PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

A WELL BY WELL METHOD FOR ESTIMATING SURFACE HEAT FLOW FOR REGIONAL GEOTHERMAL RESOURCE ASSESSMENT

George R. Stutz[1,2], Mitchell Williams[3], Zachary Frone[3], Timothy J. Reber[1,2], David Blackwell[3], Teresa Jordan[1,2], Jefferson W. Tester[1,2,*]

[1]Cornell Energy Institute, Cornell University, Ithaca, NY 14853, USA
[2]Cornell Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14853, USA
[3]SMU Huffington Department of Earth Sciences, Geothermal Laboratory, Dallas, TX, 75275, USA
*Email: jwt54@cornell.edu

ABSTRACT

To accurately map local temperature variations, resource assessments have relied largely on bottom hole temperature (BHT) measurements, primarily from oil and gas wells because of the high density of well sites in explored areas. As the volume of BHT data grows due to increased drilling activity, the ability to quickly analyze and incorporate additional data is critical. Currently, in the Appalachian basin of West Virginia and Pennsylvania, more than 1,000 wells are being drilled every year. Incorporating this number of BHT points using current techniques may take weeks to months. This paper presents an approach to quickly and efficiently incorporate additional well data into existing geothermal resource maps.

MOTIVATION AND SCOPE

The process developed in the study utilizes the techniques of mapping potential geothermal resources adopted by the Southern Methodist University (SMU) Geothermal Laboratory and new functional routines to rapidly calculate the estimated surface heat flow, temperature at various depths, and other properties from large quantities of oil and gas well data (Blackwell et al., 2010). In addition, this technique permits incorporation of a more accurate estimate of sediment thickness at each well location and can utilize these estimates of thickness in subsequent calculations, greatly increasing their accuracy. The combination of improved accuracy and speed in incorporating additional data will enable more flexibility in analyzing potential Enhanced Geothermal System (EGS) resources. The resulting maps will aid in locating small temperature gradient variations that may be required for any proposed EGS system in a lower grade region.

The economic success of any potential low grade EGS system in the United States will depend on locating geothermal anomalies at a spatial scale sufficient to establish relative high grade areas large enough to act as a functional heat production system. In the Eastern United States particularly, due to the relative low grade of potential geothermal energy resources, the accuracy and spatial resolution of maps of localized heat flow variations are of greater importance than in conventional, hydrothermal dominated areas where gradients are generally much higher. East of the Rocky Mountains, deep sedimentary basins, such as the Appalachian basin, may provide the best targets for potential EGS exploitation. Installing an EGS reservoir in a sedimentary basin assumes the ability to drill to sufficient depth to reach usable temperatures as defined by the anticipated end use of the thermal energy. To minimize the depth to the EGS reservoir, the first major step is to discover areas of relative high thermal gradient by regional mapping of heat flow and subsurface temperature.

Given the sparseness of conventional heat flow measurements in many regions of the US, mapping and modeling of subsurface temperatures has been time consuming. Additionally, sparse data has severely limited the ability to locate variations in the average heat flow that are spatially small enough to pinpoint additional exploration investment, yet broad enough to result in economically viable EGS systems. To fill in the large spatial gaps in conventional heat flow data, researchers have incorporated oil and gas data.

Oil and gas wells are routinely drilled into sedimentary basins, creating large datasets of BHT measurements and geological information for analysis. In regions with low thermal gradients (20-40°C/km), such as the Eastern United States, the cost and difficulty of drilling to a reservoir at sufficient depth may make any project technically or economically infeasible (Mock et al., 1997; Tester et al., 2006; IPCC, 2011). Therefore, to maximize the chance of success in such regions, maximum information must be extracted from these datasets, seeking understanding of small variations in heat flow and temperature gradient.

Requisite for improving accurate understanding of the magnitudes and three-dimensional spatial scale of favorable thermal anomalies is access to new data, and analytical methods for efficient addition of new data to existing regional geothermal maps. Ongoing oil and gas exploration drilling provides a stream of new data, whose locations are dictated by criteria unrelated to EGS assessment. The focus of this study is to provide a new method to use this data to quickly and accurately calculate estimated surface heat flow and predict subsurface temperature profiles for use in EGS resource assessments.

This paper describes the means by which the thermal modeling process has been streamlined and given improved accuracy while increasing the speed with which large amounts of data can be incorporated and used to improve data synthesis. The generalized method is independent of the data source and is intended to allow for user discretion when choosing inputs. One well could be processed with very precise data, or as is more likely, thousands of wells with best available data could be analyzed in minutes. The addition of either type of data should provide maps with higher granularity, thereby reducing uncertainty and risk in EGS exploration.

This automation process utilizes Microsoft Excel and user defined functions written in the Visual Basic for Applications (VBA) language. The resulting models provide routines with sufficient accuracy and speed to quickly and efficiently incorporate massive amounts of data into geothermal mapping. Presented here is a discussion of the equations used, the scientific basis behind them, and a specific review of how the programs and procedures have been applied in Southwestern Pennsylvania.

EXISTING METHODOLOGY FOR HEAT FLOW ESTIMATION

In 2007 the Geothermal Laboratory at the Southern Methodist University (SMU) Huffington Department of Earth Sciences published their work, "Assessment of Enhanced Geothermal System Resource Base of the United States" (Blackwell et al., 2007). This document provided a framework which incorporated oil and gas data into EGS resource evaluations. The maps produced, and subsequent revisions, utilized BHT data, mainly from the oil and gas industry, as a primary data source. More than 2,000 rotary rigs were active in the US as of September 2011, resulting in continued rapid growth in the quantity of BHT data. As a consequence, there is a need for reliable and simple methods to incorporate each new well data points. The BHT measurements obtained from these wells can then be used to help validate and refine resource assessment models, such as SMU's.

As discussed by Blackwell et al. (2007; 2010), and Shope et al. (2012), BHT data are commonly of very low quality. Because measurements are taken very shortly after cessation of drilling operations, the temperature presented on geophysical logs does not represent a true formation value. For this reason a correction must be applied. Entire publications have been devoted to analyzing the validity of the numerous equations and methods proposed to adjust BHT data to thermal equilibrium (Deming, 1989). The model presented in this study is independent of the technique used to adjust BHT data to thermal equilibrium. It is assumed that the BHT points input into the model have been adequately adjusted by the user through whichever technique was determined to be most appropriate.

The corrected BHT's are used to calculate an average temperature gradient for that well. The equilibrium gradient is calculated as:

$$\left(\frac{dT}{dz}\right) = \frac{T_{BHT} - T_s}{z} \tag{1}$$

Where T_{BHT} is the corrected temperature, T_s is the average annual surface temperature, both in °C, and z is the true vertical depth of the log measurement in meters.

The resulting corrected gradient can then be utilized to calculate surface heat flow, assuming 1D vertical conduction of heat through the rock column as:

$$Q_s = k\left(\frac{dT}{dz}\right) \tag{2}$$

Where gradient is in ^{o}C/km, thermal conductivity k is in W/m/K, and heat flow Q_s is in mW/m^2. Given that the depth of the well is small compared to the distance of significant structural changes in geology, and precluding recent volcanism or other changes that will negate the assumption of steady-state heat flow, this 1D case will be accurate.

To apply Eq. (2), thermal conductivity values from the surface to the well depth must be established. Conductivity values for various lithologies have been the focus of several publications including Joyner et al. (1960), Blackwell and Steele (1989), Beach et al. (1989), and Gallardo and Blackwell (1999). If the well is in crystalline basement rocks, it may be appropriate to assume a single k for the entire well section. However, oil and gas wells, the main source of data in these assessment studies, are drilled into basins with thick sedimentary covers with highly variable lithologies and, therefore, conductivities.

