Earth Science Needs for Improving Earthquake Scenarios

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USGS
science for a changing world

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The 2008 ShakeOut Scenario: Motivation

From [The ShakeOut Scenario, USGS Open-File Report 2008-1150]

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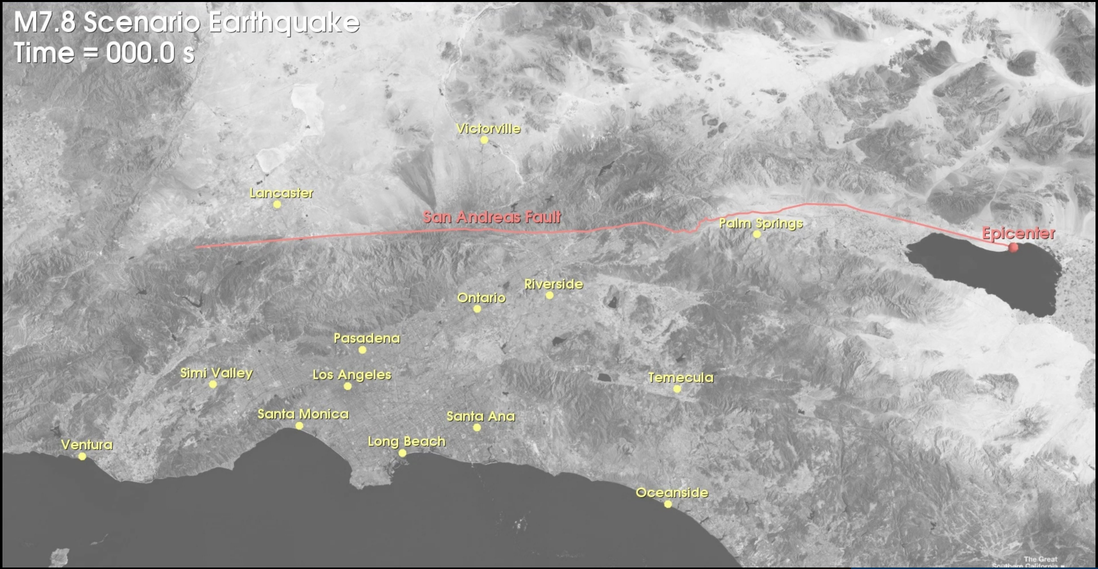
Examining the consequences and far-reaching impacts of one such event can help us prepare for other such events

ShakeOut Scenario: Animation of Ground Shaking



ShakeOut Scenario: Integrated Analysis

Earth science forms the foundation on which earthquake scenarios are built

Earth Science → **Engineering** → **Social Science** → **Policy**

Earth Science
- Earthquake source
- Ground motions
- Fault offsets
- Ground failure
- Aftershocks

Engineering
- Buildings
- Contents damage
- Utilities, lifelines
- Fire following earthquake

Social Science
- Emergency services
- Mortality and morbidity
- Business interruption
- Movement of goods

Policy

Adapted from [The ShakeOut Scenario, USGS Open-File Report 2008-1150]

2018 HayWired Scenario

Ground motions developed in parallel with ShakeOut in 2007–2008; other analyses are more recent

- Hayward Earthquake Scenarios Project, 2008
  - USGS led collaborative effort to generate 39 M6.8–7.2 Hayward fault scenario earthquakes
  - 12+ scientists developed rupture model parameters
  - Five ground-motion modeling groups computed ground-motions
- HayWired Scenario, public rollout April 2018
  - Select single realization from 2008 scenarios: M7.0 Hayward fault earthquake
  - Subsequent analyses similar to ShakeOut to assess impacts
  - Third phase to be released in April 2019

Scenarios: Intended Uses

Wide range of intended uses and expect additional uses

- Urban planning
- Emergency response training
- Schools, business, and public earthquake drills
- Prioritization of preparedness efforts
- Understanding potential impacts on financial and social systems
- Identify infrastructure vulnerabilities due to interactions among systems that are usually considered separately

Adapted from [The ShakeOut Scenario, USGS Open-File Report 2008-1150]

Earthquake Scenarios Draw National Attention

Especially important to create the most realistic earthquake scenarios possible

ShakeOut: November 13, 2008

CNN	Largest earthquake drill in history 'rattles' California
TIME	The 'Big One'
The New York Times	Californias Drill for Day None Want to Arrive

HayWired: April 18, 2018

Los Angeles Times	East Bay fault is 'tectonic time bomb,' more dangerous than San Andreas, new study finds
The Mercury News	Earthquake warning: Just how bad is Hayward Fault's night-mare scenario?
CBS EVENING NEWS	Bay Area at risk of 'Tectonic Time Bomb'

