The University of North Dakota

Refining Estimates of Geothermal Power in Sedimentary Basins

Geothermal Energy

Associated with Oil and Gas Development

November 3-4, 2009

Dallas, TX

Outline

- The ND Geothermal Team
- Heat Flow
- Williston Basin Analysis
- Refining the Resource Estimates
- North Dakota Geothermal Projects

The University of North Dakota

PREEC

Geothermal Energy Team

Will Gosnold
Geol & Geol Engr.

Richard LeFever
Geol & Geol Engr.

Mike Mann
Chemical Engr.

Hossein Salehfar
Electrical Engr.

Zhengwen Zeng
Geol & Geol Engr.

Rob Klenner
MS Geol

Preston Wahl
Soph GGE

James (Josh) Crowell
MS Student Geol

Kirtipal Barse
PhD Student ChE

Nick Low
Research Asst

Samir Dahal
PhD Elec Eng

The University of North Dakota

PREEC

Geothermal Energy Business Team

Joel Johnson
Berrendo Energy

Joshua Fershee, J.D.
Asst. Professor
UND Law School

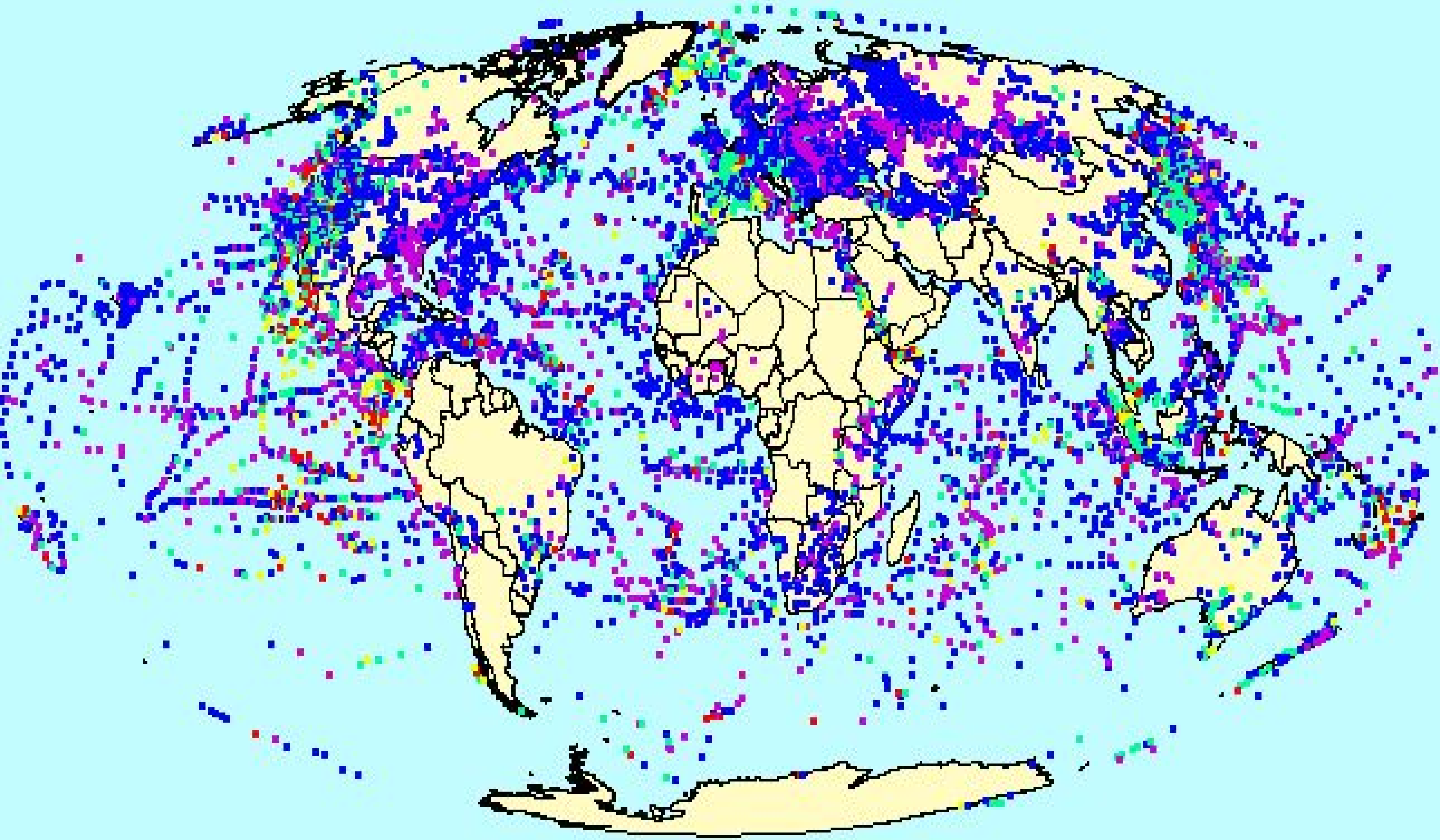
Megan Talley
Bus. Intern
UND Center for
Innovation

Jordan Schuetzle, J. D.
UND Center for
Innovation

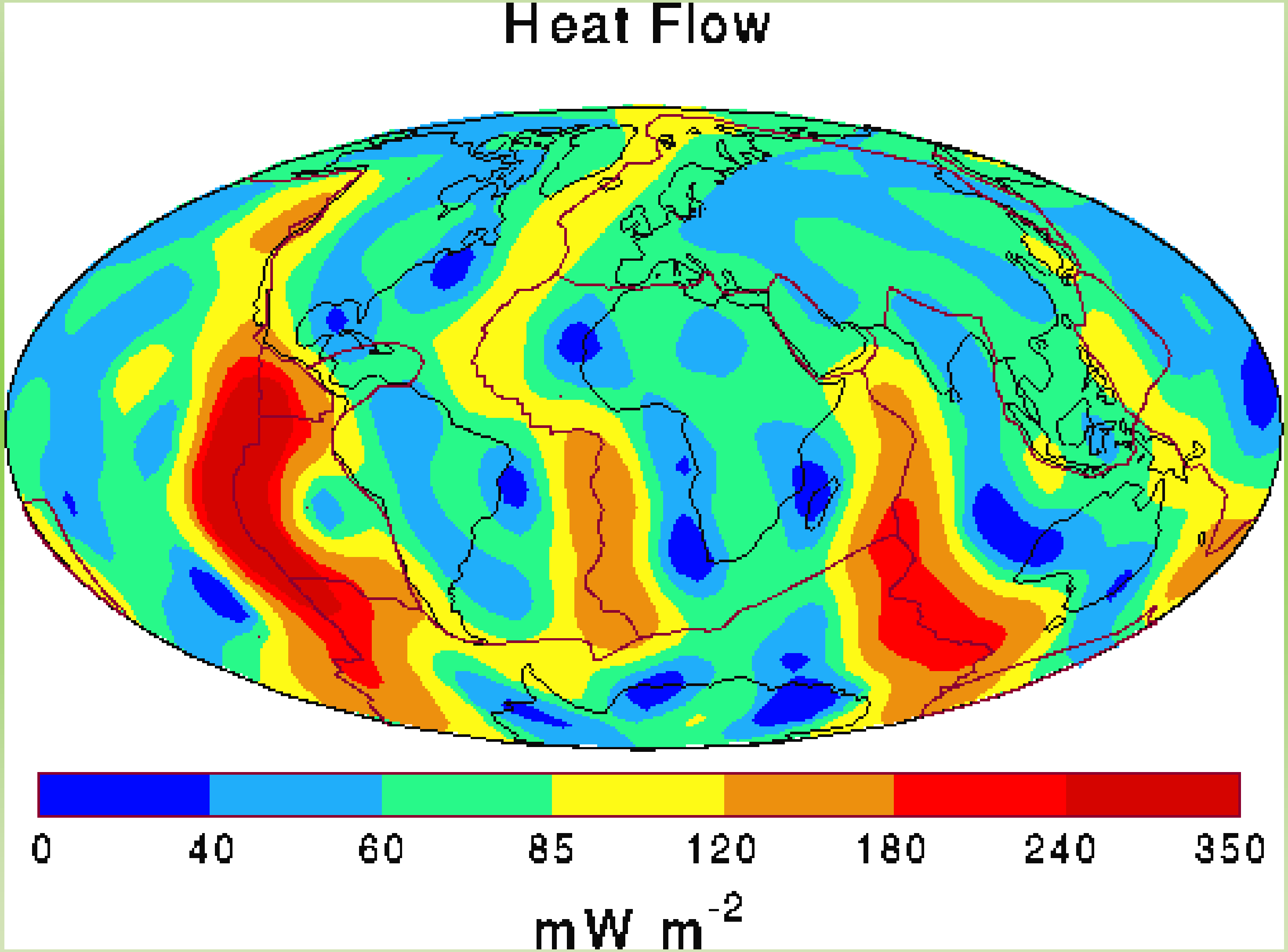
Global Heat Flow

- 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: 87 mW m^{-2}
- Total surface heat flux from Earth's interior: 44.2 TW
- 83% of present surface heat flow is due to radioactive decay of U, Th, and K
- Why is this important?
- Knowing heat flow enables estimation of subsurface temperature

The global heat flow database of the IHFC contains > 22,000 observations.

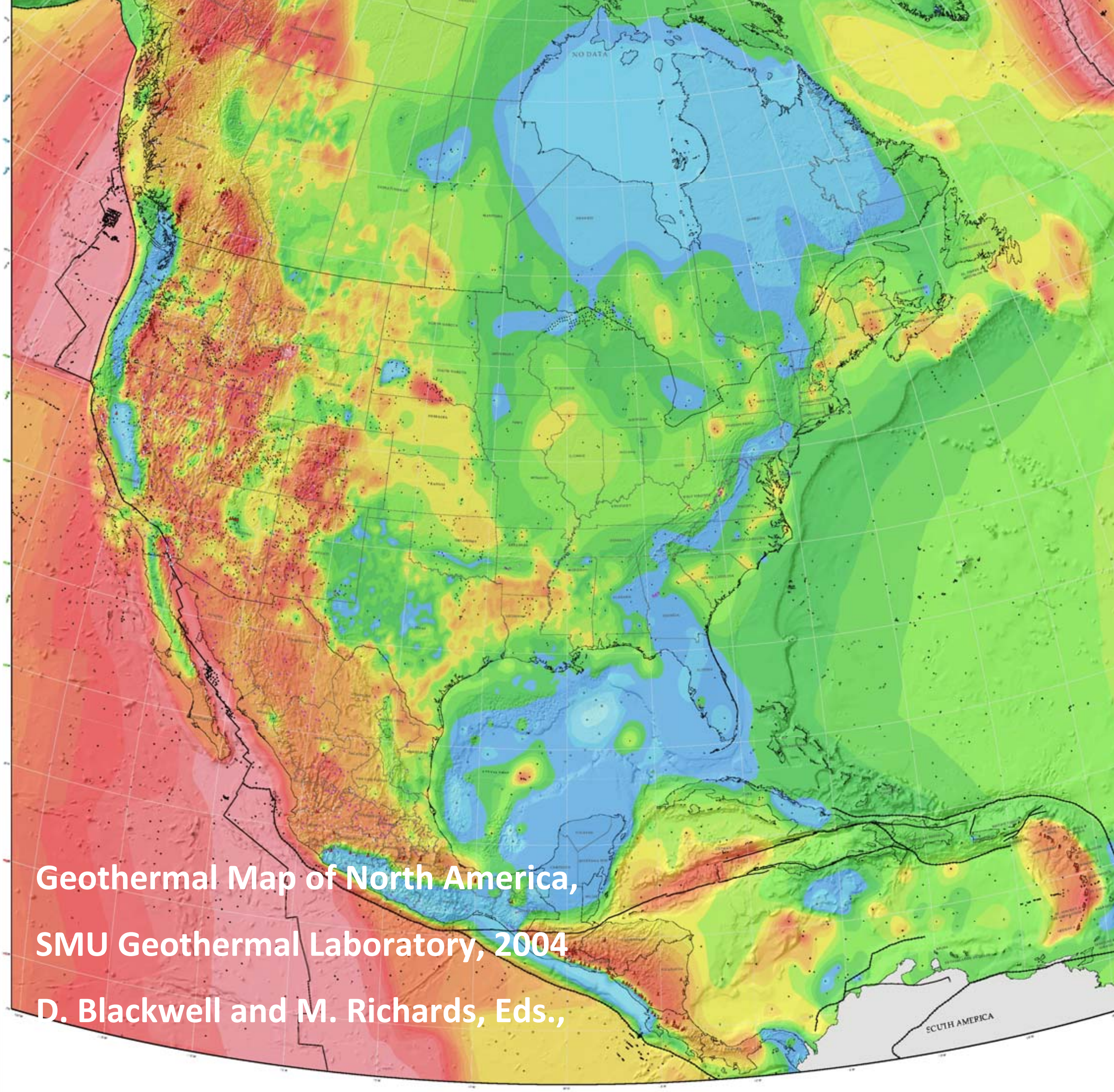


Global heat flow map by Pollack and Chapman (1984)



More than 2000 heat flow observations in the United States

- 80 percent are in the western third of the US
- 35 percent of observations in the eastern US are in Lake Superior
- Heat flow interpretations could be greatly improved with more data



Geothermal Map of North America,

SMU Geothermal Laboratory, 2004

D. Blackwell and M. Richards, Eds.,

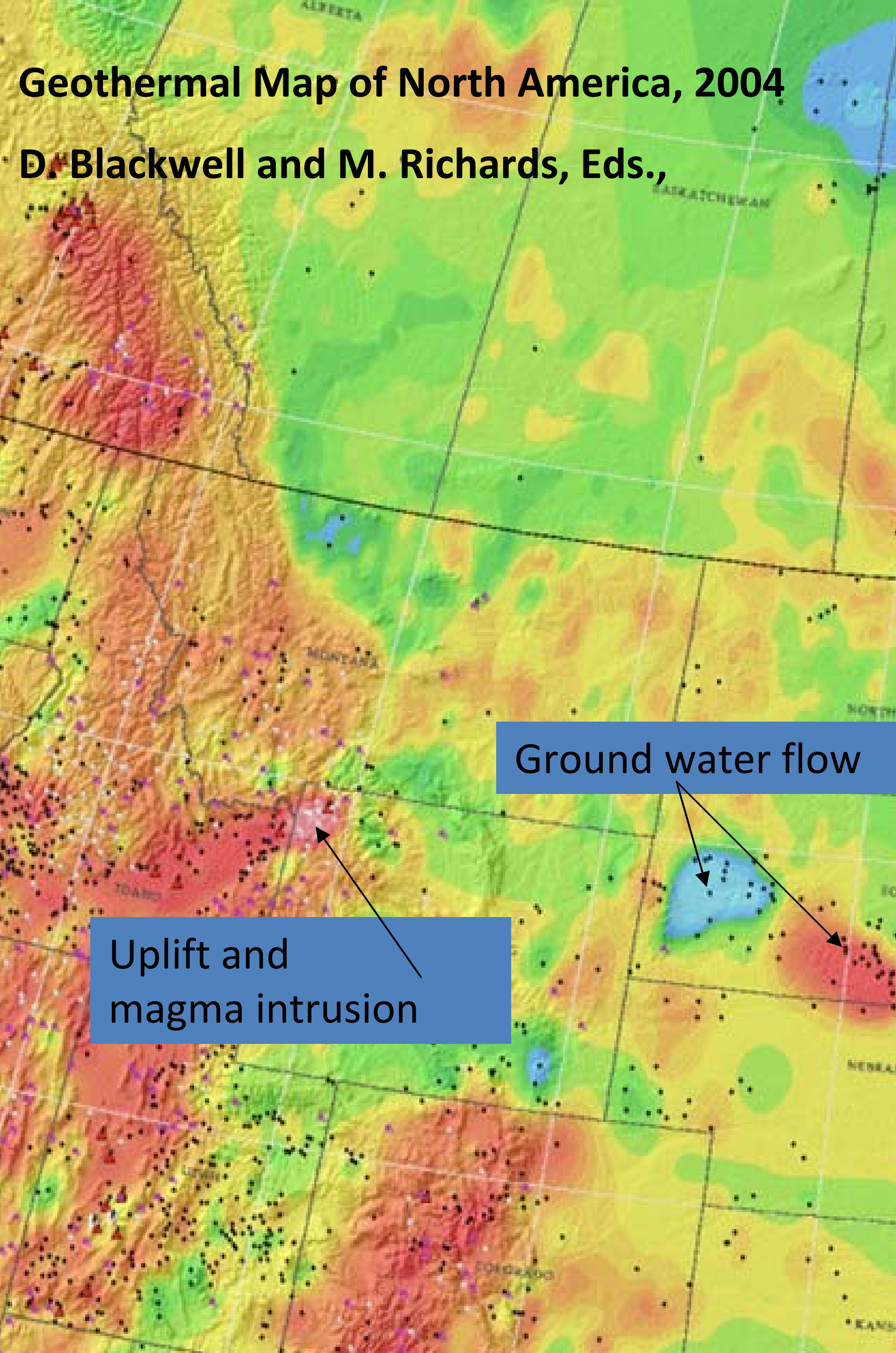
Subsurface Temperatures can be calculated if heat flow and thermal conductivity are known

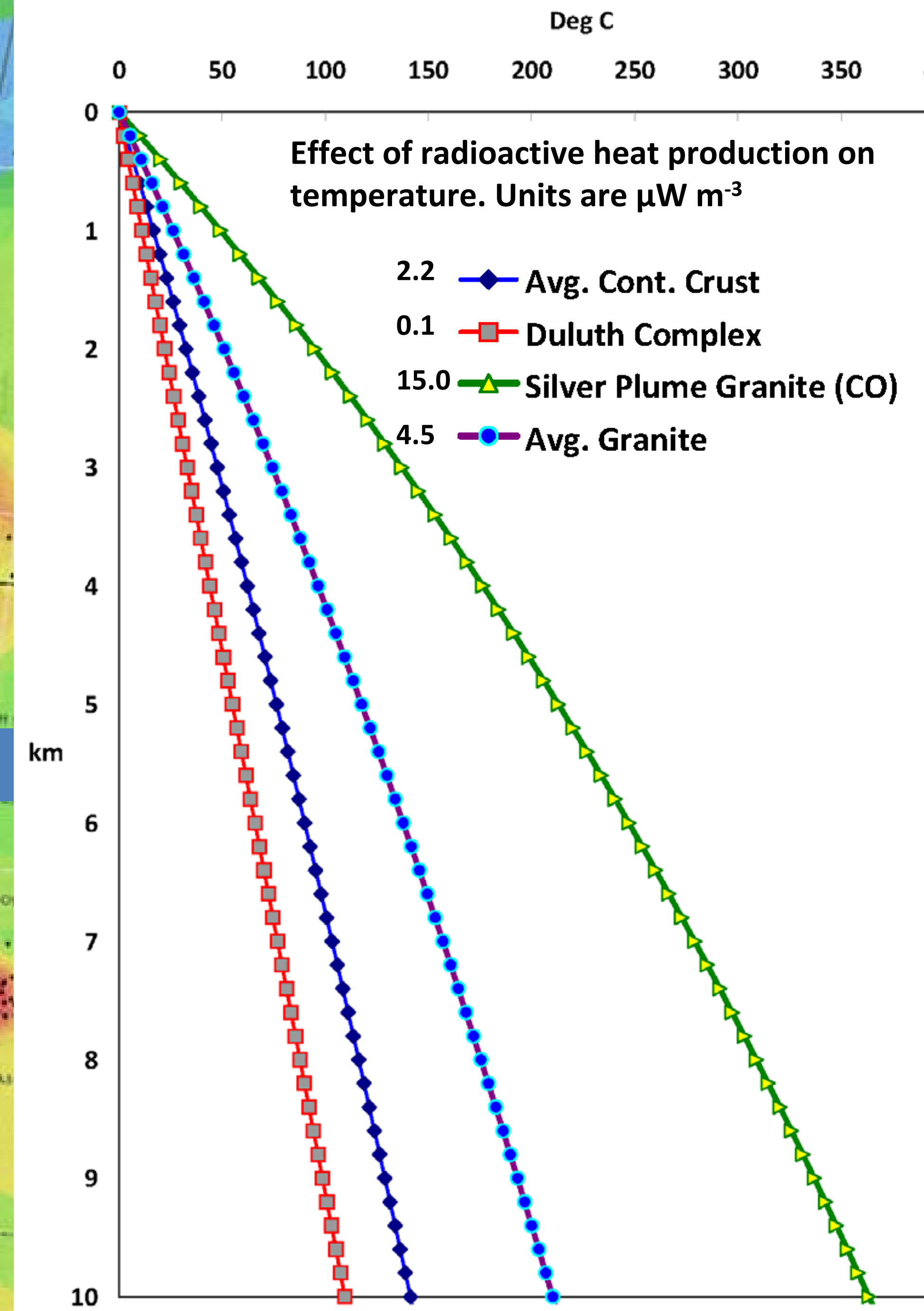
Fourier's law of Heat conduction

$$q = \lambda\Gamma$$

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

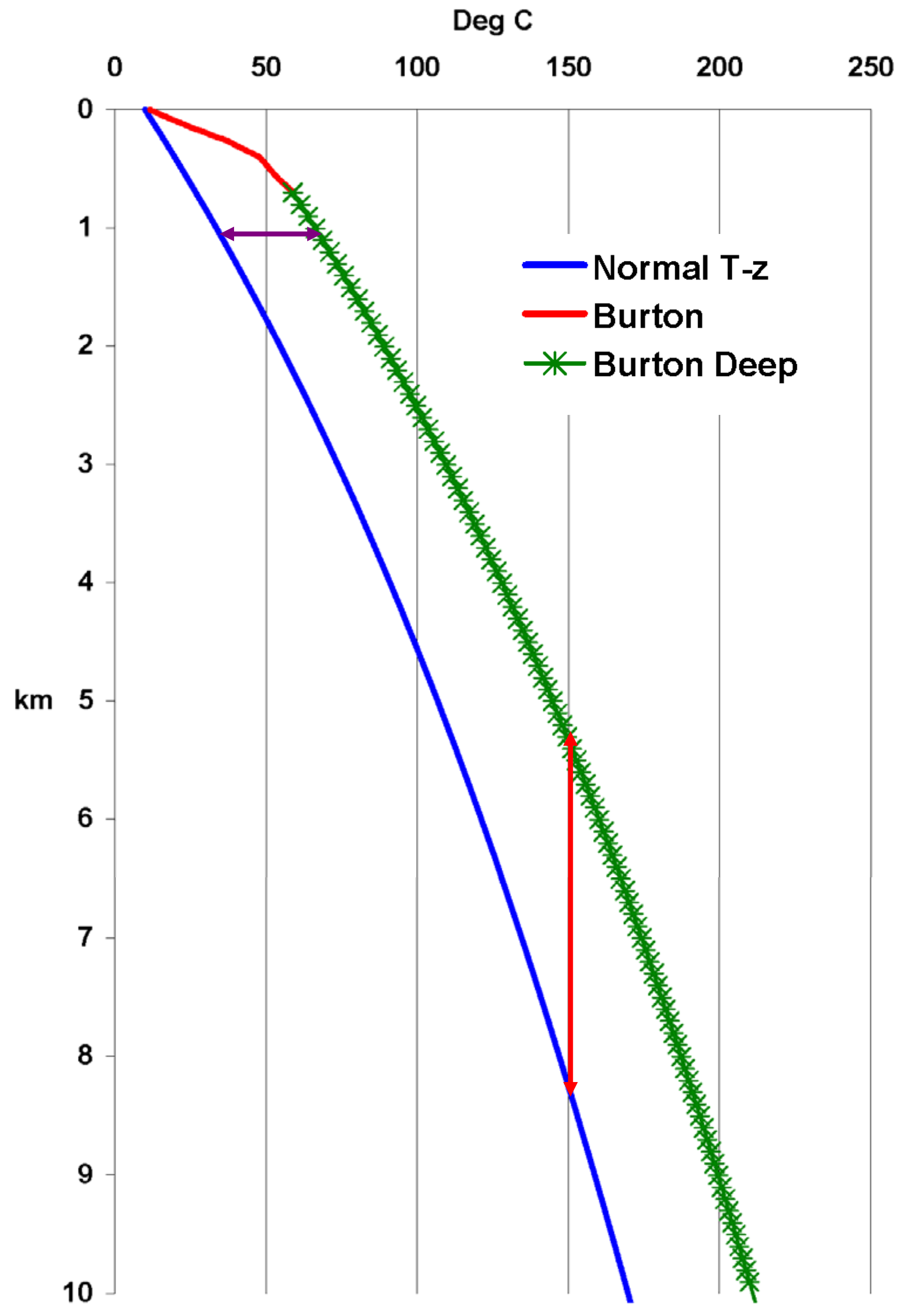
$$T_z = \sum_{i=1}^{n} \frac{qz_i}{\lambda_i}$$


Geothermal Map of North America, 2004
D. Blackwell and M. Richards, Eds.,
Ground water flow
Uplift and magma intrusion


Deg C
0
50
100
150
200
250
300
350
0
1
2
3
4
5
6
7
8
9
10
km
Effect of radioactive heat production on temperature. Units are μW m-3
2.2 Avg. Cont. Crust
0.1 Duluth Complex
15.0 Silver Plume Granite (CO)
4.5 Avg. Granite

The temperature at a depth of 1 km in the SD/NE heat flow anomaly is 48 ºC higher than expected.

