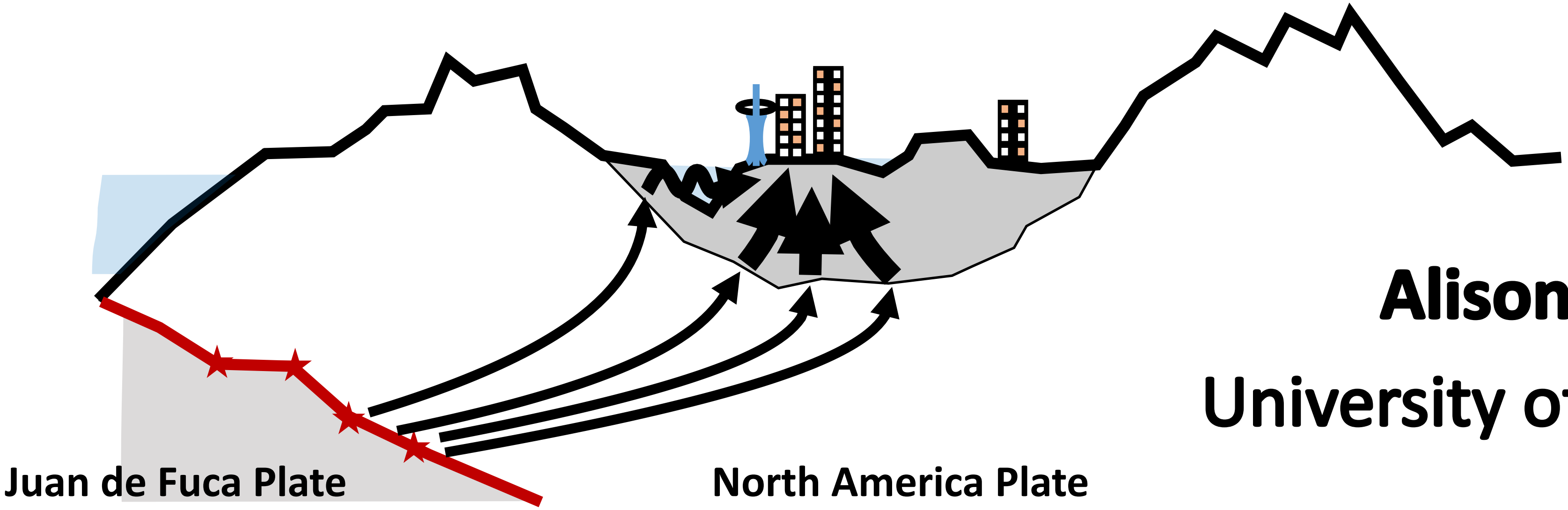
M9 Cascadia subduction zone earthquakes and landscapes – *how will the hillslopes handle the big one?*



Alison Duvall

University of Washington

NSF Hazards SEES EAR-1331412

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
[2]U.S. Geological Survey, Seattle, WA
[3]Southern California Earthquake Center, University of Southern California

NSF Hazards SEES EAR-1331412

NSF
UNIVERSITY of WASHINGTON
Quaternary Research Center
USGS science for a changing world

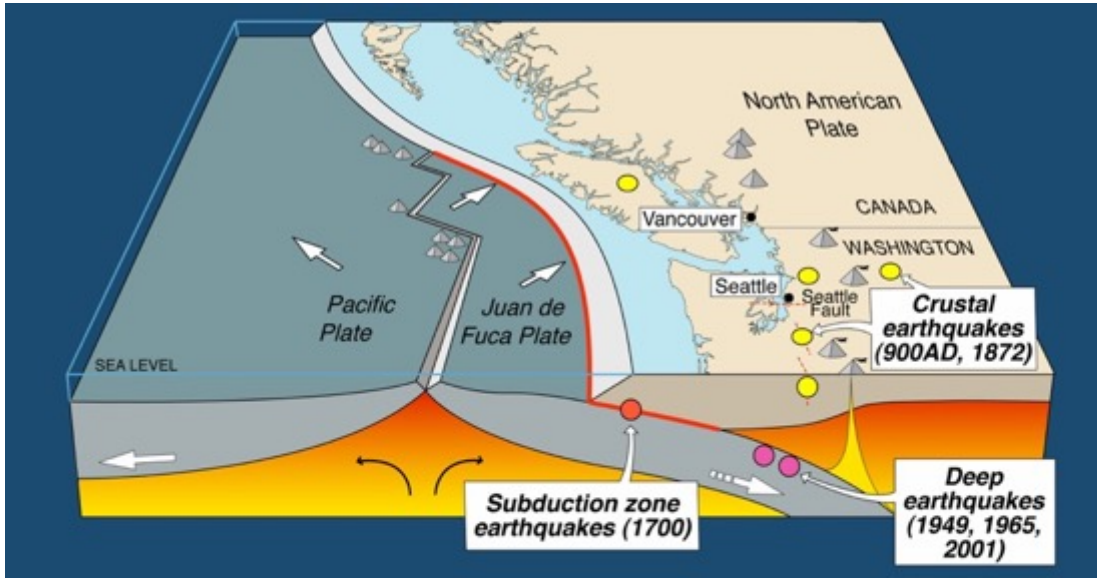
Megathrust Earthquakes in Cascadia

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

-Coastal subsidence

-Tsunami records

-Offshore turbidites (geology deposit of turbidity currents)



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]

ANNALS OF SEISMOLOGY
JULY 20, 2015 ISSUE

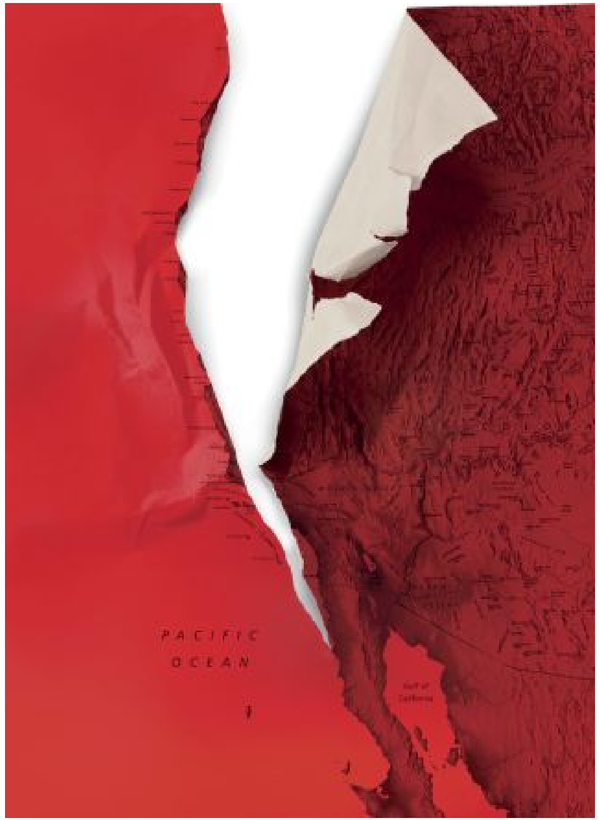
THE REALLY BIG ONE

An earthquake will destroy a sizable portion of the coastal Northwest. The question is when.

BY KATHRYN SCHULZ

The next full-margin rupture of the Cascadia subduction zone will spell the worst natural disaster in the history of the continent.

ILLUSTRATION BY CHRISTOPH NIEMANN; MAP BY ZIGGYMAJ / GETTY



When the 2011 earthquake and tsunami struck Tohoku, Japan, Chris Goldfinger was two hundred miles away, in the city of Kashiwa, at an international meeting on seismology. As the shaking started, everyone in the room began to laugh. Earthquakes are common in Japan—that one was the third of the week—and the participants were, after all, at a seismology conference. Then everyone in the room checked the time.

The M9 Project

An ambitious beginning…

Reduce the **catastrophic consequences of Cascadia megathrust earthquakes** through **advances in science, engineering, & planning**

The M9 Project

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Reduce the **catastrophic consequences of Cascadia megathrust earthquakes** through **advances in science, engineering, & planning**

The M9 Project was **unique** in terms of…

The M9 Project

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… presenting multiple M9 earthquake realizations, framed probabilistically

The M9 Project

An ambitious beginning…

Reduce the **catastrophic consequences of Cascadia megathrust earthquakes** through **advances in science, engineering, & planning**

The M9 Project was **unique** in terms of…

… presenting multiple M9 earthquake realizations, framed probabilistically

…bringing together a diverse team of experts spanning the academic, public, & non-profit sectors

The M9 Project

team members

Project Personnel:







Alison Duvall, PI
Dan Abramson, co-PI
Jeff Berman, co-PI
Ann Bostrom, co-PI
John Vidale, co-PI
Art Frankel, USGS
Erin Wirth, USGS
Kate Allstadt, Postdoctoral researcher
Jamie Mooney, WA Sea Grant
Marc Eberhard
Frank Gonzalez
Peter Guttorp
Steve Kramer
Randall LeVeque,
David Montgomery
Joseph Wartman
Joan Gomberg, USGS
Brian Atwater, USGS
Penelope Dalton, UW and WA Sea Grant

Collaborating organizations:

Sea Grant Washington
City of Seattle Seattle Police Department
Washington State Department of Natural Resources, Peter Goldmark · Commissioner of Public Lands
USGS science for a changing world
PNSN Pacific Northwest Seismic Network
Washington State Department of Transportation, Paula J. Hammond, P.E., Secretary of Transportation
State of Washington Military Department Emergency Management Division
cigiden
City of Seattle Department of Planning & Development
Oregon Department of Geology and Mineral Industries
Cascadia Region Earthquake Workgroup CREW Ahead of the Wave
Massey University
GNS Science
NSF NCALM The National Center for Airborne Laser Mapping, University of Houston • University of California, Berkeley

The M9 Project

Graduate Students (Past & Present)

Earth & Space Sciences

Elizabeth Davis
Carrie Garrison-Laney
Jiangang Han
Sean LaHusen
Ian Stone
Mika Thompson

Civil & Environmental Engineering

Alex Grant
Mike Greenfield
Nasser Marafi
Andrew Winter
Gloria de Zamacona Cervantes
Xinsheng Qin

Urban Design & Planning

Lan Nguyen
Adnya Sarasmita
Peter Dunn

Evans School of Public Policy & Governance

Alicia Ahn
Drew Bouta

Applied Math

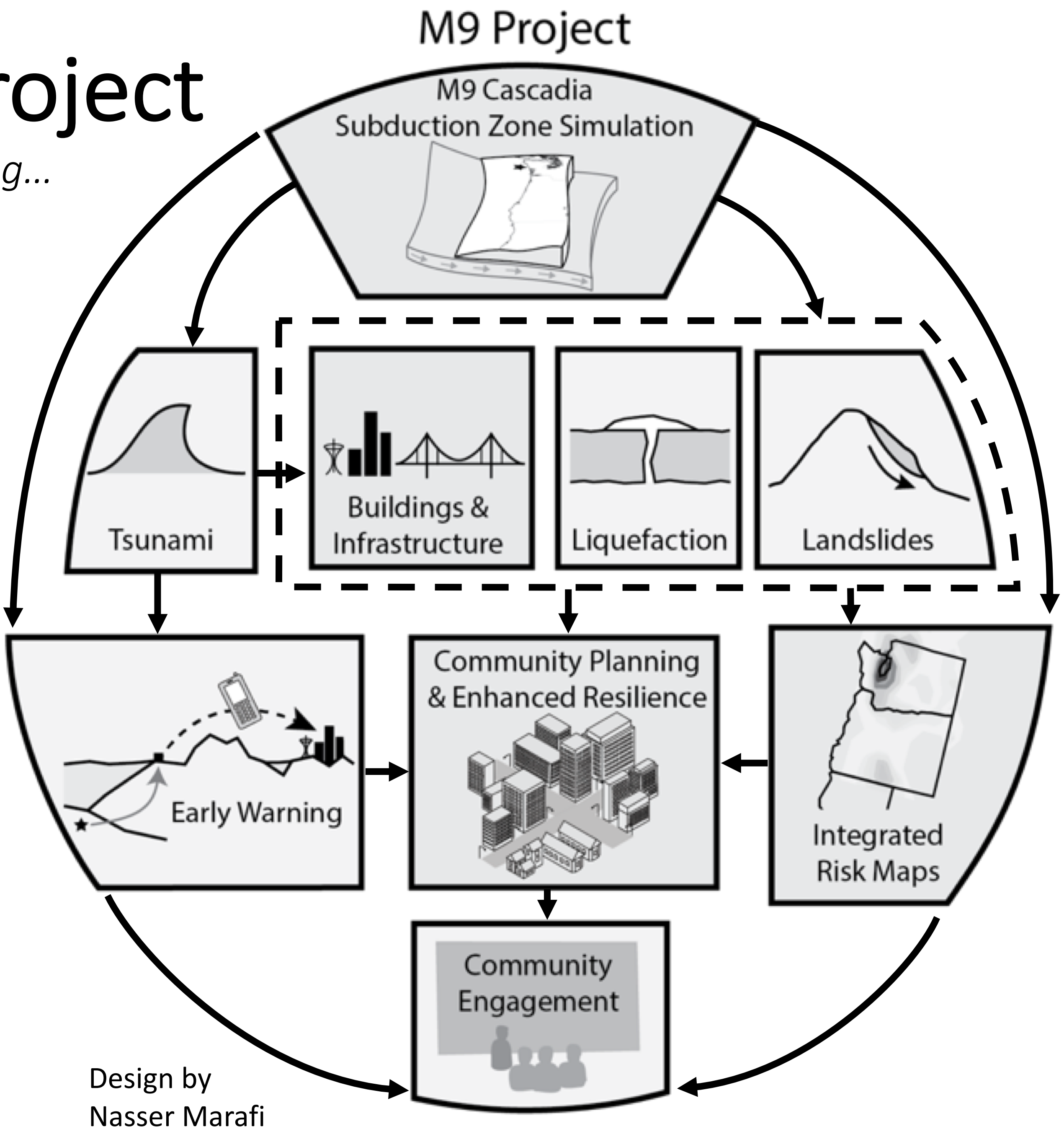
Donsub Rim
Brisa Davis

Statistics

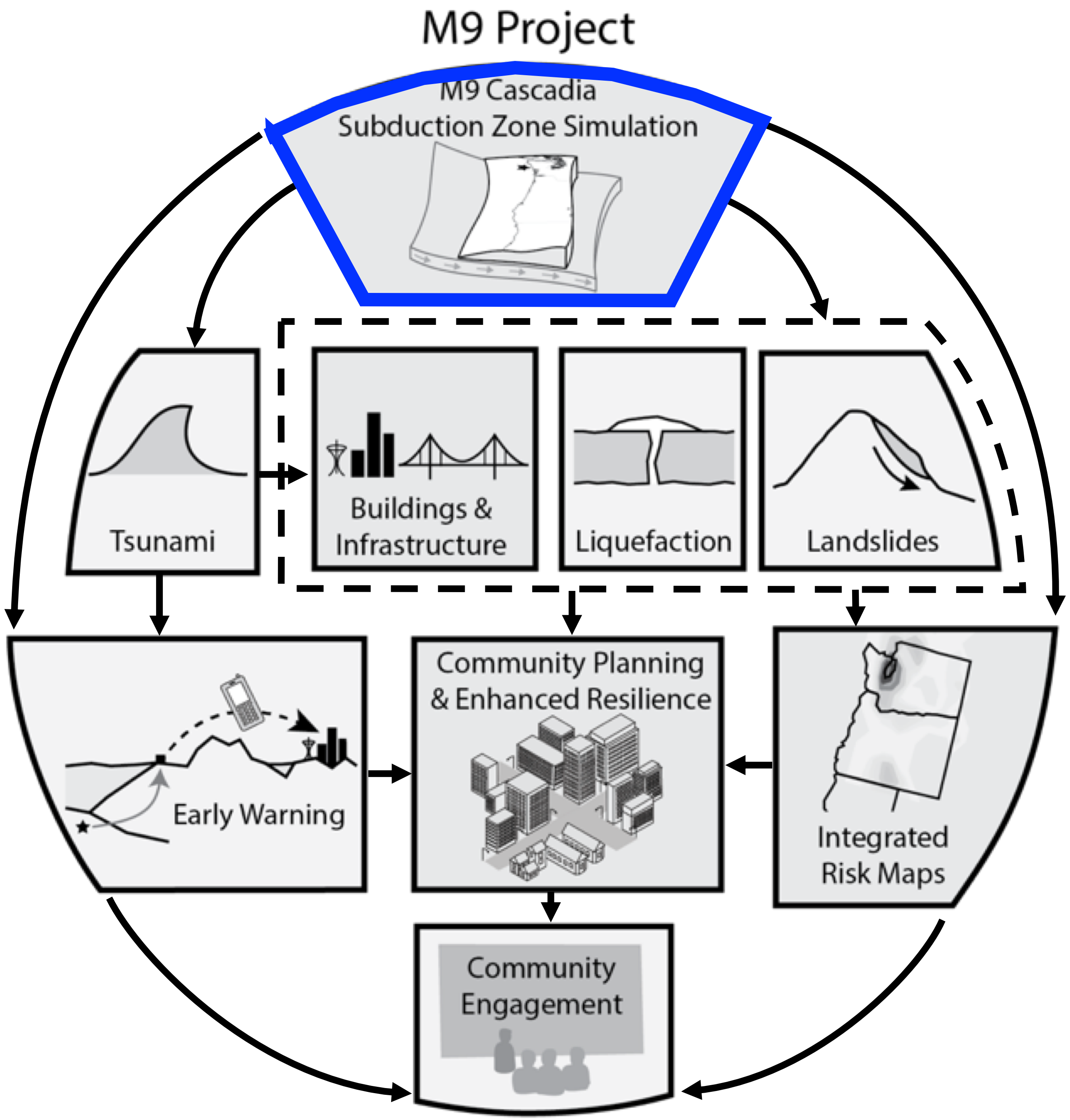
Johnny Paige
Max Schneider

The M9 Project

An ambitious beginning…

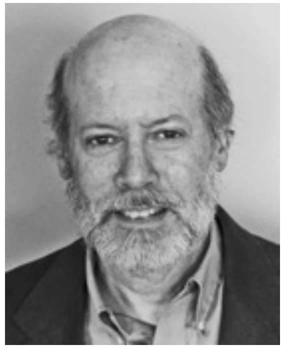


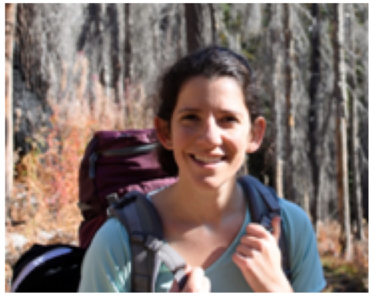
Design by
Nasser Marafi



3-D Simulations

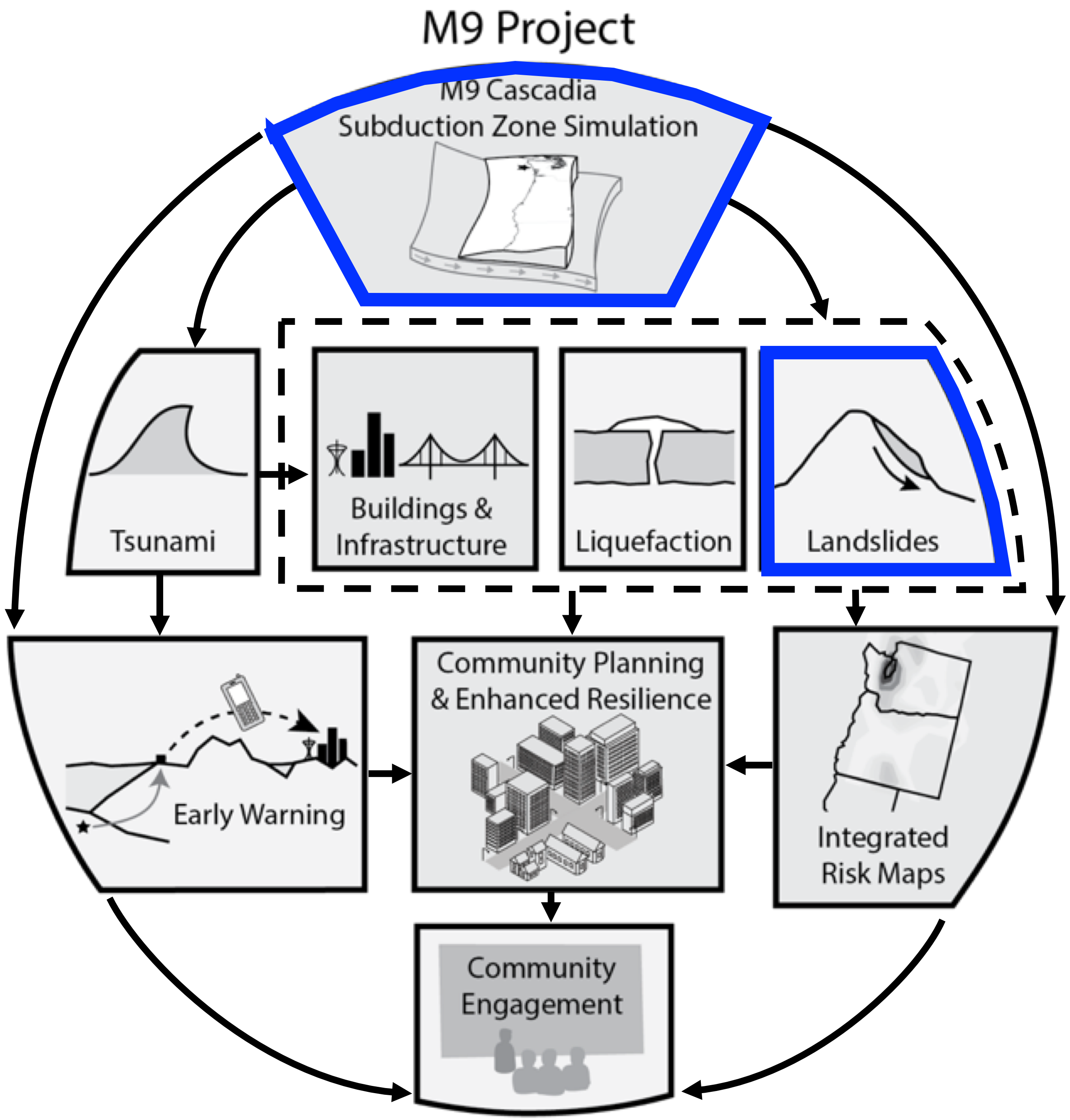
Accurately captures rupture directivity, basin amplification, edge-converted waves, duration





Art Frankel Erin Wirth

Broadband Synthetic Seismograms



Landscape response

Coseismic landslides

Landscape evolution

50+ M9 Earthquake Scenarios

Frankel et al., 2018, BSSA   Wirth et al., 2018, BSSA

DESIGNSAFE-CI
NHERI: A NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

https://www.designsafe-ci.org

Slide c/o Erin Wirth
& Nasser Marafi

50+ M9 Earthquake Scenarios

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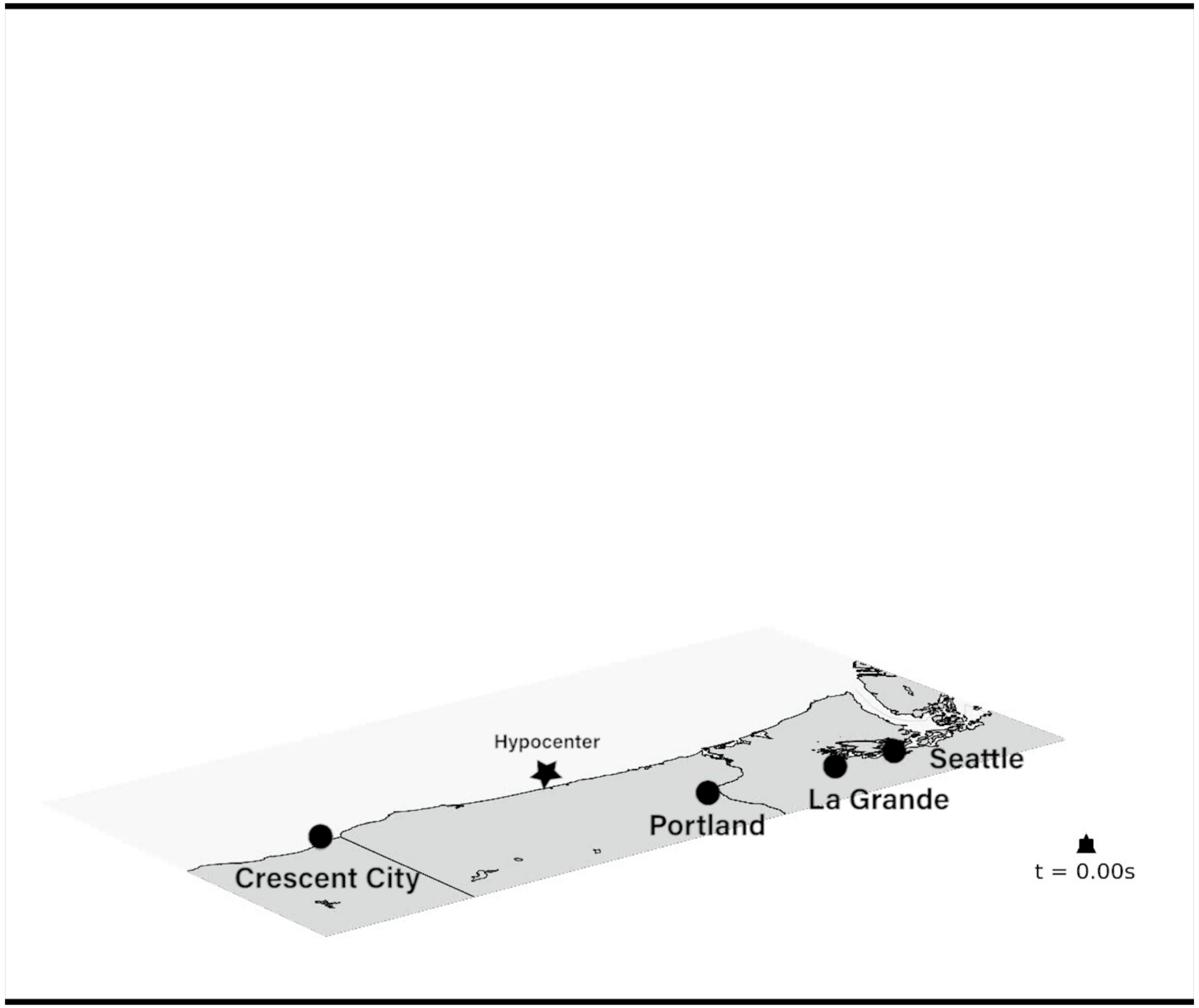

Slide c/o Erin Wirth
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50+ M9 Earthquake Scenarios

Frankel et al., 2018, BSSA   Wirth et al., 2018, BSSA

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https://www.designsafe-ci.org

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

★ What are the key rupture parameters?

