Minnesota's Deep Geothermal Energy Potential

Donald Fosnacht – *Natural Resources Research Institute*
University of Minnesota Duluth, 5013 Miller Trunk Hwy.
Duluth, MN 55811-1442
218-720-4282, 218-720-4329
dfosnach@nrri.umn.edu

Steven A. Hauck – *Natural Resources Research Institute*
University of Minnesota Duluth, 5013 Miller Trunk Hwy.
Duluth, MN 55811-1442
218-720-4273, 218-720-4239
shauck@nrri.umn.edu

Robert Klenner – *Department of Geology and Geological Engineering*
University of North Dakota, 81 Cornell Street, Stop 8358
Grand Forks, ND 58202
rklenner@undeerc.org

William Gosnold – Department of Geology and Geological Engineering
University of North Dakota, 81 Cornell Street, Stop 8358
Grand Forks, ND 58202
218-791-5543, 701-777-4449
will.gosnold@engr.und.edu

John Heine – *Natural Resources Research Institute*
University of Minnesota Duluth, 5013 Miller Trunk Hwy.
Duluth, MN 55811-1442
218-720-4231, 218-720-4239
jheine@nrri.umn.edu

Mark Severson – *Natural Resources Research Institute*
University of Minnesota Duluth, 5013 Miller Trunk Hwy.
Duluth, MN 55811-1442
218-720-4239, 218-720-4239
mseverso@nrri.umn.edu

This investigation greatly improves the original heat flow map of Minnesota [1] that was based upon four points within the landmass of Minnesota and 162 samples collected 2.5 m below Lake Superior (Fig.1a-b). The new map incorporates:

1) new heat flow data from exploration drill holes and water wells throughout Minnesota [2];
   - 795 wells inspected, and over 100 boreholes were measured;
   - about half of these 100 wells had noise disturbances creating isothermal or perturbed gradients and could not be used in heat flow calculations; and
   - 57 new temperature measurements were made and compiled into 31 new heat flow sites.
2) removal of the paleoclimate signal from previous data [3-5] that caused the heat flow to be underestimated. These climatic changes have affected temperature gradients up to 30% in the upper two kilometers (km) of the crust; and

