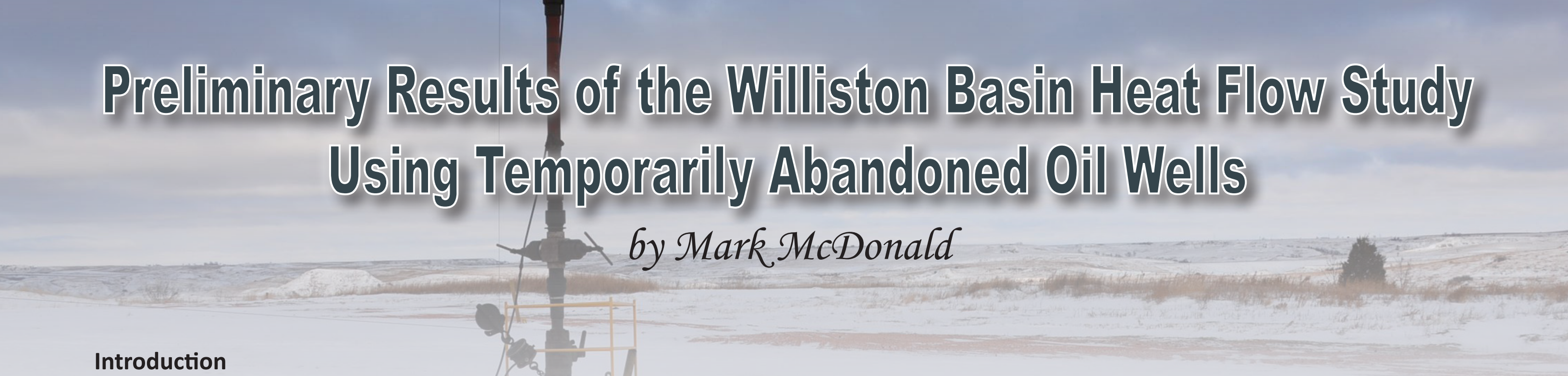


Preliminary Results of the Williston Basin Heat Flow Study Using Temporarily Abandoned Oil Wells

by Mark McDonald

Introduction

As presented in the January and July 2014 issues of Geo News (Nordeng, 2014; McDonald and Nordeng, 2014) the North Dakota Geological Survey has initiated a temperature logging program in the Williston Basin. Additional funding for this project was obtained from the North Dakota Petroleum Council. To date we have logged 21 temporarily abandoned oil wells to depths ranging from 3,000 ft. (914 m) to 13,000 ft. (3,962 m) operated by 11 different companies. The wells were selected based on location, depth, length of time being undisturbed and the ability to obtain permission to log the wells from the current well operators. The locations of the wells are shown on figure 1.

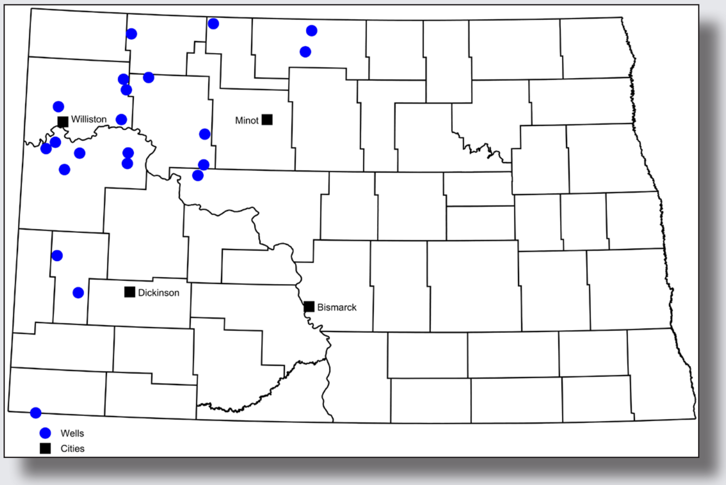


Figure 1. Location of temporarily abandoned wells that were logged (blue) in North Dakota.

