

Report for 2025 SCEC Grant 25057
Integrating a multi-parameter 3D thermal model of California and Nevada toward an open-sourced Community Thermal Model

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Objectives

The goal of this year's project was to further the development and public accessibility of a new multi-disciplinary crustal thermal model for California and Nevada (Fig. 1), an effort which was initiated last year under SCEC award 24026. This project directly supports the research priority of the Statewide California Earthquake Center (SCEC) to broaden the Community Thermal Model (CTM) to a statewide scale. Our thermal modeling approach consists of an open-source Python script that is accessible, user-friendly, and customizable to incorporate user-specified inputs and parameters. When available, the model can leverage available relevant temperature proxy datasets for any geographic region, including surface heat flow, relocated seismicity as it relates to the temperature-sensitive seismogenic thickness, Curie point depth, crust-mantle boundary temperature and depth estimates derived from P_n velocity models, and lithosphere-asthenosphere boundary depths and temperatures (Fig. 1).

For this year's project, we finalized a three-dimensional (3D) thermal model of the California and Nevada crust (Fig. 1). The Python scripts and final 3D temperature volume is available on Zenodo (<https://zenodo.org/records/18462713>). Furthermore, we cross evaluated our temperature model with other published models that span California or the United States. With the assistance of SCEC staff, we developed a web-based explorer that hosts our 3D temperature model, and other published models, which can serve as the publicly available CTM for users (<http://moho.scec.org/research/ctm-explorer/>). The new web portal allows for extraction of 1D vertical thermal profiles, 2D horizontal-slice maps, and 2D vertical profiles across the datasets.

Methodology

Our temperature model incorporates available temperature-depth constraints (Fig. 1a), which are fit by vertical 1D conductive heat transport solution (Fig. 1b). We incorporate surface heat flow data of Williams et al. (2007), recently published by Mordensky and DeAngelo (2023) (Fig. 1a). The seismogenic thickness of the crust is calculated by finding the 95th percentile of the hypocenter distribution (D95) using >40 years of merged relocated earthquake catalog data from southern California (Waldhauser and Schaff, 2008; Waldhauser, 2009) and northern California (Hauksson et al., 2012), and Nevada (Trugman, 2023; 2024). Combination of the catalogs involved removal of redundant seismic events and generating a uniform vertical datum for hypocentral depth normalized to surface elevation. We also removed seismic events within the lithospheric mantle by filtering the hypocentral depths that are deeper than the Moho depth from the crustal thickness model of Buehler and Shearer (2017). We incorporate adaptive binning using a quadtree structure (Finkel and Bentley, 1974) to accommodate regions lacking seismicity and to increase the spatial resolution in seismically active zones (Fig. 1a). D95 uncertainty was determined by taking the standard deviation of the D95 distributions derived

from 1,000 iterations of bootstrap resampling of the original hypocentral depth distribution. Lastly, we approximate lower crustal and Moho temperatures by integrating P_n-wave (P wave that refract along the seismic Moho) derived crustal thickness (Buehler and Shearer, 2017) and Moho temperature models (Schutt et al., 2018). The Moho temperature model of Schutt et al. (2018) relies on inverting P_n-velocity through assuming homogenous upper-mantle composition, as well as their mineral elastic properties.

