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GEOTHERMAL RESOURCE ASSESSMENT: A DETAILED APPROACH TO LOW-GRADE RESOURCES IN THE STATES OF NEW YORK AND PENNSYLVANIA

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ABSTRACT

The potential to utilize widespread low-grade geothermal resources of the Northeastern U.S. for thermal direct use and combined heat and power applications can be realized using technologies embodied in Enhanced Geothermal Systems (EGS). In lower grade regions, accurate knowledge of small variations in temperature gradient will be crucial to the economic viability of EGS development. In order to facilitate EGS project placement and design, this study draws a more complete picture of geothermal resources in the Northeastern United States—with a particular focus on New York and Pennsylvania—by incorporating thousands of new temperature-depth data collected as a result of continuing drilling for unconventional natural gas in the region. Using these new data, a series of maps covering the Appalachian Basin of New York and Pennsylvania were produced that show variations in subsurface thermal gradient and surface heat flow. The increased spatial accuracy and resolution compared to earlier geothermal maps of the Northeast U.S. illuminate better spatial variations in the resource quality, and have a much smaller degree of uncertainty in both extent and magnitude. The maps indicate that the temperatures required for direct-use applications are available at economically viable drilling depths over a majority of the region. Smaller "hot spot" areas of higher than average heat flow are found in the Pennsylvania counties of Indiana, McKean, Lawrence, and Warren, as well as Cayuga County in New York. These anomalies represent the most ideal candidates for further exploration and characterization of their EGS potential.

INTRODUCTION

Public and scientific perceptions of geothermal energy as a viable and necessary component of our energy future continue to be constrained by a widespread focus on electricity generation. For example, the current inability of relatively low-grade geothermal resources in the Northeastern United States to efficiently generate electricity severely limits their economic viability if thermal direct use and combined heat and power applications are not also considered. With direct use and co-generation applications, development of Enhanced Geothermal Systems (EGS) technology provides a feasible path for these lower grade resources to be economically competitive in today's energy markets.

Unlike traditional hydrothermal resource projects, EGS can be deployed in areas with high subsurface temperatures that lack a flow of natural water. Unfortunately, the drilling depths and uncertainties associated with accessing these systems results in both increased risk and increased cost for potential developers. While electricity generation typically requires well-head temperatures in excess of 150°C, direct-use of geothermal heat for space heating, water heating, and industrial and agricultural processes can be achieved with well-head temperatures as low as 80°C - reducing required drill depths and, subsequently, risk and cost. The lower temperatures also effectively expand the potential resource-base and make EGS much more viable in areas with generally lower subsurface temperatures such as the northeastern and mid-Atlantic U.S. The proceeding work has been completed with EGS direct-use in mind.

This project is part of a joint effort with Southern Methodist University (SMU) to create an updated heat flow map of the United States. SMU's 2004 geothermal map of North America was based on very limited data in the northeastern and mid-Atlantic regions of the country. Consequently, the 2004 treatment was unable to characterize potential geothermal resources in these regions with the same accuracy or fidelity as was possible in the midwesten and western regions of the U.S. (Blackwell and Richards, 2004). With the use of recently acquired oil and gas well-log data from many eastern states, it is now possible to develop a refined map of heat flow that can be used to identify areas with the potential for development of EGS.

The initial assessment presented here examines the states of New York and Pennsylvania with the intent of future expansion into the New England region. Well-log data consisting of bottom hole temperatures (BHTs) and vertical depth measurements from the two states were assembled and then corrected to account for drilling-induced errors in the temperature measurements (discussed in further detail below). A spatially variable (in both depth and surface extent) model of subsurface thermal conductivity was constructed based on the AAPG COSUNA (Correlation of Stratigraphic Units of North America) publication for the Northern Appalachian Basin (Orlo, 1985). The modeled thermal conductivity and corrected thermal gradients were then used to produce comprehensive maps of heat flow at the surface and temperature at depth, using the methods described by Stutz et al. (2012).

