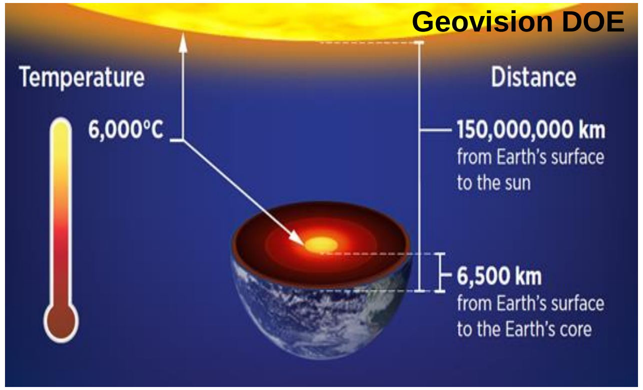
COLORADO SCHOOL OF MINES

Revolutionizing Geothermal Mapping: A Path Forward

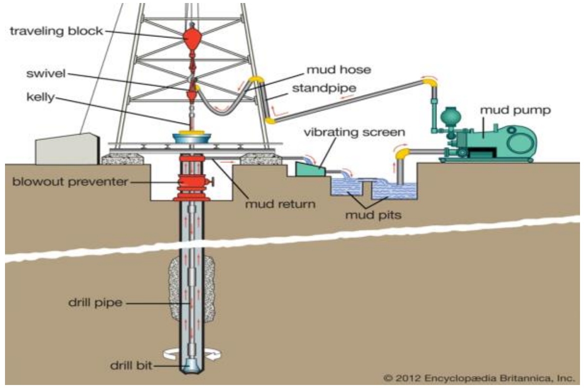
Mohamed Shafik Khaled, Ph.D. Nov. 19th, 2024

Challenges in Geothermal Data



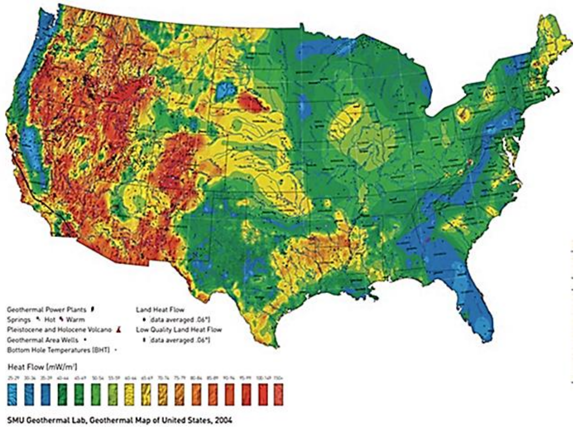
Heat Transfer in the Earth's Crust

- Radiation
- Convection
- Conduction
  - $\mathbf{q = \lambda . grad\, T}$
  - q: heat flow
  - λ: thermal conductivity
  - T: temperature



Temperature Data Sources

- High-quality temp. logs
- P tests from shut-in wells
- Down hole temp. (DHT)
  - Recorded T skew colder than In-situ reservoir T due to the cooling effect of the drilling fluids



U.S Heat Flow (HF) Database

- The U.S. HF Database contains outdated & uncertain data
- Heterogenous description and evolution of measurement methods
- Multiple BHT correction methods are used to estimate DHT

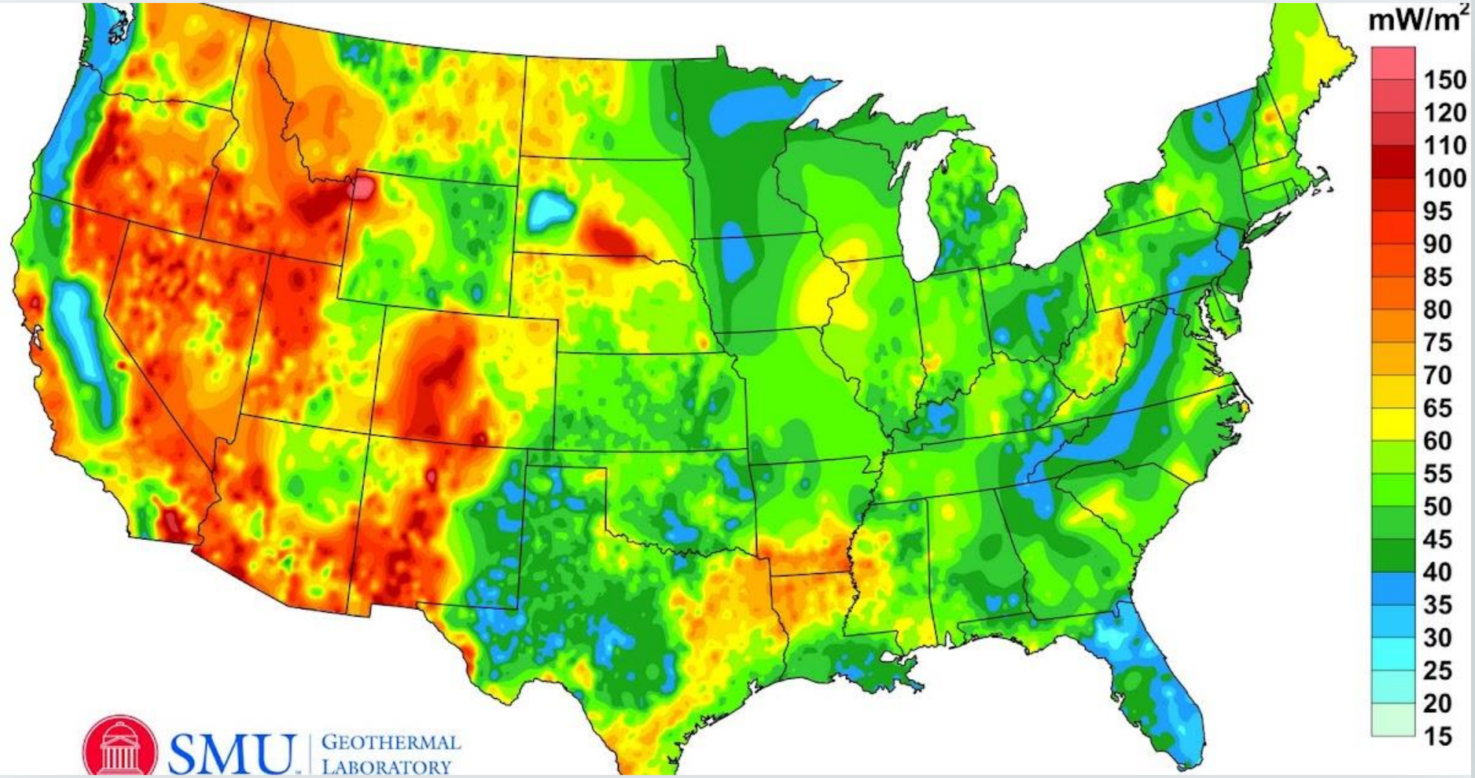
Why does this Research Matter?

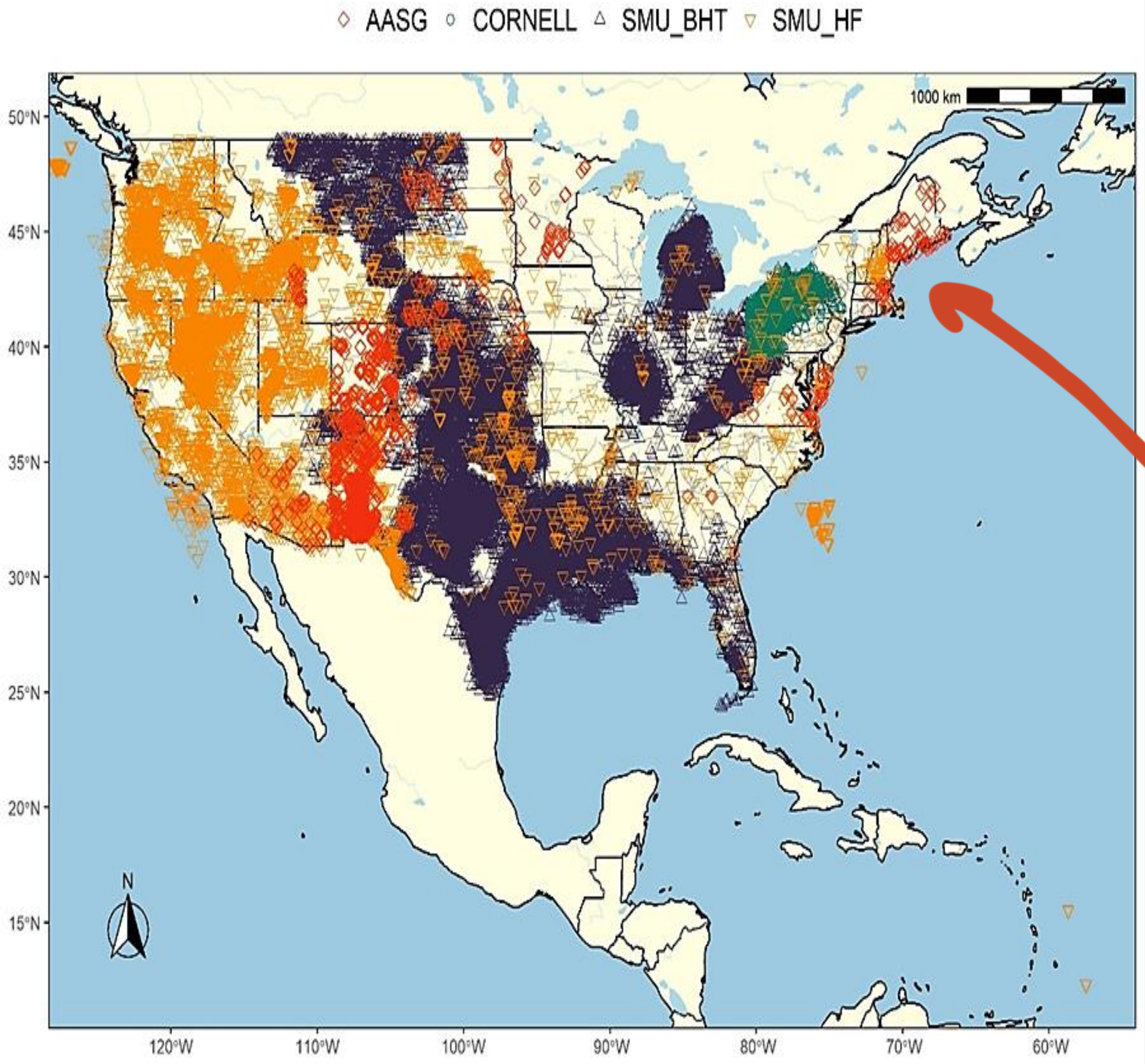
Q1: What strategies can pinpoint high-potential geothermal zones?

