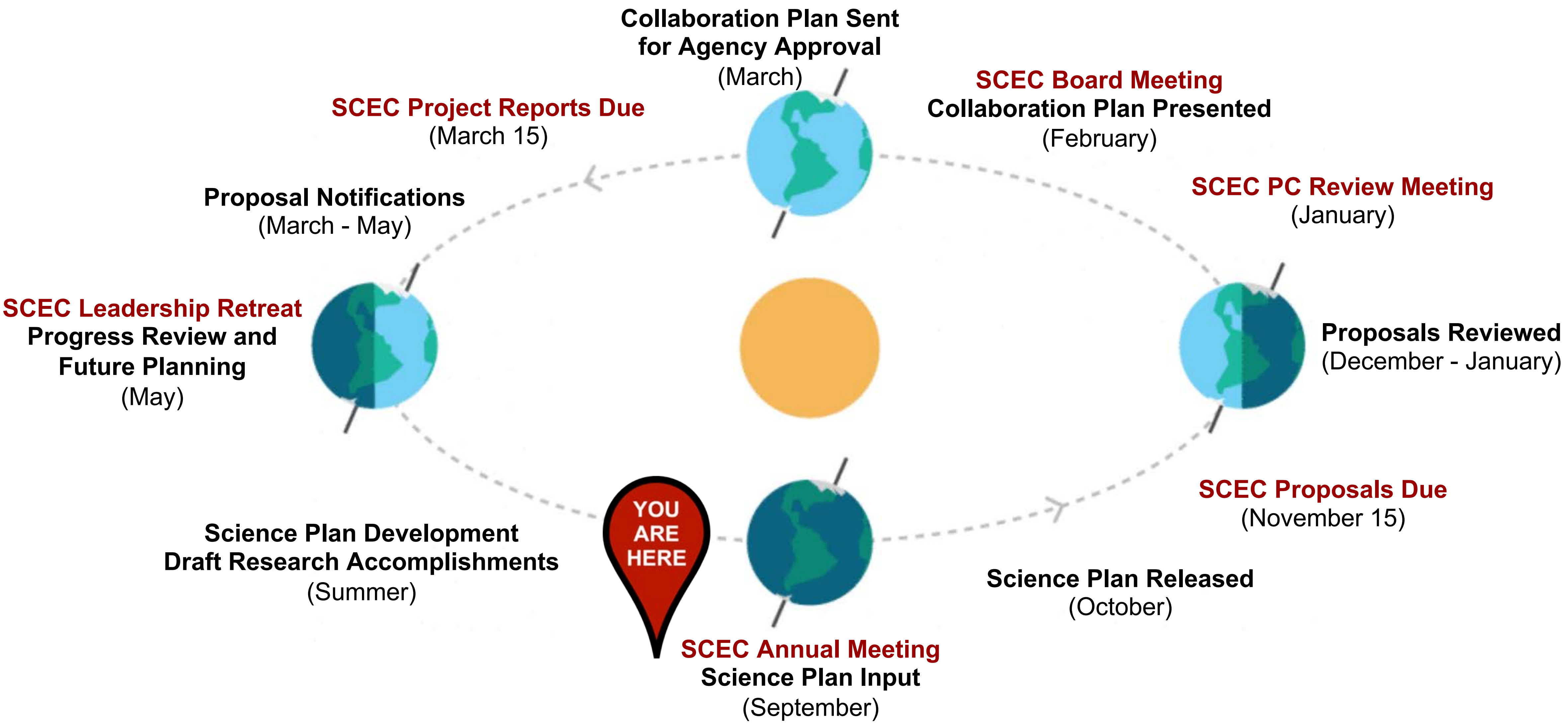
# SCEC Science Accomplishments
## (A Highlights Tour)

**SCEC Planning Committee**

September 9, 2019

# *The SCEC Science Planning Cycle*



# *Themes and Topics of the SCEC5 Plan*

**Theme A. Modeling the Fault System**
1. Stress and Deformation Over Time
2. Special Fault Study Areas: Focus on Earthquake Gates
3. Community Models
4. Data-Intensive Computing

**Theme B. Understanding Earthquake Processes**
5. Beyond Elasticity
6. Modeling Earthquake Source Processes
7. Ground Motion Simulation
8. Induced Seismicity

**Theme C. Characterizing Seismic Hazards**
9. Probabilistic Seismic Hazard Analysis
10. Operational Earthquake Forecasting
11. ~~Earthquake Early Warning~~ *
12. Post-Earthquake Rapid Response

**Theme D. Reducing Seismic Risk**
13. Risk to Distributed Infrastructure
14. Velocity and Rheology of Basin Sediments

* We set no milestones for topic 11, which the USGS considers to be adequately covered under existing research programs.

## Topic 1: Stress and Deformation Over Time

We will build alternative models of the stress state and its evolution during seismic cycles, compare the models with observations, and assess their epistemic uncertainties, particularly in the representation of fault-system rheology and tectonic forcing.

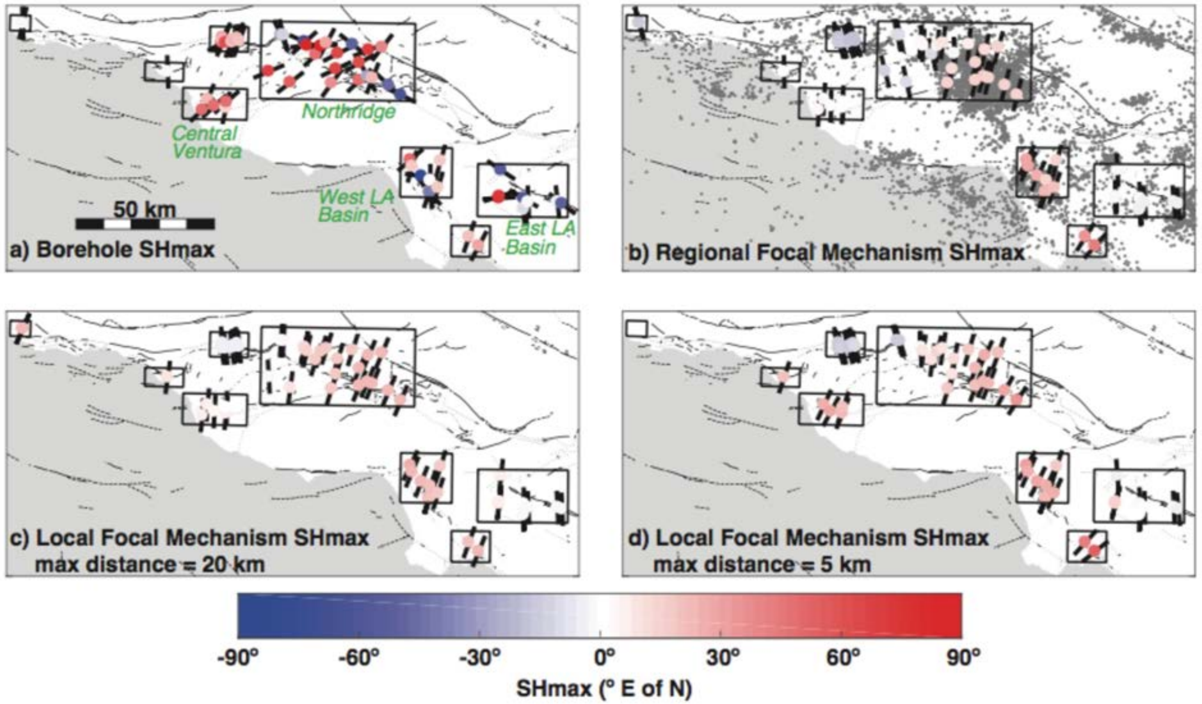
# *Highlights: Stress and Deformation Over Time*

- **Quantifying stress heterogeneity and synthesizing observations used to constrain absolute stress**

  [*SCEC Award #18148 Lutrell and Hardebeck*]
  → 1800 new stress state inversions of local focal mechanisms centered around boreholes; stress heterogeneity exists at small length scales, in some cases down to a few kilometers or less (poster 143).

  [*SCEC Award #18026 Abolfathian, Martinez-Garzon and Ben-Zion*]
  → High-resolution spatial variations of stress patterns are correlated with topographic variations. SHmax rotates clockwise with increasing depth (poster 192).

- **Community Stress Model Workshop**
  [*SCEC Award #18132 Hardebeck et al.*]
  → Restoration of CSM website; compilation of stress orientation and stress rate models of the upper crust



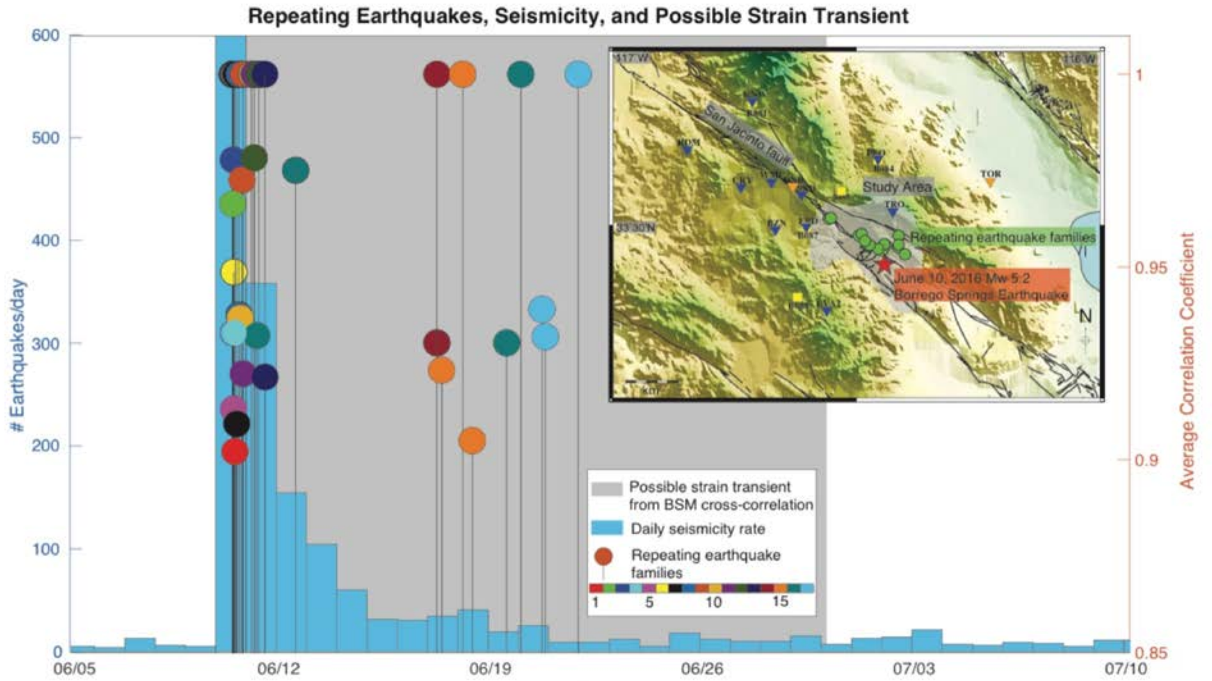

**Stress orientations from boreholes and focal mechanisms** a) Published SHmax azimuths (black bars and central circle color) derived from borehole breakouts across the Los Angeles region. b) SHmax azimuths derived from regional inversion of earthquake focal mechanisms (Yang and Hauksson, 2013; gray dots), shown at locations of boreholes in (a). SHmax azimuth derived from local inversion of focal mechanisms within c) 20 km and d) 5 km of each borehole [Luttrell and Hardebeck].

# *Highlights: Stress and Deformation Over Time*

- **Assimilating geodetic and seismic data for aseismic transient detection**
  [*SCEC Award #18160 Bartlow, Schwartz, Shaddox*]
  ⟶ combined seismic and borehole strainmeter data to identify a new strain transient on the Anza segment of the SJFZ in June 2016 (poster 193)

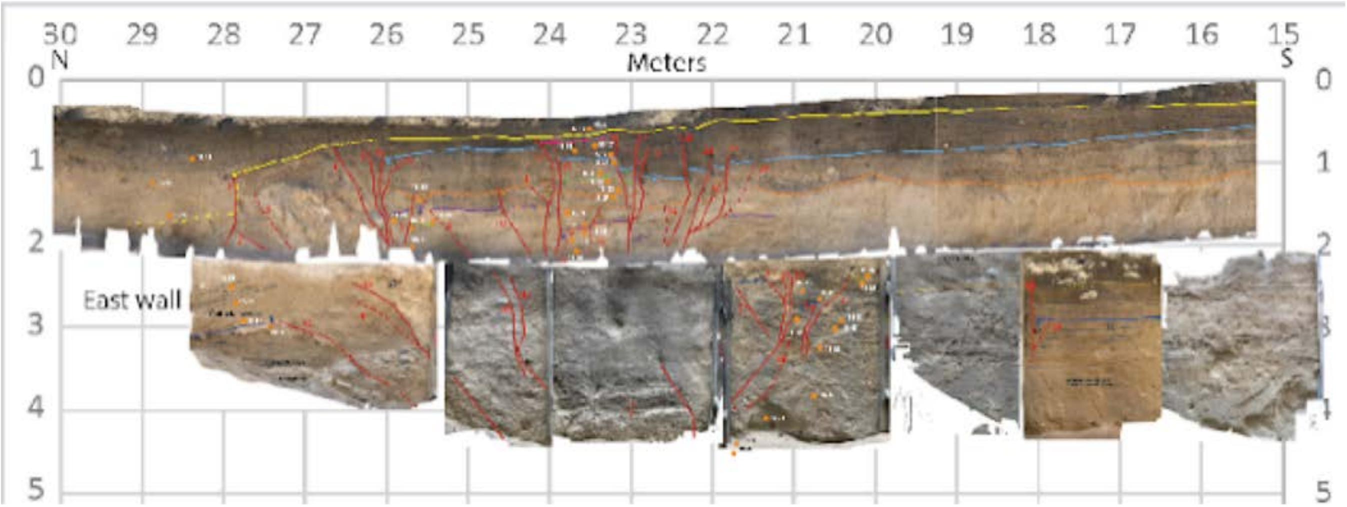
- **Temporal and spatial studies of non-secular deformation from CGM data**
  [*SCEC Award #18208 Shen and Liu*]
  ⟶ 3D continuous deformation field of Southern California by integrating precise GPS and InSAR line-of-sight data

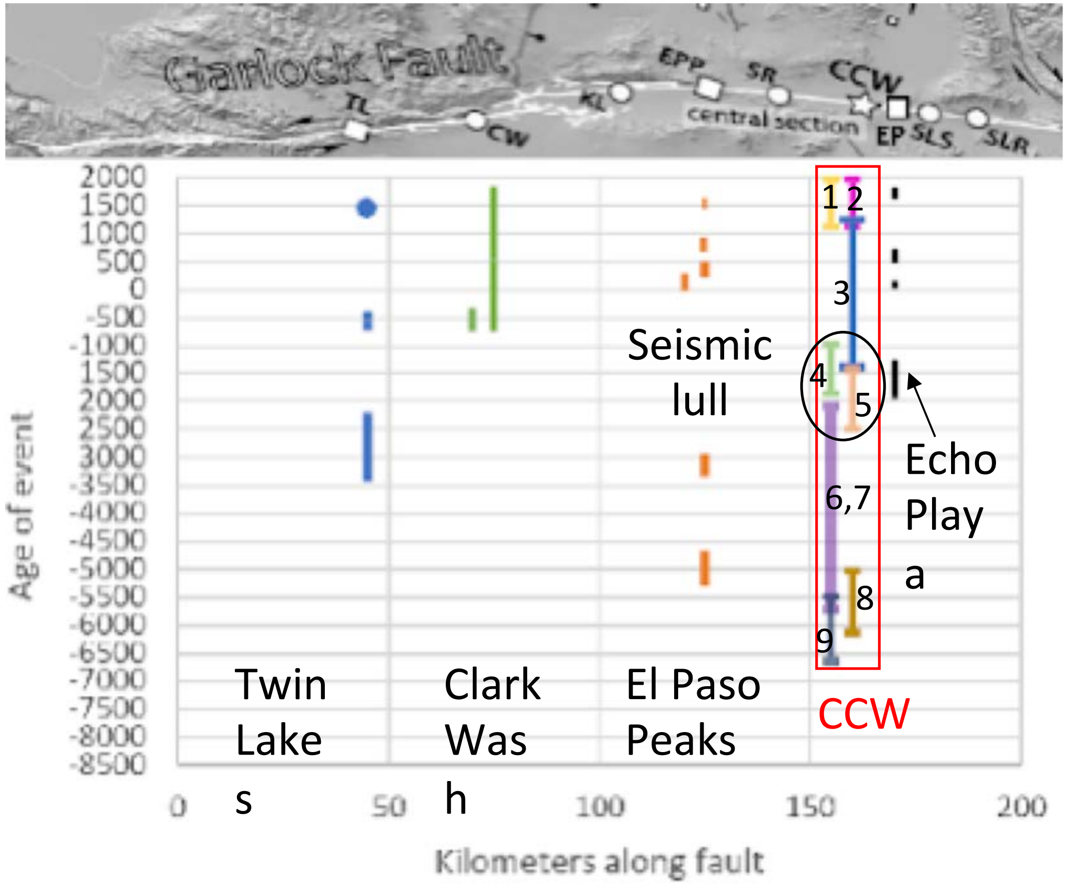
  [*SCEC Award #18228 Holt*]
  ⟶ using cGPS data to quantify a 13-year history of seasonal horizontal deformation as a result of the solid Earth's elastic response to precipitation patterns in California




**Anza slow slip and strain event in June 2016.** Seismicity rates (blue bars) and repeating earthquake candidates (color circles at y-axis location indicating average cross-correlation coefficient) during newly detected slow slip episode along the Anza segment of the SJFZ (inset map). The gray shaded area indicates time of coincident strain anomaly detected at nearby borehole strainmeters (yellow squares in map, inverted triangles are local seismometers). [Barlow, Schwartz, Shaddox]

# *Highlight: New event record for eastern Garlock Fault*




One, and possibly two events occurred Christmas Canyon site during a seismic lull at the El Paso Peaks site.

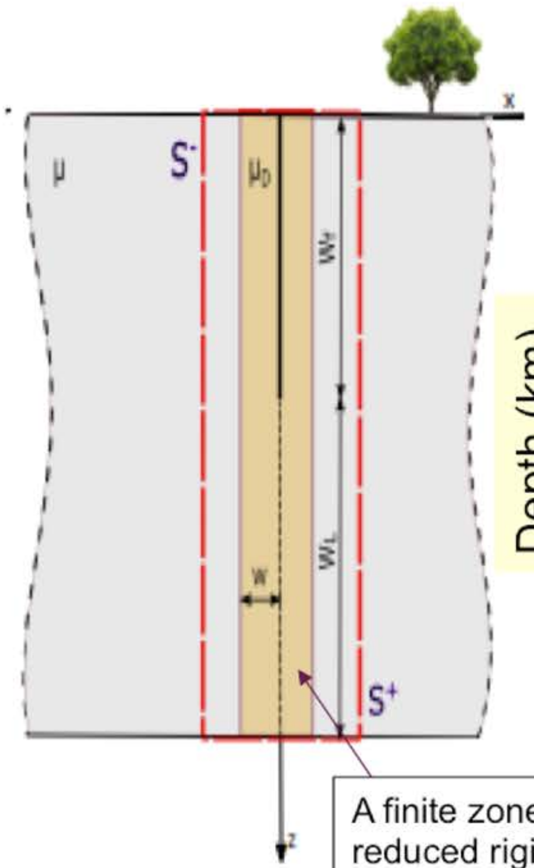
Peña et al., 2019, MS thesis, CSUSB; SCEC poster 107

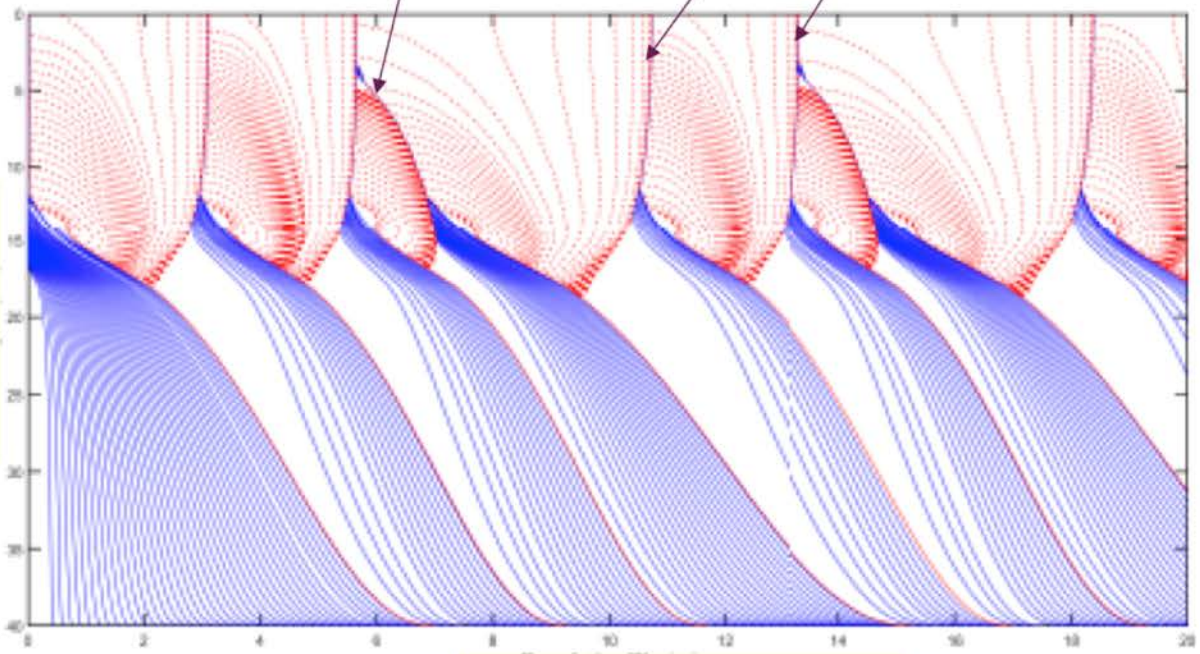
# *An Efficient Computational Algorithm for Modeling Sequence of Earthquakes and Aseismic Slip (SEAS) in Complex Fault Zones (Poster 167)*

- We develop a hybrid numerical techniques combining finite element and spectral boundary integral equation methods to efficiently model earthquake cycles

- As an example we apply the new algorithm on a fault embedded in a LVFZ.