METHODS

Data Collection

Well data in the form of archived oil and gas well logs were collected from SMU, the Pennsylvania Geological Survey, the New York State Museum, and the New York State Department of Environmental Conservation (NYSDEC, 2011). The total collection was reduced to include only wells with BHT measurements taken at depths greater than 600 meters, thereby minimizing the effects of groundwater movement and near-surface temperature variations on thermal gradient calculations. This depth cutoff was applied by Frone (2010) and has been used to maintain consistency across datasets for the compilation of a final heat flow map by SMU and Cornell. The resulting dataset contained 814 data points in New York and 3,771 data points in Pennsylvania. Due to the spatially-variable nature of oil and gas deposits (and thus oil and gas drilling), the BHT data points in this dataset are not spatially homogeneous. Rather, they are often clustered together in certain areas where oil and gas drilling are more prevalent, such as west-central Pennsylvania in the deepest parts of the Appalachian Basin. No new data points have been identified in northeastern New York and southeastern Pennsylvania.

BHT Corrections

BHT data is commonly of poor quality and often the exact conditions leading up to and at the time of measurement are not well documented. Additionally, BHT points are taken from open hole well logs where near field temperatures will have been significantly disturbed due to the circulation of large quantities of drilling mud utilized in the drilling process. As such, the true "equilibrated" BHT measurements are not obtained. This inherent error must be removed by calibration with oil and gas wells of similar depth that are at thermal equilibrium in order to calculate representative geothermal gradients and surface heat flow. The most mathematically robust, and therefore commonly regarded as most accurate, correction utilizes a Horner plot as originally proposed by Bullard (1947). However, this correction method requires multiple temperature readings through time following cessation of well drilling—a practice that is seldom applied in the oil and gas industry—and thus cannot be applied to wells with a single BHT measurement (Demming, 1989).

As a practical alternative to Horner plots, purely empirical BHT corrections are often developed and applied within a field or geological basin. Within a single field or basin, most wells will be drilled in a very similar fashion, through similar geological units, and to similar depths. As a result, they will have experienced comparable magnitudes of deviation from thermal equilibrium. The majority of empirical corrections attempt to estimate this deviation as a function of depth. For example, in the AAPG Geothermal Survey of North America, Kehle (1972) proposed that a 3rd order polynomial could be fit to the difference between measured BHT temperature and equilibrium temperature. This resulted in an equation similar to Equation 1, where ΔT is the difference between equilibrium temperature and the observed temperature on a geophysical log at depth z.

$$\Delta T = a + bz + cz^2 + dz^3 \qquad (1)$$

The correction coefficients a, b, c, and d could be estimated empirically by least squares regression given data within any specific region.

Similarly, Harrison et al. proposed a second order polynomial, based on data from the state of Oklahoma (1983). The simplified form of this correction can be seen in Equation 2, where ΔT is in °C and depth (z) is in meters.

$$\Delta T = -16.51 + 0.018z - 2.34E10^{-6}z^2 \qquad (2)$$

The number of significant figures in Equation 2 is consistent with the accuracy of temperature-depth measurements and still retains the precision of the quadratic correlation. The resultant ΔT value is a correction factor that can be added to the BHT from a geophysical log header to yield a corrected equilibrium temperature.

The Harrison correction was successfully applied in basin analysis studies of the Anadarko Basin in Oklahoma (Gallardo and Blackwell, 1999). Additionally, by incorporating the work of H. C. Spicer (1964), which provided a set of equilibrium data wells in multiple states, the Harrison equation (1983) has been shown to provide a suitable correction in many other areas, including the Northeastern U.S. Frone et al. (2011), for example, applied this correction to New York, Pennsylvania, and West Virginia with reasonably accurate results. Thus, based on the nature of this dataset and other factors, the Harrison correction was selected as the most practical and feasible correction for the analysis presented here.

The resulting BHTs were plotted against fourteen thermally equilibrated Spicer wells in New York and Pennsylvania, the majority of which extended to depths of 1500 to 2000 meters. As shown in Figure 1, it was found that the Harrison correction adequately adjusted BHTs for wells in excess of 1000 meters. However, for wells shallower than 1000 meters, uncorrected values were more likely to be representative of thermal equilibrium. Given that the Harrison correction is an empirical correlation based in Oklahoma, it accounts for warm mud that has been stored at surface temperatures before being circulated downhole. Average drilling mud temperatures in NY and PA will be approximately 6°C lower than those in Oklahoma (Gass, 1982) while being stored at surface prior to, and during, initial down-hole circulation, thus diminishing the need for correction at shallow depths.

