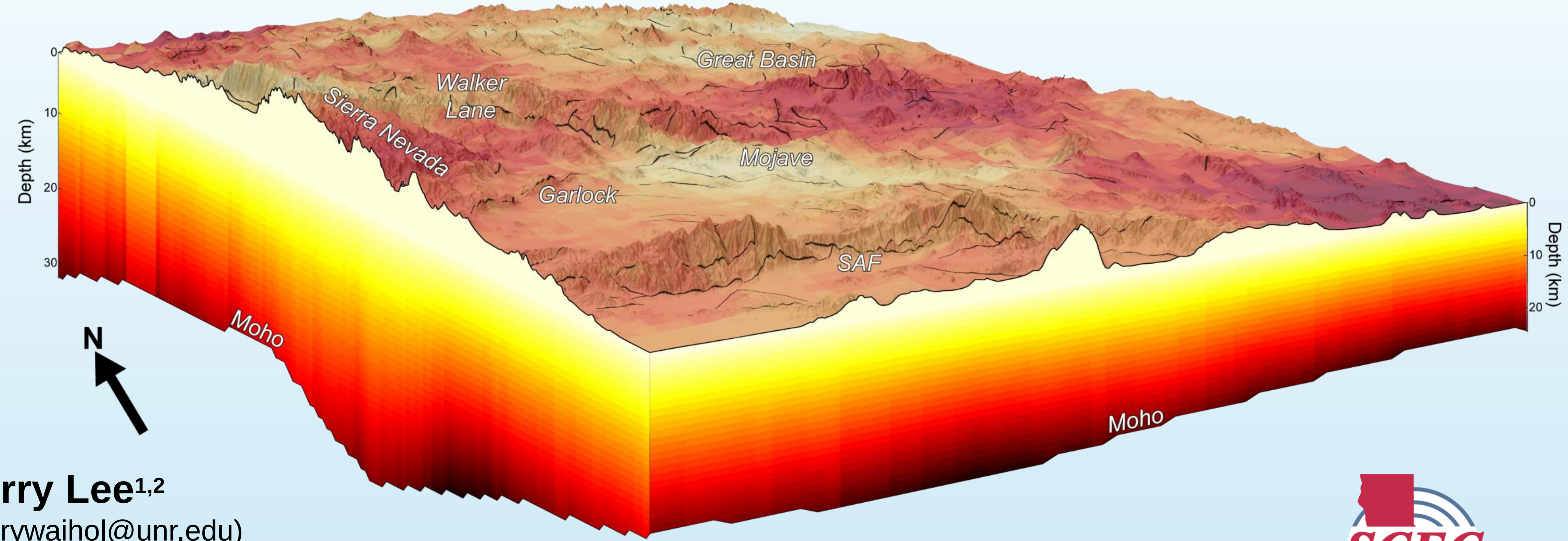
A multidisciplinary construction of the 3D thermo-rheological structure in California and Nevada

Implications on the transtensional deformation along the active margin



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Supported by the Statewide California Earthquake Center

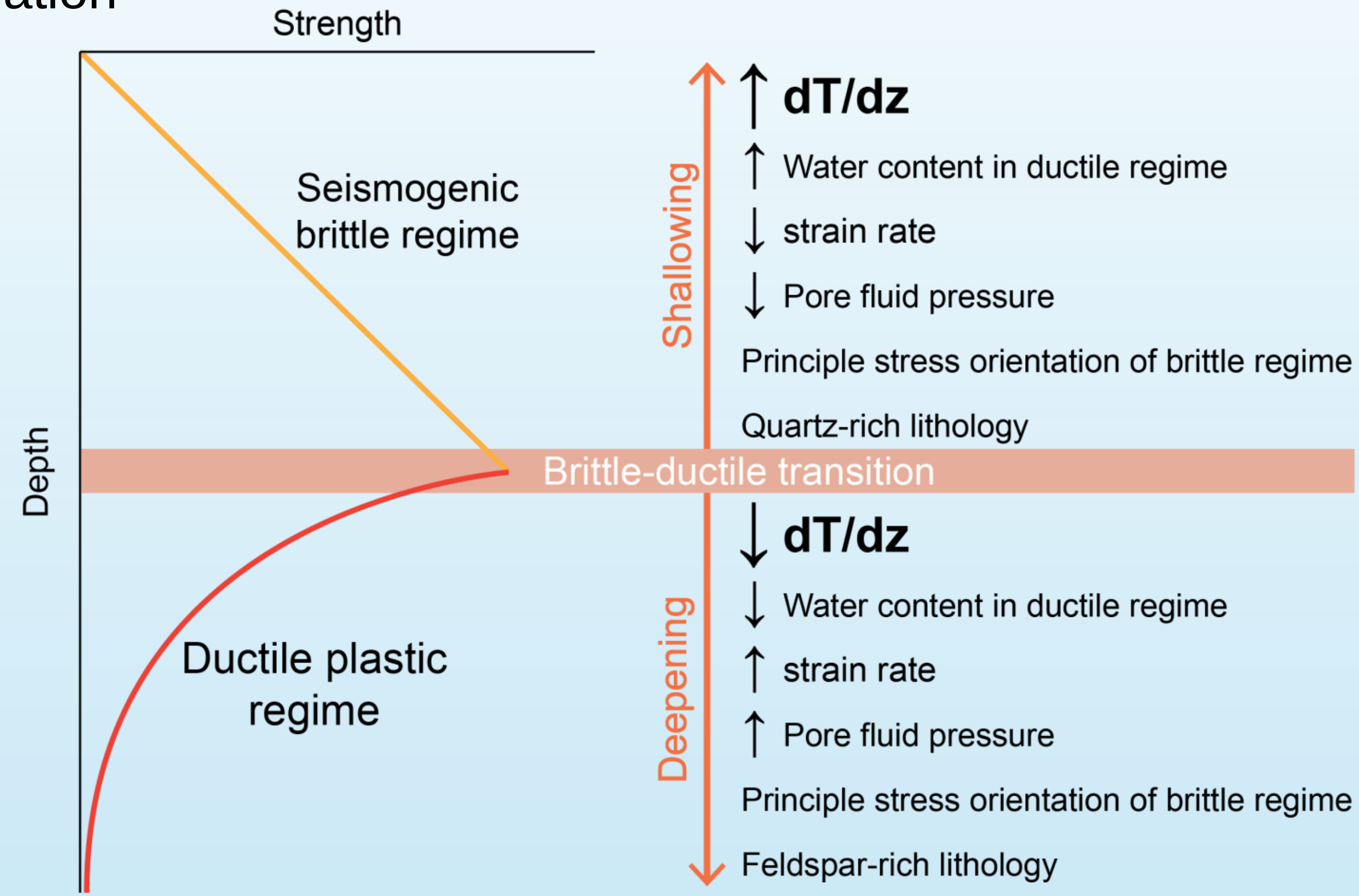
Thermal architecture: a fundamental control on crustal properties

Exerts a first-order control on continental deformation

- **Seismicity (seismogenic thickness)**
- **Crustal flow (ductile strength)**

Controls the evolution of orogens

- **Temperature-dependent rheology**
  (Wolf et al., 2022 *Nature*)
- **Deformation**
  (Meltzer et al., 1998 *EOS*)
  (Yang et al., 2023 *Tectonics)*
  (Vlaha et al., 2024 *Nature communication)*
- **Metamorphism**
  (Brown, 1993 *Journal of the Geological Society)*



↑ **dT/dz**
↑ Water content in ductile regime
↓ strain rate
↓ Pore fluid pressure
Principle stress orientation of brittle regime
Quartz-rich lithology

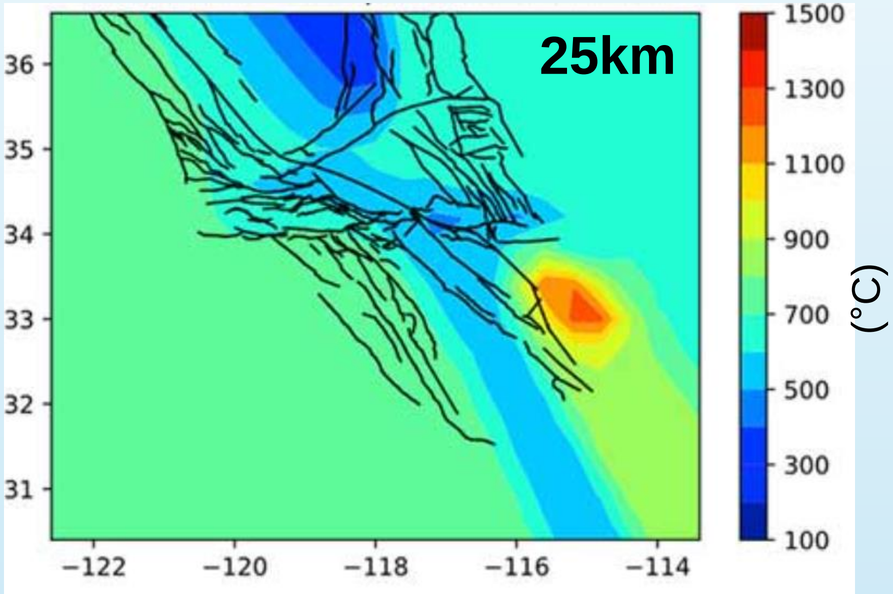
↓ **dT/dz**
↓ Water content in ductile regime
↑ strain rate
↑ Pore fluid pressure
Principle stress orientation of brittle regime
Feldspar-rich lithology

Modified from Sibson (1984 *JGR SE)*

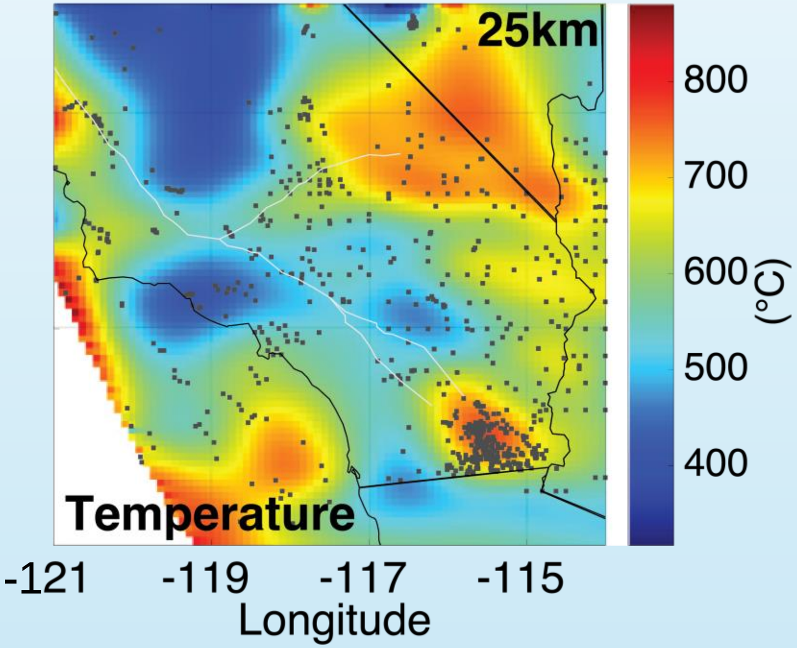
Mid-lower crustal temperature uncertainty

Common approach on estimating crustal temperature relies solely on **surface heat flow (*q_s*)** observations

$$q_s \; \alpha \; \frac{dT}{dz}$$



Thatcher and Chapman (2020 *SCEC)*



Shinevar et al. (2018 *EPSL)*

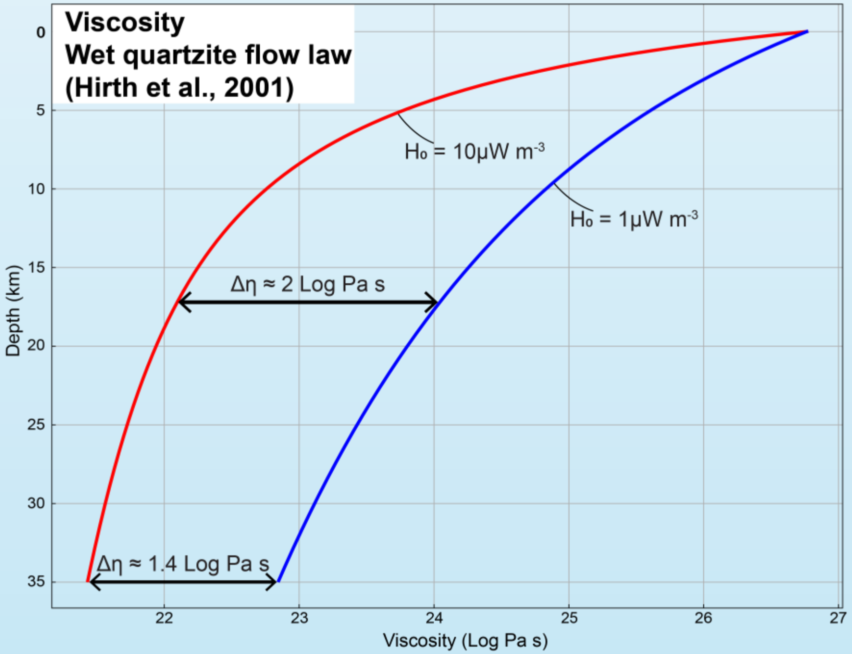
Mid-lower crustal temperature uncertainty