Scenarios versus Probabilistic Seismic Hazard Analysis (PSHA)

Scenarios: one realization, regional scale; PSHA: all earthquakes, single site

Scenarios

- Focused on one or small number of earthquake realizations
- Often include detailed modeling, such as 3-D ground-motion simulations
- Examine broad range of impacts and cascading failures

Probabilistic Seismic Hazard Analysis

- Usually applied to single location
- Includes all earthquakes (weighted by probability) expected to occur over a given time period
- Accounts for variability in rupture (slip, hypocenters)

Outline

- Describe earth science used in ShakeOut and HayWired earthquake scenarios
- Research needs
  - Earthquake source
  - Ground motions
  - Fault offsets
  - Ground failure
  - Aftershocks
- Concluding remarks

Earthquake Source: ShakeOut

Main parameters established during series of workshops; see [Graves et al., 2011]

Rupture end points Based on paleoseismic studies and SoSAFE workshops

Hypocenter San Andreas fault loaded at Bombay Beach from Brawley Seismic zone

Fault geometry Consensus version in SCEC CFM

Background slip Slip-predictable approach

Slip distribution Stochastic using Mai and Beroza (2002)

Rupture speed Correlated with slip, tapered at top and bottom of rupture

Rise time Correlated with maximum slip velocity and increases with slip

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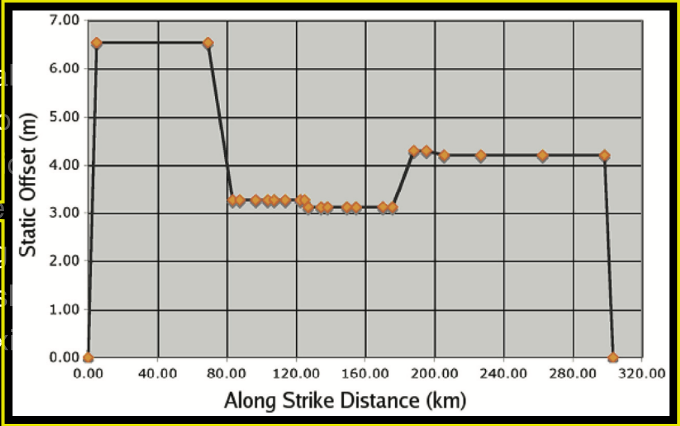

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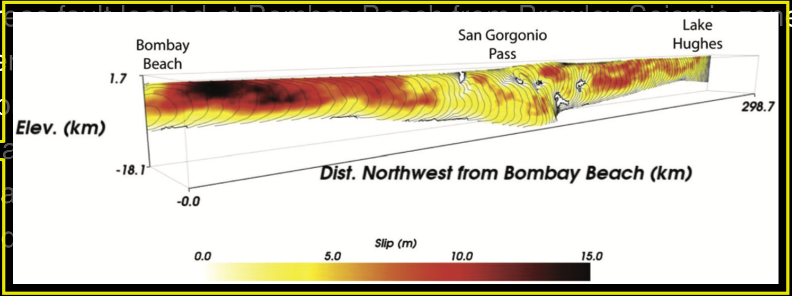

Earthquake Source: HayWired

Similar methodology but need to account for interseismic creep

Rupture end points Based on 2003 Bay Area probabilities study and fault geometry

Hypocenter Based on seismicity and discontinuities in geologic structure

Fault geometry USGS Bay Area geologic model (Jachens, 2006)

Background slip Taper slip in regions with aseismic creep

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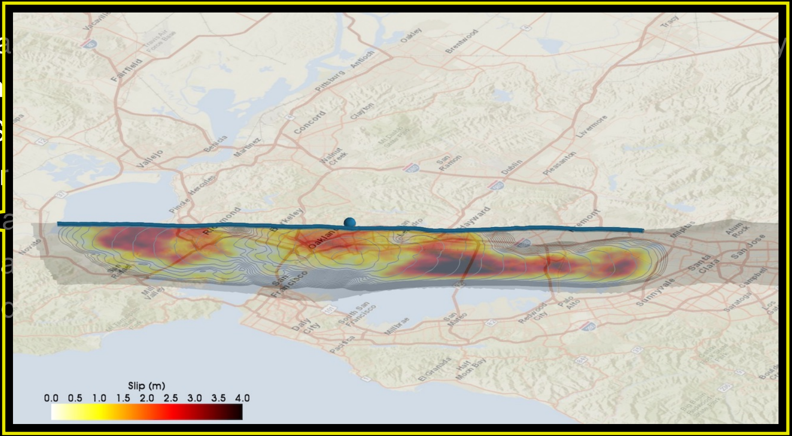