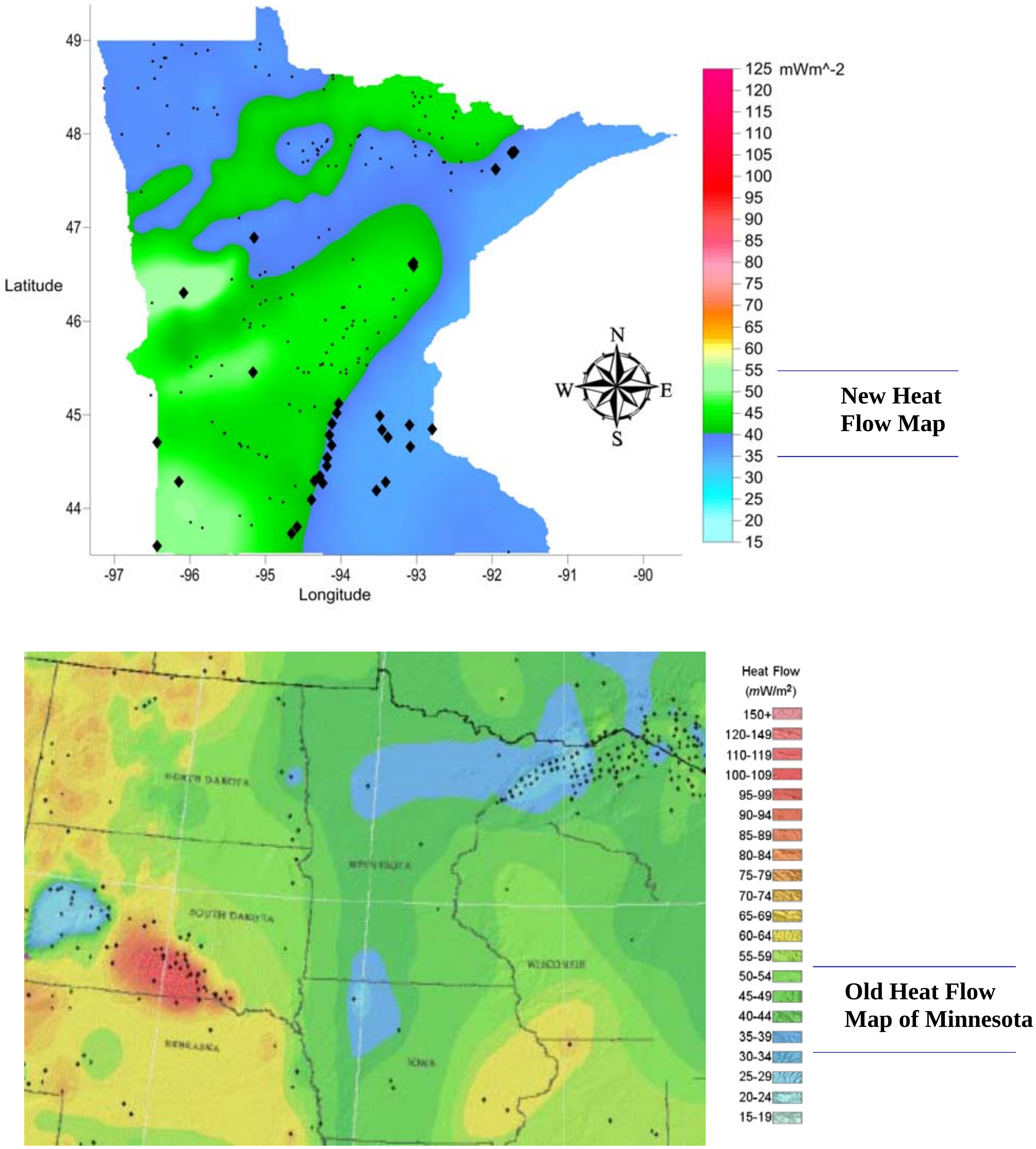


Figure 1a. The 2004 map [1] (below) was developed to show heat flow ranges for the continent and uses a range of 15-150+ mW m-2. MN has a range 25-55 mW m-2. Applying the same range employed for the national study to Minnesota shows the difference in results for maps using the same scale (above [2]). Changing scale to take advantage of the additional data collected for this project allows for finer granularity. These improved data use a heat flow range of 20-115 mW m-2.