Thermal Gradient Calculations

The Harrison-corrected BHT values, measurement depth, and average annual surface temperature of the

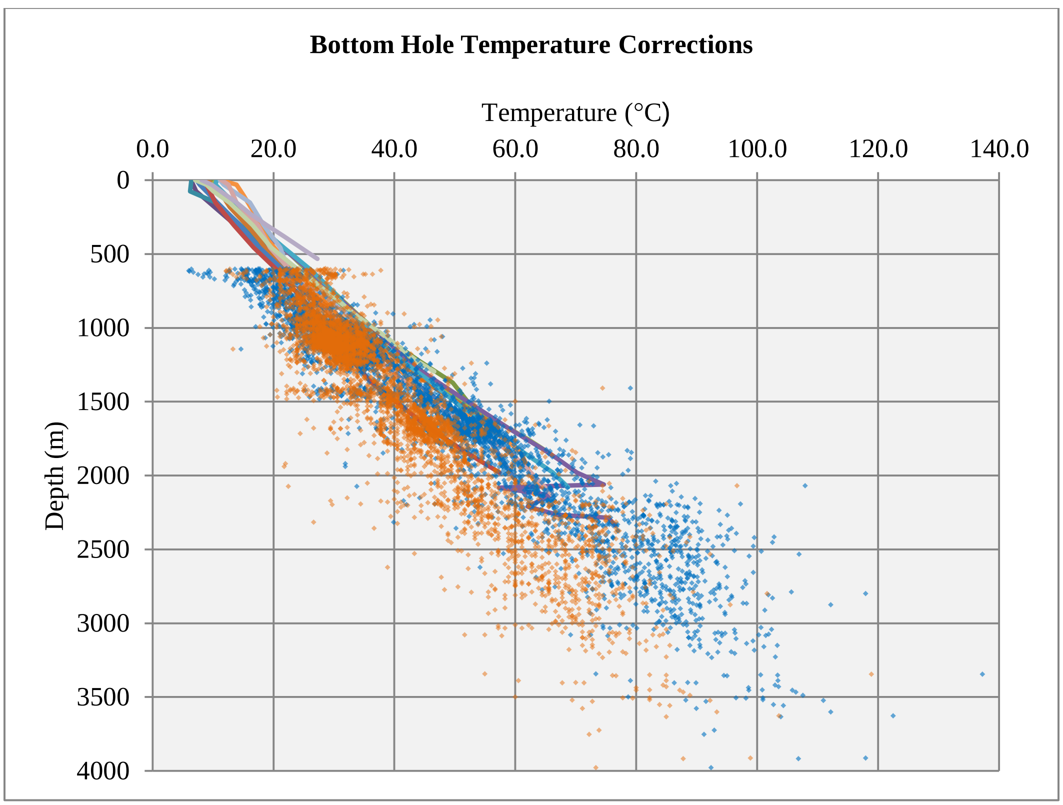

Figure 1: Temperature measurements from 14 equilibrated wells are compared to Harrison-corrected (blue) and uncorrected (orange) bottom hole temperatures (data sources: SMU; PA Geological Survey; NYS Museum; NYSDEC, 2011). The applied Harrison correction is viable for depths greater than 1000 m. Data points shallower than 600 m and deeper than 4000 m were not included in the figure due to near-surface temperature variations and sizing of the chart, respectively.

region were used to calculate an average thermal gradient (dT/dz) at the location of each data point. Equation 3 defines T_{BHT} as the corrected bottom hole temperature in °C, T_S as the average annual surface temperature in °C, and z as the vertical depth in kilometers.

$$\left(\frac{dT}{dz}\right) = \frac{T_{BHT} - T_S}{z} \tag{3}$$

The vertical depth was assumed to be the lesser of either the logging depth, as measured by the well-logger, or the true vertical depth (TVD), as reported by the driller. The value of T_S was estimated to be 9°C based on Gass' (1982) map of U.S. surface temperatures. In the case of duplicate well entries (due to logging of the same well at different depths), the gradients were averaged based on the simplification that, below the domain of fresh water aquifers, the temperature gradient is constant with depth for a given location.

Heat Flow Calculations

Surface heat flow at a given location was calculated as the product of the thermal gradient and an average thermal conductivity value (k), as shown by Equation 4.

$$Q_s = k\left(\frac{dT}{dz}\right) \tag{4}$$

At each individual well location, the thermal conductivity values of the underlying geologic formations were calculated as a weighted average based on their thicknesses. The formation lithologies and thicknesses were derived from the AAPG Northern Appalachian COSUNA (Correlation of Stratigraphic Units of North America) cross section (Orlo, 1985). COSUNA defines a generalized stratigraphic column containing the formation names, range of unit thicknesses, and primary lithology for a set of regions, with the regions consisting of multiple counties. This information was digitized and supplemented with additional descriptions from the USGS. Using a previous compilation of lithology-specific thermal conductivities by Beardsmore and Cull (2001), which included the mean values from eleven different studies, the thermal conductivities of each rock type were averaged and assigned to individual formations within the COSUNA sections.

