Workshop Proposal: Developing, Testing, and Using SCEC's Community Rheology Model

Conveners: Laurent Montesi and Elena Miranda

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Location: Kellogg West Conference Center, Pomona, CA

SCEC Award: 22109

Website: https://www.scec.org/workshops/2023/crm

Workshop summary

The SCEC5 research objectives featured an enhanced focus on community model development, including the Community Rheology Model (CRM). The first release of the CRM (Hearn et al., 2020) contains rheological flow laws to describe the ductile creep of the various rock types that are present in the Southern California crust. In combination with the CTM (Thatcher et al., 2020) and assuming a strain rate, these flow laws make it possible to define an effective viscosity at each point in the Southern California lithosphere (Hearn et al., 2021), which can then be used in a variety of projects, such as the calculation of long-term stress transfer and possible postseismic creep transients.

As the level of maturity of the CRM grows, it is important to give the community interested in contributing to and using the CRM opportunities to meet and discuss the features and functionality of the model. To achieve these goals, a small group of investigators met in Pomona, CA, for a day of in-depth discussions facilitated by short presentations. The participants were selected based on their involvement in SCEC projects and to include a broad range of perspectives on the CRM project. The one-day workshop was followed by a field excursion to Cucamonga Canyon to observe geological structures that reveal the modes of deformation of the lower crust and to provide further opportunities to initiate collaborations.

Feedback from participants was recorded in a collaborative *Google Doc*. The priorities of the CRM working group and the community over various time scales were discussed in a live session. The results have been documented and will be used to refine SCEC research objectives. Major findings are presented below.

Findings

Session 1: Current Status of the CRM

- The CRM is part of a family of community models that constitute the CXM. All are accessible at https://scec.org/research/cxm. A growing number of models can be accessed through interactive web interfaces.
- The CTM provides definitions of geotherm in various heat flux provinces throughout Southern California. Each geotherm is defined based on a surface heat flux (using the SMU Geothermal Laboratory database), radioactive heat production assumed to contribute 40% of the surface heat flux, and seismic constraints on crustal thickness and Lithosphere-

Asthenosphere Boundary (LAB) depth. Most models correspond to 1D steady-state solutions, but several include transient effects because the range of LAB is much less than the range of surface heat flux. The audience suggested using layered models of the crust or adding constraints from xenoliths.

- Laboratory-derived flow laws must be compared with geological observations to ensure they are relevant to natural conditions. Grain size, which adjusts to stress, provides a basis for comparison. However, the effects of stress cycles produced, for example, by earthquakes, are not yet fully understood. Low-temperature creep and pressure solution creep flow laws are difficult to characterize in the lab.
- The CRM provides a definition of the rheology of each lithology that appears in the Geological Framework using a mixing rheological relationship, the mineralogical assemblage that defines this lithology, and selected mineral flow laws. It makes it possible for users to use the full non-linear flow law or define effective viscosities based on the desired usage. Approximations to shear zone rheologies are based on alternative mixing theories. The audience suggested adding petrological phase equilibrium relationships.
- Shear zones were described as an important component of the CRM but are associated with much uncertainty, such as: Is the mineralogical assemblage of a shear zone the same as that of the protolith? How do different wall rock types mix in the shear zone? How wide are shear zones under mature and juvenile faults? How do transient events, including melt infiltration and pseudotachylite formation, influence shear zone rheology? Fieldwork is crucial to understand shear zone rheology, but exposures are limited. Nevertheless, once tectonically restored, the Tumamait, Alamo Mountain, Cucamonga, and Eastern Peninsular Ranges shear zones form a continuous belt that reveals shear zone architecture at 10 to 15 km depths.

Session 02: Future CRM developments

- *Alexis Ault – The importance of rheology on on-fault and off-fault damage*. Earthquake processes are the center of a Venn diagram comprising seismology & geodesy, exhumed faults, and deformation experiments. Outcrops of the Southern San Andreas Fault reveal how damage around faults is distributed. Hematite helps with dating deformation, is sensitive to redox conditions, and is involved in slip surfaces. Adding to the CRM, the rheology of shallow faults requires characterizing fault structures from the field and the lab.
- *Nick Beeler – A brittle rheology model?* The CRM currently lacks the upper crust, with is brittle. Defining brittle rheology is more complex than just assuming friction, as issues of fault roughness, shear zone width, and damage zone width need to be addressed. The importance of morphological gradients, discontinuities, segmentation at depth, and possible ductile processes in the fault zone, such as solution transfer mechanisms, must be evaluated.
- *Billy Shinevar - Integrating the CVM into the CRM.* Composition and temperature control viscosity in the lower crust. Alternative temperature models need to be considered and evaluated with numerous datasets, such as seismic velocity. Considering both Vp and Vs from tomographic inversions can make it possible to unravel the tradeoffs between composition and temperature.
- *Sylvain Barbot - Mantle flow distribution beneath the California margin.* Strain at depth can be constrained by seismic anisotropy, gravitational gradient models, interseismic

deformation models, and strength profiles. Geodetic data is sensitive to plastic deformation at depth but filtered through the elastic upper crust and locked faults. Deformation models predict long-term strain components, large-scale rotation across Southern California, and the history of activity of Eastern California Shear Zone faults, which used to be more active than today but have been pushed out to the East.

