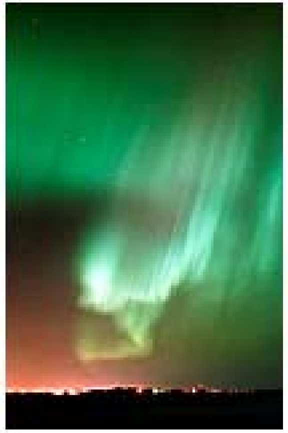
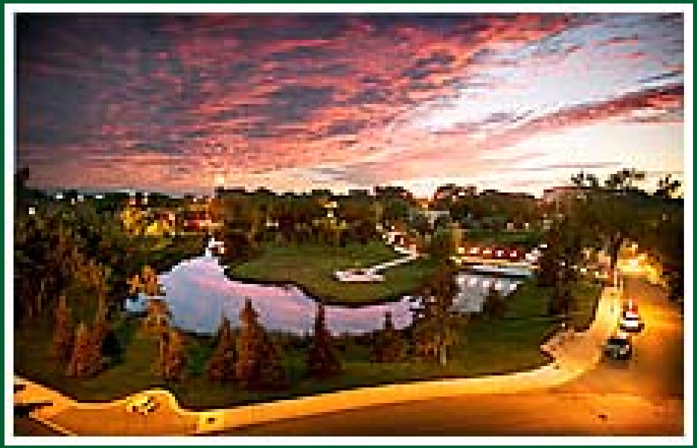
The University of North Dakota



Geothermal Prospects in the North Central United States



Will Gosnold

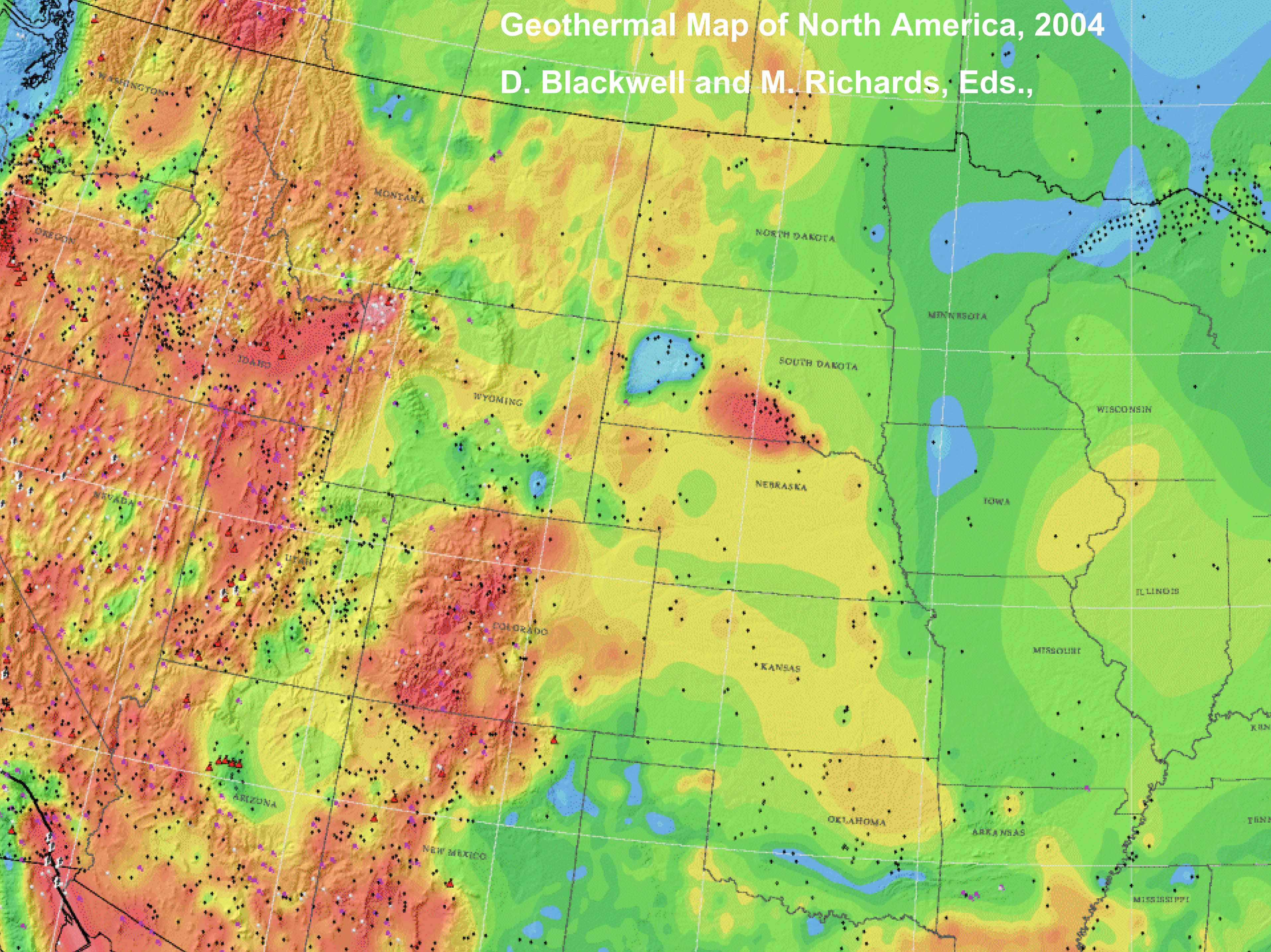
Dept. of Geology and Geological Engineering

Outline

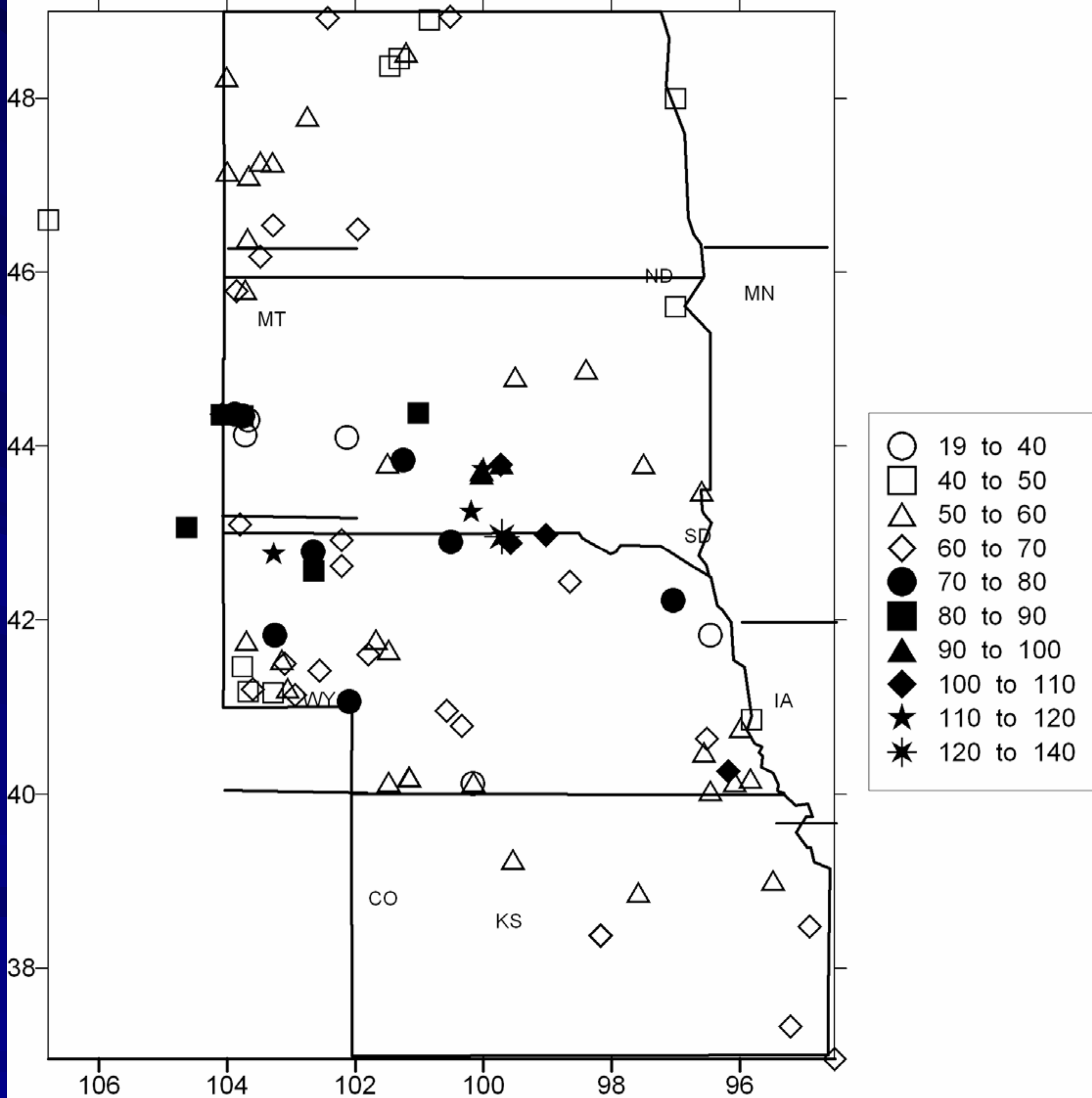
- Heat flow and subsurface temperatures in the north central US
- Thermal blanketing effect of shales and heat advection in regional groundwater flow systems
- Thermostratigraphy
- Bottom hole temperatures and equilibrium temperatures
- Estimates of the energy resource

