Challenges



Patrick Lynett

University of Southern California

OUTLINE:

- **Basic Framework of a Probabilistic Tsunami Hazard Assessment (PTHA) for Landslides**
- **Combination of Seismic and Landslide Sources into a PTHA analysis**
- **Focus on data gaps and computational challenges**

Rick Wilson

California Geological Survey

Timothy McCrink

California Geological Survey

Probabilistic Approach for the Waves Generated by a Landslide

- The probabilistic approach, in principle, can provide a consistent presentation of the hazard (e.g. max flow depth or speed) from a range of sources (e.g. EQ tsunami, slide tsunami, meteo tsunami, infragravity runup, storm surge, river flood, dam break, extreme tides, etc.), all combined into a single hazard surface (hazard curve w/ confidence limits)
- Lets first discuss what a PHTA for landslide tsunamis might look like

Geist, E. L., and T. Parsons (2005): ***Probabilistic Analysis of Tsunami Hazards***, *Nat. Hazards, 37 (3), 277-314.*

Geist, E. L., T. Parsons, U. S. ten Brink, and H. J. Lee (2009), ***Tsunami Probability***, in The Sea, v. 15, edited by E. N. Bernard and A. R. Robinson, pp. 93-135, Harvard University Press, Cambridge, Massachusetts.

Grilli, S.T., Taylor, O.-D.S., Baxter, C.D., Maretzki, S., (2009). ***A Probabilistic Approach for Determining Submarine Landslide Tsunami Hazard along the Upper East Coast of the United States***. *Mar. Geol.* 264, 74–97

Geist, E. and ten Brink, U. (2012). ***Tsunami Landslide Source Probability and Potential Impact on New and Existing Power Plants***. USGS Report, JCN V6166

Pampell-Manis, A., Horrillo, J., Shigihara, Y., & Parambath, L. (2016). ***Probabilistic assessment of landslide tsunami hazard for the northern Gulf of Mexico***. *Journal of Geophysical Research: Oceans*, *121*(1), 1009-1027.

Probabilistic Approach for the Waves Generated by a Landslide

- What we need for a probabilistic landslide tsunami analysis:
  - Frequency-Volume Distribution (as a function of location)
    - ✓ Data driven or trigger (EQ) driven – G-R / Char model for slides
    - ✓ Spatial limits showing data locations used to create relations (segmentation or zonation)
  - Landslide "Scaling Laws"
    - ✓ EQ's **have** scaling laws to connect **slip & area** with **moment**
    - ✓ LS's **need** scaling laws to connect **thickness & area** with **volume**
  - Distribution or logic tree showing how the slide might fail
    - ✓ Then need distribution or logic tree for EACH of the parameters within EACH of the possible failure mechanisms
  - A model or set of models to simulate the landslide and/or the tsunami generation & propagation
  - A model or set of models to simulate the tsunami propagation from source to nearshore site of interest

Probabilistic Approach for the Waves Generated by a Landslide

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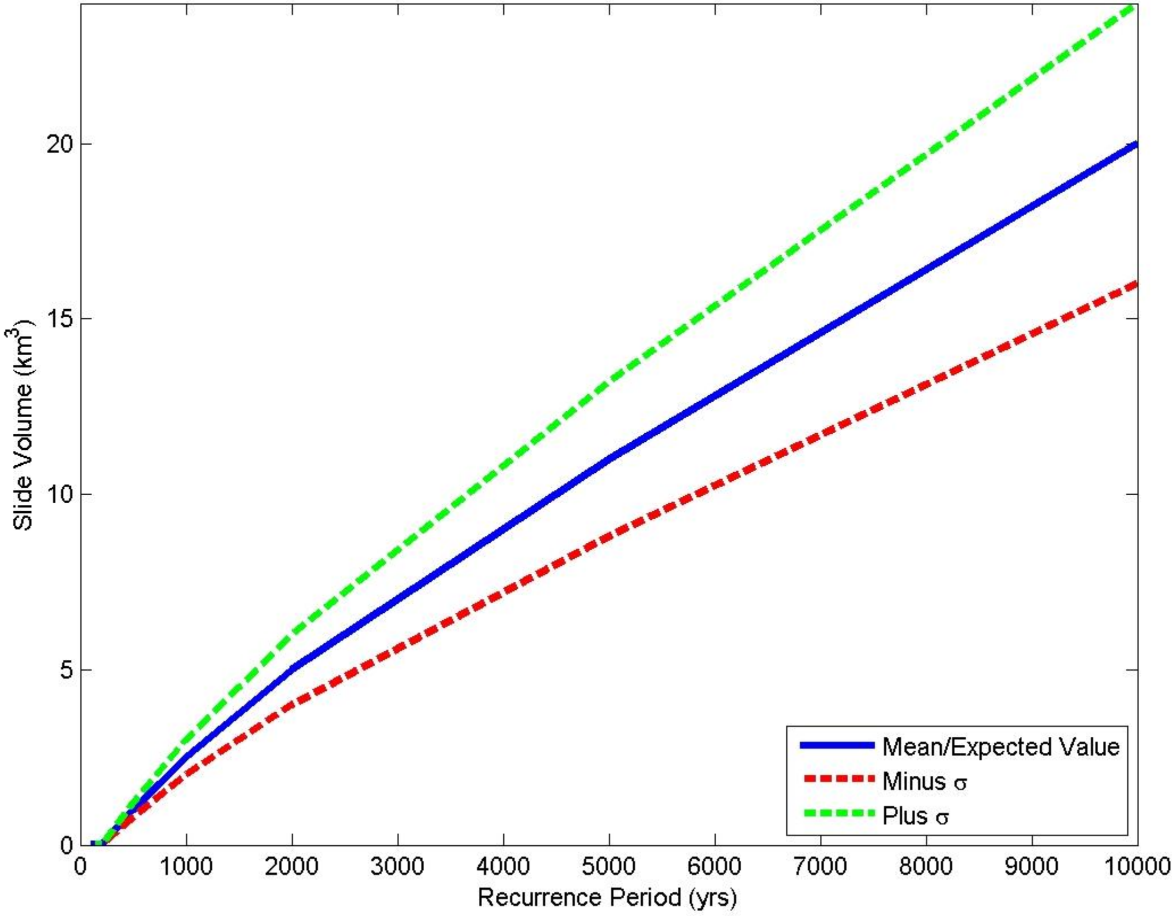
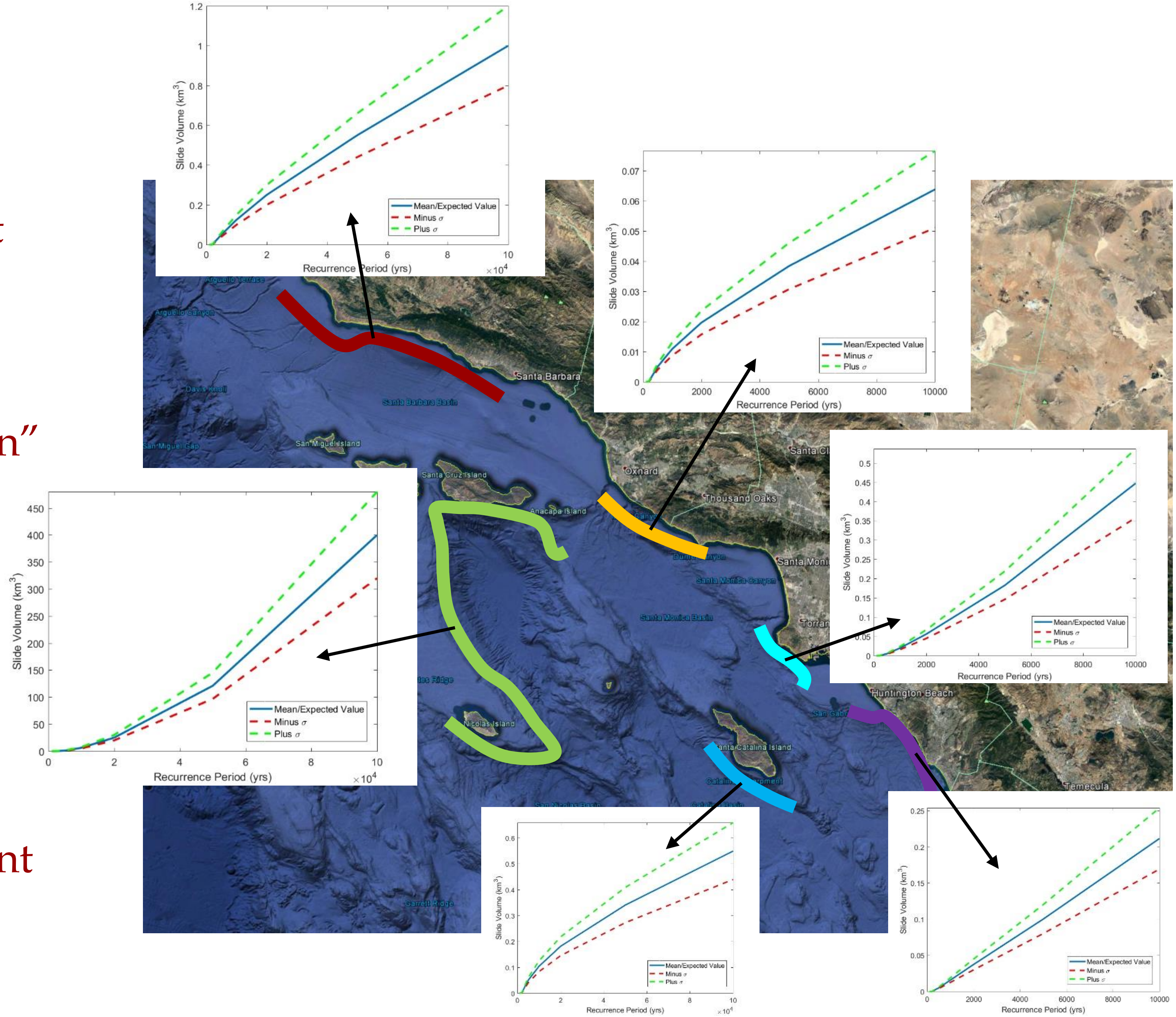
Probabilistic Approach for the Waves Generated by a Landslide