- LVFZ lead to emergence of alternating subsurface and surface reaching events and nonuniform event sizes.




Abdelmeguid, Ma, and Elbanna (2019) JGR (to appear) https://eartharxiv.org/xwhbs.

# Theme A: Modeling the Fault System

## Topic 2: Earthquake Gates

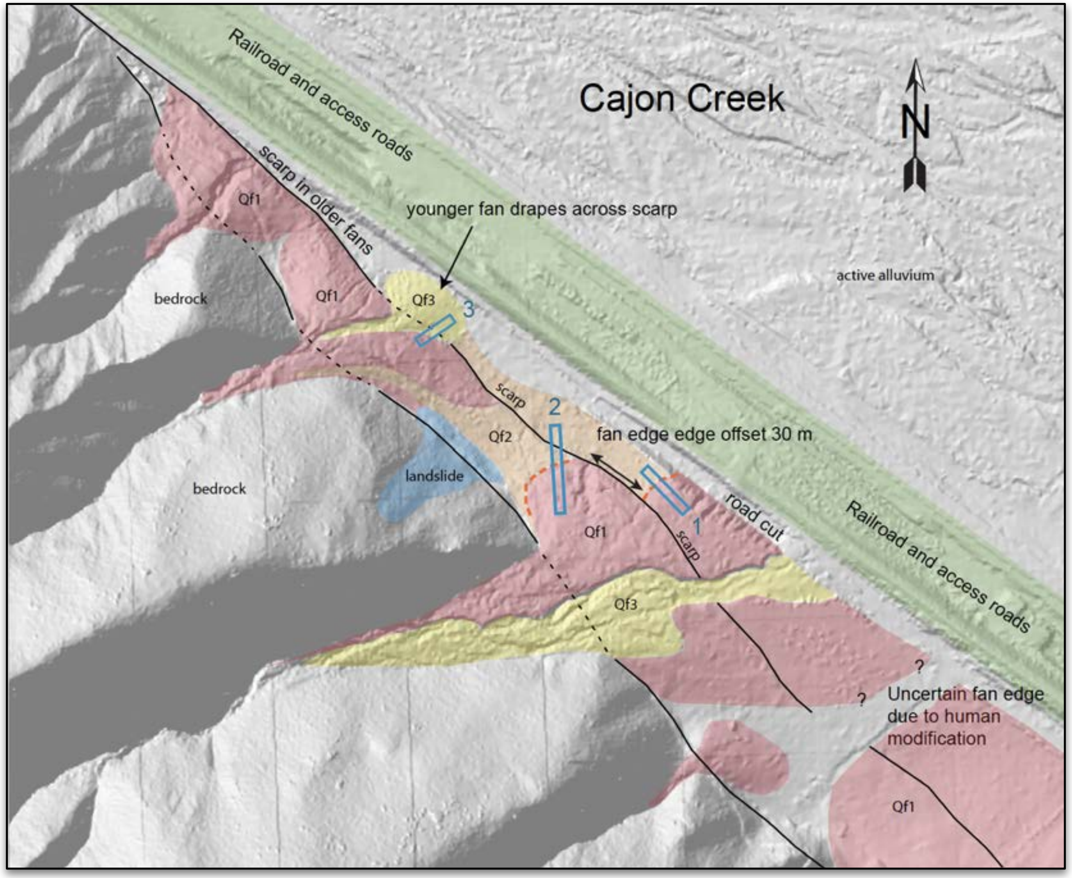
Earthquake gates are regions of fault complexity conjectured to inhibit propagating ruptures, owing to dynamic conditions set up by proximal fault geometry and material properties, distributed deformation, and earthquake history. We will test the hypothesis that earthquake gates control the probability of large, multi-segment and multi-fault ruptures.


*Drone photo (courtesy of Art Sylvester) looking North across the SAF at Lost Lake showing the Lost Lake sag pond, fault scarps, and various terrace risers that were used as piercing lines for determination of slip-rate [Weldon and Sieh, 1985].*

# Highlights: Earthquake Gates

**Slip transfer between and strain partitioning among San Jacinto and San Andreas fault**

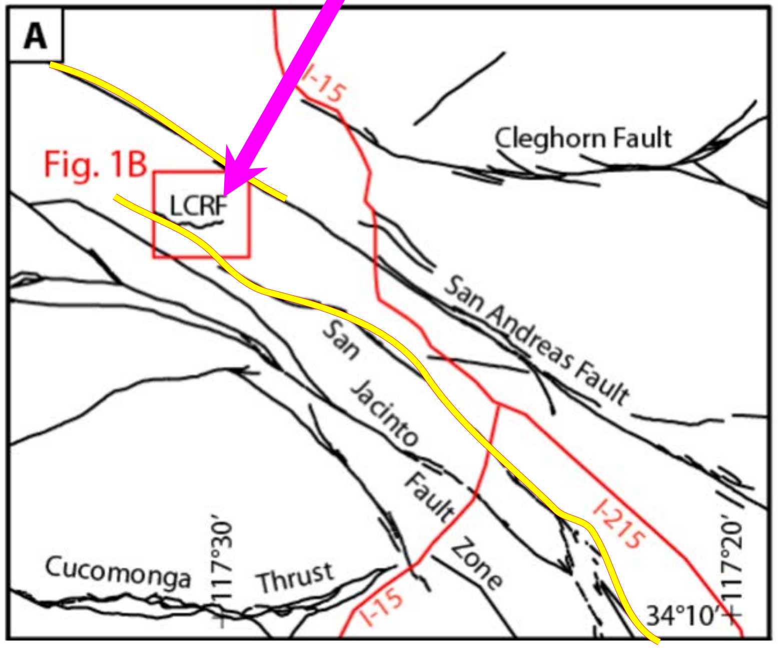
- new site along Glen Helen suggests that Glen Helen is the most active strand of SJF. *Onderdonk et al (poster 136)*
- Trench at Lytle Creek Ridge (see next slide)




LiDAR DEM of the Kenwood site with faults (black lines), Quaternary deposits (colored shading), and proposed trench locations (blue rectangles). Taken from Onderdonk, Figueiredo & Weldon SCEC report 18124.

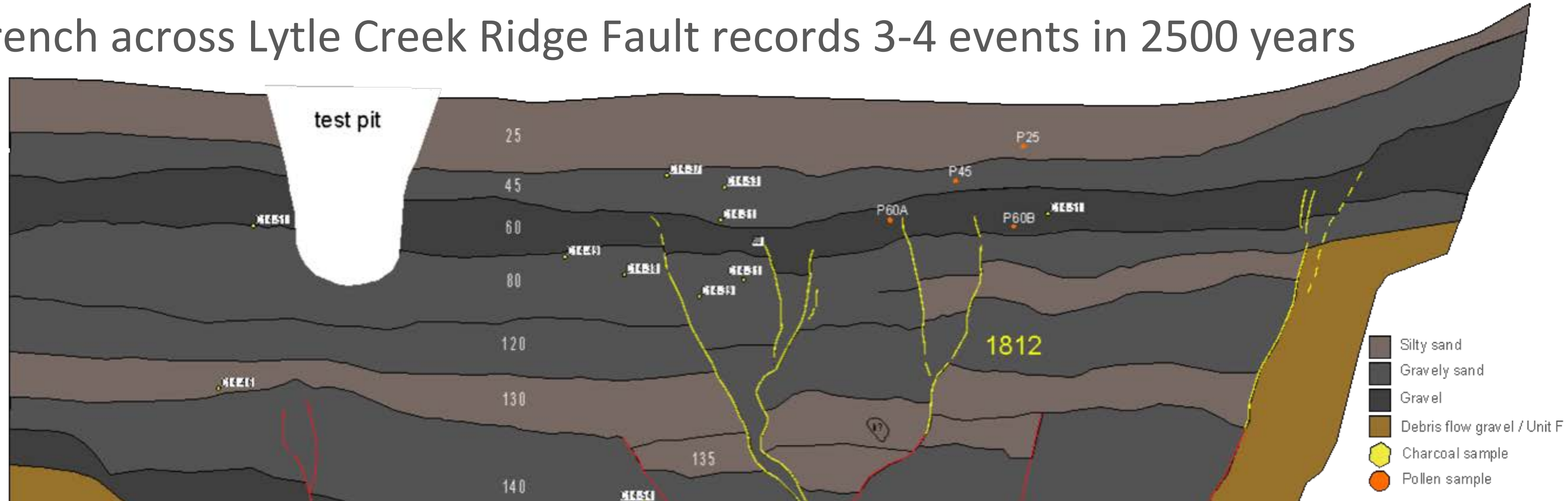
# *Highlights: Earthquake Gates*

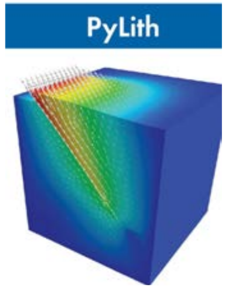
The Lytle Creek Ridge Fault (LCRF) is wrenched apart by earthquakes that jump the Cajon Pass Earthquake Gate, including, possibly, 1812.



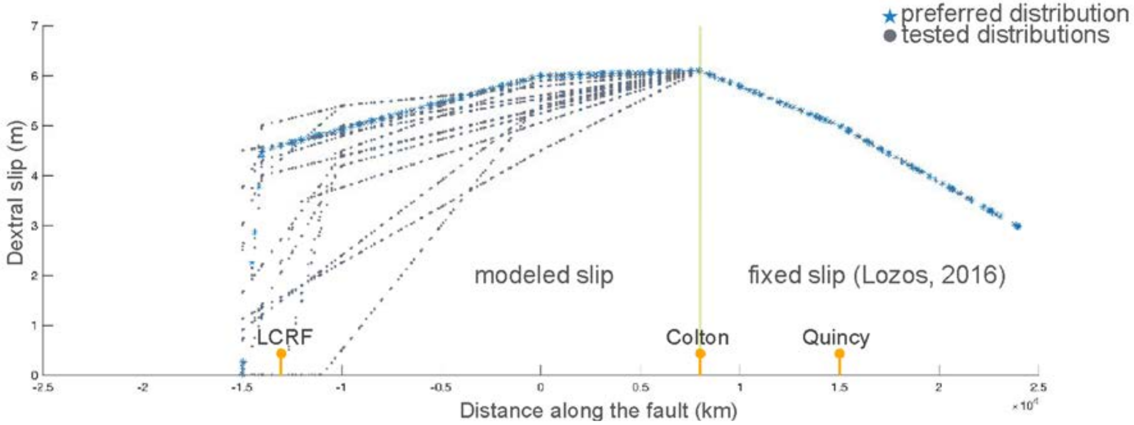

**Rodriguez-Padilla et al., Poster 142**

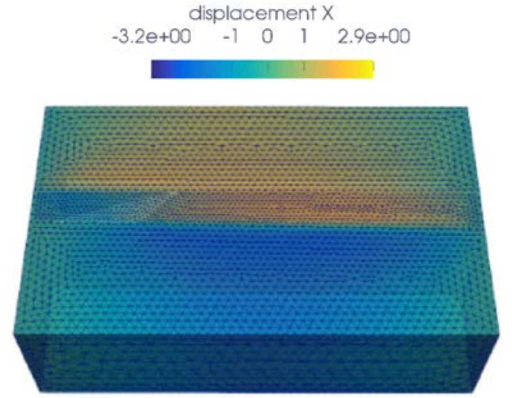
Trench across Lytle Creek Ridge Fault records 3-4 events in 2500 years



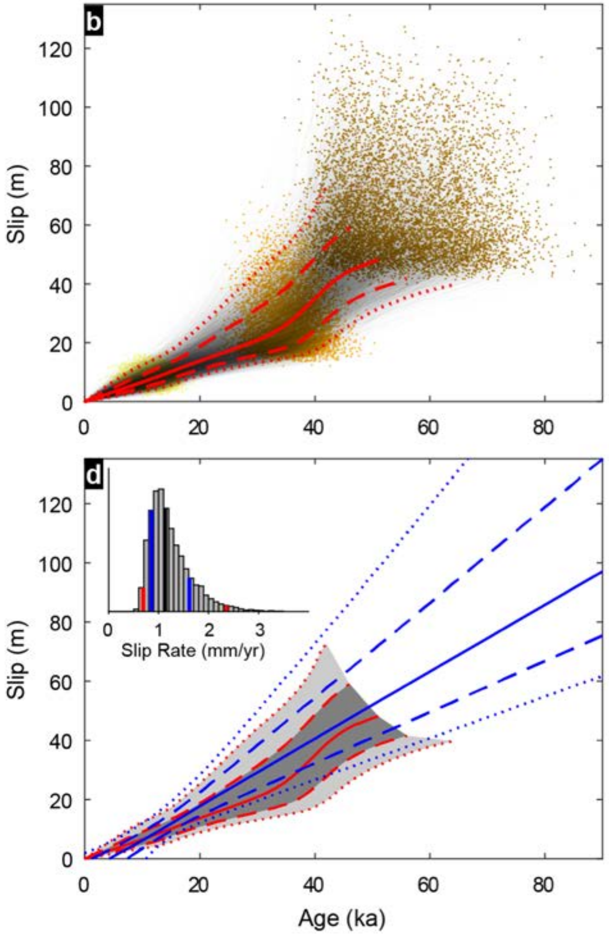

To activate the LCRF, slip on the San Jacinto fault must taper steeply (~$10^{-3}$) and halt abruptly about 2-5km to northwest.



# *Highlights: Earthquake Gates*

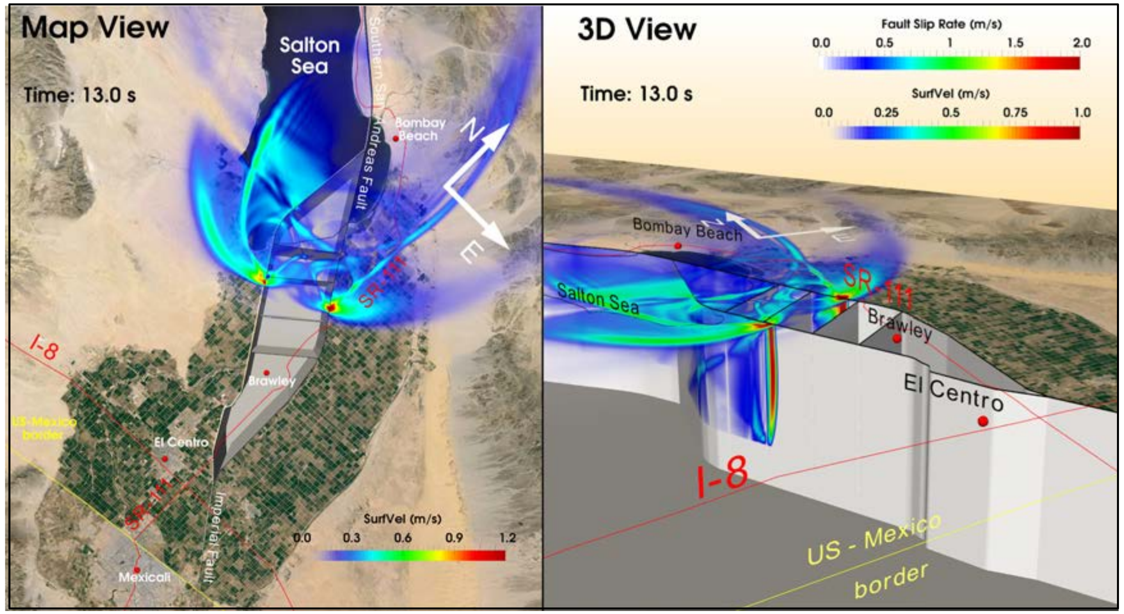
## San Andreas Fault System




### *Sierra Madre example*

Burgette et al. (in review) resolve 1.1 $^{+1.2}/_{-0.4}$mm/yr dip slip rate of the Central Sierra Madre Fault (CSMF) over the past ~60 kyr. This late Quaternary slip rate is significantly slower than most estimates based on interseismic geodetic data emphasizing the importance of contraction distributed across multiple structures.

Estimated CSMF dip slip history from three offset fan surfaces. PDFs of age show median history (red) and uncertainty (dashed red) compared to constant slip rate (blue)




Map & 3D view of supercomputer earthquake simulations in the Brawley Seismic Zone.

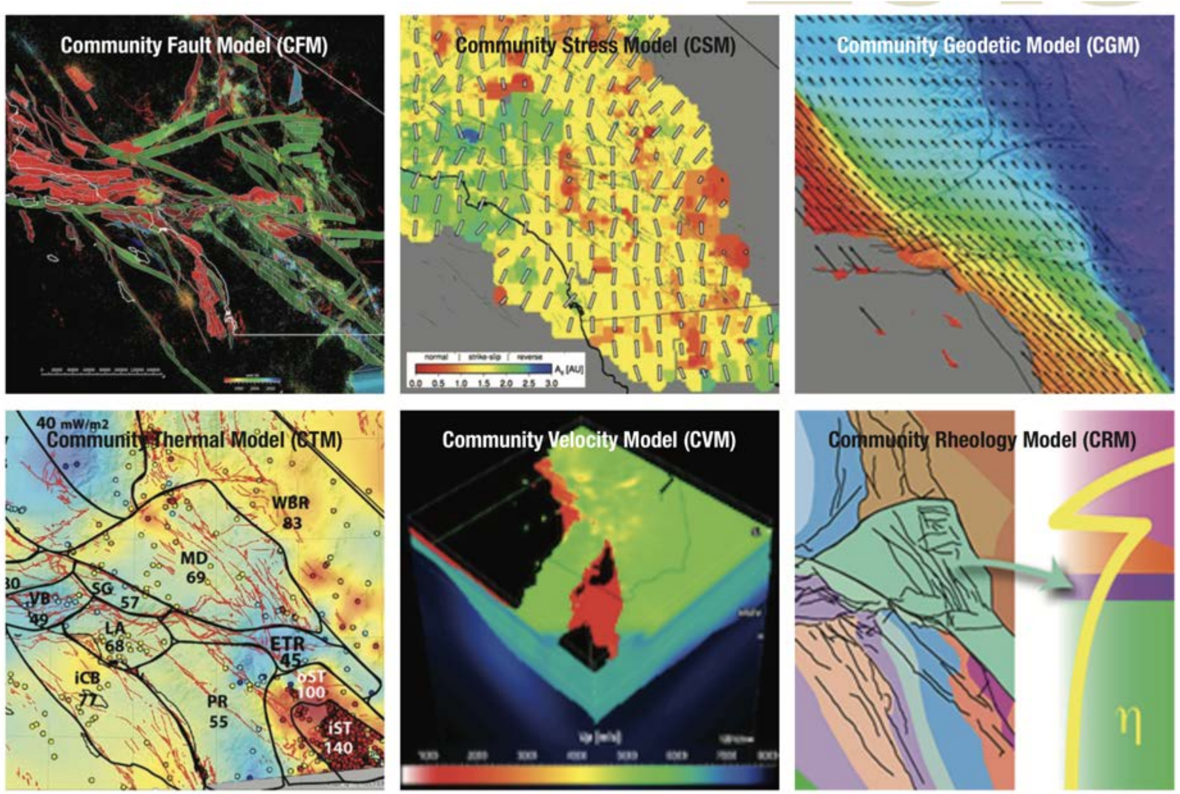
### *Salton trough example*

Kyriakopoulos et al (JGR 2019) simulate rupture through the Brawley Seismic The participation of cross-faults and pattern of rupture propagation is strongly affected by fault-to-fault dynamic stress interactions during the rupture process.

# Theme A: Modeling the Fault System

## Topic 3: Community Models

We will enhance the accessibility of the SCEC Community Models, including the model uncertainties. Community thermal and rheological models will be developed.