Utilizing a unit thickness, and thermal conductivity, a thermal resistance R can be defined as:

$$R = h/k \qquad (3)$$

Where h is the unit thickness in meters, and k the unit conductivity in W/m/K. The resistance for each unit is added to calculate the total resistance from the surface to the well depth. The resistance of the deepest lithology the well reached is calculated via a linear interpolation to account for the fraction of the lithology penetrated. By dividing the total thermal resistance $(\sum R)$ by the total well depth (z_w), the thermal conductivity $(\bar{k})$ from the ground surface to that depth is:

$$\bar{k} = \frac{z_w}{\sum R} \qquad (4)$$

This average conductivity can then be used directly in Eq. (2), yielding a surface heat flow, unless the well penetrates below 4 km. Thermal conductivity is a function of temperature and pressure, both of which in a first order sense increase in a predictable manner with depth. Consequently, conductivity asymptotically approaches a constant value at sufficient depth. According to Blackwell et al. (2007) this depth for sedimentary rocks is at or near 4 km. Therefore regardless of lithology, any well penetration below this depth is treated as a single unit with constant k. For further detail see Blackwell et al. (2007).

Once the heat flow and average conductivity are determined, the subsurface temperature $T(z)$ at a particular depth z in meters in a basement terrain, igneous or metamorphic rocks at surface, can be estimated by:

$$T(z) = T_s + Q_m \frac{z}{k} + \frac{A_b b^2 \left[1 - exp\left(-\frac{z}{b}\right)\right]}{k} \qquad (5)$$

Quantitatively Eq. (5) represents the anticipated temperature T, at depth z, given mantle heat flow Q_m, average conductivity k, radiogenic heat contribution A_b, the characteristic thickness of the heat producing layer b in meters, and the surface temperature T_s (Blackwell et al. 2007). A more complete discussion of this equation can be found later in the text.

Eq. (5) can be modified to predict the temperature within basins containing thick sedimentary covers given more specific information of the lithologies, differing thermal conductivities, and highly variable radiogenic heat production.

Blackwell et al. (2007) also proposed that each well can be classified into one of four broad categories of geological settings. These categories are divided according to the depth of the sedimentary cover as shown in Figure 1, the four divisions being 1) no sediment cover (basement at surface), 2) sediments less than 3 km thick, 3) sediment thickness between 3 and 4 km, and 4) sediment thickness greater than 4 km.

The division at 3 km in Figure 1, column B, represents a relatively thick sedimentary cover where it is believed that such a thickness would only occur over attenuated or eroded crust, resulting in a decreasing thickness of the primary radioactive heat production layer, represented by b in Eq. (6). The thickness of this layer is estimated via:

$$\begin{gathered} If\ z_{sed} < 3000\ m\ \ then \\ b = 10{,}000 \\ Else \\ b = 13{,}000 - z_{sed} \end{gathered} \qquad (6)$$

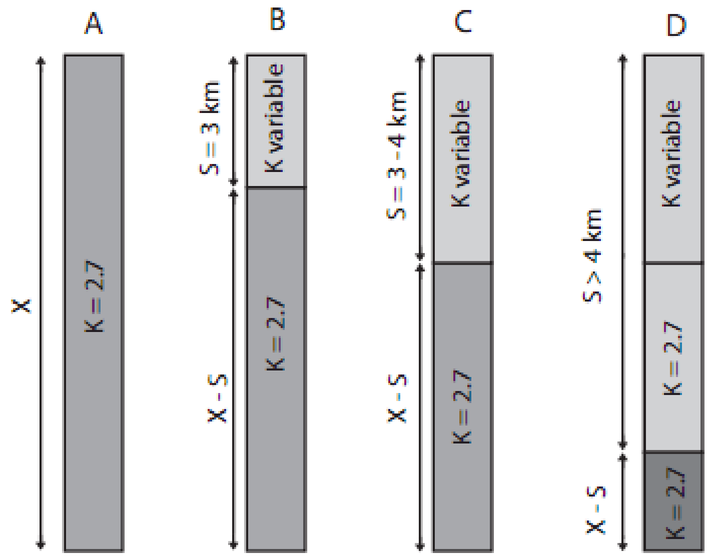


Figure 1: Geologic conductivity and radioactivity models for calculation

Blackwell (1971) states that *b* typically ranges from 7.5 km to 10 km. As shown in Eq. (6), the base case here is taken to be *b*=10 km. The final division at 4 km represents the constant thermal conductivity layer as discussed previously.

SMU's use of geological information yields a more comprehensive analysis of possible EGS resources when compared to previous works. Incorporation of data of this type reduced the need to simplify estimation, a necessity in earlier works. Additionally the study concluded that the resource potential for the United States is quite large and that EGS systems may hold promise nationwide. However current maps lack the spatial granularity to identify small to moderate regions of aberrantly high thermal gradients in regions of the eastern US.

NEW METHOD FOR HEAT FLOW AND SUBSURFACE TEMPERATURE ESTIMATION

Estimating Surface Heat Flow

The general framework for correcting to thermal equilibrium, anticipating average thermal conductivity to total well depth, calculating surface heat flow, and finally predicting temperature at depth, follows the basic procedure as outlined above.

Following earlier conventions, Microsoft Excel and Microsoft Access were utilized to store the large number of BHT data points and to perform the calculations. Therefore, Excel was the natural choice for continued development calculations. Prior work without use of Visual Basic for Applications (VBA) inevitably had to make simplifications due to the amount of data processed. For example, given time and other limitations, large groups of wells were divided by depth to basement and placed in 500 m bins. A scaled sedimentary section was then utilized for all wells within that grouping, i.e. all wells believed to have sediment cover between 4,000 and 4,500 m would be assumed to be 4,250 m. Additionally, earlier calculations of average thermal conductivities to the well depth and to the desired depth where temperature was estimated were simplified in various ways to aid in calculation.

The methods presented in this paper utilize the ability of VBA as an Excel add-on to manipulate the existing data and quickly calculate the desired values. Two gross simplifications, rounding sediment thickness and simplifying conductivity estimates, were removed in these models. The base sheet for calculation and processing of data (Table 1), illustrates information for 11 wells in Westmoreland County, Pennsylvania, which will be used as an example of the thermal modeling process.

Desired inputs are marked in yellow, and include well information, basement conductivity, deep (>4 km) sediment conductivity, and a specified isotherm of interest. Depths for temperature estimation are marked in blue and can be updated to be any set of values of interest to the user. All unmarked columns are calculated and filled in by the processing macros.

Table 1: Well data input for processing and calculation of heat flow and temperature[1]

Calculate	Basement Conductivity (W/m/K)	2.7
	Deep Sediment Conductivity (W/m/K)	2.7
	Isotherm (°C)	80

Identifier (API/Name)	BHT (°C)	Well Depth (m)	Mantle Heat Flow (mW/m2)	Depth to Basement (m)	Avg. Surface Temperature (°C)	Sediment Radiogenic Heat Generation ($\mu W/m^3$)	Basement Radiogenic Heat Generation ($\mu W/m^3$)	Gradient (°C/km)	Heat Flow (mW/m2)	Average Conductivity To Well Depth (W/m/K)	Temperature Estimation at Depth						Depth to Specified Isotherm (m)
											250	500	750	1000	1250	1500	
37129202870000	85	2346	30	5369	9	1											
37129203880000	89	2547	30	4780	9	1											
37129215570000	86	2558	30	5314	9	1											
37129239710000	66	2207	30	5320	9	1											
37129225960000	31	1177	30	4860	9	1											
37129237810000	30	1127	30	4876	9	1											
37129241990000	31	1127	30	4865	9	1											
37129243130000	30	1117	30	4832	9	1											
37129243700000	27	1171	30	4869	9	1											
37129245160000	37	1252	30	4518	9	1											
37129247300000	34	1201	30	4514	9	1											

[1]BHT values represent corrected values, not raw log data

Although the presented example shows constant surface temperature, mantle heat flow, and sediment column radiogenic heat production values, this model allows for individual values to be input for each BHT point. This may be critical if, for example, the area being modeled has large topographic relief resulting in highly variable average surface temperatures, or contains a known amount of shale or other horizons of higher than average radiogenic heat production capability. In addition to predicting temperature at the specified depths, the model iteratively solves for the depth to the input isothermal surface at each BHT location. This surface can be used to analyze the depth to the specified temperature based on the anticipated use of the thermal energy.