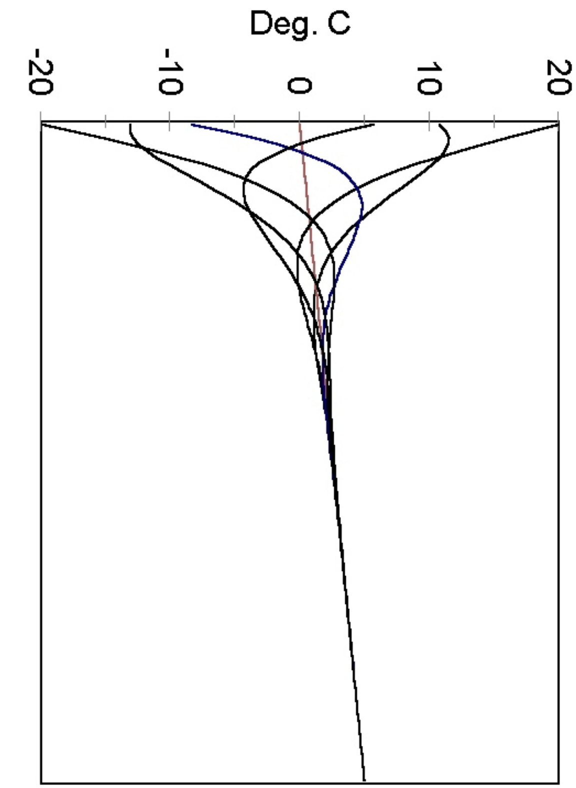
The depth to 150 ºC is 2.9 km less in the anomaly than expected.



Transient Signals in Continental Heat Flow

- Ground water flow: + or -
- Ground cover change: + or -
- Climate change: + or –
- ***Characteristic thermal length***

$$L = \sqrt{\frac{\alpha t}{Fo}}$$

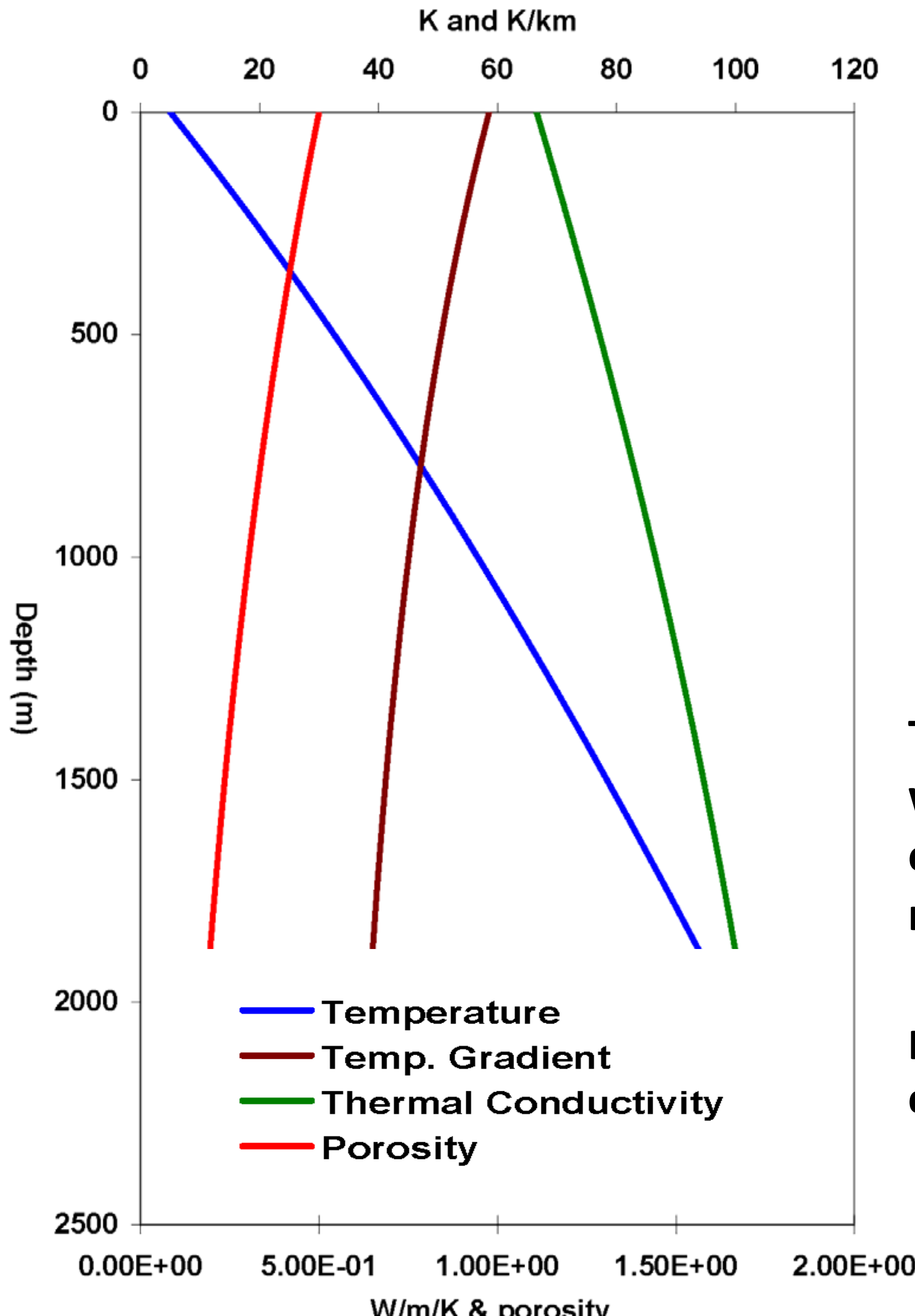


1 y	10 y	100 y	1000 y	10,000 y
13 m	42 m	131 m	415 m	1,310 m

$\alpha = 1x10^{-6}\ m^2\ s^{-1}$

1 y	10 y	100 y	1000 y	10,000 y
9 m	28 m	87 m	275 m	868 m

$\alpha = 0.44\ x10^{-6}\ m^2\ s^{-1}$



The normal temperature vs. depth profile in a thick clastic sedimentary section has a convex curvature due to the increase in thermal conductivity with depth caused by compaction which reduces porosity.

Porosity varies with depth as

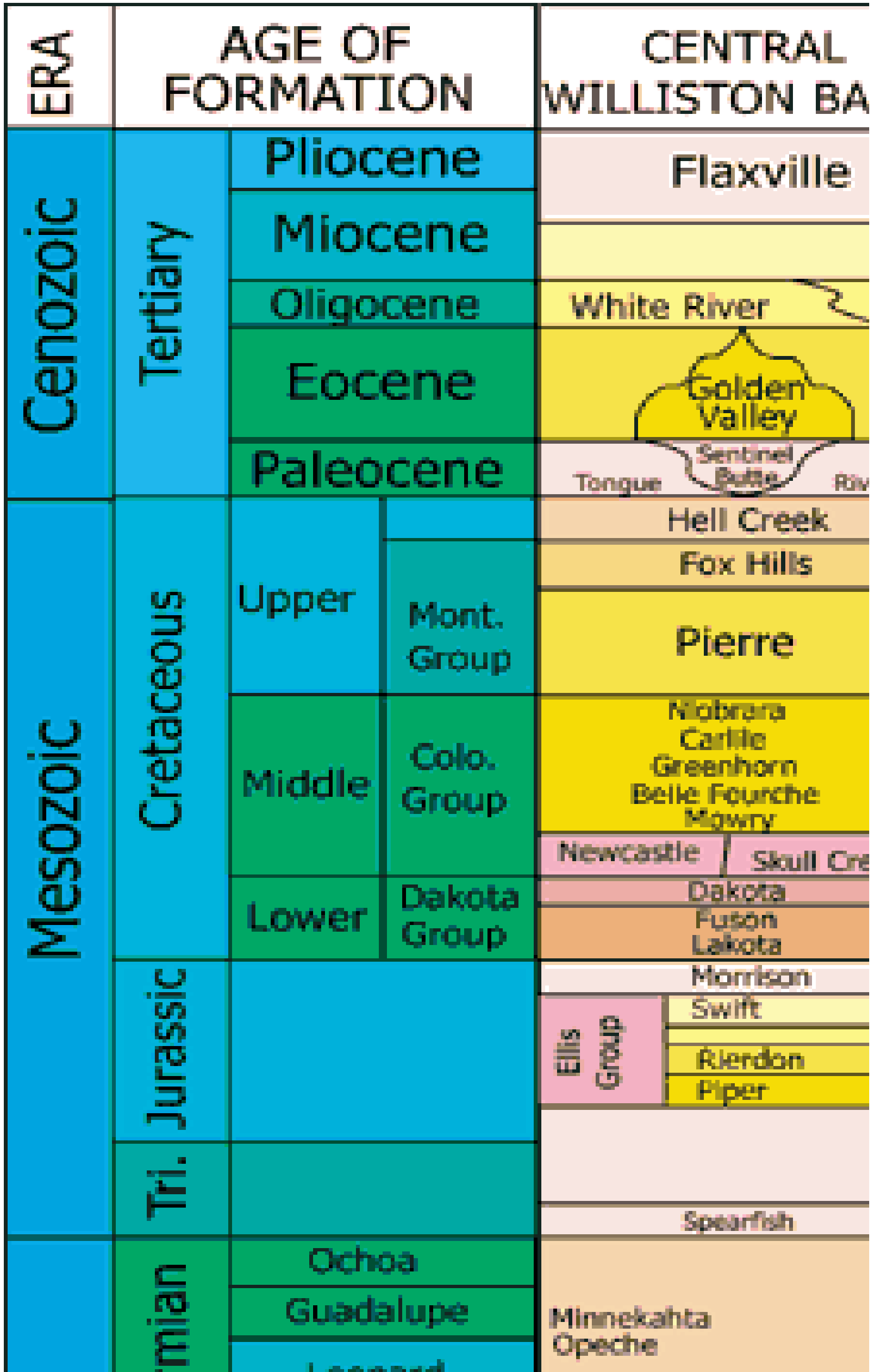
$$\Phi=\Phi_0 e^{-cz}$$

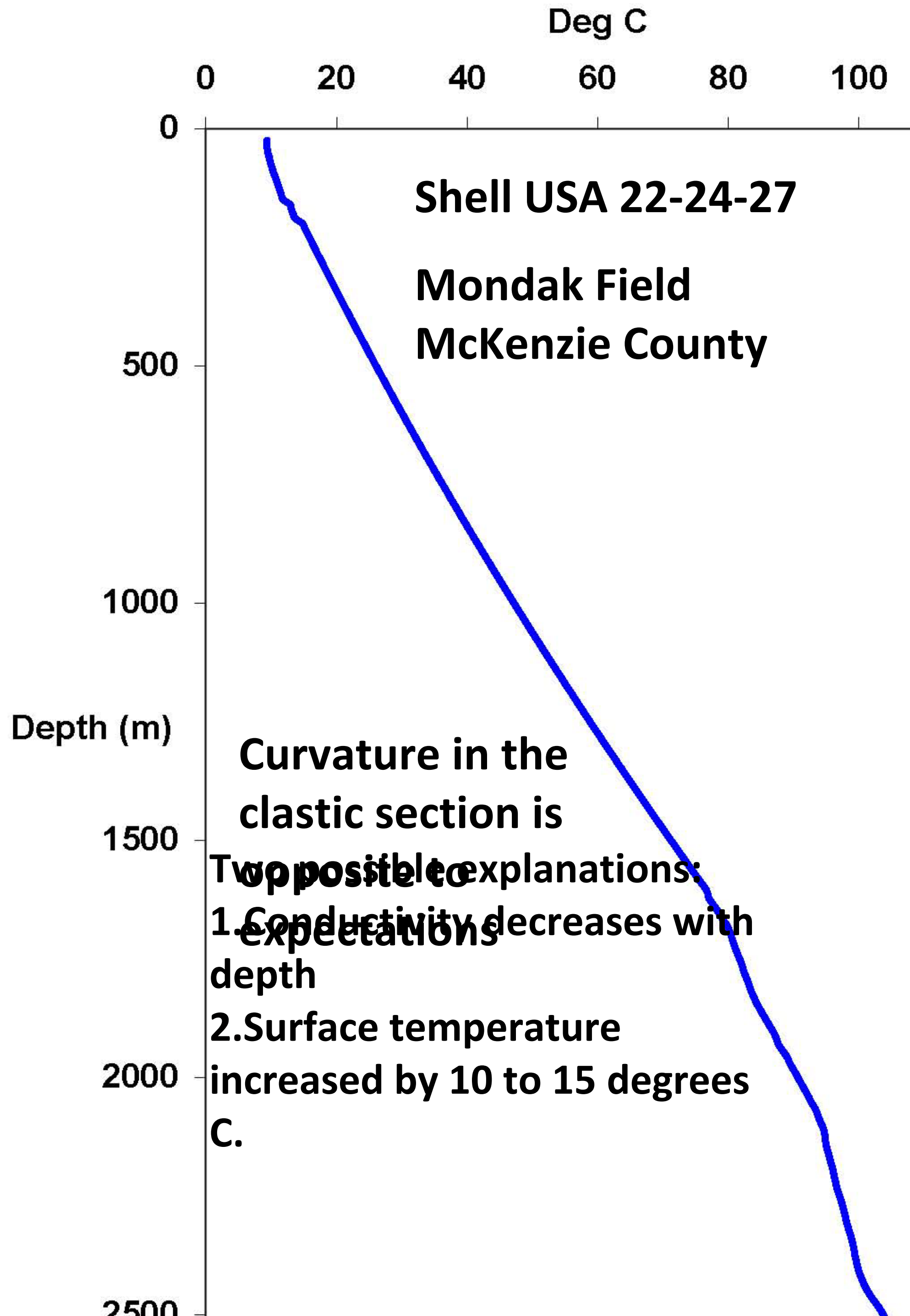
c is a constant and z is depth

Thermal conductivity, K, varies with porosity and as a function of the conductivity of the solid rock and water as $K = Kr^{1-\Phi}Kw^{\Phi}$

If heat flow is constant, the temperature at depth is calculated as

$T = T_0 + \Sigma\Gamma_i z_i$ where $\Gamma_i = q/K_i$



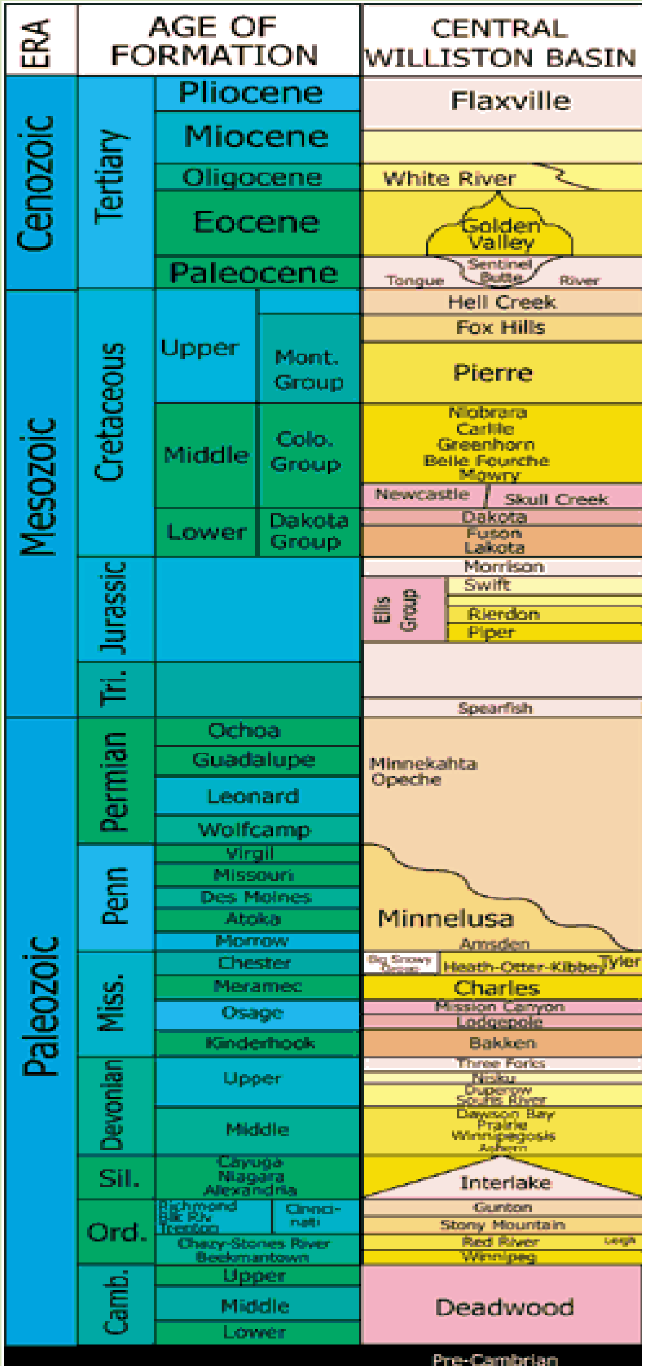


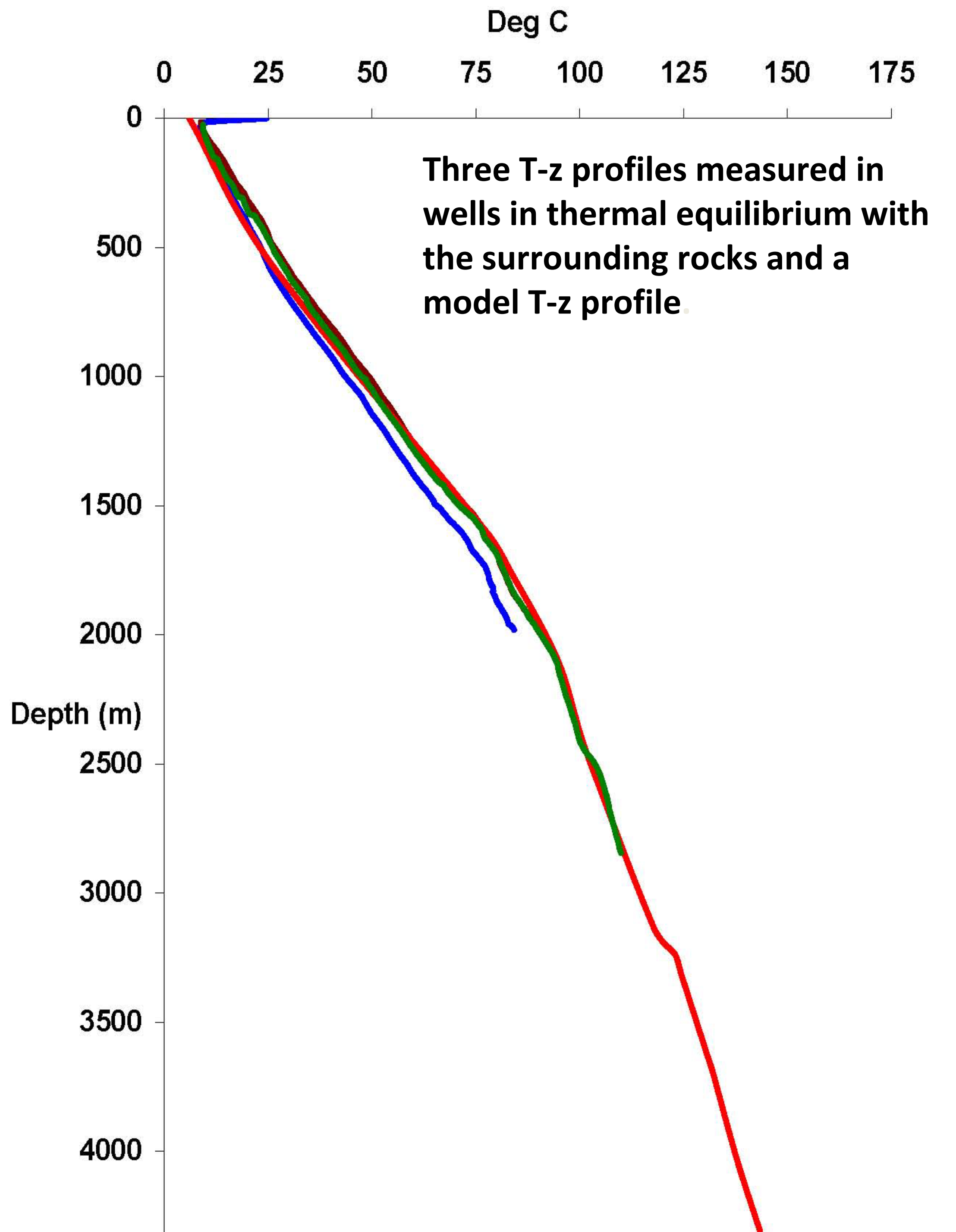
Curvature in the clastic section is opposite to expectations