# CXM Highlight 1: Improved Websites and Access Tools

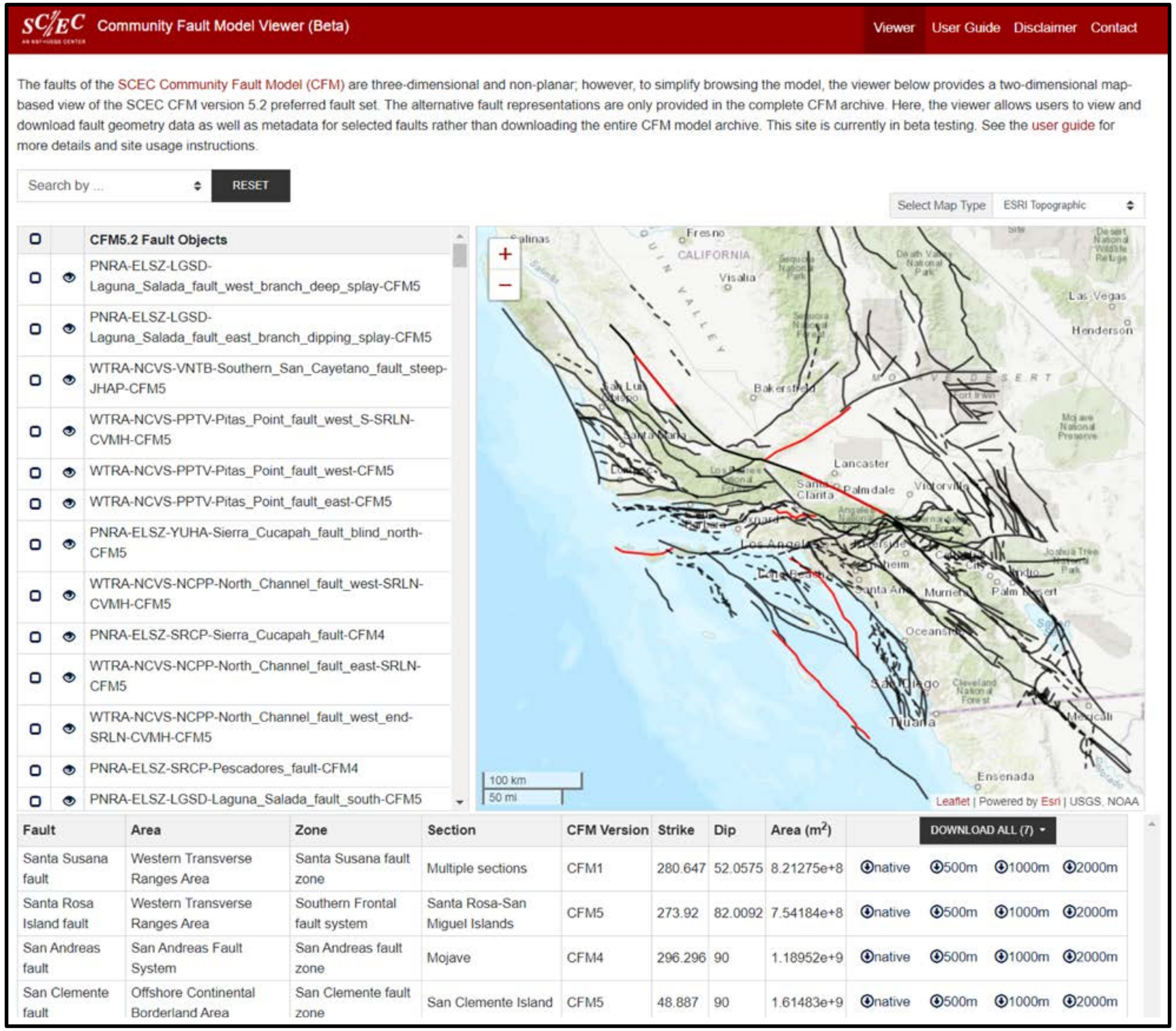
**Updated CXM website**
www.scec.org/research/cxm
Provides access to pages for all community models

**CFM Web Interface Now Available! (beta)**
www.scec.org/research/cfm-viewer/
Search/Download the CFM via map-based interface
(See poster #322 Su et al.)

**Updated CFM homepage**
www.scec.org/research/cfm
Download CFM, new CFM maps, GOCAD FAQ, and improved tools
(Poster #323, Nicholson et al. for CFM5.3 updates)

**CGM website:** development underway
(Mike Floyd + SCEC IT/Web)

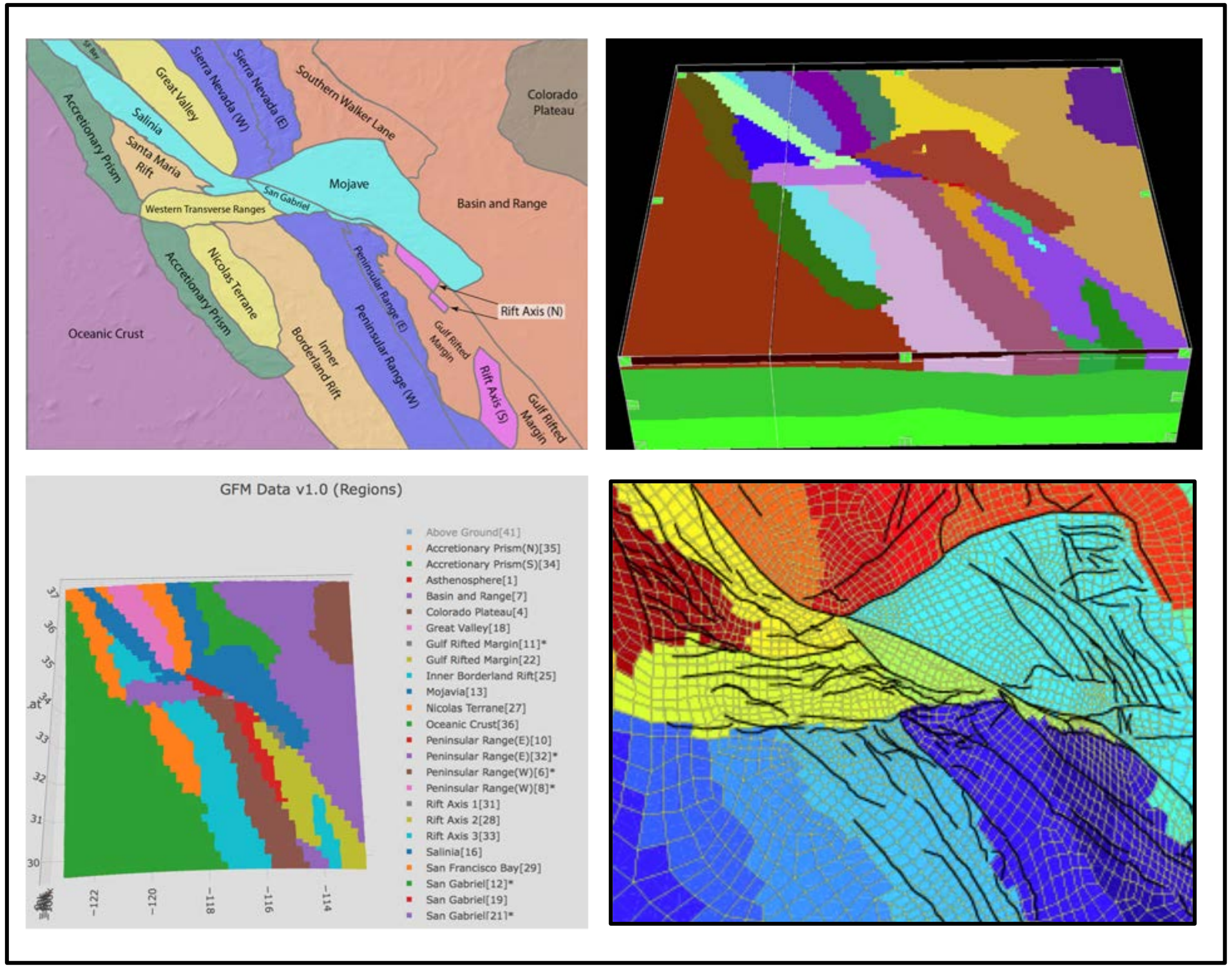
**CSM website:** returning to service
(Jeanne Hardebeck + SCEC IT/Web)




*Thanks to SCEC IT and SCEC Web*
*(Tran Huynh, Phil Maechling, Edric Pauk, Mei-Hui Su)*

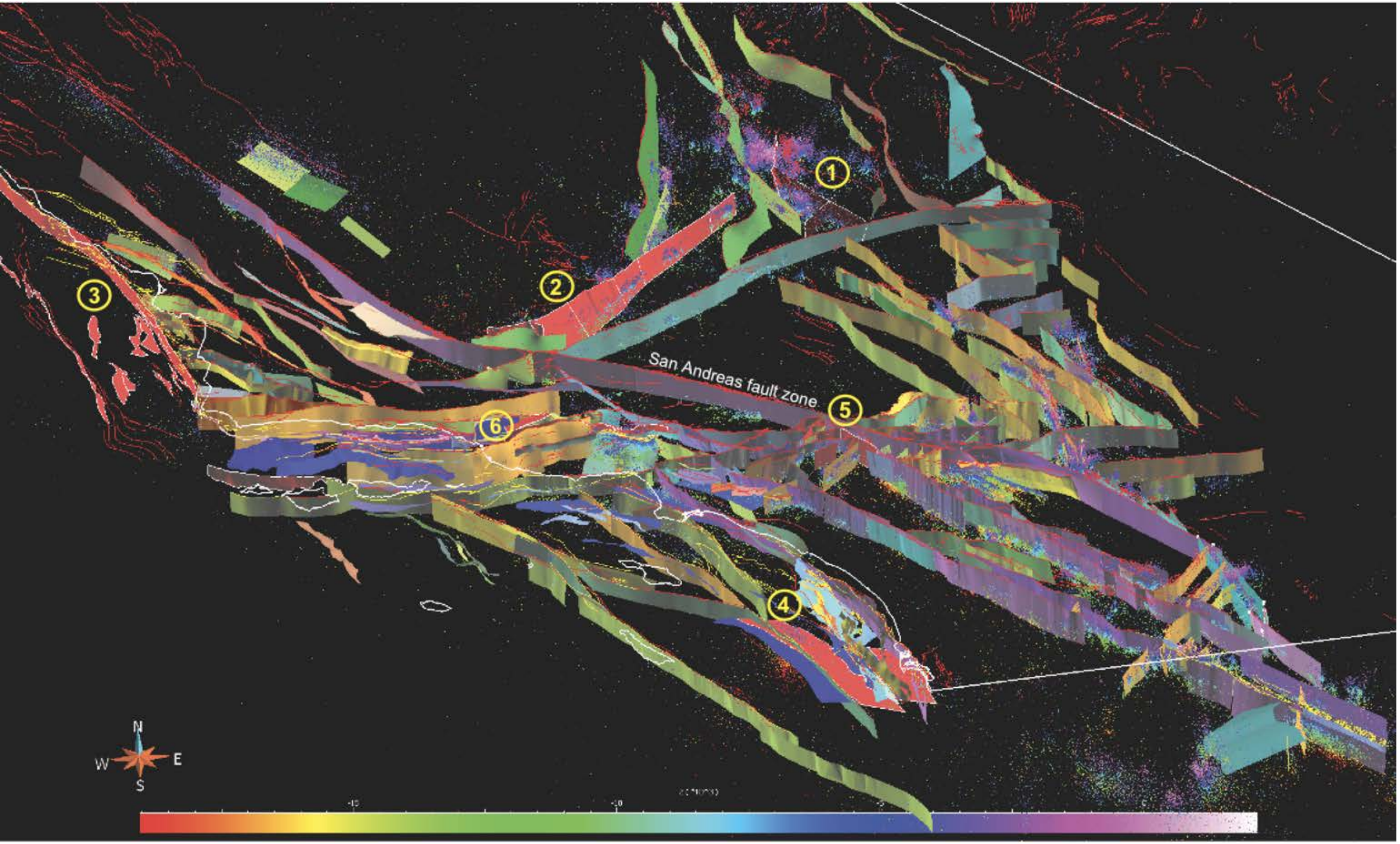
# *CXM Highlight 2: CRM progress and query tool development*

- Gridded UCVM-compatible version of the CRM geologic framework model (GFM) in development (Plesch, Shaw)
- GFM query tool in development (Su, Maechling, Oskin, Shaw, Plesch)
- Consensus on how to generate whole-rock flow laws for GFM lithologies (Montesi and Hirth)
- CTM geotherms revised for all heat flow regions (Thatcher and Chapman)
- Aug 2019 workshop on inferring 3D rheology from the SCEC CVMs (Oskin et al.)




**TOP: Preliminary geologic framework province boundaries and gridded version in development for UCVM compatibility (Oskin, Legg, Shaw). BOTTOM: GFM viewer screenshot (Su et al.), GFM represented in a FE mesh (Hearn). See poster 317 (Thatcher et al.)**

# Updated CFM v4.3 Fault Representations




1) Sierra Nevada - Ridgecrest area
2) Great Valley – White Wolf fault area
3) Offshore Santa Maria Basin area
4) Offshore Inner Borderland area
5) Cajon Pass Earthquake Gate area
6) Ventura Special Fault Study area

*Nicholson et al. (Poster #323)*

# *Highlights: CXM science and model development*

- **CRM and CTM: gridded UCVM-compatible CRM geol framework and query tool (in development), consensus approach to generating whole-rock flow laws for GFM lithologies, final CTM geotherms for all heat flow regions. Aug 2019 workshop on inferring 3D rheology from the SCEC CVMs.**

- **CVM:** ongoing F3DT (Jordan and Juarez, Tape and Thurber), upper crustal tomography of Coachella Valley (Persaud), San Bernardino seismic lines (Clayton), Moho imaging under basins (Hauksson and Yu), Mantle imaging (Humphreys and Stanciu). UCVM v19.4 (Maechling), Sept 2019 workshop resulting in prioritized action items (Thurber).

- **CFM**: CFM 5.2, CFM standardization and delivery via website, new simulator-friendly tsurf files, updated fault geometries, relocated seismicity, progress on earthquake to fault associations, kinematic compatibility modeling, and more. New CFM webpage and new CFM query tool (Shaw, Plesch, Nicholson, Marshall, Cooke, Hauksson, Su, Maechling)

- **CGM:** merged GPS time series (Floyd and Herring), new leader (Floyd), September 2019 workshop resulting in consensus on CGM v.2 deliverables

- **CSM:** modeling effect of anisotropy on stress (Becker, Behr, Schulte-Pelkum), thermomechanical seismic cycles (Dunham), stress state at Cajon Pass (Luttrell and Smith-Konter), assessing length scale of stress heterogeneity with borehole breakouts (Luttrell and Hardebeck), workshop resulting in action items for the remainder of SCEC5 (Hardebeck et al.)

# Topic 4: Data-Intensive Computing

We will develop methods for signal detection and identification that scale efficiently with data size, which we will apply to key problems of Earth structure and nanoseismic activity.

# *Highlights: Data-Intensive Computing*

SCEC released open-source community software developed by SCEC researchers, and tracked unique page-views, and unique downloads from github repositories.

| Code | Start Date | End Date | Unique Views | Unique Downloads |
|---|---|---|---|---|
| BBP | 06/08/2018 | 05/02/2019 | 578 | 51 |
| UCVM | 06/08/2018 | 05/02/2019 | 495 | 123 |
| CSEP Code | 06/08/2018 | 05/02/2019 | 14 | 8 |
| High-F (AWP) | 06/18/2018 | 05/02/2019 | 32 | 6 |
| FAST | 10/17/2018 | 05/02/2019 | 647 | 60 |

**Table ▲** Unique views and downloads over the last 6 to 11 months for SCEC open-source community software released through public github repositories.

# *Highlights: Data-Intensive Computing*

SCEC researchers performed CyberShake Study 18.8 which produced a physics- based PSHA model for Northern California using two leadership class super- computers (NCSA Blue Waters and OLCF Titan). This data intensive calculation:

- Generated: 1.2 PB
- Transferred: 157 TB
- Saved: 14.4 TB
- Generated: 203 million 2-component seismograms
- Populated: a 30.4 billion intensity measures database

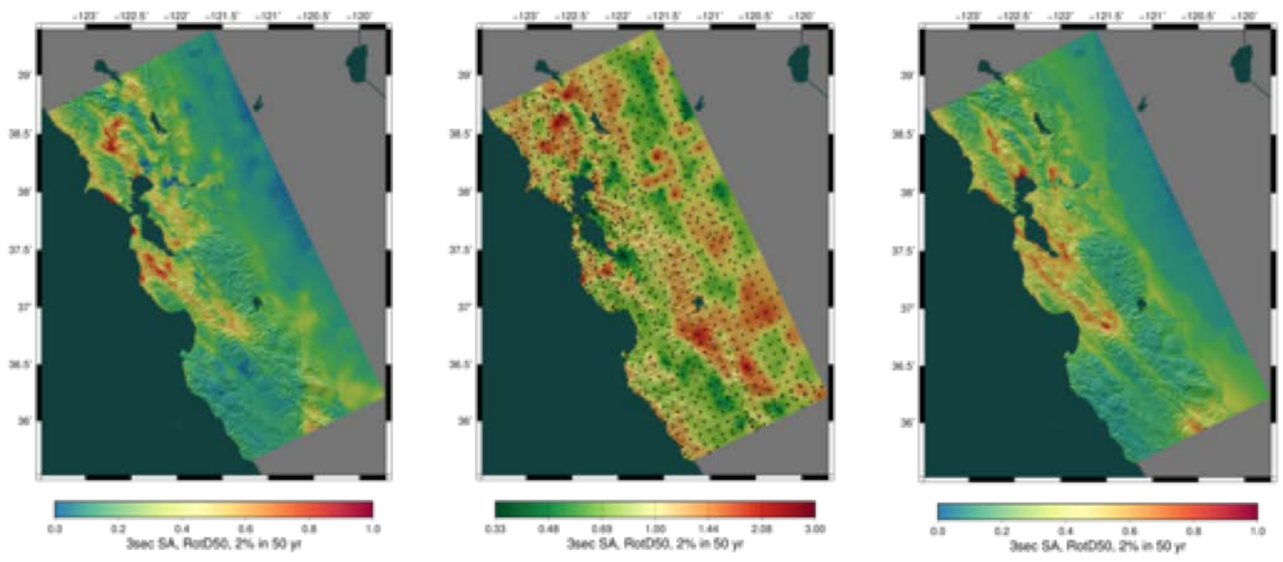


**Figure** (left) CyberShake 18.8 hazard model shows 3 secs SA of 2% in 50 years (center) Ratio of CyberShake/GMPEs (right) Average of 4 NGAWest2 GMPEs for study region for comparison. (Scott Callaghan et al)

# *Highlights: Data-Intensive Computing*

SCEC researchers developed methods that use data from dense seismic arrays to characterize material properties in the top 150 meters and to identify cultural noise sources.

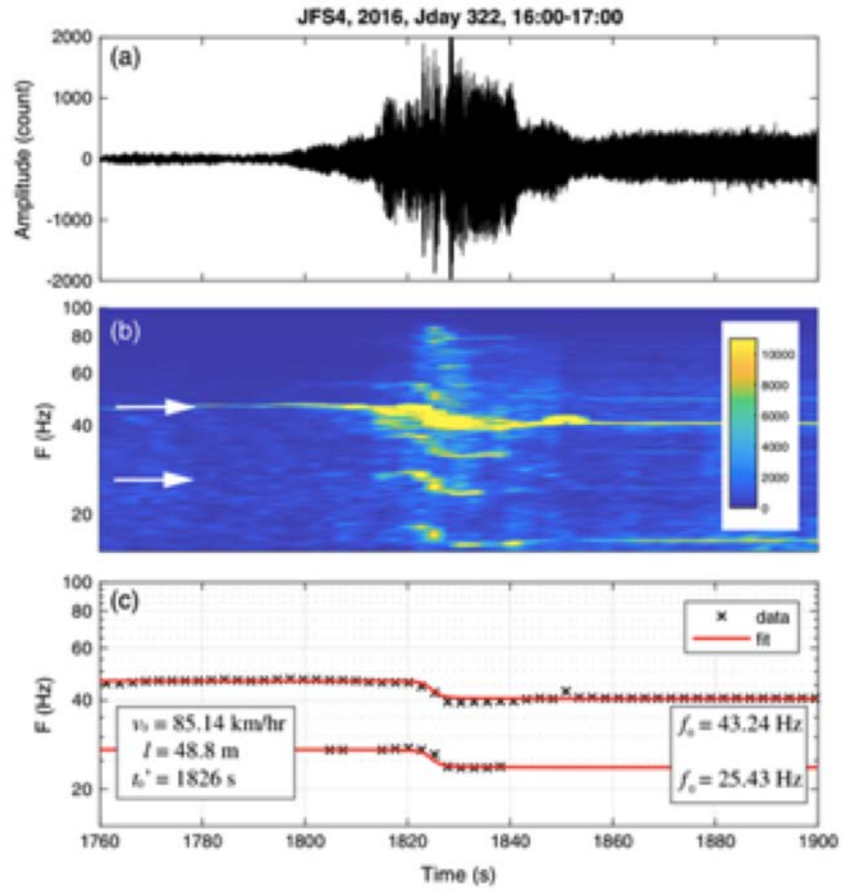



**Figure** a) A raw vertical component waveform for a known helicopter event flying over seismic station JFS4. (b) Corresponding spectrogram with vertical axis in log scale. Arrows denote two strong overtones picked for analysis. (c) Time and frequency data (black crosses) for two overtones picked in the spectrogram in (b) and line fit to the data based on equation (1) (red curves). Inferred parameters for the helicopter are indicated in the box. (from Meng and Ben-Zion, 2018).

# Highlights: Data-Intensive Computing

SCEC researchers developed methods that can detect earthquakes over a seismic network using single-station similarity measures.