- Evaluate the U.S. heat flow database to identify zones with high geothermal energy potential

Q2: How do temperature correction methods affect geothermal resource evaluation?

- Examine temperature correction methods to improve the accuracy of geothermal resource evaluations and techno-economic assessments





Bringing Consistency to U.S. Heat Flow Data

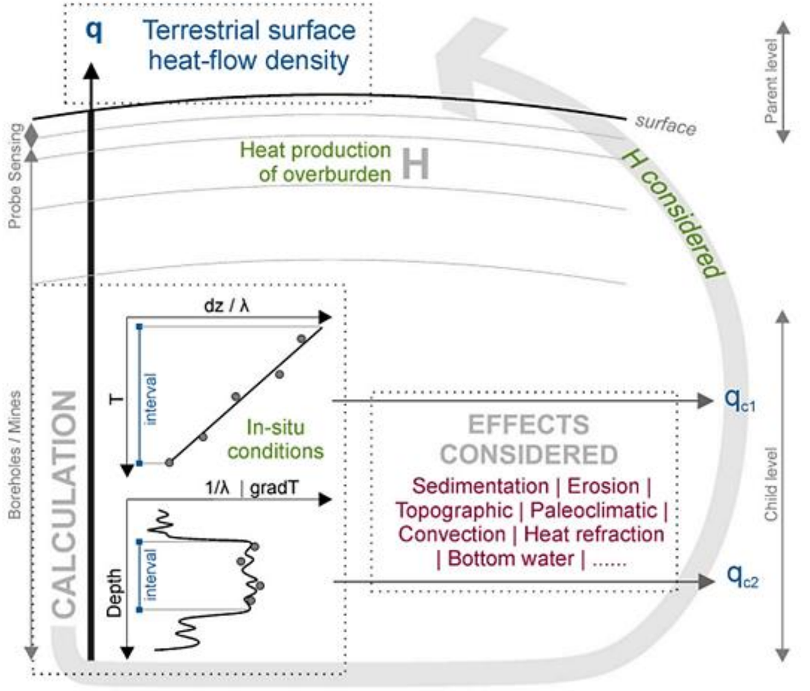
Standardizing U.S. HF Database

Collaborating with Project InnerSpace & IHFC

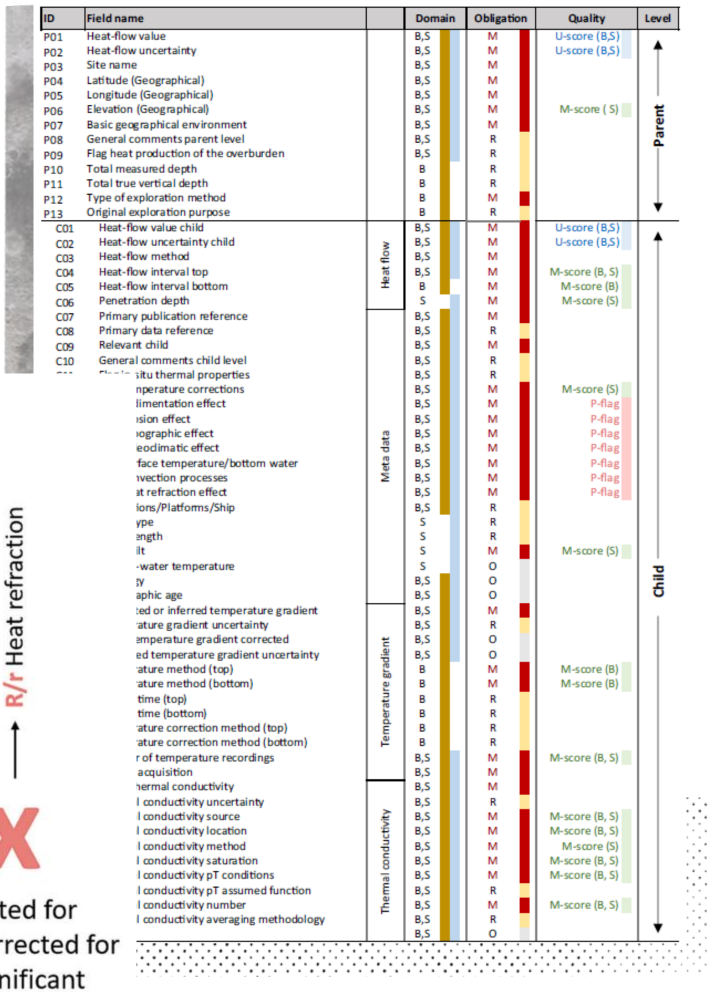
- Evaluate U.S. heat flow database accuracy
- Develop a curated database to address data gaps and inconsistencies
- Adopt standardized metadata protocols to enable consistent geothermal data digitization and exploration

International Heat Flow Commission (IHFC) Standards

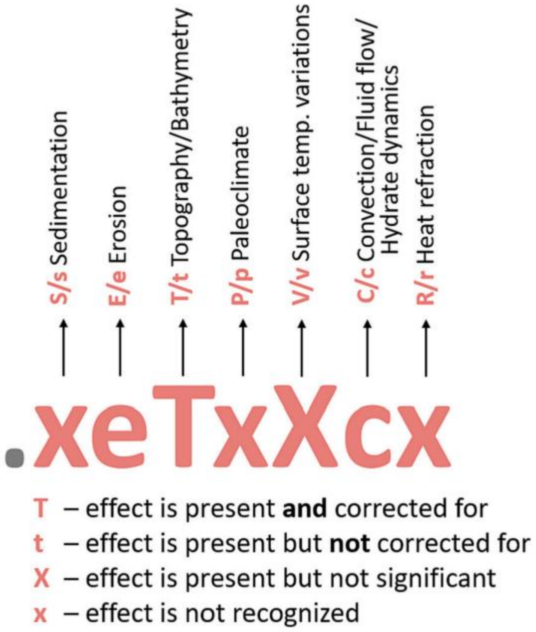
- Relational database to replace the typical table format
- One scheme for all data: mandatory (M), recommended (R), optional (O)



A Closer Look at IHFC Quality Codes



ID	Field name		Domain	Obligation	Quality	Level
P01	Heat-flow value		B,S	M	U-score (B,S)	Parent
P02	Heat-flow uncertainty		B,S	M	U-score (B,S)	
P03	Site name		B,S	M		
P04	Latitude (Geographical)		B,S	M		
P05	Longitude (Geographical)		B,S	M		
P06	Elevation (Geographical)		B,S	M	M-score (S)	
P07	Basic geographical environment		B,S	M		
P08	General comments parent level		B,S	R		
P09	Flag heat production of the overburden		B,S	R		
P10	Total measured depth		B	R		
P11	Total true vertical depth		B	R		
P12	Type of exploration method		B	M		
P13	Original exploration purpose		B	R		
C01	Heat-flow value child	Heat flow	B,S	M	U-score (B,S)	Child
C02	Heat-flow uncertainty child		B,S	M	U-score (B,S)	
C03	Heat-flow method		B,S	M		
C04	Heat-flow interval top		B,S	M	M-score (B, S)	
C05	Heat-flow interval bottom		B	M	M-score (B)	
C06	Penetration depth		S	M	M-score (S)	
C07	Primary publication reference	Meta data	B,S	M		
C08	Primary data reference		B,S	R		
C09	Relevant child		B,S	M		
C10	General comments child level		B,S	R		
	situ thermal properties		B,S	R		
	nperature corrections		B,S	M	M-score (S)	
	limentation effect		B,S	M	P-flag	
	sion effect		B,S	M	P-flag	
	ographic effect		B,S	M	P-flag	
	eoclimatic effect		B,S	M	P-flag	
	face temperature/bottom water		B,S	M	P-flag	
	vection processes		B,S	M	P-flag	
	at refraction effect		B,S	M	P-flag	
	ions/Platforms/Ship		B,S	R		
	ype		S	R		
	ength		S	R		
	ilt		S	M	M-score (S)	
	-water temperature		S	O		
	y		B,S	O		
	aphic age		B,S	O		
	ted or inferred temperature gradient	Temperature gradient	B,S	M		
	ature gradient uncertainty		B,S	R		
	emperature gradient corrected		B,S	O		
	ed temperature gradient uncertainty		B,S	O		
	ature method (top)		B	M	M-score (B)	
	ature method (bottom)		B	M	M-score (B)	
	time (top)		B	R		
	time (bottom)		B	R		
	ature correction method (top)		B	R		
	ature correction method (bottom)		B	R		
	r of temperature recordings		B,S	M	M-score (B, S)	
	acquisition		B,S	M		
	hermal conductivity	Thermal conductivity	B,S	M		
	l conductivity uncertainty		B,S	R		
	l conductivity source		B,S	M	M-score (B, S)	
	l conductivity location		B,S	M	M-score (B, S)	
	l conductivity method		B,S	M	M-score (S)	
	l conductivity saturation		B,S	M	M-score (B, S)	
	l conductivity pT conditions		B,S	M	M-score (B, S)	
	l conductivity pT assumed function		B,S	R		
	l conductivity number		B,S	M	M-score (B, S)	
	l conductivity averaging methodology		B,S	R		
			B,S	O		