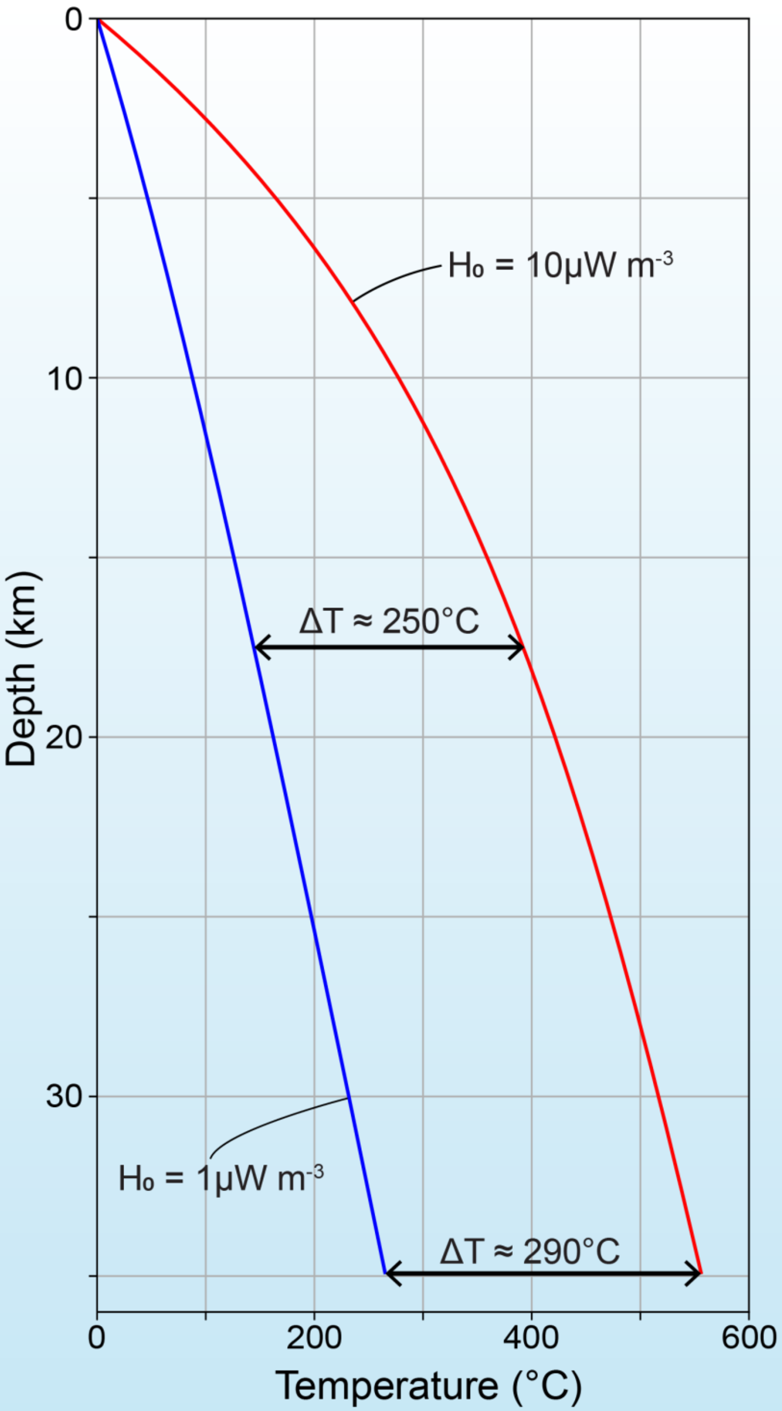
Common approach on estimating crustal temperature as a function of depth relies solely on **surface heat flow (q_s)** observations

$$q_s \; \alpha \; \frac{dT}{dz}$$

Thermal profile only constrains by **surface heat flow is not sufficient**

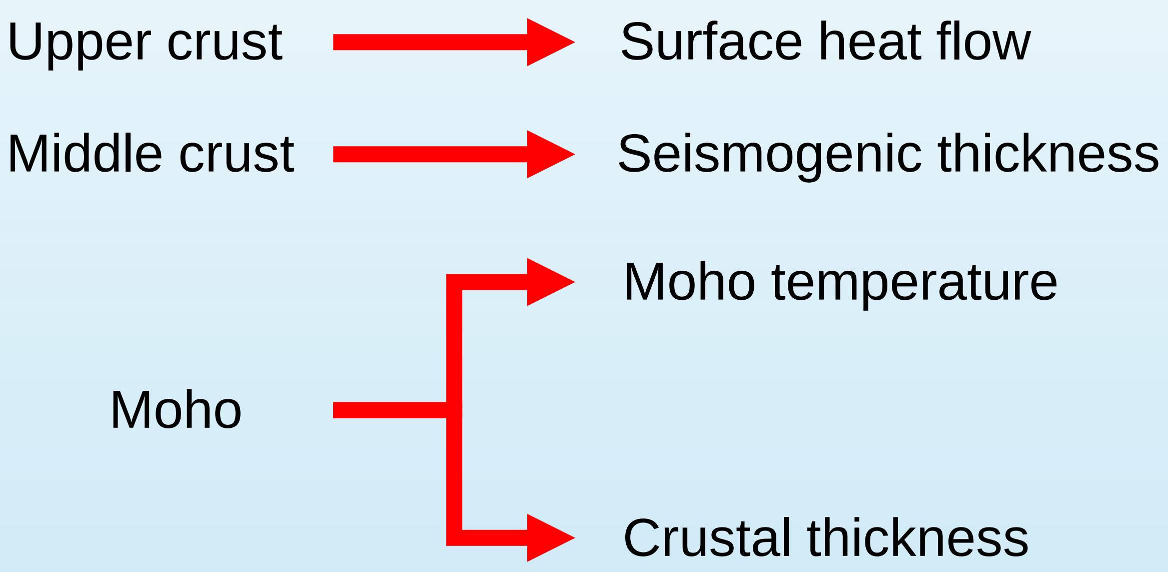
- Over/underestimates deep crustal temperature and rheology





Multi-parameter 3D thermal model

Multi-depth-level temperature constraints:

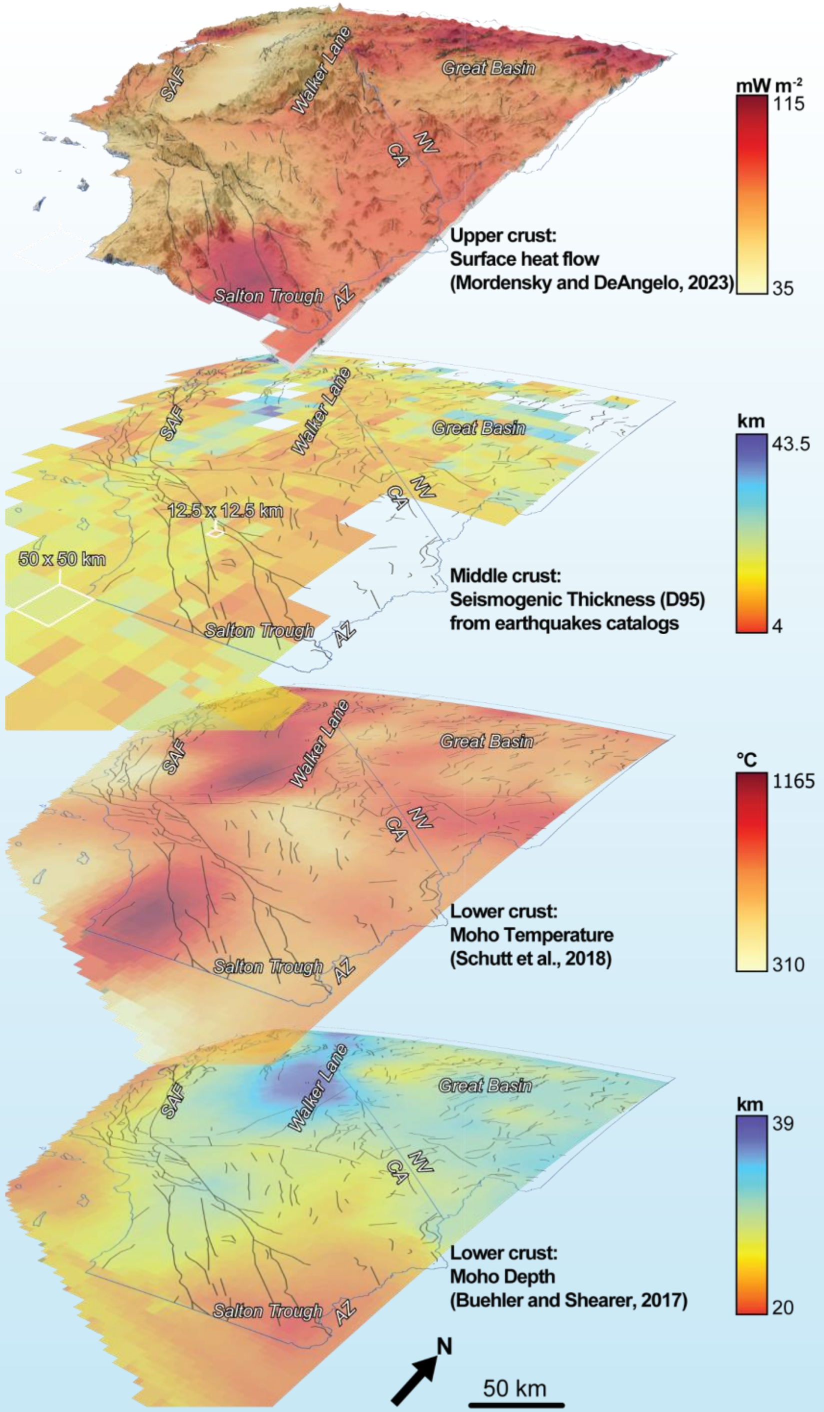


Upper crust → Surface heat flow

Middle crust → Seismogenic thickness

Moho → Moho temperature

Crustal thickness



Upper crust:
Surface heat flow
(Mordensky and DeAngelo, 2023)

Middle crust:
Seismogenic Thickness (D95)
from earthquakes catalogs

Lower crust:
Moho Temperature
(Schutt et al., 2018)

Lower crust:
Moho Depth
(Buehler and Shearer, 2017)

Surface heat flow

Multi-depth-level temperature constraints:

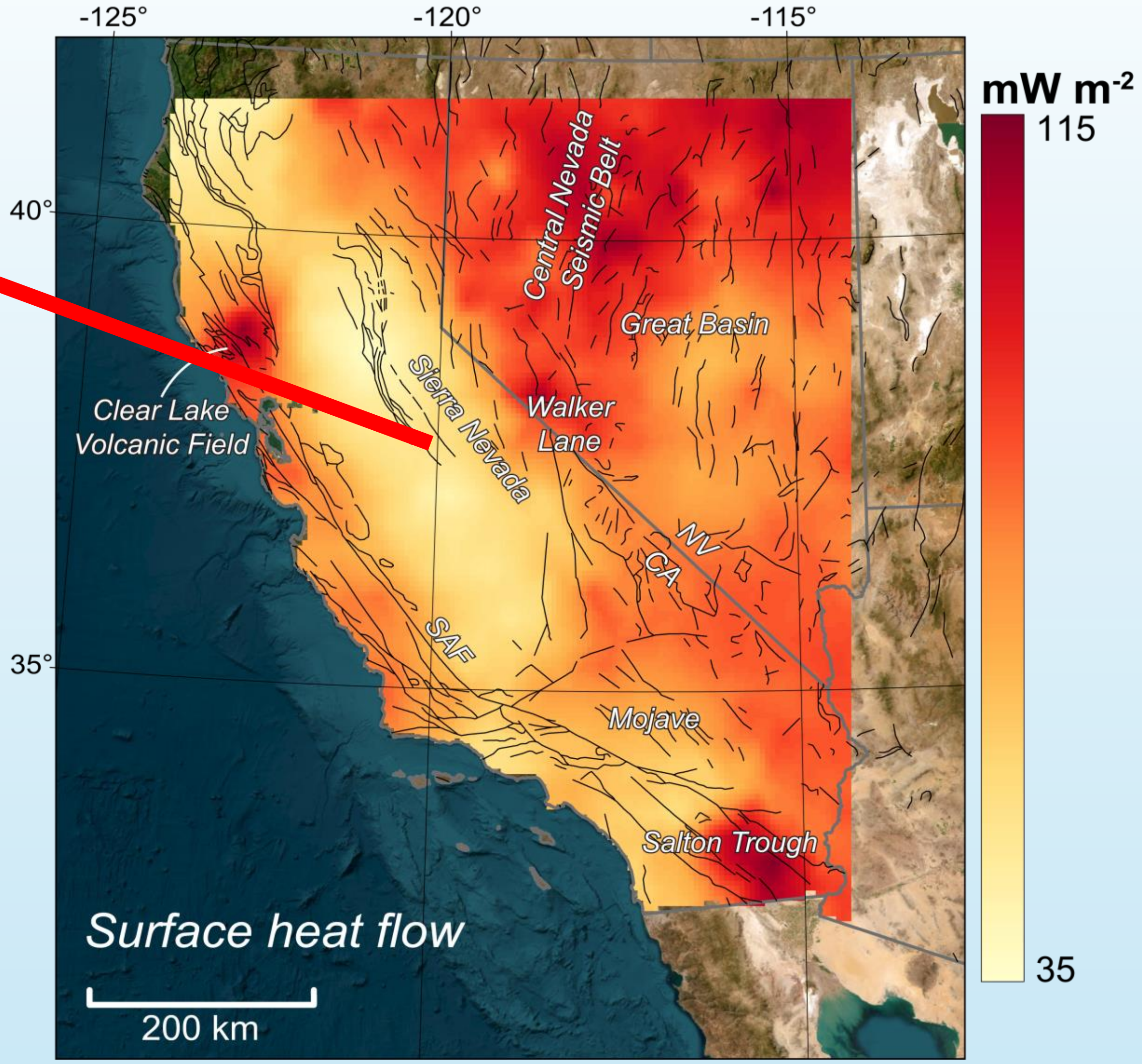
Upper crust → **Surface heat flow**

Middle crust → Seismogenic thickness

Moho → Moho temperature

Moho → Crustal thickness

$$q_s \ \alpha \ \frac{dT}{dz}$$



Mordensky and DeAngelo, 2023 *USGS*

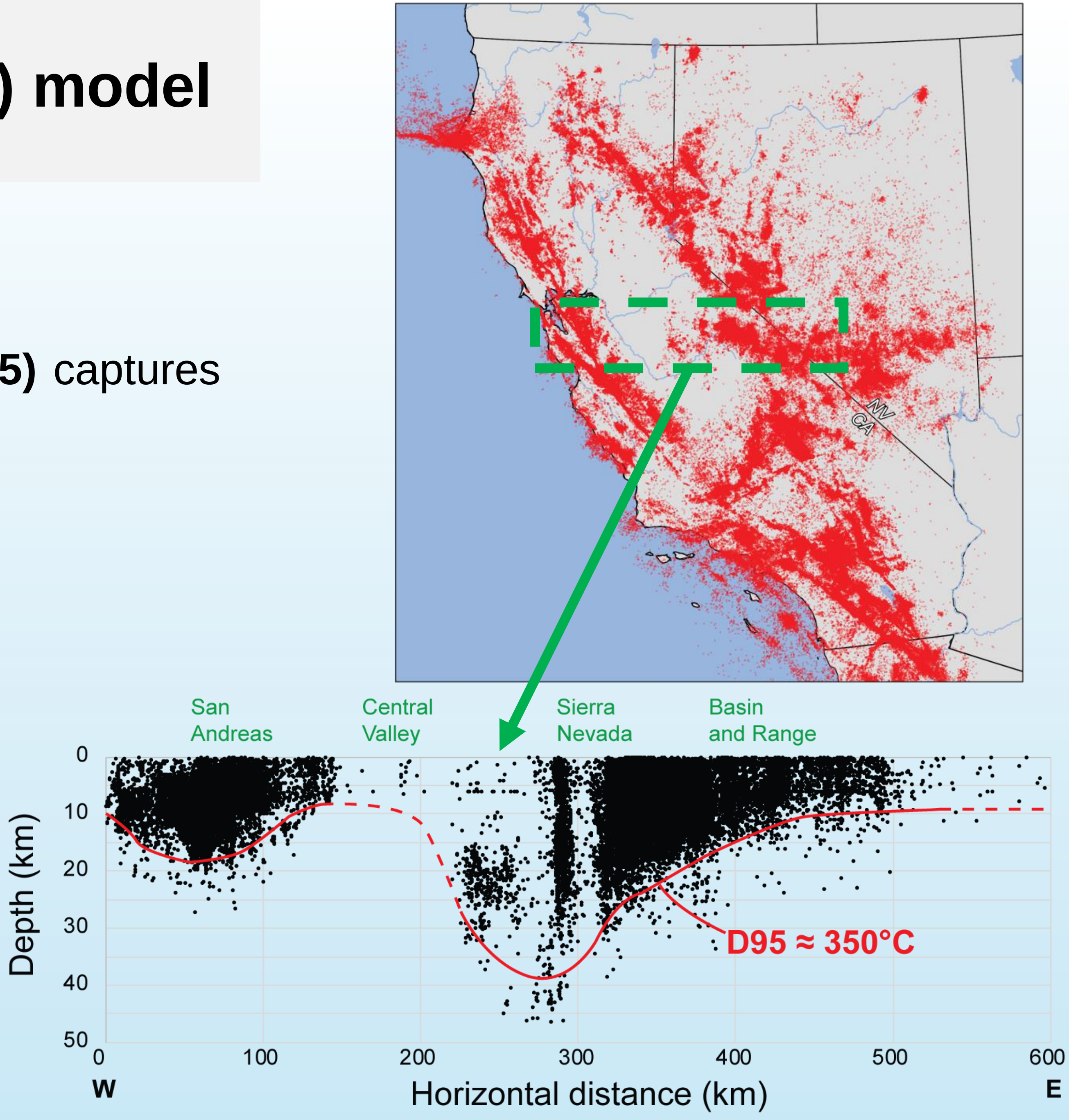
New seismogenic thickness (D95) model

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

- **D95 ≈ BDT ≈ 350 ± 50 °C**

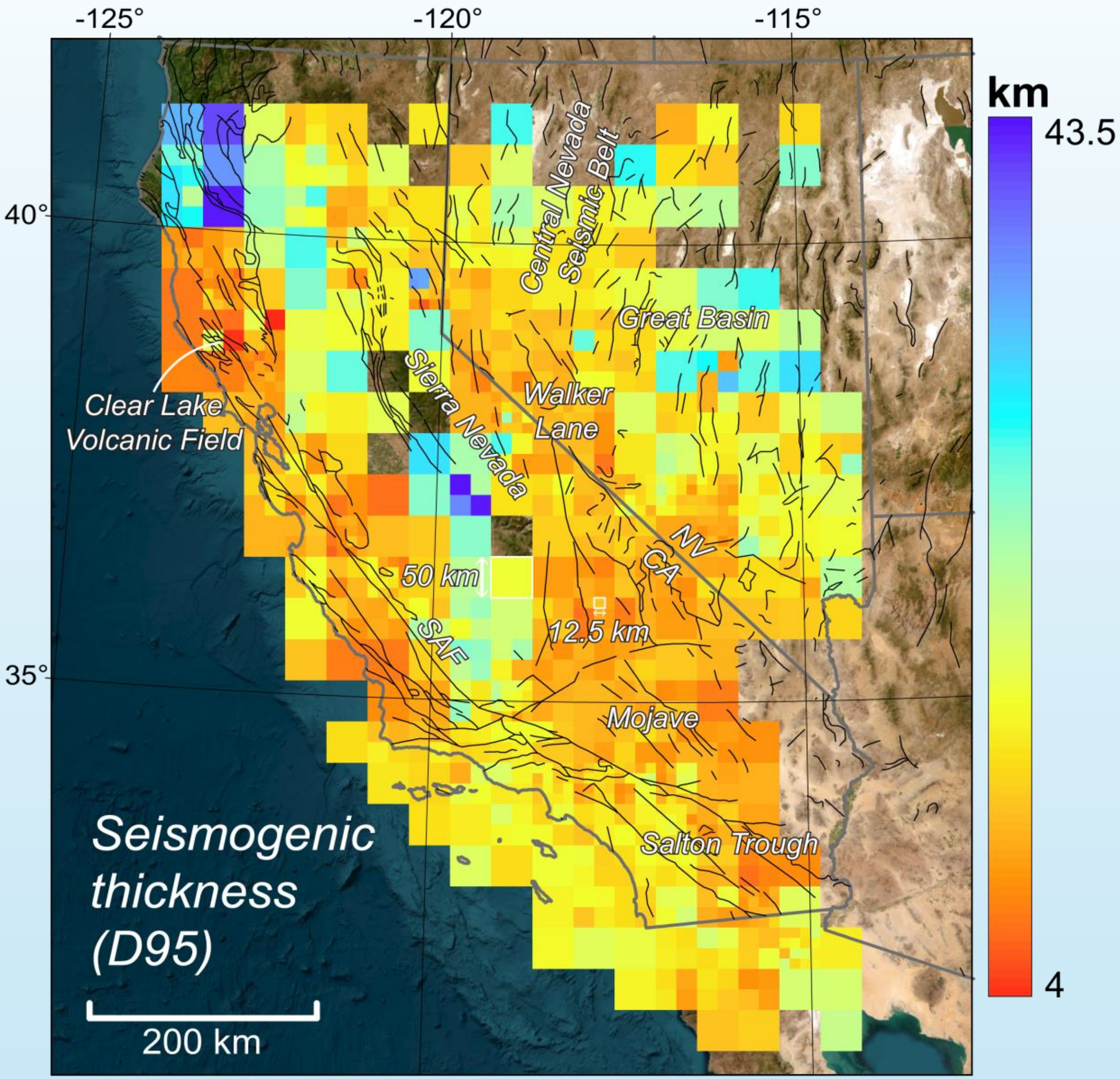
Merged >40 years of earthquake records from:

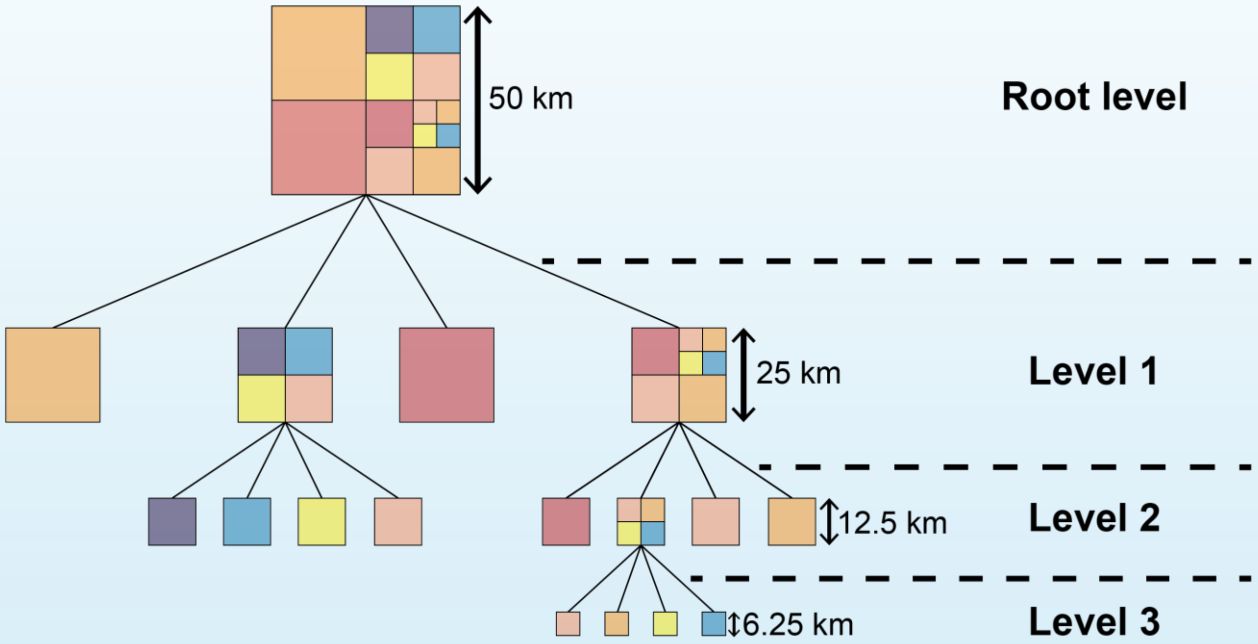
- 1984-2024 Northern California
  (Waldhauser and Schaff, 2008; Waldhauser, 2009)
- 1981-2023 Southern California
  (Hauksson et al., 2012)
- 1980-2024 Nevada
  (Trugman, 2024)



Modified from Zuza and Cao (2020 *Tectonophysics*)

Adaptively sized seismogenic thickness (D95) model



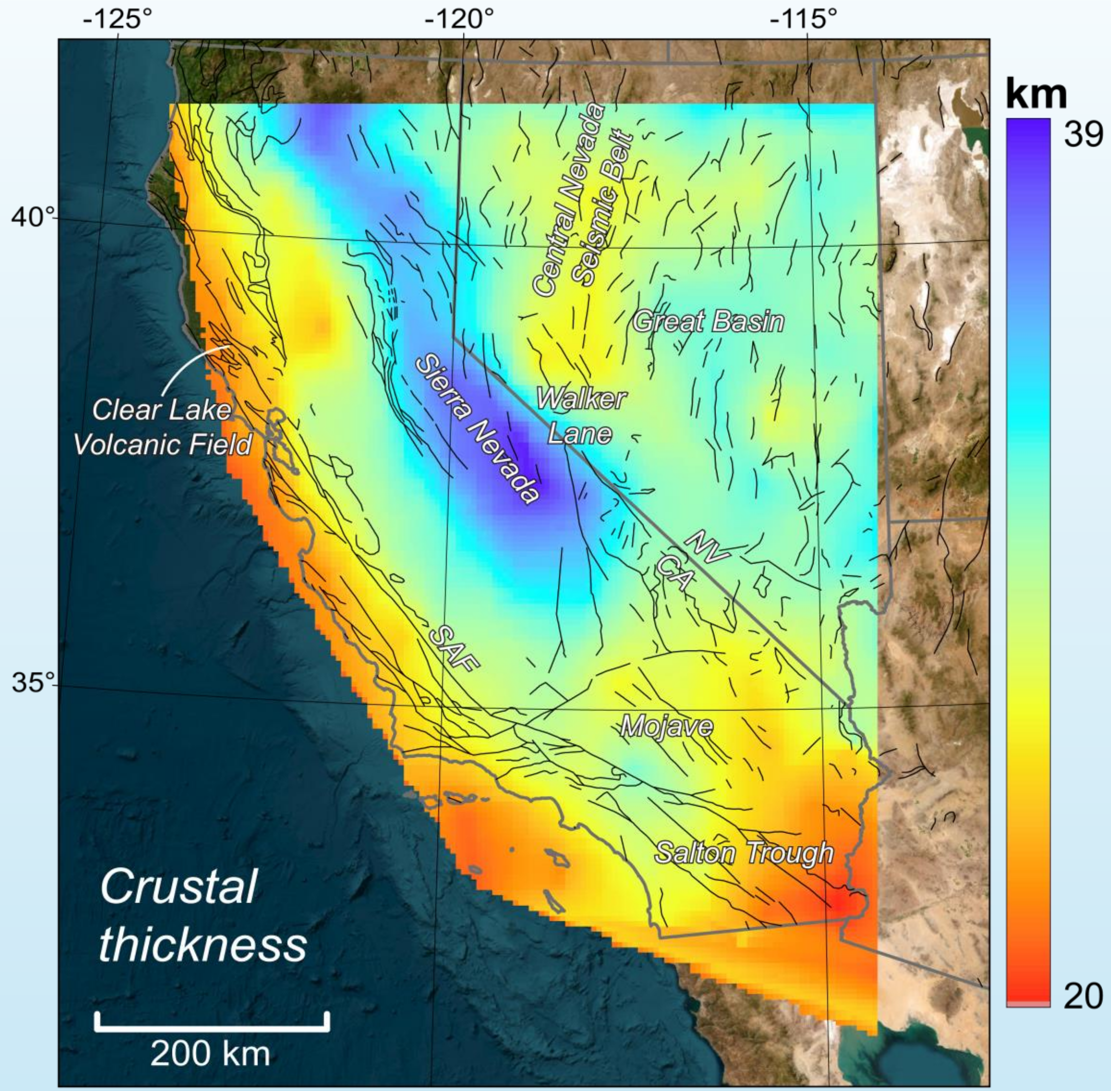


Adaptively sized bin — **quad tree structure**
(Finkle and Bentley, 1974 *Acta Informatica*)

