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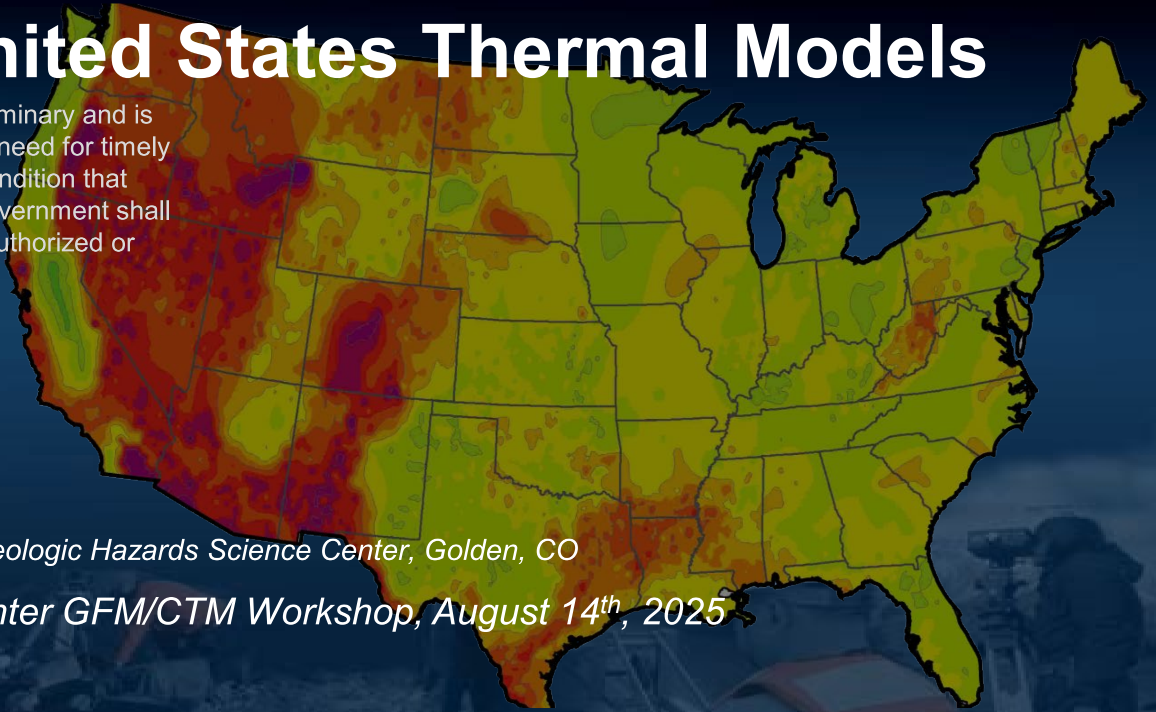
Earthquakes ★ Floods ★ Hurricanes ★ Landslides ★ Tsunamis ★ Volcanoes ★ Wildfires

Conterminous United States Thermal Models



Blackwell et al. (2011)

Presented by Oliver Boyd

olboyd@usgs.gov, U.S. Geological Survey, Geologic Hazards Science Center, Golden, CO

Statewide California Earthquake Center GFM/CTM Workshop, August 14th, 2025

U.S. Department of the Interior
U.S. Geological Survey

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- **Walter Mooney**—USGS, Earthquake SC

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Conterminous U.S. thermal models

Geophysical Journal International
Geophys. J. Int. (2025) **241**, 1711–1724 https://doi.org/10.1093/gji/ggaf118
Advance Access publication 2025 March 28
GJI General Geophysical Methods

A crustal thermal model of the conterminous United States constrained by multiple data sets: a Monte–Carlo approach

Siyuan Sui[1,2] Weisen Shen[1] and Oliver S. Boyd[3]

GRC *Transactions*, Vol. 35, 2011

Temperature-At-Depth Maps for the Conterminous U. S. and Geothermal Resource Estimates

David Blackwell, M. Richards, Z. Frone, J. Batir, A. Ruzo, R. Dingwall, and M. Williams
SMU Huffington Department of Earth Sciences, Geothermal Laboratory, Dallas TX

Aljubran and Horne *Geothermal Energy* (2024) 12:25
https://doi.org/10.1186/s40517-024-00304-7
Geothermal Energy
RESEARCH Open Access

Thermal Earth model for the conterminous United States using an interpolative physics-informed graph neural network

Mohammad J. Aljubran[1*] and Roland N. Horne[1]

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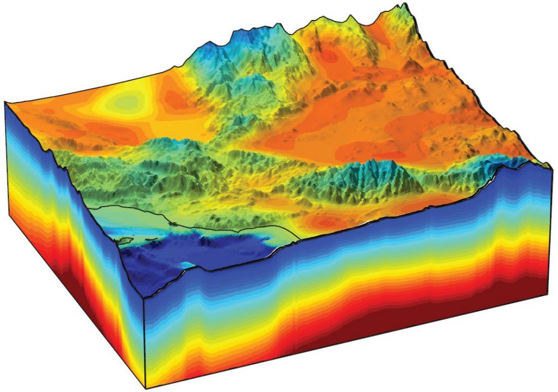
Temperature Model in Support of the U.S. Geological Survey National Crustal Model for Seismic Hazard Studies



Open-File Report 2019–1121
U.S. Department of the Interior
U.S. Geological Survey

Boyd (2019)

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MOTIVATION

Motivation

- ✓ Geothermal energy
- ✓ Rheology
- ✓ Brittle-to-ductile transition and the base of seismicity
- ✓ Mineral physics/Phase transitions
- ✓ Seismic velocity