Heat Flow

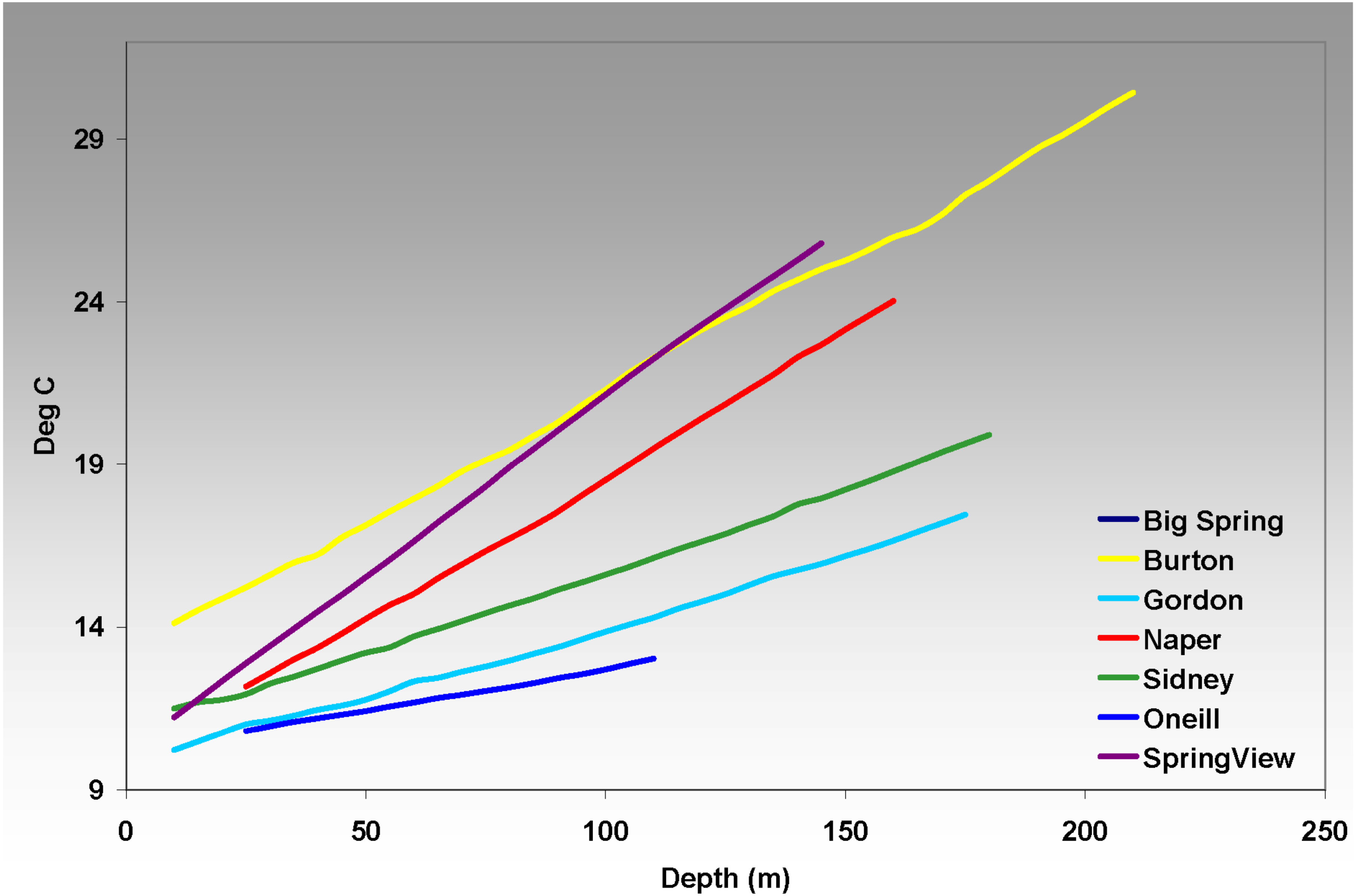
- Normal continental heat flow and subsurface temperatures characterize most of the region.
- Thermal blanketing effect of shales and heat advection in regional groundwater flow systems cause regional thermal anomalies.

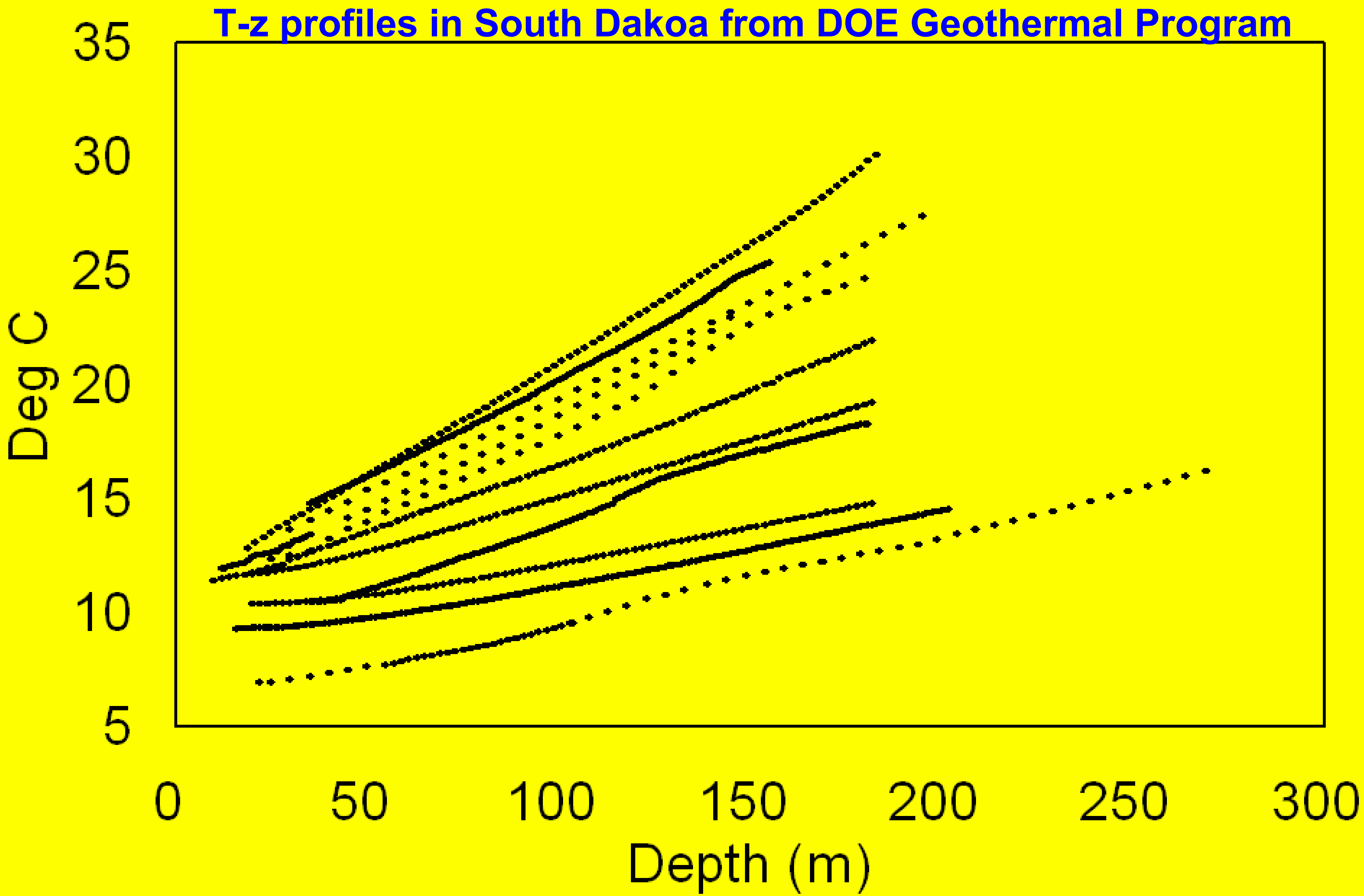

Geothermal Map of North America, 2004
D. Blackwell and M. Richards, Eds.,
MONTANA
NORTH DAKOTA
MINNESOTA
SOUTH DAKOTA
IDAHO
WYOMING
WISCONSIN
NEBRASKA
IOWA
COLORADO
ILLINOIS
MISSOURI
KANSAS
ARIZONA
OKLAHOMA
ARKANSAS
NEW MEXICO
MISSISSIPPI

