USGS Bay Area Seismic Velocity Model

Construction and Earthquake Simulations

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USGS science for a changing world

July 15, 2013

Outline

- Overview of Earth Structure Models
- USGS Bay Area Geologic and Seismic Velocity Models
  - Methodology of construction
  - Querying the seismic velocity model
  - Examples from validation
  - Application to scenario earthquakes
  - Ideas for improving the models

Earth Structure Models

Objective: Describe 3-D geologic structure

- Geometry of faults
- Geometry of major lithologic boundaries
- Physical properties
  - Elastic properties
  - Attenuation

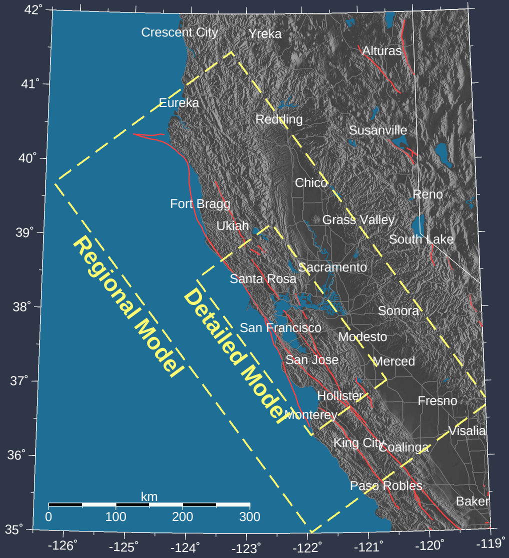
Earth Structure Models

USR approach provides framework for integrating multiple geophysical datasets

- Tomographic approach
  - Relate seismic velocity to point in space
  - Permits arbitrarily complex variations in wave speeds
  - Density not independently constrained
- Unified structural representation (USR) approach
  - Geologic block model describes geometry (faults, layers, etc)
  - Seismic velocity model relates elastic properties to geology
  - Permits sharp lithologic boundaries
  - Constraints from surface traces, gravity, tomography
  - Often relies on rules to convert rock type to elastic properties

3-D Bay Area Earth Structure Models

Region of Coverage



3-D Bay Area Earth Structure Models: History

2005 Models developed for the 1906 earthquake ground-motion modeling

- Detailed model for the Bay Area
- Coarse resolution model for surrounding area
- Thurber tomographic model (much coarser)

2006 Initial analysis by Rodgers *et al.* and Kim and Dreger

- Shear wave speed about 5% too low in East Bay
- Difficult to isolate regions needing improvement

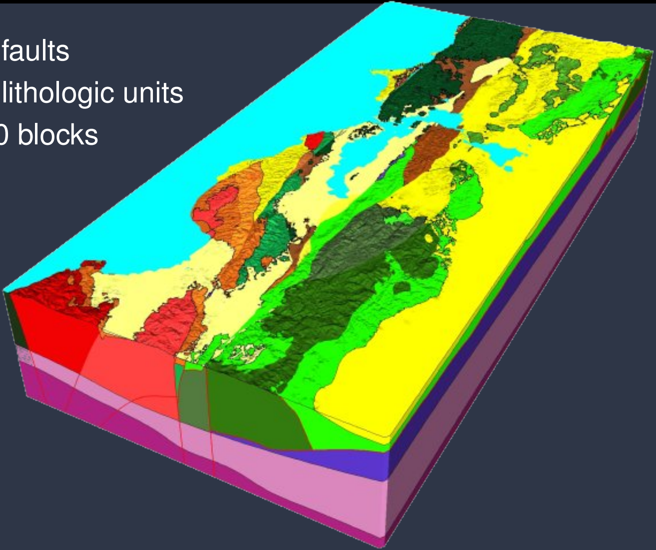
2008 Minor updates to correct significant discrepancies

- Increase shear wave speed in East Bay
- Correct significant discrepancies with Thurber tomographic model

Bay Area Geologic Block Model

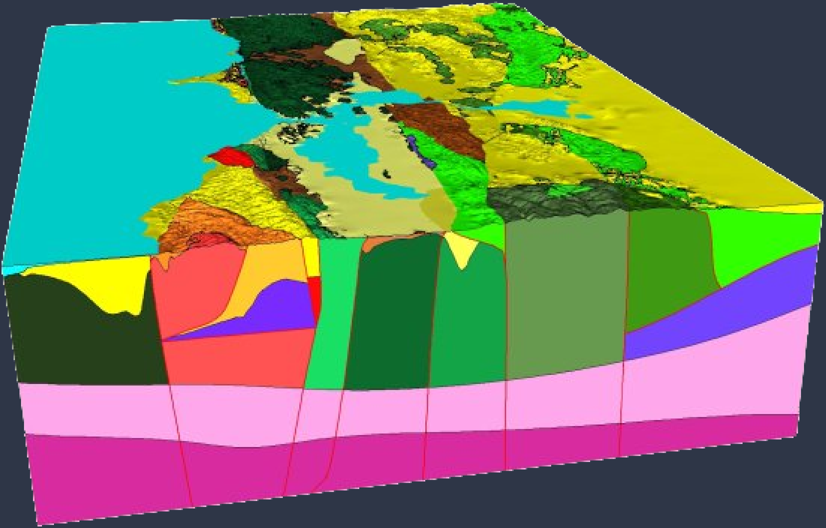
Constructed from geologic mapping, gravity, seismicity, etc using Earth Vision

