From earthquakes to landscapes in the Cascadia subduction zone –

Big questions, progress and challenges in coupled tectonics and surface processes studies

Alison Duvall

University of Washington

Acknowledgements: Sean LaHusen; Alex Grant; Philip Schoettle-Greene; Sarah Harbert; Nasser Marafi; Erin Wirth; Art Frankel; Joe Wartman; Dave Montgomery; Ann Bostram; Randy LeVeque; Jeff Berman; Dan Abramson; John Vidale; Joan Gomberg; Frank Gonzelez; Marc Eberhard; Adam Booth; Josh Roering; Will Struble

Quaternary Research Center

W

NSF

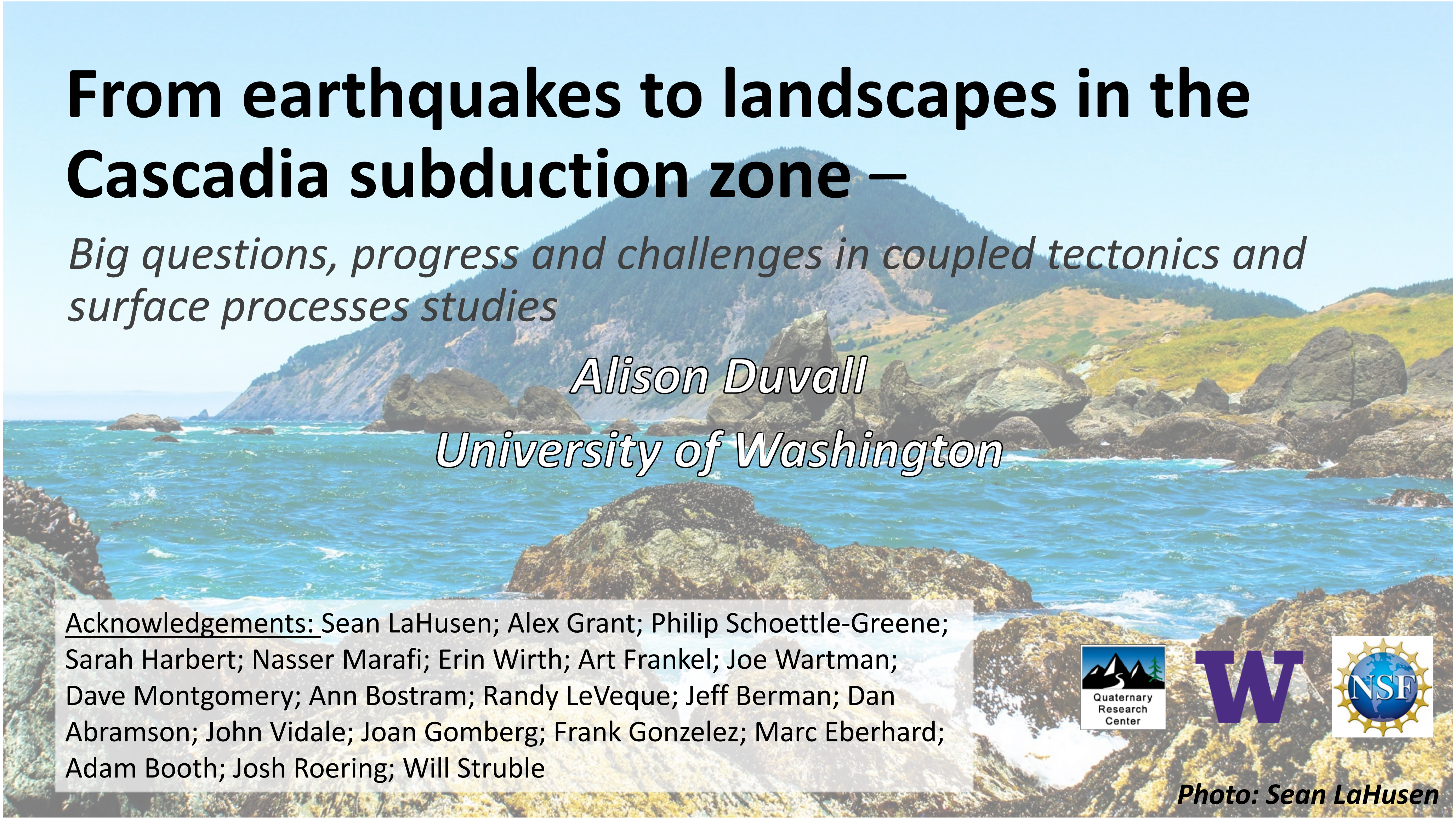

Photo: Sean LaHusen

CHALLENGES AND OPPORTUNITIES FOR RESEARCH IN TECTONICS

Huntington & Klepeis,2018

1. Understanding Planetary Evolution in 4D

2. Understanding Variations in Rheology in Lithosphere

3. Understanding Fault Zones from Surface to Lithosphere

4. Understanding the Dynamic Interactions Among Earth-Surface Processes and Tectonics

5. Synergies between Societal Needs and Advancing Tectonics Research

The SZ4D Initiative

Understanding the Processes that Underlie Subduction Zone Hazards in 4D

McGuire, J.J., T. Plank, et al. 2017.

1. When and Where Do Large Earthquakes Happen?

2. How is Mantle Magma Production Connected through the Crust to Volcanoes?

3. How do Spatial Variations in Subduction Inputs Affect Seismicity and Magmatism?

4. How do Surface Processes Link to Subduction?

CHALLENGES AND OPPORTUNITIES FOR RESEARCH IN TECTONICS

The SZ4D Initiative

Understanding the Processes that Underlie Subduction Zone Hazards in 4D

- Linking *models* over short (earthquake/hazards) & long [mountain building] timescales from *deep* to *surface*
- Interdisciplinary centers / open-source *community* resources / organizations
- Collaborative *sharing* of: data / equipment / technology / labs / training next gen users of frontier techniques
- Identifying, tackling, strategizing research problems *together*, *from the start*

The "M9" Project – 3-D Simulations of M9 Earthquakes on the Cascadia Megathrust

Alison Duvall[1], Arthur Frankel[2], Erin Wirth[2], Jeff Berman[1], Marc Eberhard[1], Nasser Marafi[1], Joe Wartman[1], Alex Grant[2], Sean LaHusen[1], Randy LeVeque[1], Frank Gonzalez[1], Ann Bostram[1], Dan Abramson[1], John Vidale[3]

[1]University of Washington, Seattle, WA
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[3]Southern California Earthquake Center, University of Southern California

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NSF Hazards SEES
EAR-1331412

USGS science for a changing world

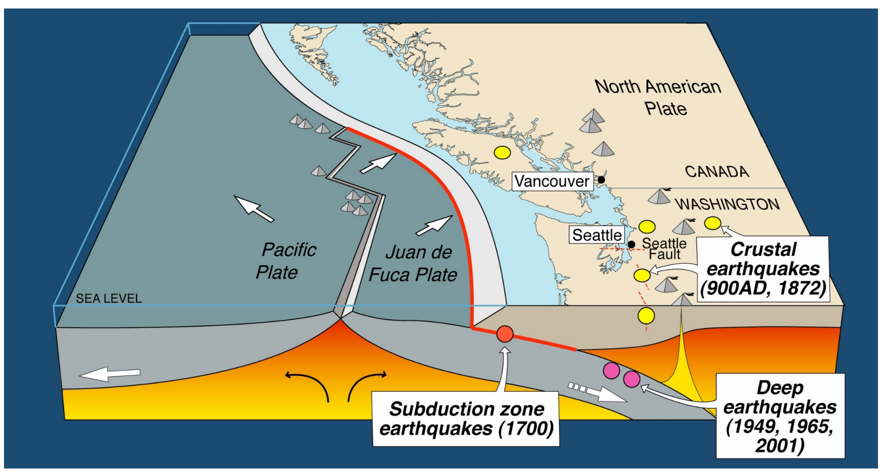
Megathrust Earthquakes in Cascadia

Cascadia Subuction Zone has a history of **M9 Earthquakes**

-Coastal subsidence

-Tsunami records

-Offshore turbidites



USGS

Ghost Forest, Greys Harbor, WA
Brian Atwater, USGS

Tsunami Deposits, Lynch Cove, WA
Carrie Garrison-Laney, UW

Megathrust Earthquakes in Cascadia

Cascadia Subuction Zone has a history of **M9 Earthquakes**

-Coastal subsidence

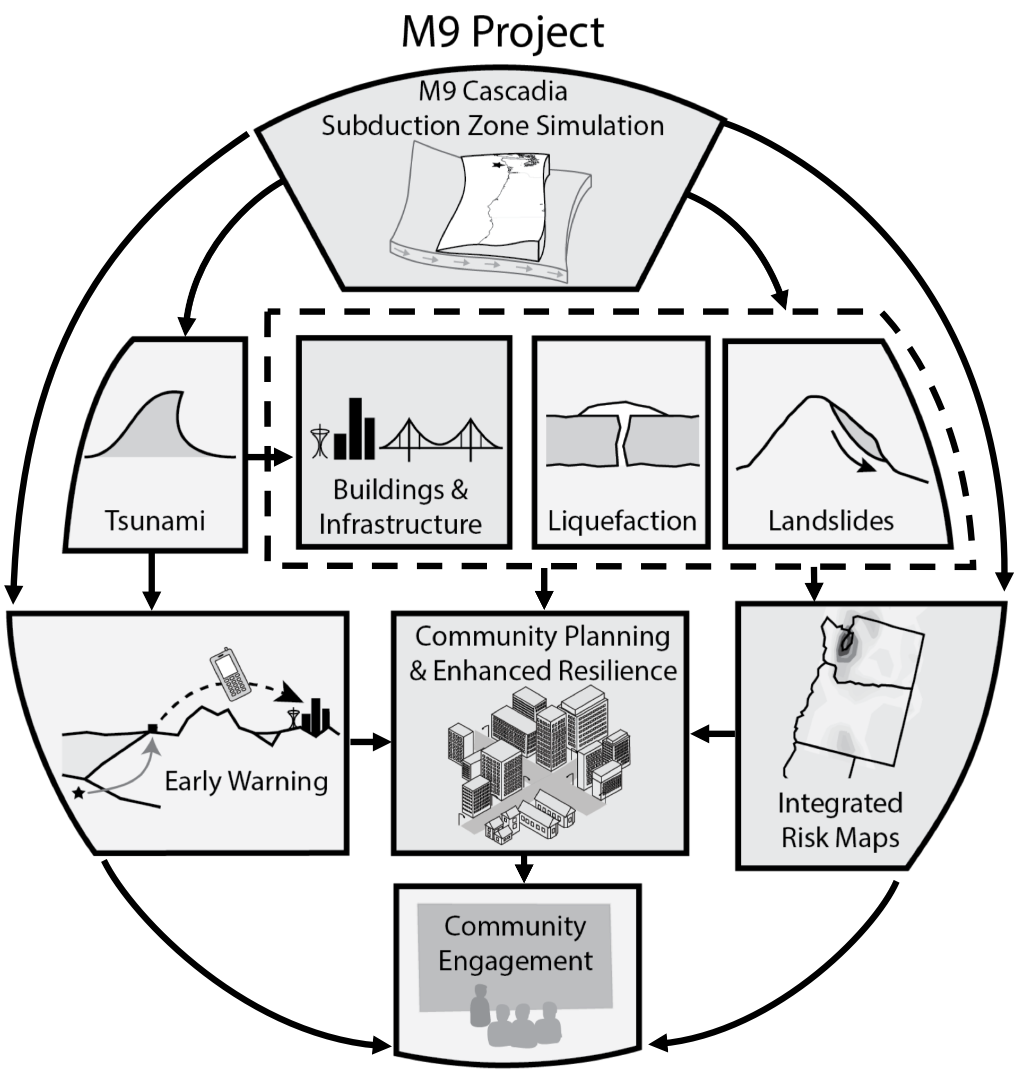
-Tsunami records

-Offshore turbidites

•Last Cascadia Earthquake in 1700 AD

-Estimated M ~ 8.7 – 9.2 [Satake et al., 2003]

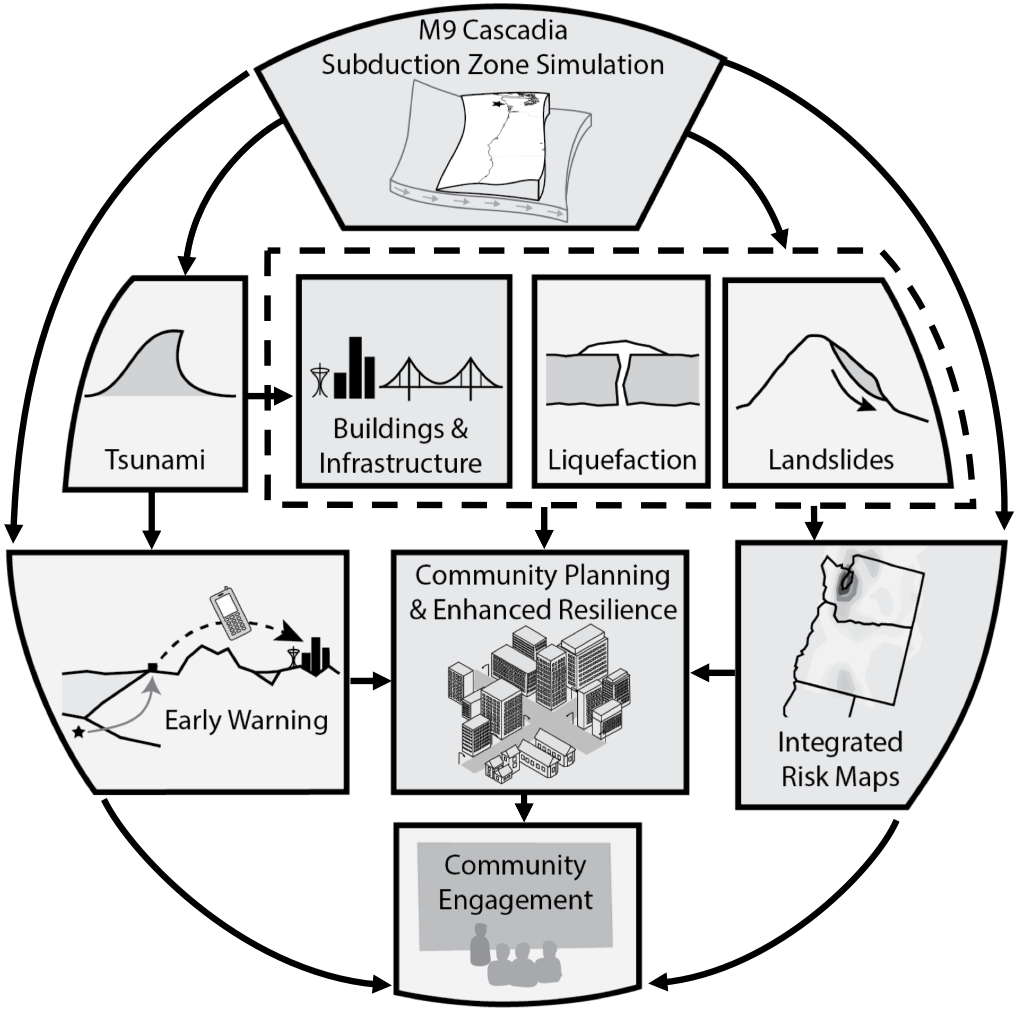
10-14% chance of another M9 earthquake in the next 50 years [Petersen et al., 2002]



Slide c/o Nasser Marafi – UW CEE

Reduce catastrophic potential of **Cascadia earthquakes** through advances in hazard assessment & adaptive planning