Two possible explanations:

1. Conductivity decreases with depth

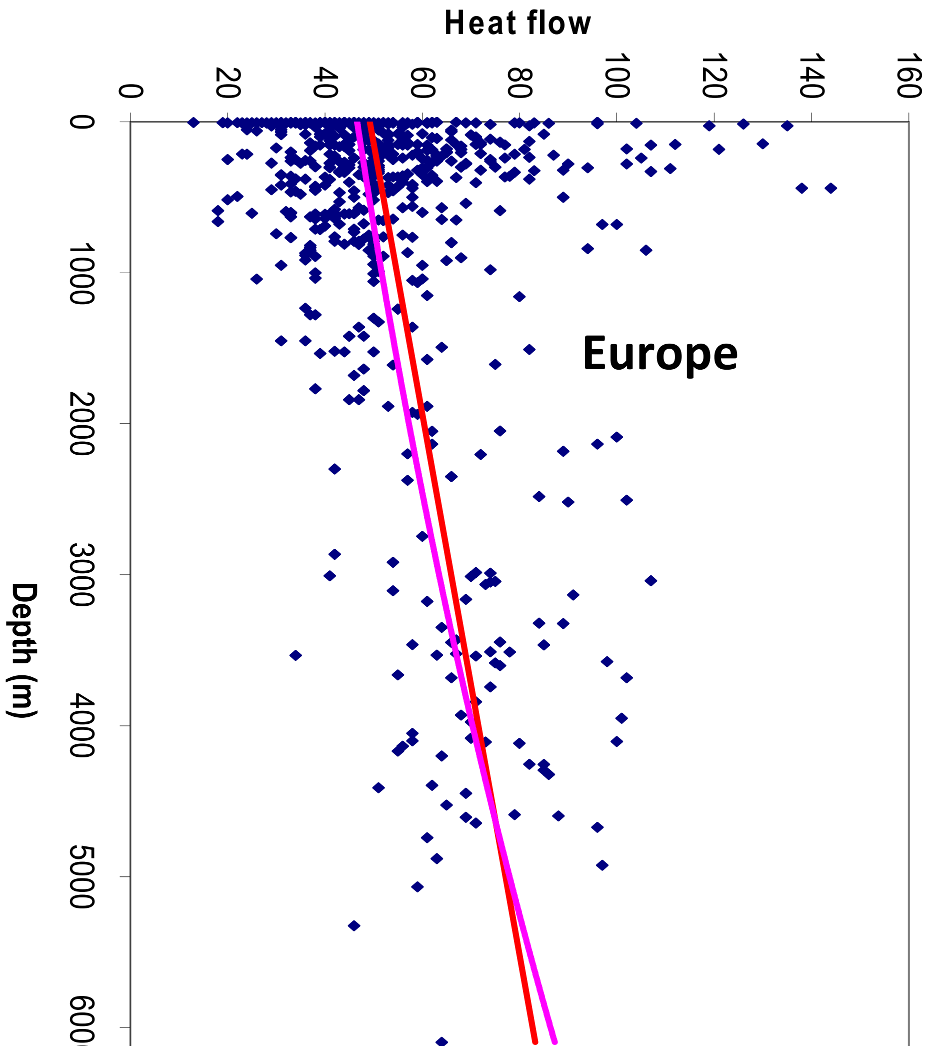
2. Surface temperature increased by 10 to 15 degrees C.

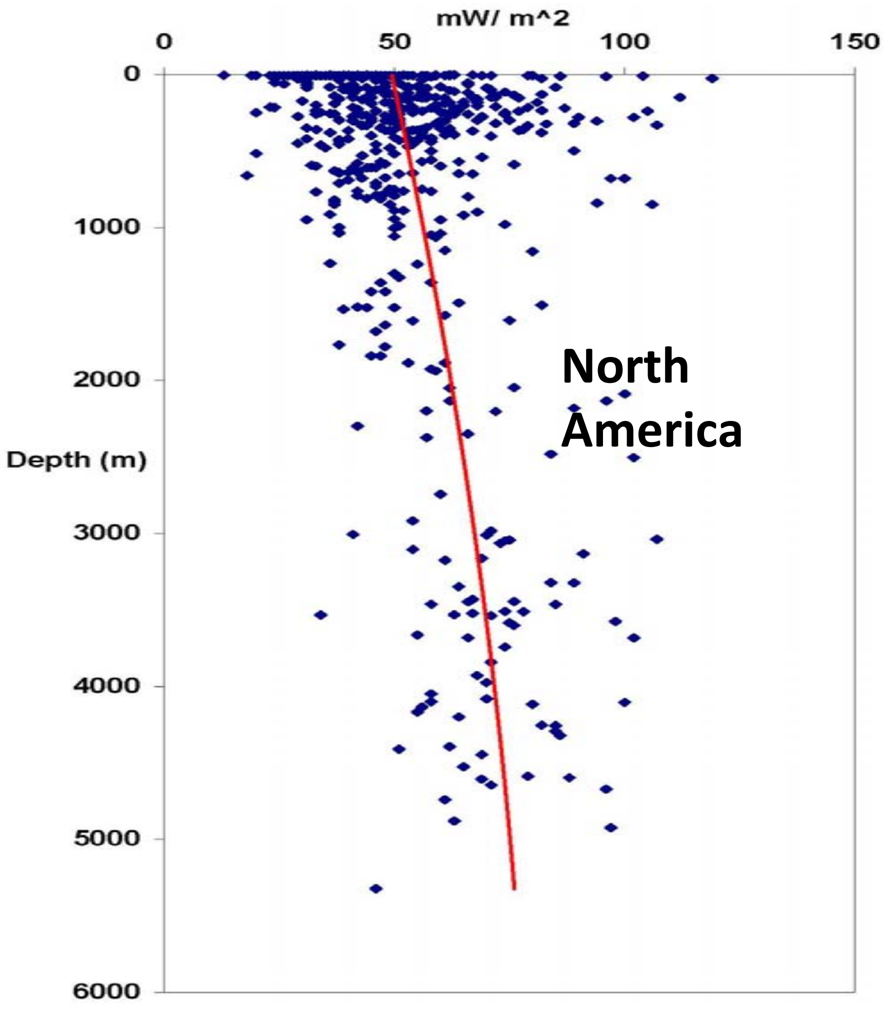

ERA
AGE OF FORMATION
CENTRAL WILLISTON BASIN
Cenozoic
Tertiary
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Flaxville
White River
Golden Valley
Sentinel Butte
Tongue River
Mesozoic
Cretaceous
Upper
Middle
Lower
Mont. Group
Colo. Group
Dakota Group
Hell Creek
Fox Hills
Pierre
Niobrara
Carlile
Greenhorn
Belle Fourche
Mowry
Newcastle
Skull Creek
Dakota
Fuson
Lakota
Jurassic
Morrison
Ellis Group
Swift
Rierdon
Piper
Tri.
Spearfish
Paleozoic
Permian
Ochoa
Guadalupe
Leonard
Wolfcamp
Minnekahta
Opeche
Penn
Virgil
Missouri
Des Moines
Atoka
Morrow
Minnelusa
Amsden
Miss.
Chester
Meramec
Osage
Kinderhook
Heath-Otter-Kibbey
Tyler
Charles
Mission Canyon
Lodgepole
Bakken
Devonian
Upper
Middle
Three Forks
Nisku
Duperow
Souris River
Dawson Bay
Prairie
Winnipegosis
Ashern
Sil.
Cayuga
Niagara
Alexandria
Interlake
Ord.
Richmond
Trenton
Cinncinnati
Chazy-Stones River
Beekmantown
Gunton
Stony Mountain
Red River
Winnipeg
Camb.
Upper
Middle
Lower
Deadwood
Pre-Cambrian


Deg C
0
25
50
75
100
125
150
175
0
500
1000
1500
2000
2500
3000
3500
4000
Depth (m)
Three T-z profiles measured in wells in thermal equilibrium with the surrounding rocks and a model T-z profile

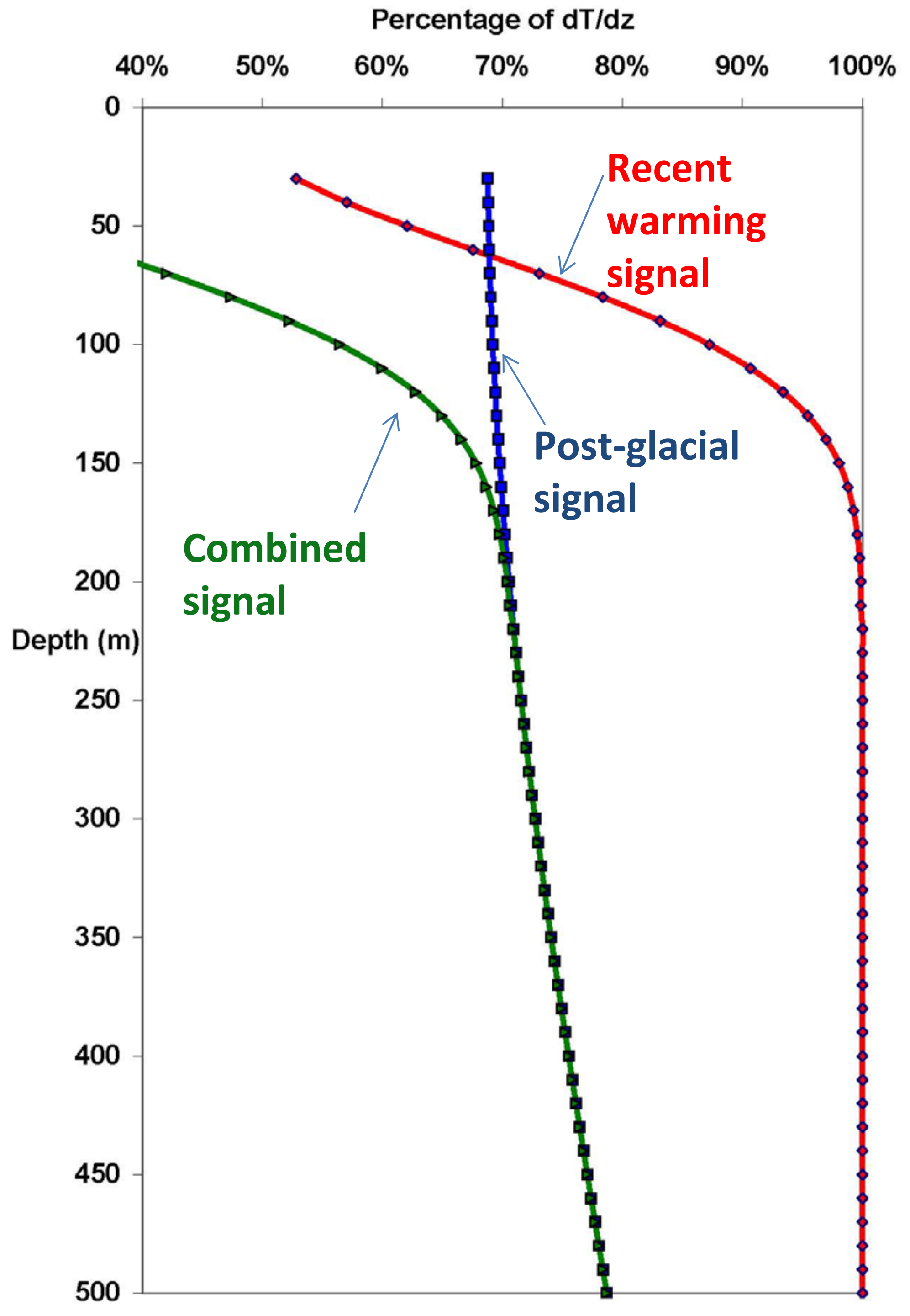
Empirical evidence for large magnitude postglacial warming

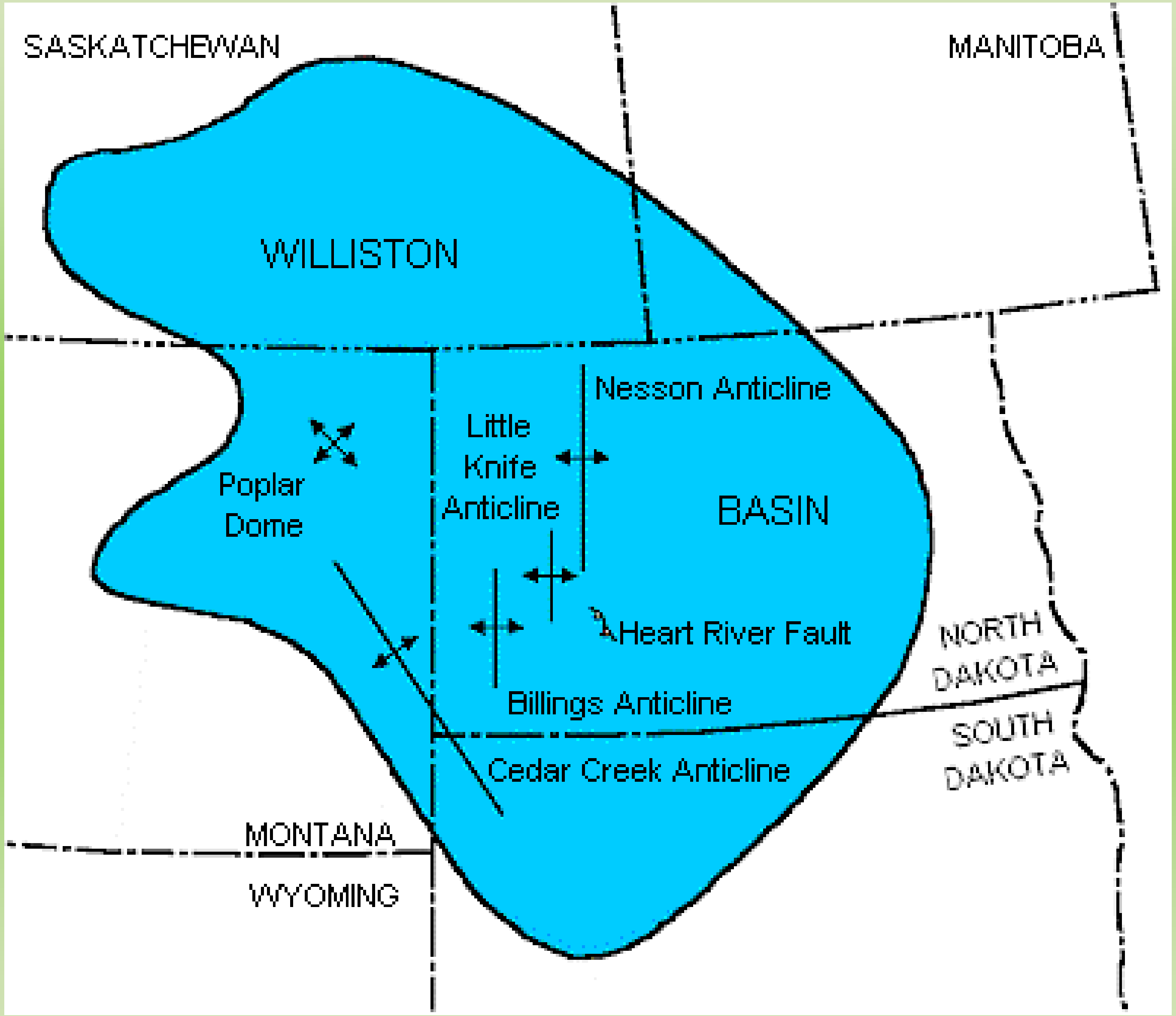
- **T-z measurements in parts of Europe and North America show a systematic increase in heat flow with depth.**





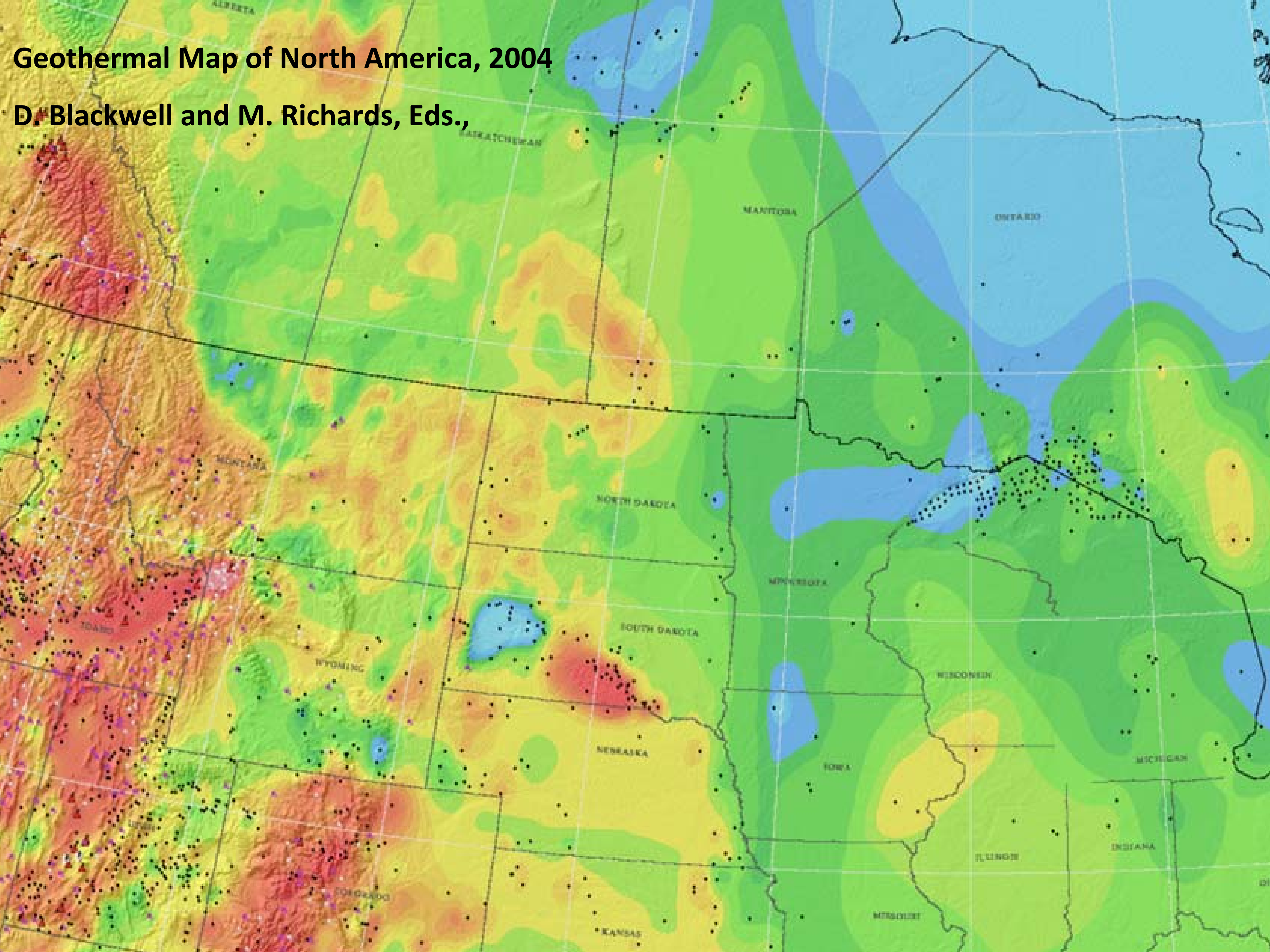
It is essential to obtain accurate temperature measurements in deep wells that are at thermal equilibrium.



