Geothermal in the Oil Field*

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Abstract

Sedimentary basins have great potential for development of geothermal energy from fluids in strata that are exploited for oil, gas and water. All categories of geothermal applications, e.g., space heating, direct use, power generation, and EGS, may be available depending on heat flow, geothermal gradients, and the depths of permeable strata. Recent advances in small scale organic Rankine cycle (ORC) and other heat-to-power conversion technologies have created interest in electrical power generation using fluid temperatures of 90 C to 150 C.

We are testing the feasibility of generating power from co-produced fluids in the Williston Basin in collaboration with an oil field operator with funding support from the DOE Geothermal Technologies program. In addition to parameters of temperature and produced fluid volume, the design, foot print, complexity/simplicity and efficiency of the power conversion system are critical. An optimized system could be economically beneficial by providing power for the oil field and extending the productive life of a field.

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The Global Heat flow Database of The International Heat Flow Commission: Web accessed 19 July 2011.
http://www.heatflow.und.edu

The University of North Dakota

AAPG EMD Theme 10

9:05 A.M.

Tuesday 12 April, 2011

Geothermal in the Oil Field

Will Gosnold

Prof. Geophysics, UND Geology and Geological Engineering

Dir. UND Petroleum Research, Education, and Entrepreneurship Center

Custodian of the Global Heat Flow Database of the IHFC of IASPEI

Outline

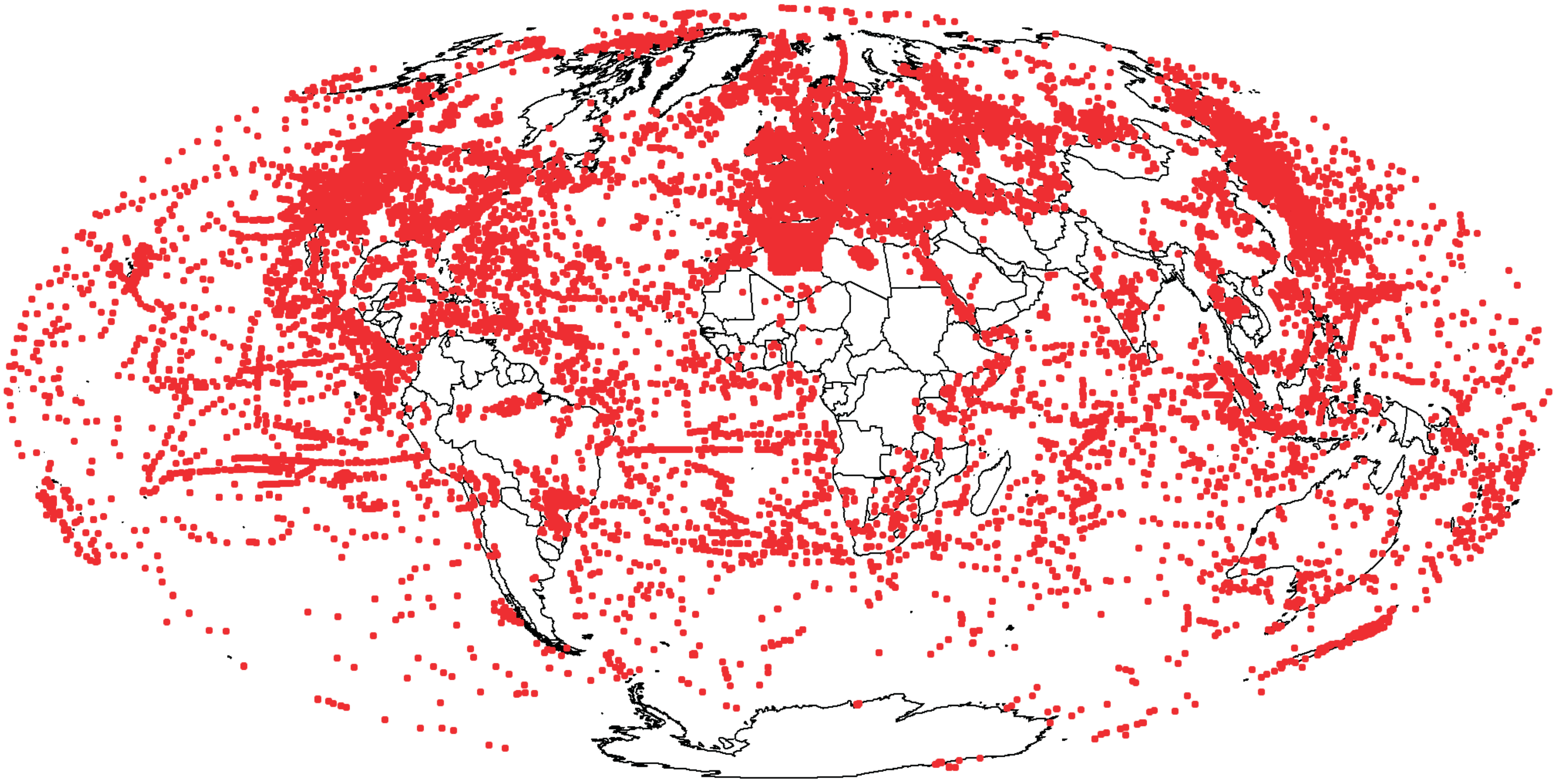
- Heat Flow Overview
- Geothermal Energy Overview
- Power Conversion Systems
- Thermal Stratigraphy
- ND Project Development
- Oil Field Geothermal Potential

Global Heat Flow

- Average solar flux at TOA: 1365 W m^{-2}
- Average solar flux at the surface: 400 W m^{-2}
- Global heat flow from Earth's interior: 92* mW m^{-2}
- Total surface heat flux from Earth's interior: 47±2TW
- Heat flow research has focused on:
  - Tectonics
  - Thermal history of the planet
  - Thermal history of petroleum source rocks
  - Geothermal energy
  - ***Understanding heat flow permits accurate estimation of subsurface temperatures.***

Heat Flow Compilations

- **1965** Lee and Uyeda
- **1968** Simmons and Horai
- **1975** Jessop, Hobart, and Sclater
- **1993** Pollack, Hurter, and Johnson, 22,000
- **2011** The current IHFC database contains 58,536 data points: 35,523 continental & 23,013 marine
- Available on web at UND and soon with AAPG http://www.heatflow.und.edu



Global distribution of heat flow data
Data can be downloaded at
http://www.heatflow.und.edu

- The temperature scheme established by the U.S. Geological Survey Circular 726 (White and Williams, 1975) categorized hot water resources as:
  - high-temperature (>150°C)
  - intermediate-temperature (150°C to 90°C)
  - low-temperature (<90°C)

Geothermal Applications

- Direct use heat (T > 90 °C)
- Electrical power (T >150 °C
- GSHP heating and cooling (T < 90 °C)

What we knew in 1983 (and are still using)

- High-temperature convection systems contain **371 EJ** (Renner, White, and Williams, USGS Cir. 726, 1975).
- Intermediate temperature systems contain **42 ±13 EJ** (Brook et al., USGS Cir. 790, 1978).
- Low-temperature resource base contains **27,000 EJ** (Sorey et al., USGS Cir. 893, 1983).
- Undiscovered low-temperature base contains**7,200 EJ** (Sorey et al., USGS Cir. 893, 1983).

What we knew we could use for power

- High-temperature convection systems

371 EJ

What has changed

- Technology advances
- More and better data on heat flow and subsurface temperatures
- Global energy economics

Current US Geothermal Energy Programs

- National Geothermal Data System
  - System Design, Development & Testing: Web-based Design(Boise State University)
  - Data Collection & Maintenance: 46 State Geological Surveys, Heat Flow Consortium (SMU, UND, BEG, TTU, GRC, Siemens)
- Enhanced Geothermal Systems
  - 7 Projects Underway in 5 States: AK, CA, NV, OR, UT
- Low-temperature Power:
  - 44 Projects underway: 2 are in ND

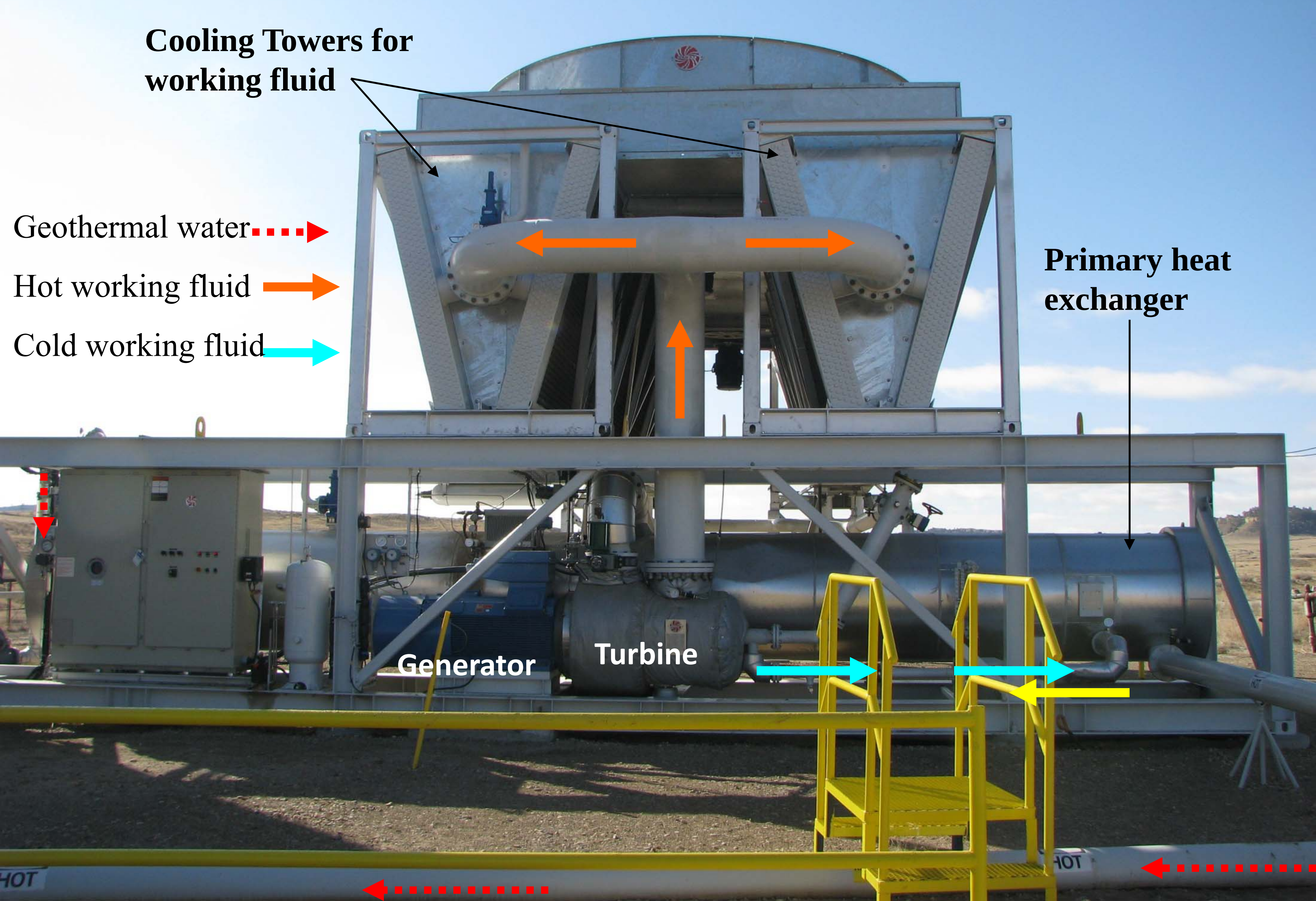
Technology Advances

Power generation with fluid temperatures >90 °C

UTC's Pure Cycle-Model 200 provides 200 kW using 165ºF water at 480 gpm at Chena Hot Springs Resort, Chena, AK.

Electricity cost dropped from 30¢ / kwh to 7¢ / kwh.