The primary goal of the program is to gain further insight into the thermal history of the basin that may result in the development of improved models for use in exploration for oil and natural gas (Prensky, 1992). The program has also been designed to gather data useful in the evaluation of the geothermal potential of the Williston Basin. Insight into the timing of petroleum generation, migration, accumulation and preservation can be gained by determining the thermal maturity of hydrocarbons and/or by using the paleoheat flux of a sedimentary basin (Nuccio and Barker, 1990). Subsurface temperature is important to understanding the origin and evolution of sedimentary basins and can also be used in the determination of important kinetic factors as described by Nordeng and Nesheim (2011) and Nordeng (2012, 2013, 2014) which can ultimately be used to predict the oil generation potential of various geologic formations within the Williston Basin. These heat flow values represent critical pieces of data that are needed to validate and, where needed, update current heat flow maps (Blackwell and Richards, 2004). Heat flow together with thermal conductivity values of subsurface rocks can be used to estimate subsurface temperatures at other locations and depths. This information can also be used in the evaluation, assessment and possible exploration and development of geothermal energy in the Williston Basin.

Methodology

The project consisted of lowering a GOWell Model GTC43C Pegasus® temperature probe with an accuracy of 0.50C into 21 temporarily abandoned oil and gas wells to the bottom of the well (depth of the plug). This memory logging tool was lowered into the wells by means of a 0.092 inch "slickline" (nonconductive cable) operated by Gibson Energy Inc. (WISCO Division). After setting the equipment up over a well (figs. 2 and 3), a gauge ring (dummy or slug) was lowered into the well to

Figure 2. Logging crew connecting the tool to the slickline. From left to right: Mike Harden, WISCO, David Smith, WISCO, Jay Jamali, GoWell, and Kevin Hammer, WISCO.

Figure 3. Slickline unit set up over NDIC Well # 12363, Astrid-Ongstad 14-22 north of Tioga, ND.