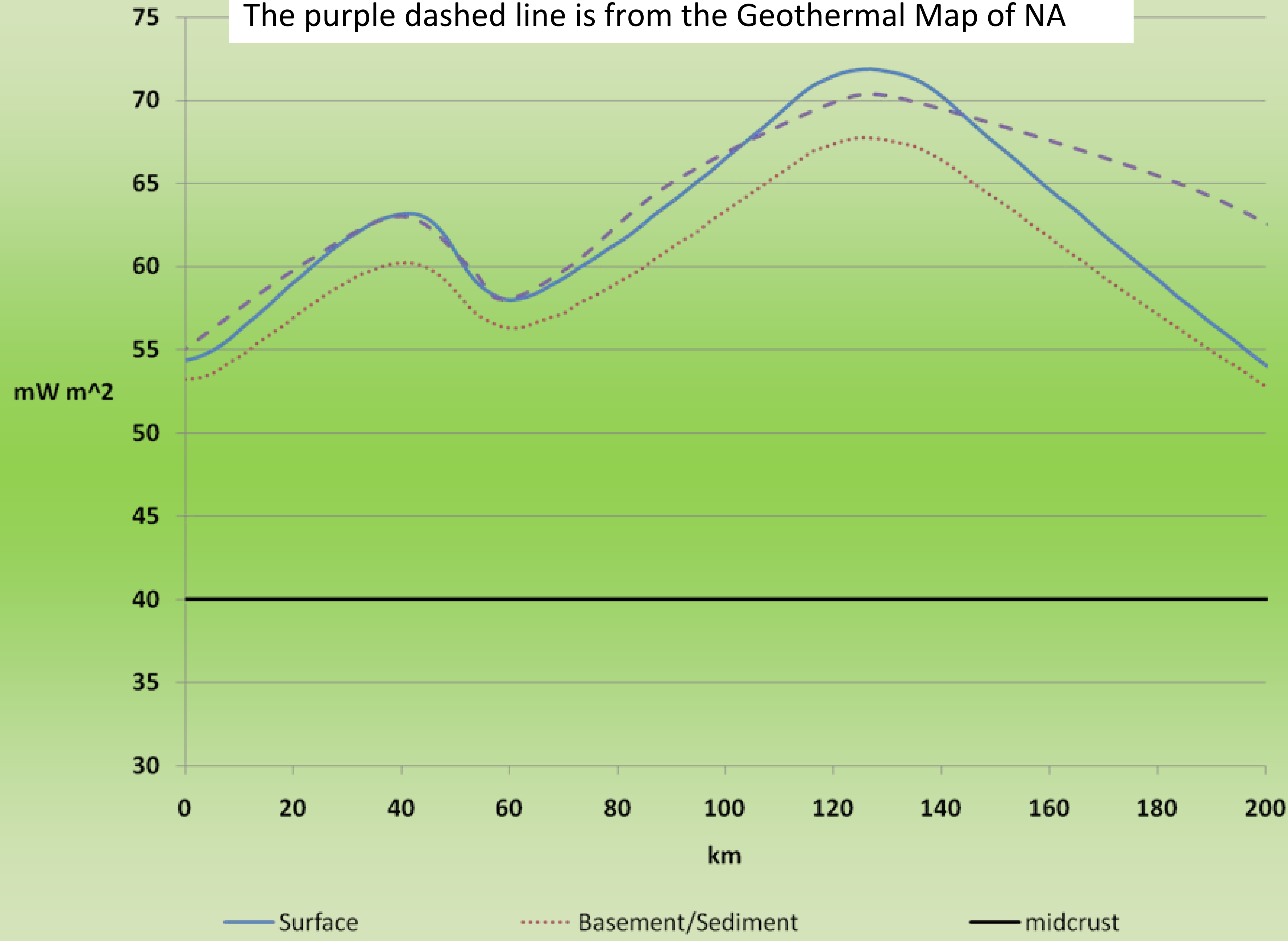

SASKATCHEWAN
MANITOBA
WILLISTON
BASIN
Nesson Anticline
Little
Knife
Anticline
Poplar
Dome
Heart River Fault
Billings Anticline
Cedar Creek Anticline
NORTH
DAKOTA
SOUTH
DAKOTA
MONTANA
WYOMING

Geothermal Map of North America, 2004

D. Blackwell and M. Richards, Eds.,

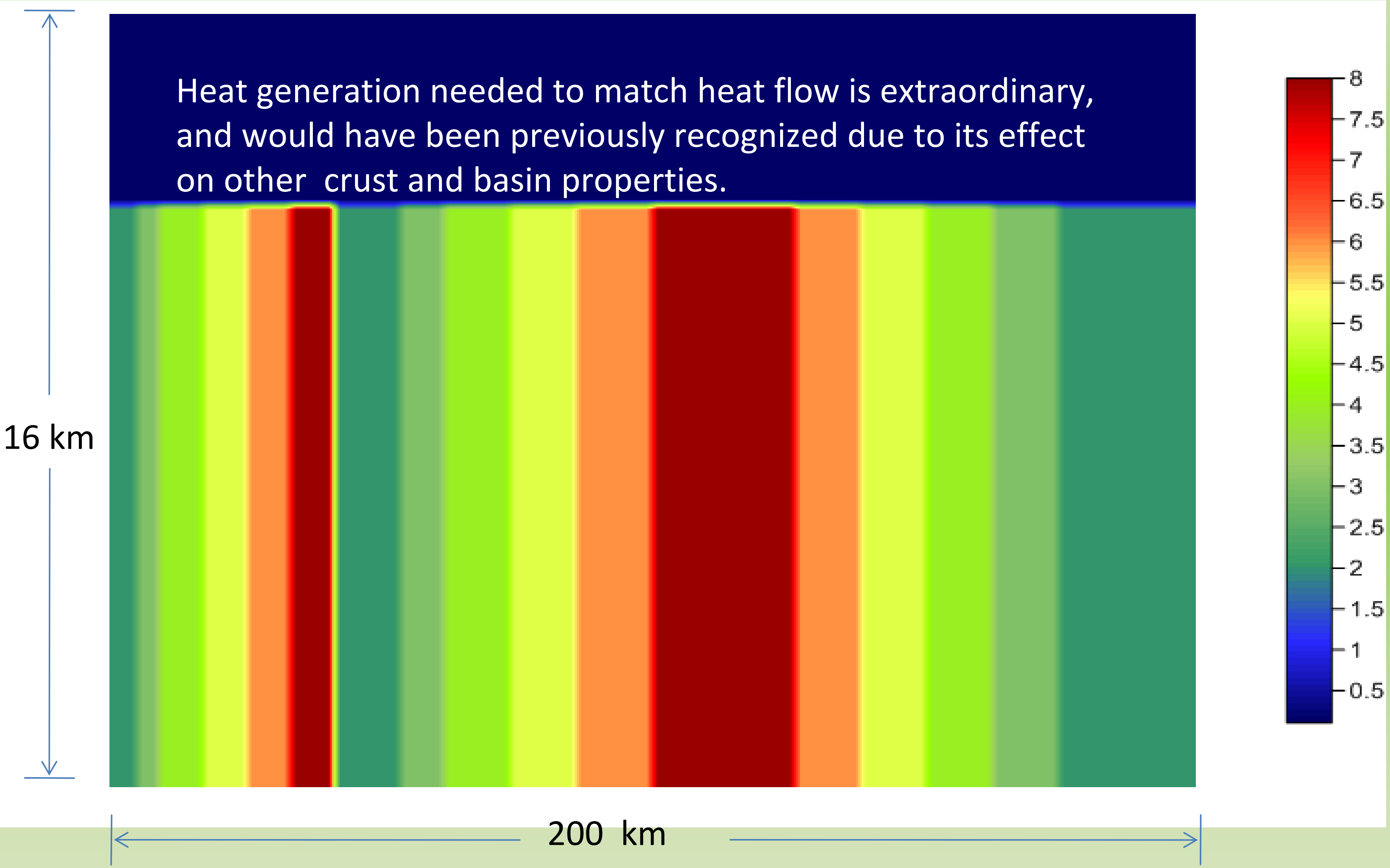


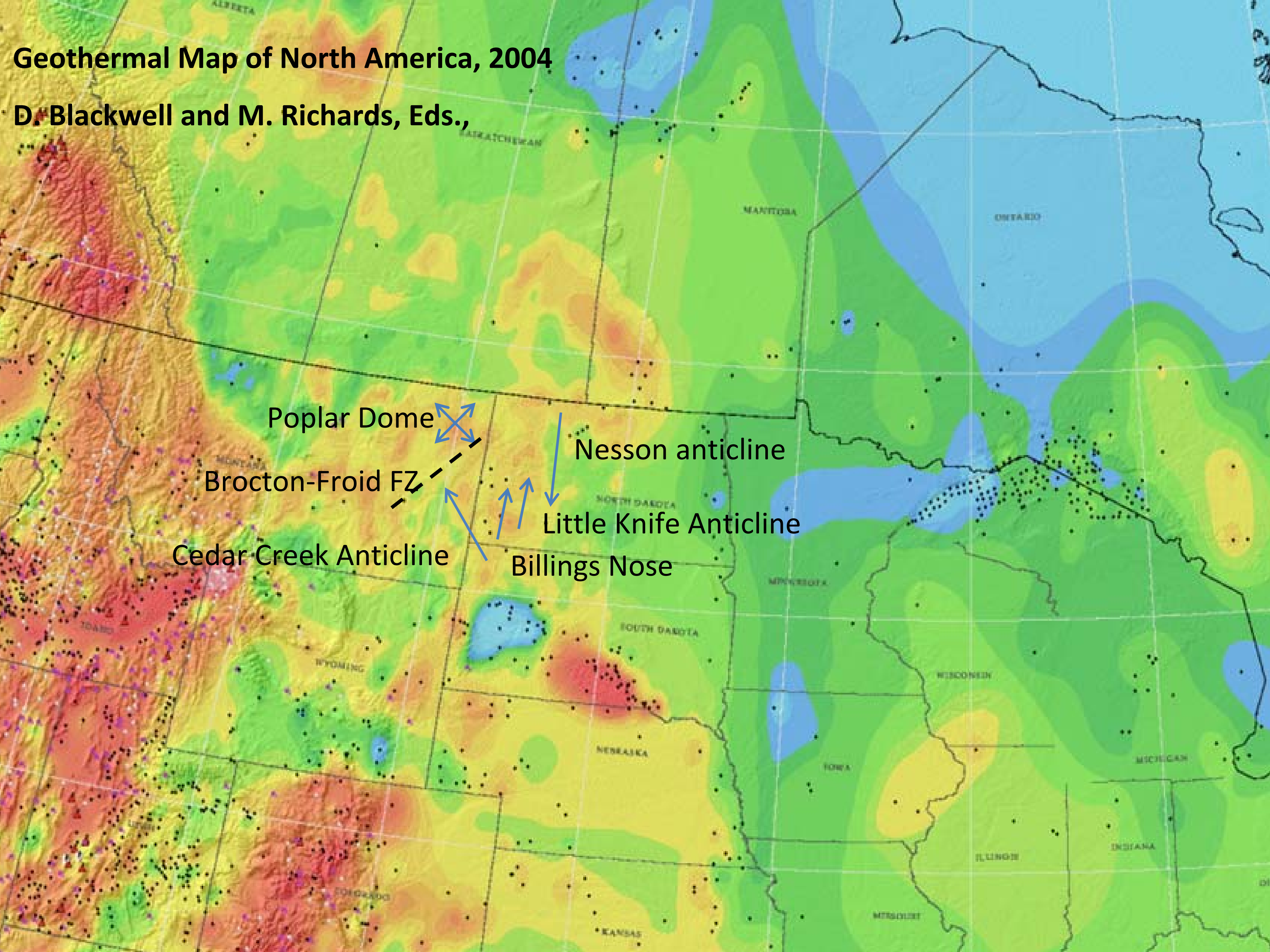
Modeling heat flow as a function of crustal radioactivity
The purple dashed line is from the Geothermal Map of NA



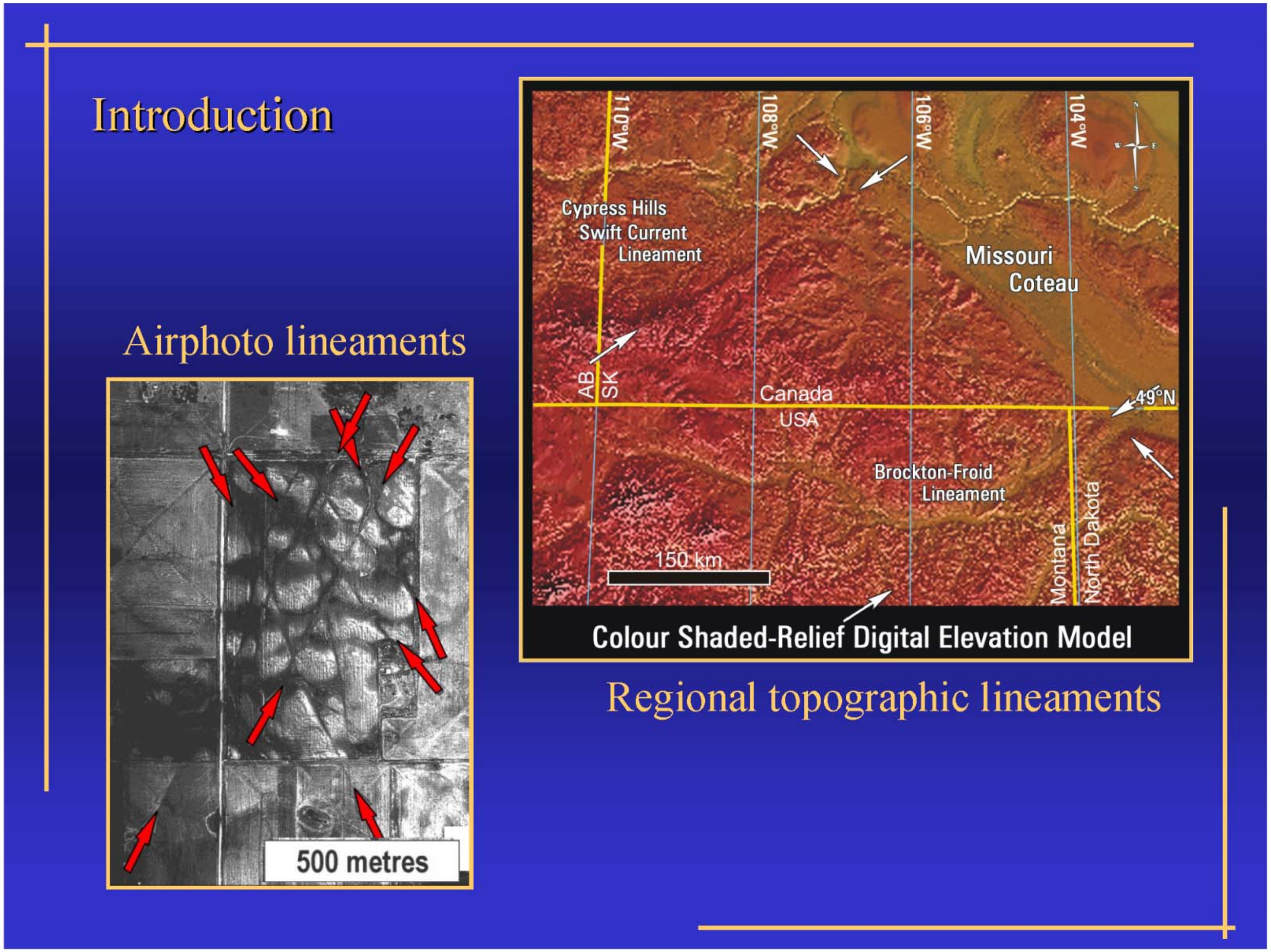
Radioactive heat generation model fit to observed heat flow

Units are μW m^{-3}



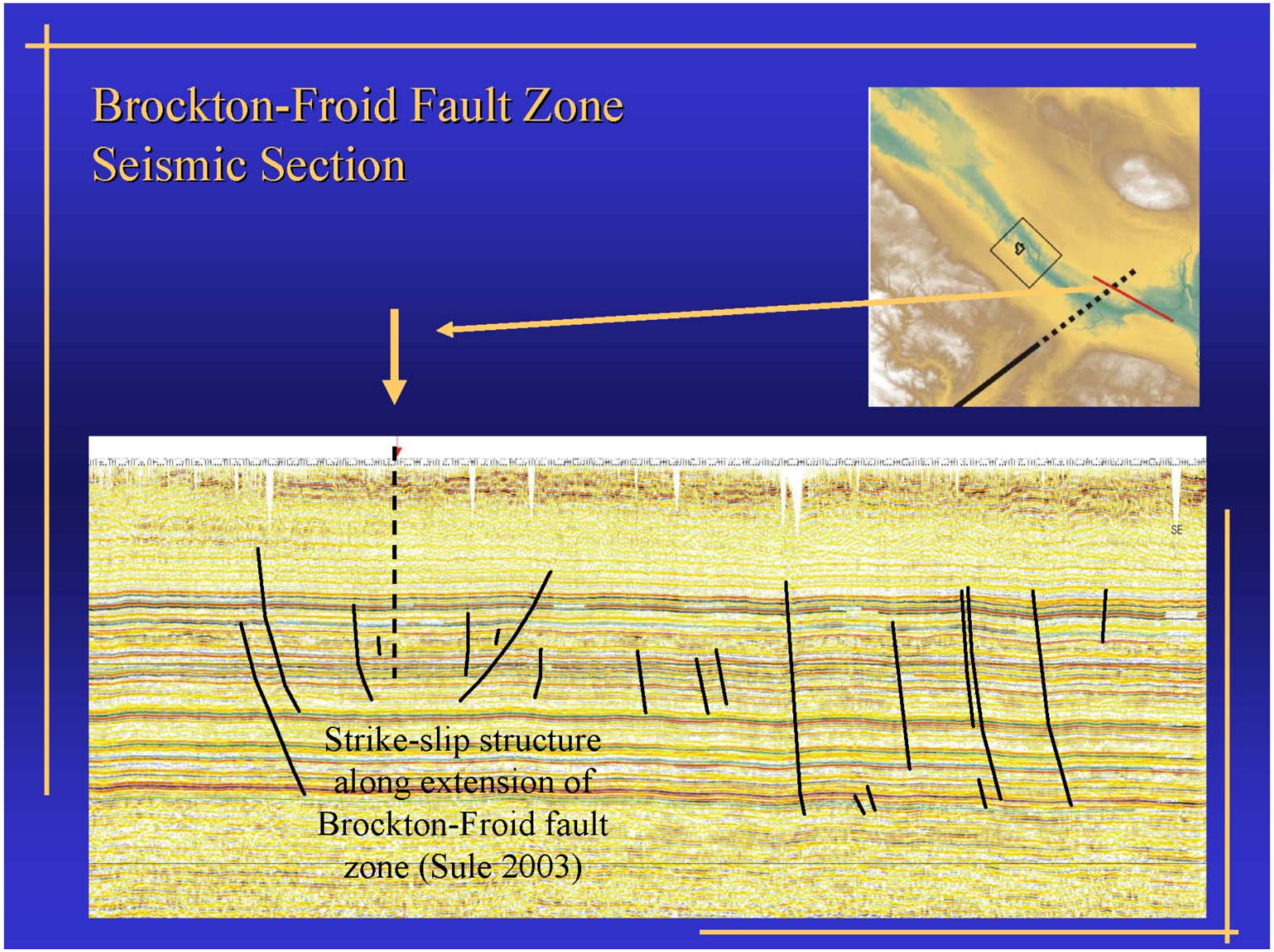

Geothermal Map of North America, 2004
D. Blackwell and M. Richards, Eds.,
Poplar Dome
Nesson anticline
Brocton-Froid FZ
Little Knife Anticline
Cedar Creek Anticline
Billings Nose
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
MINNESOTA
WYOMING
NEBRASKA
IOWA
WISCONSIN
MICHIGAN
ILLINOIS
INDIANA
MISSOURI
KANSAS

A better candidate for heat flow complexity is fluid flow



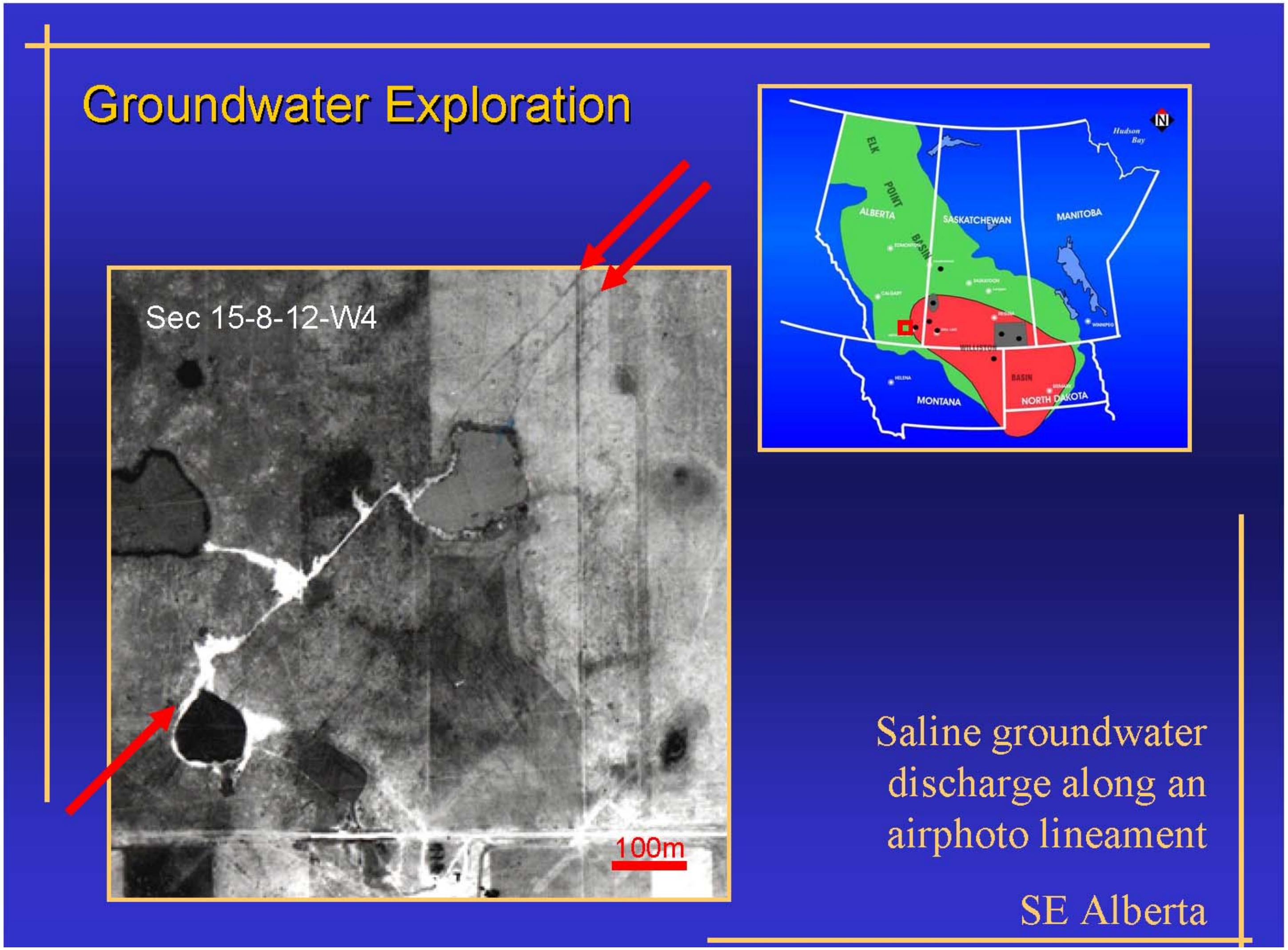
Source: Penner, Lyndon, Evidence Linking Surface Lineaments, Deep-seated Faults, and Fracture-controlled Fluid Movement in the Williston Basin, 14th Williston Basin Petroleum Conference and Product Expo, May 2006, Minot, ND