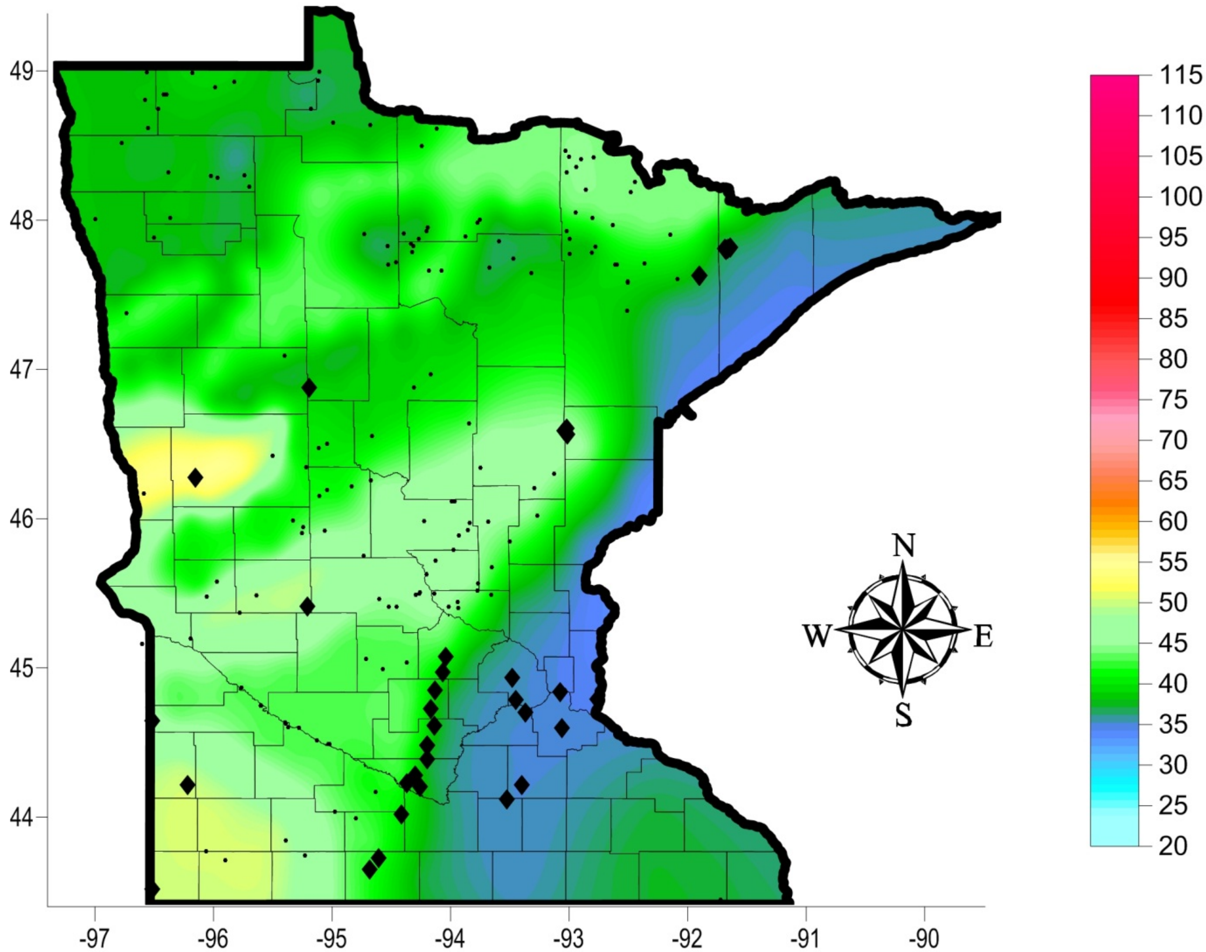


Figure 1b. Final heat flow map of Minnesota [2] using a different-colored temperature scale to illustrate the greater heat flow detail in the new map. Note the presence of the Mid-Continent Rift (blue color) and high heat flow areas in west-central Minnesota in Otter Tail-Wilkin counties, in southwest Minnesota in Murray-Nobles-Pipestone-Rock counties, and in central Minnesota in Pope County. (Vertical colored scale in mW m^{-2} and vertical and horizontal scales on the map represent latitude and longitude.)

3) collection of granitic samples from across MN from outcrops and mineral exploration drill holes for:
   - whole rock and trace element chemistry, including uranium and thorium;
   - thermal conductivity; and
   - radionuclide analyses (^{238}U, ^{232}Th, and ^{40}K) to supplement and infill heat flow data between and around water well and drill hole temperature data.

The newly constructed downhole temperature maps [2] (Fig. 2) indicate:

1) the available heat and electrical power potential is three times greater than previous estimates, i.e., 96,794 exajoules (EJ) or 18,409 MW more are available at depths >7-10 km (Fig. 3) compared to the previous [6] assessments of 6,161 MW;
2) this vast amount of energy found in this study could essentially power Minnesota through a clean base load power;
3) together, the new heat flow measurements, thermal conductivity measurements, and correction of heat flow data has raised the mean heat flow from 40 mW m^{-2} to 44.1 mW m^{-2}, an increase of 10%;
4) the 10% increase in heat flow positively affects the enhanced geothermal resources for power production (Fig. 3), e.g., in Otter Tail-Wilkin counties at 7 km depth, and also potentially in Murray-Nobles-Pipestone-Rock and Pope counties at 8.8 to 9 km depth;
5) the new map shows that certain counties, e.g., in Wilkin and Otter Tail counties, have the best currently-estimated environments for enhanced geothermal heat extraction and that the depth for extraction of heat from these counties is just over 7 km in depth. This depth is over 3 km shallower than the previous measurements would indicate for extracting this potential resource. This depth will dramatically reduce drilling costs associated with this type of technology implementation;
6) to have to drill to 150°C heat on the original map [1] would have been about 10 km. These new data have reduced the drilling depth by 3 km, a definite savings in drilling and related costs; and
7) To drill to 100°C temperature rocks, many more areas of the state (Fig. 2), e.g., at 8 km, Murray-Nobles-Pipestone-Rock and Pope counties have availability for enhanced geothermal electrical power generating systems using organic Rankine or Kalina cycle heat transfer technology.

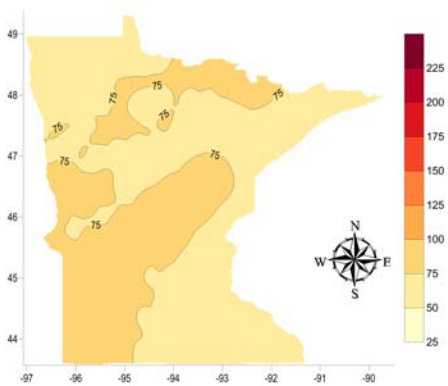
In addition to recording the downhole temperature data from wells and mineral exploration drill holes (Fig. 4), various granitic rock samples were also collected [2] and processed (Fig. 5) to determine:

1) the chemistry and mineral composition of 100 granitic rock samples from throughout Minnesota;
2) the thermal conductivity (Fig. 6) of the granitic rocks (rate at which heat flows through the rock);
3) the general whole rock and trace element chemistry of the rock to determine how granitic the rock is and what other elements it contains, especially uranium and thorium; and
4) the radioactivity of the sample to determine the heat production ability of the rock.

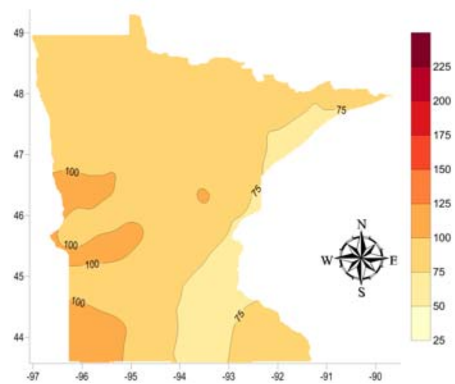
Combining these data together with the downhole temperature data allowed us to construct the new heat flow map of Minnesota.

Figure 2. New depth (5-10km) versus temperature (°C) maps based on the new heat flow map of Minnesota.

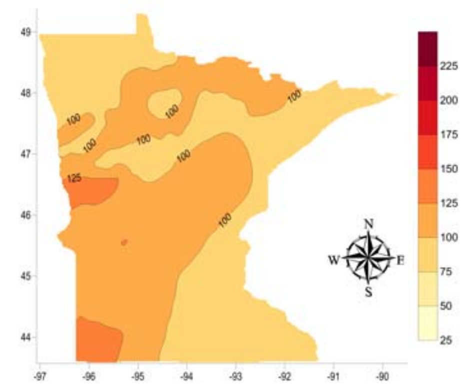
(Vertical colored scale in °C and vertical and horizontal scales are degrees latitude and longitude)



