

**2020 Project Report for SCECAward 20190:  
Delivering the preliminary CRM and CTM: Websites, manuscripts and modeling**

**E. H. Hearn (PI)**

Most of my SCEC research this past year was devoted to seeing that initial versions of the CRM and the CTM were “out the door” in time for the 2020 SCEC Annual Meeting. Between then and the end of the grant period, I developed tools for calculating CRM effective viscosities and importing them into PyLith (Aagard et al., 2017) finite-element models, and began comparing CRM effective viscosities to values inferred from postseismic deformation and surface loading models.

*CRM TAG coordination and completion of CRM v.20.9 and CTM v.20.8.* At the start of the 2020 grant period, the final CTM and synthetic aggregate flow laws for CRM Geological Framework (GF) rocks were not quite complete. Our TAG had a conference call on April 30, 2020 to hash out the final details of generating synthetic aggregate flow laws for low-strain rocks, and to discuss progress on the CTM and its nascent website.

Over the summer, I coordinated with TAG members Laurent Montesi and Mike Oskin to assemble the CRM into a downloadable suite of directories and files. This package contains the GF (lithology descriptions, province boundaries, depth intervals for lithologies), CRM rheologies (document with GF rock synthetic aggregate flow laws, parameter values, description of approach and assumptions; software and input files, tables of parameter values) and README files describing all of the files in each directory and their contents. Some checking was required to resolve minor discrepancies in nomenclature and compositions used for the lithology (Oskin) and rheology (Montesi) files.

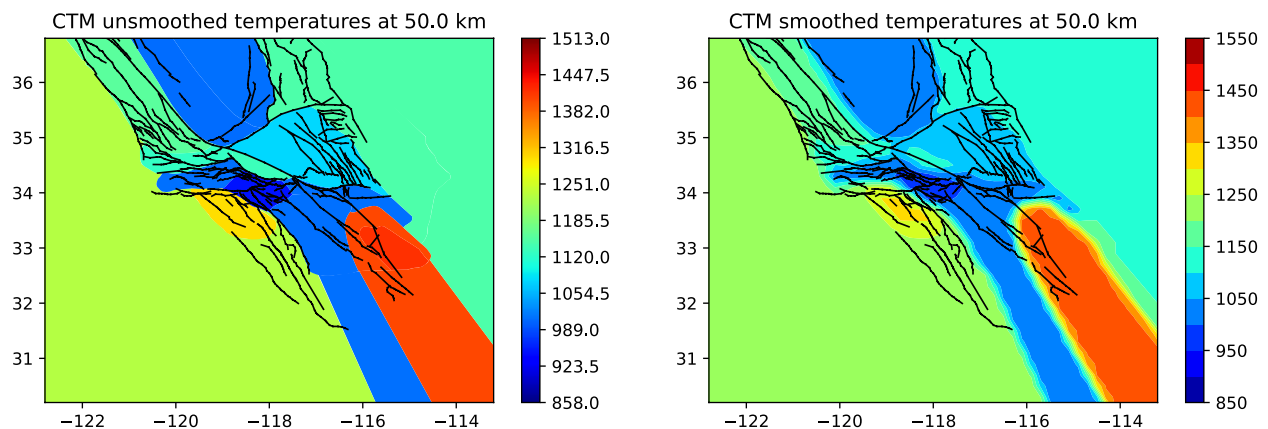
Beginning in the spring of 2020, I coordinated with Wayne Thatcher to generate a downloadable CTM with files, metadata and README files, and to complete the CTM webpage. I added several CTM heat flow regions to extend the CTM to the same geographic footprint as the CRM. I also developed a Python code for viewing and querying the CTM, as well as generating a smoothed version (see CTM website section below).

