Toward Development of a SCEC Community Rheology Model

Report for SCEC Award #15147
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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The SCEC Community Rheology Model (CRM) workshop was held on Saturday September 12, 2015 in Palm Springs. This day-long workshop was by invitation only, with 25 participants, to encourage an engaged and participatory group. The workshop began with an overview of the CRM including a summary of work done to date and goals of the workshop. Three science sessions followed, dealing with constraints on rock type and rheology from seismic investigations (led by Gary Fuis), constraints from exhumed rocks and laboratory deformation tests (led by Greg Hirth), and constraints from numerical models of deformation (led by Yuri Fialko). A final, wrap-up session included brief summaries from the science sessions and open discussion on priorities and plans for the CRM during the final year of SCEC4 and SCEC5. A summary of the workshop and the workshop program are included in the technical report, and the workshop website (with names of participants, and PDF files of presentations) is at *https://www.scec.org/workshops/2015/crm*.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Seismology
Tectonic Geodesy
Earthquake Geology
Computational Science
Unified Structural Representation (USR)
Fault and Rupture Mechanics (FARM)
Earthquake Forecasting and Predictability (EFP)
Ground Motion Prediction (GMP)
Southern San Andreas Fault Evaluation (SoSAFE)
Stress and Deformation Through Time (SDOT)
Community Modeling Environment (CME)
Working Group on California Earthquake Probabilities (WGCEP)
Collaboratory for the Study of Earthquake Predictability (CSEP)
Central California Seismic Project (CCSP)
Ground Motion Simulation Validation (GMSV)
Aseismic Transient Detection
Source Inversion Validation (SIV)
Dynamic Rupture Code Validation
Earthquake Simulators.
Communication, Education, and Outreach

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

NA

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

1b, 1e, 2d

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

NA

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

NA

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.
NA - workshop proposal.

II. Technical Report

The technical report should describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the report. (Maximum 5 pages, 1-3 figures with captions, references and publications do not count against limit.)

A. Report

The SCEC CRM workshop was held on Saturday September 12 in Palm Springs. This day-long workshop was by invitation only, with 25 participants, to encourage an engaged and participatory group. The convenors (and PI's) were Liz Hearn (Capstone Geophysics), Wayne Thatcher (USGS), Yuri Fialko (Scripps), Greg Hirth (Brown), Gary Fuis (USGS) and Thorsten Becker (USC). The workshop began with an overview of the CRM including a summary of work done to date and goals of the workshop. Three science sessions followed, dealing with constraints on rock type and rheology from seismic investigations (led by Gary Fuis), constraints from exhumed rocks and laboratory deformation tests (led by Greg Hirth), and constraints from numerical models of deformation (led by Yuri Fialko). A final, wrap-up session included brief summaries from the science sessions and open discussion on priorities and plans for the CRM during the final year of SCEC4 and SCEC5. The workshop program is attached and the website (with names of participants, and PDF files of presentations) is at https://www.scec.org/workshops/2015/crm.

Rather than reiterate who spoke about what and when, which is clear from the workshop program, this report summarizes topics of the presentations that were most pertinent to development of the CRM, and the major points made during the (often lively) discussions from each session.

Seismic and Geologic Constraints on Rock Type

Gary Fuis pointed out the need for active source experiments to better delineate rock types in the southern California upper crust. Reverse moveout reflectivity was offered as a technique to better identify vertical (or at least, not sub-horizontal) reflectors and hence material contrasts. The importance of mid-crustal low-velocity zones at 16-20 km depth was pointed out in the discussion, as were uncertainties as to their cause (possibly, overpressured fluids). The effect of water saturation on seismic characteristics of shallow rocks was outlined by Rufus Catchings, and participants suggested that the CRM might need to link with a SCEC Community Hydrological Model at some point. There was much discussion of b-values vs. depth and how this could link to stresses, but this discussion was cut short to keep the focus on the CRM; it may be pertinent to the CSM. Tools for inferring rock type from Vp, Vs, and Vp/Vs to rock type were presented by Gary Fuis, and he showed examples of their use. Participants pointed out that this method is not vetted for the middle crust or below. Water saturation and temperature could also affect this method's utility. It was pointed out that in general, seismic studies do a poor job of imaging the velocity structure of the lower crust. Also, the propellor-like geometry of the SAF was mentioned, and mismatches with the SAF as represented in the USR were noted. For a CRM, the SAF (where it juxtaposes different rocks) must have the same geometry it has in the USR.

Rheology from Laboratory and Rock Microstructure Studies

Greg Hirth pointed out that mixing laws are required to characterize the rheology of rocks because most flow laws are for monomineralic rocks (e.g., Shinevar et al., 2015). Discussion on the lower crust noted opposing views on silica content in recent papers by Shinevar et al. (2015), Huang et al. (2013) and Hacker et al. (2015). The former was on inferring viscosity based on volume fraction of different minerals, but if mineral content is uncertain then so is the method. Presentations on stress meters from xenoliths and using LPO to measure temperature and/or water content were also made. Participants noted the need for uppermost crust plastic rheological parameters, the need for the CRM to include parameters such as Byerlee friction, rate dependent friction on faults, pore pressure (again, a community hydrologic model). Participants noted width and rheology trade-offs of viscous shear zones at depth, and raised questions about heterogeneity of shear zone materials. A “fault maturity index” was proposed as a way to aggregate/upscale and simplify representation of mature vs immature fault zones in the CRM.

