

*A Remarkable Effort to Test the Concept of
Electrical Power Generation from Co-Produced
Oil Field Geothermal Waters*



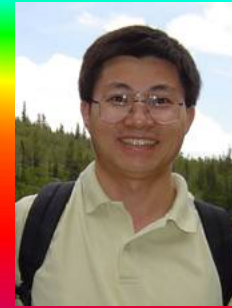
Will Gosnold



Mike Mann



Hossein Salehfar



Zhengwen Zeng

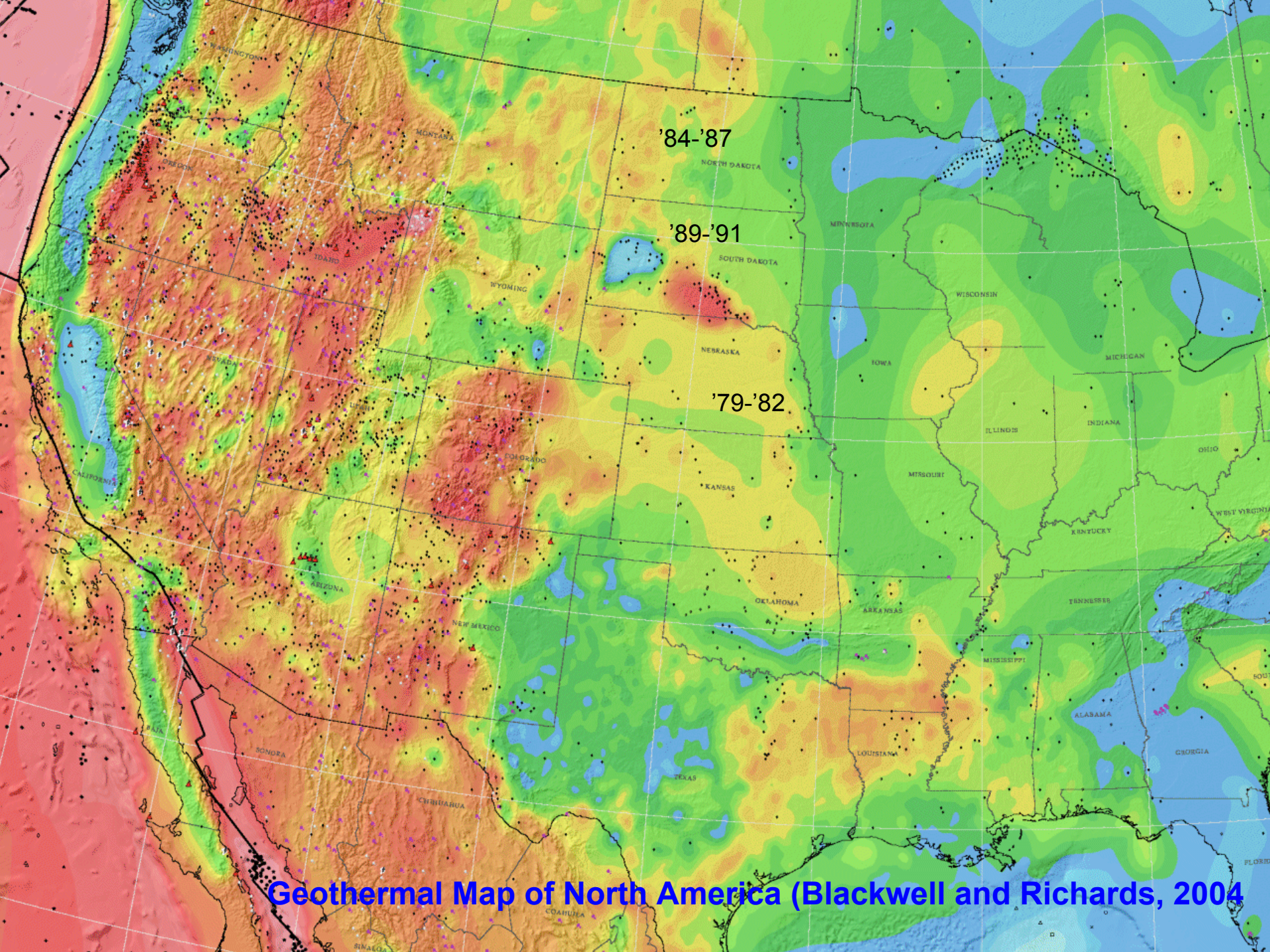


Gopal Bandyopadhyay

Geothermal Energy Utilization Associated with Oil & Gas Development
June 17-18, 2008
Southern Methodist University
Dallas, TX

Outline

- **Mid continent Geothermal Resources**
- **Impact of ORC**
- **DOE FOA**
- **Our Project**
- **Outcomes**



'84-'87

'89-'91

'79-'82

Geothermal Map of North America (Blackwell and Richards, 2004)

150 °C to 90 °C ND and SD basins

- USGS Circular 893: The principal water producing formations, the Dakota Group and the Madison aquifer contain **2,050 EJ**.
- Analysis of all potential aquifers in South Dakota and North Dakota indicates that the total accessible resource base in the two basins is approximately **33,700 EJ**.
- The MIT report used the Circular 893 numbers and estimated the US resource base as **100,000 EJ**.

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!

- **NSF EPSCOR**
- **E**xperimental **P**rogram to **S**timulate **C**ompetitive **R**esearch
- **Call for Proposals: Sustainable Alternative Energy**
 - **Two Stage Program**
 1. **Assess Geology, Geophysics, Engineering, and Economics**
 2. **Demonstration Project**

FINANCIAL ASSISTANCE

FUNDING OPPORTUNITY ANNOUNCEMENT

U.S. Department of Energy

Geothermal Technologies Program

**Electric Power Generation Using Geothermal Fluid Coproduced
from Oil and/or Gas Wells**

Funding Opportunity Number: DE-PS36-07GO97033

Announcement Type: Initial

CFDA Number: 81.087

Issue Date: 06/13/2007

Application Due Date: 07/31/2007, 11:59 PM Eastern Time

F. Application Requirements

Applicants must include clear and complete sections detailing 14 Technical, 10 Non-Technical, and Technology Transfer considerations.

- **Technical Considerations** section for projects funded through this funding opportunity must provide clear and concise information including but not limited to:
 1. Statement of Project Objectives;
 2. Geologic/geothermal reservoir data for the proposed project;
 3. Map showing proposed location and layout of wells, above-ground piping, and associated equipment for the project;
 4. Operational performance data from any previously tested units;

Technical Considerations (continued)

5. Make, model, and projected net power production of the proposed power plant;
6. Proposed power cycle including but not limited to process schematic² with stream state points at inlet and outlet of major components;
7. Handling and disposal of power plant working fluid;
8. Plans for water treatment and cleaning of scaled or fouled surfaces; and
9. Nature of cooling water supply (if used).

Technical Considerations (continued)

Actual characteristics of each well or separator that is proposed as a source of geothermal fluid, including:

10. Temperature;
11. Flow rate;
12. Quantitative analysis of produced fluids, including chemical analyses of water cuts and oil /natural gas;
13. Formation and depth from which the fluid is produced;
14. Modifications to the wellhead and/or surface systems, if necessary

(existing production and injection wells must be able to be re-entered without conducting well maintenance operations at the time of application submittal);

Non-Technical Considerations

including but not limited to:

1. Arrangements between leaseholders, developers, owners, operators, and/or others, including proof that all surface and/or subsurface rights including rights to utilize the geothermal resource and the oil and/or gas wells have been secured by the appropriate parties;
2. Proof of ability to provide the non-Federal share of project costs;
3. Status of regulatory and environmental permitting required for the project;
4. Arrangements for distribution/use of power including Power Purchase Agreement (PPA), if applicable;

Non-Technical Considerations (continued)

5. Pro forma applicable to a fully commercial project (not including federal cost share, equipment discounts, etc.) including taxes, royalties, lease payments, renewable energy credits, production tax credits, etc.;
6. Cost/benefit analysis including project benefits and impacts, and avoided cost of electricity;
7. Bill of Materials (BOM) with identification of long-lead items;
8. Deliverables;
9. Key personnel;
10. Project schedule, milestones, stage gates, go/no go decisions, etc.

Technology Transfer Considerations

including but not limited to:

- Plan for information dissemination and technology transfer (including but not limited to papers, web casts, site visits, press releases) to industry and others.

- The program required specific details that were extremely challenging to meet within the time period given.
- Our steps:
 - Commitment of the UND team
 - Contact NDGS
 - Contact UTC
 - Contact WEPC – Basin Electric

- ***University of North Dakota School of Engineering and Mines***
- **William Gosnold**, PhD, Professor of Geophysics and Chair of the Department of Geology and Geological Engineering Project PI.
- **Michael Mann**, PhD, Professor of and Chair of the Department of Chemical Engineering. Design the fluid handling system between the separator and the ORC system. Work with Dr. Zeng on all matters concerning the chemistry of the production and disposal fluids and the processing of any produced salts.
- **Hossein Salehfar**, PhD, Professor of Electrical Engineering. Design the electrical power and work with WEPC engineers to link the ORC system with the power grid.
- **Zheng-Wen Zeng**, PhD, Assistant Professor of Petroleum Engineering in the Department of Geology and Geological Engineering. Fluid handling systems and design of technology for future tech transfer to other systems.
- **Gopal Bandyopadhyay**, PhD, Chemical Engineering Research Associate. On-site engineer for all activities.