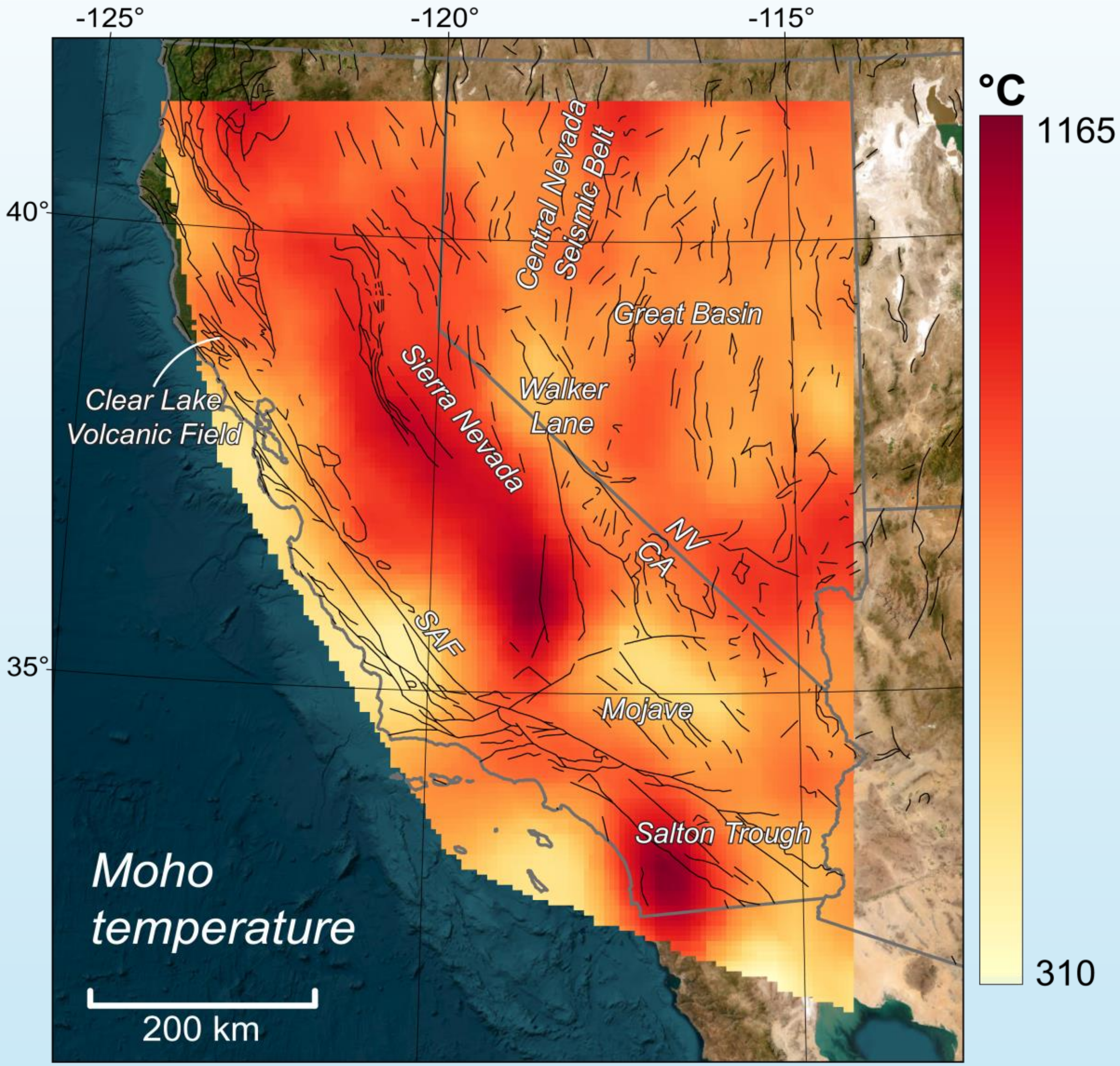
- Bin width = **50 to 6.25 km**

Moho conditions

Crustal thickness estimate is acquired from P_n tomography (Buehler and Shearer, 2017) and Moho temperature is calculated as a function of P_n velocity assuming homogenous composition (Schutt et al., 2018).



Buehler and Shearer (2017 *JGR SE)*



Schutt et al. (2018 *Geology)*

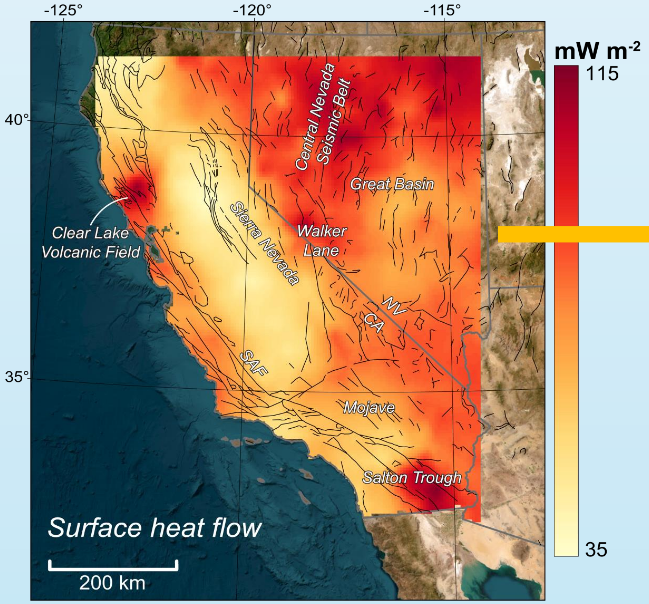
Crustal temperature modeling: Monte-Carlo type simulation

100,000 iterations of 1D steady-state heat conduction calculation per bin

Randomize $\boldsymbol{T_0, q_m, k, h, H_0}$ per iteration

Seeks good-fit results compared to the D95 and Moho conditions

- Normalized root mean square error (NRMSE)



Thermal modeling parameters

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)	10^{-6} to 10^{-5} [W m^{-3}]
$n_{simulation}$	100,000

$$q_\mathrm{m} = q_\mathrm{s} - hH_0$$

$$T(z) = T_0 + \frac{q_\mathrm{m} z}{k} + \frac{(q_\mathrm{s} - q_\mathrm{m})\,h}{k}\left(1 - e^{-z/h}\right)$$

Turcotte and Schubert (2014)

Crustal temperature modeling: Monte-Carlo type simulation

Good-fit profiles (Red)

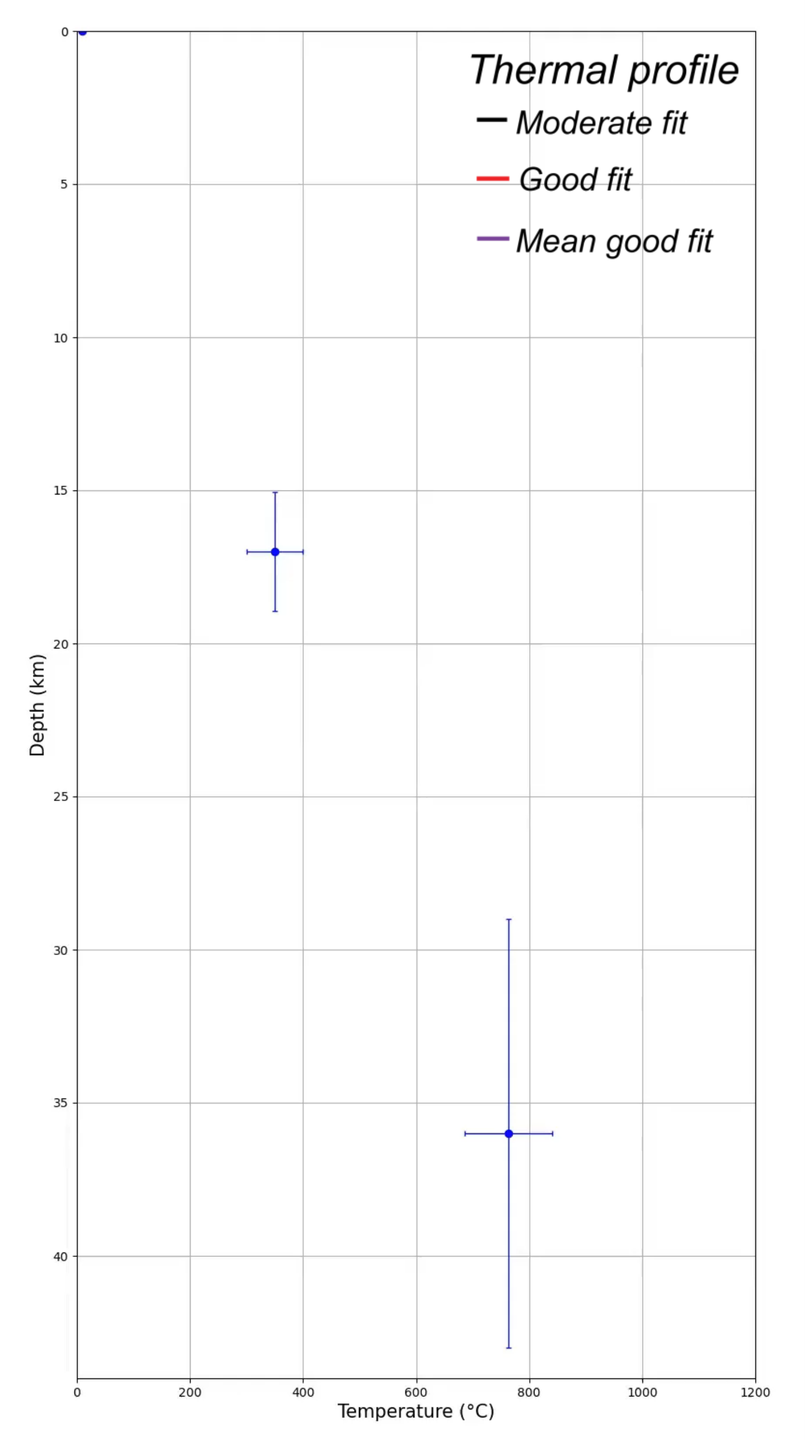
- NRMSE coefficient <0.35

Moderate-fit profiles (Black)

- NRMSE coefficient <0.55

Final best-fit profile (Purple)

- Mean of all best-fit profiles



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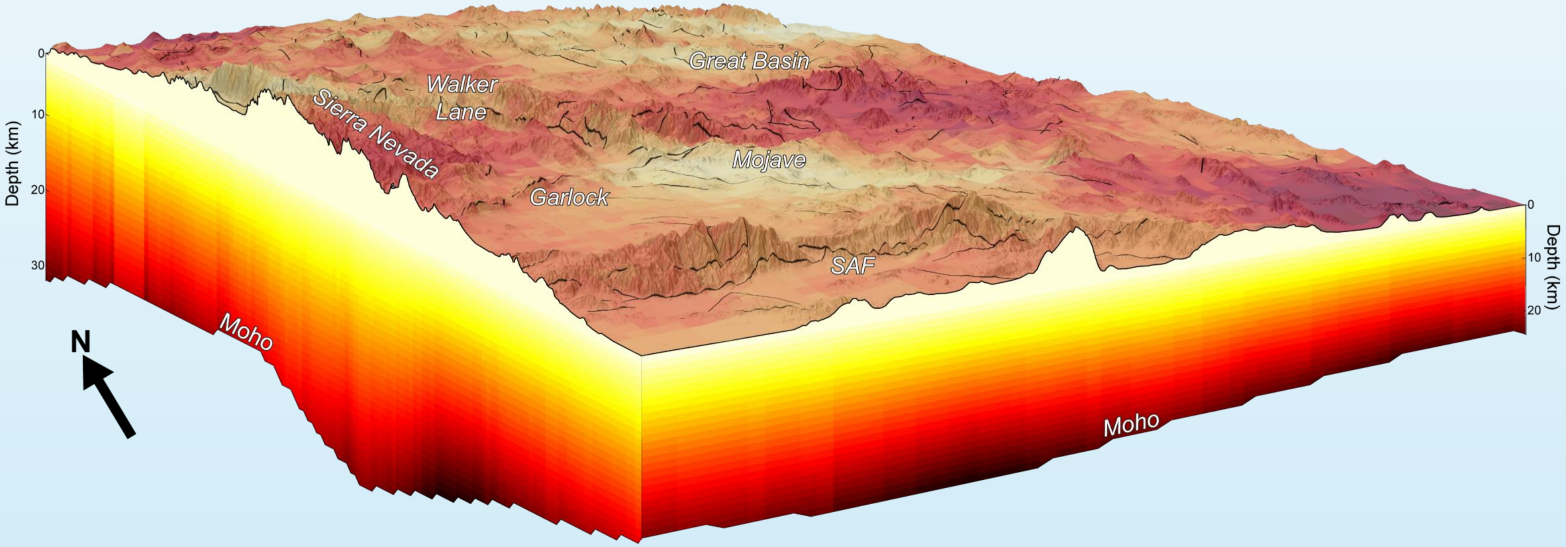
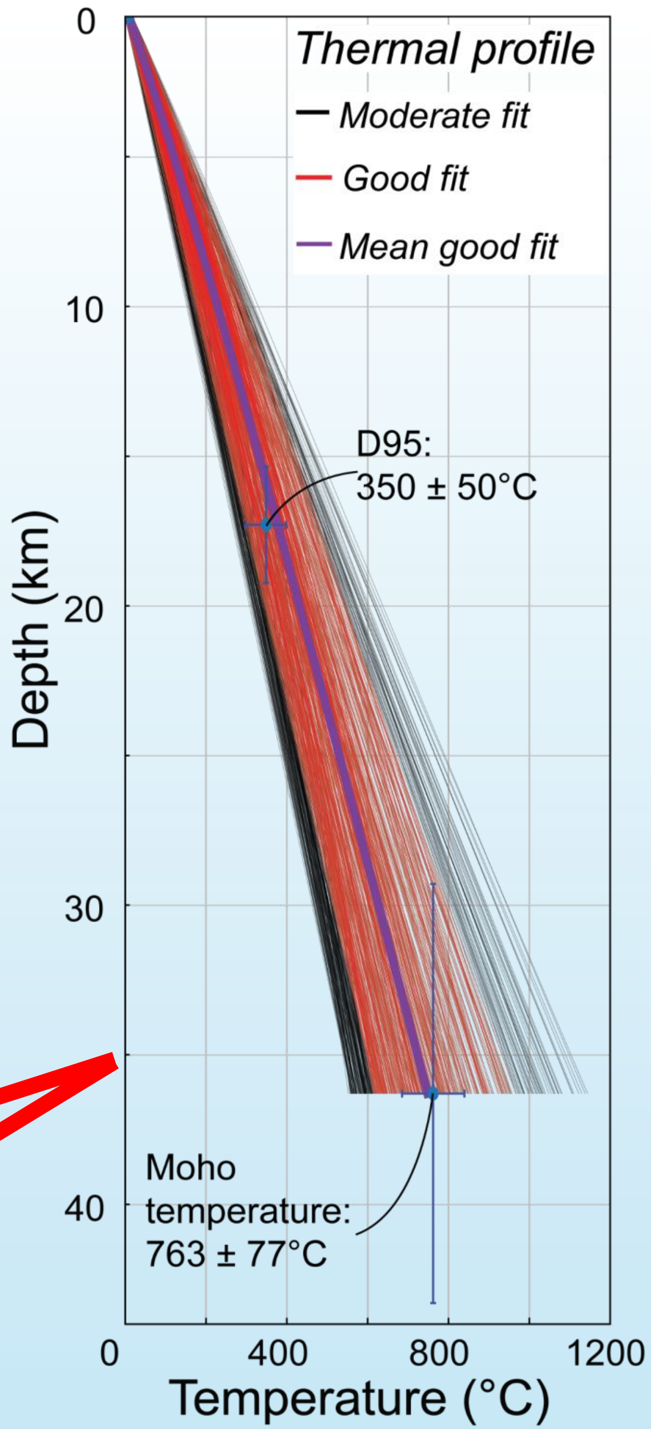
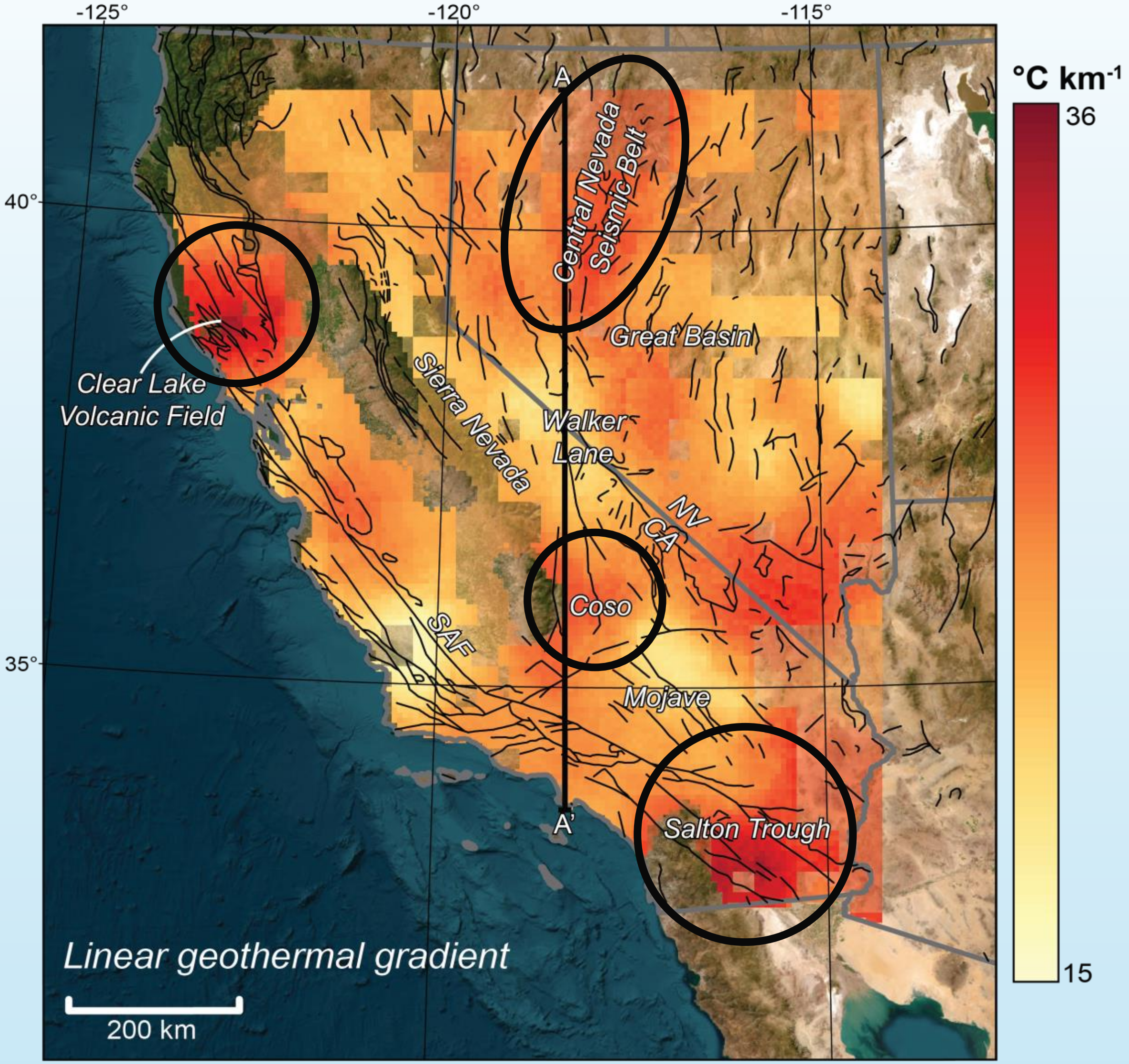