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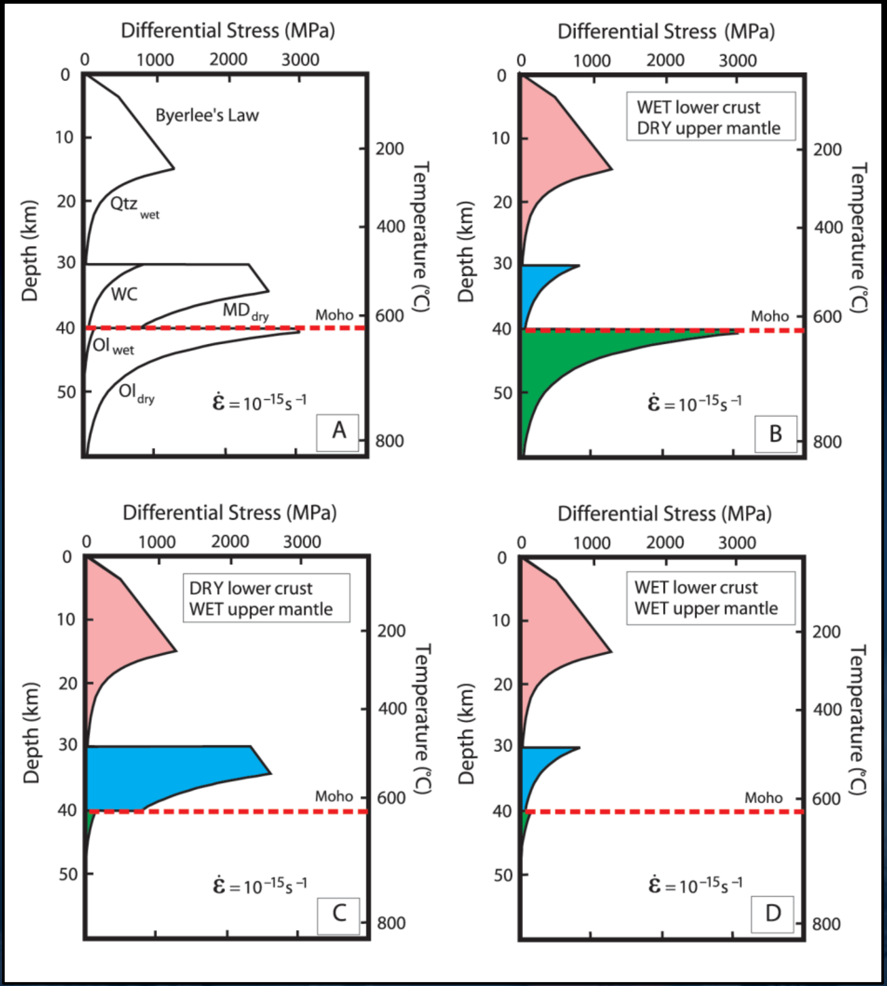
Brittle-to-ductile transition and the base of seismicity

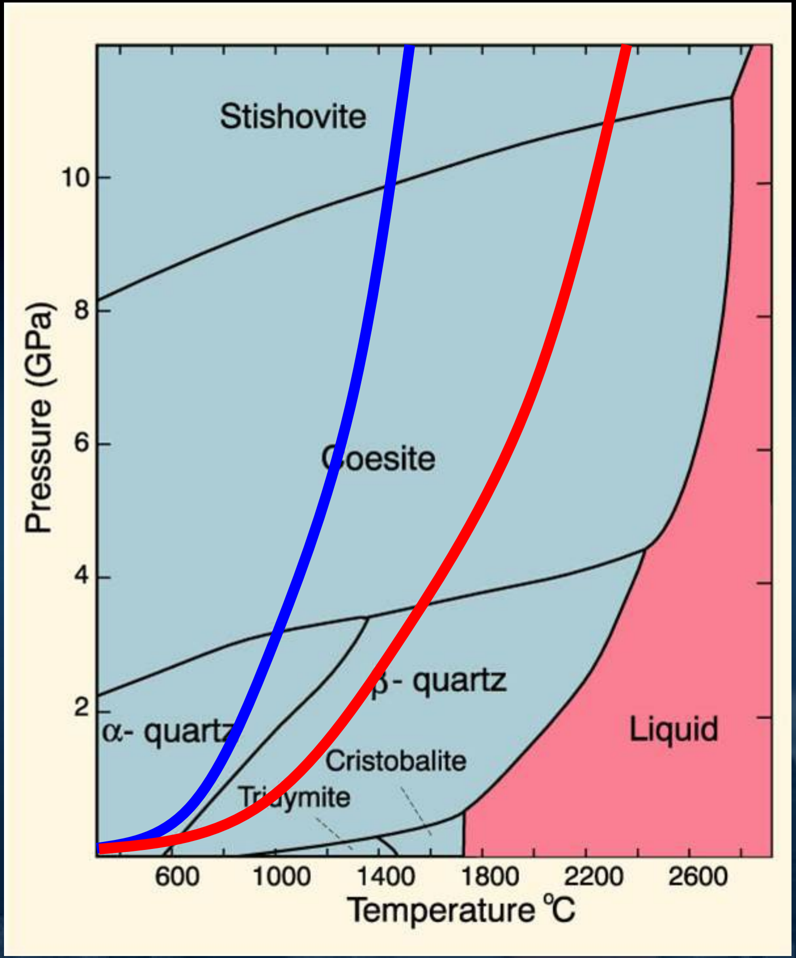
- Crustal strength is governed by flow laws dependent on composition, pressure, and temperature.
- Temperature will have a significant role in the depth of the brittle to ductile transition.
- The brittle-to-ductile transition controls in large part how deep seismicity will occur and how deep large ruptures can propagate.
- These factors have an impact on earthquake rupture forecasts and seismic hazards.



Jackson (2002)

Mineral physics, phase transitions, and seismic velocity

- Quartz has several phases with different physical properties.
- Alpha-to-beta phase transition is of particular interest because there is a large change in modulus and density, and the phase transition can occur above the Mohorovičić discontinuity (Moho).
- Whether or not and at what depth you get the transition is strongly dependent on the temperature profile.