Project Partners

- ***North Dakota Geological Survey***
 - Lorraine Manz, PhD, North Dakota Geological Survey. Principal contact and administrator for the North Dakota geothermal regulatory program.
- ***Encore Acquisition Company***
 - Robert Sutherland, P.E., Management oversight for the oil field and all agreements and interactions among the four parties.
- ***West Plains Electric Cooperative, Basin Electric***
 - David C. Schelkoph, C.E.O., West Plains Electric Cooperative Inc. Management oversight for the link with the local electrical power grid and power purchase arrangements.
- ***UTC***
 - Halley Dickey, ORC power module

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 - David C. Schelkoph, C.E.O., West Plains Electric Cooperative Inc. Management oversight for the link with the local electrical power grid and power purchase arrangements.
- ***Ormat, Inc***
 - Carl Nett, ORC power module (induction generator), the condenser, and ancillary services to install the system.

Objective 1

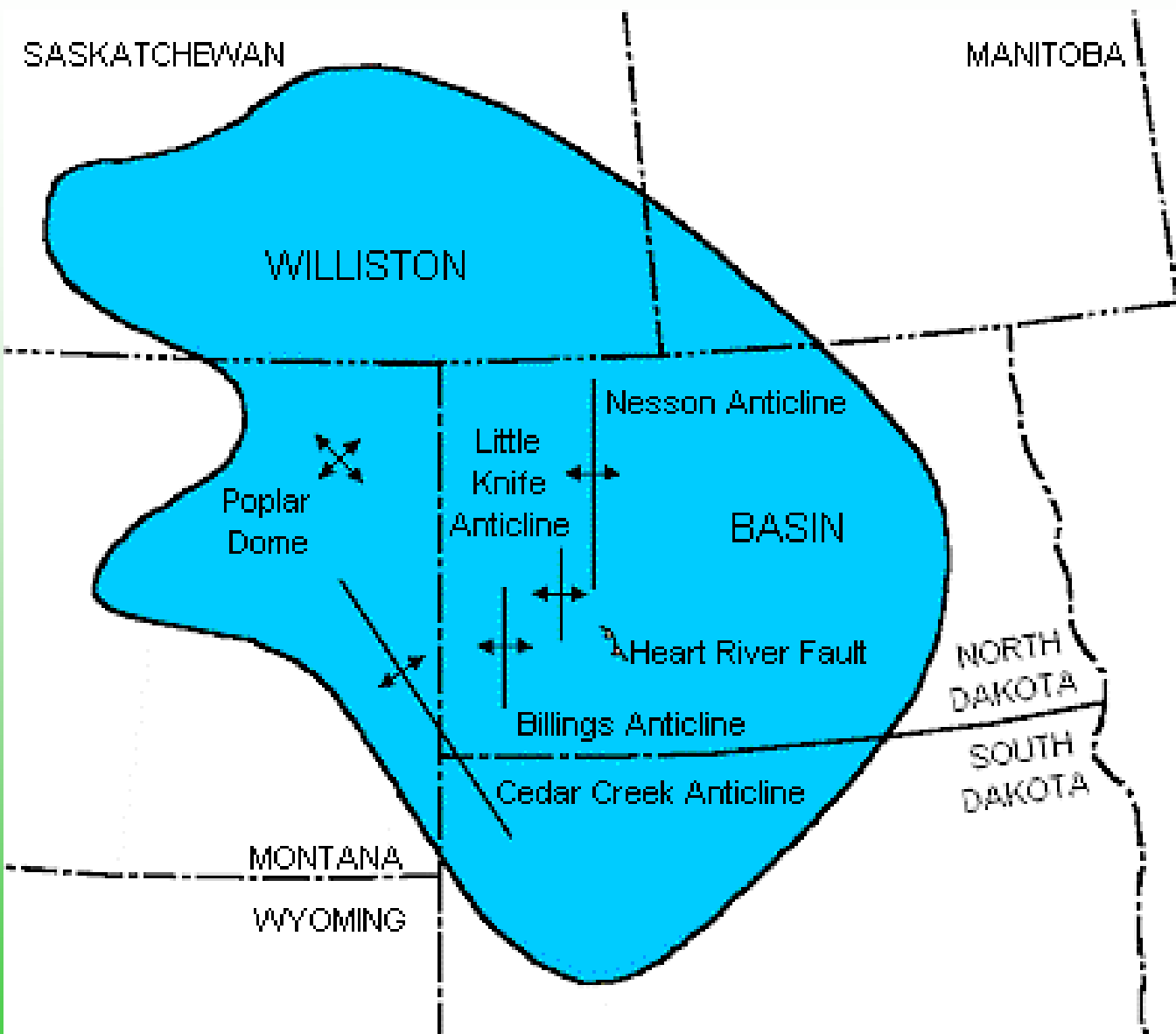
- ***Demonstrate the feasibility of adapting organic Rankine cycle (ORC) technology to generate electricity at economical rates using geothermal waters that are coproduced with oil and gas.***

Objective 2

- ***Demonstrate that the widely abundant low-to-intermediate temperature (90 °C to 150 °C) geothermal waters existing within sedimentary basins constitute a sustainable, environmentally sound, domestic energy resource that could provide a significant portion of the nation's electrical power.***

Objective 3

- ***Establish a Center of Excellence in ORC-geothermal power to grow the human resource base for large scale development of geothermal energy.***



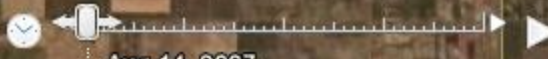
Systems	Rock Units		Permian	Minnekahta	
				Onesha	
Quaternary	Pleistocene	Pennsylvanian		Broom Creek	
	White River			Amsden	
Tertiary	Golden Valley	Mississippian		Tyler	
	Fort Union Group			Otter	
			Madison Group		Kibbey
		Charles			
	Mission Canyon				
Cretaceous	Hell Creek	Devonian		Lodgepole	
	Fox Hills			Bakken	
	Pierre			Three Forks	
	Judith River			Hindbear	
	Eagle			Duperow	
	Niobrara			Souris River	
	Carlile			Dawson Bay	
	Greenhorn			Prairie	
	Belle Fourche			Winnipegosis	
	Mowbray			Asbern	
	Newcastle		Silurian		Interlake
	Skull Creek				Stonewall
Jurassic	Inyan Kara	Ordovician		Stony Mountain	
	Swift			Red River	
	Riordan			Winnipeg Group	
Triassic	Piper	Cambrian		Deadwood	
	Spearfish				
Permian		Precambrian			

The production and reinjection unit is a reef system within the Lodgepole Fm (Miss).