M9 Project



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STATISTICS

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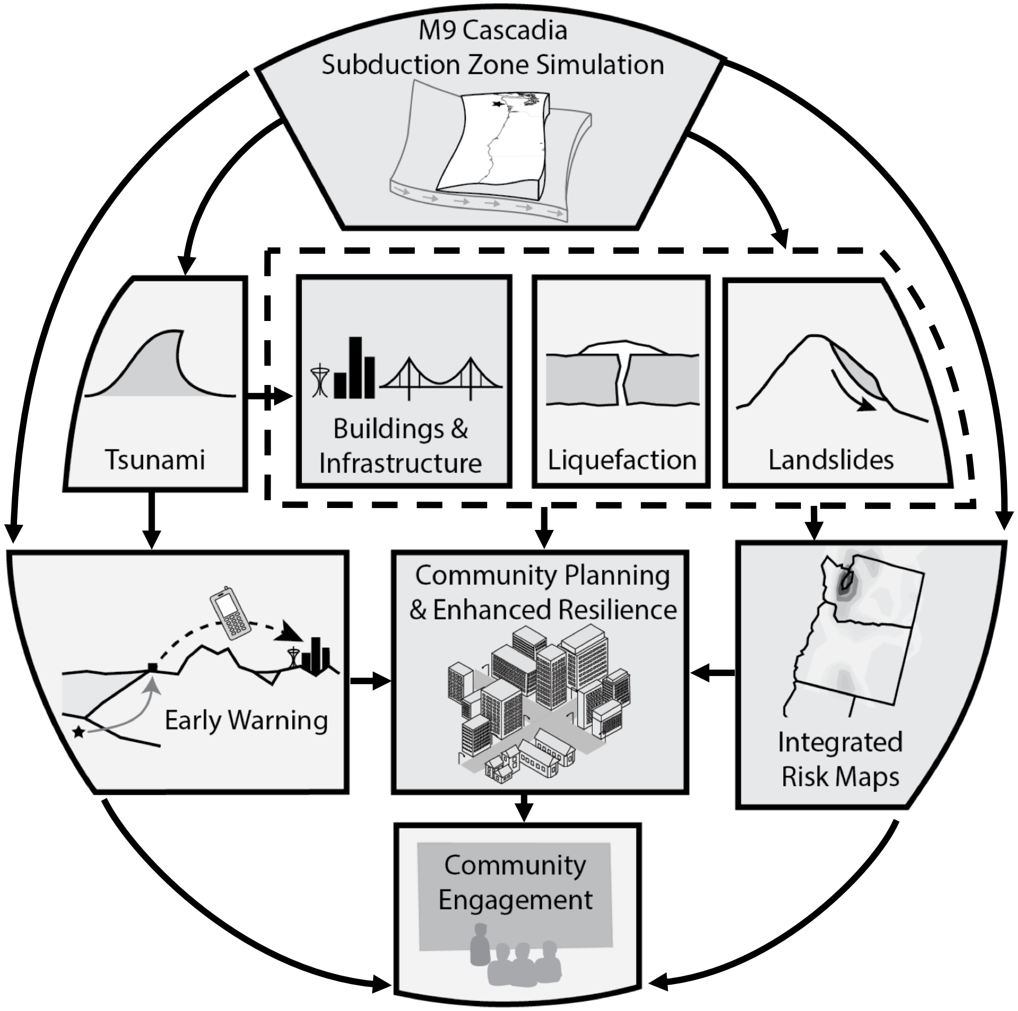
URBAN DESIGN
AND PLANNING

USGS
science for a changing world

Sea Grant
Washington

M9 Project



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FEMA

WSDOT

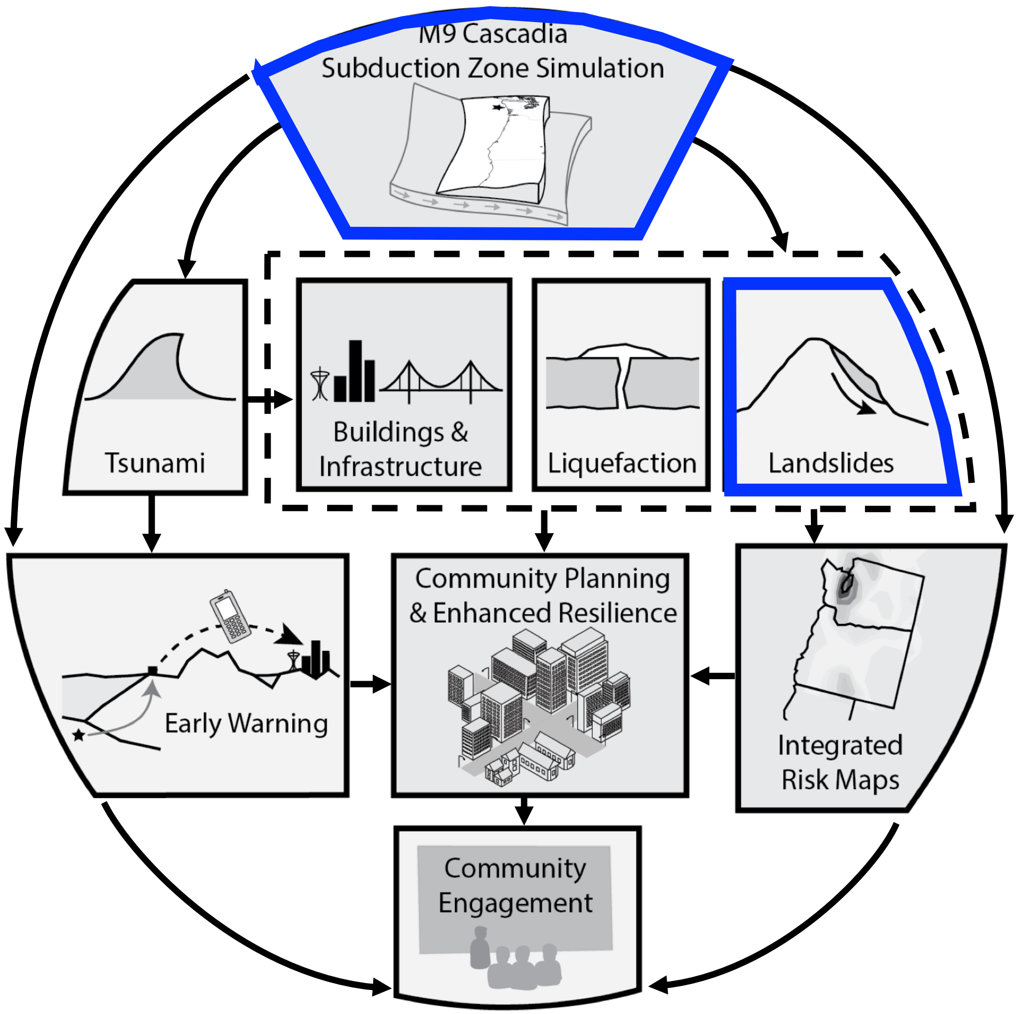
Seattle Public Utilities

Oregon Department of Transportation

Washington State Department of Natural Resources

Degenkolb

M9 Project



Slide c/o Nasser Marafi – UW CEE

3-D Simulations

Landscape response

Accurately captures rupture directivity, basin amplification, edge-converted waves, duration

Coseismic landslides

Landscape evolution

Art Frankel Erin Wirth

Alison Duvall; Joe Wartman; Sean LaHusen; Alex Grant

Broadband Synthetic Seismograms

50+ M9 Earthquake Scenarios

Frankel et al., *in revision*, BSSA   Wirth et al., *in revision*, BSSA

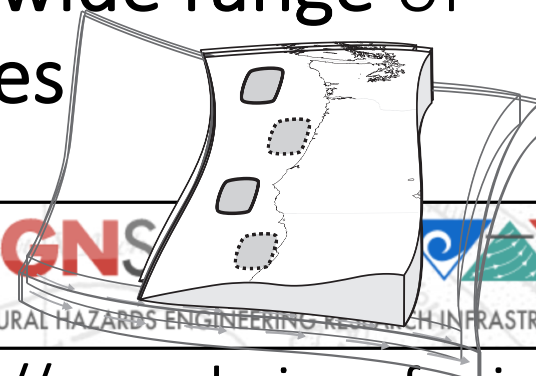
★ What is the range of possible ground shaking from an M9?

★ What are the critical rupture parameters?

Strength of ground shaking will depend on…

Main Takeaway: There are a **wide range** of possible outcomes

- **Hypocenter** (rupture starting point) / **Down-dip** (eastward) **extent** / Location of strong motion generating areas (“**sticky patches**”)



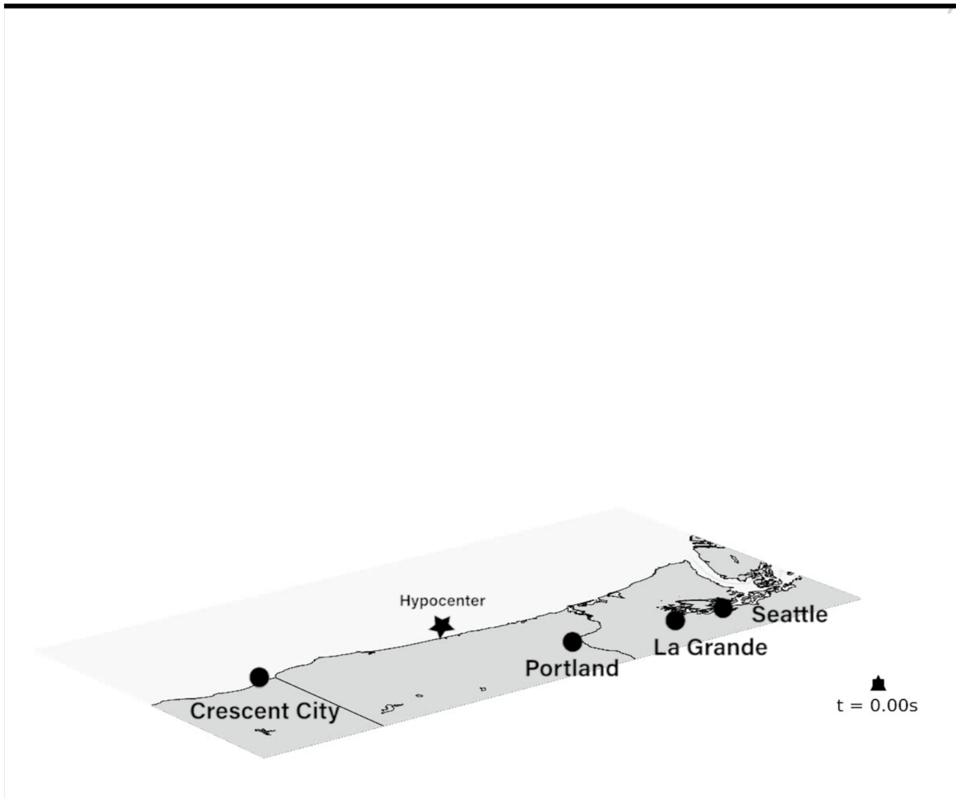
DESIGNSAFE

NHERI: A NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

https://www.designsafe-ci.org

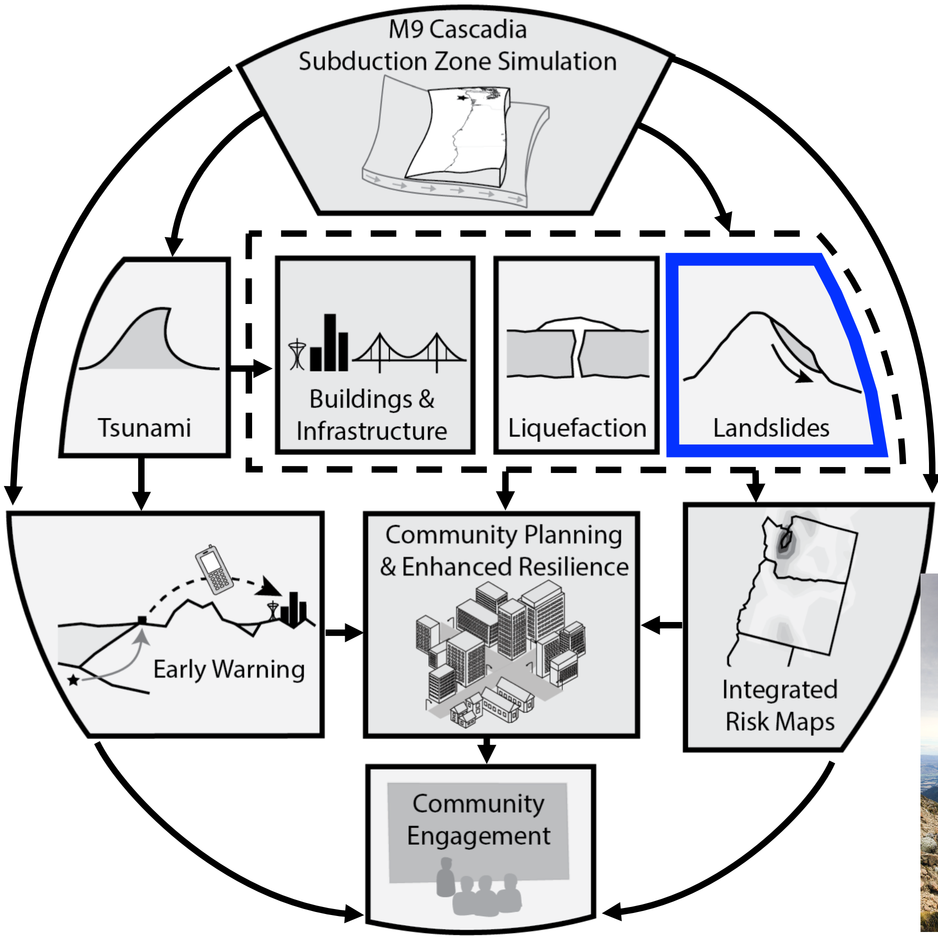
Slide c/o Erin Wirth & Nasser Marafi

M9 Earthquake Ground Motions



csz006
Movie by
Nasser Marafi

M9 Project



Landscape response

Coseismic Landslides

Landscape Evolution

Sean LaHusen UW

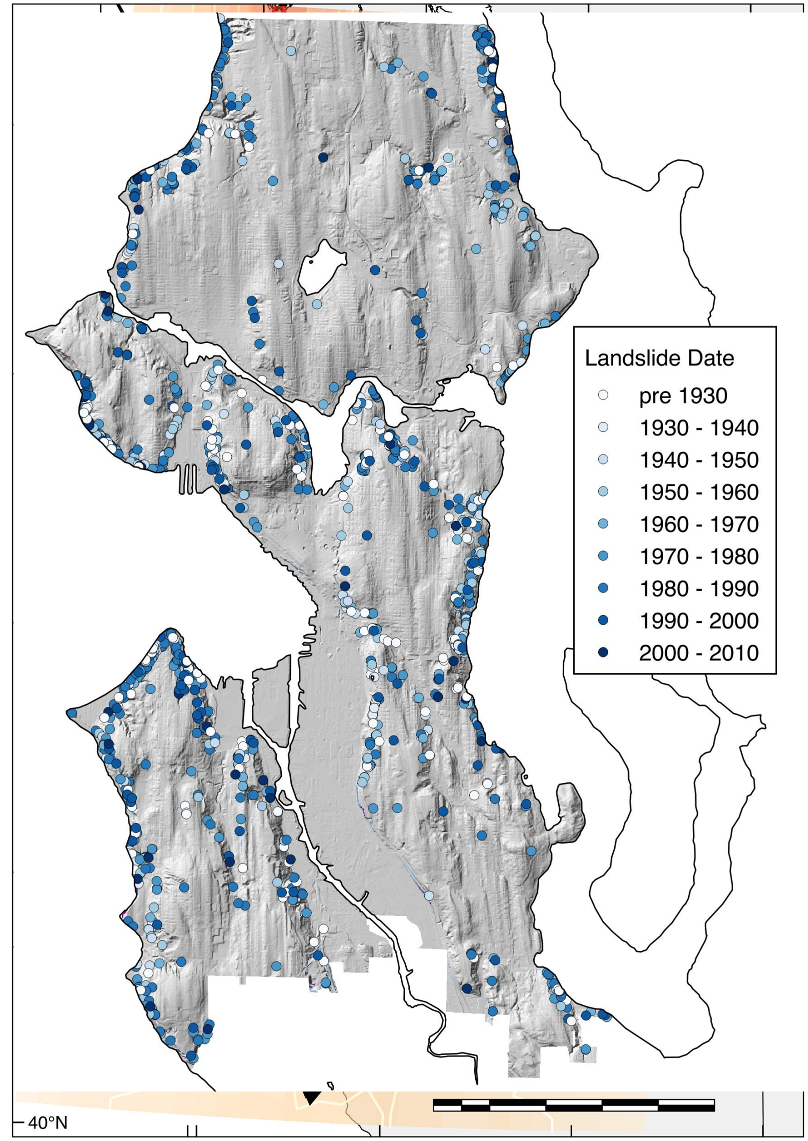
Alex Grant: USGS

M9 Coseismic Landslides

Alex Grant
PhD UW
now USGS

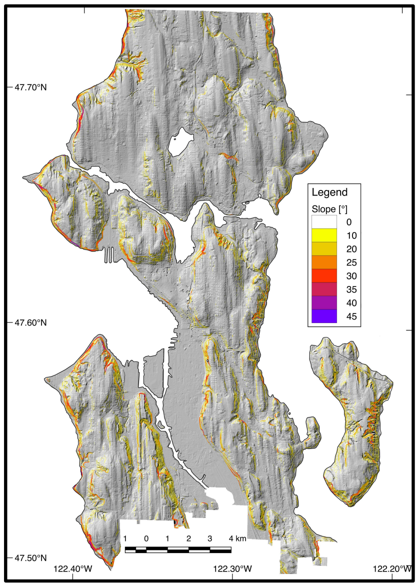
Location	Lat.	Lon.	PGA Range	$\overline{PGA}$
Forks, WA	47.95	-124.38	0.26 – 1.26	0.66
Coos Bay, OR	43.36	-124.22	0.25 – 1.34	0.65
Aberdeen, WA	46.97	-123.82	0.20 – 1.10	0.57
Tillamook, OR	45.45	-123.84	0.26 – 1.06	0.53
Olympia, WA	47.03	-122.88	0.12 – 0.71	0.32
Port Angeles, WA	48.12	-123.43	0.12 – 0.63	0.31
Longview, WA	46.14	-122.94	0.12 – 0.44	0.26
Grants Pass, OR	42.94	-123.33	0.14 – 0.43	0.24
Salem, OR	44.94	-123.04	0.10 – 0.65	0.22
Portland, OR	45.52	-122.67	0.12 – 0.47	0.21
Seattle, WA	**47.60**	**-122.33**	**0.10 - 0.34**	**0.20**
Eugene, OR	44.05	-123.08	0.11 – 0.32	0.19
Bellingham, WA	48.75	-122.48	0.07 – 0.36	0.17

