To: Appalachian Basin Geothermal Play Fairway Analysis Group

From: Jared Smith, Terry Jordan, and Zachary Frone

Date: July 31, 2015

Subject: Assignment of conductivity stratigraphy for individual wells using COSUNA columns

Applicability: The method described here was used to compute the conductivity stratigraphy for use in creating thermal maps of heat flow, temperatures at depth, and depth to temperatures of interest.

Definitions

Unit	A member, formation, or group. These are nested ranks. In general, the uniformity of lithology is greatest at the rank of member and decreases progressively through formation and group.
Group (Gp.)	A sequence of formations and/or members within a single named unit.
Formation (Fm.)	A sequence of members in a single named unit.
Member (Mbr.)	A layer, named or unnamed, in a group or formation.
COSUNA column	Generalized representation of a vertical sequence of units in the subsurface, identified by general lithology and correlated to geologic age.
COSUNA section	Geographic area in which the COSUNA column was defined by AAPG (1985a; 1985b).

Introduction

The Appalachian Basin Geothermal Play Fairway Analysis team needs to have a method for assigning lithologic unit thicknesses and corresponding thermal conductivities to locations of wells that have BHT measurements in order to calculate the geotherm using the 1-D thermal model. The AAPG (1985a; 1985b) COSUNA column thicknesses have been used in previous studies in the Appalachian Basin (Aguirre, 2014; Shope, 2012; Stutz, 2012; Frone and Blackwell, 2010) as a generalized approach to assign a representative geology to broad sub-regions of the basin, within which the geology is fairly consistent (Fig. 1). Because a single COSUNA column applies to a broad area, yet the total thickness of the sedimentary rocks varies across any one of those areas, it is also necessary to rescale the general COSUNA column unit thicknesses to the specific location of the well whose conductivity column is sought. A linear scaling of each unit was used to match the COSUNA column thickness to the sediment thickness (WVGES, 2006) at the location of each well. This approach allows for a rapid analysis of wells when a well-by-well geological analysis would be implausible to complete in the provided timeframe. A well-by-well geological analysis has been determined for a subset of the dataset as a comparison to the COSUNA column approach (see the memo “ Tests of Simplified Conductivity Stratigraphy by Monte Carlo Analysis” for more details).

COSUNA Column Data

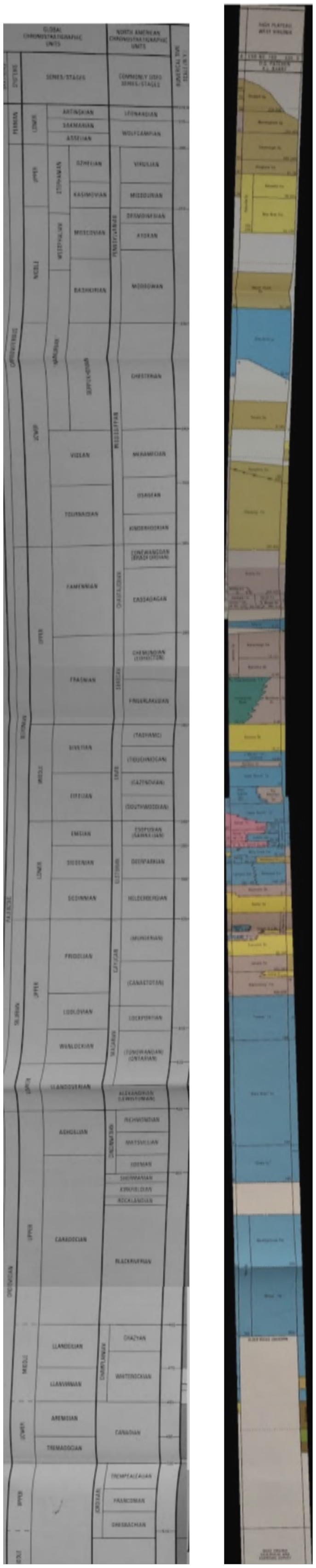
Each COUSNA column provides a vertical sequence of named units, unit age (Ma), unit thicknesses (m), and by color indicates the dominant lithology (Fig. 2). Additional, often more detailed lithologic information from the USGS mineral resources website (USGS, 2014) was coupled to the COSUNA units on a state-specific basis.

A range of unit thickness is reported for most units, and a single “normal” thickness is reported otherwise (Childs, 1985). The normal thickness is interpreted as being an average thickness, but this may not be the case. Some columns are incomplete and do not include some Lower Paleozoic units, and other columns do not have reported thicknesses for some units. For these units, if cross sections within the COSUNA section were available, the units and approximate thicknesses were added from the cross sections (Table 1). If cross sections were not available, the missing information was documented (Table 2) and the columns were used as provided by AAPG (1985a; 1985b).

The areas of the COSUNA sections vary greatly throughout the basin, with the 21 smallest sections (min ~970 km^2, mean ~ 1960 km^2, max ~3300 km^2) concentrated in the eastern margin of the basin along the Appalachian Mountains, and the largest 25 sections (min ~4430 km^2, mean ~ 13900 km^2, max ~29300 km^2) dispersed in the remaining portion of the basin (Fig. 1).

Summary of Desired Products

The goal of this analysis is to assign a conductivity stratigraphy to each well in the dataset. To arrive at this product, the time-based COSUNA columns must be transformed into thickness-based columns with lithologically distinct rock units for the assignment of conductivities. Therefore, unit lithology and thickness are the primary information to extract from COSUNA columns and organize into a useful format. The methodology for extracting this information is presented here.