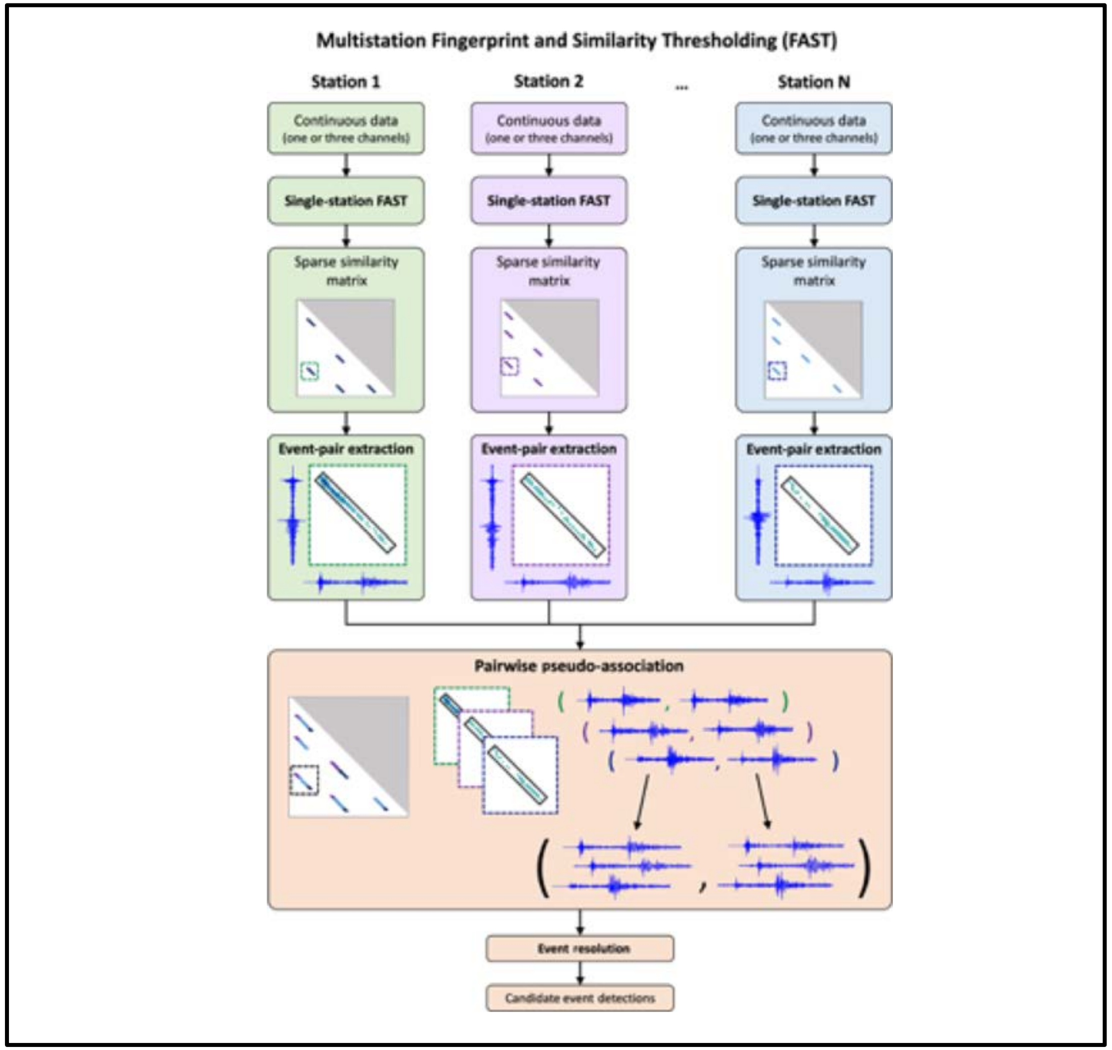
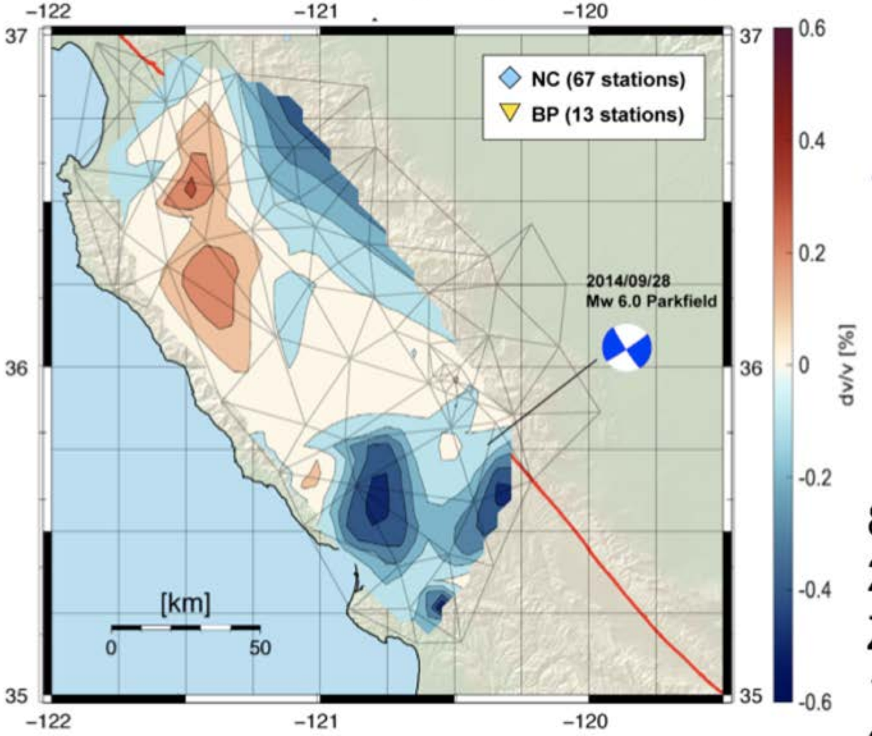



**Figure** Diagram of multi-station detection with FAST. Single-station FAST produces a sparse similarity matrix for each station, which is the input to the three-step processing pipeline for multi-station detection: (1) Event-pair extraction converts sparse similarity matrix into list of pairwise event detections for each station and (2) Pairwise pseudo-association identifies event-pairs that are observed at multiple stations in the seismic network; and (3) Event resolution converts pairwise detections into list of candidate events. (from Bergen and Beroza, 2018)

# *Data-Intensive Computing: Ambient-Field Seismology*

Poster #043 (Bryan et al.)




Sept 30, 2004

From download

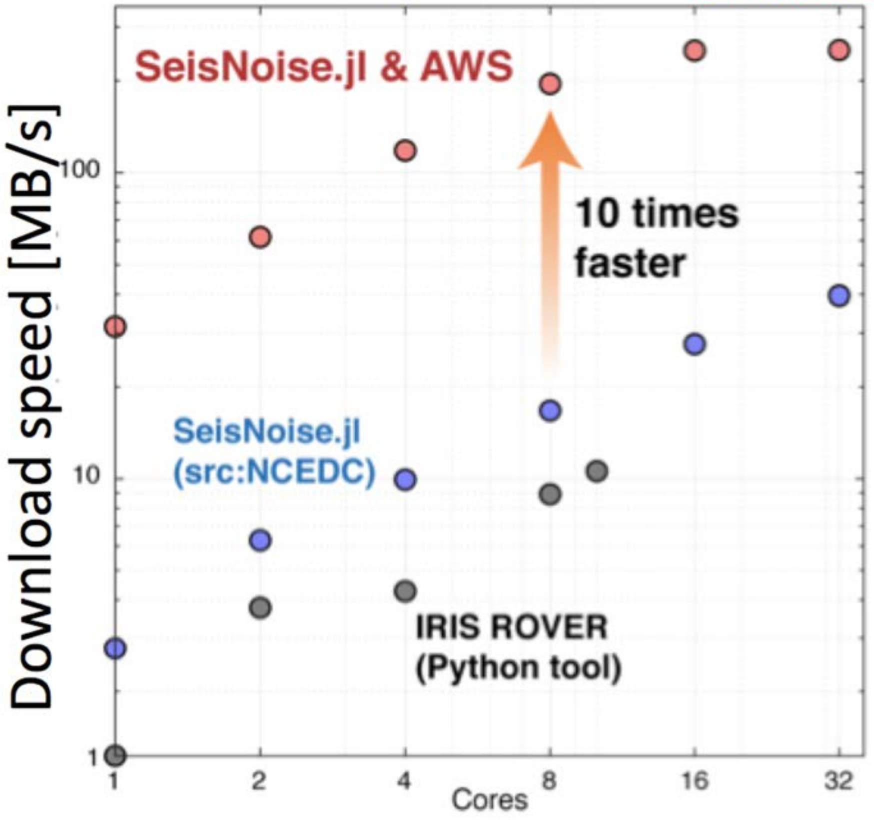
To map of change in seismic velocities

**4.4 hours**

80 stations
20 Hz
Z comp
1 year
36 cores

Cloud computing with aws

Poster #302 (Clements & Denolle)



# *Highlights: Data-Intensive Computing*

Other SCEC Researchers working on data-intensive computing-related efforts include:

- Khoshnevis and Taborda (U. Memphis) / Project 17-239: Prioritizing ground motion validation metrics using supervised and semi-supervised learning (BSSA) & Application of pool-based active learning in physics-based earthquake ground-motion simulation (SRL).

- Zhigang Peng (Gerogia Tech) / Project 18-175: Machine Learning Based Convolutional Neural Network in Earthquake Detection and Classification and its Application in Southern California.

- Ramon Arrowsmith and Jnaneshwar Das (Arizona State) / Project 18-179: Rock Traits from Machine Learning: applications to precariously balanced rocks and fault scarps in Southern California

- Phoebe DeVries (U. Connecticut) / Project 19-030: Machine learning and web-based visualization of aftershock patterns.

# *Theme B: Understanding Earthquake Processes*

## Topic 5: Beyond Elasticity

We will test hypotheses about inelastic fault-system behavior against geologic, geodetic, and seismic data, refine them through dynamic modeling across a wide range of spatiotemporal scales, and assess their implications for seismic hazard analysis.

# *Highlights: Beyond Elasticity*

- **Off-fault plasticity: Ground motion simulation for elastic, J2 elasto-plastic, and multiaxial cyclic plasticity models in Hercules framework** (Asimaki et al., Proj# 18020 and Proj#19056)

- **Site response modules on the Broadband platform:** Semi-empirical Fourier amplitude (Bayless et al., Proj#19097); Synthetic complex Fourier factors (Asimaki, Proj#19055); and wave propagation-based using Vs30-based profile generator and elastoplastic soil constitutive models (Arduino et al., Proj# 18103; Asimaki, Proj#19055)

- **Coordinated by TAG Nonlinear Effects in the Shallow Crust … see Topic 14**

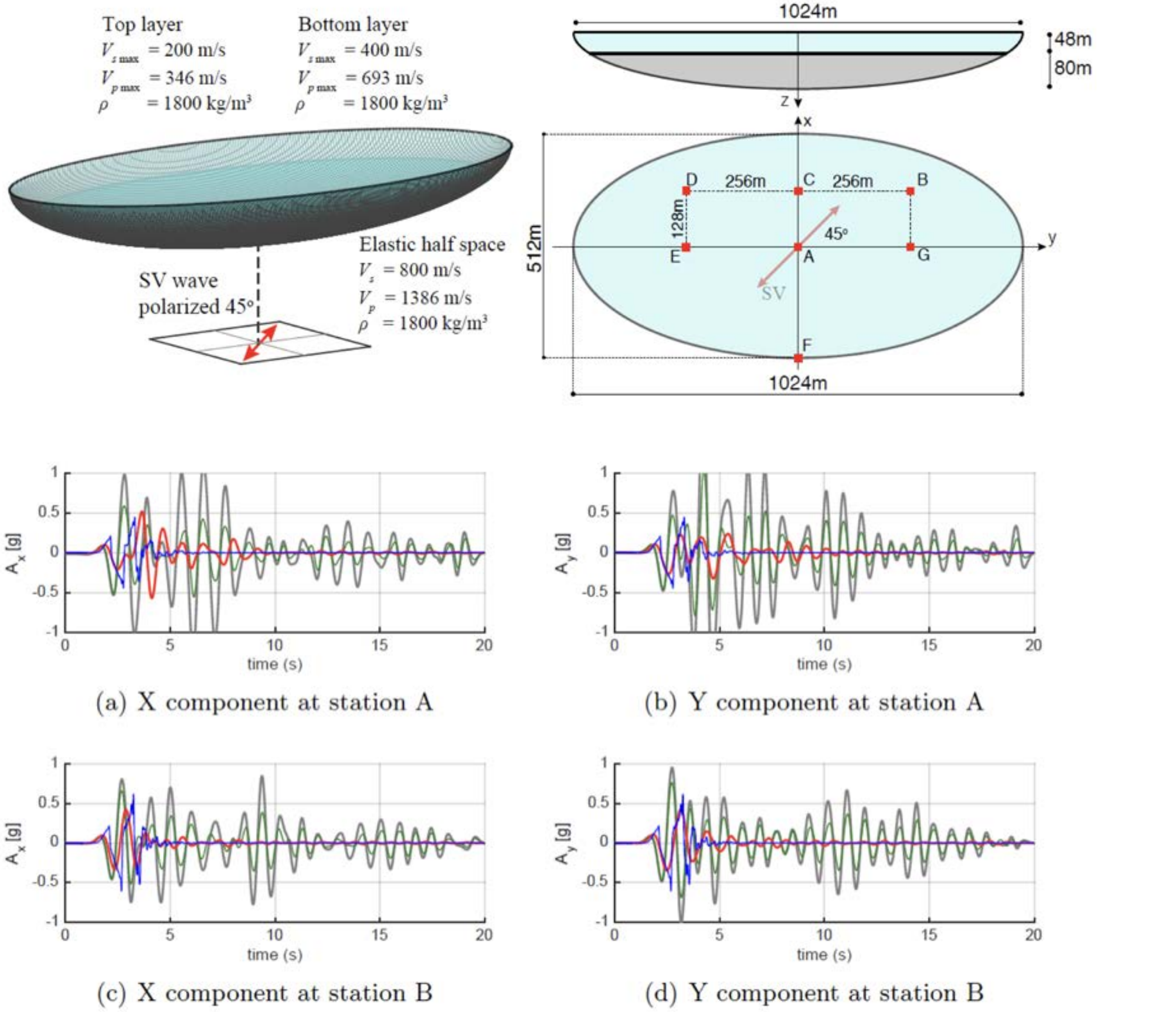


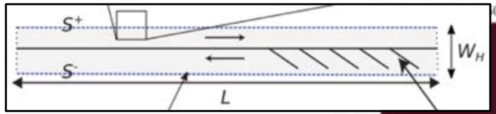

Figure 4: Acceleration responses in the basin; (—) elastic-3D, (—) J2 model-3D, (—) MCP model-3D, (—) MCP-model-1D.

Seylabi, Restrepo, Taborda, Asimaki (2019)

# Highlights: Beyond Elasticity

Other noteworthy research accomplishments

- Investigated **role of persistent fault damage zones over multiple earthquake cycles pulse-like ruptures and multiple back-propagating fronts** reminiscent of Rapid Tremor Reversals. (Ampuero et al., Proj# 18096):




- **Implemented hybrid finite element-spectral boundary integral equation scheme to investigate the dynamics of fault zones with small scale pre-existing branches** (Elbanna et al., Proj# 18157)
- Investigated role of **elastic-perfectly plastic constitutive response on near-fault directivity pulses** (Day et al., Proj# 18204): Milestones 5f, 5k

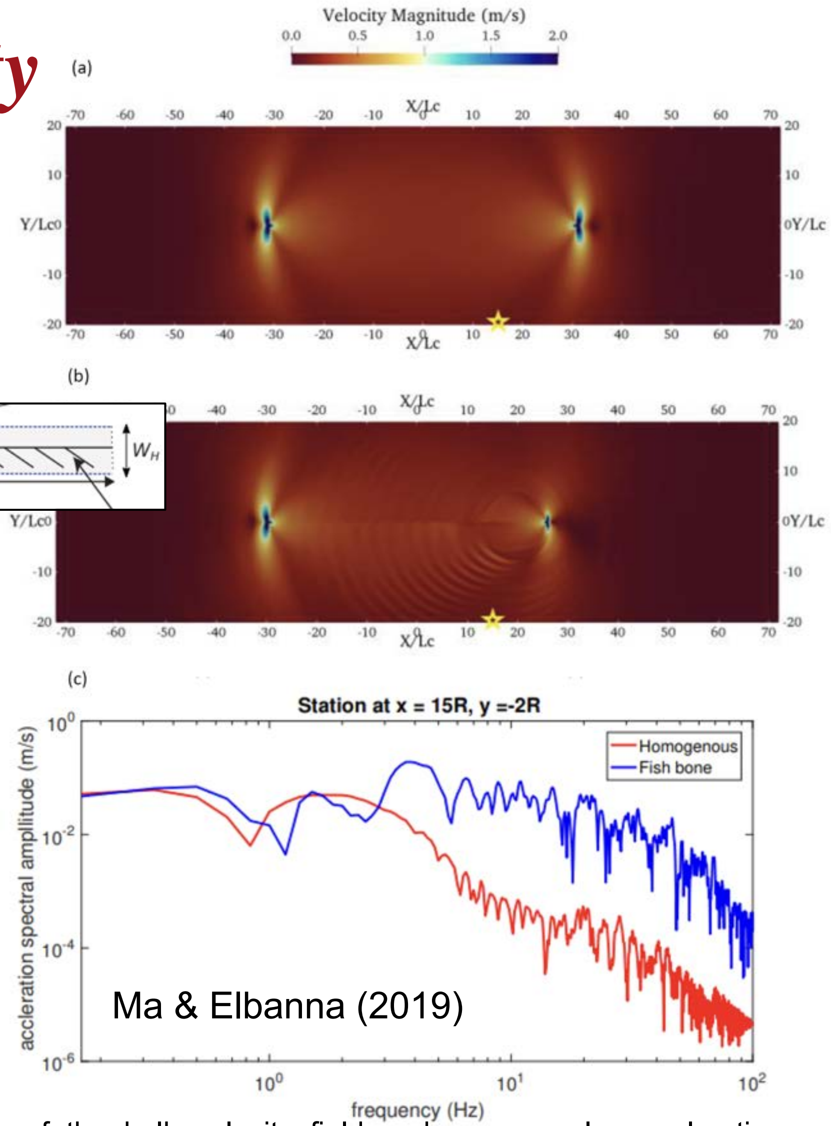


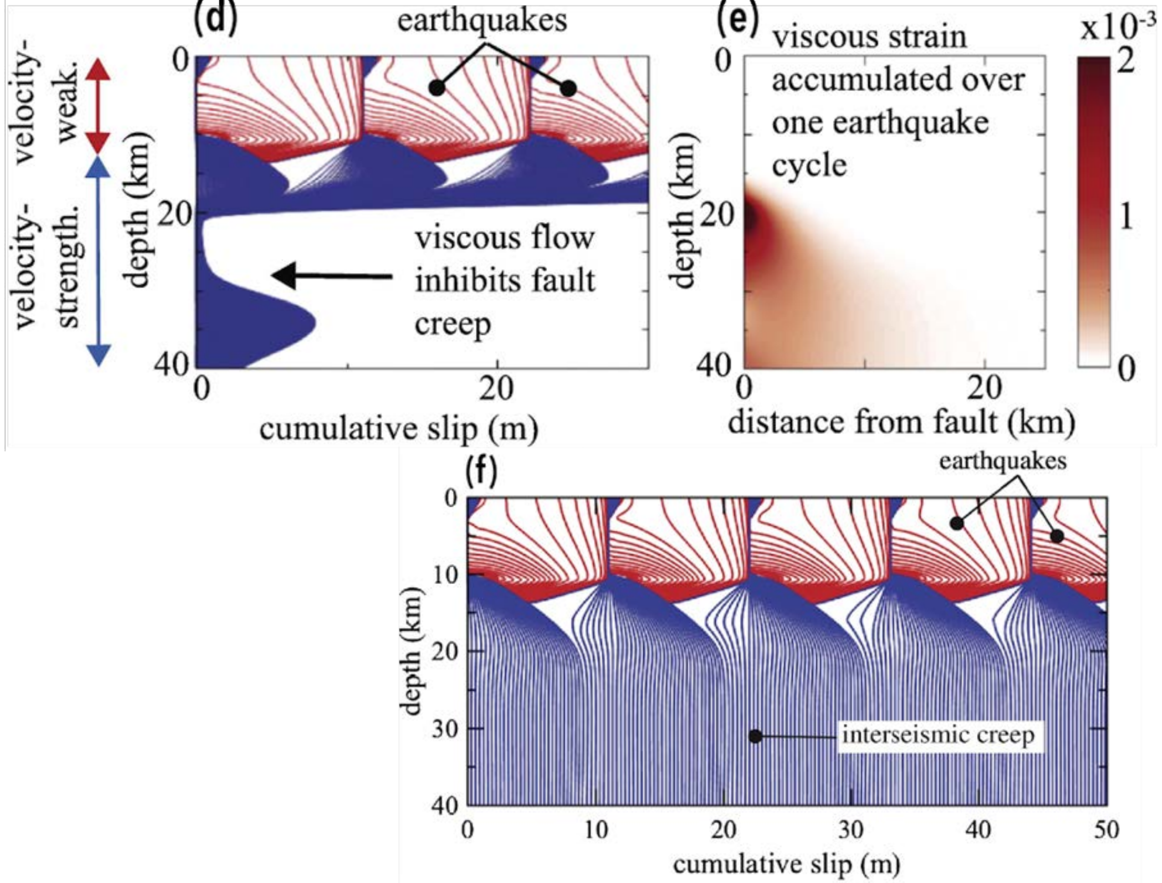

**Figure 3:** Contours of the bulk velocity field and an example acceleration spectrum at a near field station. (a) Bulk velocity field in a Homogeneous medium. (b) Bulk velocity field in a Domain with fish bone structure. (c) Fault normal acceleration spectral amplitude at station $x* = 15R$ and $y * = -2R$ showing increased high frequency content and a flat frequency spectrum in the range of 1-20 Hz for the fault zone with short branches.