- 23 faults
- 29 lithologic units
- 130 blocks

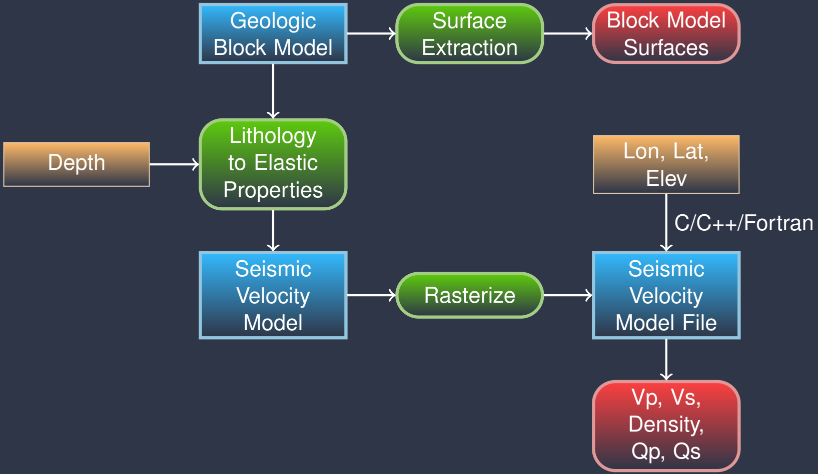


Bay Area Geologic Block Model

Vertical slice through Santa Clara Valley shows basin structure



Geologic Block Model → Seismic Velocity Model



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Geologic Block Model → Seismic Velocity Model

Franciscan (Foothills) elastic properties as a function of depth

$$Vp(km/s) = \begin{cases} a + 2.5 + 2.0d & 0 \leq d \leq 1.0km \\ a + 4.5 + 0.45(d-1) & 1.0km \leq d \leq 3.0km \\ a + 5.4 + 0.0.0588(d-3) & 3.0km \leq d \end{cases}$$

$$a = 0.13$$

$$density = 1.74\,Vp^{0.25}$$

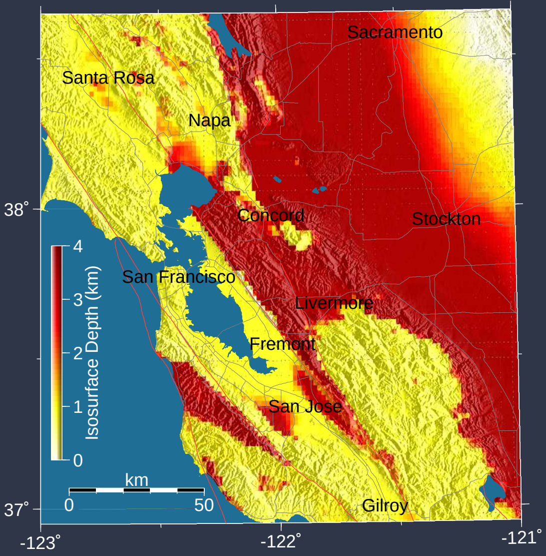
$$Vs(km/s) = 0.7858 - 1.2344\,Vp + 0.7949\,Vp^2 - 0.1238\,Vp^3 + 0.00064\,Vp^4$$

$$Qs = \begin{cases} -16 + 104.13\,Vs - 25.225\,Vs^2 + 8.2184\,Vs^3 & Vs > 0.3km/s \\ 13 & Vs \leq 0.3km/s \end{cases}$$

$$Qp = 2Qs$$

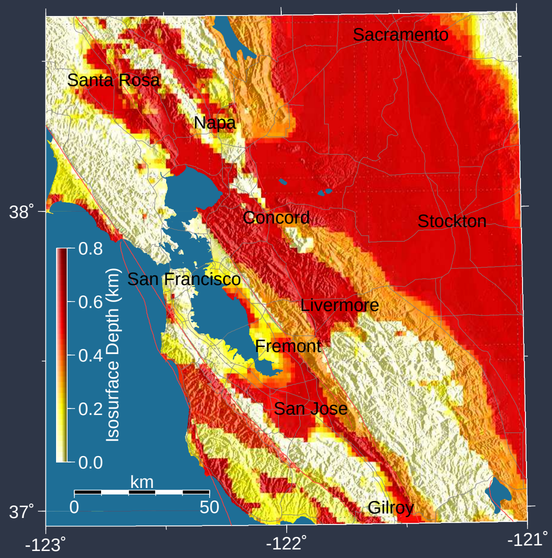
Seismic Velocity Model: Deep Sediments

Depth to Vs 2.5 km/s isosurface



Seismic Velocity Model: Shallow Sediments

Depth to Vs 1.0 km/s isosurface



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Seismic Velocity Model: Spatial Resolution