Seattle's unstable slopes



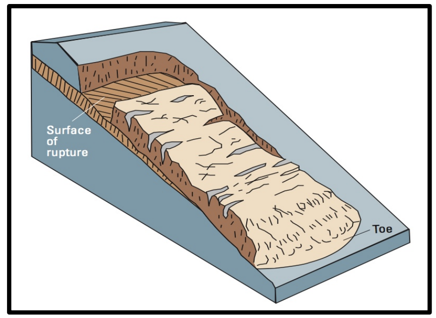
M9 Coseismic Landslides

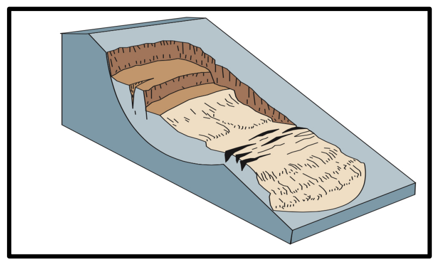
Alex Grant
PhD UW
now USGS



Place

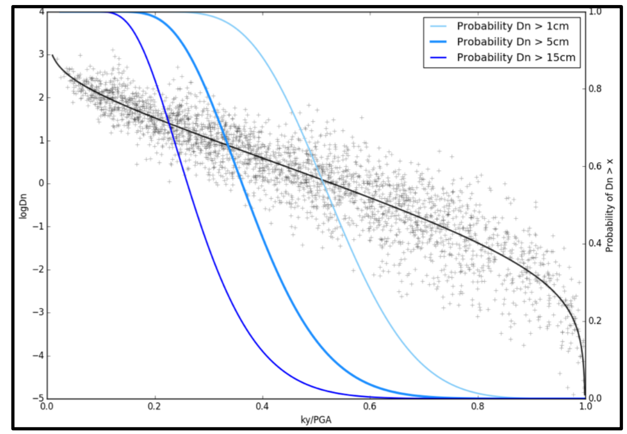
Material Strength
Ground Saturation





Landslide Models

Newmark Analysis

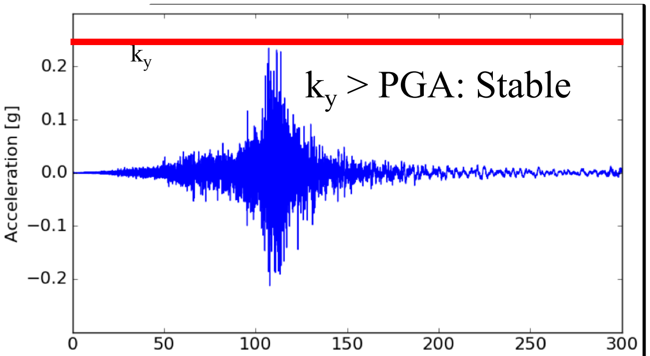


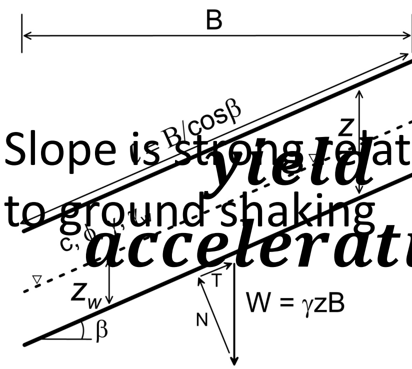
Hazard Model

Coseismic Block Displacement
Shaking Intensities

M9 Coseismic Landslides

Shallow (translational) slides



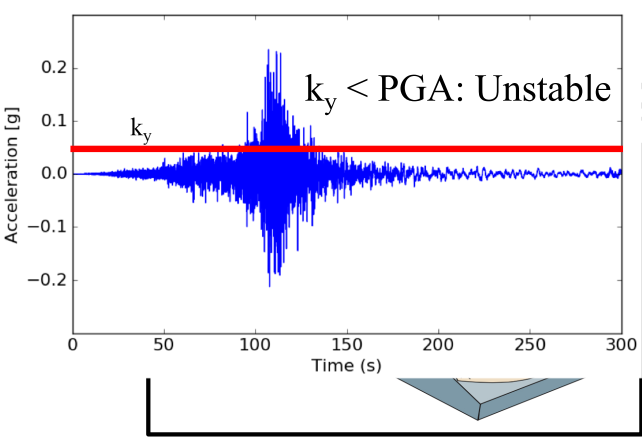


Slope is strong relative to ground shaking

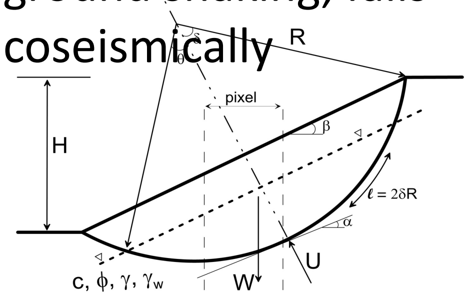
yield acceleration

$$k_y = (FS - 1)\sin\beta$$

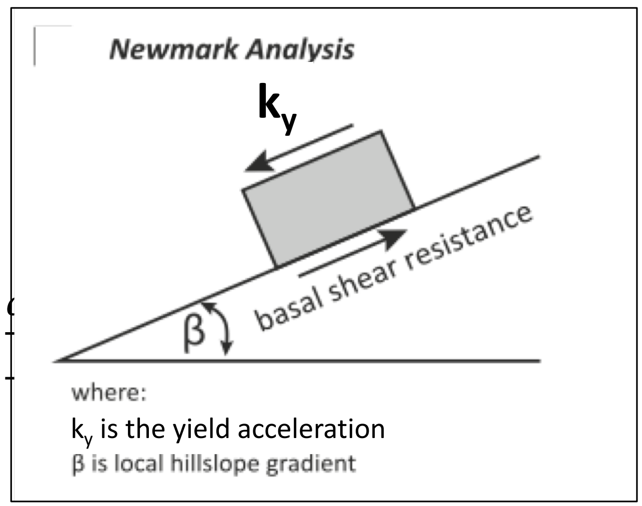
[the acceleration above which downslope motion will occur]



Slope is weak relative to ground shaking, fails coseismically



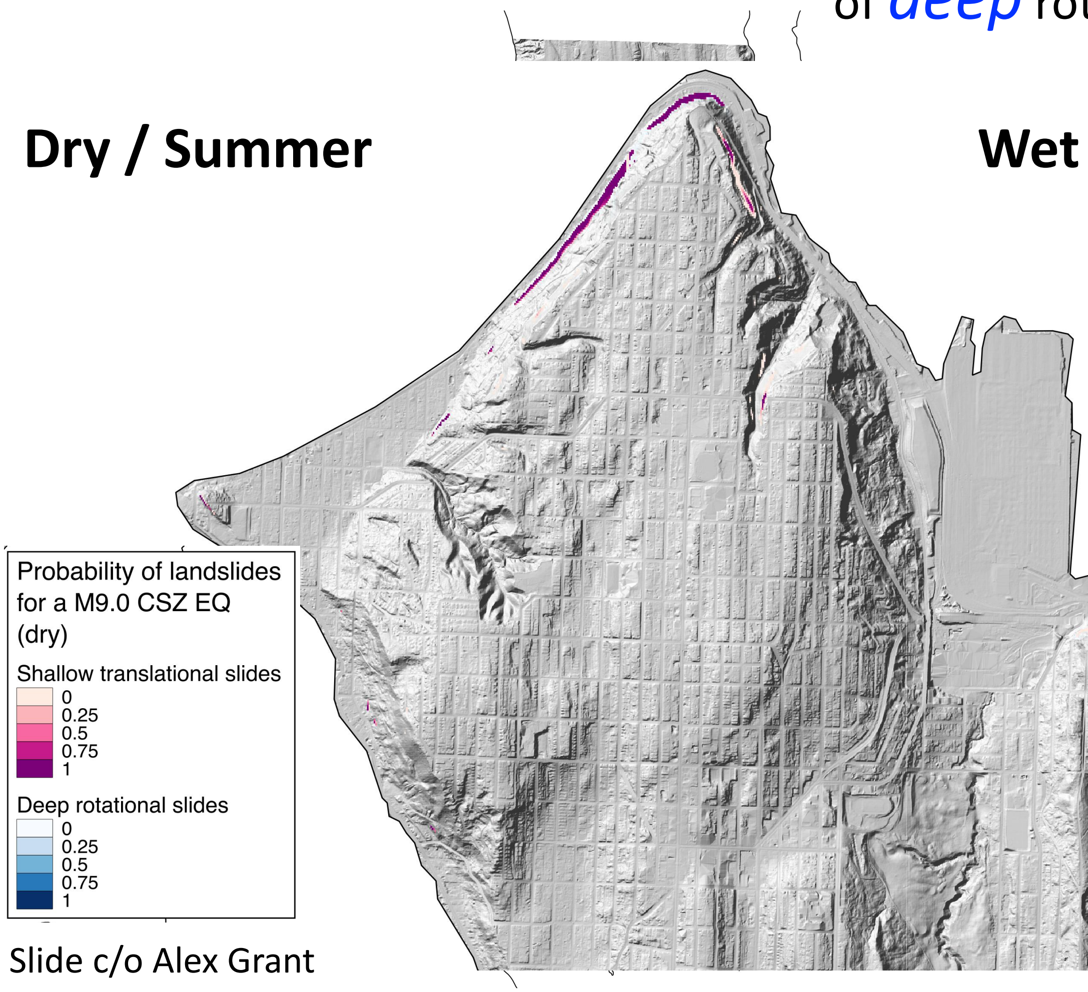
$FS =$

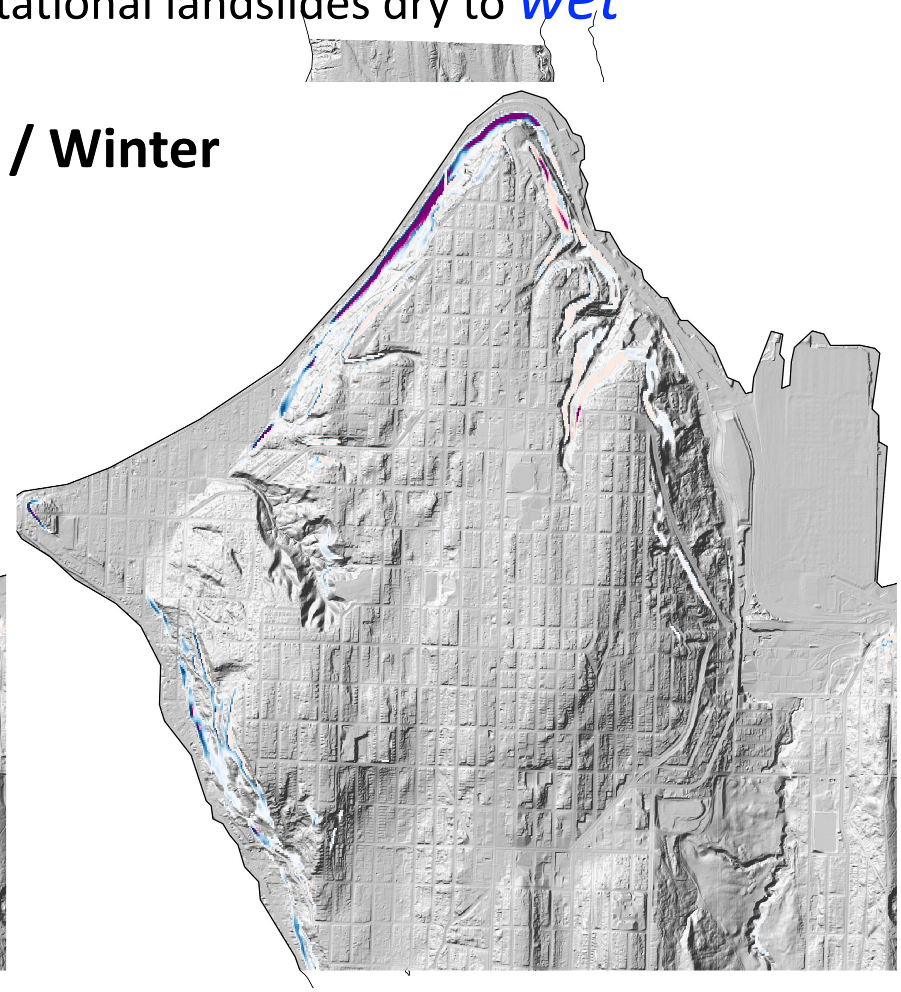


Slide c/o Alex Grant

M9 Coseismic Landslides

515% *increase* in areas of >5% predicted probability of *deep* rotational landslides dry to *wet*





Slide c/o Alex Grant

M9 Coseismic Landslides

Alex Grant

PhD UW

now USGS

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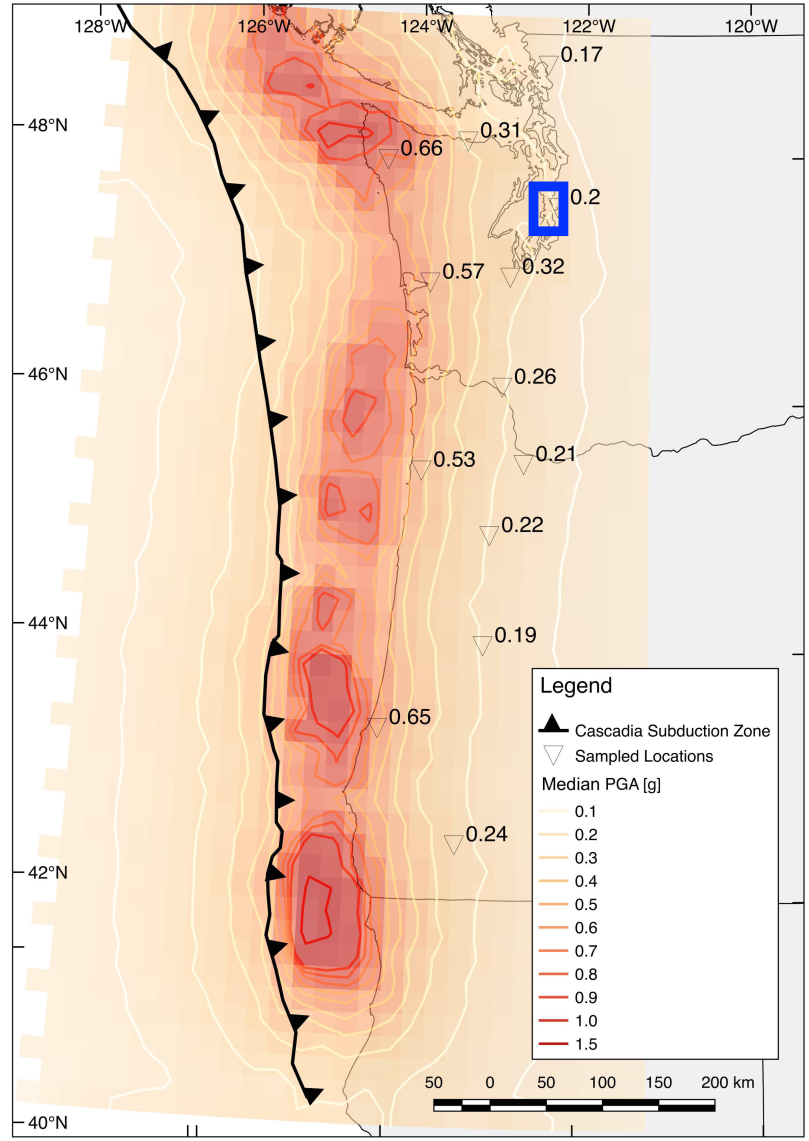
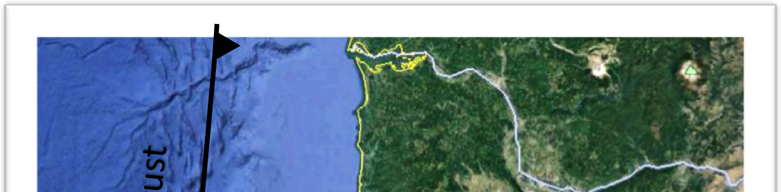
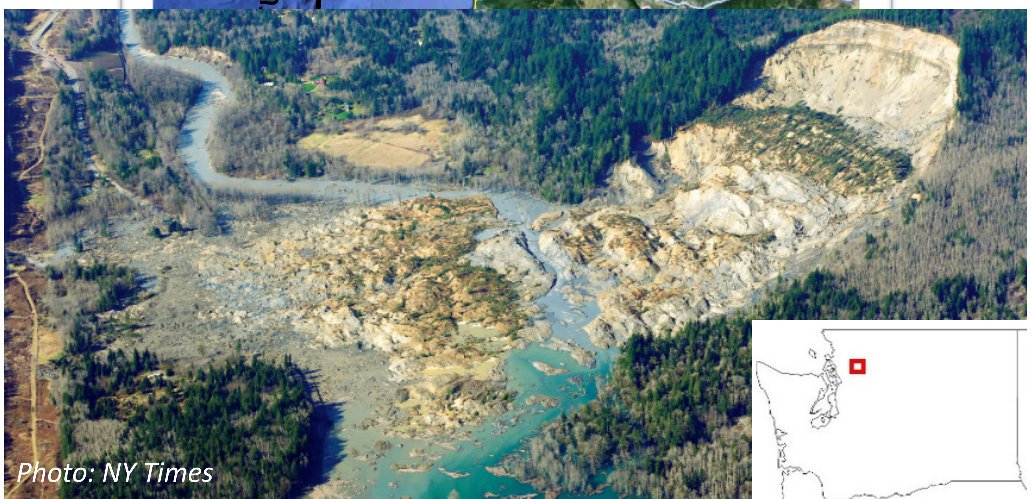


Where are the M9 Coseismic Landslides ?
And how do we date them?