Adapted from Fuchs et al. 2023

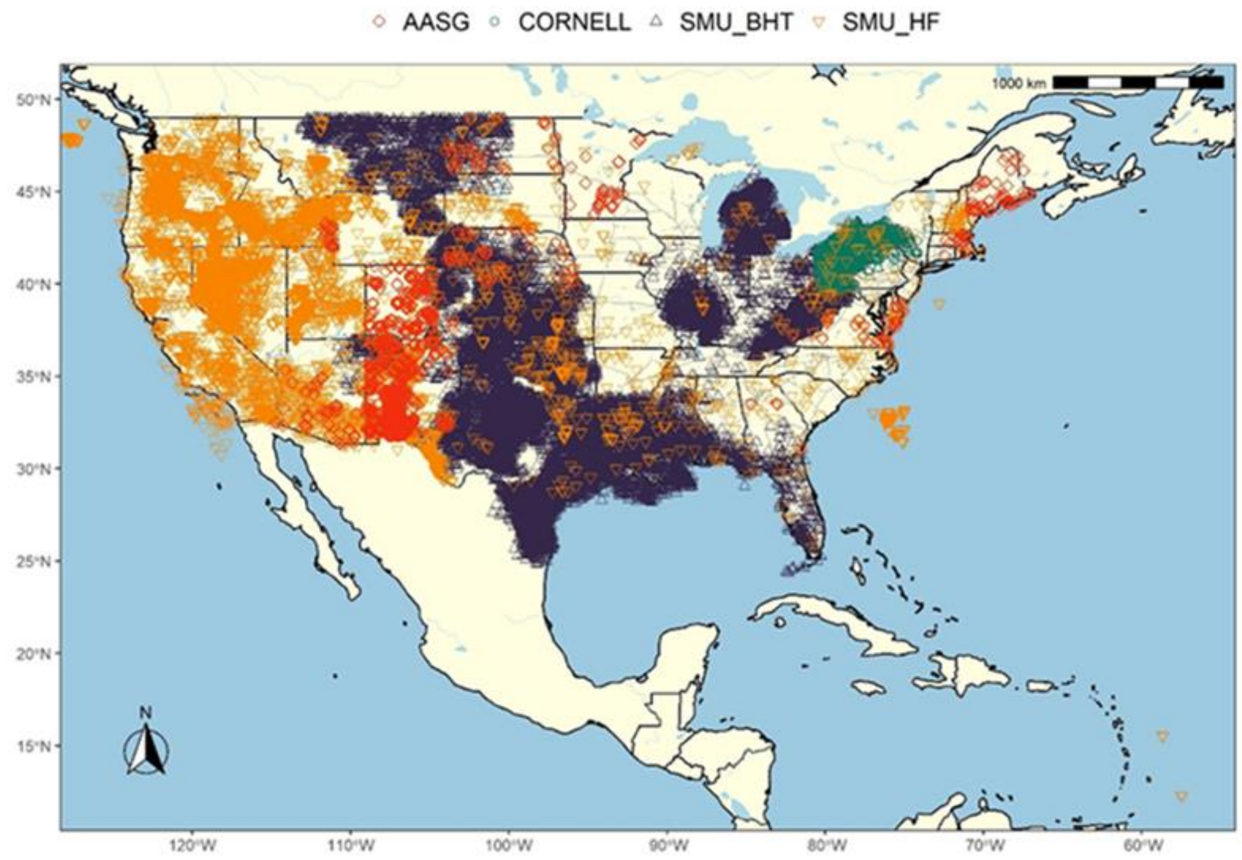
Three evaluation steps

- U-Score: Quantifies uncertainty in heat flow density
- M-Score: Evaluates methodological reliability for thermal conductivity and temp measurements
- P-Flags: Assesses site-specific effects like erosion and heat refraction

Quality Code System

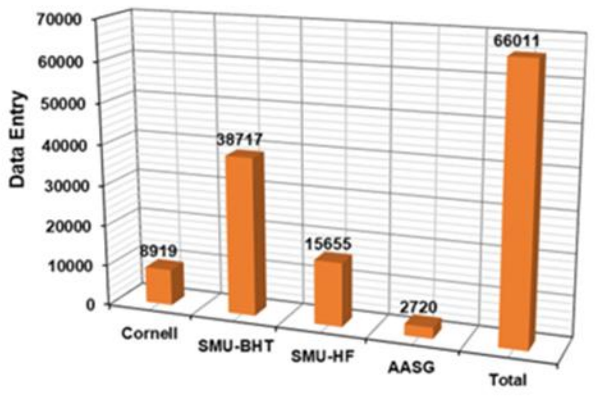
- A comprehensive 12-digit code for each entry reflecting quality assessments, for example U1M2.xeTxxCx

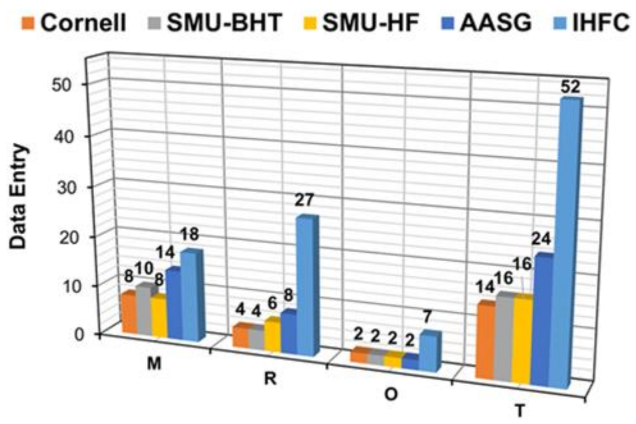
U-Score → M-Score → Perturbations → Combined Score



Aligning with Global Standards: IHFC Protocols

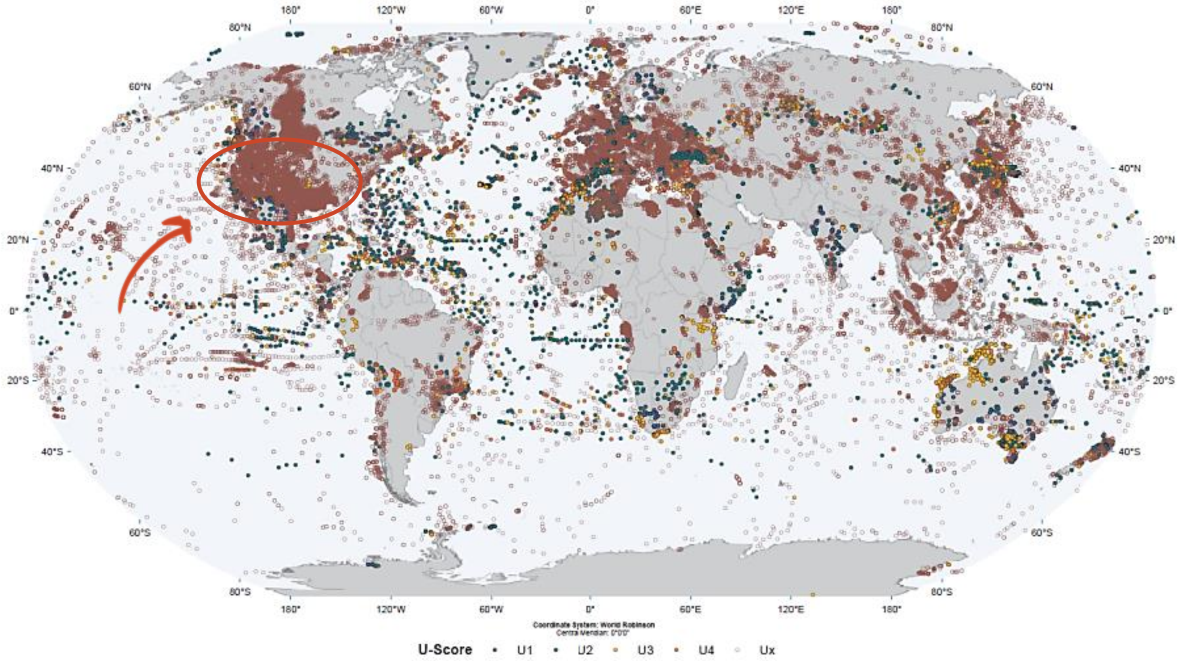
- Harmonized over **66,000** U.S. HF data entries with IHFC standards
- Eliminated null entries while retaining duplicates to maintain valuable variations in data
- **Critical data** on conductivity, temperature, and site effects is still missing from the U.S. database