John Winter, Whitman College

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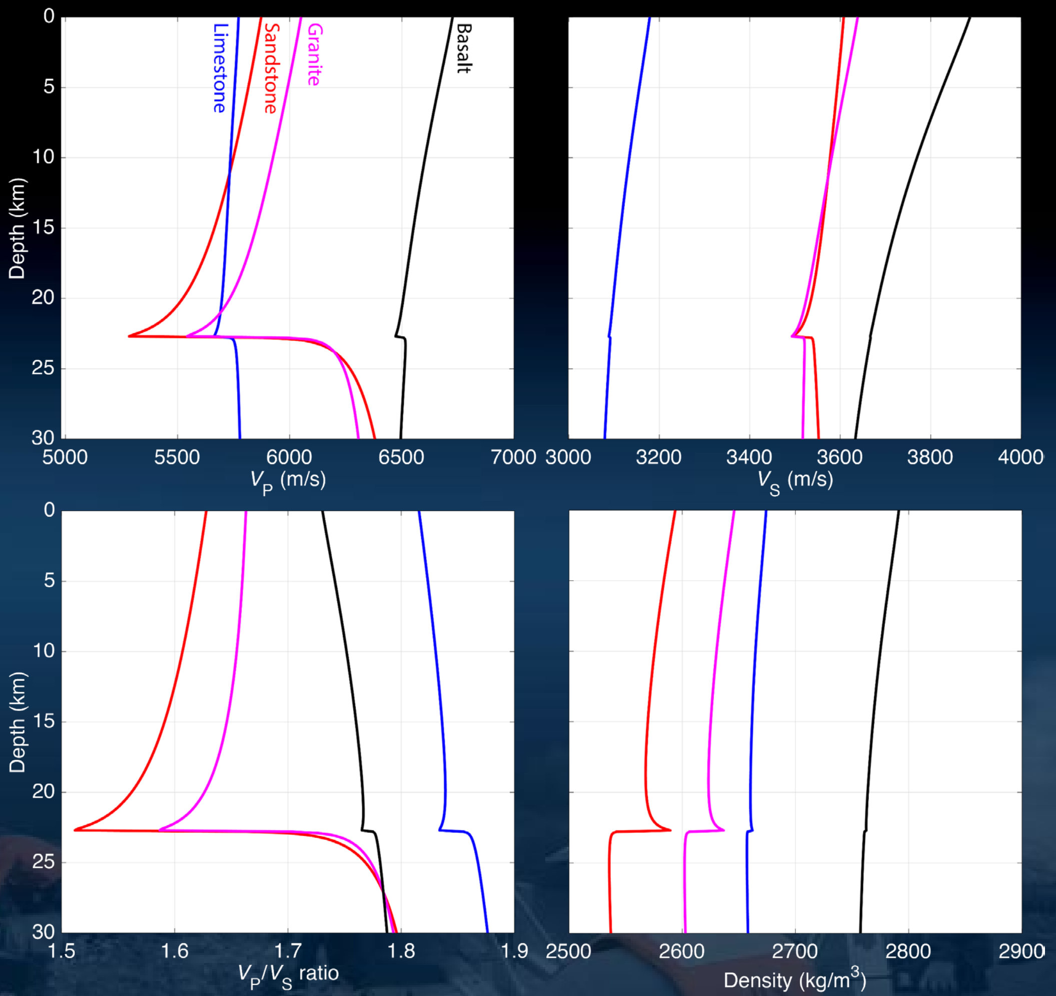
Mineral physics, phase transitions, and seismic velocity

- Each lithology in the National Crustal Model geologic framework is assigned a mineral composition.
- Equation of State methods are used to calculate V_P, V_S, and ρ of the solid rock matrix as functions of temperature and pressure.
- Alpha-to-beta phase transition of quartz causes the jump in velocity at 23-km depth.



Modified from Sowers and Boyd (2019)

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MODEL COMPONENTS

Specifications

Model	Lateral Resolution	Vertical Resolution	Depth Extent	Time-dependent	Proprietary
Blackwell et al. (2011)	unspecified	1 km from 3.5 km to 8.5 km, 10 km	10 km	No	Yes
Boyd (NCM; 2019)	1 km	Analytic: Physical models	Below the Moho	No	No
Aljubran and Horne (2024)	~4 km	1 km	7 km	No	No
Sui et al. (2025)	~70 km	Analytic: 5-pt B-spline	Moho	No	No

NCM – National Crustal Model

Blackwell et al. (2011)—SMU

Inputs

- > 35,000 data sites
- Surface temperature
- Borehole temperature gradients
- Corrected bottom-hole temperatures
- Surface and subsurface heat flow
- Thermal conductivity
- Heat production

Special consideration

- Thermal conductivity of sedimentary section

SMU—Southern Methodist University

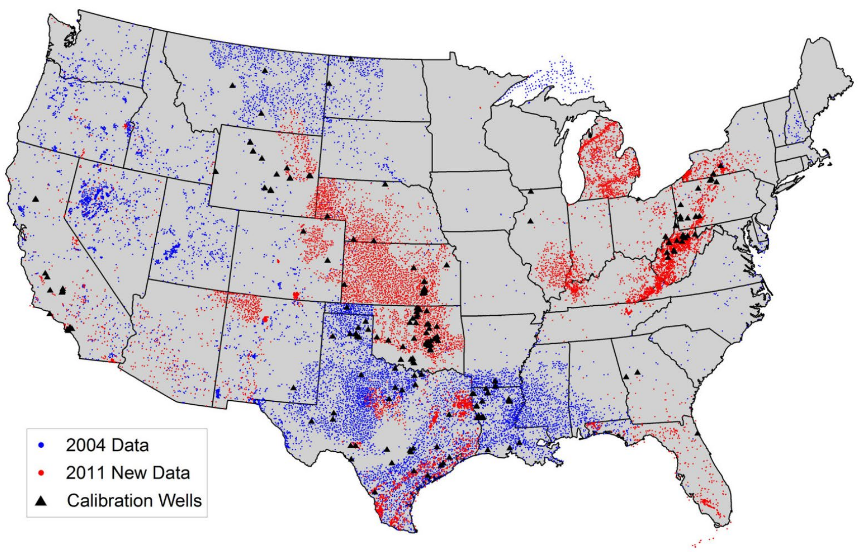


Figure 2. Data Sites for the two studies with calibration (Spicer data and equilibrium well logs) localities shown as Triangles.