Finer resolution near the surface

- Detailed Model (213 million points, 8.2 GB)

Depth	Horiz. Resolution	Vert. Resolution
0–0.4km	100m	25m
0.4km–3.2km	200m	50m
3.2km–6.4km	400m	100m
6.4km–45km	800m	200m

- Regional Model (155 million points, 6.0 GB)

Depth	Horiz. Resolution	Vert. Resolution
0–6.4km	400m	100m
6.4km–45km	800m	200m

Seismic Velocity Model Stored as Etree Database

Efficient access to multi-resolution binary file via simple API

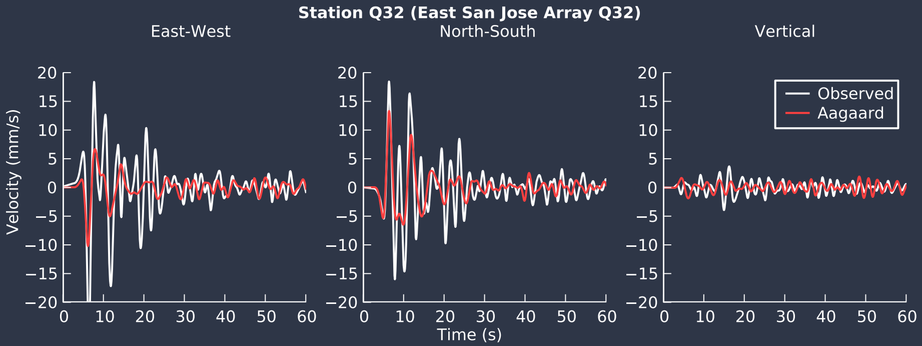
- Etree database developed by Euclid Project at CMU
- Store data points as octree grid and order points in file using tree structure
- Simple API to access Etree file
  - Very efficient access to variable resolution data
  - Set cache size for amount of model stored in memory
- Wrap seismic velocity model API around Etree API
  - Georeferencing and conversion among geographic projections
  - Remove topography via flattening/bulldozing
  - Anti-aliasing

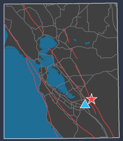
Validation via Ground-Motion Modeling

- Waveform modeling of moderate and large earthquakes
  - 1989 M6.9 Loma Prieta (SF06 project)
  - 2007 M5.4 Alum Rock (Hayward08 project)
  - 2007 M4.2 Oakland (Hayward087 project)
  - 2008 M4.1 Alamo (Frankel)
- PGV for 10 M4.1–5.4 earthquakes (Kim, Larsen, and Dreger)
- Travel-time for 12 M4.0–5.1 earthquakes (Rodgers *et al.*)

Validation: 2007 Mw 5.4 Alum Rock, T > 2.0s

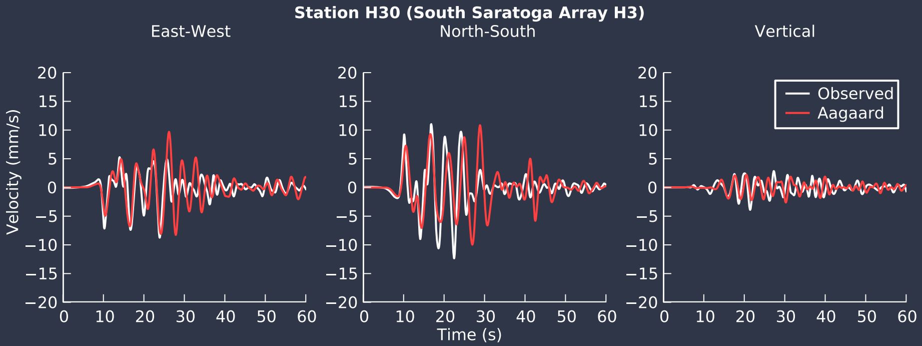
Need to refine elastic properties near edge of Evergreen basin