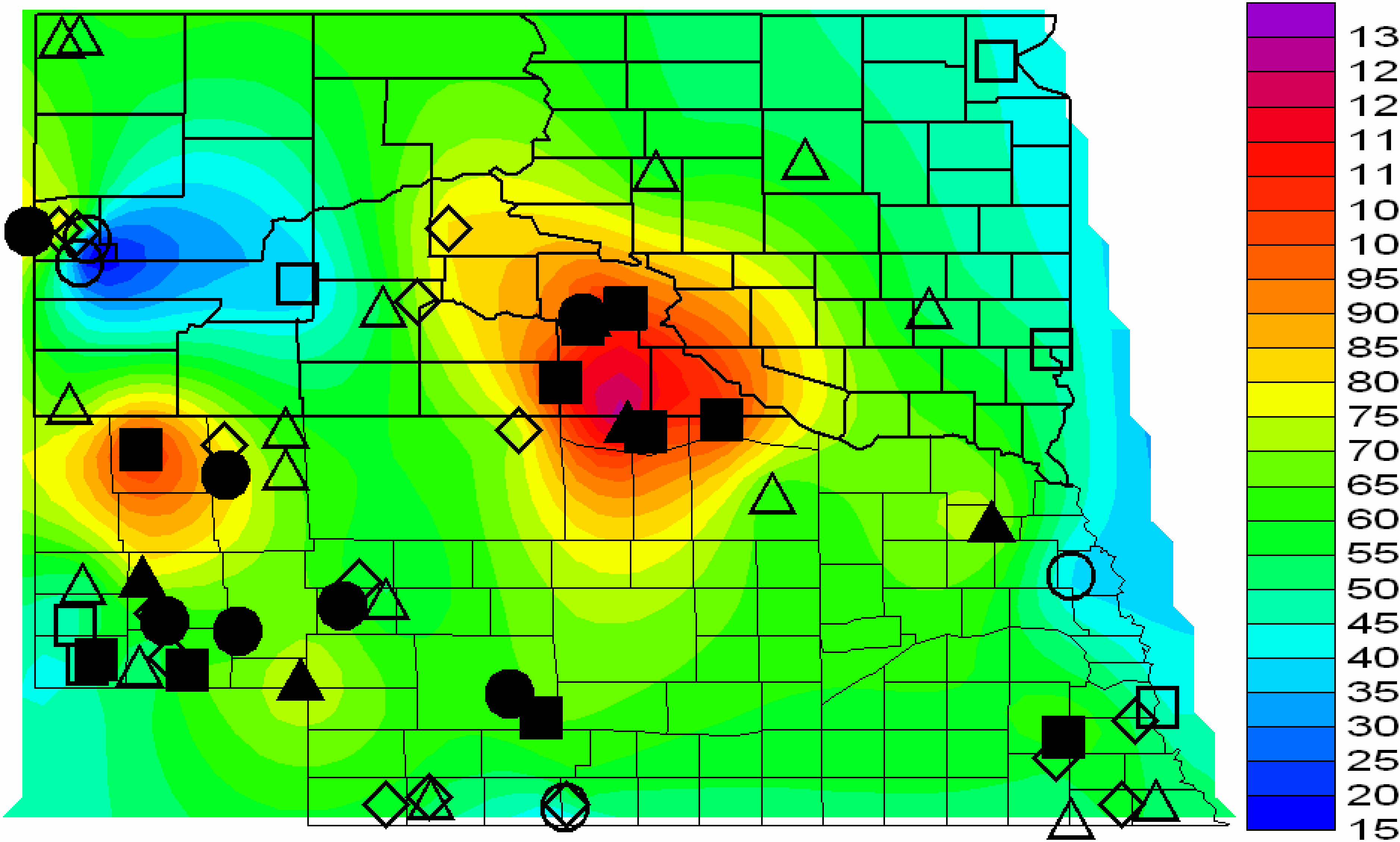
Most of the heat flow sites in Nebraska and South Dakota were drilled with funding from the US Department of Energy's geothermal programs.



T-z profiles in Nebraska from DOE Geothermal Program

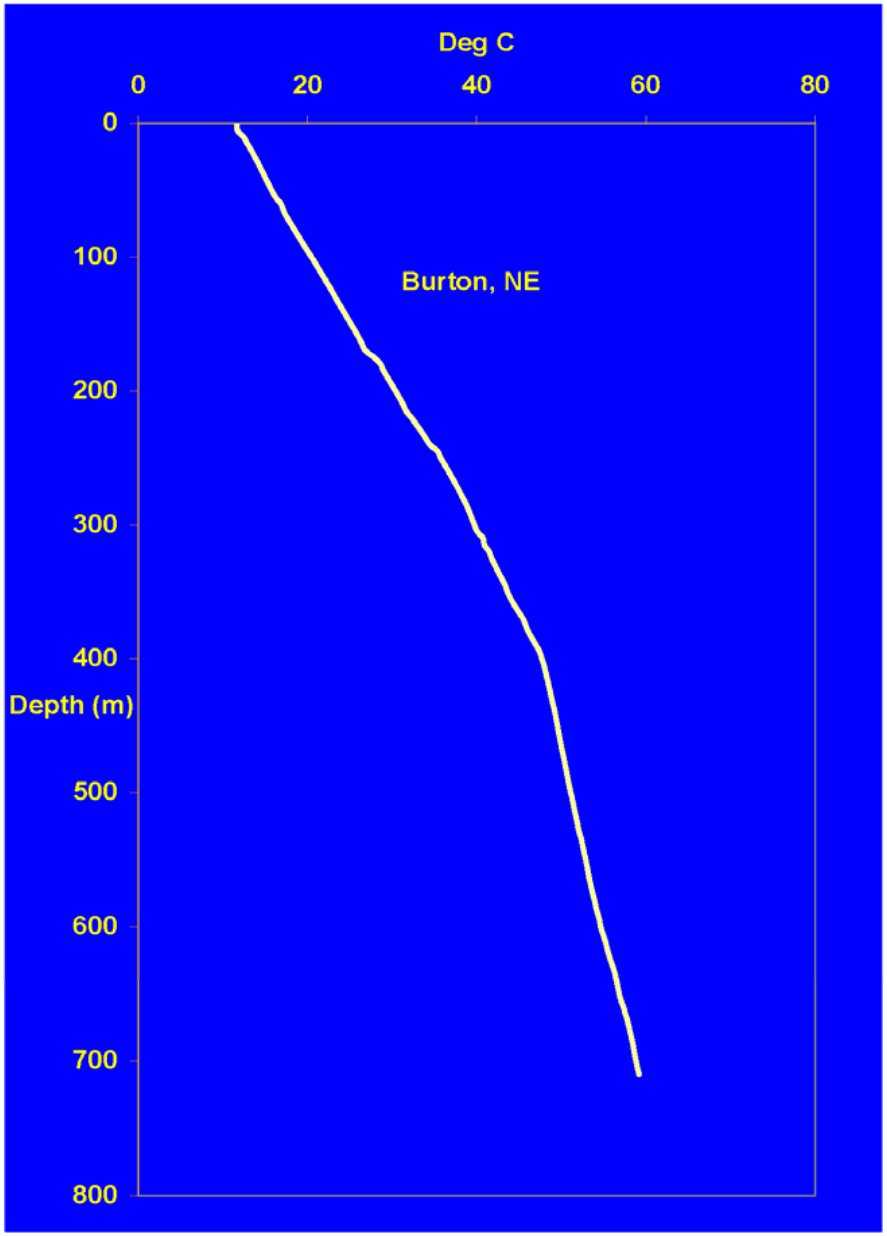



T-z profiles in South Dakoa from DOE Geothermal Program
35
30
25
20
15
10
5
Deg C
0
50
100
150
200
250
300
Depth (m)



Heat flow contours of South Dakota and Nebraska showing the effects of regional groundwater flow

The site at Burton, NE provided the crucial piece of evidence for groundwater flow as the source of the thermal anomaly.



THE AQUIFER SYSTEM

Investigation of the relationship between the heat-flow anomaly and groundwater flow requires understanding the system of confined aquifers underlying the area. Groundwater flow in the aquifer system is gravity driven from the recharge area at 1200 m elevation to the discharge area at about 400 m elevation (Fig. 7 A-7E). Downey (1986) divided the system into four major confined aquifers that are recharged where eastward-flowing streams cross their outcrops along the eastern margin of the Black Hills (Swenson, 1968).