We seek a suite of 1D steady-state conductive thermal profiles that best fit these temperature-depth constraints (e.g., Fig. 1c). For each crustal column, we sample the parameter space by generating $n=100,000$ unique combinations of surface radiogenic heat production (H_0), characteristic decay length scale of crustal heat production (h_r), mantle heat flow (q_m), thermal conductivity (k), and the resultant modeled surface heat flow (q_s^{modeled}) to construct 1D thermal profiles. The resultant q_s^{modeled} are first compared against the observed surface heat flow. Thermal profiles that have a q_s^{modeled} being $\pm 10 \text{ mW m}^{-2}$ to the observed surface heat flow values are further compared against D95 and Moho depth-temperature constraints using a normalized root mean square error (NRMSE) to define good model fits. Models that yield NRMSE value of less than 0.35 are defined as good-fit temperatures (e.g., red geotherms in Fig. 1c). The mean best-fit results from each vertical column (e.g., orange geotherm in Fig. 1c) are combined to yield a 3D temperature model. The first-order 3D temperature uncertainty estimates are approximated by taking the standard deviation of all the best-fit temperature profiles at each crustal column, yielding a temperature uncertainty envelope that widens through depth (e.g., blue envelope in Fig. 1c). To minimize lateral roughness and unrealistic temperature gradients, we diffuse the resultant 3D temperature volume laterally for 5 myr by solving the 2D conservation of heat equation. The timescale of static heat diffusion (t) is determined by applying the characteristic scaling relationship of heat diffusion ($t = \delta^2 / \kappa$), assuming a characteristic length scale (δ) of 12.5 km (i.e., the intermediate grid size of the quadtree D95 model) and a thermal diffusivity (κ) of $10^{-6} \text{ m}^2 \text{ s}^{-1}$.

Results

We constructed several versions of a thermal model across California and Nevada. This model is a 3D array of temperature information. Some pixels do not generate temperature results (i.e., white regions in Fig. 1d–f) because our modeling framework cannot identify a good fit to the input temperature proxies. These regions include southern Sierra Nevada-Isabella Anomaly, Great Valley, Salton Trough, and southern Cascadia. We interpret that observed misfit may be caused by non-steady-state temperature conditions, for example, transient lithospheric heating or crustal advection in regions of active tectonics.

To view the temperature variations in map-view, we plot the temperatures at depth slices of 10 km (Fig. 1d), 20 km (Fig. 1e), and Moho depths (Fig. 1f). These plots predictably show hot crust in regions with active volcanism and/or geothermal activity (e.g., Clear Lake Volcanic Field, Coso, Salton Trough), and colder areas that are seismically stable and inferred to be rheologically strong (e.g., the Sierra Nevada-Great Valley) (Fig. 1d). The Central Nevada Seismic Belt also shows elevated temperature anomaly (Fig. 1d).

The results of the temperature uncertainty estimates for the mid-crust are presented in Figure 2a, showing the temperature uncertainty at 20-km depth on map-view. The temperature uncertainty at 20-km depth shows weak spatial variations, with higher mid-crustal temperature uncertainty anomalies ($\sim 80 \text{ }^\circ\text{C}$) cluster near northeastern Nevada, Salton Trough, and Clear Lake

Volcanic Field (Fig. 2a). In contrast, Sierra Nevada, Great Valley, and southern Cascadia exhibit lower mid-crustal temperature uncertainty at ~ 15 °C (Fig. 2a).

Our new thermal model was compared against other published temperature models, such as the temperature model of southern California from Shinevar et al. (2018) (Fig. 2b). Our model strongly correlates with this previous model, although our temperature results are generally hotter than the Shinevar et al. (2018) model. The comparison also shows the depth-dependent temperature difference, with an overall higher temperature difference at deeper depths than the shallower crustal region, with our model ~ 45 °C warmer, on average (Fig. 2b). The strong agreement (Pearson correlation $r=0.95$) between our model with the Shinevar et al. (2018) model that utilizes a completely different approach, validates our modeling approach and temperature estimates. However, we suggest that our model still yield more accurate temperature estimates because we incorporated additional independent temperature proxies to constrain deep crustal thermal structure.

In collaboration with SCEC computing staff Mei-Hui Su and Philip Maechling, we built a new web-based CTM explorer tool (<http://moho.scec.org/research/ctm-explorer/>) for users to rapidly extract and visualize temperature information (Fig. 3). The new CTM explorer provides a similar user interface to the Community Velocity Model explorer, where it allows users to select available temperature models, and extract their temperature information in various dimensions based on their input spatial boundary (Fig. 3). Temperature data can be extract as single point temperature, 1D vertical profile, 2D horizontal-slice map, and 2D vertical cross-section. Extracted temperature information can be downloaded as .csv file, as well as visualize it immediately with our plotting function (Fig. 3b). The current CTM explorer incorporated a total of five temperature models in various scales, including our new California-Nevada CTM (Fig. 1), southern California CTMs of Shinevar et al. (2018) and (2024), and the national models of Boyd (2020) and Sui et al. (2025).