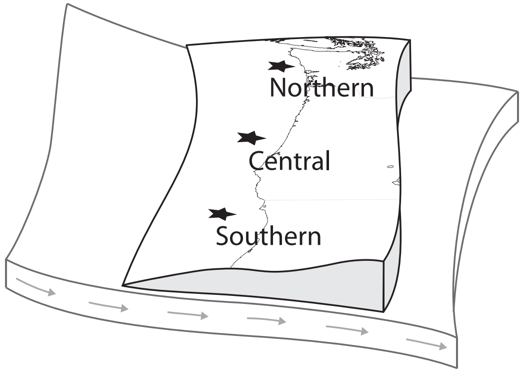
USGS
science for a changing world

Slide c/o Erin Wirth & Nasser Marafi

Key Rupture Parameters

Key Rupture Parameters

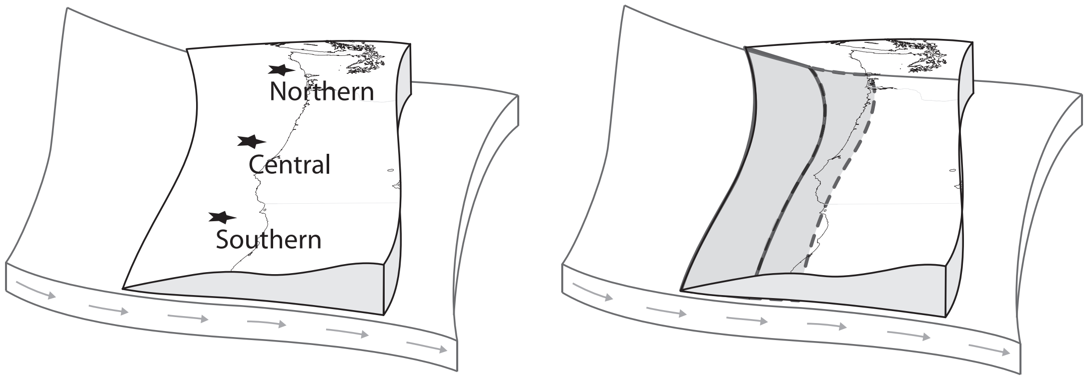
- Hypocenter Location (i.e. starting point)



Key Rupture Parameters

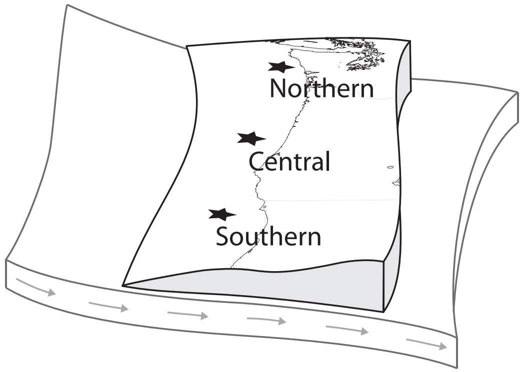
- Hypocenter Location
- Down-dip Rupture Limit

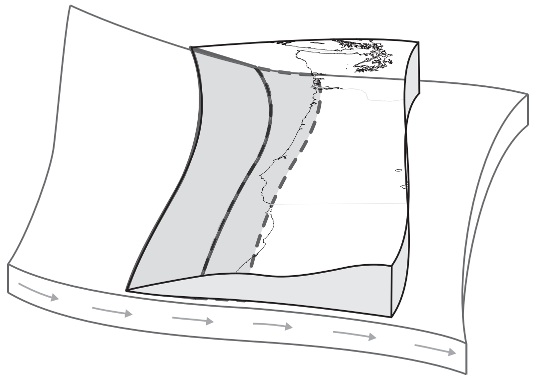
(i.e. the inland, eastward extent)

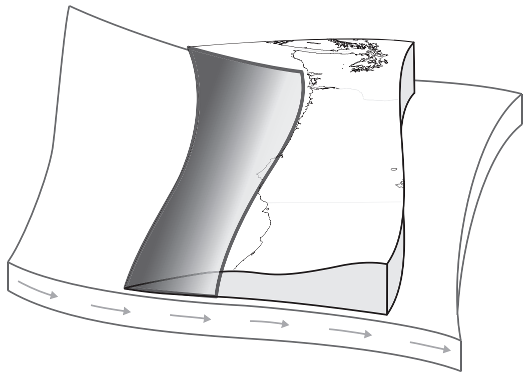


Key Rupture Parameters

- Hypocenter Location
- Down-dip Rupture Limit
- Slip Distribution



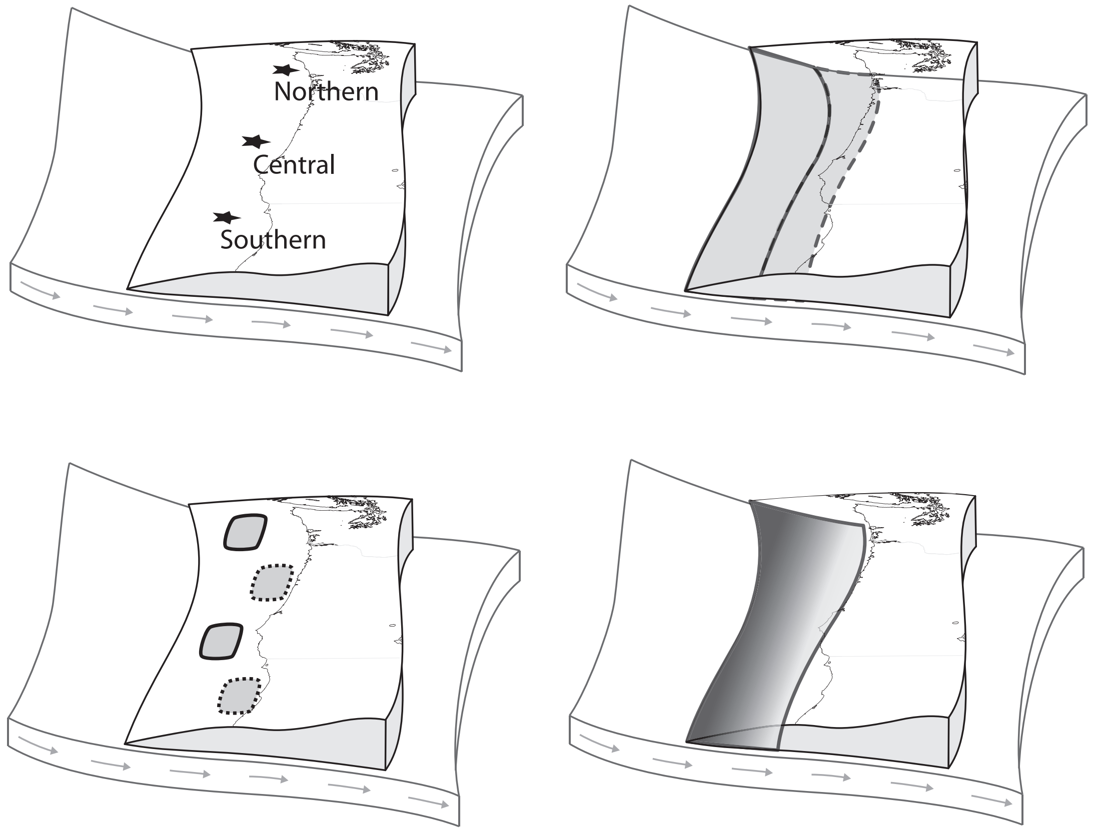




Key Rupture Parameters

- Hypocenter Location
- Down-dip Rupture Limit
- Slip Distribution
- Subevent Location

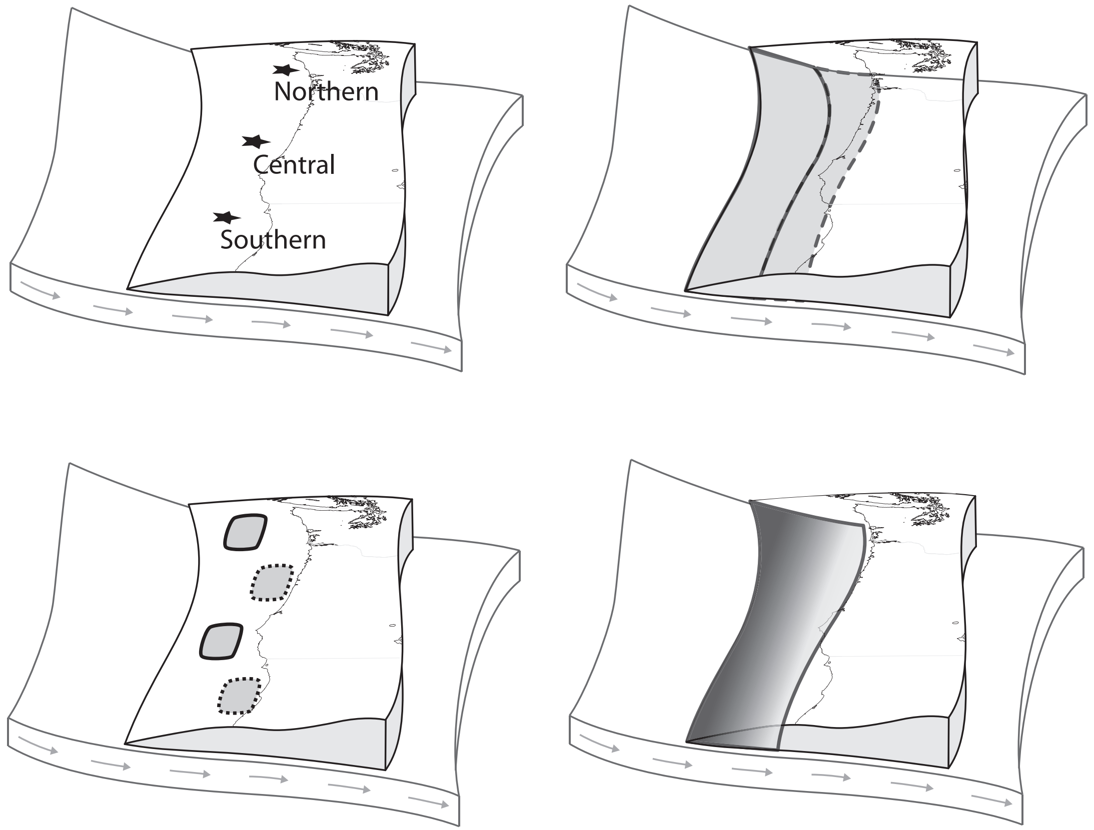
(i.e. the location of strong ground motion generating areas or “sticky patches”)



Key Rupture Parameters

- Hypocenter Location
- Down-dip Rupture Limit
- Slip Distribution*
- Subevent Location

How is ground shaking impacted by these earthquake parameters?



**Background slip and subevents, separately*

Key Rupture Parameters

How is ground shaking impacted by these earthquake parameters?

Main Takeaways:

❖ M9 earthquake simulations for Cascadia capture *a range of possible ground motions*

- Up to a **10x variation in S_a** (at individual sites)

✓Hypocenter Location	Factor of ~10
✓Down-dip Rupture Limit	Factor of ~5
✓Slip Distribution*	Small
✓Subevent Location	Factor of ~10

USGS science for a changing world

**Background slip and subevents, separately*

W

Key Rupture Parameters

How is ground shaking impacted by these earthquake parameters?

Main Takeaways:

❖ In the Seattle basin, rupture directivity effects (i.e., hypocenter location) appear to couple with basin amplification

✓Hypocenter Location	Factor of ~10
✓Down-dip Rupture Limit	Factor of ~5
✓Slip Distribution*	Small
✓Subevent Location	Factor of ~10

USGS science for a changing world

**Background slip and subevents, separately*

W

Key Rupture Parameters

How is ground shaking impacted by these earthquake parameters?

Main Takeaways:

❖ Constraining high stress drop subevents (i.e., location, magnitude, stress drop) is *critical to improving seismic hazard assessment*

✓Hypocenter Location	Factor of ~10
✓Down-dip Rupture Limit	Factor of ~5
✓Slip Distribution*	Small
✓Subevent Location	Factor of ~10

**Background slip and subevents, separately*

The M9 Project

Impact and Results

<u>Implications of the 50 Cascadia earthquake simulations</u>

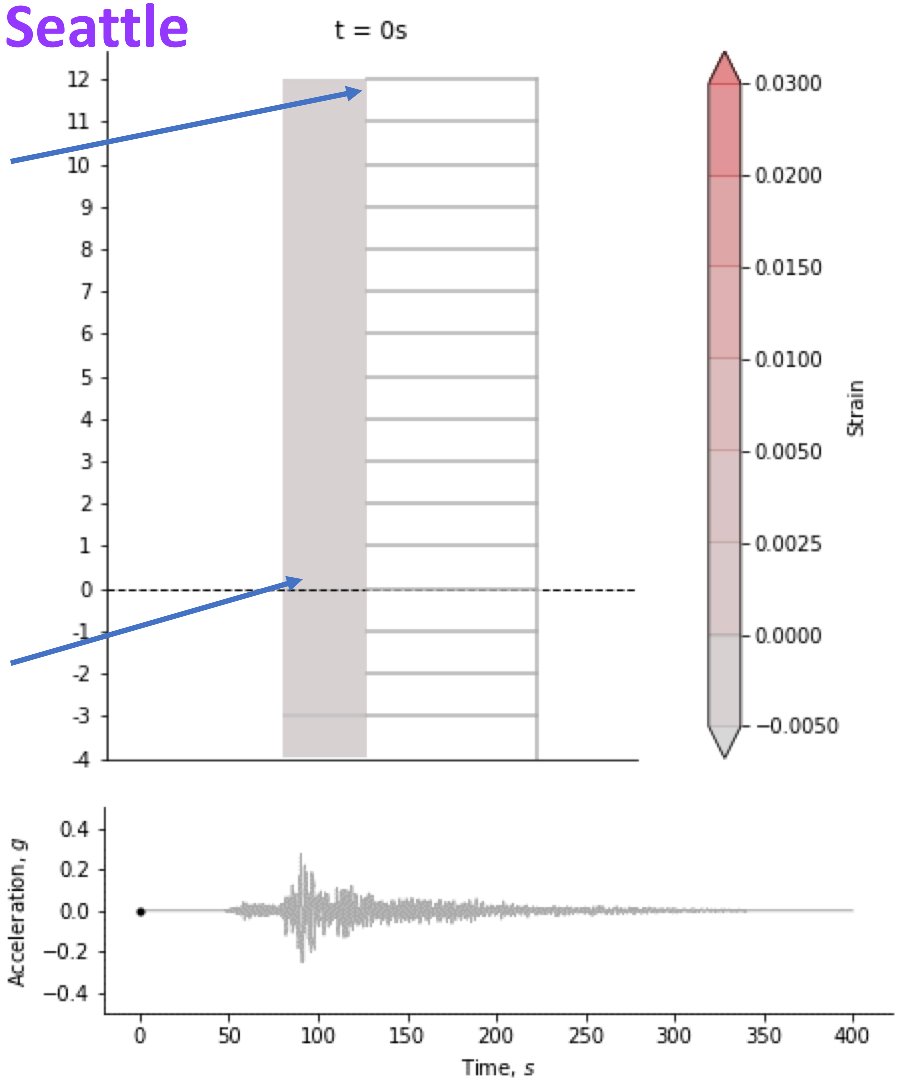
- Found the **collapse risk** of modern reinforced concrete shear wall buildings in the M9 CSZ to be larger than anticipated

Structural Response Realization Rupturing Towards Seattle

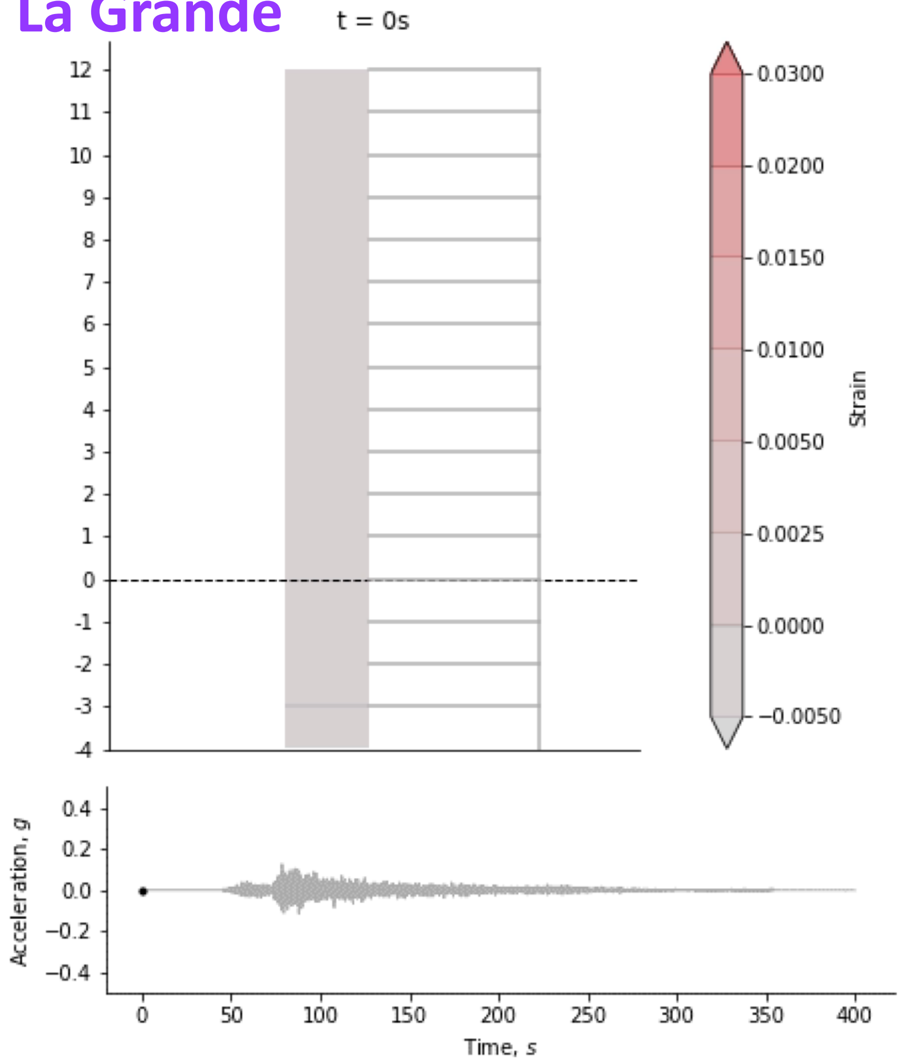
Seattle

Likely Slab-Column/Wall Failure

Steel Reinforcing Yielding



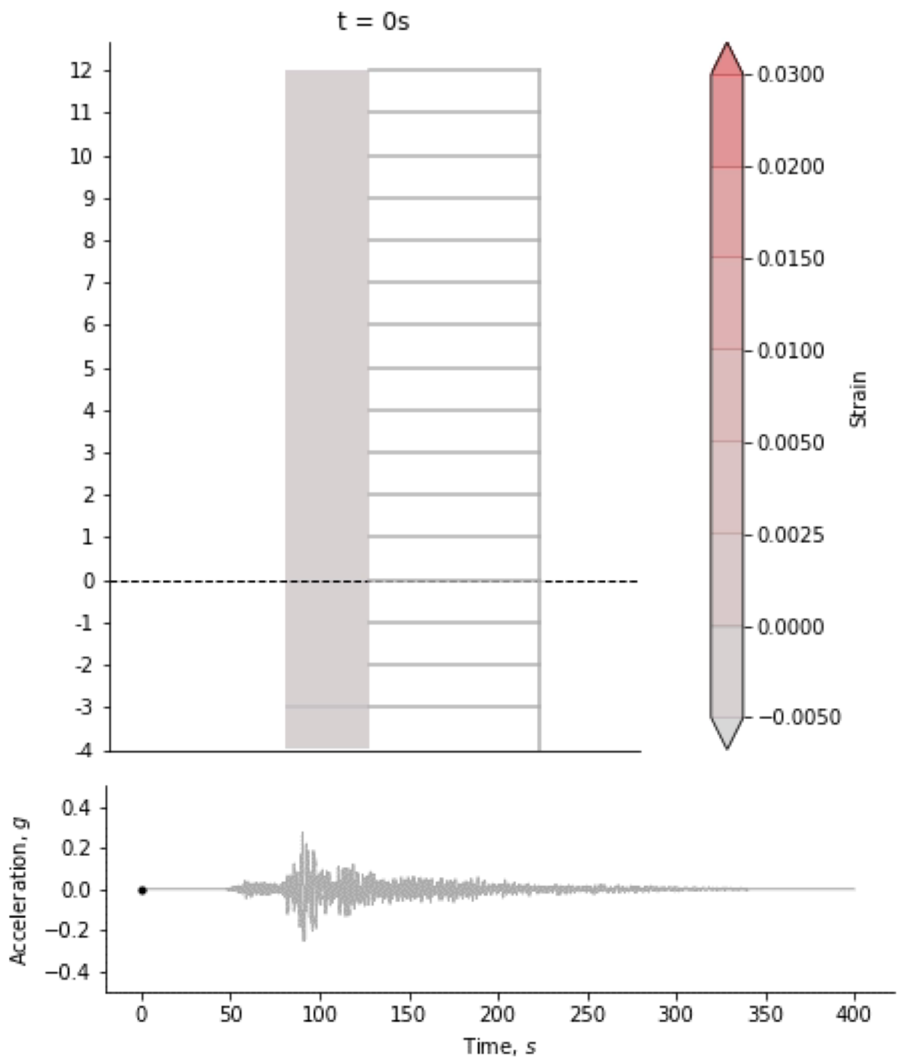
La Grande



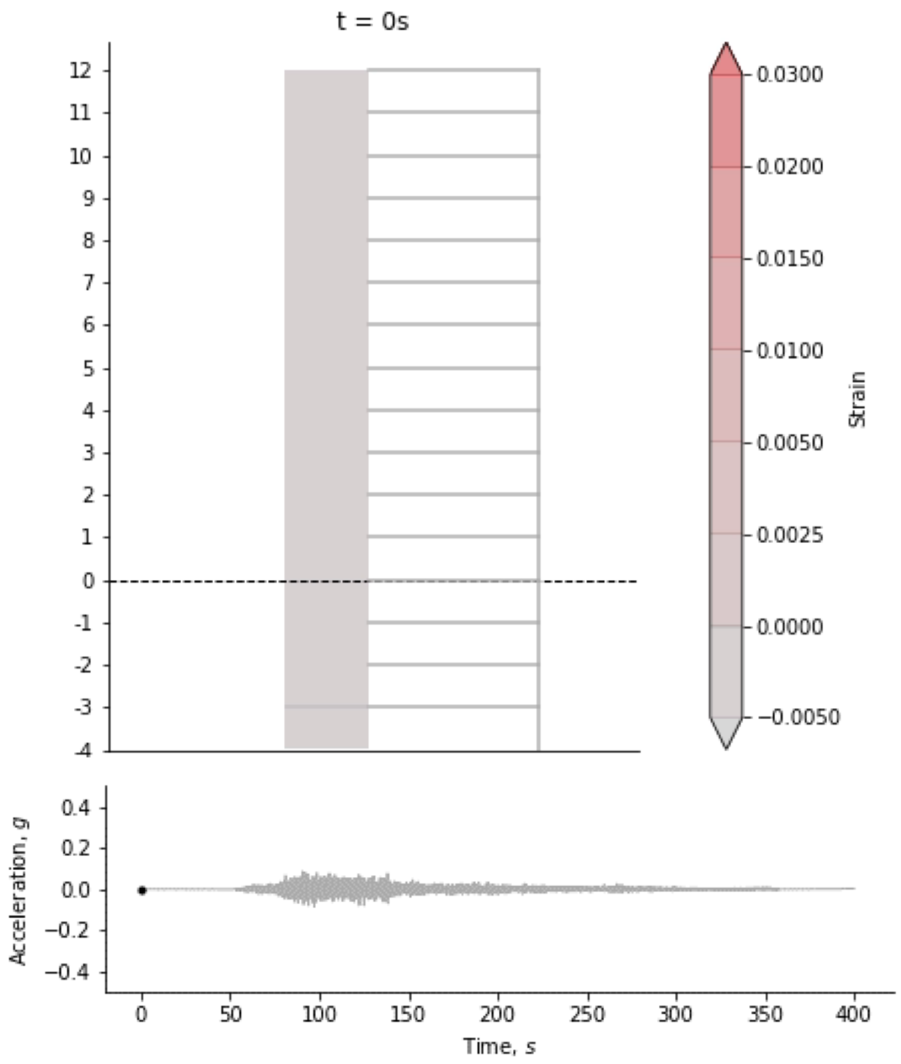
Slide c/o Jeff Berman

Structural Response for Seattle

Rupturing **Towards** Seattle



Rupturing **Away** from Seattle



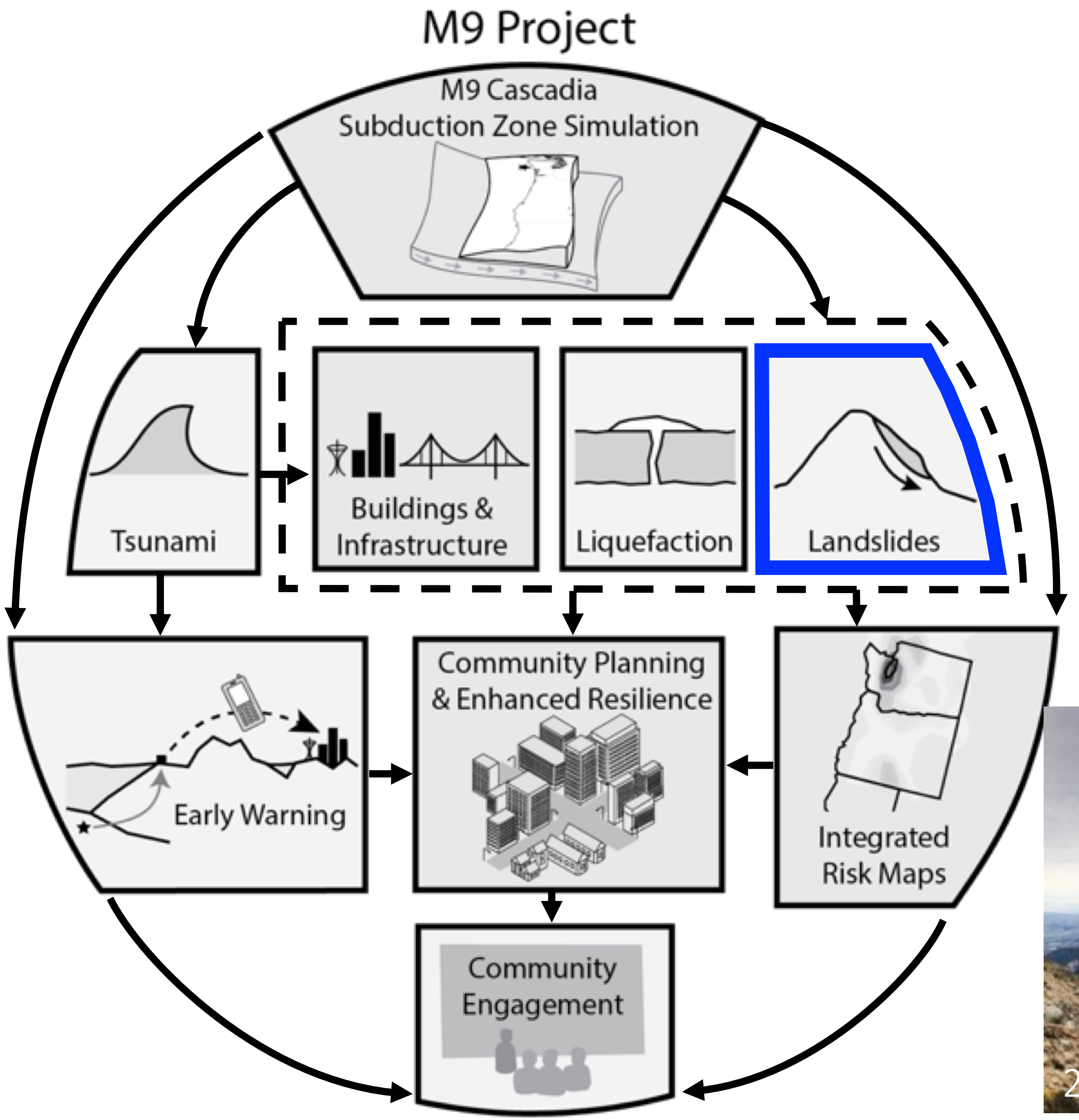
Slide c/o Jeff Berman

The M9 Project

Impact and Results

Implications of the 50 Cascadia earthquake simulations

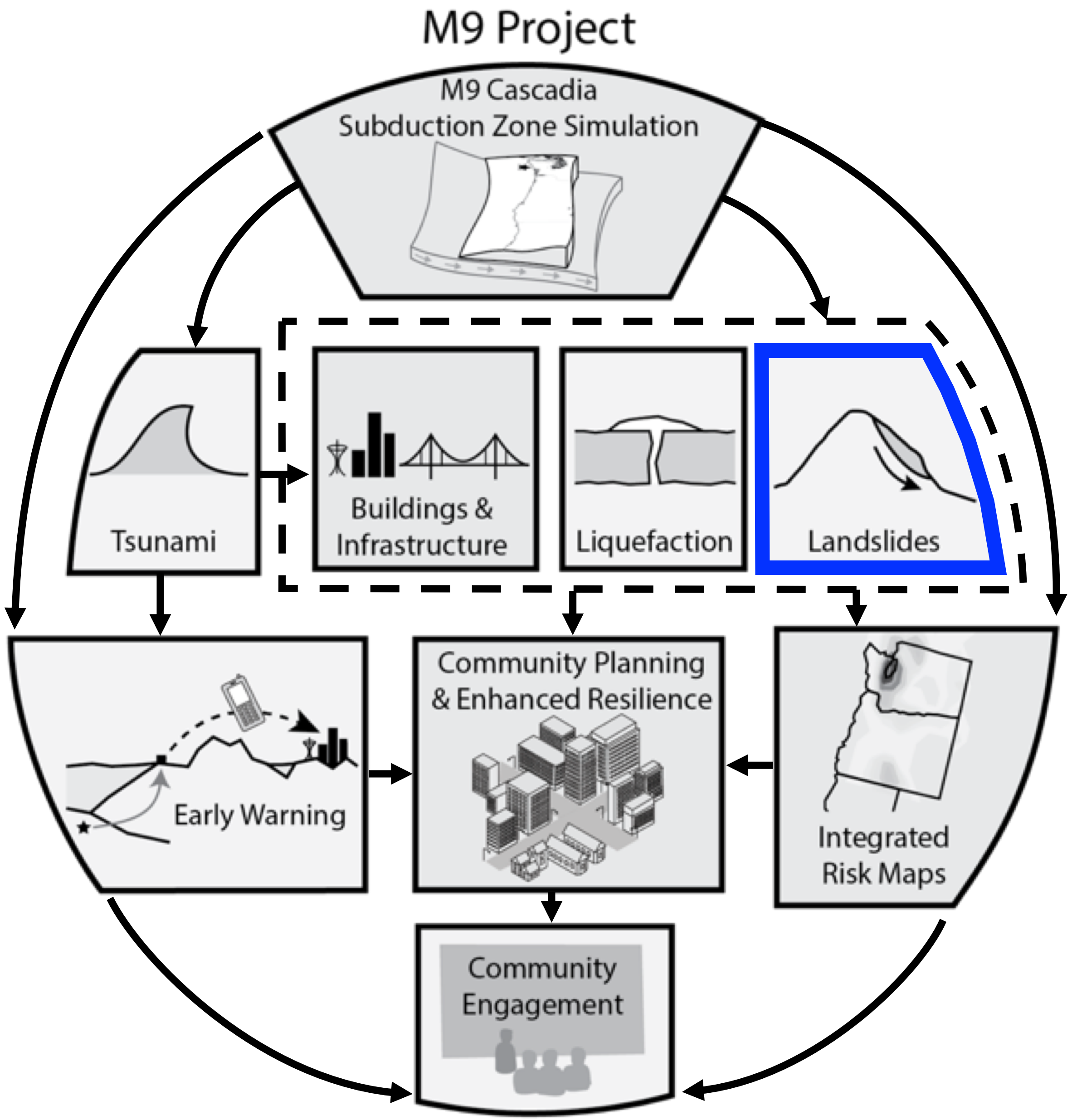
- Found the **collapse risk** of modern reinforced concrete shear wall buildings in the M9 CSZ to be larger than anticipated
- M9 results informed recommendations for the **design of tall buildings** in Seattle
- Created **landslide inventory** for Oregon Coast Range & advanced **modeling of coseismic landslides**