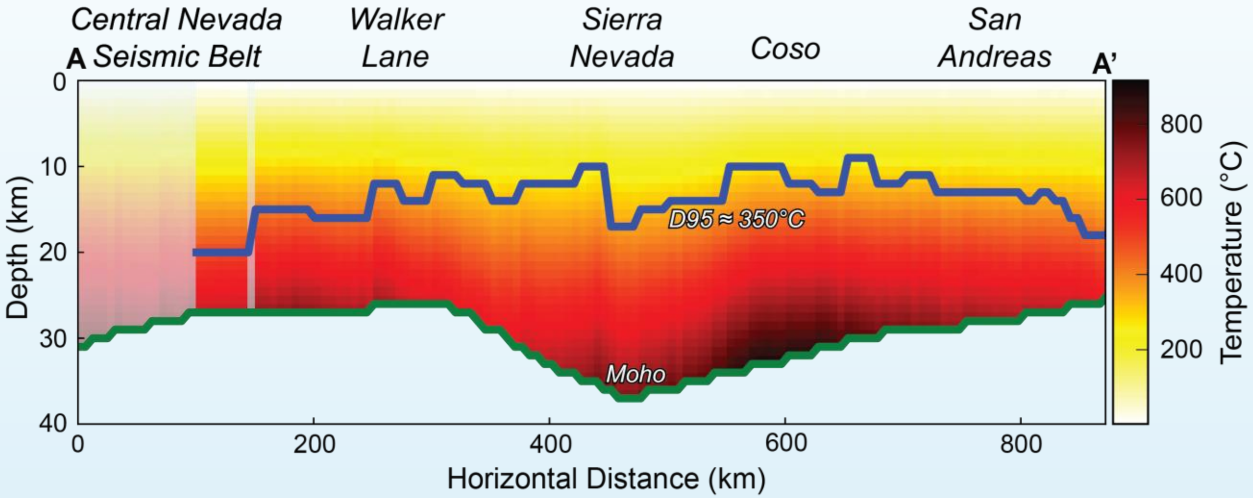
100,000 iterations at each pixel

Output of 1 pixel out of 25976 pixels

Thermal structure of California and Nevada



*Transparent results are constructed without D95 constraint



Elevated thermal gradient regions (>30 °C km^{-1}):

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

Low thermal gradient regions (<20 °C km^{-1}):

- Sierra Nevada, Mojave, Great Valley, northeastern Great Basin

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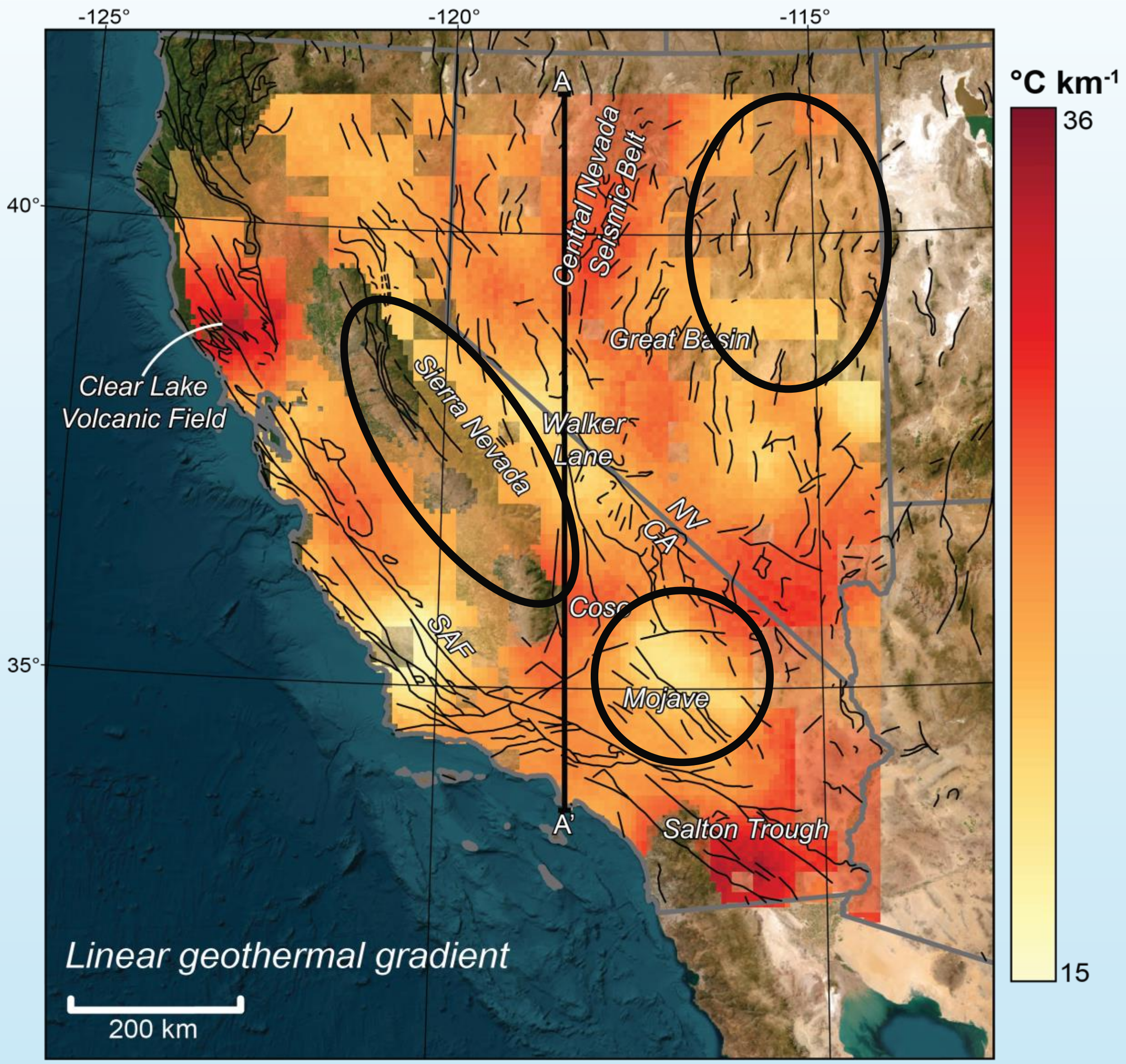

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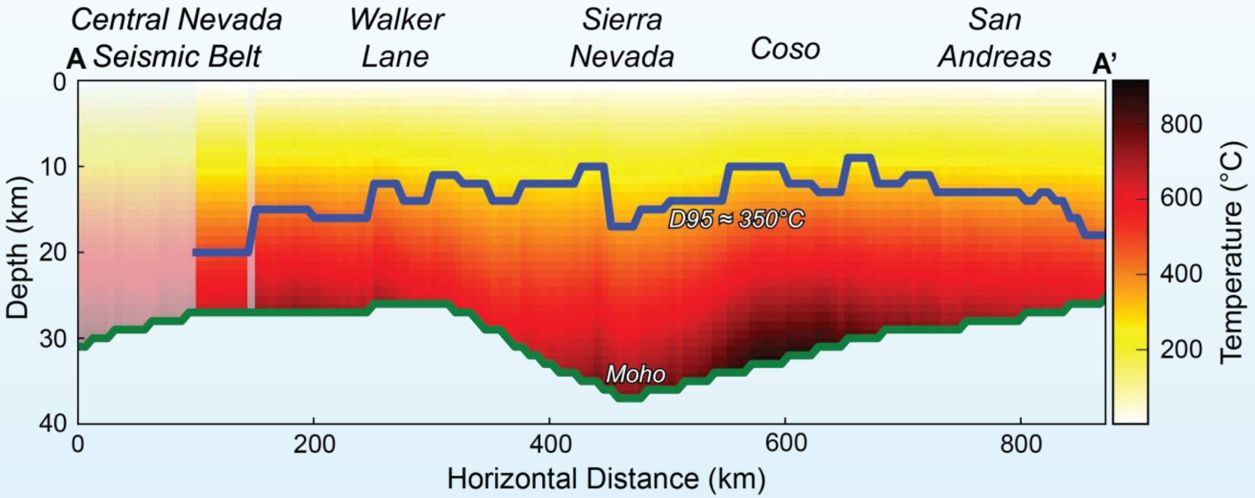

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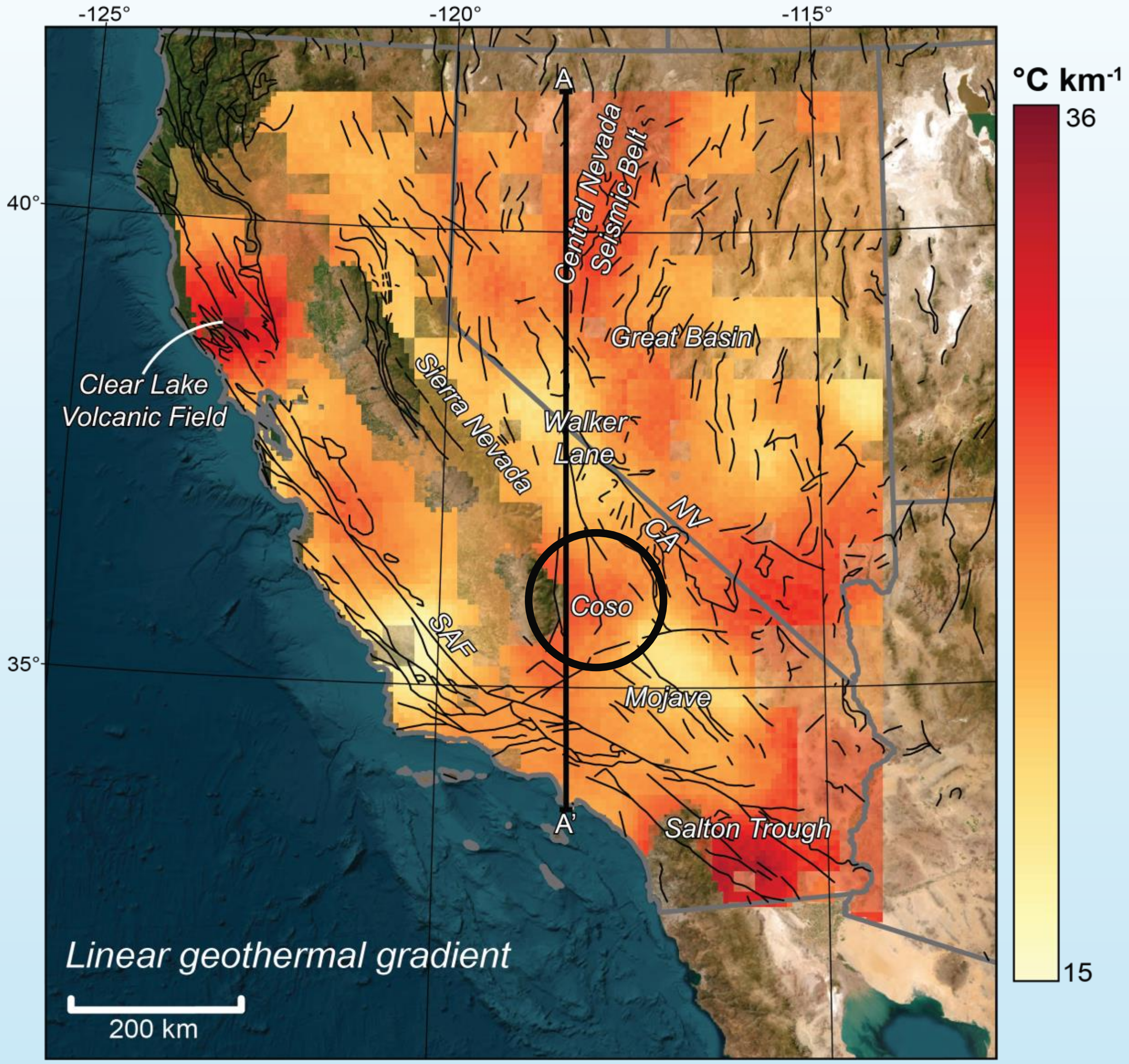