Seismic reflection indicates numerous fractures that could facilitate fluid flow



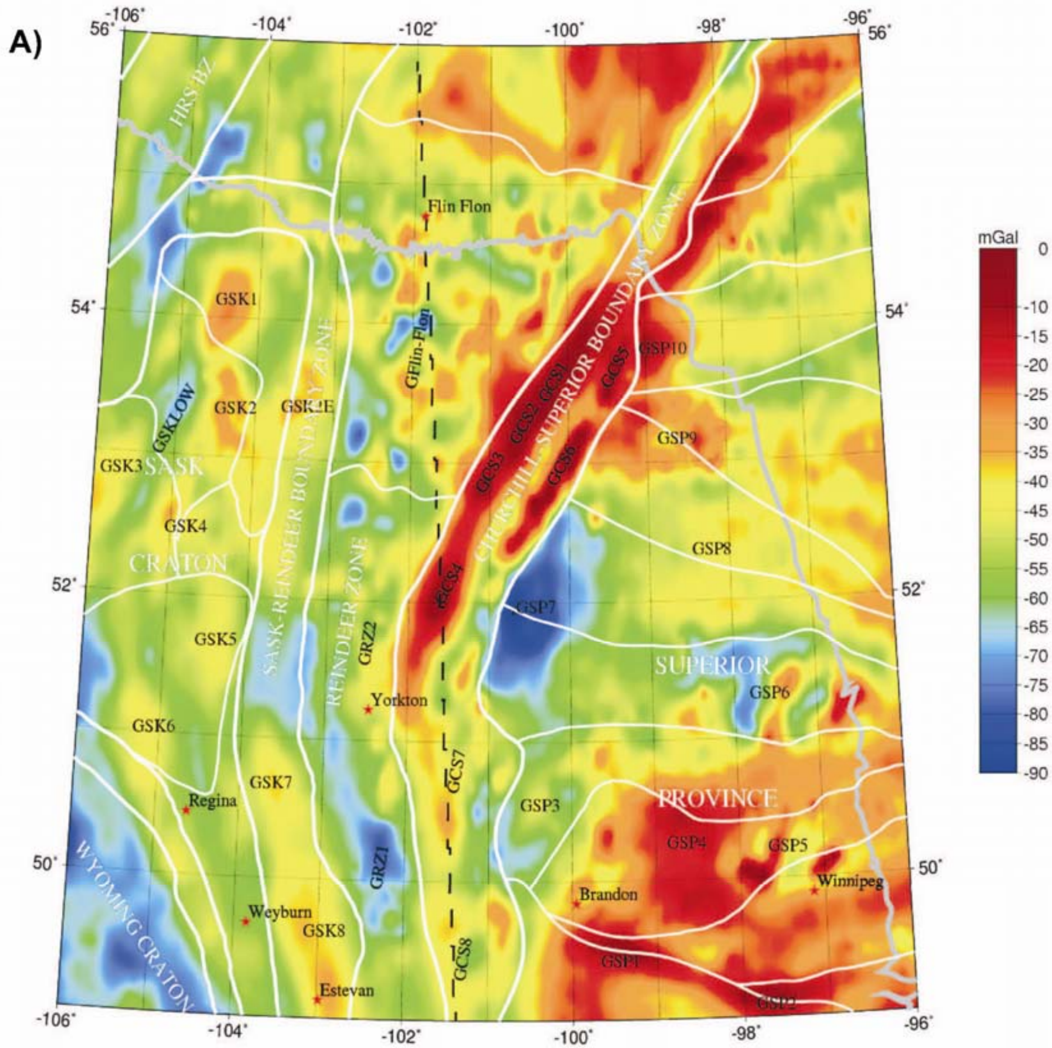
Source: Penner, Lyndon, Evidence Linking Surface Lineaments, Deep-seated Faults, and Fracture-controlled Fluid Movement in the Williston Basin, 14th Williston Basin Petroleum Conference and Product Expo, May 2006, Minot, ND

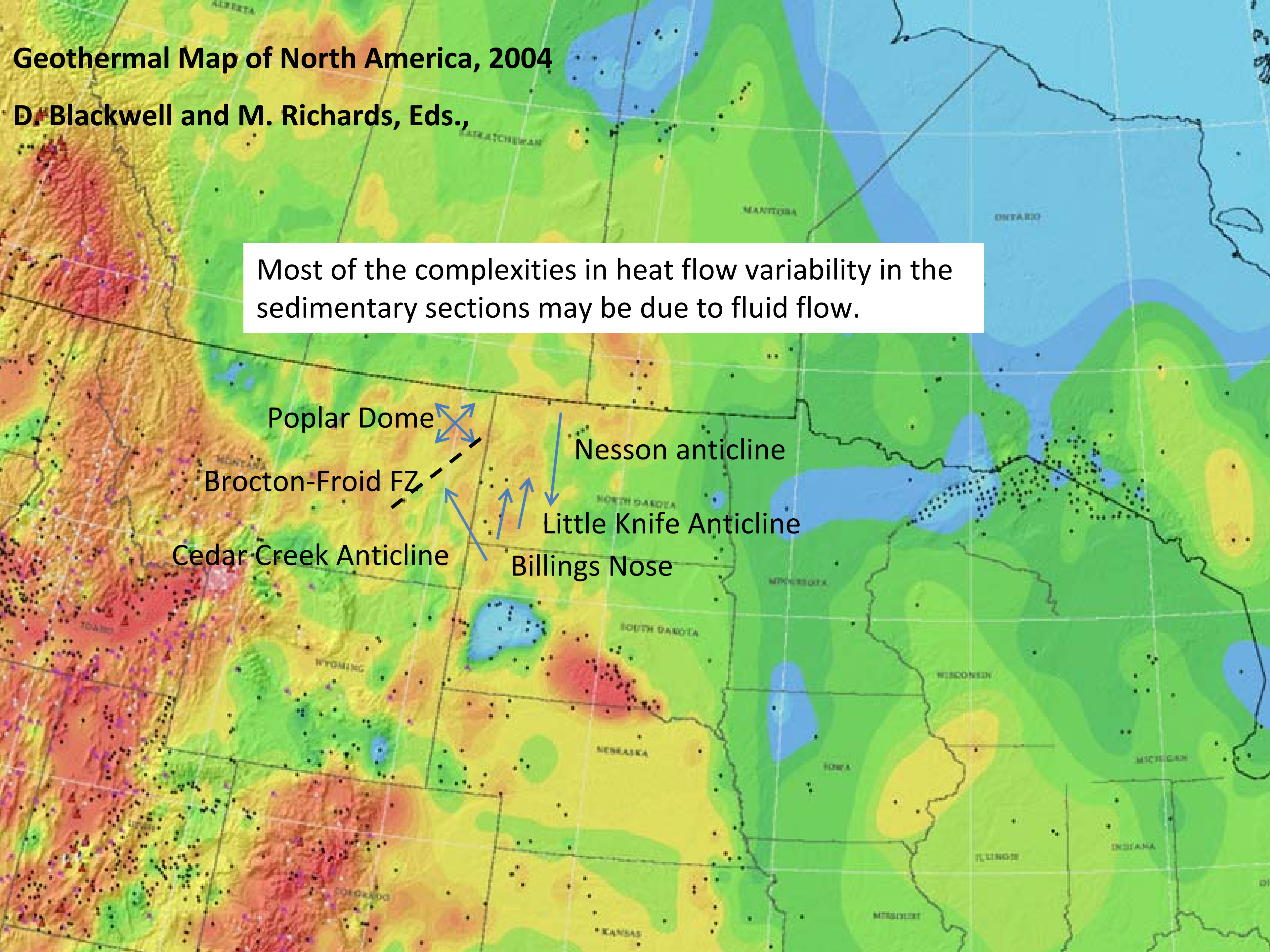
Evidence of movement of deep fluids is found in saline seeps



Source: Penner, Lyndon, Evidence Linking Surface Lineaments, Deep-seated Faults, and Fracture-controlled Fluid Movement in the Williston Basin, 14th Williston Basin Petroleum Conference and Product Expo, May 2006, Minot, ND

Bouguer gravity anomaly map of parts of MB and SK




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.
Poplar Dome
Brocton-Froid FZ
Nesson anticline
Little Knife Anticline
Cedar Creek Anticline
Billings Nose

Resource Estimates

- **US Geological Survey**
  - **Circular 726 (1975)**
  - **Circular 790 (1979)**
  - **Circular 892 (1983)**
- **DOE - State Coupled Program**
  - **Geothermal resource maps and reports**

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.

What we knew

- High-temperature convection systems in the western U.S. contain 371 EJ (Renner, White, and Williams, USGS Cir. 726, 1975).
- Intermediate temperature systems, which exist primarily in the western U.S., contain 42 ±13 EJ (Brook et al., USGS Cir. 790, 1978).
- The accessible low-temperature resource base in the central United States contains 27,000 EJ (Sorey et al., USGS Cir. 893, 1983).
- Undiscovered low temperature resources contain an additional 7,200 EJ (Sorey et al., USGS Cir. 893, 1983).

What has changed

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

Low-to-intermediate temperature resources were underestimated

- USGS Circular 892: The GRA considered only one or two potential geothermal aquifers within well-known sedimentary basins.
- Large basins such as the Williston Basin, Denver Basin, Powder River Basin, Anadarko Basin, and the US Gulf Coast region contain more than a dozen potential geothermal aquifers having temperatures greater than 100 °C.

How large is the resource?

- The geothermal energy potential of the hot waters in sedimentary basins in the US is a huge resource that could have a significant impact on the nation's energy future. The 2007 MIT report estimated the resource at approximately 100,000 EJ, but that estimate was based on only one-fourth of the existing water bearing sedimentary formations
- Using all potential geothermal aquifers in the Williston Basin in North Dakota and Montana, we estimate that the resource is approximately 31,800 ExaJoules or 8.6 GW

Mid Continent Geothemal

• North Dakota & Montana	31,800 EJ
• Eastern Colorado	2,640 EJ
• South Dakota	5,950 EJ
• Nebraska	3,720 EJ
• Kansas	4,980 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.

Refining the estimate

- Major formations
  - Thermal conductivity estimated by lithology
  - Porosity estimated by depth of burial
- All formations
  - Thermal conductivity estimated by lithology
  - Porosity estimated by depth of burial
- All formations
  - Thermal conductivity measured
  - Porosity measured
  - Permeability measured

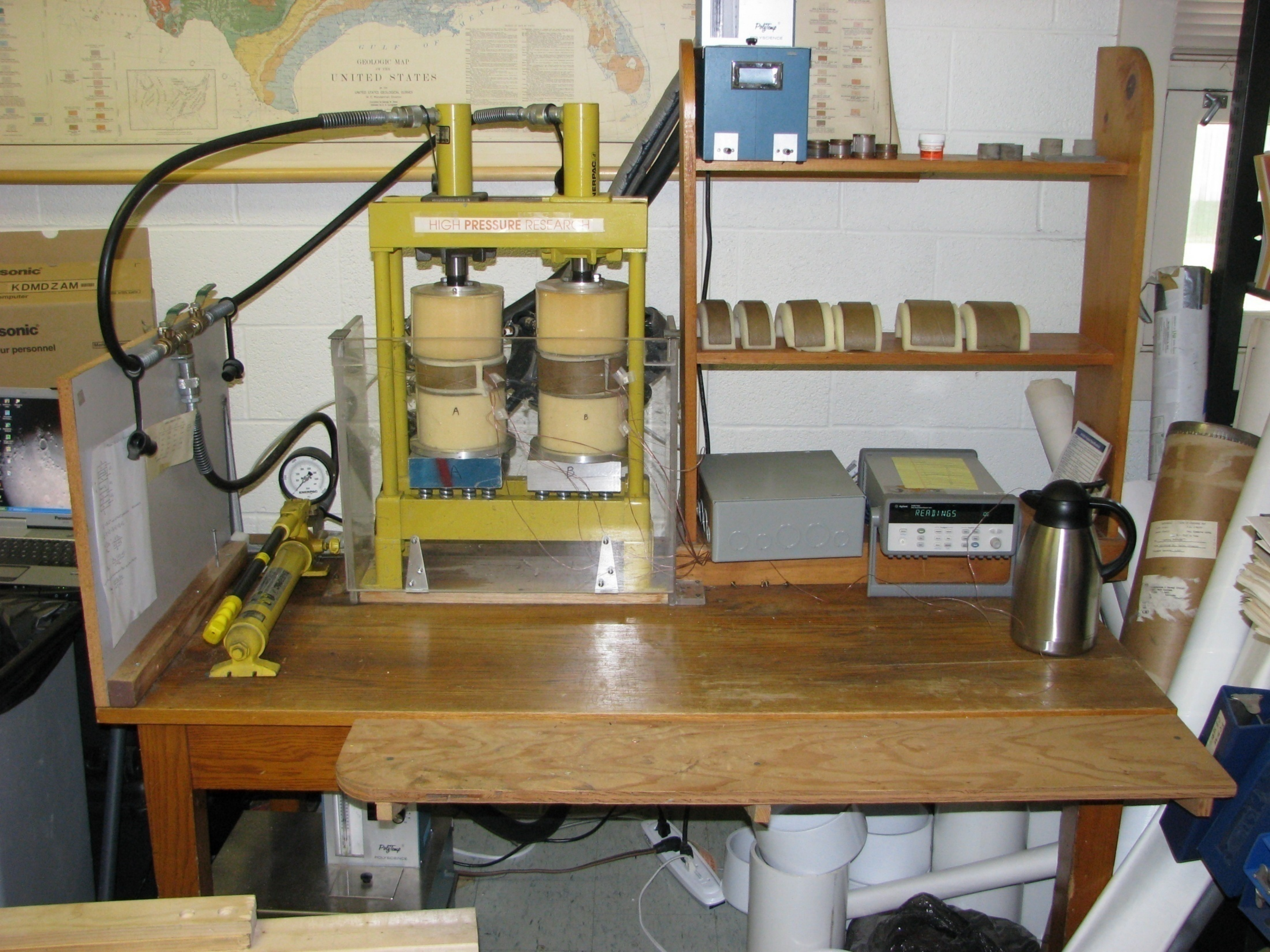
Williston Basin 1984

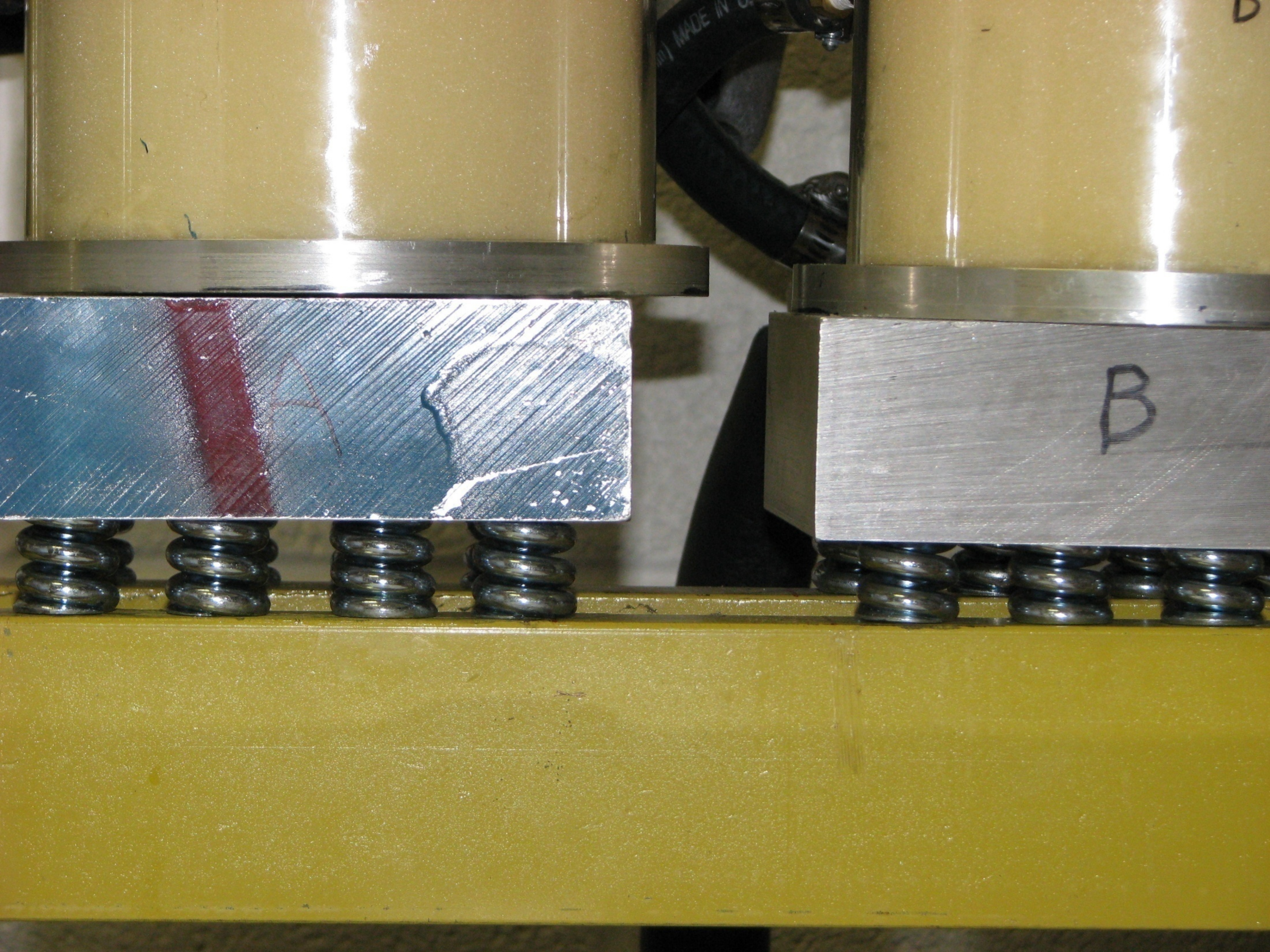
Formation Surface	Depth meters	Thickenss meters	λ W/m/K	Temperature °C	Γ °C/km
	0	0		6	
Brule	581	581	1.7	23	30
Pierre	1608	1027	1.2	76	52
Inyan Kara	1744	136	1.6	82	43
Swift	2089	345	1.8	96	39
Spearfish	2383	294	3.1	102	23
Otter	2519	136	2.8	106	25
Mission Canyon	3135	616	2.5	123	28
Lodgepole	3235	100	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

System	Rock Units	Lithology	Max. Thickness	Depth	Conductivity	°C
Quaternary	Cole harbor +	Clay, silt, sand, gravel	510	0	1.4	6
Tertiary	White River	Siltstone, clay, sand	75	53	1.3	8
	Golden Valley	Clay, siltstone, lignite	65	98	1.1	10
	Fort Union	Silt, clay, sand	600	518	1.2	33
	Hell Creek	Sand	200	658	1.7	40
	Fox Hills	Silt, shale, sandstone	120	742	1.2	43
Cretaceous	Pierre	Shale	700	1232	1.1	68
	Niobrara	Shale	75	1285	1.1	71
	Carlisle	Shale	120	1369	1.1	75
	Greenhorn	Shale, shaly limestone	45	1400	1.4	77
	Bell Fourche	Shale	105	1474	1.1	80
	Mowry	Shale	55	1512	1.1	82
	Newcastle	Sandstone, shale	45	1544	1.6	84
	Skull Creek	Shale	40	1572	1.2	85
	Inyan Kara	Sandstone	135	1666	1.6	90

System	Rock Units	Lithology	Max. Thickness	Depth	Conductivity	°C
Jurassic	Morrison	Shale, siltstone	80	1722	1.3	92
	Swift	Shale	150	1827	1.2	97
	Rierdon	Shale	30	1848	1.2	98
	Piper	Limestone, anhydrite, shale	190	1981	1.5	104
Triassic	Spearfish	Siltstone, shale	225	2139	1.3	111
	Minnekahta	Limestone	12	2147	3.1	111
Permian	Opeche	Shale; dolomitic and silty	120	2231	2.7	113
	Broom Creek	Sandstone, dolomite	100	2301	3.1	114
	Amsden	Dolomite, sandstone	35	2325	3.3	115
Pennsylvanian	Tyler	Shale, limestone	80	2381	1.4	116
	Otter	Shale"	60	2423	1.2	117
	Kibbey	Sandstone, limestone	75	2476	1.4	120
Mississippian	Madison	Limestone	600	2896	3.1	138

System	Rock Units	Lithology	Max. Thickness	Depth	Conductivity	°C
Devonian	Bakken	Shale	35	2920	1.2	139
	Three Forks	Siltstone, shale	75	2973	1.4	141
	Birdbear	Limestone, dolomite	40	3001	3.5	142
	Duperow	Limestone, dolomite	140	3099	3.5	144
	Souris River	Dolomite, limestone	105	3172	3.8	145
	Dawson Bay	Limestone, dolomite	55	3211	3.5	146
	Prairie	Evaporites	200	3351	1.5	148
	Winnipegosis	Dolomite, limestone	120	3435	3.5	152
Silurian	Interlake	Dolomite, limestone	335	3669	3.5	156
	Stonewall	Dolomite, limestone"	35	3694	3.5	156
Ordovician	Stony Mountain	Dolomite, limestone	60	3736	3.5	157
	Red River	Limestone, dolomite	215	3886	3.1	159
	Winnipeg Group	Siltstone, sandstone, shale	125	3974	1.5	161
Cambrian	Deadwood	Limestone, sandstone, shale	300	4184	1.7	170