Landscape response

Coseismic Landslides

Landscape Evolution



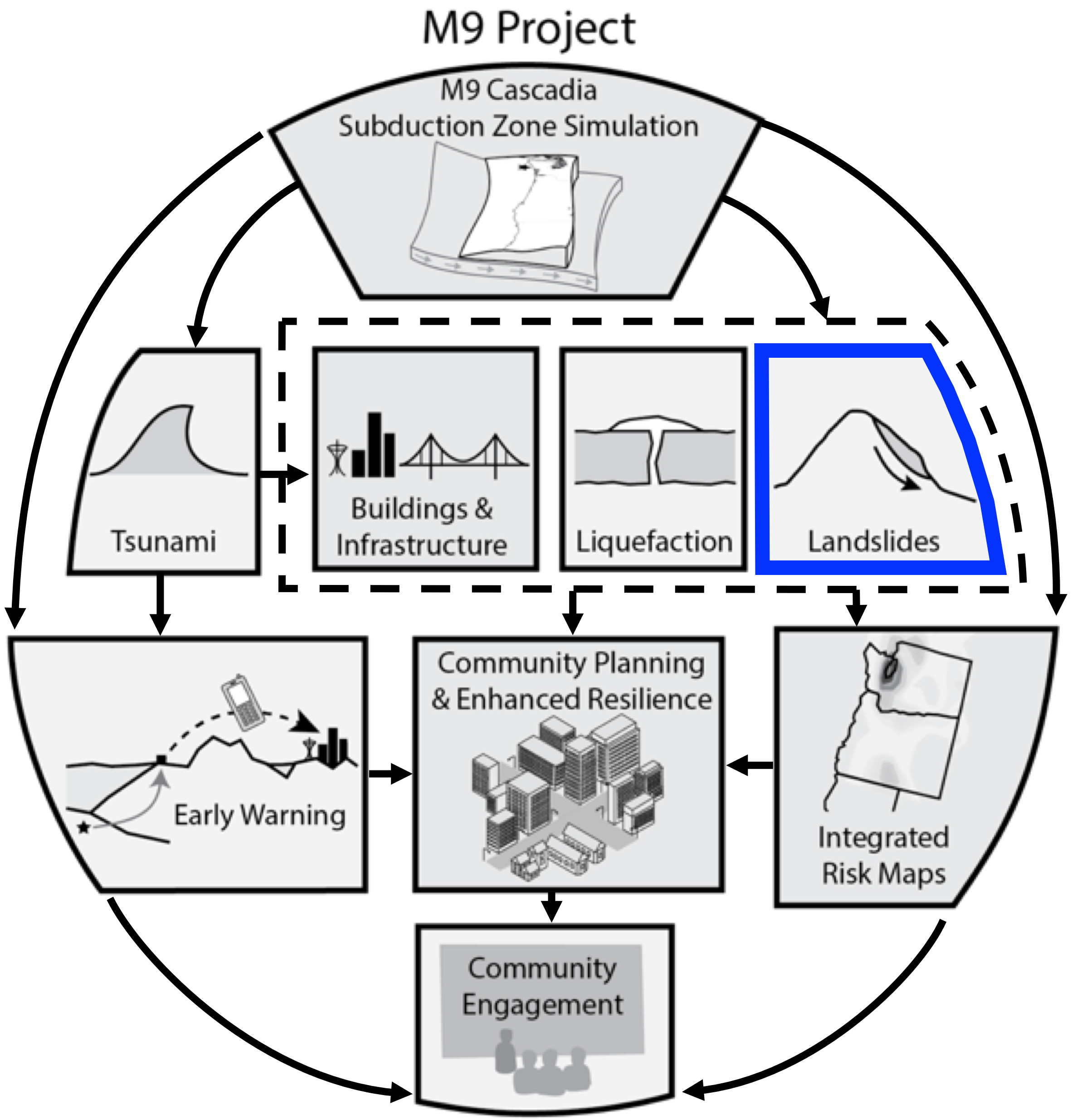
Landscape response

Coseismic Landslides

Landscape Evolution

Alex Grant: USGS

- Predict coseismic displacement from modeled strong ground motion



Landscape response

Coseismic Landslides

Landscape Evolution

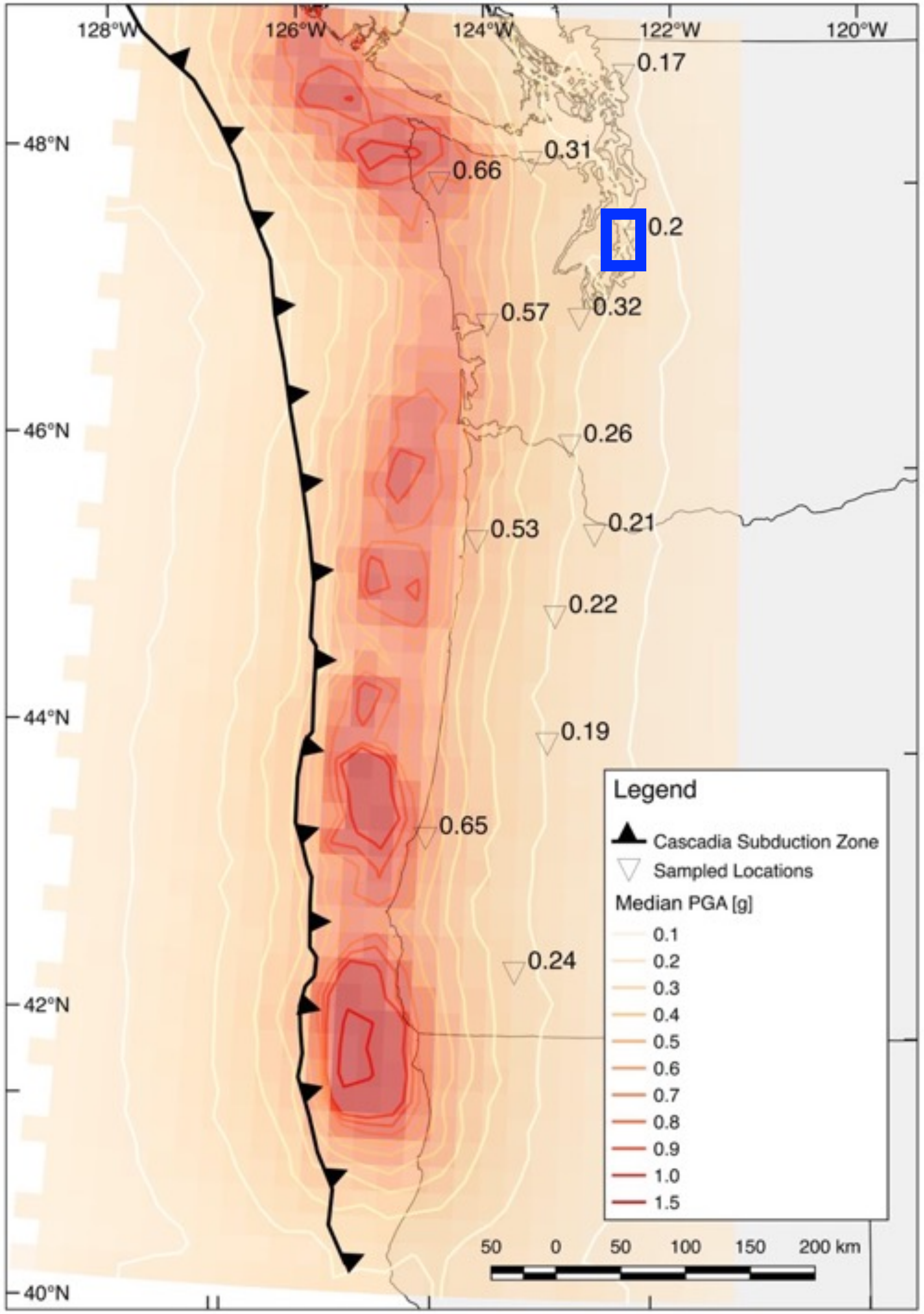
Sean LaHusen: UW

- Map and date Cascadia coseismic slides (1700 and earlier)

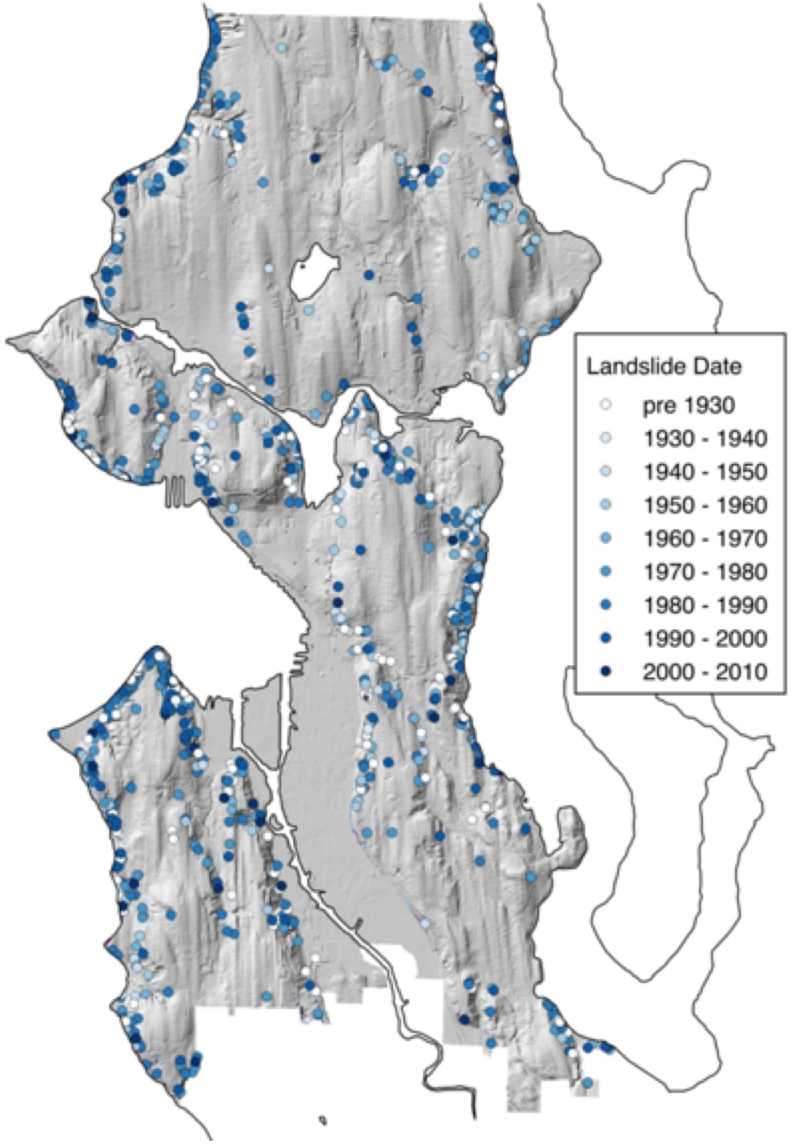
M9 Coseismic Landslides

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



Seattle’s Unstable Hillslopes



Sources: Seattle Times, https://data.seattle.gov/dataset/City- Of-Seattle-Environmentally-Critical-Areas/zwze-9nv3

Seattle Landslide Inventory (showing events through 2010)

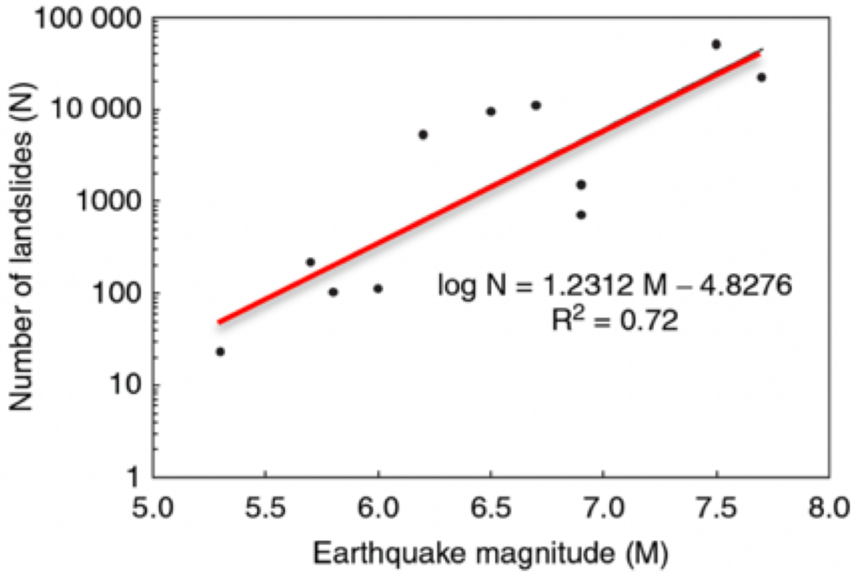
ANNALS OF SEISMOLOGY JULY 20, 2015 ISSUE

THE REALLY BIG ONE

An earthquake will destroy a sizable portion of the coastal Northwest. The question is when.

By Kathryn Schulz

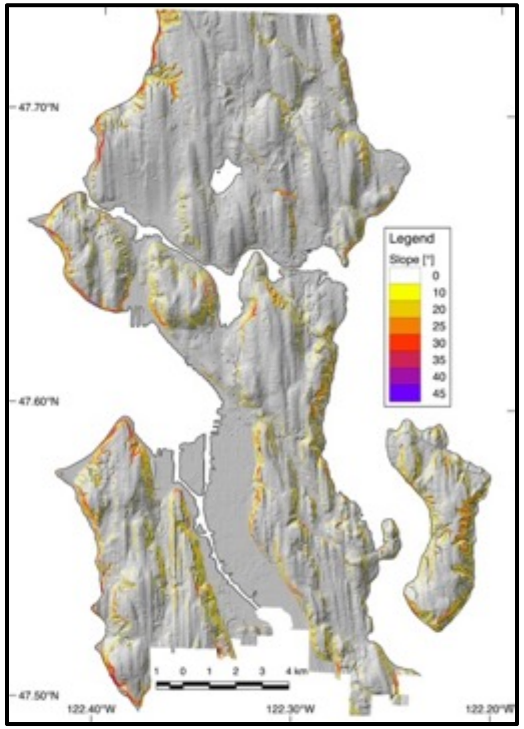
"The shaking from the Cascadia quake will set off landslides throughout the region—*up to thirty thousand of them in Seattle alone*, the city's emergency-management office estimates."



???

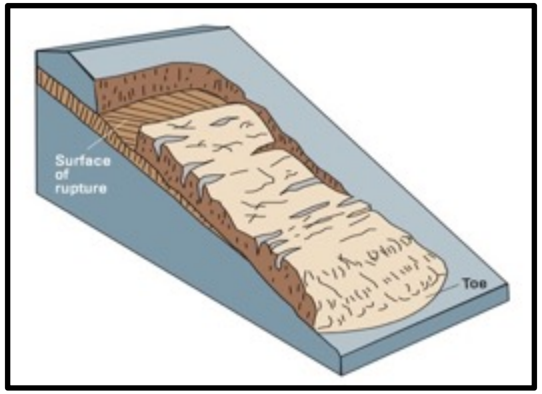
Sources: Kathryn Schulz, The New Yorker; Keefer (2002)

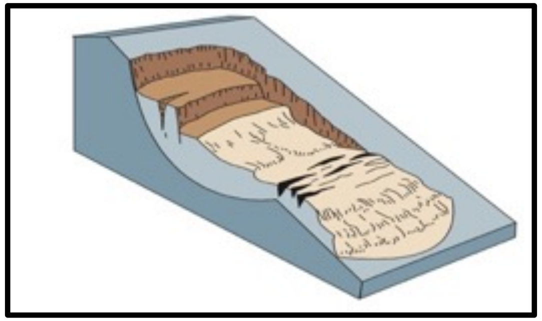
M9 Coseismic Landslides



Place

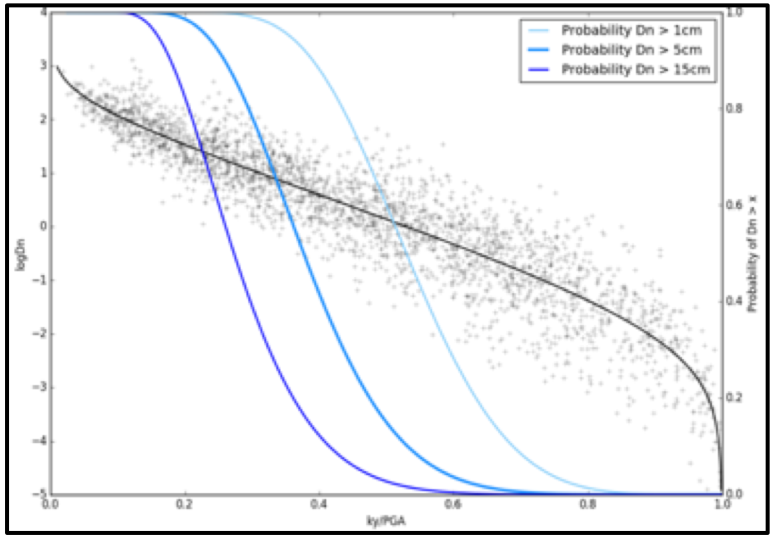
Material Strength
Ground Saturation





Landslide Models

Newmark Analysis

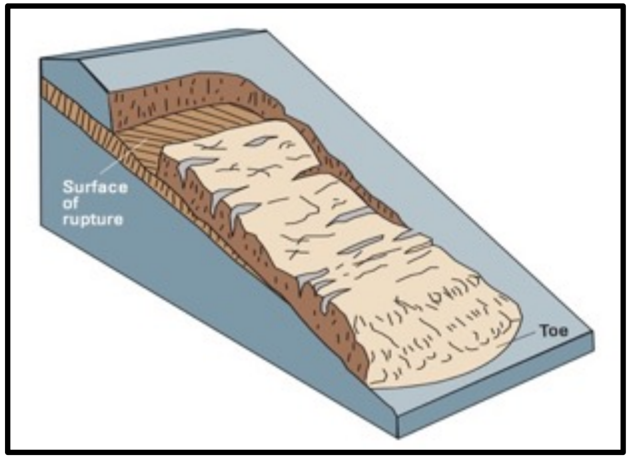


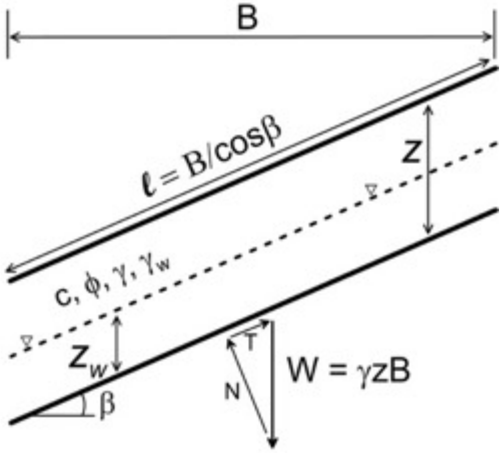
Hazard Model

Coseismic Block Displacement
Shaking Intensities

M9 Coseismic Landslides

Shallow (translational) slides



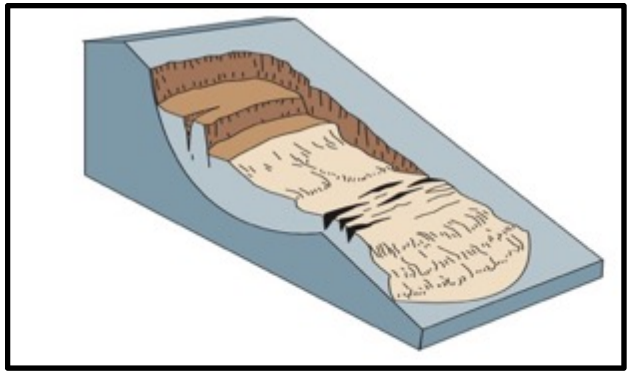


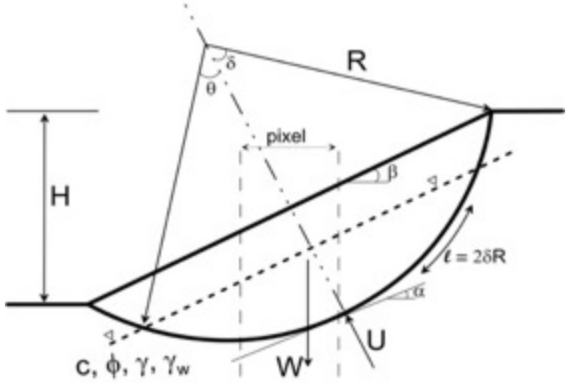
$$FS = \frac{c}{z sin\beta cos\beta} + \left(1 - m\frac{\gamma_w}{\gamma}\right)\frac{tan\phi}{tan\beta}$$

Factor of Safety Calculation (Resisting Forces vs. Driving Forces)

$\mathbf{k_y}$

Deep-seated (rotational) slides



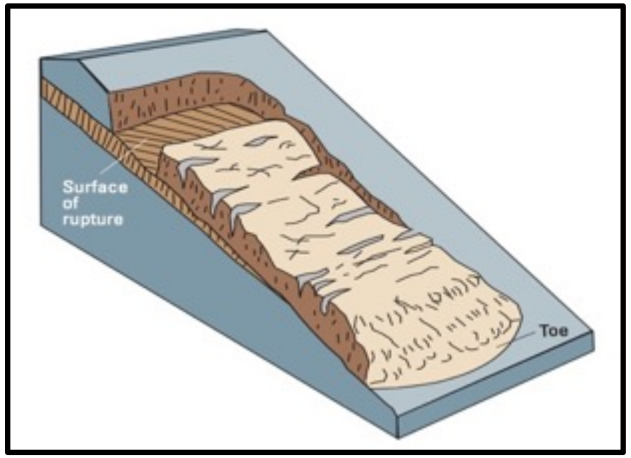


$$FS = \frac{cl + (W cos\alpha - U)tan\phi}{W sin\alpha}$$

Slide c/o Alex Grant

M9 Coseismic Landslides

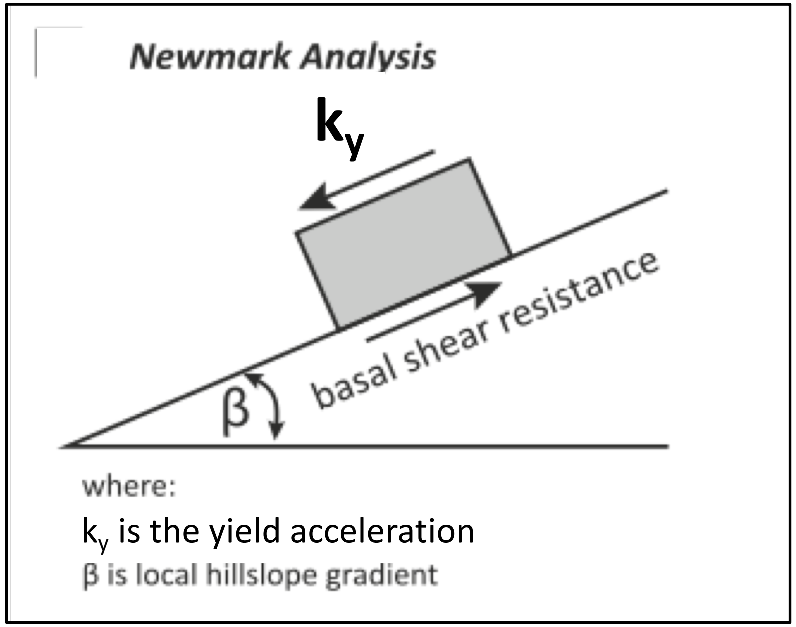
Shallow (translational) slides



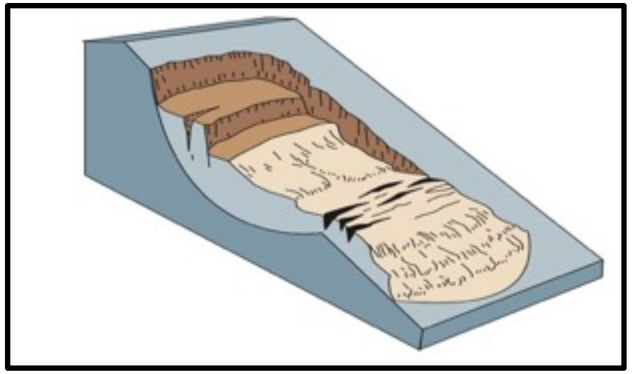
yield acceleration →

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

[the acceleration above which downslope motion will occur]

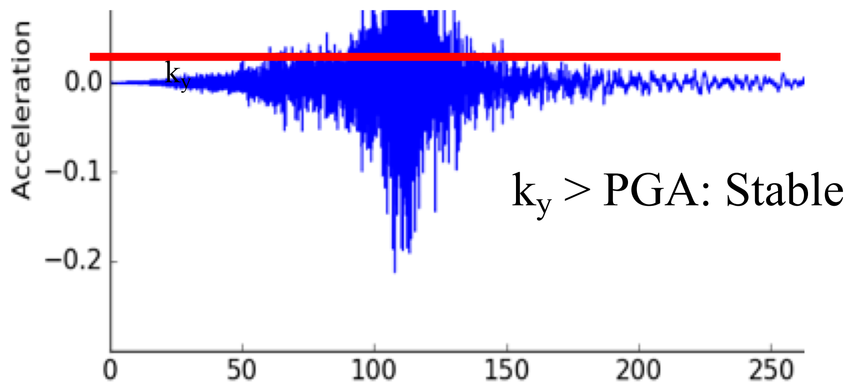


Deep-seated (rotational) slides



Slide c/o Alex Grant

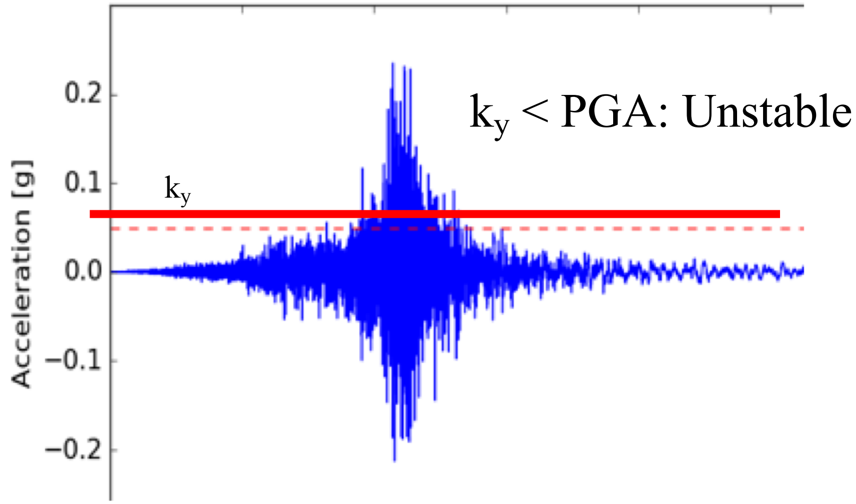
M9 Coseismic Landslides



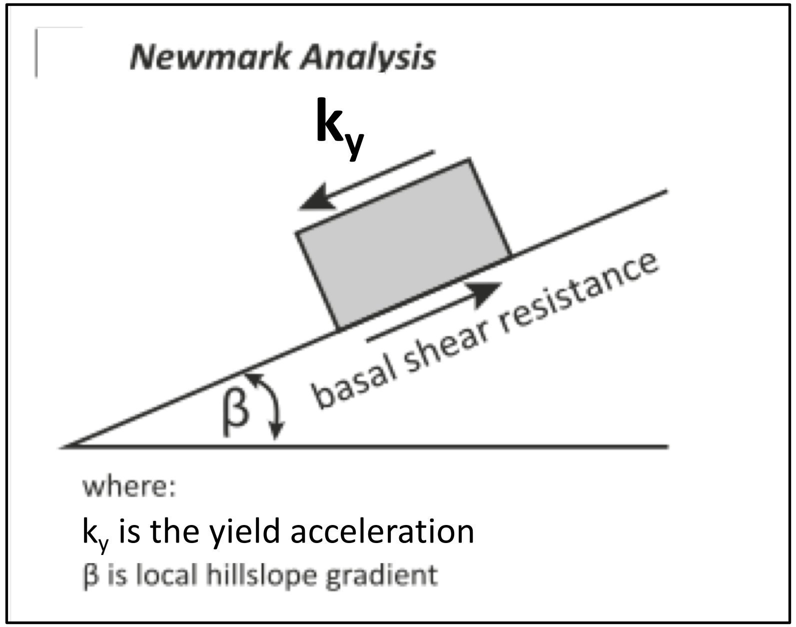
Slope is strong relative to ground shaking

