To: Appalachian Basin Geothermal Play Fairway Analysis Group

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Date: August 11, 2015

Subject: Well database organization and thermal model methods.

Applicability: This memo describes the reorganization of the GPFA well database into a format with additional data fields that is more useful for the thermal model. It also describes the methods and assumptions used in the thermal model. These methods were used for creating the 3rd quarter and final thermal maps for this project.

Nomenclature:

A_B – Radiogenic heat generation in basement rocks (W-m^{-3})

A_s – Radiogenic heat generation in sedimentary rocks (W-m^{-3})

a – Amplitude of the annual surface temperature fluctuation (°C)

B – Thickness corresponding to one log decrement in radiogenic heat generation in basement rocks (m)

BHT_{corr} – Corrected BHT (°C)

G(x, y, z) – Geothermal gradient at spatial location (x, y) and depth z (°C-km^{-1})

$\bar{k}$ – Average thermal conductivity (W-m^{-1}-°C^{-1})

k_B – Thermal conductivity of basement rocks (W-m^{-1}-°C^{-1})

$\bar{k}_w$ – Average thermal conductivity from the surface to the depth of the well (W-m^{-1}-°C^{-1})

$\bar{k}_s$ – Average thermal conductivity from the surface to the top of the basement (W-m^{-1}-°C^{-1})

P – Period of the annual surface temperature fluctuation (s)

Q(z) – Heat flow at depth, z (W-m^{-2})

Q_B – Heat flow contributed to Q_s from basement rocks (W-m^{-2})

Q_m – Mantle heat flow (W-m^{-2})

Q_s – Surface heat flow (W-m^{-2})

Q_{sb} – Heat flow at the boundary between the sediment and basement rocks (W-m^{-2})

Q_{sed} – Heat flow contributed to Q_s from sedimentary rocks (W-m^{-2})

T_s – Surface temperature (°C)

t – Time since mean annual surface temperature (s)

Z_s – Sediment thickness (m)

Z_w – Depth of the well (m)

z – Depth below the surface (m)

z_{bottom} – Depth from the surface to the bottom of a rock formation (m)

z_{calc} – Calculation depth (m)

z_{top} – Depth from the surface to the top of a rock formation (m)

α – Thermal diffusivity (m^2-s^{-1})

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Introduction

The Appalachian Basin Geothermal Play Fairway Analysis (GPFA-AB) team needs to have a method for calculating the thermal field properties from corrected bottomhole[1] temperature (BHT) measurements. The method used in this project calculates the desired variables based on a vertical (1-D), steady-state conduction heat flow model developed in Python 2.7.9. A 1-D model is used rather than a 3-D model because published cross sections available for the basin are sparse in New York and Pennsylvania, and constructing a volume of basin stratigraphy based on individual wells would be infeasible for the time constraints of Phase 1. Steady state conditions are assumed so that the thermal field in the rock can be modeled without regard to surface temperature fluctuations (Attachment 3): other transient variables, such as radioelement decay and mantle heat flow, would not affect calculations because the time scale of impact for these variables is much greater than the time scale over which the wells were sampled. Advection and convection of heat via moving fluid are not considered because the rock is essentially stationary, and information about groundwater transport is not available for the entire basin and would be infeasible to collect and/or model in Phase 1. Additionally, Frone et al. (2015) showed via a 2-D model along a cross section in West Virginia that heat conduction modeling alone is sufficient for reproducing BHTs at depth. Therefore, it is likely that neglecting advection via fluid in this analysis provides an adequate representation of the thermal field in the rock for Phase 1 products. Further details about the thermal rock model are provided in the section Thermal Model Methods.

A primary necessity before running any model is preparation of the input data. The well database described in this memo and generalized stratigraphic columns from the American Association of Petroleum Geologists (AAPG) (1985a; 1985b) Correlation of Stratigraphic Units in North America (COSUNA) project are the inputs to the thermal model. This memo discusses the organization of the well data into a useful format for the thermal model. Processing of the COSUNA data is described in another memo entitled

"COSUNA_Documentation_NewConductivity_Final.docx".

Another necessity for any model is careful selection of parameters. The parameters in the thermal model are the heat flow at the interface between the mantle and the crust (referred to as mantle heat flow), the radiogenic heat generation in sedimentary rocks, the thermal conductivity of basement rocks, and the log decrement of radiogenic heat generation in basement rocks. These parameters are selected from published studies.

Following these sections, the memo describes the methods, assumptions, and equations used for calculating properties of the thermal field at each well using the thermal model. Appendices provide derivation of equations that have not been documented in previous studies. Attachments provide references to databases and additional methodological details.

[1] Though some temperature measurements do not correspond to the bottom of the well, BHT is used as an abbreviation, as per traditional use.

Selecting and Processing Wells for Analysis

Wells were gathered from the American Association of State Geologists (AASG) Geothermal Data Repository for the states of New York (Slater, 2012), Pennsylvania (Shank et al., 2012), West Virginia (WVGES, 2011), Maryland (Brezinski, 2011), Virginia (VDGMR, 2011), Kentucky (Curl, 2011), and Ohio (Leftwich, 2011). All of the available wells were combined into a single spreadsheet with common field headers (Attachment 1, "AASG_Combined.xlsx"). There were a total of 41,099 records from approximately[2] 39,000 wells in this database. Some processing steps were needed to make this dataset useful for the assessment of the thermal field.

First, additional data fields beyond those provided by AASG were needed to use these wells in the thermal model. Table 1 lists all of the additional fields and respective sources. All information was joined to the well data based on spatial location (ArcGIS Spatial Join tool) or added from the output of an R function written for this project (Table 1).

Then, to limit edging effects that would occur from using interpolations near state boundaries, only those wells within New York, Pennsylvania, West Virginia, and a 50 km buffer zone into surrounding states were retained in the database for analysis (32,385 total records remained). Further, only those wells with a depth of BHT measurement were retained for quality purposes, as opposed to a total/true vertical depth or driller/log depth that may or may not correspond to the depth of the BHT measurement (21,104 total records remained). Then, records lacking any of the information in Table 1 as a result of spatial coverage of the map layer were removed (29 records were not in a COSUNA section and an additional 324 records did not have a basement depth, so 20,751 total records remained). An additional record was removed because the depth of measurement was less than 10 m (minimum depth to run the thermal model) so the final record count is 20,750. These records were sent to the thermal model (Attachment 1, AASG_Processed.xlsx). An exploratory data analysis (EDA) was conducted on these wells after processing in the thermal model (see interpolation memo for discussion of the EDA).

[2] This number is approximate because the number of unique API numbers was used as a surrogate for the number of unique wells. Some wells do not have an API number, so the well name was used instead of the API number for these records. Other wells do not have either, so these 1,500 records were not counted. Therefore, the actual number of unique wells is likely greater than reported.

Table 1: Information added to the AASG combined well database. Attachment 1 (AASG_Processed.xlsx) contains field names for these data types.

Data Type	Source
COSUNA section	"All_COSUNA_Sections_Final.shp", created for this project.
Sediment thickness	Derived from Trenton-Black River (TBR) Project (WVGES, 2006) Precambrian basement contours. Map created for this project (Attachment 2).
Rome Trough identifier	Traced from a georeferenced figure in Repetski et al. (2008) (See COSUNA memo for image). "Rome trough final.shp", this project.
Average annual ground surface temperature	Derived from Gass (1982) shallow (15 m – 46 m) groundwater temperature measurements. These measurement depths are considered resistant to annual surface temperature fluctuations, as shown by Lovering and Goode (1963). (Attachment 3)
BHT correction section	"BHTCorrectionSections.shp". See BHT memo.
Corrected BHT	Output from BHT correction code. See BHT memo.
Drilling Fluid	Whealton (2015) well database for NY and PA (1755 records), modified with generalized drilling fluid groups (air and mud) in this project. A PostgreSQL query in PgAdmin III was used to select all wells in this database that matched with wells in the AASG database. 687 records (245 wells) matched. Attachment 4 contains the query used and a more detailed description.
Proportion Air or Mud Drilled Neighbor Wells	Proportion of nearest neighbor wells that are air or mud drilled. Nearest neighbor wells are from the Whealton (2015) database. Attachment 5 describes how this proportion was calculated.
Mantle Heat Flow	Parameter in the thermal model. Discussed below.
Sediment Radiogenic Heat Generation	Parameter in the thermal model. Discussed below.