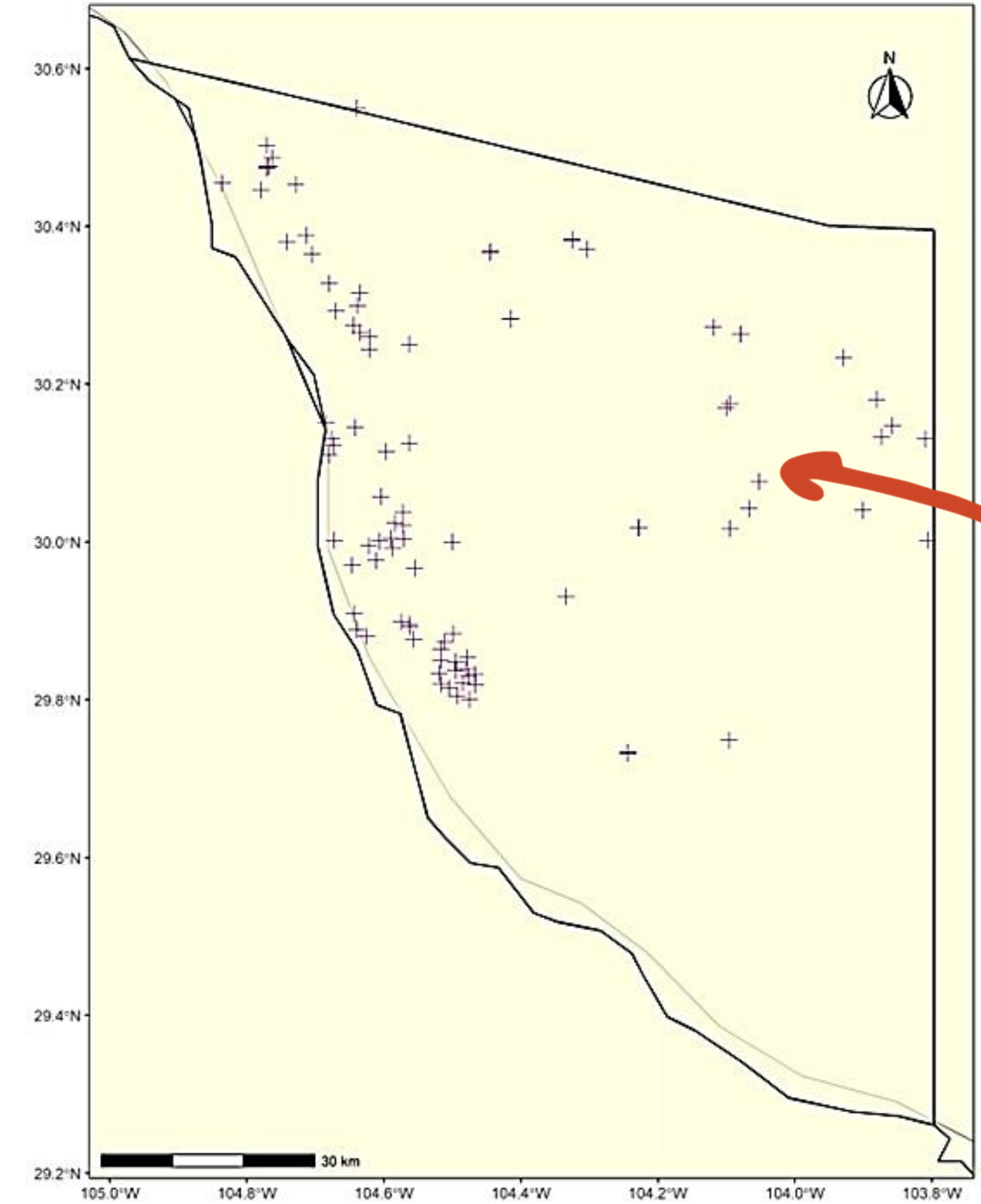




Key Outcomes from IHFC Data Integration

- The 2024 IHFC global release includes 20,000 U.S. data points, standardized to improve reliability
  - https://doi.org/10.5880/fidgeo.2024.014
- Additional datasets remain under review for potential integration





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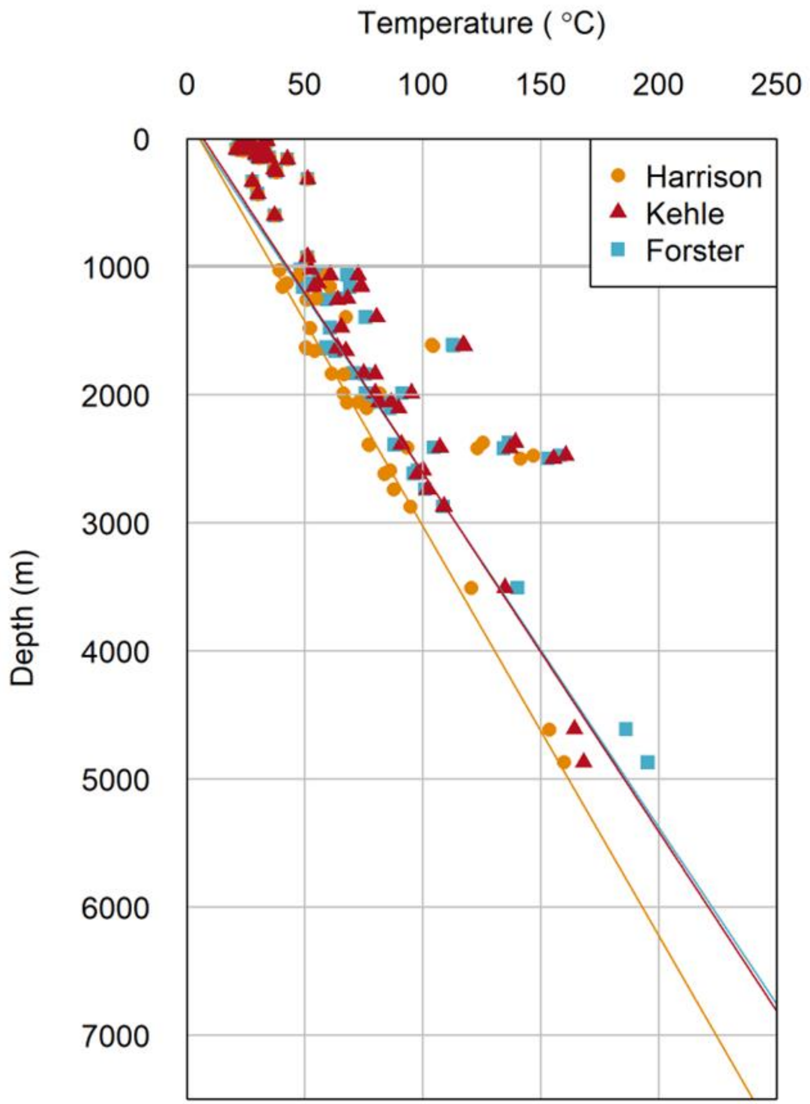
Analyzing BHT Correction Approaches – Presidio County Case Study

Temp. data from 101 wells



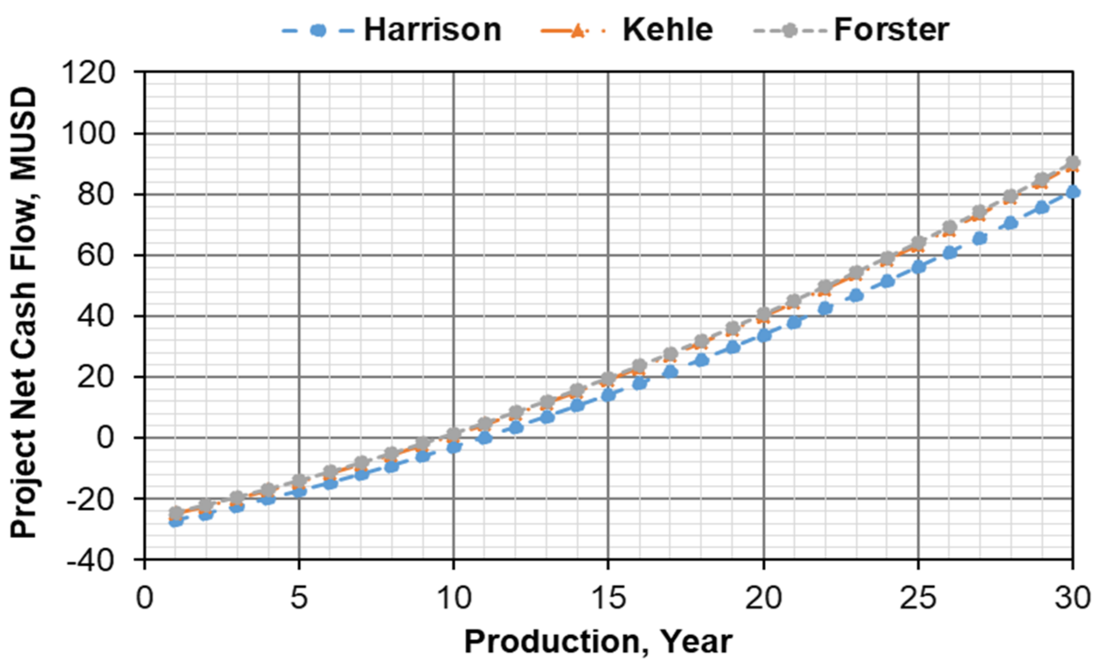
Presidio Case Study

Correction Method	Setting	Observed Variation
Kehle (1980)	Diverse Geological Settings (AAPG)	Similar to Förster
Harrison (1983)	Anadarko & Arkoma Basins (Oklahoma)	~15% lower
Förster (1995)	Southeastern Kansas	Like Kehle