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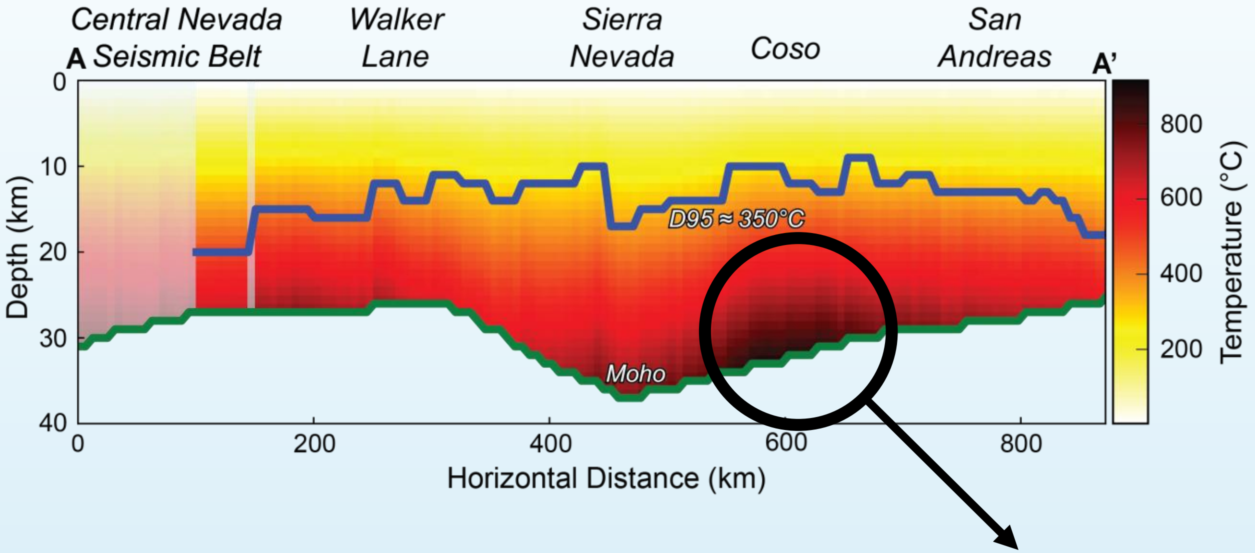


>800 °C

Example — Coso:

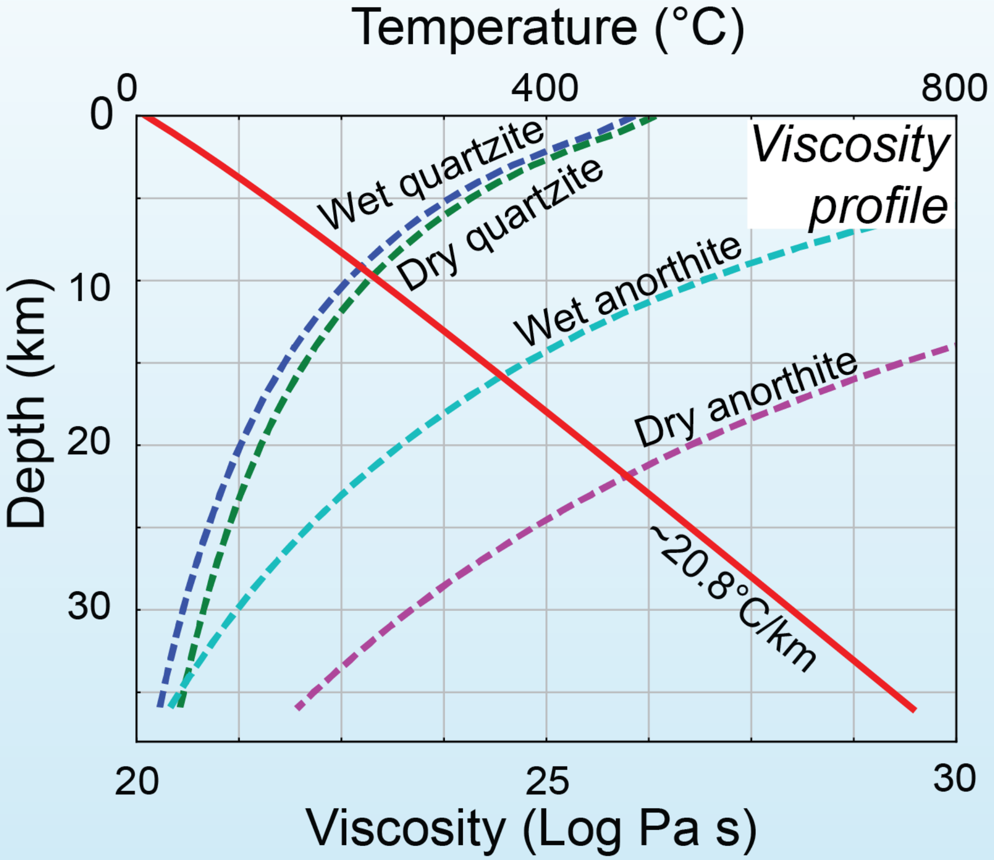
- > 800 °C for the bottom 7 km of the crust
- Exceeds the granite solidus
- Active partial melting/magma body?

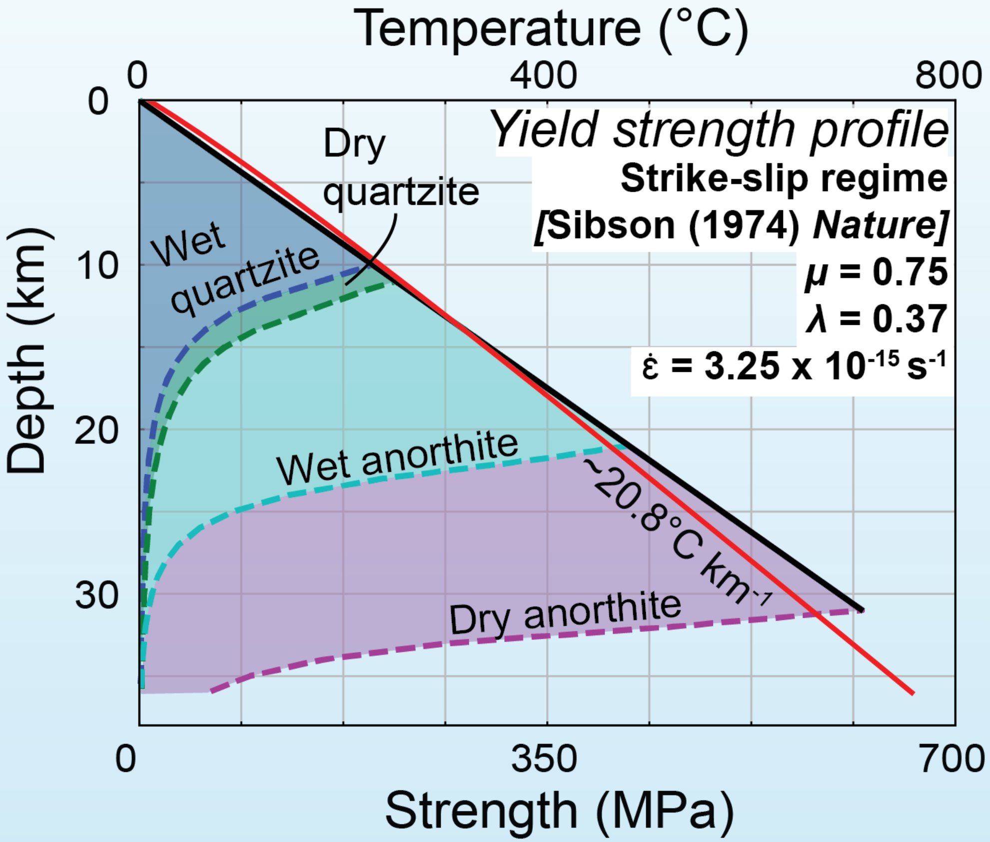
Extract crustal rheology

Quartzite flow law: Hirth et al. (2001 *International Journal of Earth Sciences)*

Anorthite flow law: Rybacki et al. (2006 *JGR SE)*

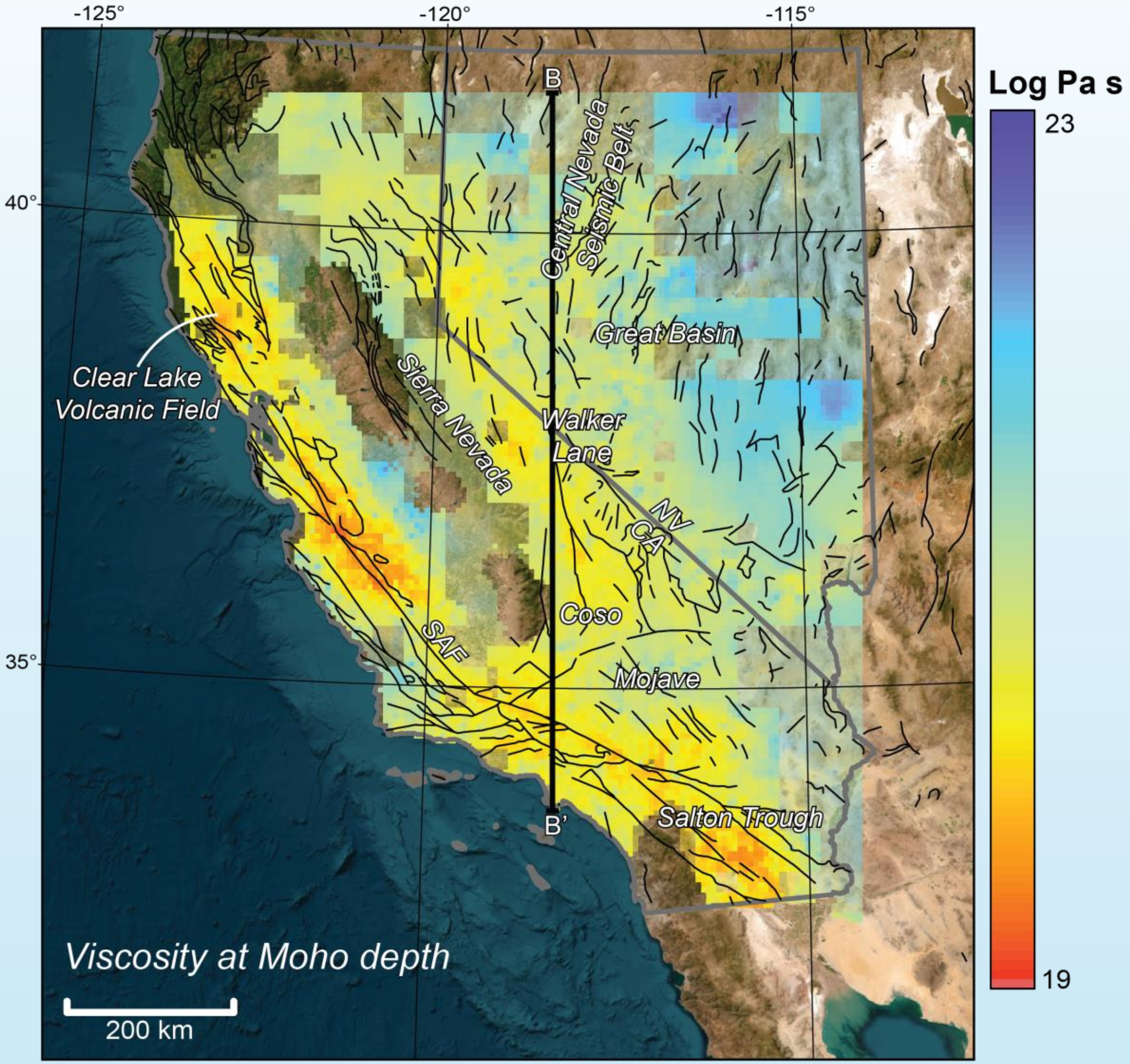
Strain rate: Kreemer et al. (2012 *EGU)*





$$\dot{\varepsilon} = A f_{H_2O}^{r} \sigma^{n} \exp\left(-\frac{Q + PV_a}{RT}\right)$$

Rheology of California and Nevada



Wet quartzite dislocation creep (Hirth et al., 2001)