Thermal Model Methods

A vertical (1-D) steady state conduction heat flow model was developed in Python 2.7.9 (Horowitz, Smith, and Whealton, 2015). A schematic is provided in Figure 1. This model calculates the geothermal gradient at the surface, heat flow at the surface, and the geotherm (i.e. temperatures at depth) for wells in the input database. This model assumes the traditional approach to subsurface 1-D heat conduction modeling (Jaeger, 1965) that at some depth there is a constant value of heat flowing upward from the mantle, Q_m, and that all variations in the surface heat flow, Q_s, are a result of differences in the radiogenic heat production, A_s or A_B, in overlying sedimentary and basement rocks, respectively. Frone et al. (2015) showed that these assumptions of radiogenic heat contribution to surface heat flow are appropriate to estimate the BHTs using a 2-D conduction model along a cross section in West Virginia. Another approach to 1-D heat conduction modeling is described by Lachenbruch (1980), who points out that one could assume that the radiogenic contribution is constant and that all variations in surface heat flow are a result of changes in the mantle heat flow. This approach is more likely relevant for locations that have recently experienced rifting, not for the stable continent settings, like the Appalachian Basin.

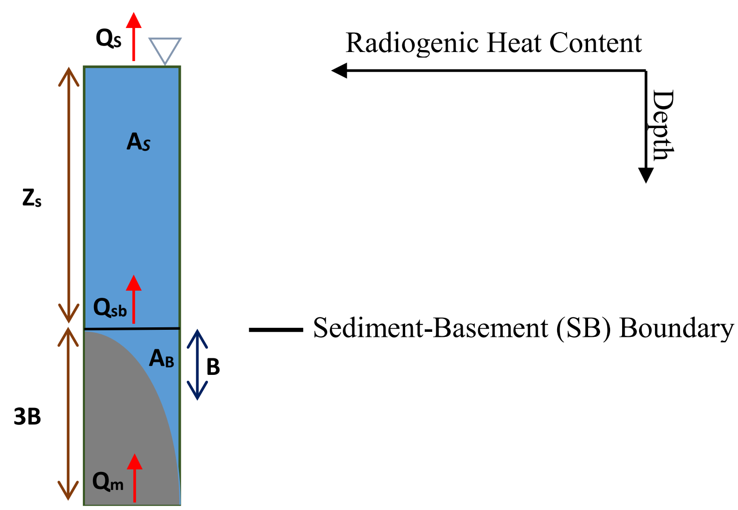

Figure 1: Schematic of the 1-D conduction heat balance.

A 1-D model is an appropriate first-order estimation of heat flow and temperatures at depth in the basement (Lachenbruch, 1970; Jaupart, 1986). Additionally, Lachenbruch (1970) states that the consistency in the relationship between heat flow and heat production across a variety of geologic settings indicates that lateral heat flow must be much less important than vertical heat flow (e.g. $\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y} \ll \frac{\partial T}{\partial z}$) in cases for which advection of heat may be neglected. Therefore, a 1-D model is adequate for a basin scale evaluation of the thermal field: higher dimensions may be assessed for smaller scale analyses in Phase 2, if data are available.

Using a 1-D model, there is an implicit assumption that strata are perfectly horizontal, or that the input formation thicknesses have been adjusted for folds, because heat preferentially flows normal to the bedding plane. Reliable folding information is available on published cross sections, but these cross sections are not available throughout the extent of the basin (Ryder, 1992; Ryder et al., 2008; Ryder et al., 2009; Ryder et al., 2012; Harris et al., 2002). Based on available cross sections, areas west of the eastern margin of the Rome Trough have minimal folding, and areas east of the eastern margin of the Rome Trough (e.g. Valley and Ridge) have folds that may violate the assumption of perfectly horizontal strata. Even so, based on the location of available wells, only small portions of West Virginia and Pennsylvania would be affected by this assumption. The expected effects of 2-D heat conduction are higher temperatures on anticlinal crests, and lower temperatures on synclinal troughs as compared to horizontal strata (Frone et al., 2015). Additional effects may happen where abrupt changes in lithology occur (e.g. the eastern margin of the Rome Trough).

Input Variables

The inputs to the model are the processed AASG well database described above, and the COSUNA-based conductivity stratigraphy for each COSUNA section, described in the COSUNA memo.

Parameter Selection

Radiogenic Heat Generation: Sedimentary Rocks

This model assumes that radiogenic heat generation is constant and uniformly distributed in sedimentary rocks, and decreases exponentially in the basement crustal rocks, as per Lachenbruch (1968; 1970). Uniformly distributed radiogenic heat generation in sedimentary rocks is not accurate; however, the range of radiogenic heat generation in sedimentary rocks is small, typically between 0.5 μW-m^{-3} (for non-clastic rocks) to 2.0 μW-m^{-3} (for radiogenic clastic rocks) (Waples, 2002). One exception is organic rich shale, which tends to have higher concentrations of uranium. These shales may have radiogenic heat generation values as great as 5.5 μW-m^{-3} (Waples, 2002). Even so, a greater value was not assigned to black shales because so few formations in the basin consist of only black shales, and those that are black shale are not a great enough thickness to significantly deviate from thermal model calculations assuming 1 μW-m^{-3} (difference in heat flow of 0.45 mW-m^{-2} per 100 m thickness). Therefore, for this project, a value of 1 μW-m^{-3} was assigned to all sedimentary rocks within the basin.

As an alternative to assuming a single heat generation value, formation specific values may be calculated from ordinary (Bücker and Rybach, 1996) or spectral (Rybach, 1973) gamma ray logs. The availability of spatially well distributed and interpreted gamma ray logs, and time to process them resulted in lithologic complexity in radiogenic heat generation to be undetermined for the basin. Waples (2002) suggests that published values should be used for each lithology in lieu of gamma log measurements for more accurate surface heat flow calculations. Despite this claim, formation specific values were not added into the thermal model because it is unlikely that the heat flow or temperatures at depth will deviate significantly from small changes to sediment heat generation relative to the assumed value. Phase 2 models on the project scale can include these formation specific values, along with appropriate uncertainty analysis, in order to improve the accuracy of the model.

Radiogenic Heat Generation: Basement Rocks

Heat generation in basement rocks is mainly a result of potassium-bearing felsic rocks. These rocks may exist as plutons (thick mass of intrusive igneous rock), or as part of the matrix rock. The basement rocks of the Appalachian Basin are Grenville age, consisting from east to west of a granulite terrane, a metasedimentary belt, and a gneiss belt, all separated by shear zones (DeWolf and Mezger, 1994). The Grenville basement is exposed nearest the Appalachian Basin in the Canadian Shield, the Adirondack Highlands in New York, and the Blue Ridge of Maryland, Virginia, and further south. Based on the lithology of these rocks surrounding the basin, it is likely that the Appalachian Basin basement does contain plutons (charnockitic suites and other granitoids (Bartholomew and Lewis, 1984)); however the plutons may not be the same thickness or composition throughout the basin. Without detailed knowledge of the composition and thickness of plutons, the basement rocks are assumed to be similar composition (e.g. granitic gneisses and schists, (Saylor, 1999)), with any variation in heat production estimated by the radiogenic heat production at the sediment-basement interface calculated in this model. It is possible that the multiscale potential field edges (see memo "Identifying Potentially Activatable Faults for the Appalachian Basin Geothermal Play Fairway Analysis") identify locations of plutons and/or locations where the composition of the crust is different on either side of the boundary. Therefore, revisions to the assumption of similar basement rocks throughout the basin can be made in future model iterations based on these edges.

From a geochemical perspective, radiogenic heat generation decreases with depth in basement rocks as a result of a decrease in felsic rocks with increasing depth in the crust, and radioelement decay with time. An exponential decay modelling the decrease in radiogenic heat generation with depth has been the traditional assumption since the relationship was first discovered (e.g. Birch et al., 1968; Lachenbruch, 1968, 1970). More recent studies (Sandiford and McLaren, 2002; Vendanti et al., 2011) have shown that the exponential model does not provide the best fit for all basement rocks. For example, Vendanti et al. (2011) demonstrate that power law decay models fit well for six deep boreholes around the world; however the power decay selected for most of these boreholes does not deviate far from the exponential fit. The exponential model is likely a low-end estimate of the heat produced in the crust because it decays faster than the power law fits in Vendanti et al. (2011). Therefore, the exponential model is assumed for this project as a conservative model of heat generation in the basement.

For the exponential model, the scale parameter is the crustal thickness corresponding to a one log decrease in heat generation. Previous studies that have assessed Grenville basement found a variety of estimates for the scale parameter. Variation in the scale parameter is generally thought to represent differences in the geochemical composition of the continental crust (Lachenbruch, 1970). Jaupart (1986) reports 10 km, Jaupart and Mareschal (1999) suggest 9 km, Frone et al. (2015) suggest 7.5 km for West Virginia, Artemieva and Mooney (2001) report a range of 4.6 km – 13.6 km for North American cratons, and Blackwell et al. (2007) suggest using a varying value based on the thickness of sedimentary rock overlying the basement. The logic behind the varying value is that thick sedimentary basins would form only over attenuated (post-rifting) or eroded continental crust; thus the radioactive contribution from the basement would be reduced due to the reduced crustal thickness. This approach is also used in this model, and will capture the wide variety of reported values for this region. The variable thickness used in this model is provided in Equation 1

$$B(Z_s) = \begin{cases} 10\ km, & Z_s \le 3\ km \\ 13\ km - Z_s, & Z_s > 3\ km \end{cases}$$ [1]

where $B(Z_s)$ is the value of B as a function of Z_s, and Z_s is the sediment thickness. The maximum value of B is taken to be 10 km for Grenville basement, and areas that have more than 3 km of sediment have a reduced B value. This is the same approach used in Blackwell et al. (2007) and Stutz et al. (2012). The spatial distribution of the calculated values of B using this approach are provided in Figure 2.