GULF OF
GEOLOGIC MAP
UNITED STATES
HIGH PRESSURE RESEARCH
KDMDZAM
A
B
READINGS


A
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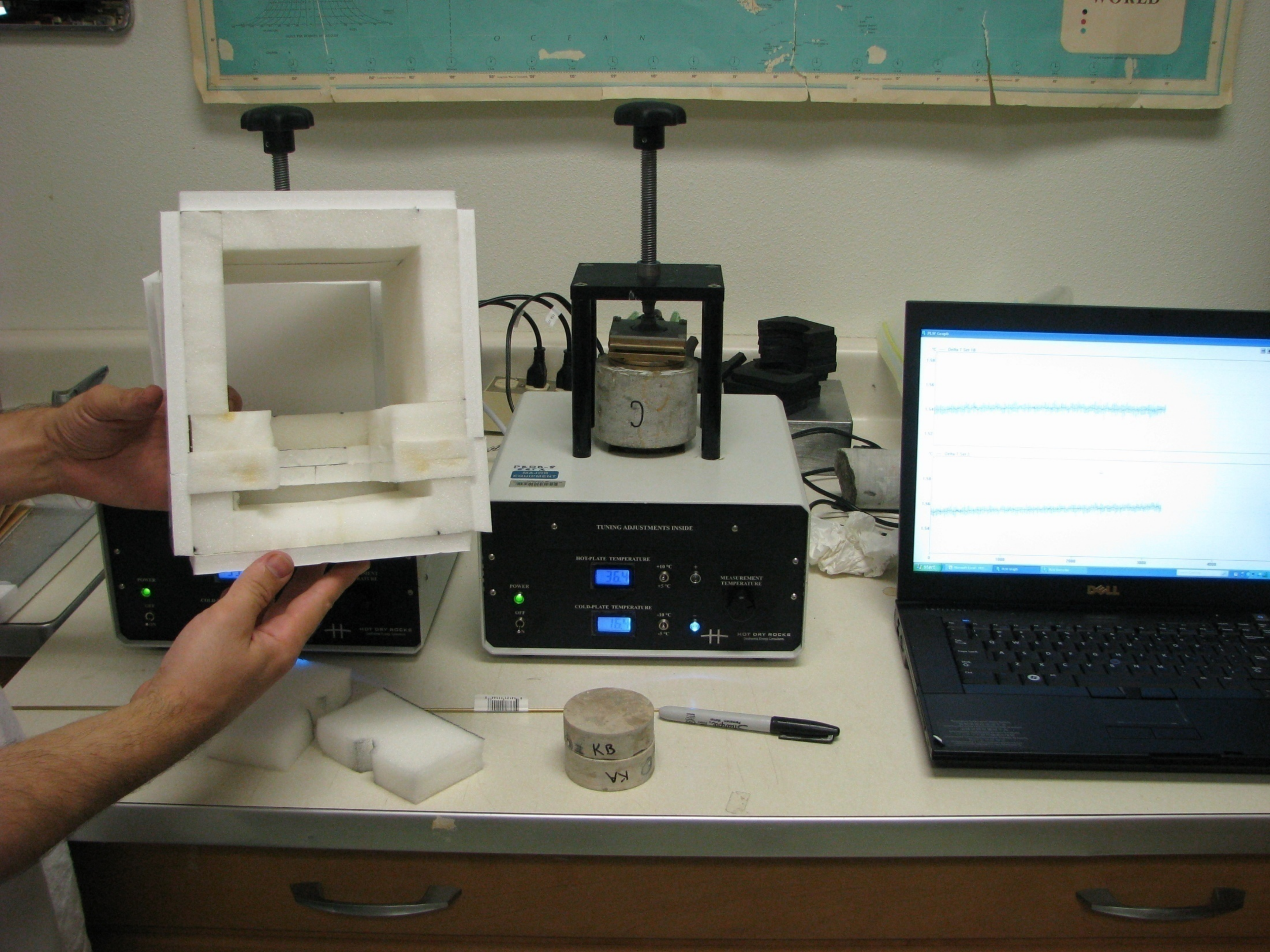
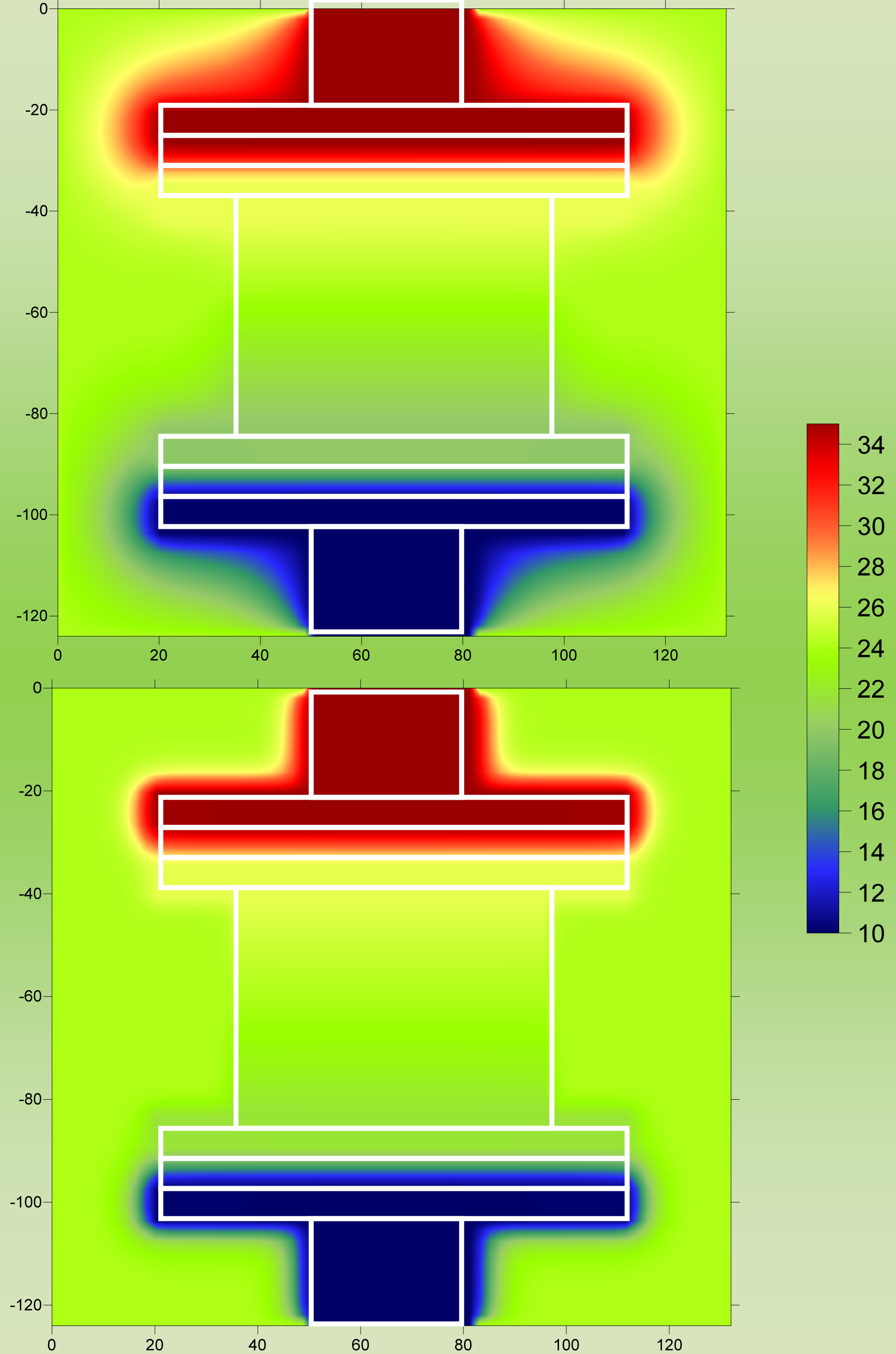


TUNING ADJUSTMENTS INSIDE
HOT-PLATE TEMPERATURE
COLD-PLATE TEMPERATURE
MEASUREMENT TEMPERATURE
POWER
OFF
HOT DRY ROCKS
MAJOR EQUIPMENT
KB
KA
DELL



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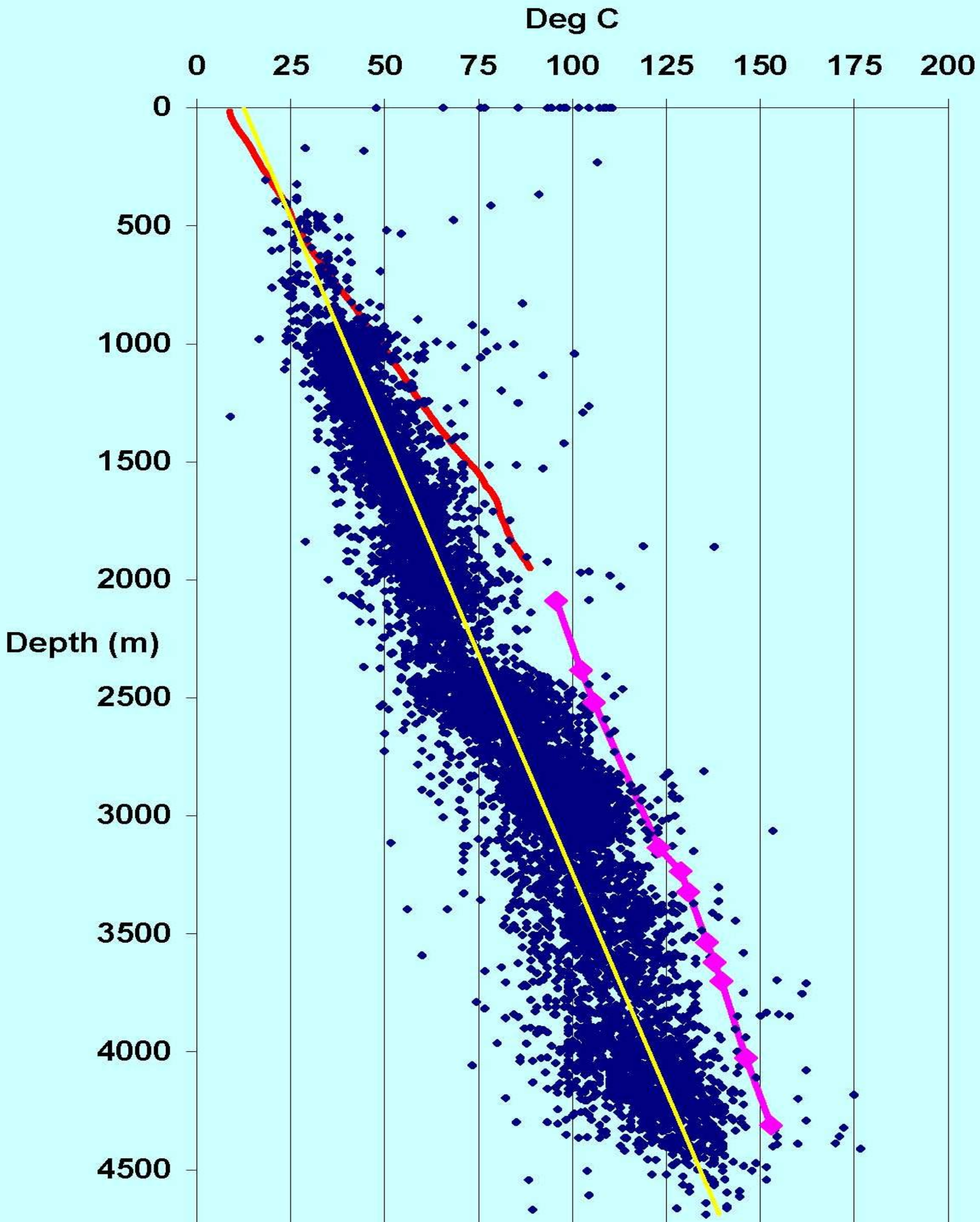
22
20
18
16
14
12
10

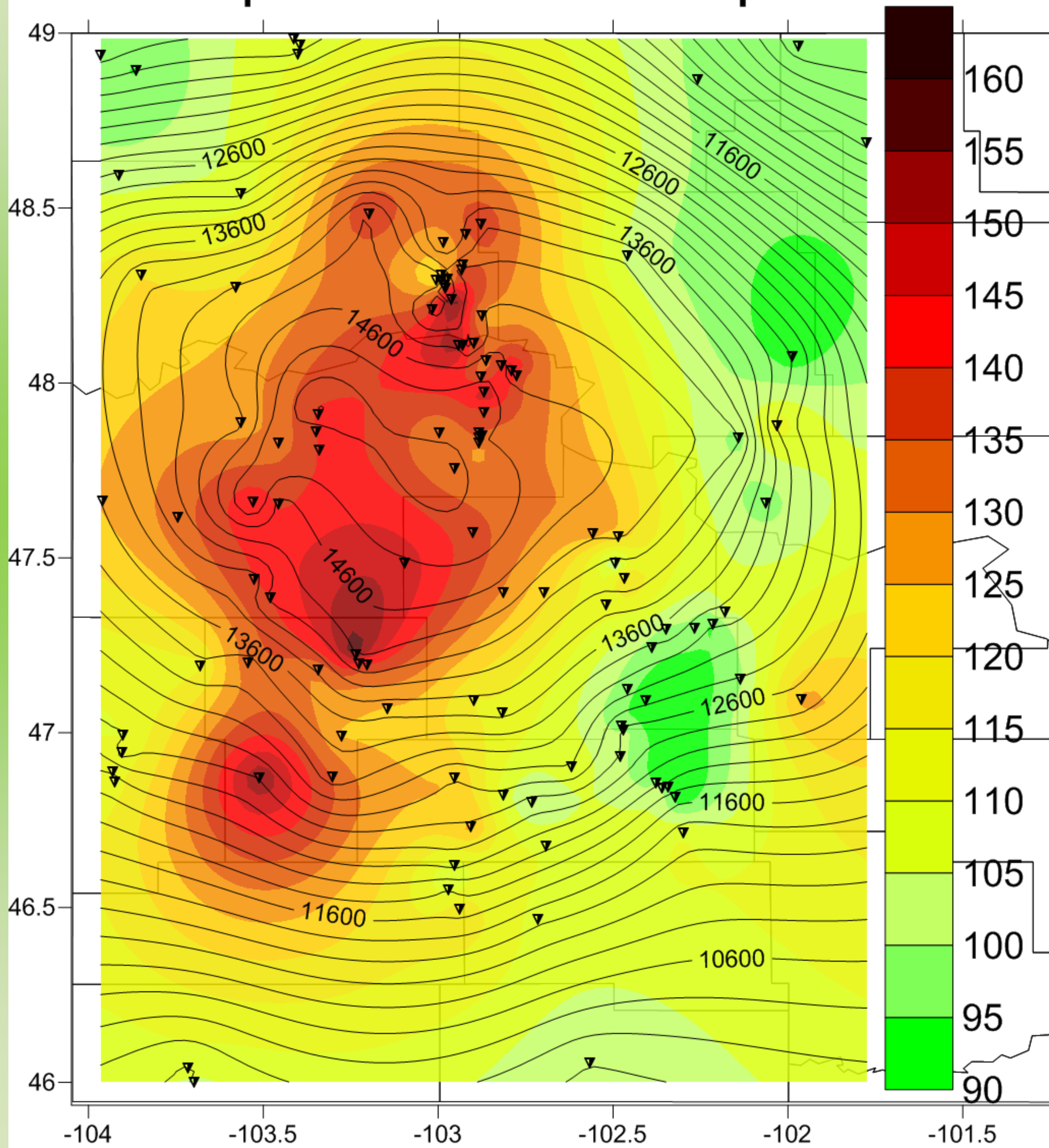

OCEAN
S O U T H
P A C I F I
O C E A N
A T L A N T I C
O C E A N
NEW ZEALAND
TUNING ADJUSTMENTS INSIDE
HOT-PLATE TEMPERATURE
35.9
+10 °C
+5 °C
+
MEASUREMENT TEMPERATURE
POWER
OFF
ON
COLD-PLATE TEMPERATURE
16.5
-10 °C
-5 °C
-
HOT DRY ROCKS
Geothermal Energy Consultants
TUNING ADJUSTMENTS INSIDE
HOT-PLATE TEMPERATURE
36.4
+10 °C
+5 °C
+
MEASUREMENT TEMPERATURE
POWER
OFF
ON
COLD-PLATE TEMPERATURE
16.4
-10 °C
-5 °C
-
HOT DRY ROCKS
Geothermal Energy Consultants
KB
KA



Deg C
0
25
50
75
100
125
150
175
200
0
500
1000
1500
2000
Depth (m)
2500
3000
3500
4000
4500