In order to better represent the conductivity at a specific location, it was necessary to refine the total sedimentary thicknesses shown on the large-scale COSUNA sections. The area of study is located in the northern Appalachian Basin with sedimentary thicknesses ranging from 0 to 10 km, increasing steadily to the southeast and reaching maximum thicknesses along the western edge of the Appalachian Mountain range. A map of the sedimentary thickness from the AAPG Basement of North America (1978) was used to generate a 3D surface representing depth to basement rock over the aerial extent of the wells (Figure 2).

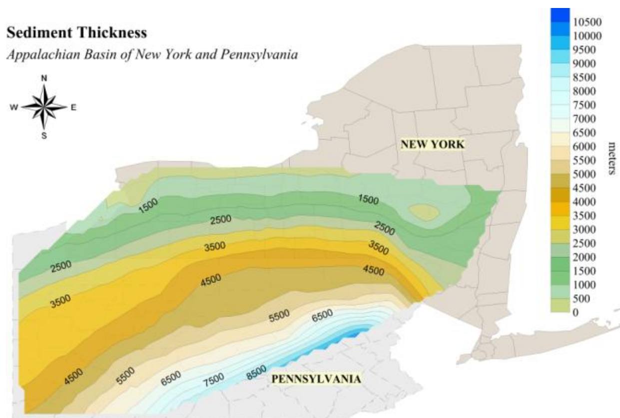

Figure 2: The thickness of the sedimentary units within the Appalachian Basin of New York and Pennsylvania, representing the depth from the surface to the underlying basement rock, from AAPG (1978). From this map, the sedimentary thickness at a given well location was predicted.

Given the location of an individual well, the 3D surface interpolated the depth to the basement; the resulting value was applied as a scaling factor to the overall thickness of the COSUNA cross-section. The average thermal conductivity to a given well depth was then calculated using the procedure described by Stutz et al. (2012).

Temperature at Depth Calculations

The thermal model developed by Stutz et al. (2012) was used to calculate the anticipated temperature as a function of depth. Several assumptions were used in the model as deemed appropriate for the Appalachian basin of NY and PA. Based on the work of Blackwell, Negraru, and Richards (2007), the thermal conductivity of rocks will approach a constant value at depth as a function of increasing temperature and pressure. Therefore below a depth of 4 km, a value of 2.7 W/m/K was used regardless of lithology (Birch and Clark, 1940; Sibbit, Dodson, and Tester, 1979; Clauser and Huenges, 1995). It was also assumed that mantle heat flow could be estimated as 30

mW/m^2 over the entire area and that the sedimentary strata could be modeled as a uniform radiogenic layer producing 1.0 $\mu W/m^3$ (Birch, Roy and Decker, 1968; Allen and Allen, 2005; Blackwell, Negraru, and Richards, 2007). The radiogenic contribution of the basement (A_b) was then calculated using these assumptions and Equation 5.

$$A_b = \frac{Q_s - Q_m - A_s z_s}{b} \quad (5)$$

Q_s and Q_m are sedimentary and mantle heat flow (respectively), A_s is the radiogenic contribution of the sediments, z_s is the thickness of the sediments, and b is the characteristic thickness of the basement (that which produces a meaningful level of radiogenic heat).

Any well temperature that resulted in a lower heat flow than what would be expected from the mantle heat flow and the sediment radiogenic contribution was neglected. Based on the assumptions described, it would be possible to have a negative A_b value returned. It was assumed that convective flow or some other force was removing heat from this location, or that the assumption of 1.0 $\mu W/m^3$ radiogenic contribution from the sediments was too high. However, without more detailed information it was not possible to determine the exact nature of the error. As this situation affected a very small proportion of wells (approximately 2.5%), data from those wells were disregarded. We intend to evaluate wells in this category in greater detail in future research in an effort to glean more information regarding basin-wide, as well as more localized, processes. The remaining wells used in this analysis were then thermally modeled to estimate temperature at depth.