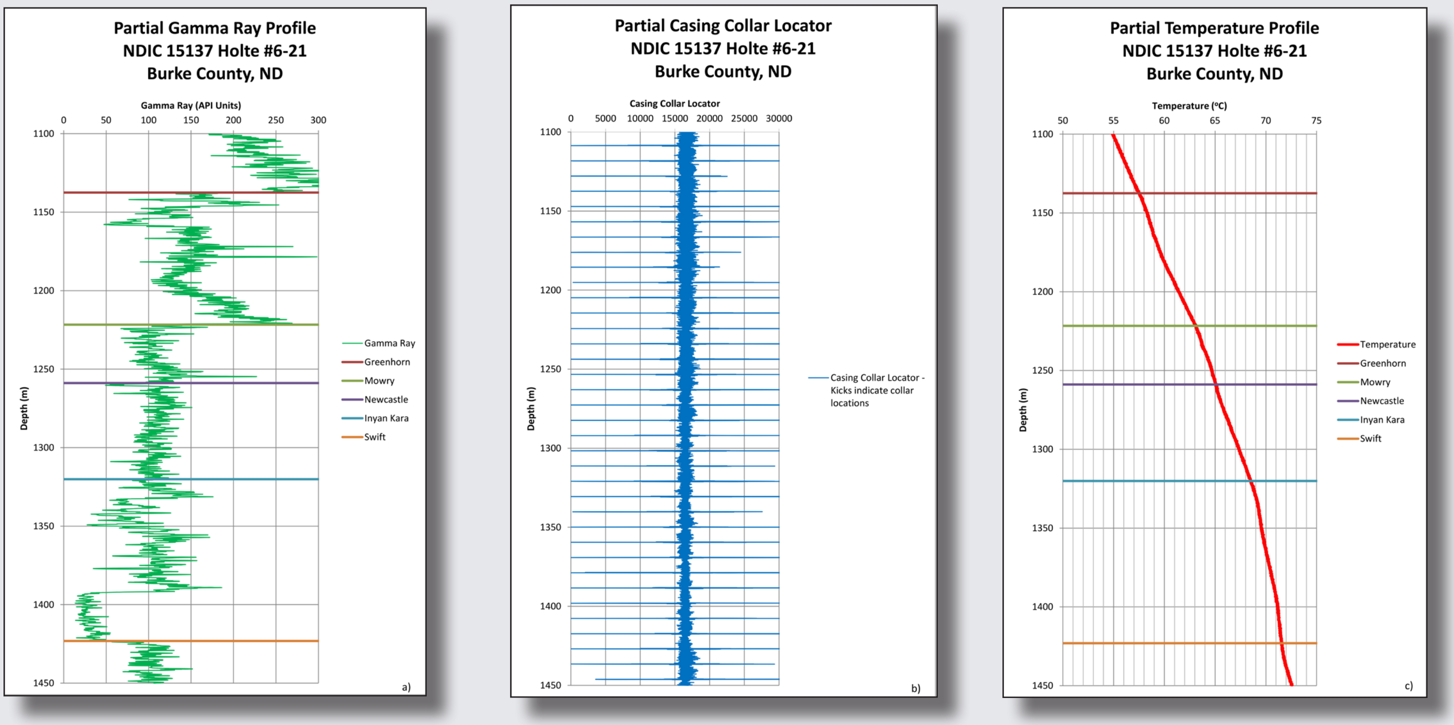


Figure 4. Partial profiles of the Holte #6-21 well: a) partial gamma ray profile illustrating formation top picks; b) partial casing collar locator profile; c) partial temperature gradient profile with formation top picks.

verify that there were no obstructions within the well and to determine the maximum depth that could be logged for wells containing production tubing or where other potential obstructions might exist within the wellbore. After removal of the gauge ring, a period of time (generally on the order of an hour or more) was allowed to elapse in order that the well fluid temperatures could re-equilibrate before lowering the logging tools. For wells that were known to not contain production tubing, the gauge ring was not deployed. The wells were then logged as the tool was lowered into the well to minimize temperature disturbance or mixing of the fluids arising from the displacement of fluids by the volume of the tool. In addition to temperature, the tool was also equipped with a casing collar locator (CCL) and a gamma ray probe to aid in correlation of the temperature probe with depth and with the geologic formations (fig. 4). As noted above, a memory tool was used which recorded the probe readings at a rate of one reading every 40 milliseconds (ms). The readings were downloaded to a computer after the tool was brought back to the surface. For comparison purposes, the wells were also logged on the way back out of the wellbore.

Gradient or station stops were also made as the tool was lowered into the wells. On the first few wells, these stops were made more frequently (every 2,000 to 3,000 ft.) to ascertain the response time of the tool in an effort to optimize the logging speed and to obtain an indication of the tool's precision. Once a reasonable logging speed was determined, a ten minute gradient stop was typically made at the approximate midpoint of the well and again at the bottom of the logging interval for the remaining wells.

After the data had been downloaded from the tool into the computer, it was processed using Scientific Data Systems Warrior®

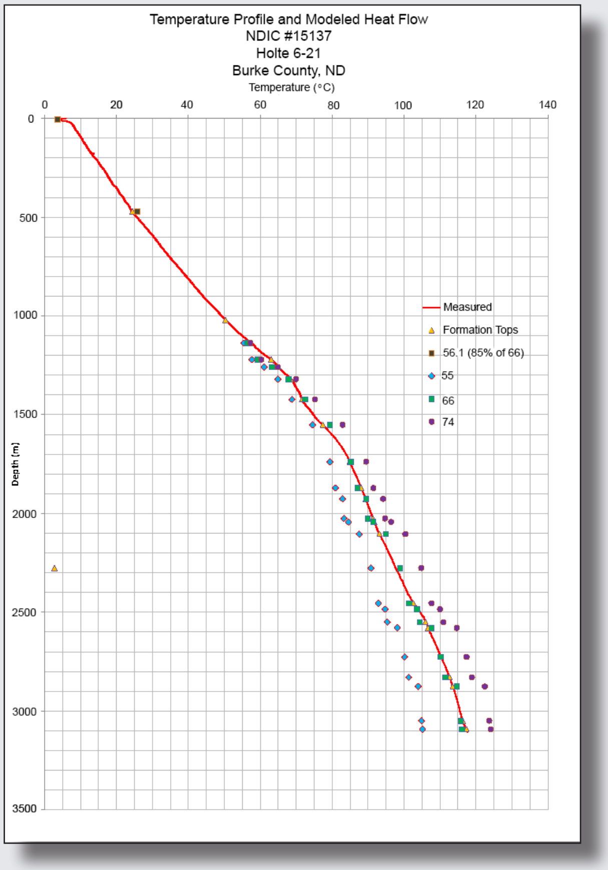


Figure 5. Measured temperature profile and modeled estimates using various assumed heat flow values. After a close match was obtained, values of thermal conductivity were adjusted to further refine/match the measured profile. Heat flow units are in mW m^{-2}.

