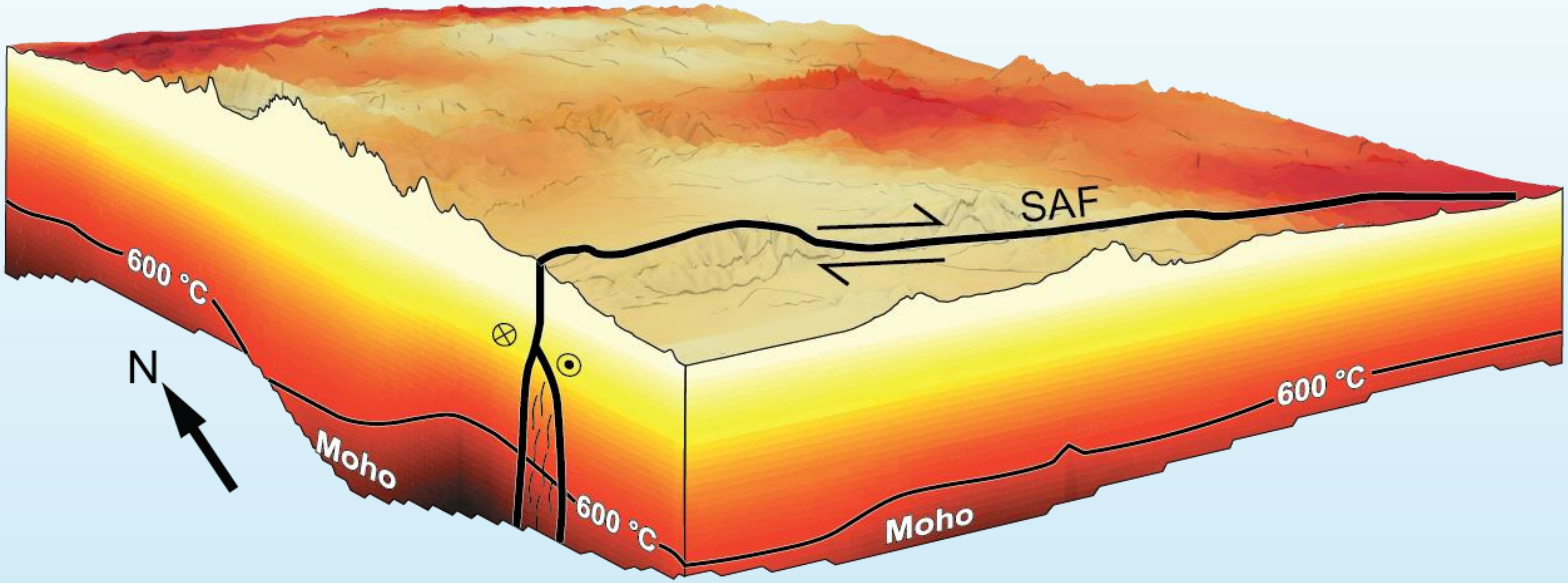
GFM-CTM Workshop 2025

Updates on the Community Thermal Model (CTM)



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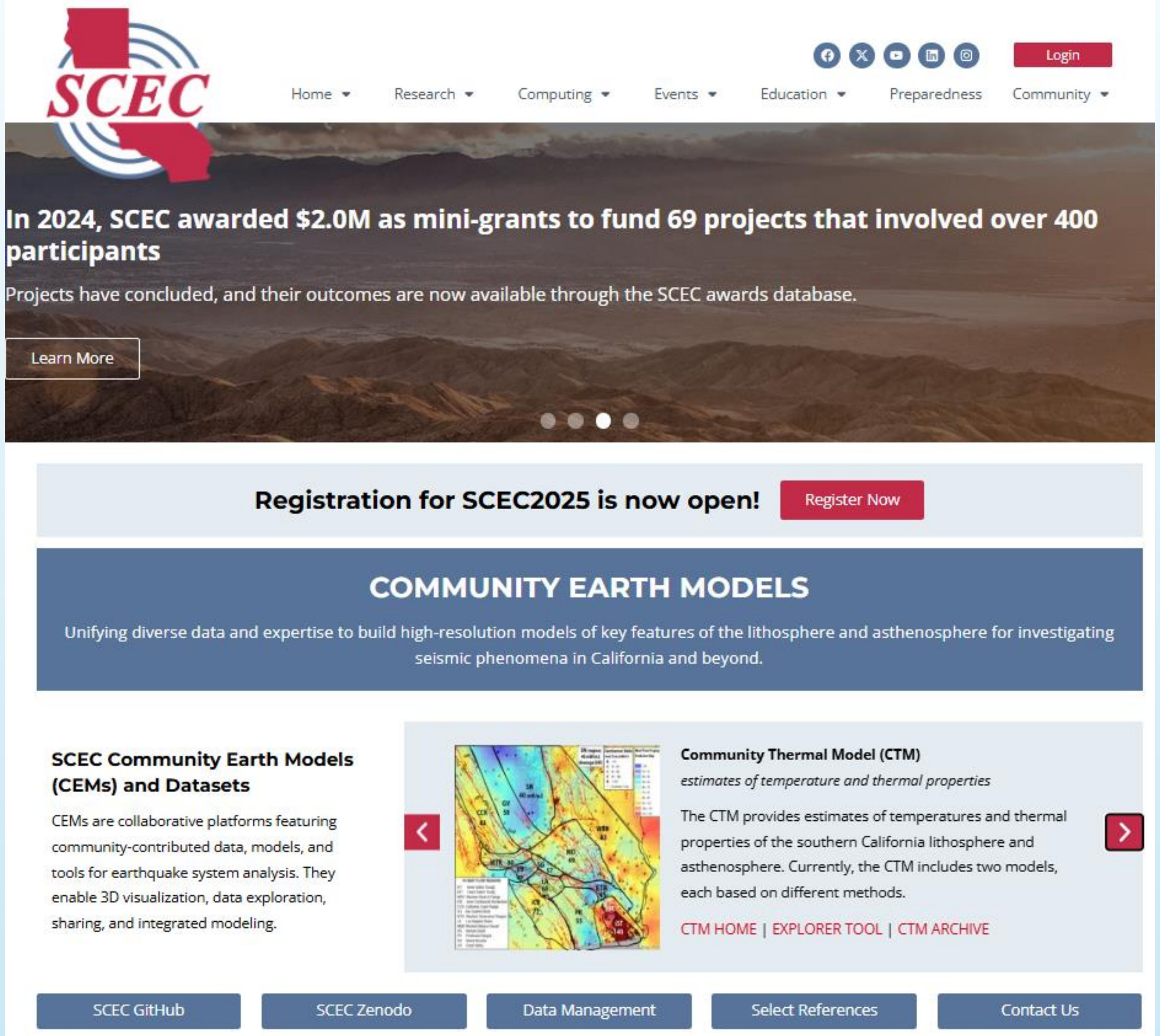
Dominik Vlaha, Wenrong Cao

NEVADA GEOSCIENCES University of Nevada, Reno
nbmg
NEVADA SEISMOLOGICAL LABORATORY
SCEC

Community Earth Model (CEM)

- Community Fault Model (CFM)
- Community Geodetic Model (CGM)
- Community Rheology Model (CRM)
- Community Stress Model (CSM)
- **Community Thermal Model (CTM)**
- **Geological Framework Model (GFM)**
- Community Velocity Model (CVM)



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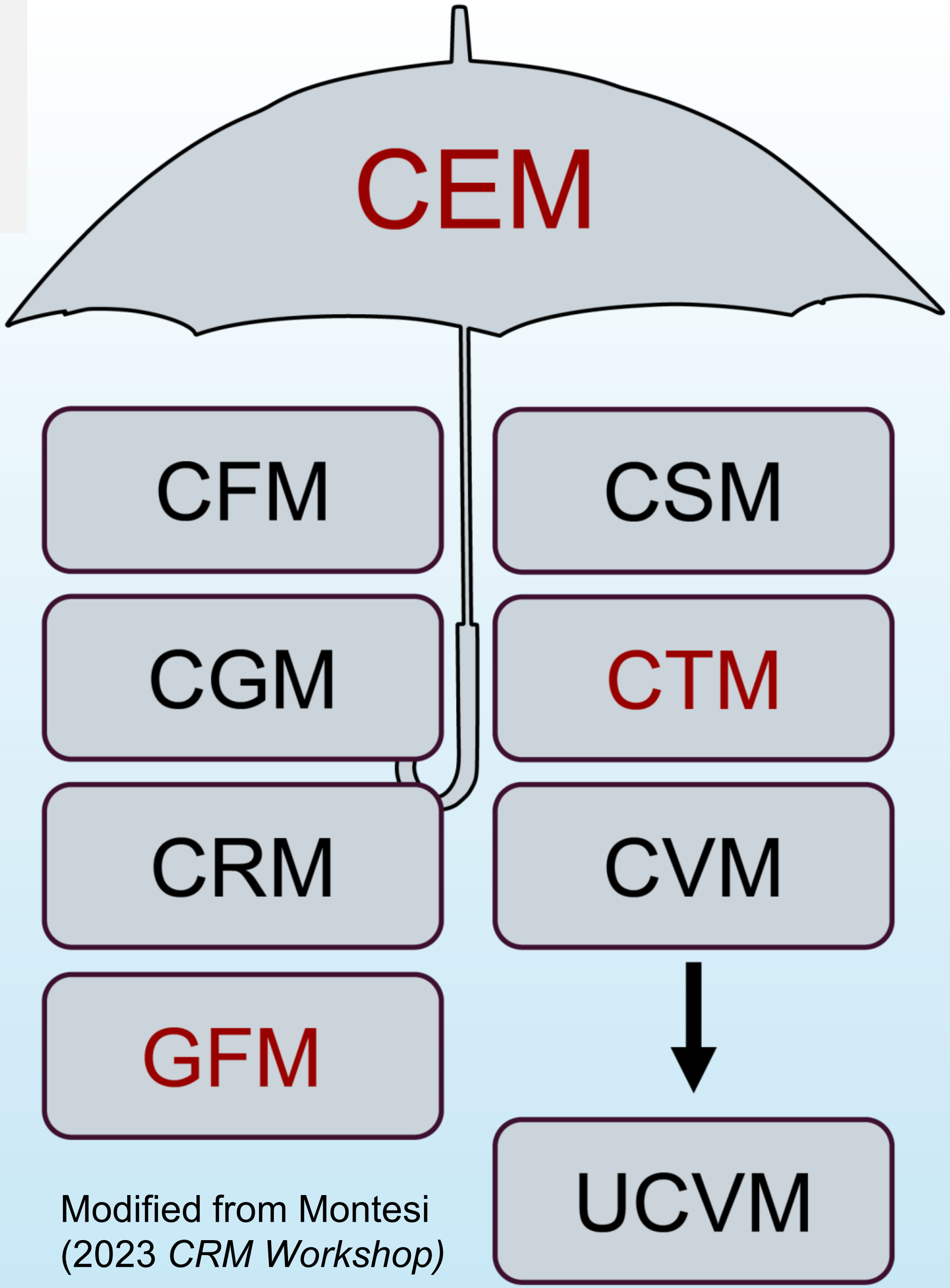


Modified from Montesi
(2023 *CRM Workshop*)

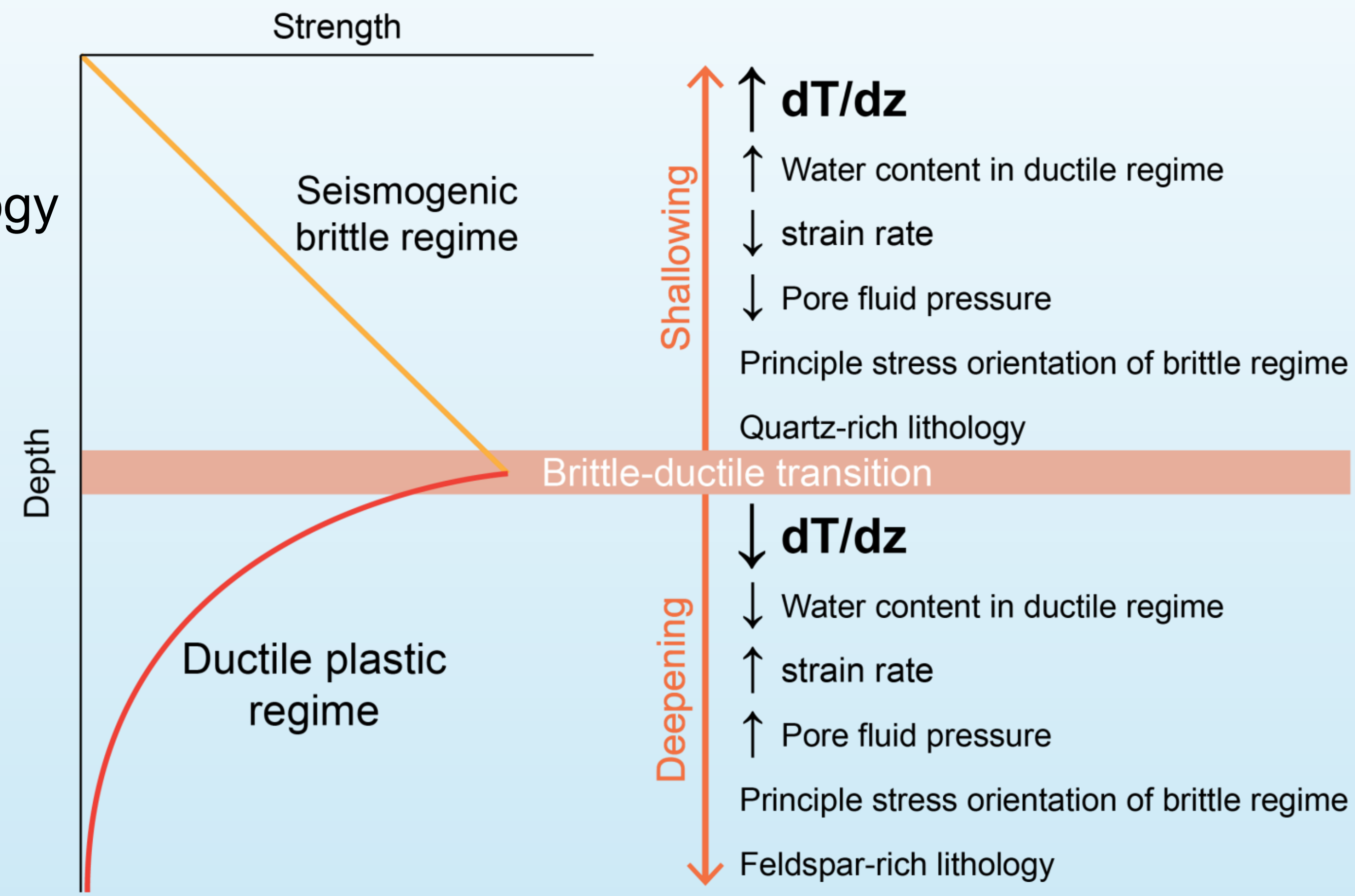
Thermal structure modulates rheology

Exerts a first-order control on lithospheric rheology

- Seismogenic thickness → **seismicity**
- Ductile strength → **crustal flow**
- Temperature-dependent rheology

$$\textbf{Viscosity} = f(T)$$

$$\textbf{Temperature} \ \alpha \ \textbf{Viscosity}^{-1}$$



Modified from Sibson (1984 *JGR SE*)

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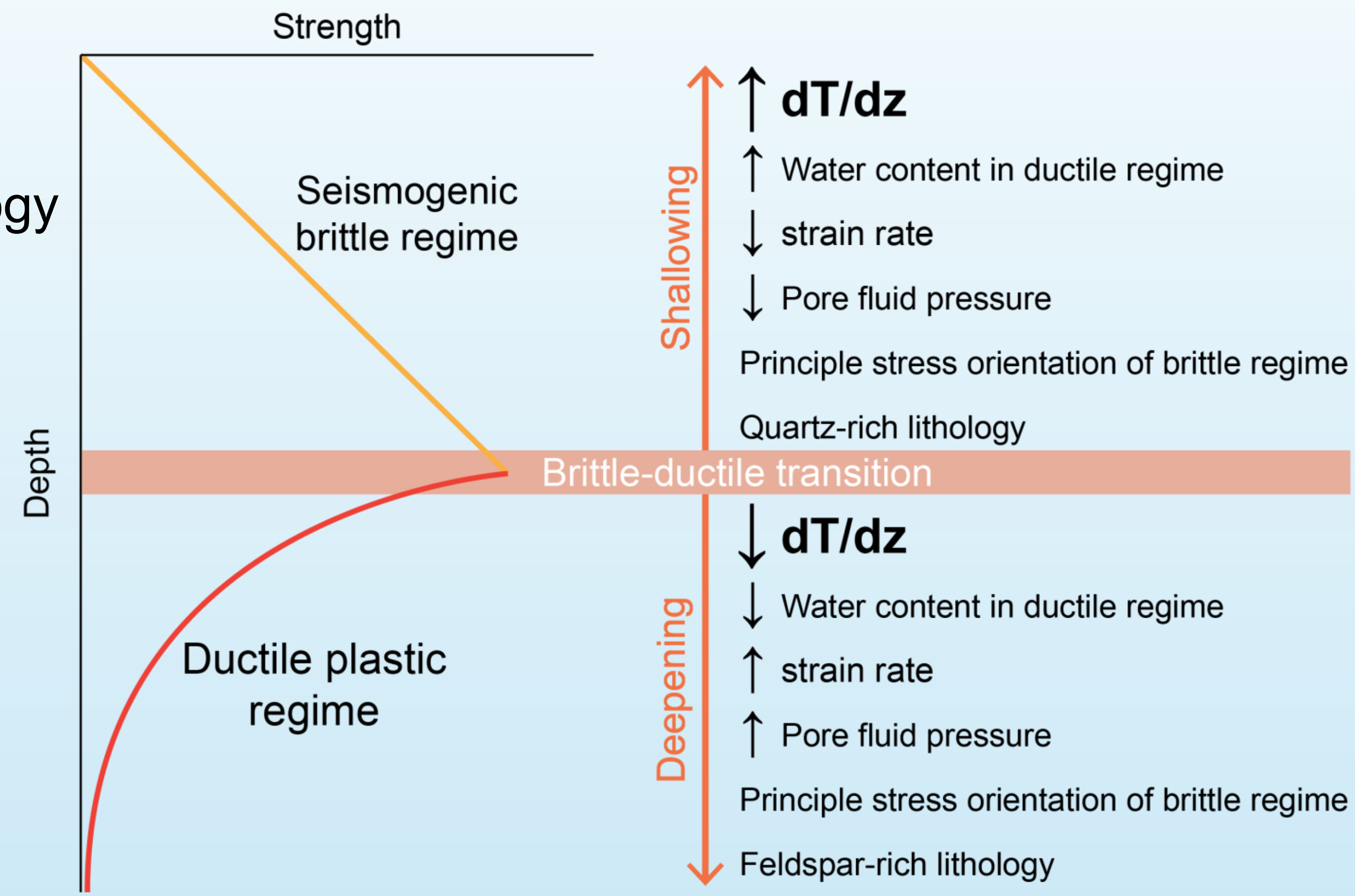


Modified from Sibson (1984 *JGR SE*)

Thermal modeling for the continental lithosphere

1D heat equation:

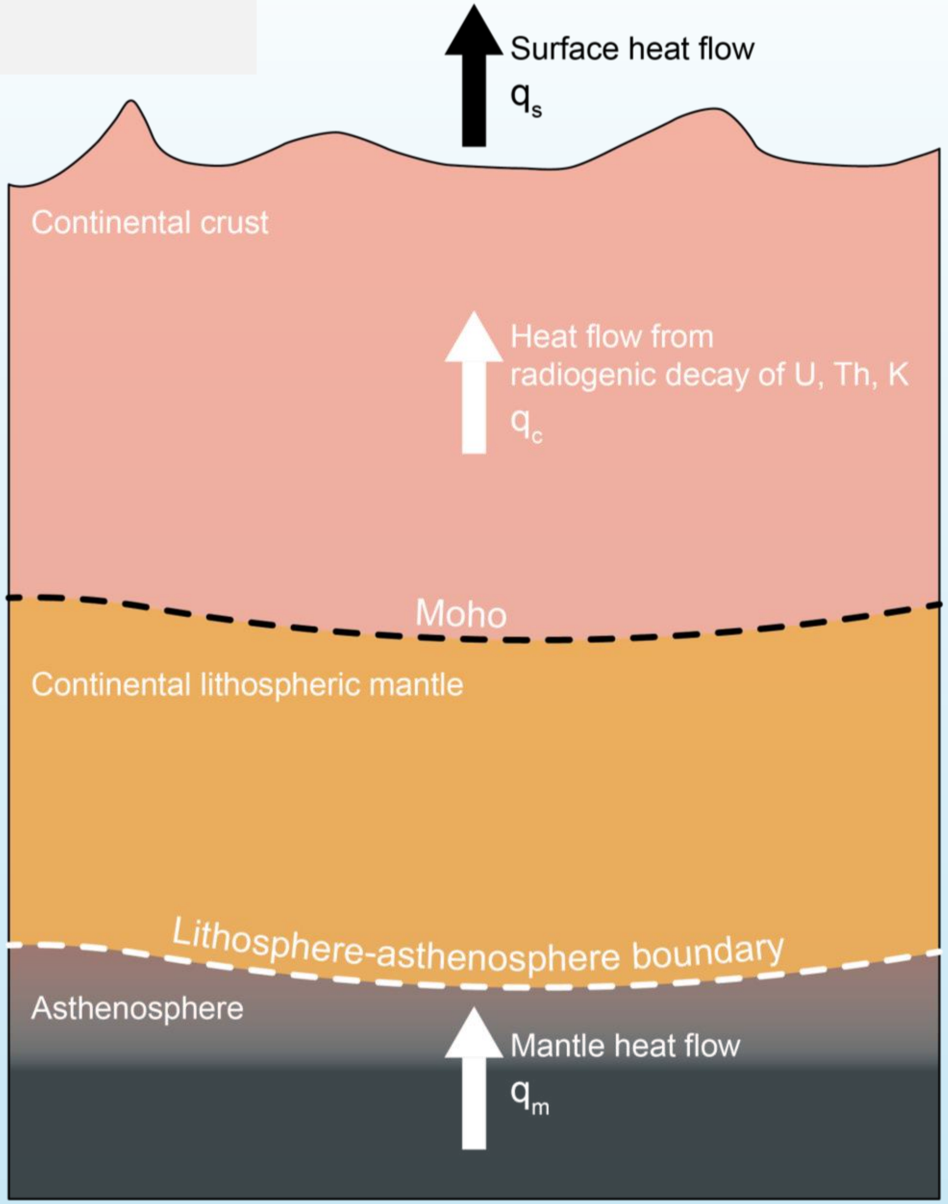
$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2}\frac{k}{\rho c_p} + \text{Heat source}$$

