Impactful Science:
Earthquake Hazards and Earthscope

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Society and earthquakes hazards

- Fault systems are **complex**
- We understand them better than we used to
- But knowledge is still **partial**
- As geophysicists society demands **simple** answers
  - When, or how frequently, will earthquakes happen?
  - How big can they be?
  - What are their impacts?

2010 M7.2 El Mayor earthquake
Mexico/US border

Ken Hudnut, USGS
Conceptualizing hazards

Hazard maps drive critical legislation
- Building codes
- Tsunami evacuation zones
- Landslide requirements, and more
Conceptualizing hazards

Hazard maps drive critical legislation.

They are underpinned by basic research.
Conceptualizing hazards

- This requires converting **uncertain** knowledge into **absolute** statements

  - You need **this much** concrete and rebar
  - The school **cannot be** within X km from the shore

- This is contrary to scientific epistemology, we never know an **absolute** truth.
We are left with **two choices**:

- **Paralysis**: admit our fallibility and do nothing
- Or, formalisms that **maximize information** content of our imperfect knowledge
Conceptualizing hazards

**Probabilistic Seismic Hazard Analysis**

1. **Step 1: EARTHQUAKE SOURCES**
   - Fault (Line source)
   - Point source
   - Area source

2. **Step 2: RECURRENCE MODEL**
   - Log of No. of Earthquakes vs. M
   - Magnitude M

3. **Step 3: GROUND MOTION ATTENUATION**
   - Uncertainty in attenuation
   - Peak Acceleration vs. Magnitude M

4. **Step 4: PROBABILITY OF EXCEEDANCE**
   - Probability of Exceedance vs. Acceleration

Source: FEMA

**Scenario Driven Tsunami Evacuation Maps**

Source: DOGAMI
How has basic science influenced hazards?
The Cascadia Subduction Zone
Is Cascadia active? A brief history

Earthquake Hazards on the Cascadia Subduction Zone

Thomas H. Heaton and Stephen H. Hartzell

Science

Radiocarbon test of earthquake magnitude at the Cascadia subduction zone

Brian F. Atwater*, Minze Stuiver†
& David K. Yamaguchi‡

NATURE · VOL 353 · 12 SEPTEMBER 1991

Tree-ring dating the 1700 Cascadia earthquake

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Boyd E. Benson
GeoEngineers Inc., 8410 154th Avenue N.E.,
Redmond, Washington 98052, USA

Marion S. Reid
The Nature Conservancy, 2600 Broadway,
Suite 230, Boulder, Colorado 80302, USA

Turbidite Event History—Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone


Professional Paper 1661-F
U.S. Department of the Interior
U.S. Geological Survey
2001
Cascadia’s motion

- **1278** PBO stations built out to supplement local networks
- Direct measurements of plate deformation
- Where are the faults and are they locked or not?

Courtesy of Dave Mencin
Cascadia’s landward movement

Is Cascadia locked?
- Yes!

Image by John Delaney
Is Cascadia active? The geodetic perspective
Is Cascadia active? The geodetic perspective

Locking is **heterogenous** and **segmented**
Is Cascadia active? The geodetic perspective

The locking **offshore** remains ambiguous.
Why this pattern and is it a long term feature?

Tomography reveals buoyant asthenosphere accumulating beneath the Juan de Fuca plate

William B. Hawley, Richard M. Allen, Mark A. Richards

Science, 2017

Buoyant Asthenosphere Beneath Cascadia Influences Megathrust Segmentation

Miles Bodmer, Douglas R. Toomey, Emilie E. Hooft, and Brandon Schmandt

Geophys. Res. Lett, 2018
Why this pattern and is it a long term feature?

Bodmer et al. 2018

A physical mechanism for locking
The spectrum of behavior: Slow slip

Image by John Delaney

Animation by Noel Bartlow
The spectrum of behavior: Slow slip

The slow slip area cannot participate in big earthquakes (maybe)
2014 Update of the Pacific Northwest Portion of the U.S. National Seismic Hazard Maps

Arthur Frankel, a) M.EERI, Rui Chen, b) Mark Petersen, c) M.EERI, Morgan Moschetti, c) and Brian Sherrod a)

EQ Spectra, 2015

How deep will the next M9 go?

Hazard change
(2015/2008)
Simulations of the next event require deep understanding of the fault and crustal structure.
The San Andreas Fault System
The California Hazard Model (UCERF3)

- The most **comprehensive** earthquake hazard model
- **Combines** seismology, geodesy, and geology
- **New research** incorporated with new iterations
How fast are faults moving?

Trench through a fault
Ray Weldon

Uniform California Earthquake Rupture Forecast, version 3 (UCERF3)—The Time-Independent Model
The California Hazard Model (UCERF3)

How fast are faults moving?

Trench through a fault
Ray Weldon

UCERF3, Field et al., 2014
The slip budget on the SAF

Is there a discrepancy between geological and geodetic slip rates along the San Andreas Fault System?