Blackwell et al. (2011)

Boyd (2019)

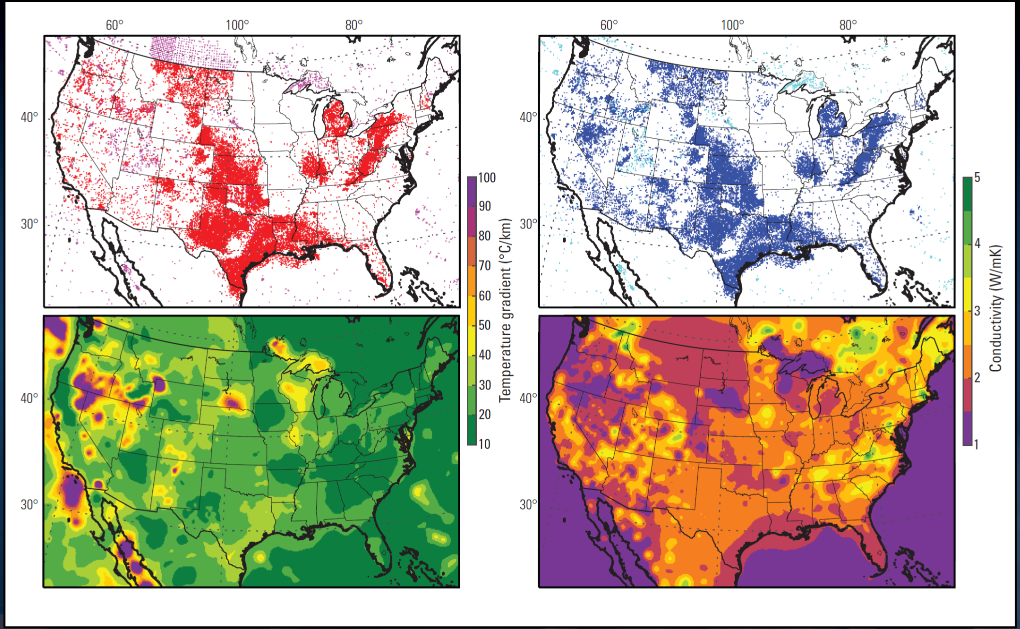
Inputs

- Surface temperature
- Corrected borehole temperature gradients (SMU; UND)
- Surface heat flow (SMU)
- Thermal conductivity (SMU, UND)
- Heat production (Hasterok and Webb, 2017)

Special consideration

- Moho depth and temperature

SMU, 2015
UND—University of North Dakota, 2015



Boyd (2019)

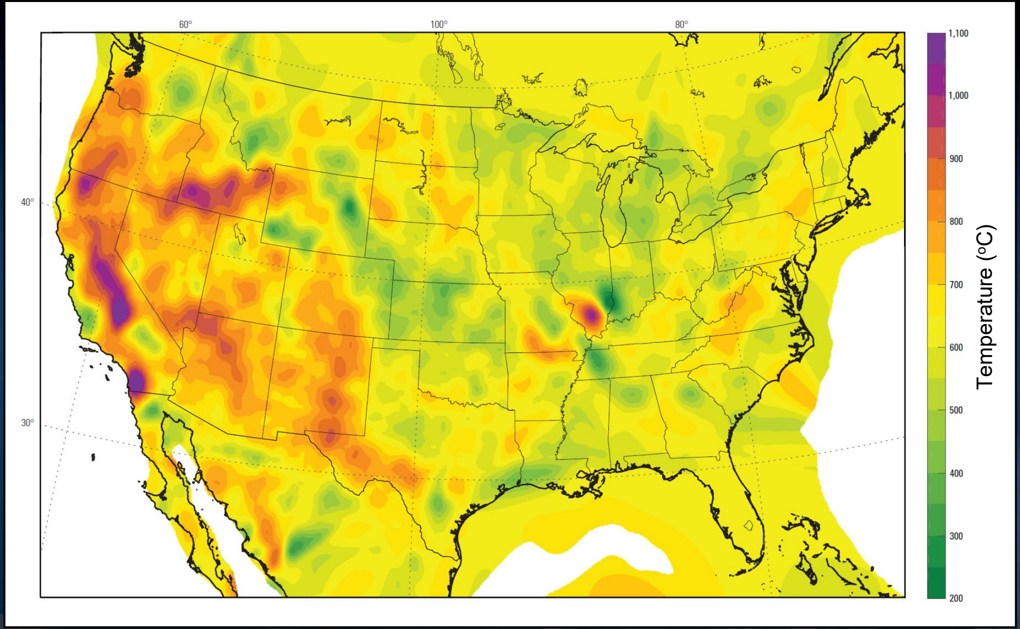
Boyd (2019)

Inputs

- Surface temperature
- Corrected borehole temperature gradients (SMU; UND)
- Surface heat flow (SMU)
- Thermal conductivity (SMU, UND)
- Heat production (Hasterok and Webb, 2017)

Special consideration

- Moho depth and temperature



Boyd (2019)

SMU, 2015
UND—University of North Dakota, 2015

Aljubran and Horne (2024)