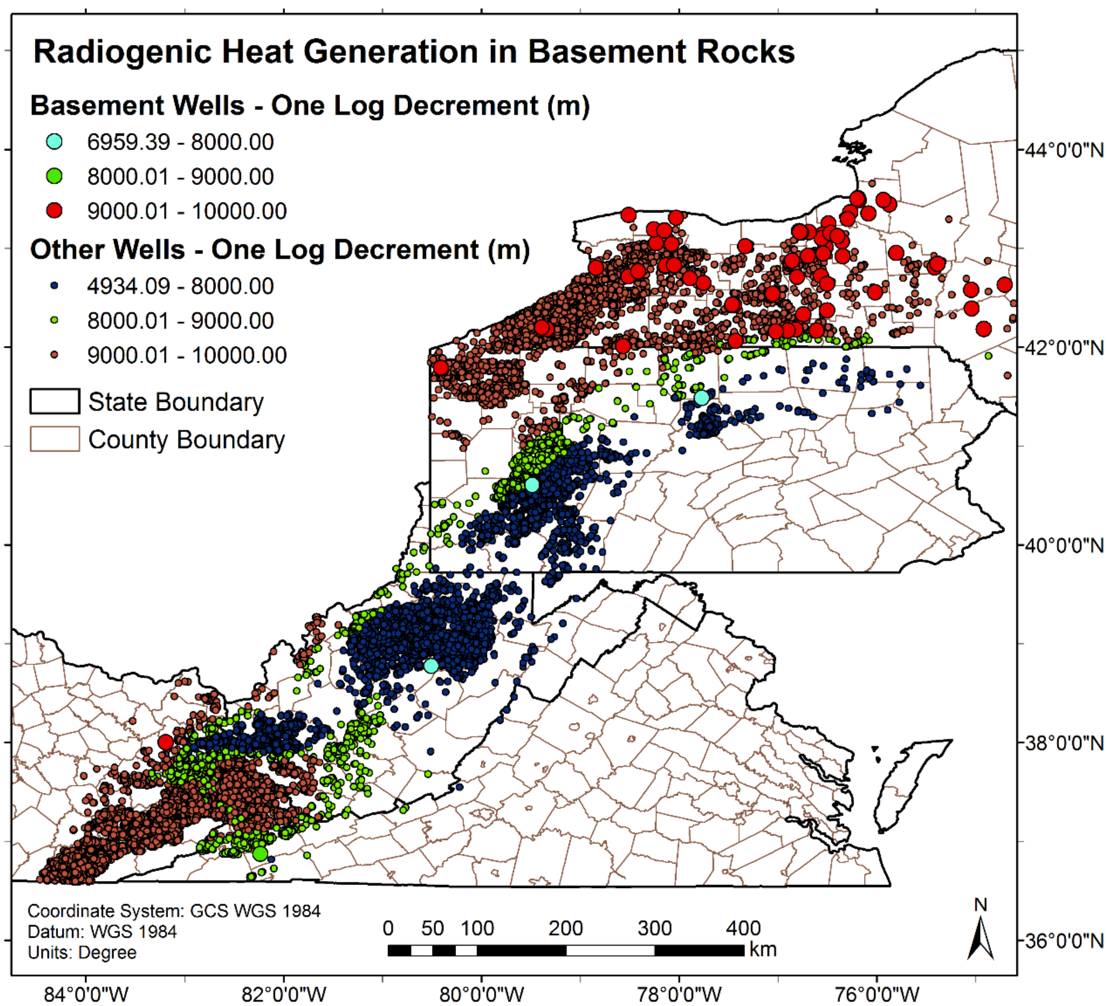

Figure 2: Spatial distribution of calculated values of B using the thermal model. Wells drilled into the basement are shown as larger circles with lighter colors.

Thermal Conductivity of Basement Rocks

A value of 2.7 W-m^{-1}-°C^{-1} was selected as the thermal conductivity for basement rocks. This is the mean value of the basement rocks in the regional heat flow database for the United States (Blackwell et al., 2007). This value could be changed in future models and made variable based on location within the basin based on the multiscale potential field analysis. As part of this project, a value of 2.83 W-m^{-1}-°C^{-1} was determined for basement rocks consisting of gneiss, marble, and quartzite. The COSUNA memo outlines the approach taken to arrive at this value. Even so, 2.7 W-m^{-1}-°C^{-1} was used for calculations in this project.

Mantle Heat Flow

The final parameter is the heat flow at the base of the basement rocks. A mantle heat flow of 30 mW-m^{-2} is assumed for the Appalachian Basin region of interest in New York, Pennsylvania, West Virginia, and surrounding 50 km buffer zone. This is a lower than average value of the mantle heat flow for the Central Stable Region of the continents as reported by Roy, Blackwell, and Birch (1968), a higher than average value for stable continents as reported by Sclater, Jaupart, and Galson (1980), and about average as reported by Artemieva and Mooney (2001) and Jaupart and Mareschal (1999). This value could be changed based on spatial location in future models based on the multiscale potential field analysis.

Model Output

The properties of the thermal field determined from this model include the thermal gradient, the surface heat flow, temperatures at depths of interest, depths to temperatures of interest, the average thermal conductivity from the surface to the depth of BHT measurement, and the average thermal conductivity for the entire sedimentary rock section at the location of the well. The output thermal variables are stored in a spreadsheet (Attachment 1, "AASG_Thermed.xlsx").

Equations

The general equations used in the thermal model and their assumptions are discussed in this section. This model updates and corrects three equations previously published by Blackwell et al. (2007), Stutz et al. (2012), and Stutz et al. (2015). These corrections are:

1) the heat balance used to estimate the value of radiogenic heat generation at the sediment-basement interface,

2) the calculation of surface heat flow relative to the assumptions made, and

3) a sediment radiogenic heat generation term in the calculation for the temperature-at-depth for depths deeper than the well.

This model also provides an analytical solution to the Ordinary Differential Equation (ODE) that results from a two-layer model of heat conduction; thus eliminating the need for numerical approximations to the solutions of temperatures at depth, and surface heat flow.

Geothermal Gradient

The geothermal gradient at the surface is computed using Equation 2

$$G(x,y,z=0) = \frac{\partial T}{\partial z} = \frac{BHT_{corr} - T_s}{Z_w}$$

[2]

where G(x, y, z = 0) is the geothermal gradient at spatial location (x, y) at the surface (z = 0), BHT_{corr} is the corrected BHT, T_s is the average annual surface temperature, and Z_w is the depth of the BHT measurement in the well. This is a linear approximation of the geothermal gradient at location (x, y) from z = 0 to z = Z_w. Under the assumptions made, the temperature gradient is curved with depth because heat is generated at all locations in the crust. The temperature gradient is also different for each lithology as a result of differences in thermal conductivity.

Some interest may lie in knowing what the geothermal gradient is for a depth range of interest (e.g. from the top of a reservoir to the bottom of a reservoir). This equation is not currently provided in the model, but will be implemented in future versions in Phase 2.

Average Thermal Conductivity

The average thermal conductivity for a column of rock with perfectly horizontal strata is calculated using Equation 3

$$\bar{k} = \frac{z_{calc}}{\left(\sum_{i=1}^{n-1} \frac{z_{bottom,i} - z_{top,i}}{k_i}\right) + \frac{z_{calc} - z_{top,n}}{k_n}}$$

[3]

where $\bar{k}$ is the average thermal conductivity to calculation depth z_{calc}, k_i is the thermal conductivity for lithologic unit i, $z_{bottom,i}$ is the distance from the ground surface to the bottom of unit i, $z_{top,i}$ is the distance from the ground surface to the top of unit i, and n is the number of lithologic units to z_{calc}. The denominator is a summation of thermal resistance in the vertical column. All thicknesses of units would have been scaled to the sediment thickness at the location of the well prior to this calculation, as described in Equation 3 of the COSUNA documentation. Calculation of thermal conductivity values for sedimentary rock formations (k_i) is also described in the COSUNA documentation. The conductivity of basement rocks is a parameter in the model, described above.