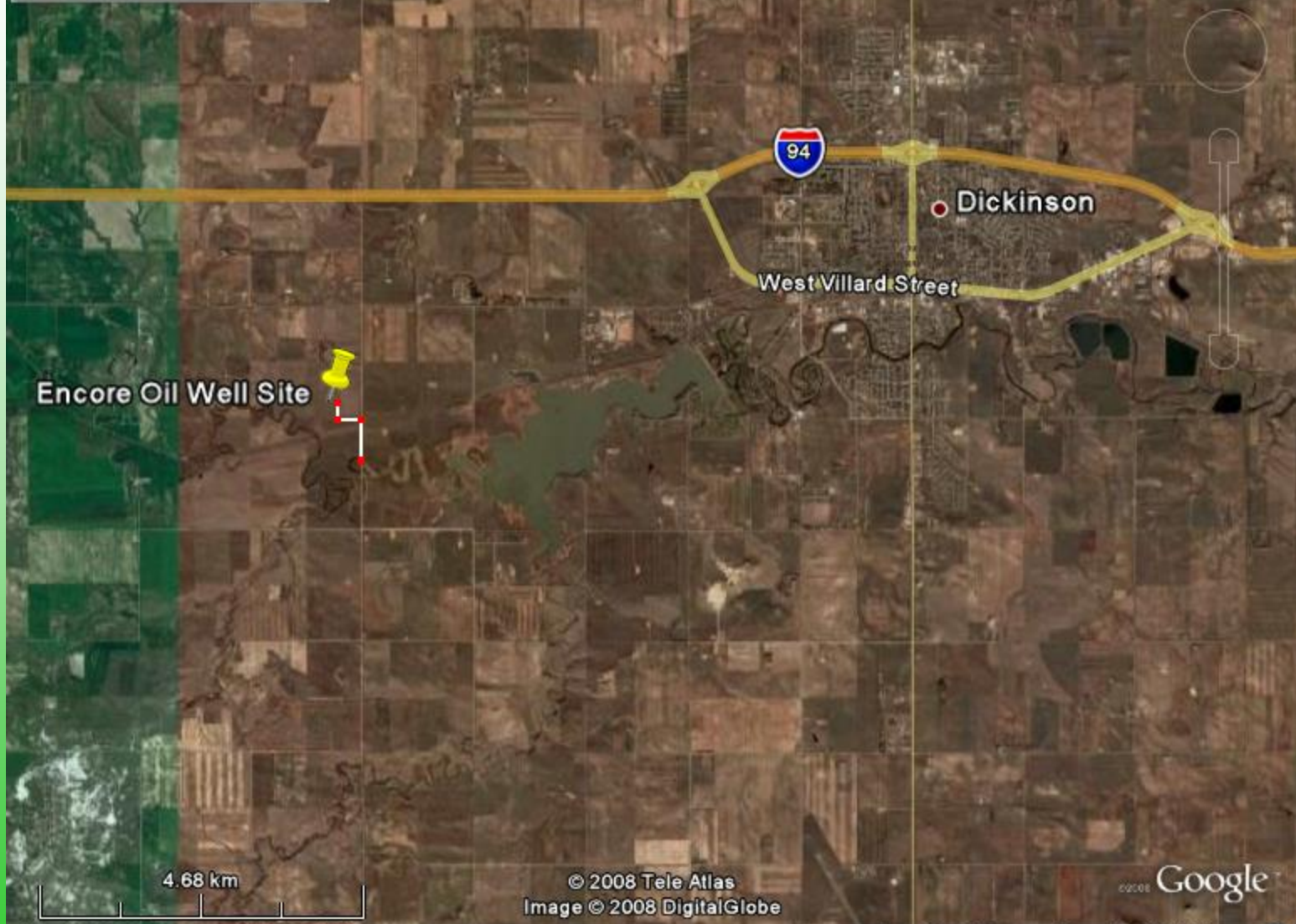
Fm depth is between 2787 m (9142') to 3023 m (9918') below ground surface.

Formation temperature is 118 °C (244 °F) and produced water temperature at the surface is above 100 C.

The selected well currently produces approximately 11,500 bbl per day (400 gpm) of water.



Aug 14, 2007
4:50:40pm



Encore Oil Well Site

Dickinson

West Villard Street



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Image © 2008 DigitalGlobe

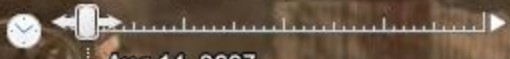
©2008 Google

lat 46.864948° lon -102.839112°

Nov 23, 2003

Eye alt 16.18 km

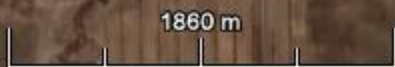




Aug 14, 2007
4:50:40pm



Encore Oil Well Site



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Image © 2008 DigitalGlobe

©2008 Google

lat 46.861372° lon -102.877460°

Nov 23, 2003

Eye alt 6.43 km



DICKINSON RESERVOIR PATTERSON LAKE

STARK COUNTY

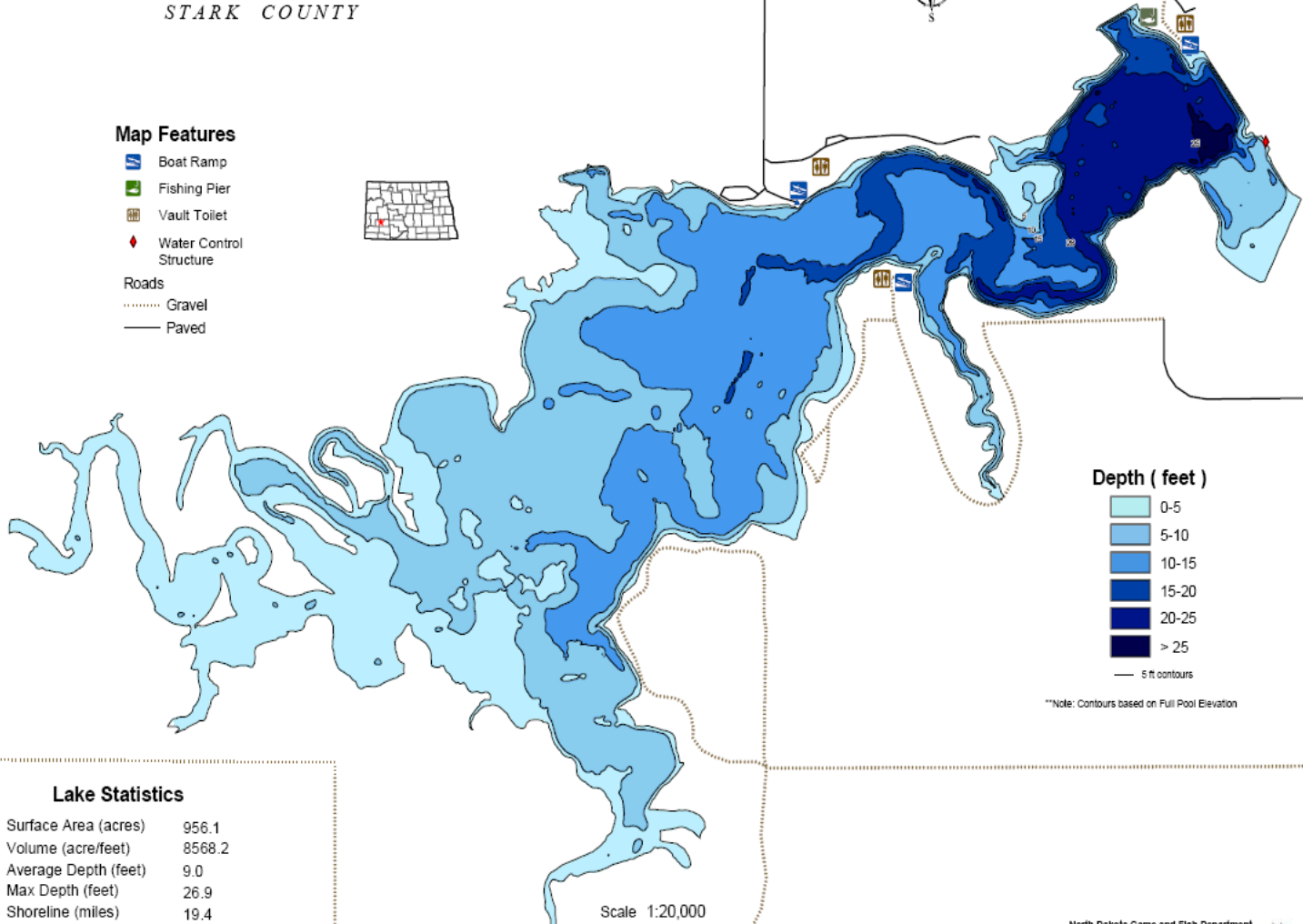
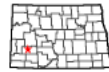
DICKINSON - 2MI ----->

ND GAME & FISH
SW DISTRICT OFFICE



Map Features

-  Boat Ramp
-  Fishing Pier
-  Vault Toilet
-  Water Control Structure
- Roads
 -  Gravel
 -  Paved



Depth (feet)

-  0-5
-  5-10
-  10-15
-  15-20
-  20-25
-  > 25
-  5 ft contours

**Note: Contours based on Full Pool Elevation

Lake Statistics

Surface Area (acres)	956.1
Volume (acre/feet)	8568.2
Average Depth (feet)	9.0
Max Depth (feet)	26.9
Shoreline (miles)	19.4

Scale 1:20,000



North Dakota Game and Fish Department
2003-04 Fisheries Division
NDGF-GIS-2303061.008.0-Krapp



Some Engineering Aspects

- Water chemistry
- Cooling cycle of the heat exchanger
- Fluid disposal
- A prototype water-cooled Ormat Energy Converter (OEC) estimated at 330 kW gross and 280 kW net.

Water Chemistry for Knopik #1-11 (NDGS 13715)

Cations	#1 (mg/L)	#2(mg/L)	#3(mg/L)	#4(mg/L)	#5(mg/L)	#6(mg/L)
Na	92500.0	101800.0	104200.0	104800.0	105200.0	82600.0
Ca	5262.6	9209.6	9773.4	9021.6	9397.5	13156.5
Mg	1785.8	4881.1	5119.2	3452.4	5833.4	5119.2
Fe	0.6	1.3	1.1	1.1	1.3	1.2
K	600.0	860.0	870.0	930.0	1060.0	2150.0
Ba	1.6	8.9	9.2	9.0	9.8	7.7
Cr	0.1	0.2	0.2	0.2	0.2	0.2
Anions						
Chloride	158089.0	189919.0	192041.0	189919.0	193102.0	164455.0
Carbonate	1995.4	0.0	0.0	0.6	0.0	0.0
Bicarb.	3600.2	280.7	396.6	414.9	372.2	384.4
Sulfate	411.8	197.0	159.1	70.8	220.9	64.5
Nitrate	0.0	0.0	0.0	0.0	0.0	0.0
TDS	264247.1	307137.7	312569.8	308619.1	315197.4	267938.7

Cooling cycle of the heat exchanger

- During the winter months, the low ambient temperature of the air would be used to condense the turbine outlet vapor using banks of high finned tubes.
- During the summer months, plate heat exchangers would be used to transfer the heat to cooling water drawn from a bank of shallow tube wells sunk in the bed of the Heart River that flows about 1/2 mile south of the project site.