Economic Impact of BHT Corrections

Cumulative Revenue for EGS

- Utilize GEOPHIRES for techno-economic study
- Drilling targets a reservoir temperature of 150 °C
- The geothermal energy plant is projected to operate for 30 years, producing an estimated net power of ~3.3 MW
- Harrison method predicts revenue approximately $10 million lower than Kehle & Förster methods



Correction Method	Depth to 150°C (km)	Depth to 200°C (km)	Depth to 250°C (km)
Harrison	4.31	5.91	7.51
Kehle	3.78	5.18	6.58
Förster	3.73	5.11	6.49

Key Insights & Path Forward

1. **Standardized U.S. heat flow data using IHFC protocols enhances geothermal resource evaluation**
    - Introduces quality score evaluations for enhanced reliability
    - Continuous updates to the U.S. Heat Flow Database are essential for improving geothermal resource evaluations
2. **Temperature correction methods can affect project cost**
    - The Harrison method underestimates results compared to Kehle and Förster methods, impacting project costs
3. **Prioritize High-Quality Data to Mitigate Risks**
    - Incorporate new BHT and rock thermal conductivity measurements
    - Conduct deep well thermal logging to validate and enhance regional BHT corrections

Thank YOU & Acknowledgements

TEXAS
The University of Texas at Austin

IHFC
INTERNATIONAL HEAT FLOW COMMISSION

project innerspace

Presidio Municipal Development District

Questions & Discussion

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Petroleum Engineering

Standardization: Implementing IHFC Protocol

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P05	Longitude (Geographical)		B,S	M		
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C06	Penetration depth		S	M	M-score (S)	
C07	Primary publication reference		B,S	M		
C08	Primary data reference		B,S	R		
C09	Relevant child		B,S	M		
C10	General comments child level		B,S	R		
C11	Flag in-situ thermal properties		B,S	R		
C12	Flag temperature corrections		B,S	M	M-score (S)	
C13	Flag sedimentation effect		B,S	M	P-flag	
C14	Flag erosion effect		B,S	M	P-flag	
C15	Flag topographic effect		B,S	M	P-flag	
C16	Flag paleoclimatic effect	data	B,S	M	P-flag	

From Fuchs et al. 2023

SEG | AAPG image
International Meeting for Applied Geoscience & Energy

Methodology for Harmonizing U.S. Heat Flow Database

IHFC Standards

$$HFD_{unc} = \sqrt{\left(\lambda_{mean} \cdot \frac{\partial T}{\partial z_{unc}}\right)^2 + \left(\frac{\partial T}{\partial z_{mean}} \cdot \lambda_{unc}\right)^2}$$

- **U-Score**: $COV(\%) = \frac{HFD_{unc}}{HFD_{mean}}$
    - Based on COV(%), the entry is assigned U1 (excellent) through U4 (poor)

COV	U-score (Numerical uncertainty)	Ranking description
$<$ 5%	U1	Excellent
5–15%	U2	Good
15–25%	U3	Ok
$>$ 25%	U4	Poor
not applicable	Ux	not determined / missing data

From Fuchs et al. 2023

M-score

Temperature gradient

T score start value: 1.0
value range: 0.4-1.1

Source type and number of T points

Measurement type		Relevant DB field(s) full {short}	Relevant methods/entries	Condition in field {...}	Penalty
Continuous T log	equilibrium/ corrected	Temperature method (top) {T_method_top}, Temperature method (bottom) {T_method_bottom}	[LOGeq], [cLOG], [DTSeq], [cDTS]	{T_number} >3	0.1
	perturbed		[LOGpert]		-0.1
Multiple single T point	equilibrium/ corrected		[LOGeq], [cLOG], [DTSeq], [cDTS], [BHT], [DST], [RTDeq], [RTDc], [ODDT-PC], [ODDT-TP]		-0.1
	perturbed		[LOGpert], [DTSpert], [BHT], [DST], [RTDpert], [BLK]		-0.3
	estimated		[CPD], [XEN], [GTM], [BSR]		-0.5
One single T point + surface T	equilibrium/ corrected		[cBHT], [cDST], [RTDeq], [RTDc], [ODDT-PC], [ODDT-TP]	{Temperature_method_top} = [SUR]	-0.3
	perturbed		[BHT], [DST], [RTDpert]		-0.5
	estimated		[CPD], [XEN], [GTM], [BSR]		-0.6

Thermal conductivity

TC score start value: 1.0
value range: 0.1-1.2

Localization

Question		Relevant DB field(s) full {short}	Relevant methods/entries	Condition in field {...}	Penalty
Interval depth reported?	NO	Heat-flow interval top {q_top}, Heat-flow interval bottom {q_bottom}	*value*	-	end: TC score = 0.1
	YES				continue
TC data from actual heat-flow location		Thermal conductivity location {tc_location}	[Actual heat-flow location]	-	0
TC data from nearby or other location			[Other location]		-0.1
TC assumed from literature or unknown localization			[Literature/unspecified]		-0.2

Source type

Measurement type	Relevant DB field(s) full {short}	Relevant methods/entries	Condition in field {...}	Penalty
In-situ probe	Thermal conductivity source {tc_source}	[*In-situ* probe]	-	0.1
Core-log integration		[Core-log integration]		0.1
Core measurements		[Core samples]		0
Cutting measurements		[Cutting samples]		-0.1
Outcrop measurement		[Outcrop samples]		-0.1
Log interpretation		[Well-log interpretation]		-0.1
Mineral calculation (mixing model)		[Mineral computation]		-0.2
Lithology/Textbook		[Assumed from literature]		-0.2

Number of conductivities

Number of conductivity points	Relevant DB field(s) full {short}	Relevant methods/entries	Condition in field {...}	Penalty

Probe sensing

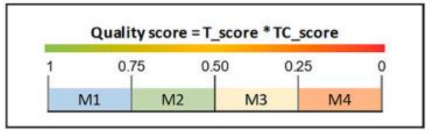
Temperature (T) score (columns) × Conductivity (TC) score (rows)

	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
1.2	1.44	1.32	1.20	1.08	0.96	0.84	0.72	0.60	0.48	0.36	0.24
1.1	1.32	1.21	1.10	0.99	0.88	0.77	0.66	0.55	0.44	0.33	0.22
1.0	1.20	1.10	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20
0.9	1.08	0.99	0.90	0.81	0.72	0.63	0.54	0.45	0.36	0.27	0.18
0.8	0.96	0.88	0.80	0.72	0.64	0.56	0.48	0.40	0.32	0.24	0.16
0.7	0.84	0.77	0.70	0.63	0.56	0.49	0.42	0.35	0.28	0.21	0.14
0.6	0.72	0.66	0.60	0.54	0.48	0.42	0.36	0.30	0.24	0.18	0.12
0.5	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10
0.4	0.48	0.44	0.40	0.36	0.32	0.28	0.24	0.20	0.16	0.12	0.08
0.3	0.36	0.33	0.30	0.27	0.24	0.21	0.18	0.15	0.12	0.09	0.06
0.2	0.24	0.22	0.20	0.18	0.16	0.14	0.12	0.10	0.08	0.06	0.04

Borehole/Mines

Temperature (T) score (columns) × Conductivity (TC) score (rows)

	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.4
1.2	1.32	1.20	1.08	0.96	0.84	0.72	0.60	0.48
1.1	1.21	1.10	0.99	0.88	0.77	0.66	0.55	0.44
1.0	1.10	1.00	0.90	0.80	0.70	0.60	0.50	0.40
0.9	0.99	0.90	0.81	0.72	0.63	0.54	0.45	0.36
0.8	0.88	0.80	0.72	0.64	0.56	0.48	0.40	0.32
0.7	0.77	0.70	0.63	0.56	0.49	0.42	0.35	0.28
0.6	0.66	0.60	0.54	0.48	0.42	0.36	0.30	0.24
0.5	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20
0.4	0.44	0.40	0.36	0.32	0.28	0.24	0.20	0.16
0.3	0.33	0.30	0.27	0.24	0.21	0.18	0.15	0.12
0.2	0.22	0.20	0.18	0.16	0.14	0.12	0.10	0.08
0.1	0.11	0.10	0.09	0.08	0.07	0.06	0.05	0.04