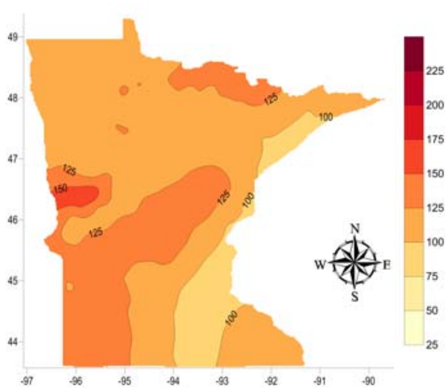
Depth at 5 Kilometers



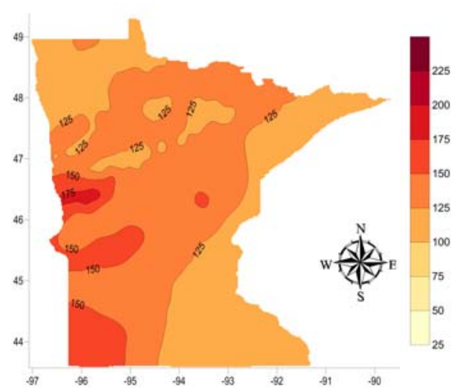
Depth at 6 Kilometers



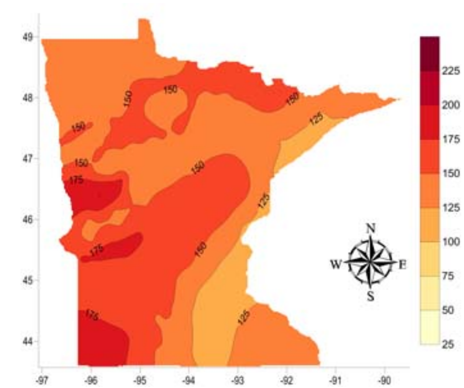
Depth at 7 Kilometers



Depth at 8 Kilometers



Depth at 9 Kilometers



Depth at 10 Kilometers

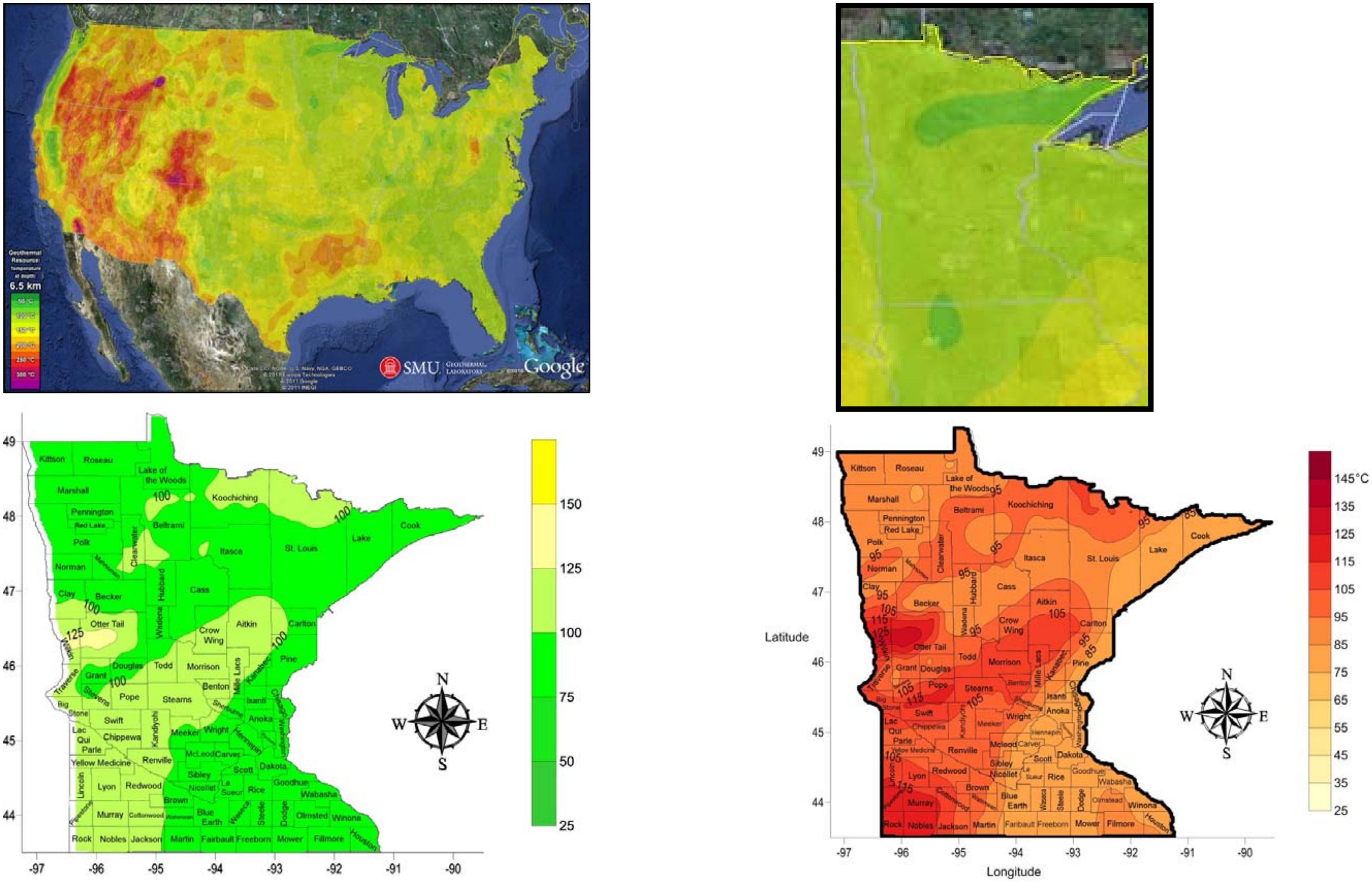


Figure 3. Comparison of temperature data (°C) at 6.5 km [6] – at the top left and right) and this study (bottom left and right [right figure has additional temperature detail). Note