SCEC Workshop on San Gorgonio Pass: Structure, Stress, Slip, and the Likelihood of Through-Going Rupture

Organizers: Doug Yule, Michele Cooke, David Oglesby
Date: June 1 and 2, 2012
Location: Las Palmas resort in Rancho Mirage, CA.
Participants: 33

Objective

This workshop explored the San Gorgonio Pass "knot" region as a candidate for a SCEC Special Fault Study Area and outlined a plan to fill existing knowledge gaps. Specific topics included the geometry of active subsurface faulting, the potential for earthquakes on the complex fault system in this region, and the likelihood of a 'super-earthquake' that would propagate along the San Andreas system through the pass, leading to a very large-magnitude and damaging event. The workshop brought together geoscientists from a wide spectrum of interests including tectonic geomorphology, structural geology, mechanical modeling, rupture modeling, gravity and magnetic modeling, seismology, geochronology, geodesy, and fault and rock mechanics. The first day was a blend of short science talks on case studies with discussions of specific topics. On the second day, we took a field trip to view key sites in San Gorgonio Pass.

FRIDAY, JUNE 1, 2012

10:00	Welcoming Remarks and Perspectives on Special Fault Study Areas (SFSA)	T. Jordan
10:15	Introduction and Workshop Overview	D. Yule
Session 1: Structure, Seismology, and Paleoseismology		
	Views from the Surface	
10:30	The Complex Evolution of the San Andreas Fault System	J. Matti
10:45	Primary Active Faults and Their Paleoseismology	D. Yule
11:00	Perched Boulders and Constraints on Strong Motion Shaking in the Region	J. Brune
11:15	Geochronology of Landforms	K. Kendrick
11:30	Recent Slip Rates Along the San Andreas Fault System	S. McGill
11:45	Group Discussion	
12:00	*Group Lunch*	*Salon H*
	Views from Depth	
13:00	Active Faults and Crustal Deformation in San Gorgonio Pass: The View from Below and in 3D from Seismicity	C. Nicholson
13:15	Continuity of the San Andreas fault at San Gorgonio Pass	S. Carena
13:30	Seismological Tools for Deciphering the San Gorgonio Pass Complexity	E. Hauksson
13:45	Gravity and Magnetic Data	V. Langenheim
14:00	Tests of the 'Propeller' SAF: Preliminary results from the Salton Seismic Imaging Project	G. Fuis
14:15	Group Discussion	

14:45	*Break*	

Session 2: Dynamic, Kinematic, and Mechanical Models

	Mechanical and GPS Models	
15:00	Mechanical Models of the San Andreas	M. Cooke
15:15	Modeling with San Bernardino Mountains GPS Campaign Data	J. Spinler
15:30	The Role of Fault Complexity and Secondary Faults on Fault Slip	J. Herbert
15:45	Fault Stressing Rates from GPS Block Models	J. Loveless
16:00	Group Discussion	
16:30	*Break*	
	Rupture Models	
16:45	San Andreas Rupture Models for Southern California	K. Olsen
17:00	Dynamic Rupture Simulations in San Gorgonio Pass	Z. Shi
17:15	Dynamics of Complex Strike-Slip and Thrust Ruptures	D. Oglesby
17:30	Group Discussion	
18:00-20:00	*Group Dinner*	*Salon H*

Session 3: Poster Viewing

20:00
- Shallow Seismic Data (M. Rymer)
- Cosmogenic Radionuclide Age Data from the Pass (R. Heermance)
- U-Series Age Data (K. Blisniuk)
- Continuity of the San Andreas fault at San Gorgonio Pass (S. Carena)
- Depositional Constraints on slip along the San Andreas Fault within the Eastern San Gorgonio Pass region (K. Kendrick)
- Paleoseismology of the Burro Flats Site and San Gorgonio Pass Fault Zone Sites (D. Yule)
- Geologic Map of the San Andreas Fault Zone in San Gorgonio Pass (J. Matti)
- CFM-v4: Continued Upgrades and Improvements to the SCEC Community Fault Model and Its Associated Fault Database (C. Nicholson)
- Does the Dip of the Coachella Valley Segment of the San Andreas Fault Matter? (L. Fattaruso)
- Preliminary results of the Salton Seismic Imaging Project (G. Fuis)
- Precarious Rocks and Shattered Rock Near San Gorgonio Pass (J. Brune)

22:00 *Adjourn*

SATURDAY, JUNE 2, 2012

07:00	*Group Breakfast*	*Fiesta Patio*

Session 4: Field Trip to View Key Sites in San Gorgonio Pass

08:00	*Pick up box lunches and depart from northwest parking lot*
15:00	Group Discussion: Wrap-Up and Recommendations
17:00	*Adjourn*