The second Excel sheet accepts the data for the stratigraphic column (Table 2), in which each unit is a proxy for a rock horizon with a specific thermal conductivity. In addition to providing BHT data, wells drilled for oil and gas exploration are a source of abundant data about stratigraphic units and thus can be very useful in analyzing temperature distributions. However, the full use of all the publicly available non-interpreted well log data would greatly slow the incorporation of the new BHT data into a preliminary exploration program. Thus for this example, we sought an efficient method to incorporate stratigraphic data, using the assumption that lateral extrapolation of stratigraphic columns would be valid over some distance. As a result, Table 2 represents an idealized or average column for a large area, and a thickness factor must be developed to scale the column to the well location. The specific data depicted in the example are from the Correlation of Stratigraphic Units of North America (COSUNA) (AAPG, 1985).

Table 2: Stratigraphic column from COSUNA (1994) representing the thickness and conductivity data for Pennsylvania Section 17

Unit Indentifier	Thickness (m) : Min	Max	Assumed	Conductivity
*Un-named	81	359	220	3.34
Monogahela OR Uniontown/Pittsburgh	74	108	91	2.22
Conemaugh OR Casselman/Glenshaw	264	264	264	1.60
Allegheny	85	85	85	2.91
Pottsville	54	63	58.5	3.25
Mauch Chunk	135	142	138.5	2.15
Greenbrier	0	72	36	3.10
Burgoon/Rockwell OR unnamed/Shenango	164	224	194	2.91
Venango OR Catskill OR Hampshire	272	670	471	3.17
Chadakoin/Bradford OR Lock Haven OR Foreknc	150	910	530	3.05
Brallier	697	1060	878.5	2.25
Harrell	140	140	140	1.02
Tully	20	20	20	2.45
Mahantango	73	73	73	1.98
Marcellus	37	37	37	1.52
Selinsgrove	3	6	4.5	2.45
Huntersville Chert	32	32	32	2.33
Needmore Shale	7	7	7	2.12
Ridgeley Sandstone	30	30	30	3.42
Licking Creek OR Shriver	12	39	25.5	2.08
Mandata shale	7	7	7	1.43
Corriganville limestone	3	3	3	2.45
New Creek limestone	3	3	3	2.45
Keyser formation	15	39	27	2.45
Tonoloway	6	36	21	2.31
Wills Creek	130	221	175.5	2.26
Lockport OR McKenzie	0	100	50	1.90
Clinton group	100	223	161.5	2.51
Tuscarona formation	45	133	89	4.60
Queenston OR Juniata/Bald Eagle	290	487	388.5	3.34
Reedsville shale	233	233	233	2.15
Antes formation	54	54	54	1.72
Coburn formation	75	75	75	2.50
Salona formation	39	39	39	2.01
Nealmont	78	78	78	2.50
Benner (also called "Linden Hall)	36	54	45	2.70
Snyder	14	39	26.5	3.35
Hatter	36	60	48	3.35
Loysburg	34	51	42.5	3.35
Beekmantown Gp	652	704	678	3.35
Gatesburg	246	332	289	3.35
Warrior Fm	134	134	134	3.35

To scale the representative section, the anticipated depth to igneous or metamorphic basement rock for each well had to be determined (Table 1 "Depth to Basement (m)"). In this example, a map of the thickness of sedimentary cover from the AAPG Basement of North America (1978) was used to interpolate the depth to basement at each well location.

The interpolated sedimentary cover depth was then divided by the total thickness of the stratigraphic section to calculate a scaling factor (Table 3). Each unit in the stratigraphic section was then multiplied by this factor to yield an anticipated thickness at each well.

Table 3: Scaling of thickness to anticipated well location [1,2]

Unit Indentifier	COSUNA Thickness (m)	Well Thickness (m)
*Un-named	220	197
Monogahela OR Uniontown/Pittsburgh	91	81
Conemaugh OR Casselman/Glenshaw	264	236
Allegheny	85	76
Pottsville	58.5	52
Mauch Chunk	138.5	124
Greenbrier	36	32
Burgoon/Rockwell OR unnamed/Shenango	194	173
Venango OR Catskill OR Hampshire	471	421
Chadakoin/Bradford	530	474
Brallier	878.5	786
Harrell	140	125
Tully	20	18
Mahantango	73	65
Marcellus	37	33
Selinsgrove	4.5	4
Huntersville Chert	32	29
Needmore Shale	7	6
Ridgeley Sandstone	30	27
Licking Creek OR Shriver	25.5	23
Mandata shale	7	6
Corriganville limestone	3	3
New Creek limestone	3	3
Keyser formation	27	24
Tonoloway	21	19
Wills Creek	175.5	157
Lockport OR McKenzie	50	45
Clinton group	161.5	144
Tuscarona formation	89	80
Queenston OR Juniata/Bald Eagle	388.5	347
Reedsville shale	233	208
Antes formation	54	48
Coburn formation	75	67
Salona formation	39	35
Nealmont	78	70
Benner (also called "Linden Hall)	45	40
Snyder	26.5	24
Hatter	48	43
Loysburg	42.5	38
Beekmantown Gp	678	606
Gatesburg	289	258
Warrior Fm	134	120
Total (m):	**6003**	**5369**
Well Total Thickness (m):	**5369**	
Scaling Factor:	**0.894**	

[1]*Data for well API # 37129202870000 from Table 1*
[2]*The total thickness of the COSUNA section is 6003 m, while the total sedimentary cover at the well is anticipated to be 5369 m. This results in a scaling factor of 0.894*

Finally a representative thermal conductivity for each unit is required for calculation. In this study, each unit was given a thermal conductivity based on a 60%/40% mix of the primary and first secondary lithology from the USGS (2011) description, with the conductivities for each lithology type from Beardsmore and Cull (2001).

In addition to gradient, surface heat flow, and average thermal conductivity to well basement, the anticipated radiogenic heat generation of the underlying basement terrain, A_b, is calculated. A_b is determined from the surface heat flow Q_s, the mantle heat flow Q_m, and the radiogenic heat generation in the sediments A_s, via:

$$A_b = \frac{Q_s - Q_m - A_s z_s}{b} \qquad (7)$$

Where the assumption of 1D steady state conduction is maintained. As a result, surface heat flow is only a product of mantle heat flow and in-situ radioactive decay from the surface to the effective crust mantle interface.

Modeling Temperature at Depth

The modeling of subsurface temperatures is based on the observation of a linear relationship between observed surface heat flow, Q_s, and radiogenic heat production *(A)* when measured at or near the surface of plutonic rock intrusions. This relationship can be estimated as:

$$Q_s = Q_o + Ab \qquad (8)$$

Eq. (8) has been confirmed for many geologic provinces' including the Eastern United States, the Sierra Nevada, Scandinavia, the Basin and Range, and the Eastern Canadian Shield. As a consequence, an exponential source model can be assumed for the radiogenic basement as:

$$A(z) = A_o exp(-\frac{z}{b}) \qquad (9)$$

Where *A(z)* is the radiogenic heat generation in $\mu W/m^3$ at depth *z* in meters, given initial heat generation A_o in $\mu W/m^3$ and the scale constant for the depth of the heat generation layer *b* in meters. This linear relationship and exponential model of heat production has been found to be a typical approximation in many studies and publications (Birch et al., 1968; Roy et al., 1968; Lachenbruch, 1968, 1970; Blackwell, 1971; Allen and Allen, 2005: and Blackwell et al., 2007). Given the exponential model, b, as determined by the slope described by Eq. (8), is not a physical thickness, but a bound below which heat entering the system will be mantle heat flow only i.e. no radiogenic contribution.