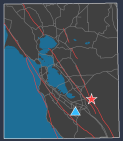




Validation: 2007 Mw 5.4 Alum Rock, T > 2.0s

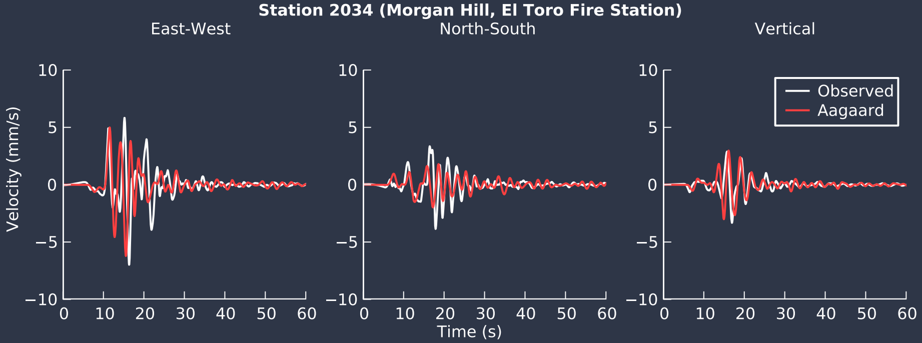
Velocity model nicely captures characteristics of Cupertino basin

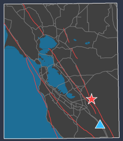




Validation: 2007 Mw 5.4 Alum Rock, T > 2.0s

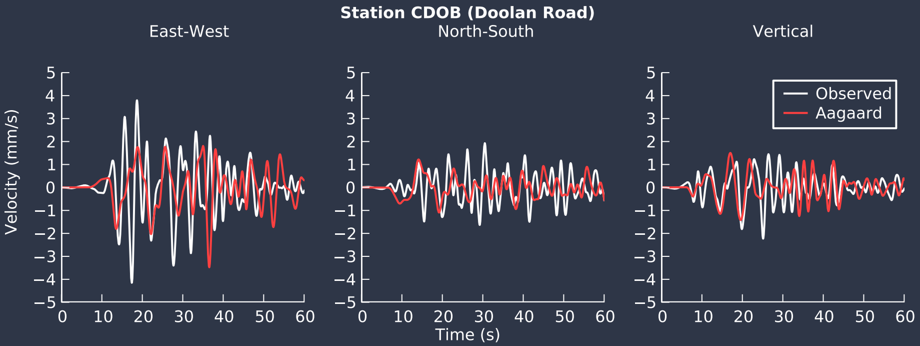
Velocity model captures structure in southern end of Santa Clara Valley

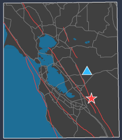




Validation: 2007 Mw 5.4 Alum Rock, T > 2.0s

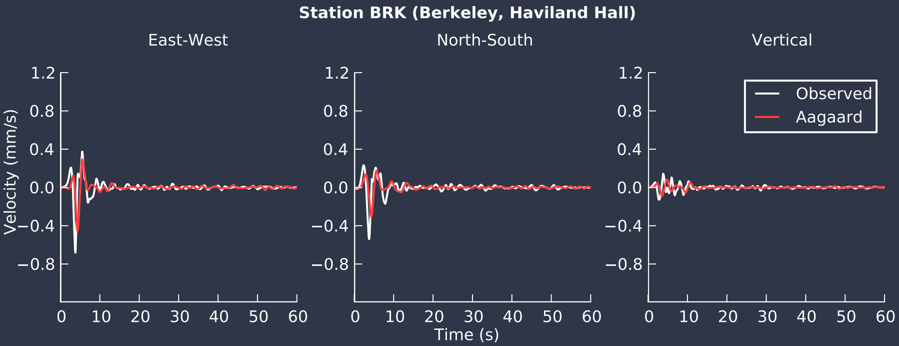
Livermore basin needs significant improvement

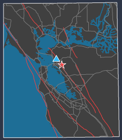




Validation: 2007 Mw 4.2 Oakland, T > 2.0s

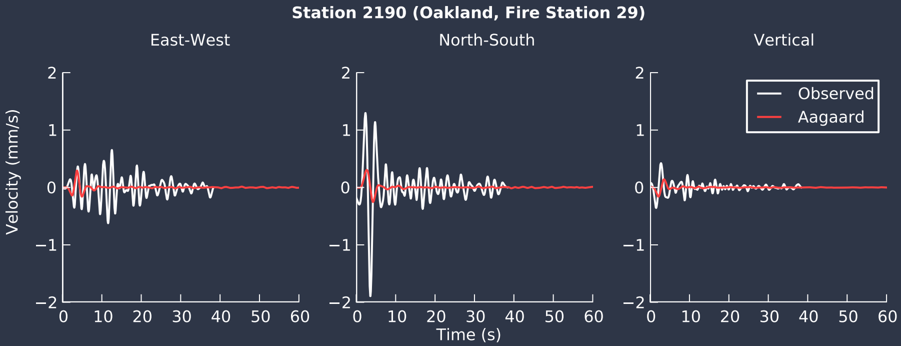
No problem for short travel path along west side of Hayward fault