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

[the acceleration above which downslope motion will occur]



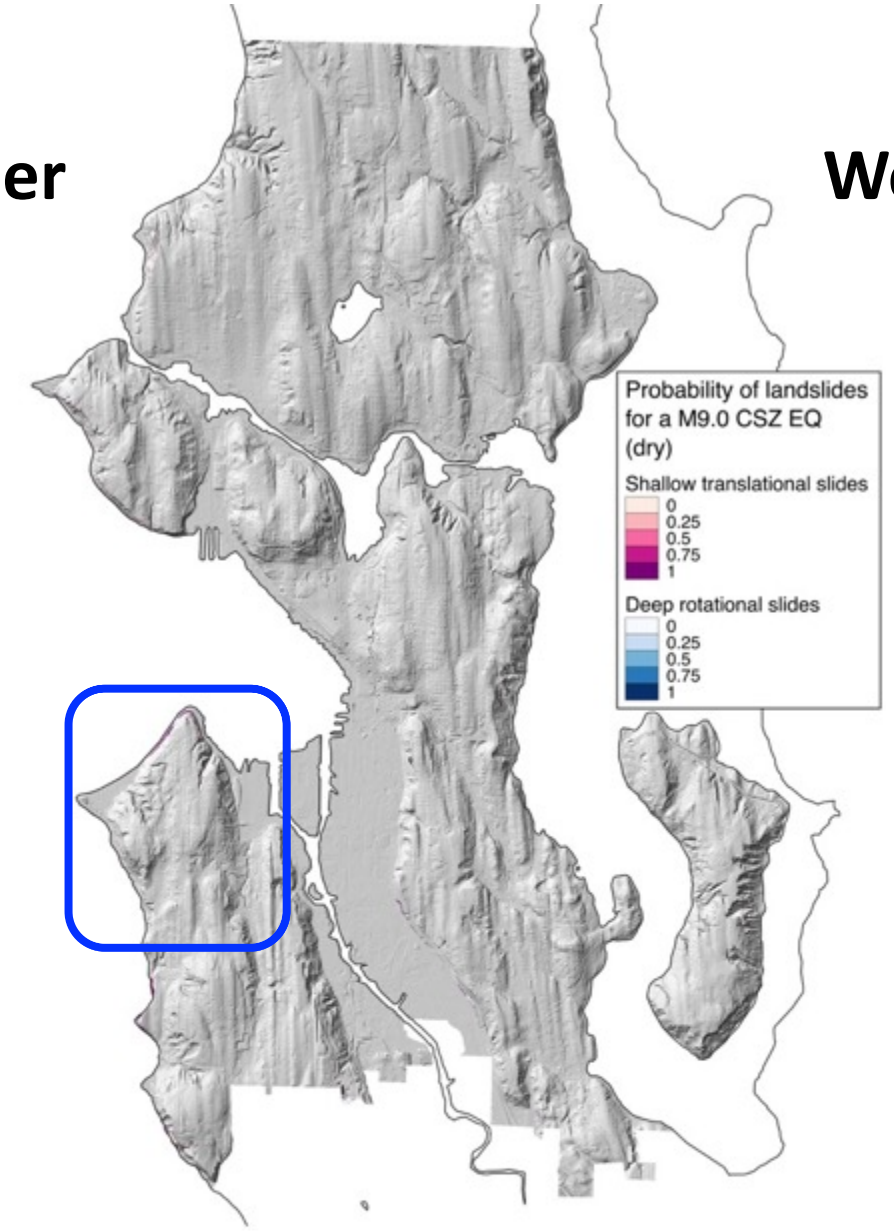
Slope is weak relative to ground shaking, fails coseismically



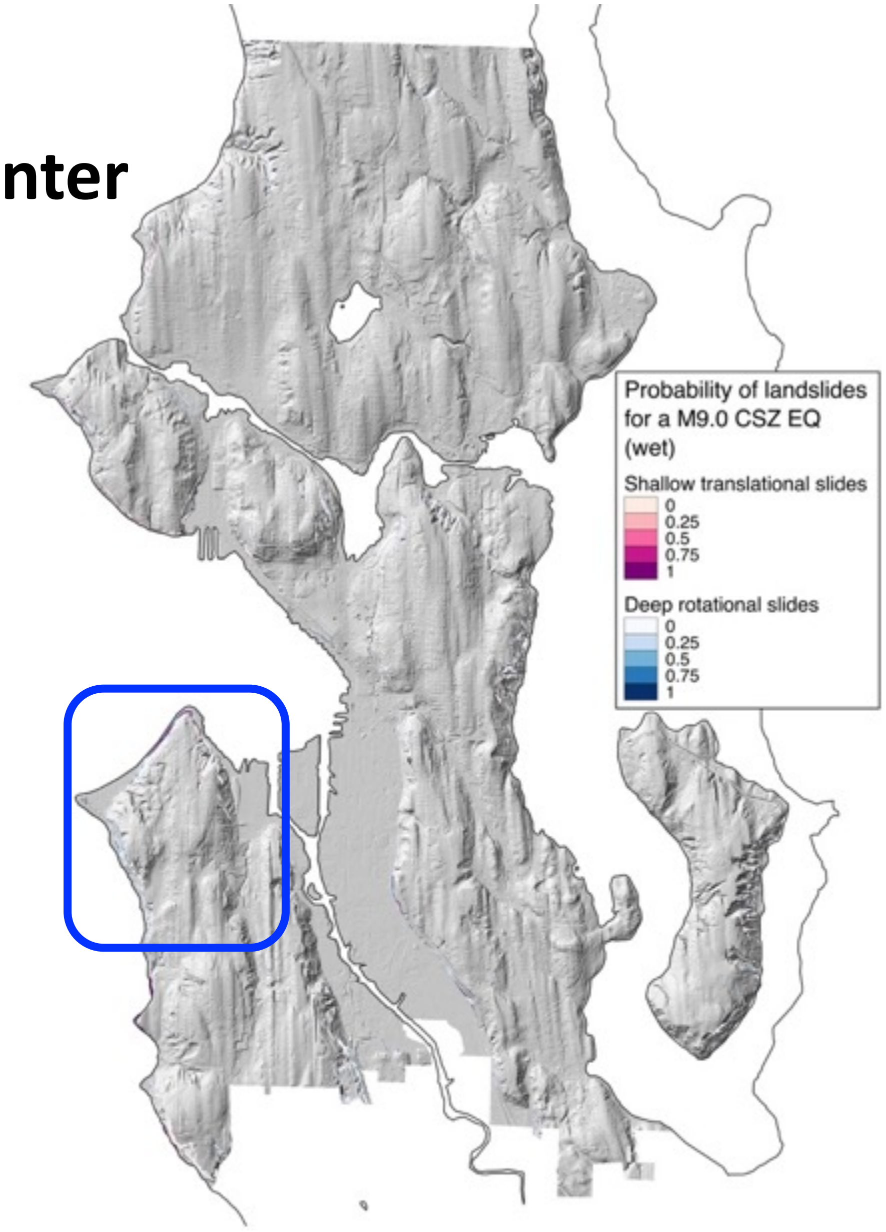
Slide c/o Alex Grant

M9 Coseismic Landslides

Dry / Summer



Wet / Winter



Probability of landslides for a M9.0 CSZ EQ (dry)

Shallow translational slides

0
0.25
0.5
0.75
1

Deep rotational slides

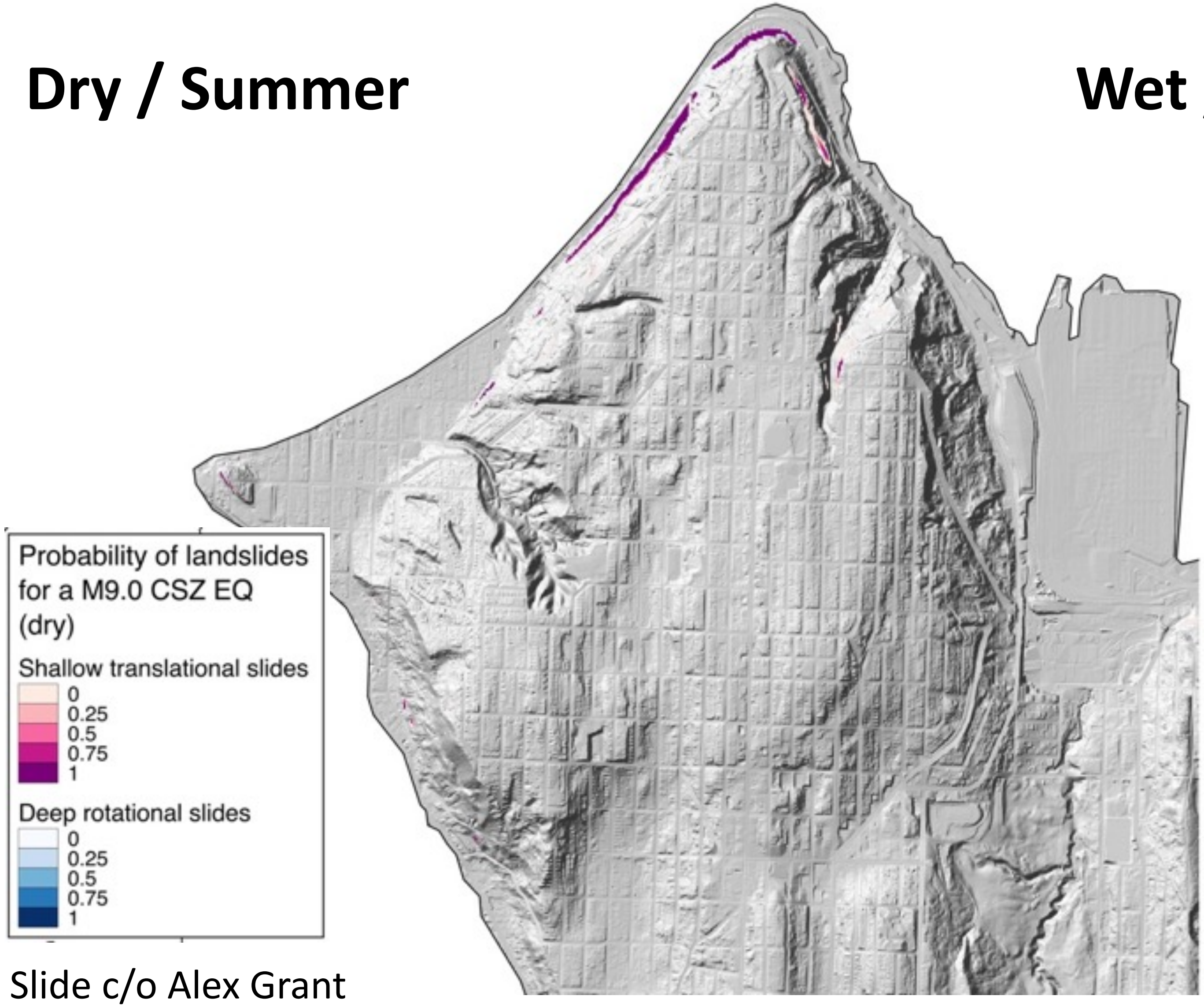
0
0.25
0.5
0.75
1

Slide c/o Alex Grant

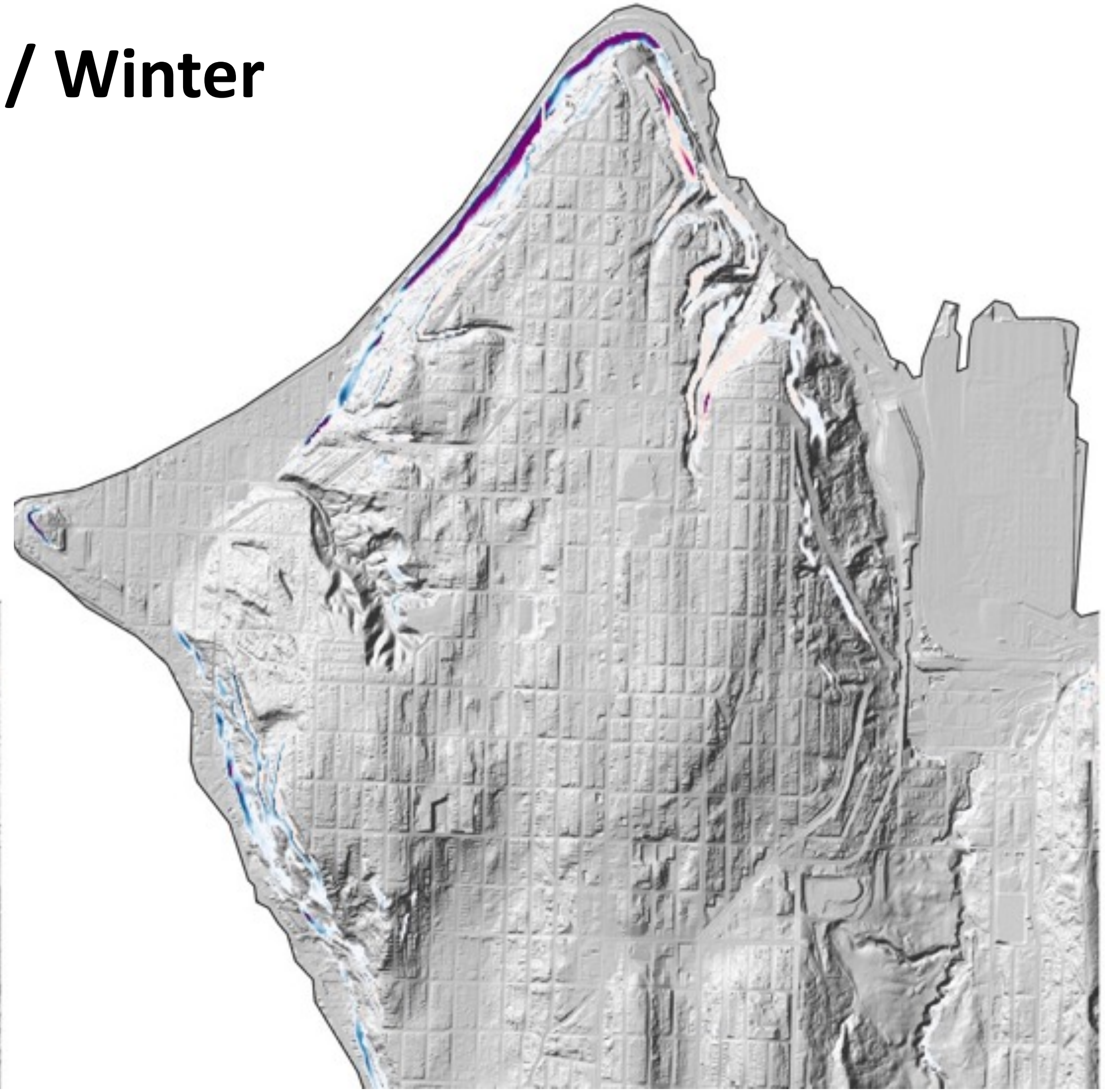
M9 Coseismic Landslides

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

Dry / Summer

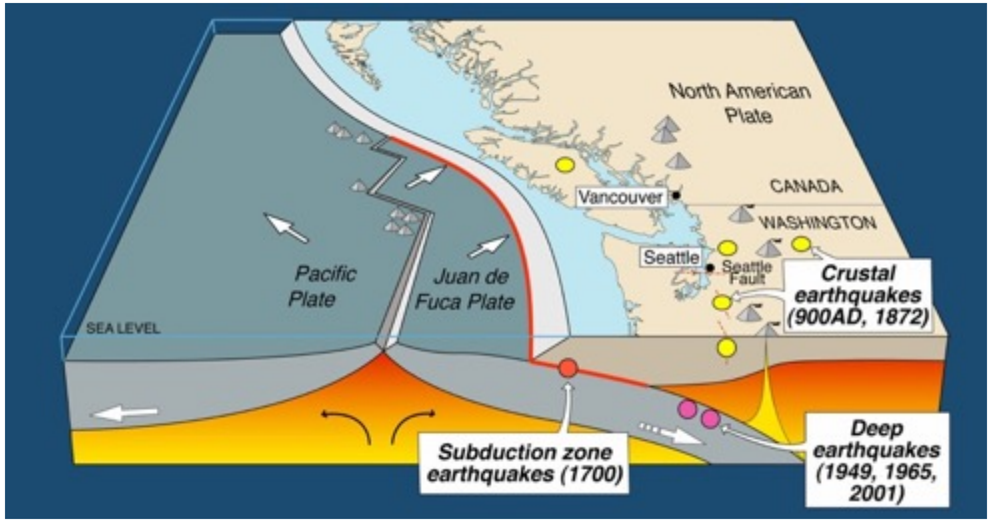


Wet / Winter

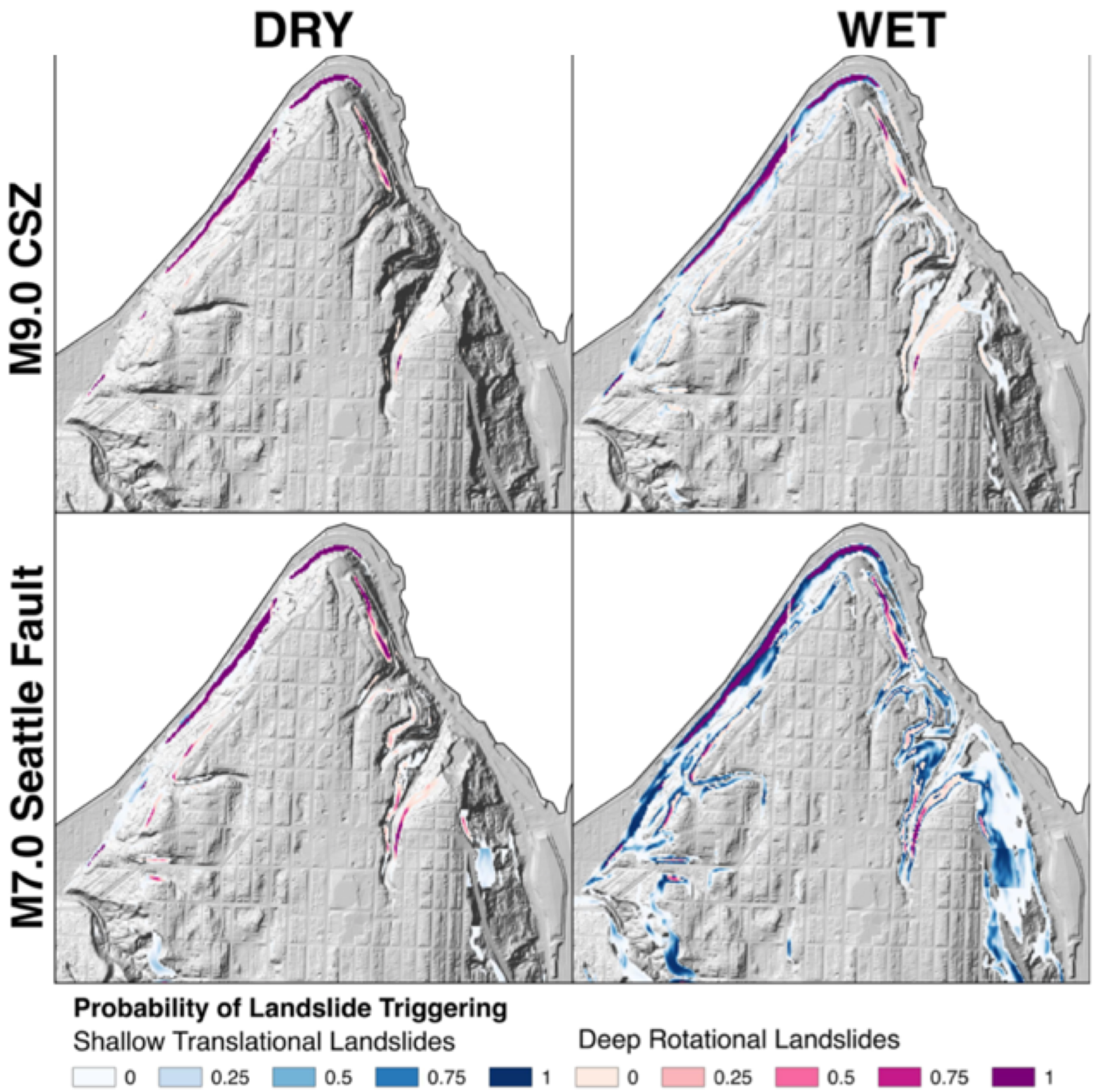


Slide c/o Alex Grant

M9 vs. Seattle Fault



USGS



Good news

We have a method that appears to provide accurate spatial (i.e., location) predictions of landslides.

M9 landslides will be numerous, but perhaps somewhat less severe than initially expected in Seattle.

Concerns

We can not predict the seasonal timing of coseismic landslides, and we know that consequences are worse under wet conditions.

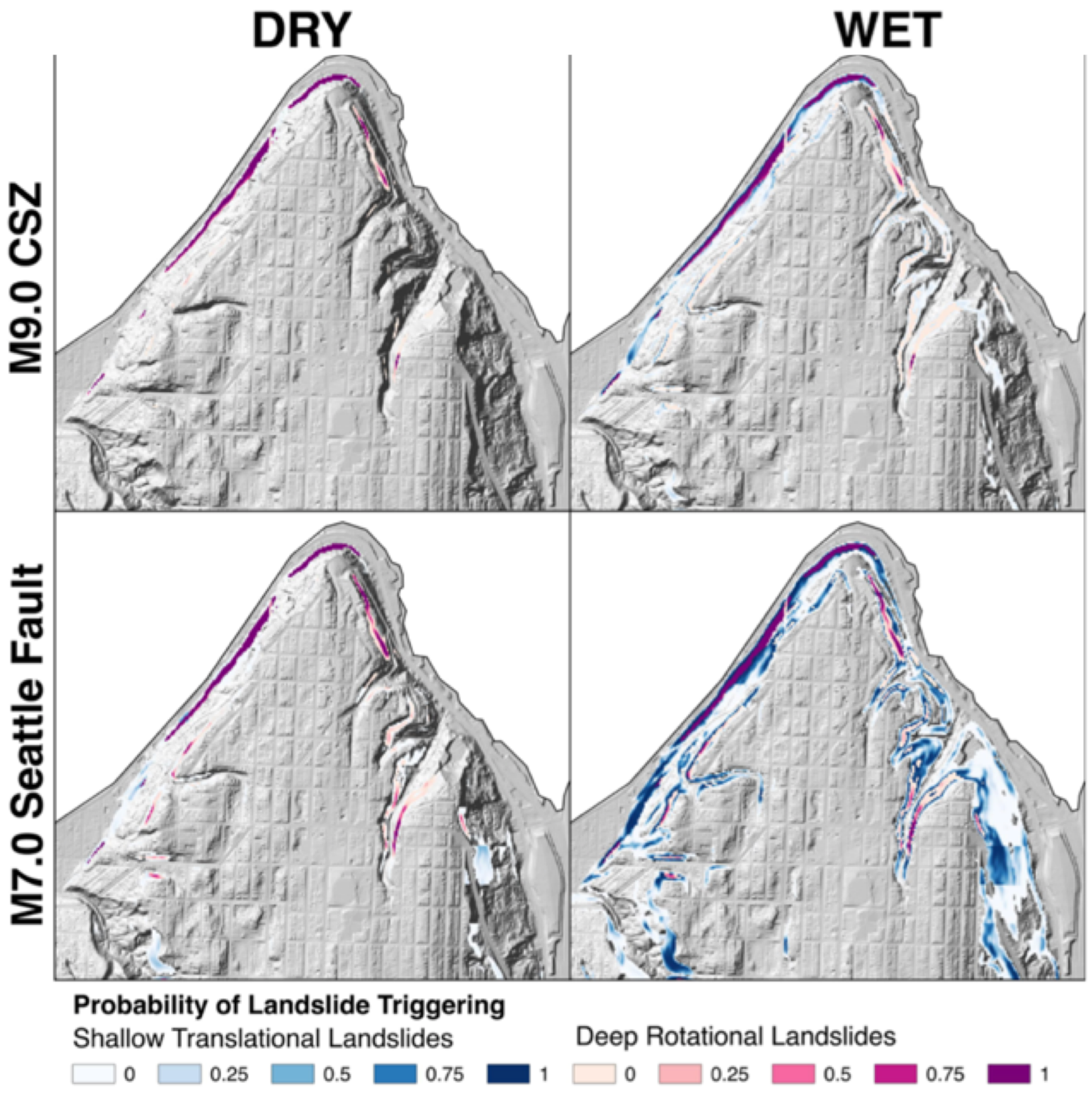
A Seattle fault earthquake is the dominant coseismic landslide event.

What remains

Mapping of other areas that will shaken more strongly by M9 (e.g., the coast)

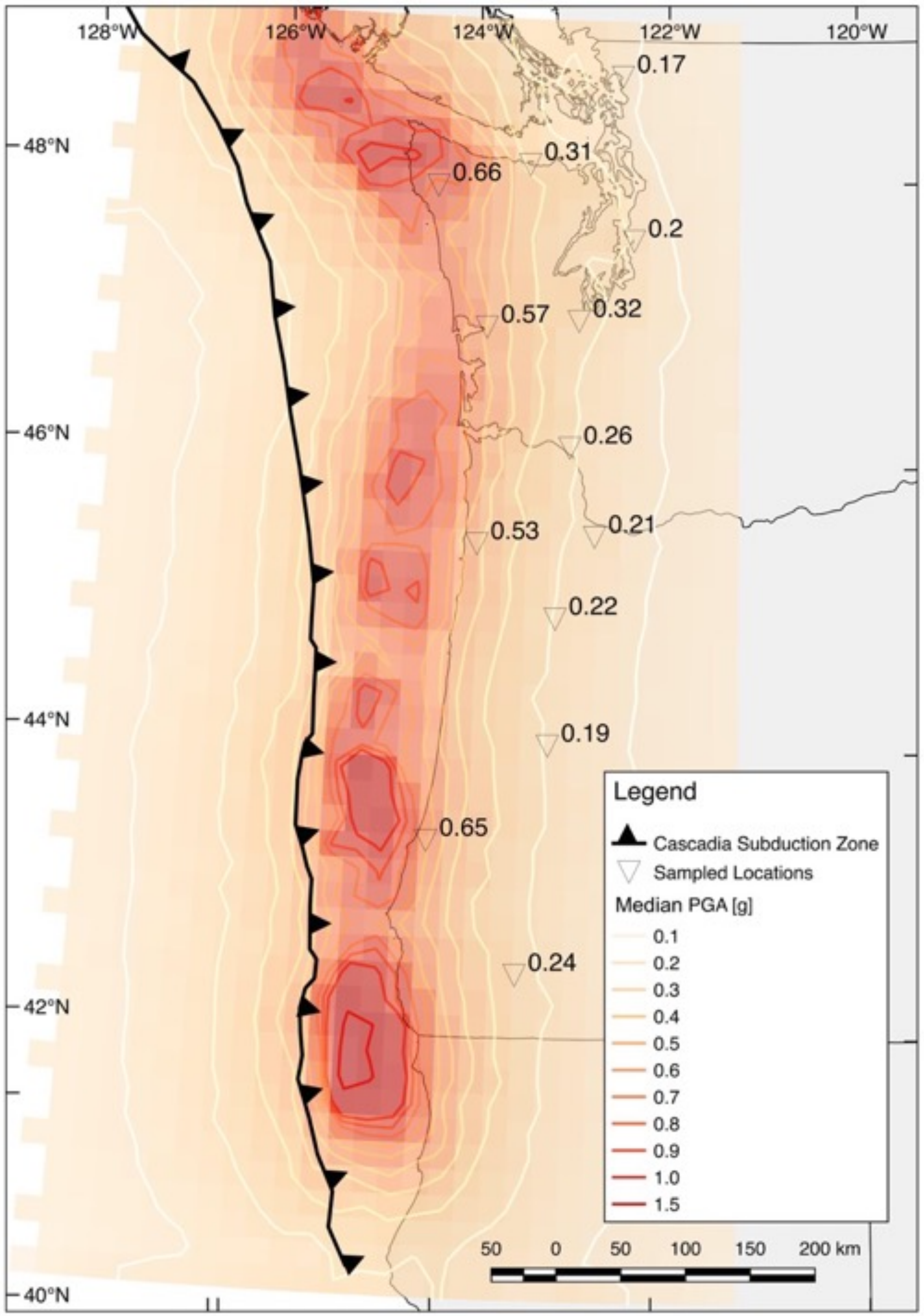
Assessment of the consequences of coseismic landslides (especially on roads and infrastructure)

Enact policy and communication with stakeholders



M9 Coseismic Landslides

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



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

Sean LaHusen – PhD student UW

Photo: Phil Schoettle-Greene

UNIVERSITY OF OREGON

Josh Roering & Will Struble

Portland State UNIVERSITY

Adam Booth

Alison Duvall, Alex Grant, Joseph Wartman, David Montgomery

Big questions

1. Is there evidence of widespread landsliding in Cascadia triggered by the last M9 Cascadia Subduction Zone earthquake, in AD 1700?
2. Where are these slides and do their locations correlate with predicted peak ground accelerations (PGA)?

