Highlights of SCEC Community Modeling Efforts and a Vision for Community Models in the Next Earthquake Center

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1. SCEC Community Models: An Introduction

The Southern California Earthquake Center (SCEC) has been coordinating research on fundamental earthquake science problems involving the physics of fault loading between earthquakes, propagation of large earthquake ruptures, and strong ground motions. A network of collaborative and interdisciplinary groups within SCEC has been tackling these questions through the development of detailed computational models. Regardless of the size and technical advancement of these models, they cannot provide useful knowledge if they are inadequately constrained by a diverse range of geophysical and geological observations. Sharing and synthesizing these increasingly complex datasets has long been a major goal of the SCEC community and is accomplished by developing integrative Community Models (CXMs). SCEC has a long history of fostering collaborations between IT experts and scientists from various disciplines to develop and serve suites of detailed, state of the art, and easily accessible data resources. This collaborative effort has accelerated in recent years, but it remains far from complete. Useful community models must undergo constant testing and revision as more data becomes available. Maintaining support for these efforts in the next earthquake center will enable the inclusion of ever growing, improving, and diversifying datasets in the collection of community models. Improved CXMs will help, in turn, to conduct improved system-science research on fundamental and applied problems associated with the San Andreas fault system's behavior and hazards.

The SCEC CXM working group currently oversees the development of and provides infrastructure for six community models which include the:

1. Community Velocity Model (CVM)
2. Community Fault Model (CFM)
3. Community Geodetic Model (CGM)
4. Community Rheology Model (CRM)
5. Community Stress Model (CSM)
6. Community Thermal Model (CTM)

The two most mature of these are the CVM and the CFM, whose initial versions were created in 1998 and 2002, respectively (Magistrale et al., 1998, 2000; Shaw and Plesch, 2002, 2007). The CFM provides geometric descriptions of active southern California fault systems and the CVM comprises 3D seismic velocity, density, and elastic property data. Both of these community resources have been used to populate detailed numerical models with increasing realism of rupture propagation and strong ground motions for large California earthquakes (e.g.

CyberShake, Graves et al., 2011), which are used by engineers for improved resilience of buildings and other structures (e.g. Bijelic et al., 2017, Teng and Baker, 2019). During SCEC4, two community models were launched as resources for quantifying plate boundary deformation and physics-based seismic hazard: the Community Stress Model (CSM) and the Community Geodetic Model (CGM). Continuing in this vein, two additional community models are being developed in SCEC5: the Community Rheology Model (CRM) and the Community Thermal Model (CTM). These newer community models, together with the continually refined earlier models, provide improved observational bases for next-generation earthquake simulations (e.g. Shaw et al., 2018), deformation models (e.g., Cooke and Dair, 2011, Marshall et al., 2017), as well as rupture and ground motion models (e.g., Ryan et al., 2015).

2. The SCEC5 CXM Collaboration: Organization and How It Works

During SCEC5 (2017-2022), the SCEC community has continued to refine and update the four community models introduced prior to 2017 while developing and beginning to populate the two new community models. SCEC does not have a large pool of permanent research scientists taking on these tasks: much of the work is done by individual researchers at various institutions working together within a collaborative framework. The CXM working group is led by three volunteers (the authors of this whitepaper), who also serve on the SCEC Planning Committee. Representatives for each of the six community models determine the needs of each CXM and share this information with us as we draft the annual science plan and request for proposals (RFP). The RFP coordinates research efforts related to the individual community models and alerts the SCEC community to topics in need of attention. Scientists who propose research responding to these needs are more likely to be funded, so careful drafting of the RFP guides and expands our collaboration and helps the SCEC collaboration meet its goals.

To demonstrate the value of the SCEC CXM collaboration in a more concrete manner, we list a few CXM research priorities directly from recent RFP's, followed by examples of funded proposals members of the SCEC community submitted to respond to each priority.

"Collect additional observations to improve resolution and/or resolve discrepancies among competing models within an individual CXM."