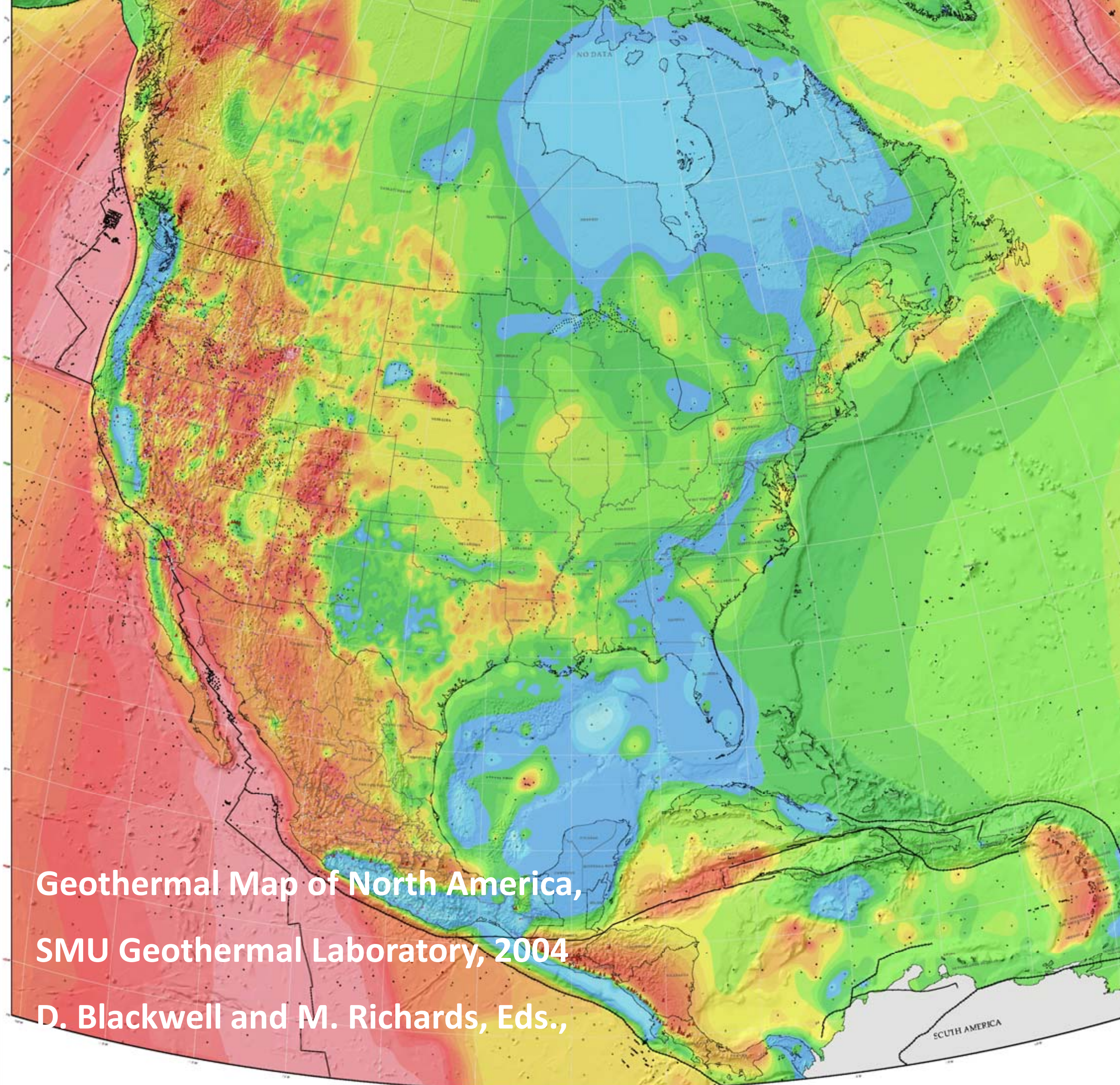
Ormat ORC Engine in Operation at RMOTC



Technology Advances

Power generation with fluid temperatures >90 °C

ENERGY CONVERSISON SYSTEM	ORMAT	PRATT & WHITNEY	DELUGE	RECURRENT ENGINEERING	ELECTRATHERM	CALNETIX
Output (kW)	350	430	1750	845	235	550
Net kW	300	407	1487.5	750	191	495
Footprint (sq. ft.)		420	2800	124	3406	100
Working fluid	not spec.	R245fa	liquid C02	H2O & NH3	R245fa	R245fa
Delivery	10 mos	4 mos	4 to 7 mos	10 mos	4 mos	9 mos
Cost						
Extra Infrastructure	none	Building	Building	Building	Building	none
Extra costs for cooling						
Outdoor/Indoor	Outdoor	Indoor	Indoor	Indoor	Indoor	Outdoor
Output voltage	480	480	480	480	480	350 -500
Infrastructure						
Total Cost						
Cost per kW						
Yearly sales $.05/kWh						
Years to cover investment						



Geothermal Map of North America,

SMU Geothermal Laboratory, 2004

D. Blackwell and M. Richards, Eds.,

Subsurface Temperatures can be calculated if heat flow and thermal conductivity are known

Fourier's law of Heat conduction

$$q = \lambda \Gamma$$

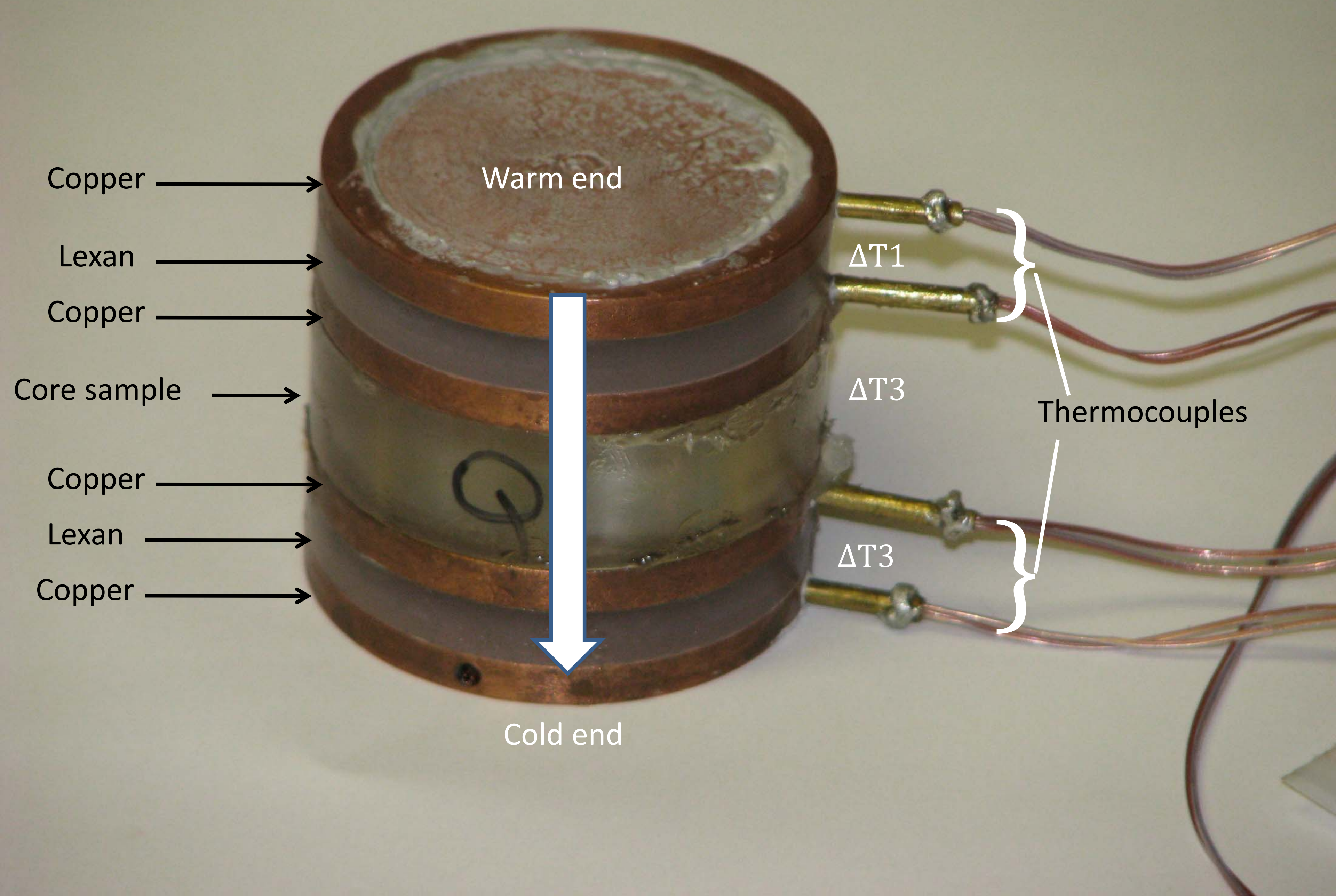
Assuming we know heat flow, temperature at depth "z" may be calculated by

$$T_z = \sum_{i=1}^{n} \frac{q z_i}{\lambda_i}$$

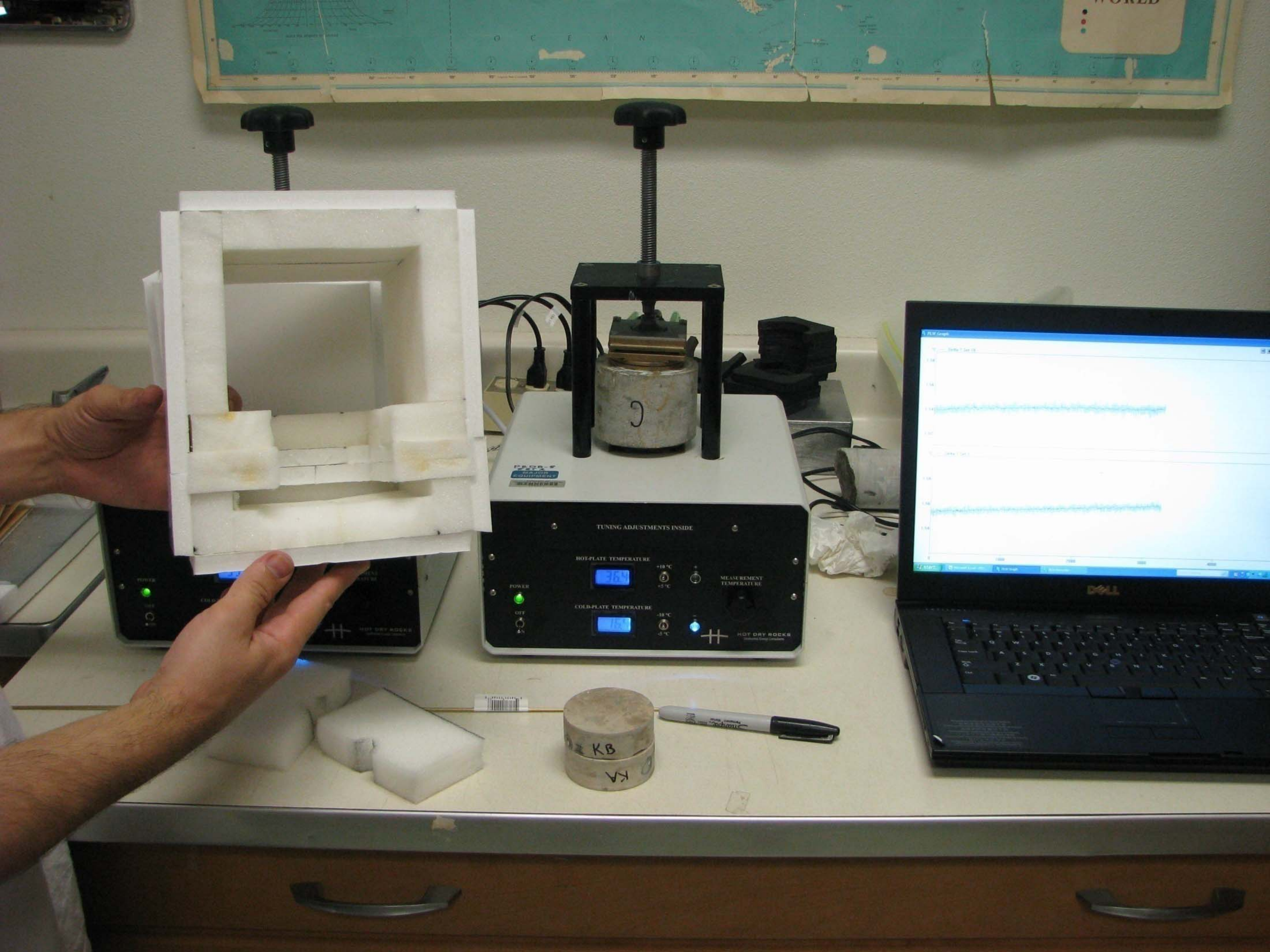
Williston Basin (1984)

Formation Surface	Depth meters	Thickenss meters	λ W/m/K	Temperature °C	Γ °C/km
	0	0		6	
Brule	581	581	1.7	23	30
Pierre	1608	1027	1.2	76	52
Inyan Kara	1744	136	1.6	82	43
Swift	2089	345	1.8	96	39
Spearfish	2383	294	3.1	102	23
Otter	2519	136	2.8	106	25
Mission Canyon	3135	616	2.5	123	28
Lodgepole	3235	100	1.2	129	58
Three Forks	3322	87	3	131	23
Duperow	3536	214	3	136	23
Dawsonbay	3620	84	3	138	23
Winnepegosis	3700	80	3	140	23
Red River	4027	327	3.5	146	20
Deadwood	4311	284	3	153	23