A single uniform layer of thickness b and radiogenic heat production A has also been proposed. In this uniform case b may represent the physical thickness of the radiogenic body. The primary argument in favor of Eq. (9) is that Eq. (8) is maintained during differential erosion (Lachenbruch, 1968 and Blackwell, 1971). In either model, as discussed earlier, b must be reduced for sediment covers greater than 3 km (Blackwell et al., 2007). This assumption is reflected in the temperature calculations in this model by direct subtraction of additional sedimentary thickness from b according to Eq. (6).

The steady state 1D conduction Eq. (10) is used to solve for temperature at depth when Eq. (8) is substituted for the generalized source term g(z):

$$-k\frac{d^2T}{dz^2} = g(z) \tag{10}$$

$$-k\frac{d^2T}{dz^2} = A_o exp(-\frac{z}{b}) \tag{11}$$

By integrating and applying the boundary condition, that as depth z approaches infinity $Q=Q_m$, Eq. (11) becomes:

$$\frac{dT}{dz} = \frac{Q_m}{k} - \frac{A_o bexp(-\frac{z}{b})}{k} \tag{12}$$

By integrating Eq. (12) and applying the boundary condition $T(0)=T_s$, Eq. (12) will reduce to Eq. (4). However if the sedimentary cover is not fully penetrated, i.e. $X< z_{sed}$, then Eq. (11) would be replaced with:

$$-k\frac{d^2T}{dz^2} = A_S \tag{13}$$

Where A_s is the uniform radiogenic heat production in sediments. Following the same integration scheme and applying the boundary condition that Q at z=0 is Q_s and $T(0)=T_s$, Eq. (13) becomes:

$$T(z) = T_o + Q_s\frac{z}{k} - \frac{A_s z^2}{2k} \tag{14}$$

From these generalized solutions to the steady state 1D conduction equation, all equations in Appendix A were derived to handle temperature calculations for any combination of geological and thermodynamic inputs. This decision process and calculations are run in VBA through a series of nested IF statements, as visually represented by the decision tree in Appendix A.

In Appendix A, terms described as “before basement”, meaning thickness between the BHT point and above basement rocks, are introduced and signified by the subscript *bb*. This is a generalized term to account for the incremental temperature and thermal conductivity between the well depth and a depth of interest that is smaller than the sediment thickness. Thermal conductivity for this incremental depth (k_{bb}) was calculated using a thickness weighted average approach via:

$$\bar{k} = \left[\sum_{i=1}^{n} k_i * d\hbar_i\right] \Big/ \hbar_t \tag{15}$$

Where k_i and h_i are the individual unit thickness and conductivity, and h_t is the total column thickness. In this model the conductivity of the column to the depth of interest, conductivity to the well depth and their respective thicknesses are used to solve for the k_{bb} value in Eq. (15). This is completed in an attempt to match as closely as possible the observed BHT.

Additionally the model will iteratively solve for a specified depth to an isothermal surface of the users choosing. Determination of this surface enables basic techno-economic analyses of potential EGS resources as the drilling depth to the level of thermal energy desired in each location can be estimated.

EXAMPLE CASE EVALUATED

To demonstrate the new method described above, eleven wells in Westmoreland County, PA were analyzed (see Tables 1 and 2). Westmoreland County lies in the central part of the Appalachian basin, a deep foreland basin containing up to 10 km of sedimentary strata over a variable and poorly understood basement complex. Basins such as this have some of the best potential for EGS exploitation outside of hydrothermal locales.

As discussed earlier in the Existing Methodology section, BHTs must be corrected to thermal equilibrium. Commonly, given typical data constraints with publicly available oil and gas well information, an empirical correction factor will be used, such as demonstrated by Harrison et al. (1983), Blackwell et al. (2007), Frone and Blackwell (2010), and Shope et al. (2012).

The Harrison correction is a second order polynomial function of depth in meters. Based on empirically adjusting BHT data to equilibrium temperature proxies in a study in the state of Oklahoma, the resultant ΔT value in °C is a correction factor that can be added to the BHT from a geophysical log header to yield an estimated equilibrium temperature.

The Harrison correction equation utilized in this example is:

$$\Delta T = -16.51 + 0.018z - 2.34E10^{-6}z^2 \qquad (16)$$

By selecting the textbox "Calculate", the macro titled RunCalc() will execute and model the subsurface temperature regime based on the geological and thermodynamic properties inputs (Tables 1 and 2). VBA was a good choice for this model, as it is able to use IF statements to make decisions, read inputs, manipulate data and cease when all wells are processed.

Previous work identified a potential geothermal anomaly in Westmoreland County. The method presented in this paper for processing well data is for the specific purpose of mapping and locating such anomalies. Consequently it serves as an excellent test case. The degree of spatial refinement in this county, and several others in New York and Pennsylvania, are discussed in more detail by Shope et al. (2012).

To validate the accuracy of this model and the assumptions that went into it, the results were compared to temperature data published by Spicer (1964). These wells are taken to represent actual thermal equilibrium in the area, as the wells were drilled without mud circulation, which changes the borehole temperature. A total of 5 wells were within Westmoreland or bordering Allegheny County. Figure 2 shows these 5 wells, PA-6, 7, 8, 9, and 11 (their Spicer data set designations), as well as the thermal modeling results for the nearest 11 new oil and gas wells. The model was also used to predict temperatures to a depth of 10 km, as shown in Figure 3.

With a lack of equilibrium well data to this depth, validation of the model is lacking. In lieu of such data, published information of temperature with depth was used. With similar assumptions, Q_m= 30 mW/m^2 and T_s=10^{o}C, Allen and Allen (2005) present a series of models utilizing a similar 1D conduction assumption and various radiogenic heat production conditions that result in temperatures of approximately 170-270^{o}C at 10 km. The temperatures at this depth were predicted to be between 150°C and 300^{o}C when calculated using the model presented here.

This model was then applied to 4,585 wells with BHT readings across Pennsylvania and New York. The exact source and precursory processing of this data and additional maps are discussed in depth by Shope et al. (2012). The resulting heat flow map over the sedimentary basin regions of these two states is shown in Figure 4. In Figure 4, areas on the scale of 100 km^2 can be seen with heat flow 15-20 mW/km^2 above an average background of ~50mW/km^2 previously not evident in earlier studies.

Table 4: Modeled geothermal properties for selection of wells in Westmoreland County, PA

Calculate

Basement Conductivity (W/m/K)	2.7
Deep Sediment Conductivity (W/m/K)	2.7
Isotherm (^{o}C)	80

Identifier (API/Name)	BHT (°C)	Well Depth (m)	Mantle Heat Flow (mW/m2)	Depth to Basement (m)	Avg. Surface Temperature (^{o}C)	Sediment Radiogenic Heat Generation (μW/m^3)	Basement Radiogenic Heat Generation (μW/m^3)	Gradient (°C/km)	Heat Flow (mW/m2)	Average Conductivity To Well Depth (W/m/K)	Temperature Estimation at Depth 1500	3000	4500	6000	7500	10000	Depth to Specified Isotherm (m)
37129202870000	85	2346	30	5369	9	1	6.2	32.2	82.7	2.57	57	106	160	204	243	299	2249
37129203880000	89	2547	30	4780	9	1	4.7	31.3	73.8	2.36	51	102	142	180	213	264	2456
37129215570000	86	2558	30	5314	9	1	5.3	30.1	76.3	2.53	53	99	149	189	224	277	2414
37129239710000	66	2207	30	5320	9	1	4.1	25.7	66.4	2.59	47	87	131	166	197	243	2719
37129225960000	31	1177	30	4860	9	1	1.4	18.4	46.3	2.52	36	66	92	115	137	171	3771
37129237810000	30	1127	30	4876	9	1	1.4	18.6	46.4	2.49	36	66	92	116	137	172	3764
37129241990000	31	1127	30	4865	9	1	1.7	19.6	48.9	2.49	38	69	97	121	144	180	3587
37129243130000	30	1117	30	4832	9	1	1.4	18.4	45.9	2.49	36	66	91	114	136	170	3806
37129243700000	27	1171	30	4869	9	1	0.6	15.8	39.7	2.51	32	58	80	100	118	149	4510
37129245160000	37	1252	30	4518	9	1	2.8	22.5	57.9	2.58	42	79	112	140	167	208	2927
37129247300000	34	1201	30	4514	9	1	2.3	21.0	53.9	2.56	40	74	104	131	156	194	3244