Mapping Techniques

Contour maps of the calculated geothermal gradients and heat flow were produced through the Surfer Mapping System from Golden Software, Inc. The Natural Neighbor gridding method, ideal for varying data densities, accounted for the spatial irregularity of the data points throughout New York and Pennsylvania. It also gave weight to values with proximity to each grid node. Grid values were not extrapolated beyond the spatial extent of the data; areas lacking data points were left blank to avoid misrepresentation, as seen in the eastern regions of the states.

DISCUSSION

The thermal gradient and heat flow maps produced for this study (Figure 3 and Figure 4) provide a detailed visual representation of the potential geothermal resources in western New York and Pennsylvania.

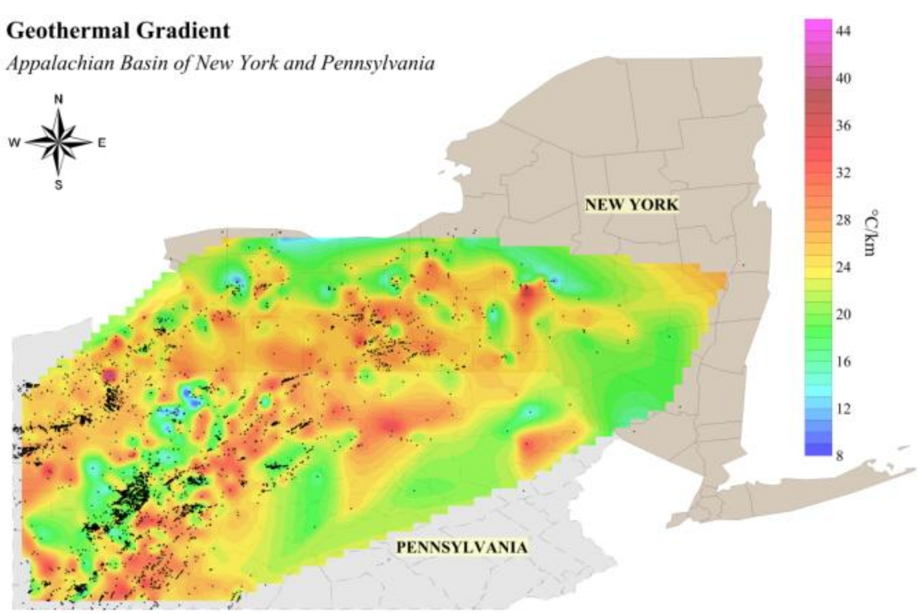

Figure 3: The thermal gradient of geothermal resources within the Appalachian Basin of New York and Pennsylvania. The black points are locations of the individual well whose bottom hole temperature and depth measurements are included (data sources: SMU; PA Geological Survey; NYS Museum; NYSDEC, 2011).

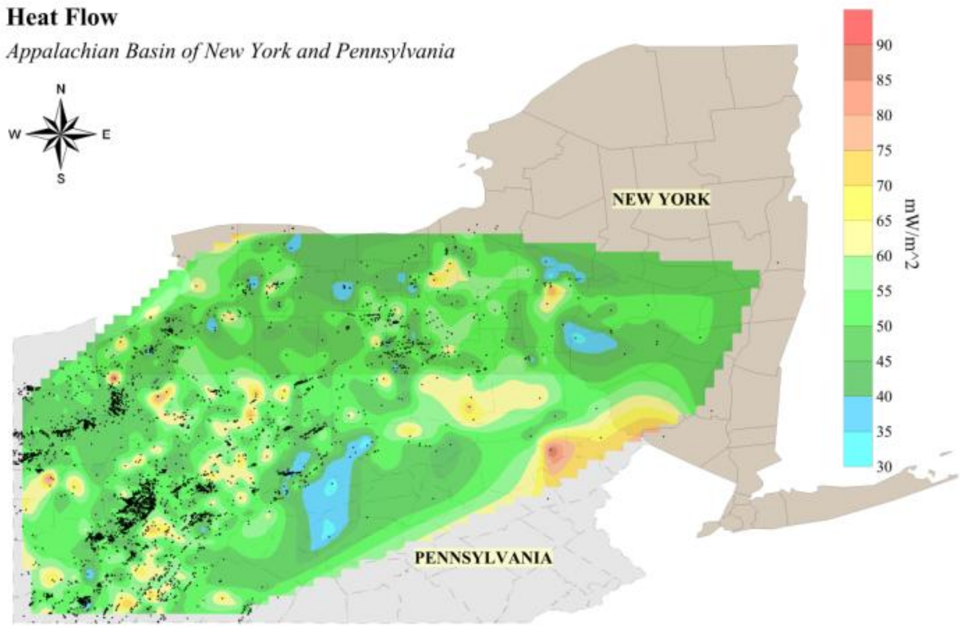

Figure 4: Surface heat flow in the Appalachian Basin of New York and Pennsylvania, calculated as the product of thermal gradient and average thermal conductivity for a specified location. The black points are locations of the individual well whose thermal gradients were derived (data sources: SMU; PA Geological Survey; NYS Museum; NYSDEC, 2011)