PARTICIPANTS: Pablo Ampuero (Caltech), Glenn Biasi (UNR), Kim Blisniuk (BGC/UC Berkeley), Jim Brune (UNR/UCI), Sara Carena (U Munich), Michele Cooke (UMass Amherst), Tim Dawson (CGS), Steve Day (SDSU), Ian Desjarlais (CSUN), Laura Fattaruso (UMass Amherst), Gary Fuis (USGS), Lisa Grant Ludwig (UCI), Egill Hauksson (Caltech), Dick Heermance (CSUN), Justin Herbert (CSUN), Tran Huynh (USC/SCEC), Tom Jordan (USC/SCEC), Katherine Kendrick (USGS), Vicki Langenheim (USGS), Jack Loveless (Smith), Jon Matti (USGS), Sally McGill (CSUSB), Craig Nicholson (UCSB), David Oglesby (UCR), Kim Olsen (SDSU), Nate Onderdonk

(CSULB), Mike Rymer (USGS), Kate Scharer (USGS), Zheqiang Shi (SDSU), Josh Spinler (U Arizona), Jennifer Tarnowski (UCR), Jerry Treiman (CGS), Doug Yule (CSUN)

Presentations are posted at: http://www.scec.org/workshops/2012/sgp/

Summary of Discussions

1. **How do we reconcile near-surface observations with subsurface evidence for active fault configuration?**
   The pattern of active faulting revealed by seismicity seems to be quite different below about 10-12 km from that expressed in the upper crust or at the surface. Furthermore, potential field data (e.g. gravity and aeromagnetic) suggest fault configurations representative of older fault strands with larger cumulative displacements than those interpreted as currently active from other data sets.

   - Additional data from a passive seismic array may help resolve some of these discrepancies and bridge the data gap. Tomographic inversions may also help reveal subsurface fault geometry where current data are lacking in the upper crust.
   - Reprocessing old seismograms (e.g. for the 1944 Kitching Peak earthquakes) may provide more insights.
   - Explore ways to evaluate the potential field data in terms of how it may reveal long-term structure vs presently active structure.
   - To what extent does the seismicity in the catalog provide a complete picture? Is the seismicity catalog representative of the longer-term geologic deformation? How do we interpret the 'gaps' in the seismic data set? For example in San Gorgonio Pass, a cloud of diffuse seismicity occurs at depth within the San Andreas fault system, yet it remains unclear as to what part of this seismicity is 'on fault' and what is 'off fault'.
   - Mechanical models of both geologic and interseismic time-scales deformation may provide tests for both shallow and deep fault geometry. For example, are existing 3-D fault models structurally reasonable, kinematically compatible, and capable of producing deformation consistent with slip rate and GPS data?
   - Data from an extensive network of water wells may help constrain the near-surface geologic structure, especially in the northern Coachella Valley and San Bernardino basin.

2. **What is the earthquake potential of faults in the San Gorgonio Pass?**
   Slip rates, slip per event and uplift rates provide critical data for assessment of earthquake potential. While the UCERF3 seeks to provide critical seismic hazard information for the state of CA, it fails to capture active deformation within the SGP because it incorporates inactive fault configurations. Furthermore, forward mechanical models show that small changes in fault geometry can produce large differences in slip rates and uplift patterns. We currently have no slip rate data between Millard Canyon (near Cabazon) and Indio Hills, a region with multiple interpretations of active fault geometry.

- Paleoseismic and tectonic geomorphologic projects can provide slip rates and slip per event across longer time spans to provide more robust analysis of slip. 'Megatrenches' may be necessary to constrain slip and event records for dip-slip (thrust) faults where fault deformation zones can be >20 m wide and vertical separation is > 2 m per event.
- On-going projects on the San Gorgonio Pass fault zone, and the San Bernardino, Mission Creek, and Banning strands will provide important constraints. More rates are needed on the Crafton Hills fault, the Garnet Hill strand and the Beaumont Plains faults.
- Holocene uplift rates can constrain off-fault deformation to provide critical information on kinematic compatibility of faults in the region. These data can also be used to test fault geometry as the mechanical models show that uplift is sensitive to fault geometry in the SGP.
- Results from 3D mechanical models that incorporate complex and accurate fault geometry can be used to provide detailed slip rates where geologic rates are not available. These can be folded into the UCERF3 to provide more accurate estimation of hazard within and around the SGP.