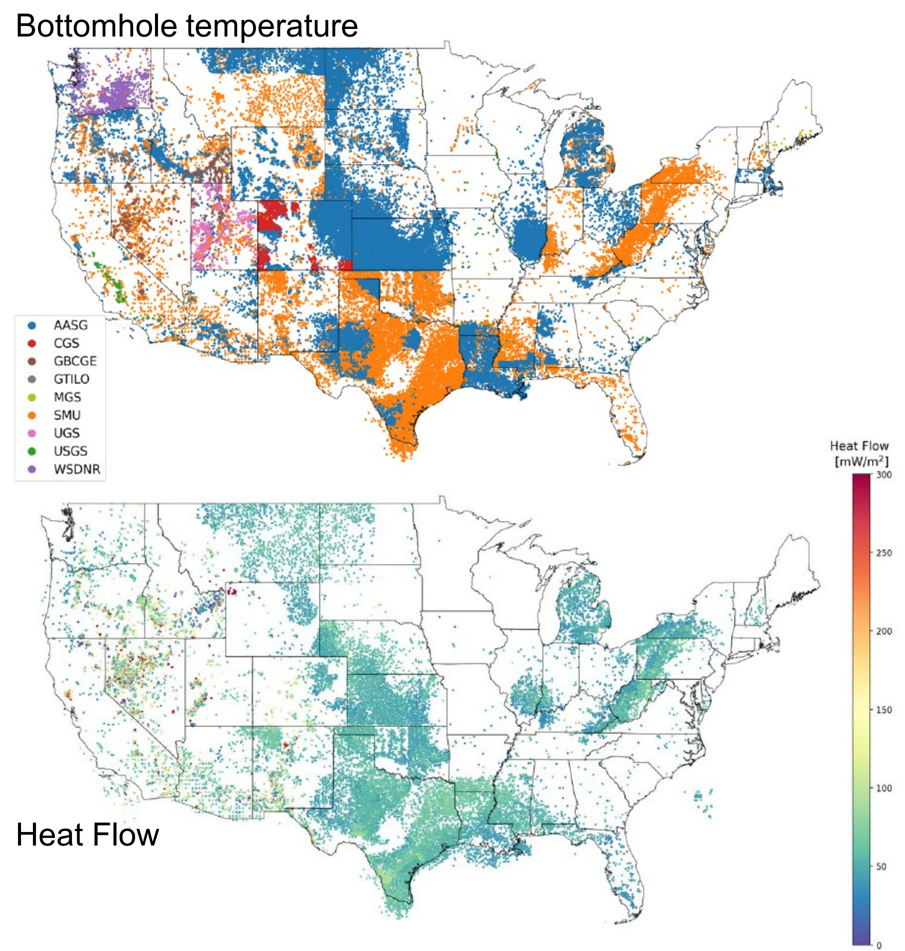
Inputs

- Surface temperature
- Corrected bottomhole temperature
- Surface heat flow
- Thermal conductivity

Special consideration

- Interpolation with a physics-informed graph neural network

Depth, location, elevation, sediment thickness, magnetic anomaly, gravity anomaly, radioactivity, seismicity, electrical conductivity, and proximity to faults and volcanoes



Aljubran and Horne (2024)

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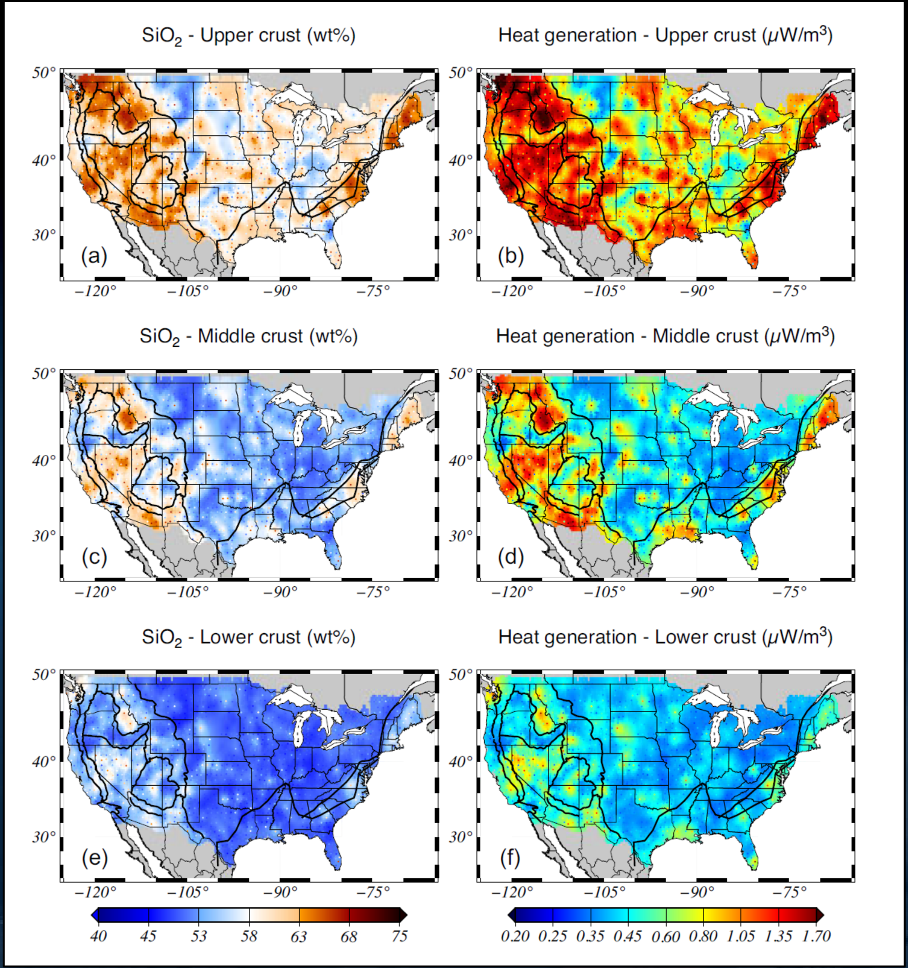
Sui et al. (2025)

Inputs

- Surface temperature
- Surface heat flow
- Thermal conductivity
- Moho depth and temperature

Special consideration

- Crustal heat generation, Curie Depth, Monte Carlo uncertainty analysis



Sui et al. (2025)