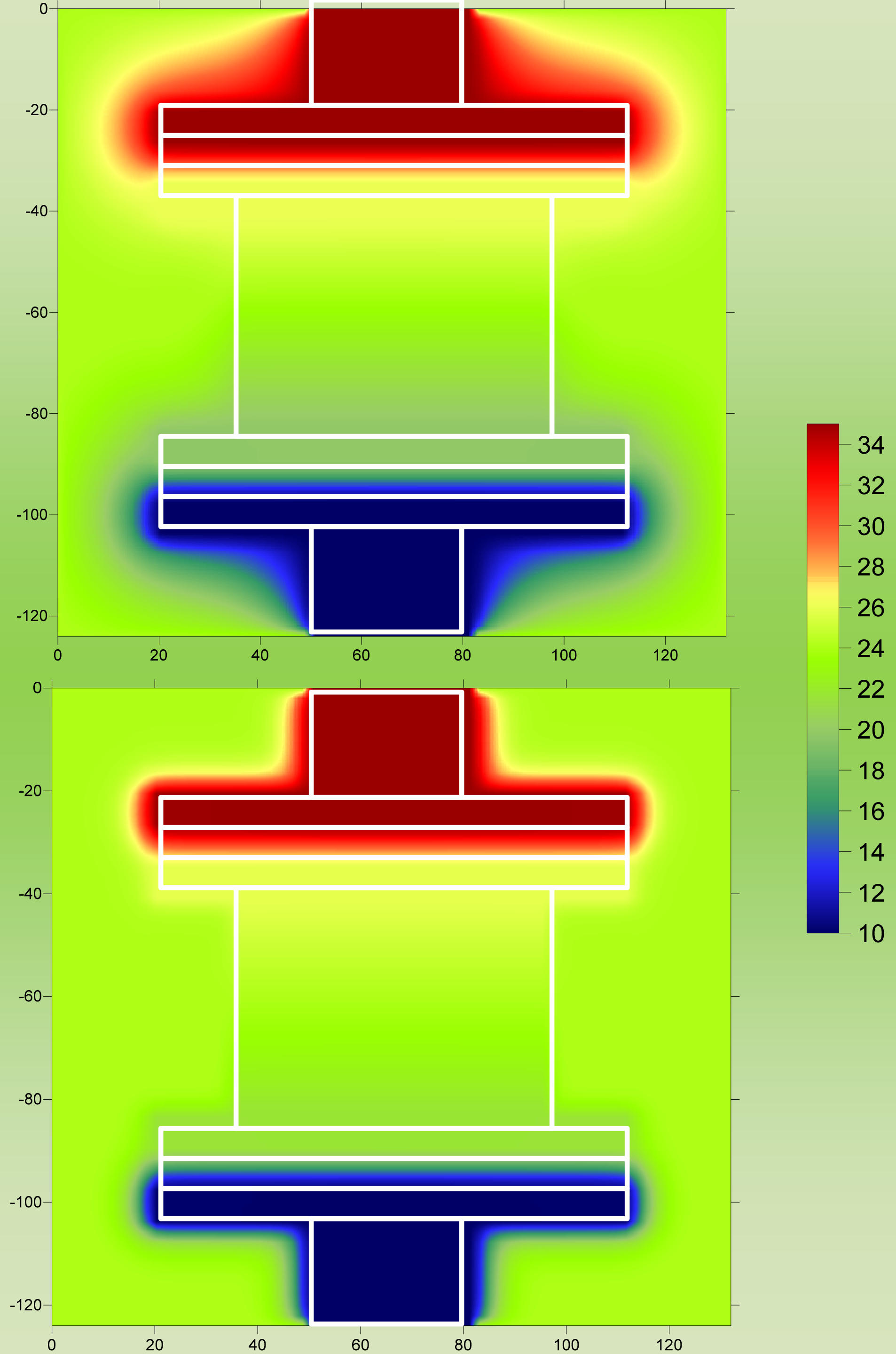
Divided bar thermal conductivity




GEOLOGIC MAP
UNITED STATES
HIGH PRESSURE RESEARCH
A
B
READINGS
KDMDZAM


O C E A N
WORLD
MAJOR EQUIPMENT
TUNING ADJUSTMENTS INSIDE
HOT-PLATE TEMPERATURE
COLD-PLATE TEMPERATURE
MEASUREMENT TEMPERATURE
POWER
OFF
HOT DRY ROCKS
KB
KA
DELL


TUNING ADJUSTMENTS INSIDE
HOT-PLATE TEMPERATURE
35.9
+10 °C
+5 °C
MEASUREMENT TEMPERATURE
POWER
COLD-PLATE TEMPERATURE
16.5
-10 °C
-5 °C
OFF
ON
HOT DRY ROCKS
TUNING ADJUSTMENTS INSIDE
HOT-PLATE TEMPERATURE
36.4
+10 °C
+5 °C
MEASUREMENT TEMPERATURE
POWER
COLD-PLATE TEMPERATURE
16.4
-10 °C
-5 °C
OFF
ON
HOT DRY ROCKS
KB


0
-20
-40
-60
-80
-100
-120
0
20
40
60
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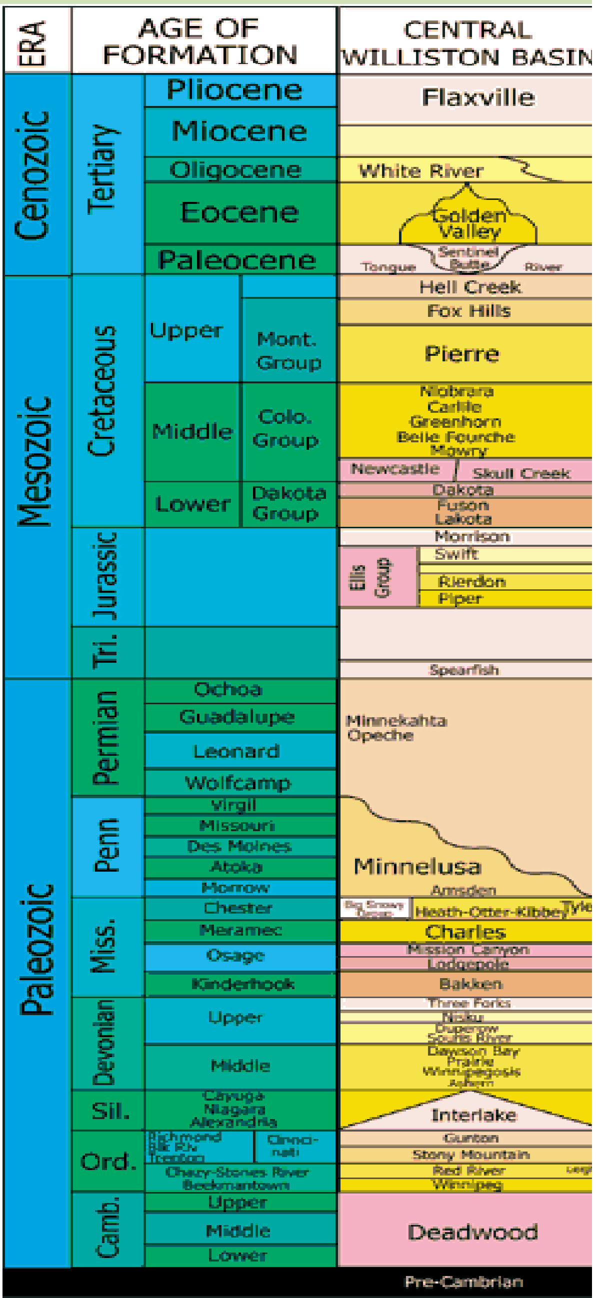
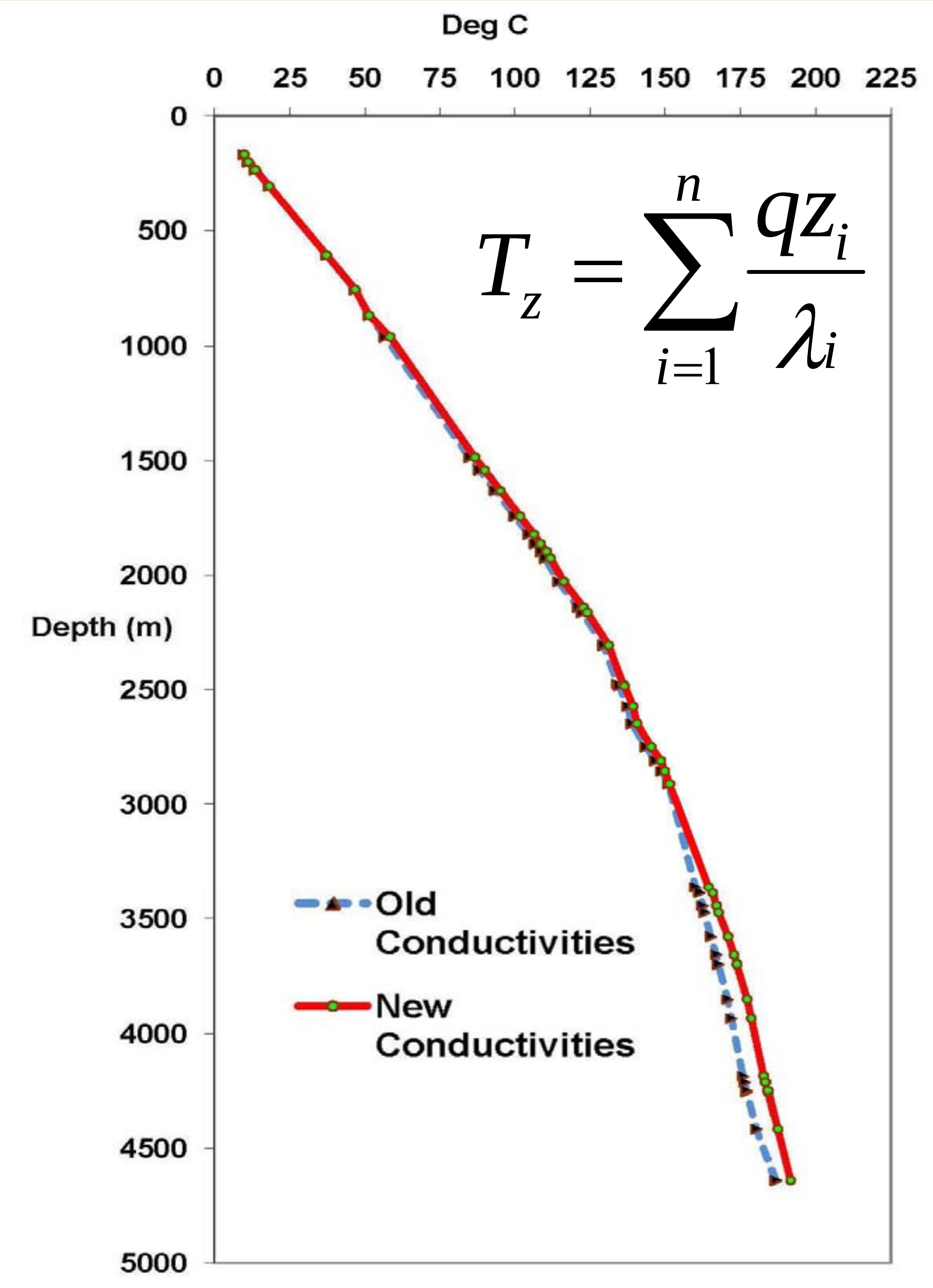
100
120
34
32
30
28
26
24
22
20
18
16
14
12
10

Thermal conductivities measured on core samples from Williston Basin, 2010-2011.