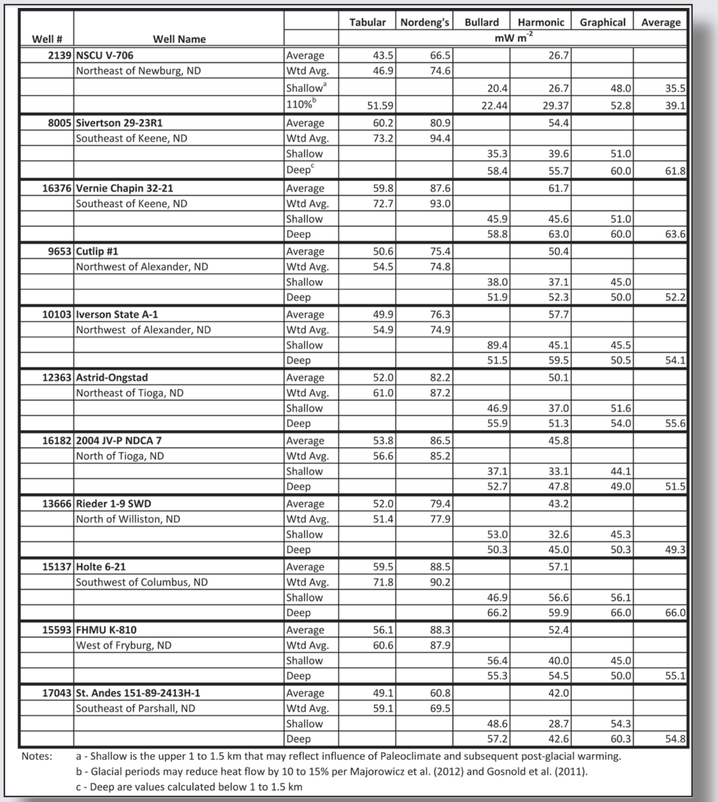
Logging software. The processed data were exported to text files which were subsequently imported into spreadsheet software for formation correlations and heat flow calculations. Nordeng (2014) and McDonald and others (2015) present more detailed information on the calculations that were performed. The Survey also plans to publish a Report of Investigation on the project later this year which will include data as well as providing more detailed information about the study.

To briefly summarize, heat flow was calculated by several methods. The first method used was to match the measured graphical temperature profile with initial assumed estimates of thermal conductivity and heat flow (Gosnold et al., 2012). The heat flow was adjusted until modeled temperatures approached the measured profile and then refinements were made to the individual formation thermal conductivity values until a relatively close approximation (match) between the measured and modeled profiles was obtained as illustrated in figure 5. These thermal conductivity values were then used in the remaining methods. Results are summarized in table 1. It should be noted that the heat flow of the upper 1 to 1.5 km was adjusted by a factor of about 90% to account for cooler temperatures prevalent during recent glacial periods and subsequent post-glacial warming per Majorowicz and others (2012) and Gosnold and others (2011).

The second method used was to calculate heat flow for each formation by multiplying the thermal gradient across the formation (change in temperature divided by the formation thickness) by the thermal conductivities obtained from the graphical method described above. The average heat flow of all the formations was then determined. A variation of this method employed finding a “weighted” thermal conductivity that was then multiplied by the thermal gradient of the entire well. The weighting factor applied was arrived at by multiplying the thermal conductivity of each formation times the formation thickness divided by the total well depth. The results for each well are included in table 1.

For comparison purposes, average heat flow and weighted heat flow estimates were also calculated using the thermal conductivity values utilized by Nordeng and Nesheim (2011) and Nordeng (2014) and the results are presented in table 1. Nordeng arrived at his thermal conductivity values by utilizing a digitized version of the North American heat flow map published by Blackwell and Richards (2004) and backing out the thermal conductivity values for each formation from the Rauch Shapiro Fee #21-9 well (NDIC #7591) located in Billings County, North Dakota.

The third approach employed the methodology of Bullard (1939) as cited by Beardsmore and Cull (2001). This method uses what Bullard refers to as the Thermal Resistance (R) plotted against the temperature. The thermal resistance is defined as the formation thickness divided by the formation thermal conductivity. Heat flow is determined by calculating the slope of the best fit line of temperature versus thermal resistance as illustrated in figure 6. Separate slopes were calculated for the shallow portions (upper 1 to 1.5 km) of the well bore that have been influenced by Pleistocene glacial climates and deeper portions that may be more representative of heat flow within the basin that has not been influenced by climatic changes. Results are presented in table 1.