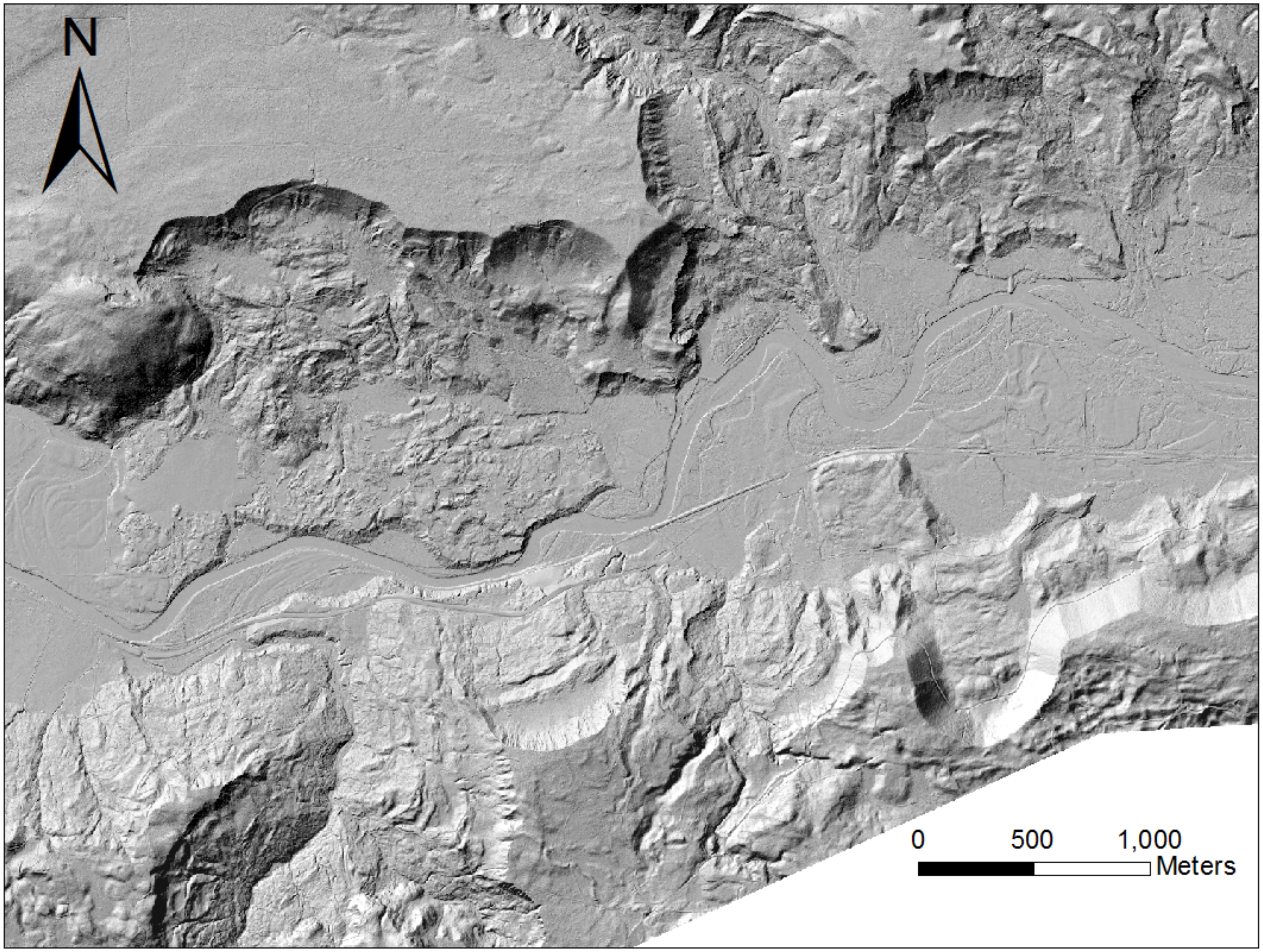
March 22, 2014 Oso Landslide, WA

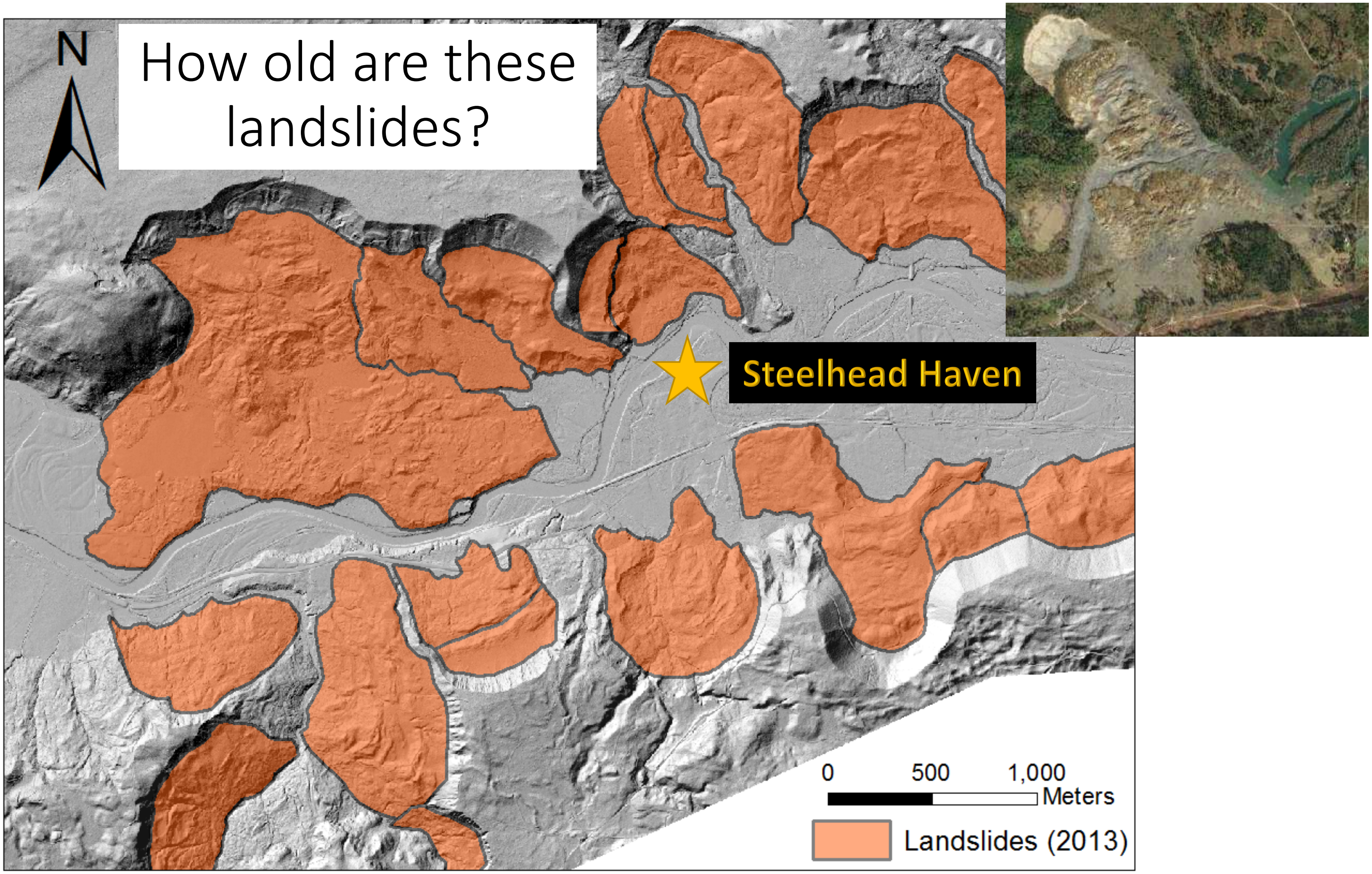
Sean LaHusen – PhD student UW

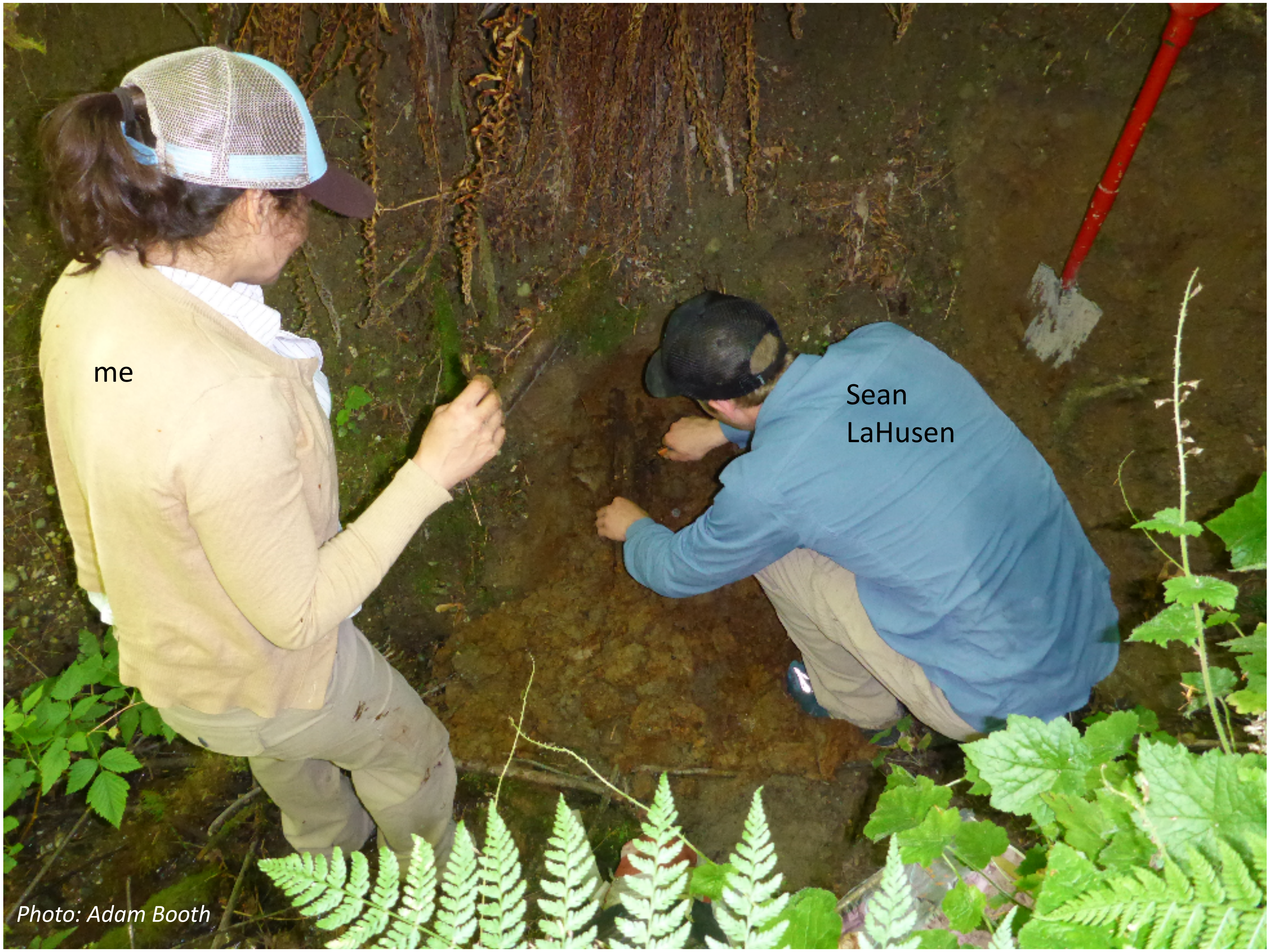
Adam Booth
Portland State University

Dave Montgomery
University of Washington

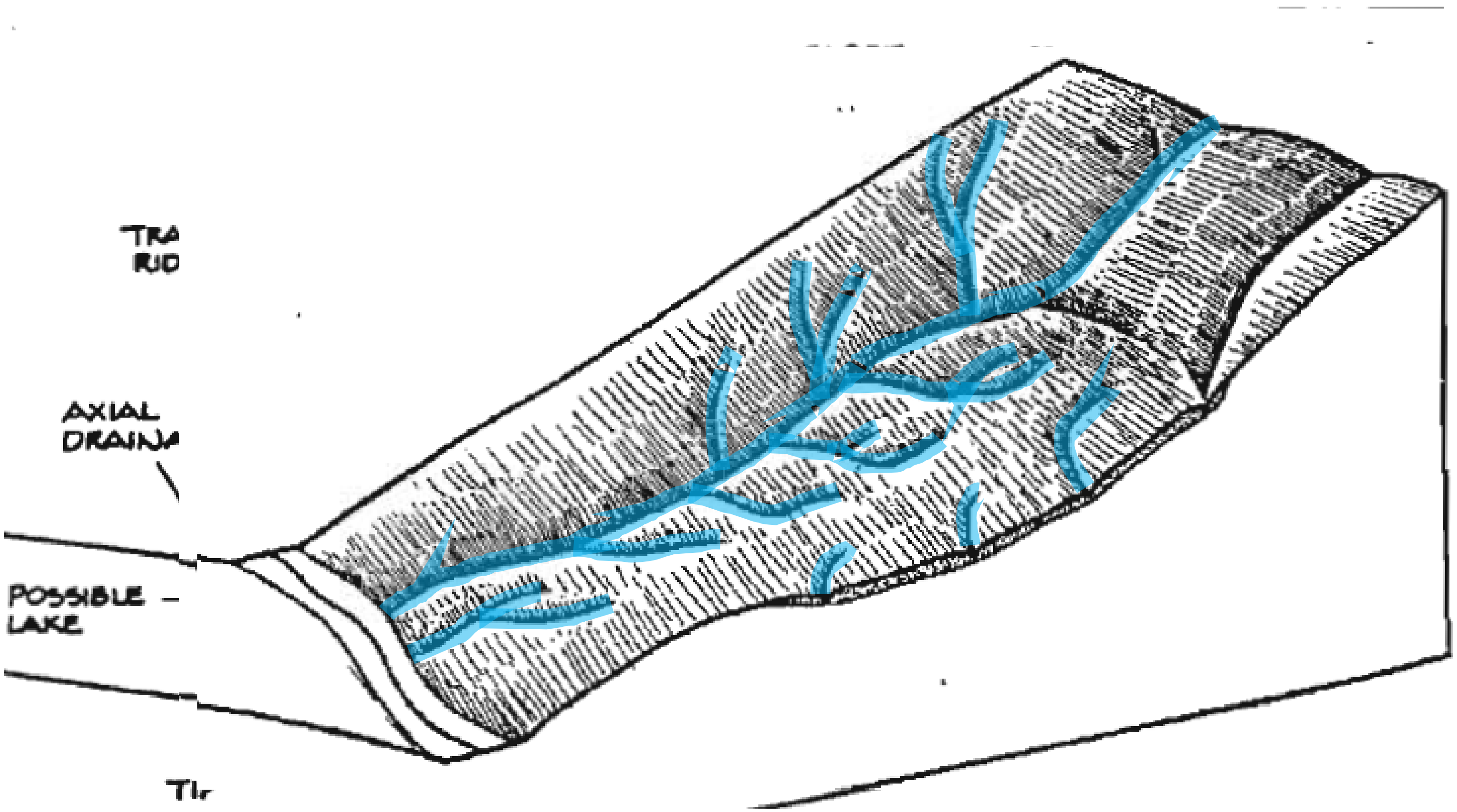
North Fork Stillaguamish River 2014


N
0
500
1,000
Meters


N
How old are these landslides?
Steelhead Haven
0
500
1,000
Meters
Landslides (2013)