Where do we start?

- Need to connect bulk properties of slides (volume) in a given area to recurrence rate
- Trends can be data curve-fits, based on volumes inferred from bathymetry
- **Can also be developed using a specific trigger (i.e EQ ground acceleration) with its own frequency-magnitude distro, and some model to predict LS volume from trigger magnitude (more about this in a bit)**



- Different regions will have different frequency-volume distributions
- “Segmentation” approach
- Requires a community-driven discussion of location of “boundaries” and assessment of segment properties



ELSEVIER
Marine Geology 169 (2000) 103–136
MARINE GEOLOGY
www.elsevier.nl/locate/margeo

Submarine landslide geomorphology, US continental slope

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Received 25 March 1999; accepted 13 March 2000

Table 2.1.6-1: Documented Mass Failures along the California Coast (from McAdoo et al., 2000).

Longitude	Latitude	Estimated Volume [km^3]
40.41	124.89	3.2
40.01	124.93	0.6
39.96	124.92	0.2
39.73	124.66	4.3
39.73	124.97	10.0
39.7	[illegible]	[illegible]
39.6	[illegible]	[illegible]
39.6	[illegible]	[illegible]
39.6	[illegible]	[illegible]
39.6	[illegible]	[illegible]
39.2	[illegible]	[illegible]
39.2	[illegible]	[illegible]
38.8	[illegible]	[illegible]
38.8	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	123.32	1.2
[illegible]	123.32	6.2
[illegible]	122.76	0.1
[illegible]	122.85	8.0
[illegible]	122.44	6.2
[illegible]	122.45	18.2

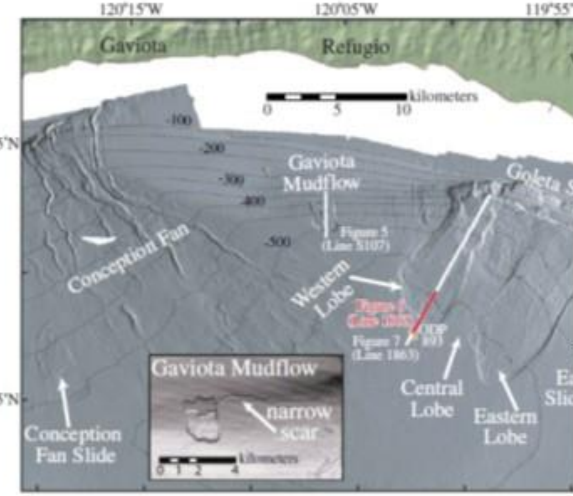

Figure 2.1.6.3-2: Multi-beam Image of Submarine Landslide Complexes i[n Santa]
Barbara Basin (taken from Greene et al., 2006).

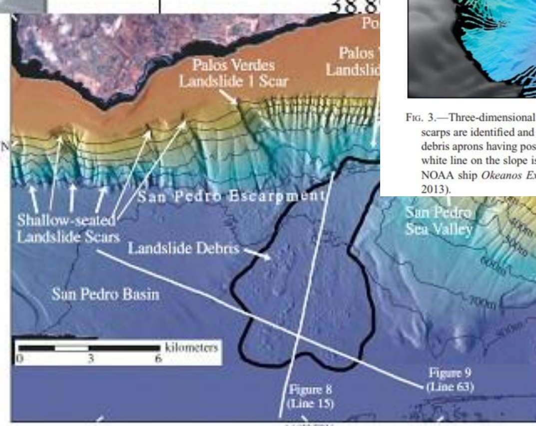

Figure 2.1.6-4. The San Pedro escarpment and the Palos Verdes debris avalanche. Taken from Borrero et al. (2004).

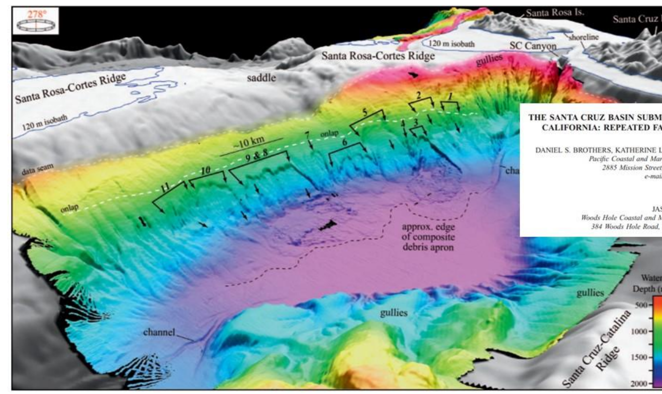

Fig. 3.—Three-dimensional perspective view looking west (278°) at the eastern flank of the Santa Rosa–Cortes Ridge. Distinctive headwall scarps are identified and numbered based on the extent and angularity of the scarp. The dashed black line marks the approximate edge of the debris aprons having positive relief, although subbottom profiles show the distal slide deposits extending across the entire basin floor; dashed white line on the slope is the approximate location of Pliocene onlap (see Figs. 5–7). Colored multibeam bathymetry data were acquired by NOAA ship *Okeanos Explorer* in 2011; grayscale bathymetry is from the 90 m Coastal Relief Model (National Geophysical Data Center 2013).