- Disposal of the geothermal fluids in three existing disposal wells in the Eland-Lodgepole field.
 - NDGS 13731 (1/2 miles)
 - NDGS 13819 (1/2 mile)
 - NDGS 13764 (1.5 miles)
- Fluid injection into Lodgepole formation.
- The combined injectivity of these three wells is 21,000 bbl/day and our requirement is 11,500 bbl/ day.

Objective 2

- ***Demonstrate that the widely abundant low-to-intermediate temperature (90 °C to 150 °C) geothermal waters existing within sedimentary basins constitute a sustainable, environmentally sound, domestic energy resource that could provide a significant portion of the nation's electrical power.***

Williston Basin

- 41 hydrocarbon producing formations, 39 produce oil and 2 produce nitrogen and methane.
- Total oil 1,602,055,219
- Total water 2,927,574,334

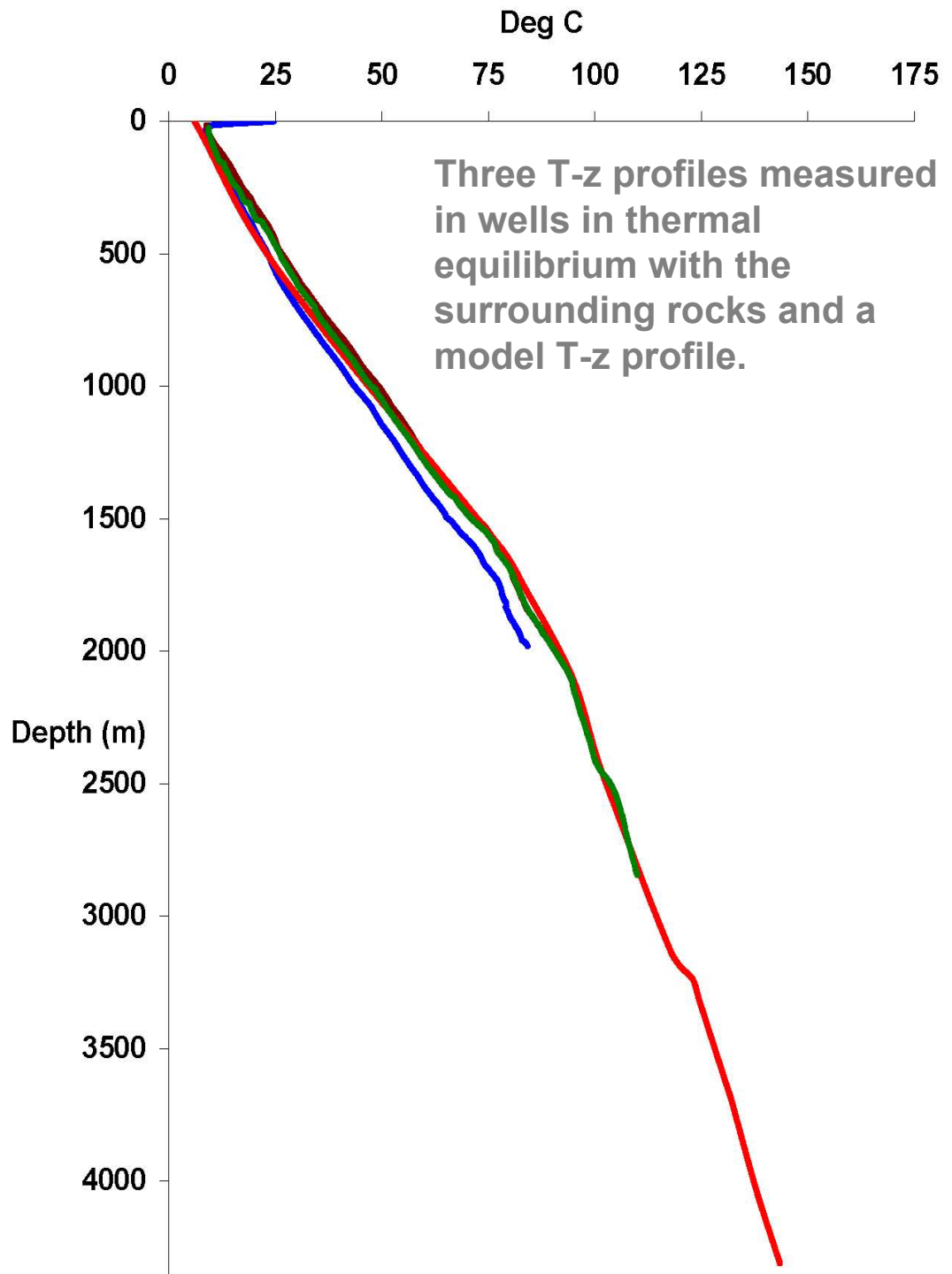
Thermostratigraphy is the application of Fourier's law of heat conduction to calculate temperature at depth

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

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

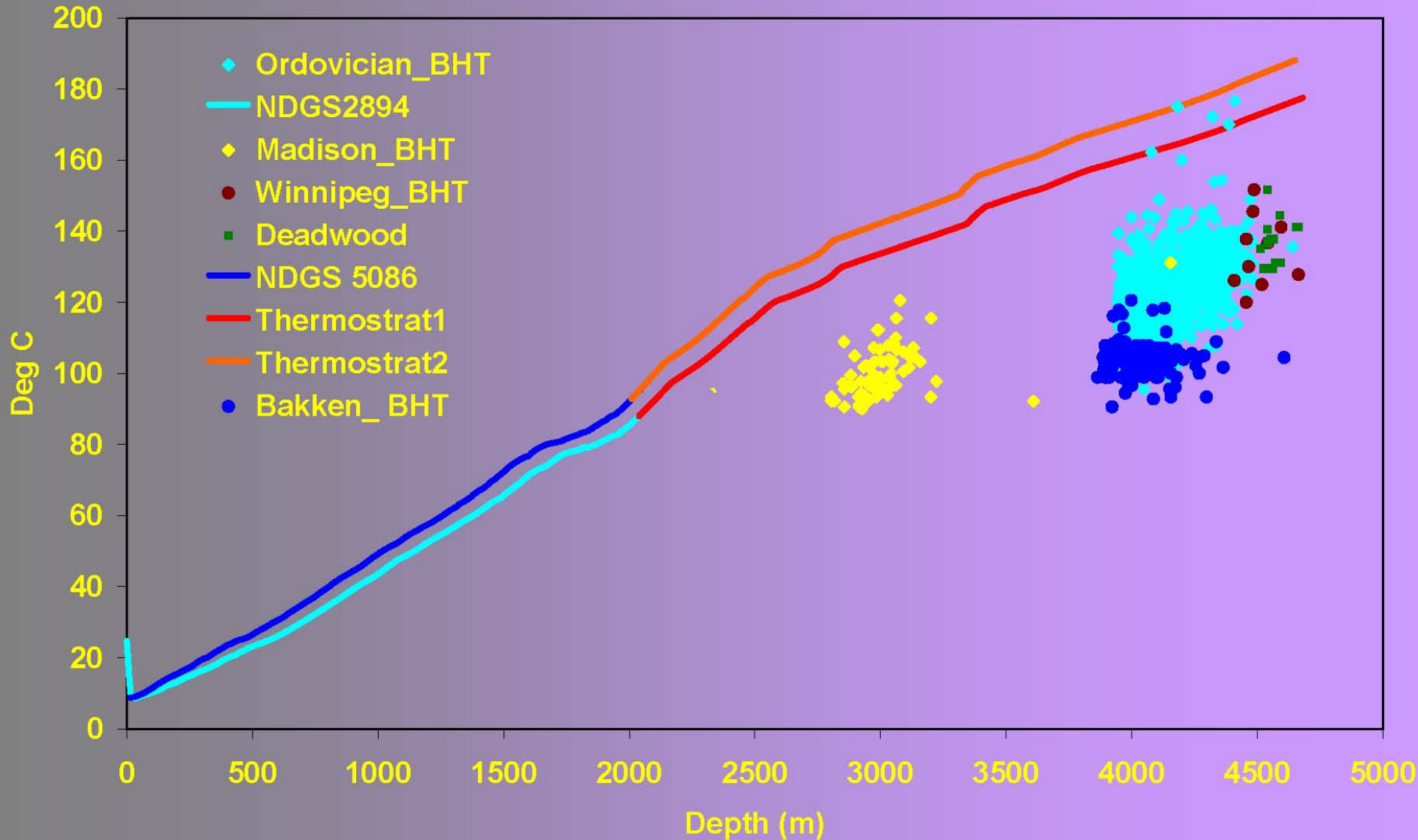
$$T(z) = T_0 + \sum_{i=1}^n \frac{Z_i}{K_i} Q$$