Surface Heat Flow

Using the calculated gradient at the surface and the average thermal conductivity to the depth of the BHT allows for the computation of the surface heat flow. Equation 4 is a rearrangement of Equation 6 solved for surface heat flow

$$Q_s = \begin{cases} G(x,y,0) * \bar{k}_w + \dfrac{A_s Z_w}{2}, & Z_w \leq Z_s \\ \dfrac{(BHT_{corr} - T_s) + \dfrac{A_s Z_s^2}{2\bar{k}_s} - \dfrac{Q_m (Z_w - Z_s)}{k_B} + (Q_m + A_s Z_s)\left[\dfrac{B * \left(1 - e^{-\frac{Z_w - Z_s}{B}}\right)}{k_B * (1 - e^{-3})}\right]}{\dfrac{Z_s}{\bar{k}_s} + \left[\dfrac{B * \left(1 - e^{-\frac{Z_w - Z_s}{B}}\right)}{k_B * (1 - e^{-3})}\right]}, & Z_w > Z_s \end{cases}$$

[4]

where Q_s is the surface heat flow, Q_m is the mantle heat flow, G(x, y, 0) is the geothermal gradient at the surface as computed in Equation 2, T_s is the surface temperature, $\bar{k}_w$ is the average thermal conductivity to the depth of the well, $\bar{k}_s$ is the average thermal conductivity of the sedimentary rocks, k_B is the thermal conductivity in basement rocks, A_s is the radiogenic heat generation in the sediment, Z_w is the depth of the well, Z_s is the thickness of the sedimentary rocks, and B is the log decrement in radiogenic heat production in the basement rocks. This equation is the exact solution to the heat flow present under the assumptions of heat generation in this model from the depth of the BHT to the surface. Not including heat generation would cause a 1 $mW\text{-}m^{-2}$ difference in surface heat flow for every kilometer of sediment above the well measurement. Differences in basement rocks would vary depending on the value of B.

Heat Generation in Basement Rocks

The heat generation at the sediment-basement interface is determined from the 1-D heat balance (Appendix 1), which leads to Equation 5

$$A_B = \frac{Q_s - Q_m - A_s Z_s}{B * (1 - e^{-3})}$$

[5]

where A_B is the value of radiogenic heat generation at the sediment basement interface and all other terms are described above. It is assumed that no radiogenic heat generation exists at depths greater than 3B, such that mantle heat flow is present at 3B. Mathematically, the exponential decay in heat generation would only reach a value of zero at a depth of infinity. This depth is unrealistic because the crust is not infinitely thick. Three times B is selected as a representative thickness of radiogenic heat generation in the crust (Lachenbruch, 1968); however the total thickness of the crust may be greater than 3B. The variation in the value of B across the basin introduces variability in pluton thickness throughout the basin as a function of sediment thickness.

For wells drilled into basement rocks, Equation 4 is derived using Equation 5 as the second equation needed to solve for the two unknowns of Q_s and A_B. Therefore, the most reasonable estimates of the value for A_B within the basin come from these deep wells, but rely on the assumptions of mantle heat flow, the exponential decay model, the BHT correction equation, and accurate well log information. Even so, the values can inform what reasonable values of A_B for the region would be under these assumptions. Values of A_B generated from the thermal model are provided in Figure 3 and a spatial distribution is provided in Figure 4.

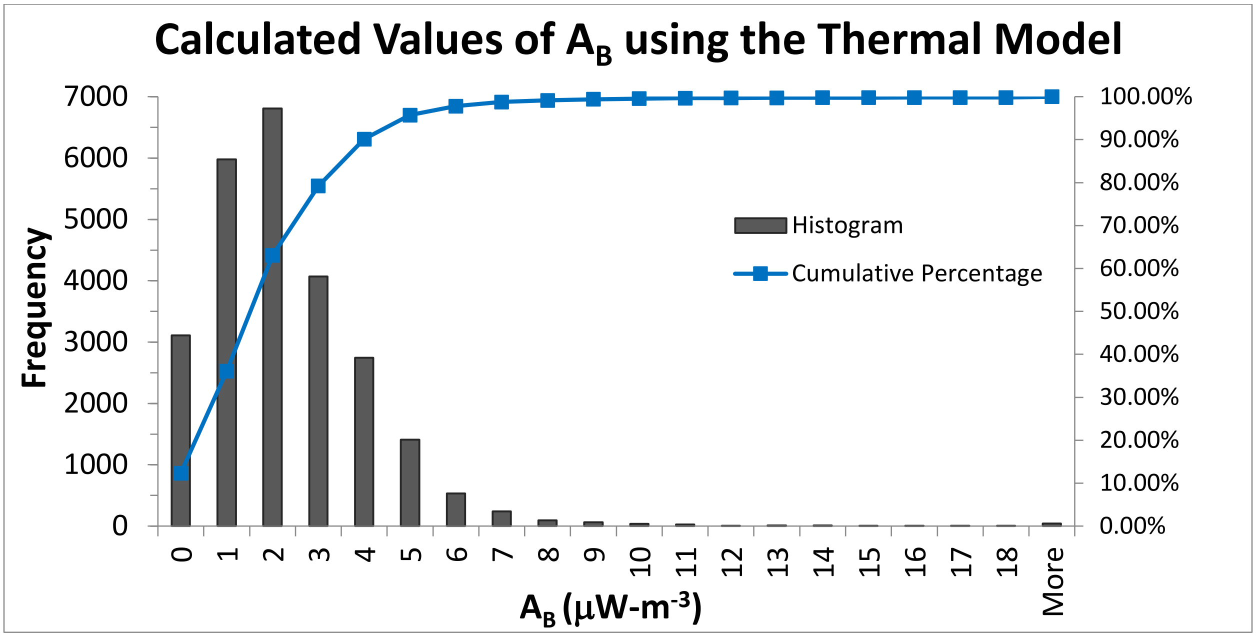

Figure 3: Histogram of A_B values calculated using the thermal model. All 0s are from wells that had negative A_B values (see below for discussion on negative values).

The average value of radiogenic heat generation throughout the entire crustal thickness for Grenville basement is reported as ranging between 0.39 μW-m^{-3} and 0.95 μW-m^{-3} (Artemieva and Mooney, 2001). Adjusting these values to an equivalent exponential decay model corresponds to A_B values between 1.4 μW-m^{-3} and 3.6 μW-m^{-3}. Approximately 90% of the calculated A_B values are less than 4.0 μW-m^{-3}. All wells deeper than the basement have A_B values less than 5 μW-m^{-3} (Figure 4), and approximately 95% of the records used in the thermal model have values less than or equal to 5.0 μW-m^{-3}. Those wells with A_B values greater than 10 μW-m^{-3} all have very high heat flow values (> 100 mW-m^{-2}). Some of these may be identified as outliers (see EDA discussion in interpolation memo).