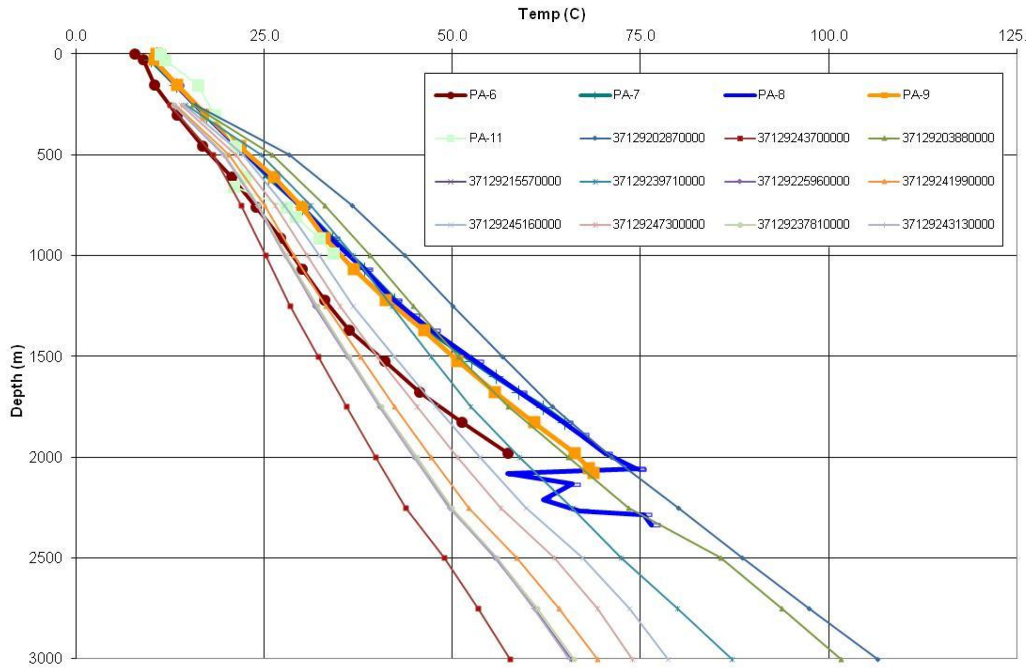


Figure 2: Chart of 5 equilibrium wells (PA-6, PA-7, PA-8, PA-9, and PA-11) and 11 nearby BHT point wells (labeled by API number) calculated using the VBA thermal modeling routine

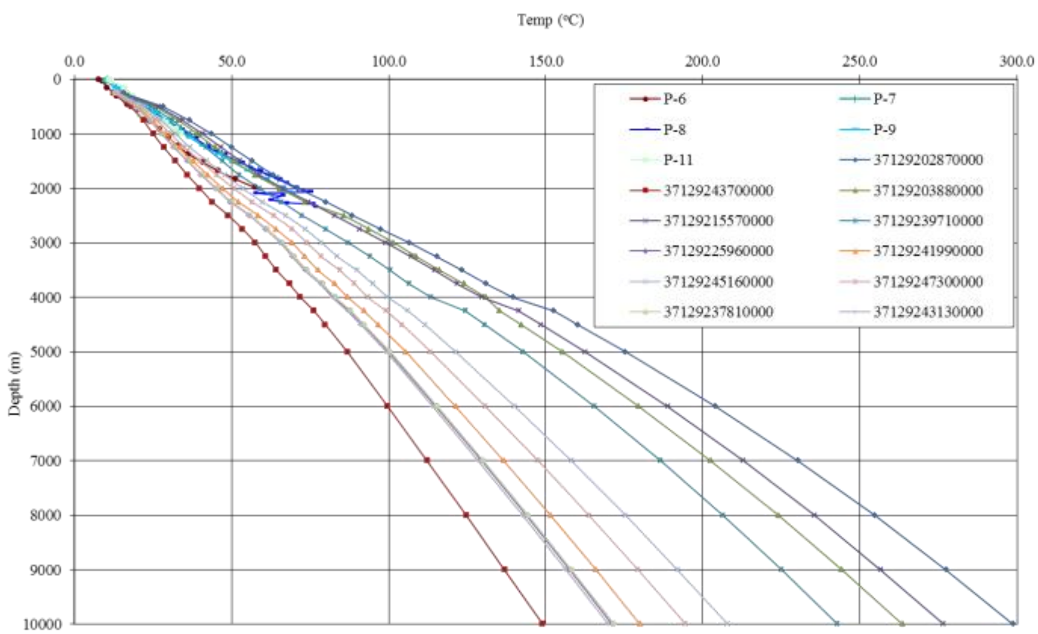


Figure 3: Chart of 5 equilibrium wells (P-6, P-7, P-8, P-9, and P-11) and 11 nearby BHT point wells (labeled by API number) calculated using the VBA thermal modeling routine to 10 km depth

Based on the data collected and presented by Shope et al. (2012), there may be a geothermal anomaly in Westmoreland County of sufficient magnitude and spatial area to be a potential EGS site. Figure 5 shows a detailed thermal map of the area outlined in black in Figure 4. The locations of the five Spicer wells and the 11 wells in Figures 2 and 3 are shown in red and black respectively.

According to Fox et al. (2011), about 25% of the US annual primary energy demand is consumed as thermal energy at or below 100 °C. This provides an opportunity for lower grade EGS to economically provide direct thermal energy for these low to mid temperature applications. In the example presented here, 80°C was analyzed in the model. Energy consumption up to this temperature is estimated to be approximately 19 EJ/yr for the US (Fox et al. 2011). The resulting isothermal surface at 80 °C is shown in Figure 6.

Different temperature values based on the intended use of the thermal energy can be specified by the user. As a result, this modeling method will aid in specific economic analyses as drilling depths can be estimated.