I also coordinated with Phil Maechling and Mei Su of SCEC IT, to insure consistency between the CRM and CTM website downloads and the SCEC GF query tool ([http://moho.scec.org/GFM\\_web/web/viewer.php](http://moho.scec.org/GFM_web/web/viewer.php), Maechling et al., 2020), and to provide SCEC IT with files as needed. The web-based GF query tool enables “one-stop shopping” for point queries of GF lithologies and provinces, CVM properties, CTM heat flow regions, and temperatures interpolated from a gridded version of the CTM. Gridded CTM temperatures for this tool were generated by Mei Su using the Python CTM code, assuming the default Gaussian kernel parameters.

The CRM (v. 20.9) and the CTM (v. 20.8) were released in time for the 2020 SCEC Annual Meeting, and both research websites went live at that time. On our CRM poster (Hearn et al., 2020), we presented profiles of effective viscosity for various GF provinces assuming a reference strain rate of  $10^{-14}$  /s and mean CTM temperatures within each province, and explored sensitivity of effective viscosity to temperature and strain rate. We had another CRM TAG telecon on November 11, 2020 to discuss implementing ductile shear zones and whether other potential CRM refinements are plausible during our final, one-year timeframe.

*Preliminary Community Thermal Model (CTM) website and laterally-smoothed CTM.* I worked with Wayne Thatcher and Edric Pauk this spring to generate the CTM website, which is now linked to the SCEC CXM website ([www.scec.org/research/ctm](http://www.scec.org/research/ctm)). This website contains a description of the CTM (Thatcher and Chapman, 2020, Thatcher, 2020), an alternate CTM (Shinevar et al., 2018), and a download link for both models, their metadata, and the query tool described below. The first version of the CTM is v20.8, and its DOI has been assigned (<https://doi.org/10.5281/zenodo.4010834>).

As the CTM was being finalized this spring, I developed a Google Colab notebook /Python tool for smoothing, querying and plotting the CTM. This tool is in the CTM download package and can also be accessed directly at the scecpedia page for the CTM here: <https://strike.scec.org/scecpedia/CTM>. Optional lateral smoothing is implemented with Gaussian kernels, and the approach is explained in both the Colab notebook and a README file in the CTM download. Users may adjust smoothing and plotting parameters, and export plots and/or a file of CTM



**Figure 1.** CTM v20.8 unsmoothed (left) and smoothed (right) temperatures (C) at 50 km depth, generated using the smooth, view and query tool provided with the CTM download.

temperatures and province ID numbers in ascii format. **Figure 1** shows unsmoothed and smoothed temperatures generated by the CTM query tool, at 50 km depth.

*Preliminary Community Rheology Model (CRM) website.* After the synthetic aggregate flow laws were complete, I coordinated with the CRM TAG and Edric Pauk to put together a CRM