Future work

With the construction of our 3D thermal model, implementation of the online CTM explorer, and comparison with available published thermal models, our primary goals of the CTM development are complete. A manuscript summarizing the main findings and utility of the thermal model is currently in review for publication. After publication, researchers can use our thermal model to investigate influence and correlation between crustal temperature, heat flow, Quaternary fault density, strain rate, earthquake productivity, crustal thickness, and other parameters. As discussed at the 2025 SCEC Statewide GFM/CTM Workshop in summer 2025, an important next step will be to further validate any of these temperature models with independent datasets. Example validation datasets might include deep well data or geophysical proxies such as the α - β quartz transition, which is associated with a pronounced acceleration in P-wave velocity.

Figures and captions

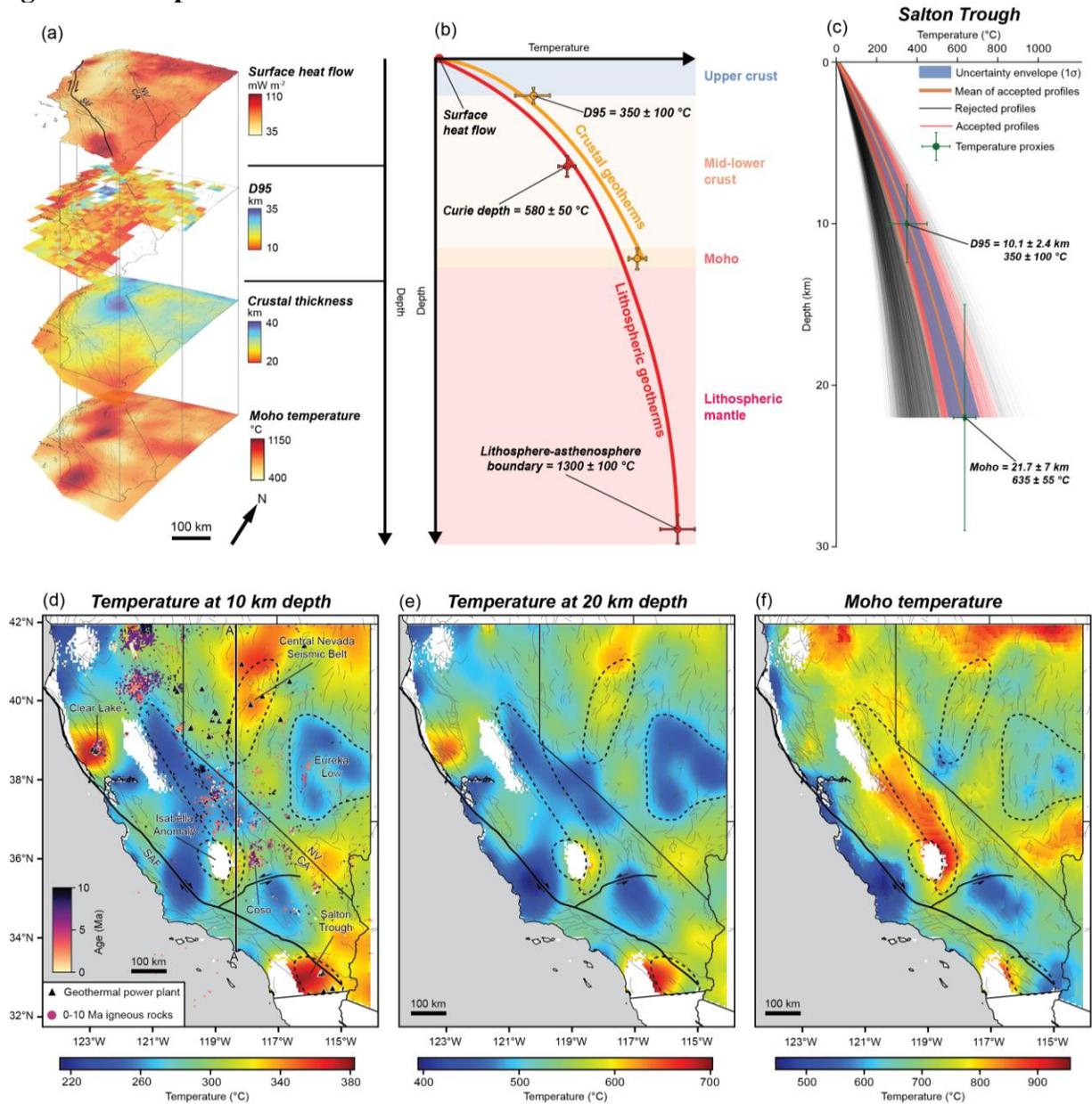


Figure 1. (a) Oblique view of crustal temperature proxies in the western United States, including surface heat flow (Williams et al., 2007; Mordensky and DeAngelo, 2023), seismic thickness (D95), crustal thickness (Buehler and Shearer, 2017), and Moho temperature (Schutt et al., 2018). SAF: San Andreas fault. (b) Schematic 1D vertical steady-state crustal (orange) and lithospheric (red) thermal profiles constrained by two different combinations of temperature proxies. Note that the difference between the two schematic geotherms is to enhance visualization. (c) A representative 1D thermal modeling result in the Salton Trough. (d–f) Horizontal slice maps of the temperature distribution across Nevada and California at depths of 10 km (d), 20 km (e), and Moho depths (f). Panel (d) plots geothermal power plants and <10 Ma igneous rock (<http://portal.earthchem.org>). Thin black lines are Quaternary active faults (McCafferty et al., 2023). Black dash lines are the boundaries of tectonic domains. White and grey regions highlight areas that do not have accepted results.