- The open discussion covered the need to integrate various CXM components, for example linking the boundaries of GFM blocks to the CFM or using the CVM in relation to the GFM and the CTM. Including faults requires defining conceptual models, including creeping segments and off-fault damage. New developments of the CRM could also consider a physics-based approach that includes self-consistently the long-term deformation field and thermodynamics equilibrium.

Session 03: Using The CRM

- *Bill Holt: Crustal architecture across Southern California and its implications on San Andreas Fault development*. The rheology of the crust and mantle is the key to linking geologic history to dynamic processes such as metamorphic core complexes, landscape evolution coupled to dynamics, and consideration of GPE. Vp/Vs is relative to composition and is inversely related to strain rate, which may indicate lithology-based differences in rheology. Finite Element models confirm that strain rates are controlled by compositional anomalies. Zones of thicker intermediate composition are locations of predicted lower-crustal flow, although strain rates in Southern Salton Trough are controlled by thermal anomalies.
- *Roland Burgmann - Can post-Ridgecrest deformation reveal heterogeneous California rheology?* The postseismic deformation following the Landers and Hector Mine earthquakes can be explained by a 1-D model with transient and steady-state rheology. After the Ridgecrest earthquake, the far-field stations show transient deformation. The direction of displacement is scattered but includes systematic directions of motion. Variations in rheology can also be explored using hydrological signals. Lake, rivers, snow, and mining create a forcing term for periodic loading of the asthenosphere. As a result, a measurable phase shift can be found between the geodetic seasonal signal and the load, up to 0.25 years.
- *Laurent Montesi - Temperature variations at the base of the seismogenic zone throughout Southern California*. The depth to which earthquakes are possible may be controlled by the brittle-ductile transition or by a temperature-controlled transition to stable sliding. The depth at which earthquakes in the SCSN catalog stop is converted to temperature using the CTM. Preliminary results show that earthquakes persist to higher temperatures in more active regions, as might be expected if they are controlled by the brittle-ductile transition. A comparison with CRM-derived strength profiles is warranted.
- *Nikki Seymour - Rheology: view from the field.* Northern Chile is traversed by the Atacama fault, with many outcrops showing mylonitic shear zones with occasional brittle overprint. The same lithology is found away from plutons, but there is no mylonitic shear zone. There are abundant fluids, as shown by common hydrothermal tourmaline. In Northern Chile, quartz accommodates the strain in lower-strain rocks. Its rheology changes from dislocation to diffusion creep as the rock becomes increasingly polymineralic.

Session 04: Wrap up.

Themes that appeared during the discussions and various suggestions on how to further develop the CRM were compiled in a summary table and projected for all to discuss. Each theme was given a level of priority as follows:

First-priority topics (next year)

- Provide guidance on shear zone locations, widths, and rheology
- Compare and update the GFM using the CVM
- Develop CTM2.0 so that it is consistent with the CVM, GFM, and seismicity

Second-priority topic (next two years)

- Discuss the mineralogy of ductile shear zones and possible temporal variations
- Update the GFM with considerations of thermodynamics equilibrium, petrography, gravity, and melt (Electromagnetic techniques)
- Consider the importance of shear heating for the CTM.
- Add diffusion creep and anisotropy to the ductile flow laws.

Medium-term priorities

- Incorporate fault properties, including location, width (damage zone), and rheology
- Consider off-fault behavior, determining if it is brittle or ductile, where it is important, and how it relates to the off-fault fabric.
- Add transient creep formulations to the CRM

Long-term priority

- Use the CRM in earthquake cycle models.

In addition, workshop attendees emphasized the importance of testing the CRM using geodynamic flow models and geodetic signals, including postseismic deformation and hydrological loadings.

Field Trip

The second day of the 2023 SCEC Rheology Workshop featured a field trip to local exposures of shear zones that were exhumed by deformation along the San Andreas Fault System. The field trip was led by co-leaders Elena Miranda and Josh Schwartz (both CSUN), and featured exposures of rocks in Cucamonga Canyon, near Rancho Cucamonga. The morning of the field trip was dedicated to a traverse through the Cucamonga mylonites (lower crust), and the afternoon included a planned traverse through key exposures in the Black Belt mylonites (middle crust). Field trip participants were issued printed field guides that featured an overview of the geology in the SE corner of the San Gabriel Mountains and provided geologic context for both the Cucamonga and Black Belt mylonites.