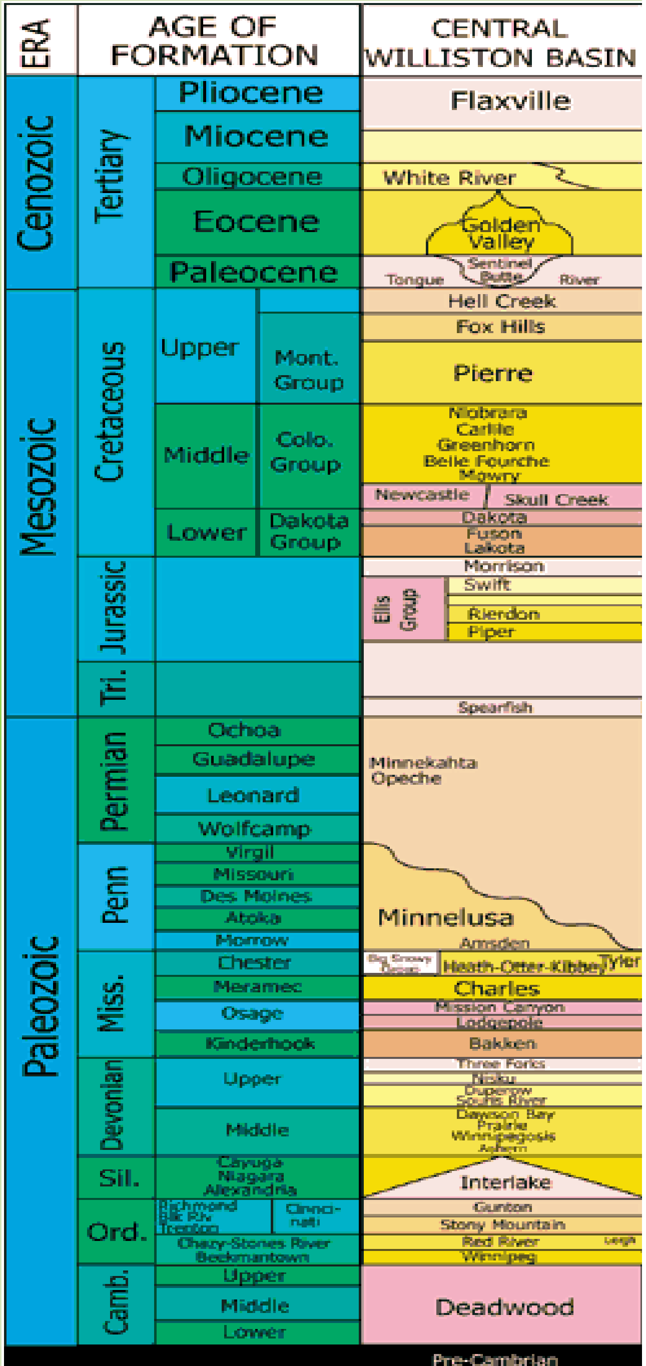
Formation	System	Rock Type	Cond. W/m/K	N	RBT 1981	Difference
Pierre	Cretaceous	Sh	0.88 ± 0.26	23	1.1	-19.10%
Madison	Mississippian	Ls	2.49 ± 0.48	36	3.5	-30.60%
Birdbear	Devonian	Ls	3.13 ± 0.73	29	3.5	-30.60%
Duperow	Devonian	Ls	3.19 ± 0.51	44	3.5	-11.40%
Souris River	Devonian	Ls	2.92 ± 0.48	23	3.5	-18.00%
Dawson Bay	Devonian	Ls / Do	2.75 ± 0.60	18	3.5	-22.90%
Winnipegosis	Devonian	Ls / Do	2.99 ± 0.70	10	3.5	-18.60%
Ashern	Devonian	Ls / Do	3.10 ± 0.24	6	3.5	-12.30%
Interlake	Silurian	Do / LS	3.77 ± 0 .64	29	3.5	20.30%
Stonewall	Silurian	Do / Ls	3.89 ± 0 .01	2	3.5	12.30%
Stony Mt.	Silurian	Do / Ls	3.79 ± 0.67	13	3.5	18.30%
Red River	Ordovician	LS / Do	3.28± 0.94	47	3.5	-3.40%
Black Island	Ordovician	Do / SS	4.71 ± 0.52	5	3.5	36.00%
Winnipeg	Ordovician	Do / SS	4.07 ± 0.39	14	3.5	12.90%
Deadwood	Cambrian	Do /SS	3.46 ± 1.02	69	2.4	54.60%

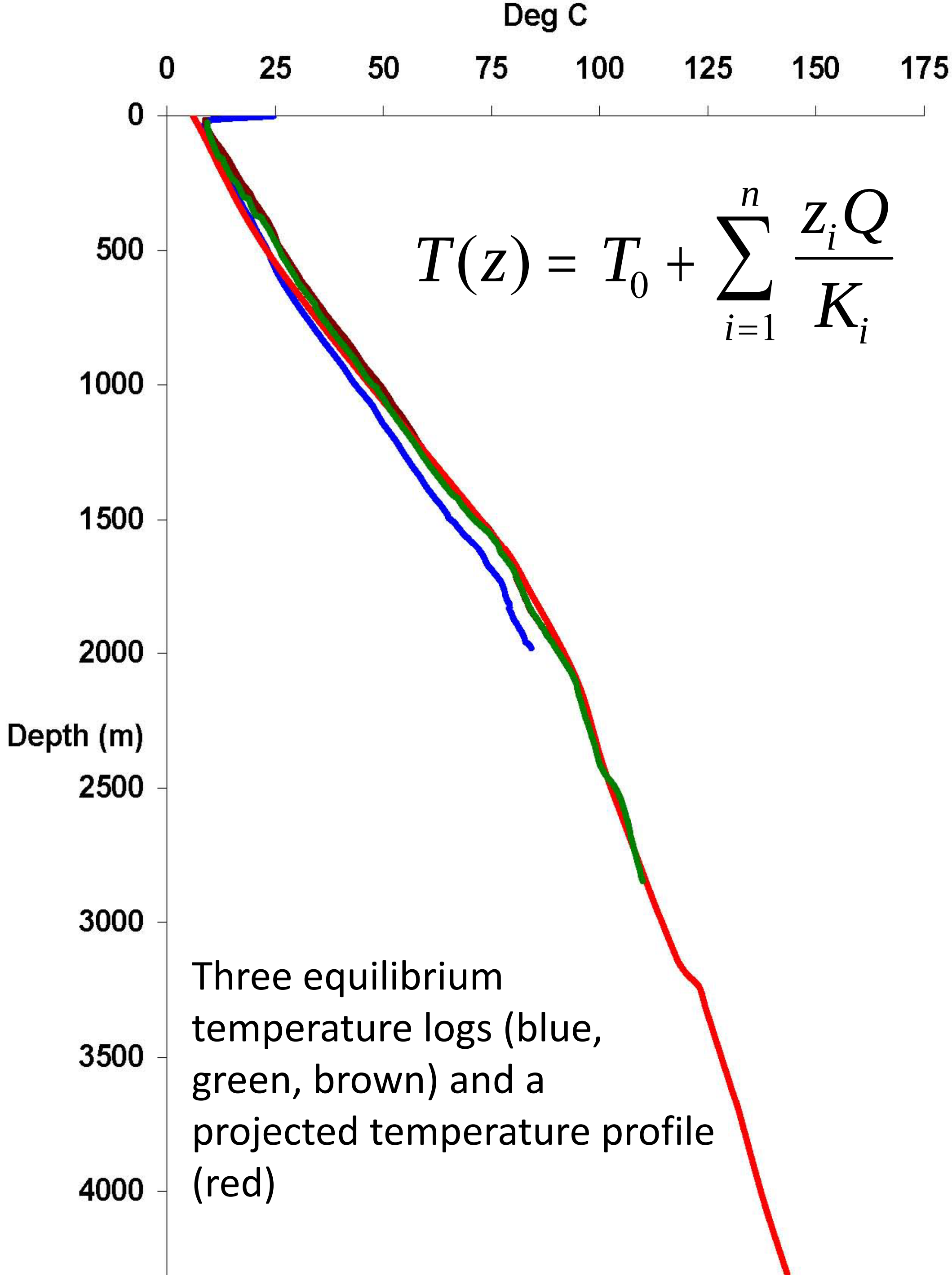
Temperature vs. Depth in Williston Basin





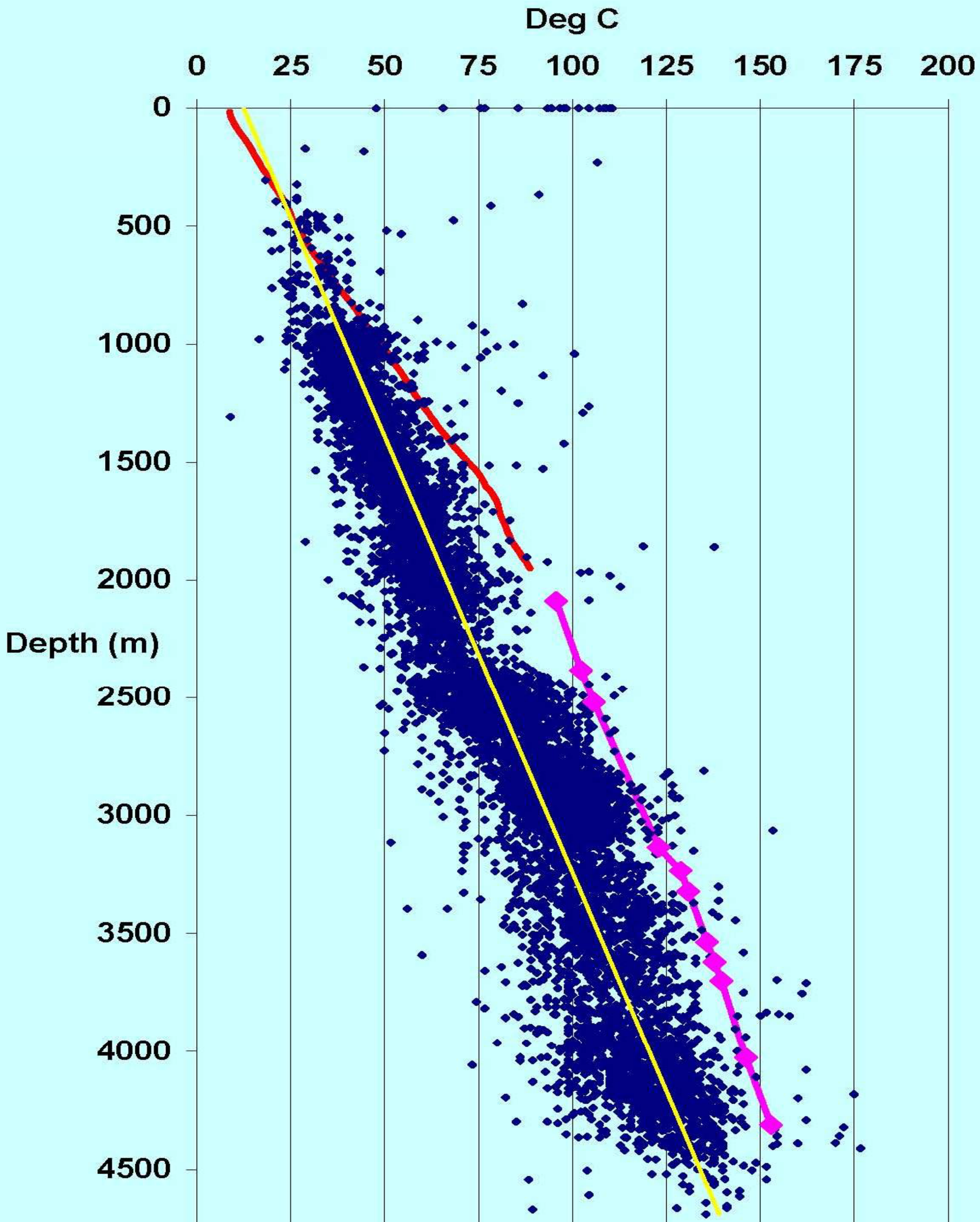
$$T_z = \sum_{i=1}^{n} \frac{q z_i}{\lambda_i}$$





$$T(z) = T_0 + \sum_{i=1}^{n} \frac{z_i Q}{K_i}$$

Three equilibrium temperature logs (blue, green, brown) and a projected temperature profile (red)

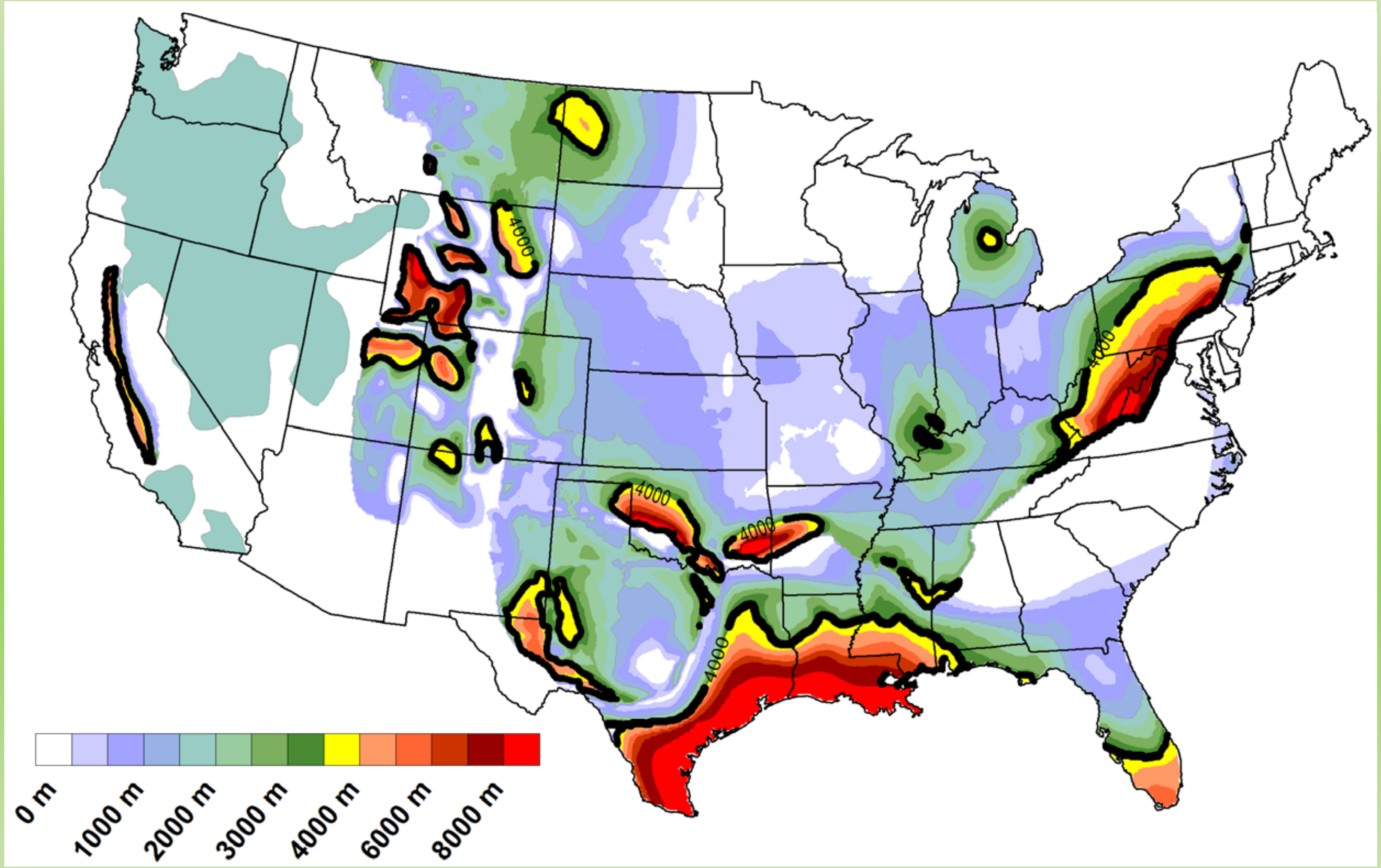


BHT data and measured T vs. Z in the Williston Basin.