Probe sensing – Temperature (T) score (columns) × Conductivity (TC) score (rows)

	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
1.2	M1	M1	M1	M1	M1	M1	M2	M2	M3	M3	M4
1.1	M1	M1	M1	M1	M1	M1	M2	M2	M3	M3	M4
1.0	M1	M1	M1	M1	M1	M2	M2	M2	M3	M3	M4
0.9	M1	M1	M1	M1	M2	M2	M2	M3	M3	M3	M4
0.8	M1	M1	M1	M2	M2	M2	M3	M3	M3	M4	M4
0.7	M1	M1	M2	M2	M2	M3	M3	M3	M3	M4	M4
0.6	M2	M2	M2	M2	M3	M3	M3	M3	M4	M4	M4
0.5	M2	M2	M2	M3	M3	M3	M3	M3	M4	M4	M4
0.4	M3	M3	M3	M3	M3	M3	M4	M4	M4	M4	M4
0.3	M3	M3	M3	M3	M4	M4	M4	M4	M4	M4	M4
0.2	M4	M4	M4	M4	M4	M4	M4	M4	M4	M4	M4

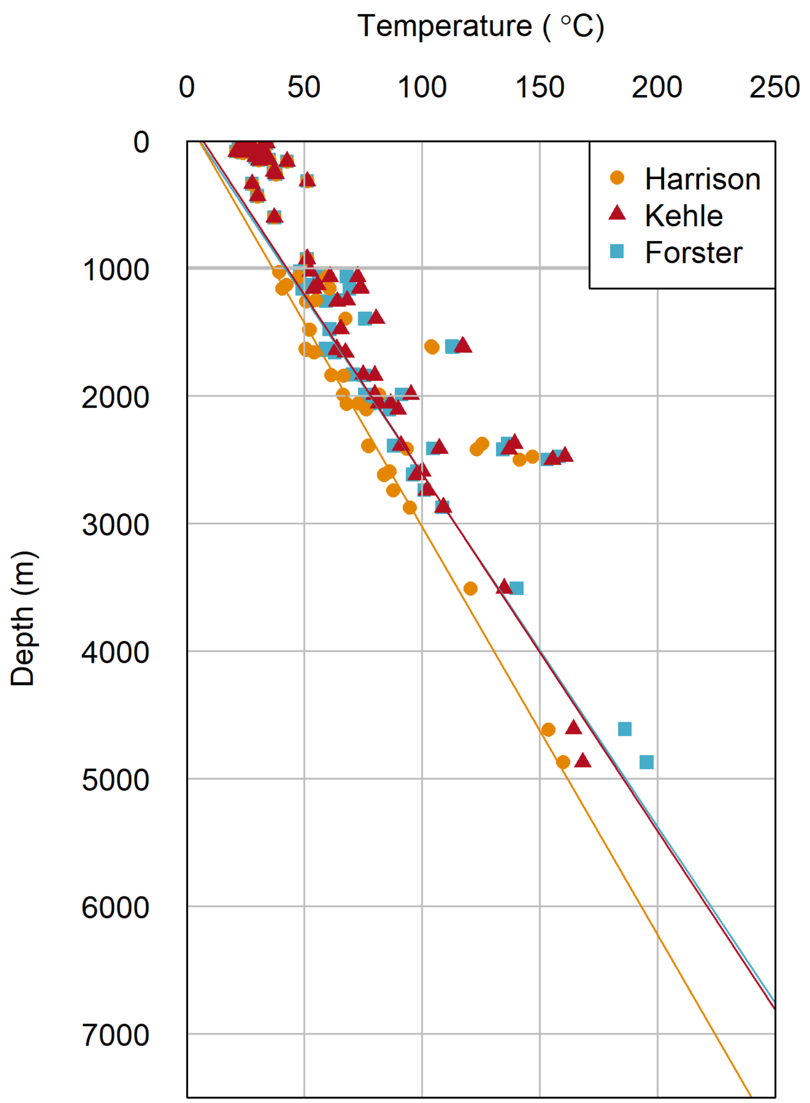
Borehole/Mines – Temperature (T) score (columns) × Conductivity (TC) score (rows)

	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.4
1.2	M1	M1	M1	M1	M1	M2	M2	M3
1.1	M1	M1	M1	M1	M1	M2	M2	M3
1.0	M1	M1	M1	M1	M2	M2	M3	M3
0.9	M1	M1	M1	M2	M2	M2	M3	M3
0.8	M1	M1	M2	M2	M2	M3	M3	M3
0.7	M1	M2	M2	M2	M3	M3	M3	M3
0.6	M2	M2	M2	M3	M3	M3	M3	M4
0.5	M2	M2	M3	M3	M3	M3	M4	M4
0.4	M3	M3	M3	M3	M3	M4	M4	M4
0.3	M3	M3	M3	M4	M4	M4	M4	M4
0.2	M4	M4	M4	M4	M4	M4	M4	M4
0.1	M4	M4	M4	M4	M4	M4	M4	M4

Note: In case information required for the individual T_score or TC_score is missing, an x is added to the quality classification.

From Fuchs et al. 2023

- Linear regression using surface temp of 15°
- Depth to certain temperature variability
- Kehle/Forster similar results
- Harrison ~15% lower



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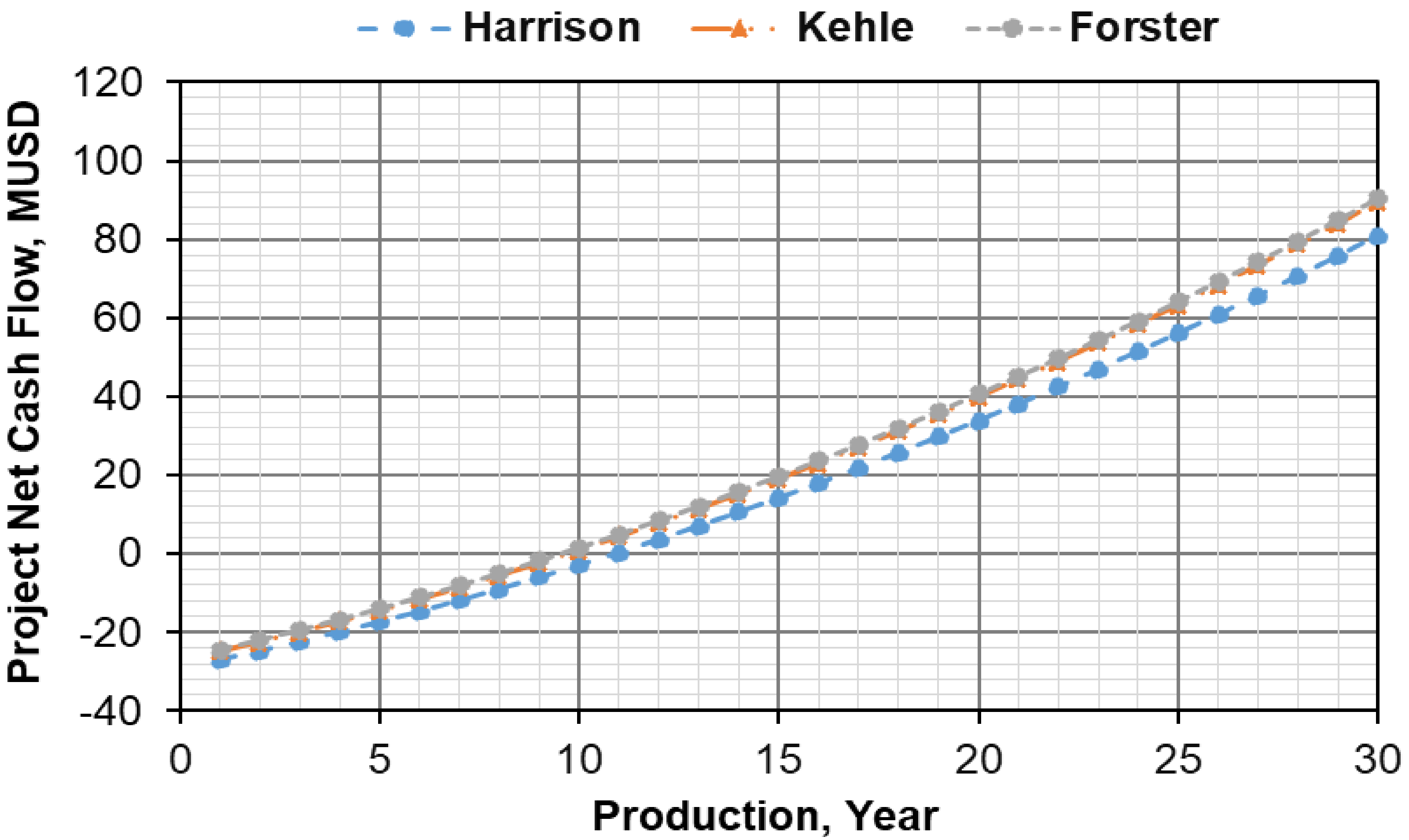
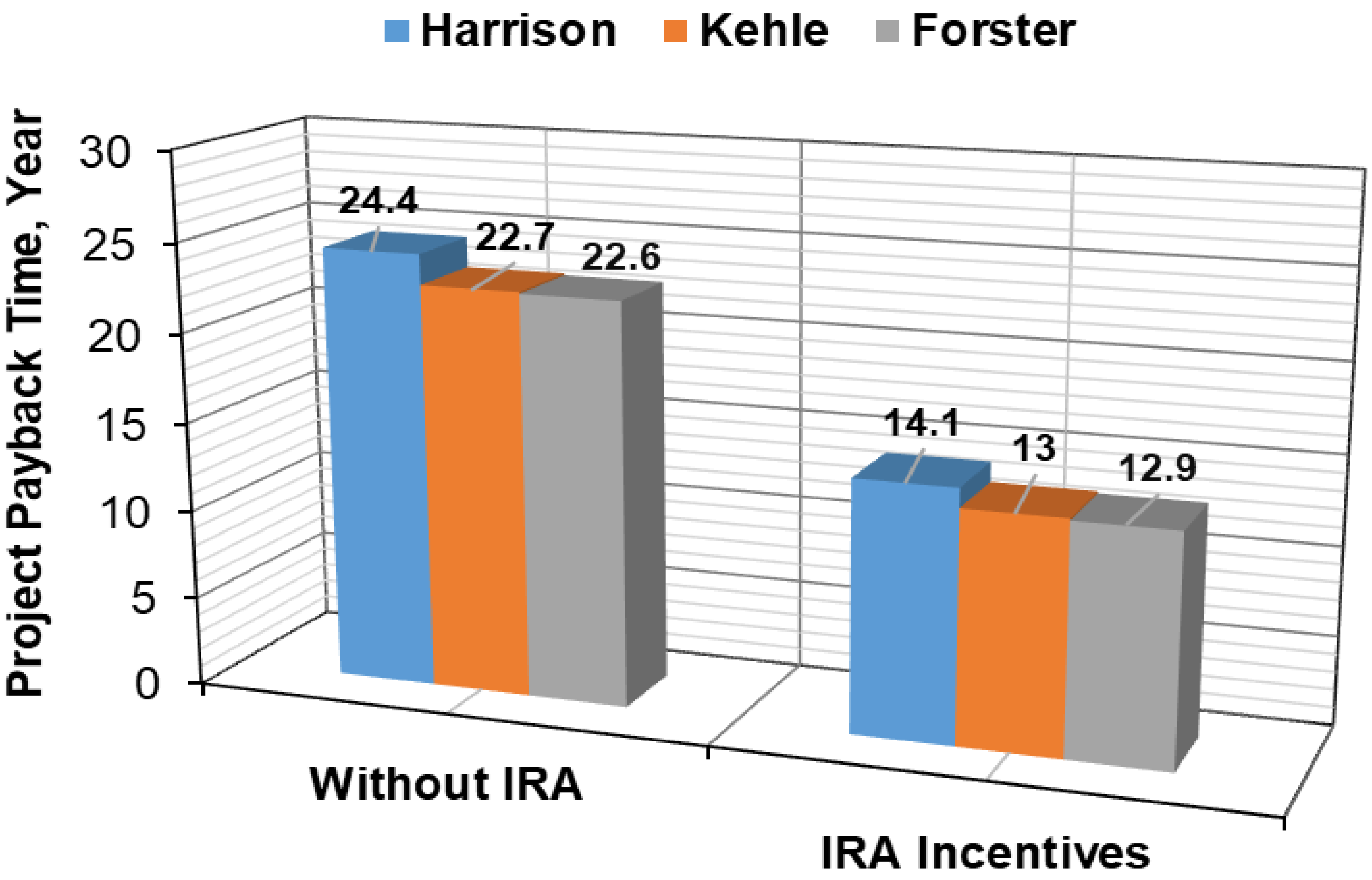
Harrison	4.31	5.91	7.51
Kehle	3.78	5.18	6.58
Forster	3.73	5.11	6.49