- Robert Clayton (Caltech), SCEC Award #18029, "*Funding to Facilitate Additional San Bernardino Seismic Lines*" This SCEC project helped support the deployment of seismic arrays in the San Bernardino Basin in 2018. The purpose was to collect seismic data to improve the ground motion prediction of potential earthquakes on the southern San Andreas Fault (SAF). This basin is thought to be a conduit for shaking from the SAF into downtown Los Angeles, so its structure and properties needed to be better understood. The SCEC CVM will be improved by the addition of better-characterized sedimentary basins.

"Integrate new data (especially the Salton Sea Imaging Project) into the existing CVMs with validation of improvements in the CVMs for ground- motion prediction."

- Patricia Persaud (Louisiana State), SCEC Award #18074, "*Improved 3-D Vp Models Near the Southern San Andreas Fault from SSIP Explosive Shots and Local Earthquakes*". This project used a joint inversion of first P-wave travel times from the SCSN (39,998 local earthquakes) and 251 explosive shots from the 2011 Salton Seismic Imaging Project to produce a detailed 3-D Vp model. The result is a highly detailed map of the basement-sediment interface in the northern Salton Trough and the Coachella Valley, which will improve the SCEC CVM in this area.

"Develop tools to assist users in visualizing and using the CFM in a range of computational models."

- John Shaw (Harvard), Scott Marshall (Appalachian State), and Philip Maechling (USC/SCEC), SCEC Award #19102, "Providing infrastructure for the Community Fault Model (CFM) to support SCEC science, community model development, and hazard assessment". This proposal involved a collaboration between the CFM developers and SCEC IT to improve access to the CFM. This work produced a map-based web-viewer for the SCEC CFM. Previously, the CFM was simply distributed as a zip archive of thousands of files. This project also greatly updated CFM website with new visualizations, maps, and other model data. As a result, the CFM is more accessible and user-friendly.

Community model workshops are also vitally important to collaborative development of the CXM's. At these events, CXM developers and other members of the SCEC community share updates on community models with potential users and contributors. Feedback and guidance on CXM development are solicited, and attendees present examples of CXM-enabled science. SCEC typically funds and provides logistical support for several of these workshops per year. They may be led by any member of the SCEC community, though for coordination purposes at least one CXM group leader attends each.

3. Hosting/Serving Increasingly Complex Community Models

As the community models have grown in size and complexity and a greater number of users want to use these models, SCEC has begun to face a new challenge: how to host and serve large CXM datasets to the community over the long term in a way that is user friendly, supports reproducibility, is consistent with documentation and open data requirements of both journals and Federal agencies, and is possible on a limited budget. In recent years, datasets and community models have expanded exponentially in size, and the task of serving community models involves increasing IT infrastructure. Despite the limited resources, SCEC has made significant progress in serving community models. It is clear that the next earthquake center needs to provide significant dedicated IT support for community models and data archiving/sharing.

SCEC has responded to the increased demand for community models by first creating the CXM group. Through the CXM collaboration with SCEC scientists and the SCEC web teams, we have developed and improved software tools for querying individual community models, created a uniform template for CXM websites (including metadata), provided model citation guidance, and created a CXM homepage with links to individual community model webpages to centralize and facilitate data discovery. At the beginning of SCEC5, nearly all of the CXM components were hosted at individual investigators' personal websites. Throughout SCEC5, the community models were brought progressively to the www.scec.org domain. Currently, all but one of the existing community models are hosted on www.scec.org, while the remaining model is currently being migrated.

The current IT-related CXM priorities include:

1. Instituting community model versioning (e.g., through assigning DOI's) and serving data from permanent hosting sites (e.g., Zenodo).
2. Improving accessibility to the CXM by creating new web-based tools for querying and visualizing the various models.

One example of CXM deliverables featuring improved accessibility is the 2019 release of the CFM web-based viewer and search tool for the CFM, developed by the SCEC IT team in collaboration with SCEC researchers (Figure 1). The web-based viewer serves a new and improved set of preferred fault representations that utilize a nearly regularized mesh with 500, 1000, and 2000 meter element sizes as well as a significantly updated MATLAB-based CFM visualization tool (plotMesh.m). This tool enables SCEC researchers that do not have access to CAD software to directly import and visualize GOCAD or any type 3D files. Based on user feedback, SCEC also created and posted 1) a series of CFM fault trace maps (with several different basemaps), 2) downloadable CFM5.2 trace data as both shapefiles and GMT multi-segment files, and 3) a GOCAD file Frequently Asked Questions document to help users better understand the content and structure of GOCAD t-surf files. The release of the CFM viewer website has resulted in several constructive user requests, many of which are planned to be addressed with the subsequent release of CFM5.3.