THE SANTA CRUZ BASIN SUBMARINE LANDSLIDE COMPLEX, SOUTHERN CALIFORNIA: REPEATED FAILURE OF UPLIFTED BASIN SEDIMENT

DANIEL S. BROTHERS, KATHERINE L. MAIER, JARED W. KLUESNER, JAMES E. CONRAD
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Woods Hole Coastal and Marine Science Center, US Geological Survey, 384 Woods Hole Road, Woods Hole, Massachusetts 02540 USA

Probabilistic Approach for the Waves Generated by a Landslide

- What we need for a probabilistic landslide tsunami analysis:
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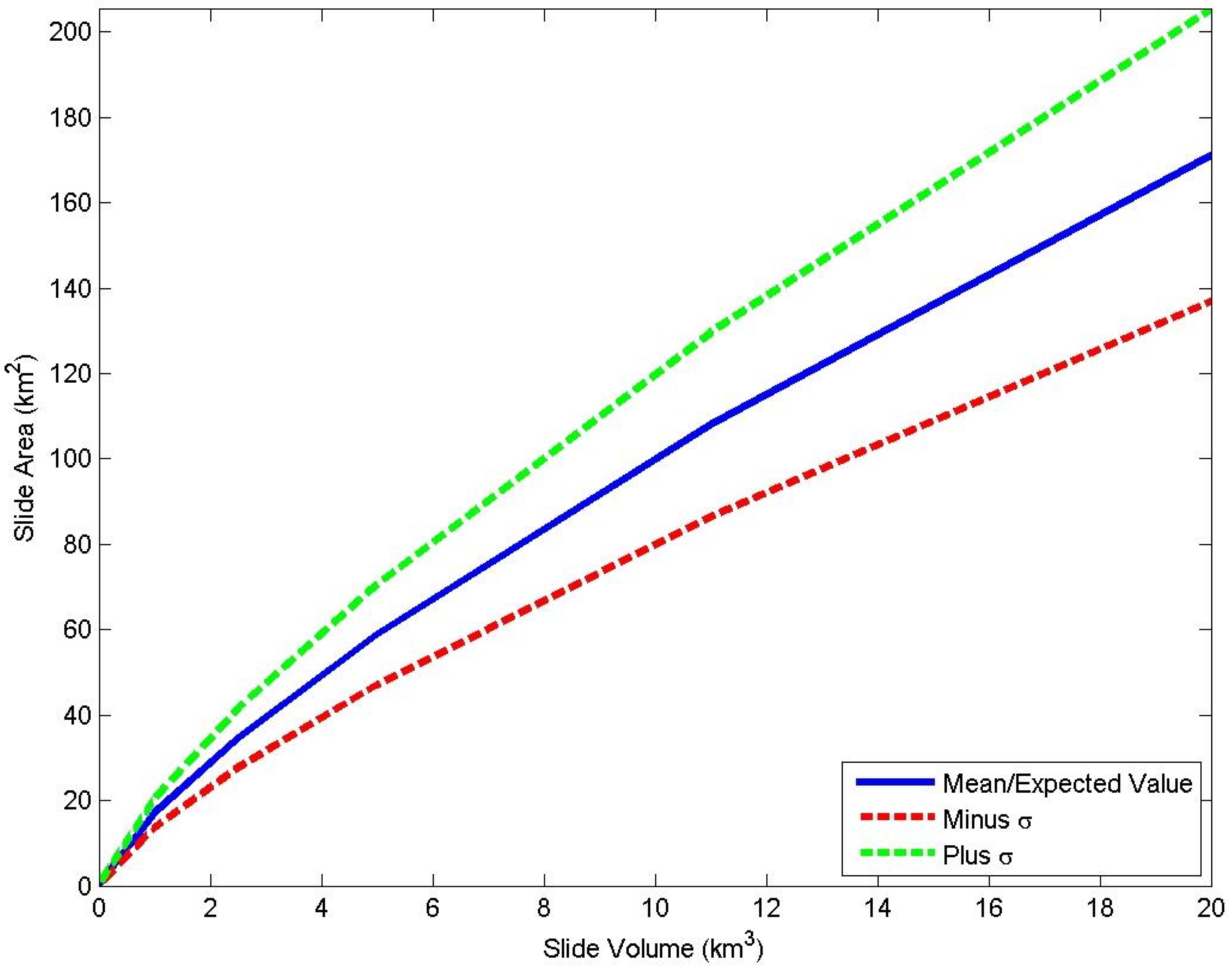
The slide volume is not enough to characterize the mass

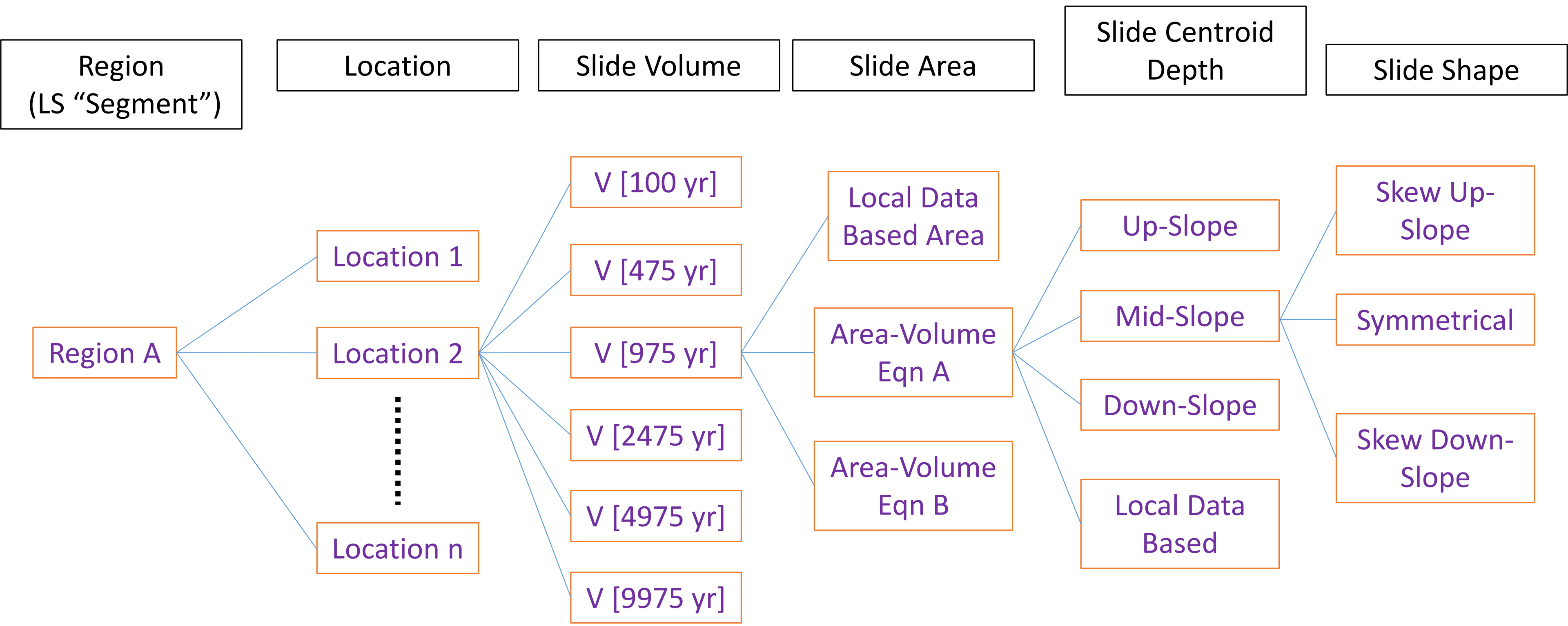
- Connect slide volume and surface area:
  - Vol=a*Area^b
  - (e.g. ten Brink et al., 2006 for north PR, a~0.025, b~1.3):
- Data based curve fit for a specific region
- With Volume and Area, next we need to decide how to distribute the mass…



ten Brink, U. S., Geist, E. L., & Andrews, B. D. (2006). Size distribution of submarine landslides and its implication to tsunami hazard in Puerto Rico. *Geophysical Research Letters*, *33*(11).