Xiaopeng Tong¹, Bridget Smith-Konter², and David T. Sandwell¹

The slip budget on the SAF

Tong et al., 2016
The slip budget on the SAF

We know the moment budget of the entire fault

Tong et al., 2016
And elsewhere in California!

And it’s not just the Andreas Fault
Lithospheric Thinning Beneath Rifted Regions of Southern California

Vedran Lekic, Scott W. French, Karen M. Fischer

Localized shear in the deep lithosphere beneath the San Andreas fault system

Heather A. Ford, Karen M. Fischer, and Vedran Lekic

1Department of Geological Sciences, Brown University, 324 Brook Street, Box 1846, Providence, Rhode Island 02912, USA
2Department of Geology, University of Maryland, College Park, Maryland 20742, USA

Science 2011

Geology 2014
Long-term geodynamics

Transportable array and local networks
Long-term geodynamics

- LAB velocity contrasts **across** faults
- Implications for **long-term** interseismic velocities
- It can change the **slip budget** on faults
The New Madrid Seismic Zone
New Madrid: Far from the plate Boundary
New Madrid: Far from the plate Boundary

A hazards bullseye
It’s not moving!

A new paradigm for large earthquakes in stable continental plate interiors

E. Calais, T. Camelbeeck, S. Stein, M. Liu, and T. J. Craig


GPS velocity as a function of Publication year

Present GPS velocity

B

Seismic structure concentrates stress

Seismic structure of the Central US crust and shallow upper mantle: Uniqueness of the Reelfoot Rift
Fred F. Pollitz*, Walter D. Mooney
USGS, 345 Middlefield Road, MS 977, Menlo Park, CA 94025, USA

Stress development in heterogenous lithosphere: Insights into earthquake processes in the New Madrid Seismic Zone
Yan Zhan a, Guiting Hou a,b, Timothy Kusky b, Patricia M. Gregg c
a Key Laboratory of Oreogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China
b Center for Global Tectonics, State Key Laboratory for Geologic Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China
c Department of Geology, University of Illinois at Urbana-Champaign, 132 Computer Applications Building 405 E. Spring St Ave, Champaign, IL 61820, USA
Tectonophysics 2016

TA seismic tomography

Old “fossil” structures
Transient unloading leads to failure

Incision of the Mississippi river removes sediment and unclamps the faults
Transient unloading leads to failure

Far-field loading has nothing to do with it.

Strain is accumulated over far longer time scales related to when the structures formed.

It is transient changes in strength lead to failure.

This view argues that once broken reloading of the fault will not happen.
Will it happen again?

⚠️ Is the bullseye warranted?

→ Can we find other similar regions in the “stable” US?
Technology breakthroughs: Earthscope and Early Warning
Through Earthscope we learned to use GPS to in real-time

Caught some significant events M7.2 El Mayor, M6.1 Napa, etc.
Geodesy for the largest earthquakes

Operational real-time GPS-enhanced earthquake early warning
R. Grapenthin$^{1,2}$, I. A. Johanson$^1$, and R. M. Allen$^1$

Real-time inversions for finite fault slip models and rupture geometry based on high-rate GPS data
S. E. Minson$^{1,2}$, Jessica R. Murray$^3$, John O. Langbein$^1$, and Joan S. Gomberg$^1$

Demonstration of the Cascadia G-FAST Geodetic Earthquake Early Warning System for the Nisqually, Washington, Earthquake
by Brendan W. Crowell, David A. Schmidt, Paul Bodin, John E. Vidale, Joan Gomberg, J. Renate Hartog, Victor C. Kress, Timothy I. Melbourne, Marcelo Santillan, Sarah E. Minson, and Dylan G. Jamison
Geodesy for the largest earthquakes

Development of a Geodetic Component for the U.S. West Coast Earthquake Early Warning System

by J. R. Murray, B. W. Crowell, R. Grapenthin, K. Hodgkinson, J. O. Langbein, T. Melbourne, D. Melgar, S. E. Minson, and D. A. Schmidt

Seism. Res. Lett., 2018
The ultimate goal is to use GPS to issue forecasts in 2-3 mins following a large earthquakes
The Future
The next frontier is offshore

- Go offshore in a concerted way
  - Shallow coupling
  - Structure of the wedge
  - Tsunamigenesis
  - Role and budget of fluids

- Catch a large rupture in action
  - What happens at nucleation?
  - Are all earthquakes created equal?
  - How do foreshocks behave?
The next frontier is offshore!

Seismometers

Pressure gauges (tsunami)

2016 M6.9 offshore Fukushima
The next frontier is offshore!

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Alaska Amphibious Community Seismic Experiment

Abers et al., 2018
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Conclusions
Impactful science serves society

Basic research

Lag time

Hazards applications
Policy
Planning/Mitigation
Warning
Education