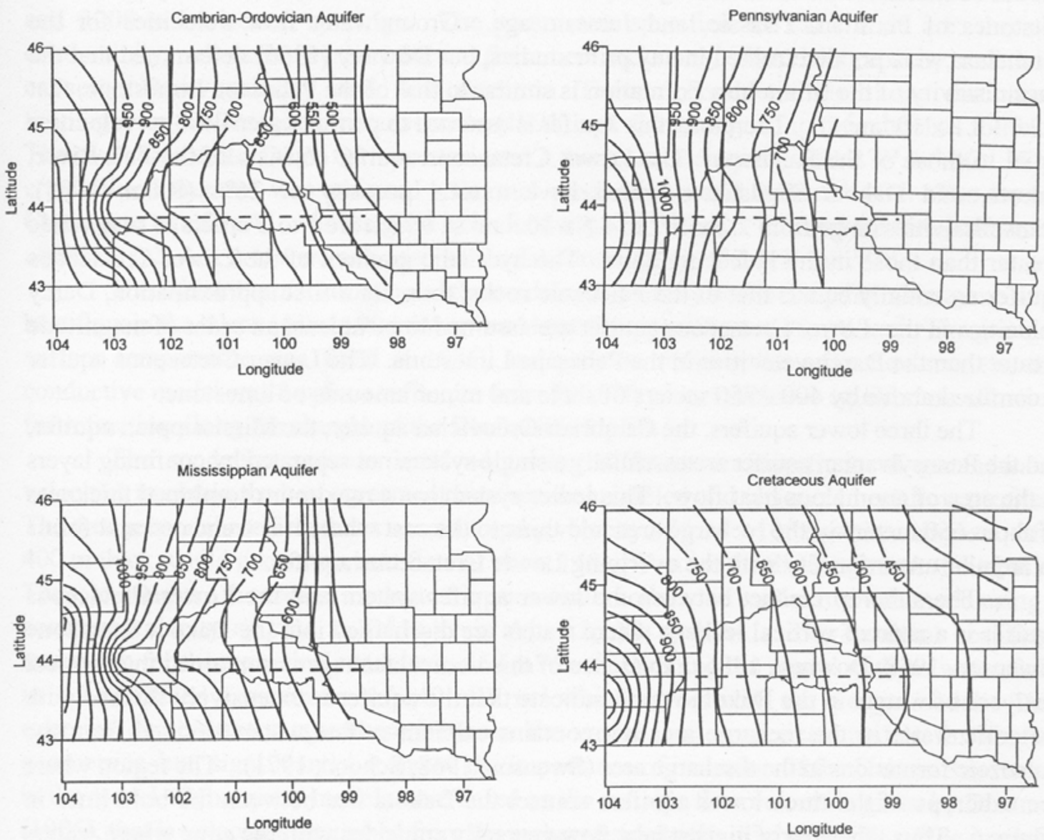


Figure 7. Potentiometric surface contours on tops of four major aquifer systems showing west to east flow pattern modified from Downey (1986). Contours are in meters and datum is sea level. East-west dashed line designates heat-flow profile shown in Figure 8.

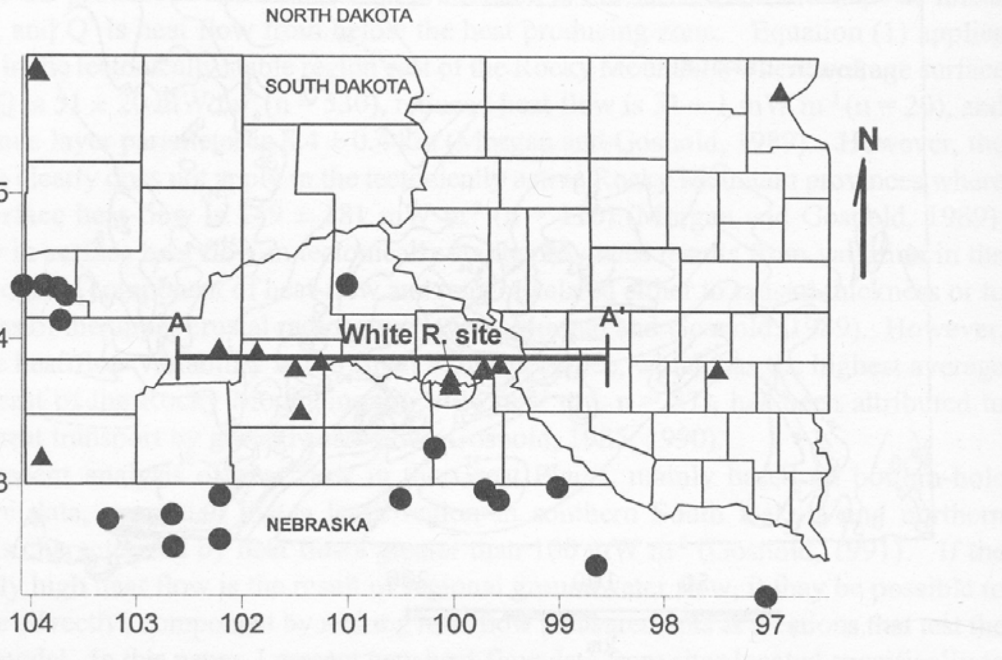


Figure 2. Locations of heat-flow sites. Sites previously published are shown by dots (Sass and others, 1971; Sass and Galanis, 1983; Gosnold,1990) and new sites are shown by triangles. Three heat-flow holes at White River site lie within ellipse. Line A - A' locates cross section for Figures 3, 8.

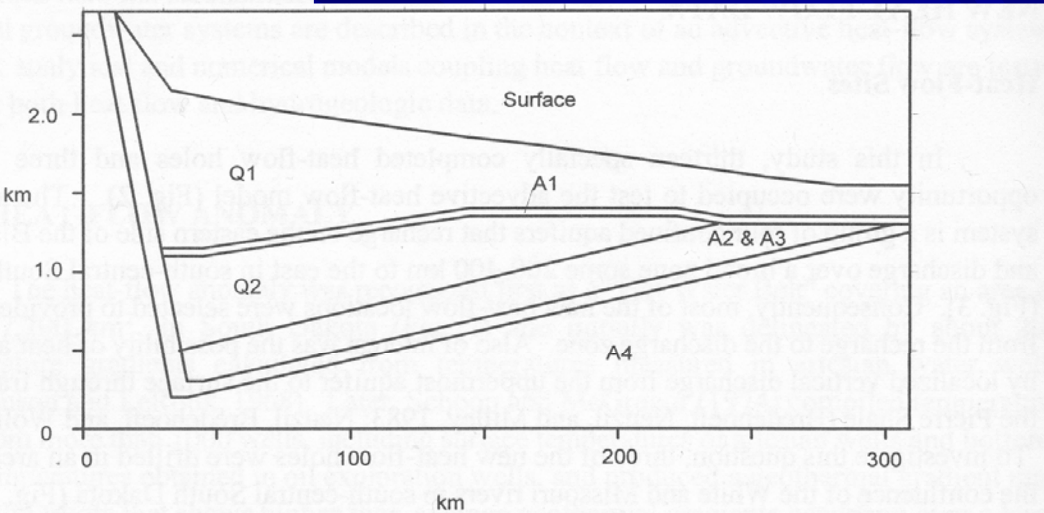
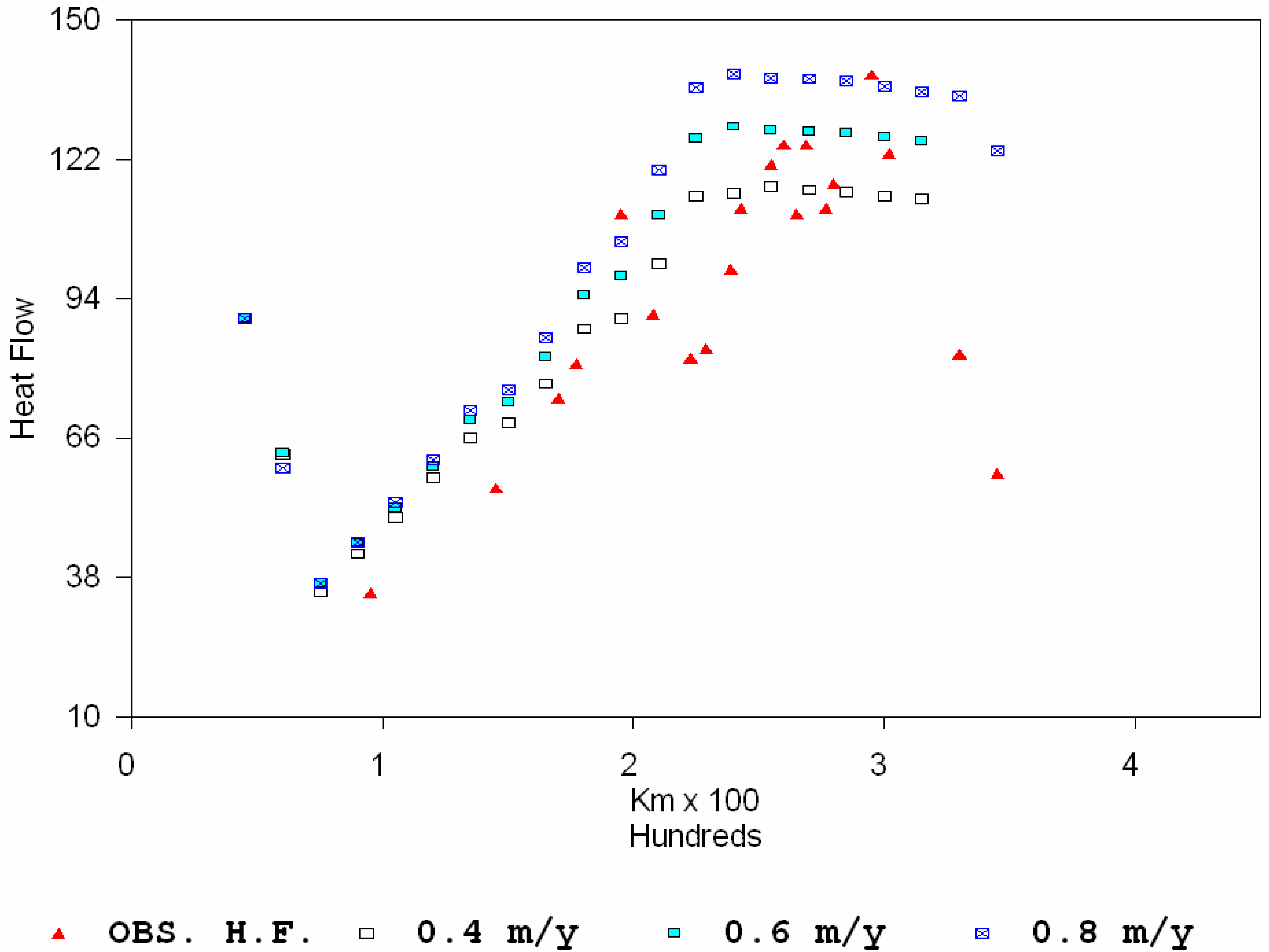


Figure 3. Four regional aquifers, A1 - A4, and three confining units, Q1 - Q3 are shown in schematic cross section along line A - A' in Figure 2. A1 - Fall River, Lakota and Dakota Sandstones (Cretaceous); A2 - Pahasapa (Madison) Limestone (Mississippian); A3 - Minnelusa Formation (Pennsylvanian); A4 - Deadwood Sandstone and Red River Formation (Cambrian - Ordovician). Q1 - Cretaceous shales; Q2 - shales of Permian to Jurassic age; Q3 - crystalline basement.