- Cumulative revenue for EGS scenario
- 4 wells – 2 producers and 2 injectors
- Drill to 150°C
- Energy production plant with 30-year lifespan
- Est. net power ~3.3 MW

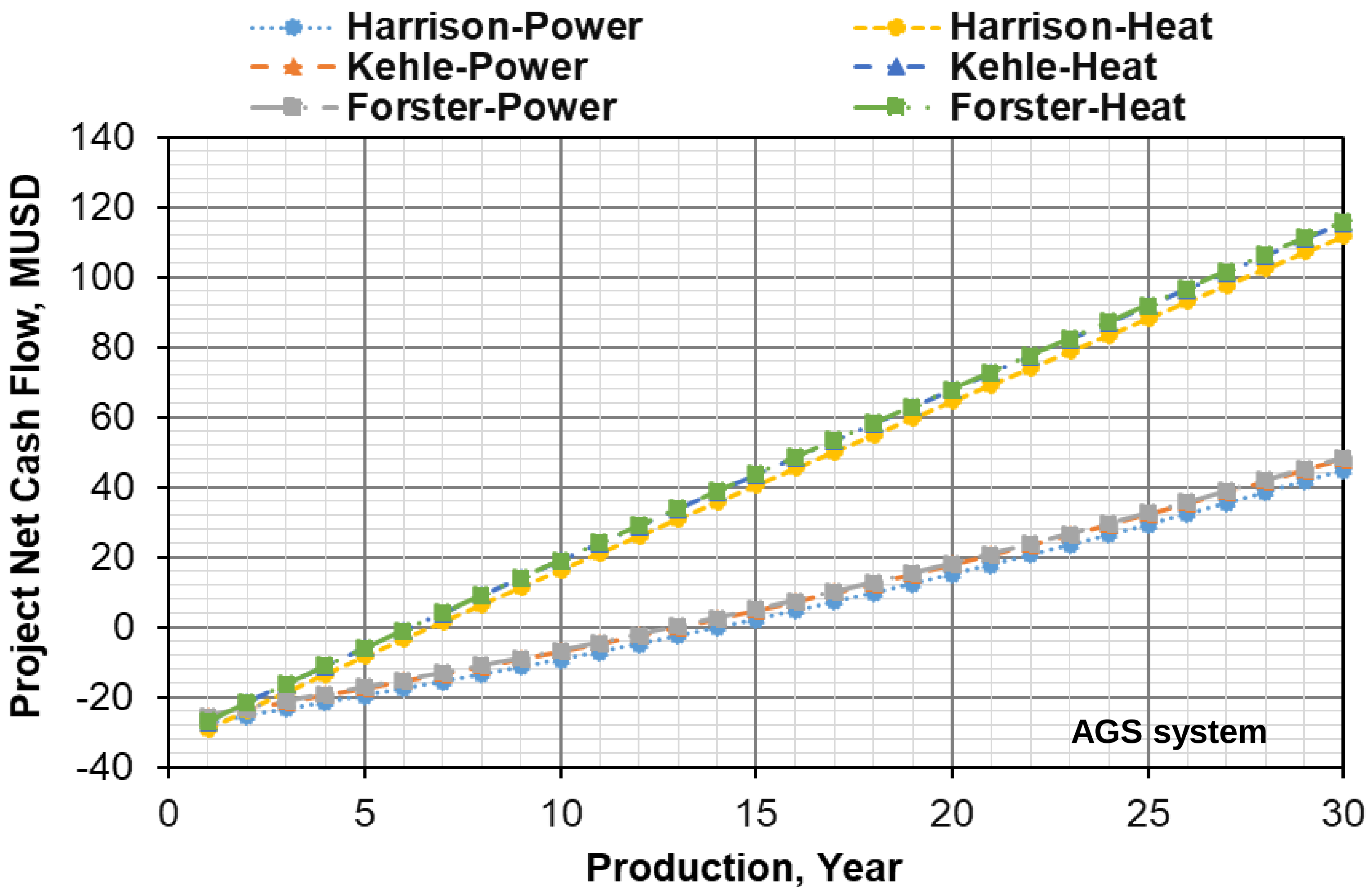


AGS system of Yuan et al. (2021)

- 8.5 inch hoz open hole
- Five 3 km laterals
- 90 kg/sec production flow rate
- Vertical depth determined by the calculated depth to temp for each correction method



- Direct use has higher efficiency than power generation
- Direct heat requires lower temperatures and minimal energy conversion loss
- For both AGS and EGS the temp correction methods can impact Net Production Value by $3-5 million USD