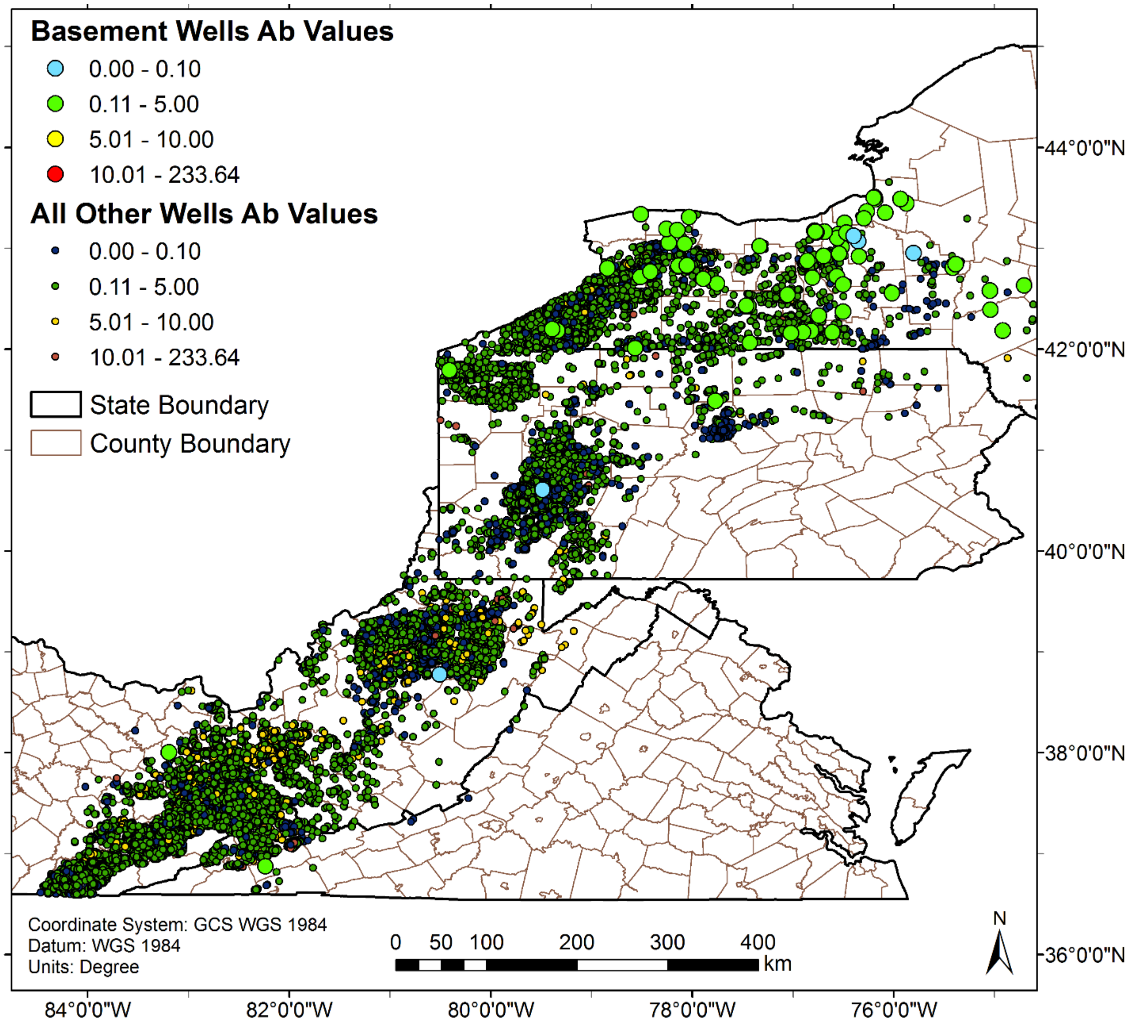

Figure 4: Spatial distribution of calculated A_B values in wells. Wells that are deeper than the basement are shown in larger circles and lighter colors.

Negative values of A_B and very high values of A_B may result from this method, which indicates that any input parameter (Q_m, A_s, and/or B) may be incorrect. For negative values, the mantle heat flow or A_s is likely too high. For very high values, the mantle heat flow is likely too low. Because none of the inputs are well constrained, it is not possible to adjust one parameter to make A_B a reasonable value. Additionally, Jaupart (1986) observes that it is not possible to vary the mantle heat flow and the basement radiogenic heat production independently. Even so, A_B and Q_m are treated as independent values in this model because when A_B is negative, the value of A_B is set to 0 without adjusting another parameter (e.g. decreasing mantle heat flow). This means that the estimates of temperature at depth and surface heat flow are greater for these wells than they should be.

Temperature at Depth

The general equations used for calculating temperature at depth are provided in Equation 6 (e.g. Jaeger, 1965). The thermal conductivity subscripts indicate over what depth range the thermal conductivity ought to be calculated.

$$\mathrm{T(Z_{calc})} = \begin{cases} \mathrm{T_s} + \dfrac{\mathrm{Q_s Z_{calc}}}{\bar{\mathrm{k}}_{\mathrm{Zcalc-0}}} - \dfrac{\mathrm{A_s Z_{calc}^2}}{2\bar{\mathrm{k}}_{\mathrm{Zcalc-0}}}, & \mathrm{Z_{calc} \le Z_w < Z_s} \\ \mathrm{T(Z_w)} + \dfrac{\mathrm{(Q_s - A_s Z_w) * (Z_{calc} - Z_w)}}{\bar{\mathrm{k}}_{\mathrm{Zcalc-Zw}}} - \dfrac{\mathrm{A_s * (Z_{calc} - Z_s)^2}}{2\bar{\mathrm{k}}_{\mathrm{Zcalc-Zw}}}, & \mathrm{Z_w < Z_{calc} \le Z_s} \\ \mathrm{T(Z_s)} + \dfrac{\mathrm{Q_m * (Z_{calc} - Z_s)}}{\mathrm{k_B}} + \dfrac{\mathrm{A_B B^2} * \left(1 - \mathrm{e}^{-\left(\frac{\mathrm{Z_{calc} - Z_s}}{\mathrm{B}}\right)}\right)}{\mathrm{k_B}}, & \mathrm{Z_{calc} > Z_s} \end{cases} \quad [6]$$

Using this equation, BHT values are calculated exactly for all wells except the 3 basement wells that had negative values of A_B. The BHT in these 3 wells are not perfectly predicted because the A_B value was set to 0; it would need to be negative for it to perfectly reproduce the BHT, which is geologically implausible. The temperature difference from the BHTs in all 3 wells is about 0.1 °C. This difference is not worrisome.

Improvements for Phase 2

The methods presented in this memo were sufficient for Phase 1 time constraints, but can be improved with more time and resources in Phase 2. Accuracy of the thermal model results may be improved by using Appalachian Basin specific thermal conductivities (see COSUNA memo for a discussion of potential sources of basin-specific data). Another improvement in accuracy may be accomplished by 1) calculating the surface heat flow at all wells, 2) performing a spatial interpolation of the surface heat flow using the methods presented in Phase 1 to obtain a 1 km^2 grid of surface heat flow, then 3) using the thermal model on each grid cell to calculate temperatures at depth throughout the basin. This would be an improvement over the current methods because this method will include information about the sediment thickness at all locations of prediction.

On the small-scale of a single play or reservoir for which a detailed economic analysis is to be performed in Phase 2, inclusion of formation specific radiogenic heat generation may become important for estimating the lifetime of the reservoir, and the necessary operating conditions and expenses. Values of heat generation may be obtained from gamma ray logs, if available. The current formulation of the model is not written to handle formation specific radiogenic heat producing elements. From a mathematical perspective, using a different value of radiogenic heat generation in each formation would mean that each formation represents a new layer within the thermal model (as opposed to the 2-layer sediment-basement model used in this analysis). This generalization of the model will prove useful for this project, and possibly to other researchers, but will be computationally more time consuming.

Other potential improvements are listed throughout this memo. Generally speaking, these improvements are related to understanding of the basement rocks via interpretation of the potential field analysis, and assigning appropriate values according to the types identified.

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Appendix 1

Derivation of 1-D Conduction Heat Balance

Assumptions:

Steady state, one dimensional heat conduction with constant, uniform heat generation from decaying radiogenic constituents in the sediment, and an exponential decrease of heat generation from radiogenic constituents with increasing depth in the basement. Effects of convection and advection are neglected.

This derivation proceeds from the bottom to the top of the column in Figure 1A.

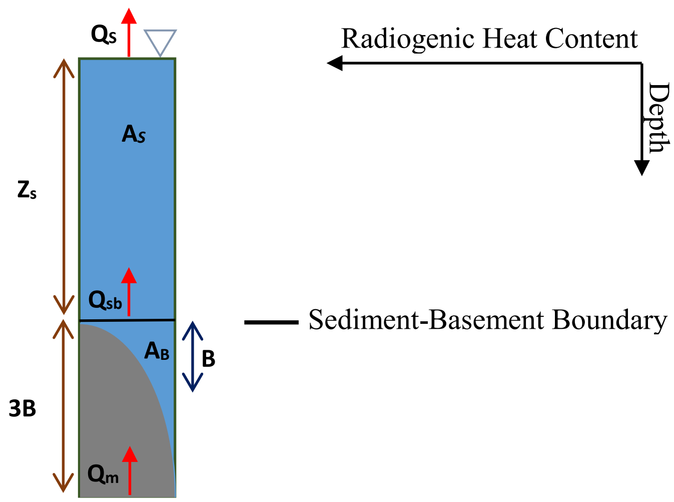

Figure 1A: Schematic of the 1D conduction heat balance. The thickness of heat generation may vary according to the thickness of the sedimentary rocks.