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Ground-Motions

Same ground-motion simulation methodology for both ShakeOut and HayWired

- Broadband (0–10 Hz) computing using Graves and Pitarka (2010) hybrid approach
  - Deterministic: 0–1 Hz
  - Stochastic: 1–10 Hz
- Elastic properties from SCEC CVM 4.0 (ShakeOut) and USGS Bay Area seismic velocity model (HayWired)
- Minimum shear wave speed: 620 m/s
- Period-dependent, nonlinear amplification factors (Walling et al., 2008) using Vs30 (Wills et al., 2000)
- Ground-motion time histories on 2 km grid

Fault Offsets

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  - Particular attention paid to offset at Cajon Pass (4.2 m) in selecting random slip realization
  - Afterslip not considered

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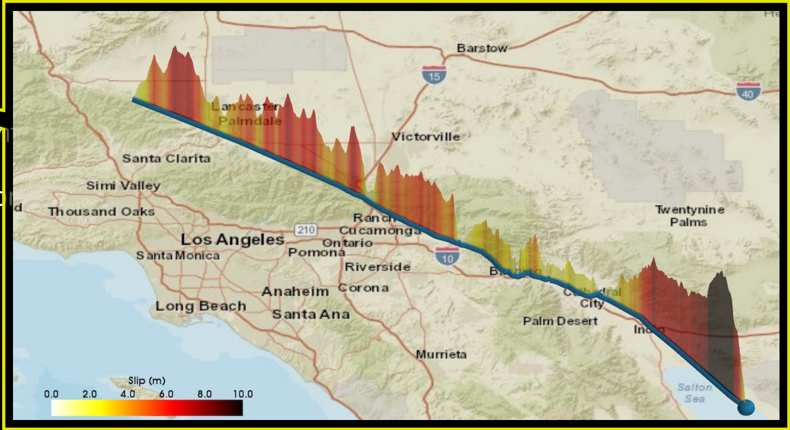

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- HayWired
  - Surface slip affected by tapering associated with surface creep
  - Separate (but related) afterslip model using Monte Carlo simulations

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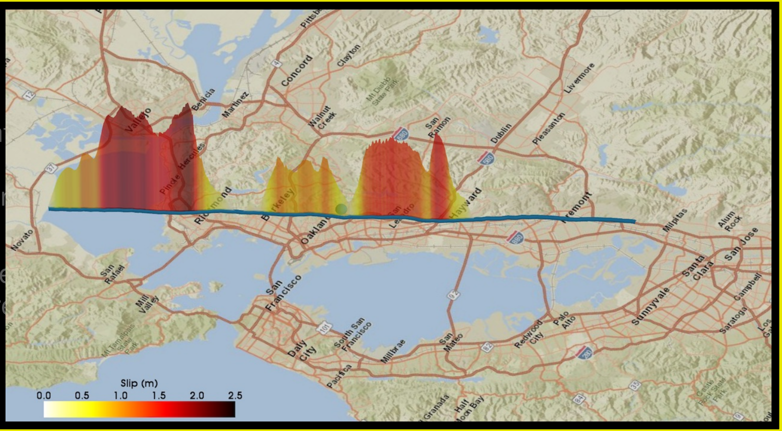

Ground Failure

Open data and high-resolution mapping facilitates detailed landslide and liquefaction models

- Landslides
  - ShakeOut
    - HAZUS-MR3 with landslide susceptibility map via Wilson and Keefer (1985)
    - 10 landslide susceptibility classes based on 3 groups of geologic units and 8 slope categories
  - HayWired
    - Jibson (2007) Newmark rigid sliding-block displacement analysis regression equation
    - 66 geologic units with material-strength values
    - Slope failure on 10-m resolution grid

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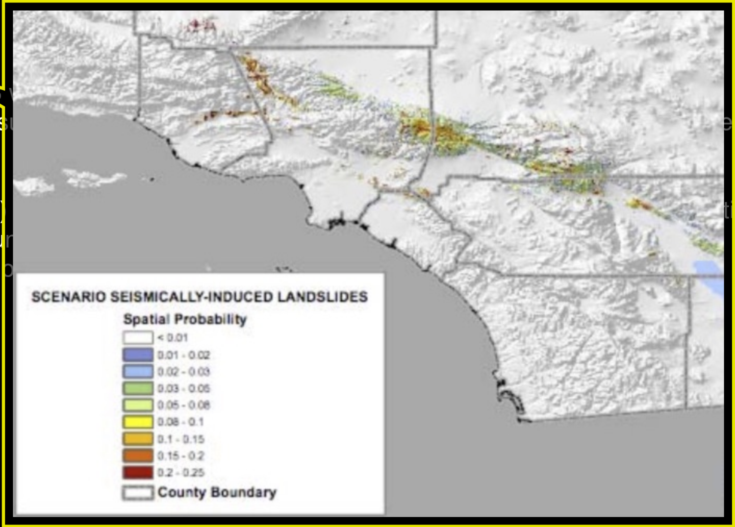

