An Assessment of Heat Flow and Enhanced Geothermal System Resources in Minnesota

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ABSTRACT

Low heat flow has been previously reported in Minnesota (40±6 mWm⁻²) and the Superior Province of the Canadian Shield (42 ± 8 mWm⁻²). These heat flow averages are significantly lower than the rest of the eastern U.S. and lower than shields in the southern hemisphere. We find that the low heat flow in Minnesota is due to heat flow measurements only in the mafic rocks of the Mid-Continent rift system, which have low radiogenic heat production, unlike the granitic and gneissic rocks that make up the Canadian Shield; and post-glacial climatic changes that affect temperature in the upper two kilometers of the crust, which has not been accounted for in previously published heat flow values.

We have obtained new heat flow measurements, and collected over two hundred rock samples, obtained from cores and outcrops, for measurement of ²³⁸U, ²³²Th, and ⁴⁰K concentrations and thermal conductivity in Minnesota. Based on corrections for post-glacial warming, we find the average heat flow in Minnesota to be 44.8± 8 mWm⁻² which is similar to heat flow in the Quetico, Wawa, and Wabigoon Superior Subprovinces. Previously published maps of the U.S. suggest that because of low heat flow values the potential for developing Enhanced Geothermal Systems (EGS) in Minnesota may be small. We find that the newly acquired data on heat flow, thermal conductivity, and radiogenic heat production, allows us to give an assessment of the EGS resource, at depths from 3 to 10 kilometers, for the state. This new data and correcting regional heat flow values for climatic changes has reduced the depth to the 150°C isotherm, making EGS applications viable in Minnesota at a more reasonable depth.

Geology Background

Located almost entirely in the Superior Province and the Minnesota River Valley Subprovince of the Canadian Shield (Figure 1), Minnesota contains some of the oldest rocks in the world. The stratigraphic column of Minnesota provides information to various geologic events spanning from 3,500 Ma ago to today. Primarily, the Precambrian basement rock consists of greenstone belts situated between Achaean granites and gneisses, and mafic rocks of the Midcontinent Rift System.

About 3500Ma, the Minnesota River Valley micro-continent collided with the Canadian Shield causing subduction, mountain building and the creation of volcanic island arcs (Ojakangas, 2009). After a period of mountain building, metamorphism, and erosion, rifting started to occur in North America around 1,100 Ma. The arc-shaped rift extends from the lower peninsula of Michigan, up through Lake Superior and down through eastern Minnesota and into Nebraska where there is a carbonatite next to the rift in the basement rocks (Figure 1). During this time, mafic magma rose to...
the surface creating pillow basalts in the sea floor and covering the land with lava flows. Soon after, the Duluth Complex, composed of gabbros and other coarse grained igneous rocks, intruded the lava flows and crystallized beneath the surface.

During the Paleozoic, sandstones, limestones and shales were deposited throughout Minnesota. Eroded in most of the state, rock units of this age are still currently present in the southeast. Another advancement of seas deposited sediment in northwestern Minnesota during the Jurassic and then again in the western part of the state during the Cretaceous.

Erosion during the Tertiary was followed by glaciation as the climate cooled between about 1.8 Ma and 10 ka. Over forty glacial advancements shaped the landscape into what we see today throughout the state (Ojakangas, 2009). These advancements covered the land with glacial till and created many depositional features, including the kettle lakes that give rise to Minnesota’s nickname, “The Land of 10,000 Lakes”.

**Previous Research**

Prior to this study there were only four heat flow measurements in Minnesota (Roy et al., 1968, 1972) and those measurements were either in the mafic rocks of the Midcontinent Rift System or in a shallow lake. One heat flow measurement, near Bemidji, MN, was made outside the Midcontinent Rift (37 mWm⁻²) and the other three measurements were made in the Midcontinent Rift near Ely, St. Paul, and Duluth (average: 40±6 mWm⁻²). Other research in the Midcontinent Rift includes 162 heat flow measurements using marine techniques in Lake Superior (Hart et al., 1994). These heat flow values are low compared to the continental average (i.e., 70.9 mW⁻²) and those corresponding to other Precambrian rocks (i.e., 50.5 mW⁻²) Davies and Davies, 2010).