The Tuesday morning north-to-south traverse included three stops that demonstrated the compositional diversity of host rocks to the granulite facies Cucamonga mylonites and the variation in mylonitic fabric intensity with increasing proximity to the Quaternary Cucamonga Fault. Stop #1 featured a garnet gneiss and charnockite, where gneissic and mylonitic foliation is complexly folded but generally oriented with SE strikes and moderate dips to the SW. Stop #2 featured a mylonitic tonalite and garnet-bearing mafic gneiss. On the approach to Stop #3, participants noted the increasing intensity of mylonitic fabric development and near-complete

transposition of folds into parallelism with mylonitic foliation. Stop #3 showed where Cucamonga mylonites are cut by a splay of the Quaternary Cucamonga Fault and its gouge zone.

The planned Tuesday afternoon traverse through the Black Belt mylonites had to be canceled due to inclement weather and the wash-out of the access road from winter storms. Instead, the field trip leaders set up a projector-enabled petrographic microscope and hand sample lab at the Kellogg West Conference Center to show field trip participants the oriented hand samples from two of the planned field trip localities within the Black Belt mylonites and the thin sections derived from those samples. The hand samples corresponding to the three localities of the morning field trip through the Cucamonga mylonites were also brought to the lab. The field trip leaders pointed out key deformation textures of the mylonites with the projector screen images from the petrographic microscope and with the hand samples.

Workshop Agenda

MONDAY, FEBRUARY 27, 2023		
09:00 - 09:30	Breakfast	
9:30 - 09:45	**Session 0: Workshop objectives and SCEC update**	*Montesi, Huynh*
09:45 - 12:00	**Session 1: Current Status of the CRM**	
	Status of the SCEC Community Models (CXM)	*Montesi*
	Community Thermal Model (CTM) Update	*Thatcher*
	Perspectives on Lithosphere Rheology through Integration of Experimental Rock Mechanics with Geological and Geophysical Observations	*Hirth*
	Community Rheology Model (CRM) Update	*Montesi*
	The Importance of Shear Zones for the CRM	*Miranda*
	Discussion: feedback on current product and publication plans	
12:00 – 13:00	Lunch	
13:00 – 15:00	**Session 2: Future CRM Development**	
	Importance of the rheology of shallow on- and off-fault damage	*Ault*
	A “Brittle” Rheology Model?	*Beeler*
	Integrating the CVM constraints into CTM/CRM	*Shinevar*
	Mantle flow distribution beneath the California margin	*Barbot*
	Open Discussion	
15:00 – 15:30	Break	
15:30 – 17:00	**Session 3: Using the CRM**	

	Crustal architecture across Southern California and its implications on San Andreas Fault development	*Holt*
	Can Post-Ridgecrest Deformation Reveal Heterogeneous California Geology?	*Bürgmann*
	Temperature Variations at the Base of the Seismogenic Zone in Southern California	*Montesi*
	Rheology: View from the field	*Seymour*
	Discussion: Seed ideas for SCEC and other proposals	
17:00 – 17:30	**Session 4: Wrap-up**	
	Discussion on prioritization, call for volunteers, SCEC request for proposals	
17:30	Adjourn	
18:00	Group dinner	

TUESDAY, FEBRUARY 28, 2023		
07:00 – 07:30	Breakfast for participants lodging at KWCC	
08:00	Vehicles depart from KWCC and Pasadena	
09:00 – 17:00	**Cucamonga Canyon excursion**	*Miranda, Schwartz*
	Vehicles arrive at the first field locality at the eastern edge of Cucamonga Canyon. Cucamonga Foothills Preservation Alliance (CFPA) will open the gate for the vehicles to access. *First set of field stops*: Cucamonga mylonites near the Cucamonga Thrust Lunch on site *Second set of field stops*: Black Belt mylonites, further upstream of the Cucamonga mylonites.†	
18:00	Group dinner	

Workshop Participants

†Field trip only; ‡Workshop only; * CRM working group member

Alexis Ault‡	Utah State University
Sylvain Barbot	University of Southern California
Nick Beeler	USGS
Roland Bürgmann‡	University of California Berkeley
Greg Hirth*	Brown University
Bill Holt	Stony Brook University

Tran Huynh	University of Southern California /SCEC
Devin McPhillips†	USGS
Elena Miranda*	California State University Northridge
Laurent Montesi*	University of Maryland
Carolina Ortiz Guerrero†	California State University Northridge
John Platt†	University of Southern California
Josh Schwartz†	California State University Northridge
Nikki Seymour	Occidental College
Billy Shinevar	University Colorado
Wayne Thatcher‡	USGS

Figure 1: The participants to the formal workshop gathered in the Kellogg West Conference Center.

Figure 2: The field excursion party in Cucamonga Canyon.

Figure 3: Discussion of microstructures from the Black Belt Mylonites.