Heat Flow at depths ≥ 3B:

At depths greater than or equal to 3B it is assumed that there are no longer any radiogenic elements in the crust that contribute to additional heat generation. In effect, 3B is taken to be the depth to the mantle heat flow value, even if the depth does not correspond to the crustal thickness. Therefore, the heat flow, Q(z), at depths greater than or equal to 3B is the mantle heat flow, Q_m.

$$Q(z) = Q_m, \qquad z \geq 3B \tag{1A}$$

Heat Flow at the Sediment – Basement Boundary:

The heat generated by radiogenic material within the basement rocks is assumed to be 0 at depths greater than 3B. At depths from Z_s (taken as 0 m for integration to the top of the basement) to 3B, A_B decays exponentially according to Equation 2A

$$Q_B = A_B \int_0^{3B} e^{\left(-\frac{z}{B}\right)} dz$$

$$Q_B = -A_B B \left[e^{\left(-\frac{z}{B}\right)}\right]_0^{3B}$$

$$Q_B = -A_B B * \left[e^{\left(-\frac{3B}{B}\right)} - 1\right] = A_B B * [1 - e^{-3}]$$

[2A]

Generally, the heat flow at any location within the basement rocks is the sum of the mantle heat flow and the generated heat from 3B to location z in the basement.

$$Q(z) = Q_m + A_B B * \left[e^{\left(-\frac{z - Z_{sed}}{B}\right)} - e^{-3}\right], \quad Z_s \leq z \leq 3B + Z_s$$

[3A]

Note that when $z = 3B + Z_s$ the radiogenic heat generation term goes to 0, and $Q(Z_s+3B) = Q_m$. When $z = Z_s$, the heat flow at the boundary between the sediment and basement rocks is

$$Q_{sb} = Q_m + Q_B$$

.[4A]

<u>Heat Flow at the Surface</u>:

Radiogenic heat generation in sedimentary rocks is assumed to be uniformly distributed. Under this assumption, the total heat produced in the sediments from decaying radioactive material is given by Equation 5A.

$$Q_{sed} = A_s Z_s$$

[5A]

The heat flow at any depth, z, within the sediments is the summation of the heat from the mantle, basement rocks, and sediment below z, as shown in Equation 6A.

$$Q(z) = Q_m + Q_B + A_s(Z_s - z), \quad 0 \leq z \leq Z_s$$

[6A]

Note that at $z = Z_s$, $Q(Z_s) = Q_{sb}$. The heat flow at the ground surface ($z = 0$) is provided in Equation 7A.

$$Q_s = Q_m + Q_B + Q_{sed}$$

[7A]

In this thermal model, the value of radiogenic heat generation at the sediment-basement interface is unknown. This heat balance in Equation 7A may be rearranged to solve for this variable for each well based on known or assumed variables and parameters, as discussed in the body of the text.

$$A_B = \frac{Q_s - Q_m - A_s Z_s}{B * [1 - e^{-3}]}$$

[8A]

Attachments

These attachments provide references to databases (attachments 1-2) and additional methodological details (attachments 3-5).

List of attachments

1) Well Databases Folder
2) Trenton-Black River Sediment Thickness Map
3) Influence of Annual Temperature Fluctuation on Near-Surface Temperatures
4) Drilling Fluid Query in SQL
5) Probabilistic assignment of Drilling Fluid based on Nearest Neighbor Wells

1. **Name**: Well Databases Folder

File 1: All_States_BHT_HeatFlow_Raw_Combined.xlsx

Description

This file contains all of the raw well data gathered for this project. These state databases do not necessarily have BHT measurements for all wells, and may contain duplicate records within-database and between databases.

For data quality purposes, only those records that were submitted to the American Association of State Geologists (AASG) State Geothermal Data Repository were selected for use in the project. AASG wells were selected because all of these records had BHT data, and they were submitted by state geological surveys. Additional data sources collected include 1) Pennsylvania records from American Association of Petroleum Geologists (AAPG), 2) New York records from Empire State Oil and Gas Information System (ESOGIS) 4) West Virginia records from NGDS (had 1000 less records than AASG), and 5) Ohio heat flow wells. Many of the wells with BHT measurements available in these databases are likely recorded within AASG wells, though this was not checked for all databases.

File 2: AASG_Combined.xlsx

Description

The data contained within this database are taken from the Association of American State Geologists (AASG) Geothermal Data Repository (all references in body of text for each state). This database has 41,099 records. Duplicate records have not yet been removed. The spreadsheets for each state did not have the same field names, or the same fields. When combining the data, only those fields needed for analysis (listed below) were placed into the AASG_Combined file. All of the original data may be joined to this database using the StateID field if further information is desired*.

* StateID is used because some wells do not have an APINo. A StateID field was added into the original state databases for joining purposes.

This database was screened for obvious data entry errors in fields important to the project. These fields included the latitude, longitude, depth of measurement, and the BHT. Latitude and longitude were checked by ensuring that all wells were located in the county specified. All wells passed this test. Depth of measurement and BHT were screened for abnormally high or low values. Several obvious instances were found and corrected as described below. As part of this screening, an additional record was found and added for API number 31003042480000 at 7560 ft. and 140 F based on the log data for the well.

Corrections to Records

RowID numbers 19375 and 35927 had a very high depth of measurement. RowID 19375 had 2 leading 3s but one 3 was deleted to match the driller depth. RowID 35927 had a depth of measurement of 36,885, but it seemed like the 6 was a typo because by deleting the 6 the depth was the same as the TVD. RowID 35939 depth of measurement was about 10 times deeper than the TVD and driller depth with no apparent typo, so the depth of measurement for this well was deleted. RowID 37534 has a depth of measurement that is about 10000 ft. more than the TVD, with a BHT that did not match that depth, so the depth of measurement was deleted. RowID 22772 had a -9999 as the depth of measurement, so this value was deleted.

Database Fields

RowID	Unique identifier for the wells, starting at 1.
StateID	Unique identifier that matches the original state database. Labels have the state postal code followed by a number, starting at 1.
WellName	Name of the well as listed by the state datasets (blank if not available).
APINo	API number for the well, if one exists (blank if not available).
County	County where the well is located.
State	State where the well is located.
LatDegree	Decimal degree latitude for the well.
LongDegree	Decimal degree longitude for the well.
SRS	Coordinate reference system as listed by the state database.

DrillerTotalDepth	Total depth as logged by the driller. This may include any horizontal, non-vertical component of the drilling (m, ft).
TrueVerticalDepth	The vertical depth of the well (m, ft).
DepthOfMeasurement	The depth of temperature measurement as listed by the state database (m, ft).
ElevationGL	Ground level elevation (m, ft.)
LengthUnits	Units used for the depth fields (m or ft).
MeasuredTemperature	Temperature measured at the depth of measurement (C or F).
TemperatureUnits	Unit of the temperature measurement (C or F).
DrillingFluid	Fluid used to drill the well, if provided. Blank otherwise.

File 3: AASG_Processed.xlsx

This file has all of the above fields, and the following additional fields. Before running through the thermal model, all wells were checked for depth of measurement being greater than the first increment of calculation in the thermal model (10 m). It was found that RowID 35925 had a depth of measurement shallower than 10 m, so this record was removed from the database before using the thermal model.

Additional Fields Added Before Thermal Model Calculations

BHT_C	The MeasuredTemperature in Celsius.
CalcDepth_m	The well depth corresponding to temperature measurement based on quality hierarchy of 1) DepthOfMeasurement, 2) TrueVerticalDepth, and 3) DrillerTotalDepth. If no depth is available, NA is listed. (This field was not used for this project, but it is provided for reference).
MeasureDepth_m	The DepthOfMeasurement in meters. If no depth is available, NA is listed.
ReportedElevation_m	The ElevationGL in meters.
CRS	Coordinate reference system rewritten as WGS84 and NAD83 for database consistency.

API_14Dig	14 digit API number for each state, when available. If no API number exists, NA is listed. This is intended to be a well identifier, but values may be truncated in some programs.
Fluid_Type	Generalized fluid type based on Whealton (2015). (all_agfs, all_mgpw for air and mud, respectively; blank if not available).
Pct_Air	Proportion of nearest neighbor wells that are air drilled. 1 if the well is known to be air drilled, 0 if the well is known to be mud drilled. All values are between 0 and 1, inclusive.
Pct_Mud	Proportion of nearest neighbor wells that are mud drilled. 1 if the well is known to be mud drilled, 0 if the well is known to be air drilled. All values are between 0 and 1, inclusive.
BHTReg	BHT correction region.
CorrBHT	Corrected BHT. (°C)
Corr_error	Error code for corrected BHT. 0 if there's not an error.
UTM_Long	Universal Transverse Mercator (UTM) Zone 17N longitude. (m)
UTM_Lat	Universal Transverse Mercator (UTM) Zone 17N latitude. (m)
BasementDepth	Depth to the basement (i.e. sediment thickness). (m)
SurfTemp	Average annual surface temperature derived from Gass (1982).
COSUNA_ID	The ID number assigned to the COSUNA section for the well.
COSUNA_NAME	COSUNA column name corresponding to the COSUNA_ID.
ROME_ID	Binary. 1 if a well is in the Rome Trough, 0 if it is not.
SedRadHeat	Radiogenic heat generation in sedimentary rocks ($\mu W\text{-}m^{-3}$)
QMantle	Mantle heat flow ($mW\text{-}m^{-2}$)

File 4: AASG_Thermed.xlsx

This is the data after processing in the thermal model. This file has all of the above fields and the following additional fields calculated in the model. Enough information is reported in this database such that calculations may be made using the heat flow equations in the text. The temperature at depth equations require knowledge of the thermal conductivity and thickness of each rock layer, scaled to the sediment thickness. This information is not provided here, but is provided in the NGDS data submission.