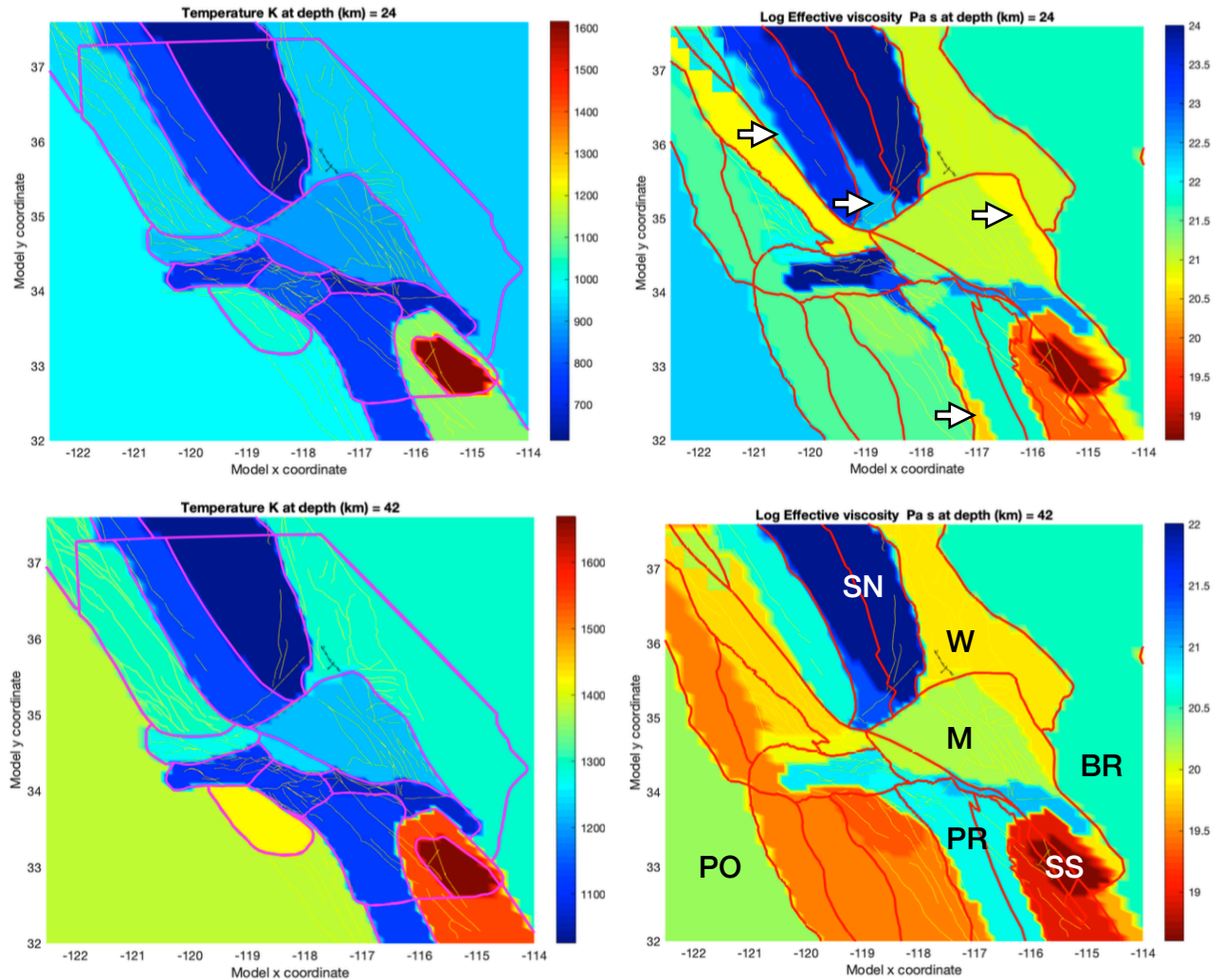
webpage ([www.scec.org/research/crm](http://www.scec.org/research/crm)). The webpage includes a description of the CRM and its components (i.e. the Geologic Framework and the synthetic aggregate flow laws), and a download link. The initial version (v. 20.9) provides ductile rheologies for low-strain rocks. The DOI is <https://doi.org/10.5281/zenodo.4579627>.

*Additional CRM products and tools.* Based on my conversations with members of the SCEC community, it's clear that there is demand for a gridded effective viscosity product and perhaps integrated strength profiles. I have computed effective viscosities on a 3D grid and plotted slices for inspection by the TAG. This grid approximately covers the CRM GF region (-123.4 to -112.2 lon and 29.5 to 37.6 lat), and grid spacing is 8 km in most of the domain, with 1 km depth intervals. Example slice plots are shown on **Figure 2**. The CRM TAG group convened on Monday February 22, 2021 (after the grant period) to discuss these plots, and to identify problems that should be cleared up before we publicly share these figures or the gridded effective viscosities online (see **Figure 2** caption).

*Comparing the CRM with findings from deformation models.* A comparison of the CRM effective viscosities with values inferred from postseismic deformation and surface loading models will be given in the manuscript we are preparing for publication. This comparison is complicated by the fact that observed postseismic or surface-loading deformation may reflect a transient phase of deformation, in which the effective viscosity is lower than the steady-state (Maxwell) viscosity. A Burgers rheology is often used to represent this apparent viscosity evolution with time after a stress step such as an earthquake or sudden load change (e.g., Pollitz, 2019).