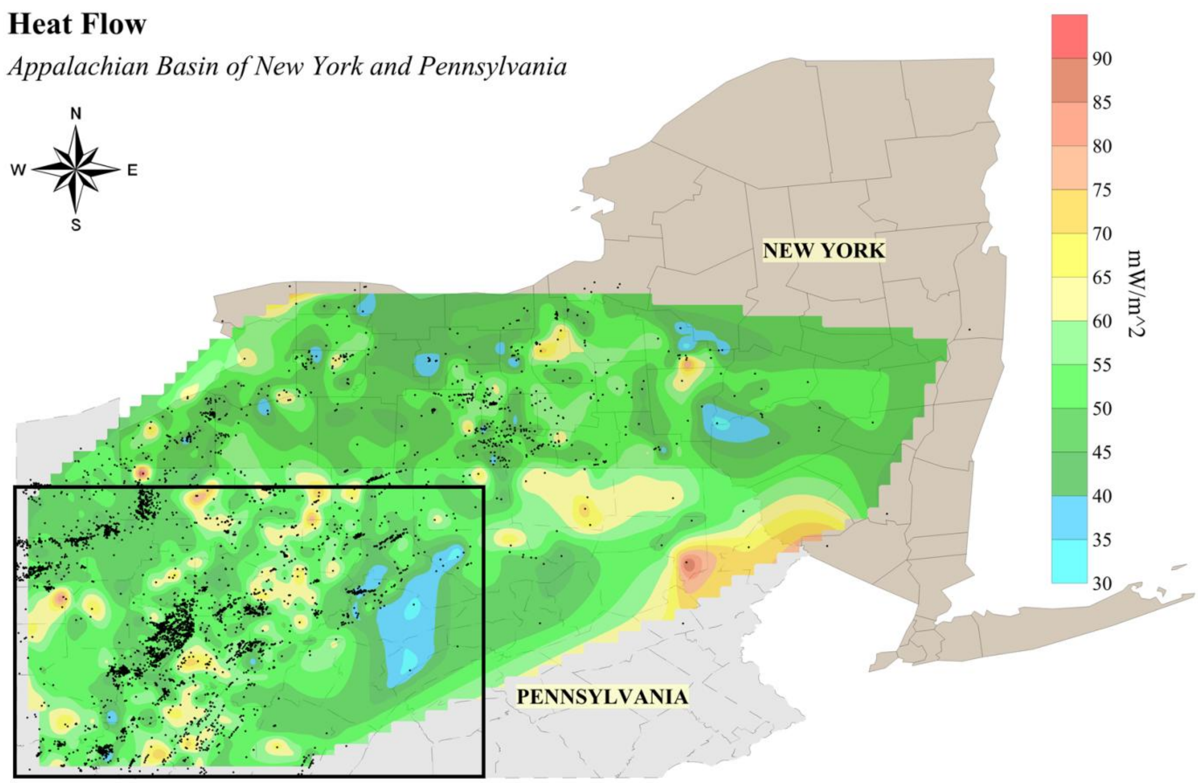


Figure 4: Map of calculated heat flow from well BHT data for NY and PA

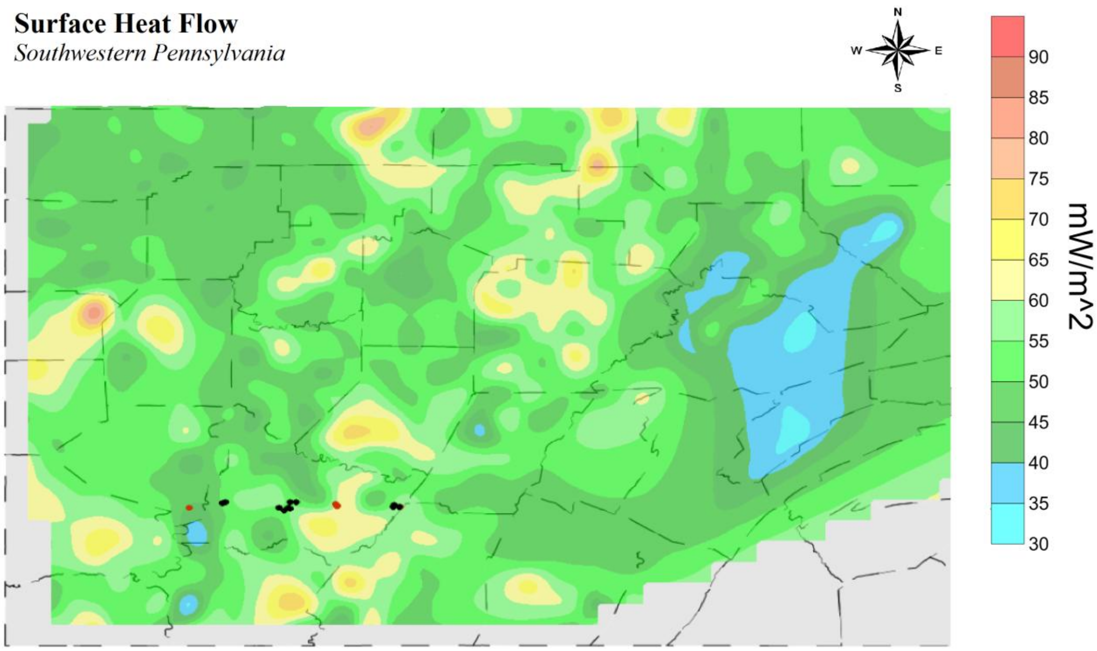


*Figure 5: Map depicting equilibrium wells (P-6, P-7, P-8, P-9, and P-11) and 11 nearby BHT point wells (labeled by API number (*Area shown in box on Figure 4)*

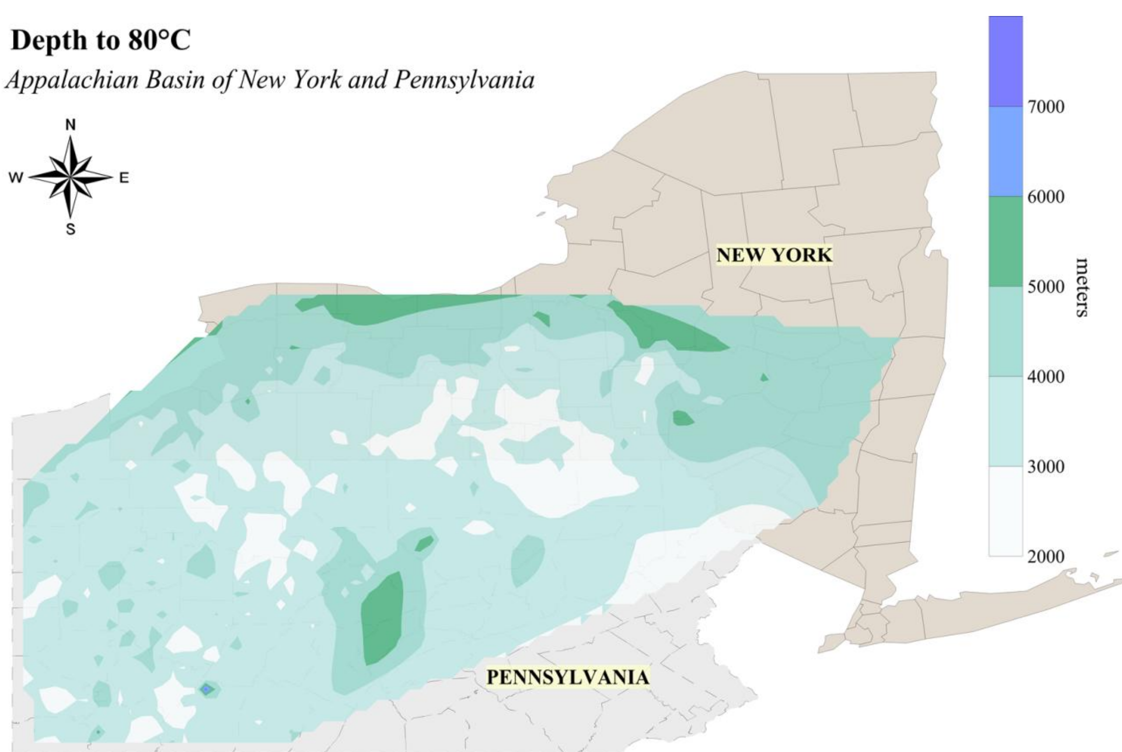


Figure 6: Map of anticipated depth to the 80 °C isothermal surface

CONCLUSIONS AND FUTURE WORK

The quality of EGS resource assessment has been improved by the progressive public availability of oil and gas borehole temperature data. These well data created a need for the development of more efficient analytical tools to incorporate large amounts of BHT and borehole depth data into geothermal resource assessments. The thermal modeling tool constructed in VBA in this study has resulted in improved accuracy and large processing time reductions allowing researchers to shift their efforts from implementing cumbersome calculations to evaluating raw data and model assumptions.