Additional Fields Added After Thermal Model Calculations

BaseRadHeat	Calculated radiogenic heat generation at the interface between sediment and basement rocks ($\mu W\text{-}m^{-3}$)
Gradient	The geothermal gradient calculated from CorrBHT at the MeasureDepth_m ($°C\text{-}km^{-1}$)
HeatFlow	Heat Flow calculated using the thermal model ($mW\text{-}m^{-2}$)
Depth50C	Depth to 50 °C calculated using the thermal model (m)
Depth80C	Depth to 80 °C calculated using the thermal model (m)
Depth100C	Depth to 100 °C calculated using the thermal model (m)
Temp2km	Temperature at 2 km calculated using the thermal model (°C)
Temp3km	Temperature at 3 km calculated using the thermal model (°C)
Temp4km	Temperature at 4 km calculated using the thermal model (°C)
Temp5km	Temperature at 5 km calculated using the thermal model (°C)
Temp6km	Temperature at 6 km calculated using the thermal model (°C)
Kw	Average thermal conductivity to the MeasureDepth_m ($W\text{-}m^{-1}\text{-}°C^{-1}$)
Kc	Average thermal conductivity to the BasementDepth ($W\text{-}m^{-1}\text{-}°C^{-1}$)
BHT_diff	Difference between the calculated BHT at the MeasureDepth_m and the CorrBHT. (°C)

2. **Name**: TBR_SedimentThickness

   Creation Steps

   The sediment thickness map was created from the Trenton-Black River (TBR) project structural contours of the Precambrian basement, relative to mean sea level (WVGES, 2006). These structural contours were converted to a raster file in ArcGIS (Contour to Raster tool). The raster represents the depth to the Precambrian basement from mean sea level. The raster was processed to represent sediment thickness by adding the elevation using 30 m resolution DEMs from the USGS National Map (2015) that were mosaicked together into a single DEM for the region using ArcGIS (Mosaic tool). Finally, the resulting TBR raster was manually clipped to an approximate 10 km distance from the extent of the Precambrian contour lines to avoid extrapolation of the sediment thickness beyond the data support. This did not greatly impact the number of wells capable of being used in the assessment of the thermal field for the basin.

   The accuracy of this sediment thickness map was in question for West Virginia because of thickness differences on the order of kilometers compared to the more recent Mooney (2011) sediment thickness map. Upon further inspection, the map created by Mooney (2011) was derived from 1985 data, which is before detailed knowledge of structural features of importance, such as the Rome Trough in West Virginia, were established in portions of the Appalachian Basin. The set of selected reliable wells drilled to the Martinsburg formation or deeper in West Virginia were used to check the accuracy of the TBR sediment thickness map. First, the depth to the touchdown formation was compared to the depth to the touchdown formation in the COSUNA columns. If the well depth-to-formation was within the minimum and maximum depth-to-formation as listed on the COSUNA column, the true sediment thickness at the well location was assumed to be within the minimum and maximum sediment thickness as listed on the COSUNA column. Using this extrapolation, the TBR sediment thicknesses were all within the COSUNA sediment thicknesses. Therefore, the TBR sediment thickness map is reasonably accurate within West Virginia. As another check for West Virginia, the depth to basement for Ryder et al. (2008) cross section E-E' is ~7.5 km in the southeast region of WV; whereas the TBR map is 7 km and the Mooney (2011) map is nearly 12 km.

   A plot comparing the reliable well depth to basement (actual depth) in all three states to the TBR map depth to basement is provided in Figure A1. Based on these results, we are comfortable with the choice of the TBR sediment thickness map for this project. It is likely that many of these wells would have been used to determine the structural contours of the Precambrian basement. Perhaps the only difference is the resolution of the USGS DEM.

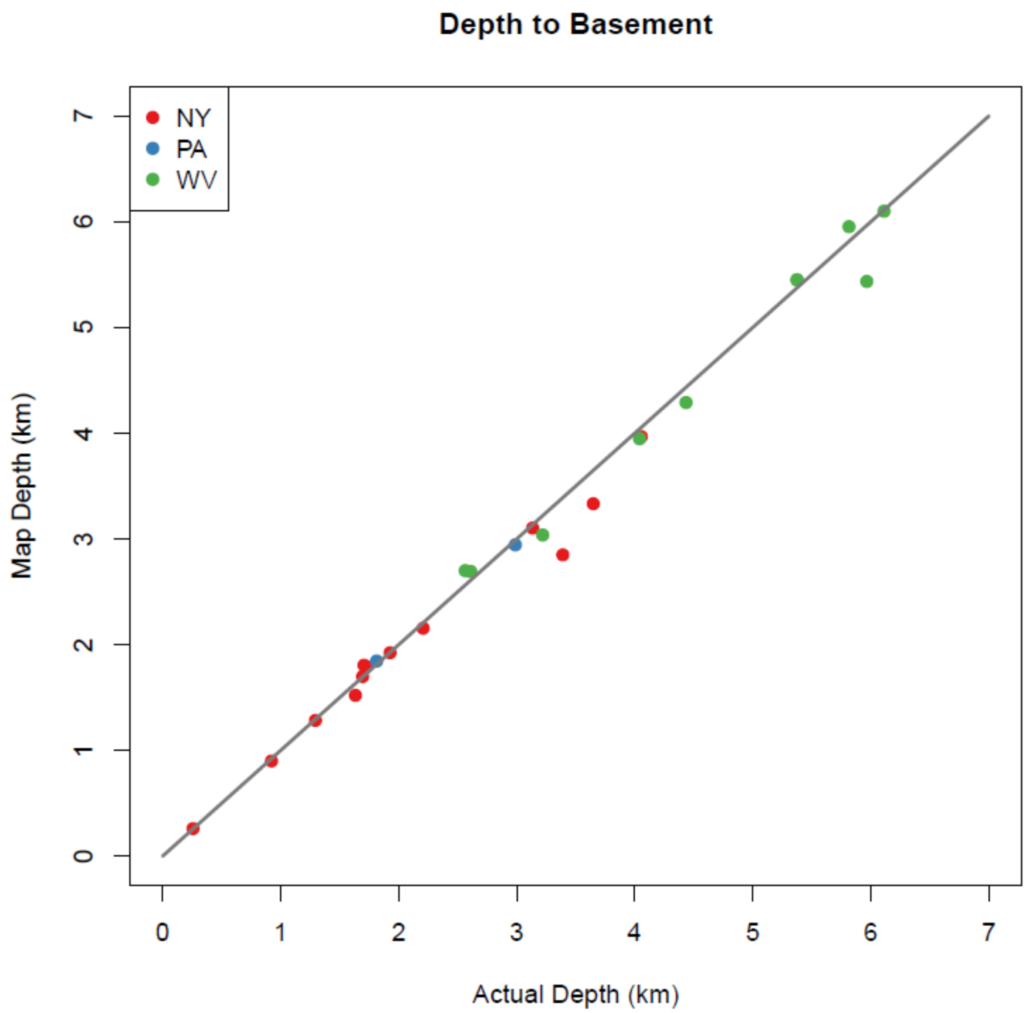

Figure A1. Comparison of TBR sediment thickness (Map Depth) to the actual sediment thickness from the favorite wells analysis. A 1:1 line is shown for reference. Depth to basement is the same as sediment thickness.

3. **Name**: Influence of Annual Temperature Fluctuation on Near-Surface Temperatures

Description

Surface temperature fluctuations on time scales ranging from annual to millennial have been shown to affect near-surface temperatures at depths from 15 m – 500 m (Beltrami, Matheroo, and Smerdon, 2015). Millennial and centennial scale variations are not of concern in this project because data used in the analysis is deeper than the maximum penetration depth for these time scales. However, it is worthwhile to assess the potential impact of the annual temperature fluctuation on the shallow groundwater temperatures taken by Gass (1982) at depths between 15 m and 46 m. This assessment only considers heat conduction. Advection of heat via groundwater could also impact the measurements taken by Gass (1982). Additionally, disturbances to the thermal field as a result of surface landscape alteration (Roy, Blackwell, and Decker, 1972) are not considered here, but may have had an effect on the temperature measurements taken by Gass (1982).