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



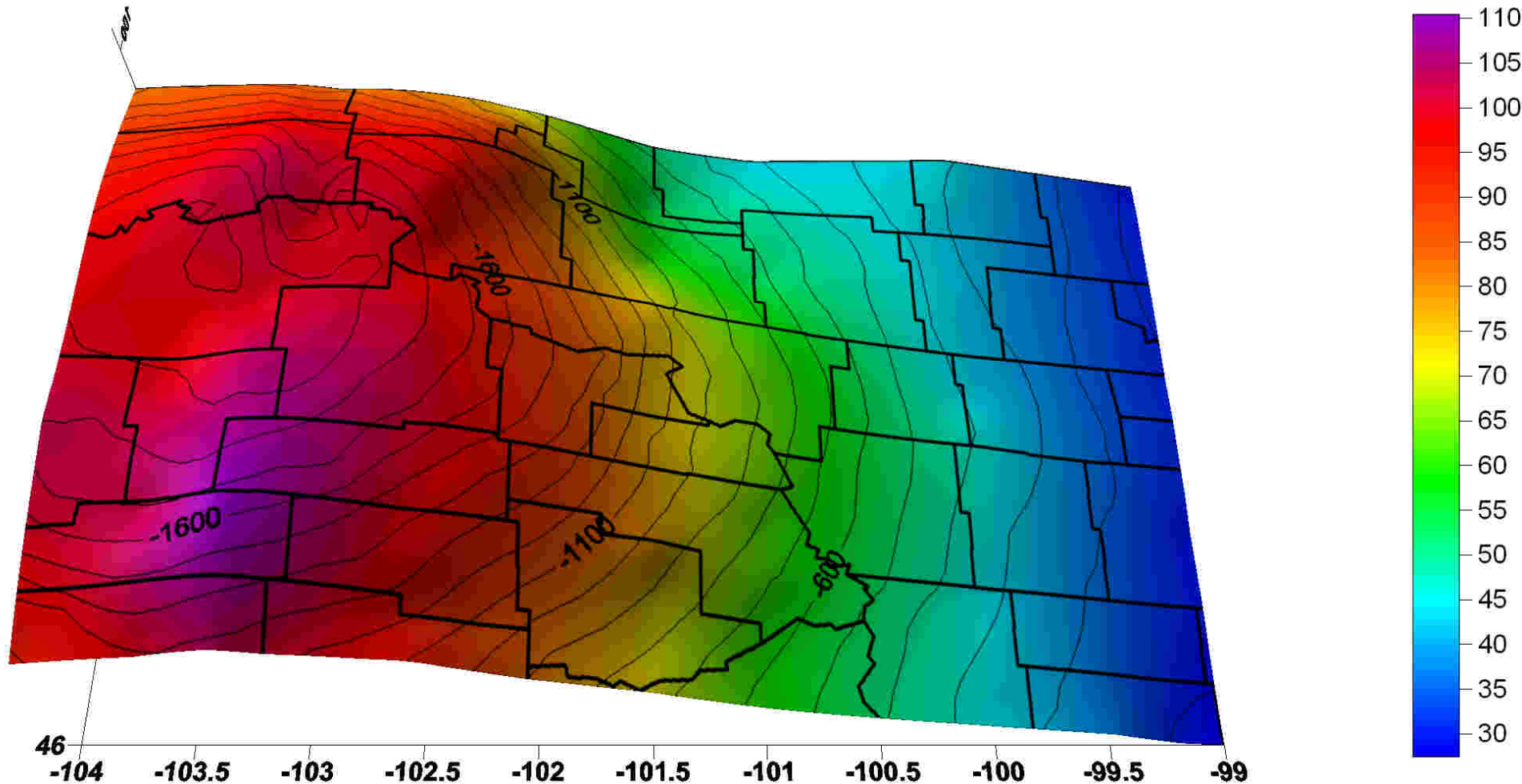
Use the equilibrium temperature not the BHT

BHT and Observation



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

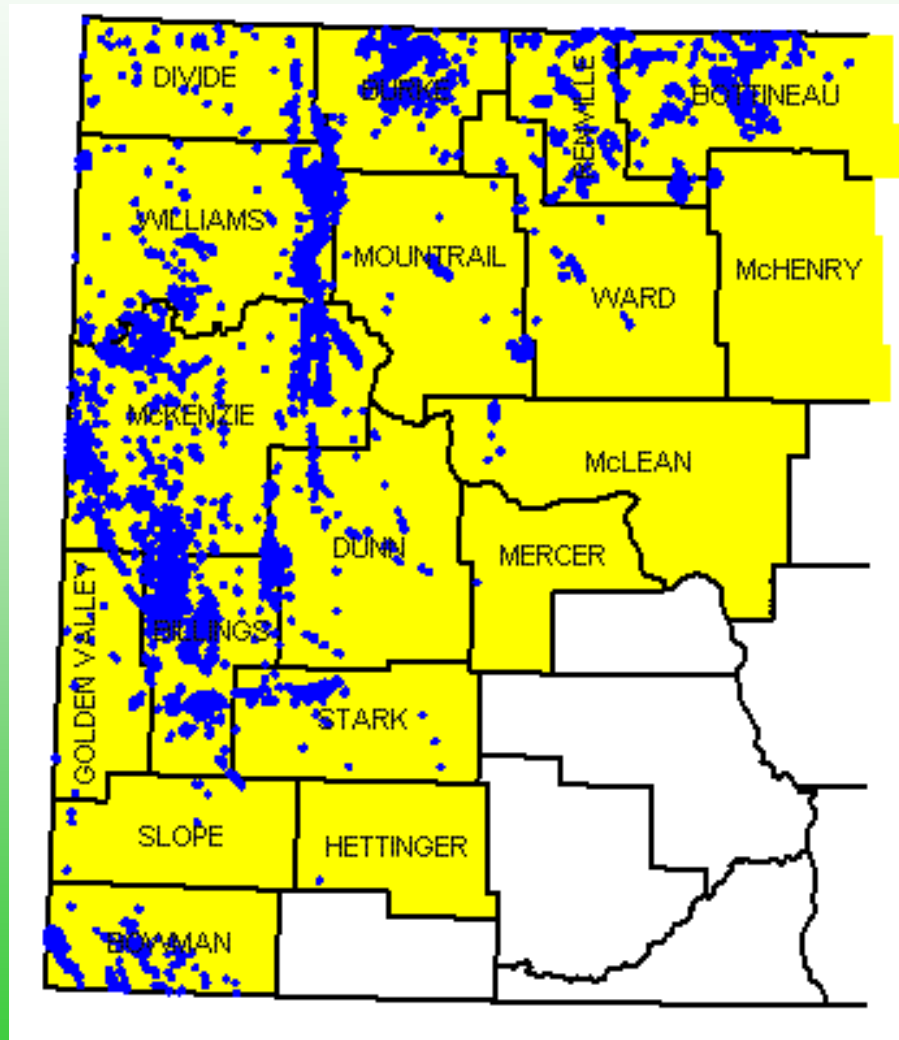
The Madison Fm in western North Dakota contains 1,476 EJ.