3. Can large earthquakes rupture through ~~the~~ San Gorgonio Pass?

Determining the rupture extent of paleo-earthquakes through the Pass is challenging. The patterns of precarious rocks and temporal correlation of slip events between trenches provide some constraints. In addition to these constraints, dynamic earthquake rupture models are an attractive tool to determine the likelihood of the SGP allowing a 'super-event' to propagate through this region of extreme fault complexity. Recent advances in numerical methodology indicate that we are ready to incorporate enough realism into such models that believable results can be obtained.

- Mega trenches within the SPG may reveal distinct slip events that can be temporally correlated to events found outside the Pass.
- Initial stresses have a controlling effect on dynamic rupture propagation and slip values, so we need data on this crucial factor. These stresses can come from the focal mechanism inversions, mechanical models or long-term earthquake simulators.
- We need accurate parameterizations of the subsurface fault geometry, with a particular need for information on the fault connectivity at depth.
- Rupture directionality (initiation location). How far north did the 1680 earthquake extend? What effect does the branching of the SAF in the Indio Hills into the Banning strand, Garnet Hill strand and the southern part of the Mission Creek strand have on rupture?
- Ground accelerations. Can a rupture scenario be consistent with the observed pattern of precarious balanced rocks?

4. **What are the useful spatial bounds of a SCEC Special Fault Study Area (SFSA) in this region?**
   It was agreed that to understand the earthquake potential of the San Andreas fault in the SGP, it is necessary to incorporate the major fault intersections NW and SE of the Pass itself. The San Gorgonio Pass SFSA would thus extend from the Cajon Pass intersection of the San Andreas and San Jacinto fault zones, to the Coachella Valley intersection of the San Andreas fault zone and the Eastern California Shear Zone , near the intersection of the Banning and Mission Creek strands of the San Andreas fault.

Potential Science Plan

An overarching objective of the research in the San Gorgonio Pass region is to answer the long-standing question: *Is a through going San Andreas rupture possible?* A definitive answer to this question has fundamental implications for forecasting the earthquake hazard in southern California. If "yes", the region can expect relatively infrequent very large earthquakes (~M_w 7.8) that rupture through the Pass and simultaneously involve the Coachella Valley, San Bernardino, and the Mojave segments; if "no", the region can expect more frequent large earthquakes (~M_w 7.4) that separately rupture on either side of the Pass region.

Related to the potential for earthquakes rupturing through the San Gorgonio Pass are several other questions. *What is the subsurface geometry of active faulting through the San Gorgonio Pass?* In order to best predict potential rupture through the San Gorgonio "knot" we need to know the active fault configuration. This question also has a significant effect on ground motion estimations in the region. *What is the earthquake potential in the San Gorgonio Pass region?* In addition to rupture length, the stress drop and slip on potential earthquake ruptures contribute to the overall energy release and consequent seismic hazard. Fault slip rates reflect the activity level of faults and have been critical in assessment of earthquake potential (*WGCEP, 2008*). A related parameter, fault stressing rates, also reflects earthquake potential and, additionally, provides initial stress conditions for earthquake physics based rupture models that simulate evolving stress drops during rupture propagation and slip. If fault geometry, stressing rates and slip rates are known, then we will be able to develop more accurate earthquake models that will in turn produce better estimates of earthquake size, earthquake interactions, ground motion, and seismic hazard.

An important discussion at the June workshop focused on deficiencies and limitations of the statewide UCERF3 model whose fault geometry, deformation and rate models, and earthquake probabilities are unrealistic in southern California because of oversimplification of the San Andreas fault geometry through the San Gorgonio Pass region. The Pass affords an opportunity to develop high-resolution alternative models and test the sensitivity of fault geometry to deformation. Factors such as partitioning of slip among faults, contribution of off-fault deformation and stress-rates may all be quite sensitive to active fault geometry through the San Gorgonio Pass. Investigation of these alternatives can illuminate which factors matter most and to what extent more realistic models affect the earthquake simulations. Designating the Pass region as a Special Fault Study Area has the potential to become a demonstration project for high-resolution earthquake simulators.

Toward answering these important scientific questions and testing the UCERF3 model we propose the following coordinated science plan for the San Gorgonio Pass as a SCEC SFSA. This science plan will be revised with input at the SCEC annual meeting. The tasks are grouped according to the three major discussion questions from the workshop.