New borehole temperature data for Westmoreland County, PA was used to successfully validate our new method of thermal modeling. We demonstrated that the calculations and techniques accurately predict temperature over the depth ranges of existing equilibrium data. The computational approach described in this study was then applied to a large data set in the Northeastern United States, substantiating the ease and rapidity of the processing techniques described here (Shope et al., 2012).

Prior to this model, establishment of thermal maps using more than 4,000 BHT measurements could take several person months of work. Using the techniques and programs shown in this paper, the same group of wells may take a single researcher only weeks to process. Additionally the enhanced automation allows removal of simplifications in previous well processing methods, with the consequence that the new techniques result in more precise and accurate results.

Additionally, it is believed that EGS in relatively low heat flow regions will have 60% or more of their capital cost consumed by drilling and completion of the geothermal wells (Tester et al., 2006). Therefore, the depth at which usable geothermal heat can be recovered will be the main economic hurdle to adoption of lower grade geothermal as an alternative energy source. Utilizing a geothermal temperature depth contour map, such as the one shown in Figure 6, will allow for cost minimization, as it provides accurate representation of where the shallowest depths to reach a specified rock temperature may be found in the area of interest. As a result, the model will help academic, governmental, and civilian investigators consider the use of EGS as a potential energy resource in previously under explored regions.

For future work, some of the simplifying assumptions will be removed to allow for more region-specific inputs. In doing so, the model has the potential to have a higher accuracy than that shown in this paper.

ACKNOWLEDGEMENTS

We would like to thank the U.S. Department of Energy (contract #DE-EE0002852), the National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) grant, and Cornell's Atkinson Center for a Sustainable Future, whose partial support made this research possible. We would also like to recognize the Pennsylvania and New York State Geology departments for their data contributions.

REFERENCES

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

AAPG (1985), Correlation of Stratigraphic Units of North America Project, The American Association of Petroleum Geologists, 1985.

Allen, P. A., and Allen, J. R. (2005), *Basin Analysis: Principles and Applications*. Malden, MA: Blackwell Publishing. Print.

Beach, R. D. W., Jones, F. W., and Majorowicz, J. A. (1989), "Heat Flow and heat generation estimates for the Churchill basement of the Western Canadian basin in Alberta, Canada," *Geothermics*, **16**, 1-16.

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

Birch, F., Roy, R. F., and Decker, E. R. (1968), "Heat flow and thermal history in New England and New York," *in* Studies of Appalachian Geology: Northern and Maritime, Zen, E., White, W. S., Hadley, J. B., and Thompson, Jr., J. B., eds., Interscience, New York, p. 437–451.

Blackwell, D. D. (1971), The thermal structure of the continental crust, *in* The Structure and Physical Properties of the Earth's crust, Heacock, J. G., ed., American Geophysical Union Geophysics Monograph, v. 14, p. 169–184.

Blackwell, D. D., and Steele, J. L. (1989), "Thermal Conductivity of sedimentary rock-measurement and significance," *in* Thermal History of Sedimentary Basins: Methods and Case Histories, Naeser, N. D., and McCulloh, T. H., eds., Springler Verlag, New York, 13-36.

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**, December 2006, 283-308.

Blackwell, D. D., Batir, J., Frone, Z., Park, J., and Richards, M. (2010), “New geothermal resource map of the northeastern US and technique for mapping temperature at depth,” *GRC Transactions*, Volume 34. Document ID 28663.

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

Deming, D. (1989), “Application of Bottom-Hole Temperature Corrections in Geothermal Studies,” *Geothermics*, **18**, Issues 5-6, 1989, 775-786.

Deming, D., and Chapman, D. S. (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,” Ithaca, NY: Cornell University. Print.

Frone, Z., and Blackwell, D. D. (2010), “Geothermal Map of the Northeast United States and the West Virginia Thermal Anomaly,” *GRC Transactions*, Volume 34, 2010.

Gallardo, J., and Blackwell, D. D. (1999), “Thermal Structure of the Anadarko Basin, Oklahoma,” *American Association of Petroleum Geologists Bulletin*, **83**, no. 2, February, 1999, 333-361.

Harrison, W. E., Luza, K. V., Prater, M. L., and Chueng, P. K. (1983), “Geothermal resource assessment of Oklahoma”, *Special Publication 83-1*, Oklahoma Geological Survey, 1983.

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

IPCC (2011), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [O. Edenhofer, O. et al. eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1075 pp.

Joyner, W.B. (1960), “Heat flow in Pennsylvania and West Virginia,” *Geophysics*, **25**, 1225-1241.

JPT (2011), “World Rotary Rig Count,” *Journal of Petroleum Technology (JPT)*, **63**, Dec. 2011.

Kehle, R. O. (1972), “Geothermal Survey of North America,” 1972 Annual Progress Report for the AAPG, **23**, p. 1973.

Lachenbruch, A. H. (1968), “Preliminary geothermal model for the Sierra Nevada,” *Journal of Geophysical Research*, **73**, 6977–6989.

Lachenbruch, A. H. (1970). “Crustal temperature and heat production: Implications of the linear heat flow relation,” *Journal of Geophysical Research*, **75**, 3291–3300.

Mock, J. E., Tester, J. W., and Wright, P. M. (1997), “Geothermal Energy from the Earth: Its Potential Impact as an Environmentally Sustainable Resource,” *Annual Review of Energy and the Environment*, **22**, 305-356.

Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, F. (1968), “Heat flow in the United States,” *Journal of Geophysical Research*, **73**, 5207-5221.

Shope, E. N. et al. (2012), “Geothermal Resource Assessment: A Detailed Approach to Low-Grade Resources in the States of New York and Pennsylvania,” *37th Stanford Geothermal Workshop*, Stanford, CA, January 30 – February 1, 2012. (In Press)

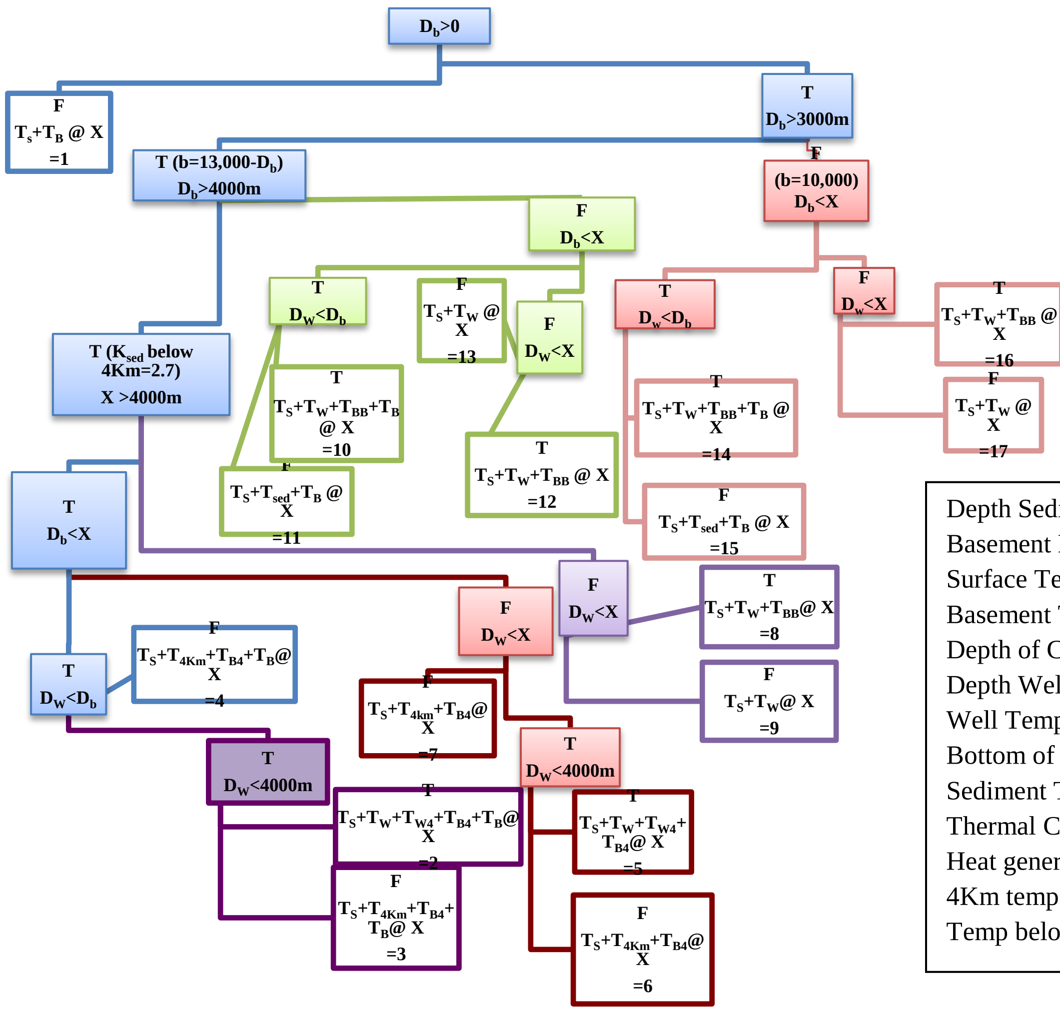
Spicer, H.C. (1964), “A compilation of deep Earth temperature data: USA 1910-1945”, *U.S. Geological Survey Open File Report*, 64-147.