Landslide deposits smooth over time

Hillslope transport coefficient

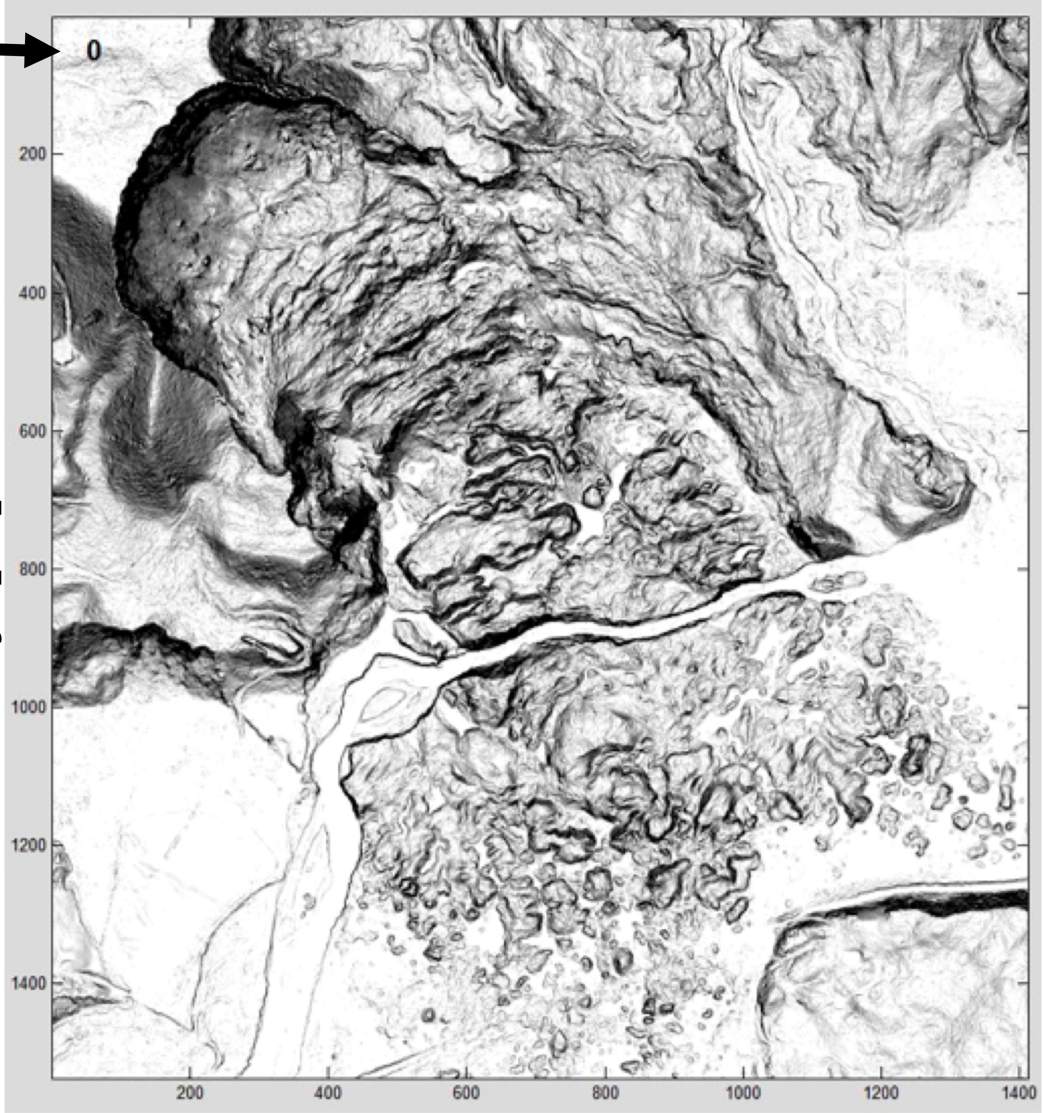
Slope

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

Soil flux

Critical slope

Time (yrs)



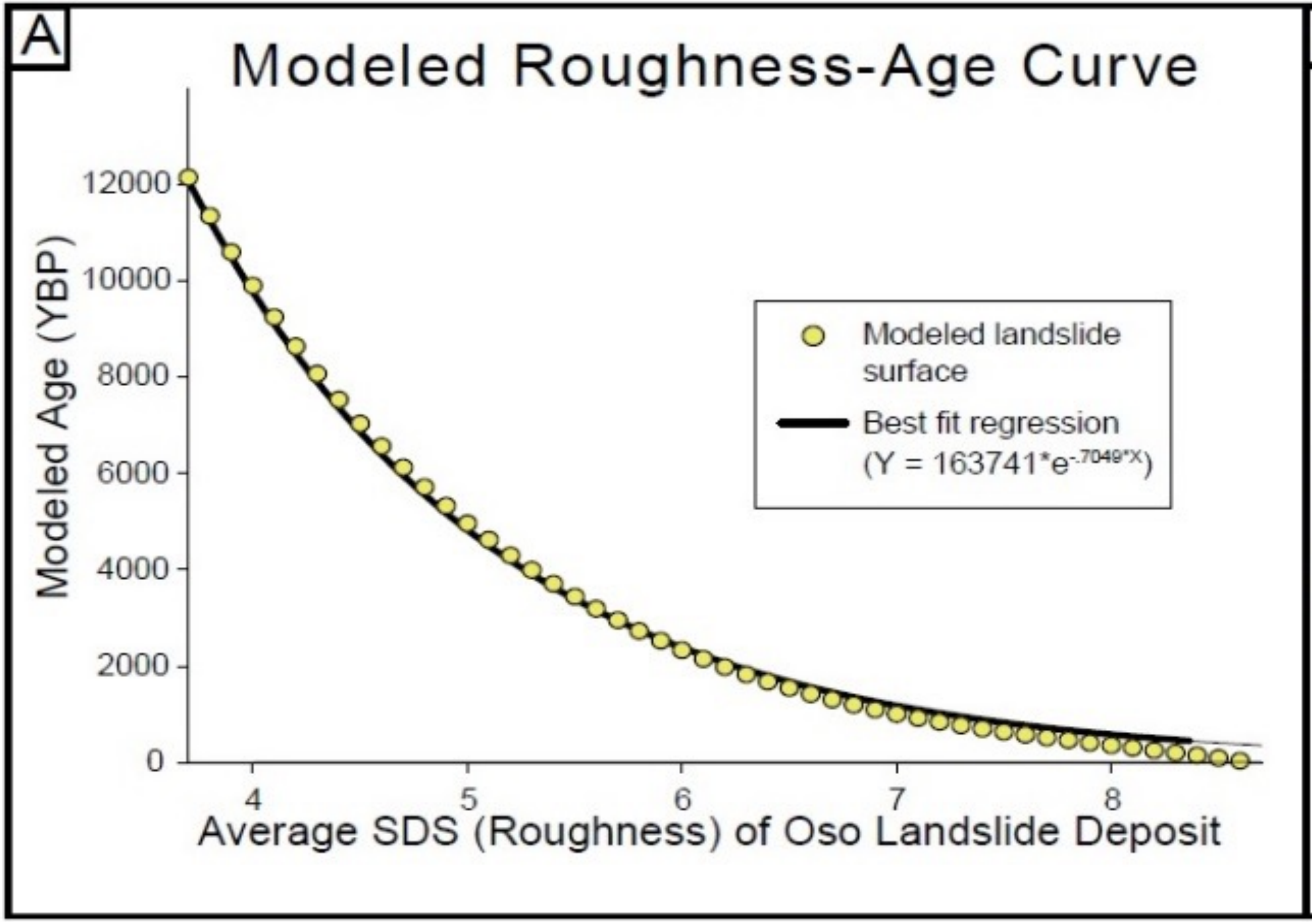
y [m]

x [m]

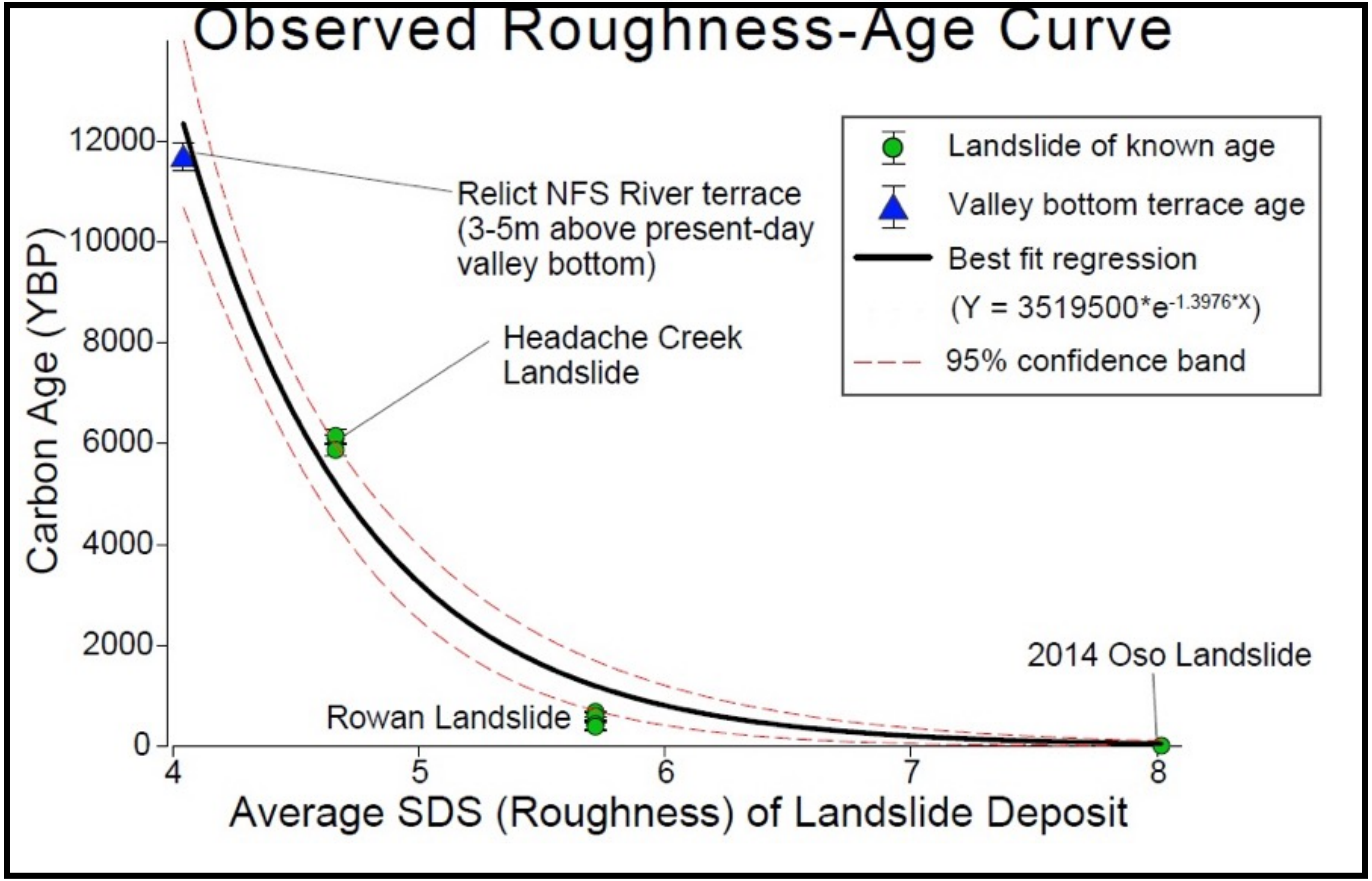
$K = 0.003\ \mathrm{m^2/yr}$

Roering et al. (1999)

Booth et al. (2017)

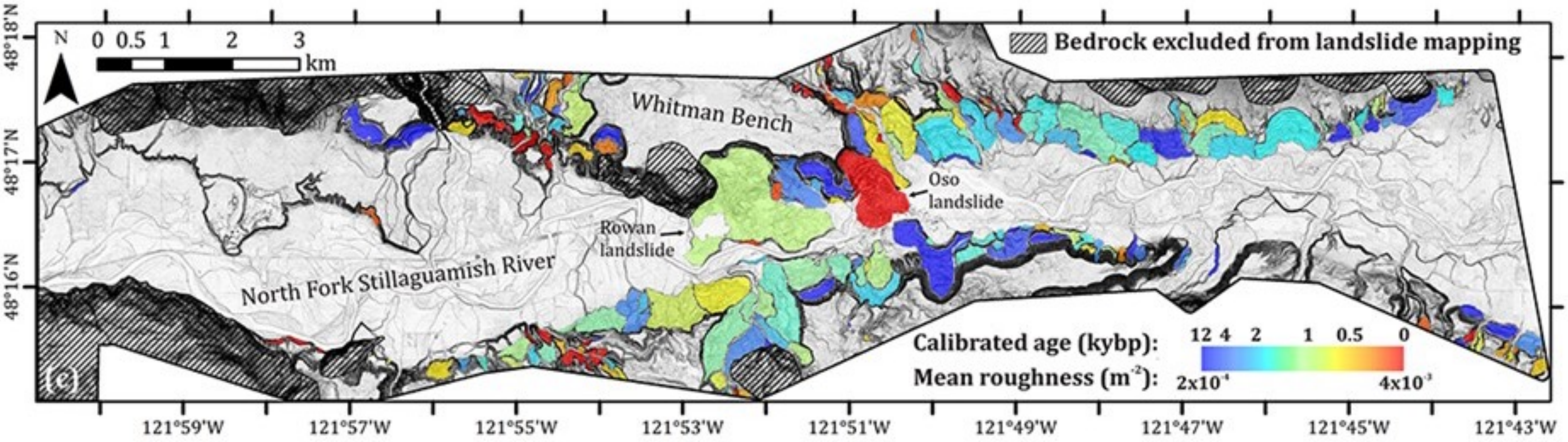


LaHusen, et al. (2016)



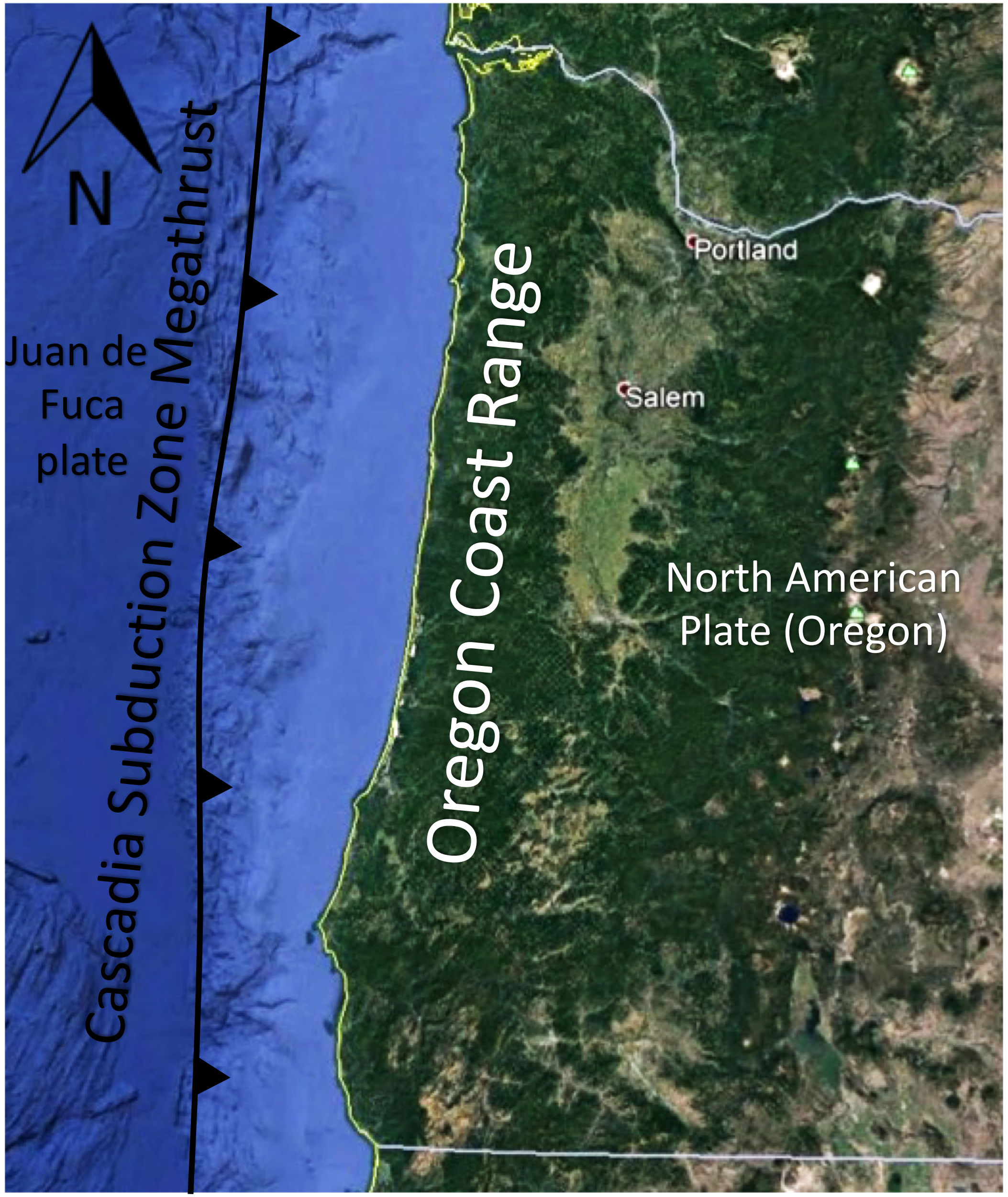
LaHusen, et al. (2016)

Construct landslide chronology

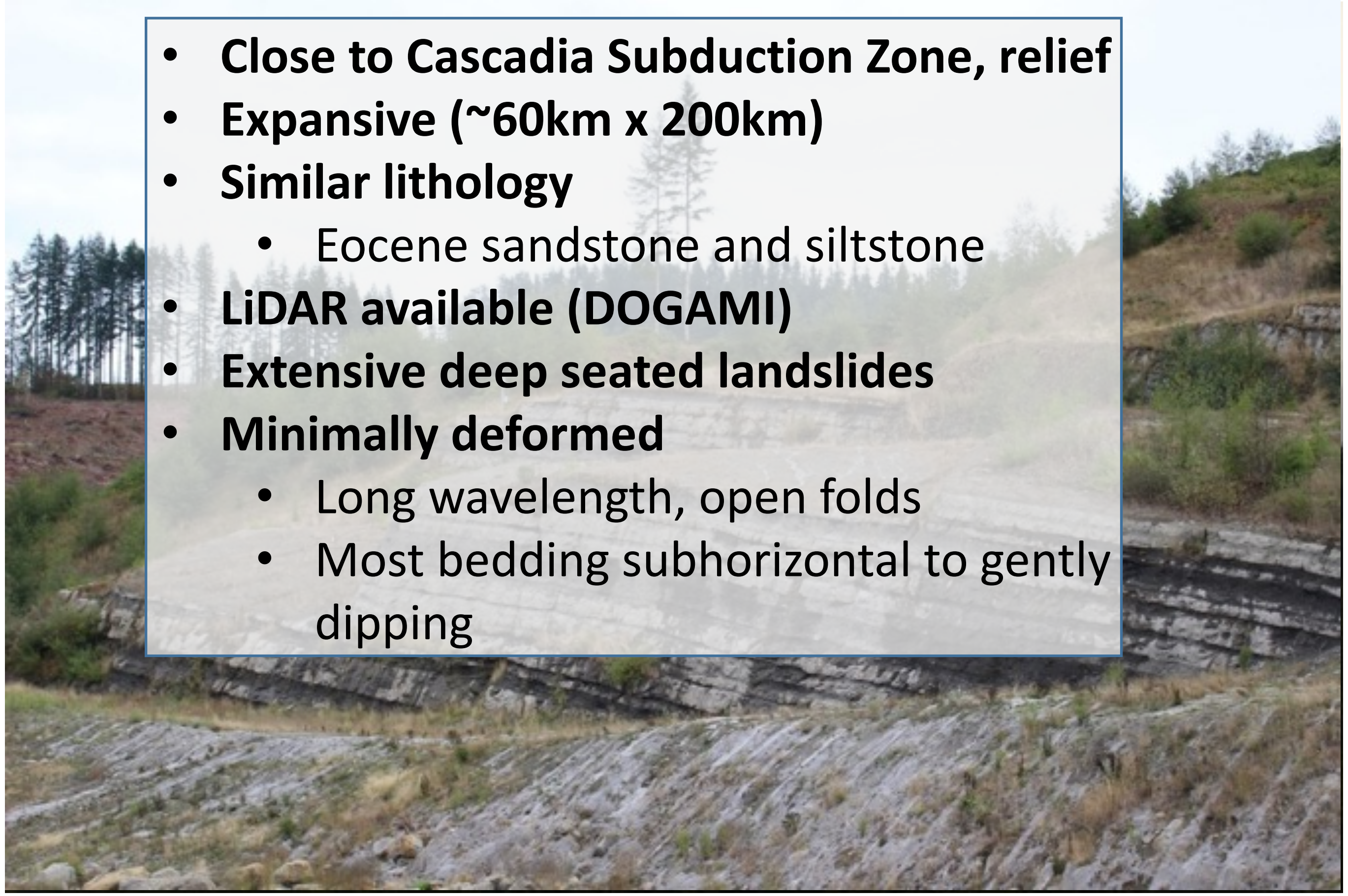


Booth, et al. (2017)

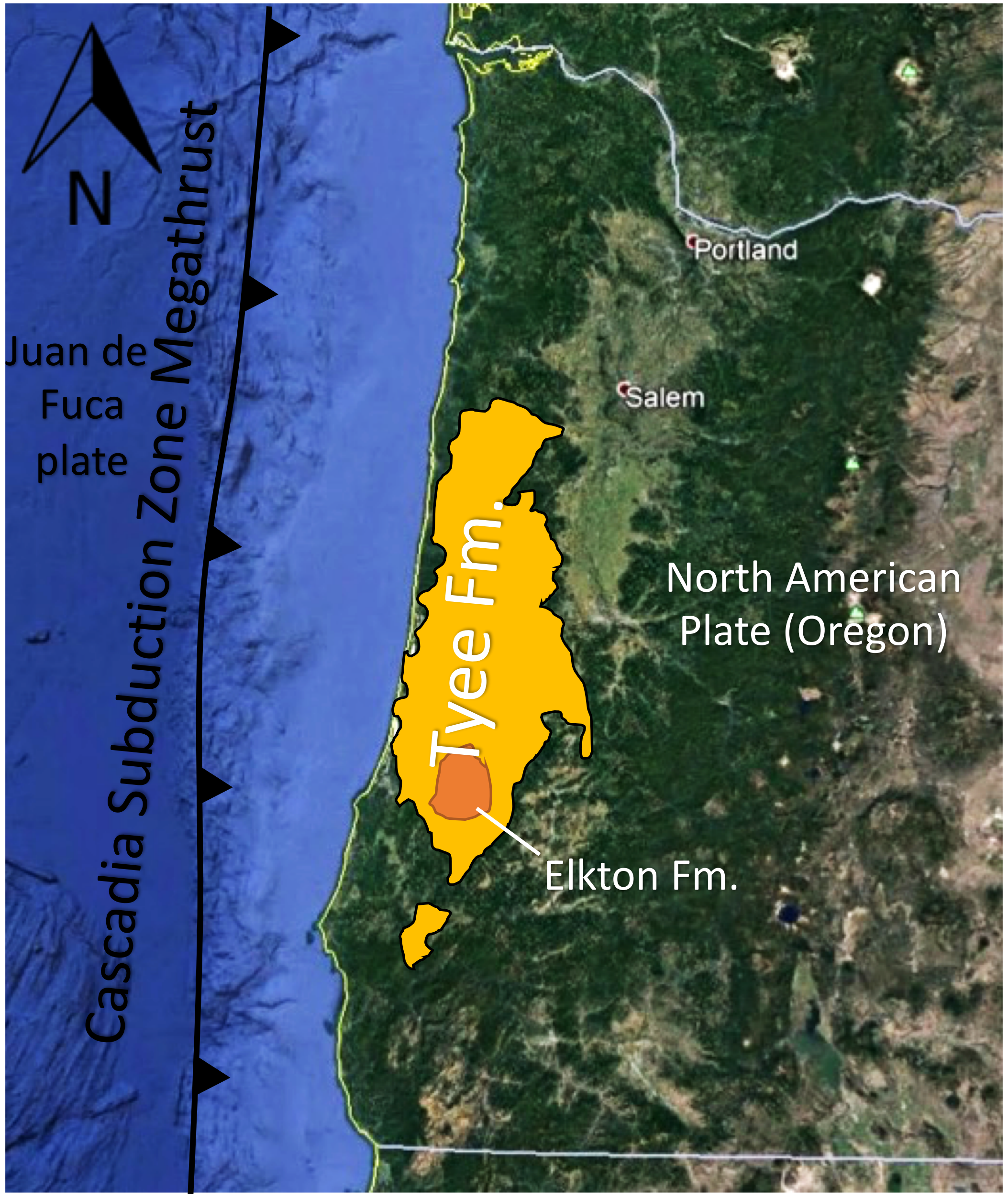
Oregon Coast Range



Oregon Coast Range

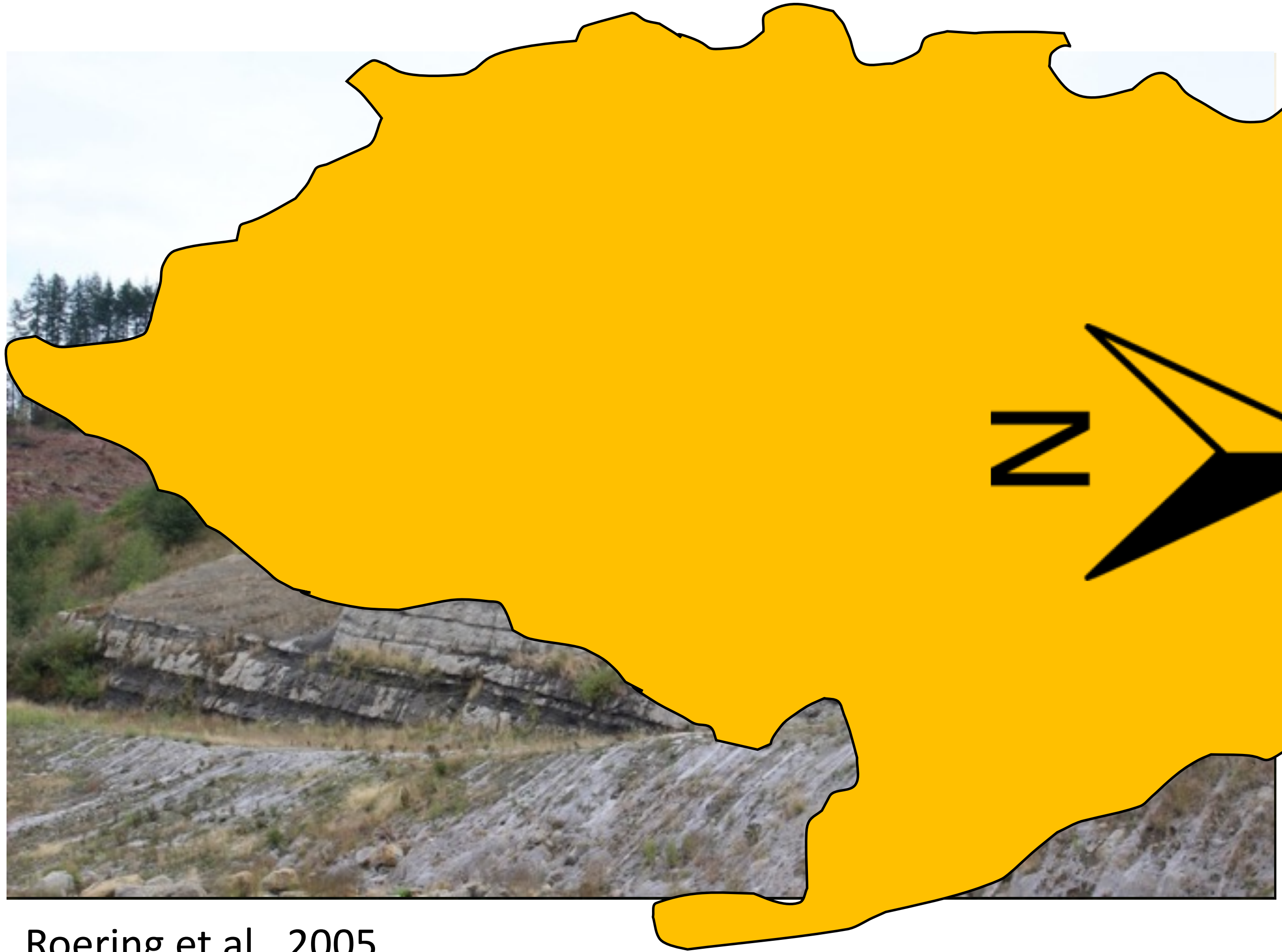


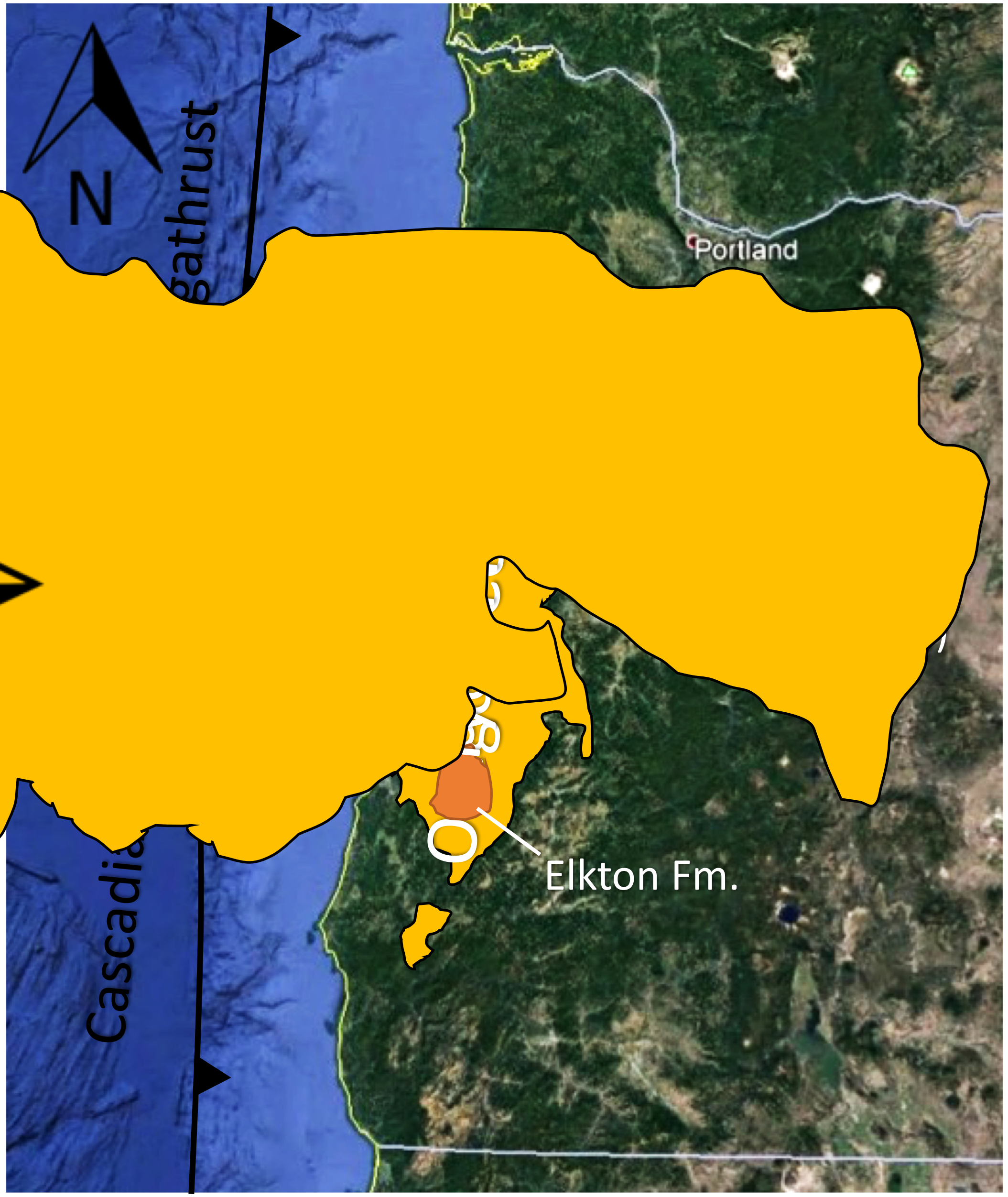
- **Close to Cascadia Subduction Zone, relief**
- **Expansive (~60km x 200km)**
- **Similar lithology**
  - Eocene sandstone and siltstone
- **LiDAR available (DOGAMI)**
- **Extensive deep seated landslides**
- **Minimally deformed**
  - Long wavelength, open folds
  - Most bedding subhorizontal to gently dipping