Under these assumptions, the depth of disturbance in the thermal field as a result of annual surface temperature fluctuation varies according to the thermal diffusivity of the subsurface medium; the more thermally diffuse, the deeper the propagation. Sandstone has the greatest thermal diffusivity of the rocks located at the surface of the Appalachian Basin, so a high-end thermal diffusivity of sandstone (0.014 cm^2-s^{-1}) was used to see the worst-case impact on Gass' (1982) measurements. The dampening of the annual surface temperature fluctuation with depth follows an exponentially decaying sine curve given in Equation A1 (Ingersoll, Zobol, and Ingersoll, 1946)

$$T(z) = a * \left(\left(e^{-z\sqrt{\frac{\pi}{\alpha P}}} \right) * \sin\left(\frac{2\pi t}{P} - z\sqrt{\frac{\pi}{\alpha P}} \right) \right) \tag{A1}$$

Where *a* is the amplitude of the surface temperature fluctuation (°C), α is the thermal diffusivity (cm^2-s^{-1}), *z* is the depth below the surface (cm), *P* is the period of the annual temperature fluctuation (1 year, in seconds), *t* is time since the annual average surface temperature (s). The bounds of the annual near-surface temperature with depth are provided by Equation A2.

$$T(z) = a\left(e^{-z\sqrt{\frac{\pi}{\alpha P}}} \right) \tag{A2}$$

From Figure A2 it is clear that the shallow groundwater temperature measurements taken by Gass (1982) would have been relatively stable with regard to the annual temperature fluctuation, which is ≤ ± 0.5 °C at the depths measured. Because the depths of measurement were taken between 15 m and 46 m, the thermal model calculations implicitly assume that the map of surface temperature that was created by the Gass (1982) measurements is also the average annual temperature at the surface (0 m). This is a reasonable assumption based on this analysis. The uncertainty in the value of Gass (1982) measurements may be assumed to be 0.5 °C based on the temperature fluctuation with depth. Additional uncertainty in the derived map results from spatially interpolating between Gass' measurements. These uncertainties may be used to inform values of uncertainty to use in Monte Carlo analyses of the thermal model.

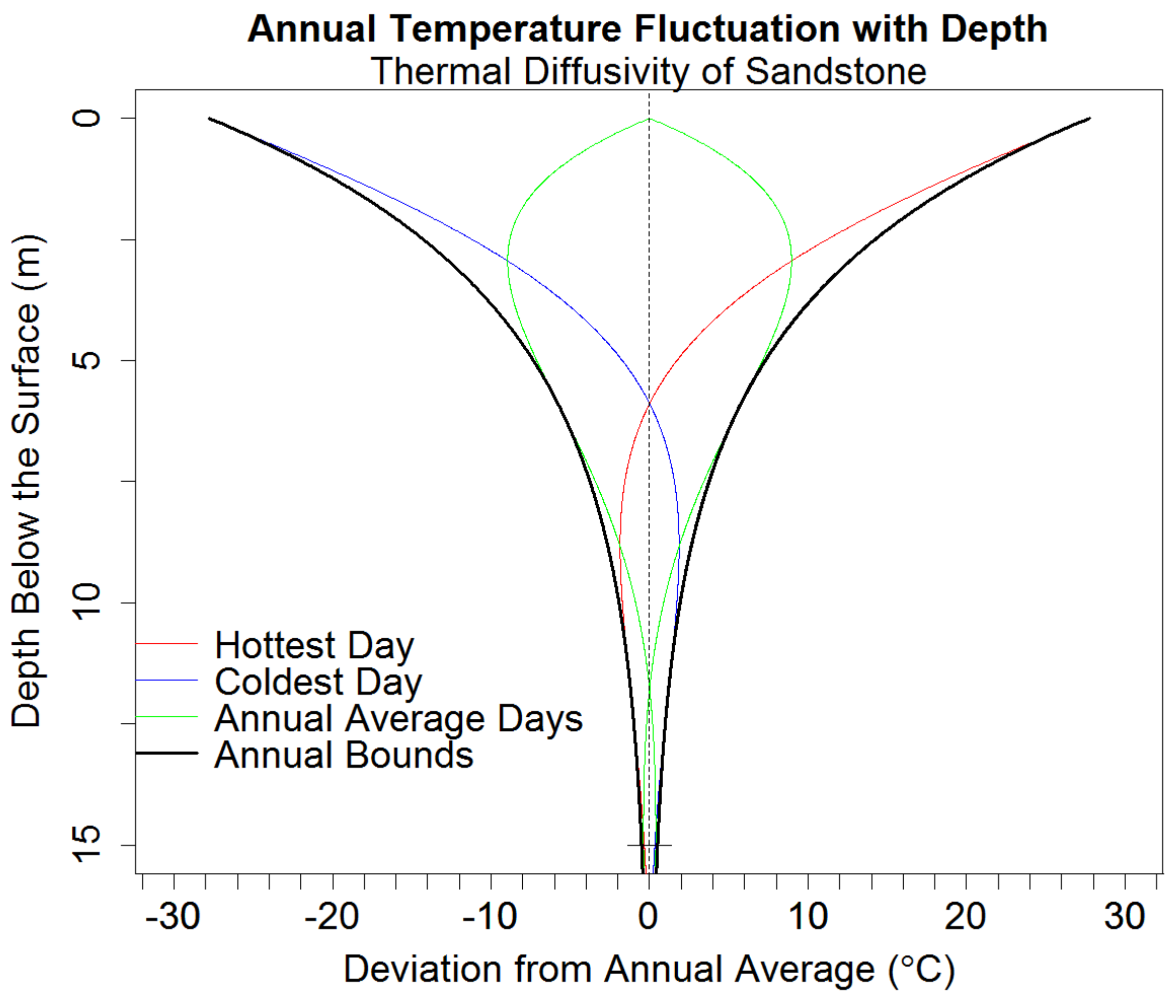

Figure A2: Annual temperature fluctuation with depth for a sandstone with higher than average thermal diffusivity (0.014 cm^2-s^{-1}). The annual surface temperature is assumed to fluctuate ±28 °C from the annual average surface temperature.

4. **Name:** DrillingFluidQuery_ALL.SQL

Query:

```
SELECT * FROM ("Whealton_Wells_GDB"
                JOIN "aasg_whealton"
                ON "aasg_whealton".whealton_pk = "Whealton_Wells_GDB".id)
JOIN "AASG_Wells_GDB"
ON "aasg_whealton".aasg_pk = "AASG_Wells_GDB".id
```

Description

Because the API number is not a unique identifier (e.g. a well with 2 BHT measurement creates 2 records with the same API number) a method for joining many wells with the same API numbers in the Whealton (2015) database to many wells with the same API numbers in the AASG database was needed. This is called a many-to-many join.

First, a link table called [aasg_whealton] was created by combining the [AASG_Wells_GDB] and [Whealton_Wells_GDB]. This table consists of five fields: 1) a primary key (unique identifier) for the Whealton database [whealton_pk] 2) primary key for the AASG database [aasg_pk], 3) API number for AASG database [aasg_api], 4) API number for the Whealton (2015) database, and 5) spatial geometry of the data.

This code selects all [*] information from the wells in the Whealton (2015) database for which the API number [id] equals the Whealton primary key in [aasg_whealton]. Then, the AASG wells for which the API number [id] equals the AASG primary key in [aasg_whealton] are joined to the previous table. This resulted in 687 matching records for 245 unique wells in NY and PA before processing of the data as described in Selecting and Processing Wells for Analysis. Post processing, only 137 records matched.

5. **Name:** Drilling Fluid Nearest Neighbors [WhealtonWells_NAD_FinalProcessing.xlsx] and [whealtonAir&Mud_NAD3_RemovedNoLongLatPts_Reg_Unique.shp]

   Description

   All wells in the Allegheny Plateau BHT section in New York and Pennsylvania needed to have drilling fluid information in order to use the BHT correction equation, as defined in the BHT memo. For the 137 records in the processed AASG database that matched the Whealton (2015) drilling fluid database, the use of the BHT equation for air or mud drilled wells is not a problem. The question arises, though, about what to do for wells for which no drilling fluid information is available.

   When a well did not have drilling fluid information, a weighted average of the BHT corrections for air and mud drilled wells was used based on the drilling fluid used to drill nearest neighbor wells. The nearest neighbor wells were the Whealton (2015) wells. The logic behind using a probabilistic assignment of nearest neighbors is that the wells close to each other are more likely to be drilling for the same resource and drilled by the same company, and therefore use a similar drilling fluid.

   An important step prior to running the nearest neighbor function was to check the Whealton (2015) database for wells with the same API number. Multiple records for the same well would count that well's drilling fluid multiple times, thus assigning an inappropriate proportion of air and mud to a well with unknown drilling fluid. Of the 2233 records in the Whealton (2015) database, there were 1755 unique wells.

   A function was written to determine the proportion of air and mud drilled wells (see Whealton code repository). This function uses the nearest 25 points within 50 km to compute the proportion of air and mud for an unknown well. The algorithm is defined such that the distance to the 25^{th} nearest neighbor is the distance cutoff for the inclusion of wells in the calculation of the proportion. If the 25^{th} nearest point happens to have another point the same distance away (same location or different location), then there may be more than 25 points used to compute the proportion of air and mud. If 25 points did not exist within 50 km, then that well was assigned the regional average proportion of air and mud drilled wells of 0.194 air drilled and 0.806 mud drilled. It is not a problem that some wells use more than 25 points to calculate the proportion, but should be noted because this is the reason that some wells have proportions other than multiples of 1/25.