Heat flow (q):

$$q = -\frac{dT}{dz}k$$

Surface heat flow (q_s):

$$q_s = q_c + q_m$$



Thermal modeling for the continental lithosphere

1D heat equation (steady state):

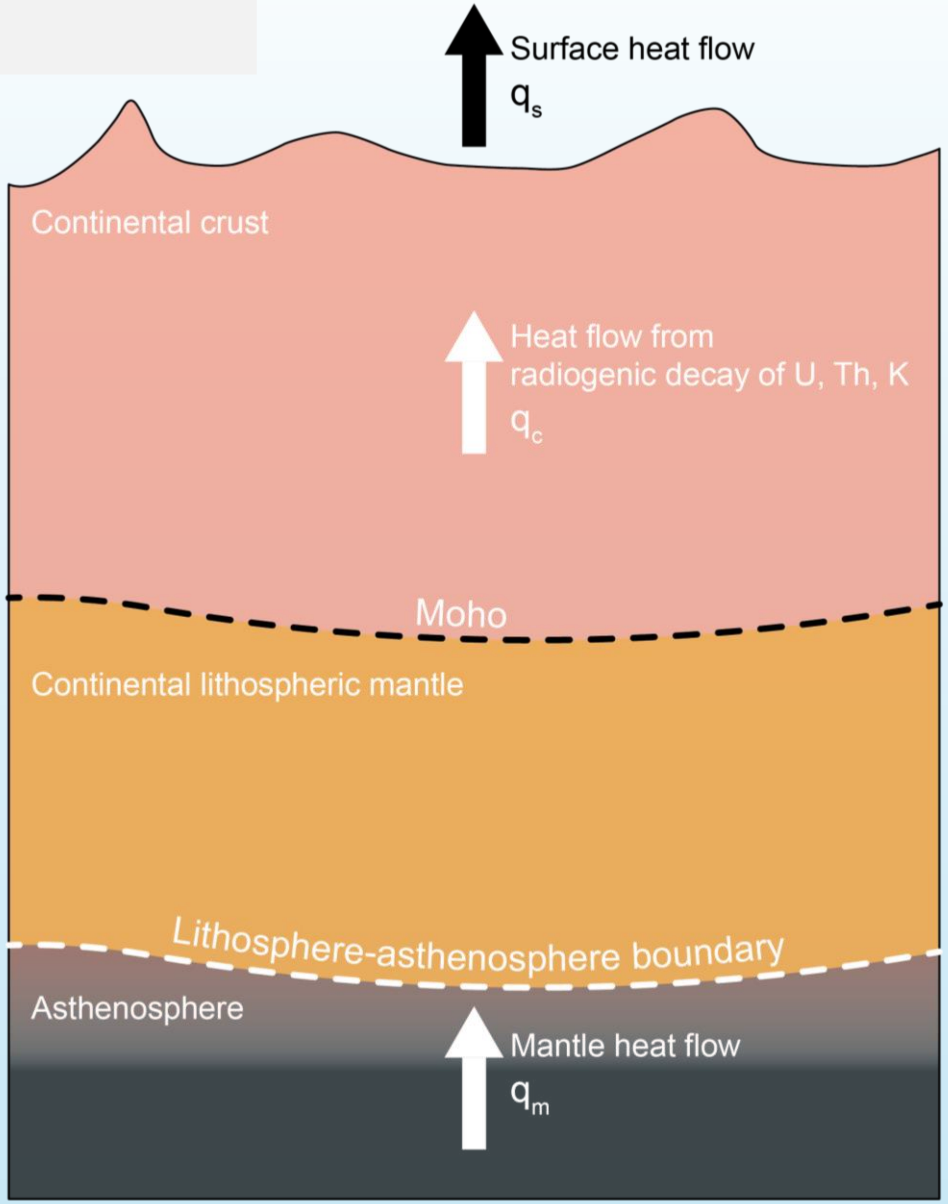
$$0 = \frac{d^2T}{dz^2}\frac{k}{\rho c_p} + \text{Heat source}$$

Heat flow (q):

$$q = -\frac{dT}{dz}k$$

Surface heat flow (q_s):

$$q_s = q_c + q_m$$



Thermal modeling for the continental lithosphere

Surface heat flow (q_s):

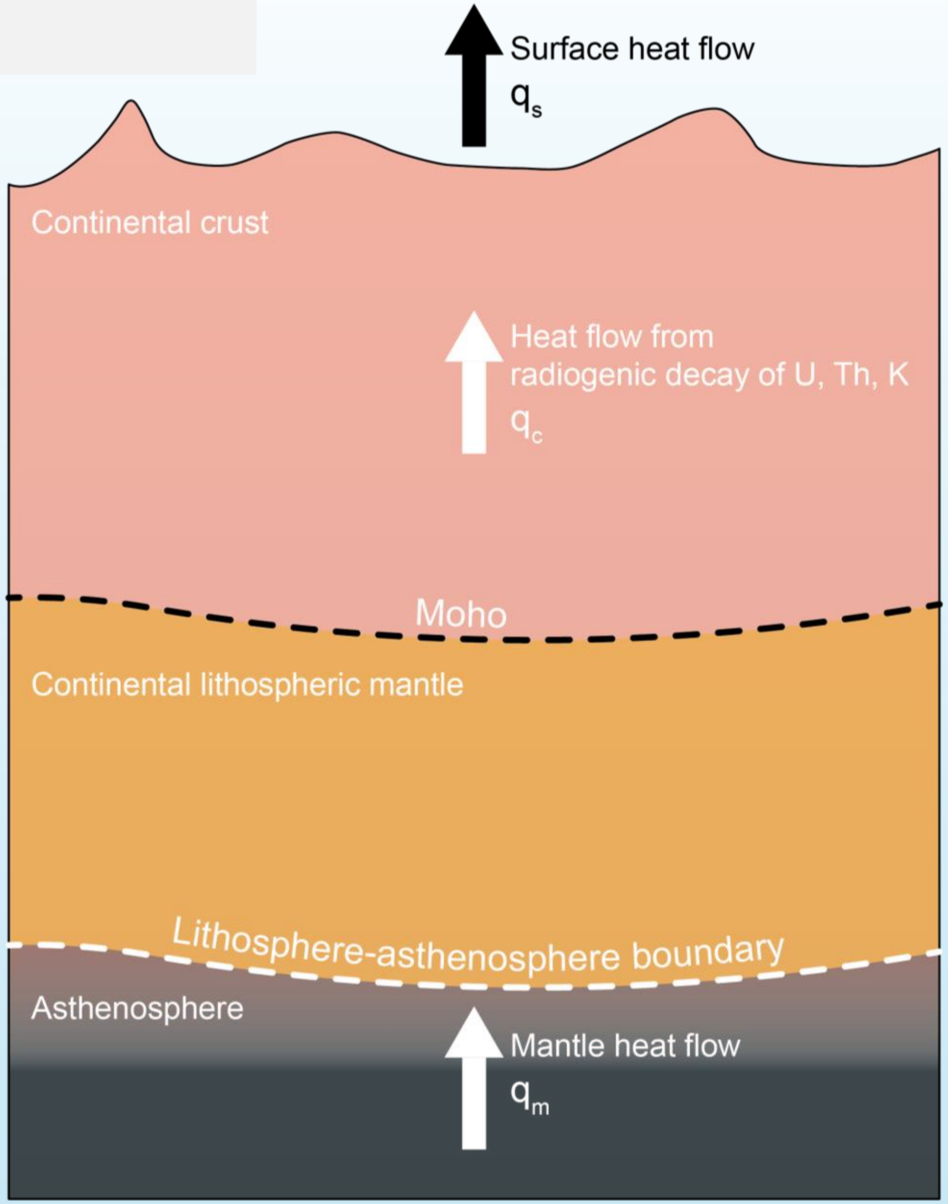
$$q_s = q_c + q_m$$

Empirical heat flow relationship (a.k.a geotherm families)

$q_c \approx 0.26–0.4\ q_s$

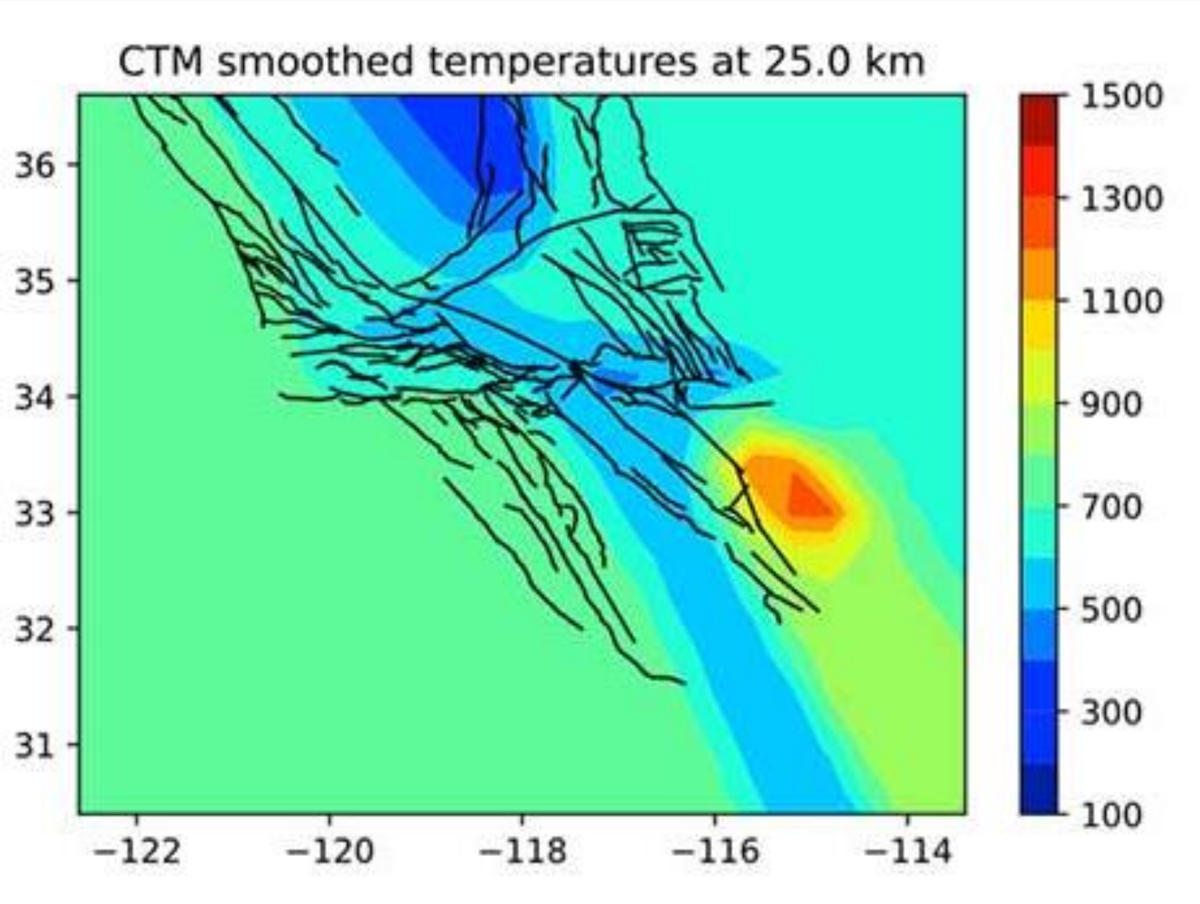
$q_m \approx 0.6–0.74\ q_s$

Pollack and Chapman (1977 *Tectonophysics*)
Vitorello and Pollack (1980 *JGR SE*)
Artemieva and Mooney (2001 *JGR SE*)
Hasterok and Chapman (2011 *EPSL*)

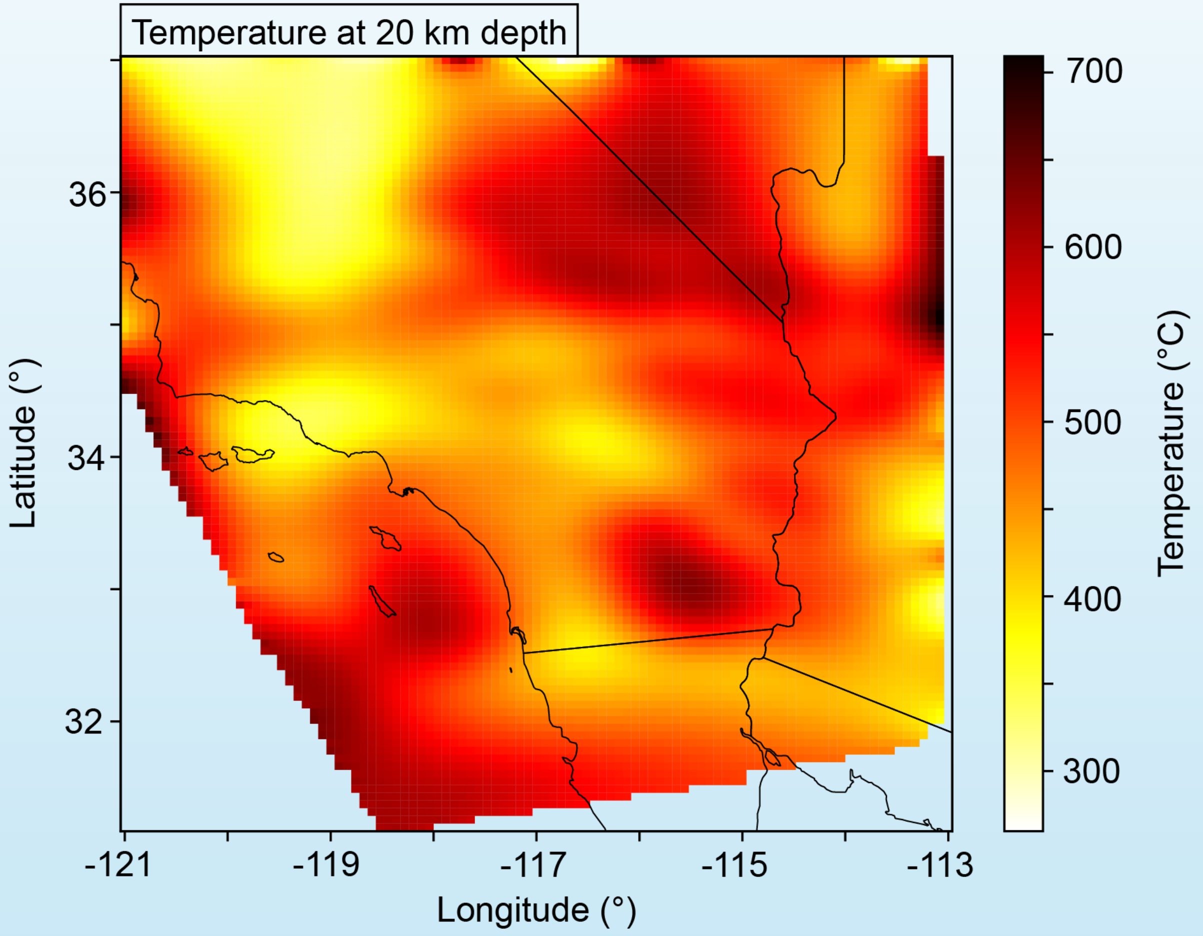


Southern California CTMs

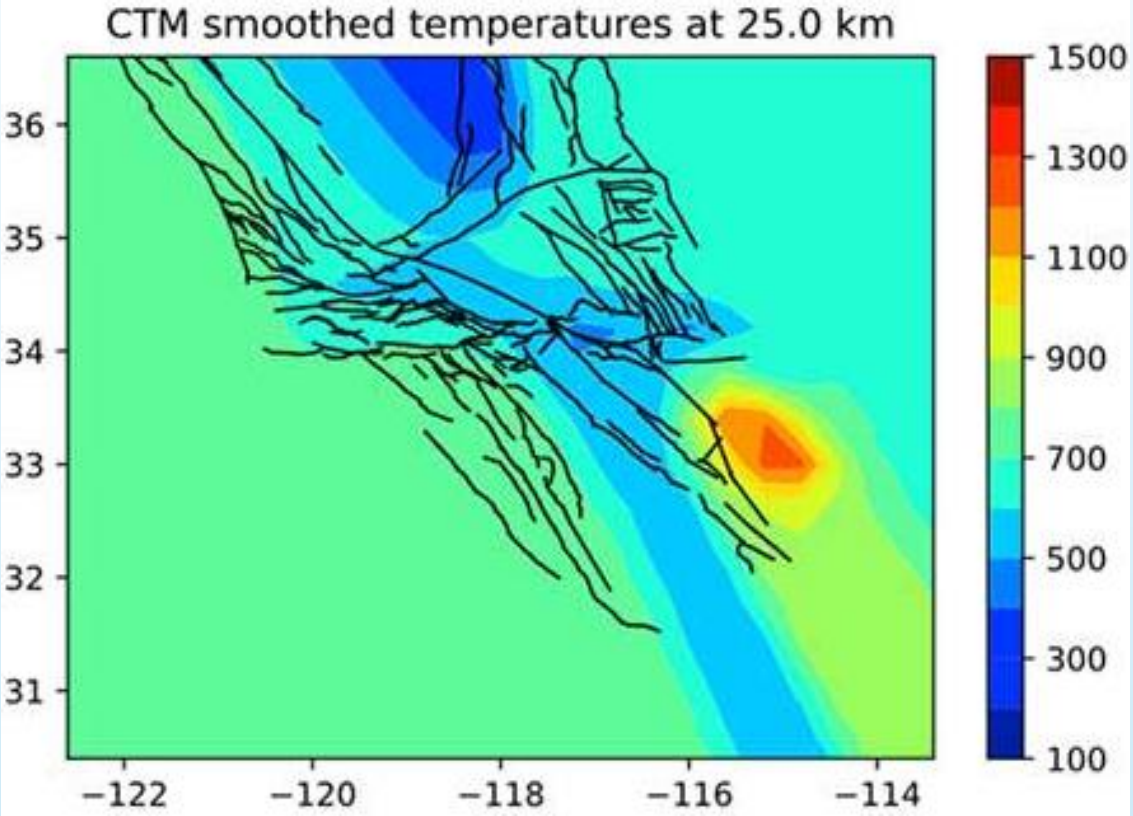
Thatcher and Chapman (2020)



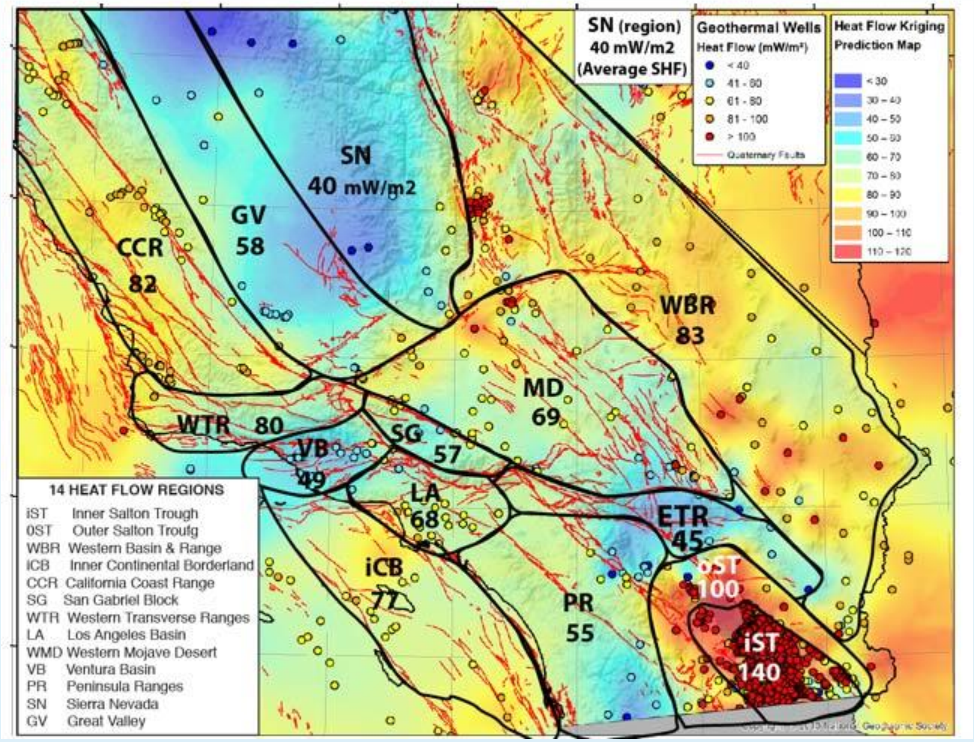
Shinevar et al. (2018)