Low heat flow in Minnesota is most likely caused by the following two reasons: 1) past heat flow measurements were made in mafic rocks of the Mid-Continent rift system (mafic rocks tend to have low radiogenic heat production, unlike the granitic and gneissic rocks that make up much of the Canadian Shield); and 2) post-glacial climatic changes have affected temperature gradients up to 40% in the upper two kilometers of the crust and was not accounted for in previously published heat flow values.

Higher heat flow in the Wabigoon, Quetico, and Wawa Sub-provinces of the Superior Province in Ontario and Manitoba, which also underlie Minnesota, (40.3, 46.6 and 45.1 mW⁻², respectively, Perry et al., 2006) incorporated the climatic correction developed by Jessop (1971). The estimated EGS resources for Minnesota have been presented in a 2006 report issued by MIT, and maps produced by Roberts (2009), which show small heat flow values; i.e., Minnesota ranked lowest of the lower 48 states. New heat flow data and corrections of regional values for climatic changes have increased the EGS resources available in the state, as will be discussed below.

**Temperature Gradient Measurements**

Temperature measurements were made in exploration boreholes drilled by mining companies and water observation wells owned by the Department of Natural Resources (Figure 2). Although boreholes drilled specifically for heat flow measurements are ideal, due to the high cost of drilling, these are wells of opportunity. A team of three University of North Dakota students, and two researchers from the Natural Resource Research Institute, University of Minnesota Duluth, measured temperature gradients throughout Minnesota where wells were available. Data were collected at nine new heat flow sites in 17 wells that showed stable temperature gradients. A sealed thermistor probe, calibrated to ±.001°C was used to make accurate temperature measurements.

In this study, temperature gradients have been corrected for post-glacial warming effects. Although the signal is subtle, it affects the gradient up to 2000 m depth. Previous work in Minnesota has gone uncorrected for climatic effects since warming has occurred during the retreat of the Laurentide ice sheet between 12 and 9 ka. As mentioned earlier, other work done in the Canadian Shield used the climatic correction developed by Jessop (1971). This correction implies that temperatures averaged a warming of 3-8°C in Minnesota depending on latitude. However, recent modeling of the surface temperature during the Pleistocene shows that the warming since the last glacial maximum may have been 15-20°C in Minnesota
(Ganopolski et al., 1997; Schneider von Deimling et al., 2006). Other results confirming a temperature warming of 15°C came from measurements in a deep borehole in the Pierre Shale (Gosnold et al., 2005) and pollen analyses (Ritchie, 1983). Using a warming value of 15°C, gradients were corrected by almost 40% (Figure 3).

Thermal Conductivity Measurements

Samples of Precambrian gneisses and granites, along with rocks associated with the Midcontinent Rift System were collected in over 200 drill hole and outcrop locations throughout the entire state. Thermal conductivity measurements were made using two portable electronic divided bar (PEDB) apparatus at the University of North Dakota Geothermal Laboratory. Knowing the conductivity in the Precambrian bedrock helped understand the thermal properties of the granites, gneisses, and mafic rocks unique to the area.

Cores were available for some temperature gradient wells. Well logs and a database at UND were used to estimate thermal conductivities at those sites, and also for the thermal properties of the sedimentary rocks.

Low conductivity, 1.5-2.3 W/(m*K), is present in the Midcontinent Rift due to the dominance of mafic rocks. Outside the rift, the granitic and gneissic bedrock has higher conductivities, 2.3-3.4 W/(m*K), because of its higher silica content. The difference in mafic and felsic rock thermal properties is the reason behind the contrasting values shown in Figure 4.

Heat Flow Calculations

Surface heat flows are calculated using Fourier’s Law of heat conduction,

\[ Q = -k(\Delta T/\Delta z) \]  

where, \( Q \) is the heat flow; \( k \) thermal conductivity; \( \Delta T \) temperature gradient; \( \Delta z \) depth as described above (Fig. 3). Using regional heat flow data for climatic changes helped us understand the heat flux outside of the Midcontinent Rift System (at Trimont, Courtland, Tyler, Glencoe and Gaylord), in and around the gneissic and granite terranes of the Superior Province and Minnesota River Valley.