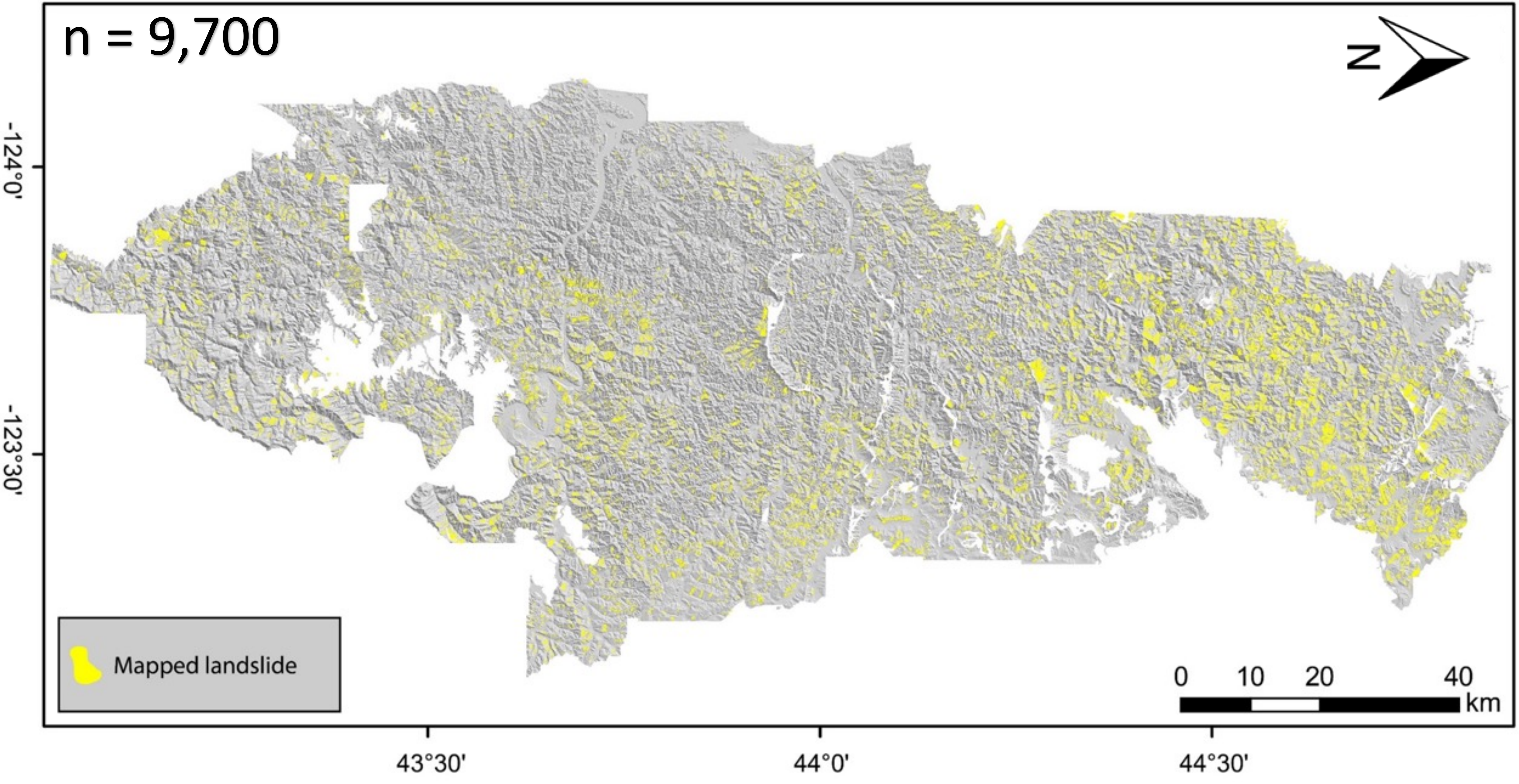
Roering et al., 2005
Burns et al., 2017
Hammond et al., 2009

Oregon Coast Range



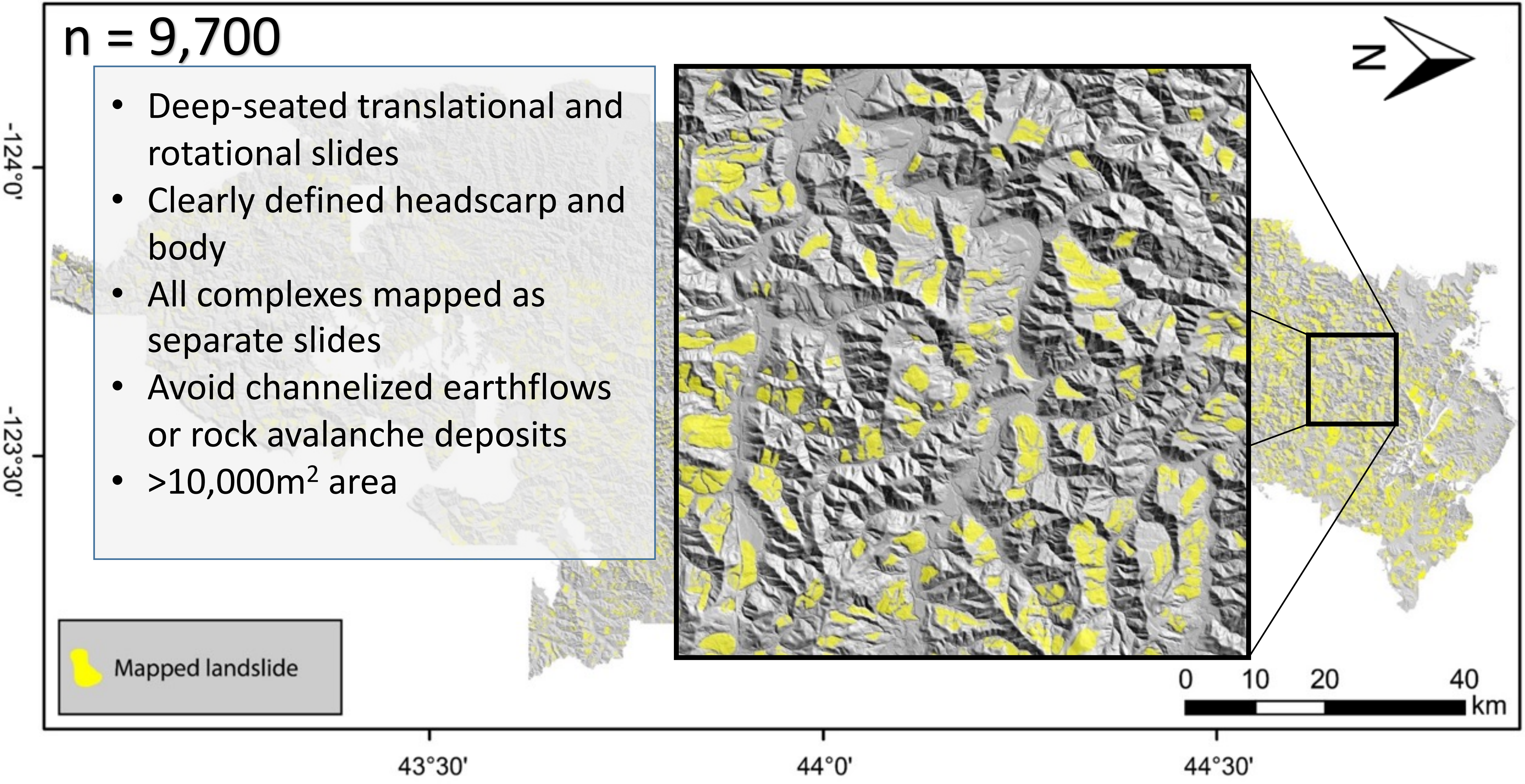


Roering et al., 2005
Burns et al., 2017
Hammond et al., 2009

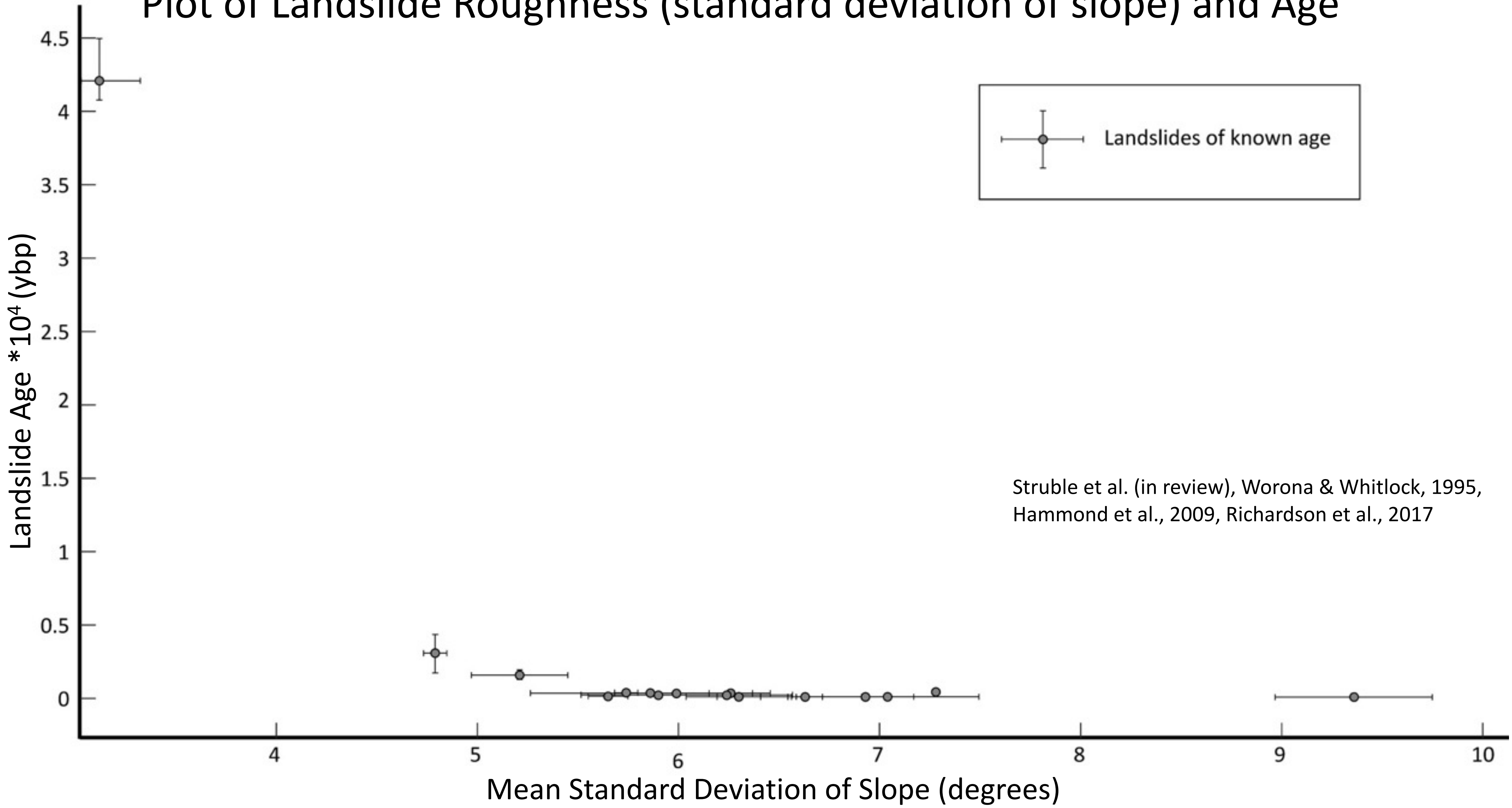

n = 9,700
N
-124°0'
-123°30'
43°30'
44°0'
44°30'
Mapped landslide
0
10
20
40
km

n = 9,700

- Deep-seated translational and rotational slides
- Clearly defined headscarp and body
- All complexes mapped as separate slides
- Avoid channelized earthflows or rock avalanche deposits
- >10,000m^2 area

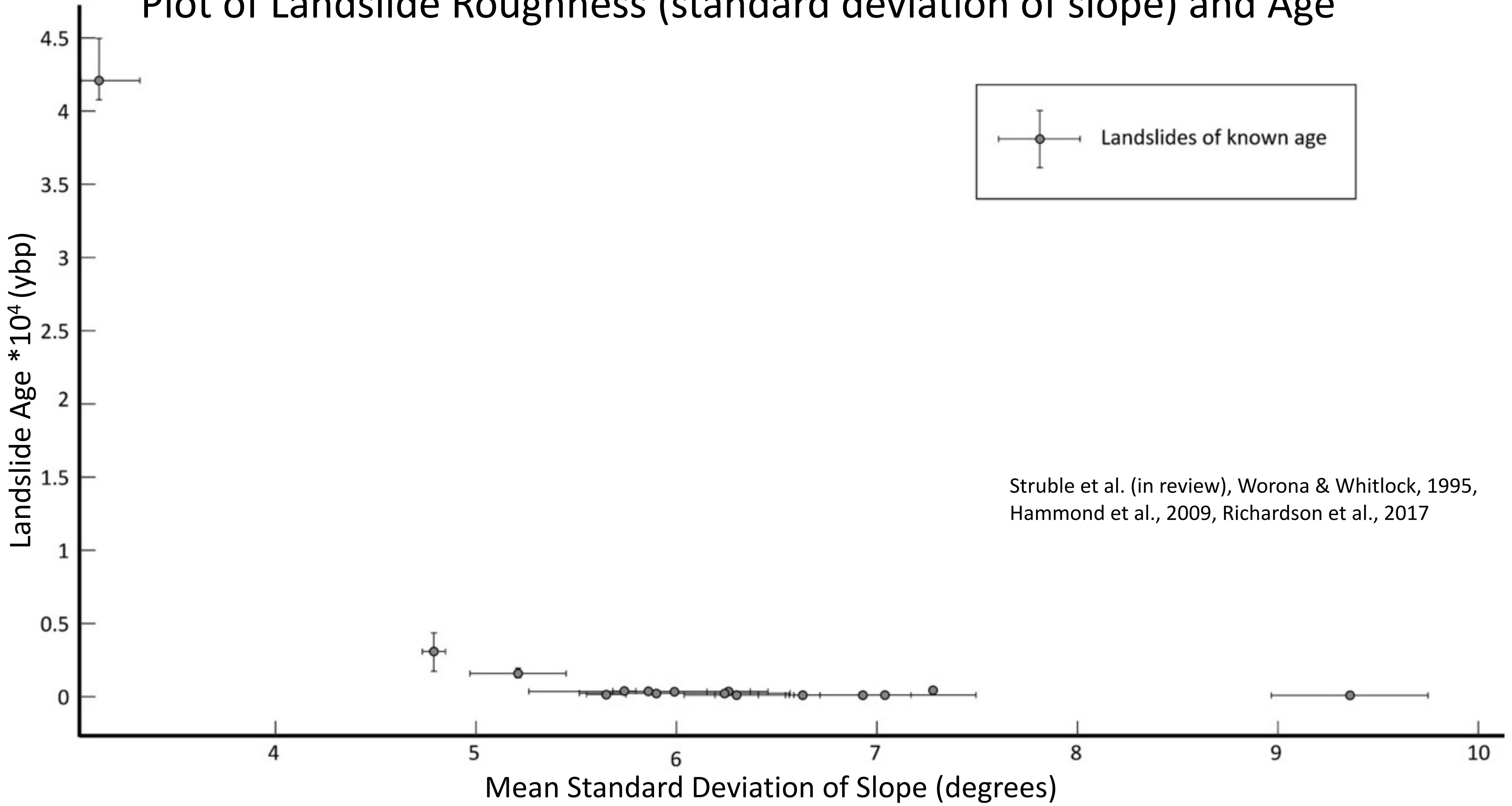


Plot of Landslide Roughness (standard deviation of slope) and Age



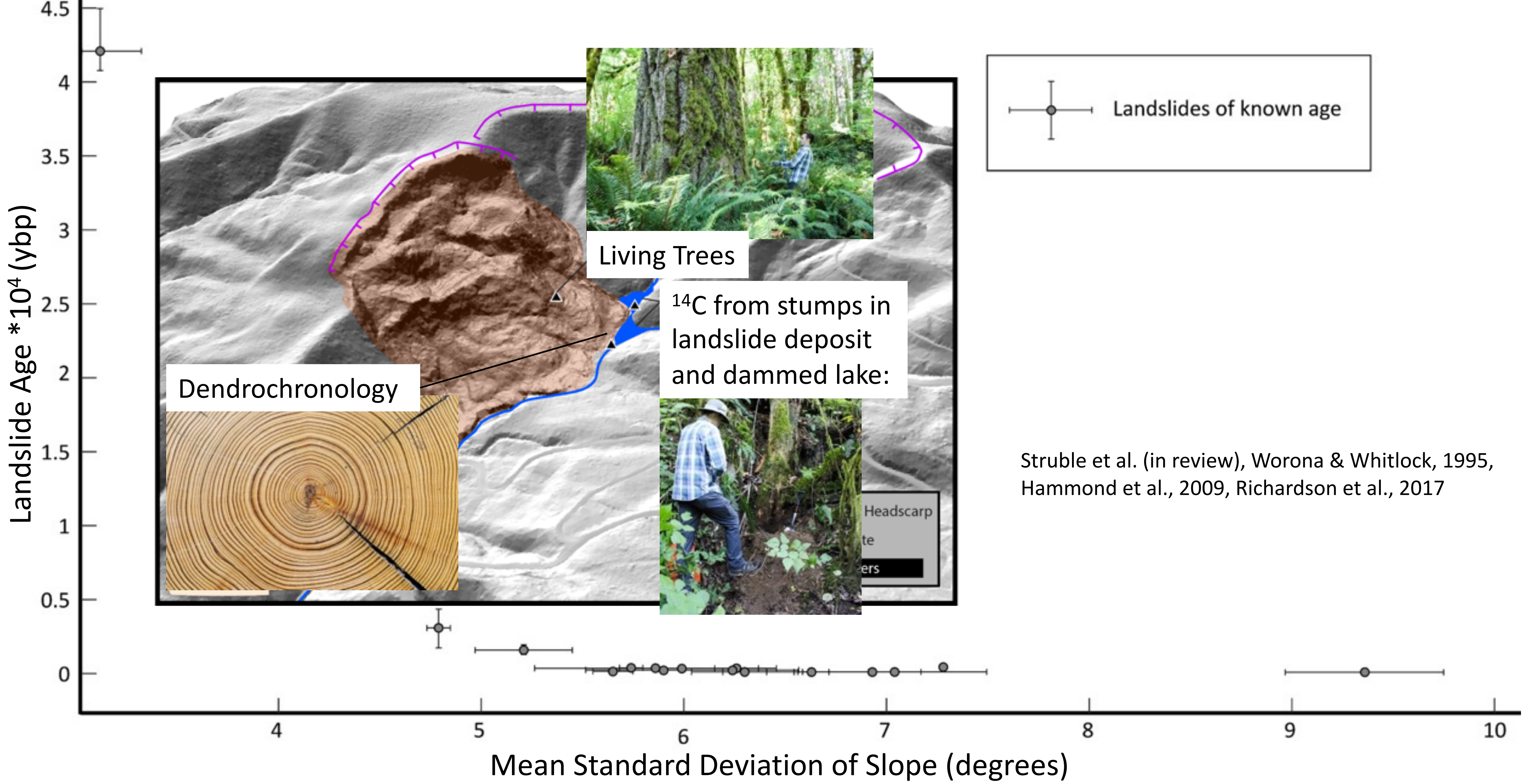
Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017

Plot of Landslide Roughness (standard deviation of slope) and Age



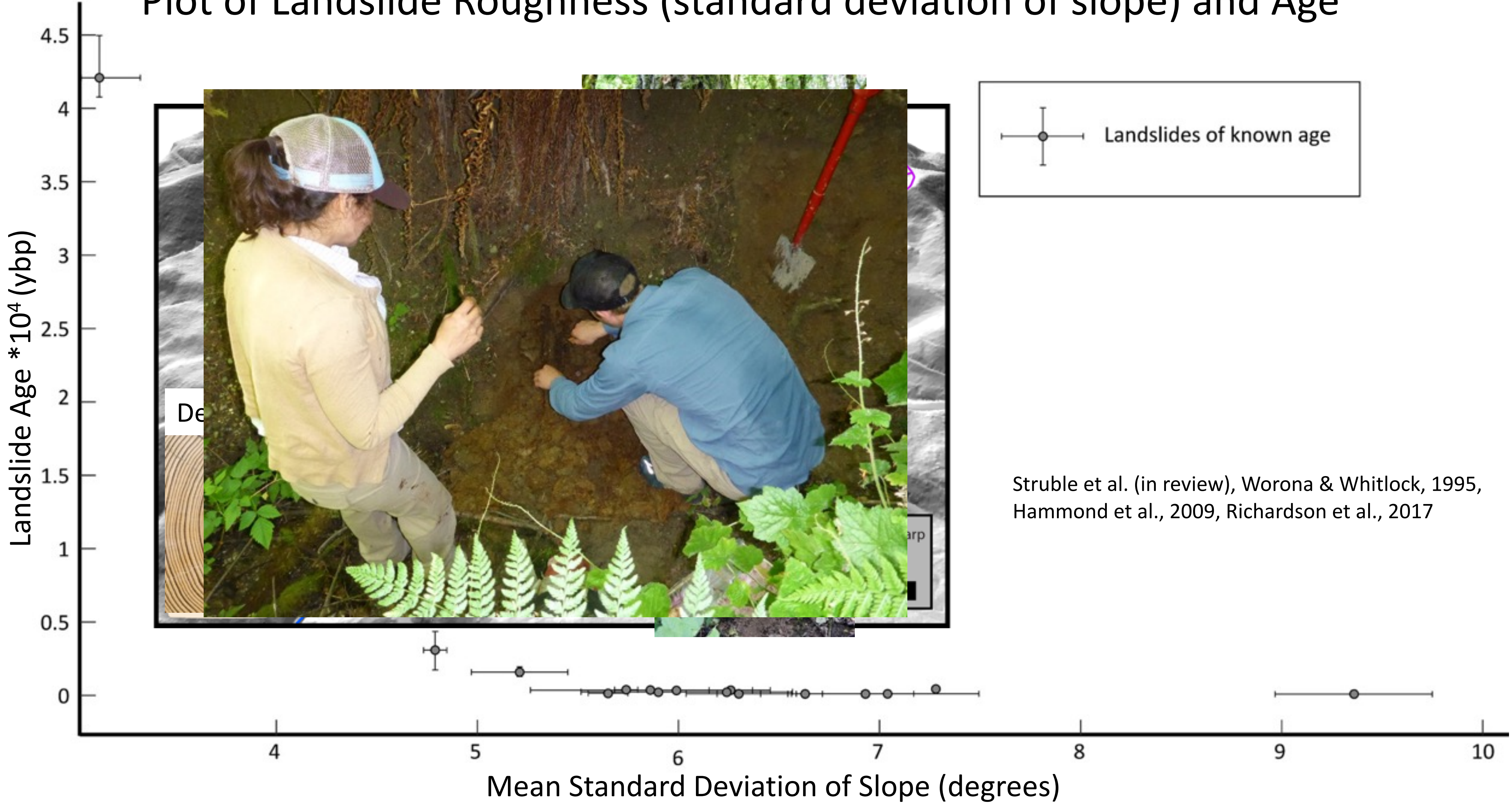
Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017