# Topic 6: Modeling Earthquake Source Processes

We will combine coseismic dynamic rupture models with inter-seismic earthquake simulators to achieve a multi-cycle simulation capability that can account for slip history, inertial effects, fault-zone complexity, realistic fault geometry, and realistic loading.

# *Highlights: Modeling Earthquake Source Processes*

- **Damage zones (just reviewed):** effects of low-velocity zones over multiple earthquake cycles (Ampuero et al., #18096); complexity due to small-scale pre-existing branches (Elbanna et al., #18157); changes in near-fault directivity pulses (Day et al., #18204).
- **Deeper near-fault deformation in models with depth-variable friction + bulk power-law creep:** (Dunham et al., #18050; **Figure**).
- **Sequences of earthquakes and aseismic slip (SEAS), code comparison exercise:** workshop with 36 participants, 20 students/postdocs (Erickson and Jiang, #18102); simulation results from 11 modeling groups for a basic 2D problem generally in good agreement, importance of proper resolution (Erickson and Jiang, #18099); future benchmarks with rupture jumping, inelasticity, fluids, inertial effects.
- **Complexity of earthquake sequences on faults with realistically small nucleation size:** Gutenberg-Richter scaling of event sizes + fracture-mechanics-based explanation (Cattania and Segall, #18166)



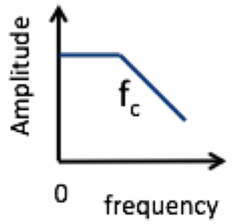

Simulations of sequences of earthquakes and aseismic slip (SEAS) in a 2D quasi-dynamic model with depth-dependent friction properties, a power-law creep rheology and full thermomechanical coupling. The viscoelastic creep can shut down the fault slow slip (d-e), which would exist otherwise (f). Adapted from Allison and Dunham (2018).

# *Highlights: Modeling Earthquake Source Processes*

- **Improving estimates of stress drops:** second-moment-based estimates result in 10-50 MPa stress drops for ~30 Mw > 3.5 events in SoCal (McGuire and Ben-Zion, #18062); Madariaga's approach overestimates the area and hence underestimates the stress drop (Lapusta et al,  #18085; **Figure**); depth-dependent effects of path/attenuation (Abercrombie and Shearer, #18086).

- **Quantifying the complexity of faults/stress:** significant stress parameter variations around major faults from focal mechanisms of declustered catalogs (Ben-Zion et al., #18026); power-spectrum descriptions of fault roughness neglect phase information and hence asperity distributions need to be quantified separately (Brodsky et al., #18224)

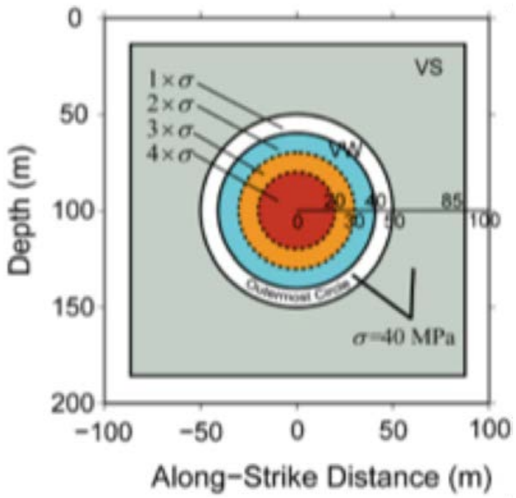
- **Fluid effects:** aseismic slip due to fluid injection into a fault zone outpaces the fluid overpressure (Viesca et al., #18043, induced seismicity); accelerated slow slip on creeping faults may be due to fluid pressure contrast across the fault (Dunham et al., #18047); radiation efficiency for pulse-like ruptures is much larger than typically observed (Lapusta et al,  #18085).

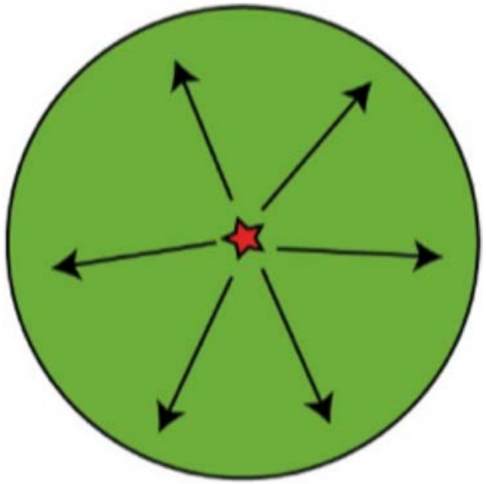


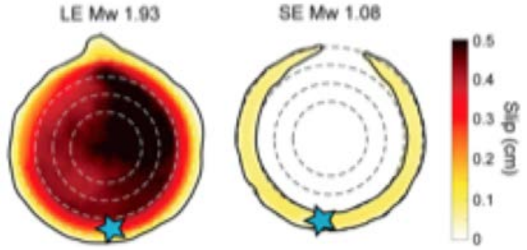

$$t_{dur} = \frac{k}{f_c}$$

$$r = t_{dur} v_r$$

$$\Delta\sigma = C\frac{M_0}{A^{3/2}} = \frac{7M_0}{16r^3}$$






Directivity and/or non-circular shape of the source region can result in Madariaga-like stress drop estimates 10-100 times lower than the actual stress drops (Lapusta and Lin, 2018); second-moment-based estimates can account for some of these effects.

# Topic 7: Ground Motion Simulation

We will validate ground-motion simulations, improve their accuracy by incorporating nonlinear rock and soil response in the shallow crust, and integrate dynamic rupture models with wave-scattering and attenuation models. We will expand our simulation capabilities to capture the frequency band of engineering interest, 0.1-10 Hz. In collaboration with geotechnical engineers and engineering geologists, we will develop or implement nonlinear rheological models of near-surface rock and soil layers tailored to the computational constraints and parameter scarcity of full-physics earthquake simulations and calibrated against observed site responses from recordings.

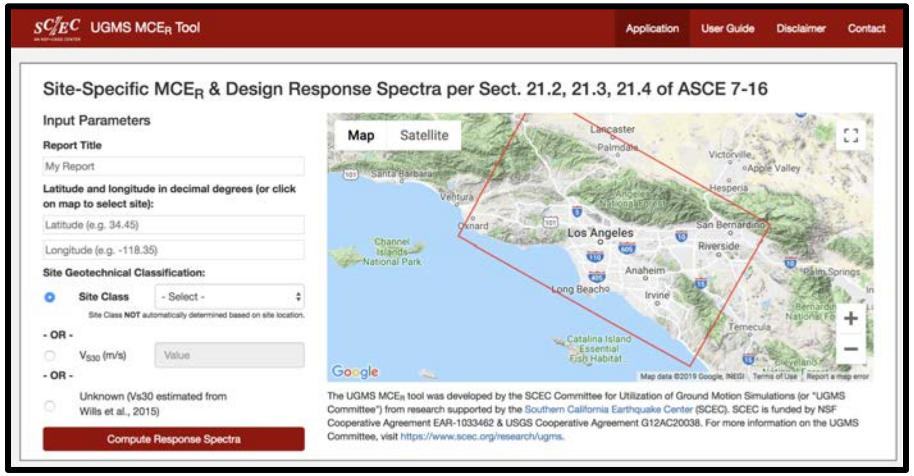
# *Highlights: Ground Motion Simulation*

**Ground-Motion Simulation Validation TAG**
[*SCEC Award #18161 Rezaeian and Stewart*]. Milestone 7c
→Validation for GMPEs: develop a standardized method for validating Cybershake simulations (PSA and duration, for mean values and trends with source, path, site parameters). Improve, as needed, stochastic simulation procedures.
→Validation for engineering: White paper on how to use simulated motions for building response studies.

**Dynamic Rupture Code  TAG**
[*SCEC Award #18217 and previous years, Harris*]. Milestone 7g
→Ongoing TAG/project for code validation and verification of dynamic rupture codes.
→2018: Focus on fault geometry. Plan to address: fault friction (2019), initial stress conditions, and rock properties iin future workshops.
→Dynamic vs. kinematic for GM validation?

**TAG: … Nonlinear Effects in the Shallow Crust**… see Topic 14.

**Beyond Elasticity**… see Topic 5




**UGMS MCEr web-based lookup tool.**

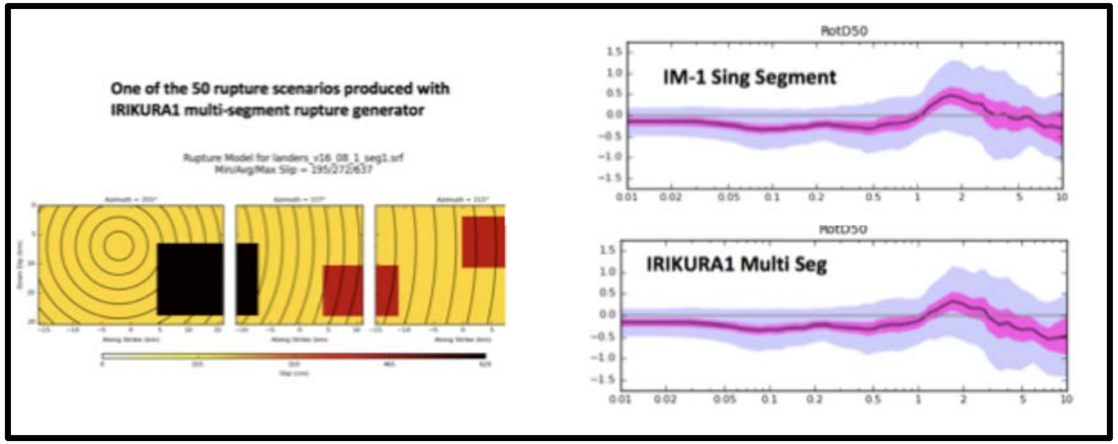
**SCEC Utilization of Ground Motion Simulations Working Group**
[*SCEC Award #18141 Crouse and Goulet*]. Milestone 7k
→Development of web-based data access tool for site-specific MCER SA. Plans for deaggregation data and CyberShake accelerograms.

# Highlights: Ground Motion Simulation

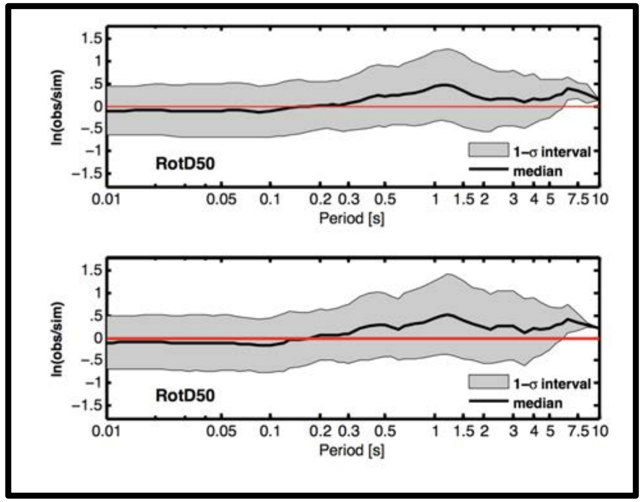
**Multi-Segment Fault Rupture Modeling, implementation into BBP.**
[*SCEC Award #18092 Pitarka; pub: Pitarka et al., 2019 PAAG*]. Milestone 7a
→ Implemented the multi-segment Irikura method into BBP; tested against GMPEs and recorded EQs (incl. Landers).

**Temporal-Spatial Ground Motion correlation**
[*SCEC Award #18146 Olsen; pub: Wang et al., 2018*]. Milestone 7a
→ Developed post-processing to add interperiod correlations to synthetic time series which were otherwise deficient.

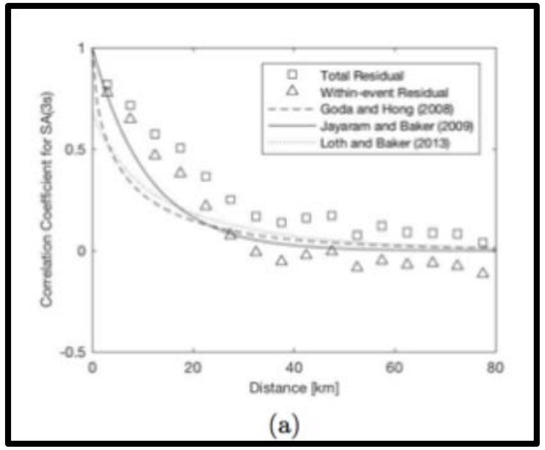
**Spatial Correlations in CyberShake**
[*SCEC Award #18033 Baker*]. Milestone 7j
→ Found good agreement of distance-dependent spatial correlation structure between CyberShake "data" and empirical recordings




**Multi-segment Rupture for Landers.** (a) One of 50 rupture scenarios. (b) comparison of Landers BBP goodness-of-fit for single segment (top) and multi-segment (bottom) (*Pitarka*)




**Spatial Correlations for Loma Prieta.** GOF for Loma Prieta (top) uncorrelated, and (b) with interperiod correlations (Olsen)



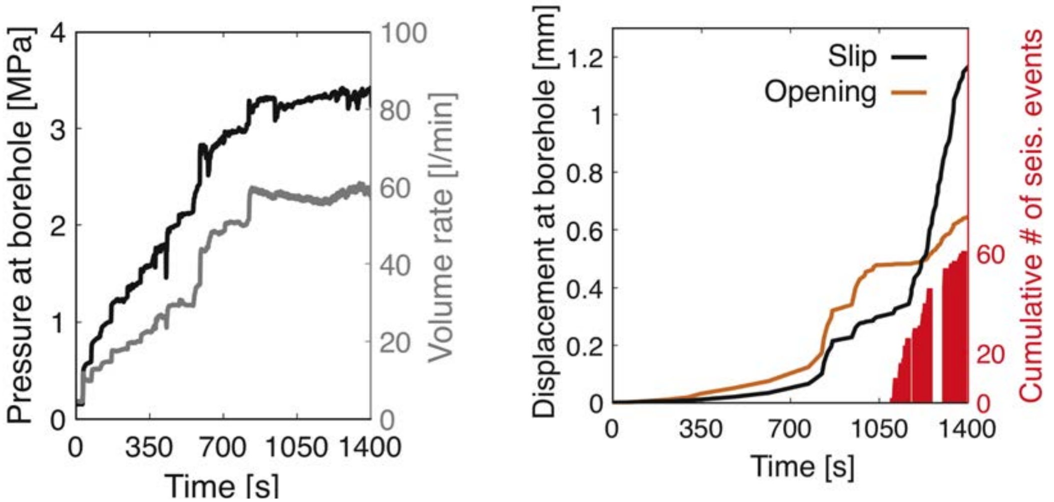

**Spatial Correlation Coefs. from CyberShake.** (a) San Andreas rupture at T=3s. (*Baker*)

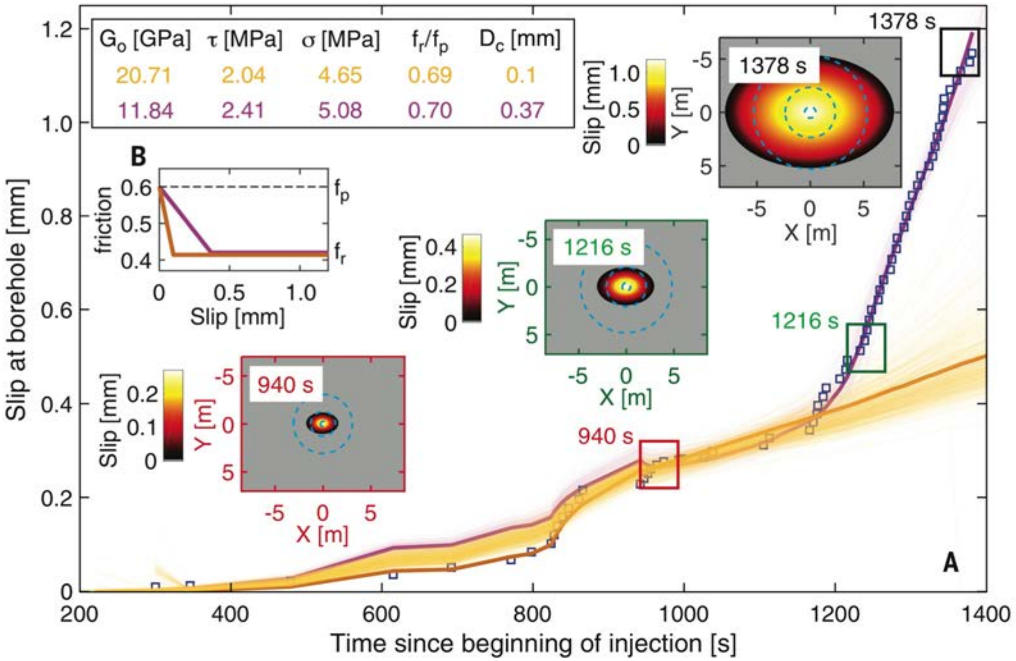
# *Theme B: Understanding Earthquake Processes*

## Topic 8: Induced Seismicity

We will develop detection methods for low magnitude earthquakes, participate in the building of hydrological models for special study sites, and develop and test mechanistic and empirical models of anthropogenic earthquakes within Southern California.

# *Highlights: Induced Seismicity - Research & Community Activities*

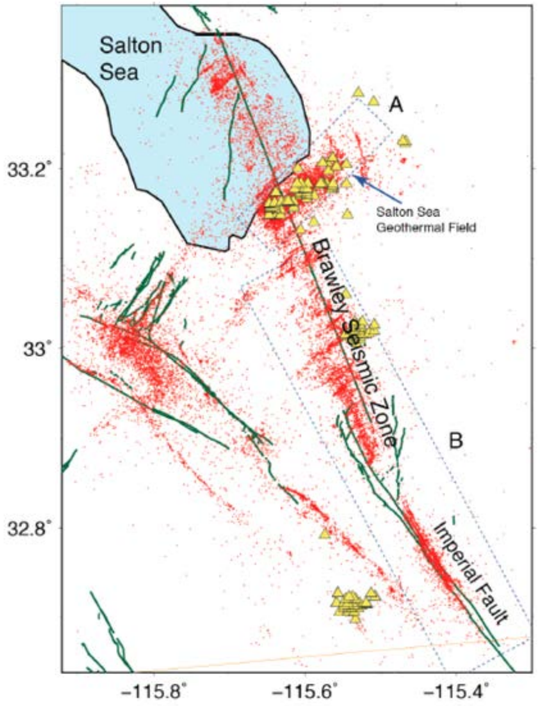


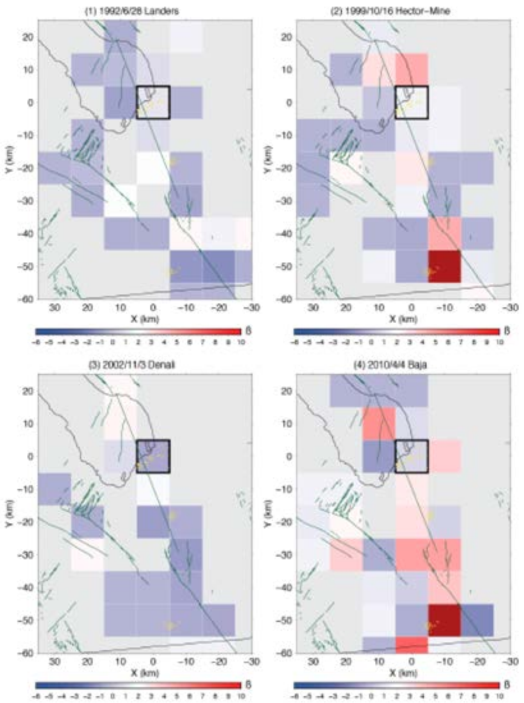



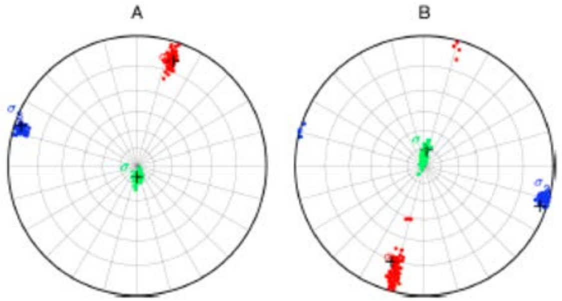

**Induced seismicity from aseismic slip** Bhattacharya and Viesca, *Science,*(2019) (18043)

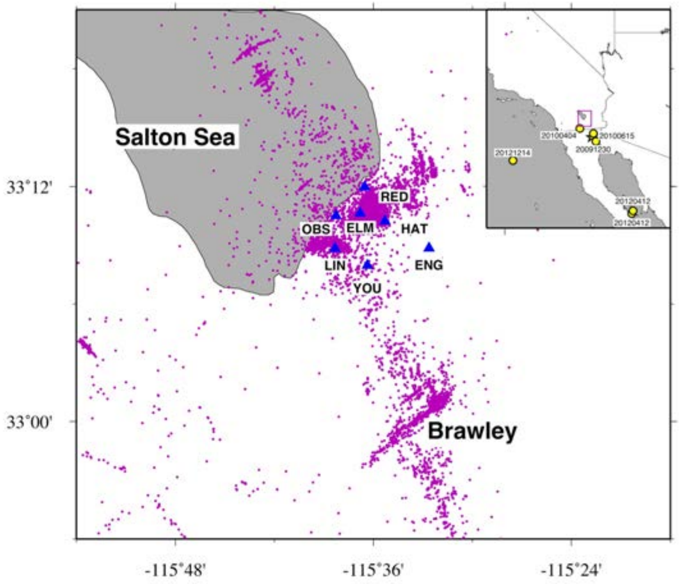

**International Conference on Induced Seismicity**, Carpenter et al (18206).

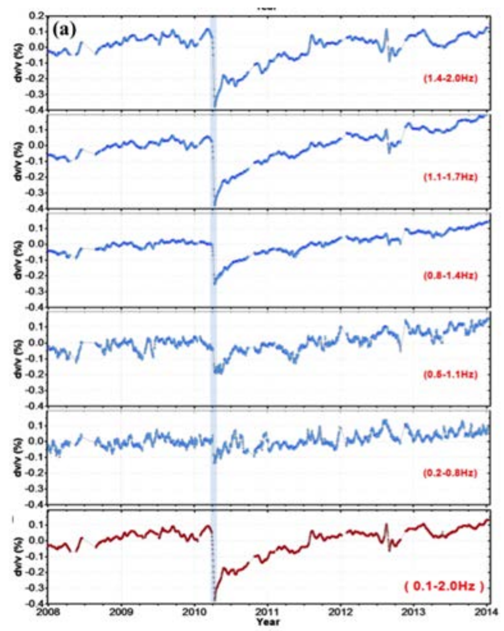
# *Highlights: Induced Seismicity - Southern California*