me
Sean
LaHusen
Photo: Adam Booth

Landslide deposits smooth over time



McCalpin, 1984

Landslide deposits smooth over time

Hillslope transport coefficient

Slope

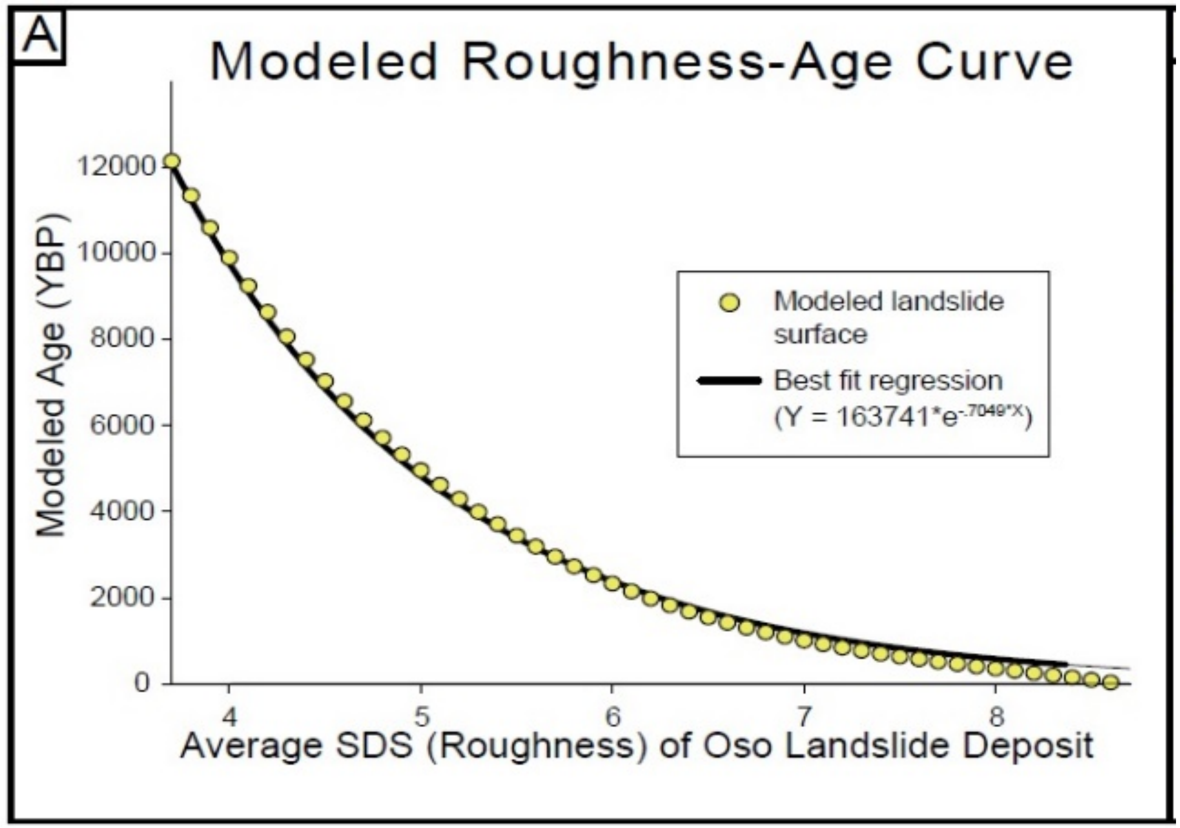
$$\boldsymbol{q_s} = -\frac{K\boldsymbol{\nabla z}}{1-\left(|\boldsymbol{\nabla z}|/S_c\right)^2}$$

Soil flux

Critical slope

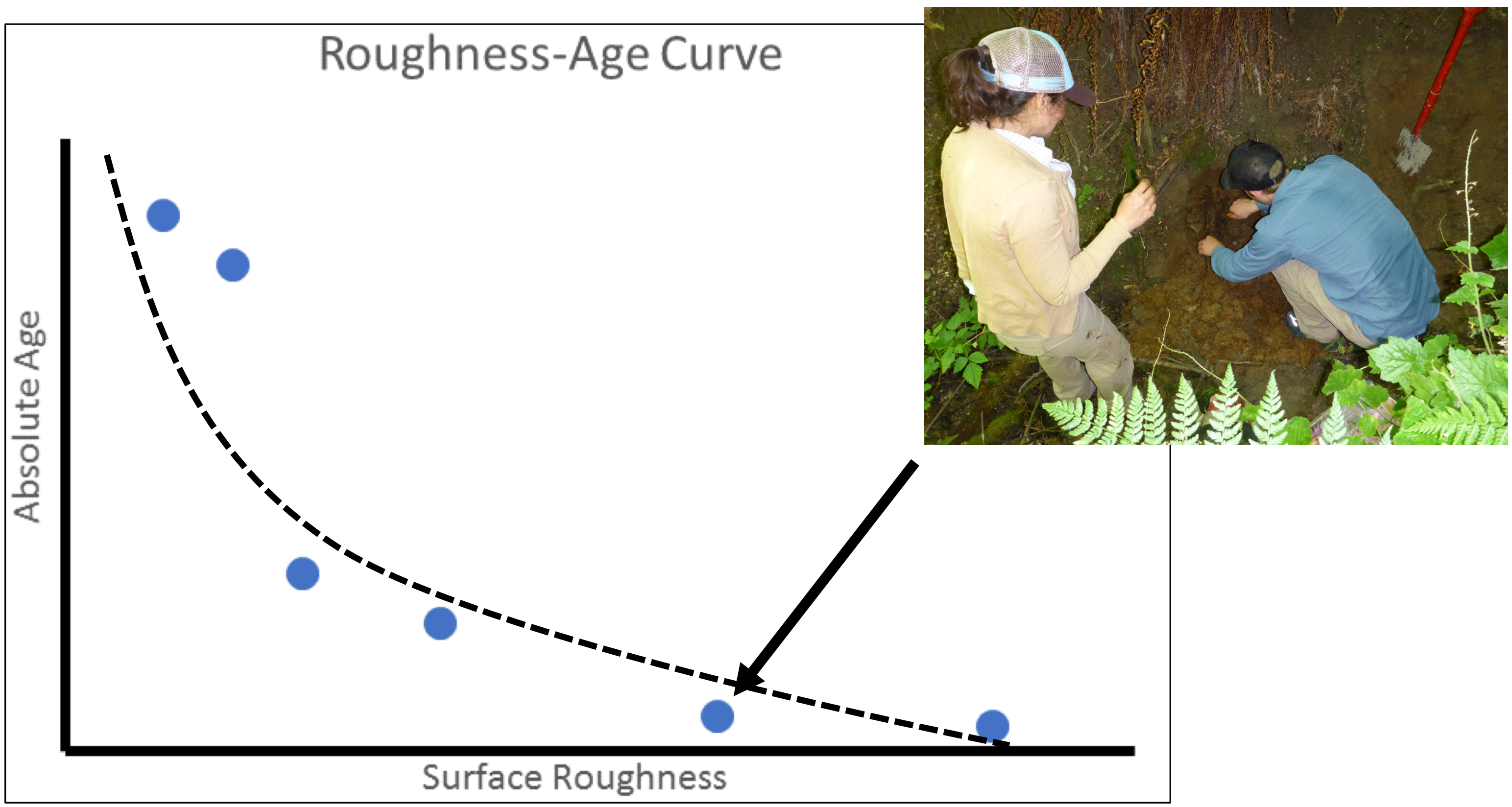
Roering et al. (1999)

Non-linear hillslope sediment flux



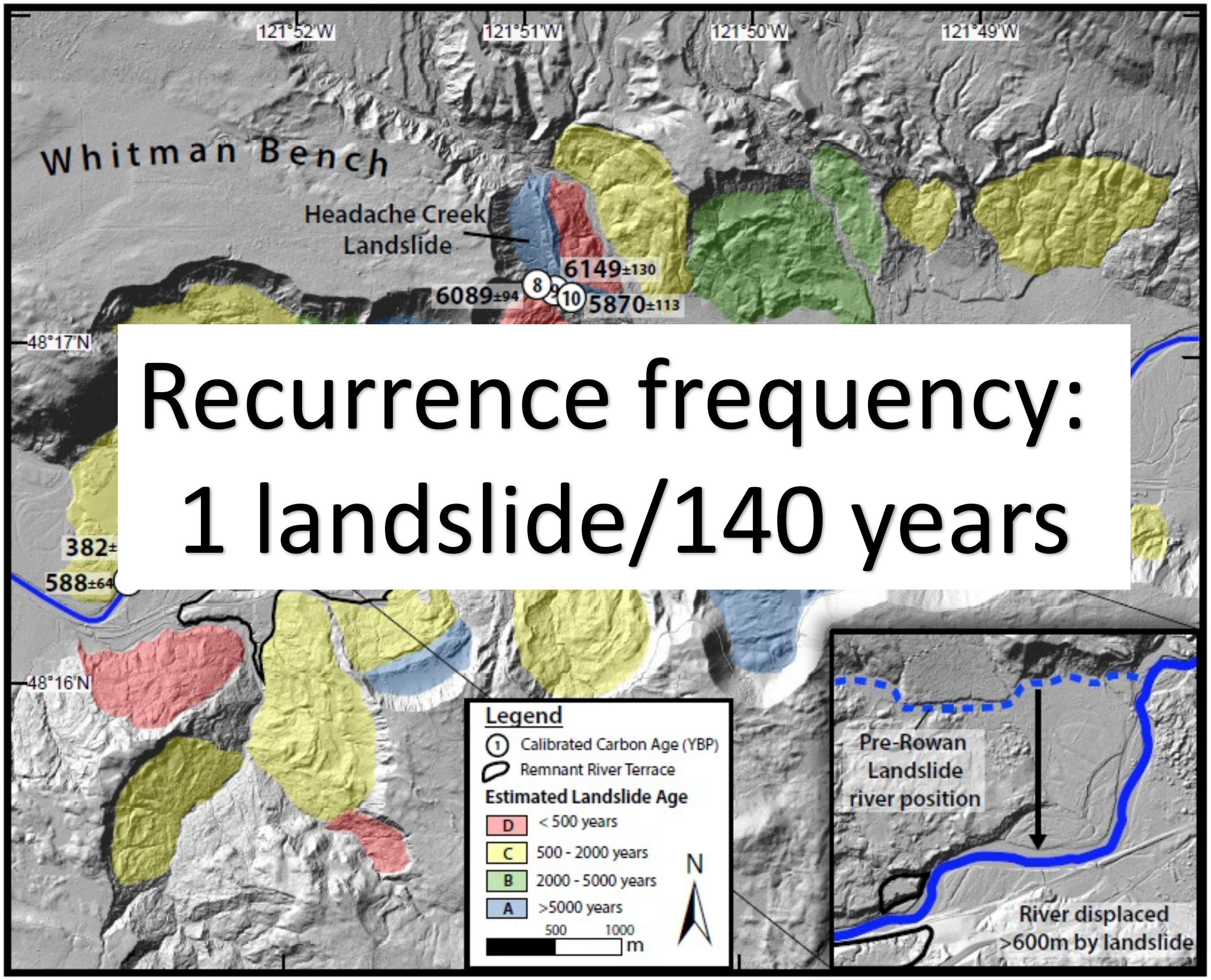
LaHusen et al. (2016)

Dating large landslide inventories



Calibrated surface roughness-age curve

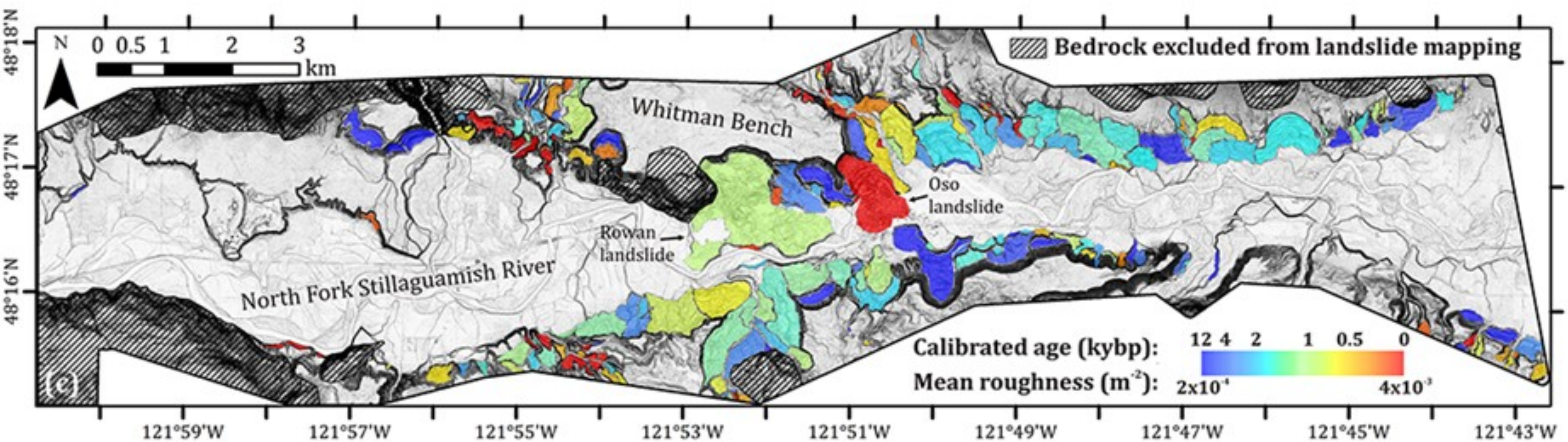
Recurrence frequency:
1 landslide/140 years



LaHusen, et al. (2016)

>200 mapped slides in North Fork Stillaguamish River Valley

Adam Booth
Portland State University

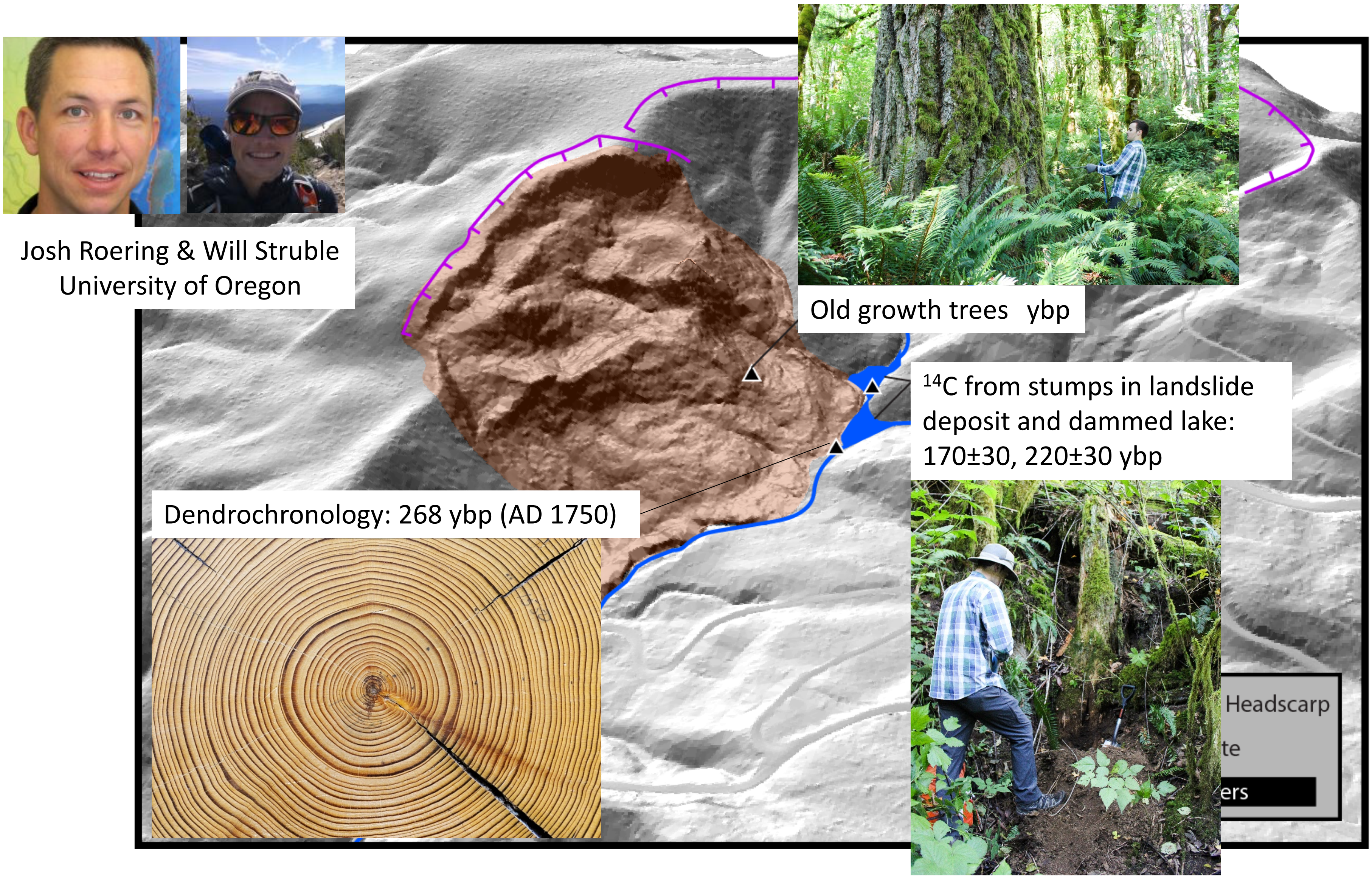


Booth et al., (2017)

Characterizing structural and lithologic controls on deep-seated landsliding: Implications for topographic relief and landscape evolution in the Oregon Coast Range, USA