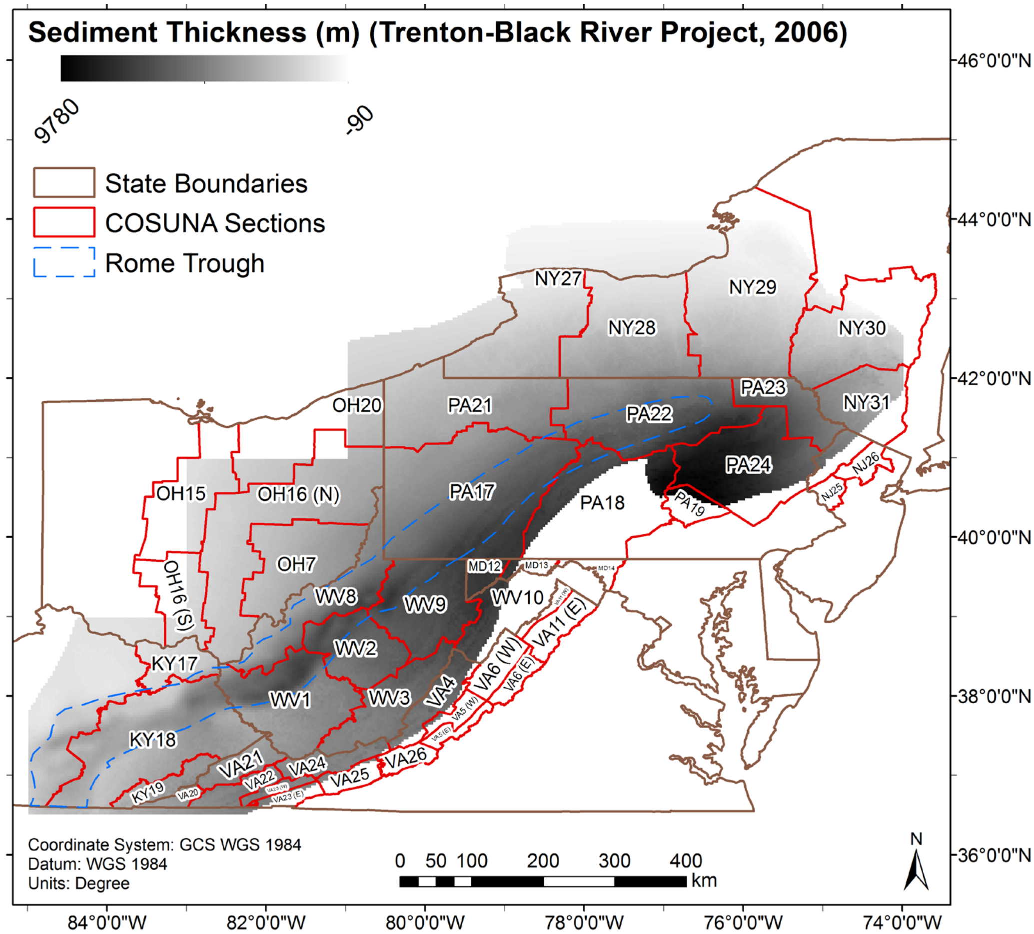


Figure 1: Map of the regions, referred to as sections, whose generalized sedimentary rocks are described by single COSUNA columns. The sections used in this study are labeled by state, followed by the number of the column and, where needed, the cardinal direction in parenthesis. For Virginia, cardinal directions indicate separate columns for the eastern and western side of the North Mountain Fault or the Pulaski Fault. For Ohio, the cardinal direction indicates on which COSUNA sheet (North (N) or South (S) Appalachian Basin) the column can be found. The sediment thickness derived from the Trenton-Black River Project (WVGES, 2006) is shown for reference. COSUNA sections that intersect the Rome Trough (Repetski et al., 2008) require adjustment and addition of some units (discussed below).

Figure 2 (left): West Virginia 9 COSUNA Column and geological ages. Time progresses upward from the bottom. Colors: Blue – carbonate; Pink – evaporite; Grey – Shale, mudstone, siltstone; Tan – Interbedded sandstone, siltstone, shale; Teal – Chert; Yellow – Sandstone. Column shows examples of units occupying only portions of the column (first unit from top), and of multiple units in the same time period (Shale\Chert units in the middle of the column).

Method for Extracting Thickness from COSUNA Columns

The pictorial COSUNA column information is transformed into a spreadsheet that records as rows the individual named units of the COSUNA column. Spreadsheet columns are assigned subsidiary information about each rock unit. An effort was made to preserve as much detail as possible from the COSUNA columns. Groups and formations were split into the individual formations/members that comprised the group/formation, when possible. If a group/formation was all the same rock type (e.g. all limestone) then a single row in the spreadsheet was used to represent the group/formation, and all formations/members composing the group/formation were listed in the row, ordered from the geological top downward. Occasionally the minimum and maximum thicknesses of the formations/members did not sum up to the group/formation minimum and maximum thicknesses. In this case, the reported minimum and maximum thickness for each formation/member was listed in a separate row.

Rome Trough Units

The COSUNA columns reported knowledge that existed up to the date of publication in 1985, and they are spatially simplified such that lateral variability, which likely occurs across individual faults or folds, is not necessarily represented (Childs, 1985). In some cases knowledge of structural features today known to be important, such as the Rome Trough, were not integrated into the early 1980's COSUNA data compilation. For the case of the Rome Trough (Fig. 3), knowledge of the thicknesses of the deeply buried Appalachian basin sedimentary units evolved significantly as the spatial extent of very deep drilling increased and as deep penetration reflection seismic data progressively moved into the public domain. Thus, the COSUNA columns characterize well the Lower Paleozoic units of the Kentucky sector of the Rome Trough, but lack this information for parts of West Virginia and Pennsylvania. Therefore, an early step in this project's methods was to adjust several COSUNA columns to account for the Rome Trough units and associated thicknesses (Table 1). The Rome Trough was located within only a portion of each of the COSUNA sections listed in Table 1, so the addition of these units only applies to the portion of the COSUNA column located within the Rome Tough (Fig. 1). The thickness change represents the additional thickness of Lower Paleozoic strata present in the Rome Trough portion of the COSUNA column.