Probabilistic Approach for the Waves Generated by a Landslide

Template PTHA-LS Logic Tree - Slide Geometry / Location



216 Different Slide Geometry Scenarios for Each Location. Need weighting factors for Area, Shape, and Depth

Probabilistic Approach for the Waves Generated by a Landslide

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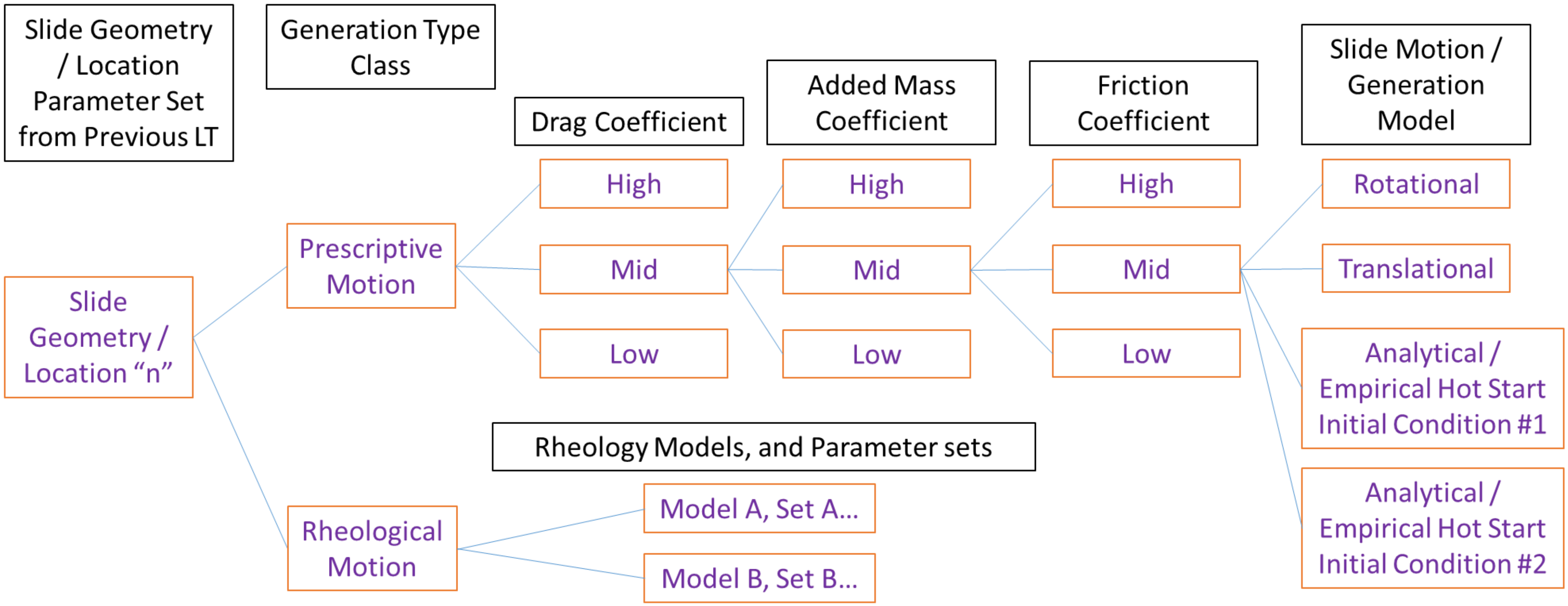
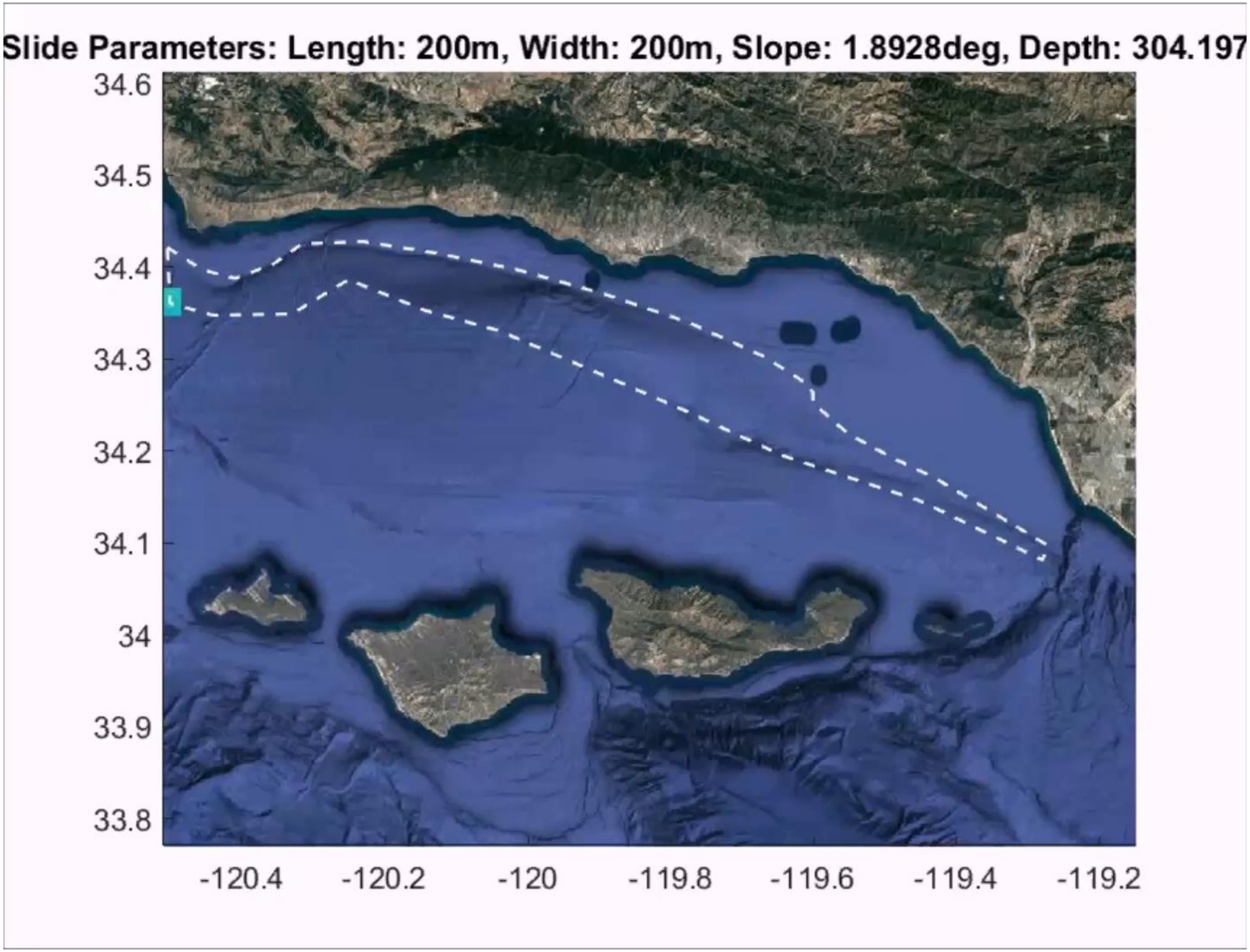
Probabilistic Approach for the Waves Generated by a Landslide

Template PTHA-LS Logic Tree – Tsunami Generation & Propagation



108 Different Prescriptive Slide Generation Scenarios for Each Slide Geometry. ~23,000 scenarios for each Location. ~2,000,000 scenarios for each Region. ~20,000,000 scenarios for all of CA. Each scenario must require <5 minutes to make this feasible.