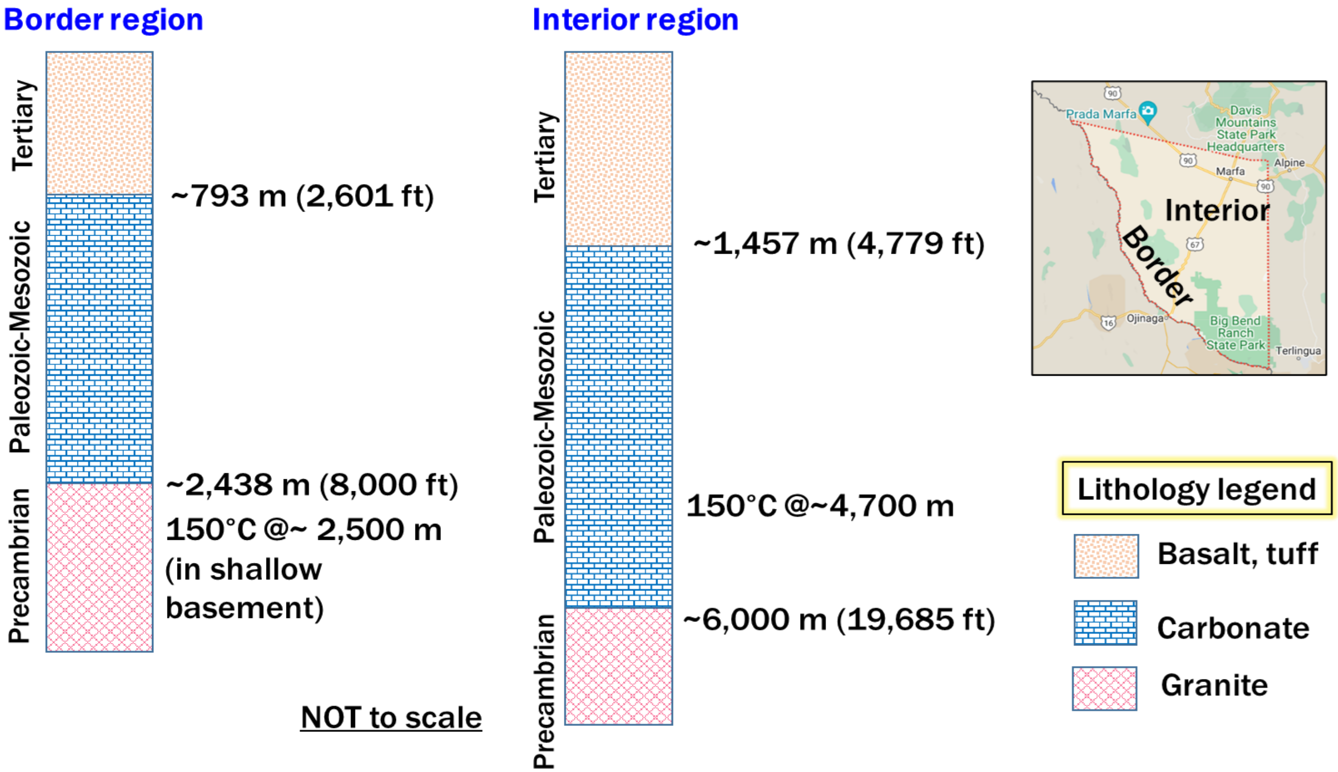


Geological Setting

SW Texas along Rio Grande River

3 main stratigraphic units

Shallower basement near border may contribute greater radiogenic heat flow



From Wisian et. al., 2024; Bhattacharya et al., 202

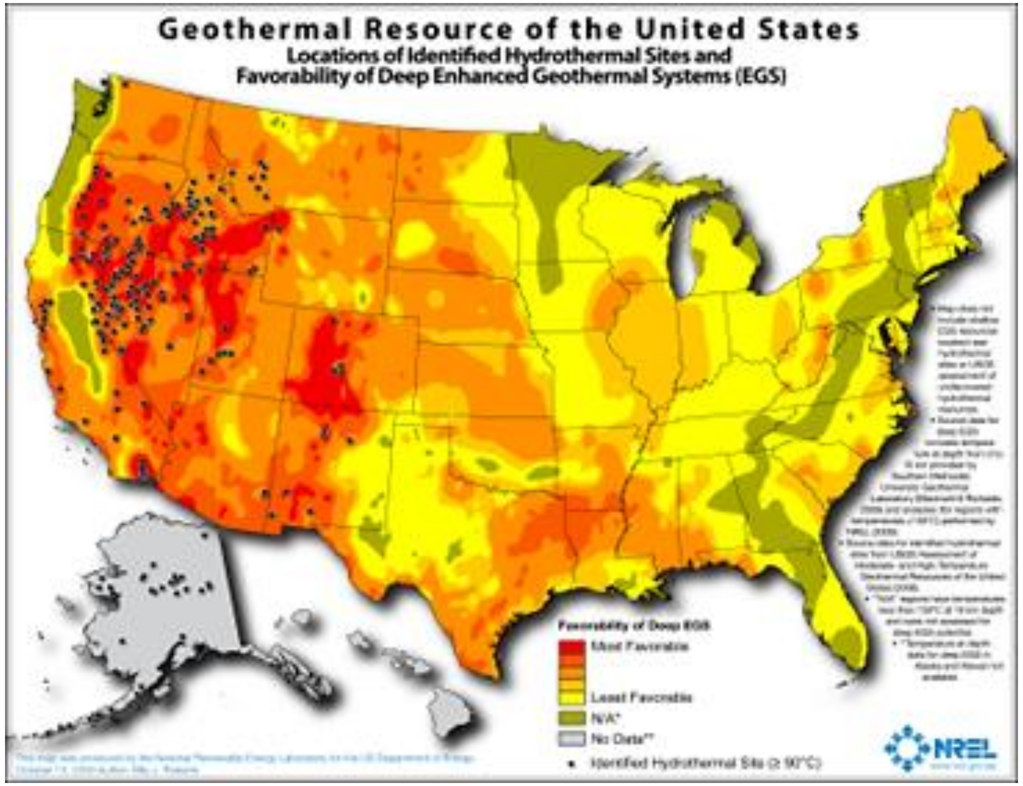
Why this Research Matters?

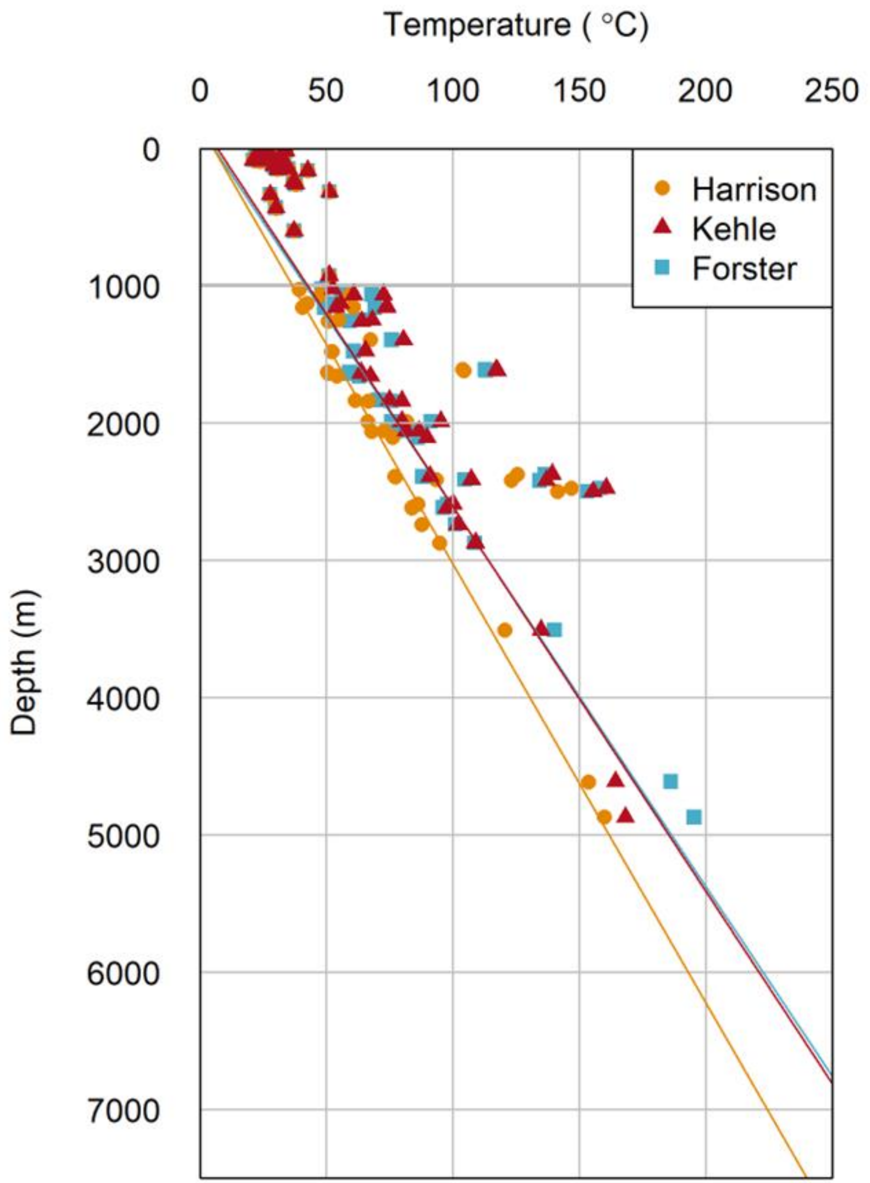
Q1: What strategies can pinpoint high-potential geothermal zones?

- Assess the U.S. heat flow database for high-potential geothermal sites

Q2: How do temperature correction methods affect geothermal resource evaluation?

- Investigate various temperature correction methods to enhance techno-economic analyses





Presidio Case Study

Correction Methods

1. Harrison (1983): Anadarko & Arkoma basins in Oklahoma
2. Kehle (1980): Diverse geological setting (AAPG)
3. Förster (1995): Southeastern Kansas

Observation

- Depth to certain temperature variability
- Kehle/Forster similar results
- Harrison ~15% lower