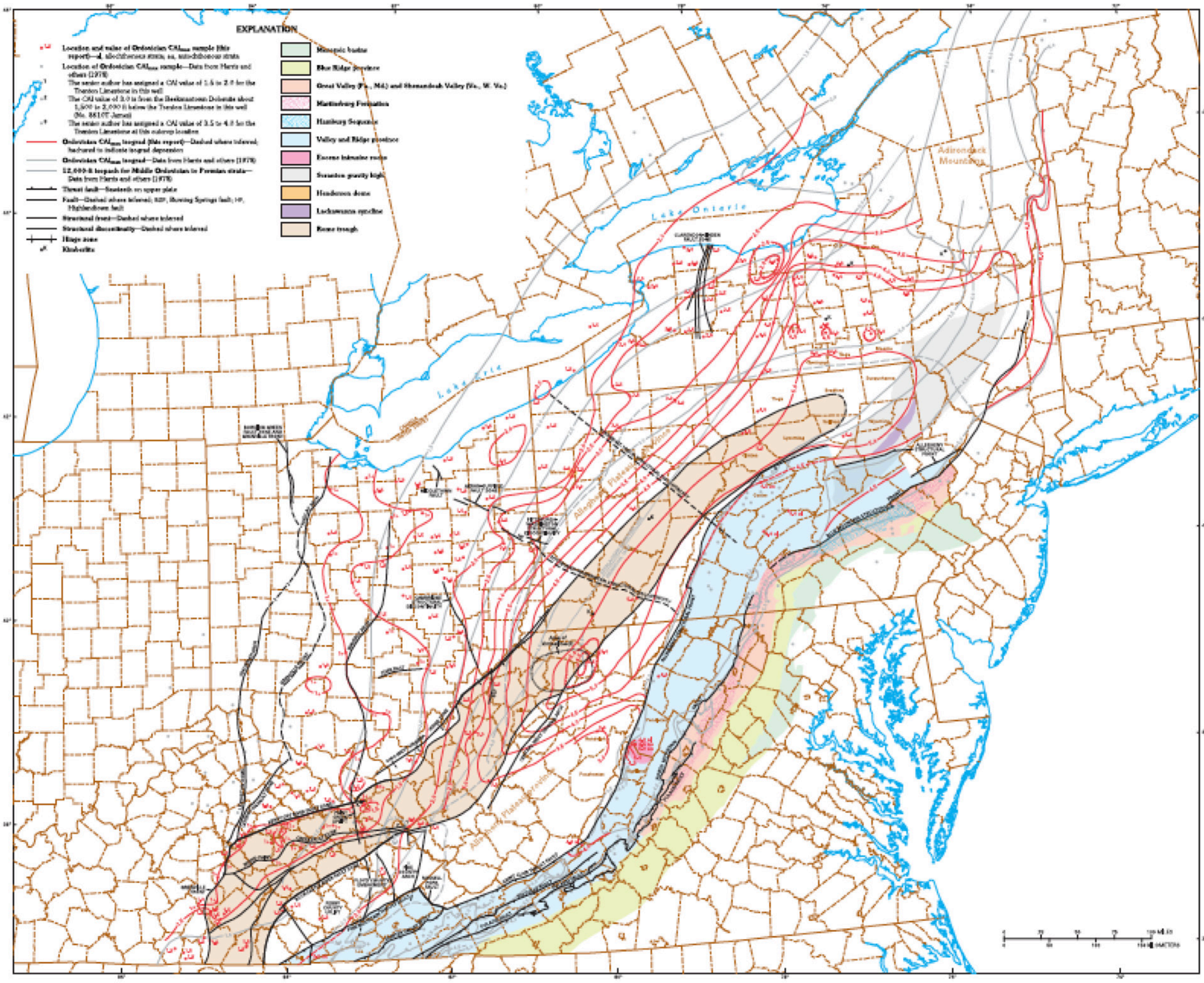


Figure 3: Map illustrating the location of the Rome Trough (light brown shading) from Repetski et al. (2008). There is little disagreement among researchers about the location of the southwestern half of the Rome Trough (southern Pennsylvania, West Virginia, and Kentucky). However, there is a high degree of uncertainty about location and magnitude of this deeply buried feature in central and northern Pennsylvania, as well as in southernmost New York (e.g., Harper, 2004).

The COSUNA columns are as much as 1775 m thicker on average in the Rome Trough than outside of the Rome Trough (Table 1). This thickness change might occur: 1) over a horizontal distance of a kilometer if the trough at this location is bounded by a single major fault, 2) across a series of hundred-meter-scale steps spanning a width of 10-30 km via a series of minor faults, or 3) progressively across a wide ramp (Fig. 3). Ideally the structural style of the structural border zone would be known and dictate the thickness of strata assigned to each well. But that information is not known or not available, and a simplified strategy is needed for interpolation of thicknesses across the borders of the Rome Trough. Because the sediment thickness map governs the thickness transition across the Rome Trough boundary via scaling of the COSUNA columns, it is more important to capture the lithologic differences in and out of the Rome Trough with the COSUNA columns than it is to have a separate thickness scaling factor for columns of the Rome Trough based on, for example, distance to the Rome Trough boundary. Therefore the method adopted is to use a sharp division of column thickness across the Rome Trough boundaries, and allow the scaling of sediment thickness to account for the "true" thickness change.

Addition of Rome Trough Units

The units added to each column are provided in Table 1. Column KY18 was unique in that it contained thicknesses of Rome Trough units on the COSUNA charts, but a division for units in and out of the Rome Trough was not provided. For example, the thicknesses of units at the bottom of the column ranged from about 1700 m to 4700 m, which suggests that the KY18 region (section) straddles one or more faults that comprise the borders of the Rome Trough (Fig. 1). Lacking information about the transition between these thicknesses, Equation 1 was used to assign the unit thicknesses in and out of the Rome Trough from the Brassfield Dolomite to the basal sandstone

$$Thick = \begin{cases} average + \frac{[max - average]}{2}, & \text{In Rome Trough} \\ average - \frac{[average - min]}{2}, & \text{Not in Rome Trough} \end{cases} \qquad [1]$$

where *Thick* is the thickness of the unit, *average* is the average thickness of the unit, *max* is the maximum thickness of the unit, and *min* is the minimum thickness of the unit. This equation is only used for Rome Trough units in column KY18.

Table 1: Rome Trough units and sources. Details for each unit are provided in the spreadsheet (DOE_NY-PA-WV-VA-OH-KY-MD_ v6_Q3.xlsm). Units to the left of forward slashes overlie units to the right of forward slashes. Units listed have been added to the bottom of the COSUNA columns, unless otherwise stated. Thickness change is relative to the COSUNA columns without Rome Trough adjustment, unless otherwise stated.