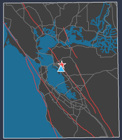




Validation: 2007 Mw 4.2 Oakland, T > 2.0s

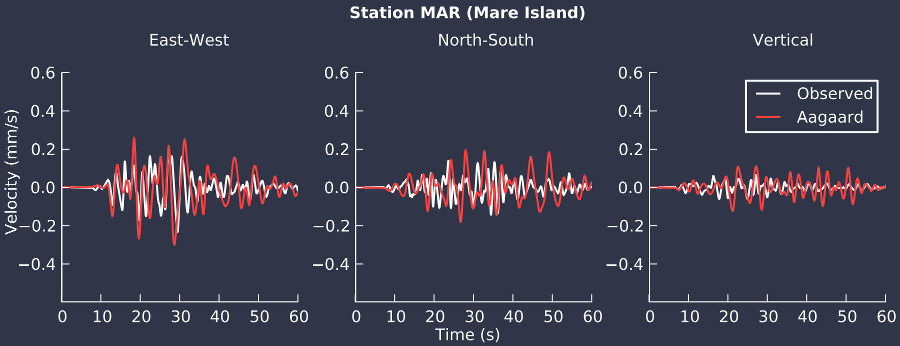
Velocity model is missing shallow sediment in Oakland

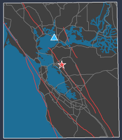




Validation: 2007 Mw 4.2 Oakland, T > 2.0s

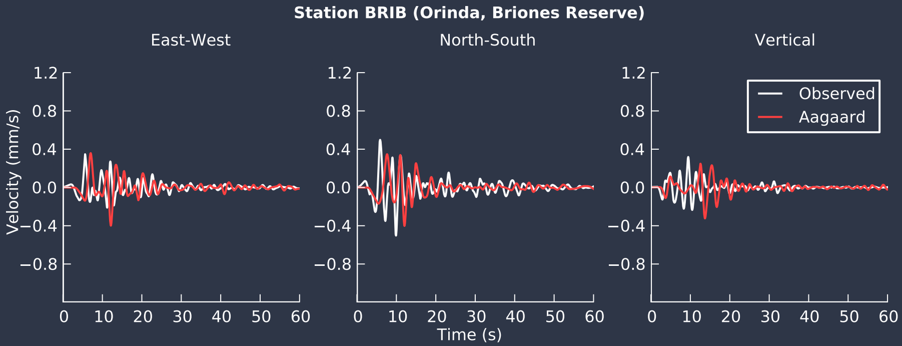
Velocity model captures main features of San Pablo basin

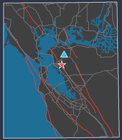




Validation: 2007 Mw 4.2 Oakland, T > 2.0s

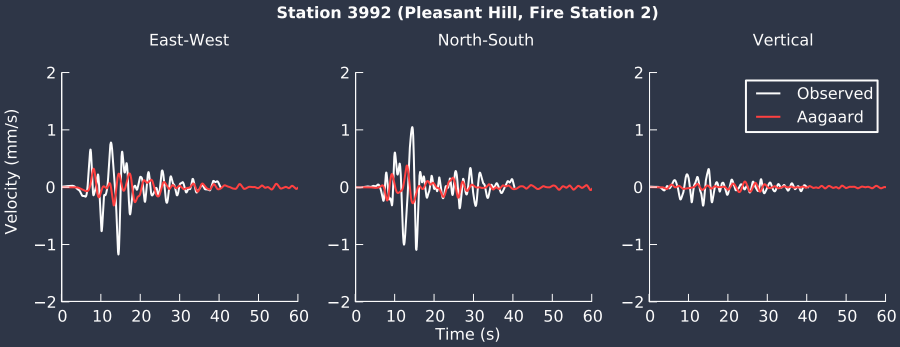
Velocity model is too slow, but waveform amplitudes are close

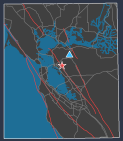




Validation: 2007 Mw 4.2 Oakland, T $>$ 2.0s

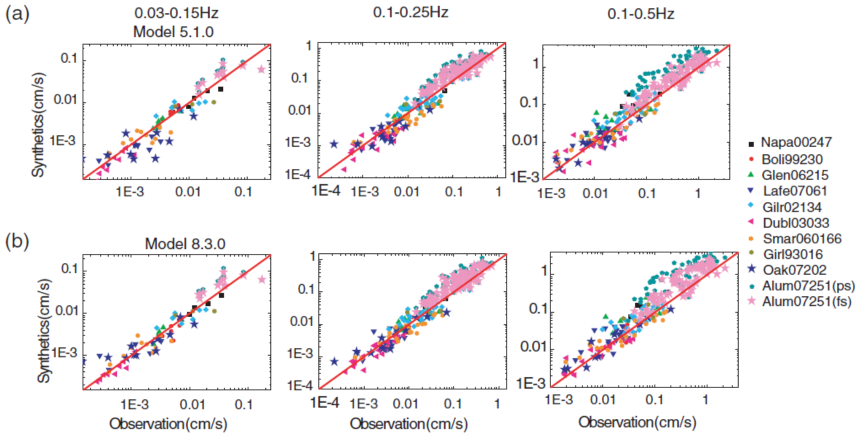
Velocity model is slightly slow but under-predicts waveform amplitudes