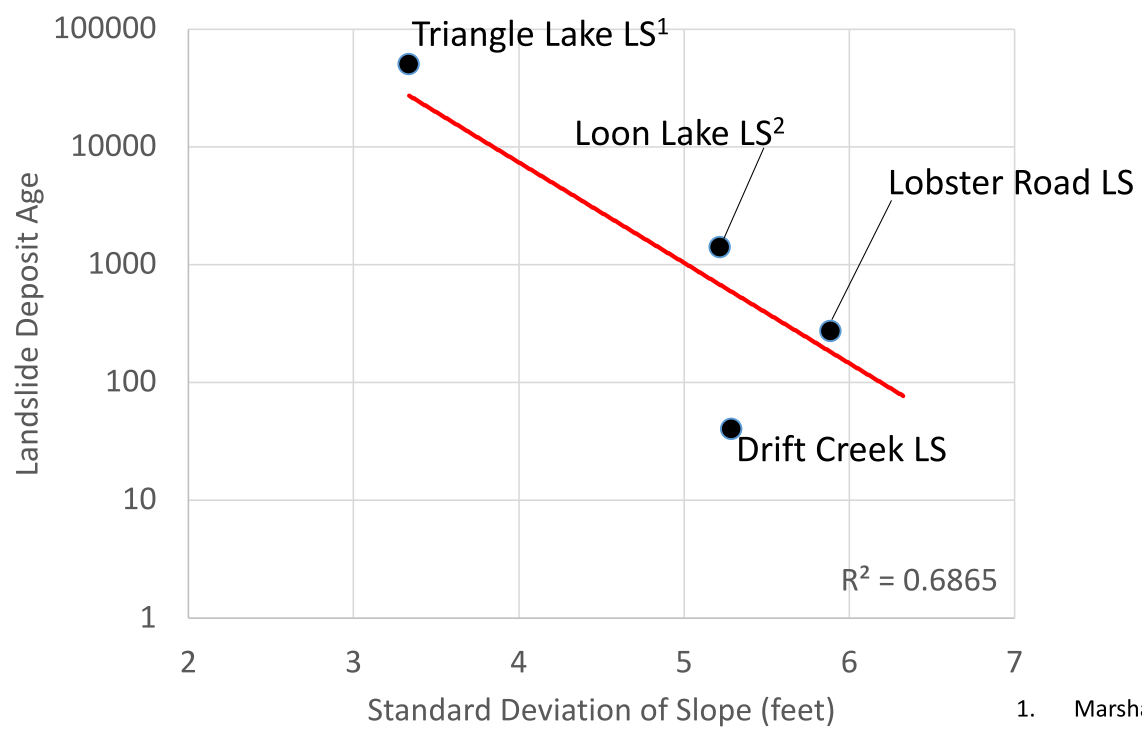
Sean LaHusen; Kyle Lowery; Valerie Bright

GSA Bulletin; May/June 2005; v. 117; Roering et al. (2005)



Josh Roering & Will Struble
University of Oregon
Old growth trees ybp
^{14}C from stumps in landslide deposit and dammed lake: 170±30, 220±30 ybp
Dendrochronology: 268 ybp (AD 1750)
Headscarp

OCR Roughness-Age Plot

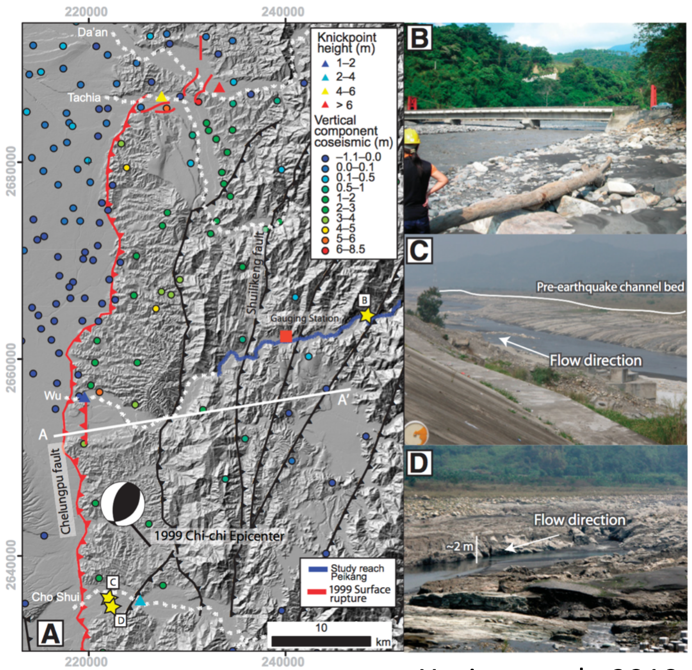


1. Marshall et al., 2015
2. Lane, 1987

Next steps: Modeling coseismic landslides (& cascading geomorphic effects)

How will this affect landscape evolution over long timescales?

How rivers react to large earthquakes:

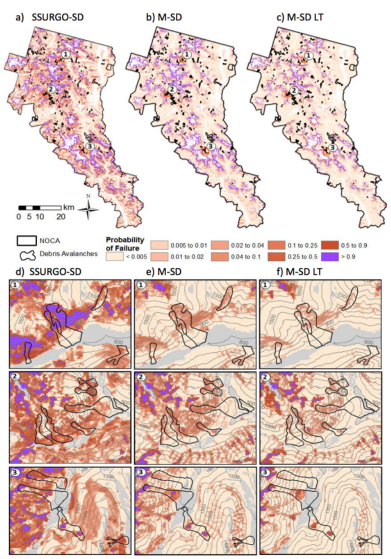


Yanites et al., 2010

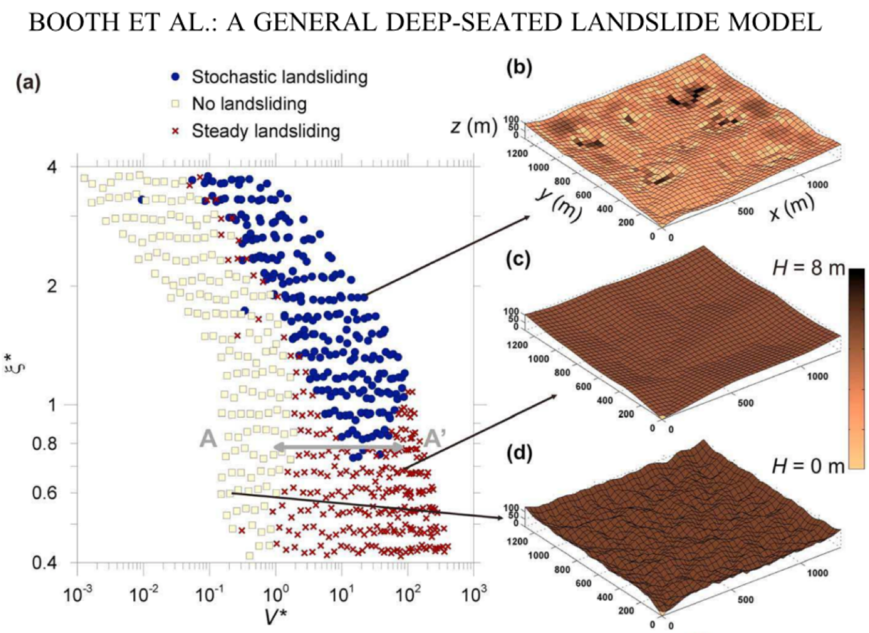
Next steps: Modeling coseismic landslides (& cascading geomorphic effects)

How will this affect landscape evolution over long timescales?

Predicting regional shallow landslide probability using Landlab



Strauch et al. (2017)



Booth, Roering, Rempel (2013)

Next steps: coupling tectonics and surface processes in subduction zones over short & long time scales

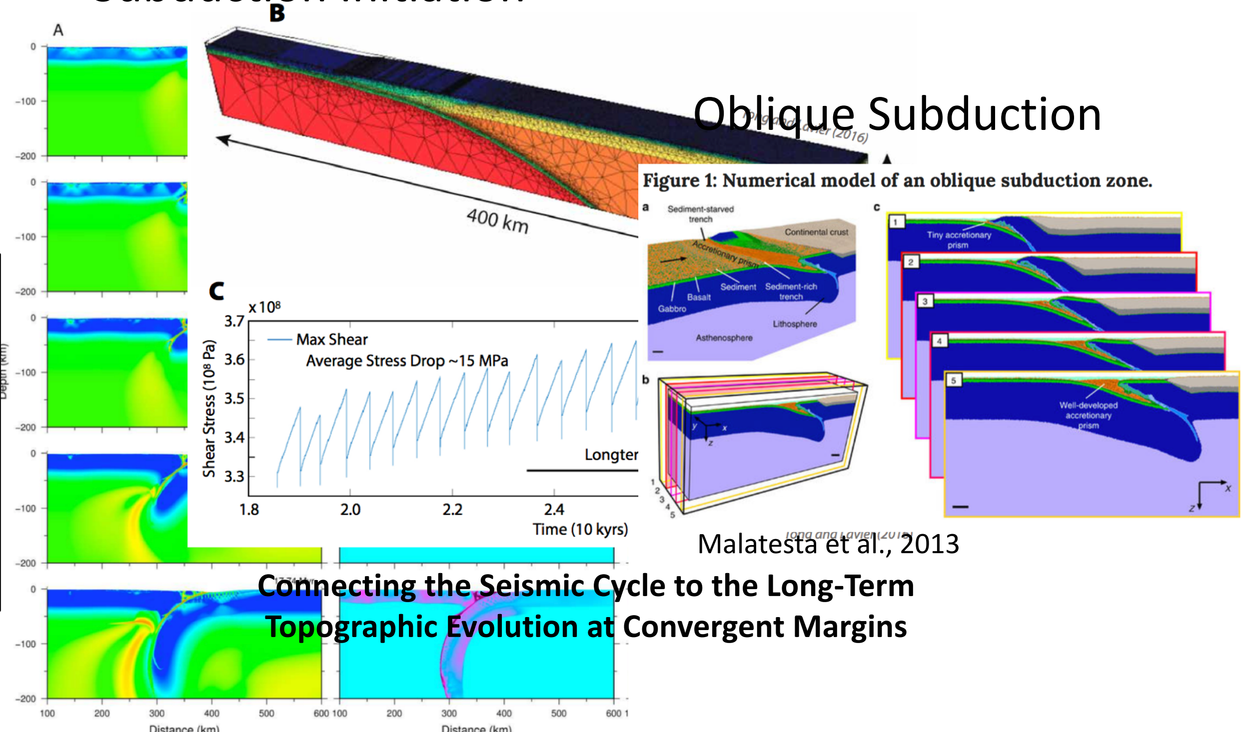
Modeling the Dynamics of Subducting Slabs

Summary of Types of Subduction Models			
Model type	**Model design**	**Output parameters**	**Observations**
Instantaneous	Density and viscosity structure; model size; side, top, and bottom boundary conditions	Instantaneous velocity and pressure field	Dynamic topography, geoid, strain rate, stress orientations
Time-dependent			
Fully dynamic	Initial density, viscous, or visco-plastic flow law; model size; side, top, and bottom boundary conditions	Time-dependent velocity, pressure, temperature, composition, and density anomalies owing to phase changes	Same as instantaneous, plate rates and directions, uplift rates, time-dependent slab shape, correlation of slab geometry with other parameters
Dynamic with kinematic BC	Same as dynamic, prescribed plate motions at surface	Same as dynamic	Same as dynamic, except no uplift rates or dynamic topography
Coupled kinematic-dynamic	Slab geometry, subduction rate, thermal and viscosity structure of dynamic region, model size, boundary conditions	Steady-state velocity, pressure, and temperature	Heat flow, dynamic topography (upper plate), strain rates, accumulated strain

Billen, 2008

Subduction Initiation

Oblique Subduction



Malatesta et al., 2013

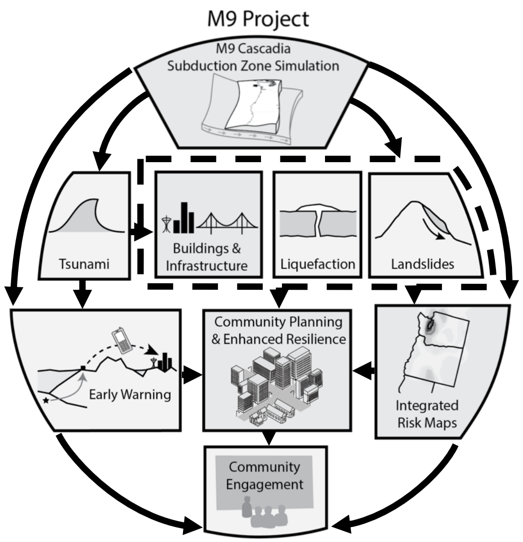
Connecting the Seismic Cycle to the Long-Term Topographic Evolution at Convergent Margins

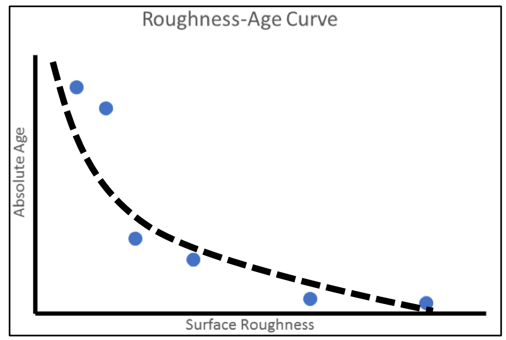
Tong and Lavier – AGU Fall Meeting Abstracts, 2016

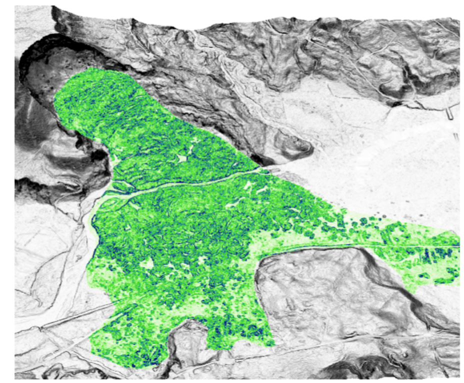
Mao, Gurnis, and May, 2017

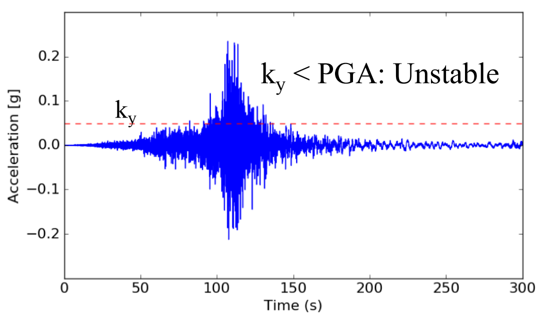
McGuire, J.J., T. Plank, et al. 2017.

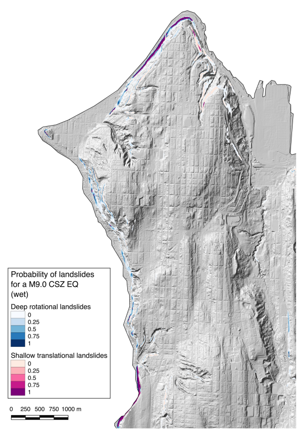
Summary



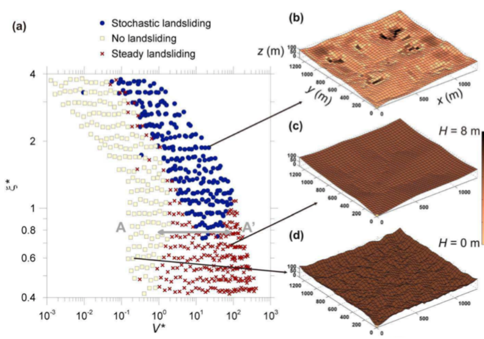


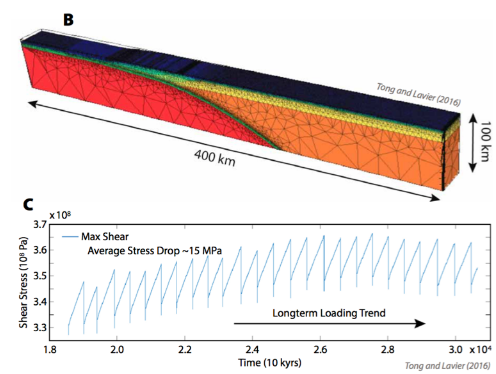






BOOTH ET AL.: A GENERAL DEEP-SEATED LANDSLIDE MODEL





Thank You, Questions? Discussion!