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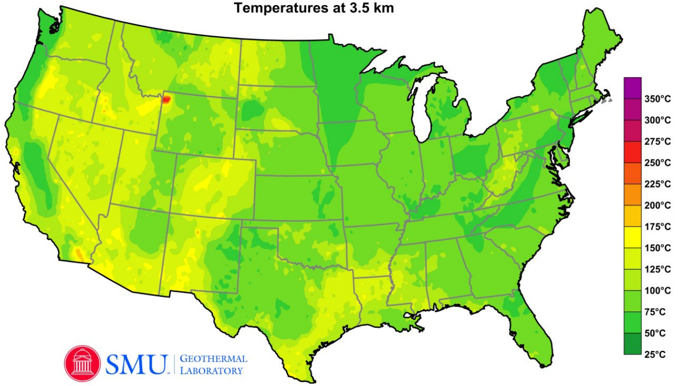
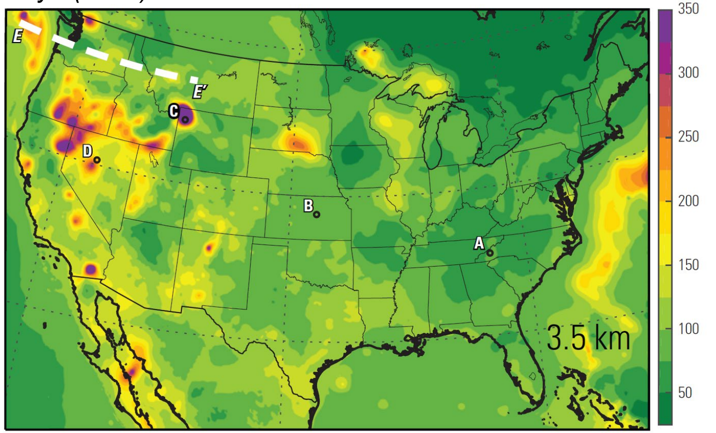
TEMPERATURE COMPARISONS

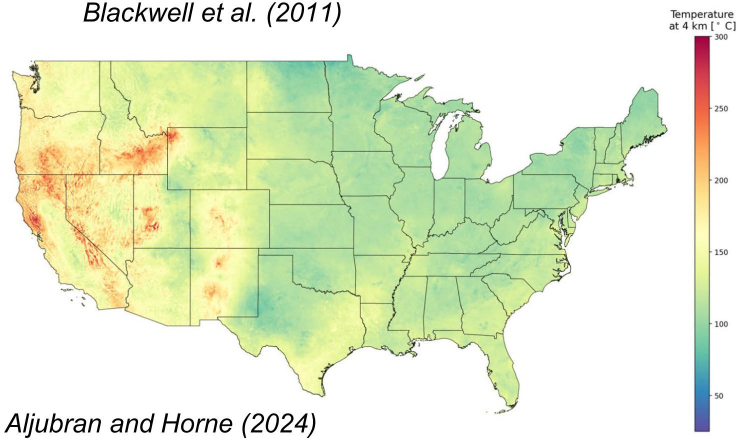
3–5-km depth



Blackwell et al. (2011)

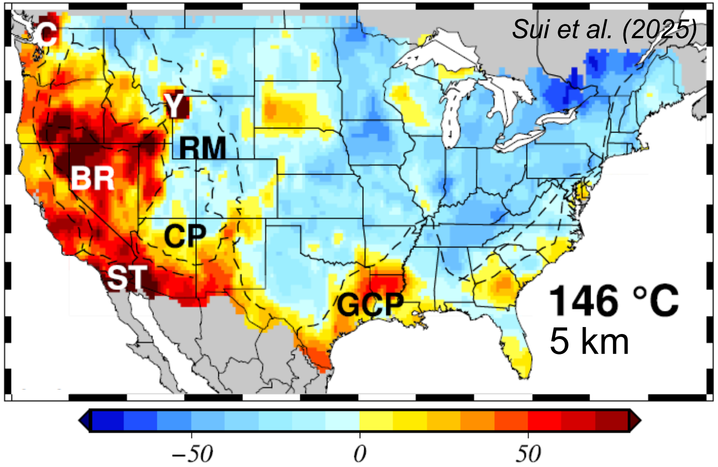
Boyd (2019)



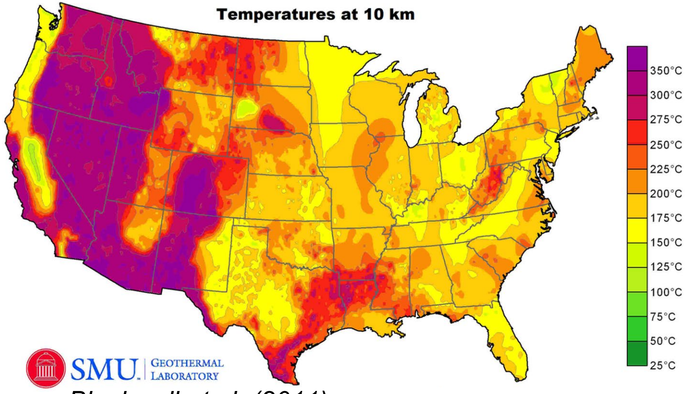


Aljubran and Horne (2024)