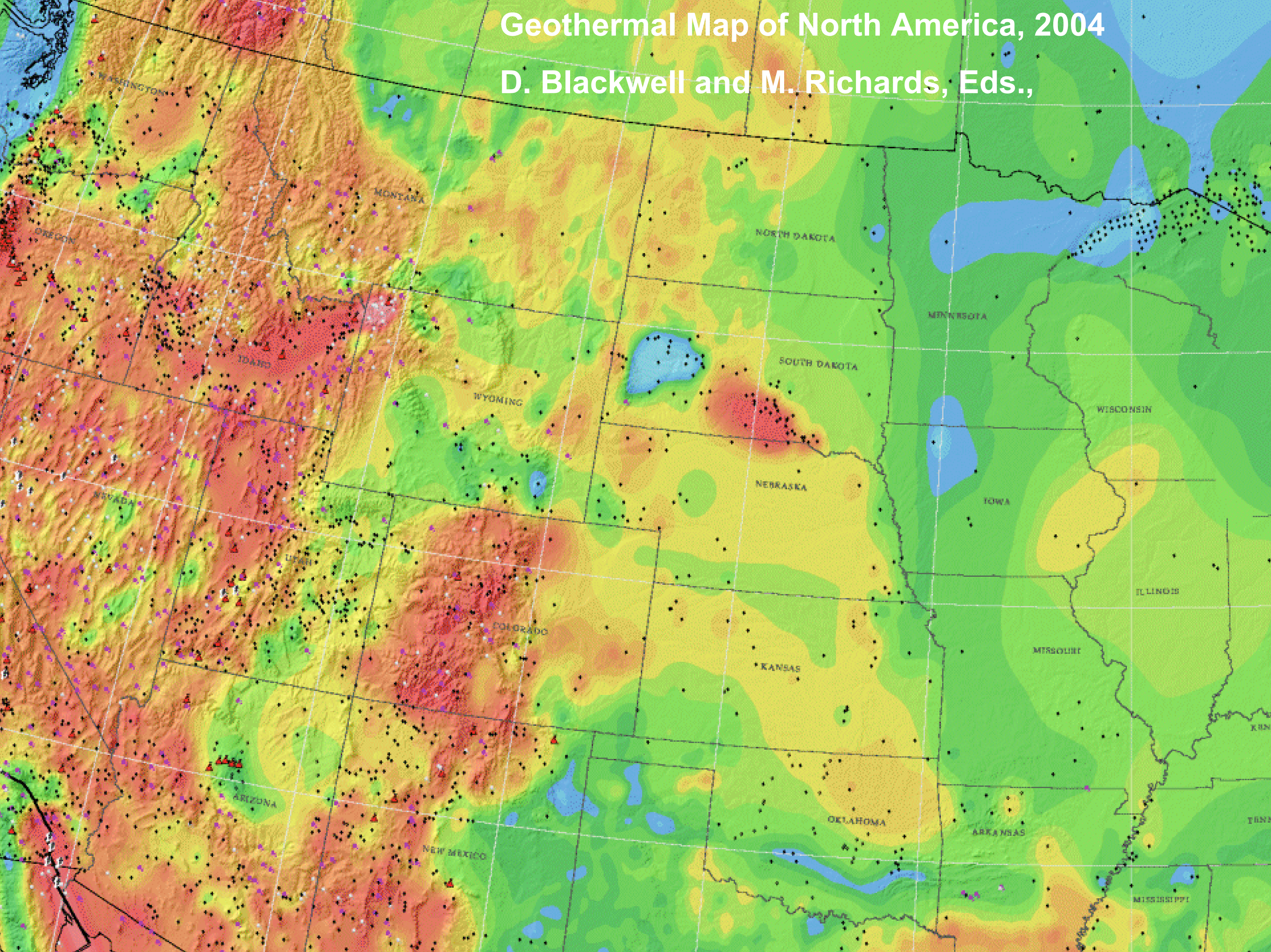
A simple geological profile tested a model of the thermal effects of water flow from the Black Hills eastward.



150
122
94
66
38
10
Heat Flow
0
1
2
3
4
Km x 100
Hundreds
OBS. H.F.
0.4 m/y
0.6 m/y
0.8 m/y

Geothermal Map of North America, 2004

D. Blackwell and M. Richards, Eds.,



Thermostratigraphy is the application of Fourier's law of heat conduction to calculate temperature at depth

$$Q = \frac{dT}{dZ} K$$

Determine Q from equilibrium T-z and K.
Assume Q is constant, K and dz are known

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

TABLE 1. GENERALIZED STRATIGRAPHY OF THE NORTH-CENTRAL GREAT PLAINS*

System	Rock Units	Lithology	Maximum Thickness
Quaternary	Coleharbor + unnamed units	Clay, silt, sand, gravel	510
Tertiary	White River	Siltstone, clay, sand	75
	Golden Valley	Clay, siltstone, lignite	65
	Fort Union	Silt, clay, sand	600
Cretaceous	Hell Creek	Sand	200
	Fox Hills	Silt, shale, sandstone	120
	Pierre	Shale	700
	Niobrara	Shale	75
	Carlile	Shale	120
	Greenhorn	Shale, shaly limestone	45
	Belle Fourche	Shale	105
	Mowry	Shale	55
	Newcastle	Sandstone, shale	45
	Skull Creek	Shale	40
	Inyan Kara	Sandstone	135
Jurassic	Morrison	Shale, siltstone	80
	Swift	Shale	150
	Rierdon	Shale	30
	Piper	Limestone, anhydrite, shale	190
Triassic	Spearfish	Siltstone, shale	225
Permian	Minnekahta	Limestone	12
	Opeche	Shale; dolomitic and silty	120
	Broom Creek	Sandstone, dolomite	100
Pennsylvanian	Amsden	Dolomite, sandstone	135
	Tyler	Shale, limestone	80
	Otter	Shale	60

Jurassic	Morrison	Shale, siltstone	80
	Swift	Shale	150
	Rierdon	Shale	30
	Piper	Limestone, anhydrite, shale	190
Triassic	Spearfish	Siltstone, shale	225
Permian	Minnekahta	Limestone	12
	Opeche	Shale; dolomitic and silty	120
	Broom Creek	Sandstone, dolomite	100
Pennsylvanian	Amsden	Dolomite, sandstone	135
	Tyler	Shale, limestone	80
	Otter	Shale	60