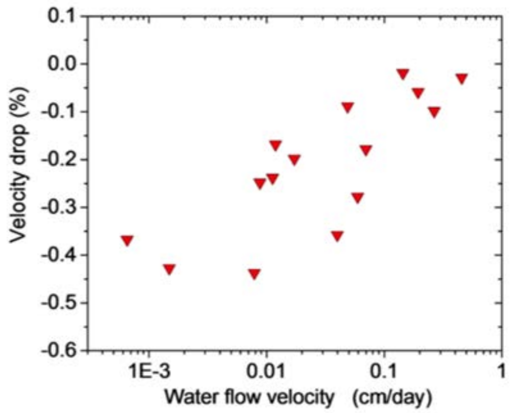



**Improved locations, triggering and stress orientation in Salton Sea Geothermal Field**, Lin (17006).

**Matched filter catalog, triggering, wavespeed, and fluid flow in Salton,** Peng (17055).

# *Highlights: Induced Seismicity - Southern California*

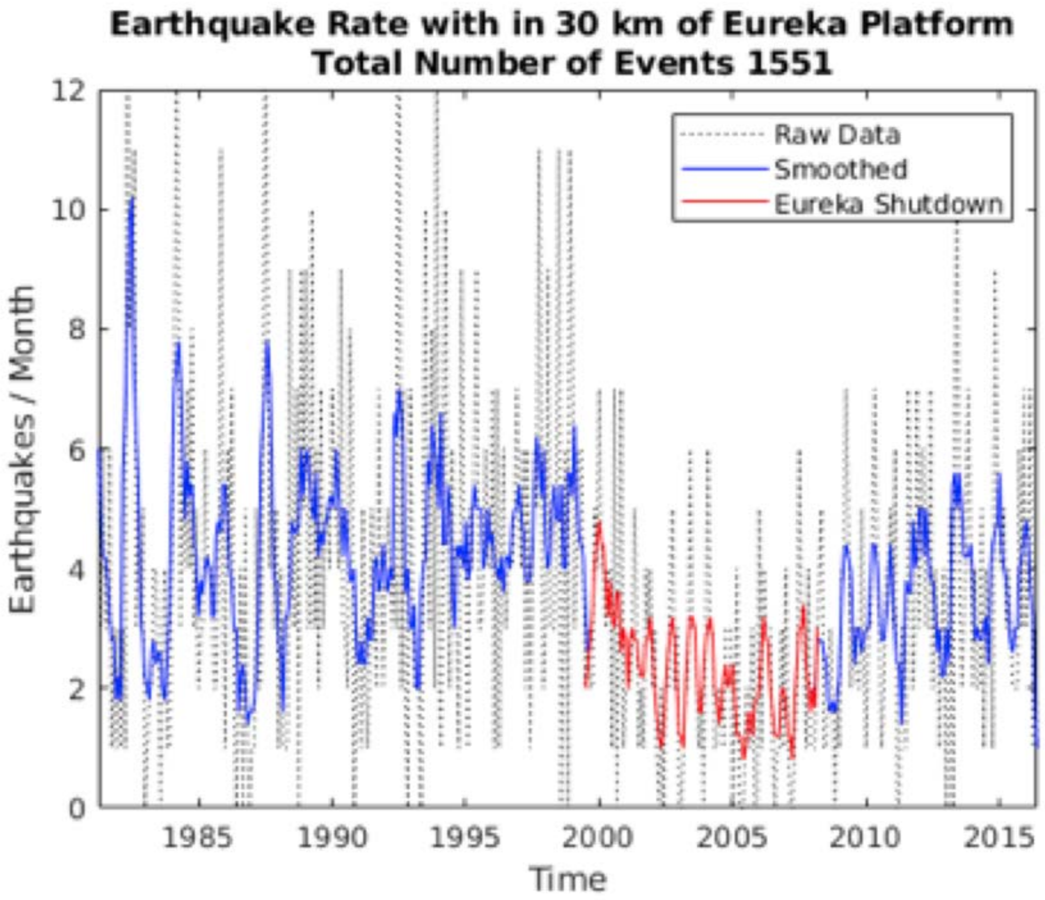



**Figure 4. Earthquake rate within 30 km of the Eureka platforms near the Palo Verdes Fault.** Operations on Eureka were shut down during the early 21st century (shown in red) and the seismicity rate in the area appears to have dropped during this period as well. Brodsky (18226).

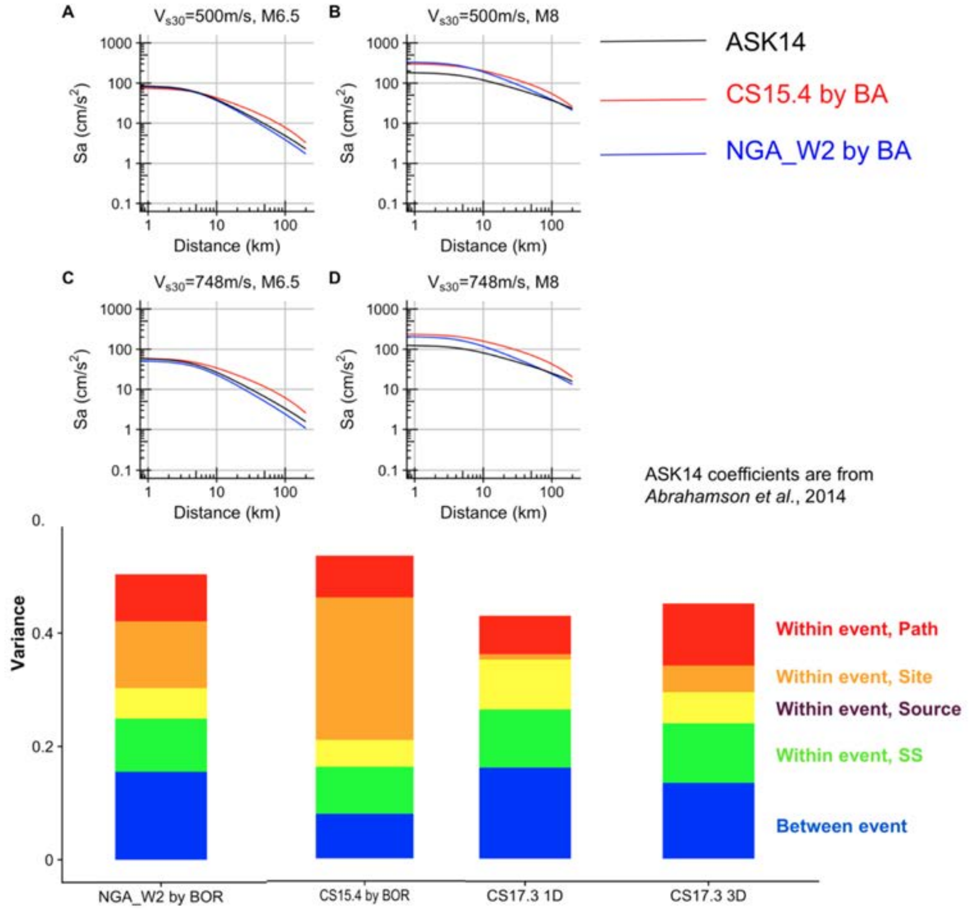
# Topic 9: Probabilistic Seismic Hazard Analysis

We will attempt to **reduce** the **uncertainty** in **PSHA** through physics-based earthquake rupture forecasts and ground-motion models. A special focus will be on **reducing the epistemic uncertainty in shaking intensities due to 3D along-path structure**.

# Highlights: Probabilistic Seismic Hazard Analysis

- Validation of CyberShake ground motions for SoCal and CCA (3D vs. 1D) *[Meng and Goulet **Poster #023**]*
  - Evaluation and interpretation of differences between empirical ground motions and simulations through different CVMs.

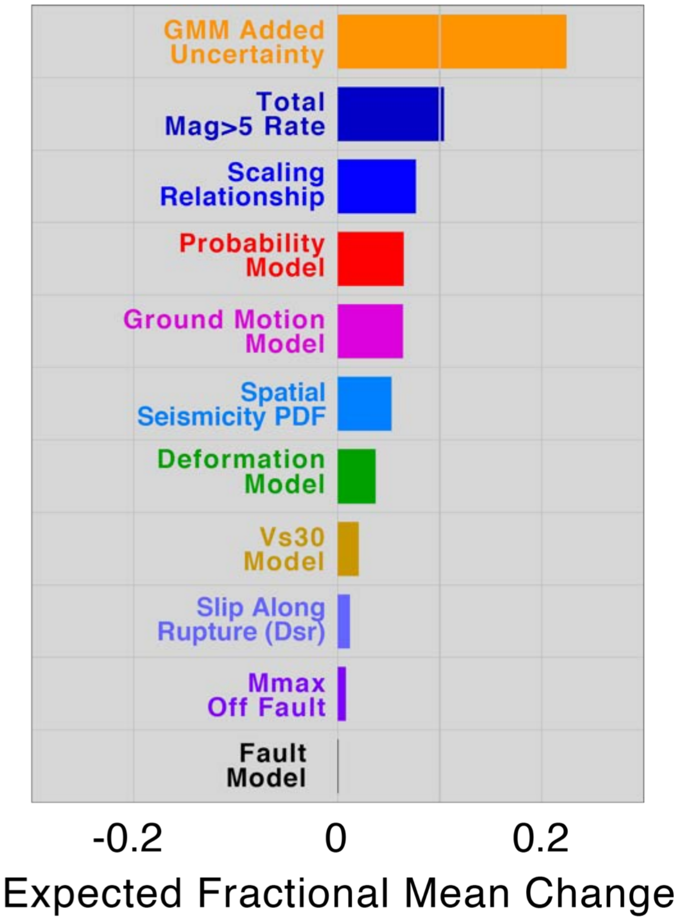
- Leveraging by Collaboratory for Interseismic Simulations and Modeling (CISM):
  - PSHA using RSQSim coupled with GMMs and Comparison with UCERF3-TI *[Shaw et al., 2018, SciAdv]*
  - CyberShake hazard curves using RSQSim as the ERF *[**Poster #297**]*




**CyberShake validation using mixed-effects regression.** Top: fitted ground motion models to NGA-West2 data, CyberShake results and Abrahamson et al 2014 (ASK) for different site conditions. Bottom: achieved partitioned variances from data and three CyberShake maps.

# Highlights: Probabilistic Seismic Hazard Analysis

- Completion of CyberShake Study 18.8 for Northern CA [Callaghan et al. **Poster #297**]
  - Science collaboration with USGS. Needed to achieve (near) state-wide map. Useful as it provides a baseline set of results against which wto compare as we improve the modeling.
- Development of improved seismic hazard design tool *[Crouse, Jordan, Goulet #18141]*
  - Added computational capabilities making use of CyberShake results for two more design standards (ASCE41-17 and LATSDC) targetting tall buildings.
- Improving ERFs *[Field et al.* ***Poster #027****]*
- Workshops
  - *How Physics-Based Earthquake Simulators Might Help Improve Earthquake Forecasts* (June 18)
  - *Assessing UCERF3 and Planning for an Eventual UCERF4* (upcoming)




**The value of resolving UCERF3-TI & GMM epistemic uncertainties (in terms of implied fractional change in mean annual statewide loss), which should help guide research priorities** (Field *et al.*, Submitted)

# *Theme C: Characterizing Seismic Hazards*

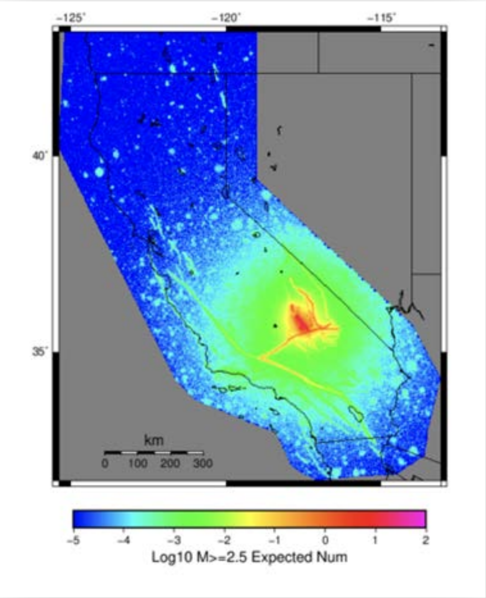
## Topic 10: Operational Earthquake Forecasting

We will conduct fundamental research on **earthquake predictability, develop physics-based forecasting** models in the new Collaboratory for Interseismic Simulation and Modeling, and **coordinate the Working Group** on California Earthquake Probabilities.

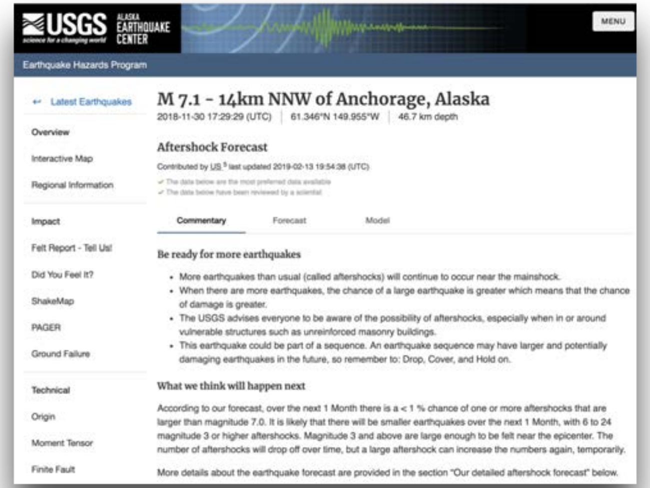
# *Highlights: OEF Progress at USGS*

- Aftershock forecasting product now delivering automatic forecasts for US M5+ earthquakes
- UCERF3-ETAS is run when needed (e.g., to inform fault-specific Ridgecrest aftershock probabilities)
- Global Aftershock Tool for Developing Countries

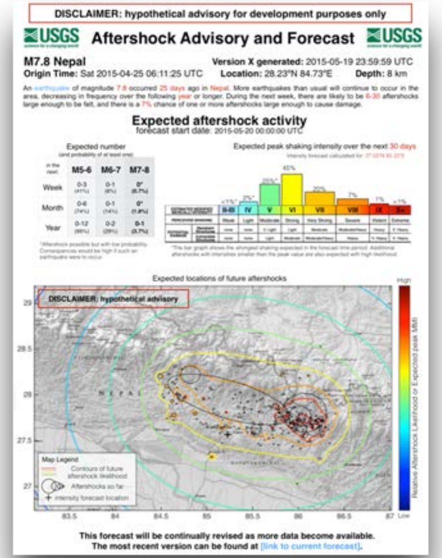
**Poster #108 Barall et al.**




UCERF3-ETAS



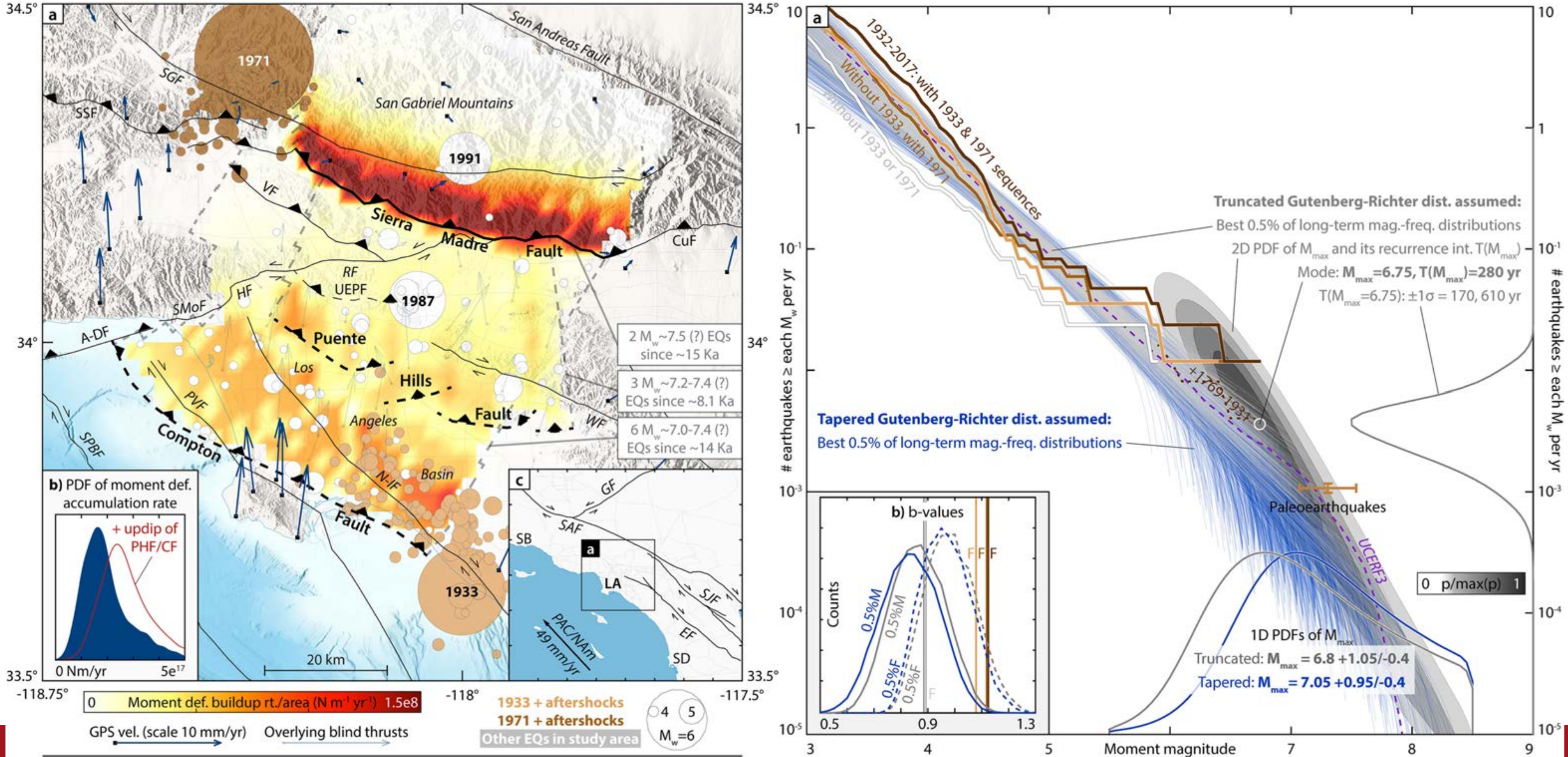

Aftershock forecasting product for M5+ earthquakes in US




Global Aftershock Forecasting Tool (Fast-ETAS)