the local increases in temperature and detail at the same depth with the new data [2]. The colored vertical scale is temperature in degrees Celsius. Horizontal and vertical axes on the map are in degrees latitude and longitude.

Figure 4. Hand crank used to lower temperature probe into the wellbore.

Figure 5. Various sample shapes used to measure thermal conductivity in this study.

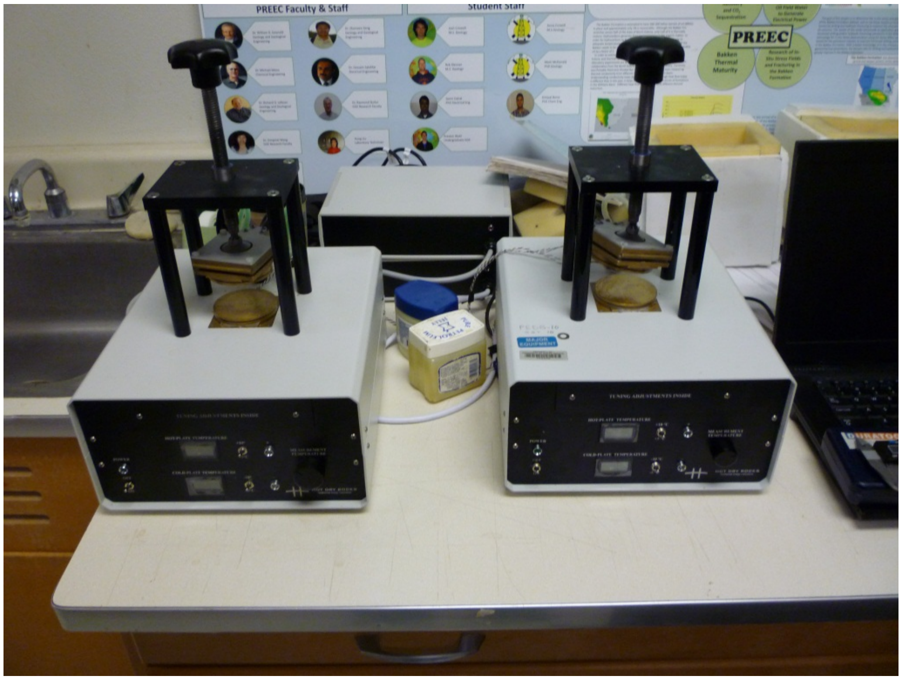


Figure 6. PEDB used for measuring thermal conductivity in the UNDGL.