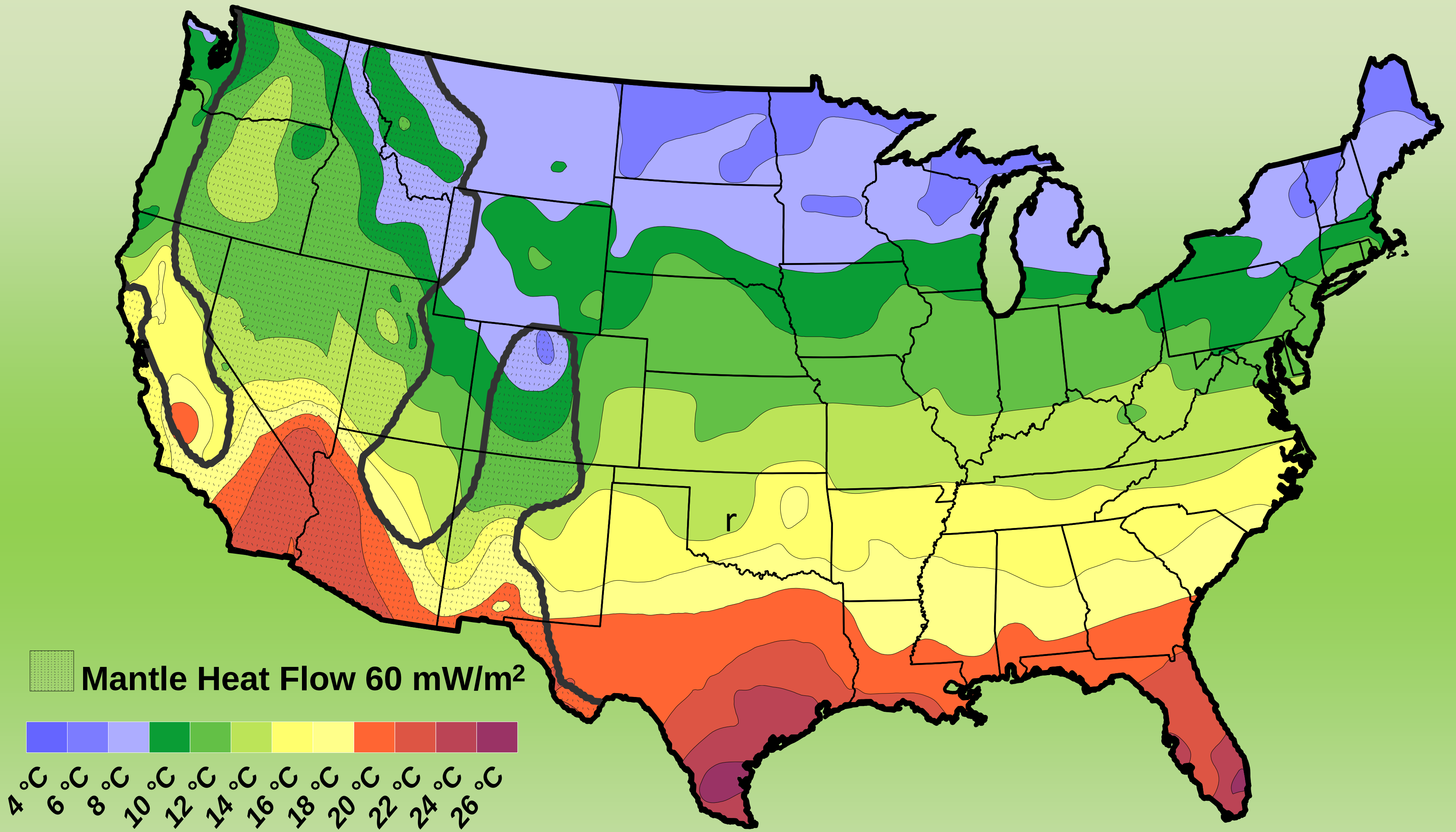
The red line is an equilibrium temperature measurement and the pink line is a projection of that line using measured thermal conductivities.

$$T(z) = T_0 + \sum_{i=1}^{n} \frac{z_i Q}{K_i}$$

Sediment thickness in the continental United States



Source: "The Future of Geothermal Energy," MIT Report, January 22, 2007.



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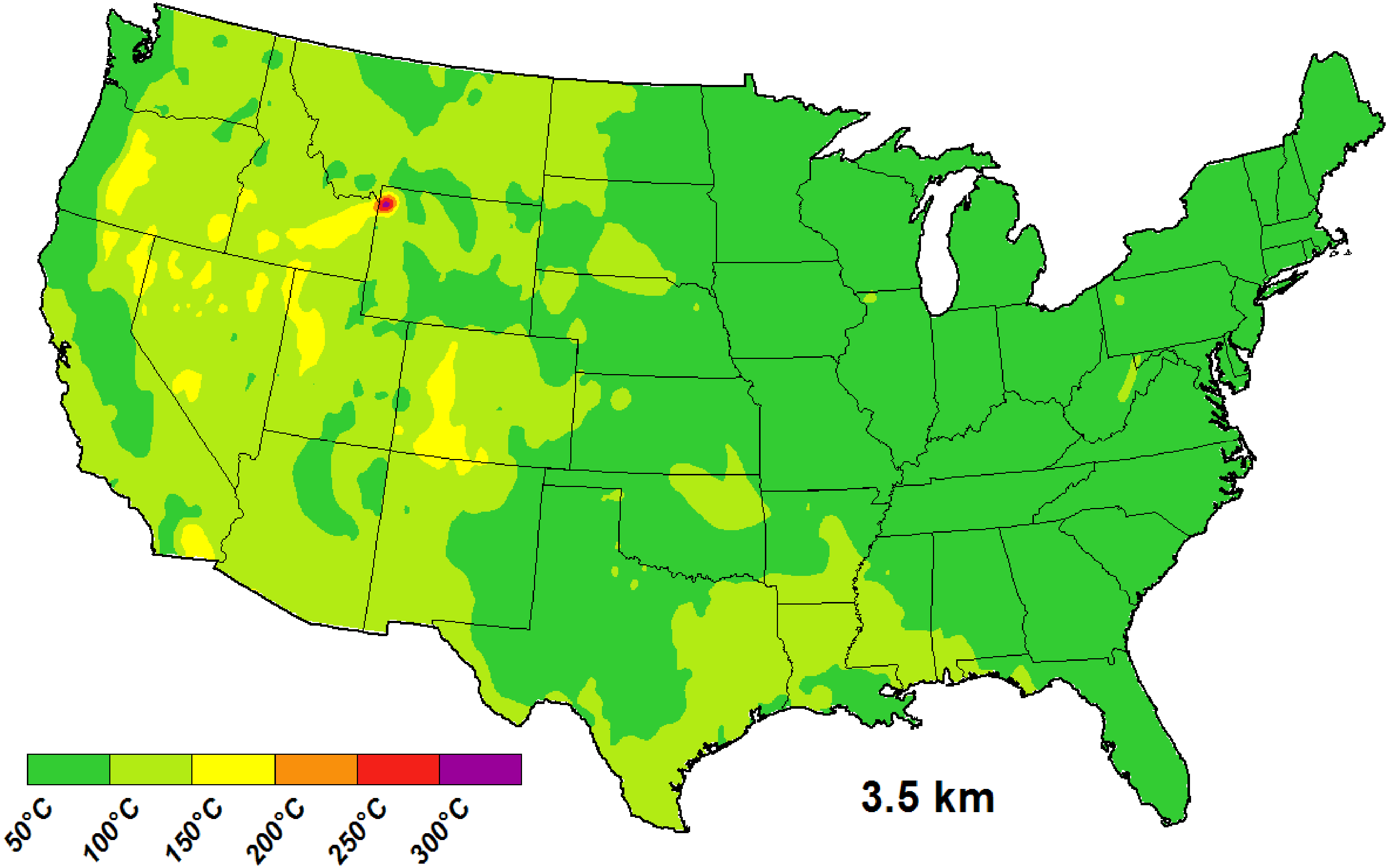

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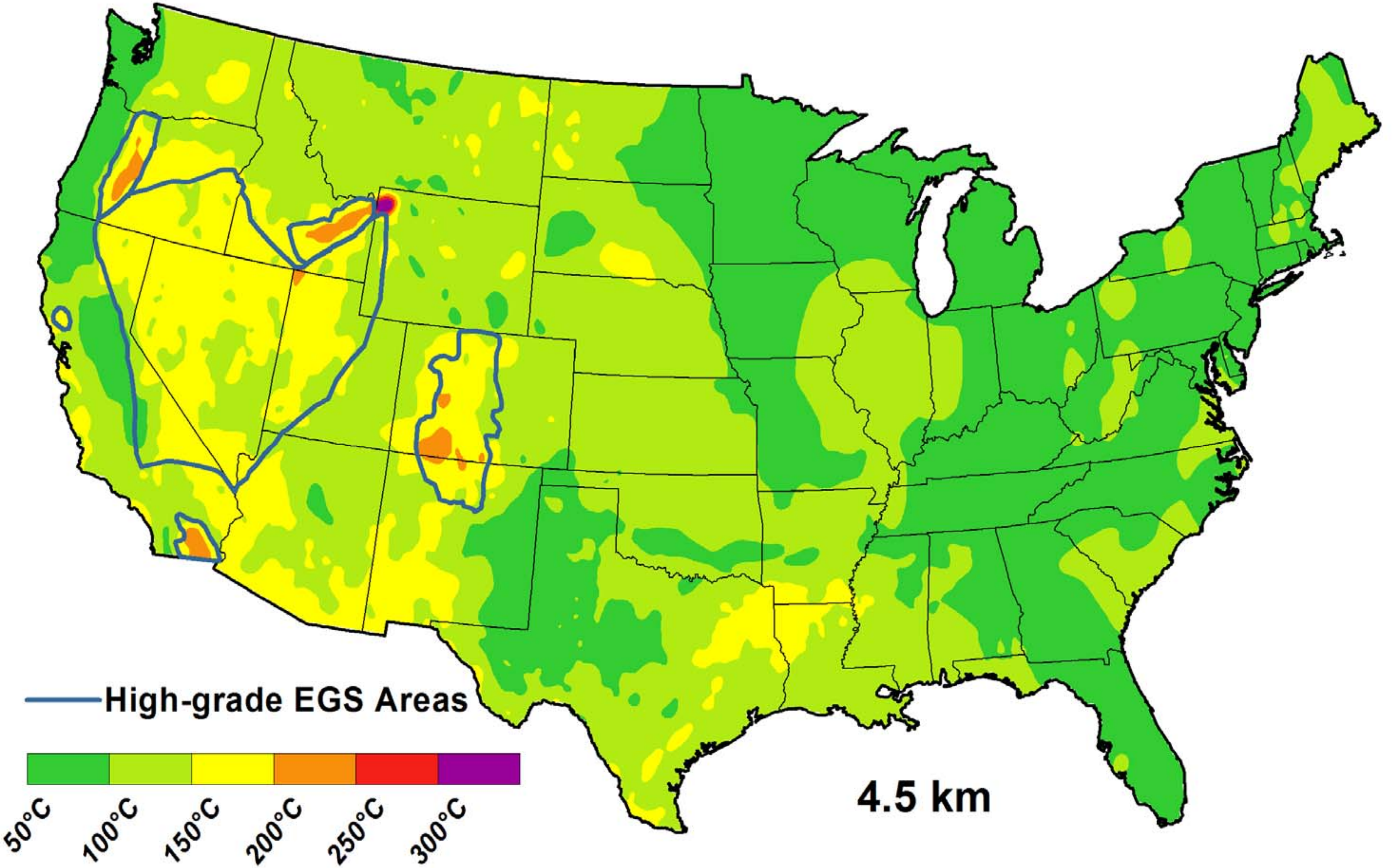