Four parameters describe the Burgers rheology: steady-state Maxwell viscosity  $\eta$ , shear modulus  $\mu$ , ratio of transient (Kelvin element) viscosity to steady-state (Maxwell) viscosity ( $R_B$ ); and ratio of  $\mu$  to the shear modulus for the Kelvin element ( $\Delta_{bar}$ ). The SCEC CRM effective viscosity is  $\eta$  in this scenario, and  $\mu$  can be assumed or inferred from the SCEC CVM. Ivins (2020) summarizes Burgers model parameters for several studies, and Chopra (1997) reports ranges for  $R_B$  and  $\Delta_{bar}$  from laboratory studies. These parameters govern the magnitude and duration of the transient response, but they are poorly constrained. Many modelers just assume that  $\Delta_{bar}$  is 1 and  $R_B$  is 0.1, though lab studies suggest ranges of 0.05 to 0.36, and 0.17 to 0.67 respectively (Chopra, 1997). Another concern is that there are likely numerous relaxation times in the Earth at decadal timescales (e.g., Ivins, 2020) and even late postseismic deformation may not be “seeing” a steady-state viscosity. This means that the *CRM effective viscosities will be at the high end of those inferred from postseismic studies, and that even in those cases where modelers have assumed a Burgers rheology, only a qualitative comparison is possible.*

**Figure 2** shows CRM effective viscosities at 24 km and 42 km depth. In areas where postseismic and surface loading estimates are available (e.g., the Salton Sea/El Mayor earthquake region, the Mojave, the southern Great Basin and the southern Walker Lane Belt), CRM lower crust and upper mantle viscosities are broadly comparable to inferred Maxwell viscosities (e.g. the compilation of Pollitz (2019); more recent estimates by Tang et al. (2020), Dickinson-Lovell (2018), and Liu et al. (2021).



**Figure 2.** (top) CTM and CRM slices at 24 km depth. (bottom) CTM and CRM slices at 42 km depth. Values were computed for points on a grid with 8 km lateral spacing in the center of the region, and the unsmoothed CTM was assumed. Pink and red lines show borders of CTM heat flow regions (HFRs) and CRM Geologic Framework (GF) provinces. CRM effective viscosities assume a strain rate of  $5 \times 10^{-15}$  /s ( $10^{-15}$  /s in the Sierra Nevada, Basin and Range, and Pacific Ocean GF provinces). We are (2021) making adjustments to some CTM HFR boundaries, and adding a new CTM HFR representing the borderland provinces offshore. Note elongate artifacts (arrows) where CTM and GF boundaries do not coincide. We are currently looking at strategies to deal with these artifacts (e.g. recommending use of a smoothed CTM when computing viscosities, and reconciling GF province and CTM HFR boundaries in some places). W = SouthernWalker Lane, M = Mojave, PR = Peninsular Ranges, SS = Salton Sea (Rift and Rifted Margin), BR = Basin and Range, PO = Pacific Ocean, SN = Sierra Nevada.

For example, recent postseismic deformation models of the El Mayor earthquake incorporate the Burgers rheology and make use of several years of GPS observations (Tang et al., 2020 and Dickinson-Lovell, 2018). These models suggest Salton Sea lower crust and mantle lid Maxwell viscosities are  $1 - 4 \times 10^{19}$  Pa s and  $0.5 - 1 \times 10^{19}$  Pa s, respectively. At 24 and 42 km depth, Figure 2 shows values of  $4 \times 10^{18} - 10^{20}$  and  $0.3 - 1 \times 10^{19}$  Pa s for the Salton Sea (i.e., the CRM

Geological Framework rift and rift margin provinces). In the adjacent Peninsular Ranges provinces, these models give  $>2 \times 10^{20}$  and  $>10^{21}$  Pa s for the lower crust and  $10^{20}$  for the upper mantle lid (defined as 30-40 km depth by Dickinson-Lovell et al., 2018). **Figure 2** indicates  $5 \times 10^{21}$  and  $5 \times 10^{20}$  Pa s, respectively, at 24 and 42 km depth. In short, the CRM Maxwell viscosities are consistent with, or somewhat higher than, values recently inferred from El Mayor-Cucapah postseismic deformation.