Validation: Peak Ground Velocity

Error in PGV increases significantly for f $>$ 0.25 Hz (T $<$ 4 s)



Kim, Larsen, and Dreger, BSSA, 2010

Seismic Hazard and 3-D Simulations

3-D simulations allow more detail but require greater understanding

- USGS National Seismic Hazard Maps
  - Earthquake description: magnitude and fault boundary
  - Ground motions from empirical regressions
    - Fault orientation, slip direction, dist. from fault
    - Path and site corrections
  - Ground motion metrics: PGV, PGA, SA
- 3-D ground-motion simulations
  - Earthquake description: earthquake rupture time history
    - Complex fault geometry
    - Spatial and temporal evolution of slip
  - Ground motions from wave propagation
    - 3-D physical properties (basin effects)
    - Rupture directivity
  - Displacement, velocity, and acceleration time histories

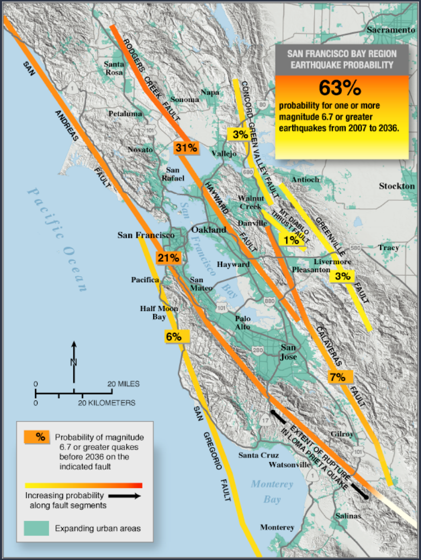
Ground-Motion Simulations

3-D ground-motion simulations can include rupture physics

- Prescribed slip rupture models
  - Driven by source inversions and spontaneous rupture simulations
  - Deterministic + stochastic slip fields
  - Complex nonplanar fault geometry
  - Complex rupture paths
  - Not necessarily consistent with underlying physics
- Spontaneous rupture models
  - Slip evolves based on stress conditions and fault constitutive model
  - Deterministic + stochastic stress fields
  - Complex nonplanar fault geometry
  - Involves more parameters and knowledge of conditions in the lithosphere