COSUNA Section	Units Added to the Bottom of the Original COSUNA column	Average Thickness Change (m)	Sources
PA17	Pleasant Hill Fm. / Waynesboro Fm / Tomstown Dolomite / Basal Sandstone	+ 1635	Shope (2012) MS Thesis
PA18	Waynesboro Fm / Tomstown Dolomite	+ 404	USGS Cross Section B-B' (Ryder, 1992)
PA21	Unnamed shale between Gatesburg Fm. and Warrior Fm. Beekmantown Fm. thickness increased within the Rome Trough.	+ 577	USGS Cross Section B-B' (Ryder, 1992)
PA22	None added. Lacking further information, maximum thickness was used as the “assumed” thickness for Rome Trough units only.	+ 46.5	No cross sections found that pass through the Rome Trough portion of this COSUNA section.
WV1	Tomstown Dolomite (a.k.a. Shady Dolomite) between the Rome Fm. and basal sandstone. Adjusted thicknesses of the Conasauga Fm. and Rome Fm.	+ 1309	Plate 10A, Rome Trough Consortium Final Report (Harris et al., 2002)
WV2	Rome Fm. added between Conasauga Fm. and Tomstown Dolomite. Adjusted thicknesses of Conasauga Fm. and Tomstown Dolomite.	+ 976	Plate 12A, Rome Trough Consortium Final Report (Harris et al., 2002)
WV8	Waynesboro Fm. and basal sandstone. Adjusted the Conasauga Fm. Increased Dunkard Gp. thickness in the Rome Trough (Ryder et al., 2008).	+ 1775	USGS Cross Section E-E' (Ryder et al., 2008) and Plate 14A, Rome Trough Consortium Final Report (Harris et al., 2002)
WV9	Rose Run Sandstone / Copper Ridge Dolomite / Nollchucky Shale / Maryville Limestone / Rogersville Shale / Pumpkin Valley Shale / Waynesboro Fm. / Tomstown Dolomite / Chilhowee Gp. None of these units were on COSUNA. Few are exclusive to the Rome Trough.	+ 1700 to original column. + 1828 in the Rome Trough	USGS Cross Section E-E' (Ryder et al., 2008) and Plate 15A, Rome Trough Consortium Final Report (Harris et al., 2002)
KY18	None added. See Equation 1.	+ 1449	COSUNA column contains thickness ranges for each unit in the Rome Trough.

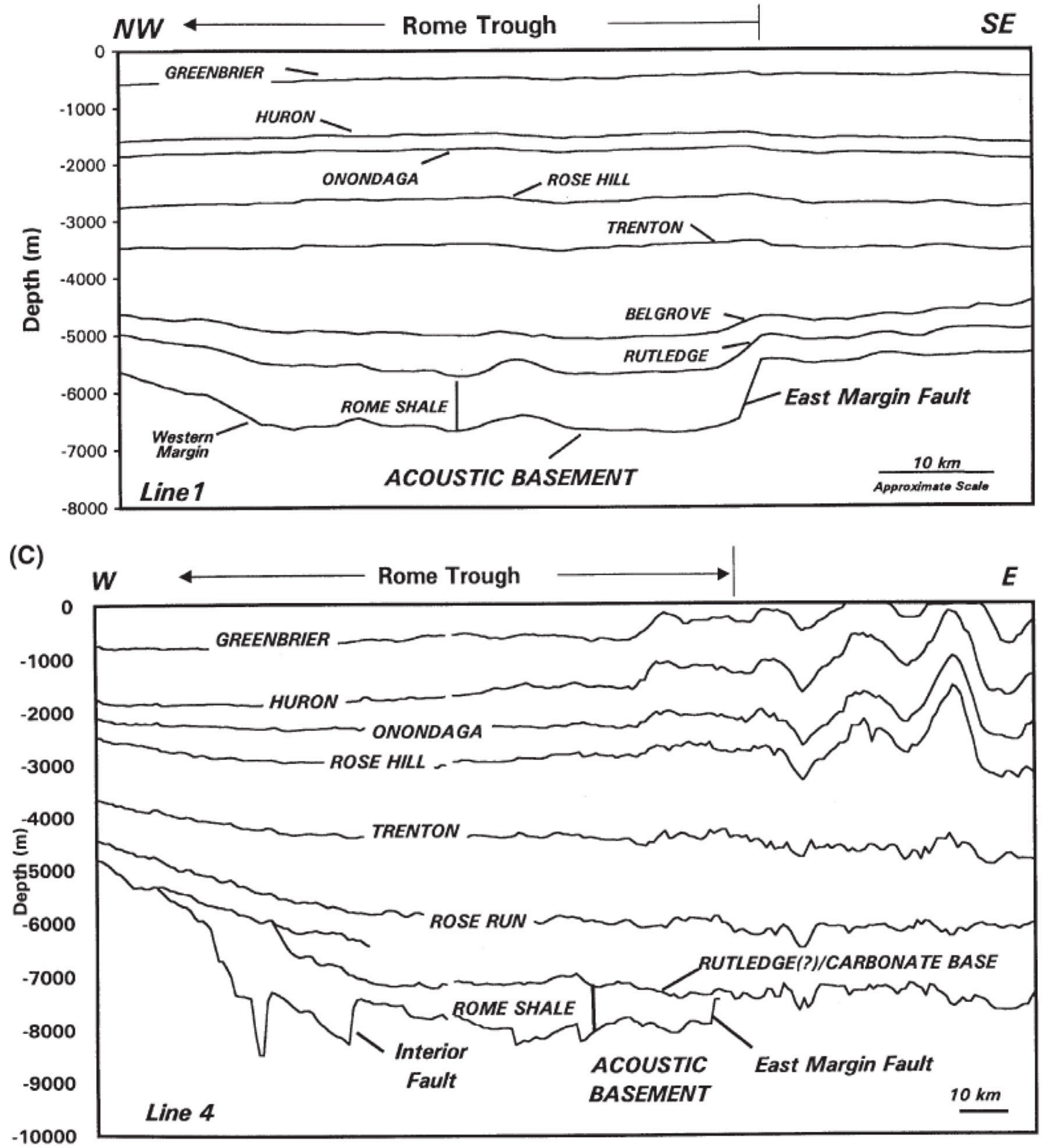


Figure 3: Depth sections of the Rome Trough in southwestern West Virginia (top) and northernmost West Virginia (bottom) that were constructed by Wilson (2000) based on seismic reflection data. Named units refer to ones that are readily recognized on seismic profiles; numerous intervening layers exist but are not labeled. Units deeper than roughly 4000 m are thicker within the Rome Trough than outside of it. The east side of the Rome Trough displays a change in thickness over a very short distance, from thin outside of the trough to thick within the trough, due to crossing the existence of a single fault zone. In contrast, the western margin displays changes across a gradual ramp (top) and a complex set of faults (bottom).

Thickness Determination

Sorting information from COSUNA columns into useful unit thicknesses is not a trivial task because the primary organization unit for COSUNA columns is geologic age, not stratigraphic unit. The simplest units to assign thicknesses to are those that are found uniformly throughout a given COSUNA section. However, it is common for a geological unit to occur in only a portion of the section, and for another age-equivalent unit (or units) to occur elsewhere in the section. Physically, this means that for the same time of deposition more than one unit formed within the COSUNA section; however there is no guarantee that the thickness of these units will be equal during that time period.