These IT infrastructure improvements also provide the ability for the SCEC community to respond rapidly to new events. In immediate response to the 2019 M6.4 and M7.1 Ridgecrest earthquake sequence, SCEC researchers developed new, preliminary 3D source fault representations, which include the Eastern and Southern Little Lake faults as part of the regional Little Lake fault zone (Wills, 1988). The IT infrastructure for the CFM allowed these preliminary 3D fault representations to be quickly available as triangulated surface representations for download through the CFM web-viewer.

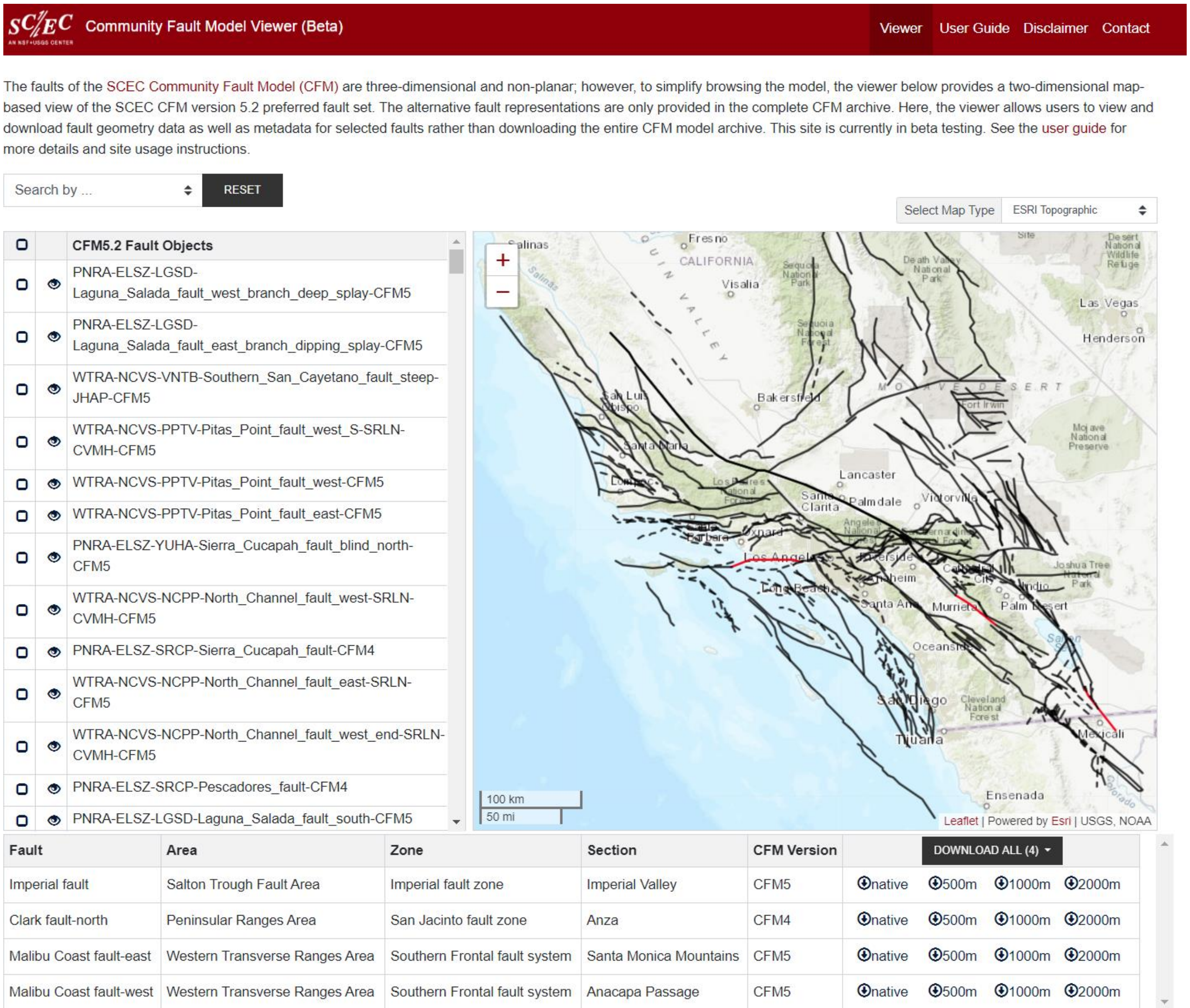

Figure 1: Screenshot of the CFM web-viewer and search tool developed through the SCEC collaboration. The web-based tool allows users to browse via a map-based interface, or query the model based on several search types. Metadata for selected faults (red traces) is provided to the user at the bottom of the screen. The web-viewer is located at https://www.scec.org/research/cfm-viewer/

4. Enabling Next-Generation Modeling in the New Earthquake Science Center

The stability and longevity of SCEC has created a collaboration (in terms of both procedures and personnel) that enables scientists to efficiently develop and update community models. We have pivoted to both maintain and serve our growing community models while adhering to evolving standards of documentation, accessibility, and reproducibility. For example, according to the USGS Survey Manual:

> “The February 22, 2013, Office of Science and Technology Policy (OSTP) memorandum “Increasing Access to the Results of Federally Funded Scientific Research” requires free public access to digital data resulting from federally funded research, including datasets used to support scholarly publications … The May 9, 2013, Office of Management and Budget (OMB) memorandum “Open Data Policy—Managing Data as an Asset” also requires agencies to provide free public access to data collected or created by using Federal funds, *and to collect or create data in a way that supports downstream processing and dissemination activities.*”

The SCEC community models have led the way of fulfilling the requirements described above and more. The OMB memo requires that the data and accessibility tools are kept up to date over the long term. SCEC community models have been used widely by the community, and recently we started to track the use of individual community models including website hits, model downloads, and citations in scientific publications. The next earthquake center should continue to develop the community models pioneered by SCEC, and update the “nuts and bolts” practices to insure data accessibility (“downstream processing”) and longevity with minimal intervention. IT efforts on serving SCEC community models with user-friendly tools appropriate to each model should also continue.

In the following sections, we present a few examples of features and activities that we anticipate could take place in a future realization of SCEC as a continuing earthquake center.