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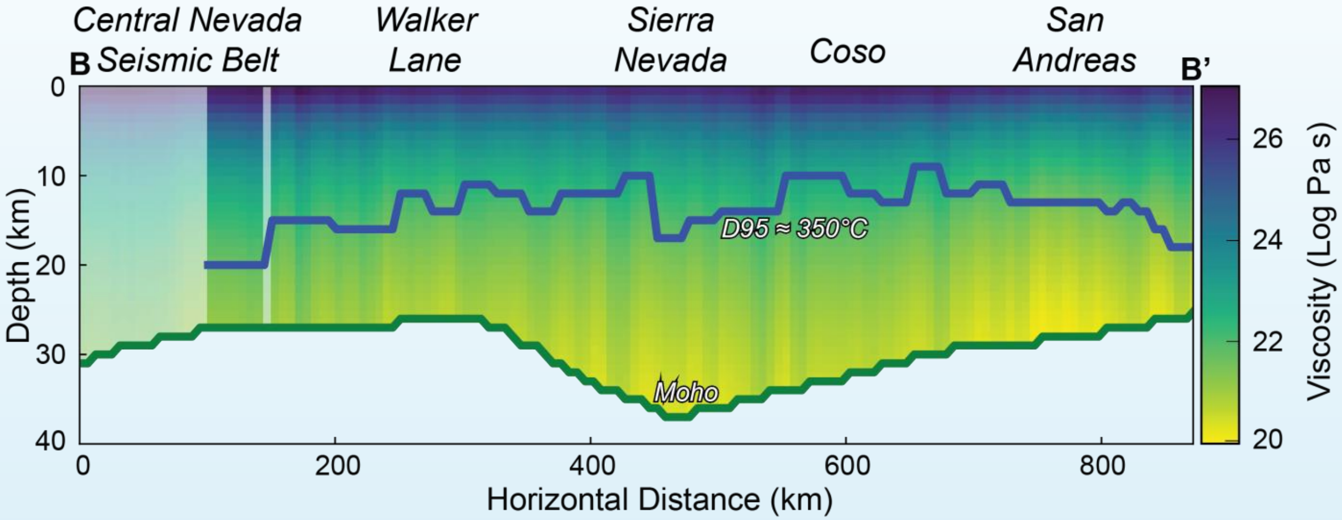


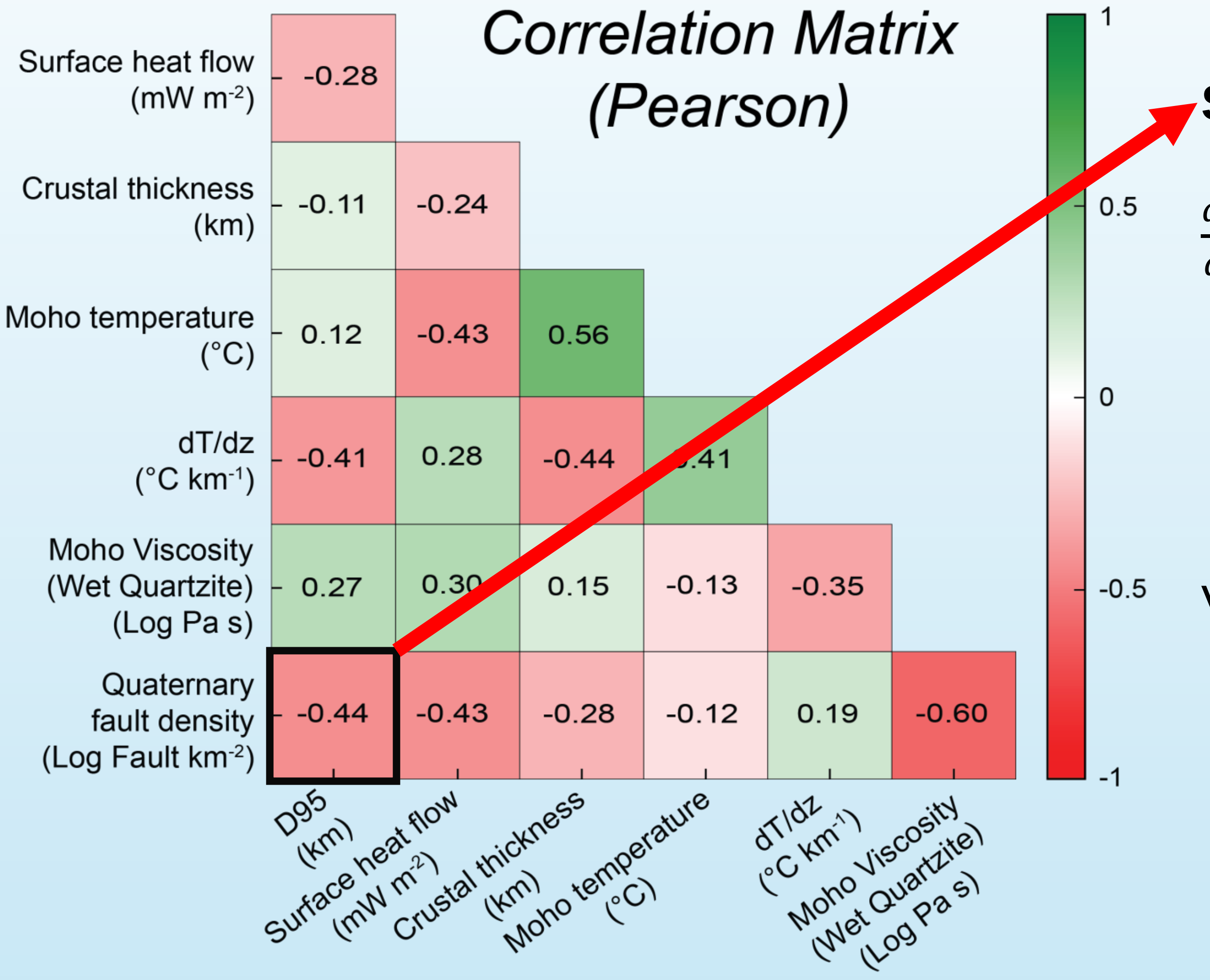
Low viscosity (weak) regions (~19-20 Log Pa s):

- San Andreas, Salton Trough, Clear Lake, Walker Lane

High viscosity (strong) regions (>21 Log Pa s):

- Sierra Nevada, Mojave, Great Valley, northeastern Great Basin

Application to active tectonics: seismicity and faulting



	D95 (km)	Surface heat flow (mW m^{-2})	Crustal thickness (km)	Moho temperature (°C)	dT/dz (°C km^{-1})	Moho Viscosity (Wet Quartzite) (Log Pa s)
Surface heat flow (mW m^{-2})	-0.28					
Crustal thickness (km)	-0.11	-0.24				
Moho temperature (°C)	0.12	-0.43	0.56			
dT/dz (°C km^{-1})	-0.41	0.28	-0.44	0.41		
Moho Viscosity (Wet Quartzite) (Log Pa s)	0.27	0.30	0.15	-0.13	-0.35	
Quaternary fault density (Log Fault km^{-2})	-0.44	-0.43	-0.28	-0.12	0.19	-0.60

Seismogenic thickness α Fault density^{-1}

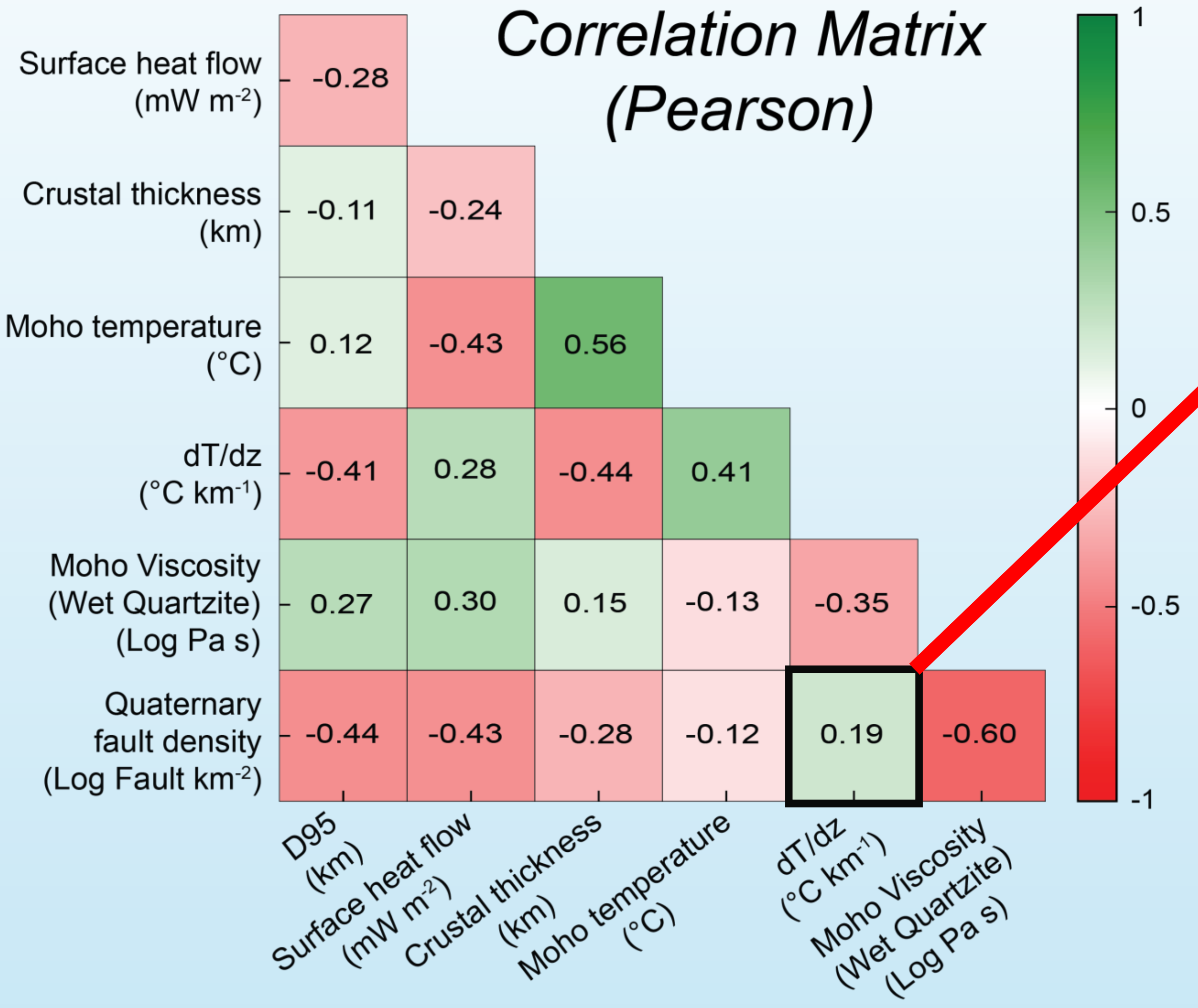
$\frac{dT}{dz}$ α Fault density

- Hot thermal gradient promotes faulting
- Faulting advects heat

Viscosity α Fault density^{-1}

- Weak crust promotes faulting
- Faulting weakens crustal strength

Application to active tectonics: seismicity and faulting



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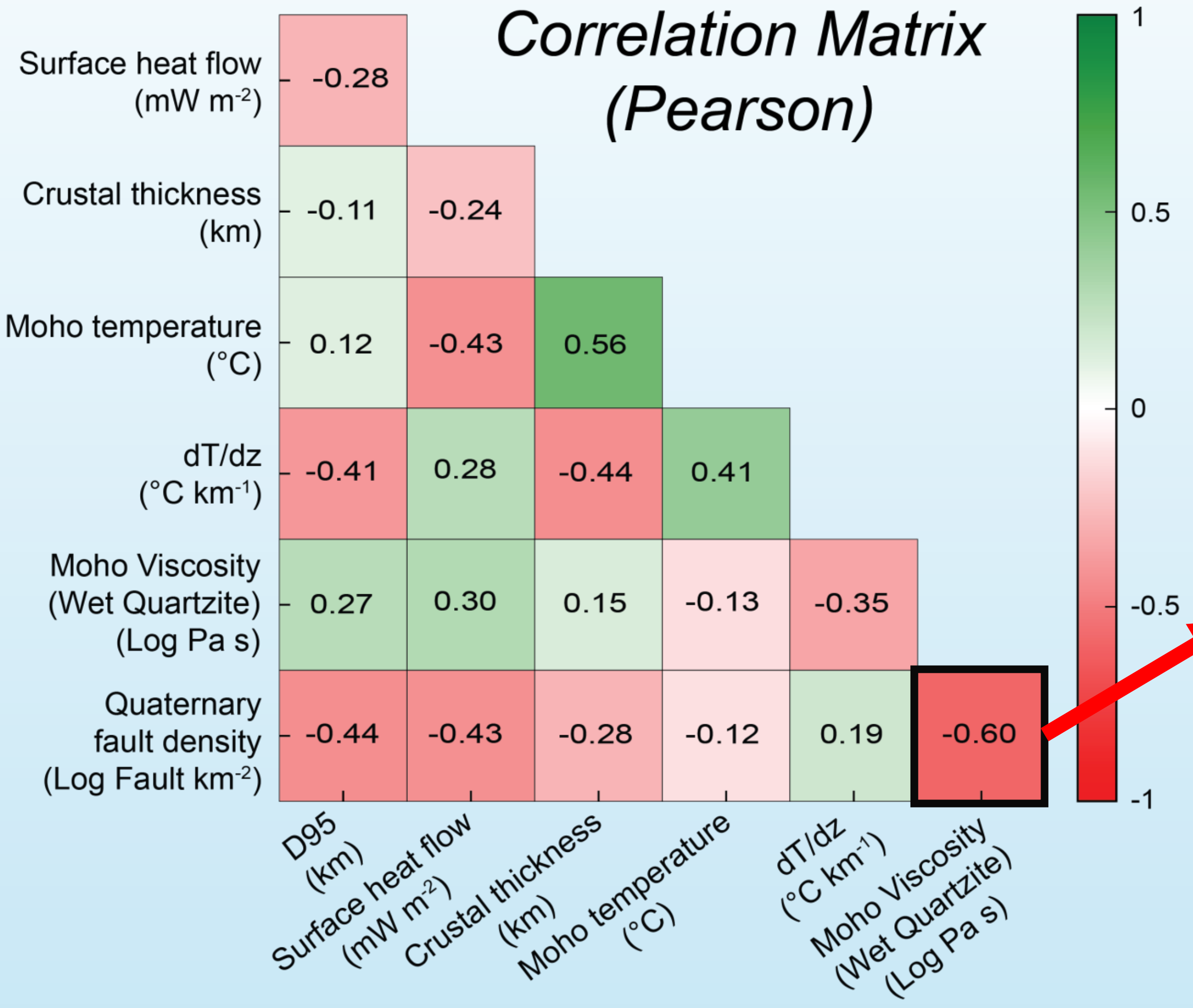

Correlation Matrix (Pearson)