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- Liquefaction
  - ShakeOut
    - HAZUS-MR3 with more detailed analysis at lifeline fault crossings
    - Liquefaction susceptibility map + depth to ground water + shaking intensity
  - HayWired
    - HAZUS-MH v2.1 across region
    - Liquefaction Potential Index (Holzer et al., 2008,2010) for eastern margin of SF Bay

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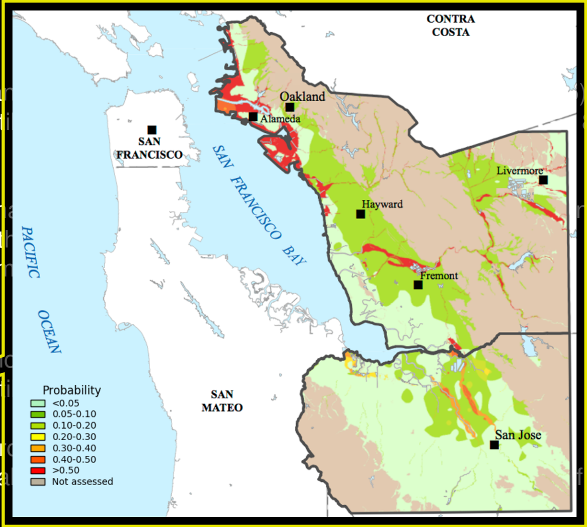

Aftershocks

More advanced and extensive aftershock forecast for HayWired

- ShakeOut and HayWired
  - ETAS model (Felzer et al. 2002) plus distribution in space
  - Aftershocks not explicitly associated with mapped faults
  - Most aftershocks occur near mainshock rupture

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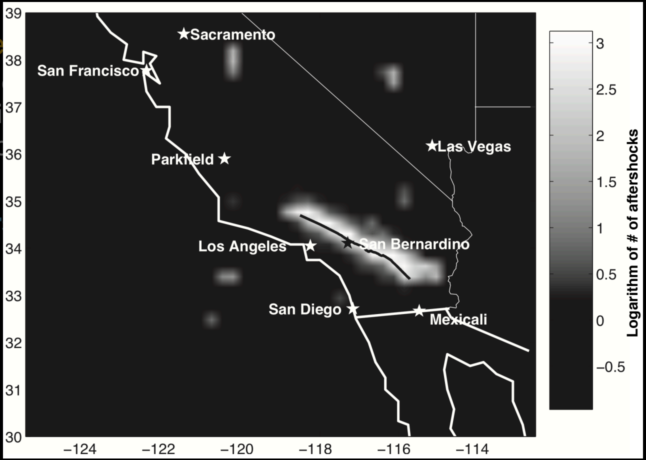

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  - 13 realizations for **two years** after mainshock
  - Sample aftershock forecasts at time intervals after mainshock
  - ShakeMaps generated for $M \geq 5$ aftershocks

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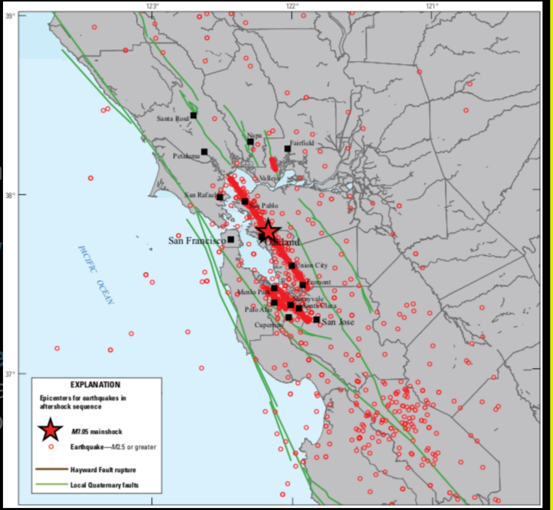

Earth Science Research Needs: Practical Considerations

First, establish general target and scope when constructing an earthquake scenario

- Select an earthquake scenario relevant to your target audience
  - Probability of occurrence: magnitude and location
  - Frequency bandwidth and spatial resolution of ground motions
  - 1, 10, 100, . . . realizations?