The average thermal gradient of the dataset (using Harrison-corrected BHTs) is 23 °C/km with an average surface heat flow of 50 mW/m^2, coinciding with conventionally-accepted average continental values of 25°C/km and 50 mW/m^2. Comparison with the 2004 heat flow map produced by Blackwell et al. (Figure 5) illustrates the degree to which spatial resolution of the geothermal resources has been increased.

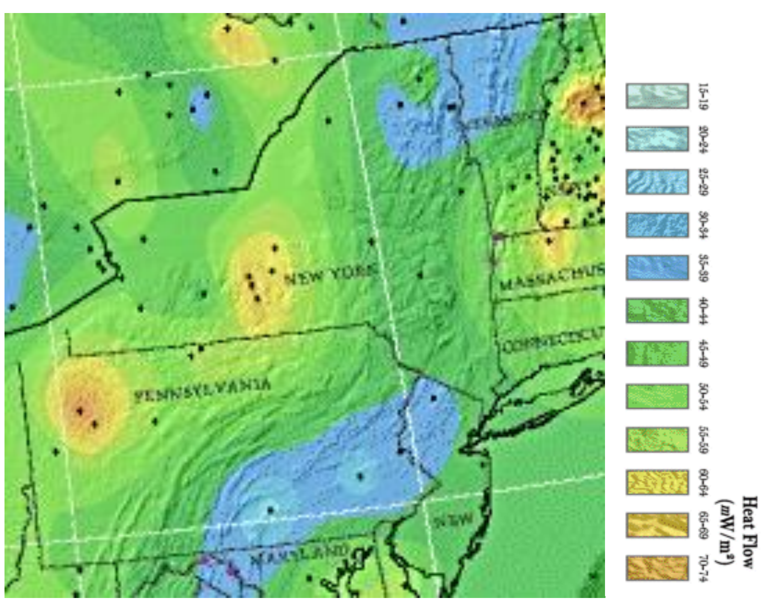

Figure 5: Limited data in the Appalachian Basin of New York and Pennsylvania as shown by the earlier SMU map (Blackwell, 2004). An increased number of data points have increased the understanding of heat flow distribution in the region.

Isothermal contour maps resulting from the methodology described in Stutz et al. (2012) show the projected depths at which temperatures of 80°C (Figure 6) and 150°C (Figure 7) can be reached. 80°C, the target temperature for a direct-use district heating system, is accessible over a large area of Figure 6 at depths shallower than 6 km (often considered the economically viable drilling depth) (Fox et al., 2011). It is therefore within reason to state that the assessed area shows great potential for deployment of geothermal district heating. Throughout a majority of the mapped area in Figure 7, the temperatures required for electric power generation (>150°C) are found at depths of 6 to 10 km; although these depths are accessible with current technology they will be very challenging to produce and develop economically at today's electricity prices. Co-generation of electricity and heat would be much more attractive for these resources (Tester et al., 2010).