Thatcher and Chapman (2020) model



14 surface heat flow (q_s) regions



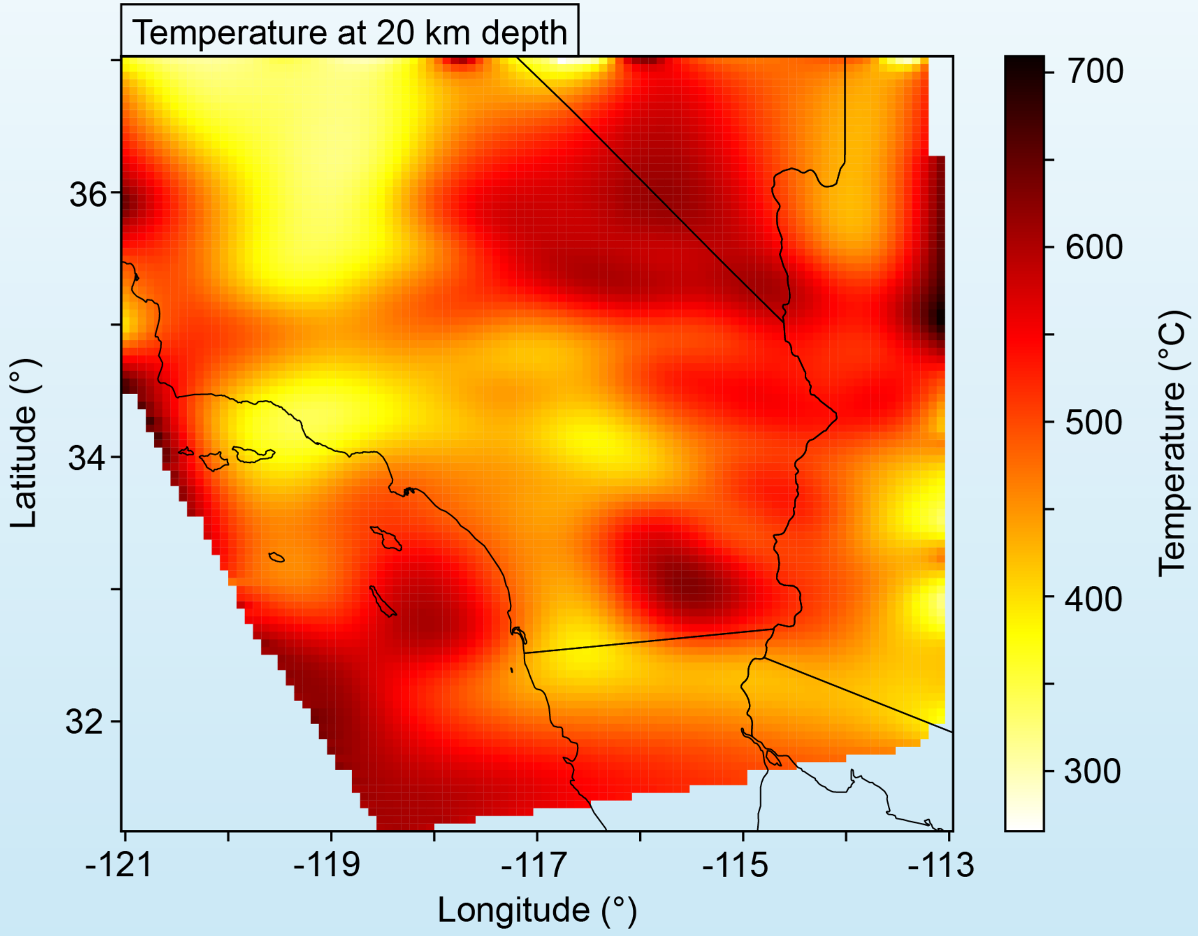
Williams and DeAngelo (2011 *GRC Transactions*)

- 1D conductive geotherm at each heat-flow province
  - Assume heat flow relationship
    - $q_c = 0.4\ q_s$
    - $q_m = 0.6\ q_s$

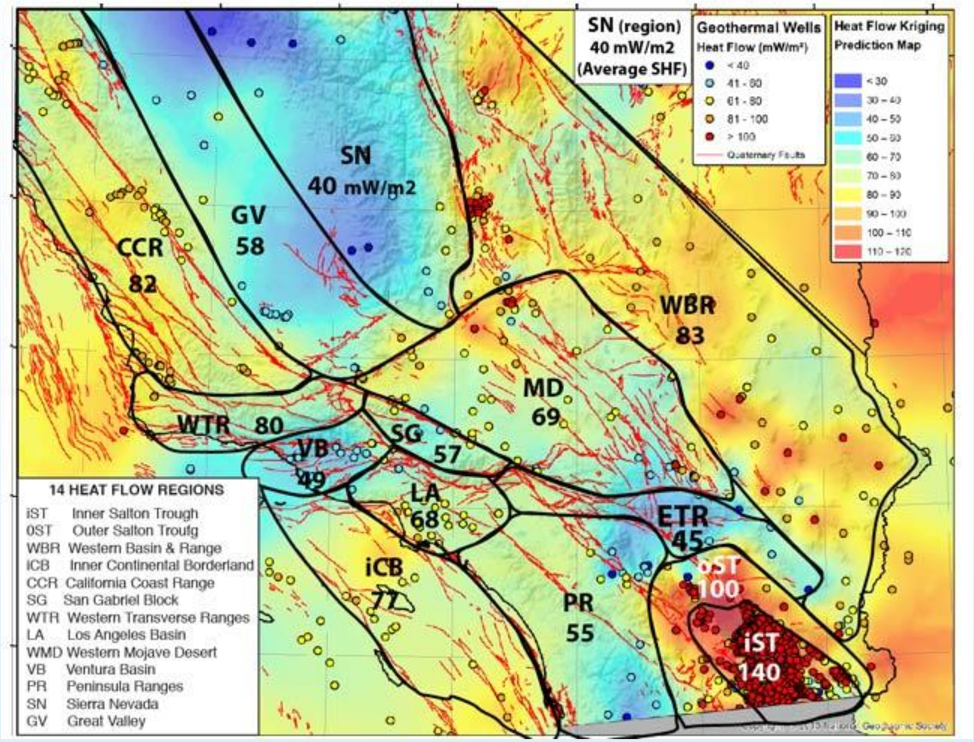
Pollack and Chapman (1977 *Tectonophysics*)

- Constrain non-steady state heat transport condition with seismic lithospheric thickness
  - Basal heating by the asthenosphere

Shinevar et al. (2018) model



Interpolated heat flow model



Williams and DeAngelo (2011 *GRC Transactions*)

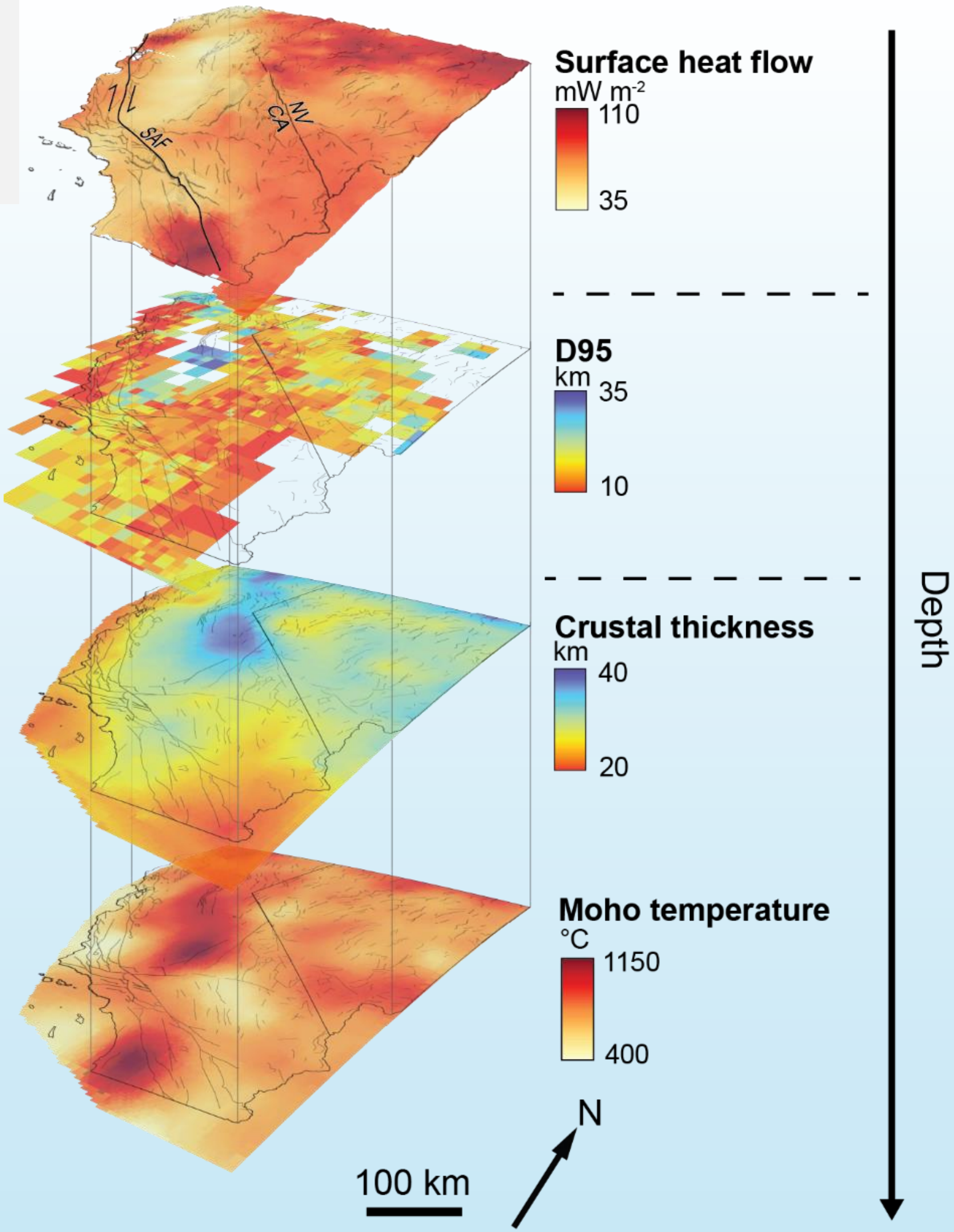
- Leverage smoothed heat flow model to calculate 1D vertical conductive geotherms
- Assume heat flow relationship
  - $q_c = 0.4\ q_s$
  - $q_m = 0.6\ q_s$

Pollack and Chapman (1977 *Tectonophysics*)

New statewide CTM—different approach

Temperature proxies through the crustal column

- Surface heat flow (Mordensky et al., 2023 *Geothermics*)
- New seismogenic thickness (D95) model
- Crustal thickness (Buehler and Shearer, 2017 *JGR SE*)
- Moho temperature (Schutt et al., 2018 *Geology*)



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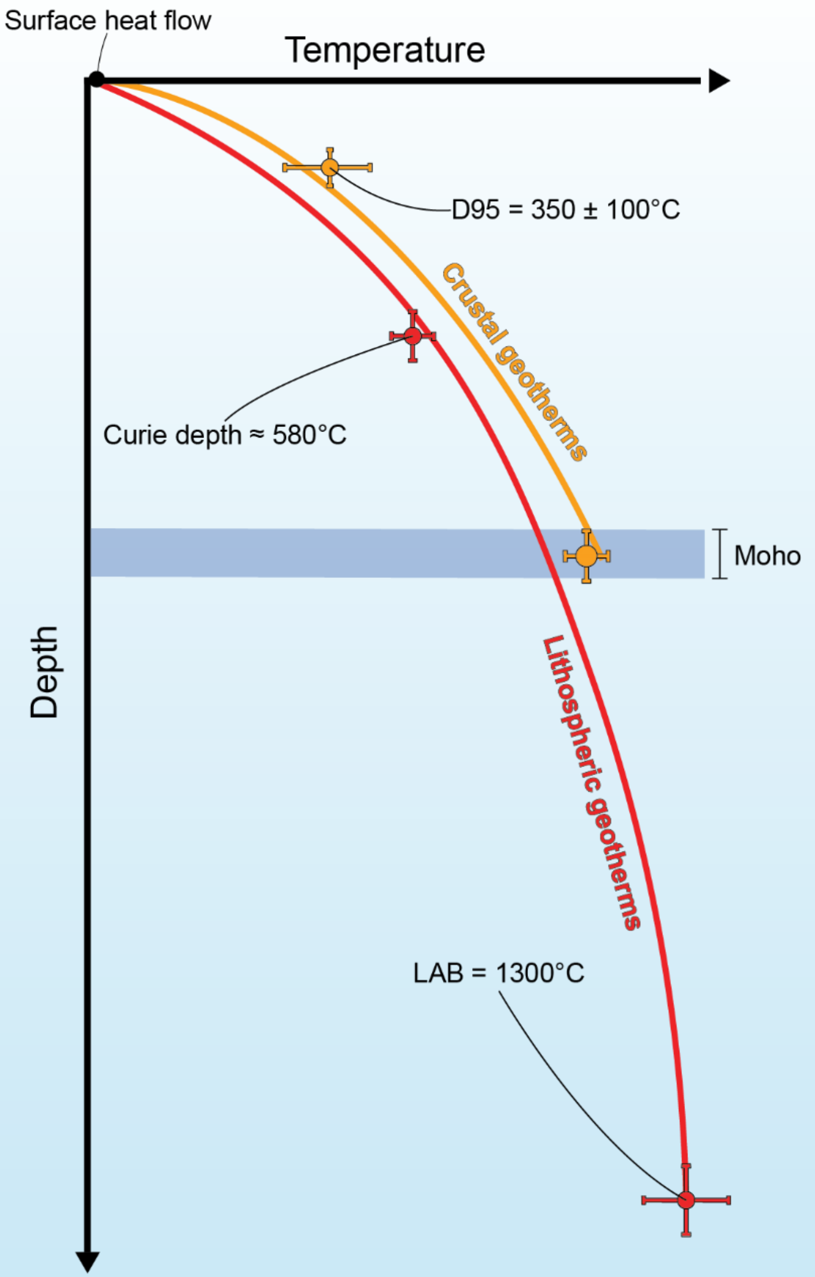


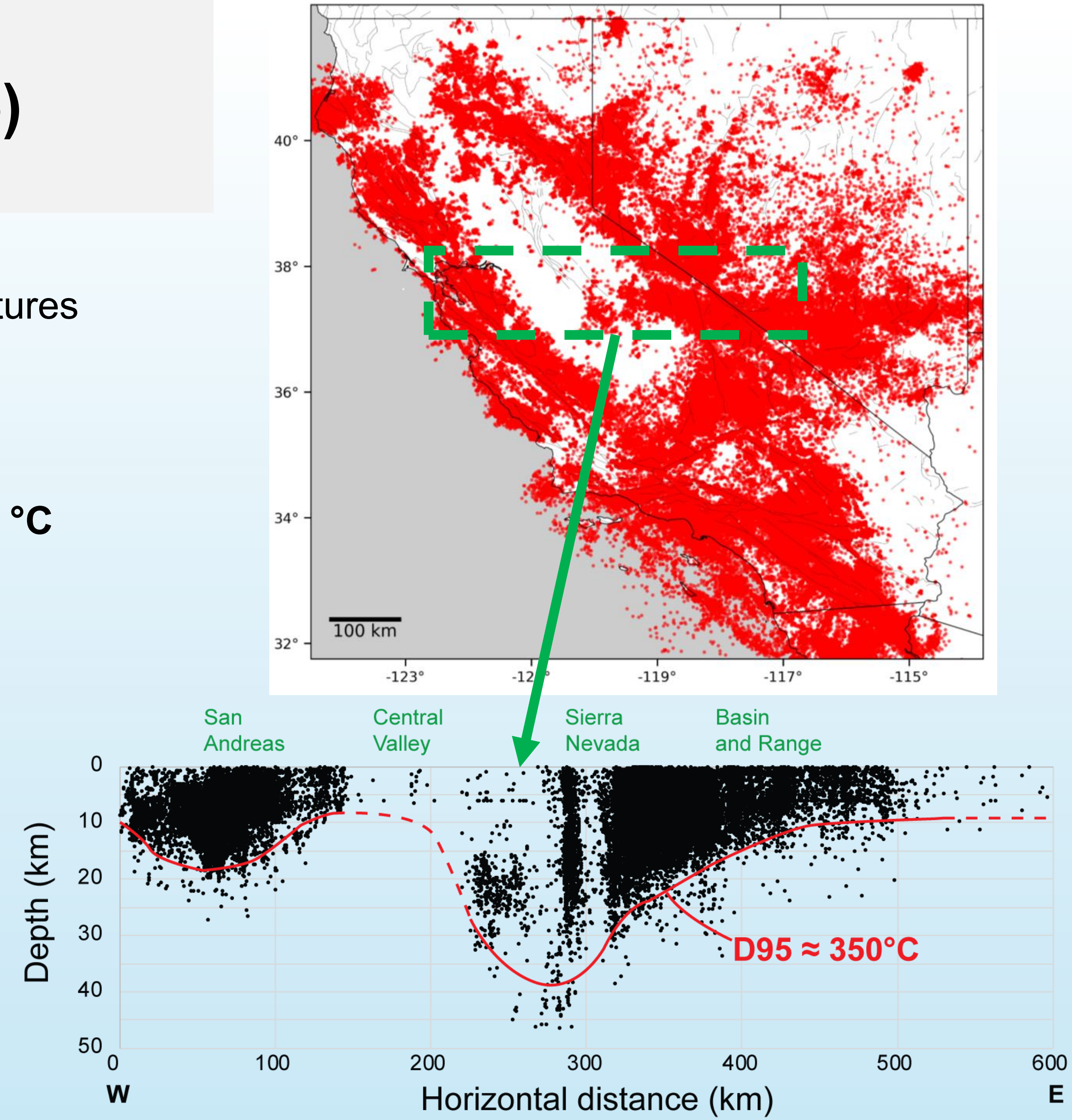
New seismogenic thickness (D95)

95th percentile of the hypocenter distribution **(D95)** captures the seismogenic thickness

- **D95 ≈ BDT ≈ 350 ± 100 °C**
- **Quartz and feldspar become ductile at ~ 350 °C**

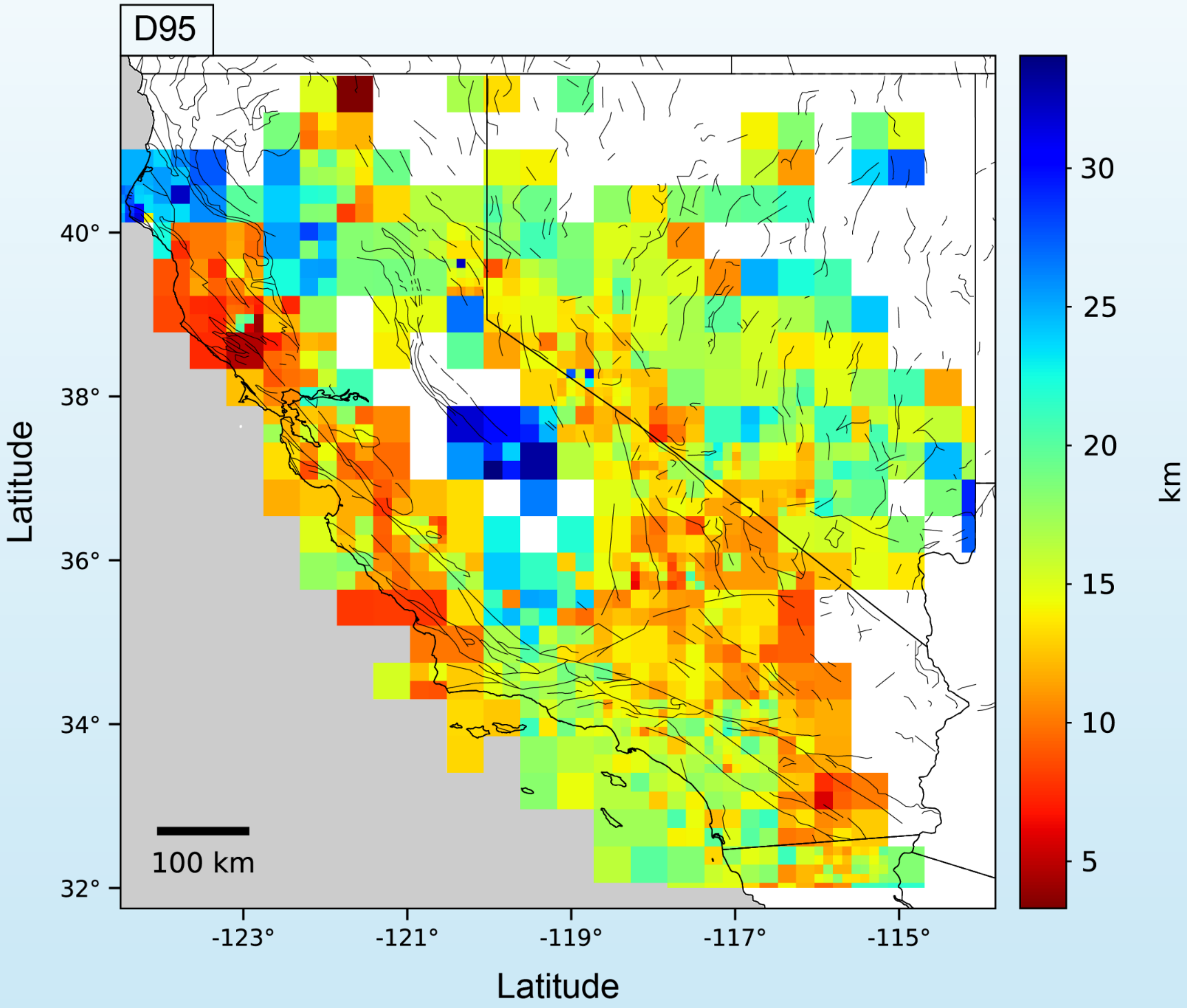
Merged >40 years of earthquake records from:

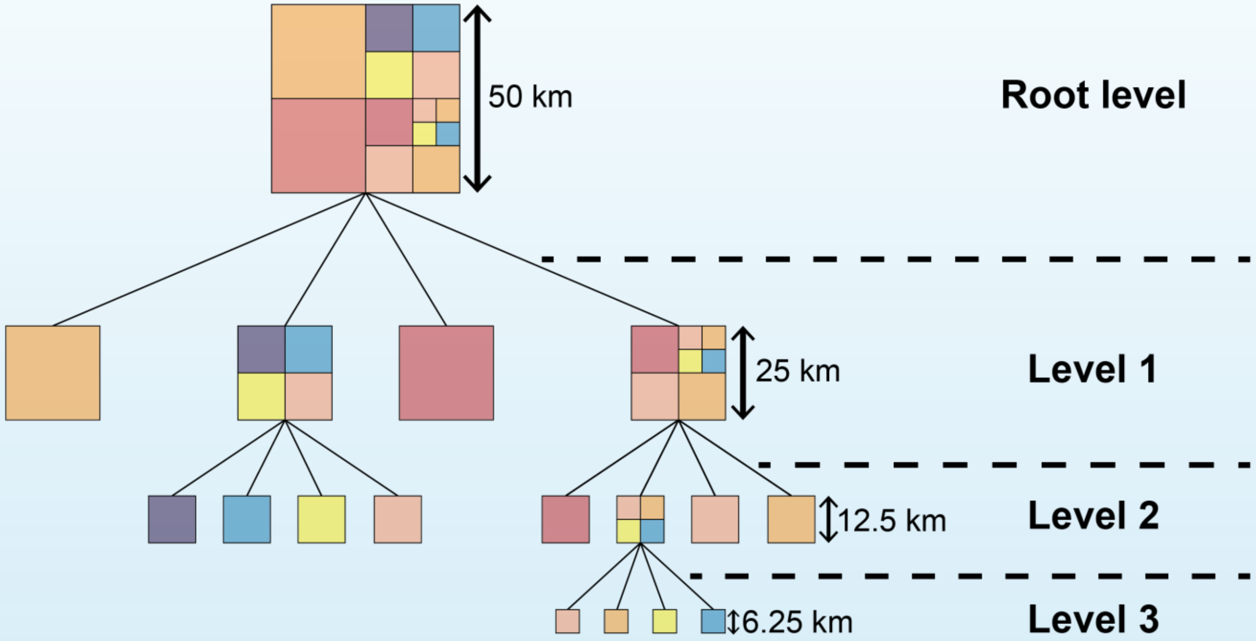
- 1984-2024 Northern California
  (Waldhauser and Schaff, 2008 *JGR SE*; Waldhauser, 2009 *BSSA*)
- 1981-2023 Southern California
  (Hauksson et al., 2012 *BSSA*)
- 1980-2024 Nevada
  (Trugman, 2023 *Zenodo*; 2024 *SRL*)



Modified from Zuza and Cao (2020 *Tectonophysics*)

Adaptive binning for D95 model





Adaptively sized bin — **quad tree structure**
(Finkle and Bentley, 1974 *Acta Informatica*)

- Bin width = **50 to 6.25 km**

Monte-Carlo sampling for the thermophysical parameters

Generate 100,000 samples of T_0, q_m, k, h, H_0 (100,000 **unique heat flow scenarios**)

Calculate 1D steady-state conductive geotherm for each scenarios

Accept geotherms based on these criteria:

1. q_s^{model} is ± 10 mW m-2 of heat flow observations
2. Normalized root mean square error (NRMSE) when compared to D95 and Moho condition

Don't follow a specific 'geotherm family'

T_0 (Surface temperature)	0 to 20 [°C]
k (Thermal conductivity)	2 to 5 [W m^{-1} °C^{-1}]
h (Radiogenic heating decay length)	0 to z_{Moho} / 2 [m]
H_0 (Surface radiogenic heat production)	1 to 10 [μW m^{-3}]
q_m (Mantle heat flow)	1 to 50 [mW m^{-2}]
$n_{simulation}$	100,000

$$q_s^{\text{model}} = q_{\text{m}} + \int_0^{z_{\text{m}}} H_0 \, e^{\frac{-z}{h}} dz$$

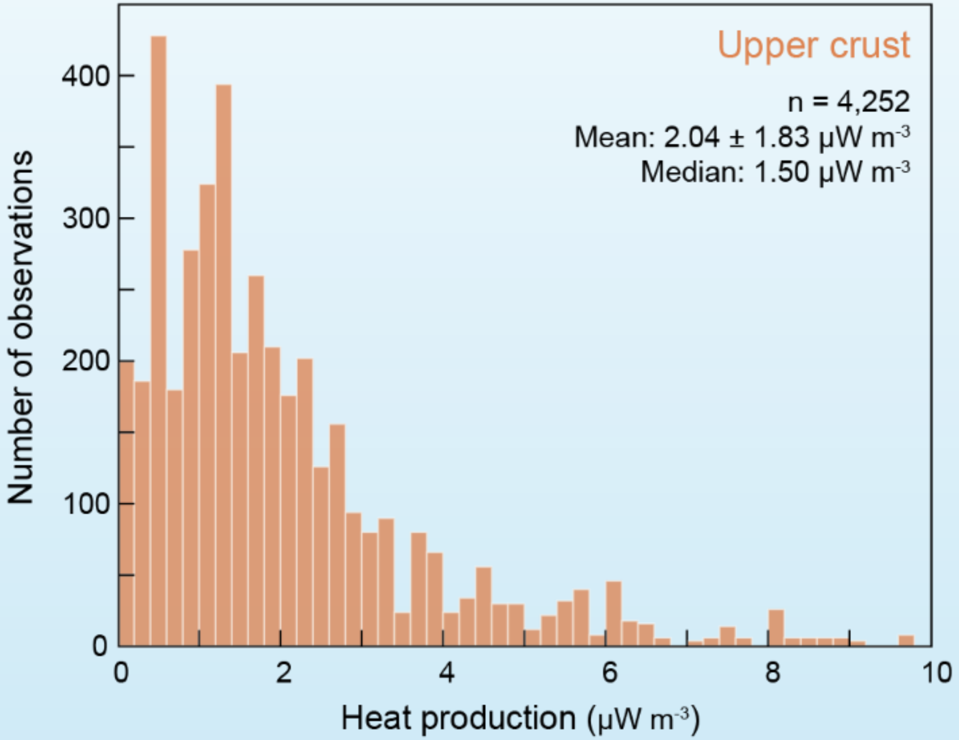
↓

$$T(z) = T_0 + \frac{q_{\text{m}} z}{k} + \frac{\left(q_s^{\text{model}} - q_{\text{m}}\right) h}{k} \left(1 - e^{-z/h}\right)$$

Turcotte and Schubert (2014)

Monte-Carlo sampling for the thermophysical parameters

H_0 is typically <5 μW m^{-3}



Modified from Furlong and Chapman (2013 *Annual review of Earth and Planetary Sciences*)

T_0 (Surface temperature)	0 to 20 [°C]
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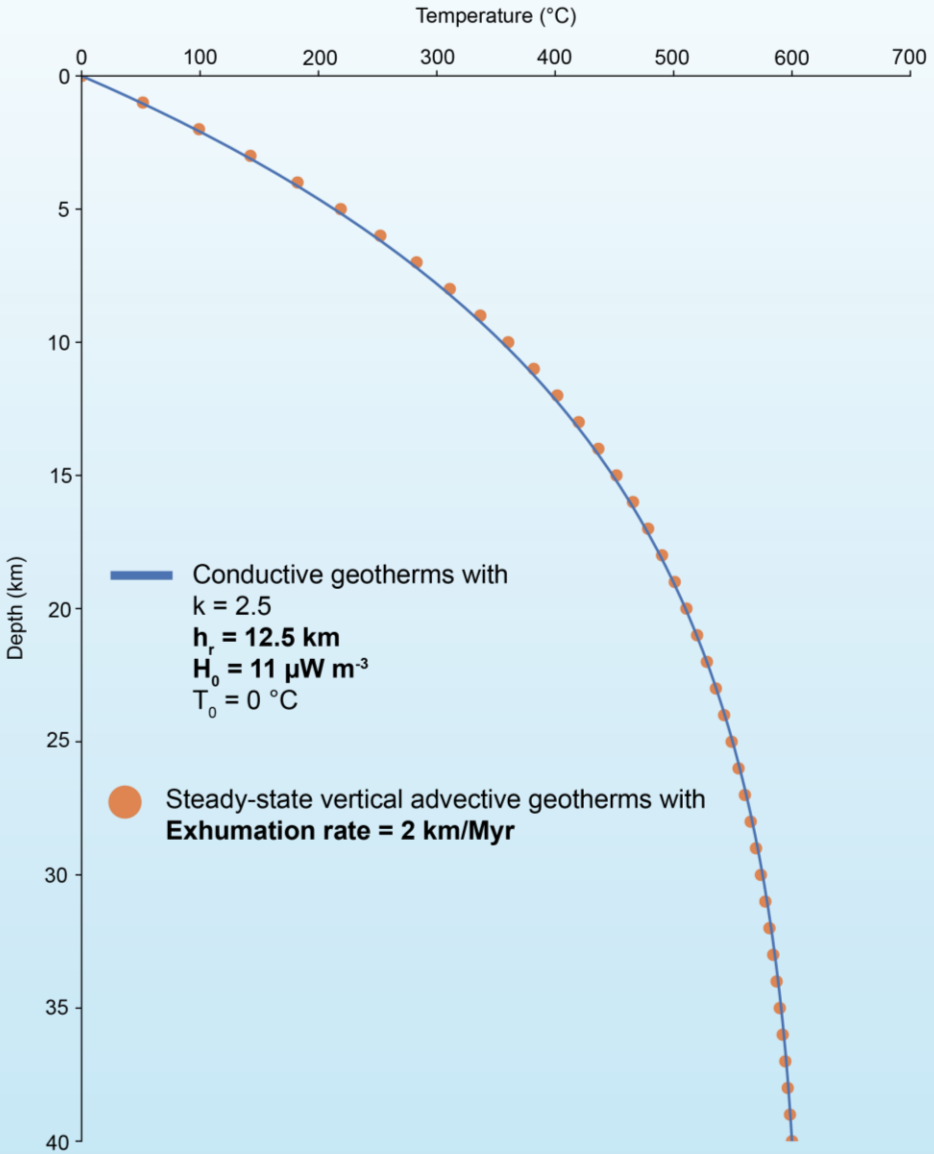

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Turcotte and Schubert (2014)

Monte-Carlo sampling for the thermophysical parameters

Accepted profiles (Red)

- NRMSE coefficient <0.35

Rejected profiles (Black)

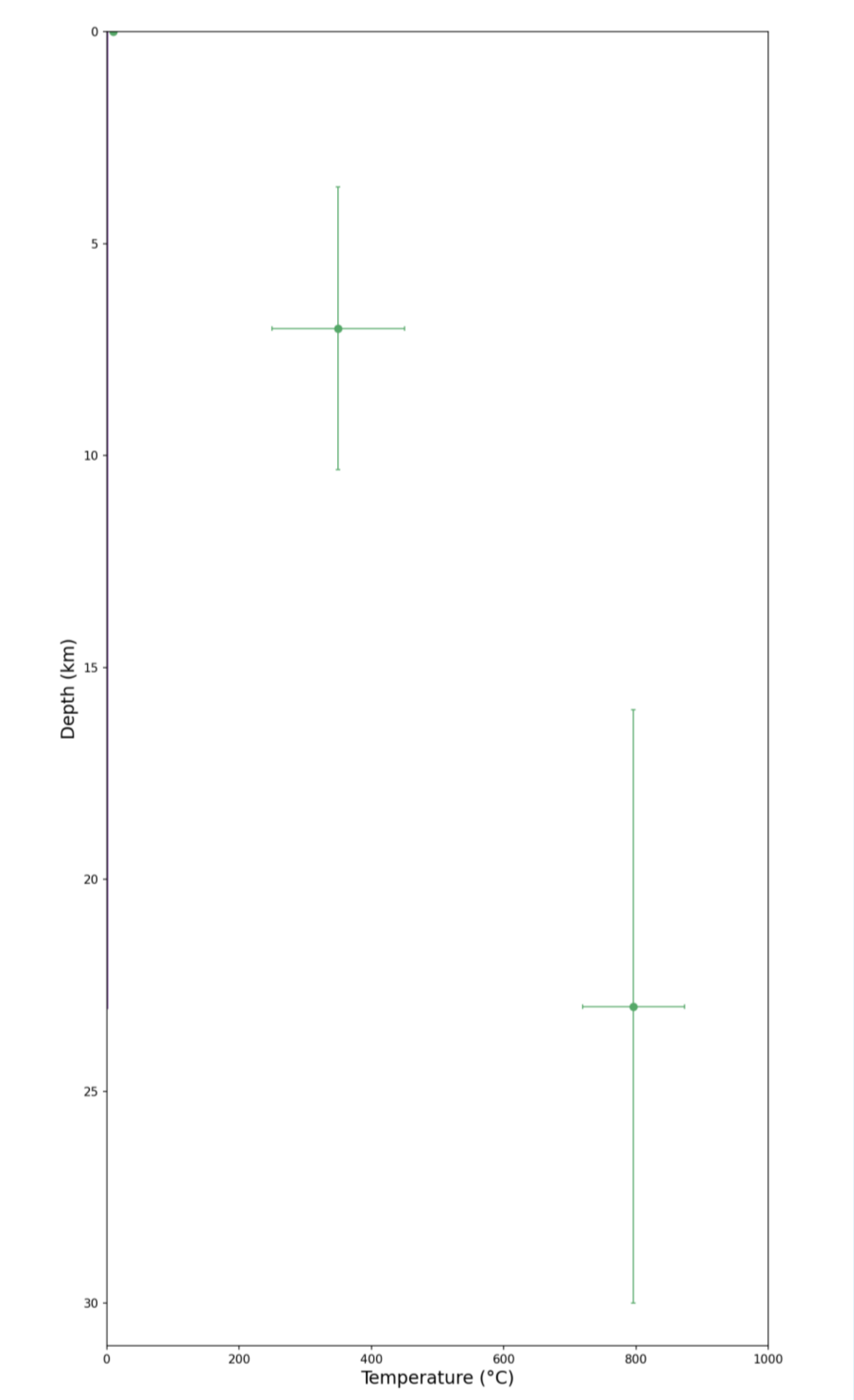
- NRMSE coefficient <0.55

Output profile (Orange)

- Mean of accepted profiles

Uncertainty (Blue envelope)

- Standard deviation of accepted profiles



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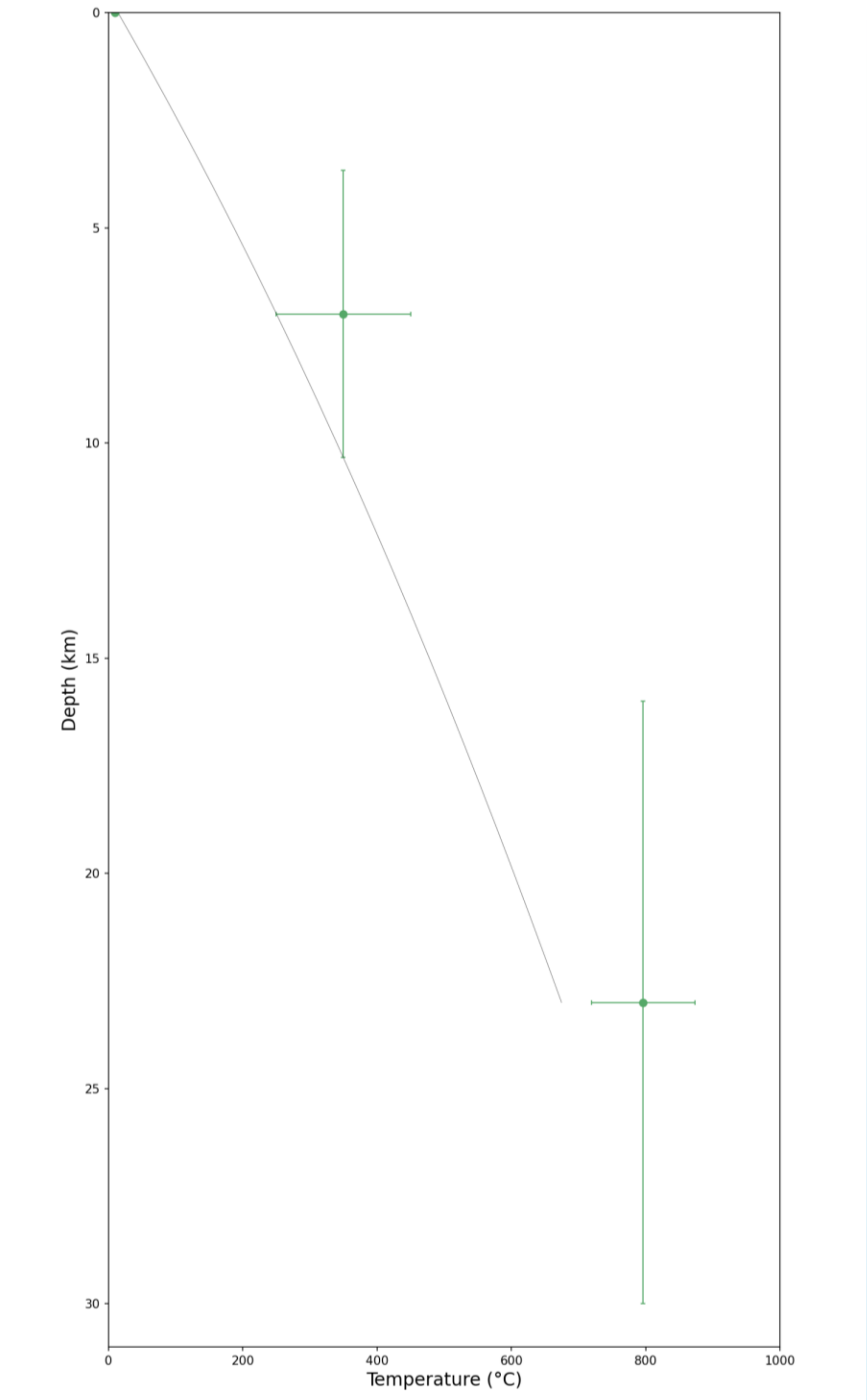
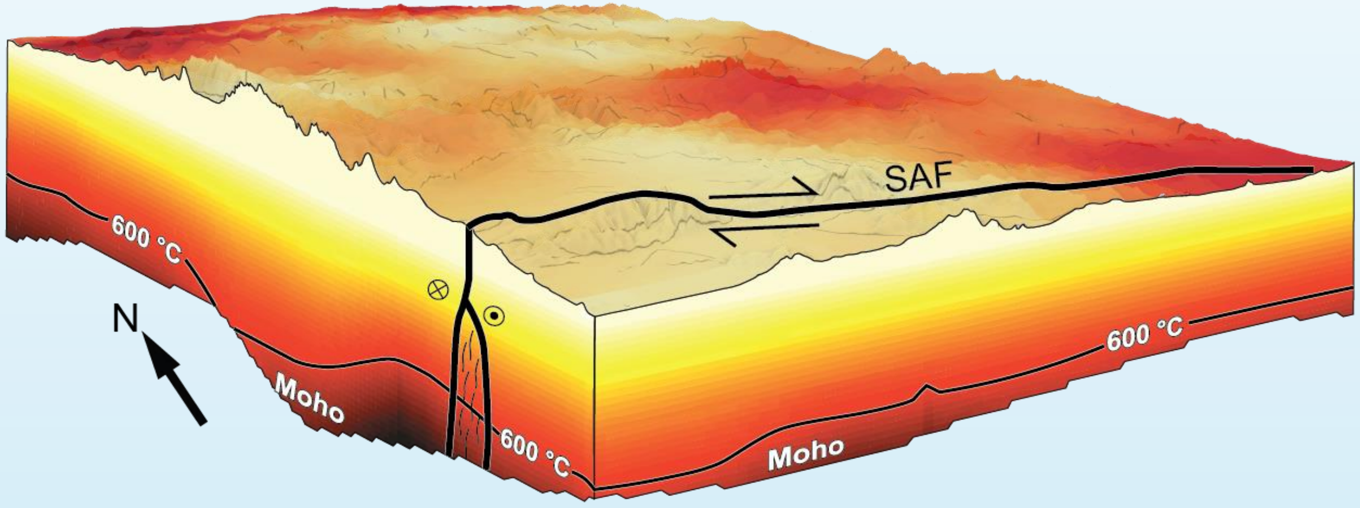
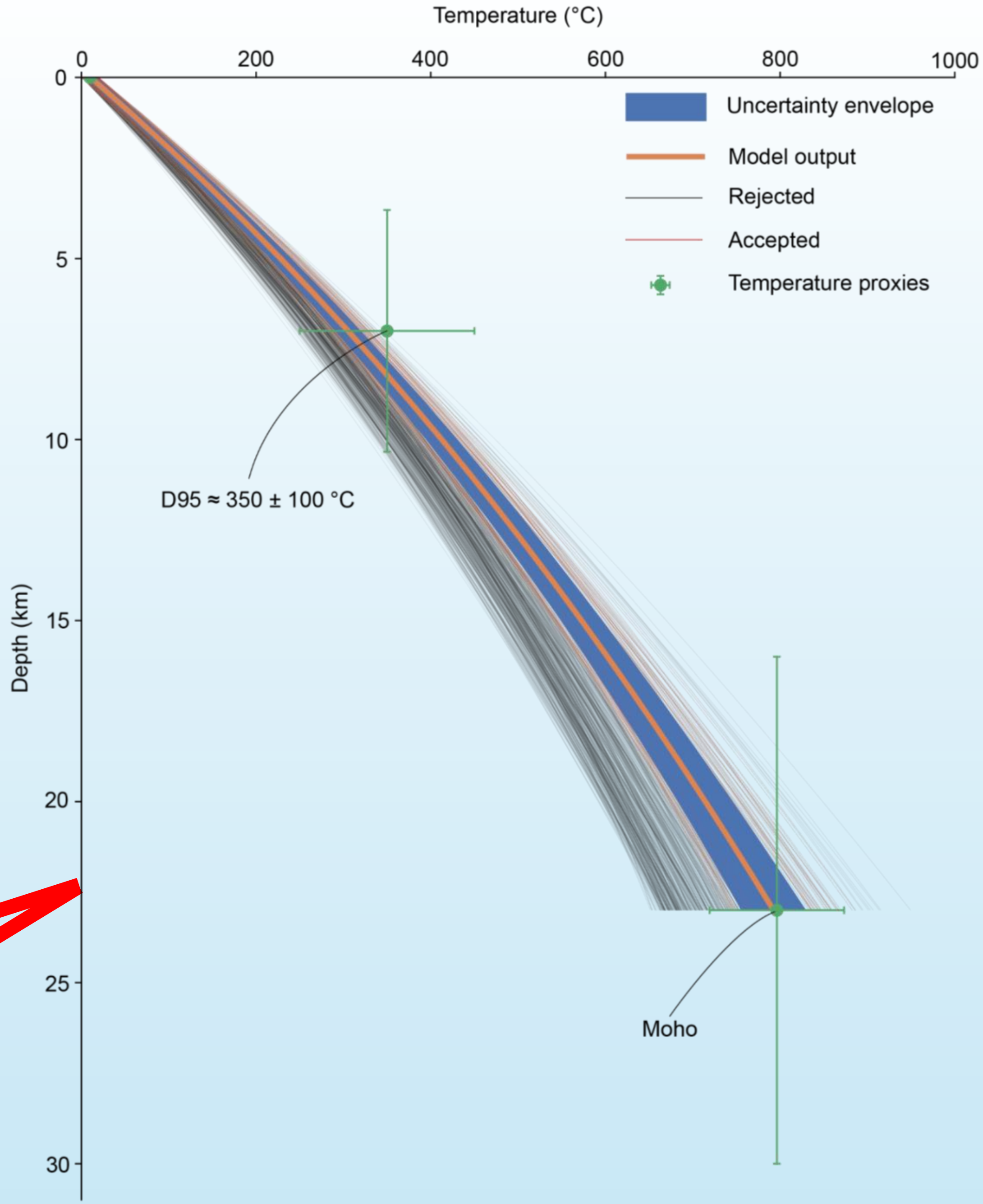