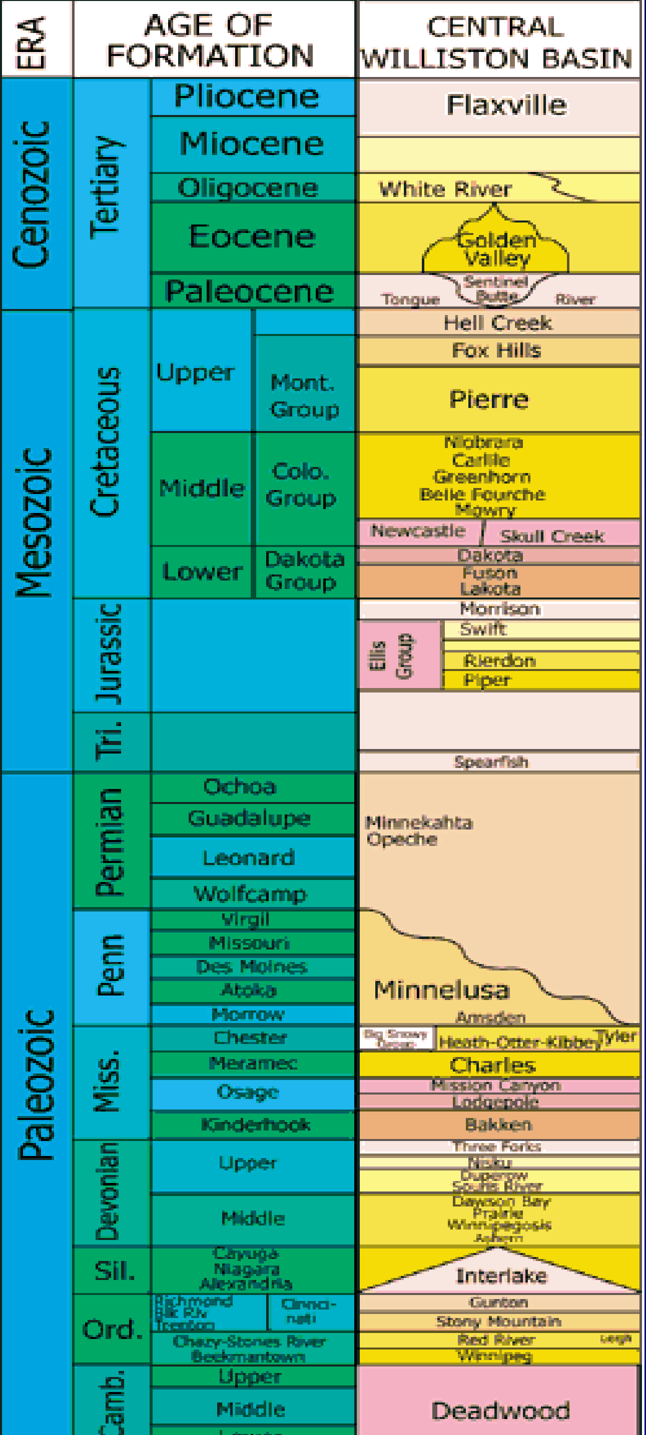
Mississippian	Kibbey	Sandstone, limestone	75
	Madison	Limestone	600
Devonian	Bakken	Shale	35
	Three Forks	Siltstone, shale	75
	Birdbear	Limestone, dolomite	40
	Duperow	Limestone, dolomite	140
	Souris River	Dolomite, limestone	105
	Dawson Bay	Limestone, dolomite	55
	Prairie	Evaporites	200
	Winnipegosis	Dolomite, limestone	120
Silurian	Interlake	Dolomite, limestone	335
	Stonewall	Dolomite, limestone	35
Ordovician	Stony Mountain	Dolomite, limestone	60
	Red River	Limestone, dolomite	215
	Winnipeg Group	Siltstone, sandstone, shale	125
Cambrian	Deadwood	Limestone, sandstone, shale	300

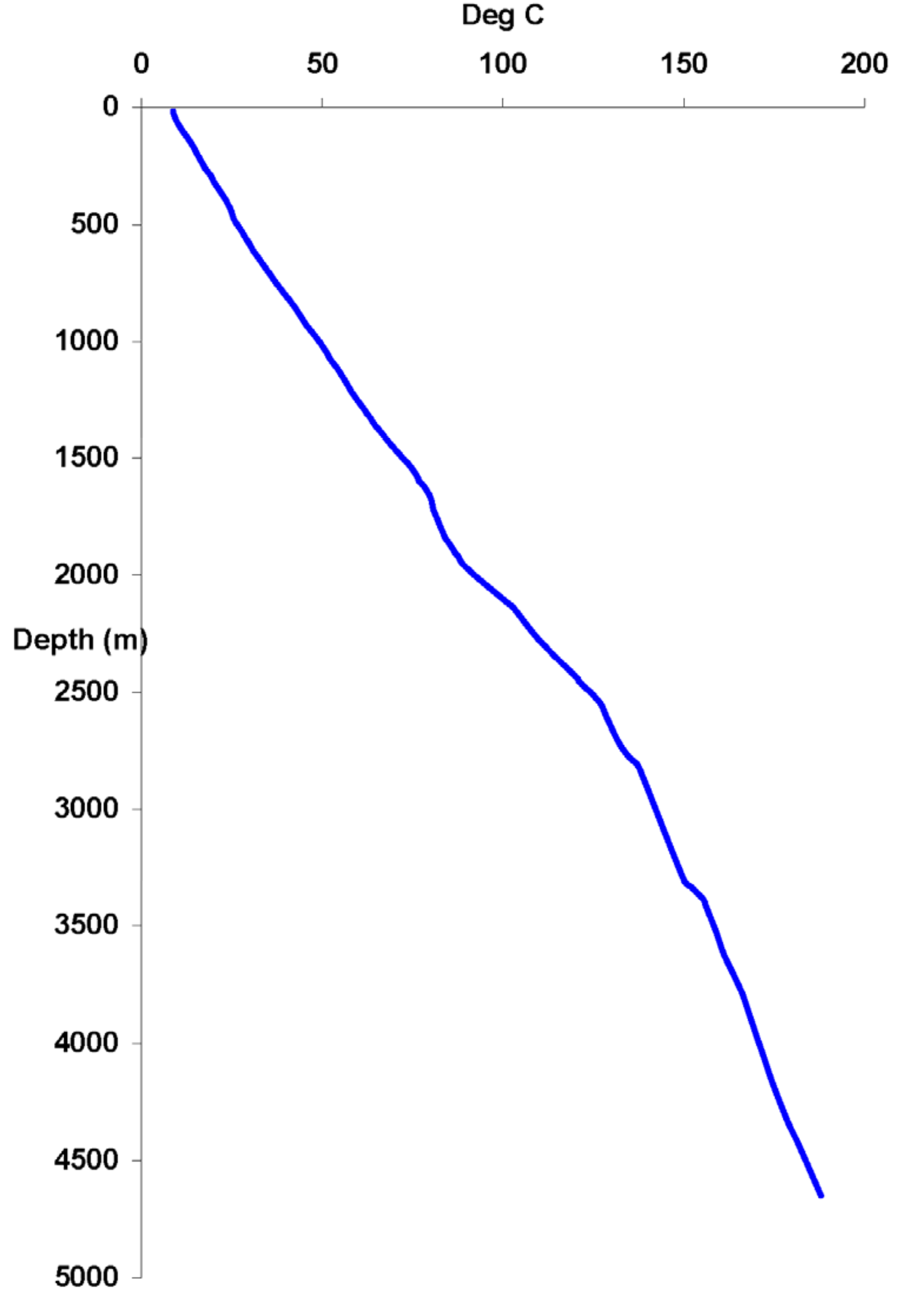
*Stratigraphy generalized from Blumle and others (1986).