Plot of Landslide Roughness (standard deviation of slope) and Age



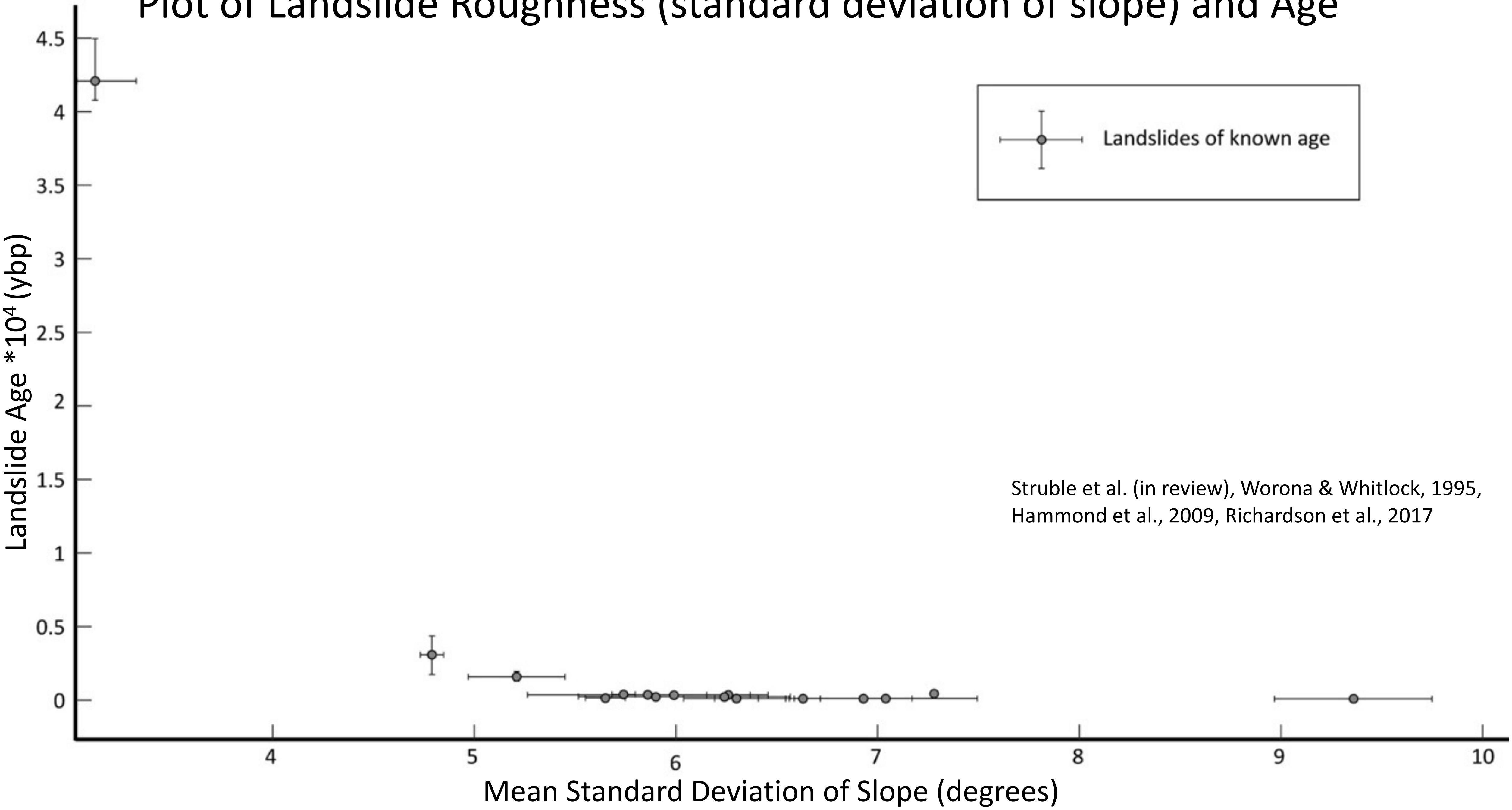
Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017

Plot of Landslide Roughness (standard deviation of slope) and Age



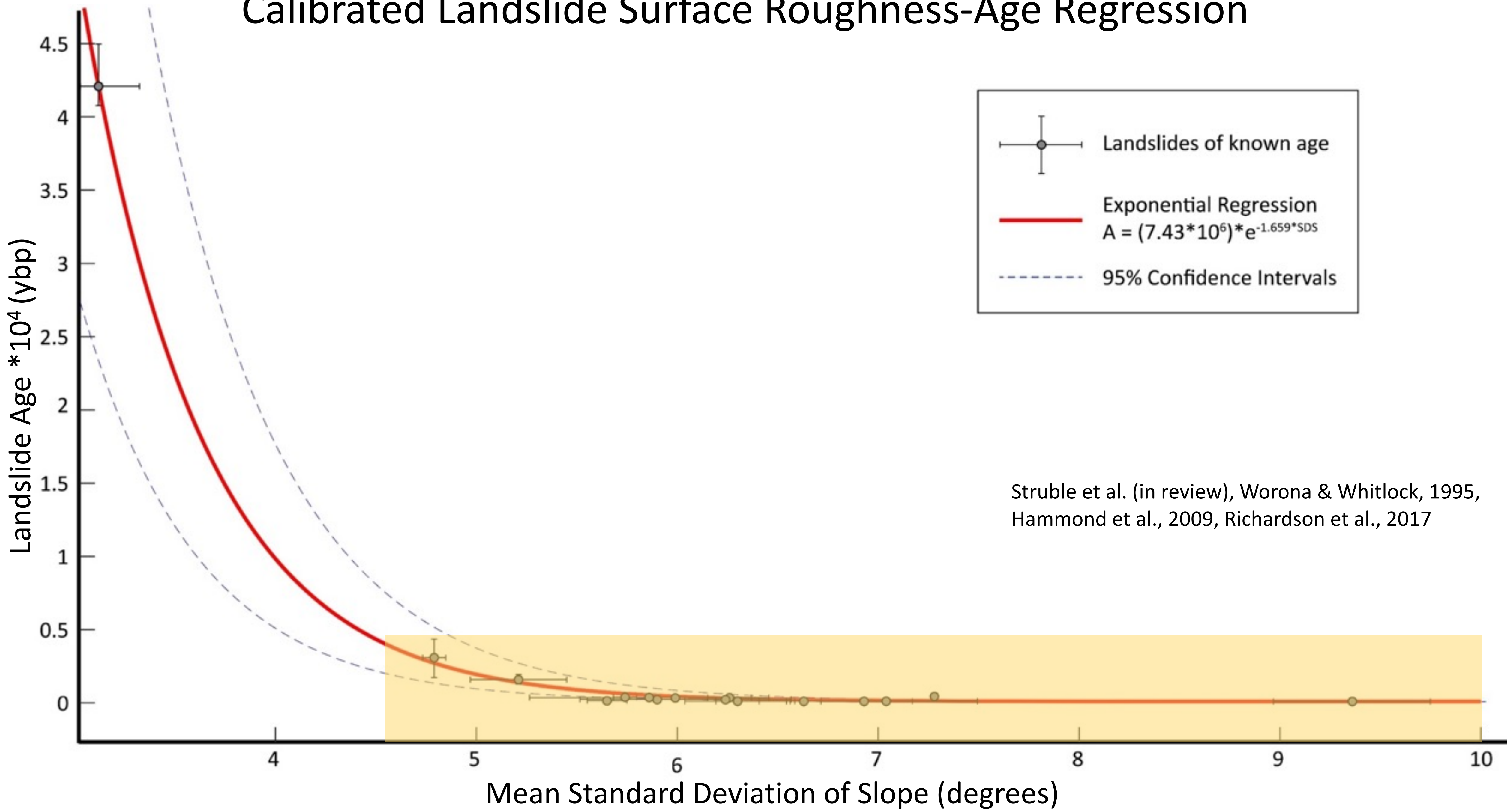
Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017

Plot of Landslide Roughness (standard deviation of slope) and Age



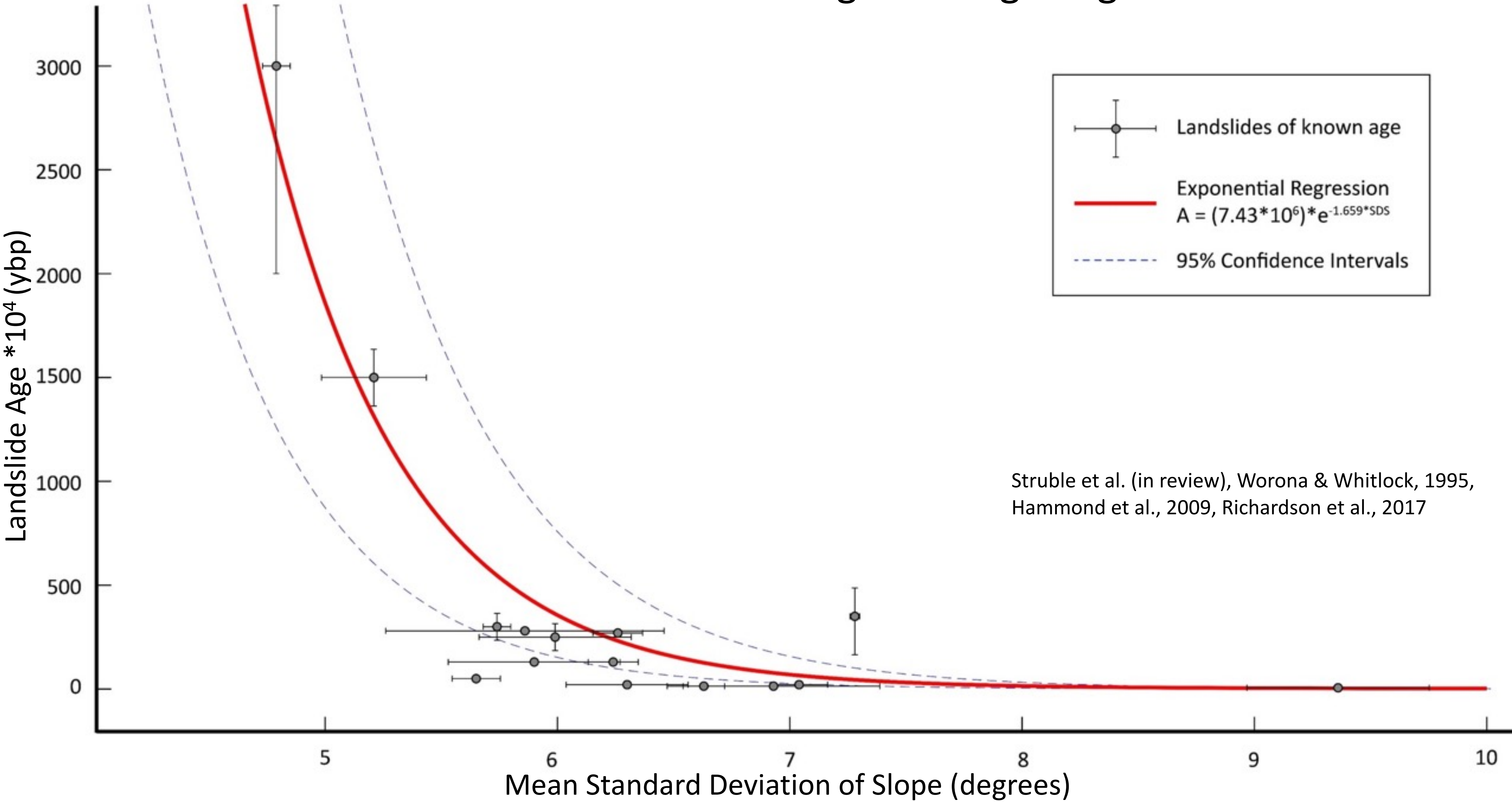
Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017

Calibrated Landslide Surface Roughness-Age Regression

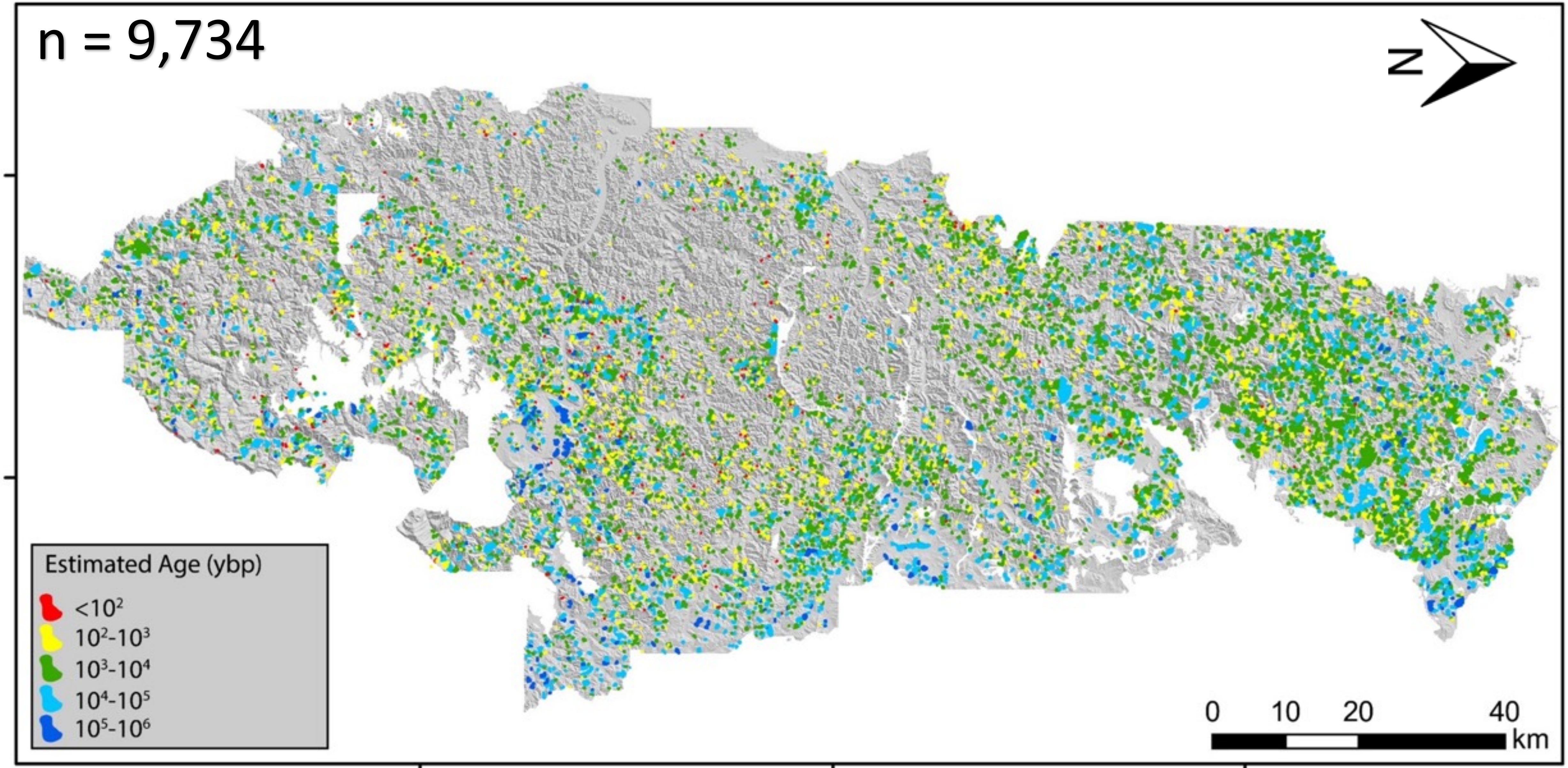


Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017

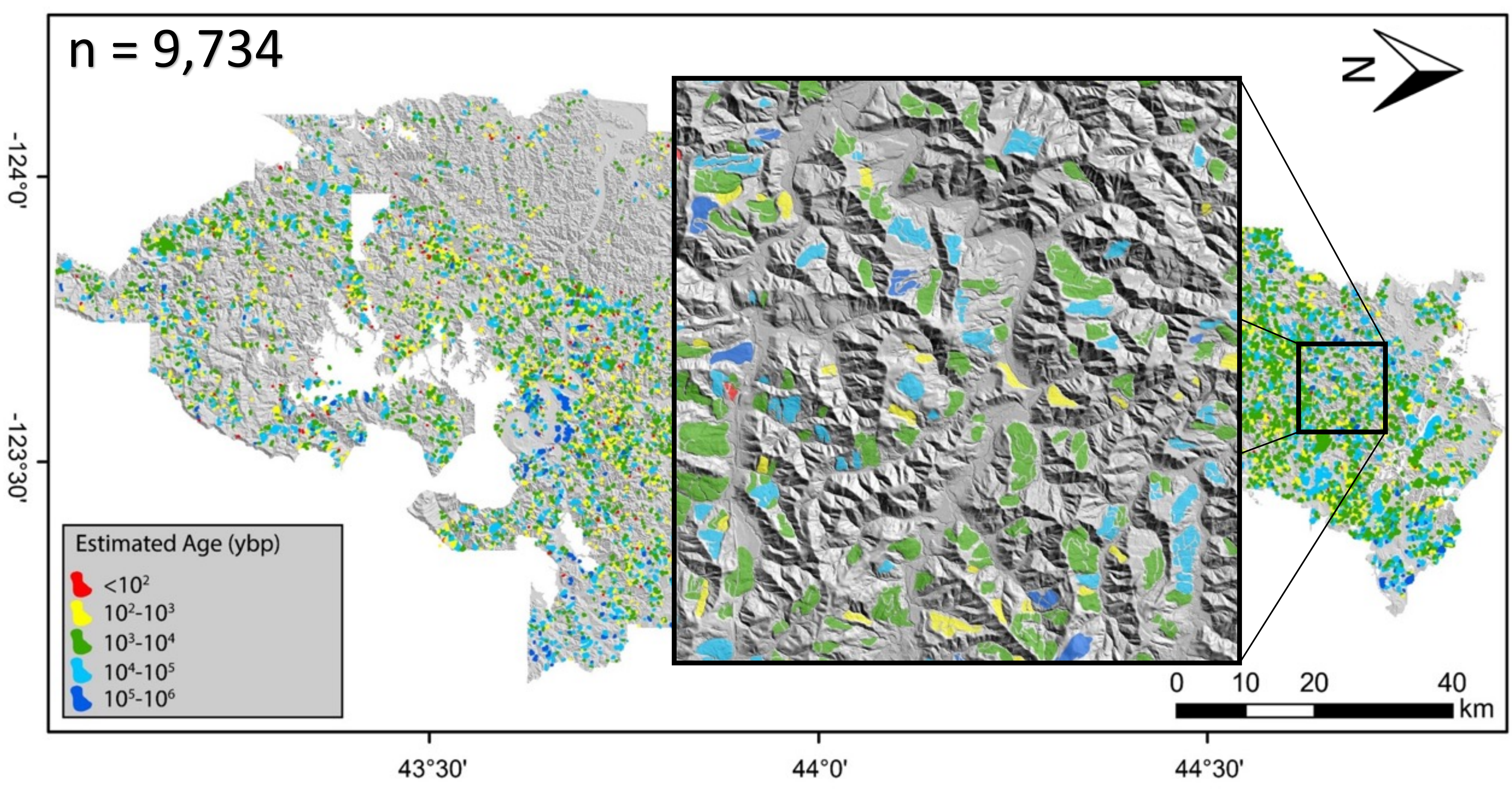
Calibrated Landslide Surface Roughness-Age Regression



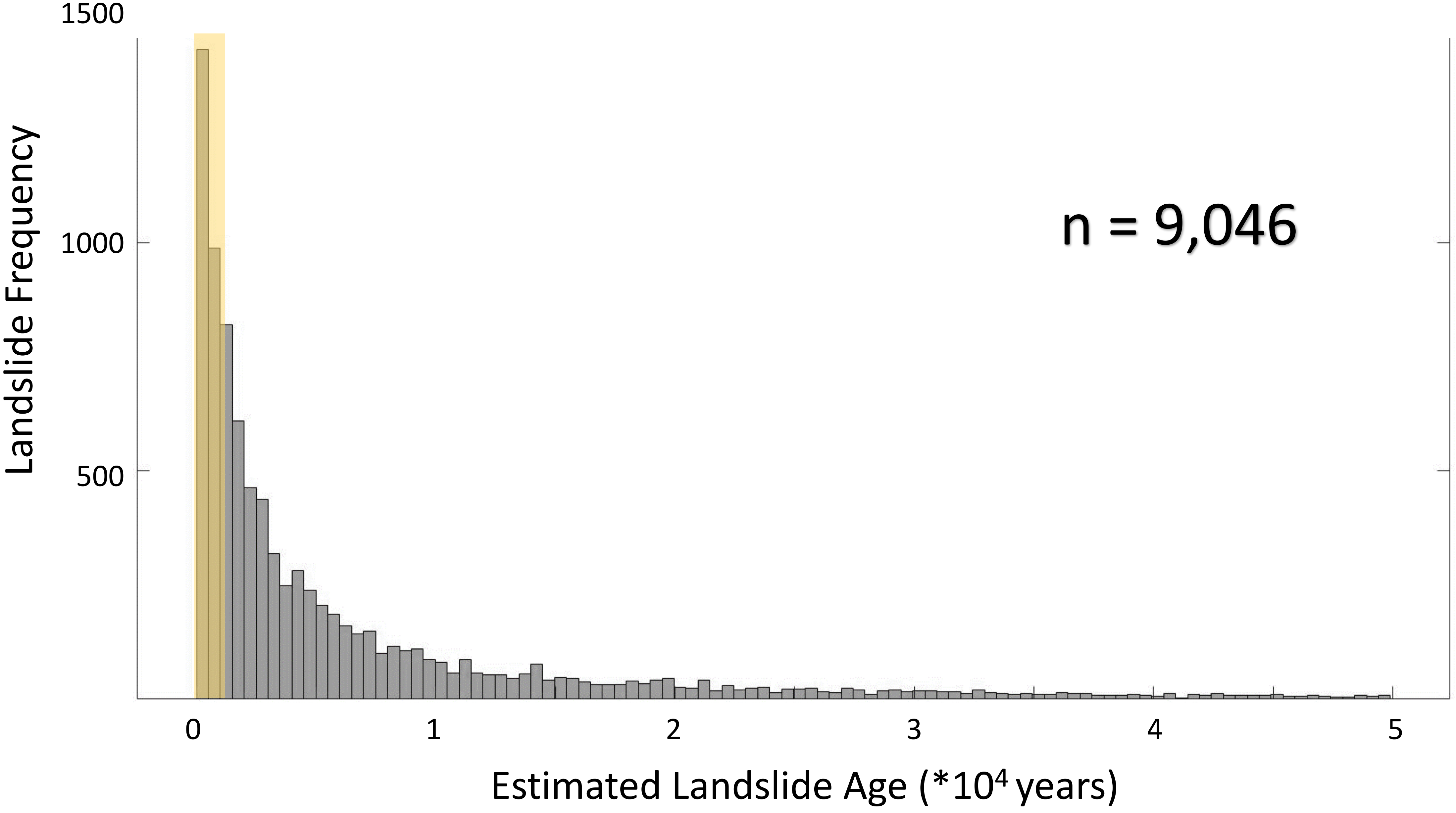
Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017



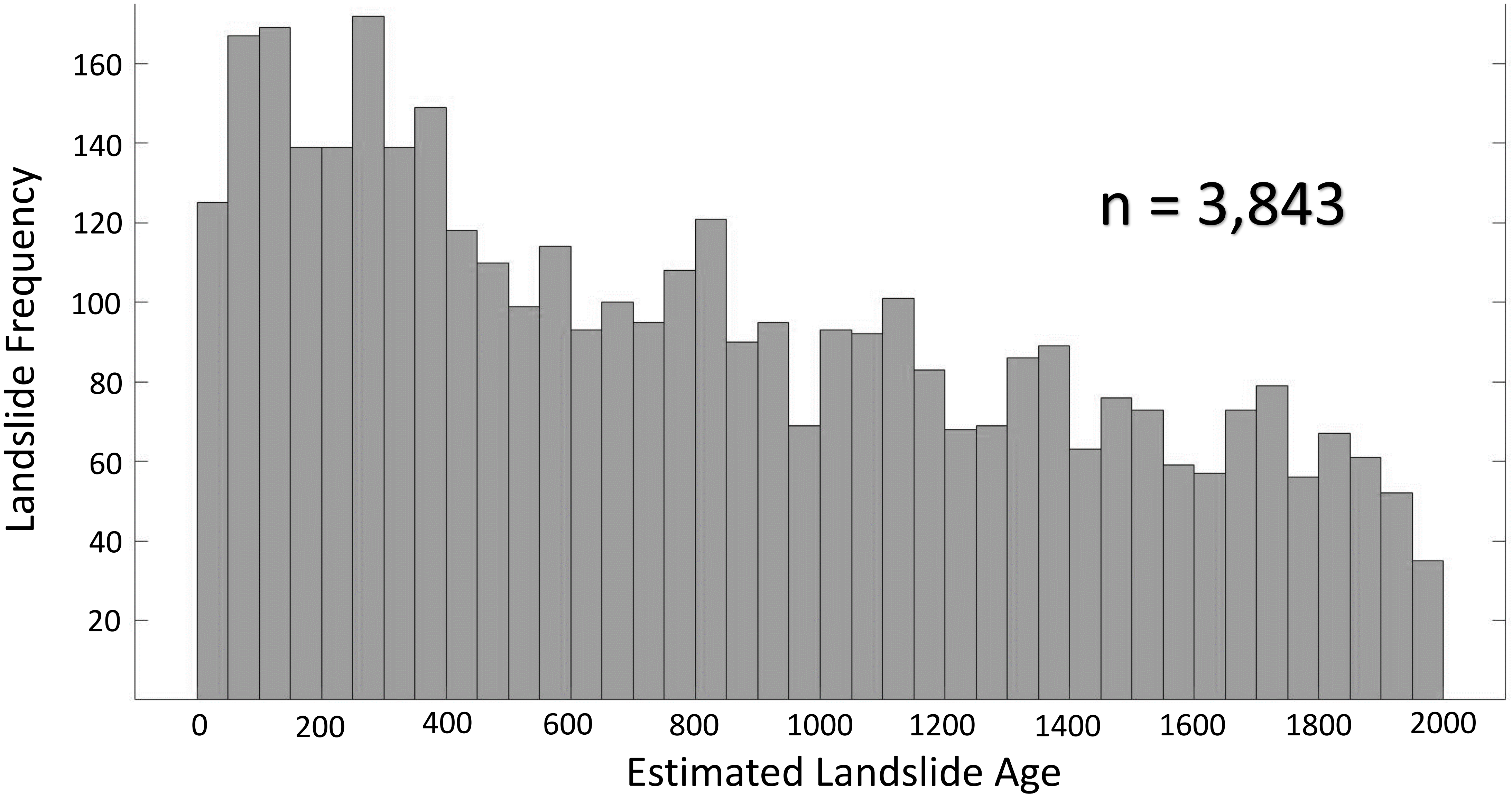
n = 9,734
N
-124°0'
-123°30'
43°30'
44°0'
44°30'
Estimated Age (ybp)
<10²
10²-10³
10³-10⁴
10⁴-10⁵
10⁵-10⁶
0 10 20 40
km


n = 9,734
N
-124°0'
-123°30'
43°30'
44°0'
44°30'
0 10 20 40 km
Estimated Age (ybp)
<10^2
10^2-10^3
10^3-10^4
10^4-10^5
10^5-10^6

Landslide Age Histogram: 50kya to present



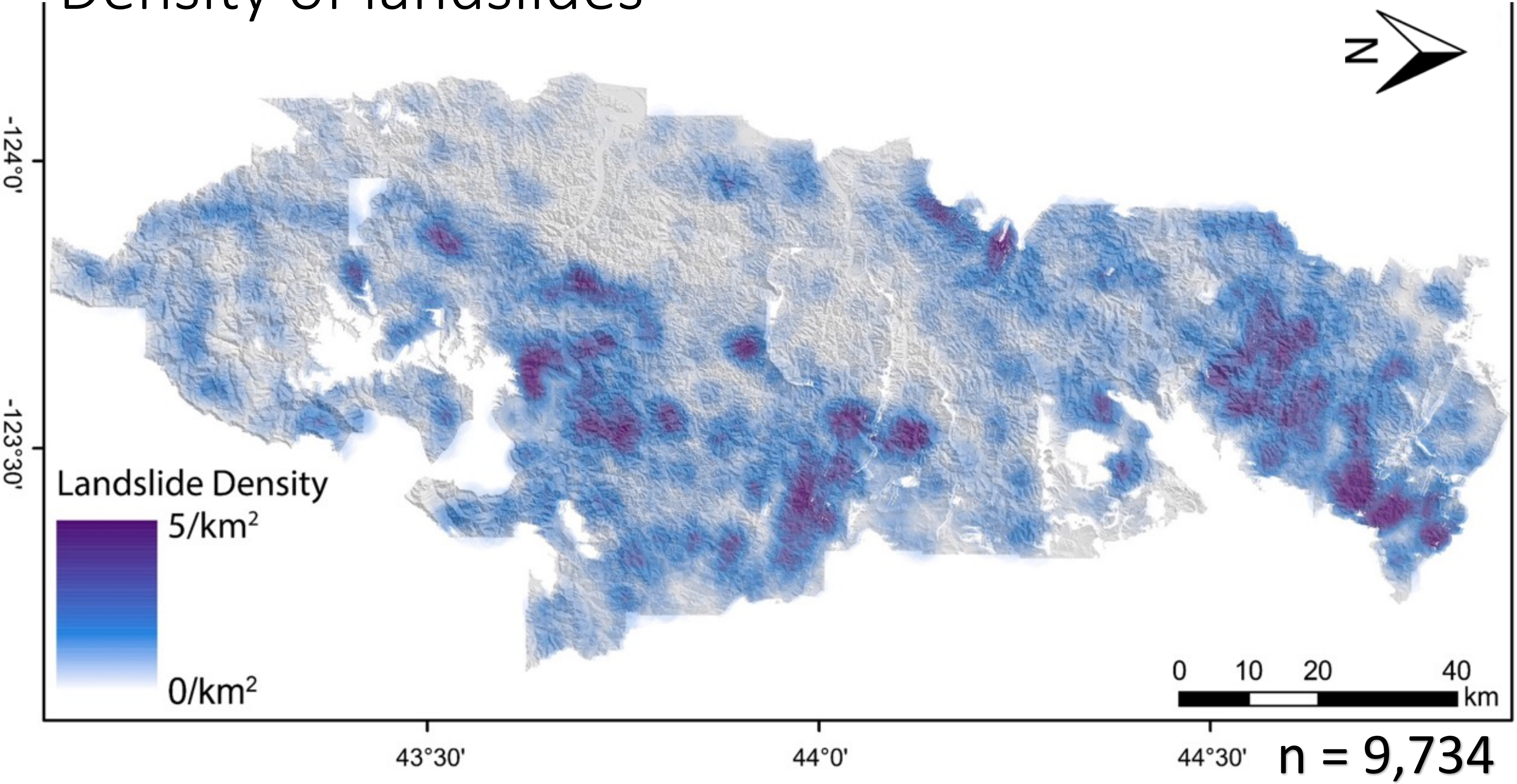
Landslide Age Histogram: 2kya to present