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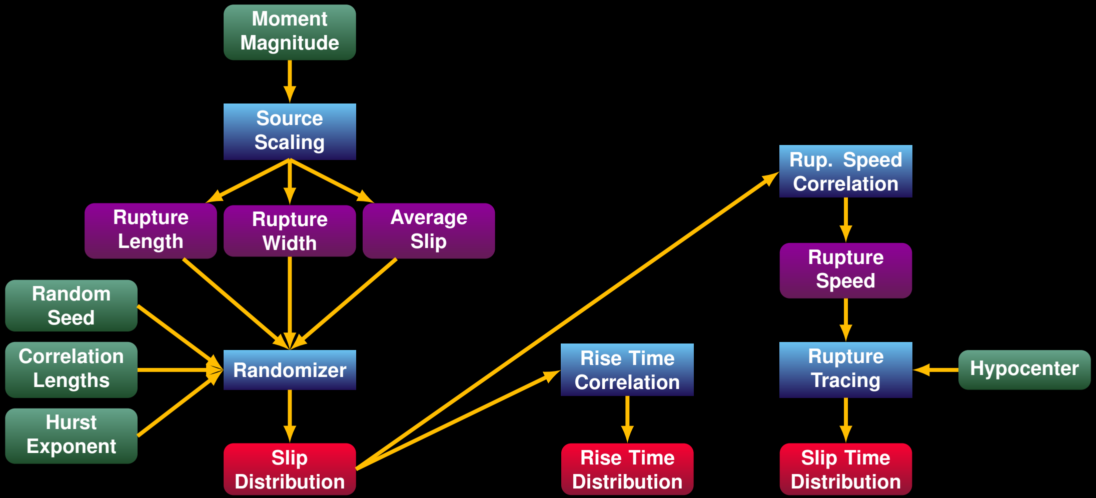
  - Advancing science requires extra time for development and review
- Identify observations and empirical models to use as relative baselines

  Example: Ground-motion amplitudes are slightly greater than median values of ground-motion prediction equations but within range of observations

Earthquake Source Parameters: Workflow

Numerous research areas involved in generating rupture models

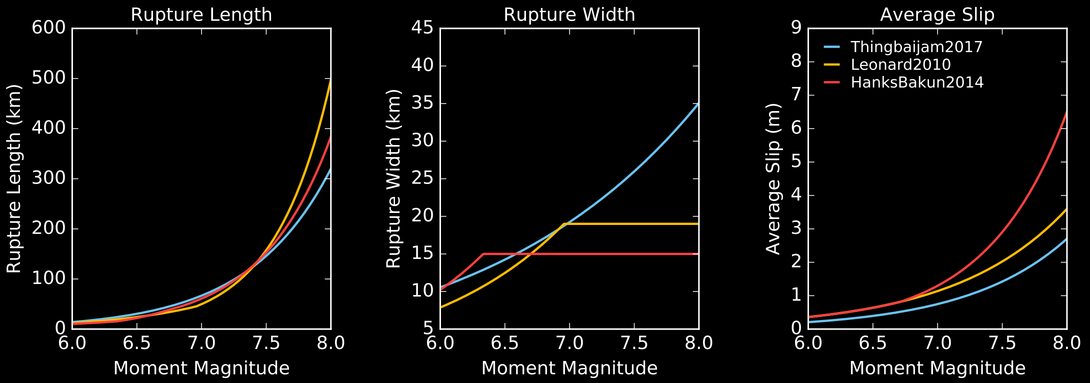


Earthquake Source Parameters: Scaling Relations

Can we discriminate or reconcile differences among proposed scaling relations?

Average slip is very sensitive to scaling of rupture area with magnitude.

[Hanks and Bakun, 2014]



Earthquake Source Parameters: Hypocenter Selection

- Do we select the hypocenter based on seismicity?
  - [Lomax, 2008] relocated 1906 hypocenter using microseismicity
  - [Michael, 2012] builds on Agnew and Jones (1991) for foreshock probabilities: Does Gutenberg-Richter magnitude-frequency distribution apply at local scales?
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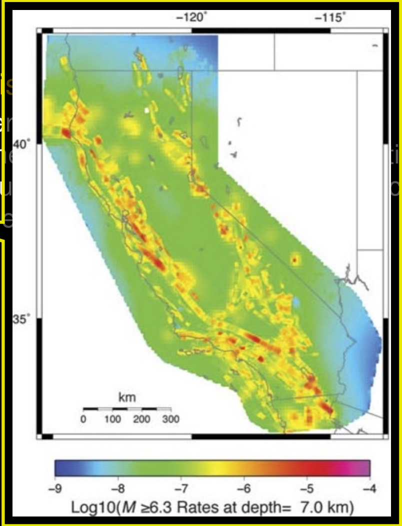