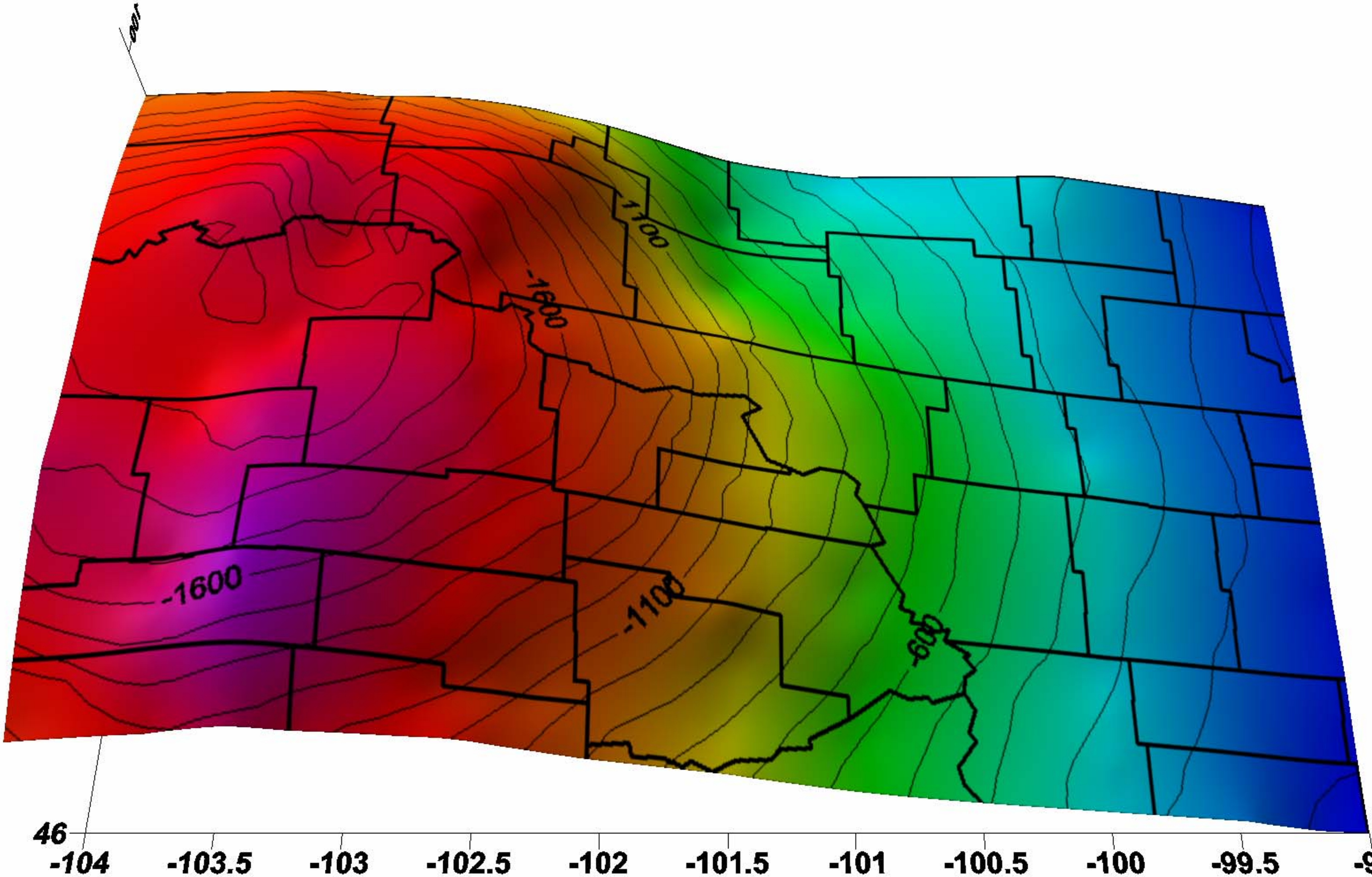
TABLE 2. THERMOSTRATIGRAPHY OF A GENERALIZED SECTION OF THE WILLISTON BASIN

Stratigraphic Horizon	Temperature (°C)	Thickness (m)	Depth (m)	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	Gradient ($K\ km^{-1}$)
Fort Union	6.0	152.4	0.0	1.2	50.0
Fox Hills	13.6	36.6	152.4	1.2	50.0
Pierre	15.4	1,127.8	189.0	1.1	54.5
Inyan Kara	77.0	42.7	1,316.8	1.6	37.5
Jurassic (undiv.)	78.6	61.0	1,359.4	1.4	42.9
Sundance	81.2	167.6	1,420.4	1.4	42.9
Spearfish	88.4	167.6	1,588.0	1.3	46.1
Minnekahata	96.1	12.2	1,755.7	3.0	20.0
Opeche	96.3	44.2	1,767.9	1.4	42.9
Minnelusa	98.2	137.2	1,812.1	2.2	27.3
Madison	102.0	390.1	1,949.2	3.5	17.1
Devonian (undiv.)	108.7	368.8	2,339.4	3.5	17.1
Cambrian (undiv.)	115.0	207.3	2,708.2	2.4	25.0
Precambrian	120.2		2,915.4		

Note: Heat flow = 60 $mW\ m^{-2}$. Surface temperature taken from NOAA climate data. Thermal conductivities from Gosnold (1987).


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
Mont. Group
Middle
Colo. Group
Lower
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
Sil.
Cayuga
Niagara
Alexandria
Interlake
Ord.
Richmond
Elk Riv
Trenton
Cinncinati
Chazy-Stones River
Beekmantown
Gunton
Stony Mountain
Red River
Winnipeg
Camb.
Upper
Middle
Deadwood