Multiple Units for the Same Time of Deposition

Unequal unit thickness within a section at a time of deposition results from variations in sediment supply, subsidence, or post-depositional erosion. The width of the unit on the COSUNA column chart (e.g., Fig. 2) represents the approximate percentage of area within the corresponding COSUNA section occupied by that unit. In the case of equal or roughly equal thicknesses for each unit during a time of deposition, a weighted average of the unit thicknesses was taken according to the percentage of column width occupied by each unit. The weighted thickness of each unit is then calculated from Equation 2

$$\text{Weighted Thickness} = \sum_{i=1}^{n} \text{Thick}_\text{i} * \text{w}_\text{i}\,, \quad 0 < \text{w} \leq 1 \qquad [2]$$

where w_i are the weights that are determined from the percentage of the column width for unit *i*, and Thick_i is the thickness of unit *i*. The weights in this equation must sum to the total extent of the unit(s) within the COSUNA section. For instance, for a single time period, if Gp. 1 was in 10% of the column, Gp. 2 was in 20% of the column, and Gp. 3 was in 50% of the column, the sum of the weights would be 0.8, indicating that for this time period, units were only present in 80% of the COSUNA section. If the lithology associated with these units was different, a note would be made regarding the percentage of each rock type for this time period.

In the case of unequal unit thicknesses or complexities in the arrangement of units for a time period of deposition (Fig. 4), the best effort was made to aggregate a sequence of formations/units into cohorts of roughly equal thickness. Finding cohorts of equal thickness solves the problem of having thicknesses specified for a portion of the section and not in others (e.g. Hampshire compared to Ohio and Chemung in Fig. 4). Equation 2 was applied to determine the weighted thickness when suitable cohorts were found. Then, the percentage of each rock type within the cohort was determined according to the thickness of the units within the column. For example, in Figure 4, since each rock unit occupies a different portion of the section and a different amount of time, 4 cohorts were established that each occupy approximately 25% of the section. The average thickness is determined from the average of the cohort thicknesses: 1) 817.5 m Ohio/Java in 25% of the column, 780 m Chemung/lower Huron/Java in 25% of the column, 767.5 m Hampshire/Chemung/Java in 25% of the column, and 700 m Hampshire/Chemung in 25% of the column. The average thickness is 766.25 m, and the average lithology is 59%

interbedded sandstone, siltstone, and shale, 35% shale/shale, mudstone, siltstone, and 6% sandstone.

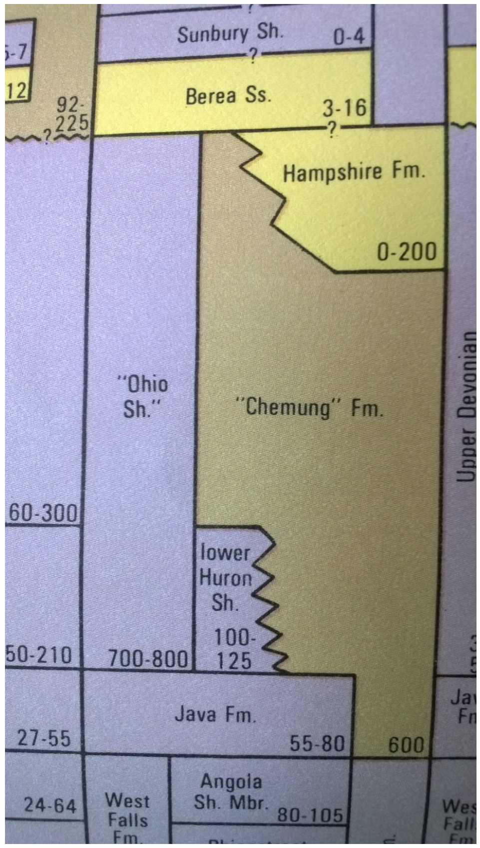


Figure 4: Example of cohorts from WV3 COSUNA column. Four cohorts were made from this section of the column: 1) Ohio/Java, 2) Chemung/lower Huron/Java, 3) Hampshire/Chemung/Java, and 4) Hampshire/Chemung. These are listed in a single cell in the spreadsheet.

Incomplete COSUNA Columns

Some of the COSUNA columns state that older rocks are unknown, or it is clear that the columns do not include sedimentary rocks down to the basement. These columns are listed in Table 2. Finding the thicknesses of the units that comprise the oldest sediment in these columns would be helpful to improve the accuracy of the COSUNA column approach.

Table 2: COSUNA columns with unknown or missing deep sediment

Column	Missing Sediment Information
PA22	Column does not reach basement rocks, but does have some Lower Paleozoic units present (e.g. Beekmantown Fm.).
PA23	Column goes to the Beekmantown Fm., undifferentiated, but states that older rocks are unknown. Even so, the minimum and maximum COSUNA thicknesses coincide well with the WVGES (2006) sediment thickness map.
PA24	There's a split in the column, with one side having thousands of meters thicker sedimentary rocks than the other. It would be great to determine where geographically this split occurs so that two columns can be made for this section. The assumed COSUNA thickness is near the maximum sediment thickness by WVGES (2006).
WV3	Cambrian and older rocks are unknown in the column. Beekmantown Fm. is the oldest formation. It is possible that no information is missing because the maximum sediment thickness according to WVGES (2006) is contained within the COSUNA column thickness range.
MD12 and MD13	Juniata is the oldest formation. Older rocks are unknown. These columns have the most time missing of all the columns. In terms of thickness, as much as 3 km are missing based on the WVGES (2006) map.
VA4	Possible formations missing based on sediment thickness map that ranges from 4.5 km - 7 km thickness (WVGES, 2006)
VA24	Possible formations missing based on sediment thickness map that ranges from 4.5 km – 5.5 km thickness (WVGES, 2006)