# Earthquake likelihoods for Central LA

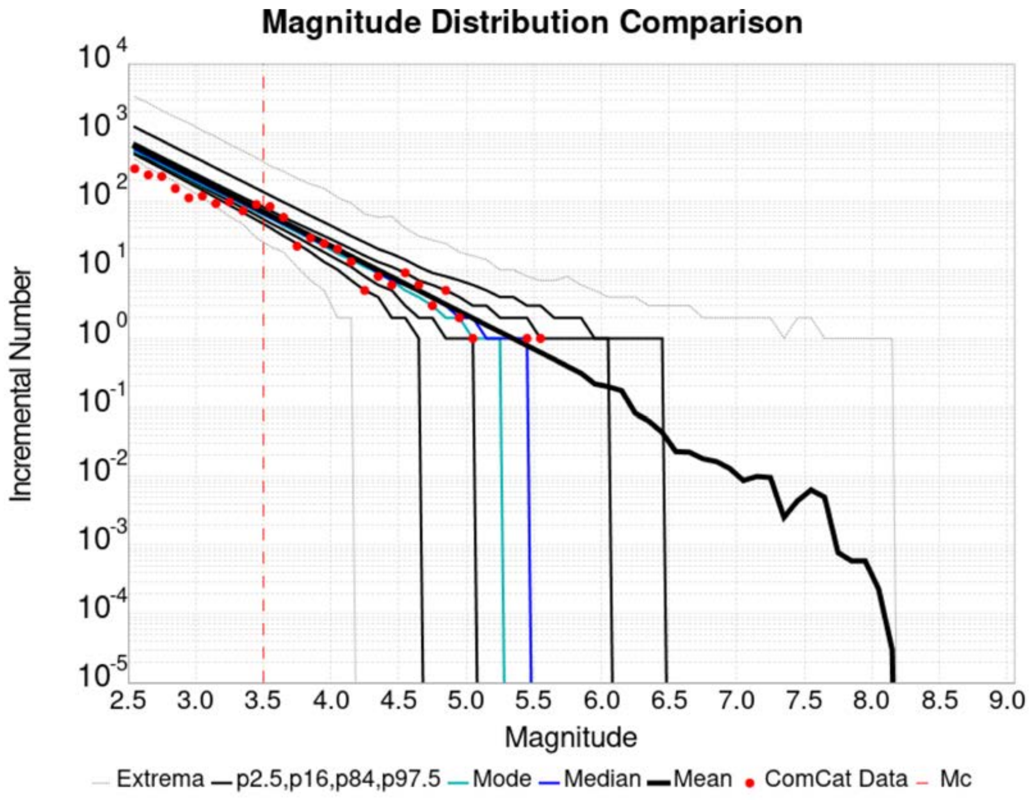
Assuming seismicity and aseismic slip balance interseismic strain, Rollins & Avouac's results imply that **"the (median) likelihood of one or more $M_w \geq 6.5$ mainshocks [in Central LA] is 0.2% in 1 year, 2% in 10 years, and 18–21% in 100 years."** **(**Rollins and Avouac, GRL, 2019)

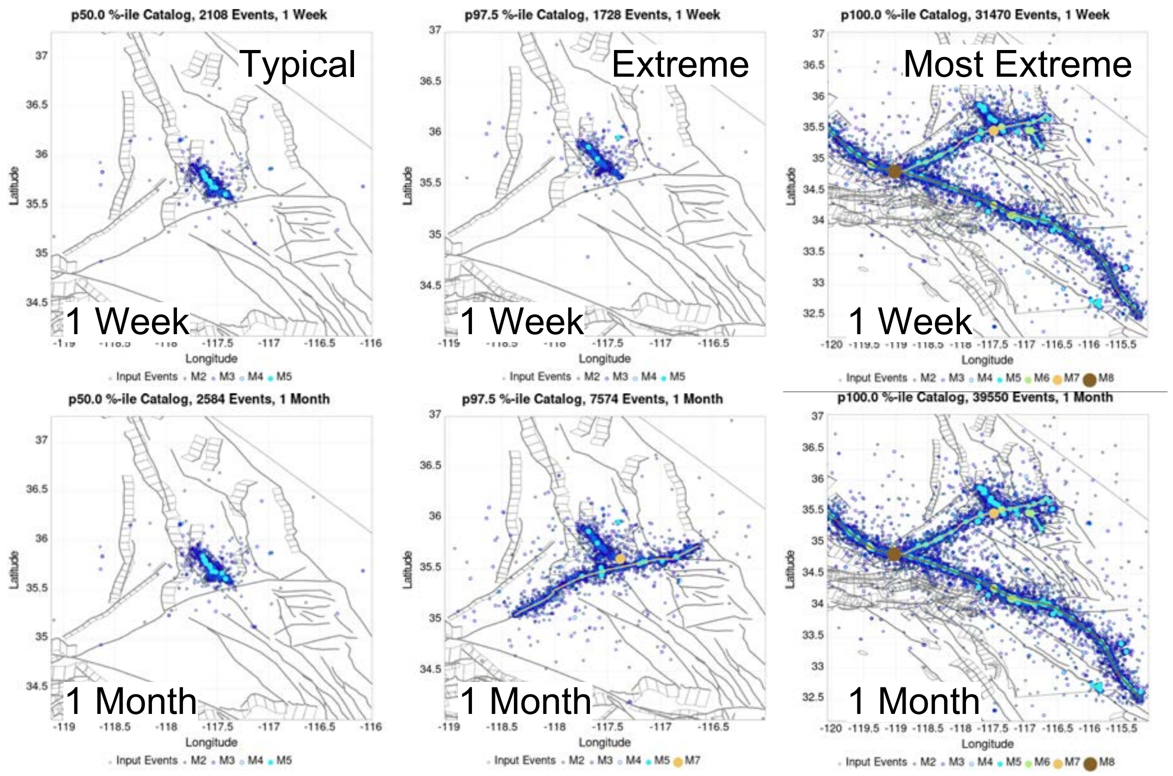


# UCERF3-ETAS Ridgecrest Simulations

**Poster #271 Milner et al.**

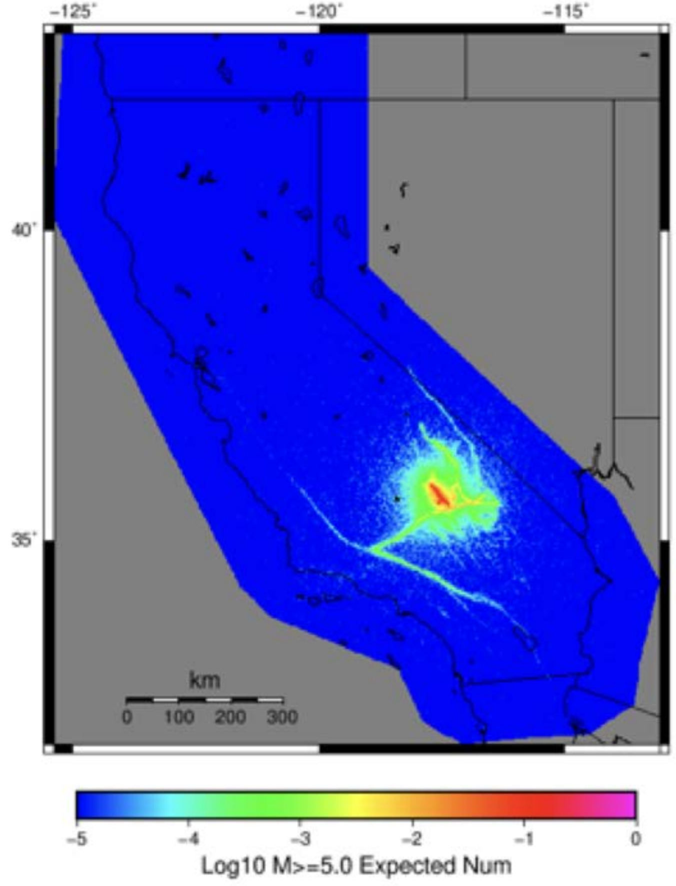
UCERF3-ETAS estimates the probability of triggering nearby faults (e.g. Garlock) after the Ridgecrest sequence. First simulation results were posted an hour after the M6.4, with many model improvements since.



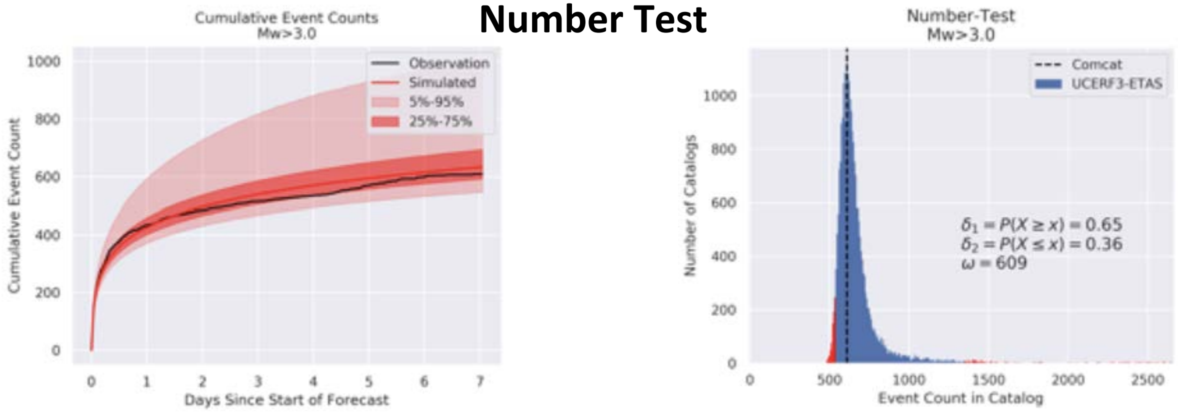



# Highlights: CSEP testing of UCERF3-ETAS

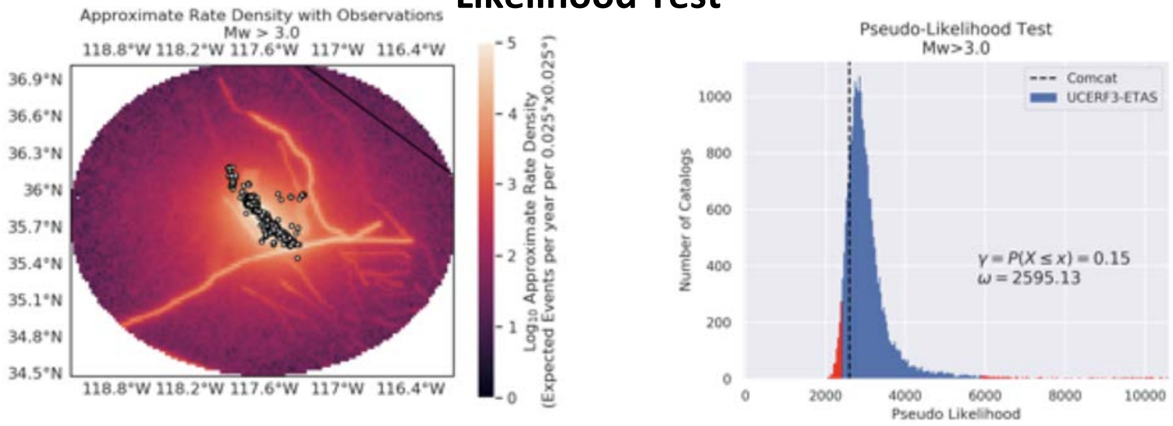
***UCERF3-ETAS Forecast Evaluations After $M_w$ 7.1 Ridgecrest*:** We developed **new evaluations** for **forecasts** that produce **synthetic** earthquake **catalogs**. We apply them to **UCERF3-ETAS** forecasts after the Mw 7.1 **Ridgecrest Eq**. In general, UCERF3 tends to **overpredict** the expected **number of earthquakes**, but the observations **fall** within the **forecasted distribution**.




**Number Test**




**Likelihood Test**

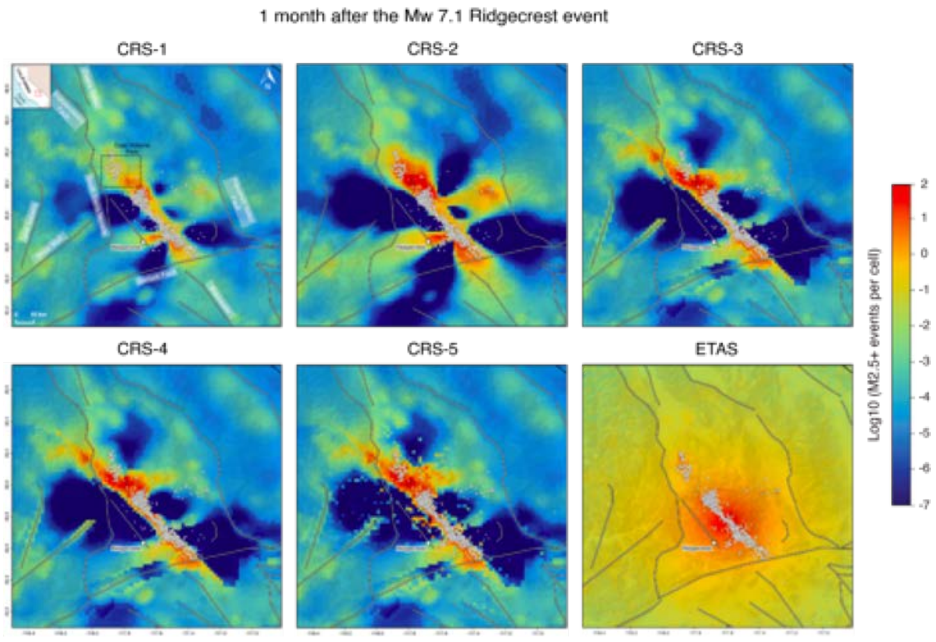


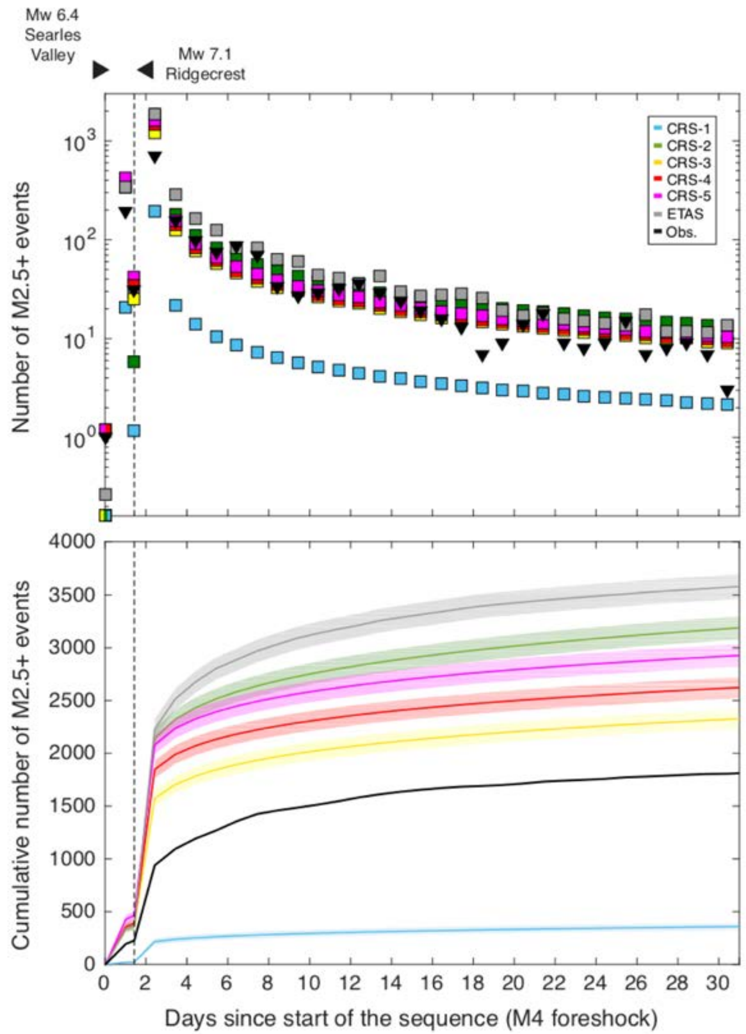

**Poster #269 Savran et al.**

# Highlights: Predictive Skill of Static Coulomb Hypothesis

**Poster #268**

- Mancini et al. investigated model & data ingredients that improve the predictive skill of Coulomb/rate-state aftershock models during the 2019 Ridgecrest sequence:
  - Secondary stress triggering, variable receiver geometry, kinematic source models
- They also calculated probabilities of UCERF faults rupturing.



# *Theme C: Characterizing Seismic Hazards*

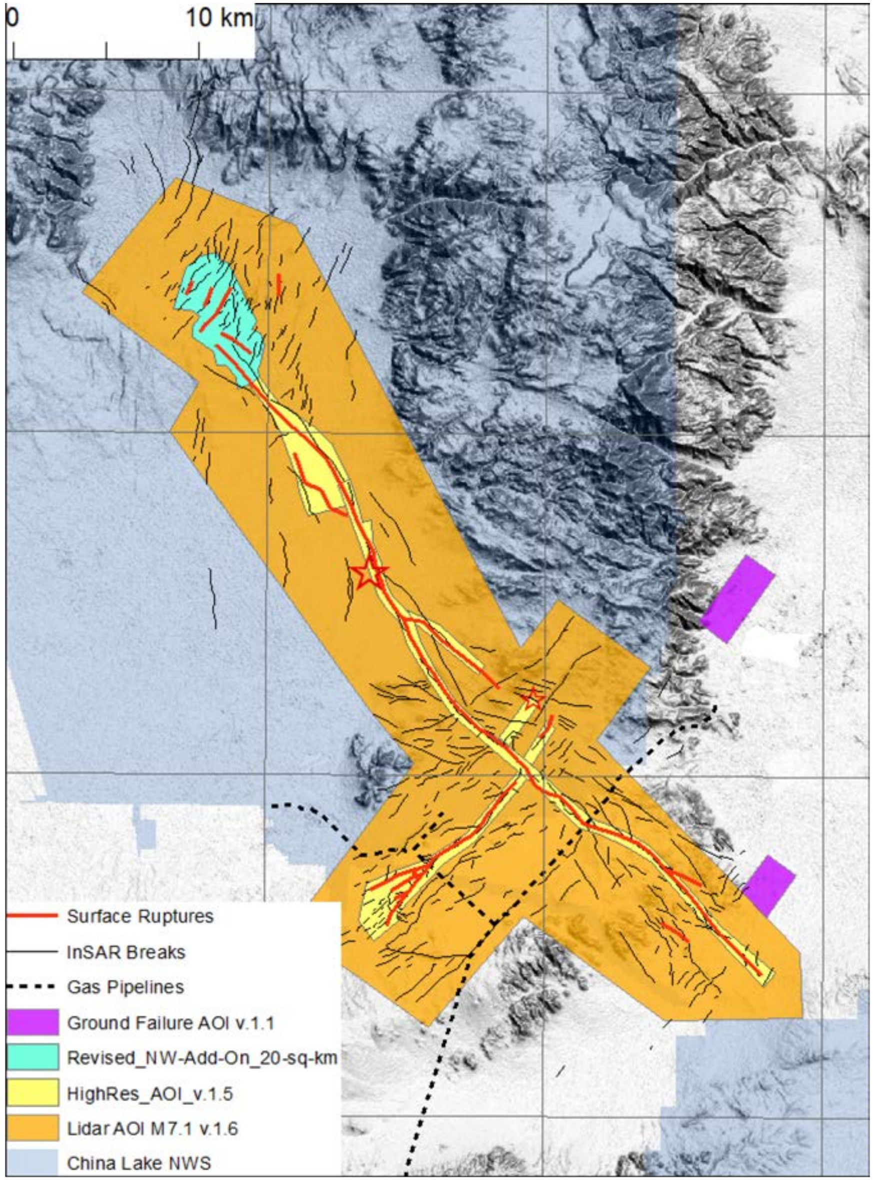
## Topic 12: Post-Earthquake Rapid Response

We will improve the rapid scientific response to strong earthquakes in Southern California through the development of new methods for mobilizing and coordinating the core geoscience disciplines in the gathering and preservation of perishable earthquake data.

# *Highlights: Post-Earthquake Rapid Response*

<u>**THIS IS NOT A DRILL**</u>

- **Ridgecrest Earthquake sequence** put our response coordination plan to the test!
- **Massive, coordinated community response** effort, with USGS, CGS, and SCEC leadership working together.
- **RAPID scientific response** instrument deployment and lidar survey supported by USGS and NSF
- Additional collaborations through GEER, CA Earthquake Clearinghouse




**Post-Earthquake Lidar Surveys:** 660 sq. km of lidar data collected less than one month after the earthquakes and prior to any significant rainfall.