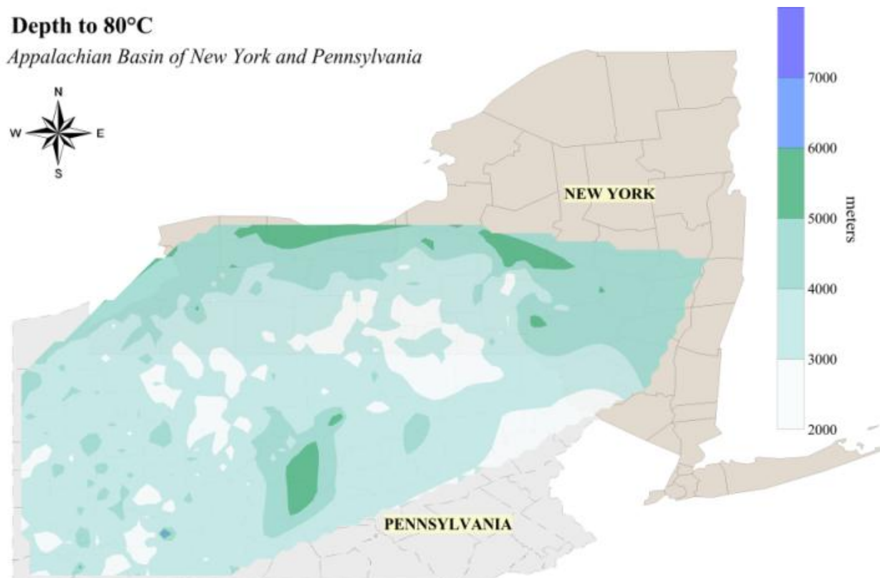

Figure 6: Isothermal map of depths at which 80°C temperatures are predicted to exist. This temperature is ideal for direct-use district heating systems.

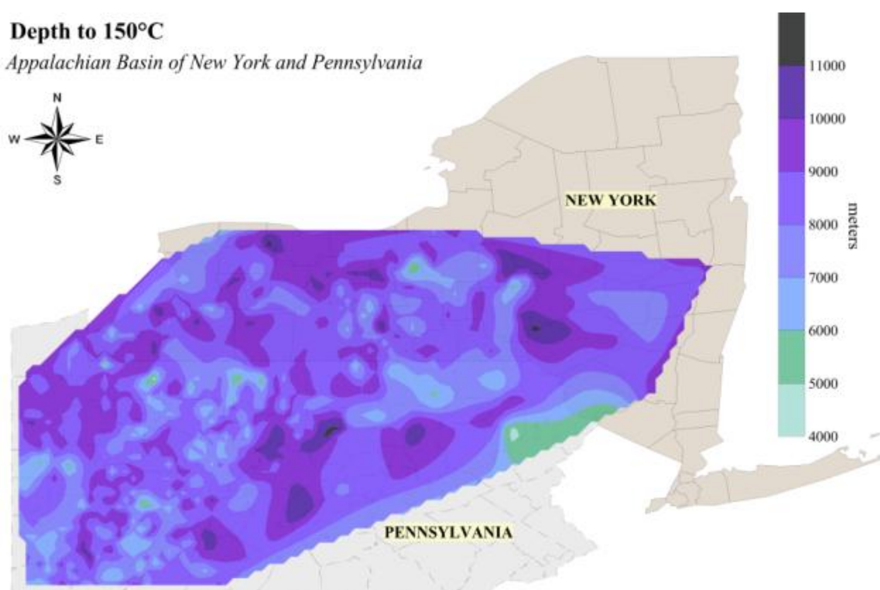

Figure 7: Isothermal map of depths at which 150°C temperatures are predicted to exist. This temperature is applicable for electricity generation.

By increasing spatial resolution over previous geothermal resource maps of the Appalachian Basin, several localized “hot spots” can now be identified. In some cases, temperatures capable of producing electric power are projected at depths as shallow as 5 km (Figure 7). The Pennsylvania counties of Indiana, McKean, Lawrence, and Warren contain such potential “hot spots”, as does Cayuga County in New York. The “hot spots” are defined by heat flows 20 mW/m^2 or more above the regional average and are constrained by nearby data points. The surface area of each is approximated to be tens of square kilometers in size. These anomalies warrant a more spatially resolved analysis to better define their potential for EGS development.

There is an inherent level of uncertainty associated with producing gradient and heat flow maps such as those presented here. Apart from the uncertainty associated with the temperature measurements themselves and their corrections, data density is also of primary concern. BHT data points are most concentrated in areas of heavy oil and gas drilling; as a result, there is a highly variable spatial distribution of data points across the study area, ranging from 1 data point in some New York counties (Schoharie and Oneida) to 931 data points in Armstrong County, Pennsylvania. The gridding method used to create each map was selected because of its suitability for density-varying data sets; however, the exact weight given to each data point and its leverage on the overall contouring is uncertain. Anomalies contained completely within the interior of the study area are, therefore, slightly more reliable than those transected by the outer boundary. Hot spot anomalies in areas of dense data are also more reliable than those represented by only one or two data points, and are deserving of future geochemical, geophysical, and drilling investigations.