Carefully reviewing past literature on previous sites in and around Minnesota, the regional and new heat flow measurements were corrected for post-glacial climatic changes dependent on depth as described above (Fig. 3). Using regional heat flow data

### Table 1. New Heat Flow Measurements in Minnesota

<table>
<thead>
<tr>
<th>Site</th>
<th>Lat Degree</th>
<th>Long Degree</th>
<th>( \kappa ), W/m*K</th>
<th>( \Delta h ), m</th>
<th>Conductivity statistics</th>
<th>( G ), mW/m²</th>
<th>( Q ), mW/m²</th>
<th>( \sigma Q ), mW/m²</th>
<th>( \Delta Q ), climatic correction</th>
<th>( Q_c ), mW/m²</th>
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<tbody>
<tr>
<td>Rio Tinto</td>
<td>47.6435</td>
<td>-91.9932</td>
<td>2.3</td>
<td>100-120</td>
<td>Estimated</td>
<td>14.18 30.1</td>
<td>3.4</td>
<td>12.6</td>
<td>9.1</td>
<td>4.2</td>
</tr>
<tr>
<td>Duluth Metals</td>
<td>47.8089</td>
<td>-91.7027</td>
<td>1.8</td>
<td>400-600</td>
<td>Estimated</td>
<td>17.78 32 4.5 7 39</td>
<td>14.7 33.3 9.3 42.6</td>
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<td></td>
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</tr>
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<td>DM-003</td>
<td>47.8089</td>
<td>-91.7027</td>
<td>1.8</td>
<td>240-600</td>
<td>Estimated</td>
<td>18.44 33.2</td>
<td>5.5</td>
<td>9.1</td>
<td>42.3</td>
<td>31.6 40.5</td>
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<tr>
<td>DM-105</td>
<td>47.7962</td>
<td>-91.7350</td>
<td>1.8</td>
<td>100-600</td>
<td>Estimated</td>
<td>18.94 34.1</td>
<td>5.6</td>
<td>9.4</td>
<td>43.5</td>
<td>31.6 40.5</td>
</tr>
<tr>
<td>DM-109</td>
<td>47.8021</td>
<td>-91.7231</td>
<td>1.8</td>
<td>100-600</td>
<td>Estimated</td>
<td>18.94 34.1</td>
<td>4.6</td>
<td>11.5</td>
<td>45.6</td>
<td>31.6 40.5</td>
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<td>DM-111</td>
<td>47.7934</td>
<td>-91.7396</td>
<td>1.8</td>
<td>100-600</td>
<td>Estimated</td>
<td>18.61 33.5</td>
<td>4.5</td>
<td>9.2</td>
<td>42.7</td>
<td>31.6 40.5</td>
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<tr>
<td>DM-116</td>
<td>47.7934</td>
<td>-91.7396</td>
<td>1.8</td>
<td>100-600</td>
<td>Estimated</td>
<td>18.61 33.5</td>
<td>4.5</td>
<td>9.2</td>
<td>42.7</td>
<td>31.6 40.5</td>
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<td>PolyMet</td>
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<td>29.4 10.4</td>
<td>39.8</td>
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<td>00-457</td>
<td>47.6235</td>
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<td>2.3</td>
<td>88-261</td>
<td>Estimated</td>
<td>13.09 30.1</td>
<td>4.3</td>
<td>10.4</td>
<td>40.5</td>
<td>31.6 40.5</td>
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<tr>
<td>2</td>
<td>47.6243</td>
<td>-91.9580</td>
<td>2.3</td>
<td>100-180</td>
<td>Estimated</td>
<td>12.48 28.7</td>
<td>4.2</td>
<td>10.4</td>
<td>39.1</td>
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<tr>
<td>Trimont</td>
<td>44.8040</td>
<td>-94.5826</td>
<td>3.7</td>
<td>100-120</td>
<td>Estimated</td>
<td>8.38 31 2.2</td>
<td>11.5</td>
<td>42.5</td>
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<td>Courtland</td>
<td>44.2952</td>
<td>-94.3527</td>
<td>2.75</td>
<td>80-130</td>
<td>Estimated</td>
<td>12.36 34 4.7</td>
<td>12.6</td>
<td>46.6</td>
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<tr>
<td>Tyler</td>
<td>44.2845</td>
<td>-96.1458</td>
<td>1.5</td>
<td>170-250</td>
<td>Estimated</td>
<td>24.53 36.8</td>
<td>6.9</td>
<td>13.2</td>
<td>50</td>
<td></td>
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<td>Glencoe</td>
<td>44.7841</td>
<td>-94.1524</td>
<td>2.5</td>
<td>110-155</td>
<td>Estimated</td>
<td>11.80 29.5</td>
<td>6.8</td>
<td>10.9</td>
<td>40.4</td>
<td></td>
</tr>
<tr>
<td>Eden Prairie</td>
<td>44.8415</td>
<td>-93.4576</td>
<td>2.75</td>
<td>130-170</td>
<td>Estimated</td>
<td>14.18 35 6.2</td>
<td>12.8</td>
<td>47.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gaylord</td>
<td>44.5435</td>
<td>-94.1847</td>
<td>2.4</td>
<td>100-130</td>
<td>Estimated</td>
<td>14.17 34 5.5</td>
<td>12.6</td>
<td>46.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Heat flow sites are labeled in bold with latitude and longitude coordinates. \( \kappa \) thermal conductivity; \( \Delta h \), depth interval where heat flow was measured; \( n \), number of samples measured for conductivity; \( \Delta T \), temperature gradient; \( Q \), uncorrected heat flow, \( \sigma Q \), standard deviation; \( \Delta Q \), climatic correction; \( Q_c \), corrected heat flow value.
from surrounding states and Canada, as well as new data collected in this study, a new heat flow map of Minnesota was prepared (Figure 5). Measurements that were anomalously high, or measured at less than 50 m depth, were removed from the data set. We considered that shallow measurements were perturbed and were of lower quality than those obtained below 100 meters.