Monte-Carlo sampling for the thermophysical parameters

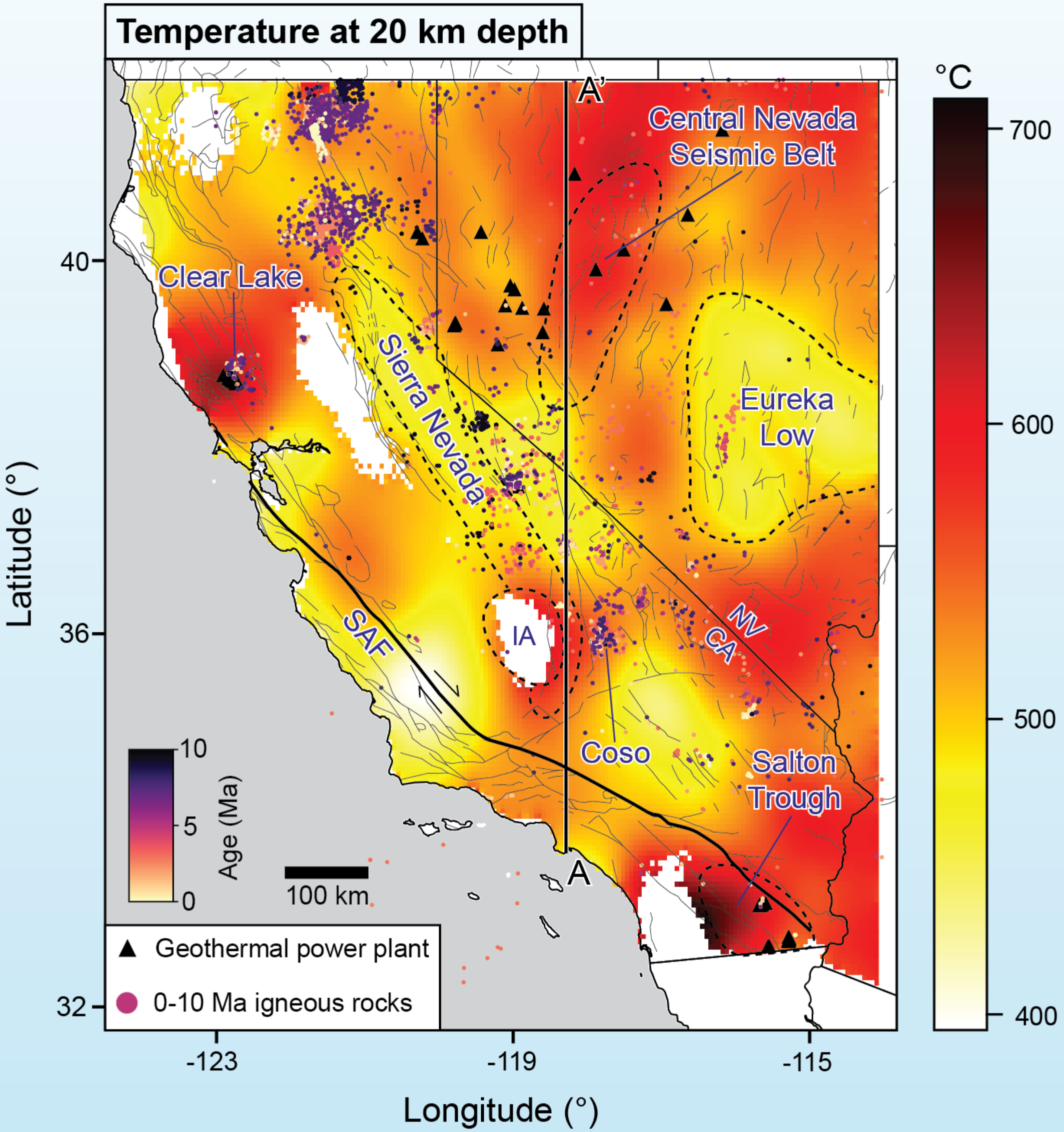


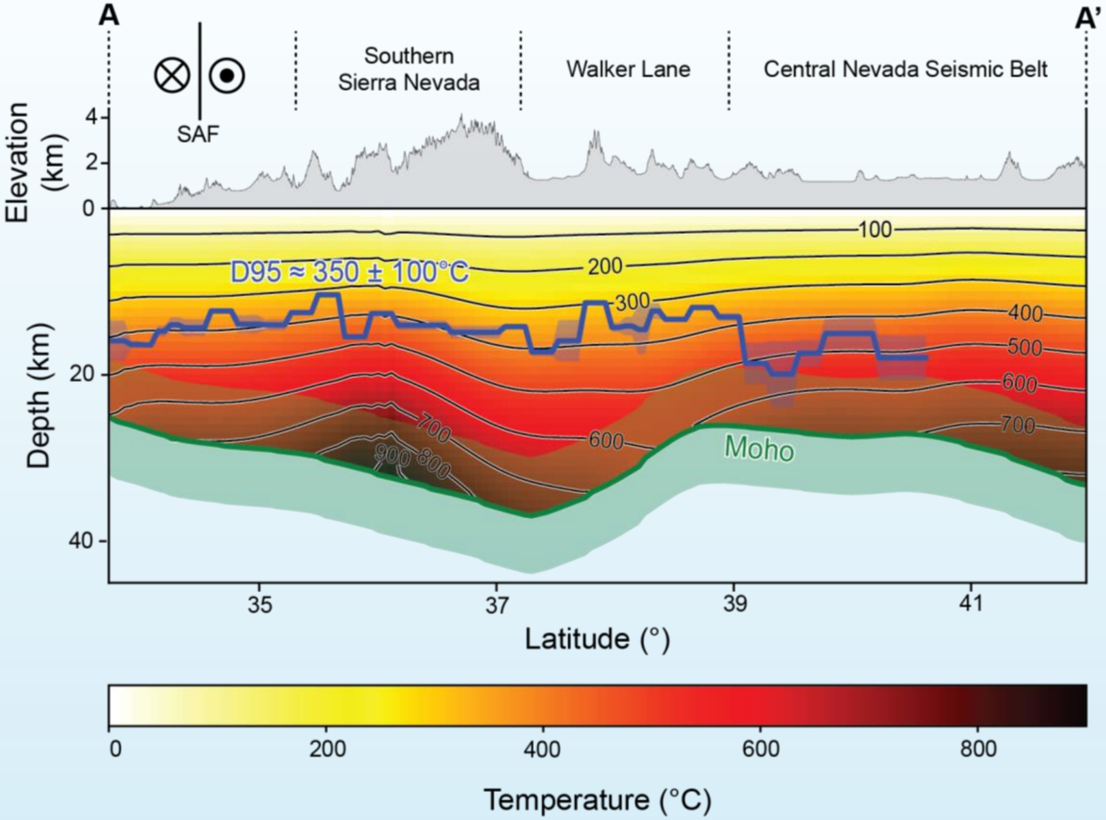


100,000 iterations at each pixel

Output of 1 pixel out of 25976 pixels

California-Nevada Statewide CTM

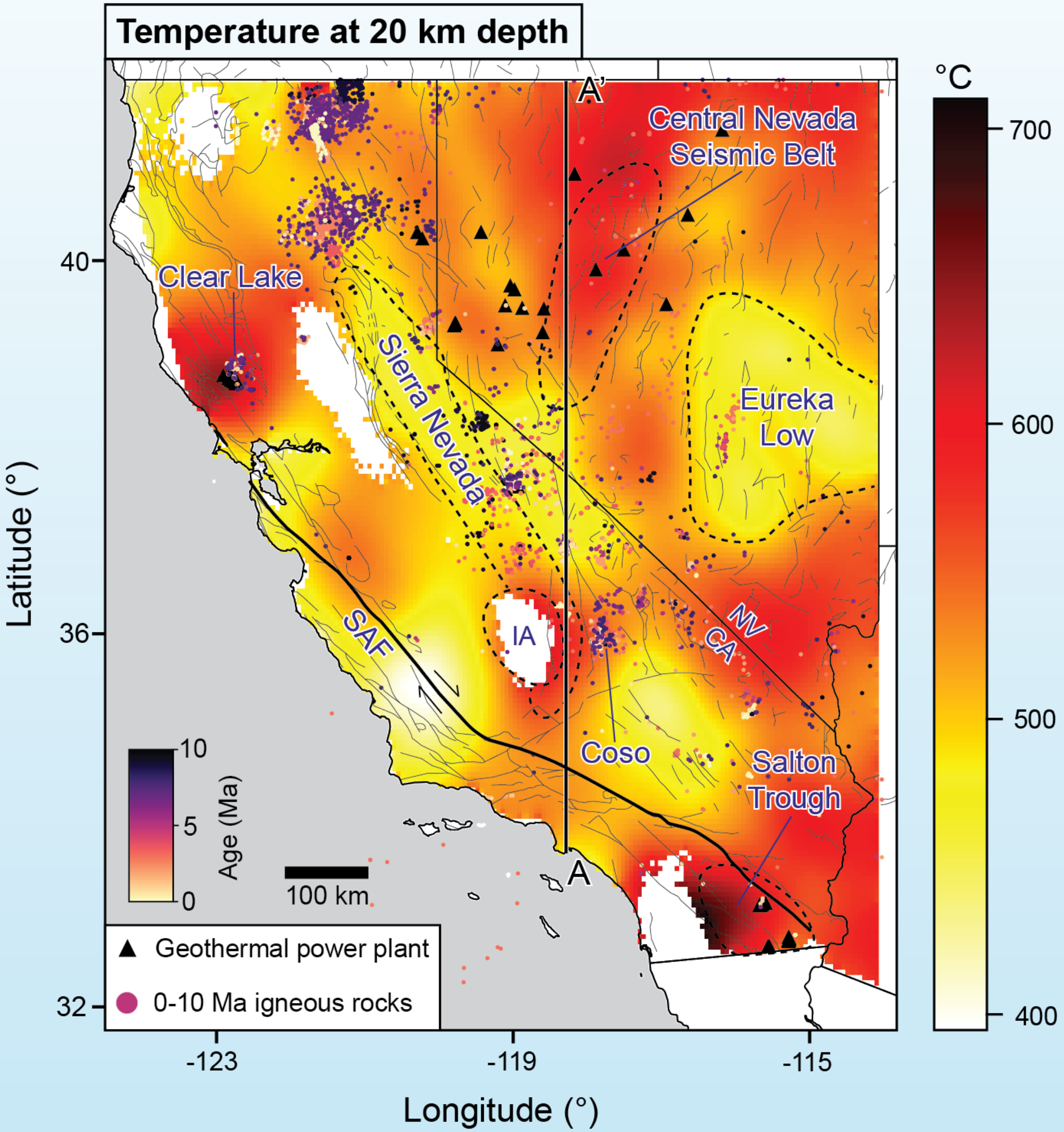


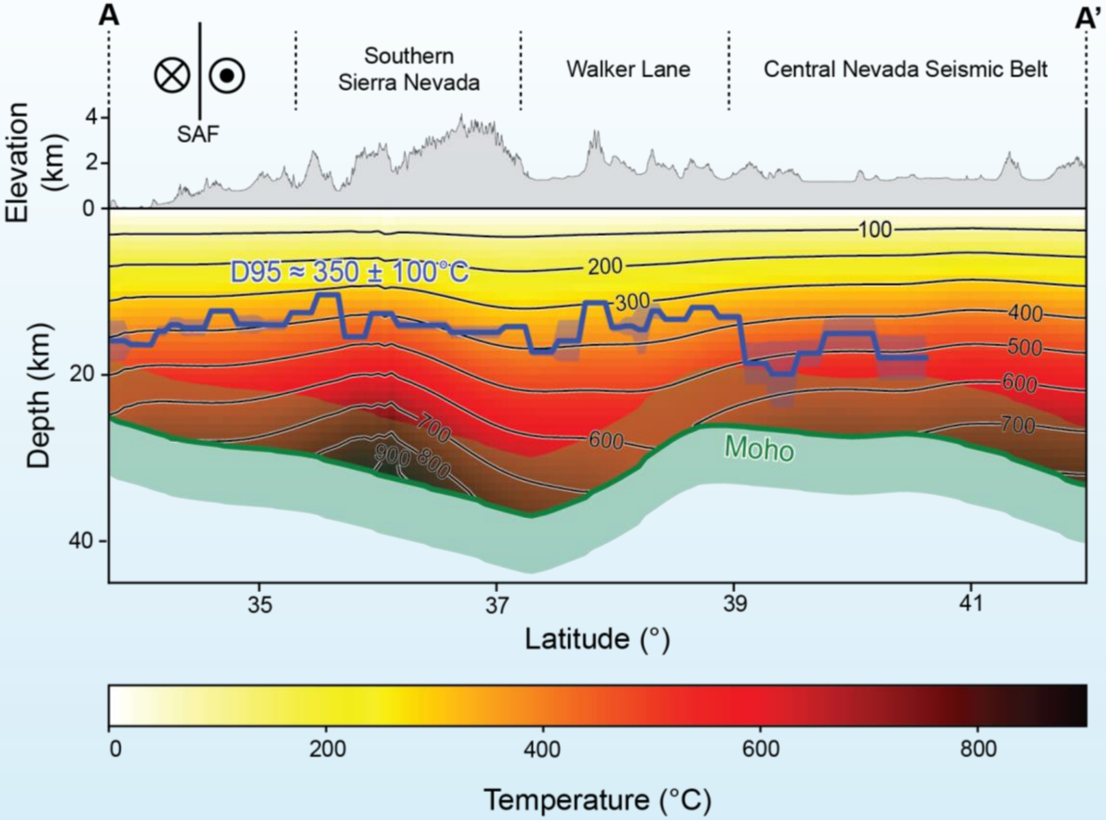


Elevated thermal gradient (>600 °C at 20 km):

- Salton Trough, Coso, Clear Lake, Central Nevada Seismic Belt

California-Nevada Statewide CTM

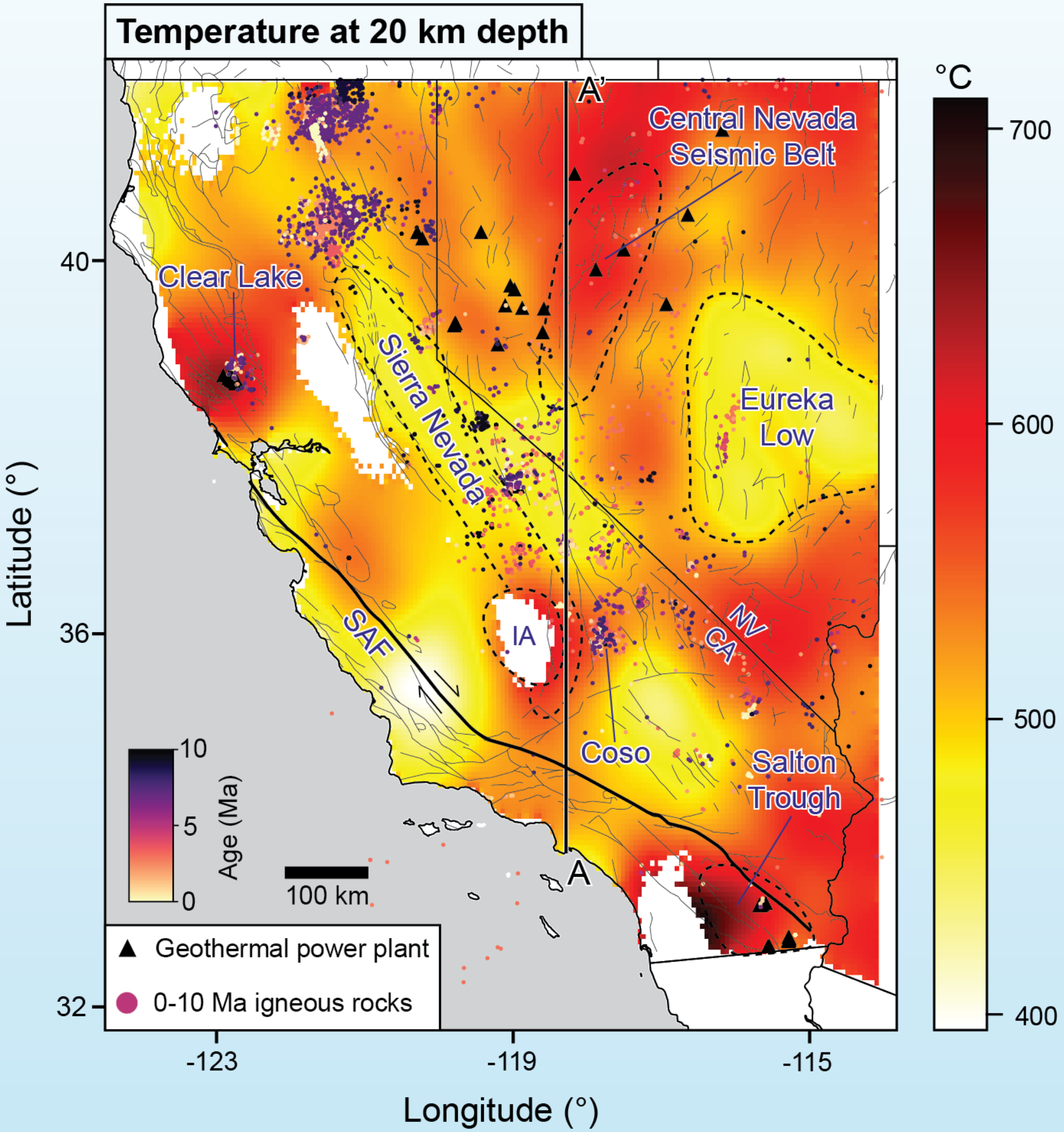


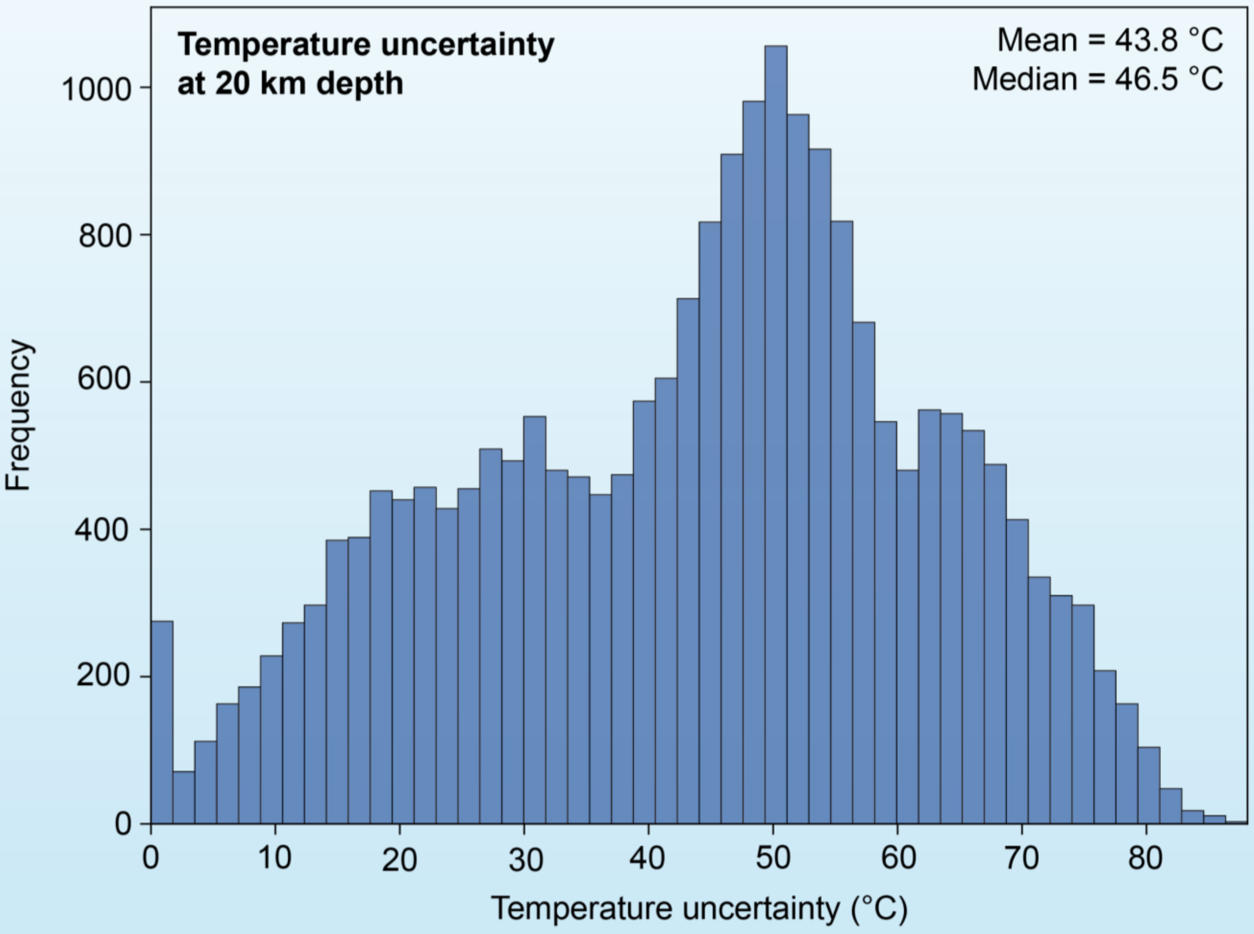


Low thermal gradient (<500 °C at 20 km):