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- Do we select the hypocenter based on the slip distribution?
  - Hypocenters are NOT randomly distributed; they are located either within or close to regions of large slip [Mai et al., 2005]
  - Most earthquakes nucleate at the edge of the major slip patch [Manighetti et al., 2005]

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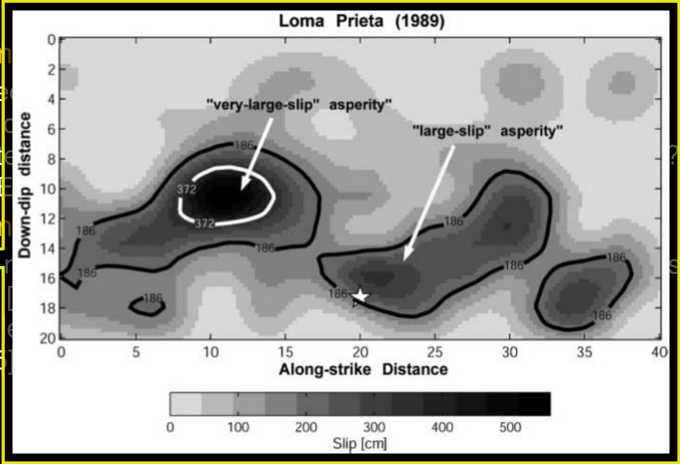

Earthquake Source Parameters: Rupture Speed

- Supershear or subshear?
  - Supershear is associated with simple fault geometry [Bouchon et al., 2010]
    1979 M6.5 Imperial Valley; 1999 M7.6 Izmit; 1999 M7.2 Duzce; 2001 M7.8 Kunlun; 2002 M7.9 Denali
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- How correlated are slip, rise time, and rupture speed?
  - [Schmedes et al., 2013] Rupture speed and slip not correlated; some correlation between parameters.
  - [Song, 2016] Complex correlation described with 1-point and 2-point statistics

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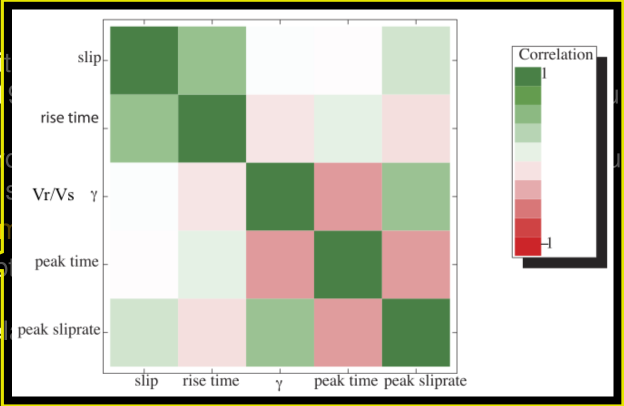

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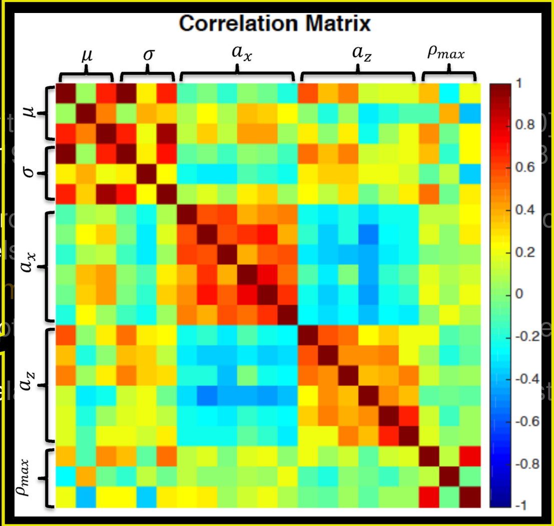

Ground Motions: Realistic 3-D Earth Structure

Need to focus on improving shallow structure and behavior

- Improve shallow characterization of elastic and anelastic properties
  - Workshop on Nonlinear Shallow Crust Effects, SCEC Award 17-140
  - SCEC Technical Activity Group: Nonlinear Effects in the Shallow Crust

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- Incorporate realistic near-surface Vs into ground-motion simulations
  - Amplification factors may be sufficient for peak amplitudes but not waveforms
  - Need to determine maximum frequency and accuracy as a function of Vs approximation