Probabilistic Approach for the Waves Generated by a Landslide



The rest of the effort relies on water wave codes, lots of ways to do it, from simple (linear, surrogate) to complex (nonlinear, dispersive, dissipative)

Probabilistic Approach for Multi-Source Tsunami Hazard

- Conceptually, including landslide tsunami with seismic tsunami into a PTHA is no different than a PTHA based on multiple seismic source regions
  - Aggregate the hazard quantity from all tsunami sources to the record point (receiver location – e.g. 100-m depth contour)
- **The challenge lies in the joint distribution of local seismic sources and local landslide sources**
- Consider a PTHA for which we wish to include:
  - Distant Source EQ Tsunami
  - Local Source EQ Tsunami
  - Distant Source Landslide Tsunami (lets ignore this for now)
  - Local Source Landslide Tsunami

Probabilistic Approach for Multi-Source Tsunami Hazard

- Distant Source EQ Tsunami Hazard is "easy"

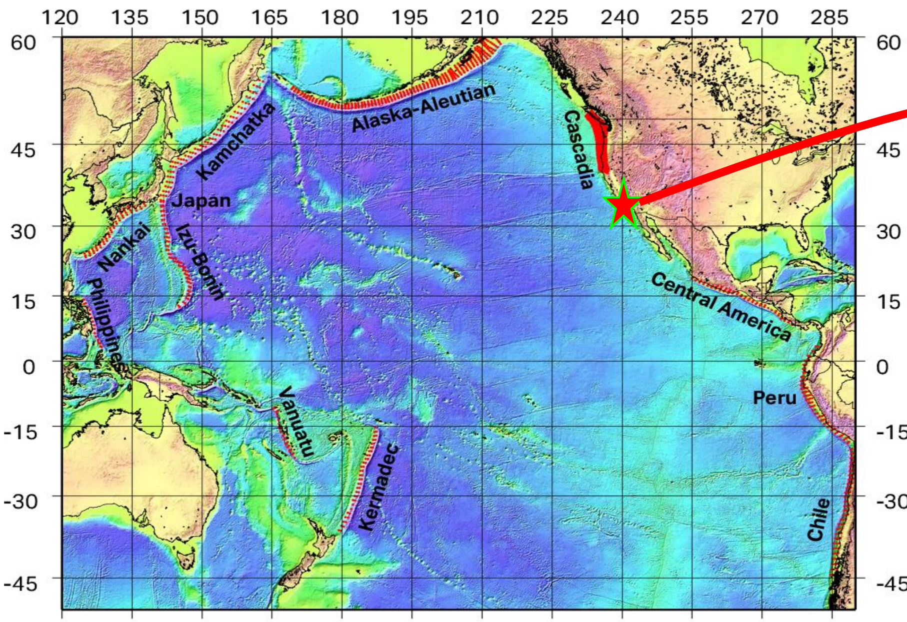
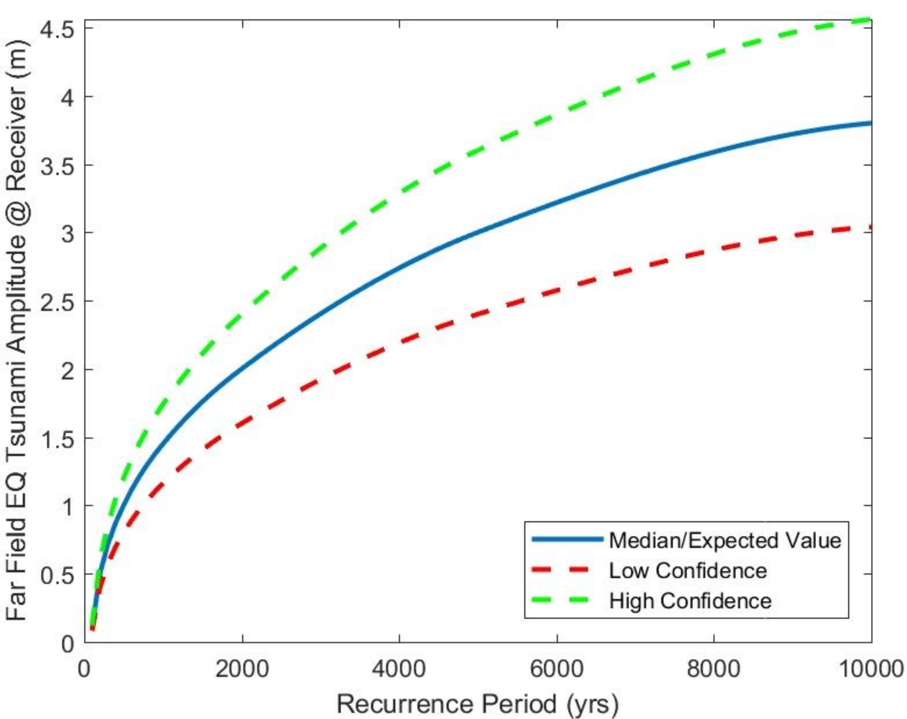
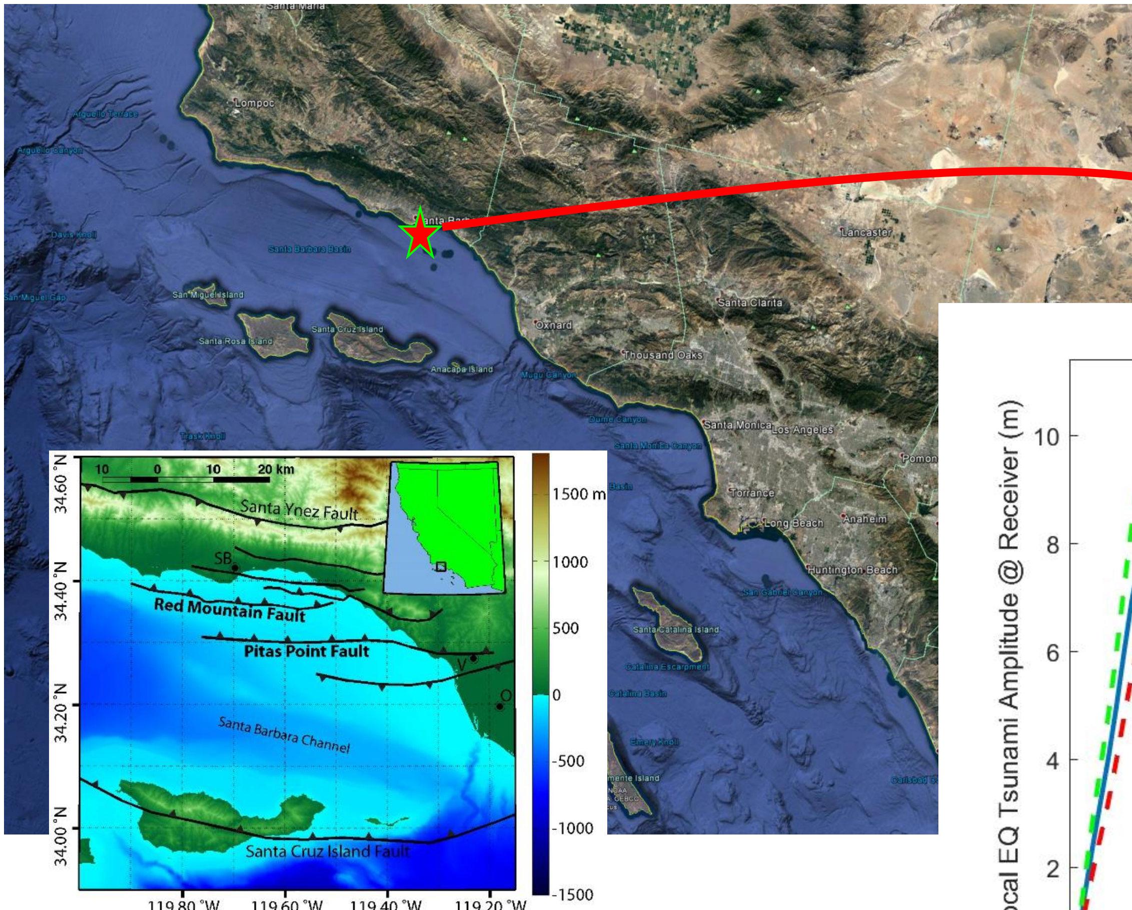