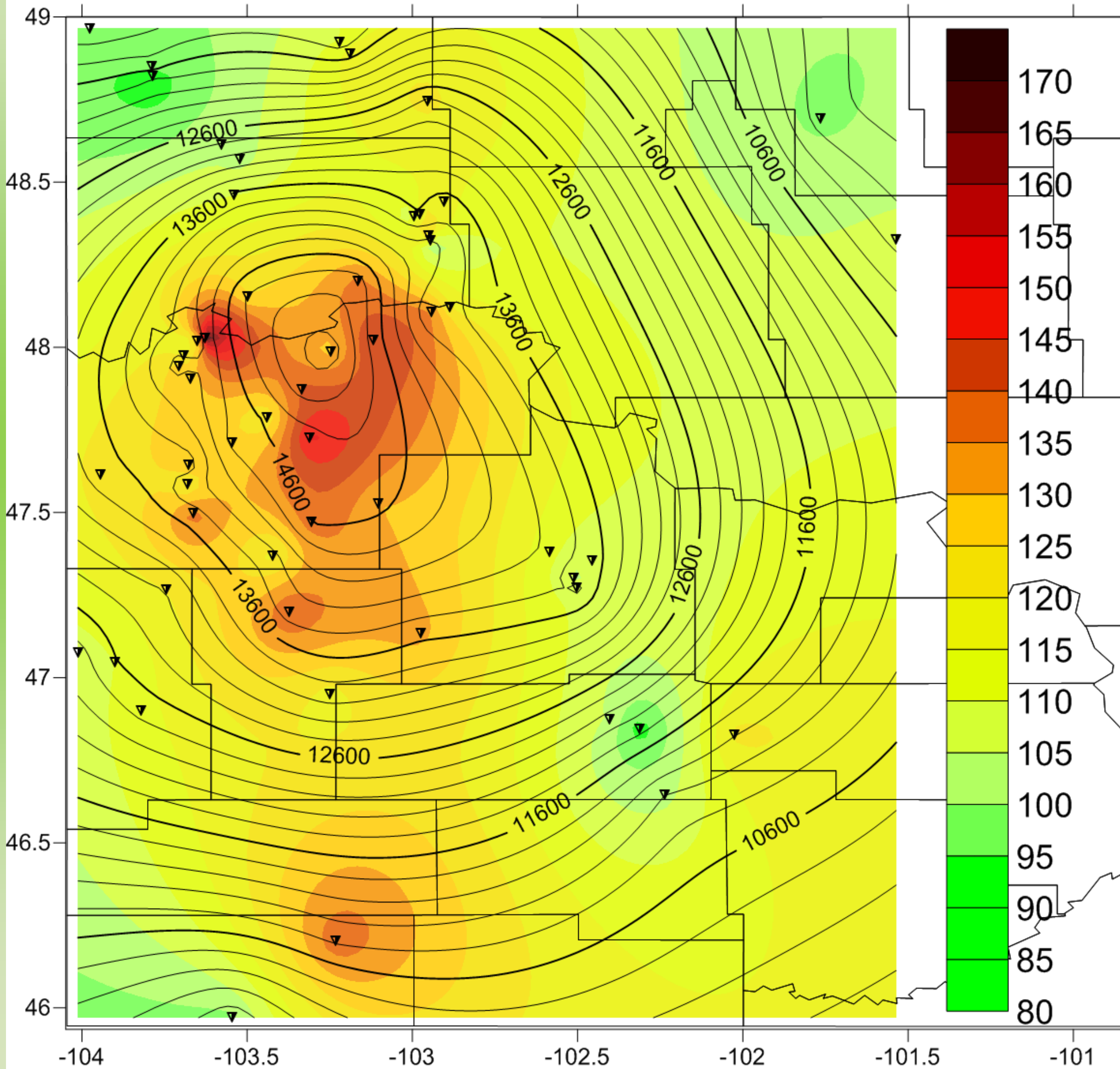
Deadwood Formation

Total Depth and Bottom Hole Temperature



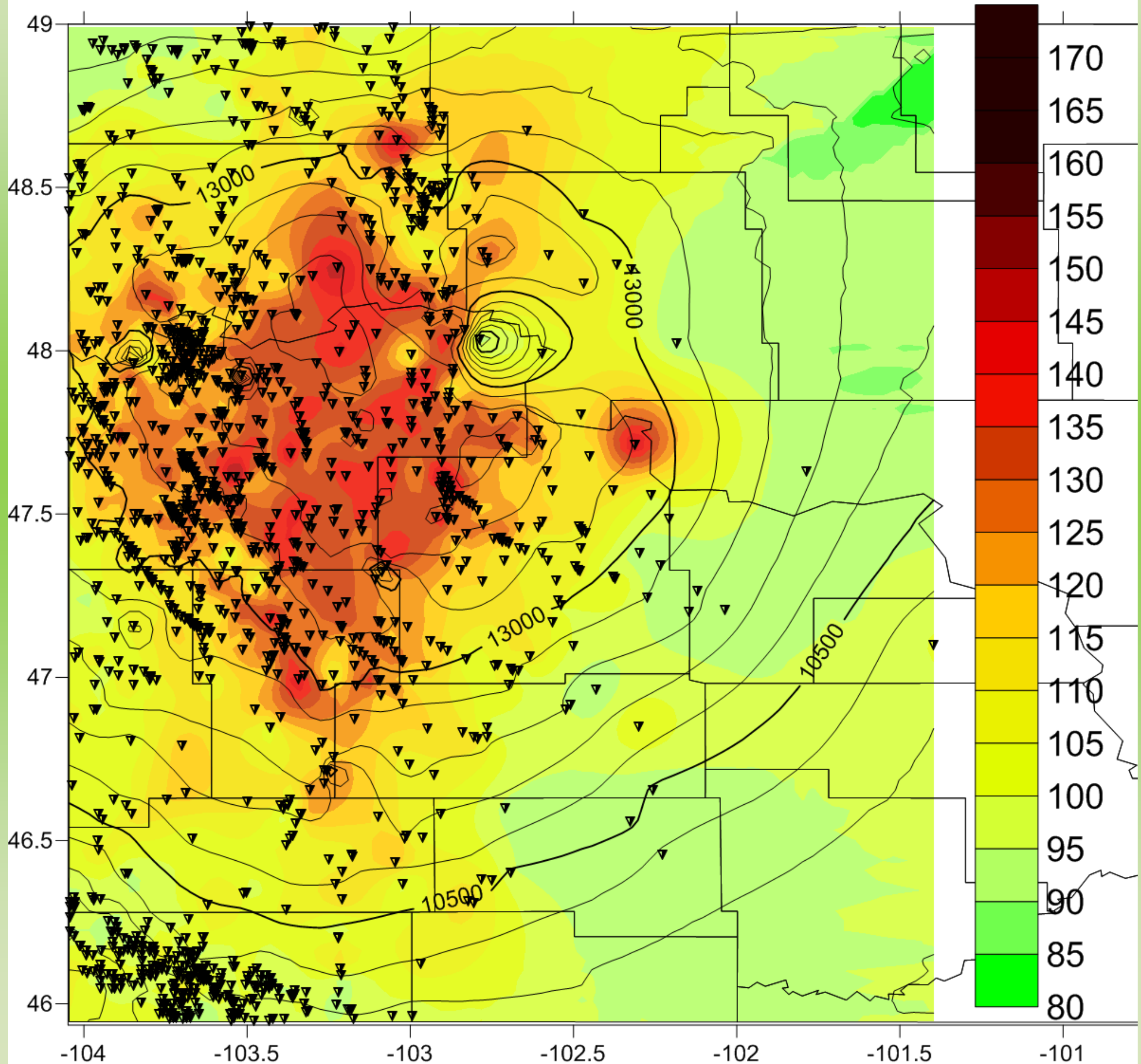
Winnipeg Formation

Total Depth and Bottom Hole Temperature



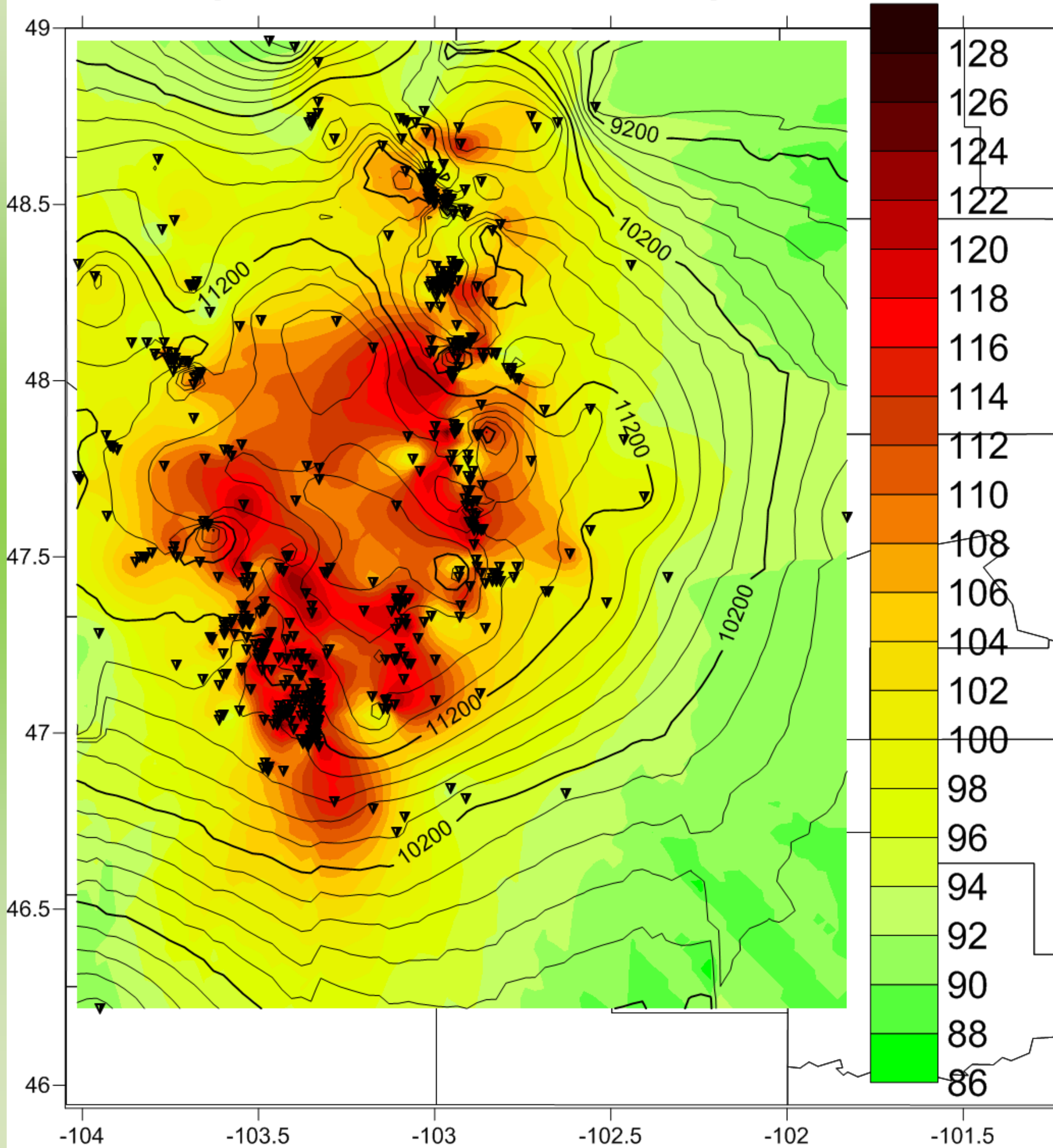
Ordovician Formation

Total Depth and Bottom Hole Temperature



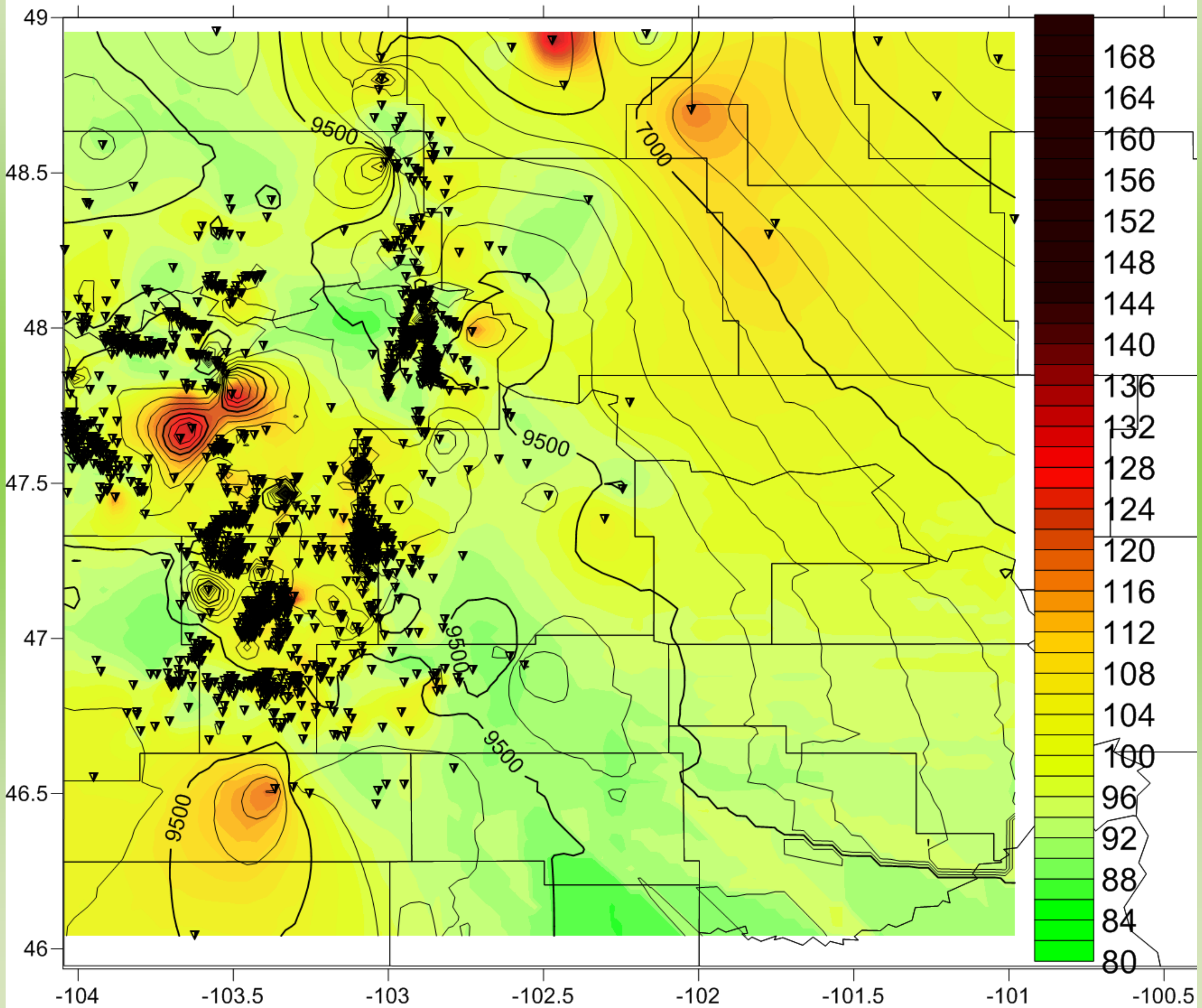
Devonian Formation

Total Depth and Bottom Hole Temperature



Madison Formation

Total Depth and Bottom Hole Temperature



NDIC Oil & Gas Division Home Page - Mozilla Firefox

https://www.dmr.nd.gov/oilgas/

North Dakota | nd.gov Official Portal for North Dakota State Government

Services

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- General Statistics
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NORTH DAKOTA OIL AND GAS DIVISION

Welcome to the North Dakota Industrial Commission, Department of Mineral Resources, Oil and Gas Division, home page.

Proposed Rule Changes!

See the proposed rule changes or the full notice

Bakken and Three Forks Information!

The ND Petroleum Council proudly announces its new Royalty Owner Information Center!

The Oil and Gas Division regulates the drilling and production of oil and gas in North Dakota. Our mission is to encourage and promote the development, production, and utilization of oil and gas in the state in such a manner as will prevent waste, maximize economic recovery, and fully protect the correlative rights of all owners to the end that the landowners, the royalty owners, the producers, and the general public realize the greatest possible good from these vital natural resources.

Phone: (701) 328-8020
Fax: (701) 328-8022
Mail:
NDIC Oil and Gas Division
600 East Boulevard Ave Dept 405
Bismarck, ND 58505-0840
General Shipping:
NDIC Oil and Gas Division
1016 East Calgary Ave
Bismarck, ND 58503-5512
Core and Samples Shipping:
ND Geological Survey Core Library
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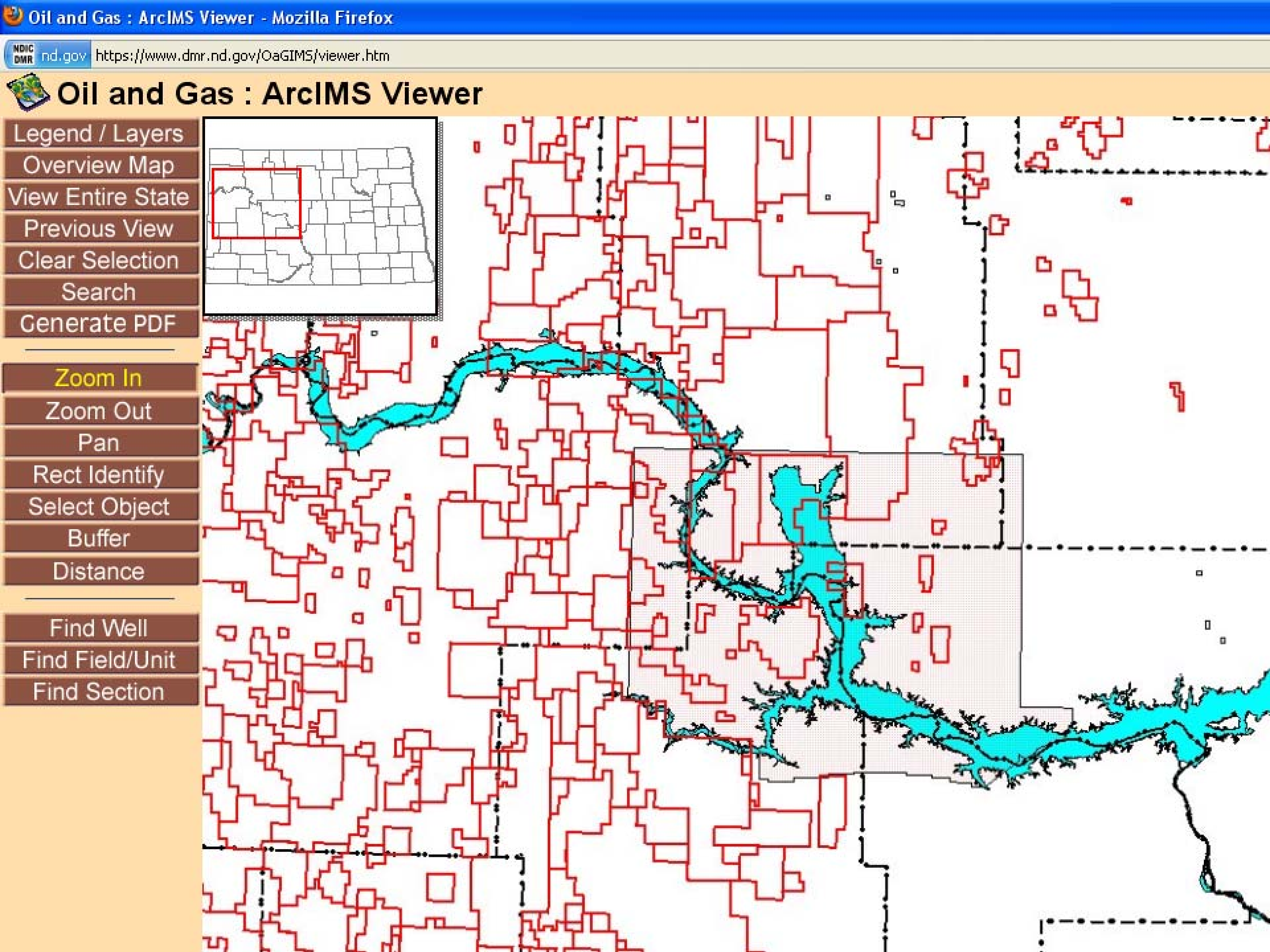
Grand Forks, ND 58202


Oil and Gas : ArcIMS Viewer - Mozilla Firefox
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Select Object
Buffer
Distance
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Find Field/Unit
Find Section

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nd.gov https://www.dmr.nd.gov/OaGIMS/viewer.htm

Oil and Gas : ArcIMS Viewer

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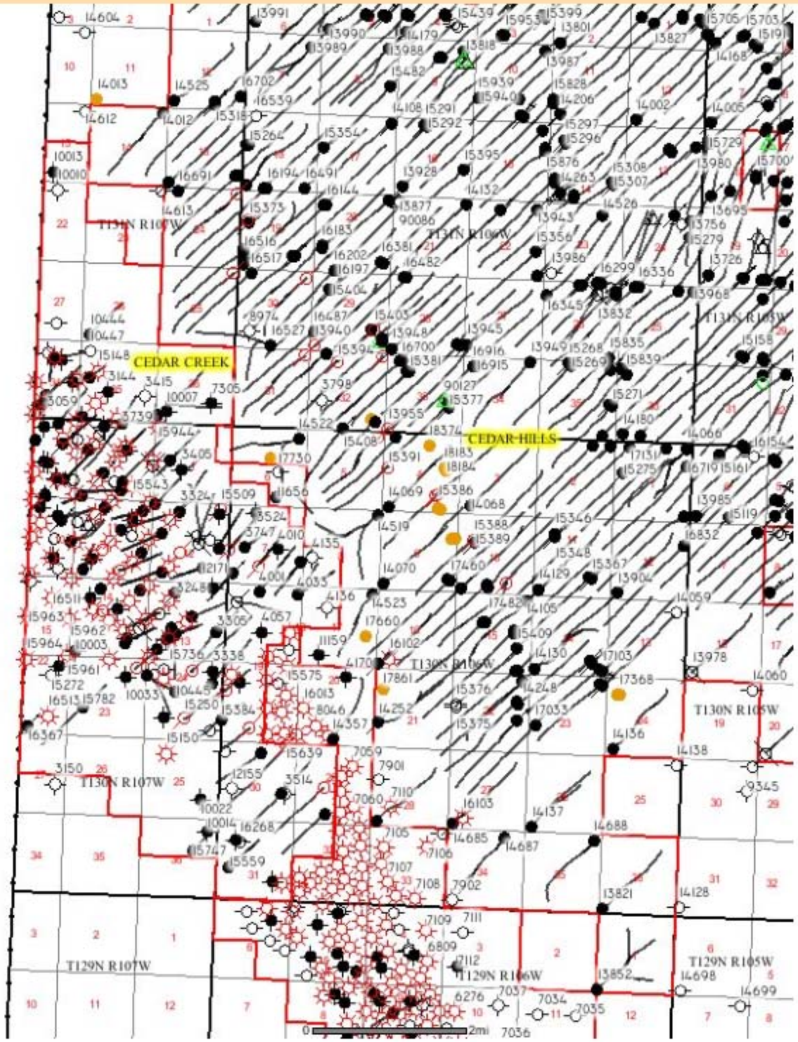
- Buffer
- Distance

- Find Well
- Find Field/Unit
- Find Section



Get a listing of all Fields / Units by name starting with the letter below.

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

Enter a partial or full Name to search for.

Search

Seach for name in

- Field
- Unit

ND OIL & GAS LAYERS

- Oil and Gas
  - Wells
  - Rig Location
  - Directional Surveys
  - Directional Legs
  - Horizontal Surveys
  - Horizontal Legs
  - Cases Docketed
  - Oil Fields
  - Unit Boundaries
  - Inspector Areas
  - Drilling / Spacing
  - Seismic
  - Gas Plants
- Other
- Imagery
  - Topo/DRG 250k
  - Topo/DRG 100k
  - NAIP 2005

Refresh Map

Auto Refresh

Help:

- A closed group, click to open.
- An open group, click to close.
- A map layer.
- A hidden group/layer, click to make visible.
- A visible group/layer, click to hide.
- A visible layer, but not at this scale.
- A partially visible group, click to make visible.
- An inactive layer, click to make active.
- The active layer.

Find

Map Data Last Updated : 10/26/2009

Done

start | Surfer - [Plo... | 3 Adobe A... | 2 Window... | 6 Microsof... | 2 Microsof... | 5 Novell Gr... | Unit Monthly... | Oil and Gas ... | performanc... | 2:17 PM

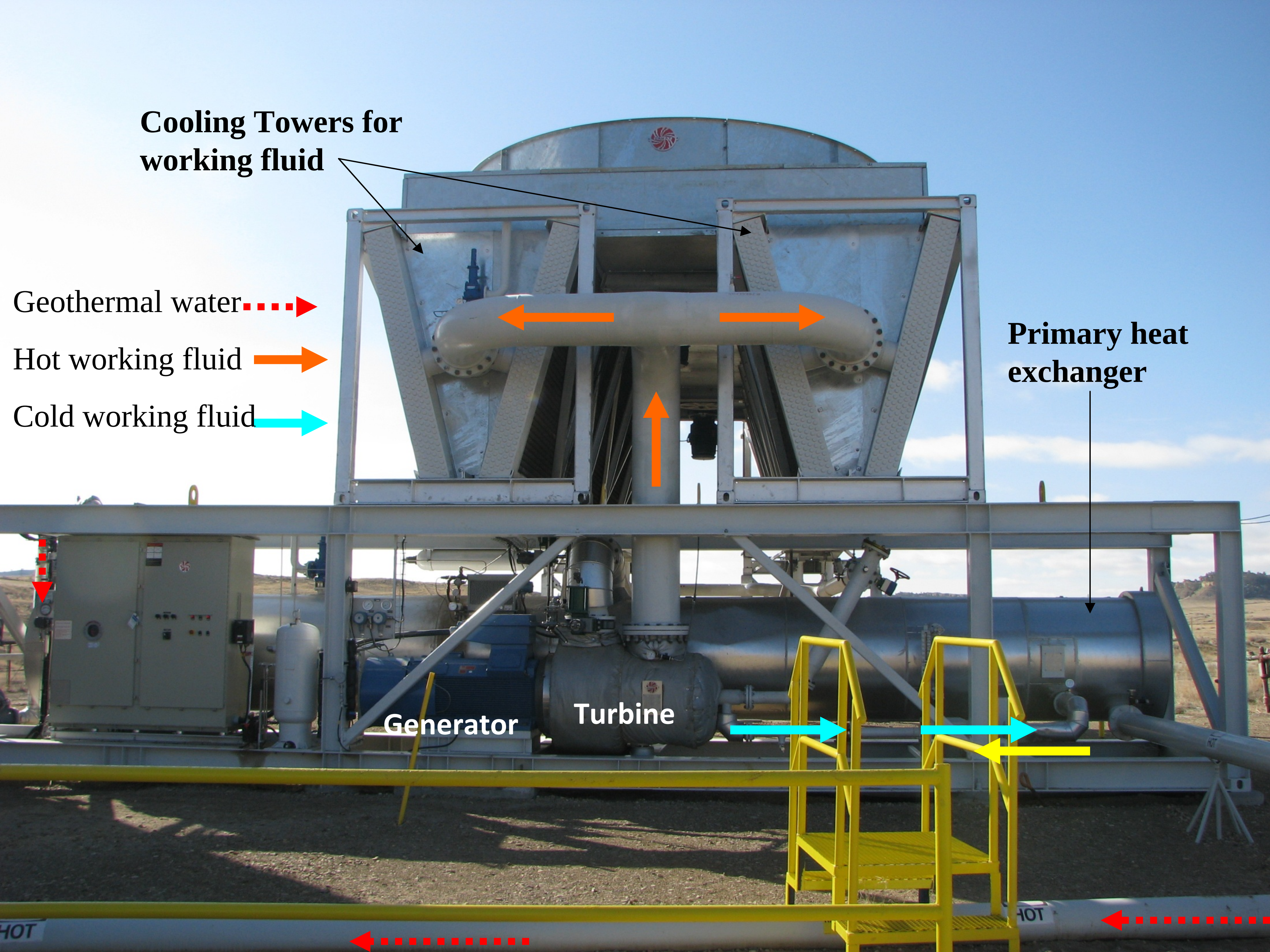
FORMATION	BARRELS OF OIL	BARRELS OF WATER	MAX. TEMP C
Spearfish	582,601	320,626	120+
Spearfish/Madison/Charles	52,923,055	81,138,008	120+
Tyler	17,279,723	9,616,114	120+
Madison	1,003,859,751	2,266,631,018	132
Bakken (Sanish)	43,079,616	4,876,685	135+
Birdbear (Nisku)	16,532,269	19,875,577	135+
Duperow	48,360,560	51,290,164	135+
Souris River	58,090	61,886	140+
Dawson Bay	3,985,365	1,191,086	145+
Winnipegosis	8,853,724	6,663,034	145+
Interlake	62,397,829	140,808,361	145+
Stonewall	14,699,878	5,134,309	145+
Winnipegosis	8,853,724	6,663,034	145+
Red River	162,448,927	162,167,866	150+
Winnipeg/Deadwood	168,170	256,474	150+
Total	1,602,219,737	2,927,676,055	

Electric Power Production from Co-produced Low-temperature Geothermal Resources

- University of North Dakota
- Berrendo Geothermal Energy, LLC
- Encore Acquistions, Inc.
- North Dakota Geological Survey
- This project will be developed in one of the 102 unitized fields in the Williston Basin.
- Co-produced fluids from the Lodgepole Fm. A unit of the Madison, are the resource. Fluid temperatures are in excess of 120 C.