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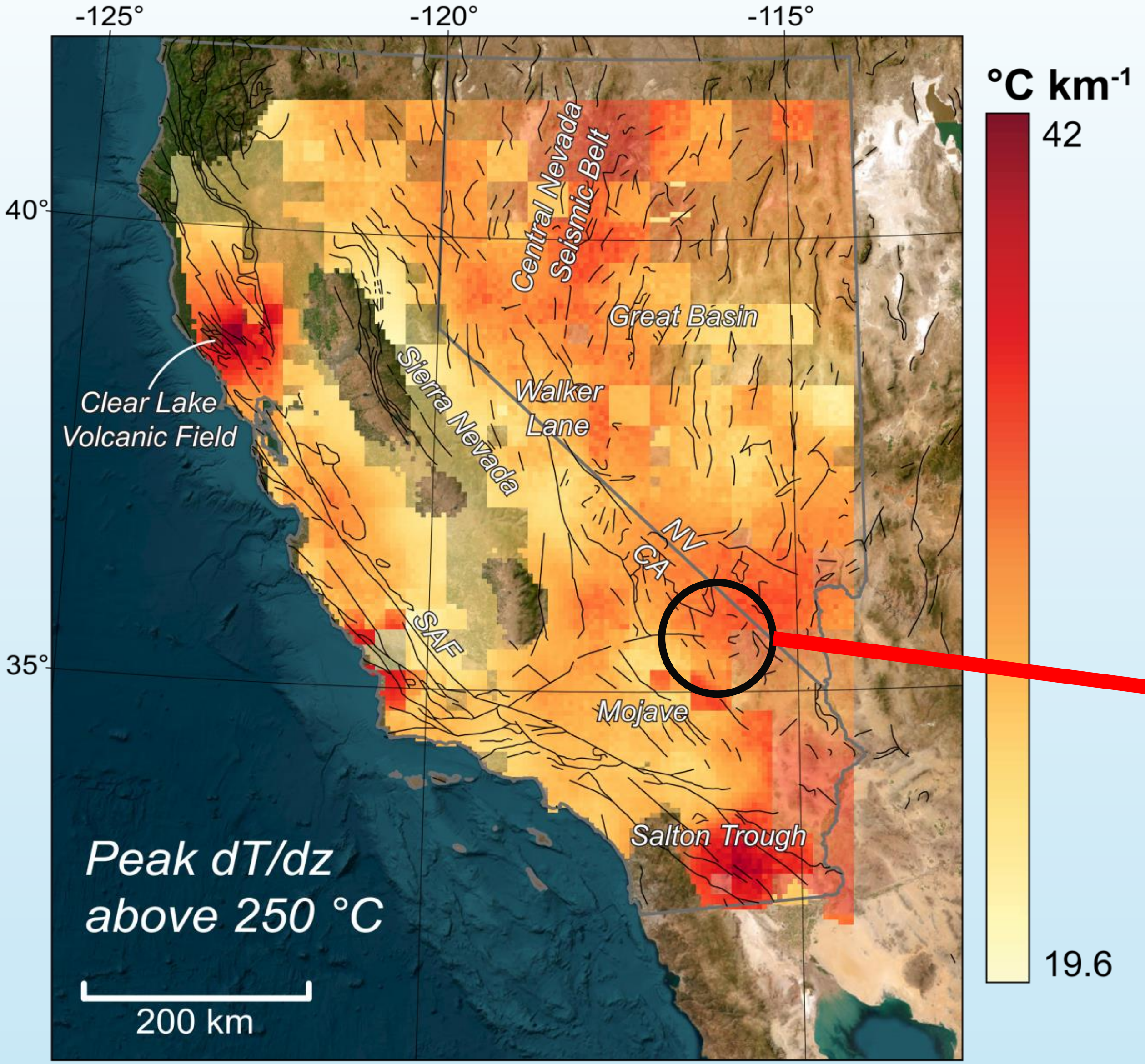
Application to active orogen: low-T thermochronology



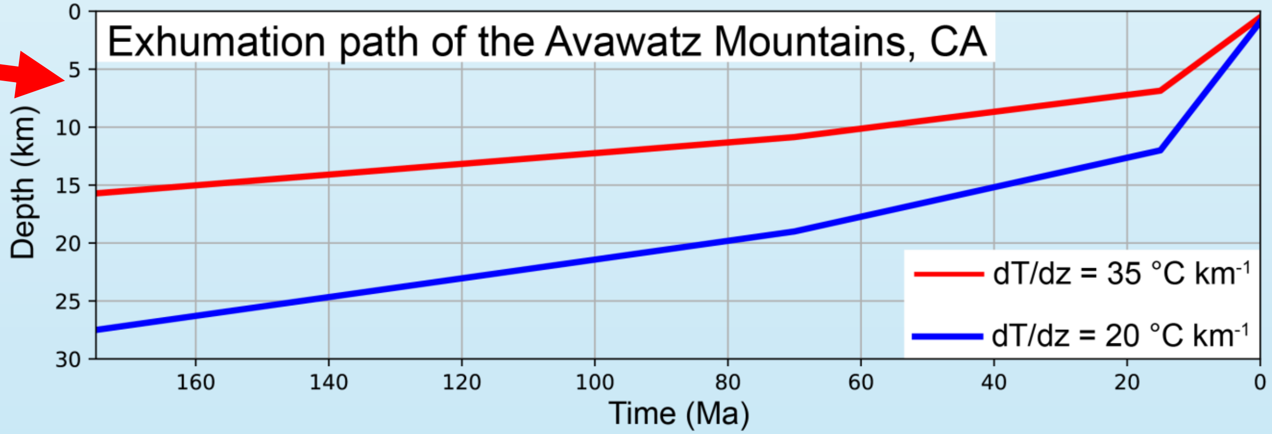
Couples low-T thermochronometers with upper crustal geothermal gradient

- **Exhumation rate**

  (Baden et al., 2023 *GSA Bulletin*)

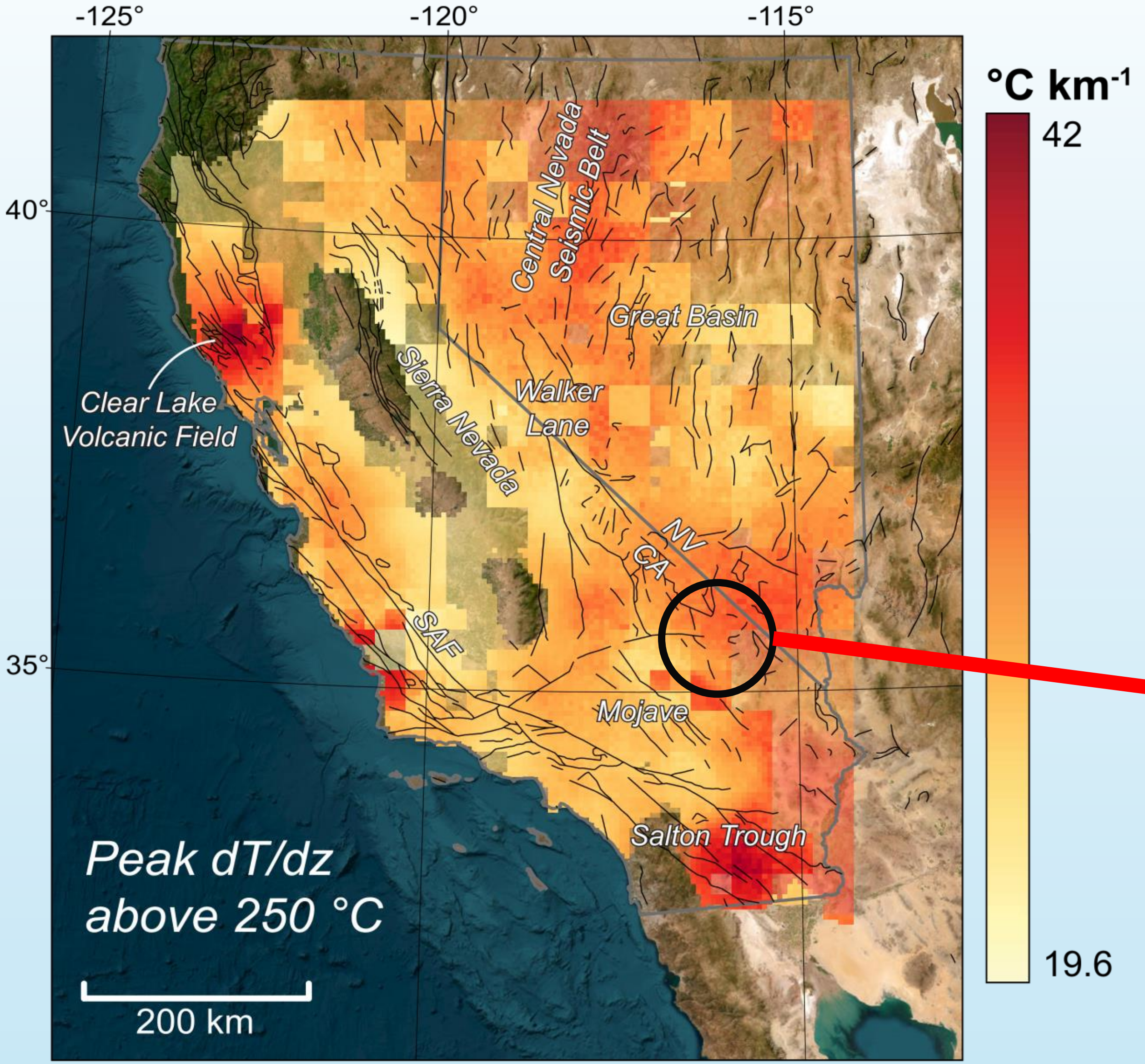
- **Erosion rate**

  (Reiners and Brandon, 2006 *Annual Review of Earth and Planetary Sciences*)



Johns (2023 *M.S. Thesis*)

Application to active orogen: low-T thermochronology



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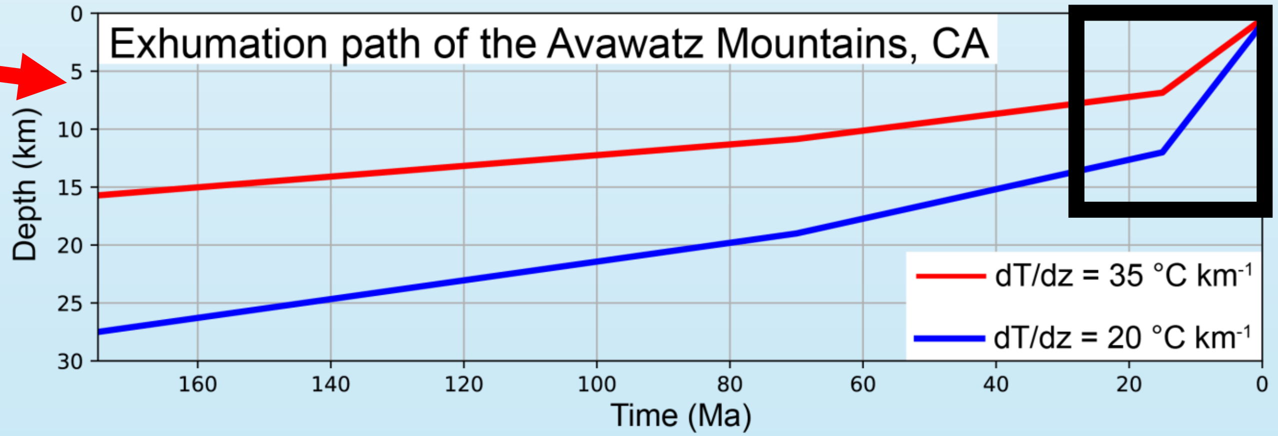
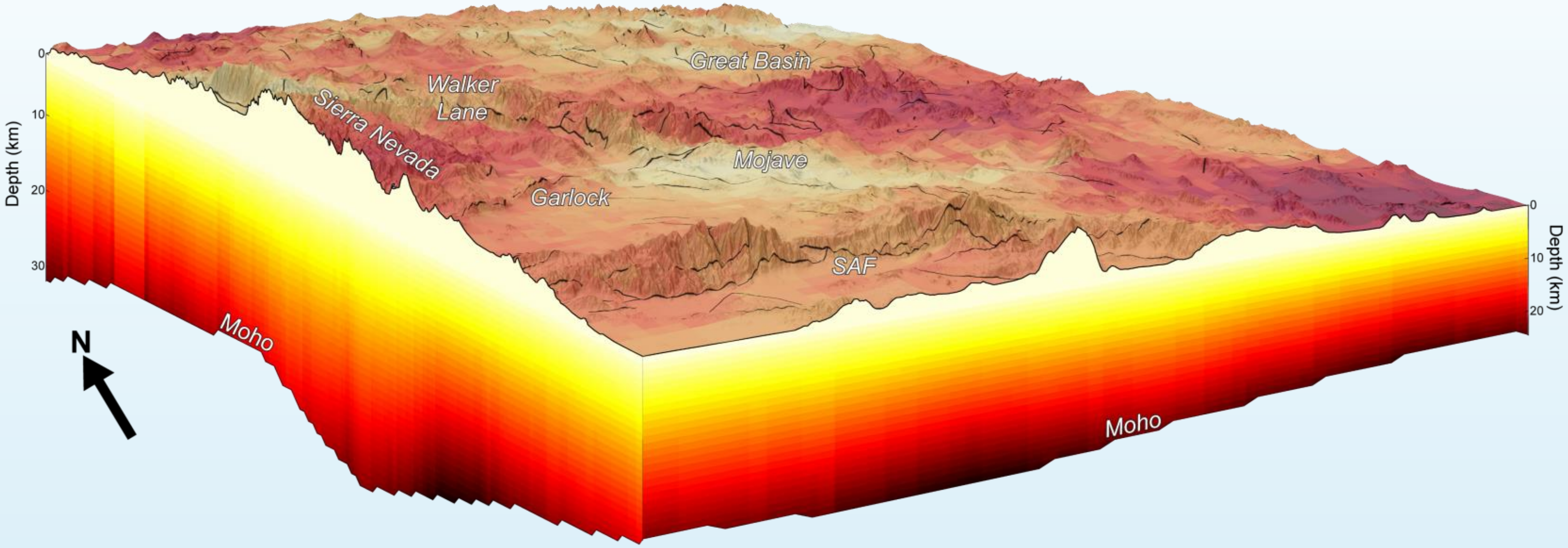


Johns (2023 *M.S. Thesis*)

An analog for the thermal structure of active and ancient orogens



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This model will be open-sourced and could allow users to apply to other tectonic regions (e.g., Himalayas-Tibet, Anatolian fault zone, Alps)

Cautious evaluation of crustal thermal structure can provide insights into the evolution of active and ancient orogens

Thermal structure governs **deformation and rheology**

This modeling approach may improve the **rigorousness of exhumation and erosion rate estimations**