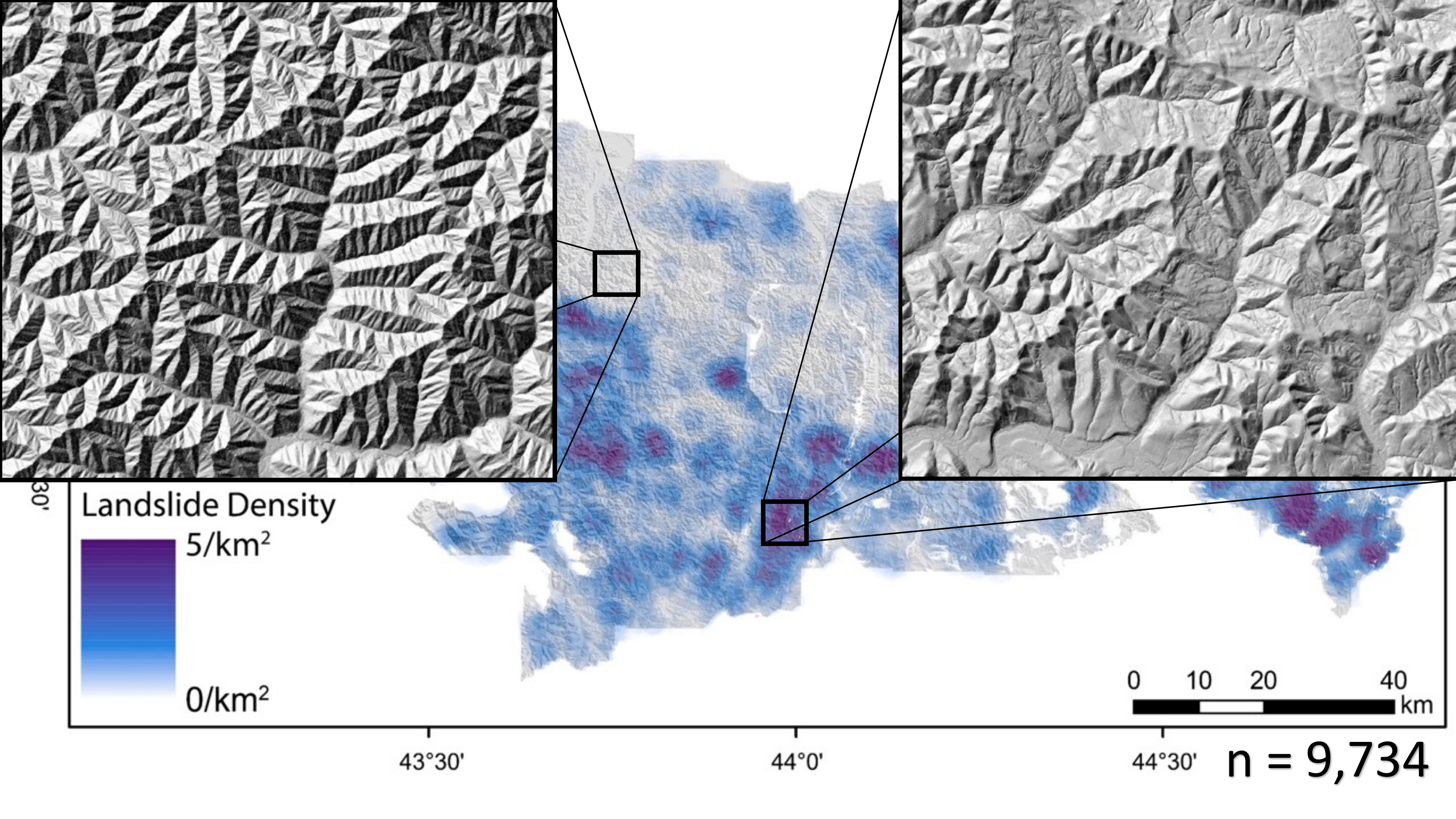
Big questions

2. Where are these slides and do their locations correlate with predicted peak ground accelerations (PGA)?

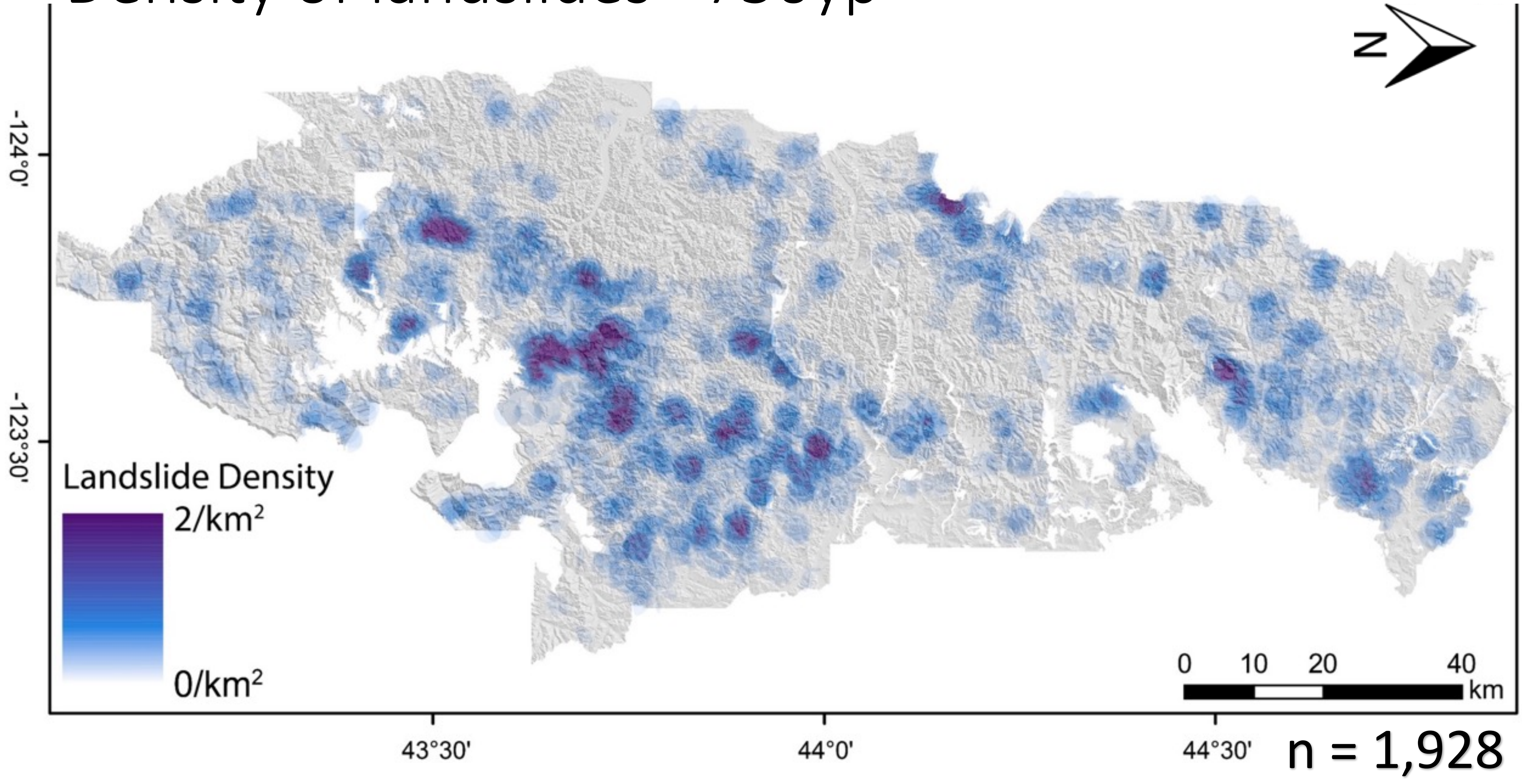
Density of landslides



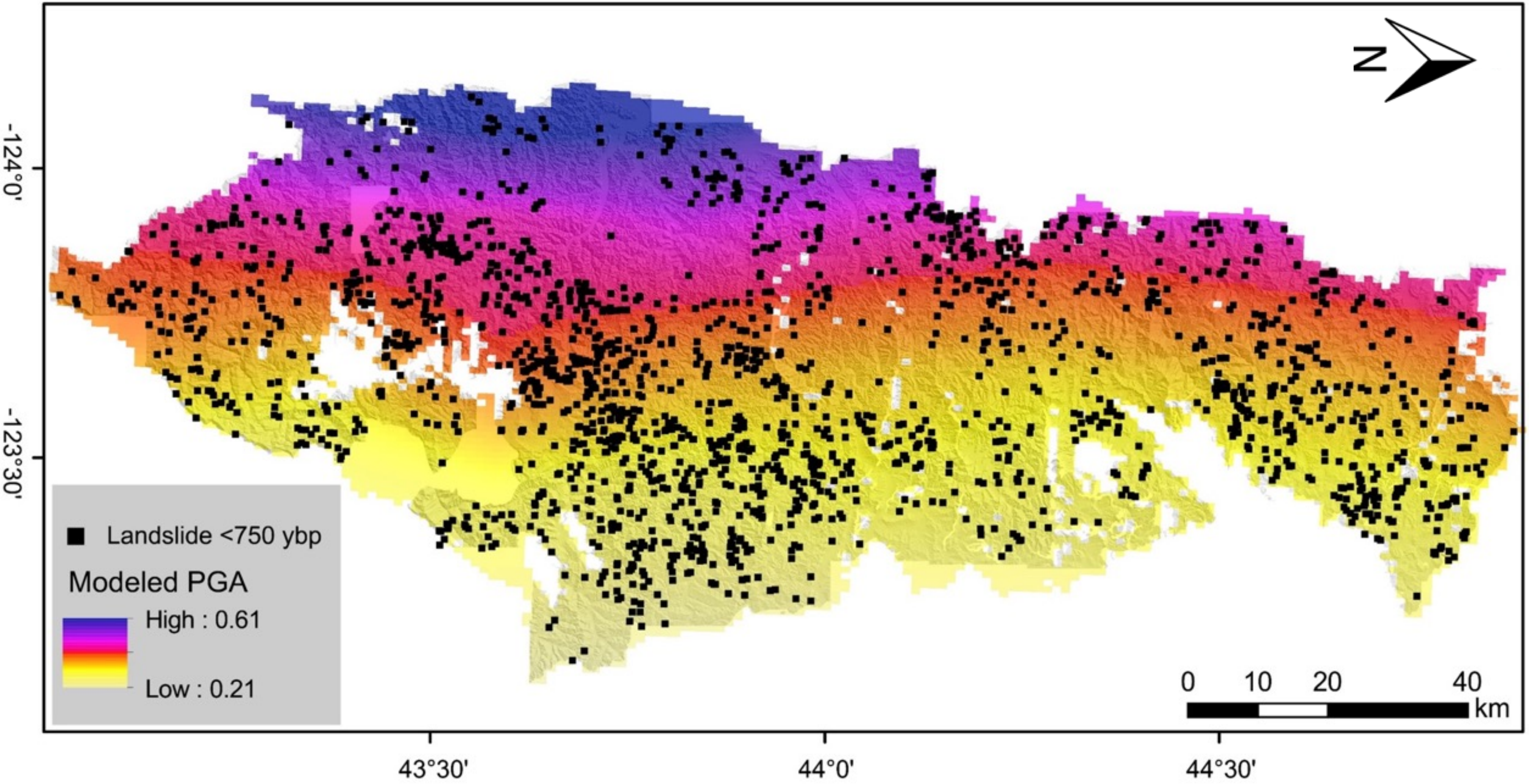
n = 9,734


Landslide Density
5/km²
0/km²
0 10 20 40
km
30'
43°30'
44°0'
44°30'
n = 9,734

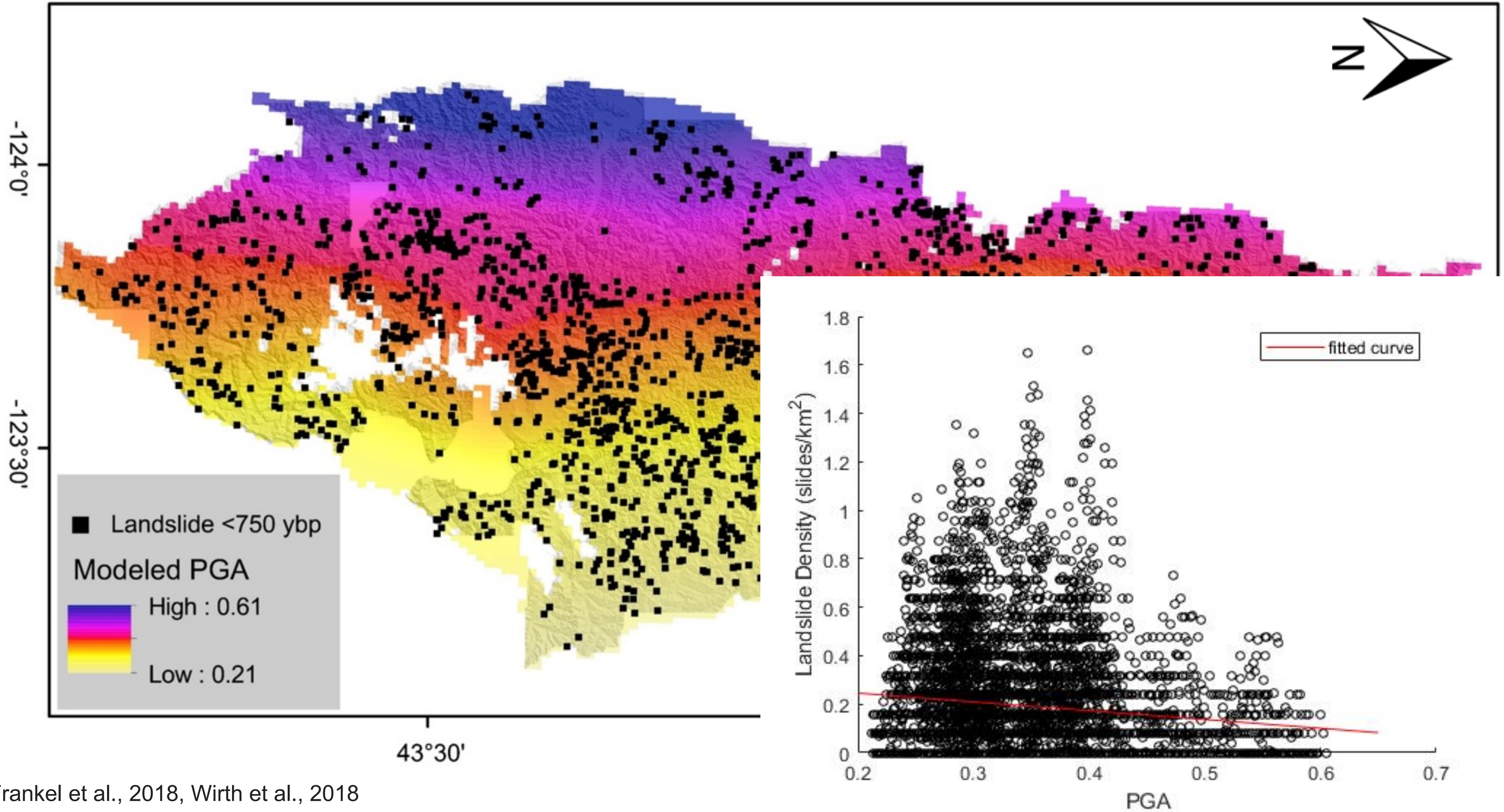
Density of landslides <750yp



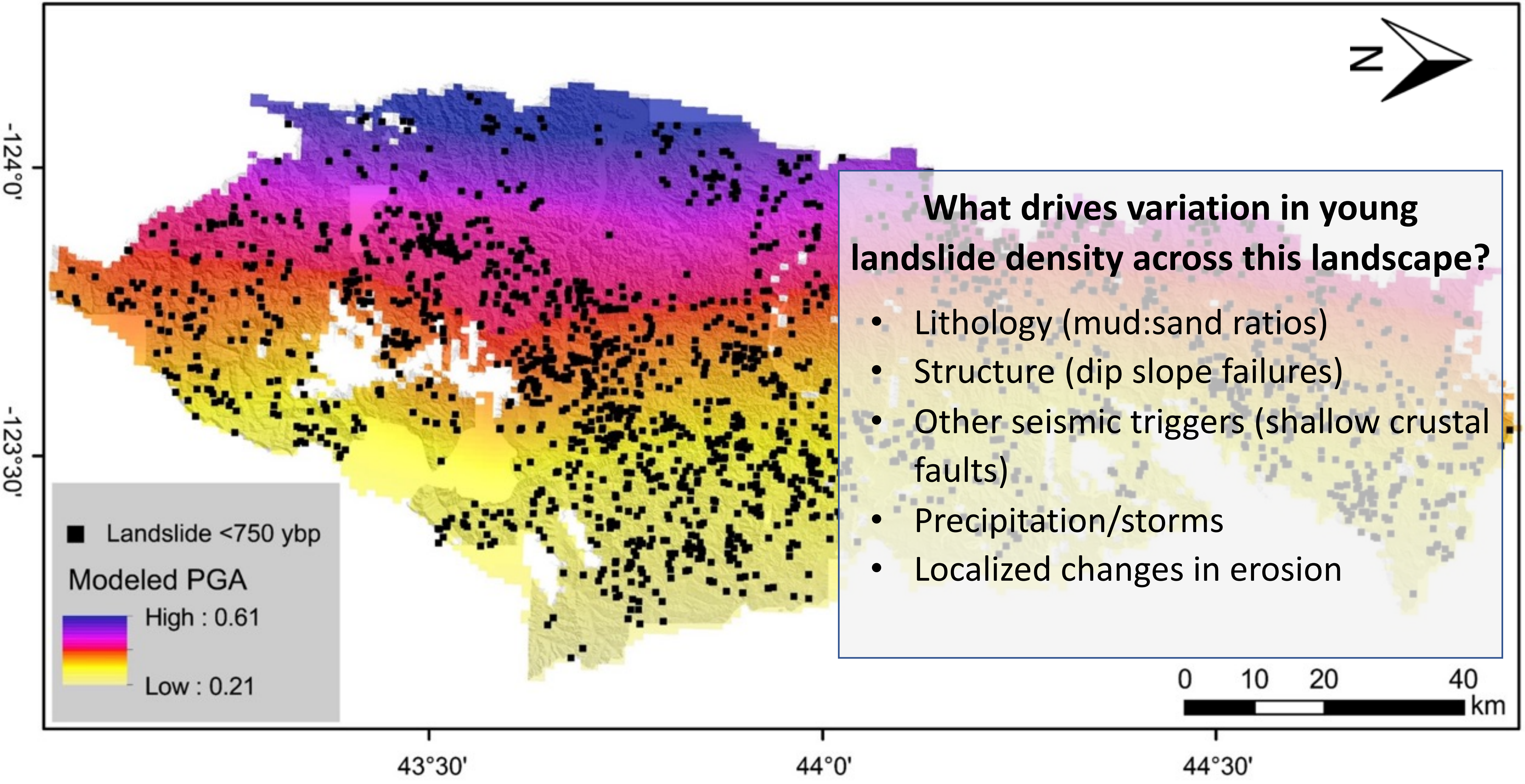
n = 1,928



Frankel et al., 2018, Wirth et al., 2018



Frankel et al., 2018, Wirth et al., 2018



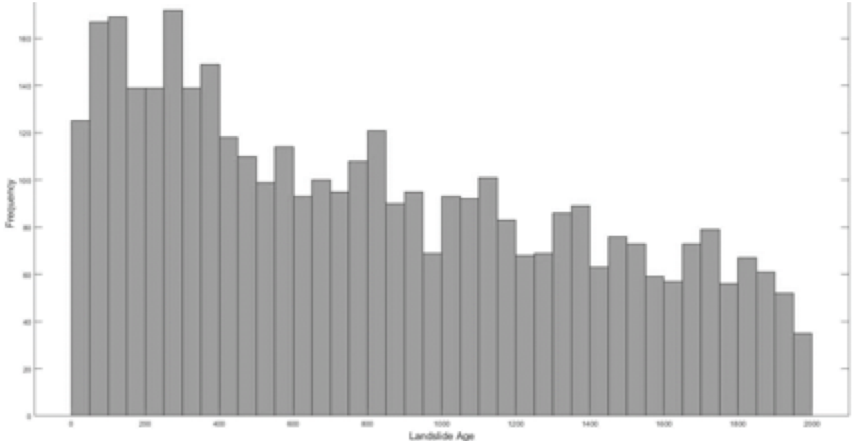
What drives variation in young landslide density across this landscape?

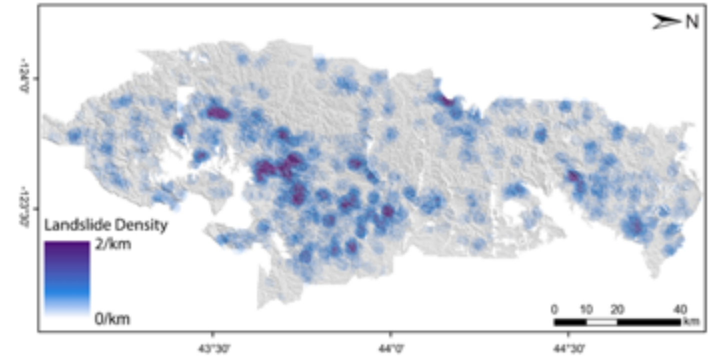
- Lithology (mud:sand ratios)
- Structure (dip slope failures)
- Other seismic triggers (shallow crustal faults)
- Precipitation/storms
- Localized changes in erosion

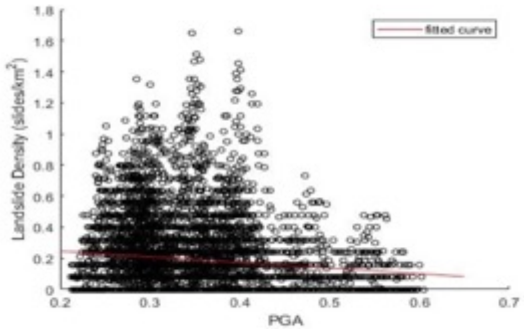
Frankel et al., 2018, Wirth et al., 2018

Conclusions and Next Steps

- Peaks in landslide age may correlate with AD 1700, requires more testing
- How many slides were triggered during the AD 1700 M9 earthquake?
- Landslide density varies substantially across the study area
- PGA does not correlate with locations of young landslides, what does it correlate with?
- How can these results inform landslide susceptibility models in Cascadia?

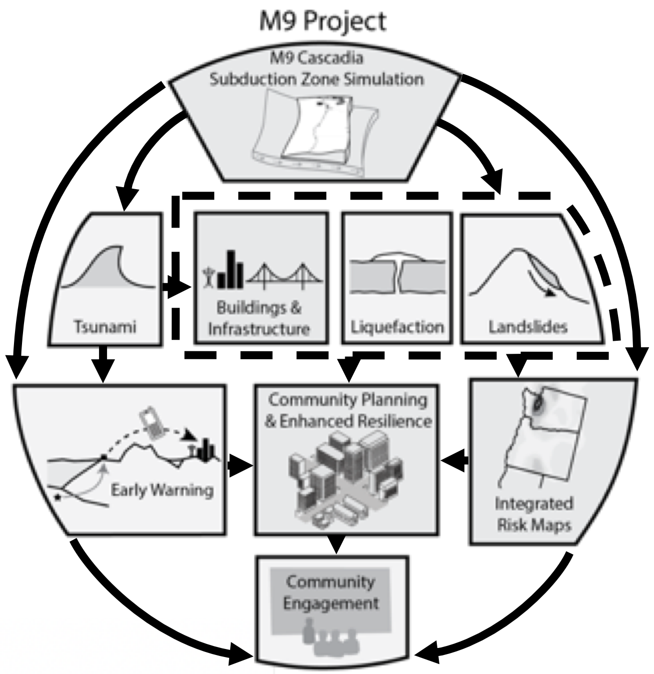


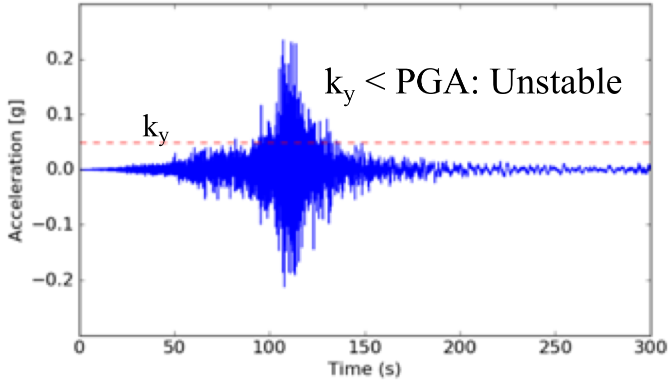


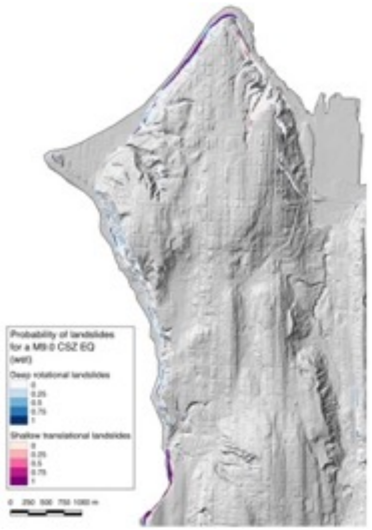


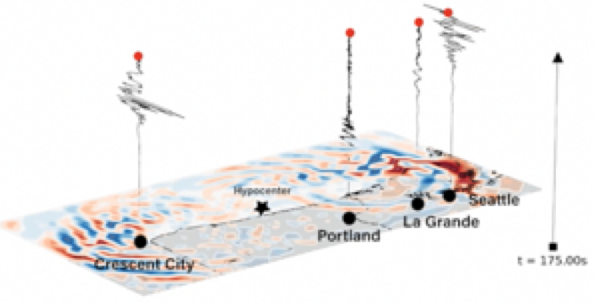
Summary

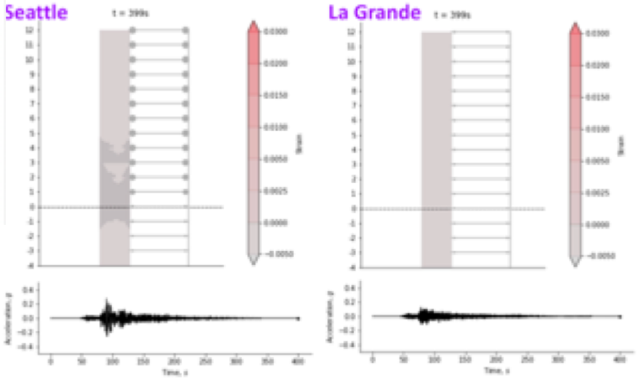
M9: http://m9.uw.edu

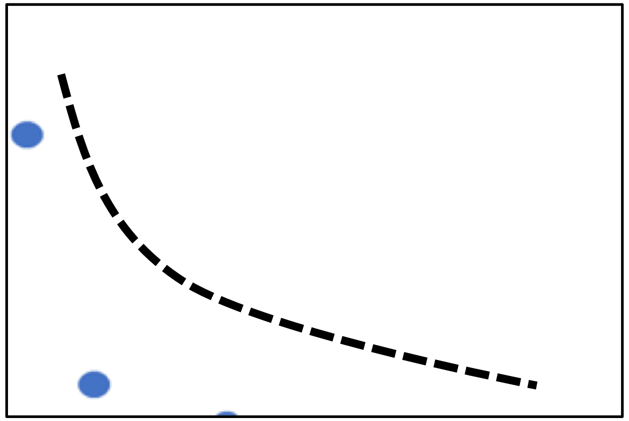


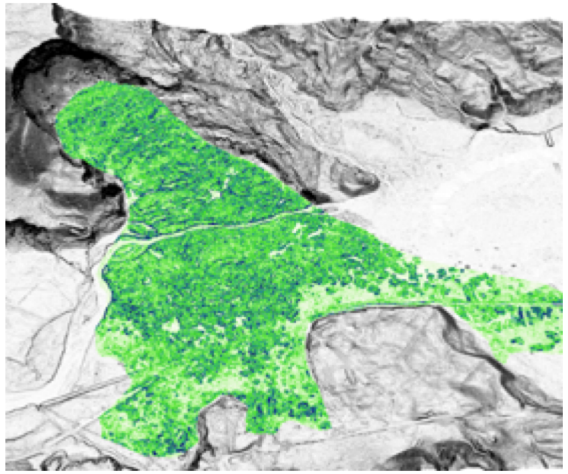












Mountain Building, Strike-Slip Faulting, and Landscape Evolution in New Zealand's Marlborough Fault System

Kaikoura Mountains, NZ
Photo: Sarah Harbert

Thank you & Acknowledgments

- Supercomputer Resources: Stampede (U. Texas), Constance (PNNL), Hyak (U. Washington)
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- UW Quaternary Research Center
- UW Department of Earth and Space Sciences
- Beta Analytic