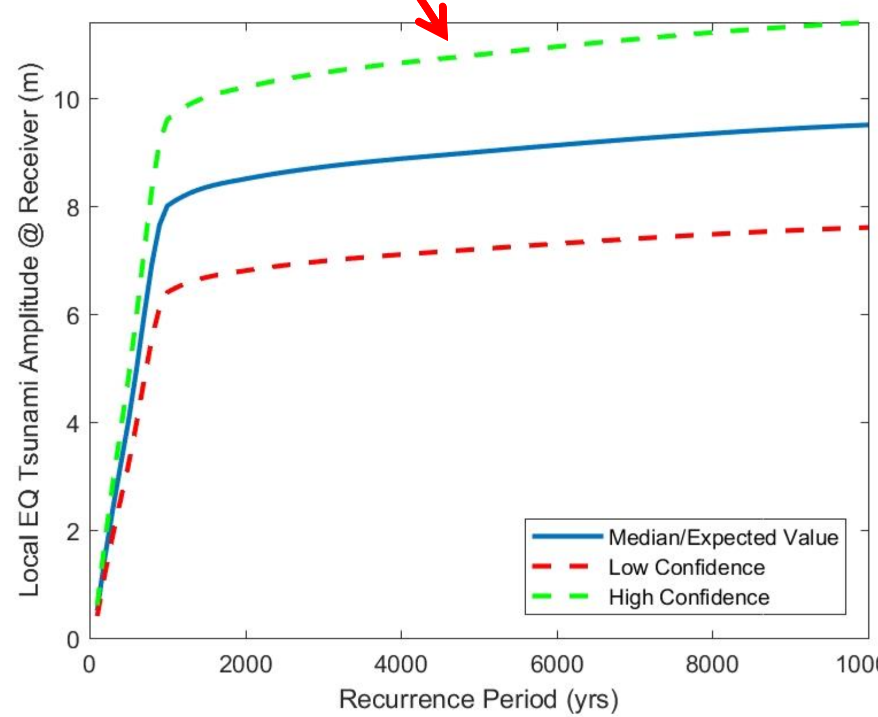
Figure 1. Source zones around the Pacific Ocean that are included in this work.



Probabilistic Approach for Multi-Source Tsunami Hazard

- Local Source EQ Tsunami Hazard is harder





Ryan, K. J., Geist, E. L., Barall, M., & Oglesby, D. D. (2015). Dynamic models of an earthquake and tsunami offshore Ventura, California. *Geophysical Research Letters*, *42*(16), 6599-6606.

Probabilistic Approach for Multi-Source Tsunami Hazard

- Local Source Landslide Tsunami Hazard - two choices to develop our frequency-volume distribution
  1) Data-driven based on volumes estimated from bathymetry (need many slide records)
  2) Data-driven based on volumes, which is used to calibrate /validate a trigger model (need enough records to calibrate model)
  3) In the absence of high-res bathymetry, or no observed slide scarps, develop a trigger model (no calibration needed!)
- Options 2) and 3) imply a joint distribution with the local EQ tsunami
  - ✓ Sample the local seismicity
  - ✓ Each sampled earthquake can generate
    - Seismic tsunami (may be ~0) and/or
    - Landslide tsunami based on the trigger model

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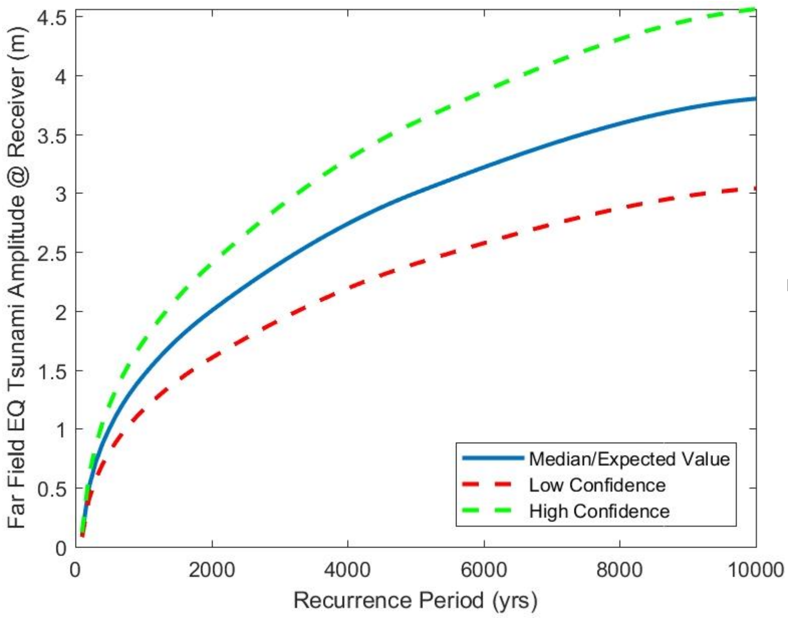
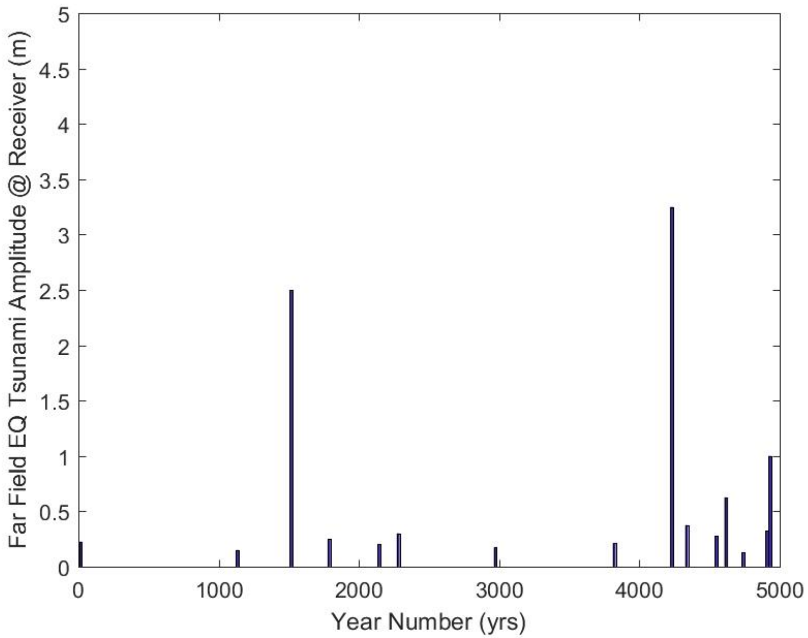
- Perform analysis using synthetic time series of hazard @ receiver
  1) Time series of far-field tsunami
  2) Time series of EQ and local seismic tsunami
  3) Time series of ground acceleration
  4) Time series of local landslide tsunami
  5) Sum to generate combined hazard time series



Requires the PTHA currently in use (this part is established)