Fig. 26 Predicted temperature-at-depth map at a depth of 4 km

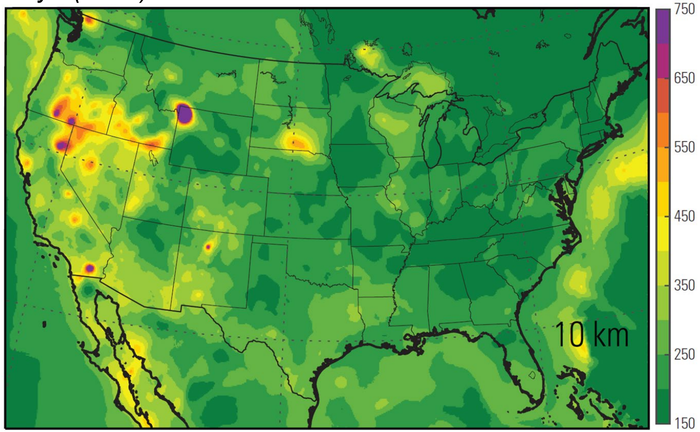


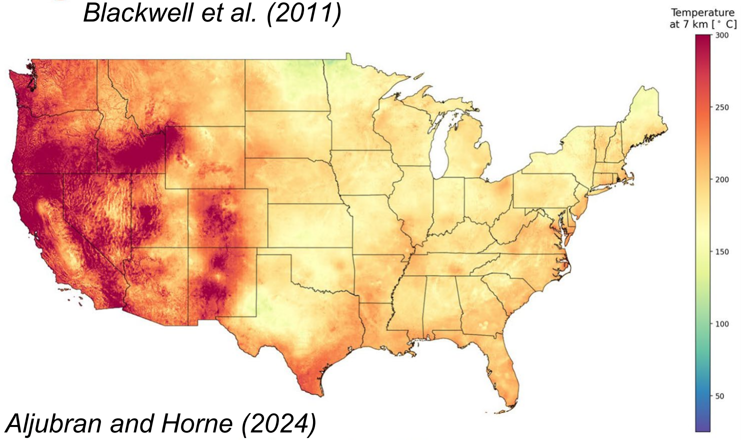
7–10-km depth



Blackwell et al. (2011)

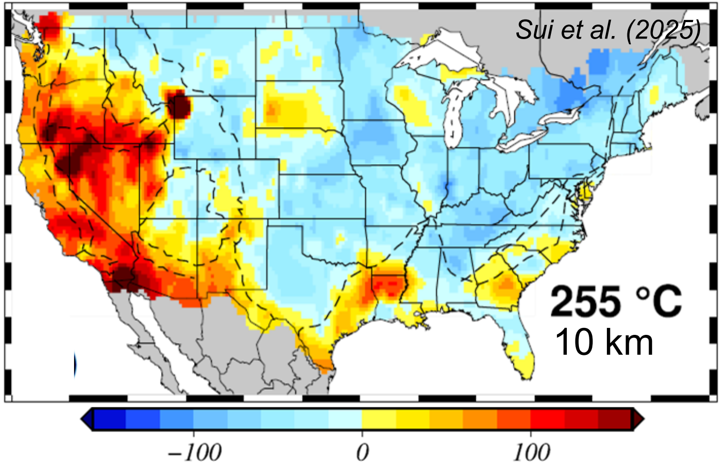
Boyd (2019)





Aljubran and Horne (2024)

Fig. 29 Predicted temperature-at-depth map at a depth of 7 km



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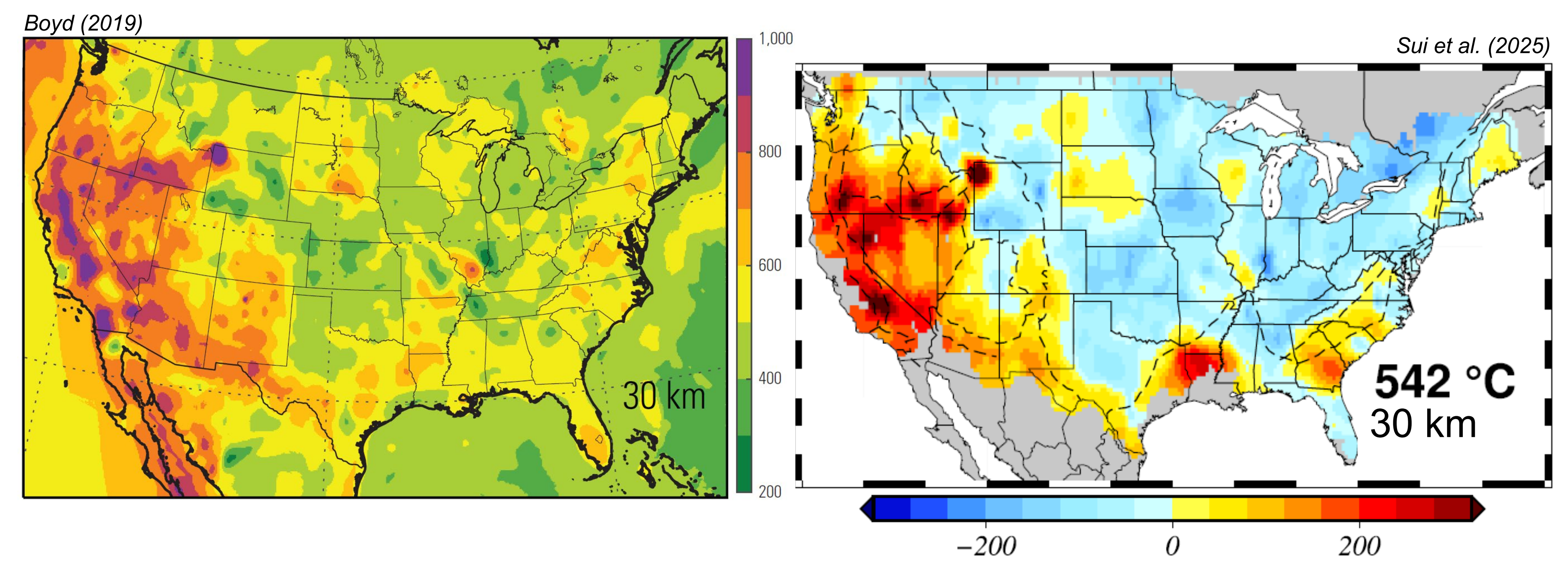
30-km depth



Boyd (2019)
1,000
800
600
400
200
30 km
Sui et al. (2025)
542 °C
30 km
−200
0
200