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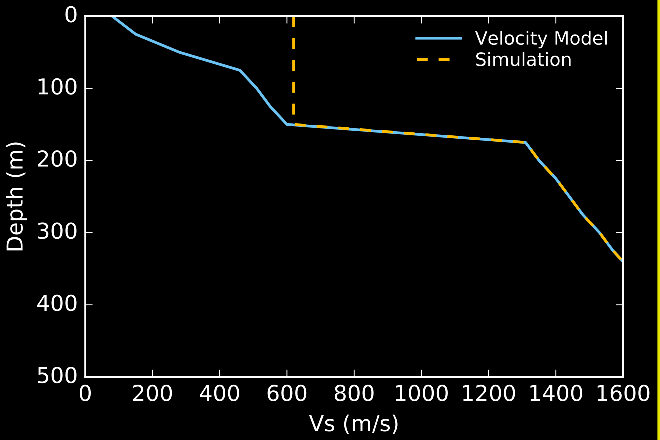
Vs profile in downtown Oakland



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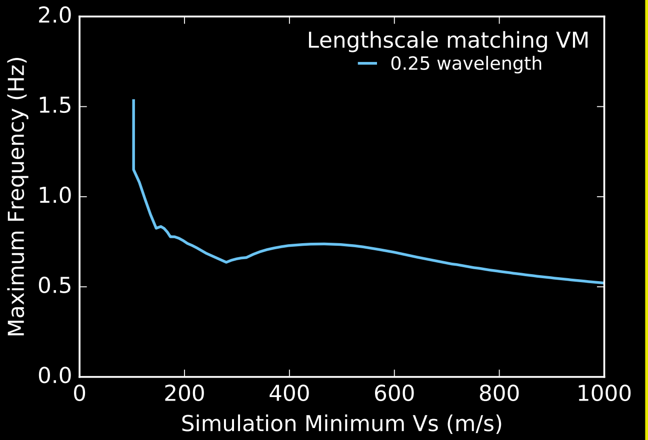
Maximum frequency while resolving velocity model



Afterslip

Much to learn in order to estimate afterslip before the next large earthquake

- Is shallow afterslip limited to faults with surface creep?
  - 2004 M6.0 Parkfield: expected afterslip based on creep and previous earthquakes [Lienkaemper and McFarland, 2017]
  - 2014 M6.0 South Napa: surprising based on lack of aseismic creep [Lienkaemper et al., 2016]

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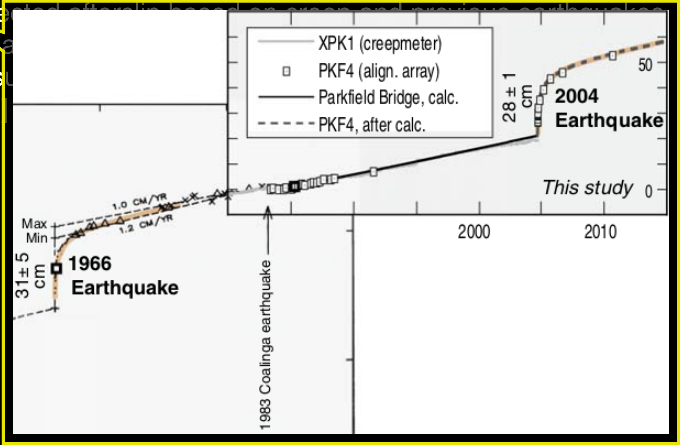

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  [Floyd et al., 2016] Afterslip complements coseismic slip

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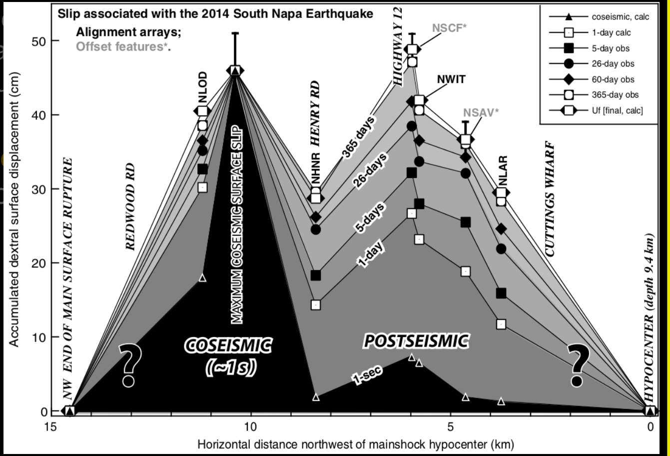