Tester, J. W. et al. (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.

USGS (2011), "Geologic Maps of US States," *USGS Mineral Resources On-Line Spatial Data*. Web. Fall 2011. http://tin.er.usgs.gov/geology/state/

APPENDIX A

Blackwell et al. (2010)



Depth Sediment= Z_{sed}
Basement Depth= Z_b
Surface Temp= T_S
Basement Temp= T_B
Depth of Calculation= X
Depth Well= Z_W
Well Temp= T_W
Bottom of well to basement temp= T_{BB}
Sediment Temp= T_{sed}
Thermal Cond Sediment= K_{sed}
Heat generation layer= B
4Km temp= T_{4Km}
Temp below 4Km in sed= T_{B4}

1. $$= T_S + \left[\frac{Q_S X}{K} - A_S \frac{X^2}{2K} \right]$$

2. $$= T_S + \left[\frac{Q_S Z_W}{K} - A_S \frac{Z_W^2}{2K} \right] + \left[\frac{Q_S (4 - Z_W)}{K_{bb}} - A_S \frac{(4 - Z_W)^2}{2K_{bb}} \right] + \left[\frac{(Q_S - A_S)(Z_B - 4)}{K_{sed>4km}} - A_S \frac{(Z_B - 4)^2}{2K_{sed>4km}} \right] + \left[\frac{Q_m (X - Z_B)}{K_b} + A_b (b)^2 \left(\frac{1 - e^{-\frac{X - Z_B}{b}}}{K_b} \right) \right]$$

3. $$= T_S + \left[\frac{4Q_S}{K} - A_S \frac{4^2}{2K} \right] + \left[\frac{(Q_S - A_S)(Z_B - 4)}{K_{sed>4km}} - A_S \frac{(Z_B - 4)^2}{2K_{sed>4km}} \right] + \left[\frac{Q_m (X - Z_B)}{K_b} + A_b (b)^2 \left(\frac{1 - e^{-\frac{X - Z_B}{b}}}{K_b} \right) \right]$$

4. $$= T_S + \left[\frac{4Q_S}{K_{ave}} - A_S \frac{4^2}{2K_{ave}} \right] + \left[\frac{(Q_S - A_S)(Z_B - 4)}{K_{sed>4km}} - A_S \frac{(Z_B - 4)^2}{2K_{sed>4km}} \right] + \left[\frac{Q_m (X - Z_B)}{K_b} + A_b (b)^2 \left(\frac{1 - e^{-\frac{X - Z_B}{b}}}{K_b} \right) \right]$$

5. $$= T_S + \left[\frac{Q_S Z_W}{K} - A_S \frac{Z_W^2}{2K} \right] + \left[\frac{Q_S (4 - Z_W)}{K_{bb}} - A_S \frac{(4 - Z_W)^2}{2K_{bb}} \right] + \left[\frac{(Q_S - A_S)(X - 4)}{K_{sed>4km}} - A_S \frac{(X - 4)^2}{2K_{sed>4km}} \right]$$

6. $$= T_S + \left[\frac{4Q_S}{K} - A_S \frac{4^2}{2K} \right] + \left[\frac{(Q_S - A_S)(X - 4)}{K_{sed>4km}} - A_S \frac{(X - 4)^2}{2K_{sed>4km}} \right]$$

7. $$= T_S + \left[\frac{4Q_S}{K} - A_S \frac{4^2}{2K} \right] + \left[\frac{(Q_S - A_S)(X - 4)}{K_{sed>4km}} - A_S \frac{(X - 4)^2}{2K_{sed>4km}} \right]$$

8. $$= T_S + \left[\frac{Q_S Z_W}{K} - A_S \frac{{Z_W}^2}{2K} \right] + \left[\frac{Q_S (X - Z_B)}{K_{bb}} - A_S \frac{(X - Z_B)^2}{2K_{bb}} \right]$$

9. $$= T_S + \left[\frac{Q_S X}{K} - A_S \frac{X^2}{2K} \right]$$

10. $$= T_S + \left[\frac{Q_S Z_W}{K} - A_S \frac{{Z_W}^2}{2K} \right] + \left[\frac{Q_S Z_{bb}}{K_{bb}} - A_S \frac{{Z_{bb}}^2}{2K_{bb}} \right] + \left[\frac{Q_m (X - Z_B)}{K_b} + A_b (b)^2 \left(\frac{1 - e^{-\frac{X - Z_B}{b}}}{K_b} \right) \right]$$

11. $$= T_S + \left[\frac{Q_S Z_B}{K_{ave}} - A_S \frac{Z_B{}^2}{2K_{ave}} \right] + \left[\frac{Q_m (X - Z_B)}{K_b} + A_b (b) \left(\frac{1 - e^{-\frac{X - Z_B}{b}}}{K_b} \right) \right]$$

12. $$= T_S + \left[\frac{Q_S Z_W}{K} - A_S \frac{Z_W{}^2}{2K} \right] + \left[\frac{Q_S (X - Z_B)}{K_{bb}} - A_S \frac{(X - Z_B)^2}{2K_{bb}} \right]$$

13. $$= T_S + \left[\frac{Q_S (X - Z_W)}{K_{bb}} - A_S \frac{(X - Z_W)^2}{2K_{bb}} \right]$$

14. $$= T_S + \left[\frac{Q_S Z_W}{K} - A_S \frac{Z_W{}^2}{2K} \right] + \left[\frac{Q_S Z_{bb}}{K_{bb}} - A_S \frac{Z_{bb}{}^2}{2K_{bb}} \right] + \left[\frac{Q_m (X - Z_B)}{K_b} + A_b (b)^2 \left(\frac{1 - e^{-\frac{X - Z_B}{b}}}{K_b} \right) \right]$$

15. $$= T_S + \left[\frac{Q_S Z_B}{K_{ave}} - A_S \frac{Z_B{}^2}{2K_{ave}} \right] + \left[\frac{Q_m (X - Z_B)}{K_b} + A_b (b)^2 \left(\frac{1 - e^{-\frac{X - Z_B}{b}}}{K_b} \right) \right]$$

16. $$= T_S + \left[\frac{Q_S Z_W}{K} - A_S \frac{Z_W{}^2}{2K} \right] + \left[\frac{Q_S (X - Z_W)}{K_{bb}} - A_S \frac{(X - Z_W)^2}{2K_{bb}} \right]$$

17. $$= T_S + \left[\frac{Q_S X}{K} - A_S \frac{X^2}{2K} \right]$$