COSUNA Column Scaling to Basement

The COSUNA column thickness is at best an average of the sediment thickness within a section; however, the actual sediment thickness within a section may vary greatly from the COSUNA derived thickness. Variations may occur due to missing units (Table 2), and due to variability in sediment thickness throughout the COSUNA section (Fig.1). To capture variations in the sediment thickness, the COSUNA unit thicknesses were scaled to the sediment thickness map developed by WVGES (2006) according to Equation 3. Scaling is performed such that all units are adjusted linearly according to the fractional thickness between the assumed sediment thickness (WVGES, 2006) and the COSUNA column sediment thickness. For example, when the "true" depth to basement is less than the assumed COSUNA column depth to basement, the scaled unit thickness is less than the unscaled unit thickness, and vice versa. One problem with this approach is that, lacking further information about the missing units, the COSUNA column is (incorrectly) assumed to contain only those units reported by AAPG (1985a; 1985b). Another problem is that the scaled unit thickness can be less than the COSUNA-stated minimum possible unit thickness or greater than the COSUNA-stated maximum possible unit thickness. Correcting this problem would require a preferential scaling of units, such that some units would be adjusted first, and the remaining units scaled iteratively to match the "true" depth to basement. To avoid this complication, Equation 3 is used as written, and all units are equally scaled.

$$ScaledUnitThickness = UnscaledUnitThickness * \left(\frac{TrueDepthToBasement}{COSUNADepthToBasement}\right) \quad [3]$$

Thermal Conductivities

Selected Published Values

Carter et al. (1998) was the primary source used for thermal conductivity values because their samples were taken from the Anadarko Basin, which has a similar burial history as the Appalachian Basin, and thus would have comparable thermal conductivities due to an expected decrease in rock porosity as a result of prolonged burial. Carter et al. (1998) measured conductivity values on cores from the Anadarko Basin, and presented average values for the major lithologies in the basin. The average thermal conductivities from Carter et al. (1998) and the associated uncertainty about the average values are listed in Table 3. Thermal conductivity values for other lithologies not listed in Carter et al. (1998) are also provided in Table 3.

Table 3: Thermal conductivities, uncertainty, and sample size. The uncertainty is the standard deviation about the mean.

Lithology	Average Thermal Conductivity ($W\text{-}m^{-1}\text{-}°C^{-1}$)	Uncertainty, 1 standard deviation ($W\text{-}m^{-1}\text{-}°C^{-1}$)	Number of Samples	Reference and Notes
Sandstone	4.27	1.19	118	Carter et al. (1998)
Siltstone	2.34	0.768	31	Carter et al. (1998)
Shale / Mudstone	1.5	0.466	57	Carter et al. (1998)
Black Shale	0.9	0.06		From Cercone, Demming, and Pollock (1996)
Conglomerate	4.13	0.396	5	Used Granite Wash from Carter et al. (1998)
Chert	4.12	0.41		Average of Chert and Flint from Horai (1971)
Chemical	5.92	0.43		Hematite in Clinton Group. Conductivity is an average of temperature dependent values for the mineral Hematite from 0-200°C from Mølgaard and Smeltzer (1971)
Limestone	2.91	0.371	56	Carter et al. (1998)
Dolomite	4.5	0.412	5	Carter et al. (1998)
Anhydrite	6.68	0.319	3	Carter et al. (1998)
Salt / Evaporite	6	1		Value for Halite at ~25°C, Thermal conductivity of Halite is highly temperature dependent. From Birch & Clark (1940)
Gneiss	2.5	0.5		Clauser, 2011
Marble	3.0	0.5		Clauser, 2011
Quartzite	5.0	0.5		Clauser, 2011

Formation-Specific

Each formation in the basin was assigned a thermal conductivity based on the average of the thermal conductivities listed in Carter et al. (1998) (Table 3) for the lithologies present within the formation. The approximate ranking of lithologies (e.g. primary, secondary, etc.) within each formation was determined from the USGS as listed on the USGS Mineral Resources website, specific to each state (e.g for West Virginia: http://mrdata.usgs.gov/geology/state/fips-unit.php?state=WV). Final thermal conductivity values for the formations were determined using a Monte Carlo analysis with 10^6 iterations, for which the percentage corresponding to ranks of the lithologies was varied.

For each lithology in a given formation, a truncated normal distribution of conductivity values and a random percentage were assigned. The normal distribution was truncated at two standard deviations from the mean thermal conductivity for the lithology in order to prevent 1) egregiously large or small values of thermal conductivity for any lithology, and 2) negative values for lithologies with large uncertainty. The random percentage assigned to each lithology for each Monte Carlo replicate represents the percent of the formation composed from each lithology. The sum of the percentages is 100 for each replicate. The highest percentage is assigned to the major (primary) lithology as determined from the USGS, the next highest percentage was assigned to the secondary lithology, and so on. All lithologies had to be assigned a percentage of at least 5% in each Monte Carlo iteration. The distribution of conductivity values and the random weighting for each lithology were used to calculate the harmonic mean thermal conductivity for each replicate, which assumes that the different lithologies are horizontal layers. The reported value of thermal conductivity for each formation is the mean of the thermal conductivities for the 10^6 replicates. The reported uncertainty is the standard deviation of the 10^6 values of the formation thermal conductivity. These are available in three files: NY_Conductivity_final.xlsx, PA_Conductivity_final.xlsx, and WV_Conductivity_final.xlsx.

COSUNA Unit-Specific

The thermal conductivity for each unit in the COSUNA column was assigned based on the output of the Monte Carlo analysis if the formations composing the unit were available on the USGS website. If a formation was not listed on the USGS website, it was not subject to the Monte Carlo analysis and the COSUNA listed lithology was used instead, with the percentage of each rock type in the unit resulting from the COSUNA formation thicknesses (process described above in the Thickness Determination section). In this case, thermal conductivities from Carter et al. (1998) were used directly for each lithology. If only a group name was listed for the COSUNA unit, then the undifferentiated conductivity for the group was used, if available from the Monte Carlo analysis. If it was not available, then a simple average of the COSUNA lithologies was used.

There is room for improvement with this method of assigning thermal conductivities to units. For example, a literature review for published values of thermal conductivity for each formation on a state-by-state basis could be conducted for more accurate values. The data from the ongoing West Virginia University thermal conductivity study (B. Anderson, personal communication,

2015) can be used to inform values to use for the Appalachian Basin. Adjustments in the thermal conductivity can also be made according to the depth of the unit.

Related Files:

1. Name: DOE_NY-PA-WV-VA-OH-KY-MD_v4.xlsm

Fields:

Unit: The group, formation, member, or cohort names.