Correcting previous heat flow values and those made in this study results in a mean heat flow value of 44.8±3.5 mWm⁻², an increase of 20% compared to the previous mean of 40±6 mWm⁻². This higher value has a positive impact on the possibility of developing EGS resources and on the subsurface temperatures that will be encountered in Minnesota, are higher than previously believed.

Areas that will most likely have a higher heat flow are in granitic rocks and in the gneissic terrane of the Minnesota River Valley Province. The heat flow value at Tyler, MN (50 mWm⁻²) gives a good insight to the heat flow of the Minnesota River Valley Subprovince. High concentrations of ²³⁸U, ²³²Th, and ⁴⁰K are also found in the Vermillion Massif, and Giants Range Batholith located in northern Minnesota (Rye and Roy, 1978). Using a mantle heat flux of 33.5mWm⁻² for the Canadian Shield (Blackwell, 1971), the estimate for these two locations would be 48-50 mWm⁻². Although the estimated heat flow is higher in both areas, compared to earlier values, there are no downhole temperature data available at this time.

**EGS Resources**

To create an EGS reservoir, wells are drilled into a hot (>150°C) dry (low permeability and porosity) rock mass, followed by hydraulic stimulation to create a subsurface reservoir that will allow the circulation of large volumes of water or CO₂ in a closed and controlled environment. After the extracted hot fluids pass through a power plant to generate electricity, they are injected back into to reservoir to close the loop.

The development of EGS projects in Minnesota had been almost entirely ruled out by past calculations. However, the newly acquired data and correcting previous data for climatic changes have positively changed previous estimates. EGS resources were recalculated using the format developed by Beardsmore et al. (2010). Heat flow, heat generation, sediment thickness, ambient temperature, and thermal conductivity are all parameters taken into account when estimating Minnesota’s EGS resources.

The following equation was used to calculate temperatures at 3-10 km depth,

\[ T_x = T_s + \left( Q_s \cdot \frac{(X-S) \cdot K_B}{2 \cdot K_B} \right) - A_B \cdot \frac{(X-S)^2}{2 \cdot K_B} \]  

Where, \( T_x \) is the temperature at depth \( X \), \( T_s \) the temperature at the top of the Precambrian basement; \( Q_s \) the heat flow at the top of the Precambrian basement; \( S \) the sediment thickness; \( K_B \) the thermal conductivity of the Precambrian basement; and \( A_B \) the radiogenic heat production of the Precambrian basement (Beardsmore et al., 2010).