4.1. Expanding the Geographic Focus

SCEC was originally designed with a regional focus, optimizing the use of limited resources to make significant scientific strides in a particularly strategic geographical location, Southern California. Over the nearly three decades of SCEC, the volume and quality of data generally available have increased dramatically, as have the computer capabilities needed to manage large datasets. It is also clear that Southern California is not an isolated geologic system. Including the extension of the San Andreas fault system in Mexico, Central and Northern California, and offshore, beyond the artificial limits of Southern California would significantly improve the capacity of conducting system-level earthquake science. For example, the M7.2 El Mayor earthquake occurred in northern Mexico, just outside the nominal SCEC region (Gonzalez-Ortega et al., 2014). This limited the data available to study this event as most of the continually-operating instrumentation was located in the U.S.

SCEC has developed a knowledge base and toolkits that make it possible to construct complex and testable community models that instruct regional earthquake studies. It would be beneficial for any earthquake center to take advantage of this expertise gained from nearly 30 years of experience. SCEC has already started to incorporate adjacent areas into some models, in particular the CTM, CRM, and CVM. The next earthquake center should continue SCEC efforts and expand the geographical extent of the existing community models.

4.2. Integrating Community Models into Seismic Hazard Analysis

Physics-based seismic hazard analysis requires probabilistic rupture forecasts and models of strong ground motion for anticipated earthquakes. As noted in the introduction, CyberShake (Graves et al., 2011) and earlier models of strong ground motion for scenario earthquakes (Jones et al., 2008, Olsen et al., 2006) relied on 3D elastic properties of the lithosphere inferred from previous versions of the SCEC CVM. Future models of earthquake rupture propagation and strong ground motions will benefit from refined versions of the CVM, as well as rheological and structural constraints from other community models. Seismic studies are currently underway to characterize the San Bernardino and San Gabriel basins near Los Angeles (Clayton et al., 2019), and update their representation in the CVM. These updates will enable modelers to investigate how much a future SAF earthquake could shake the Los Angeles Basin, and to stringently test the hypothesis that the San Bernardino and San Gabriel basins may provide a conduit for energy propagating from a SAF earthquake (Olsen, 2006). There are also current efforts to integrate various local high-resolution velocity models within the regional CVM. The combined multi-scale CVM will allow future simulations of ground motion at frequencies above 1 Hz to represent realistic structural heterogeneities.