ColumnMin: The minimum thickness of the group, formation, member, or cohort based on the extent in the section (m)

Unit Min: The minimum thickness of the group, formation, member, or cohort as listed (m)

Unit Max: The maximum thickness of the group, formation, member, or cohort as listed (m)

Min(avg): The weighted average minimum thickness of the group, formation, member, or cohort from Equation 2 (m)

Max(avg): The weighted average maximum thickness of the group, formation, member, or cohort from Equation 2 (m)

Assumed: The assumed thickness of the unit. This is the average of the "Min(avg)" and "Max(avg)" (m)

Rock Type: The COSUNA listed rock type for the group, formation, or unit.

Shope Conductivity: The conductivity assigned in Shope (2012). ($W\text{-}m^{-1}\text{-}°C^{-1}$) Only applies to NY and PA columns.

Beardsmore and Cull Conductivity: The conductivity assigned by using the Beardsmore and Cull conductivities ($W\text{-}m^{-1}\text{-}°C^{-1}$)

USGS Lithology: The lithology of the unit as listed on the USGS Mineral Resources website, specific to each state (USGS, 2014).

Example:

The assumed thickness accounts for the presence of multiple units during the same time period, units being in a portion of the section, and the minimum and maximum possible thickness of the unit in the section. For example, if a unit was listed as 5-10 m thick, but was present in only 50% of the column, then the "Column Min" would be 0 m, the "Unit Min" would be 5 m, the "Unit Max" would be 10 m, the "Min(avg)" would be 2.5 m, and the "Max(avg)" would be 5 m, and the "assumed" thickness would be 3.75 m.

Color Scheme:

The rock types are color coded according to a key in the far right of each COSUNA column. The color red is reserved as meaning "questionable". For instance, columns that do not have Lower Paleozoic rocks (Table 2) are highlighted in red at the bottom of the column.

Rock Types	Color
Sandstone	Yellow
Shale, Mudstone, Siltstone	Light Gray
Interbedded Sandstone, Siltstone, Shale	Light Brown
Carbonate	Light Blue
Conglomerate	Orange
Evaporite	Pink
Metamorphic	Dark Brown
Volcanic	Light Green

2. Name: CarterConductivities.xls

   Fields: See Table 3.

3. Name: AllCosunaSections.shp

   Attribute Metadata:

   COSUNA_ID: A unique 6-digit ID code has been assigned to each COSUNA section within the shapefile. The first two digits are the column number, the second two digits (01 or 02) indicate whether the COSUNA column may be found in the Northern Appalachian Region (AAPG, 1985a) (01) or in the Southern Appalachian Region (AAPG, 1985b) (02), and the final two digits (00, 01, or 02) indicate whether the column is for the East column (01), West column (02), or not listed (00). Only Virginia COSUNA columns stated East and West because a geographic split in the geology occurred as a result of major faults.

   Name: The COSUNA Section name.

4. Name: TBRSedimentThickness

   Description:

   This is a map of sediment thickness derived from contours of the Precambrian basement that were developed by the Trenton-Black River (TBR) Project (WVGES, 2006). The Precambrian contours were relative to sea level, so the elevation of the Appalachian Basin had to be added to arrive at a sediment thickness map. The resulting map was selected over the more recent map developed by Mooney (2011) because of the inclusion of the Rome Trough. A simple comparison of the TBR sediment thickness map to the actual sediment thickness in the favorite wells is provided in Figure A1. Based on these results, we are comfortable with the choice of the TBR sediment thickness map.

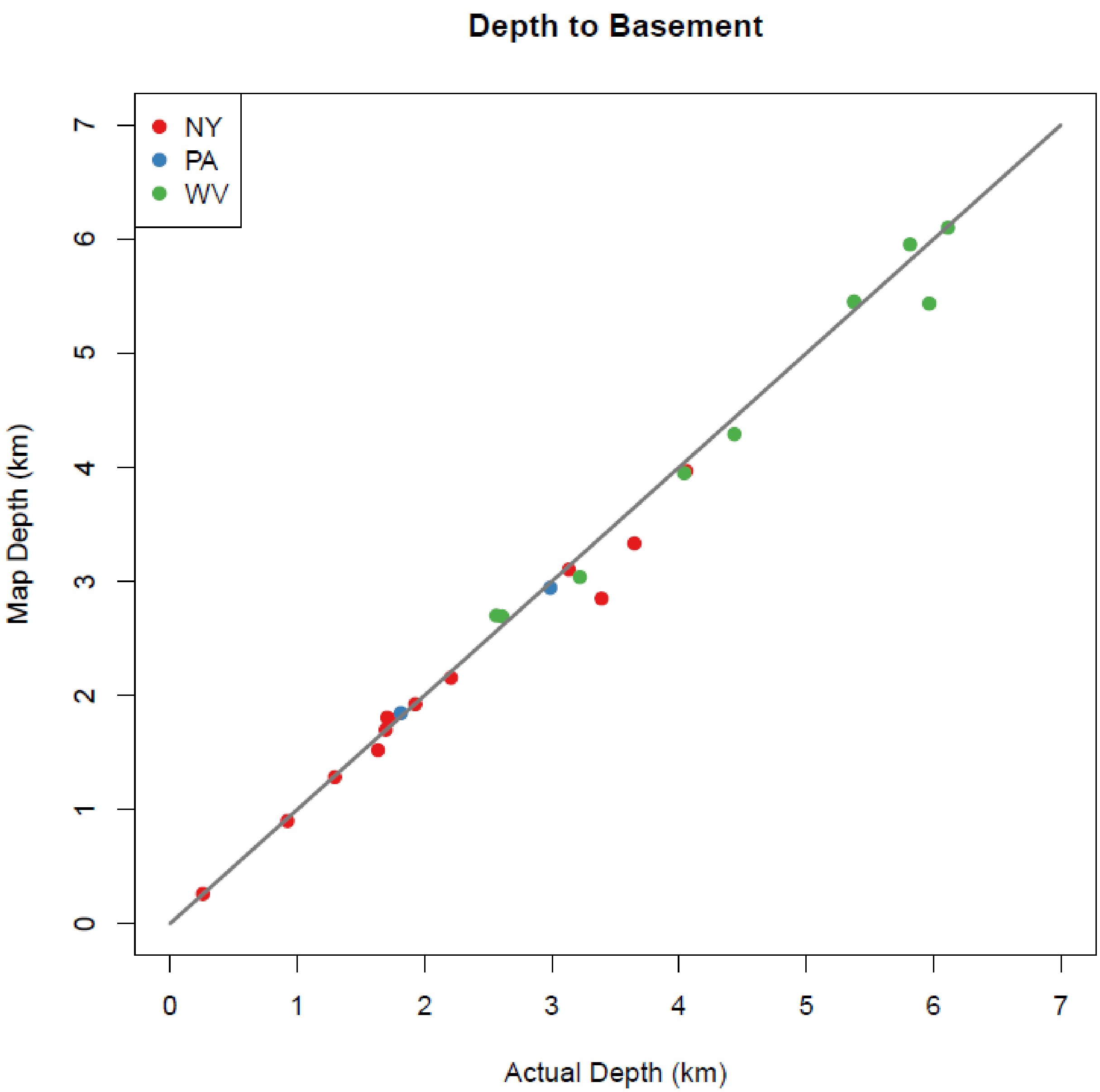


Figure A1. Comparison of TBR sediment thickness (Map Depth) to the actual sediment thickness from the subset of wells that reached basement rock. A 1:1 line is shown for reference. Depth to basement is the same as sediment thickness.