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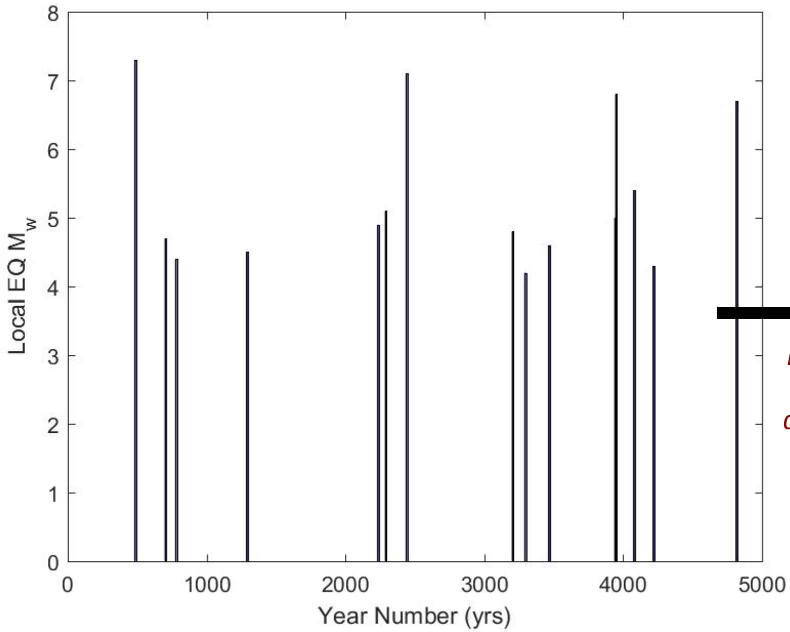
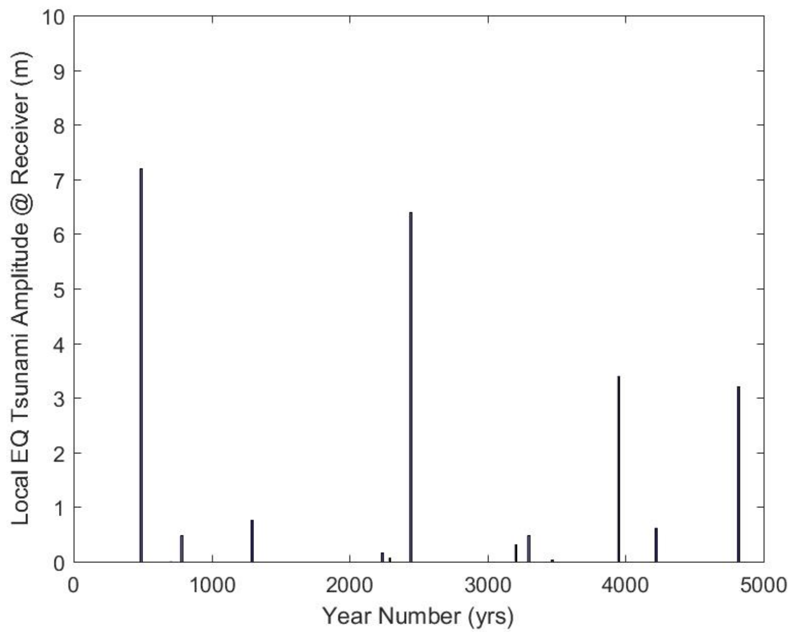


Requires that the existing distant source PTHA be adapted for local EQ sources



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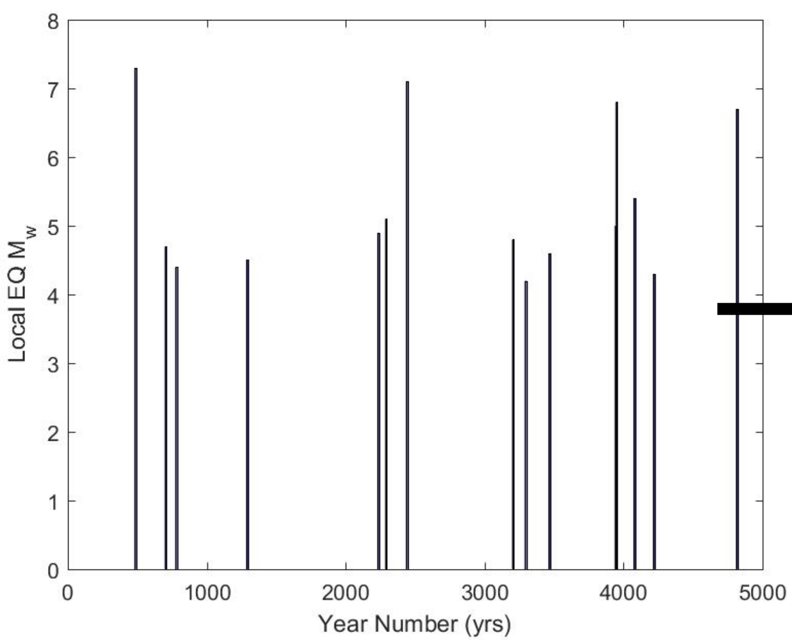
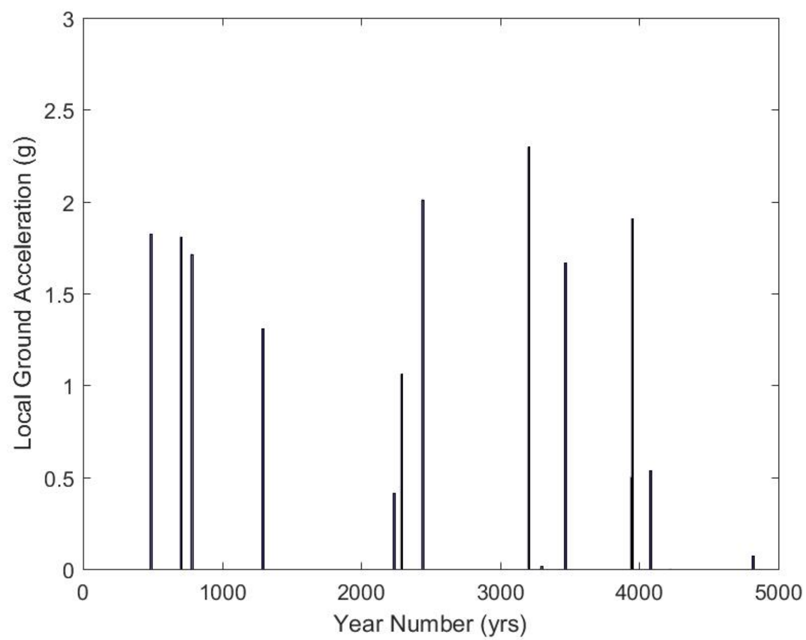


Well-established on land, but offshore…



USC University of Southern California

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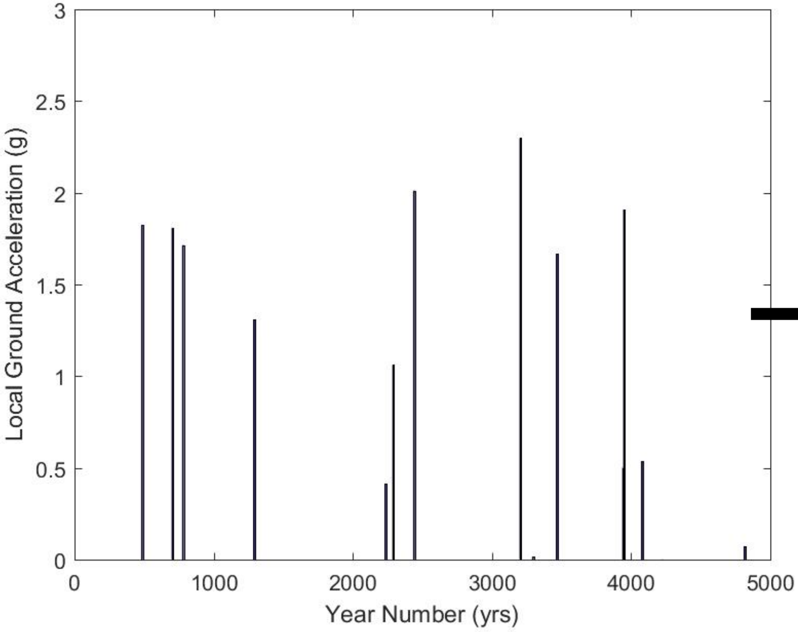
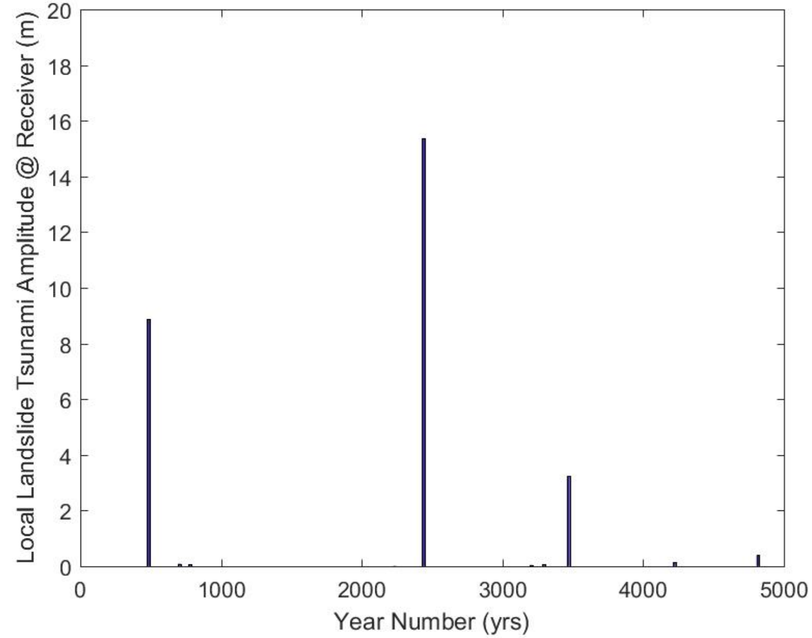