*Deformation models and the CRM.* In early 2021, I generated PyLith spatial database files from a coarser version of the gridded CRM effective viscosities mentioned above, and am testing various versions in models of southern California SAF seismic cycles for the USGS NSHMP. Versions with Maxwell viscoelasticity and various instances of General Maxwell viscoelasticity (set to represent Burgers rheologies following Müller, 1986) are being developed. These spatial database files will enable any modeler using PyLith to easily represent the CRM in southern California deformation models. I am investigating the best way to share them (for example, via the CIG PyLith community wiki).

## References

- Aagaard, B., M. Knepley, C. Williams (2017), PyLith v2.2.1, Computational Infrastructure of Geodynamics, Davis, CA, DOI: 10.5281/zenodo.886600.
- Chopra, P. N. (1997), High-Temperature Transient Creep in Olivine Rocks, *Tectonophysics*, 279, 93-111.
- Dickinson-Lovell, H., M.-H. Huang, A. M. Freed, E. Fielding, R. Bürgmann, and C. Andronikos (2018), Inferred rheological structure and mantle conditions from postseismic deformation following the 2010 Mw 7.2 El Mayor-Cucapah Earthquake, *Geophys. J. Int.*, 213, 1720-1730.
- Hearn, E., M. Oskin, G. Hirth, L. Montesi, W. Thatcher, W. Behr, and E. Pauk (2020), The SCEC Community Rheology Model, 2020 SCEC Annual Meeting Poster 179.
- Ivins, E., L. Caron, S. Adhikari, E. Larour and M. Scheinert (2020), A linear viscoelasticity for decadal to centennial time scale mantle deformation, *Rep. Prog. Phys.*, 83, 106801.
- Liu, S., Z.-K. Shen, R. Bürgmann, and S. Jónsson (2021), Thin crème brûlée rheological structure for the Eastern California Shear Zone, *Geology*, 49, 216-221.
- Müller, G. (1986), Generalized Maxwell bodies and estimates of mantle viscosity, *Geophys. J. R. Astr. Soc.*, 87, 1113-1141.
- Maechling, P. J., M. Su, E. Hearn, S. Marshall, A. Plesch, J. Shaw, M. Oskin, L. Montesi, E. Pauk, T. Huynh, and Y. Ben Zion (2020), Developing Web-based Visualization and Query Tools for the SCEC CVM, CFM, GFM, and CTM Community Models. Poster Presentation #187 at 2020 SCEC Annual Meeting.
- Pollitz, Fred F. (2019), Lithosphere and shallow asthenosphere rheology from observations of post-earthquake relaxation, *Phys. Earth Plan. Int.*, 293: 106271.
- Shinevar, W., M. Behn, G. Hirth and O. Jagoutz (2018), Inferring crustal viscosity from seismic velocity: Application to the lower crust of Southern California, *Earth Plan. Sci. Lett.*, 494, 83-91.
- Tang, C.-H., S. Barbot, Y.-J. Hsu, and Y.-M. Wu (2020), Heterogeneous Power-Law Flow With Transient Creep in Southern California Following the 2010 El Mayor-Cucapah Earthquake, *J. Geophys. Res.*, 125, e2020JB019740.
- Thatcher, W. (2020), The SCEC Community Thermal Model (CTM) Version 1.2, 2020 SCEC Annual Meeting Poster #180. (Disregard the version number in this title)
- Thatcher, W. and D. Chapman (2021), The SCEC Community Thermal Model, in USGS internal review, for *J. Geophys. Res.*