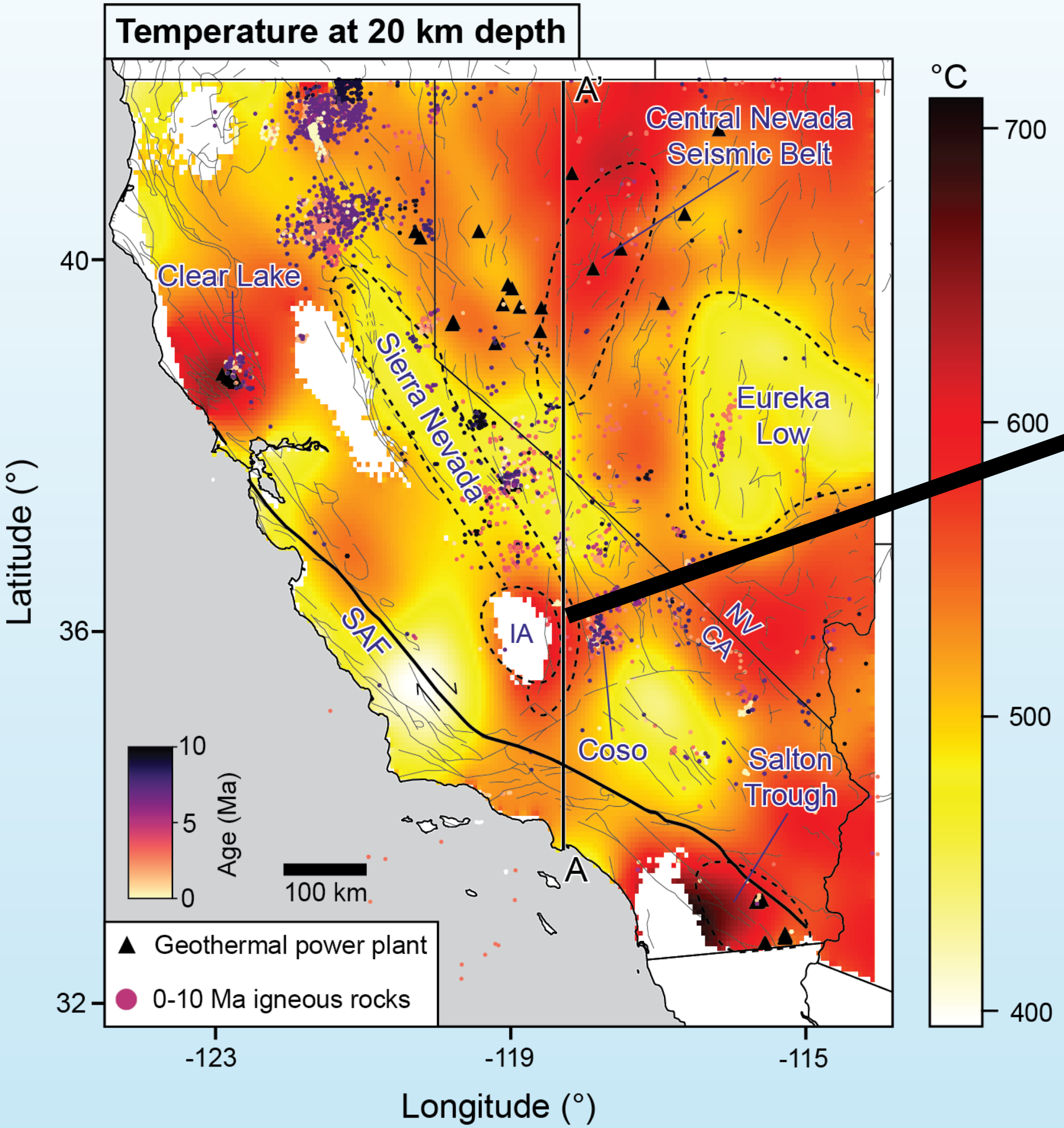
- Sierra Nevada, Mojave, Great Valley, Eureka Low

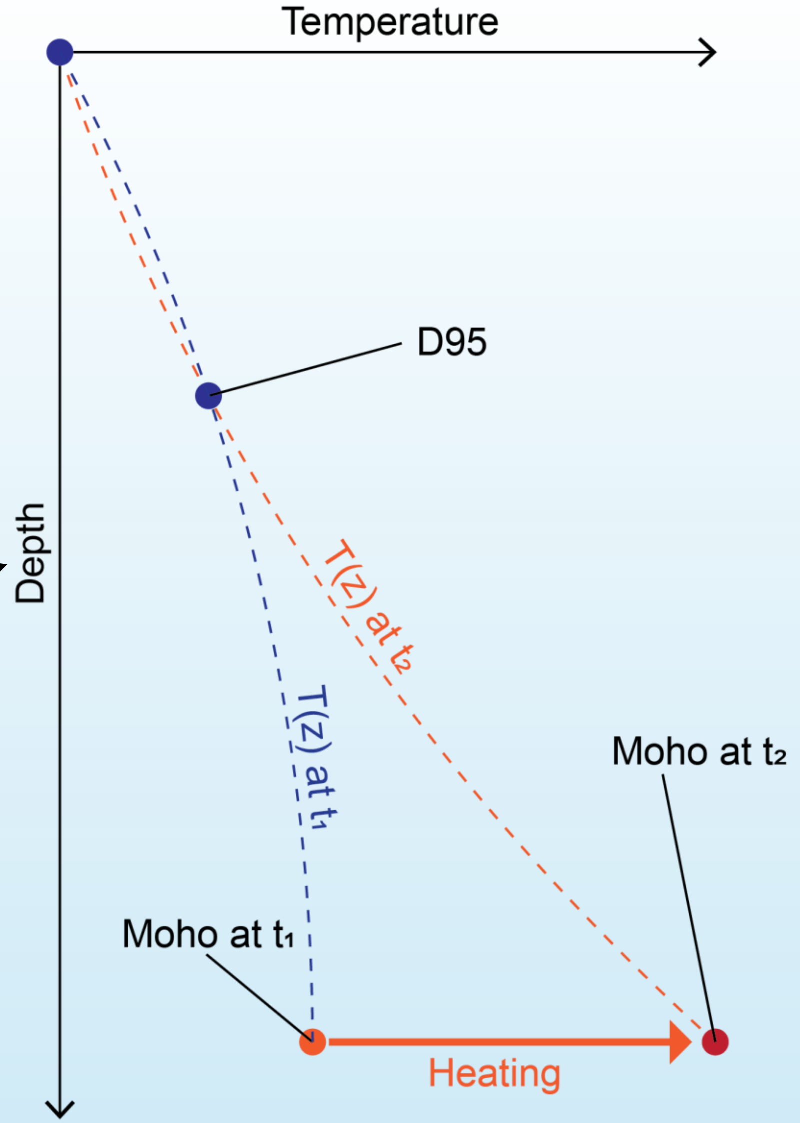
California-Nevada Statewide CTM





Null output: mapping non-steady-state





Basal heating due to lithospheric delamination (?)

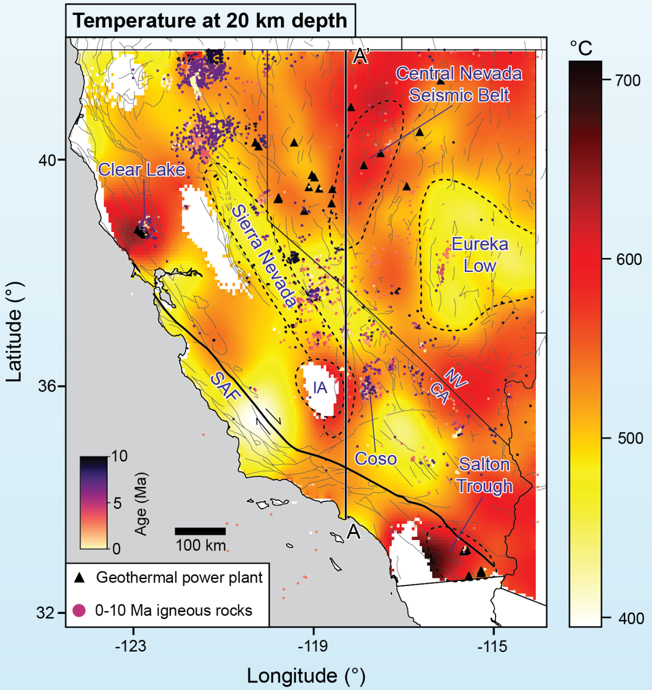
Zandt et al. (2004 *Nature*)

Boyd et al. (2004 *Science*)

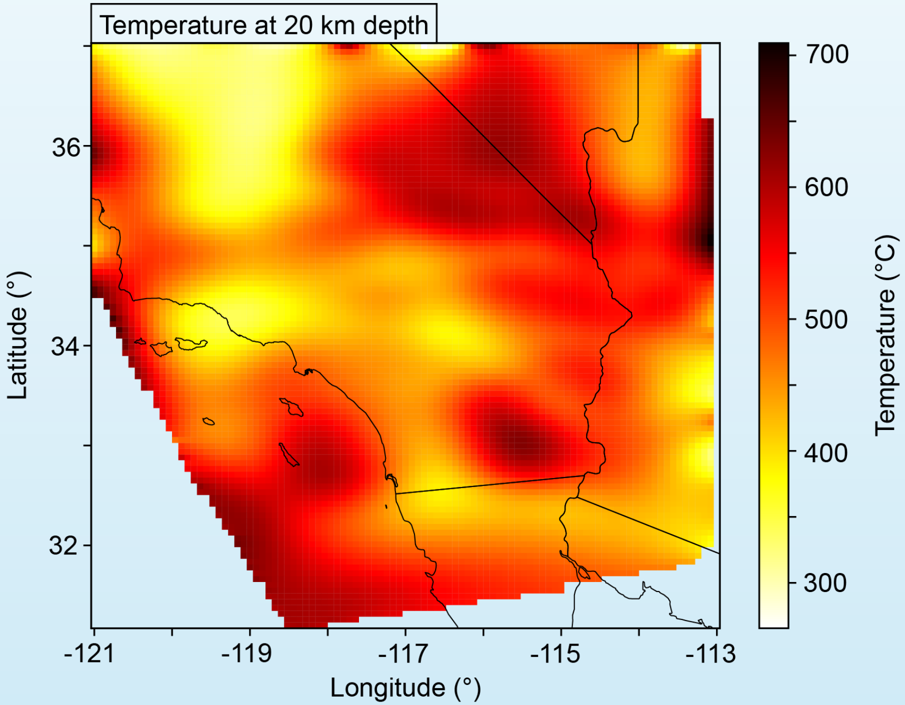
Thatcher and Chapman (2020 *SCEC*)

CTM comparison

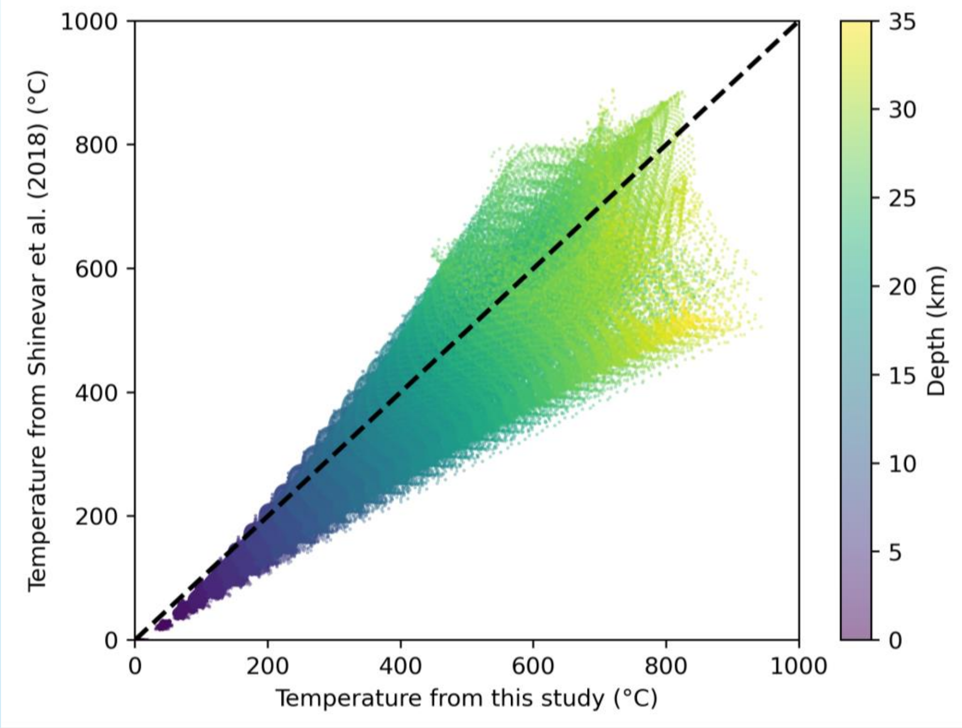
New statewide CTM:



Shinevar et al. (2018) CTM



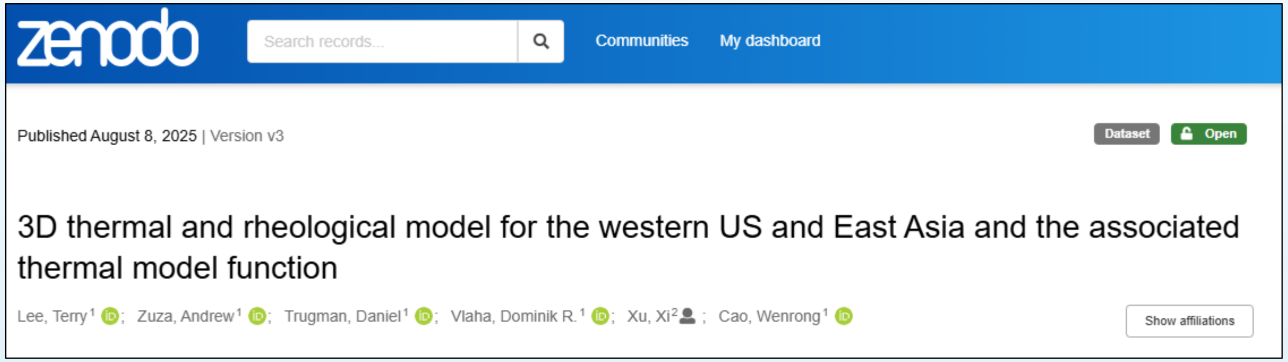
Comparison

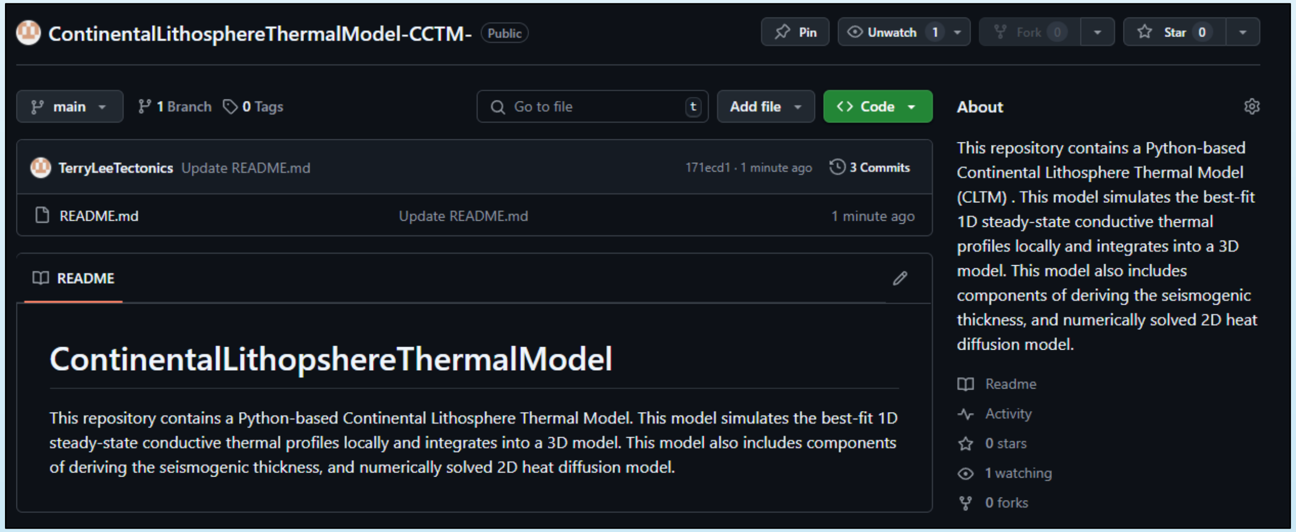


Pearson correlation = 0.95
Mean absolute error = 44.8 °C

Near one-to-one relationship
Our model yields temperatures that are ~50–100 °C higher

Open-sourced Python software



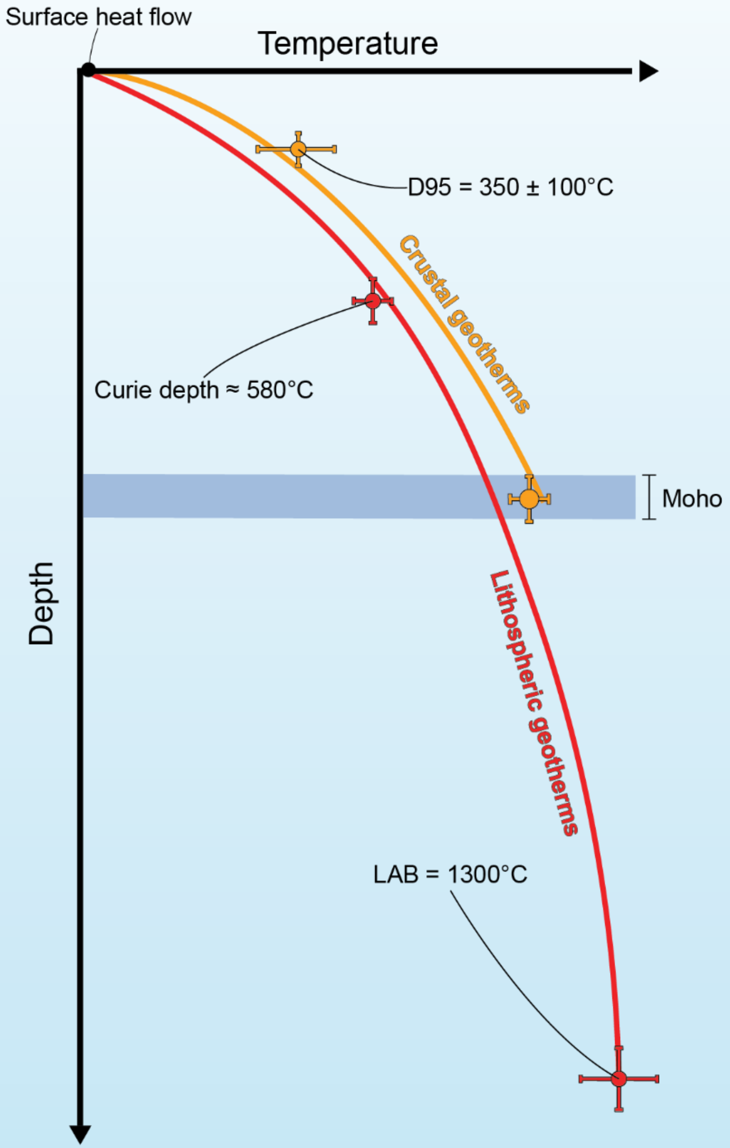


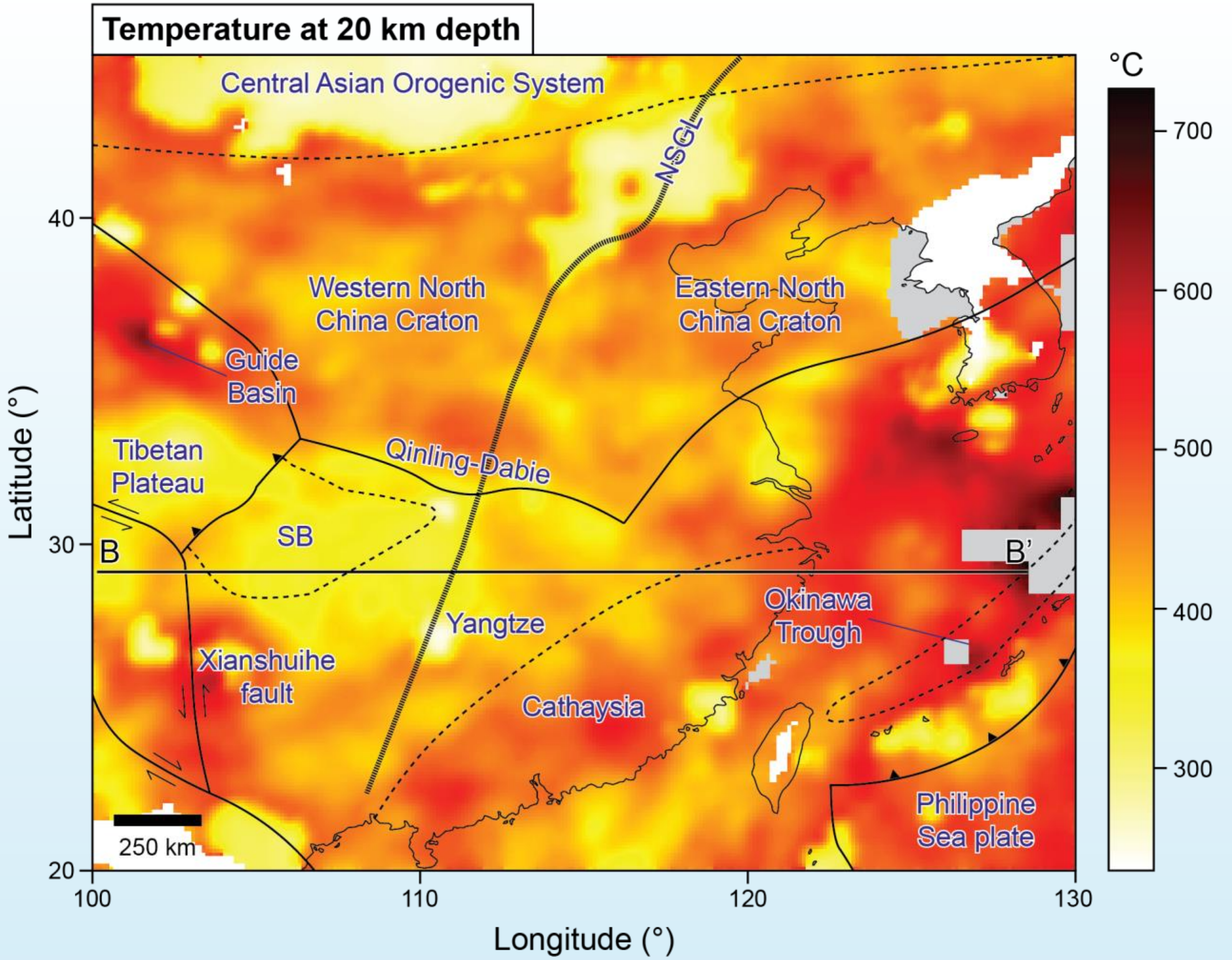

```
[ModelParameters]
Curie_depth_T = 550
Iteration = 100000
T0_range = 0, 20
k_range = 2, 5
H0_range = 1e-6, 1e-5
qm_range = 0.001, 0.05
goodfit = 0.35
moderatefit = 0.55
D95_T_config = 350
Max_goodfit_profile = 200
LAB_T_config = 1300
Uncertainty_box_fitting = False
Diffusion_2D = True
Diffusion_time = 5
```

```
[GeographicBoundary]
lat_max = 42
lat_min = 32
lon_max = -114
lon_min = -125
maximum_pixel_size = 50000
```