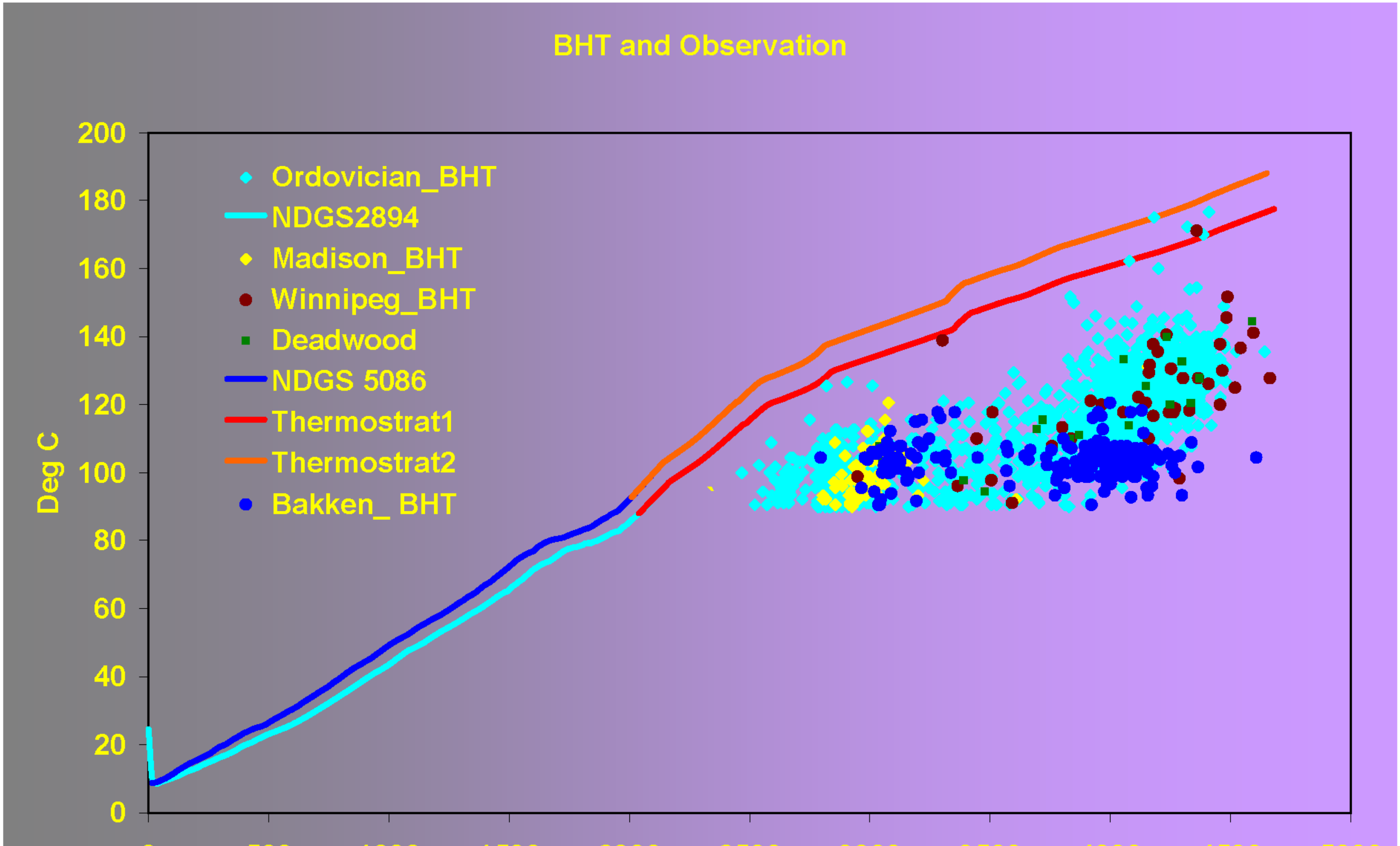

Deg C
0
50
100
150
200
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

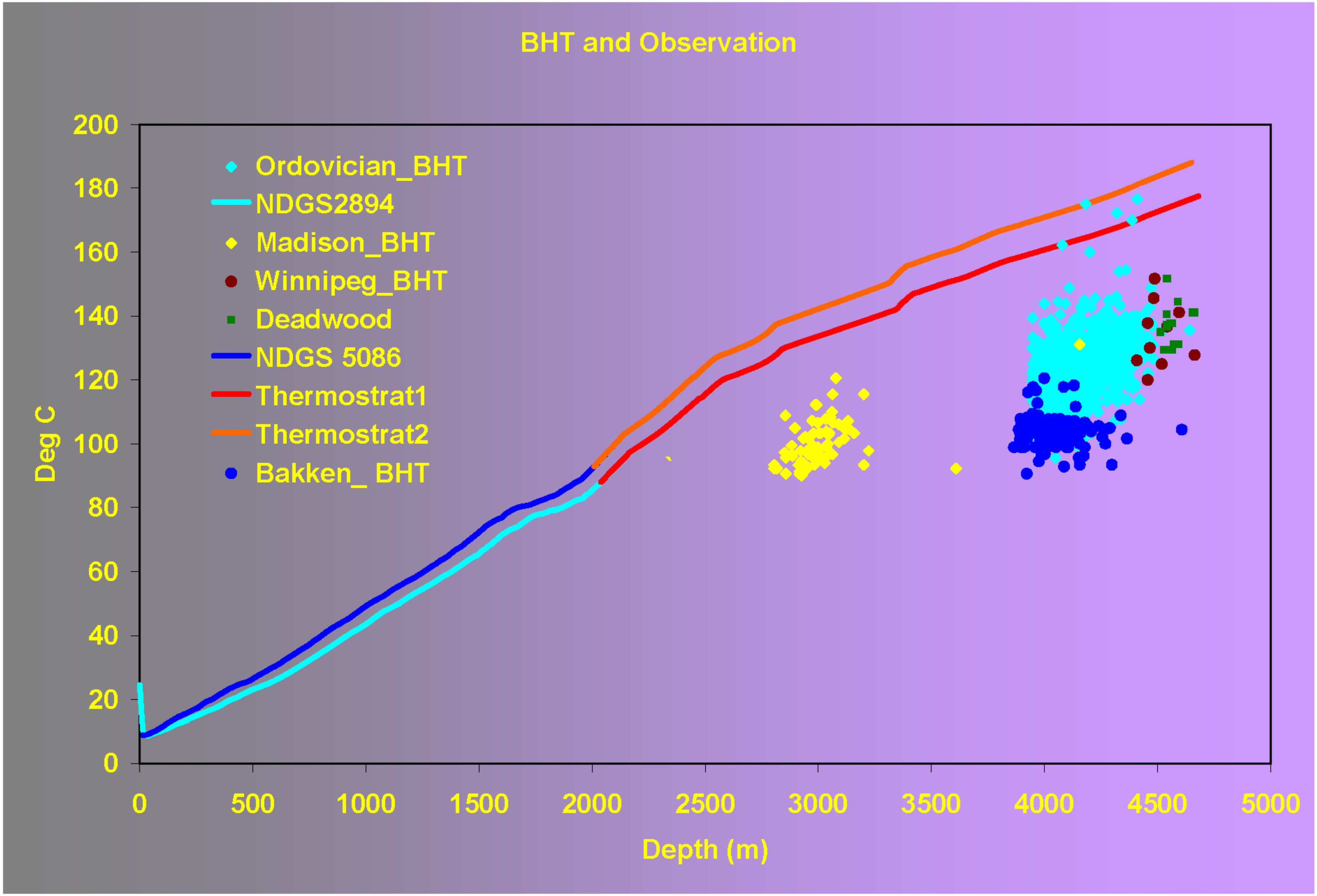


Colors are temperature, contours are depth (m), lines are county boundaries

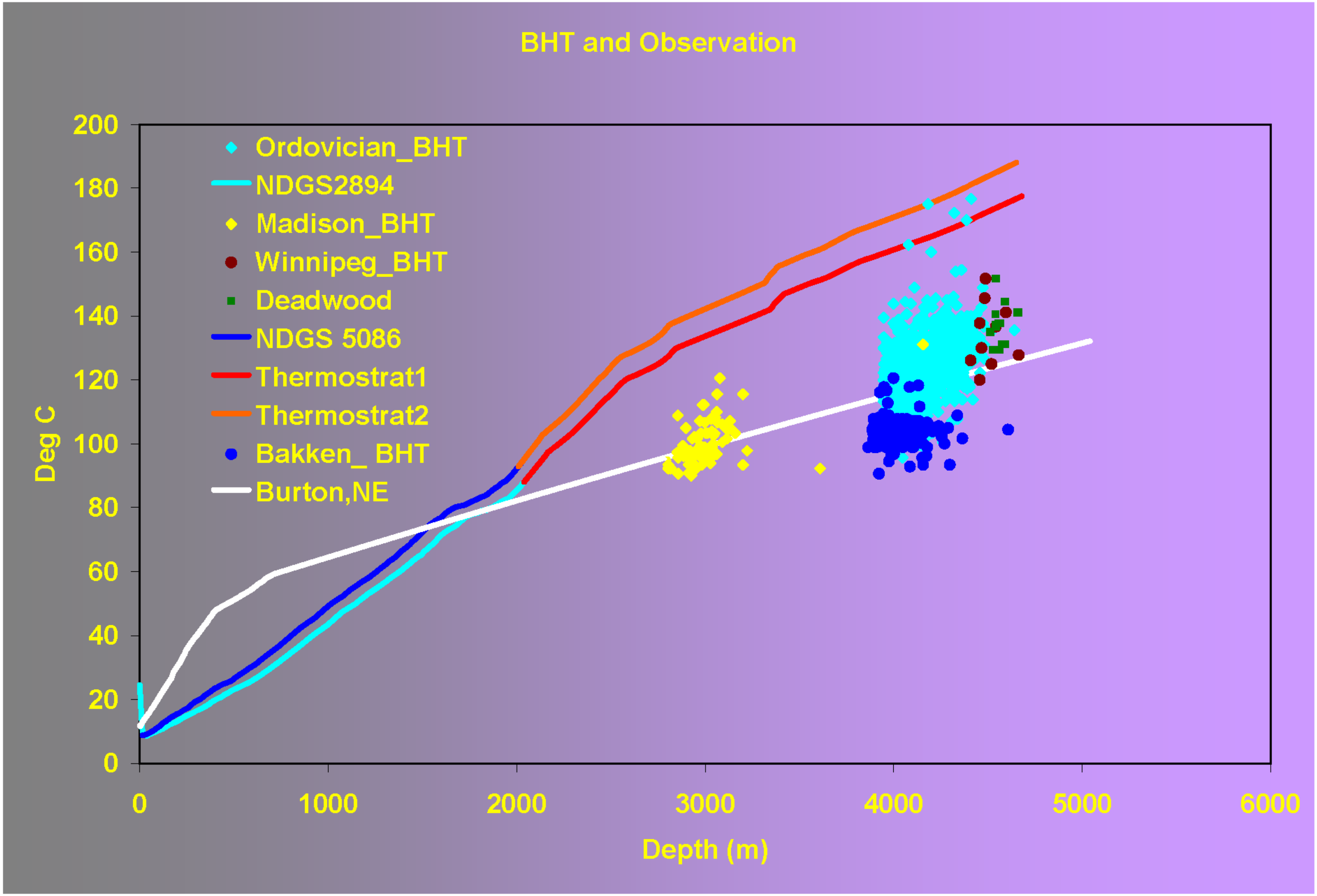
BHT's and Observations

- Although BHT data are useful, they often do not indicate actual temperatures at depth.
- The example from the Williston Basin is typical.


BHT and Observation
Deg C
0
20
40
60
80
100
120
140
160
180
200
Ordovician_BHT
NDGS2894
Madison_BHT
Winnipeg_BHT
Deadwood
NDGS 5086
Thermostrat1
Thermostrat2
Bakken_ BHT



BHT and Observation
Ordovician_BHT
NDGS2894
Madison_BHT
Winnipeg_BHT
Deadwood
NDGS 5086
Thermostrat1
Thermostrat2
Bakken_ BHT
Deg C
Depth (m)
0
20
40
60
80
100
120
140
160
180
200
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000



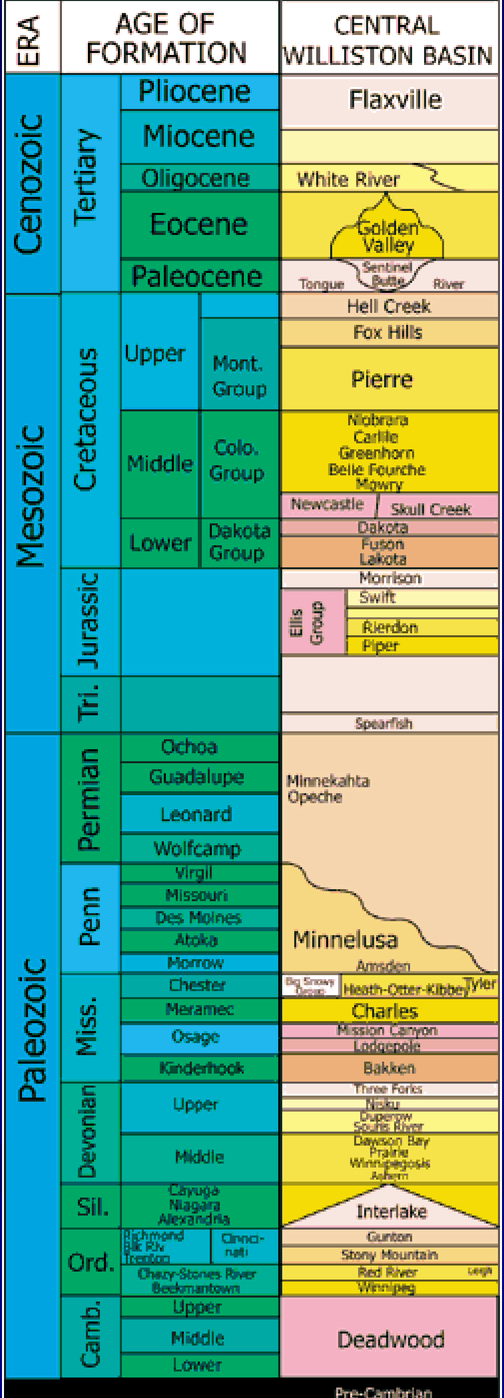
BHT and Observation
Deg C
Depth (m)
200
180
160
140
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
Ordovician_BHT
NDGS2894
Madison_BHT
Winnipeg_BHT
Deadwood
NDGS 5086
Thermostrat1
Thermostrat2
Bakken_ BHT
Burton,NE

The energy resource in Joules is calculated by

$$q_r = \rho c_v a d(t - t_{ref})$$

Surfer© GRID routines were used to calculate the volume of the formation above the reference temperature, e.g. 90 °C

Madison Fm = 1476 Quads



- Energy estimates for compared to oil and coal.
- Coal ~ 118 Quads
- Geothermal ~23 Quads
- Oil ~ 20 Quads

Summary

- Normal continental heat flow and subsurface temperatures characterize most of the region.
- Thermal blanketing effect of shales and heat advection in regional groundwater flow systems cause regional thermal anomalies.
- Heat flow, thermal properties, and stratigraphy can be used to determine subsurface temperatures with good accuracy.
- Bottom hole temperatures and equilibrium temperatures may differ.
- Temperatures of 180 °C can be found in the deeper regions of the Williston Basin and temperatures greater than 90 °C occur widely in the basin.
- In general, the recoverable stratabound geothermal resource in the region exceeds the energy that could be recovered from oil.