Electric Power Production from Low-temperature Geothermal Resources

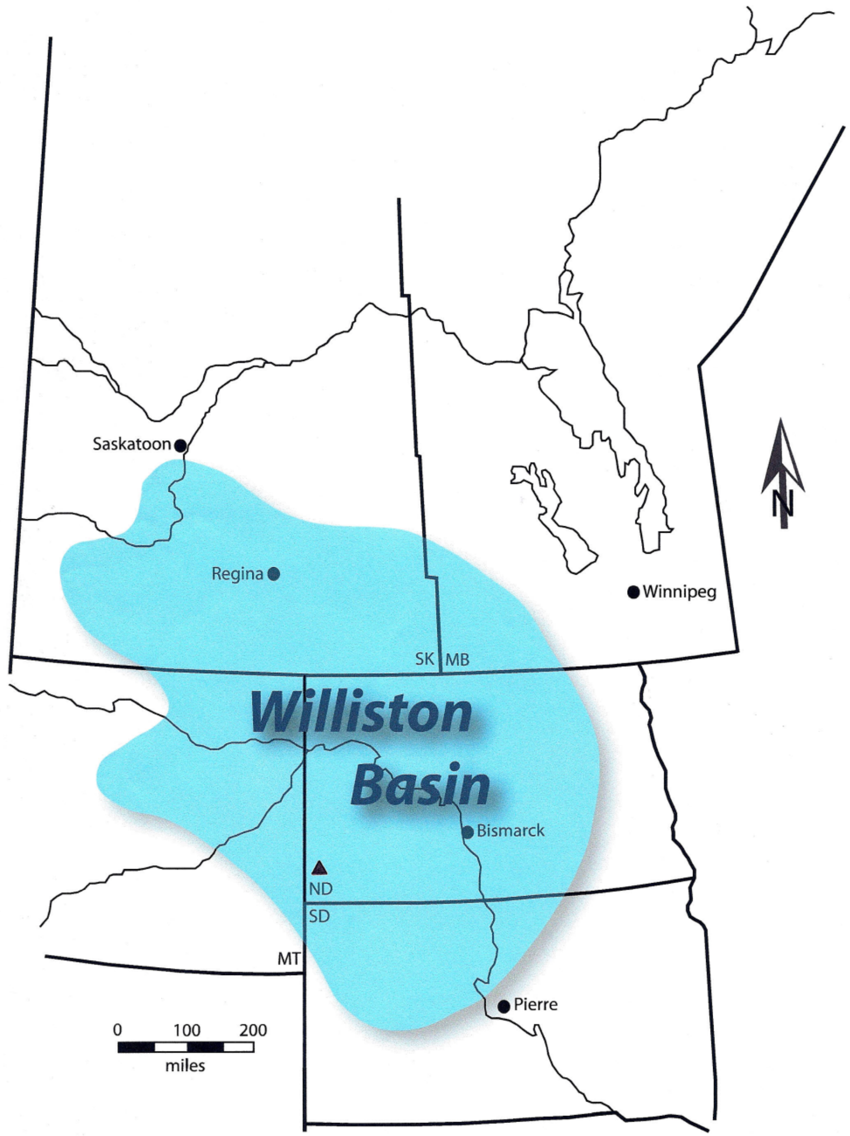
- University of North Dakota
- Berrendo Geothermal Energy, LLC
- Continental Resources, Inc.
- North Dakota Geological Survey
- This project will be developed in the Cedar Creek Field in Williston Basin.
- Water from a water-flood secondary recovery project at a a volume of 1500 gpm at temperature of 99 C is produced from the Lodgepole Fm.



Cooling Towers for working fluid
Geothermal water
Hot working fluid
Cold working fluid
Primary heat exchanger
Generator
Turbine
HOT
HOT

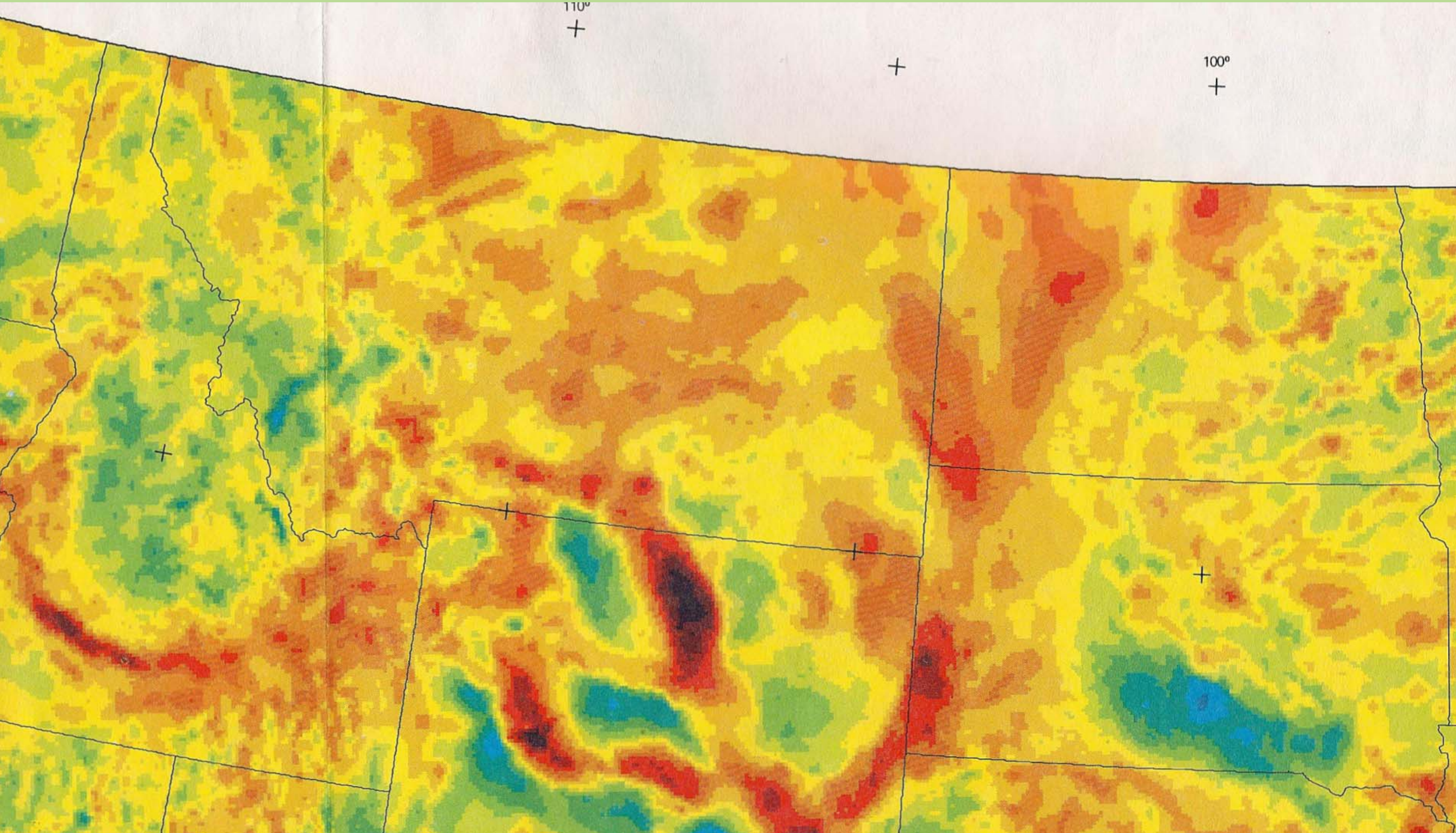
Binary Turbine Development

- The key requirement is ΔT
- ORC systems can use temperatures below the boiling point of water
- Sedimentary basins in cold climates
- The 150 °C to 90 °C resource can provide electrical power!



Saskatoon
Regina
Winnipeg
SK
MB
Williston
Basin
Bismarck
ND
SD
MT
Pierre
N
0
100
200
miles

Isostatic gravity anomaly map of North Central US

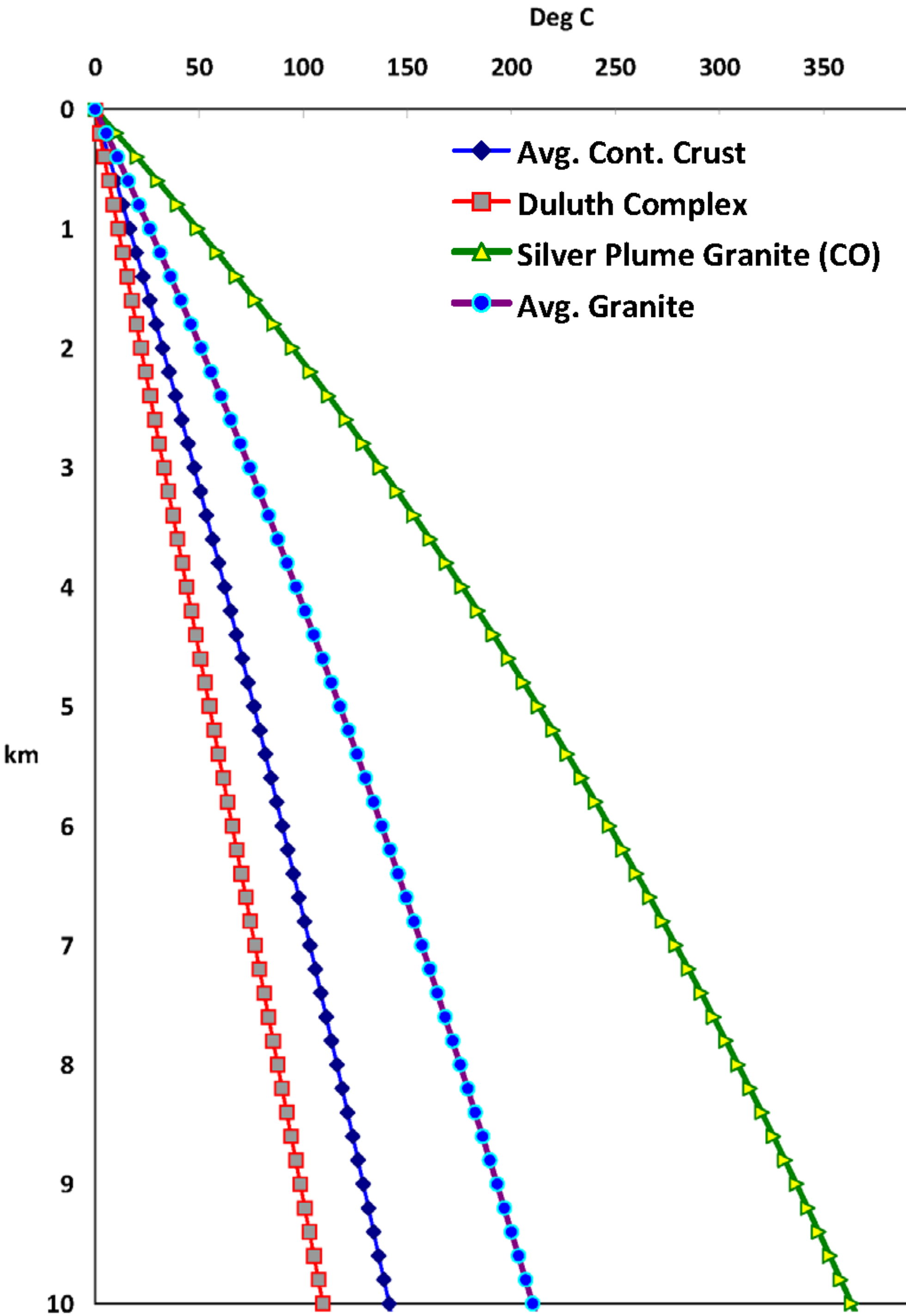


Temperature vs. depth plots based on the exponential model for the vertical distribution of crustal radioactivity.

$$A = A_0 e^{\frac{-z}{D}}$$

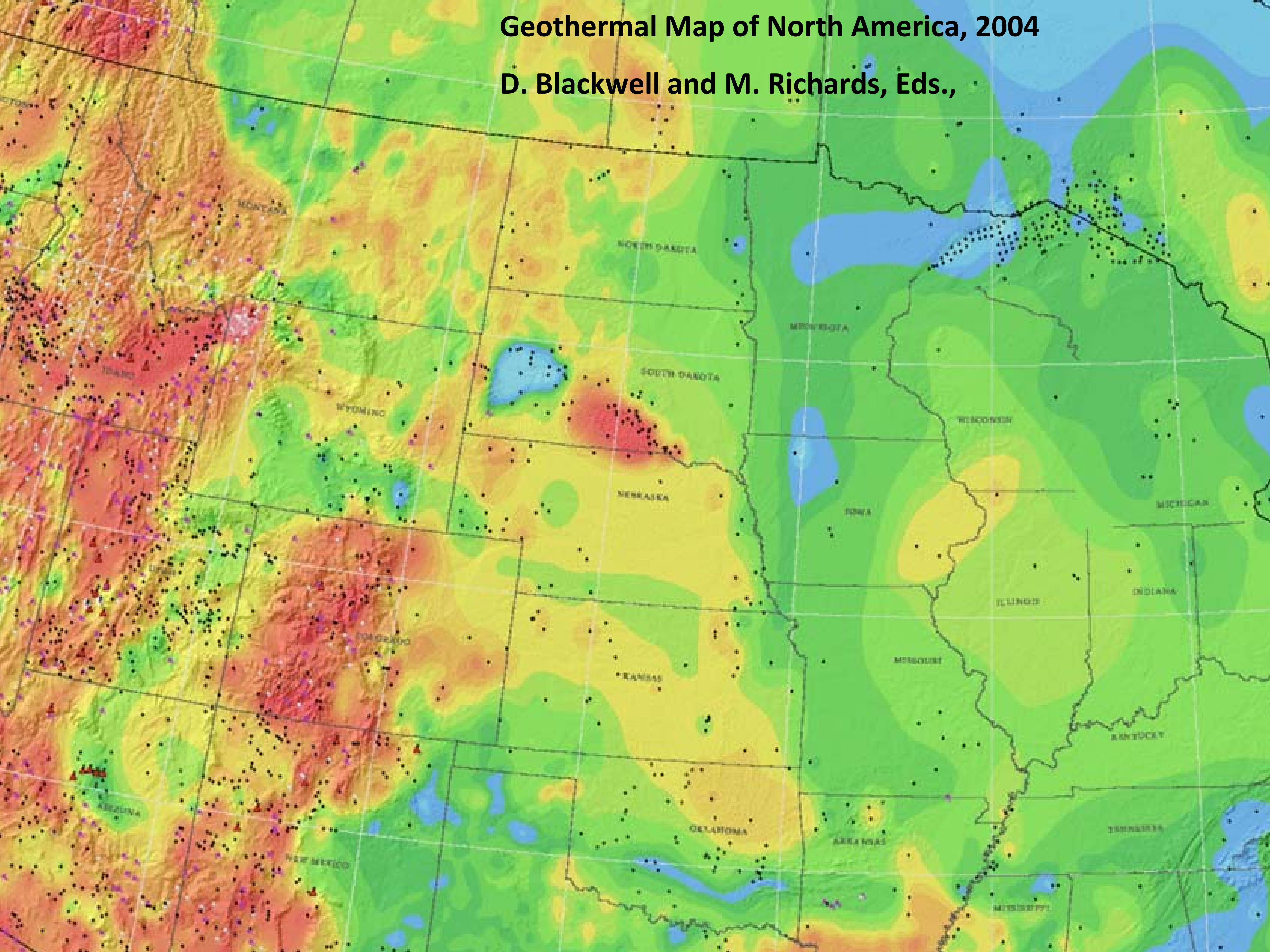
$$q = q_0 + AD$$

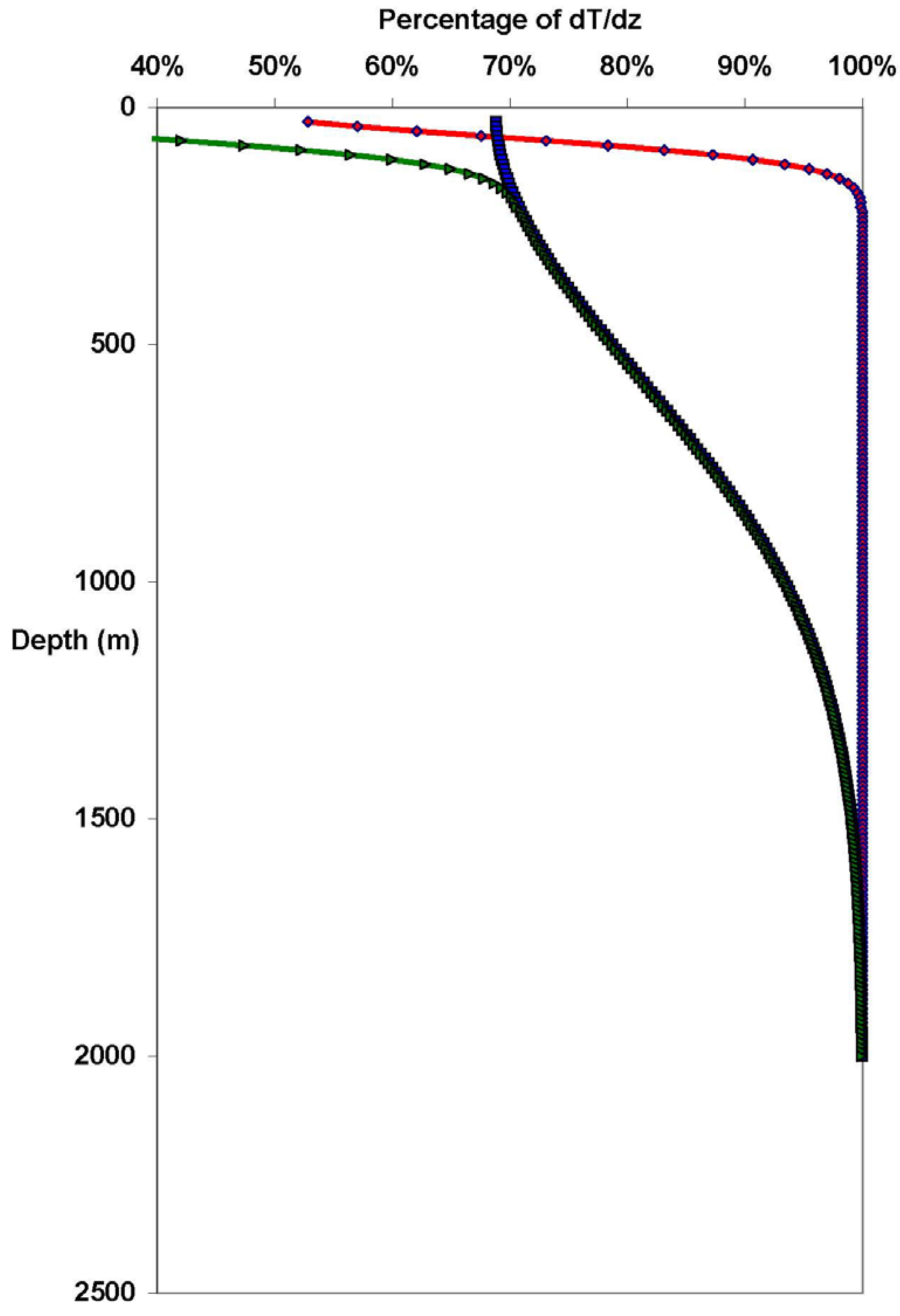
$$T(z) = T_0 + q(z)/\lambda$$



Geothermal Map of North America, 2004

D. Blackwell and M. Richards, Eds.,





Percentage of dT/dz
40%
50%
60%
70%
80%
90%
100%
0
500
1000
Depth (m)
1500
2000
2500