Constraints on the ductile rheology of the lower crust and upper mantle from the CRM and the CTM are poised to inform physics-based models of fault systems, earthquake simulators (Field et al., 2019, Shaw et al., 2018), and models of postseismic stress transfer and evolution of earthquake probabilities after large earthquakes. Such models have a role to play in earthquake rupture forecasts such as UCERF3 (Field et al., 2013 and 2019) and development of the USGS National Hazard Maps (Petersen et al., 2014). Rheological properties of the upper crust and shallow fault zones influence strong ground motions, and adding detailed distributions will be a high priority for the CRM going forward.

In the past, it has been routine for earthquake and fault system modelers to assume structure, rheologies and elastic properties for a given region based on published studies, but without addressing consistency among these representations. Moreover, in well-studied regions such as the western U.S., multiple interpretations of subsurface structure may exist, while parameters in other regions (especially in the lower lithosphere) may be poorly constrained. Tools are required for efficiently querying and comparing CXM's, so scientists can automate (or streamline) modeling workflows. One concrete example of this is the web-based CFM query tool (Figure 1), which enable modelers to test the effects of different fault geometries on rupture propagation and/or surface deformation patterns (e.g. Marshall et al., 2017). Another is a new web-based CVM and CRM geologic framework query tool which is currently being developed by SCEC IT programmers under the guidance of CXM, CVM, and CRM representatives.

Careful, continuous cross-comparison of CXM properties has been an ongoing focus for SCEC5, and it must remain an area of emphasis in the next earthquake science center. For example, analysis of the CVM and CFM has insured that basin edges and the boundaries of lithotectonic blocks in the CRM geologic framework are coincident (Nicholson et al., 2017), and CVM properties are being scrutinized to assess compatibility with CRM lithologies (Plesch et al., 2019). Two-way coupling (i.e. use and refinement of CXM's) by the SCEC modeling community insures that problems are identified and fixed in updated versions.

4.3. Extending Community Models Using Physics-Based Structural Predictions

As the various models that constitute the CXM increase in diversity and sophistication, the limits of constraining community models solely from observations is becoming clear. The CXM can be used as a modeling framework within which one can generate physics-based predictions of structures that are cannot be imaged directly but may significantly affect tectonic processes and earthquake hazards.

For example, it has been proposed that ductile shear zones are present in the downdip continuation of seismogenic faults, based on structures exposed in exhumed terrains. These shear zones would influence how faults are loaded near typical earthquake nucleation depths and how stress is transferred from one fault to another during the postseismic time interval. However, they are absent in most models because it is not possible yet to image them directly, as temperature, grain size, hydration, and composition can trade-off with each other.

The detailed knowledge of the lithosphere in Southern California provided by the integrated information contained in the CFM, CVM, CTM, and CRM, allows modeling shear zone development including physics-based predictions of the structures that may be present. These predictions provide targets for future observational studies that may be tested against the CGM, CSM, geological samples, and postseismic transients after major earthquakes. Such simulations, which build on the wealth of data integrated in the CXM's and the research computing capabilities of SCEC, should be a priority for the next earthquake science center. Similar initiatives might be expected from other proposed research centers, but the longevity and experience of SCEC will be crucial for developing integrated physics-based community models and make them accessible to a wide range of users.

5. Conclusion

The SCEC collaboration has been producing cutting-edge community models for nearly 30 years and is well-positioned to expand its geographic, scientific, and IT activities in the next earthquake center. The community models that have already been developed, and are in a continual process of improving, serve as examples of the strong SCEC collaboration and provide critical data and vision for the future of earthquake science. Expanding these existing models to cover the entire San Andreas system is the logical evolution of SCEC, and will serve the greater earthquake science community for decades to come.

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