Well #	Well Name		Tabular	Nordeng's	Bullard	Harmonic	Graphical	Average
			mW m^{-2}					
2139	**NSCU V-706**	Average	43.5	66.5		26.7		
	Northeast of Newburg, ND	Wtd Avg.	46.9	74.6				
		Shallow[a]			20.4	26.7	48.0	35.5
		110%[b]	51.59		22.44	29.37	52.8	39.1
8005	**Sivertson 29-23R1**	Average	60.2	80.9		54.4		
	Southeast of Keene, ND	Wtd Avg.	73.2	94.4				
		Shallow			35.3	39.6	51.0	
		Deep[c]			58.4	55.7	60.0	61.8
16376	**Vernie Chapin 32-21**	Average	59.8	87.6		61.7		
	Southeast of Keene, ND	Wtd Avg.	72.7	93.0				
		Shallow			45.9	45.6	51.0	
		Deep			58.8	63.0	60.0	63.6
9653	**Cutlip #1**	Average	50.6	75.4		50.4		
	Northwest of Alexander, ND	Wtd Avg.	54.5	74.8				
		Shallow			38.0	37.1	45.0	
		Deep			51.9	52.3	50.0	52.2
10103	**Iverson State A-1**	Average	49.9	76.3		57.7		
	Northwest of Alexander, ND	Wtd Avg.	54.9	74.9				
		Shallow			89.4	45.1	45.5	
		Deep			51.5	59.5	50.5	54.1
12363	**Astrid-Ongstad**	Average	52.0	82.2		50.1		
	Northeast of Tioga, ND	Wtd Avg.	61.0	87.2				
		Shallow			46.9	37.0	51.6	
		Deep			55.9	51.3	54.0	55.6
16182	**2004 JV-P NDCA 7**	Average	53.8	86.5		45.8		
	North of Tioga, ND	Wtd Avg.	56.6	85.2				
		Shallow			37.1	33.1	44.1	
		Deep			52.7	47.8	49.0	51.5
13666	**Rieder 1-9 SWD**	Average	52.0	79.4		43.2		
	North of Williston, ND	Wtd Avg.	51.4	77.9				
		Shallow			53.0	32.6	45.3	
		Deep			50.3	45.0	50.3	49.3
15137	**Holte 6-21**	Average	59.5	88.5		57.1		
	Southwest of Columbus, ND	Wtd Avg.	71.8	90.2				
		Shallow			46.9	56.6	56.1	
		Deep			66.2	59.9	66.0	66.0
15593	**FHMU K-810**	Average	56.1	88.3		52.4		
	West of Fryburg, ND	Wtd Avg.	60.6	87.9				
		Shallow			56.4	40.0	45.0	
		Deep			55.3	54.5	50.0	55.1
17043	**St. Andes 151-89-2413H-1**	Average	49.1	60.8		42.0		
	Southeast of Parshall, ND	Wtd Avg.	59.1	69.5				
		Shallow			48.6	28.7	54.3	
		Deep			57.2	42.6	60.3	54.8

Notes: a - Shallow is the upper 1 to 1.5 km that may reflect influence of Paleoclimate and subsequent post-glacial warming.
b - Glacial periods may reduce heat flow by 10 to 15% per Majorowicz et al. (2012) and Gosnold et al. (2011).
c - Deep are values calculated below 1 to 1.5 km

Table 1. Summary of Heat Flow Estimates by Well using the Various Methods

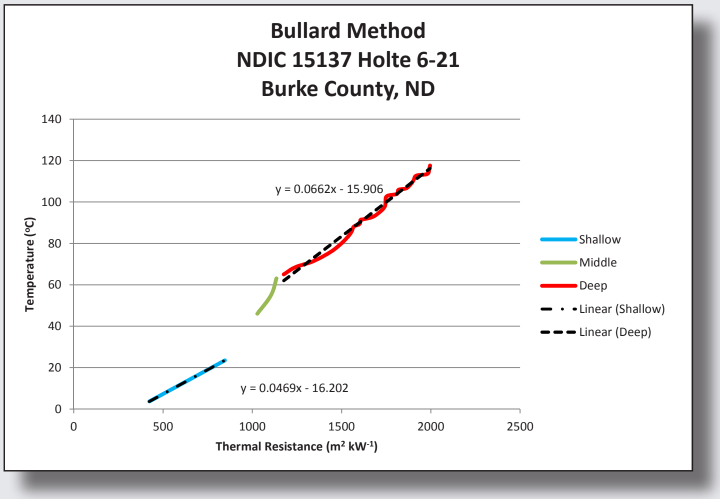


Figure 6. Example of Bullard Plot. Slope of best fit line is the heat flow. Separate values were calculated for shallow and deep portions to account for Pleistocene glacial climates.