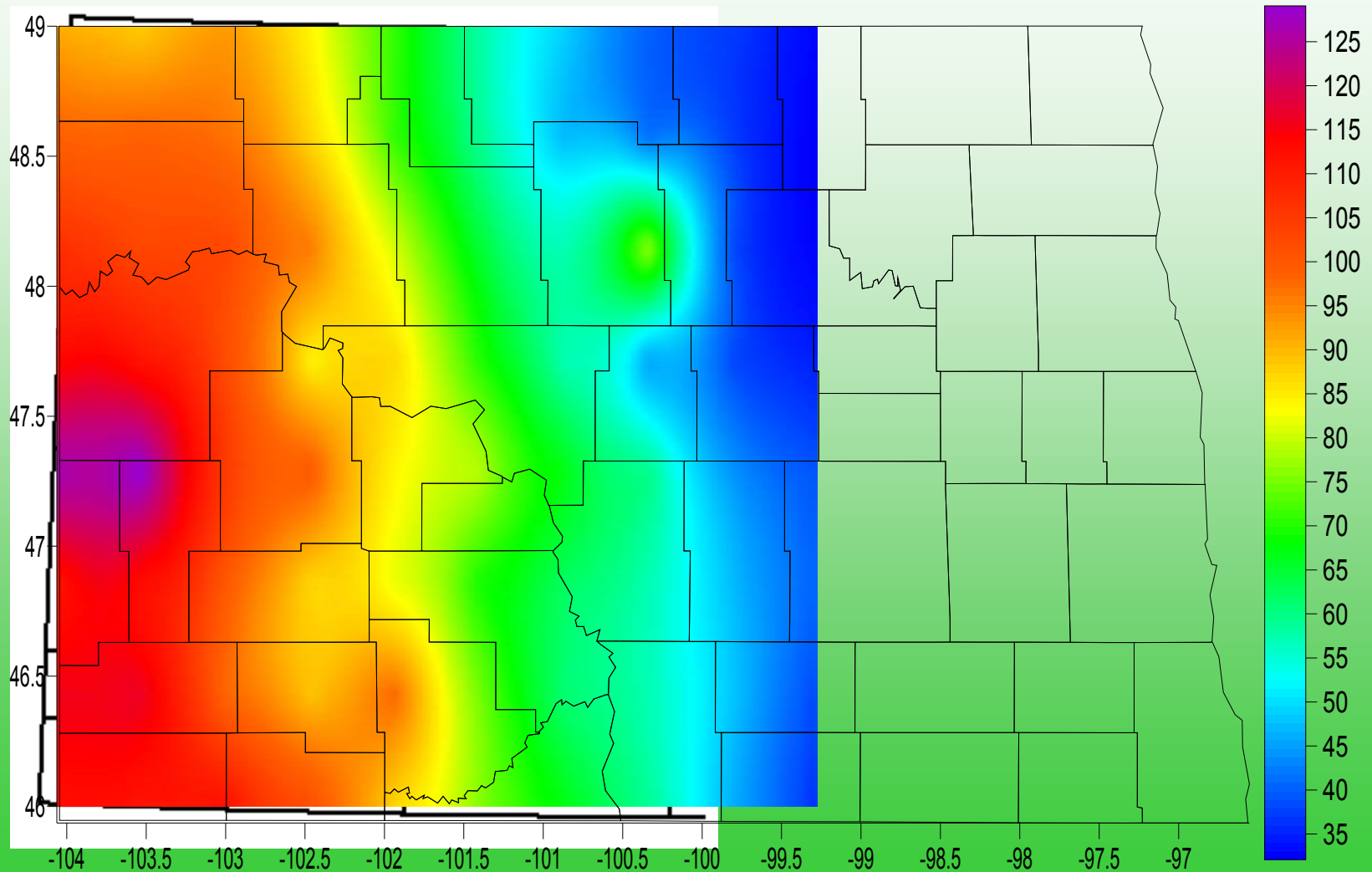
Colors are temperature, contours are depth (m), lines are county boundaries

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	

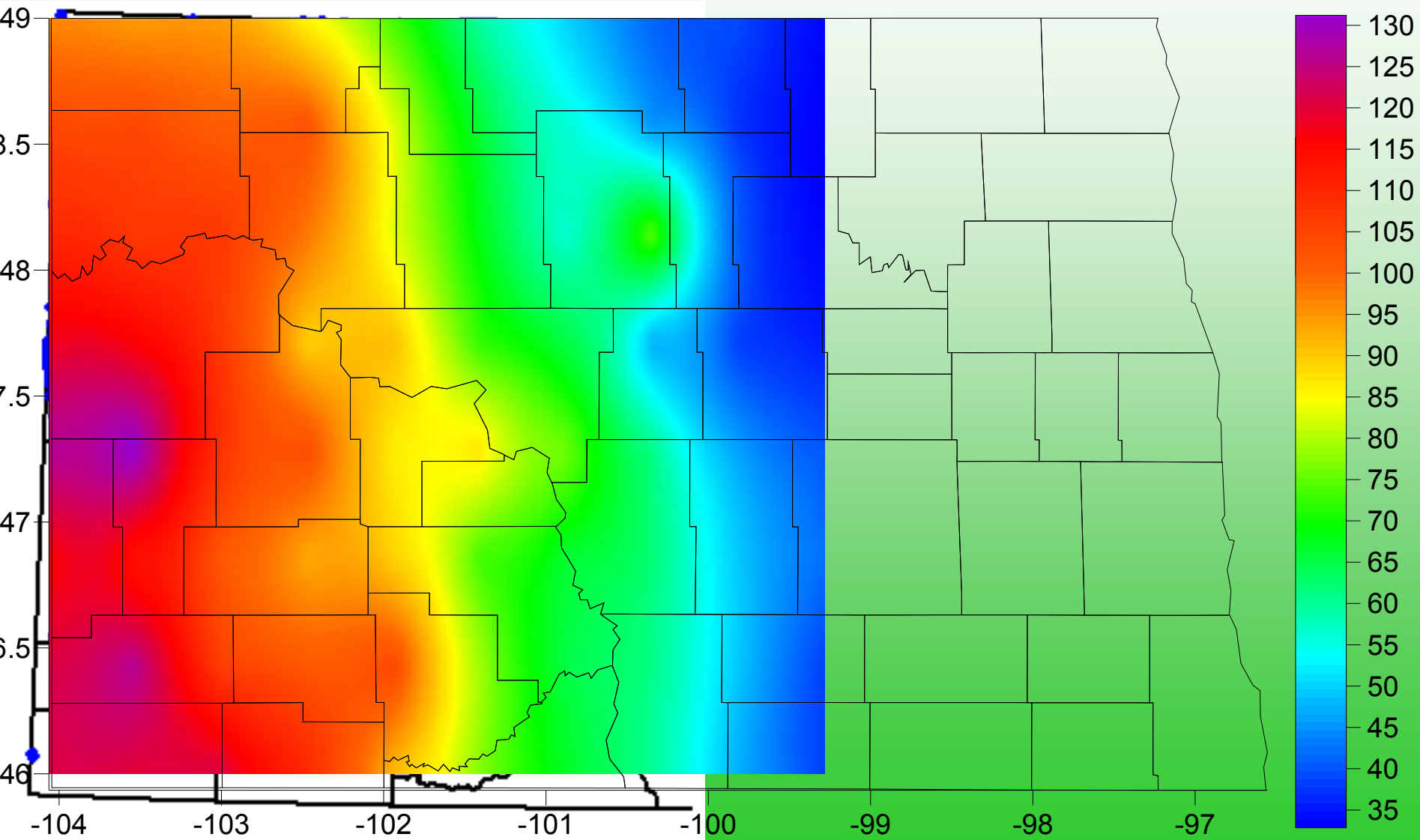
ND oil producing counties



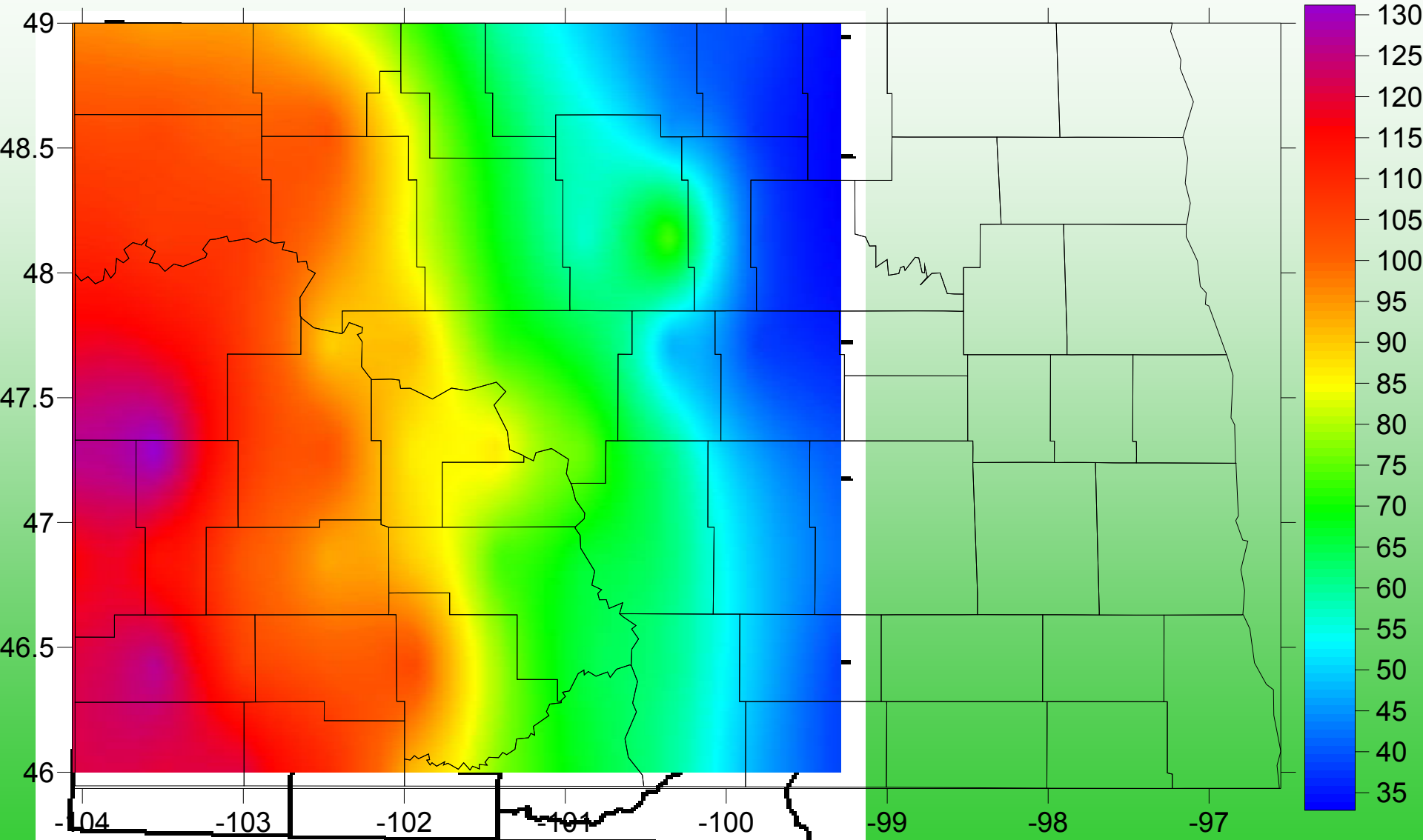
Bakken Fm (Ordovician)