- Customize model area, resolution, and parameters
- Apply different temperature proxies

Model application in East Asia





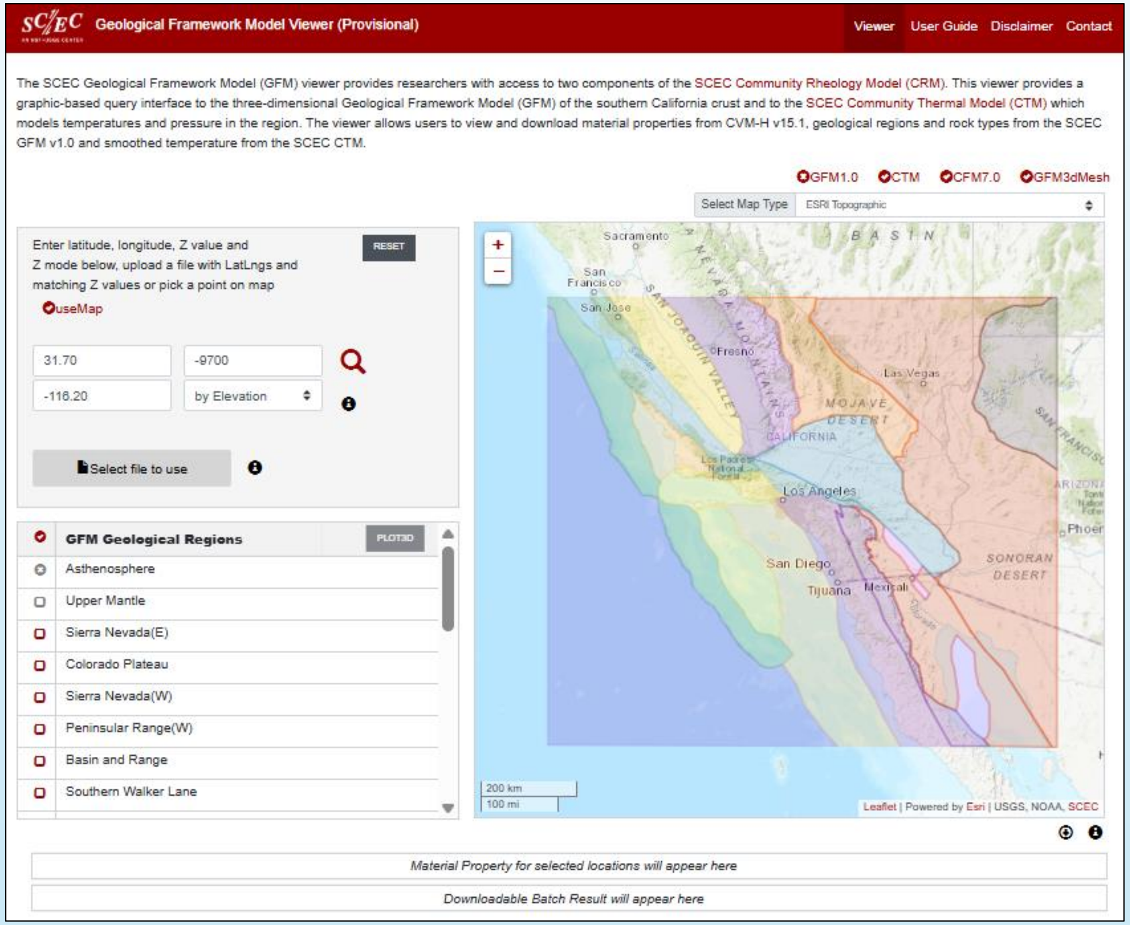
Temperature proxies:

- Surface heat flow
  (Jiang et al., 2019 *Tectonophysics*; Sun et al., 2022 *JGR SE*)
- Curie depth
  (Li et al., 2017 *Scientific Reports*)
- Lithospheric thickness
  (An and Shi, 2006 *Physics of the Earth and Planetary Interiors*)

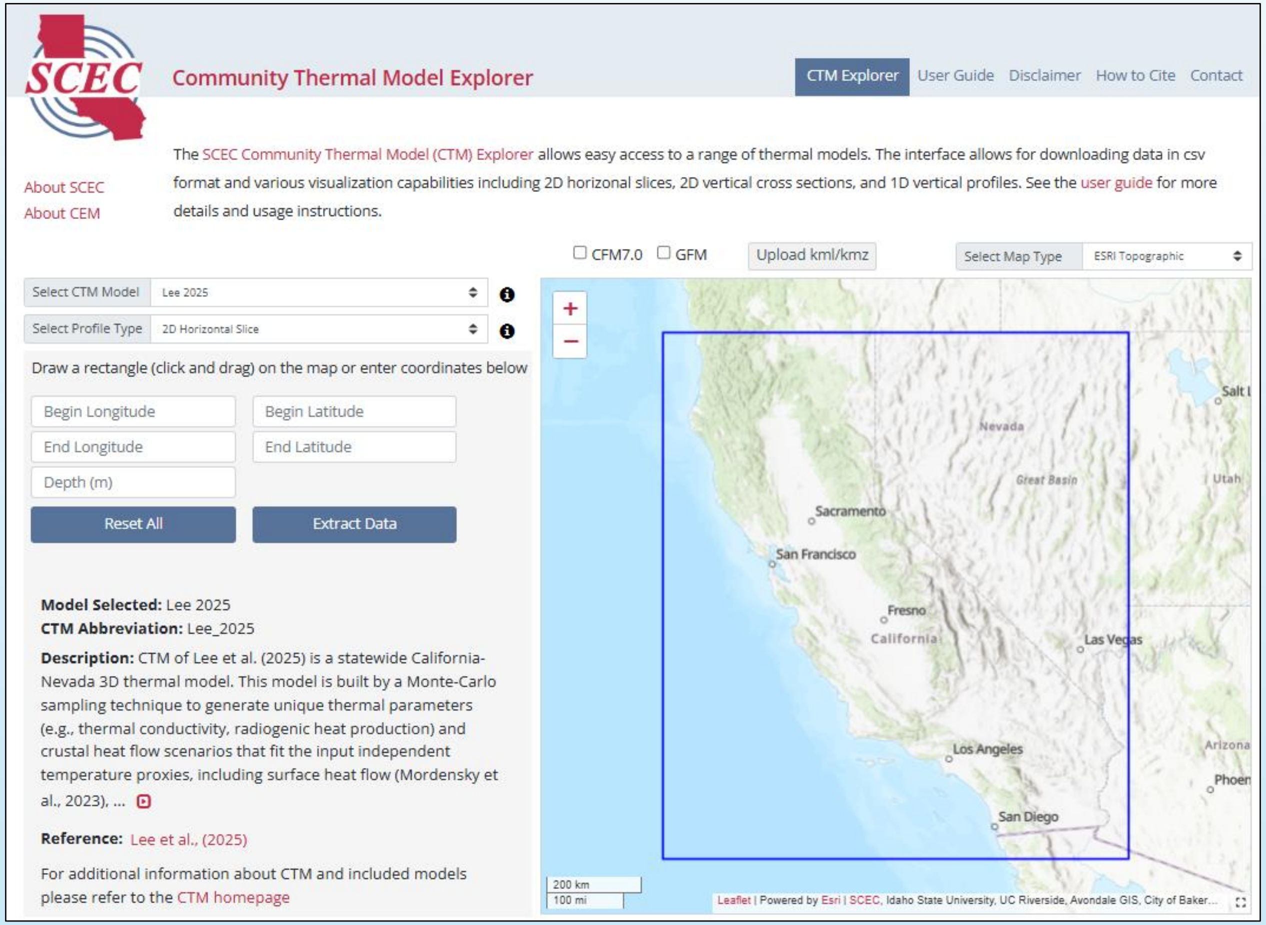
New CTM explorer!

In collaboration with:
Mei-Hui Su
Phil Maechling

Current explorer



New explorer



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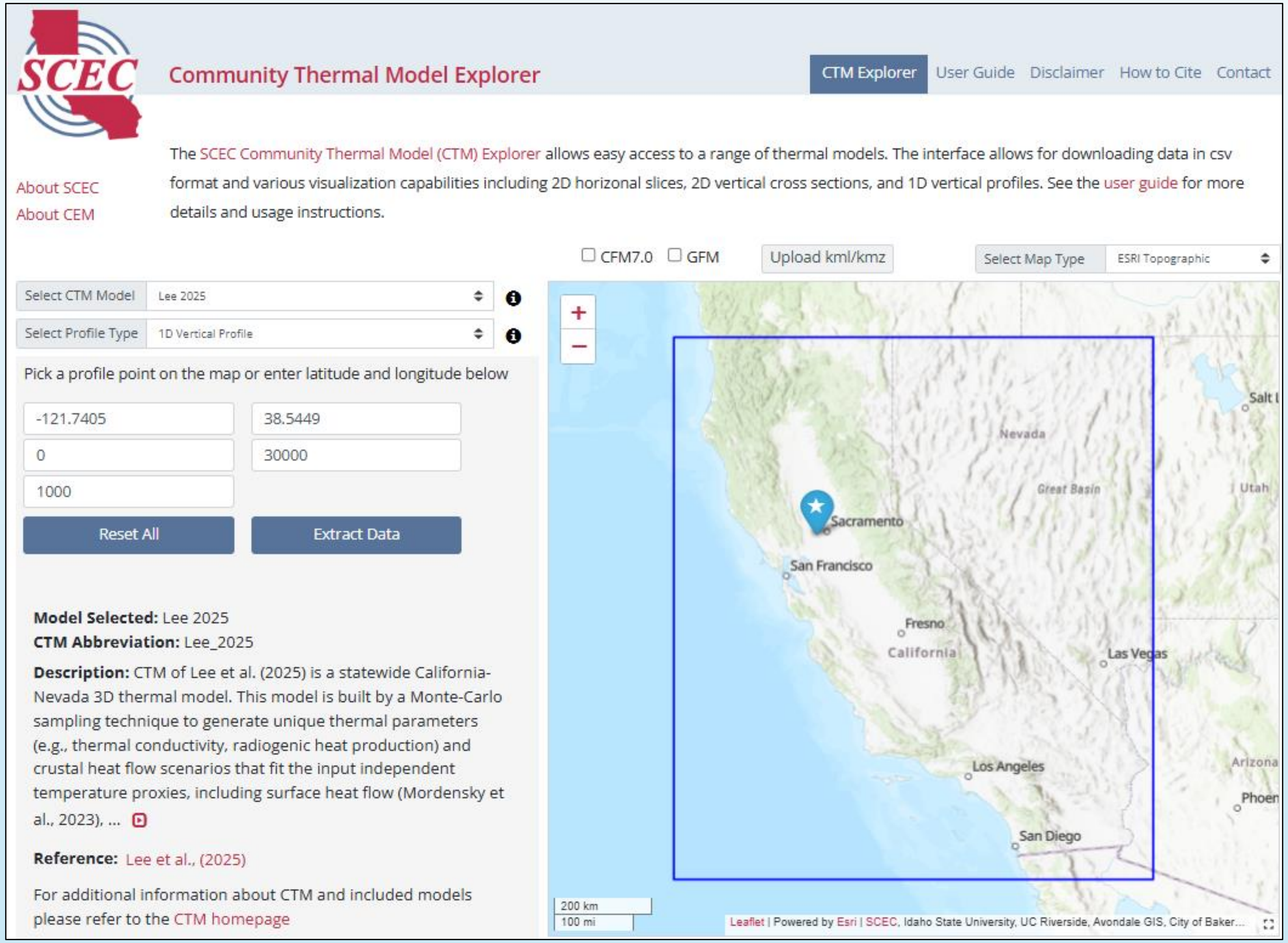
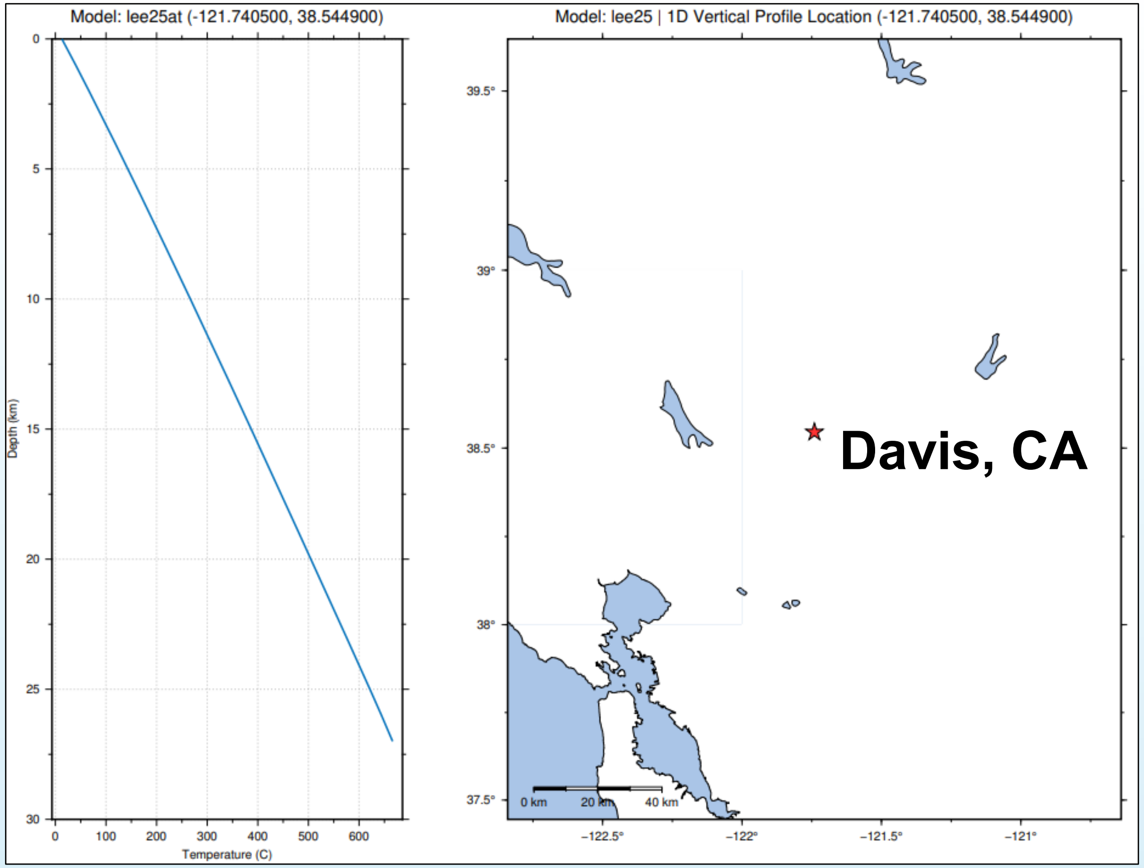
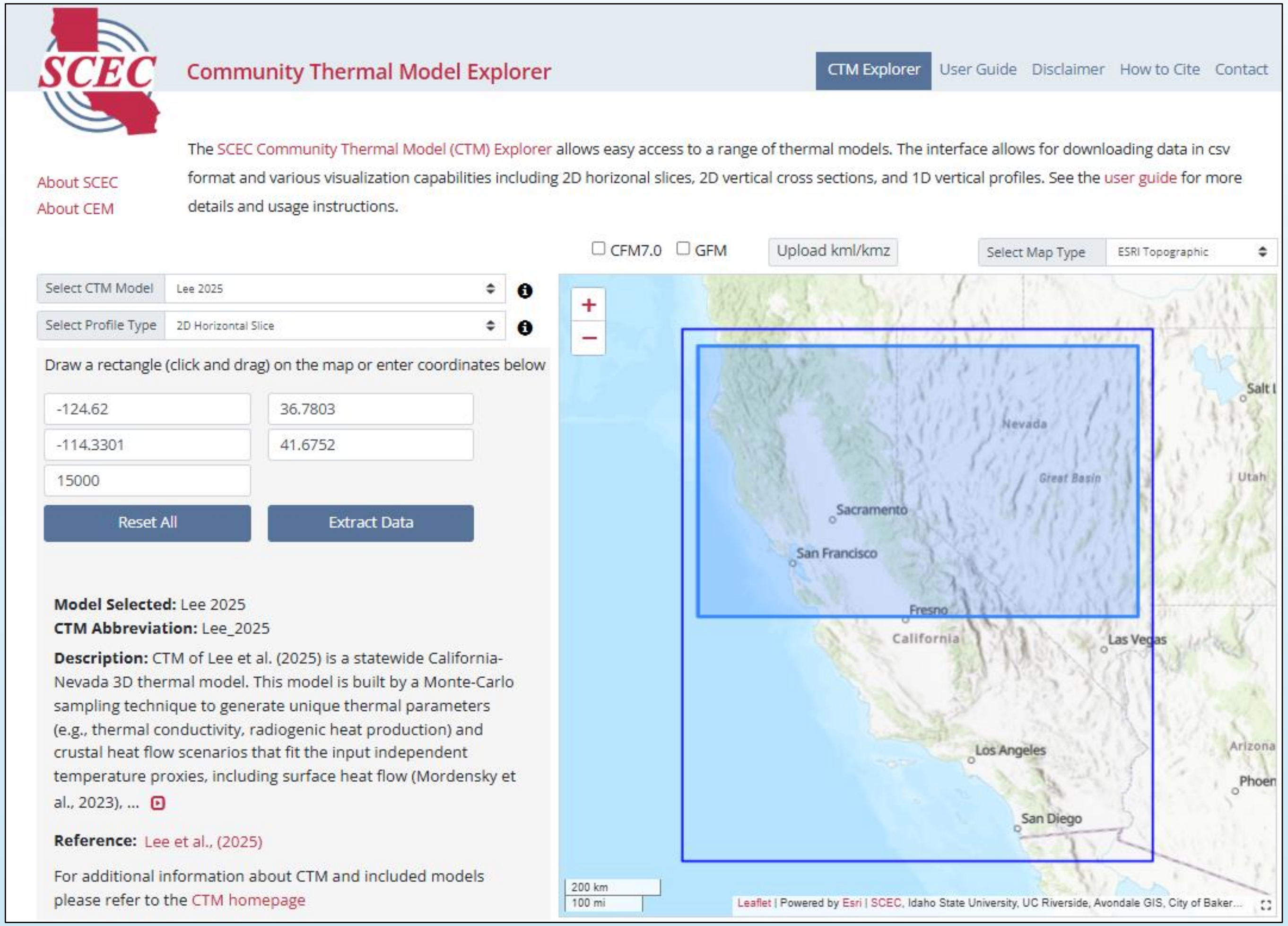
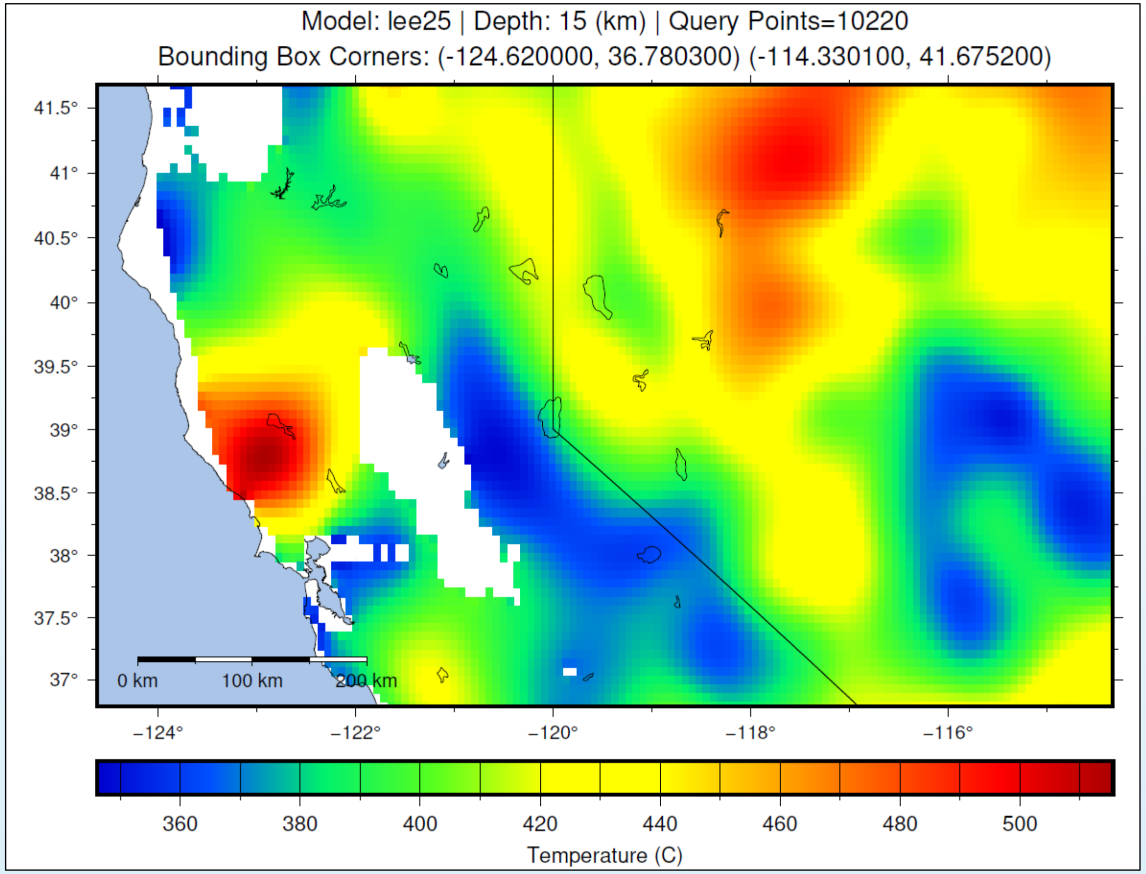