Results of this study are further validated by heat flow measurements in the other geological terrains of the stable Superior Craton in Canada (Quetico (46.5 mW m^{-2}), Wawa-Abitibi (45.1 mW m^{-2}), and Wabigoon (40.3 mW m^{-2}) Subprovinces). The finding that the average heat flow in Minnesota is 44.1 plus or minus 6.6 milliWatts per meter squared is similar to that of comparable rock types in Canada [2].

The MIT-DOE report [5] indicates Minnesota has a "low" geothermal resource for developing geothermal electrical power in the upper 10 km and rates the enhanced geothermal system potential as highly unlikely. This study refutes this observation based on new data that indicates acceptable geothermal heat occurs at 7 km in at least one location (Figs. 1a-b, 3).

With heat flow higher in the gneissic rocks of the Minnesota River Valley (MRV) subprovince and in the granites of the Giants Range Batholith and Vermilion Massif, these areas have potential for geothermal development in Minnesota. Further investigations of the MRV using traditional heat flow observations will further quantify this resource and determine if heat flow may be higher in some areas of the MRV. Also, the rock chemistry indicates elevated rare earth element (REE) concentration compared to the other granitic rocks. Elevated REE concentrations generally accompany higher uranium and thorium values. Additional follow-up sampling, chemical and radionuclide, and thermal conductivity analyses (~150 new samples) are currently being collected to add more detail to the heat flow map.

There are three economic stages in establishing a 50MW enhanced geothermal electrical generation plant [7]: 1) identification of a site [$0.5-1.0 million]; 2) exploration – geophysics and initial drilling [$5-$10 million]; and 3) delineation drilling, including a feasibility study, initial production drilling, financial closing, and production drilling (injection drilling) and plant construction [$134-$144 million]. Levelized generation costs for a 50 MW geothermal binary plant (ORC and Kalina cycle plants) are $92 per megawatt hour and for a 50 MW dual flash geothermal plant are $88 per megawatt hour, which over the lifetime of the plant can be competitive with a variety of technologies, including natural gas [8]. Geothermal power requires no fuel. It is, therefore, immune to fuel cost fluctuations. However, capital costs and risk tends to be high (over 60% of total cost) with most of these costs upfront. Drilling accounts for over half the costs, and exploration of resources entails significant risks.

Technological advancements in drilling, reservoir stimulation, and binary power plant efficiency must be met in order to economically extract this heat for geothermal electrical power. However, several organizations, e.g., DOE, Google, are currently funding some of this research.

Recommendations for Future Work in Minnesota

1) Continue to refine the new Minnesota heat flow map by:
   a. continued collection of down hole temperature data as mineral exploration and water wells become available;
   b. continued collection of granitic rock samples for geochemistry, radionuclide analyses, and thermal conductivity analyses;
2) In the selected area(s), drill “touch down” core holes, i.e., drill through the overburden and then drill (oriented drill core) 10-20 feet into the hard bedrock to define a reservoir by collecting samples for:
   a. chemistry, including radionuclides analyses;
   b. thermal conductivity;
   c. fracture(s) analysis;
3) Provide data to potential geothermal energy producers who might conduct additional deeper drilling and reservoir development to determine the reservoir’s producing characteristics; and
4) Continue to educate the public on the benefits of geothermal energy.

ACKNOWLEDGEMENTS

This project was primarily made possible by funding provided by the Office of Energy Security of the MN Department of Commerce grant through the use of XCEL Energy Renewable Development Funds (Laws of Minn. 2007, Ch 57, article 2, sec 3 subd6). We wish to thank Mr. Ken Brown and Ms. Ann Zechbauer for their effective oversight of this project and willingness to answer questions.