Madison Fm (Miss) Maximum thickness 600 m

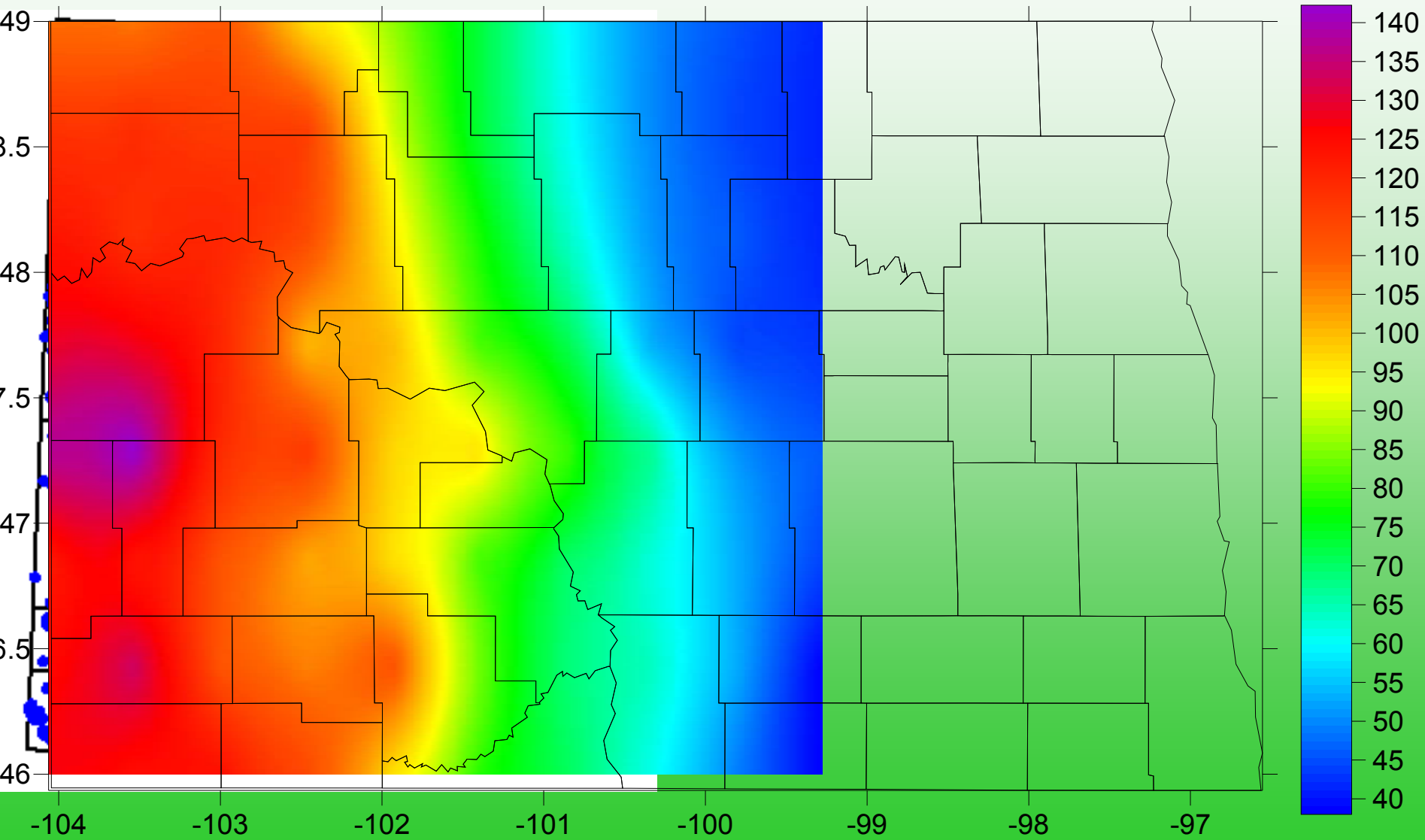


Duperow (Devonian)