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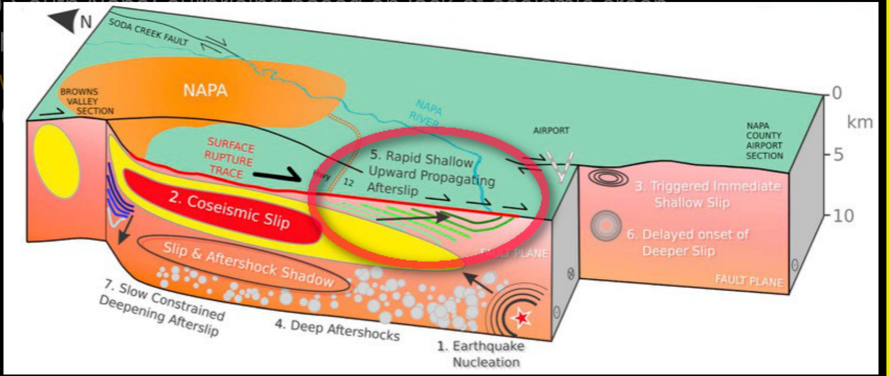

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Much to learn in order to estimate afterslip before the next large earthquake

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  - 2004 M6.0 Parkfield: expected afterslip based on creep and previous earthquakes [Lienkaemper and McFarland, 2017]
  - 2014 M6.0 South Napa: surprising based on lack of aseismic creep [Lienkaemper et al., 2016]
- How is shallow afterslip related to coseismic slip?

  [Floyd et al., 2016] Afterslip complements coseismic slip
- How well can we forecast the amount and duration of afterslip?
  - Earthquake rupture simulations using rate-state friction models
  - Empirical models [Hudnut et al., 2014]
    - Boatwright et al., 1989 – AFTER with finite duration
    - Langbein et al., 2006 – modified Omori law based on power-law creep
    - Perfettini and Avouac, 2004 – related to spring-block model with rate-state friction

Aftershocks

Synergy between aftershock tools for scenarios and earthquake response

- Leverage Operational Earthquake Forecasting to improve spatial distribution of aftershocks
  - [Field et al., 2017] UCERF3-ETAS includes aftershocks on faults

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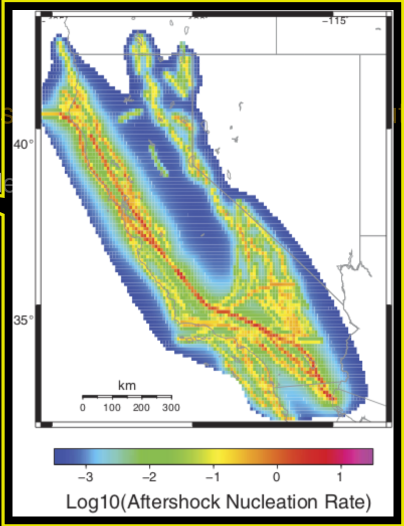

Aftershocks

Synergy between aftershock tools for scenarios and earthquake response

- Leverage Operational Earthquake Forecasting to improve spatial distribution of aftershocks
    - [Field et al., 2017] UCERF3-ETAS includes aftershocks on faults
- Produce short-term ground-motion hazard maps for an aftershock sequence
    - Useful for estimating safety of damaged structures (red tag or yellow tag)
    - Would be valuable in earthquake response
        - Safety for emergency responders and building inspections
        - Safety of red/yellow tagged buildings

Ground Failure

- Populate repository of earthquake-triggered ground failure
  - An Open Repository of Earthquake-Triggered Ground-Failure Inventories [Schmitt et al., 2017]
  - Goal: Facilitate development of robust and widely applicable models

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  - Can we use waveforms or parametric data derived directly from waveforms?
  - Build upon USGS ground-failure products (currently beta)
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  - Build upon USGS ground-failure products (currently beta)
  - Need to identify area of landslide runout in addition to initiation region
- SCEC efforts in ground failure research have been very limited

  Nonlinear effects Technical Activity Group will hopefully spark more research activity

Summary of Earth Science Research Questions

- What rupture width and slip should we expect for M$\geq$7.5 earthquakes?
- How do nonlinear soil behavior and realistic near-surface elastic properties affect our ground-motion waveform estimates?
- Where and how much afterslip should we expect?
- How can we leverage Operational Earthquake Forecasting to develop short-term probabilistic hazard models for aftershocks?
- Can we leverage waveforms or parametric data derived directly from waveforms in ground-failure models?

Also significant research needs in engineering and social science

Concluding Remarks

- Developing earthquake scenarios while integrating earth science is difficult
  - Requires planning and communication among earth scientists, engineers, and social scientists
  - Reducing uncertainty in earthquake source scaling must be done in the context of fault slip rates and finite-source rupture models
- Overlap in tools for earthquake response and earthquake scenarios
  - Aftershock forecasts
  - Afterslip forecasts
  - Ground failure estimates

Earthquake scenarios provide important opportunities to integrate our efforts, advance science, and engage stakeholders in discussions of hazard, risk, and resilience.

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