The last method employed to estimate heat flow was to determine the harmonic mean of the thermal conductivity per Beardsmore and Cull (2011). This method calculates the harmonic mean of the thermal conductivity by dividing the depth to the top of the formation by the thermal resistance calculated as described above. Next, the gradient is determined by dividing the difference between the temperature at the top of each formation and the temperature at the top of the stratigraphic column by the difference between the depth to the top of each formation and the depth to the top of the stratigraphic column under consideration. Heat flow for each formation is then calculated by taking the product of the harmonic thermal conductivity times the gradient. The results are summarized in table 1.

The mean of the weighted average, and deep portions of the graphical, Bullard, and harmonic mean methods was then determined. The results are included in table 1 and figure 7 presents a contour map illustrating the results.

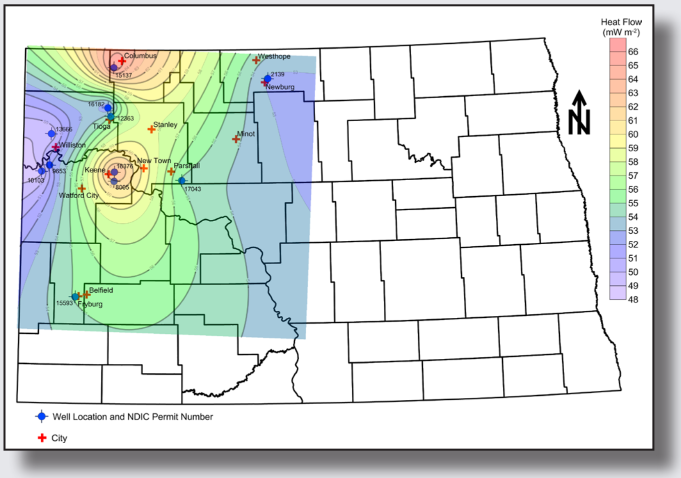


Figure 7. Mean heat flow of the weighted average, graphical, Bullard and harmonic mean methods

Discussion and Conclusions

While there is general agreement in calculated heat flow values between the various methods presented above, the results are largely predicated upon initial assumptions of either heat flow, thermal conductivity or both. This is clearly illustrated by the wide discrepancies between the values obtained by using Nordeng's thermal conductivity values and the values obtained using the other methods. In addition, the average and weighted average of "method 2" results in relatively large differences in heat flow between formations. Whereas, with exception of the surface temperature forcing signal resulting from global climatic variations during the last ice age and subsequent post-glacial warming, calculated heat flow across the various formations should be nearly equivalent if the thermal conductivity values used in the analyses are close to actual values.

The results of the harmonic method described above seem to yield the most consistent heat flow values between the formations. However the issue at hand still comes down to a "chicken or egg" scenario in that both heat flow and thermal conductivity are dependent upon each other and inaccurate assumptions of one profoundly affects the other. Although we are confident in the measurements obtained during this study with respect to thermal gradients, it is evident that additional information with regard to thermal conductivities of the geologic formations will be required to accurately determine heat flow within the Williston Basin. While geologic formations can often be differentiated on the basis of "marker" beds, there can be wide variations in actual mineralogy, lithology, porosity, permeability, density, etc. depending upon depositional environment, depth of burial, secondary processes, etc. from one location to another within the same formation which can have a profound influence on thermal conductivity.

Future Work

The NDGS currently has plans to log an additional 20 to 30 wells over the next two years. However, as noted above, some funding may be redirected to obtain additional thermal conductivity information from the wells that are being logged. Ideally, thermal conductivity values from core samples obtained from the wells that are logged would allow for the calculation of a reasonable estimate of heat flow from specific locations. This may also allow for better estimates of thermal conductivity by reverse modeling for the various formations at these locations that do not have core samples. This information, combined with thermal maturity estimates obtained by other methods (Nordeng and Nesheim, 2011) would provide better estimates of heat flow within the Williston Basin, better predictions of thermal maturity and the geothermal potential of the region.

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