Supercomputer Resources: Stampede (U. Texas), Constance (PNNL), Hyak (U. Washington)

Funding: NSF Hazards SEES (EAR-1331412); Dept. of Earth & Space Sciences, U. of Washington

Visit M9: http://m9.uw.edu

Extra Slides

3D Earthquake Simulations:
Broadband Synthetic Ground Motions (0 – 20 Hz)

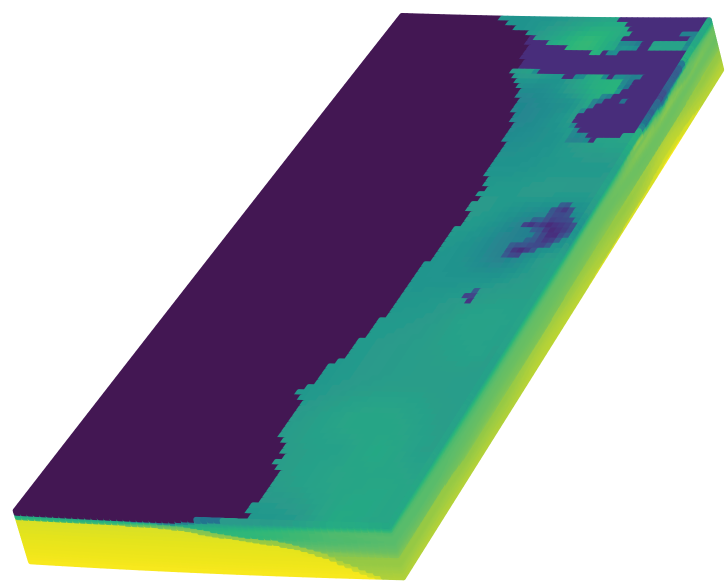
< 1 Hz (Deterministic)

- 3-D finite difference [Liu & Archuleta, 2002]
- Uses 3-D velocity model for Cascadia [Stephenson et al., 2017]

> 1 Hz (Stochastic)

- Sum point source synthetics [SMSIM; D.M. Boore]
- Subevents generate energy > 1Hz

Cascadia 3-D Model



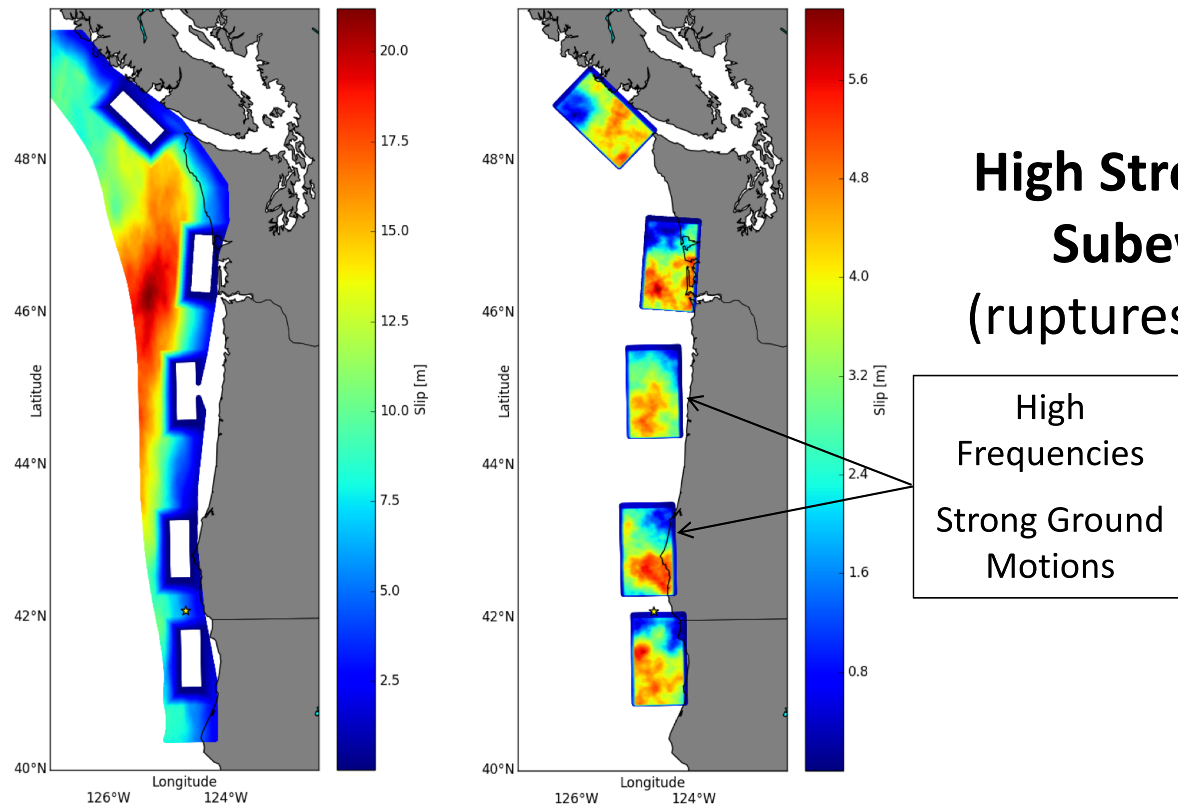
Slide c/o Erin Wirth

Earthquake Source Model

Slip on the fault consists of…

Background Slip
(ruptures slowly)

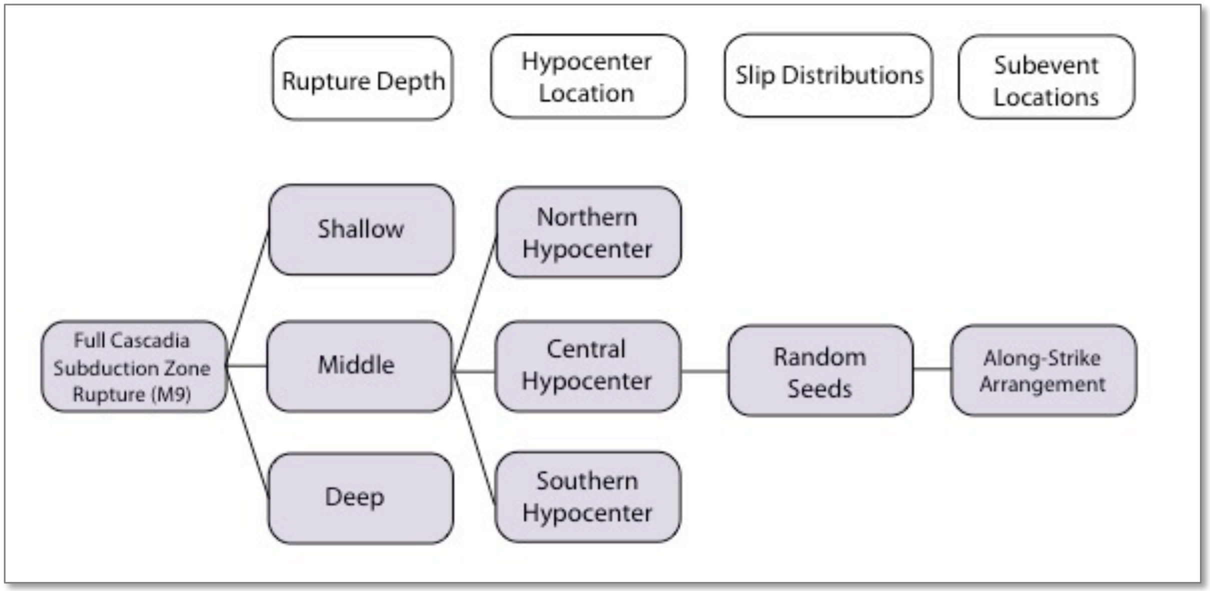
High Stress-Drop Subevents
(ruptures quickly)



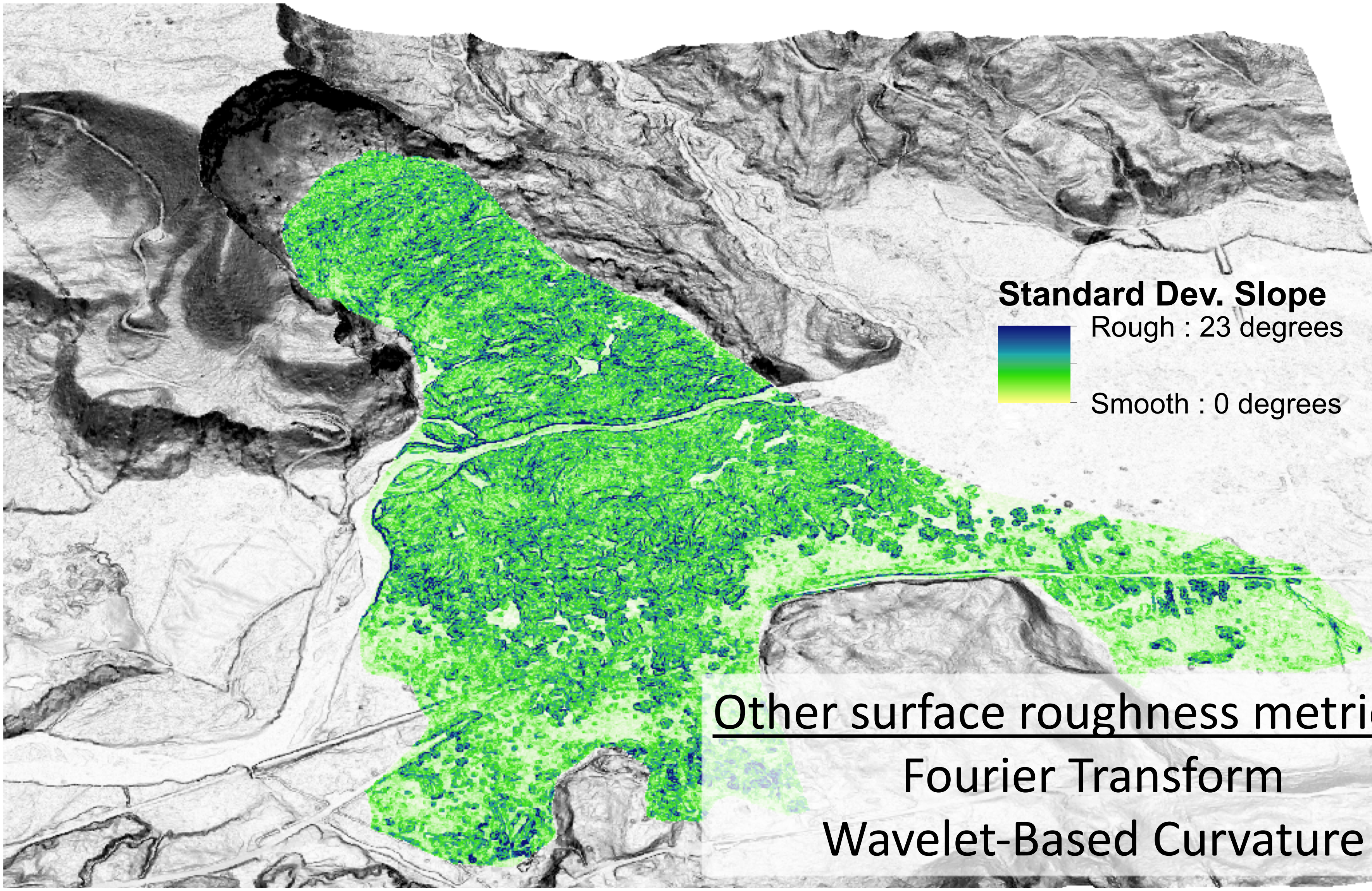
Slide c/o Erin Wirth

50+ M9 Earthquake Scenarios

- **20+ Simulations** Manually Adjusting Parameters (i.e., sensitivity tests) Wirth et al., *in revision*, BSSA
- **30 M9 Simulations** from "Logic Tree" Frankel et al., *in revision*, BSSA



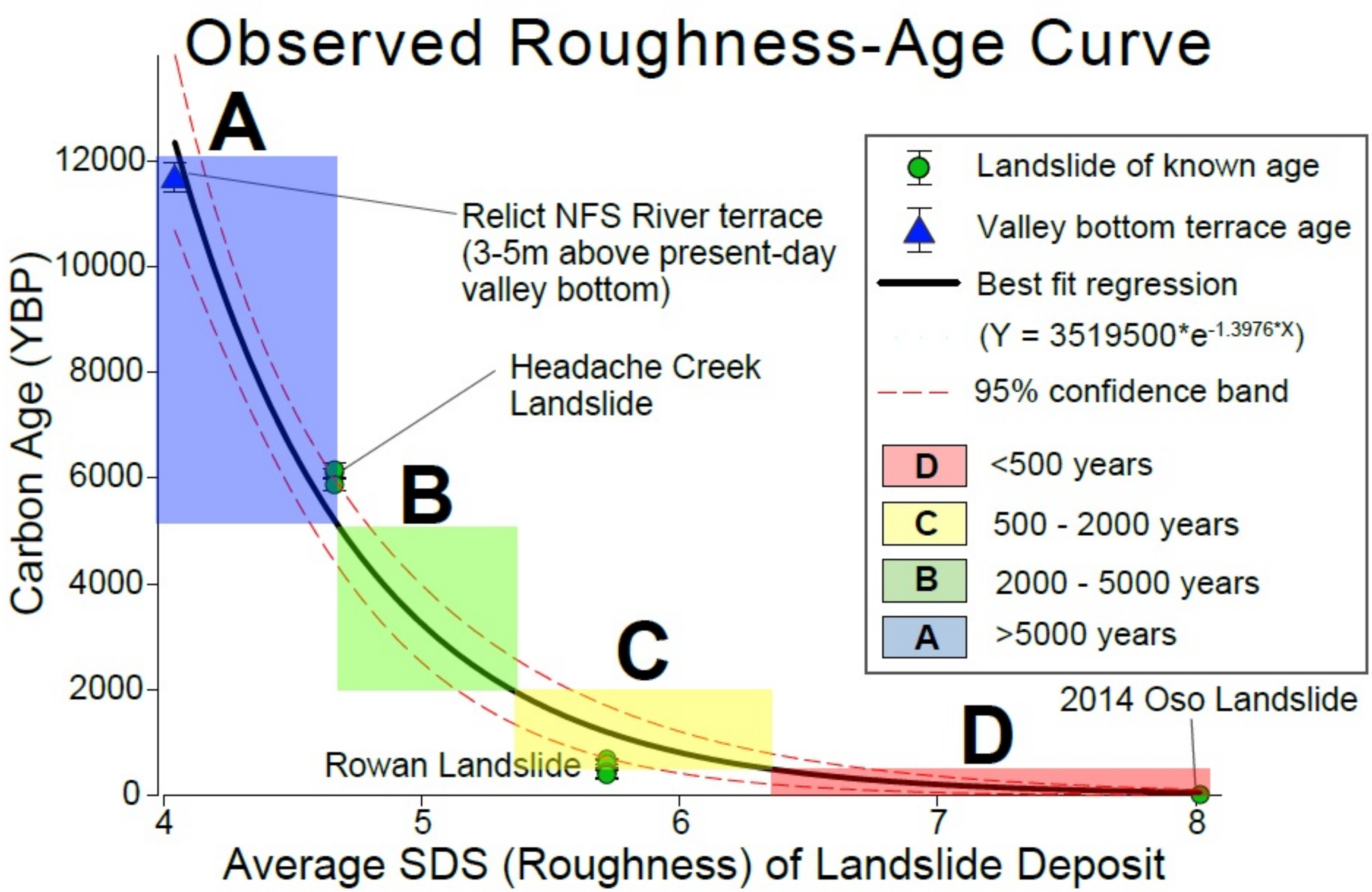
Slide c/o Erin Wirth



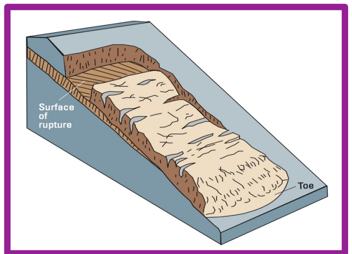
Other surface roughness metrics:

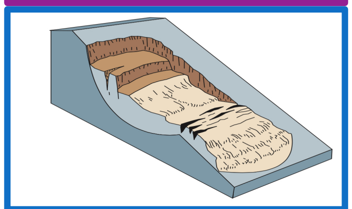
Fourier Transform

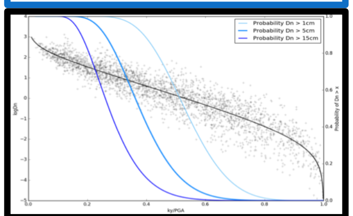
Wavelet-Based Curvature

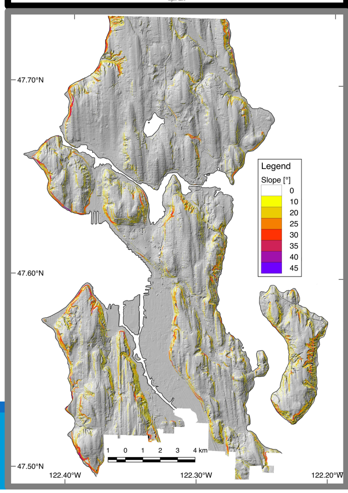


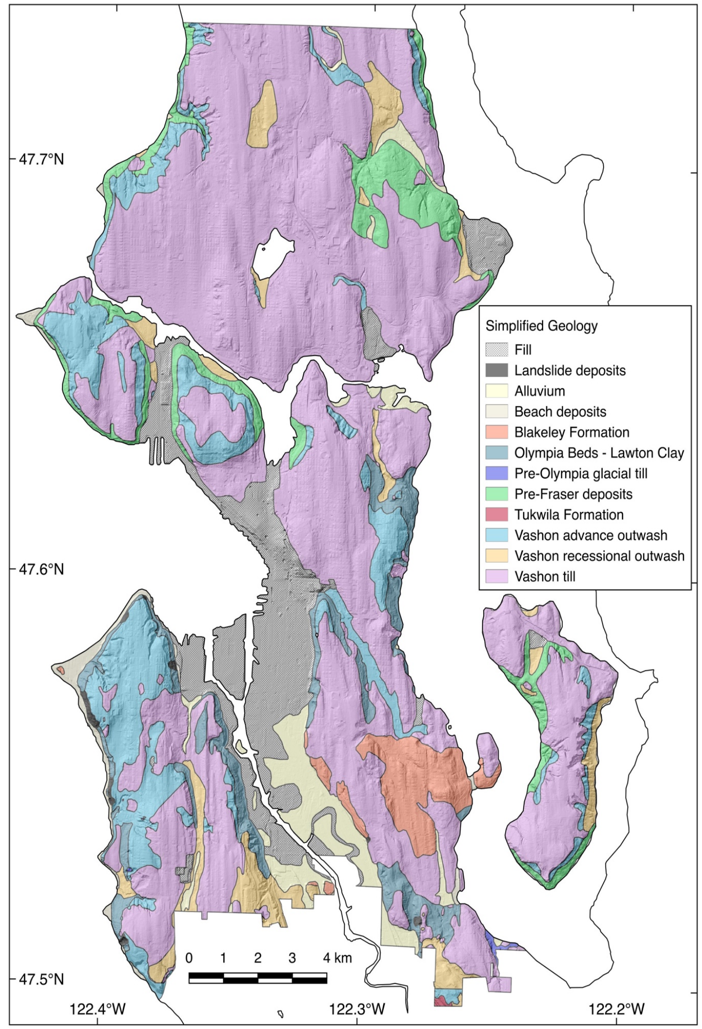
LaHusen, et al. (2016)