The authors thank Josh and Anna Crowell, who assisted in the well logging efforts, and other members of the University of North Dakota, Geophysical Laboratory (UNDGL) who assisted in making this project happen. Gratitude is expressed to the Department of Natural Resources, Division of Waters, Messrs. James A. Berg, Michael MacDonald, and Scott R. Pearson for providing access to observation water wells and related data. Gratitude is expressed for the additional data collection funding from the Initiative for Renewable Energy and the Environment grant to Dr. Martin Saar, Department of Earth Sciences, University of Minnesota Minneapolis, and to Mr. Ben Tutolo, who also collected downhole temperature data on this grant.

This material is also based upon work supported by the Department of Energy under Award Number ST OF AZ/MN-EE0002850-USDOE/DE-EE0002850. Disclaimer: “This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.”

We want to thank Messers. G. Wagoner, T. Levar, C. Maly, and Miss Sara Chelbecek, all of NRRI-UMD, for their assistance with well logging and well location.

A very special thank you goes out to all Minnesota property owners who allowed us to sample wells and collect rock samples. In particular, we extend our gratitude to Mr. Thomas Chrisfield of CenterPoint Energy, Minneapolis, MN for access to their wells and well logs over the Wakefield Gas Storage Facility.

The stored drill core at the Hibbing Drill Core Library, Minnesota Department of Natural Resources, Division of Lands and Minerals was a very valuable asset for collecting rock samples from across the State for this study.

Finally, to Minnesota Senator Yvonne Prettner-Solon (current Lt. Governor, State of Minnesota), Senator Ellen Anderson, and Minnesota Representative Bill Hilty for making funding of this project possible, and to other senators and representatives who saw the usefulness of this research to Minnesota.

REFERENCES

[1] Blackwell, D.D., and Richards, M., 2004, Geothermal Map of North America: American Association Petroleum Geologist (AAPG), 1 sheet, scale 1:6,500,000.
[2] Klenner, R., Gosnold, W., Heine, J.J., Severson, M.J., Hauck, S.A., Hudak, G., and Fosnacht, D.R., 2012, New Heat Flow Map of Minnesota Corrected for the Effects of Climate Change and an Assessment of Enhanced Geothermal System Resources: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-2012/01, 109 p.
[3] Roy, R.F., Blackwell, D.D., and Birch, F., 1968, Heat generation of plutonic rocks and continental heat flow provinces: Earth and Planetary Science Letters, v. 5, p. 1-12.
[4] Roy, R.F., Blackwell, D.D., and Decker, E.R., 1972, Continental heat flow, in Nature of the Solid Earth, Robertson, E.C. (ed.): McGraw-Hill, New York, NY, p. 506-544.
[5] Hart, S.R., Steinhart, J.S., and Smith, T.J., 1994, Terrestrial Heat Flow in Lake Superior: Canadian J. Earth Sciences, v. 31, p. 698-708.
[6] Tester, J.W., Anderson, B., Batchelor, A., Blackwell, D., DiPippo, R., Drake, E., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksoz, N., Veatch, R., Augustine, C., Baria, R., Murphy, E., Negraru, P., and Richards, M., 2006, The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century. Massachusetts Institute of Technology, DOE Contract DE-AC07-05ID14517 Final Report (FGE2006), 209 p.
[7] Eliasson, L., and Smith, C., 2011, When smaller is better - Cost/Size/Risk analysis of geothermal projects: Geothermal Resource Council, Annual Meeting, San Diego, CA, Oct. 23-26, 2011. PowerPoint Presentation (http://www.geothermal.org/powerpoints11.html).
[8] Blodgett, L. and Slack, K., eds., 2009, Geothermal 101: Basics of Geothermal Energy Production and Use: Geothermal Energy Association, Washington, D.C., 55 p.