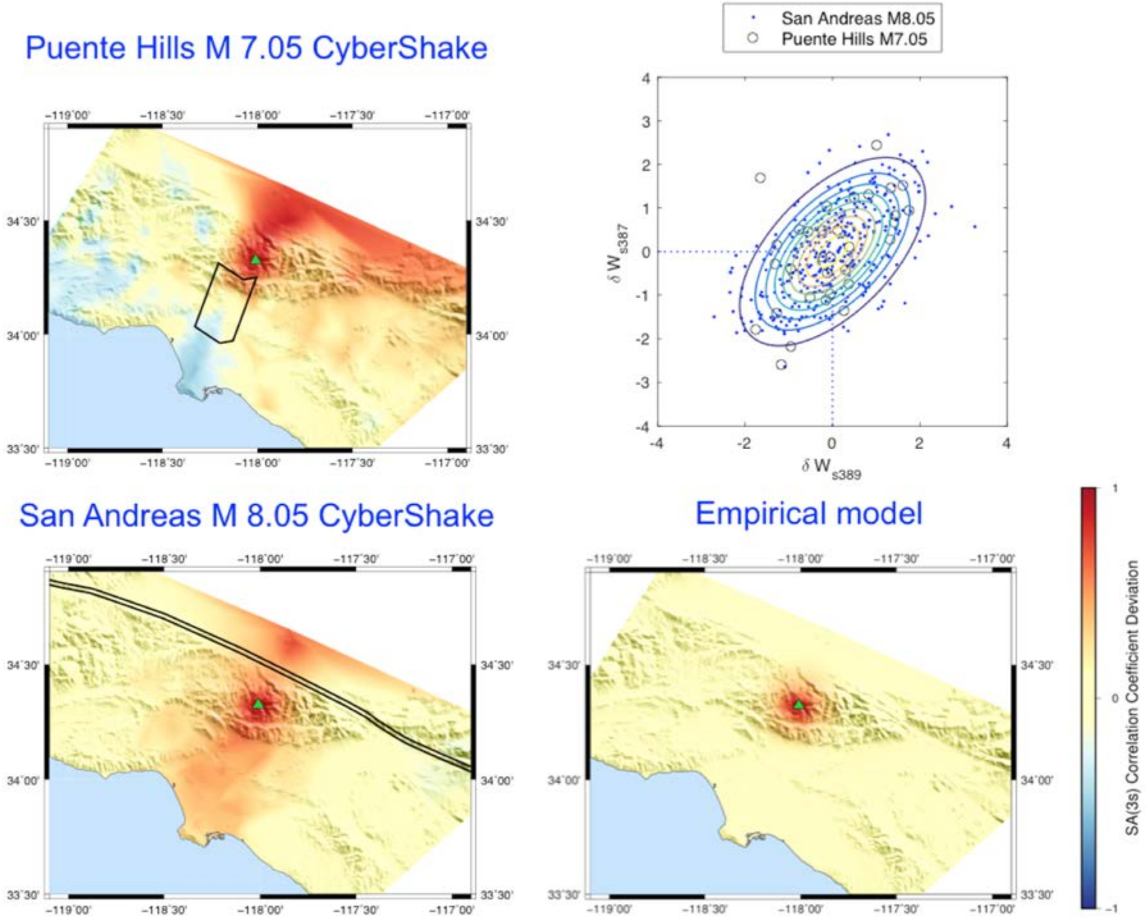
# *Theme D: Reducing Seismic Risk*

## Topic 13: Risk to Distributed Infrastructure

We will work with engineers and stakeholders to apply measures of distributed infrastructure impacts in assessing correlated damage from physics-based ground-motion simulations.

# *Highlights: Risk to Distributed Infrastructure*

- Critical issues are correlations of demands and capacities in space for a given event
- Spatial correlations of amplitudes in CyberShake simulations: comparisons with empirical data *[Baker and Chen #18033]*
  - Existing models for spatial correlations from data
  - Hybrid simulations allows study of correlation in a controlled experiment that brings along site- and region-specific information from the CVMs.
- Consultation with potential end-users to develop proposals
  - Water Task Force (LADWP, DWR, MWD)
  - Health systems (LA County Public Health; LADWP)
  - California Bay-Delta levees (CDWR)



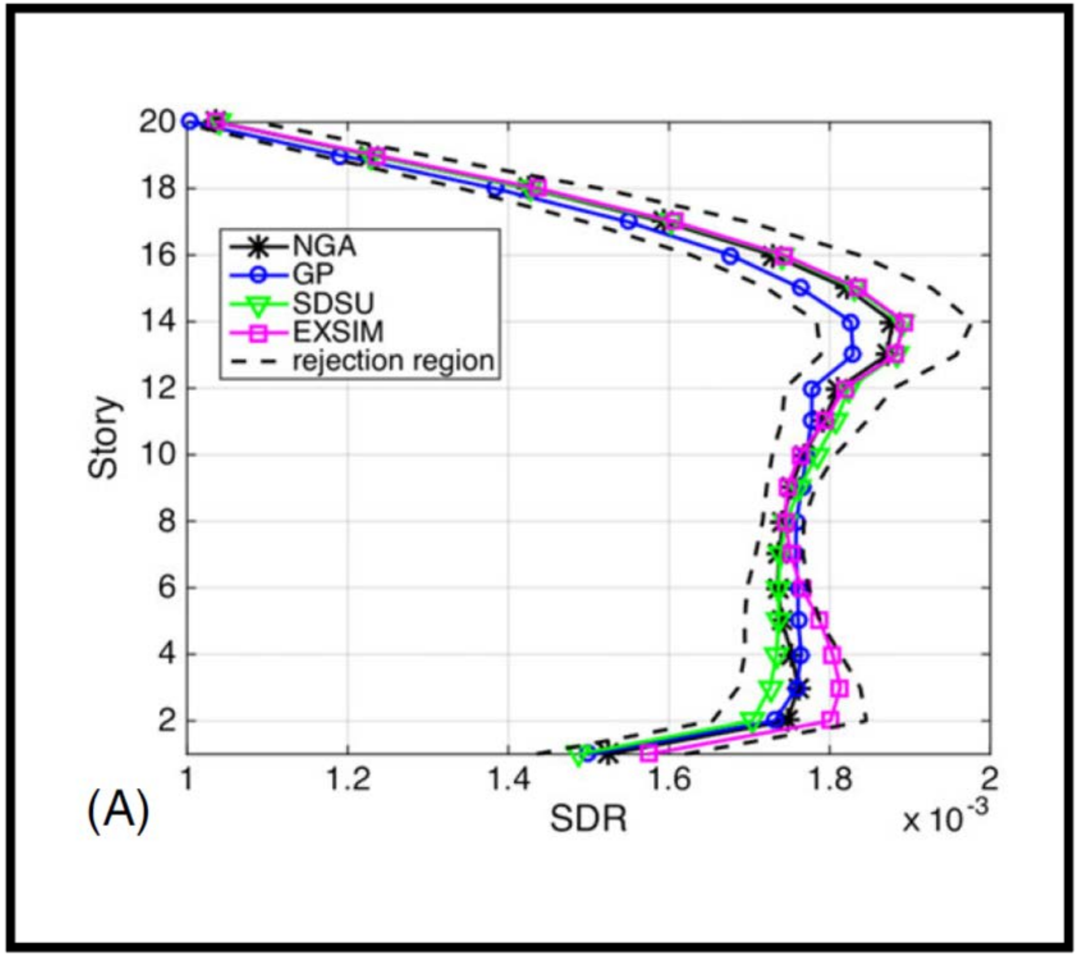

**Heatmaps of correlation coefficients of within-event residuals for PSA at 3s.** Left: results CyberShake simulations of **M** 7.05 Puente Hills and **M** 8.05 San Andreas ruptures at a reference site. Right: comparison with empirical model (Jayaram and Baker 2009).

# *Highlights: Risk to Distributed Infrastructure*

- Ground Motion Simulation Validation (GMSV) TAG [Rezaeian and Stewart #18161]. Joint simulator, GMM developer, and end-user workshop (Feb. 2018)

- Type 1 validation: GM prediction
  - Validation challenges remain (e.g., apparent over-prediction of long period motions, sigma)
  - Many needs / uses for simulations in GMM development (large M, hanging wall, subduction, non-ergodic ground motion modeling).
  - Spurred multiple proposals (e.g., FAS amplification, basin response)

- Type 2 validation: Times series analysis
  - Simulated motions used for response analysis
  - Good compatibility with recorded motions
  - White paper needed to guide application




**Story drift ratios from simulated and recorded ground motions.** (Bijelic *et al.*, 2018)

# Topic 14: Velocity and Rheology of Basin Sediments

In collaboration with geotechnical engineers, we will advance the understanding of site effects by incorporating nonlinear rheological models of near-surface rock and soil layers into full-physics earthquake simulations.

# Highlights: Imaging of Basin Sediments

**Understanding long shaking durations within the Los Angeles Basin from shallow earthquakes**
[*SCEC Award #18128, Zhan*]

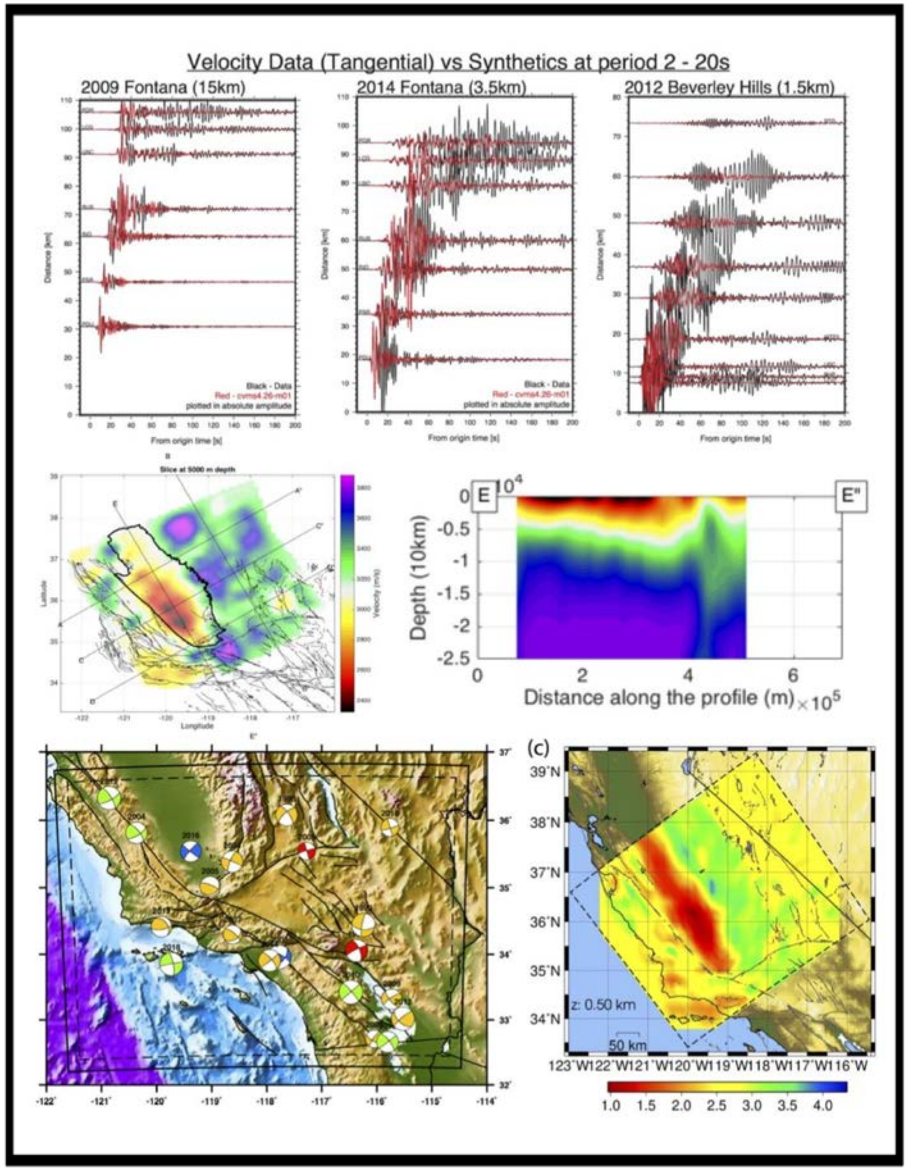
→ FD waveform synthetics with CVMS4.26-M01 are superior to CVMH15.1.0, but fail to fit 2 to 5 s, long duration signals, likely due to inadequacies in shallow structure.

**Towards 3D velocity model of central CA**
[*SCEC Award #18223, Beroza et al.* ***Poster #311***]

→ Two-step tomographic inversion of ambient noise surface wave dispersion data from many thousands of broadband station pairs, able to image very low near-surface velocities in basin areas.

**Toward full waveform tomography across California**
[*SCEC Award #18098, Tape and Thurber*]

→ Effort toward establishing an open-source workflow for tomographic updating of SCEC CVMs. To date, the work encompasses moment tensor analysis, joint inversion of body-wave and surface-wave data to improve 3D models, and meshing of models for application of SPECFEM3D.




**Basin sediment velocity.** (top) 3D synthetics at 2-20 s for 3 events showing failure to fit longer duration and higher frequency. (middle) 3D ambient noise Vs model with very low Vs near the surface in the Great Valley. (bottom) Moment tensor examples for events suitable for use in tomographic up- dating of CVMs, and example of near surface Vs from a joint inve- rsion of body wave and surface wave data..

# *Highlights: Nonlinear Rheology -- Models & Validation*

**A TAG for the Coordination of SCEC5 Research Initiatives on Nonlinear Effects in the Shallow Crust**

[*SCEC Award #18022 Asimaki & Taborda*]

→ Narrowed down goals for nonlinear sediment modeling in SCEC5: 3D implementations and validation study; 1D empirical and numerical model implementation; 3D heterogeneous model & effects

**Modeling shallow crustal nonlinearity in physics-based ground motion simulations**

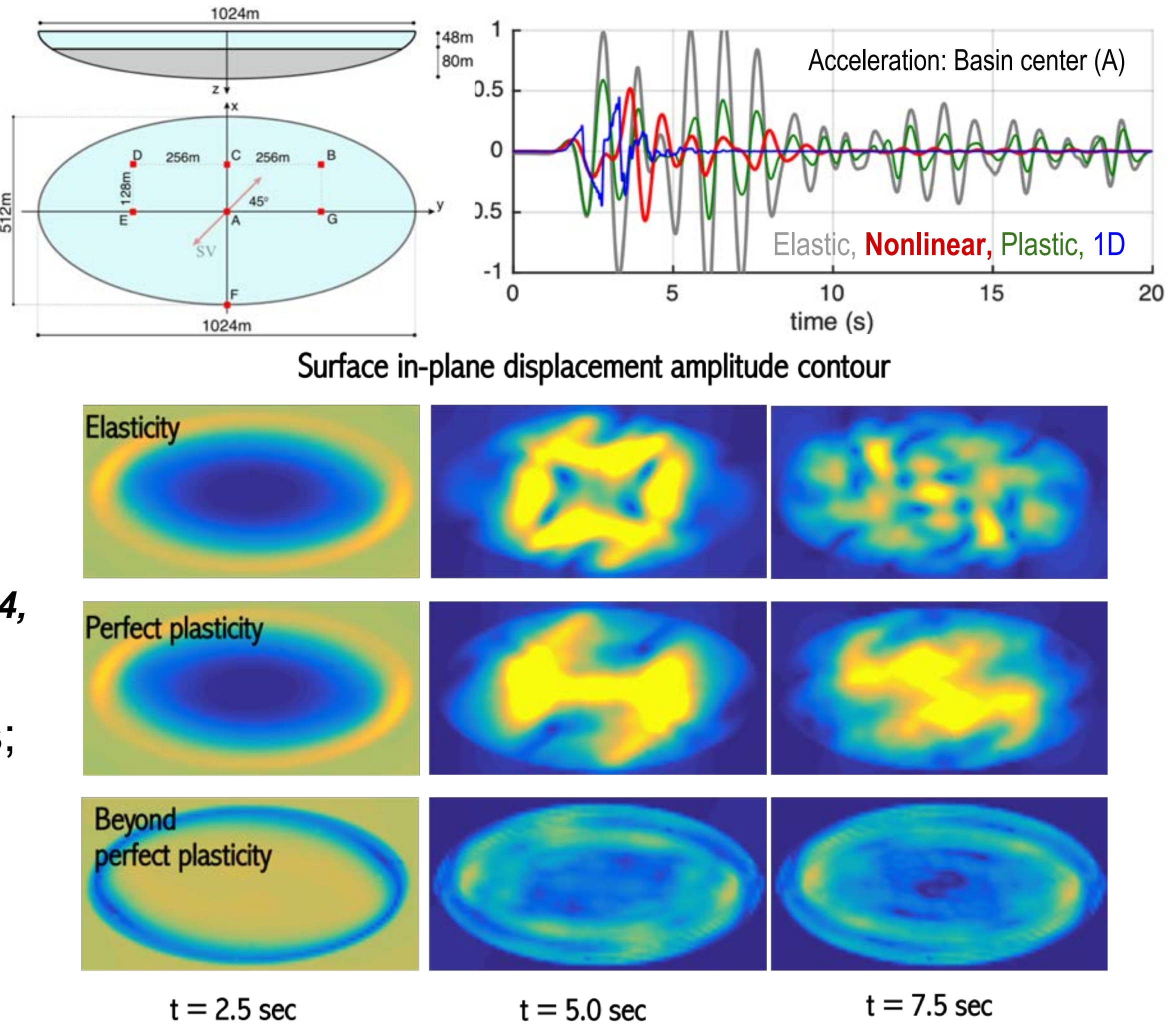
[*SCEC Award #18020 Asimaki et al.; Award #18168 Olsen et al.* ***Posters #004, #005***]

→ implemented Borja-Amies elastoplastic model in Hercules; Iwan model in AWP-OCD; verification completed; validation by comparison with recordings at GVDA in progress

**Modeling nonlinear effects in the BBP**

[*SCEC Award #18103  Arduino et al.*]

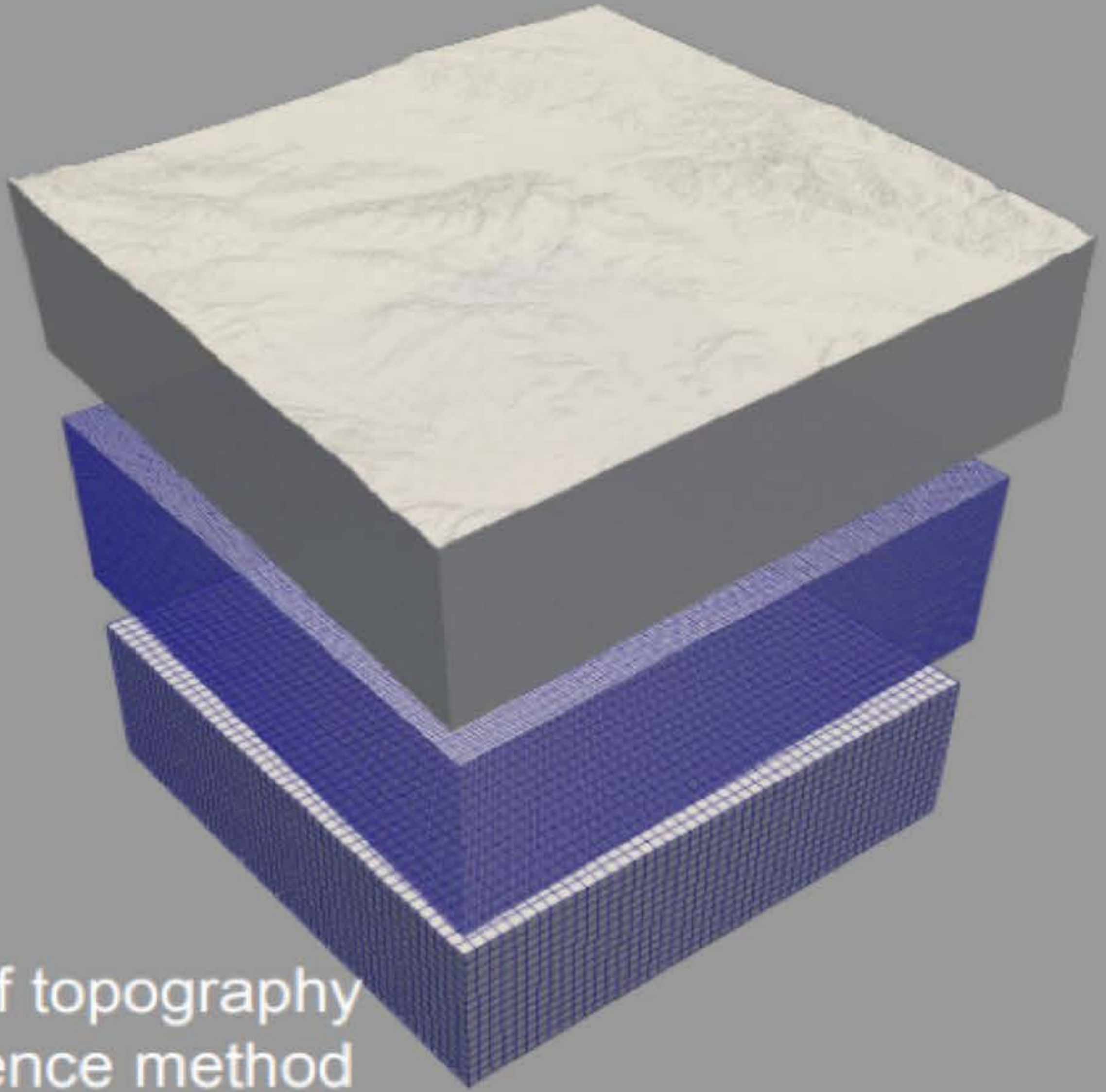
→ Development and verification of standalone site response modules based on wave propagation; empirical factors




**Nonlinear sediment rheology.** Comparison of response on the surface of an idealized 2-layer sedimentary basin (top left), evaluated using three rheology models for the shallow crust: elastic, elastic-perfectly plastic, and elastoplastic (here, Borja-Amies) (Esmaeilzadeh Seylabi *et al.*, 2018)

# Poster ID: 009

# Soon, SCEC's **PHSA** and **High-F projects** will be powered by a **GPU**-driven seismic wave propagation solver with **topography** at low computational cost



Simulation of elastic waves in the presence of topography using a curvilinear staggered grid finite difference method

Ossian O'Reilly[1], Alex Breuer, Yifeng Cui[2], Christine Goulet[1], Kim Olsen[3], Daniel Roten[3], Guillaume Thomas-Collignon[4], Te-Yang Yeh[3]

1. USC, 2. UCSD, 3. SDSU, 4. Nvidia

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# *Thank you*

(any comments or questions?)