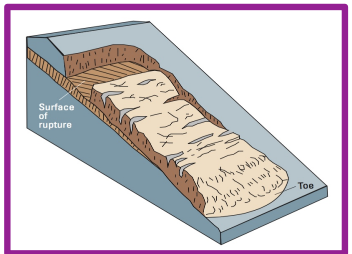

Surface of rupture
Toe

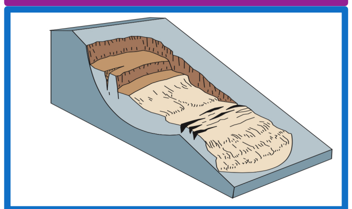


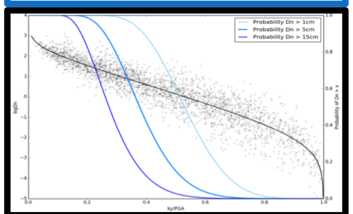


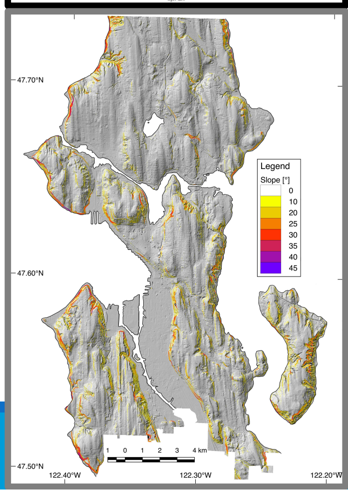

47.70°N
47.60°N
47.50°N
Legend
Slope [°]
0
10
20
25
30
35
40
45
1 0 1 2 3 4 km
122.40°W
122.30°W
122.20°W

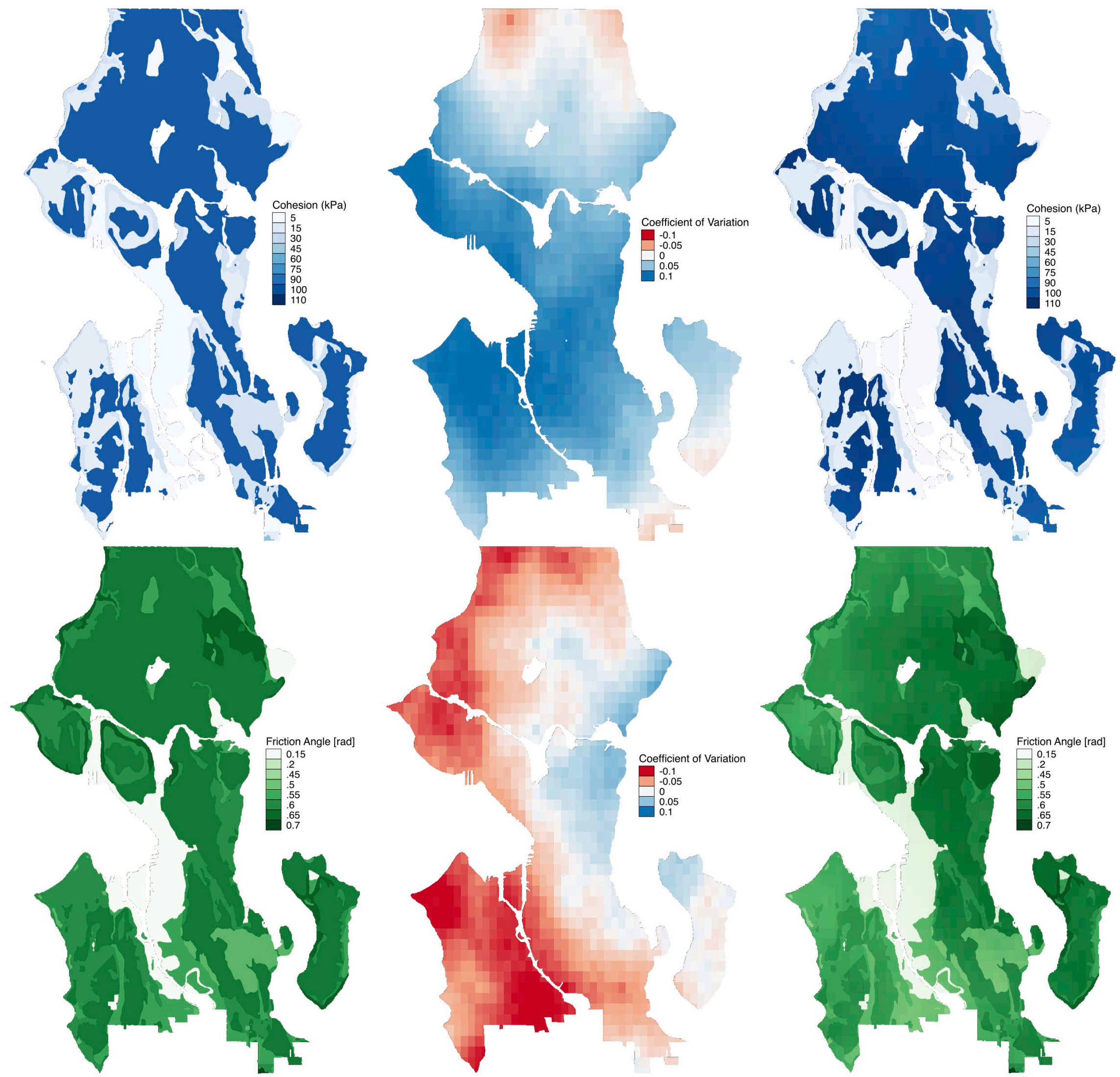

47.7°N
47.6°N
47.5°N
122.4°W
122.3°W
122.2°W
0 1 2 3 4 km
Simplified Geology
Fill
Landslide deposits
Alluvium
Beach deposits
Blakeley Formation
Olympia Beds - Lawton Clay
Pre-Olympia glacial till
Pre-Fraser deposits
Tukwila Formation
Vashon advance outwash
Vashon recessional outwash
Vashon till



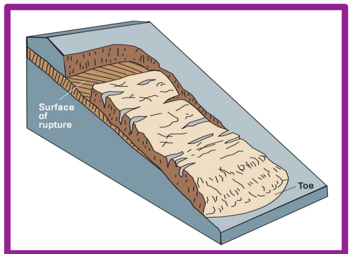


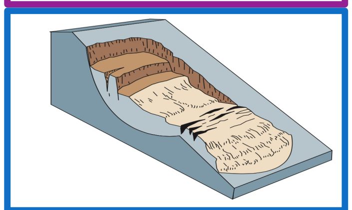


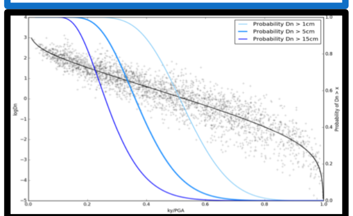


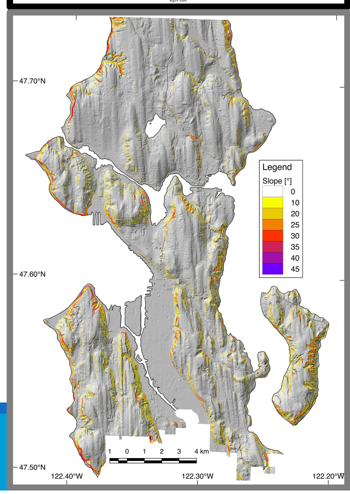


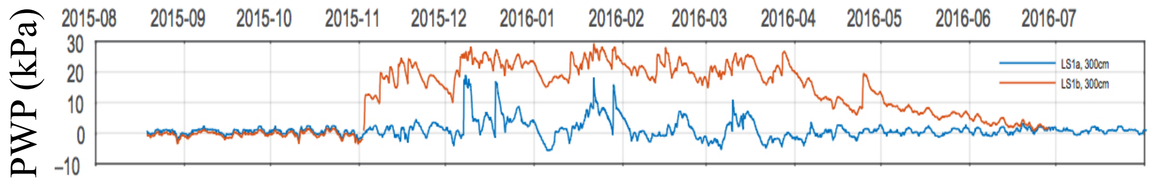
Harp et al., 2008



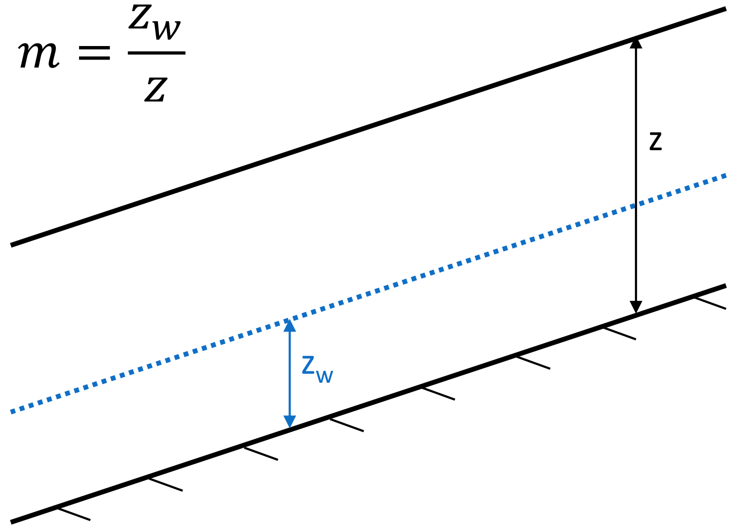




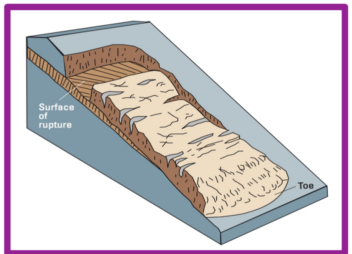


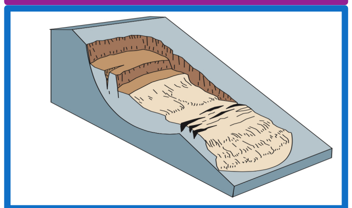


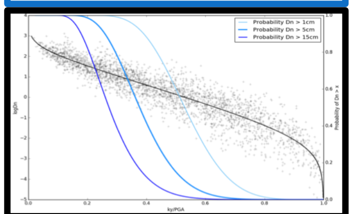
$$m = \frac{z_w}{z}$$

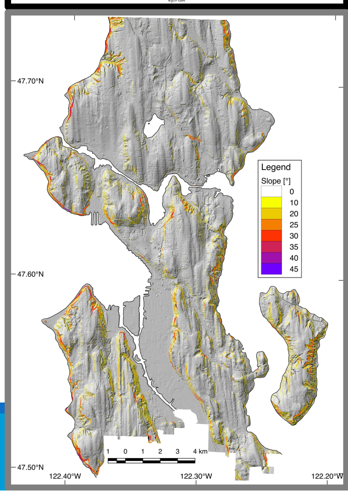


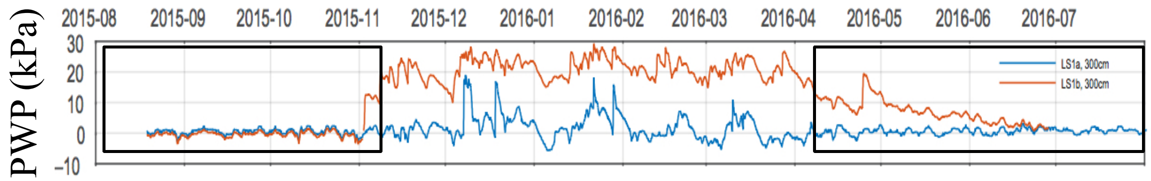
Smith et al., 2017; Harp et al., 2008





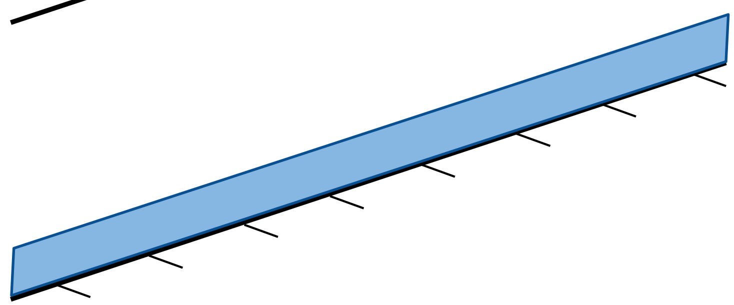




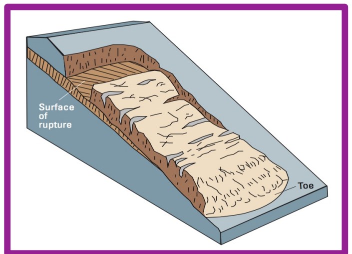


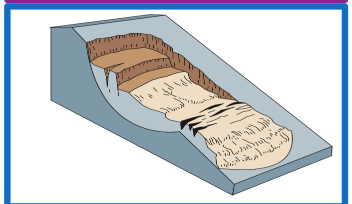
DRY:

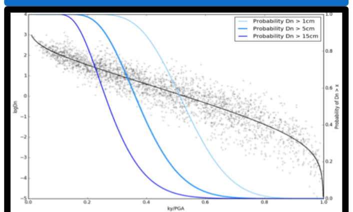
$m = 0 \; - 0.2$

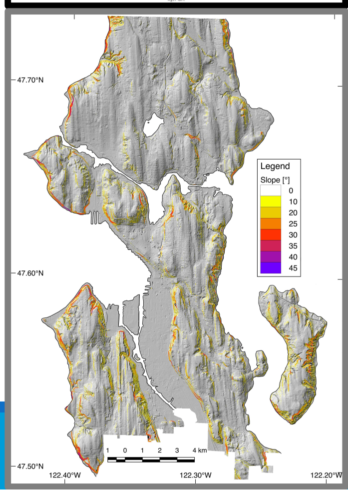


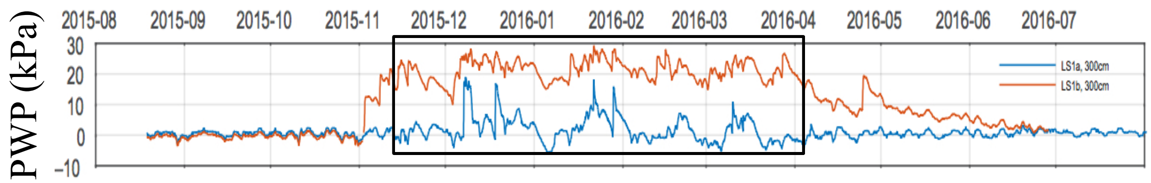
Smith et al., 2017; Harp et al., 2008





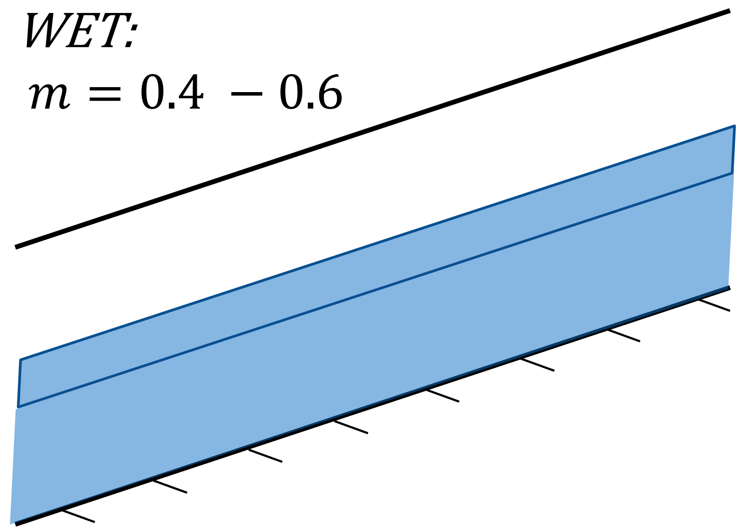






WET:

$m = 0.4 - 0.6$



Smith et al., 2017; Harp et al., 2008