UCERF Bay Area Probabilities

30 yr probability for Hayward / Rodgers Creek is now 31%

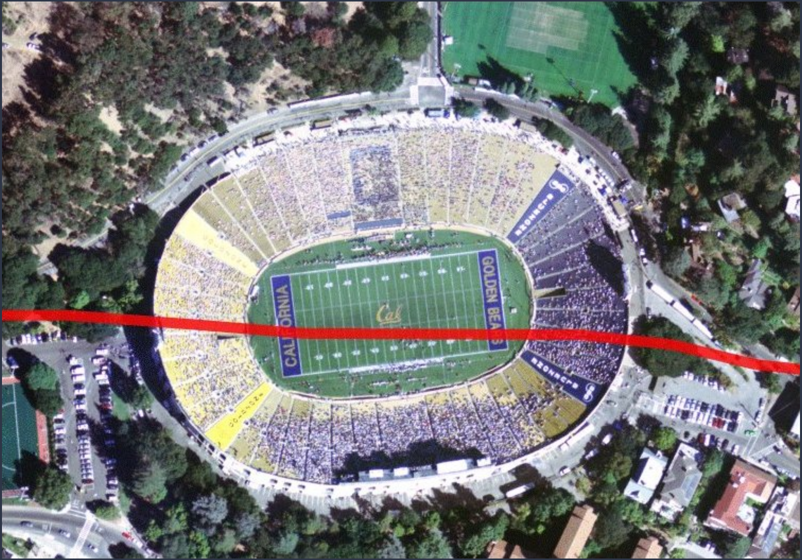


Hayward Fault

Fault runs along the edge of the densely populated East Bay

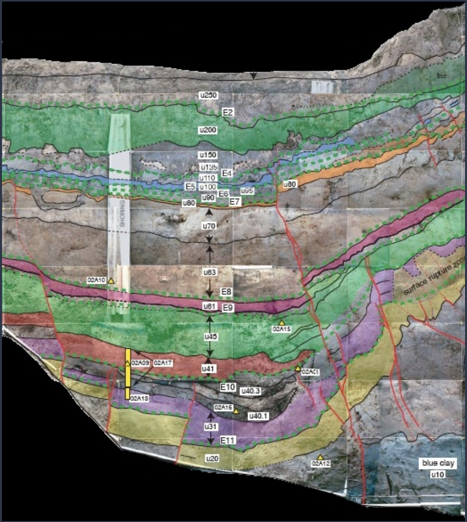
Hayward Fault

Fault runs underneath UC Berkeley's Memorial Stadium



Jim Lienkaemper's Tyson's Lagoon Trench

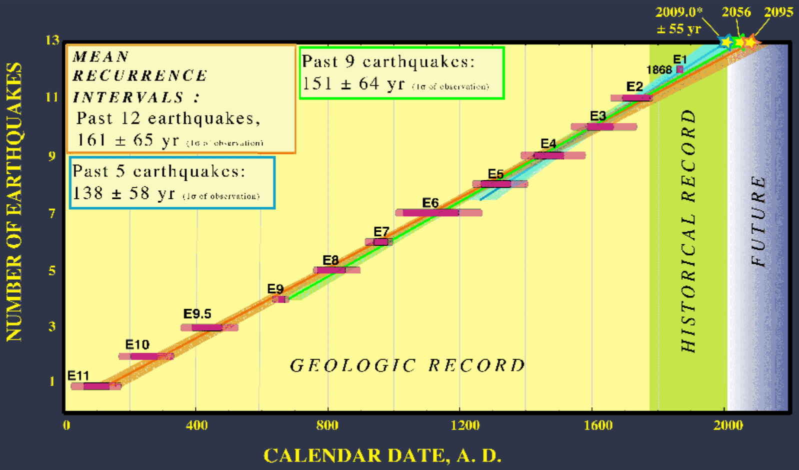
Evidence for 12 ruptures over the past 1900 years



Lienkaemper et al. USGS Open File Report 03-488

Paleoseismic Record at Tyson's Lagoon

Currently in middle of time window for next expected event



Version 080109 (SSA Mtg. abstract)

*R. W. Simpson, Monte Carlo regression of Oxcal data

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Hayward Scenario Earthquakes Project

- Compute ground motions for a suite of 39 scenario earthquakes involving the Hayward fault
  - Rupture length
  - Hypocenters
  - Distribution of slip
  - Rise time
  - Rupture speed
- Develop rupture models based on geophysical data consistent with NGA ground-motion prediction models
  - Spatial variation in slip
  - Spatial variation in rise time
  - Slower rupture speed in areas with little slip
- Account for aseismic creep in prescribed slip rupture models

Project Personnel

Collaborative effort to develop realistic ruptures and ground motions

USGS Menlo Park Brad Aagaard, John Boatwright, Thomas Brocher, Russell Graymer, Ruth Harris, Thomas Holzer, Dave Keefer, Jim Lienkaemper, David Ponce, David Schwartz, Robert Simpson, Paul Spudich, Janet Watt

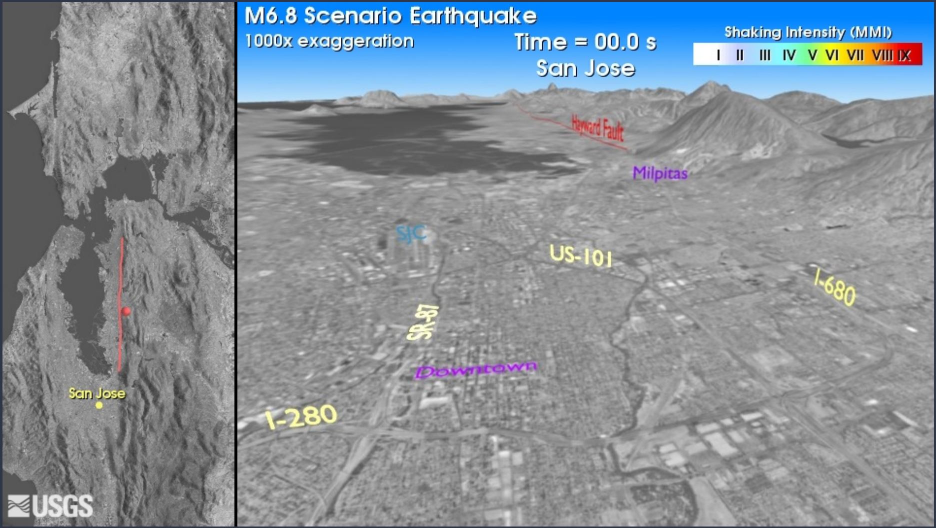
Lawrence Livermore National Laboratory Shawn Larsen, Arthur Rodgers