Variables not previously mentioned in this study were sediment thickness, ambient temperature, and radioactive heat production. Sediment thickness consists mostly from glacial till and Paleozoic rocks in the southeast. Using the information of deep wells from the County Well Index website of Minnesota (www.health.state.mn.us/divs/eh/cwi/index.html), thicknesses varied from 0-500 m across the state. Heat generation values less than 1 μW m⁻³ and greater than 1μW m⁻³ are assigned to mafic and felsic rocks, respectively (Perry et al., 2006). Ambient air temperature was assumed to be 8°C.
Temperature maps (Figure 6) determined available heat and power potential for temperatures >150°C for a 1000 meter thick 5’X5’ grid cell. The available heat was calculated using Eq. (3),

\[ H = \rho \cdot C_p \cdot V_c \cdot (T_x - T_r) \cdot 10^{-18} \]  

(3)

Where, \( H \) is the available heat; \( \rho \) the density; \( C_p \) the specific heat; \( V_c \) the volume of each grid cell; \( T_x \) the calculated temperature at depth \( X \); and \( T_r \) the reference temperature, 8°C (Beardsmore, 2010).

After calculating for available heat, the power potential was obtained using Eq. (4),

\[ P = H \cdot 10^{12} \cdot \eta_{th} / 9.46 \cdot 10^8 \]  

(4)

where, \( P \) is the power potential in MW; and \( \eta_{th} \) the thermal efficiency (8-12%).

The available heat and power potential (Table 2) is three times larger than previously assessed by MIT (2006). That is, 18,114 of MW are available at depths greater than 6 km (assuming a 2% recovering factor) compared to the previous assessments of 6161 MW. Previous estimates also found that the 150°C isotherm is found at depths >7.5 km in depth. Although present geothermal drilling technology is limited to depths of less than 6500 m, the development of EGS in Minnesota may be possible in the near future.

Continuing research at the University of North Dakota's Geothermal Laboratory is focused in determining the radiogenic heat production in the granitic, gneissic and mafic rocks of Minnesota. These data will give a better understanding of the mantle heat flux and determine the radiogenic heat production of the crust in the region. Heat flow in areas where down hole temperature data is unavailable could be estimated using a mantle heat flux of 33.5 mWm⁻², and a radioactive thickness of 7.5 km, determined by Blackwell (1971), for the Eastern U.S. This information could give a better understanding of the thermal regime of the southwestern area of the Superior Province and the Minnesota River Valley Subprovince.

Using the new heat flow data, one may conclude that 150°C temperatures (or higher) may be encountered in the Minnesota region at less than 6.5 km depth, or 1 km shallower than previously estimated. Also, the size of the thermal resource almost tripled from 35,789 EJ to 95,199 EJ. Assuming a 2% recovery factor, the electricity generating capacity increased to 18,114 MW; it was 6161 MW before.

Geothermal energy through EGS technology could essentially supply Minnesota's electrical demand. A better understanding of the magnitude and extent of the post-glacial climatic signal for various latitudes and drilling deep thermal gradient wells would refine estimates of Minnesota's heat flow, temperatures at depth, and available EGS resources.

Table 2. Power Generation and Energy at Depths 3-10 km in Minnesota (Exajoule = 10¹⁸ Joules).

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Exajoules</th>
<th>MW (2%)</th>
<th>MW (20%)</th>
</tr>
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<tbody>
<tr>
<td>3</td>
<td>35789.0</td>
<td>95199.0</td>
<td>57764.0</td>
</tr>
<tr>
<td>4</td>
<td>57764.0</td>
<td>10991.0</td>
<td>5785.8</td>
</tr>
<tr>
<td>5</td>
<td>30408.9</td>
<td>13371.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>7027.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>8</td>
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</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>0.0</td>
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</tr>
<tr>
<td>Total</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Conclusions

Based on new heat flow and thermal conductivity data, and by correcting heat flow data, the estimated mean heat flow for the Minnesota region was raised from 40 mWm⁻² to 45 mWm⁻², an increase of 12%. These values are very similar to those obtained from measurements taken in Manitoba and Ontario, Canada, in the same Superior Subprovinces (Perry et al., 2006). Although heat flow values are still lower than the continental average, the 12% increase in heat flow has a positive effect on the potential development of EGS projects in Minnesota.

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References