References:

AAPG. (1985a). Northern Appalachian Region correlation chart. D.G. Patchen, K.L. Avary, and R.B. Erwin, regional coordinators.

AAPG. (1985b). Southern Appalachian Region correlation chart. D.G. Patchen, K.L. Avary, and R.B. Erwin, regional coordinators.

Aguirre, G.A., 2014. Geothermal resource assessment: A case study of spatial variability and uncertainty analysis for the states of New York and Pennsylvania. MS Thesis. Cornell University, Ithaca, NY.

Beardsmore, G.R., and J.P. Cull. (2001). Crustal heat flow: A guide to measurement and modelling. Cambridge University Press.

Birch, A. F., & Clark, H.: The Thermal Conductivity of Rocks and its Dependence Upon Temperature and Composition, American Journal of Science, 238(8), 529-558, (1940).

Carter, L.S., Kelley, S.A., Blackwell, D.D., Naeser, N.D., 1998, Heat Flow and Thermal History of the Anadarko Basin, Oklahoma: AAPG Bulletin, v. 82, no. 2, p. 291-316.Cercone, K. R., D. Deming, & H.N. Pollack. (1996). Insulating effect of coals and black shales in the Appalachian Basin, Western Pennsylvania. Organic Geochemistry, 24(2), 243-249. http://ac.els-cdn.com/0146638096000216/1-s2.0-0146638096000216-main.pdf?_tid=5d37a0e2-ea03-11e4-b2e4-00000aacb35d&acdnat=1429826269_52360d9754a8a01680ffc0885e5e06ab

Childs, O.E.. (1985). Correlation of stratigraphic units of North America – COSUNA. The American Association of Petroleum Geologists Bulletin, V. 69, No. 2. P. 173-180

Clauser, C. (2011). Thermal storage and transport properties of rocks, II: thermal conductivity and diffusivity. In Encyclopedia of Solid Earth Geophysics (pp. 1431-1448). Springer Netherlands.

Frone and Blackwell, 2010. Geothermal Map of the Northeastern United States and the West Virginia Thermal Anomaly, Geothermal Resources Council, 34, 339-344.

Harper, J.D., 2004, The Rome Trough in Pennsylvania. Speculation in the Absence of Non-Proprietary Seismic Data: AAPG Search and Discovery Article #90031, AAPG Eastern Section Meeting, Columbus, Ohio, October 3-5, 2004, downloaded from internet on 15 February 2015.

Harris, D.C., J.A. Drahovzal, J.B. Hickman, B.C. Nuttall, M.T. Baranoski, and K.L. Avery. (2002). Rome Trough Consortium Final Report and Data Distribution.

Horai, K. I. (1971). Thermal conductivity of rock-forming minerals. Journal of Geophysical Research, 76(5), 1278-1308. http://onlinelibrary.wiley.com/doi/10.1029/JB076i005p01278/epdf

Mølgaard, J. and W.W. Smeltzer. (1971). Thermal Conductivity of Magnetite and Hematite, Journal of Applied Physics, 42, 3644-3647. DOI:http://dx.doi.org/10.1063/1.1660785

Mooney, J. (2011). Sediment thickness of North America and neighboring regions. *In* Technical Report: Central and Eastern United States Seismic Source Characterization for Nuclear Facilities. Appendix A: Description of the CEUS SSC Project Database, Figure A-14, File: CEUS_sed_thickness_USGS_R0.tif. EPRI, Pala Alto, CA, U.S. DOE, and U.S. NRC: 2012.

Repetski, J.E., R.T. Ryder, D.J. Weary, A.G. Harris, and M.H. Trippi. (2008). Thermal Maturity Patterns (CAI and %Ro) in Upper Ordovician and Devonian Rocks of the Appalachian Basin: A Major Revision of USGS Map I–917–E Using New Subsurface Collections. USGS Scientific Investigations Map 3006. Reston, Virginia.

Ryder, R.T.. (1992). Stratigraphic framework of Cambrian and Ordovician rocks in the Central Appalachian Basin from Lake County, Ohio, to Juniata County, Pennsylvania. IMAP 2200.

Ryder, R.T., C.S. Swezey, R.D. Crangle Jr., and M.H. Trippi. (2008). Geologic Cross Section *E–E'* through the Appalachian Basin from the Findlay Arch, Wood County, Ohio, to the Valley and Ridge Province, Pendleton County, West Virginia. IMAP 2985.

Shope, E.N.. (2012). A detailed approach to low-grade geothermal resources in the Appalachian Basin of New York and Pennsylvania: Heterogeneities within the geologic model and their effect on geothermal resource assessment. MS Thesis. Cornell University.

Stutz, G.R., 2012. Development, analysis, and application of a well by well method for estimating surface heat flow for regional geothermal resource assessment: M.S. thesis, Ithaca, NY, USA, Cornell University, 161 p.

United States Geological Survey (USGS). (2014). Geologic units in West Virginia (state in United States). Mineral Resources On-Line Spatial Data. http://mrdata.usgs.gov/geology/state/fips-unit.php?state=WV

West Virginia Geological and Economic Survey (WVGES). (2006). Trenton Black River Project. Data [Precambrian structure contours] available online http://www.wvgs.wvnet.edu/www/tbr/resources.asp. Map viewer available online http://ims.wvgs.wvnet.edu/TBR_ver3/viewer.htm.

Wilson, T. H., 2000, Seismic evaluation of differential tectonic subsidence, compaction, and loading in an interior basin: AAPG Bulletin, v. 84, no. 3, p. 376-398