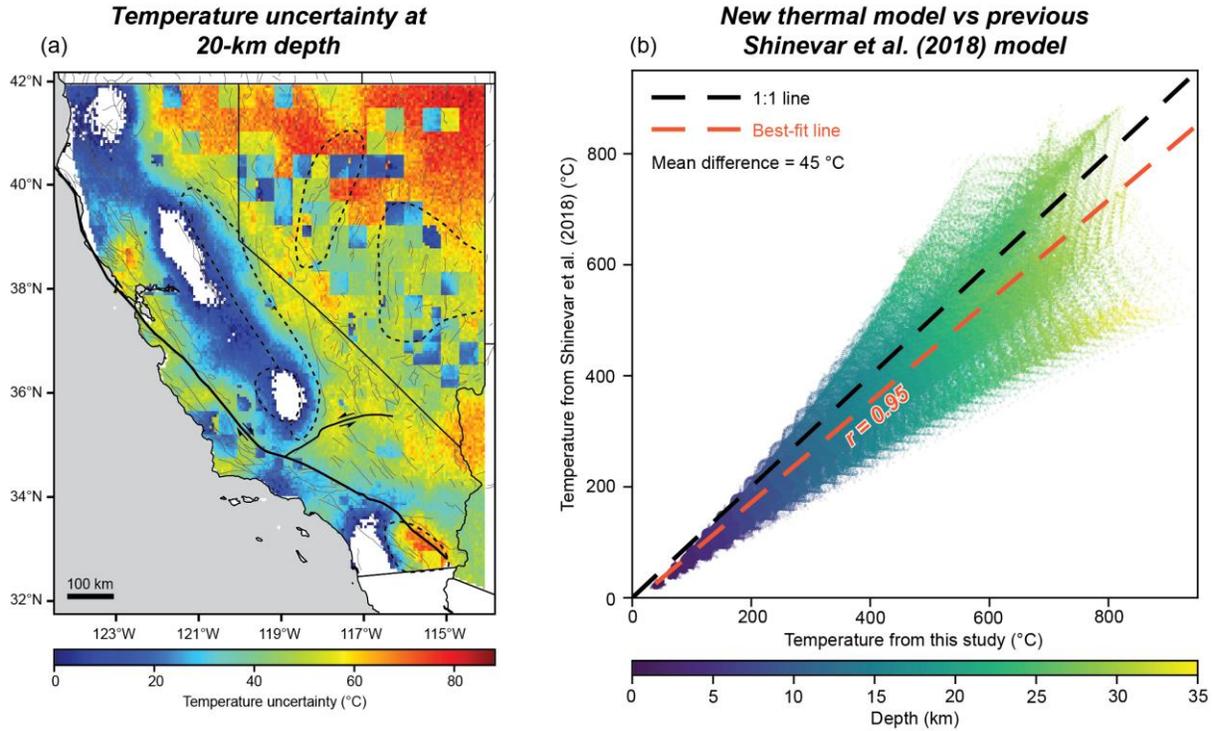


Figure 2. (a) Horizontal slice map of the temperature uncertainty at 20-km depth across Nevada and California. (b) Comparison of our new thermal model versus previous results of Shinevar et al. (2018) from southern California. Note the general 1:1 correlation ($r = 0.95$). The thermal model presented here is on average 45 °C warmer than the Shinevar et al. (2018).

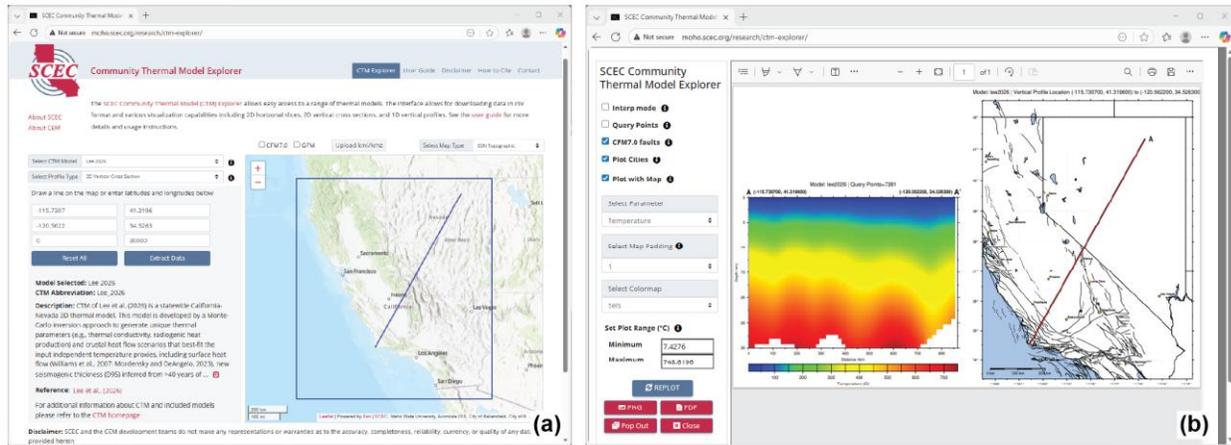


Figure 3. New SCEC Community Thermal Model Explorer webpage. (a) Map view selection window, where the user can select a CTM Model and profile type, including 2D Horizontal Slice, 2D Vertical Cross Section, 1D Vertical Profile, and 0D point. After extracting the data, users can plot the data or download data as in a .csv format. (b) Example 2D Vertical Cross Section plot, showing the temperature results as well as a map view of the selected profile trace. Users can add CTM7.0 faults, cities, and otherwise adjust the plotting results.