CONCLUSIONS

The recent availability of well log data and the development of improved methods for heat flow calculations (Stutz et al., 2012) have enabled an efficient updated assessment of the geothermal resources in the Appalachian Basin of New York and Pennsylvania. Temperature-at-depth maps indicate that direct-use and combined heat and power (co-generation) applications of these lower grade geothermal resources is widely accessible throughout the area, while suitable temperature gradients for geothermal electricity generation may be possible at select locations with favorable financials to attract investment. Future improvements of the maps and methods presented in this paper include supplementing areas of sparse data, developing a BHT correction specific to the NY and PA region, and obtaining additional equilibrated temperature data for calibration, as well as expanding the boundaries of the current study into the New England states. As a product of achieving the goal of increased spatial resolution of the geothermal resources within the Appalachian Basin of New York and Pennsylvania, a number of isolated “hot spots” have emerged. The next step is to ascertain the credibility and geologic nature of these anomalies to determine their potential for EGS development.

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REFERENCES

AAPG (1978), Basement map of North America, The American Association of Petroleum Geologists, scale 1:5,000,000.

Beardsmore, G. R., and J. P. Cull (2001), Crustal Heat Flow: A Guide to Measurement and Modeling, New York: Cambridge University Press. Print.

Blackwell, D. D., and M. C. Richards (2004), “Geothermal map of North America,” The American Association of Petroleum Geologists, 1 sheet, scale 1:6,500,000.

Blackwell, D. D., Negraru, P. T., and Richards, M. C. (2007), “Assessment of the Enhanced Geothermal System Resource Base of the United States,” *Natural Resources Research*, **15**, 283-308.

Bullard, E. C. (1947), “The Time Necessary For a Borehole to Attain Temperature Equilibrium,” *Geophysical Journal International*, **5**, 127-130.

Deming, D. (1989), “Application of Bottom-Hole Temperature Corrections in Geothermal Studies,” *Geothermics*, **18**, 775-786.

Deming, D., and D. S. Chapman (1988), “Heat Flow in the Utah-Wyoming Thrust Belt from analysis of bottom-hole temperature data measured in oil and gas wells,” *Journal of Geophysical Research*, **93**, 13657-13672.

Fox, D. B., Sutter, D. and Tester, J. W. (2011), “The Thermal Spectrum of Low-Temperature Energy Use in the United States,” *Energy and Environmental Science*, **4**, 10, 3731-3740.

Frone, Z., and D. D. Blackwell (2010), “Geothermal Map of the Northeast United States and the West Virginia Thermal Anomaly,” *Geothermal Resources Council Transactions*, **34**, 308-312.

Gallardo, J., and D. D. Blackwell (1999), “Thermal Structure of the Anadarko Basin, Oklahoma,” *American Association of Petroleum Geologists Bulletin*, **83**, 2, 333-361.

Gass, T. E., (1982), “The geothermal heat pump,” *Geothermal Resources Council Bulletin*, **11**, 11, 3-8.

Harrison, W. E., et al. (1983), “Geothermal resource assessment of Oklahoma,” Special Publication 83-1, Oklahoma Geological Survey.

Horner, D. R. (1951), “Pressure Build-up in Wells,” *3rd World Petroleum Congress*, The Hague, NL, World Petroleum Congress, May 28 – June 6, 1951.

Kehle, R. O. (1972), “Geothermal Survey of North America,” 1972 Annual Progress Report for the American Association of Petroleum Geologists, **23**, 1973.

New York State Department of Environmental Conservation (NYSDEC), “Oil and Gas Searchable Database”. Retrieved February 2011from <http://www.dec.ny.gov/cfmx/extapps/GasOil/search/wells/index.cfm>.

Orlo, E. C., et al. (1985), “Correlation of stratigraphic units in North America: Correlation chart series,” The American Association of Petroleum Geologists.

Pollack, H. N., et al. (1993), “Heat Flow from the Earth’s Interior: Analysis of the Global Data Set,” *Reviews of Geophysics*, **31**, 3, 267-280.

Spicer, H. C. (1964), “A compilation of deep Earth temperature data: USA 1910-1945,” U.S. Geological Survey Open File Report, 64-147.

Stutz, G. R., et al. (2012), “A Well by Well Method for Estimating Surface Heat Flow to Analyze the Geothermal Energy Resource Potential of the United States,” *37th Stanford Geothermal Workshop*, Stanford, CA, January 30 – February 1, 2012. (In Press)

Tester, J. W., et al. (2010), “Co-Generation Opportunities for Lower Grade Geothermal Resources in the Northeast – A Case Study of the Cornell Site in Ithaca, NY,” *Geothermal Resources Council Transactions*, **34**, 440-448.