M9 Cascadia subduction zone earthquakes and landscapes – *how will the hillslopes handle the big one?*
The “M9” Project – 3-D Simulations of M9 Earthquakes on the Cascadia Megathrust

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

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NSF Hazards SEES EAR-1331412
Megathrust Earthquakes in Cascadia

Cascadia Subduction Zone has a history of **M9 Earthquakes**
- Coastal subsidence
- Tsunami records
- Offshore turbidites (geology deposit of turbidity currents)

*Ghost Forest, Greys Harbor, WA*
*Brian Atwater, USGS*

*Tsunami Deposits, Lynch Cove, WA*
*Carrie Garrison-Laney, UW*
Megathrust Earthquakes in Cascadia

Cascadia Subduction 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]
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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The M9 Project was unique in terms of...
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... presenting multiple M9 earthquake realizations, framed probabilistically
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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:
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...

M9 Project

M9 Cascadia Subduction Zone Simulation

Tsunami → Buildings & Infrastructure → Liquefaction → Landslides

Community Planning & Enhanced Resilience → Integrated Risk Maps

Early Warning → Community Engagement

Design by Nasser Marafi
M9 Project

M9 Cascadia Subduction Zone Simulation

Tsunami
Buildings & Infrastructure
Liquefaction
Landslides

Early Warning
Community Planning & Enhanced Resilience
Integrated Risk Maps
Community Engagement

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

https://www.designsafe-ci.org
50+ M9 Earthquake Scenarios

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

https://www.designsafe-ci.org
What is the range of possible ground shaking from an M9?

What are the key rupture parameters?

50+ M9 Earthquake Scenarios

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

https://www.designsafe-ci.org
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

*Background slip and subevents, separately
Key Rupture 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

*Background slip and subevents, separately*
Key Rupture 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

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
Structural Response Realization Rupturing Towards Seattle

Seattle

Likely Slab-Column/Wall Failure

Steel Reinforcing Yielding

La Grande
Structural Response for Seattle

Rupturing **Towards** Seattle

Rupturing **Away** from Seattle
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

2016 Kaikoura Earthquake

Photo: Sean LaHusen
Landscape response

Coseismic Landslides

Landscape Evolution

- Predict coseismic displacement from modeled strong ground motion
Landscape response

Coseismic Landslides

Landscape Evolution

- Map and date Cascadia coseismic slides (1700 and earlier)
M9 Coseismic Landslides

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Seattle’s unstable slopes
Seattle’s Unstable Hillslopes

Perkins Lane Landslide

Oso Landslide

Seattle Landslide Inventory (showing events through 2010)

"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."
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

Deep-seated (rotational) slides

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

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

\[ FS = \frac{cl + (W \cos \alpha - U) \tan \phi}{W \sin \alpha} \]
M9 Coseismic Landslides

Shallow (translational) slides

\[ k_y = (FS - 1) \sin \beta \]
[the acceleration above which downslope motion will occur]

Deep-seated (rotational) slides

\[ k_y \]

where:
- \( k_y \) is the yield acceleration
- \( \beta \) is local hillslope gradient
M9 Coseismic Landslides

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

[the acceleration above which downslope motion will occur]

$k_y > PGA$: Stable

Slope is strong relative to ground shaking

$k_y < PGA$: Unstable

Slope is weak relative to ground shaking, fails coseismically

$k_y$ is the yield acceleration

$\beta$ is local hillslope gradient
M9 Coseismic Landslides

Dry / Summer

Wet / Winter

Probability of landslides for a M9.0 CSZ EQ (dry)
Shallow translational slides
Deep rotational slides

Probability of landslides for a M9.0 CSZ EQ (wet)
Shallow translational slides
Deep rotational slides

Slide c/o Alex Grant
M9 Coseismic Landslides

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

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

**Sean LaHusen** – PhD student UW

**Josh Roering & Will Struble**

**Adam Booth**

**Alison Duvall, Alex Grant, Joseph Wartman, David Montgomery**
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

Time (yrs)

Hillslope transport coefficient

\[ q_s = -\frac{K\nabla z}{1 - (|\nabla z|/s_c)^2} \]

Soil flux

Critical slope

Roering et al. (1999)

Booth et al. (2017)
Modeled Roughness-Age Curve

Modeled Age (YBP)

Average SDS (Roughness) of Oso Landslide Deposit

Modeled landslide surface

Best fit regression

$Y = 163741 \times e^{-0.7049X}$
LaHusen, et al. (2016)
Construct landslide chronology

Booth, et al. (2017)
Oregon Coast Range

Juan de Fuca plate

Cascadia Subduction Zone Megathrust

North American Plate (Oregon)
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

Juan de Fuca plate
North American Plate (Oregon)

Cascadia Subduction Zone

Roering et al., 2005
Burns et al., 2017
Hammond et al., 2009
- Deep-seated translational and rotational slides
- Clearly defined headscarp and body
- All complexes mapped as separate slides
- Avoid channelized earthflows or rock avalanche deposits
- >10,000m² 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

Landslide Age *10^4 (ybp)

Landslides of known 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

Mean Standard Deviation of Slope (degrees)

Landslide Age *10^4 (ybp)

Living Trees

14C from stumps in landslide deposit and dammed lake:

Dendrochronology

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

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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

Mean Standard Deviation of Slope (degrees)

Landslide Age *10^4 (ybp)

Struble et al. (in review), Worona & Whitlock, 1995, Hammond et al., 2009, Richardson et al., 2017
n = 9,734
Landslide Age Histogram: 50kya to present

Estimated Landslide Age (*10^4 years)

$n = 9,046$
Landslide Age Histogram: 2kya to present

n = 3,843
2. Where are these slides and do their locations correlate with predicted peak ground accelerations (PGA)?
Density of landslides <750yp

Landslide Density
2/km²
0/km²

n = 1,928
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
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)
- Ben Mishkin, Valerie Bright, Kyle Lowery, and Logan Wetherell for mapping, field, and analysis assistance
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- UW Quaternary Research Center
- UW Department of Earth and Space Sciences
- Beta Analytic