Publications

- Haproff, P. J., Zuza, A. V., Yin, A., Levy, D. A., & Lee, T. (2026). Structural controls on the spatial distribution, volume, and composition of rift-related volcanism in Owens Valley, California, USA: Geological Society of America Bulletin.
- Lee, T., Zuza, A. V., Trugman, D., Vlaha, D., & Cao, W. (2025). Statewide Community Thermal Model of California and Nevada: Model comparisons, implications, and a new explorer platform: Presentation at the 2025 Statewide California Earthquake Center Annual Meeting.
- Lee, T., Zuza, A. V., Trugman, D. T., Vlaha, D. R., & Cao, W. (2025). Updates on the Community Thermal Model (CTM): Oral Presentation at the 2025 SCEC Statewide GFM/CTM Workshop, Davis, CA.
- Lee, T., Zuza, A. V., Trugman, D. T., Vlaha, D. R., & Cao, W. (2025). Continental Lithosphere Thermal Model: Case Studies from the Western U.S. and Central Asia: Oral Presentation at the Nevada Geosciences Research Symposium.
- Lee, T., Zuza, A. V., Trugman, D. T., Vlaha, D. R., & Cao, W. (2024). Multi-parameter thermal model of California and Nevada: Insights into crustal rheology and earthquake processes along the active transtensional plate boundary: Poster Presentation at 2024 SCEC Annual Meeting.
- Lee, T., Zuza, A. V., Trugman, D. T., Vlaha, D. R., & Cao, W. (2024). A multidisciplinary construction of the 3D thermo-rheological structure in California and Nevada: Implications on the transtensional deformation along the active margin. Oral Presentation at the Geological Society of America Connects.

References

- Boyd, O.S. (2020). Temperature model in support of the U.S. Geological Survey National Crustal Model for seismic hazard studies. U.S. Geological Survey Open-File Report 2019-1121, 15 p., <https://doi.org/10.3133/ofr20191121>.
- Buehler, J. S. & Shearer, P. M. (2017). Uppermost mantle seismic velocity structure beneath USArray. *Journal of Geophysical Research: Solid Earth*, 122(1): 436-448.
- Finkel, R. A., & Bentley, J. L. (1974). Quad trees a data structure for retrieval on composite keys. *Acta Informatica*, 4(1): 1-9.
- Hauksson, E., Yang, W., & Shearer, P. M. (2012). Waveform Relocated Earthquake Catalog for Southern California (1981 to June 2011). *Bulletin of the Seismological Society of America*, 102(5): 2239-2244.
- McCafferty, A.E., San, C.A., Lawley, C., Graham, G.E., Gadd, M.G., Huston, D.L., Kelley, K.D., Paradis, S., Peter, J.M., and Czarnota, K., 2023, Shapefiles of faults for the United States, Canada, and Australia: U.S. Geological Survey data release, <https://doi.org/10.5066/P970GDD5>.
- Mordensky, S., & DeAngelo, J. (2023). Geothermal resource favorability: select features and predictions for the western United States curated for DOI 10.1016/j.geothermics.2023.102662. U.S. Geological Survey data release.
- Schutt, D. L., Lowry, A. R., & Buehler, J. S. (2018). Moho temperature and mobility of lower crust in the western United States. *Geology*, 46(3): 219-222.

- Shinevar, W. J., Behn, M. D., Hirth, G., & Jagoutz, O. (2018). Inferring crustal viscosity from seismic velocity: Application to the lower crust of Southern California. *Earth and Planetary Science Letters*, 494, 83-91. <https://doi.org/10.1016/j.epsl.2018.04.055>.
- Shinevar, W. (2024). California Thermal Model (SCTM2) (1.0). Zenodo. <https://zenodo.org/records/7842960>
- Sui, S., Shen, W., & Boyd, O. S. (2025). A crustal thermal model of the conterminous United States constrained by multiple data sets: a Monte–Carlo approach. *Geophysical Journal International*, 241(3), 1711-1724. <https://doi.org/10.1093/gji/ggaf118>.
- Trugman, D. T., 2023, Earthquake catalog for California and Nevada [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.10070513>.
- Trugman, D. T. (2024). A High-Precision Earthquake Catalog for Nevada. *Seismological Research Letters*, 95(6): 3737-3745.
- Waldhauser, F., & Schaff, D. P. (2008). Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods. *Journal of Geophysical Research: Solid Earth*, 113(B8).
- Waldhauser, F. (2009). Near-Real-Time Double-Difference Event Location Using Long-Term Seismic Archives, with Application to Northern California. *Bulletin of the Seismological Society of America*, 99(5): 2736-2748.
- Williams, C., Reed, M. J., Galanis, S. P., & DeAngelo, J. (2007). The USGS National Geothermal Resource Assessment: An Update. *Geothermal Resources Council Transactions*, 31: 99-104.