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SUMMARY

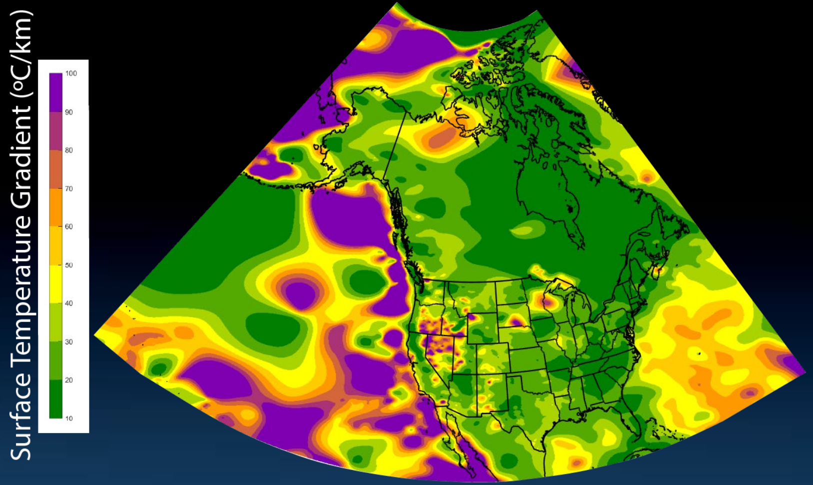
Summary

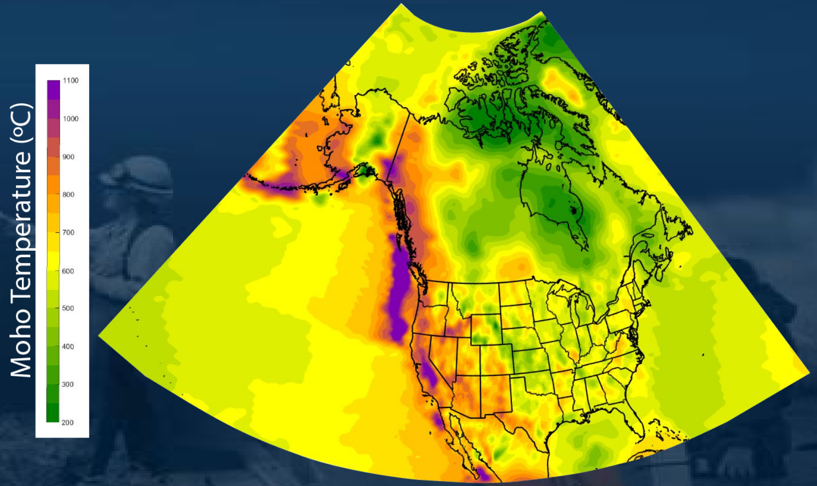
Conterminous U.S. thermal models

- Use common datasets
- Differ primarily in their methods
- May focus on more shallow depths for geothermal resource potential
- Have different resolutions
- Broadly agree on the spatial distribution of temperatures

Next Steps

- Estimate seismogenic depth across the conterminous U.S. (Zeng)
- North American thermal model to address crustal strength and seismogenic depth (Lundstern, Zeng)
- Uncertainty analysis



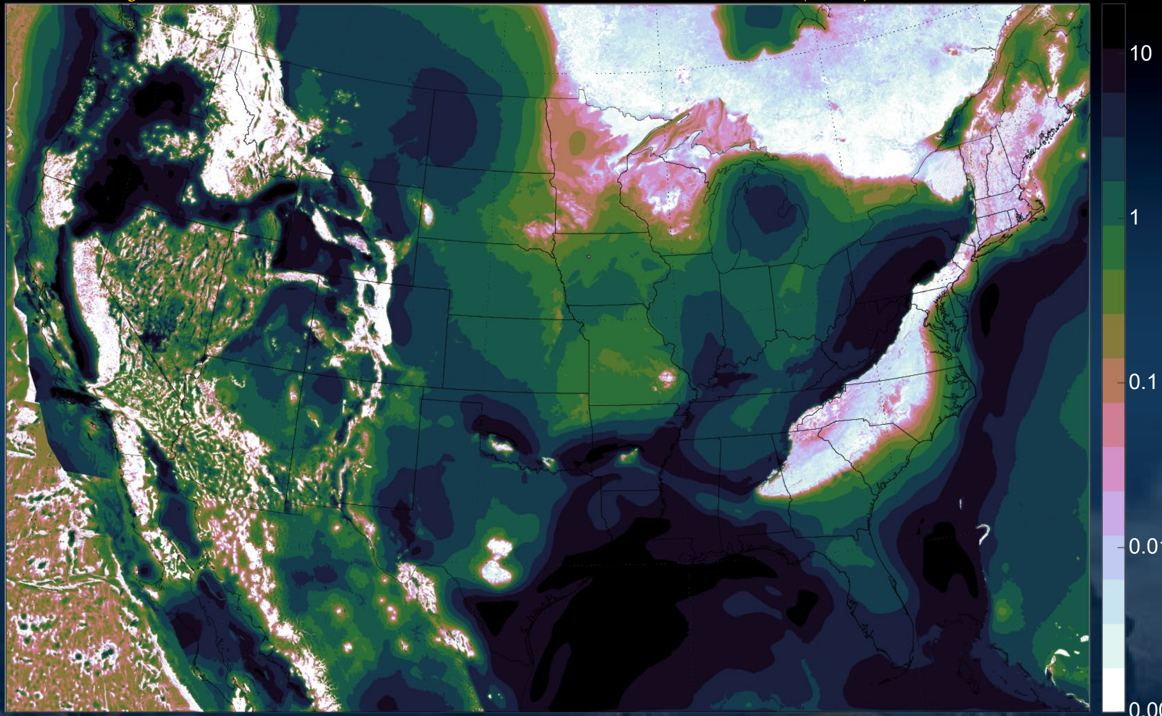


(Preliminary Information—Subject to Revision. Not for Citation or Distribution.)

Next Steps

- Use NCM geologic framework to account for the effects of sediments

Base of Phanerozoic non-intrusive rocks (km)



Boyd and Sweetkind (in review)

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Thank you

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