URS Pasadena Robert Graves (now at USGS Pasadena)

UC Berkeley Doug Dreger

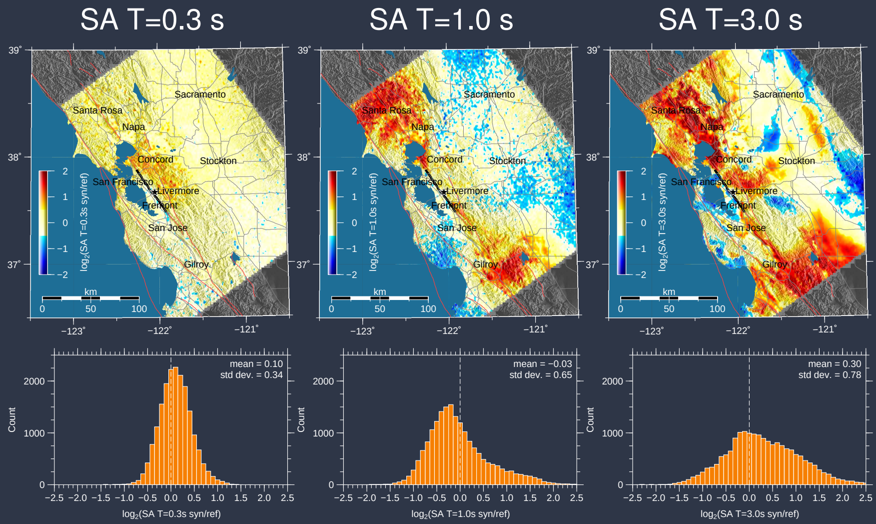
Stanford University Shuo Ma (now at SDSU)

Animation of Shaking Intensity



Comparison with Boore-Atkinson NGA GMPE

Bias with NGA ground-motion prediction models increases with period



Urban Seismic Hazard Maps

High resolution alternative to National Seismic Hazard Maps

- Reduce uncertainty in ground-motions by including
  - Basin amplification
  - Rupture directivity
  - Complex interaction between rupture directivity and basins
- Gaining momentum in USGS and SCEC
- Requires propagating uncertainties
  - Median values of most parameters are well-constrained
  - More work needed to constrain probability distributions and incorporate them into models and simulations
- Requires at least hundreds to thousands of simulations
- Storing waveform output with proper metadata is challenging
- **Requires better models of Earth structure and earthquake rupture**

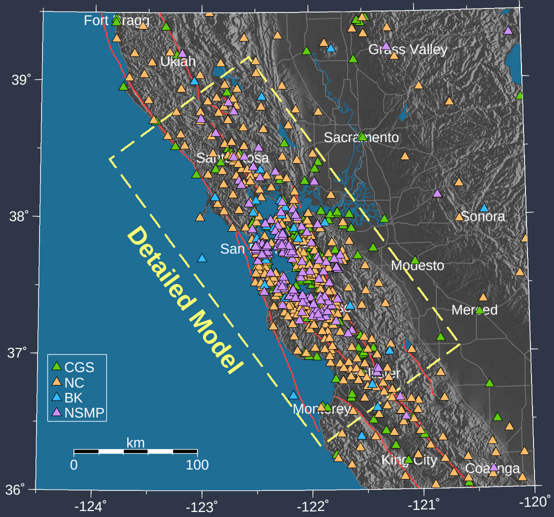
3-D Bay Area Earth Structure: Moving Forward

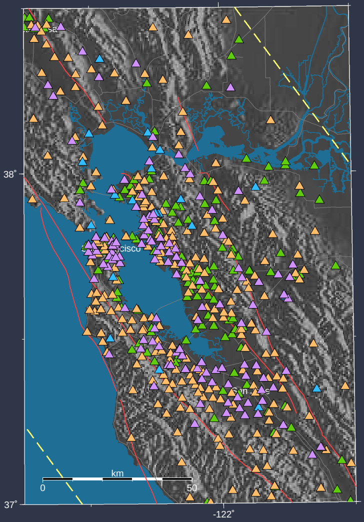
Need to improve both the block model and the seismic velocity model

- Refine geologic block model
  - Finer subdivision of lithologic units
    - Quaternary sediments (e.g., Bay Mud)
    - Tertiary-Cenozoic sediments (e.g., east of Hayward fault)
  - Regional model is too simple
    - San Andreas fault surface
    - Upper crust, lower crust, mantle
- Refine physical properties
  - Systematic application of constraints from seismic data
    - Iterate on model with full waveform tomography
    - Local analysis using dense arrays
  - Consistency with Vs30 models
  - Small scale (stochastic) variability

Improving the Seismic Velocity Model

Excellent coverage in urban area with current instrumentation





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Improving the Seismic Velocity Model

M4+ seismicity (2000–present) is limited and concentrated in space