Rheology Constraints from Deformation Modeling

The modeling discussion focused mainly on seismic cycle deformation and the importance of representing shear zones in deformation models. The depth transition between brittle and ductile deformation, water content, specifics about the ductile rheology (transient, nonlinear or linear) were all discussed. Discussion noted variation between very weak faults (with tremor) and others. One challenge of this discussion was that it often turned to stresses rather than rheology (link between strain rates and stresses). The possible importance of anisotropy measurements to calibrating regional deformation models (comparing extension axes with LPO alignments) was mentioned, as was that of having an elasto-viscoplastic rheology model for long-term deformation studies. It was noted that different levels of complexity are required depending on what we are modeling, that surface deformation models do not require or constrain subsurface complexity too well. Stresses (from earthquakes and from direct measurements), and LPO were mentioned as observations that could be more sensitive to numerical models (and rheologies) at depth.

Closing Discussion: Defining the CRM and Future Directions

Several points were made or repeated during this session. Some of the most salient:

- A database with rock properties will be required (though perhaps not a fun graduate student project!): constitutive laws, radiogenic heat production, Vp, Vs, density, magnetic susceptibility, etc.
- Mixing laws to get polymineralic flow laws are potentially useful but some noted that this is still a research problem.
- A map of where the CRM is going could be a good tool as we go forward, dimensions of spatial scale vs. complexity.
- CRM developers should engage with end-users as early as possible.
- The CRM / database should be designed as if it were being used to build the SCEC1 master model.
- Modeling should be employed to identify which processes are important to stress and deformation, hence which parameters should be in the CRM.

An active-source seismic line is needed in the Big Bend / western Transverse Ranges area before we can build a 3D geologic model of the entire region.

Restructuring and coordinating community models is planned for SCEC5, and work is going on to improve the CFM user interface, so any CRM development must take be collaborative with other USR development to prevent duplication of effort.

The possible role of EarthCube was discussed. EarthCube seems appropriate for funding a bigger project than just the CRM, may connect more with the proposed SCEC5 USR coordination/unification efforts.

The need for hydrology information in the CRM, or a CHM, was reiterated.

We should have a way to grade faults according to maturity, and come up with a way to parameterize and represent fault complexity in the CRM.

It was suggested that the CRM initially focus on a small geographic area within southern CA, such as a SCEC special study area. Others thought that a regional-scale simplified CRM was the way to start.

The Upshot

This workshop functioned to raise awareness of the possibility of a SCEC Community Rheology Model (CRM), including how participants and their groups could contribute to or benefit from a CRM, and as a brainstorming session in which requirements for a CRM were fleshed out in detail. Discussion was lively and several suggestions from participants are mentioned above. Future CRM-specific workshops should focus on implementation, for example, designing a 3D geological model and an interface to allow this model to be queried. Related efforts on (1) developing a hydrological model for southern California (or at least some general guidance on likely ranges of hydraulic parameters) and (2) finding a way to fund an active-source seismic imaging project for the western Transverse Ranges-Big Bend were clearly identified by workshop participants as priorities for SCEC.

1. Agenda

AGENDA
Toward Development of a SCEC Community Rheology Model
Palm Springs Hilton, September 12, 2015

08:30-09:00
Workshop Check-In; Continental Breakfast
09:00-09:20
Overview on CRM goals and ingredients
- CRM goals and plan per SCEC5 proposal
- Outcomes from this workshop
- Structure of today's workshop

Liz Hearn
09:20-09:30
Discussion
09:30-10:00
Active-source results for southern California; comparison with noise-source Vs modeling
Gary Fuis
10:00-10:15
Earthquake-source Vp and Vp/Vs modeling of southern CA; interpretation of top and bottom of seismogenic zone
Egill Hauksson
10:15-10:30
Interpretation of Vp/Vs in the shallow crust from active source studies
Rufus Catchings
10:30-11:00
Directed Discussion
Gary Fuis and All
11:00-11:15
Break
11:15-11:40
A Road Map to Incorporating Rheology into CRM
Greg Hirth
11:40-11:55
The problem (and potential) of using seismic anisotropy to constrain effective viscosity and strain localization in Southern California
Phil Skemer
11:55-12:10
Constraints from xenoliths on the rheology of southern California lower crust and lithospheric mantle
Whitney Behr
12:10-12:25
Integrating fault zone microstructural observations with rock mechanics data

Fred Chester

12:25-13:00

Directed Discussion

Greg Hirth and All

13:00-14:00

Lunch

14:00-14:25

How can the CRM contribute to improved understanding of secular and transient deformation in Southern California and loading of seismogenic faults?

Yuri Fialko

14:25-14:40

Role of boundary conditions and mechanical models

Thorsten Becker

14:40-14:55

Effects of heterogeneous rheology on deformation, inferred slip rates and inferred stresses

Liz Hearn

14:55-15:10

Linear rheologies versus lab-derived flow laws and heterogeneity of lithospheric deformation

Roland Bürgmann

15:10-15:30

Directed Discussion

Yuri Fialko and All

15:30-15:45

Break

15:45-17:00

Wrap-Up Session: How to put all the pieces together

- Perspectives on disciplinary sessions: 5-minute summaries and discussions
- Next steps: Priorities for SCEC4 2016 RFP; SCEC5 objectives and staged interim goals; discussion

Liz Hearn and Co-PI's

17:00

Adjourn

B. References

Hacker, B. R., Kelemen, P. B., & Behn, M. D. (2015). Continental lower crust. *Annual Review of Earth and Planetary Sciences*, 43, 167-205.

Huang, Y., Chubakov, V., Mantovani, F., Rudnick, R. L. and McDonough, W. F. (2013). A reference Earth model for the heat−producing elements and associated geoneutrino flux. *Geochemistry, Geophysics, Geosystems*, *14*(6), 2003-2029.

Shinevar, W. J., Behn, M. D., & Hirth, G. (2015). Compositional Dependence of Lower Crustal Viscosity. *Geophysical Research Letters, in press.*