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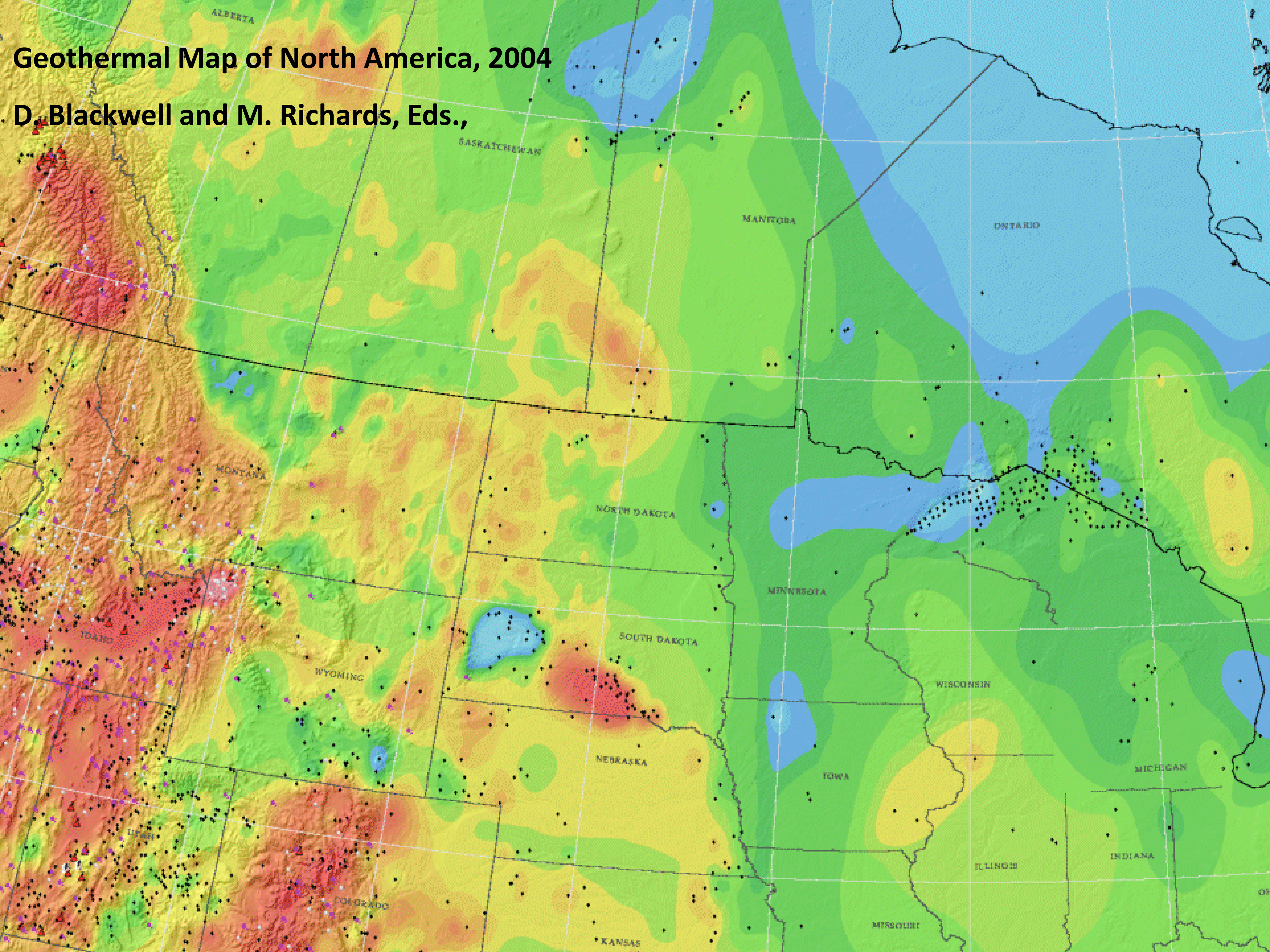
Geothermal Map of North America, 2004

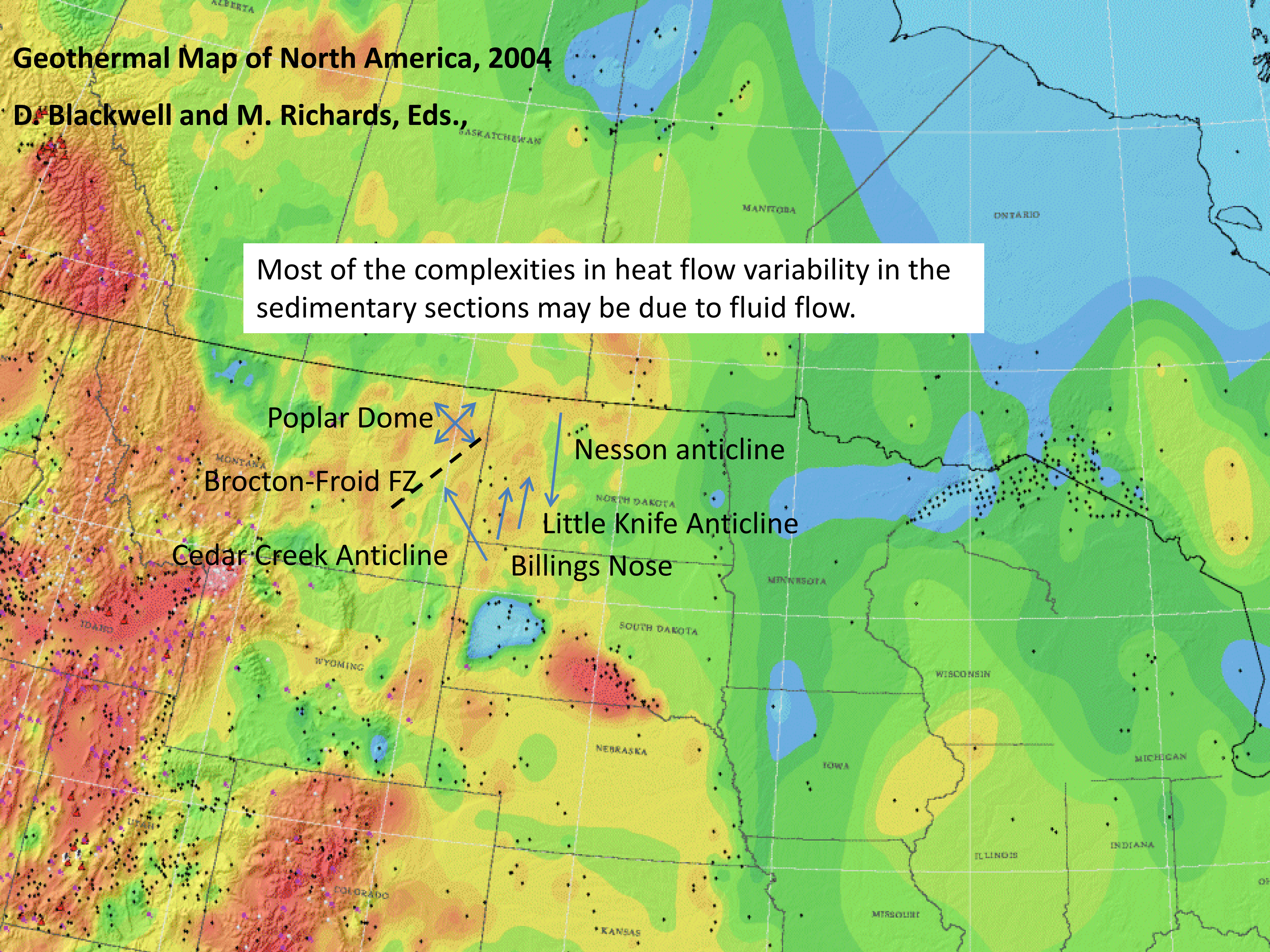
D. Blackwell and M. Richards, Eds.,



Geothermal Map of North America, 2004

D. Blackwell and M. Richards, Eds.,

Most of the complexities in heat flow variability in the sedimentary sections may be due to fluid flow.



Resource estimation

$$Q = \rho C_p V \Delta T$$

ρ is the rock density
C_p is the heat capacity
V is the volume of rock to be cooled
ΔT is the temperature difference between the geothermal fluid and temperature exiting the heat exchanger.

Geothermal Energy in Sedimentary Basins in the North Central US

- North Dakota & Montana 31,800 EJ
- Eastern Colorado 2,640 EJ
- South Dakota 5,950 EJ
- Nebraska 3,720 EJ
- Kansas 4,980 EJ
- Williston Basin (aquifers only) USGS Circular 893 2,050 EJ

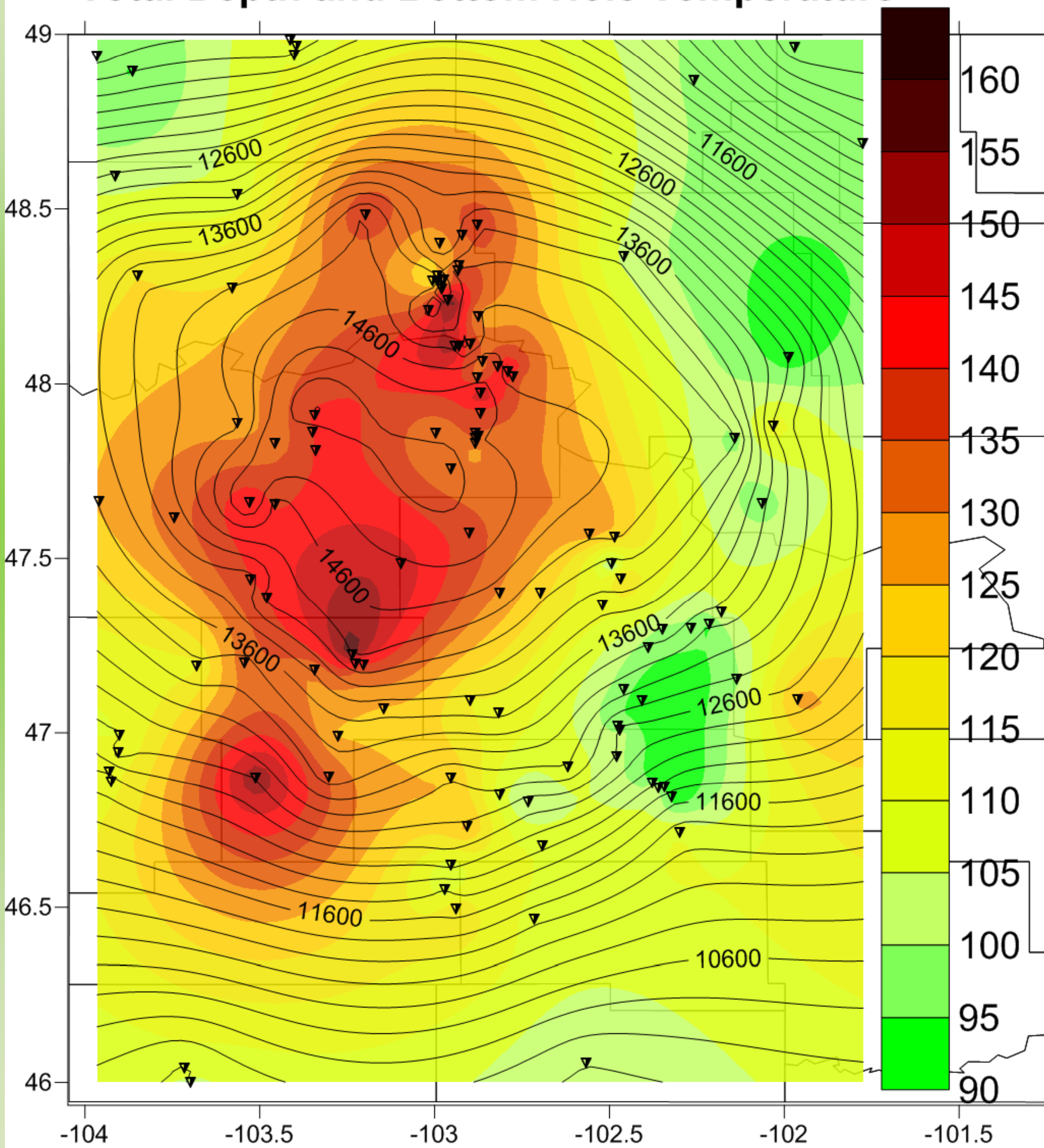
Estimated U.S. geothermal resource base to 10 km depth by category

Category of Resource	Thermal Energy, in Exajoules (1EJ = 10^{18} J)	Reference * Excludes Yellowstone National Park and Hawaii ** Includes methane content
Conduction-dominated EGS		
Sedimentary rock formations	100,000 (400,000)	MIT - 2007
Crystalline basement rock formations	13,300,000	MIT - 2007
Supercritical Volcanic EGS*	74,100	USGS Circular 790
Hydrothermal	2,400 – 9,600	USGS Circulars 726 and 790
Coproduced fluids	0.0944 – 0.4510 (x 20)	McKenna, et al. (2005)
Geopressured systems	71,000 – 170,000**	USGS Circulars 726 and 790

Source: "The Future of Geothermal Energy," MIT Report, January 22, 2007.