Year 0: things that are going on right now

- A workshop was held to delineate the important scientific questions about the San Gorgonio Pass, as well as to gather together the various forms of data we have in this region.
- Perform preliminary dynamic rupture models of earthquakes in the SGP.
- Trench studies of the San Gorgonio Pass fault zone
- Geochronologic investigations of displaced Quaternary landforms
- Relocate seismicity and revise earthquake focal mechanisms. Examine the patterns of hypocenters and nodal plane alignments in 3D to resolve the geometry of active principal slip surfaces.
- 3D Mechanical modeling of alternative active fault geometries
- Campaign and continuous GPS data acquisition

Year 1-2: Many of these are multi-year efforts to be started in Year 1 that will continue in subsequent years

- *Question 1: How do we reconcile deep and shallow structure? What is the active 3D structure?*
    - Use existing seismic array to invert for subsurface fault geometry, provide suggestions for future station siting and compose NSF proposal for 3-year project to implement passive seismic array for high-resolution study of the SGP.
    - Develop interseismic models that incorporate the active fault structures revealed by microseismicity below 10 km and test the results against those from intersiesmic models that incorporate faults structures based on surface trace geometry.
    - Reprocess old seismograms (for example, 1944 Kitching Peak events). Another look at old events (e.g., 1948 Desert Hot Springs event, 1947 Morongo Valley event, other pre-1986 N Palm Springs events) may yield new insights.
    - Collect information from existing water wells or other industry well data to help constrain sub-surface geology
    - Develop of a high resolution San Gorgonio Pass Fault Model (SGP-FM), an alternative to and more detailed version of the UCERF3 model for active fault

structures in SGP (Pass is a 'C' zone within simple geodetic block model). This can be initiated with existing data,

  - Test what factors matter and what specific region refinements might do.
  - The database should provide tags for the source data for each fault surface.
  - Test whether complex models cause issues with the earthquake simulator

- *Question 2: What is the earthquake potential?*
  - Gather existing dates for Quaternary geomorphic surfaces, compile uplift rates from available LiDAR data compare to uplift patterns from existing mechanical models and provide recommendations for further dating and model refinement (also for question 1)
  - Collect campaign GPS data from available sites and establish additional benchmarks in regions to test multiple fault interpretations.
  - Refine ground motion model for northern Coachella Valley
  - Develop crustal deformation models to validate the existing earthquake catalog. These investigations may compare focal mechanisms or inferred stresses from the focal mechanisms.
  - Incorporate slip rate data from detailed 3D mechanical models of the SGP into the larger UCERF models for all of CA.

- *Question 3: Can rupture pass through the SGP?*
  - Trench the Garnet Hill (at Garnet Hill) and Banning strands to constrain the northern extent of the ~AD 1680 event in the Coachella Valley (did this rupture reach the Pass region?). This work can also provide much needed slip rates for northern Coachella Valley region (question 2)
  - Collect megatrench data on thrust slip events, slip rates and correlate these data to earthquake events outside of the Pass
  - Use existing data (e.g. focal mechanism) to test SHmax as rupture models results depend strongly on pre-stress pattern on fault.
  - Prepare rupture models to tackle the geometry of active faulting in the SGP. Issues include 1) the step from the San Gorgonio Pass Fault zone to the San Bernardino strand 2) the branching of the Mission Creek, Garnet Hill and Banning strands from the Coachella Valley segment of the SAF and 3) the Crafton Hills fault.
  - Investigate the electrical structure within the SGP. Fluids could be very important for facilitating rupture and electrical or deep seismic reflection are the tools that help us examine whether fluids are present.

Years 3-4:

- *Question 1: How do we reconcile deep and shallow structure? What is the active 3D structure*

- Dating of additional deformed surfaces using a variety of methods to provide uplift rates in regions that mechanical models reveal as particularly sensitive to alternative fault interpretations. (also question 2)
- Testing of the SGP-FM with crustal deformation models, earthquake simulators and rupture models and suggestions for subsequent revisions.
- Tag faults within the SGP-FM database for how well they match independent data sets within various model investigations. The resulting database will contain the fault surface, the source that produced this interpretation, and some validation on whether models using this surface match independent datasets.

- *Question 2: What is the earthquake potential?*
  - Refine alternative fault configurations within the high-resolution SGP-FM and report results of comparison with UCERF3 model results,

- *Question 3: Can rupture pass through the SGP?*
  - Earthquake simulator models using detailed fault configuration can provide initial stress conditions for rupture scenario models.
  - Compare the results from rupture models with correlations from paleoseismic data (do models support rupture scenarios permitted by paleoseismic data?).
  - Refinement of rupture models to better incorporate observations from trench sites.
  - Test rupture models that generate accelerations small enough to permit the interpreted pattern of ground shaking revealed by the distribution of precarious rocks.

- Produce publications related to fault structure, earthquake potential, and the likelihood of through-going rupture in the SGP.