- Single point temperature
- **1D vertical thermal profile**
- 2D horizontal slice map
- 2D cross-section profile

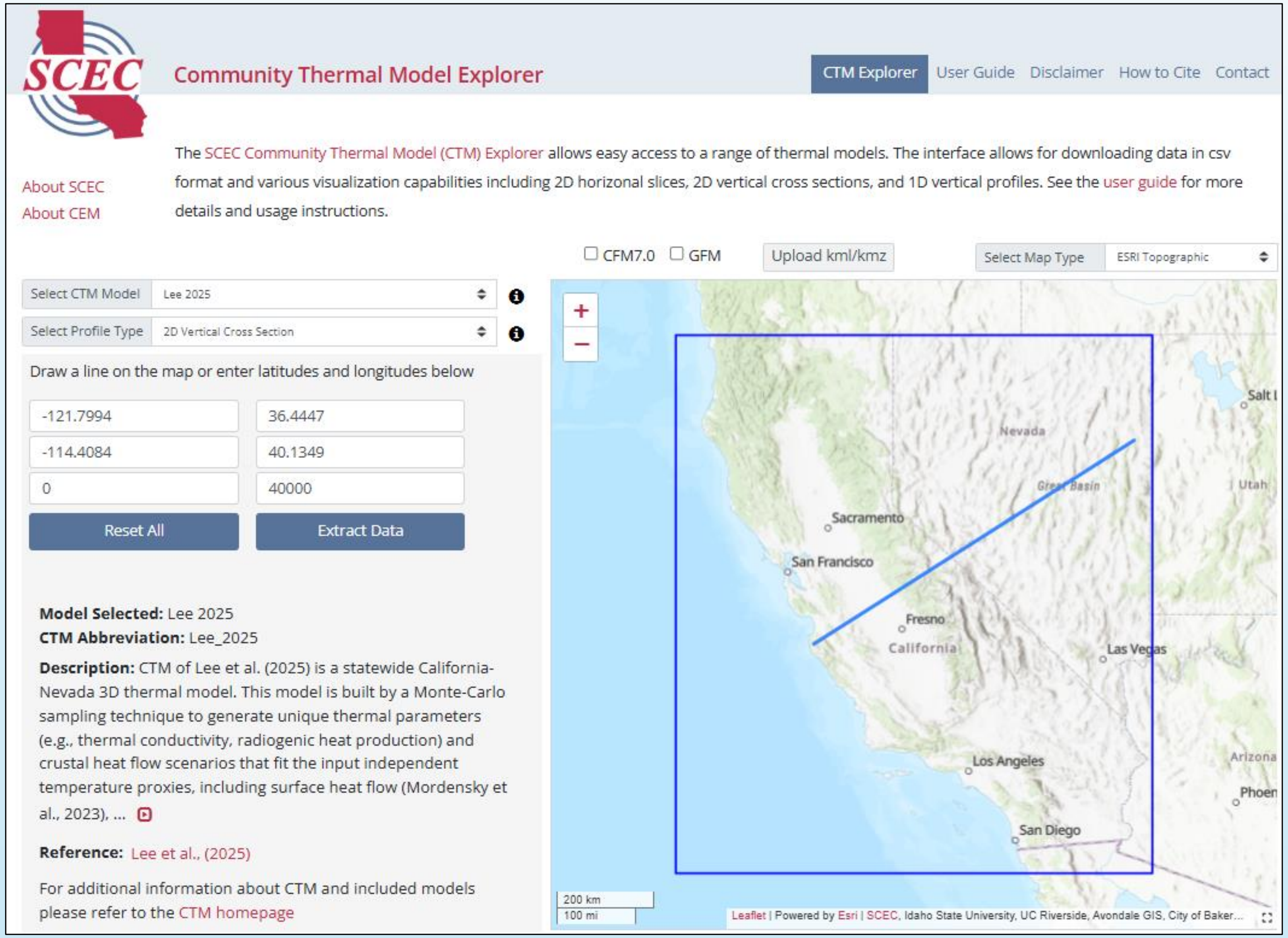
New CTM explorer!

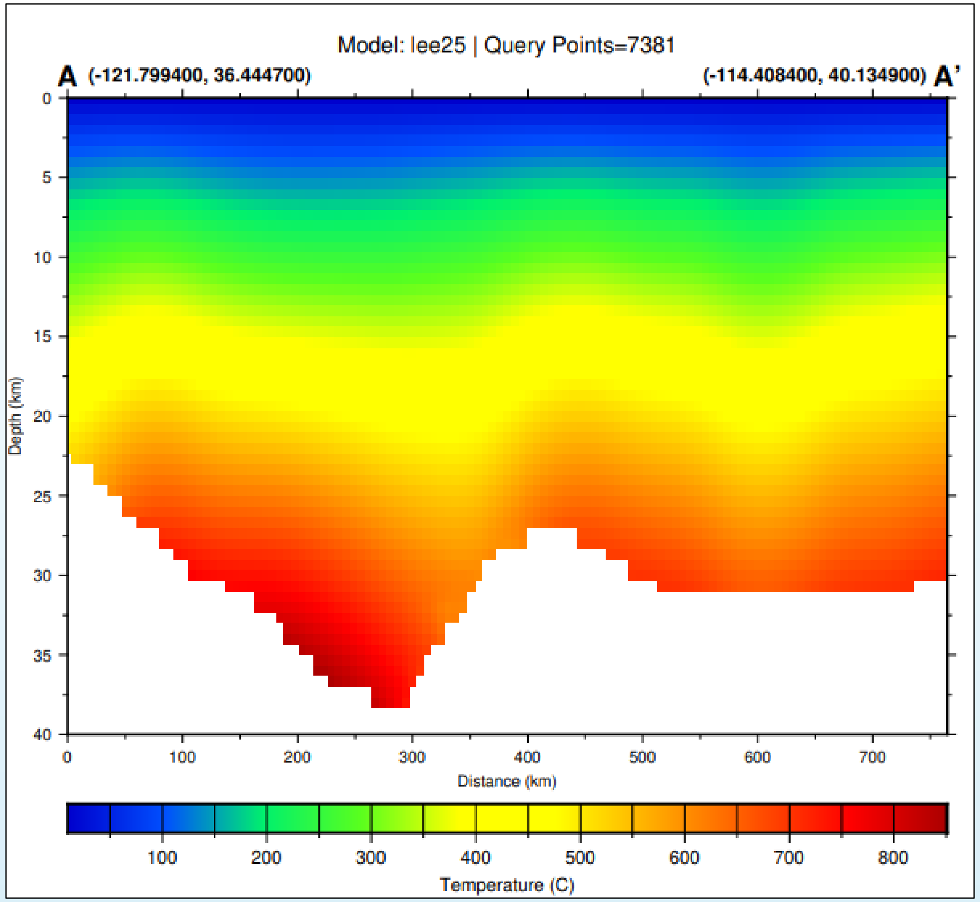




- Single point temperature
- 1D vertical thermal profile
- **2D horizontal slice map**
- 2D cross-section profile

New CTM explorer!

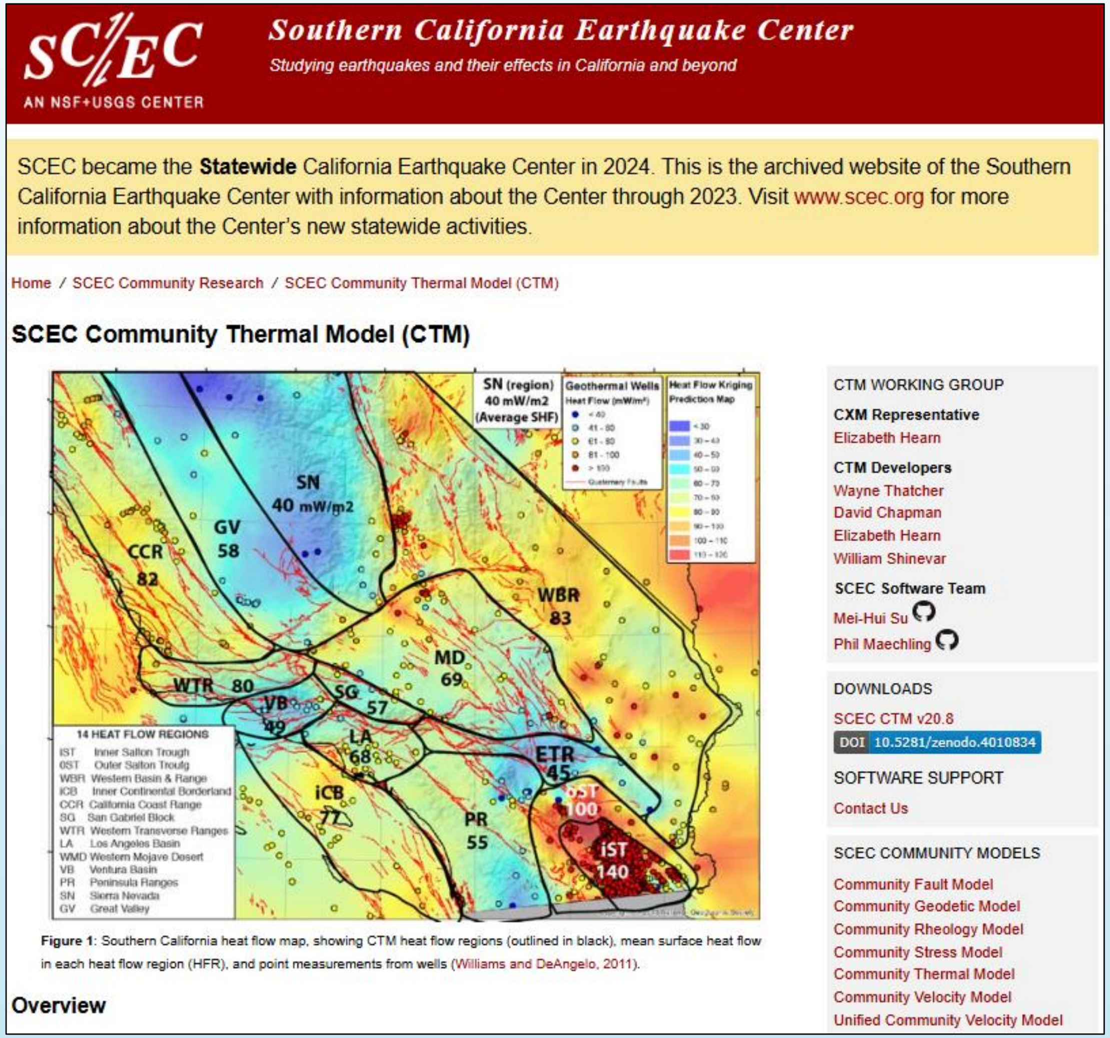




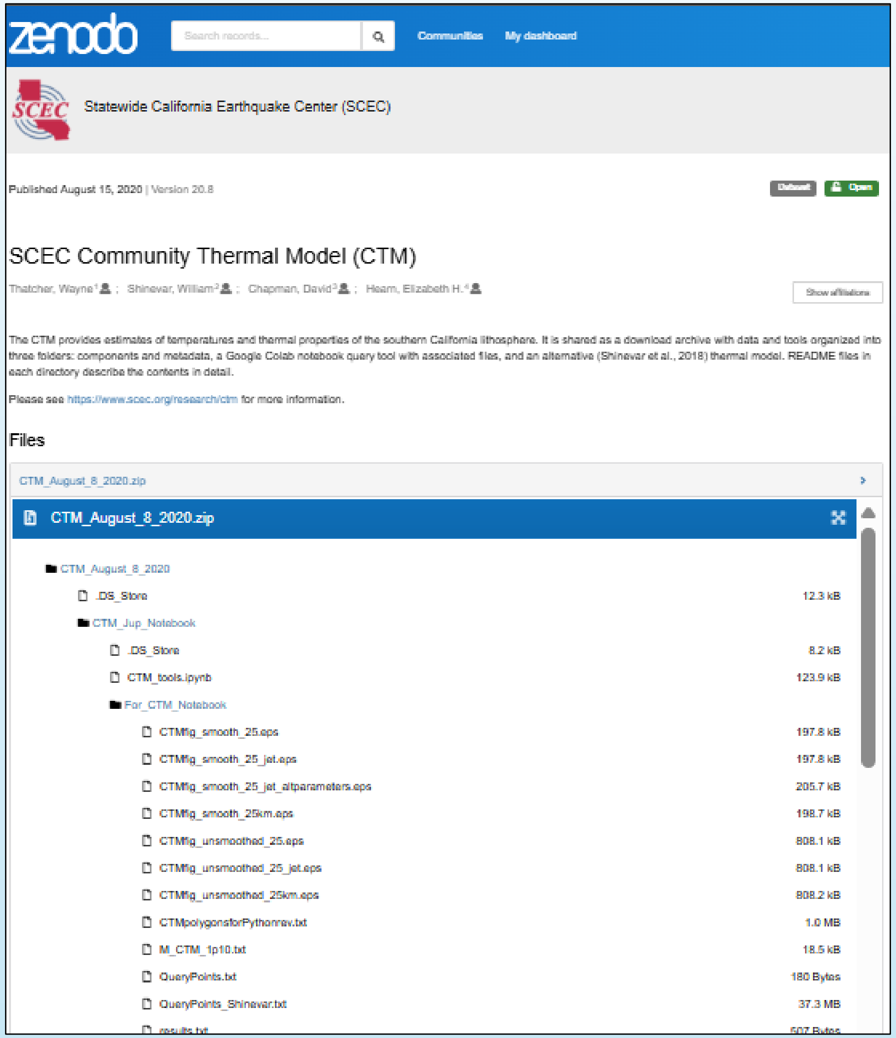
- Single point temperature
- 1D vertical thermal profile
- 2D horizontal slice map
- **2D cross-section profile**

Work in progress

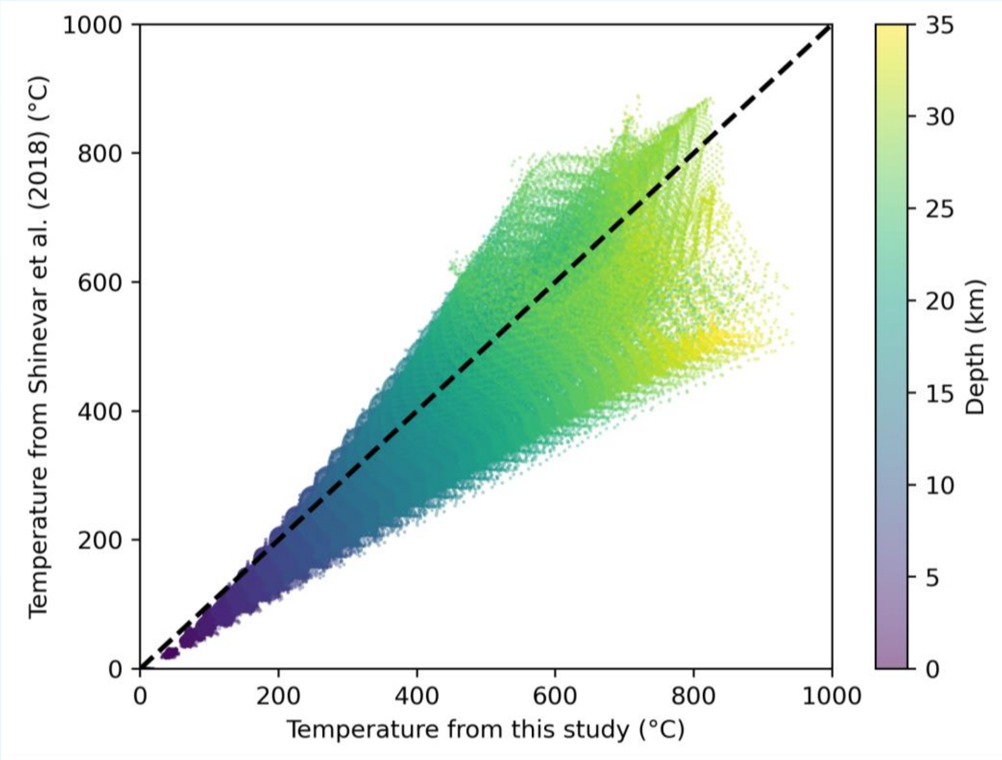
Current homepage



Zenodo repository

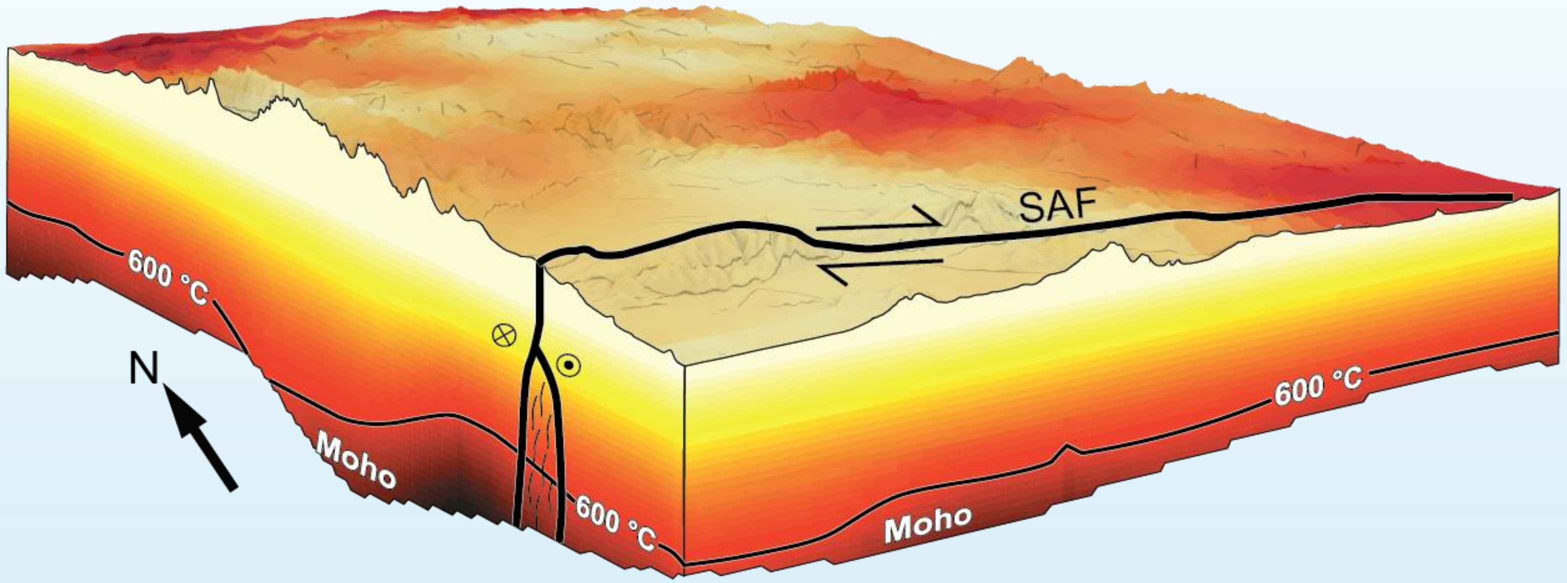


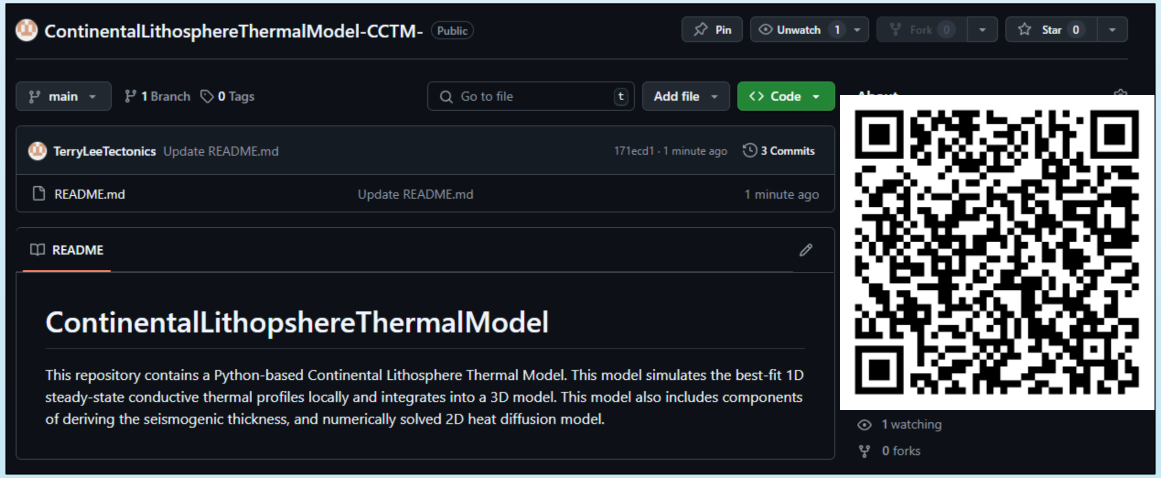
Discussion/questions



- How to evaluate model accuracy? (Compare to observables?)
- Estimate uncertainty? (Standard deviation for statewide CTM)
- How to compare and contrast between models?
- Steady state vs non-steady state
  (Shear heating, basal heating, advection)
- GFM constrain D95 temperature?
- Extend the statewide CTM to lithospheric scale?
  (include Curie depth and LAB proxies?)

Statewide California-Nevada CTM





New explorer

http://moho.scec.org/ctm-explorer/explorer.php

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Dominik Vlaha, Wenrong Cao