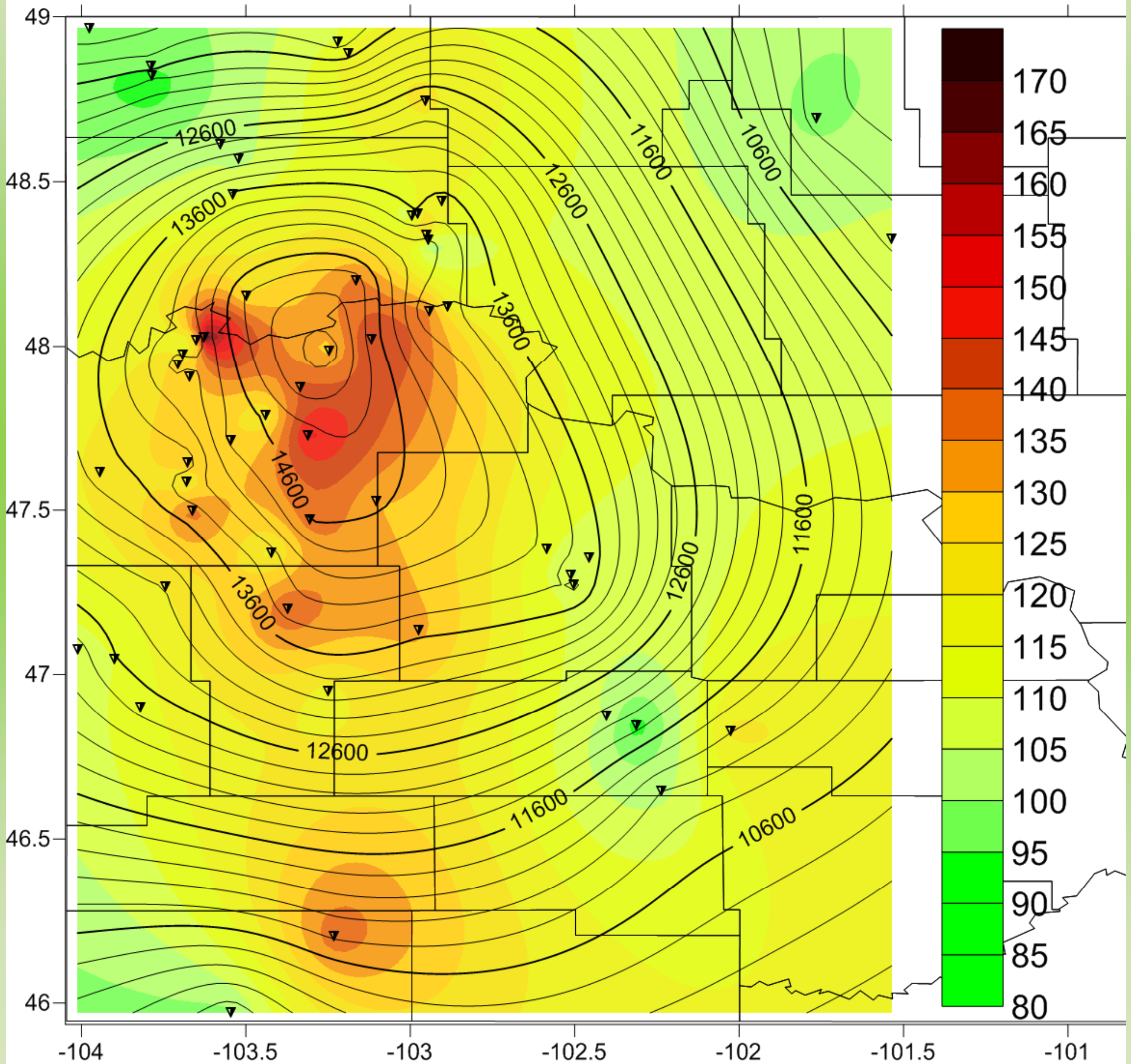
Deadwood Formation

Total Depth and Bottom Hole Temperature



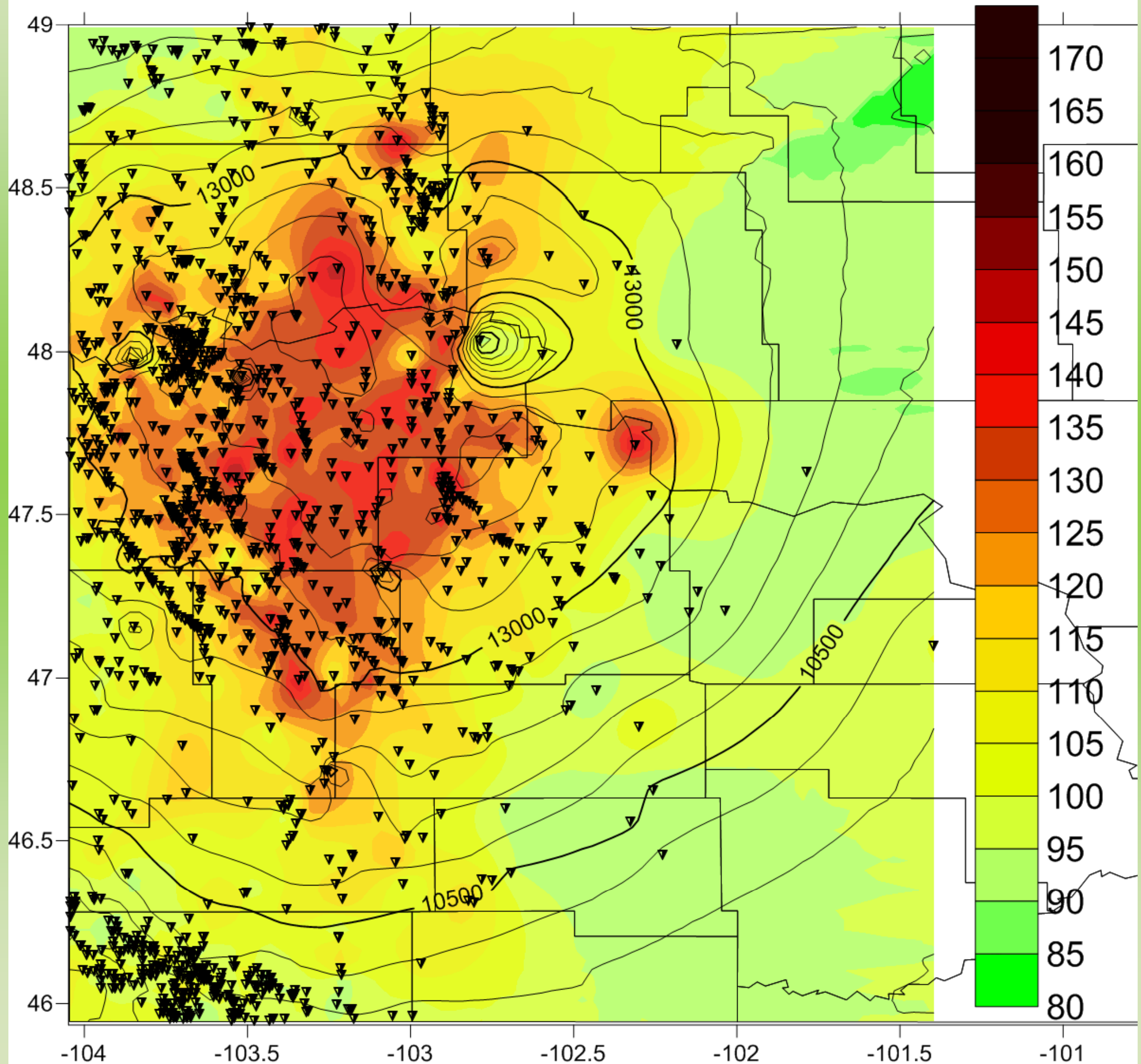
Winnipeg Formation

Total Depth and Bottom Hole Temperature



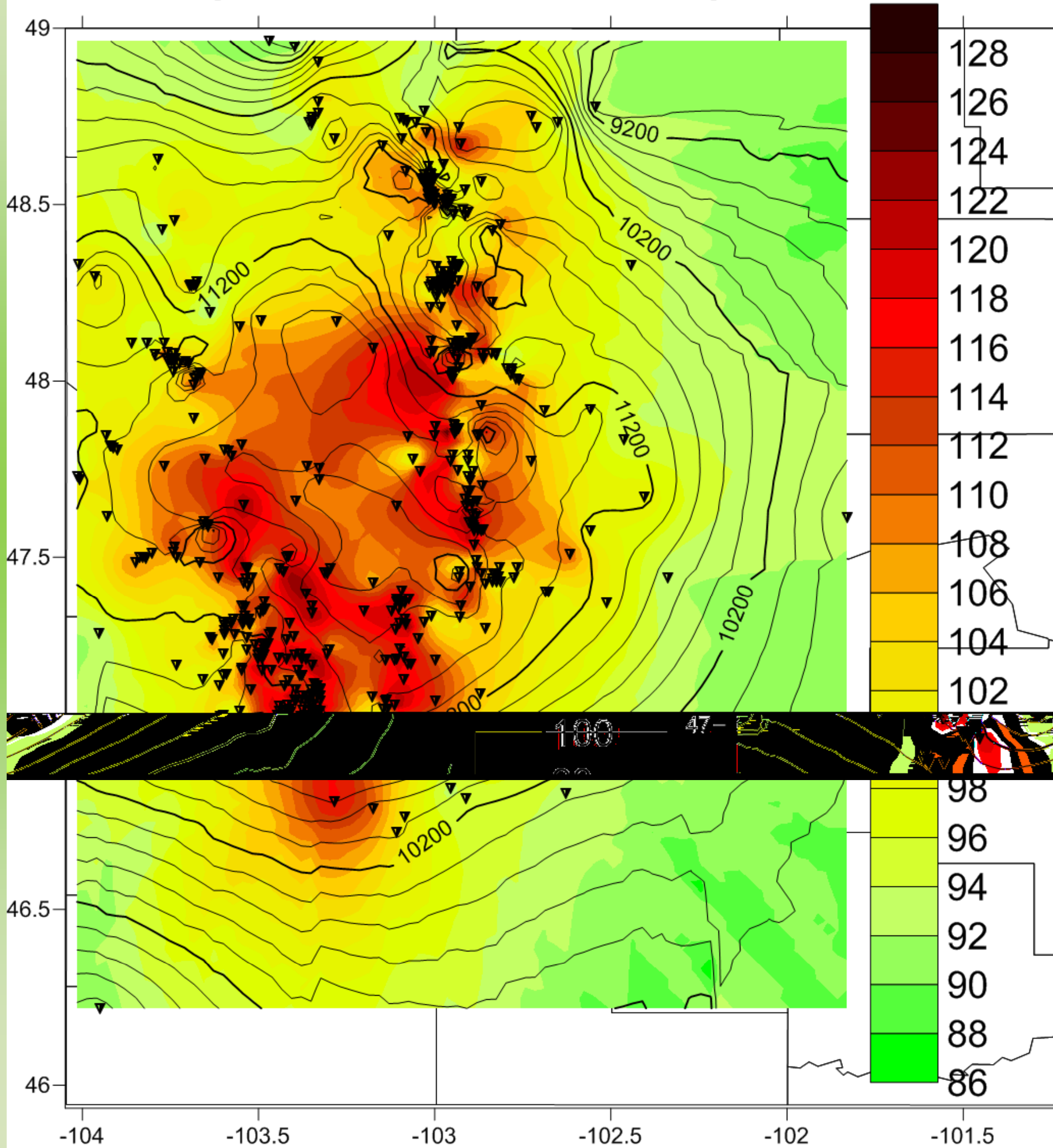
Ordovician Formation

Total Depth and Bottom Hole Temperature



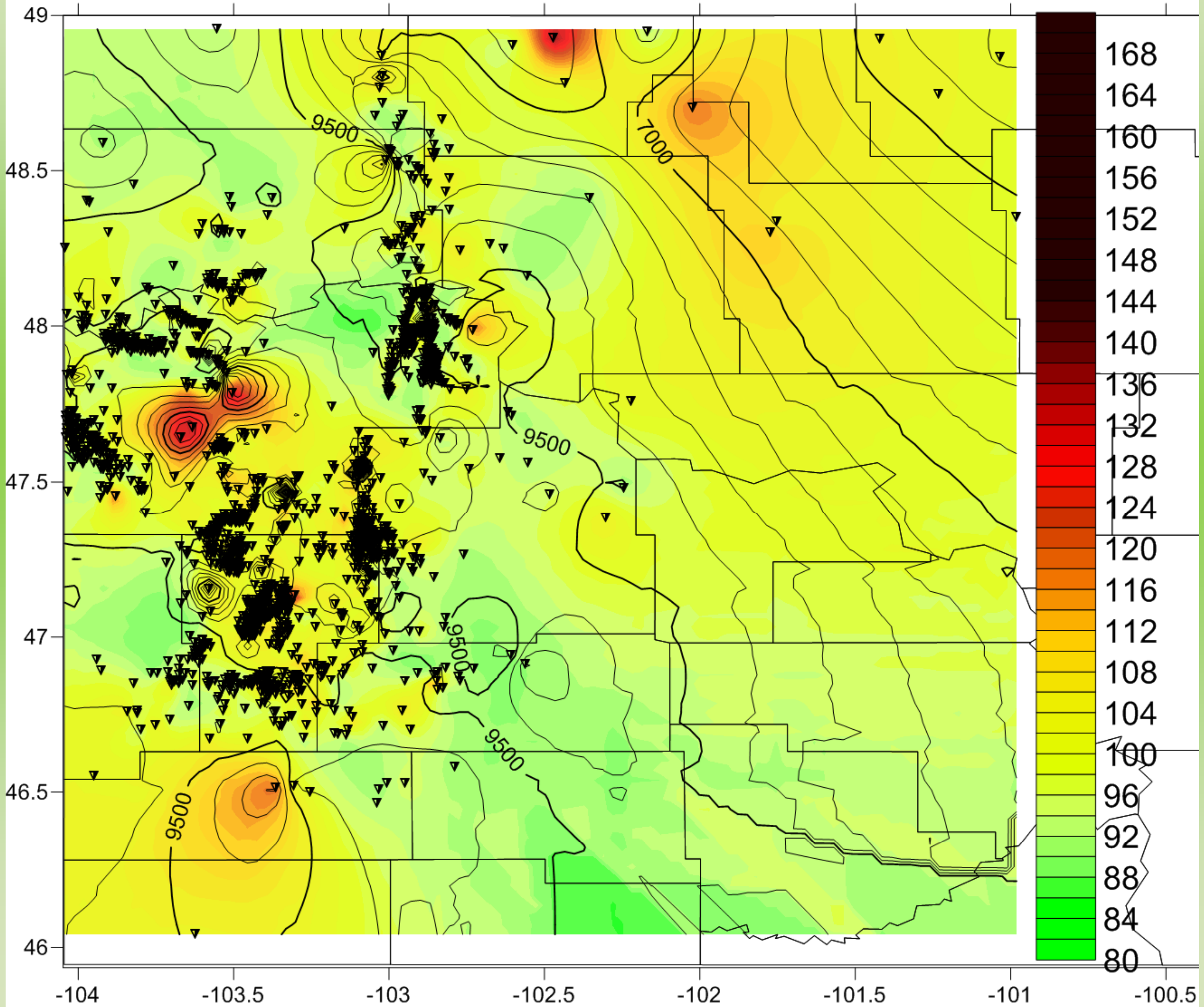
Devonian Formation

Total Depth and Bottom Hole Temperature



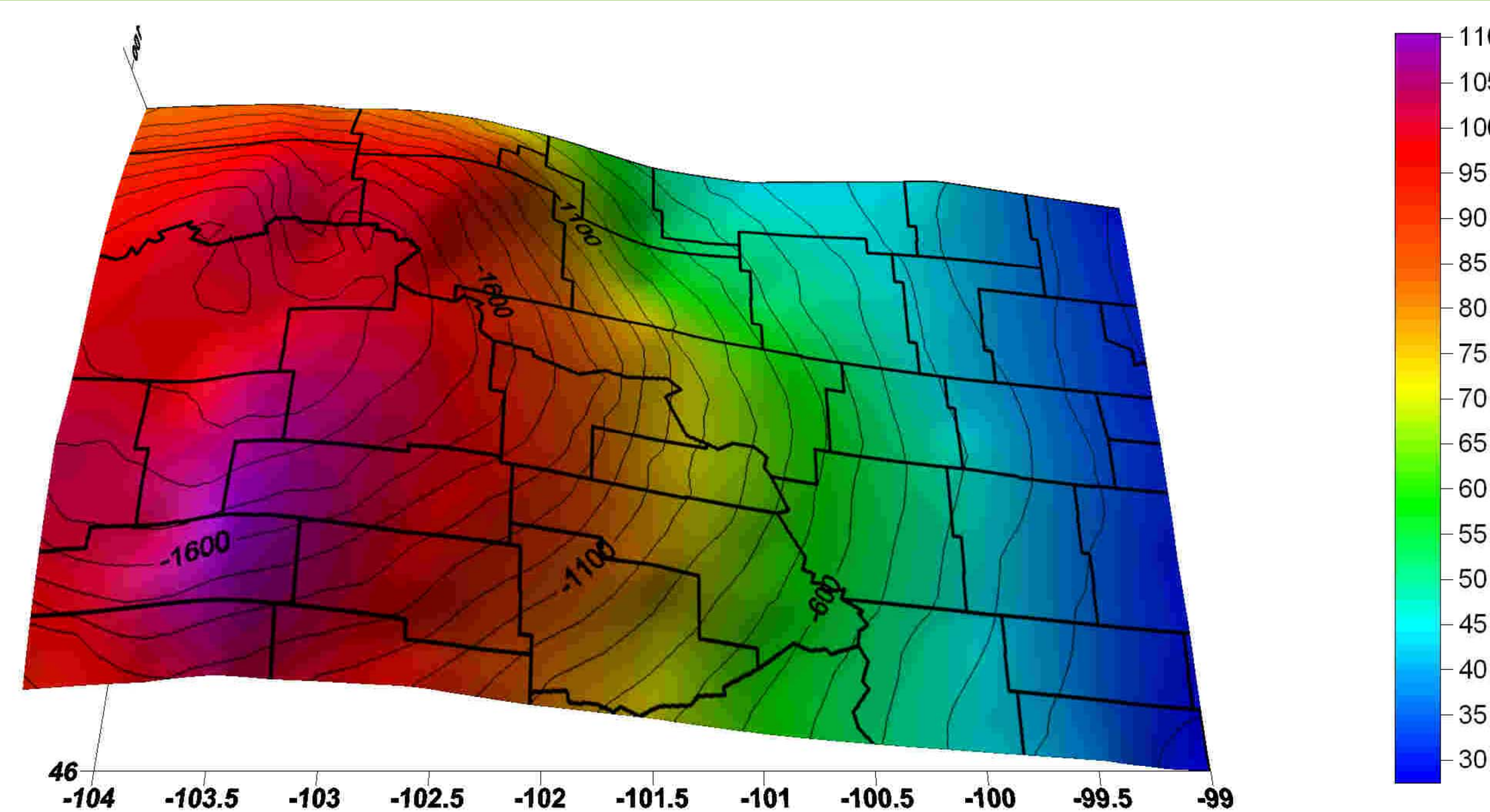
Madison Formation

Total Depth and Bottom Hole Temperature



The energy resource in Joules is the product of density*volumetric heat capacity*volume*dT $q_r = \rho c_v a d\,(t - t_{ref})$

The Madison Fm in western North Dakota contains 1,476 EJ.



Colors are temperature, contours are depth (m), lines are county boundaries

North Dakota Geothermal Projects

- Electrical Power from Low-temperature Resources
  - Continental Resources, Inc. water flood project
  - 100°C at 875 gpm from Lodgepole Fm.
  - Calnetix, Inc.
  - Phase I in review by DOE
  - Phase II installation in 2011

North Dakota Geothermal Projects

- Electrical Power from Co-Produced Resources
  - Initial partner Encore, Inc.,
  - 100°C at 400 gpm from Lodgepole Fm.
  - We are currently seeking new partner
  - DOE funding $1,7 M
  - UND funding $270 K

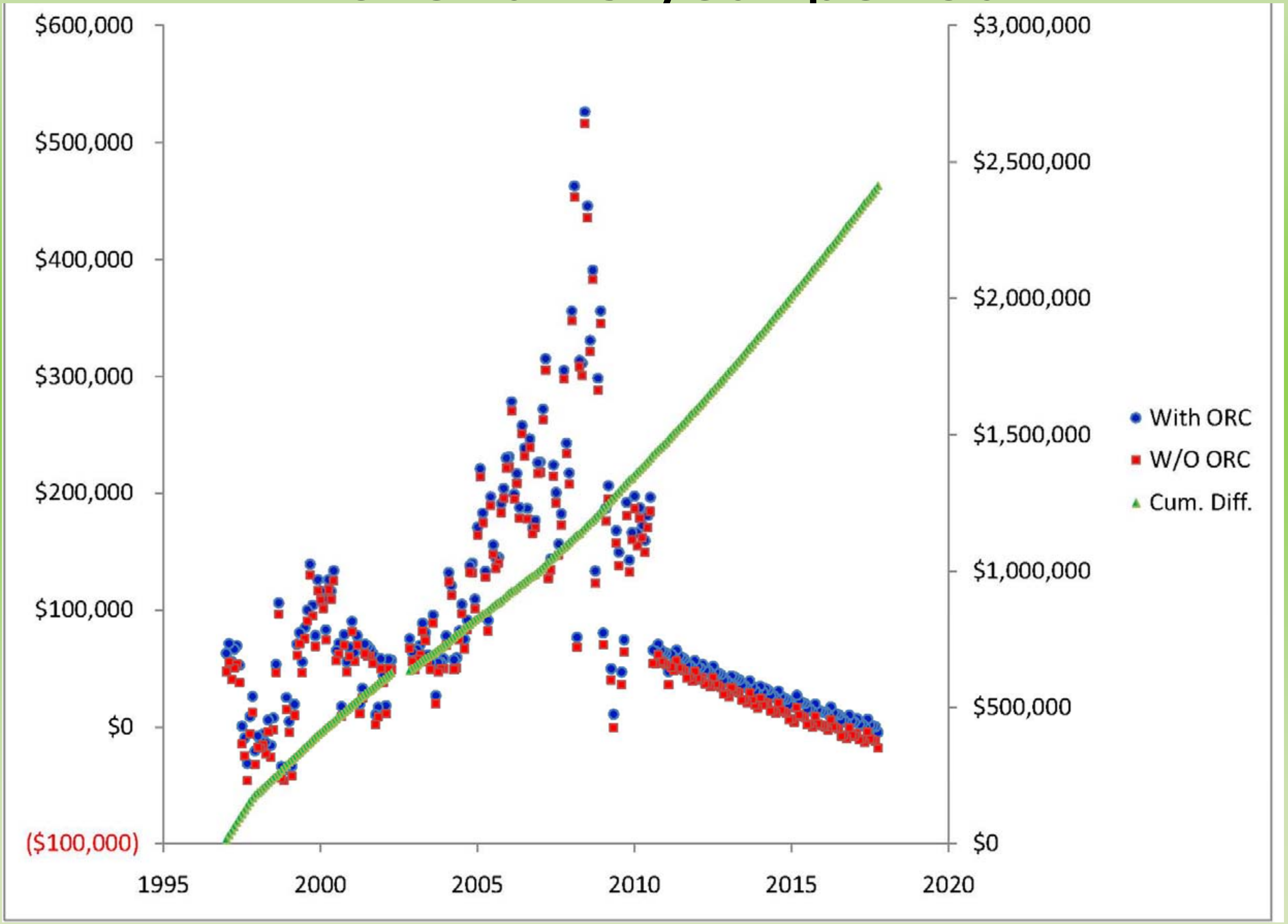
Feasibility Study

- Resource
  - Temperature
  - Flow rate
  - Total dissolved solids
  - Disposal
- Analysis of Energy Conversion Systems
- Regulatory and Permitting
- Economic Model

Impact on Oil Fields
Cost factors for economic model
1997 - 2017

- BBLS Oil
- BBLS Water
- MCF
- SWD - Disposal at $0.56/BBL
- kW/hr used (based on $.06)
- $ Electrical
- Crude Oil $/BBL
- Crude Sales
- kW produced
- Electricity Sales
- Other O&M costs (at $137/day)

Monthly income and cumulative difference over a 25 year period



Summary

- Installing binary power systems for power generation using co-produced oil field fluids has potential to make a positive impact on oil field economics.
- Extend well life
- Providing an inexpensive and environmentally benign electrical power source.
- An economic model based on oil and water production rates, water temperature, O & M, oil futures, and electrical cost, show that power generation using co-produced fluids could generate millions of dollars in additional revenue by saving on electrical costs, extending the Estimated Ultimate Recovery (EUR), and facilitating early development of the field.

Summary (cont.)

- Geothermal energy is an underestimated and largely untapped resource that could have a significant impact on the world's energy future.
- Advances in technology make electrical power generation from low-to-intermediate temperature geothermal waters a reality.
- The power that could be generated from oil field waters co-produced or produced alone is enormous.