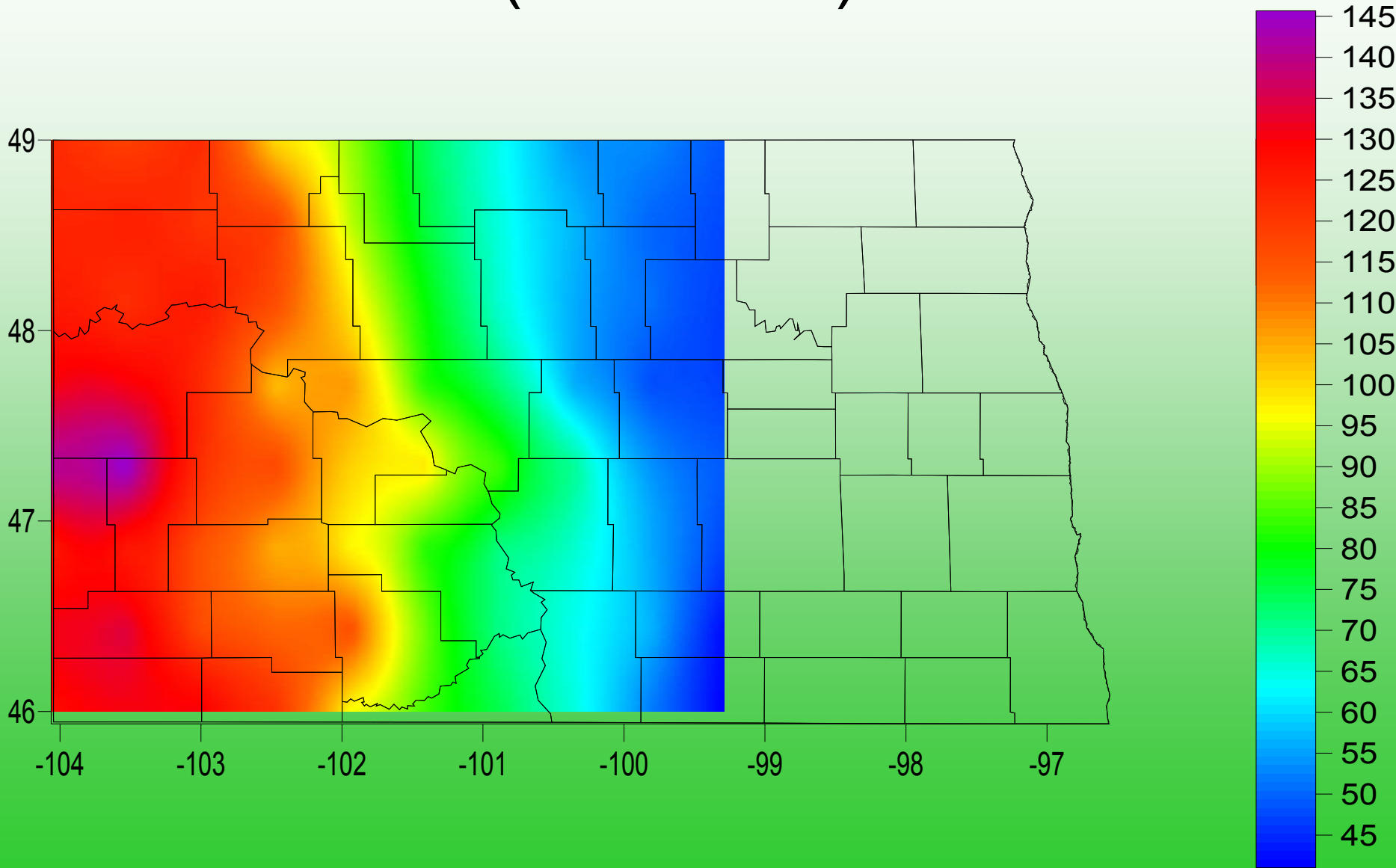


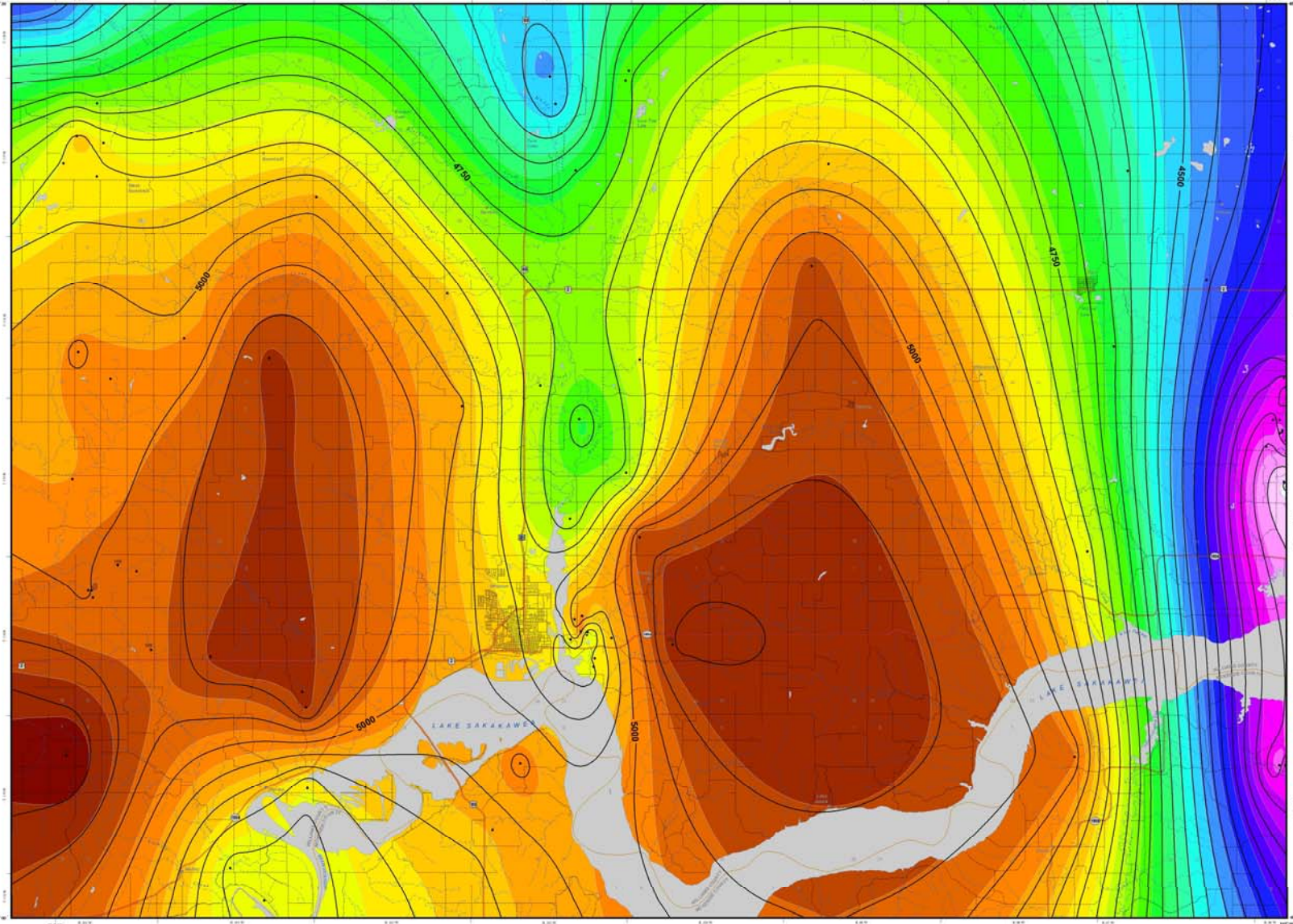
Red River Fm (Ordovician)

Maximum thickness 215 m



Deadwood Fm (Cambrian)





Geothermal energy is a clean and renewable source of producing an uninterrupted supply of electrical power and heat. In stable sedimentary basins, low-temperature geothermal energy (< 140°F) is extracted from the shallow subsurface (1-2-km) from the use in domestic and commercial heating and cooling systems. Increasingly, deeper, hotter resources in these regions have not been developed because they were not economical. However, as the nation explores ways to reduce its dependency on foreign energy sources and also begins to look more closely at recoverable energy, increasing deep geothermal energy resources, particularly the existing oil and gas wells, is attracting a great deal of interest (<http://www.nad.gov/geothermal/>).

The Dakota Group contains the shallowest of low-temperature geothermal aquifers that occur in the Williston Basin. The map shows calculated temperatures (°F) at the top of the Mowry Formation, the uppermost of the four rock units that comprise the Dakota Group (Fig. 1).

Figure 1. Generalized stratigraphy of the Dakota Group.

Thickness (ft)	Rock Column	Rock Unit	Description
100	DAKOTA GROUP	Mowry	Thin, medium to fine, gray, calc. arenaceous, highly porous, micritic, sandstone with occasional thin shaly partings.
100		Newcastle	Medium to fine, gray to reddish-brown, calc. arenaceous, micritic sandstone with occasional thin shaly partings.
100		Wart Creek	Thin, medium to fine, gray, calc. arenaceous, micritic sandstone with occasional thin shaly partings.
100		Hayes	Thin, gray, calc. arenaceous, micritic sandstone with occasional thin shaly partings.
100	Kears	Thin, gray, calc. arenaceous, micritic sandstone with occasional thin shaly partings.	

There are no reliable data sets for North Dakota that either list, or enable determination by extrapolation, subsurface temperatures in the Cretaceous study - Basin. Late temperatures from oil well logs are unreliable and to assume that a simple linear relationship exists between temperature and depth would be incorrect. Although generally lower the geothermal gradient in the upper lithologies is significantly affected by thermal insulation from the oil thermal conductivity in the earth's crust. An analytical model to accurately calculate subsurface temperature must therefore take these factors into account. The value for subsurface temperature in a given location (1985) showed here as a given depth (Z) the temperature (T) can be represented by the following equation:

$$T = T_s + \frac{Q}{k} \sum_{i=1}^n \frac{Z_i^2}{2Q_i}$$

Where:
 T = Subsurface temperature (in °C)
 T_s = Surface temperature (in °C)
 Z_i = Thickness of the overlying rock layer (in meters)
 k = Thermal conductivity of the overlying rock layer
 Q_i = Regional heat flow

For the data set used to produce this map T_s, k, and Q were assumed to be constants. Mean surface temperature (T_s = 3.1°C [31°F]) was calculated from monthly mean records for Bismarck International Airport, Fargo, Moorhead, Grand Forks International Airport, and Williston (Bismarck Airport) for the period 1971 to 2000 (<http://climate.nodap.gov/geothermal/100k/w31gkm/>). Thermal conductivities (k) for formations overlying the Mowry are shown in Table 1.

Formation	Thermal Conductivity (W/m K)
Lake Couleuvre, Pelican and Niagara shales, silt and sand	1.7
Clare	1.7
Clareton	1.7

Table 1. Thermal conductivity estimates from Goswami (1984).
 Regional heat flow (Q = 62 mW/m²) was averaged from statewide data.
 Rock units and thickness were obtained from oil well log logs (July 2006 update).
 Temperatures were only calculated for wells where all relevant log logs were given since uncertainties (particularly for the Pierre Formation) do not necessarily imply that units are absent.

A description of the geophysical method and metadata used in the compilation of this map are available on CD.

References:
 Goswami, D.K., 1984. Geothermal Resources Assessment for North Dakota. Final Report U.S. Department of Energy, Bulletin No. 36-104000-01.



- Geologic Symbols**
- Depth (in feet from surface) to Top of Mowry Formation
 - Data Point, Selected points show temperature in °F
 - Scale 1:100,000
 - Historic Petroleum Well (1927 North American Division, Grand Forks, ND)
 - Revised Well (1985 Grand Forks Engineering, ND)
- Other Features**
- Stream
 - Stream/Reservoir - Perennial
 - Stream - Intermittent
 - County Boundary
 - Federal Highway
 - State Highway
 - Paved Road
 - Unpaved Road

*Note: This map was expanded beyond the normal Williston 100K sheet to include an additional width of two miles to the western border.
 (Source: Goswami, D.K., 1984.)

Outcomes

Center of Excellence Application

- \$3 million from State Dept. of Commerce
- \$6 million from industry
- Seven objectives – one is development of electrical power from oil field waters

Minnesota Dept. Natural Resources

- EGS to meet requirement for power from renewable sources

Final Points

- Estimates of the energy that could be generated from co-produced U.S. oil field waste waters range from 4,590 to 21,933 MWe depending on the temperature of the resource.
- Development of existing capped and abandoned wells for water production can provide significant, sustainable, and environmentally sound power resource.

North Dakota Morning Commute



“If you consider it a sport to gather your food by drilling through 8 inches of ice and sitting there all day hoping that the food will swim by, you might live in North Dakota.” **Jeff Foxworthy**