Need a statistical relationship between acceleration and slide volume, may require nonlinear simulation

Requires the landslide tsunami logic tree discussed previously



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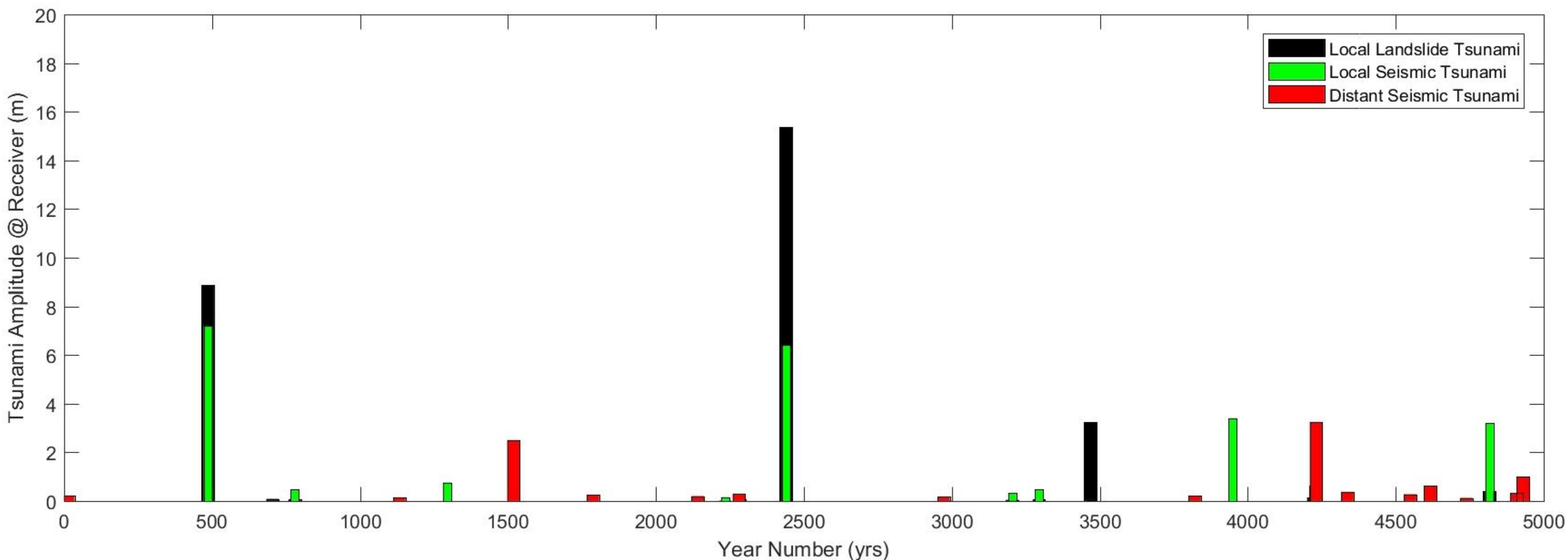

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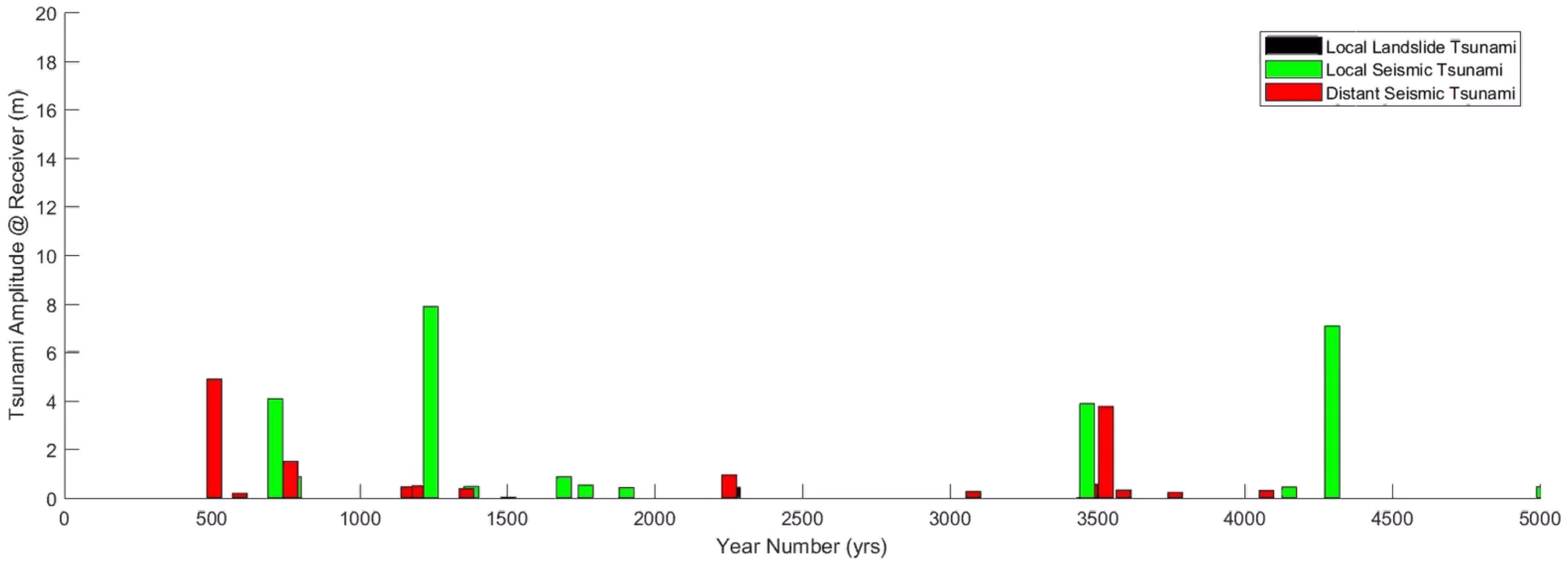

So, what is needed to include landslide tsunamis in PTHA?

1. Frequency-Volume Distribution [derived from **bathy data**, expanded with an **EQ trigger model**] for "segments"
   - ✓ Every local EQ has a chance to generate both a local seismic tsunami and/or a local landslide tsunami
2. Landslide "Scaling Laws" to connect **thickness, area, and aspect ratio** with **volume** [derived from **bathy data**, augmented with **logic tree**]
3. Description of how the slide fails / moves / evolves [ideally developed via a community-based **logic tree** approach]
4. A model or set of models to simulate the landslide and/or the tsunami generation & propagation, and a model or set of models to simulate the tsunami propagation from source to nearshore site of interest

➢ **Working through this exercise in CA, with planned workshop to bring together CA researchers and stakeholders to review available data and logic tree parameters [this Fall/Winter, hopefully]**