Chapter 2

Where to Develop Geothermal? Assessing Pennsylvania's Potential via Depth, Temperature, and Rock-Attribute Maps

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Pennsylvania has vast geothermal potential, especially for use in industrial processes and residential heating and cooling. There is also potential for geothermal electricity generation in key spots across the state. While reliable data exists for the north and west, further exploration is needed elsewhere. With the right investments, Pennsylvania can become a leader in geothermal energy.

INTRODUCTION

With its deep experience extracting coal, oil, and natural gas from the ground, Pennsylvania has the know-how and workforce necessary to tap into the next frontier in subsurface energy: geothermal. The Commonwealth can become a hub of geothermal innovation and supply chain development that could be exported to other states, regions, and countries, ensuring that the Commonwealth's position as an energy leader is strong for decades to come.

The ground in Pennsylvania stores thousands of times more energy in the form of subsurface heat than the people of the Commonwealth consume annually. The challenge is identifying where that geothermal heat can be economically extracted and utilized.

This chapter provides analyses and maps of Pennsylvania's subsurface geology and geothermal potential, starting with an overview and then delving into technical, specialized information. Consistent with past analyses of Pennsylvania's geothermal resources,[1] this study finds that actual and modeled subsurface temperatures point towards opportunities in (1) the direct use of geothermal for low-temperature industrial processes,[2] (2) the use of geothermal heat pumps and district heating for heating and cooling of buildings, and (3) geothermal electricity generation in some "hots pots" in the Commonwealth.

Theoretically, if Pennsylvania's energy industry employed its resources and workforce to drill for geothermal at the same rate it drilled for other sources (790 oil and gas wells in 2022), within a year, geothermal could produce enough energy for all of the Commonwealth's commercial heating and low-temperature (<120°C) industrial processes. At a sustained drilling rate and with emerging technology, Pennsylvania could, in as few as 10 years, drill enough geothermal wells to meet 100 percent of the Commonwealth's electricity and heating needs as well as eliminate emissions from more energy-intensive industrial processes (see calculations in Table 2.A.1 of the Appendix).

Using the same data as a recent IEA analysis, the Commonwealth has a potential 55.28 gigawatts of geothermal electricity that could be extractable for less than $300/MWh at depths of less than 18,000ft (5500m).[3] That's enough energy to meet Pennsylvania's current electricity demand 3.5 times over.

This chapter delineates the locations and depths required for geothermal wells to most easily deliver on this potential. To be sure, the maps and analyses in this chapter are meant to highlight areas with potential for geothermal resource utilization. Additional site-specific analyses, including economic, engineering, and fluid production rate analyses, are required to identify drill-ready prospects and potential uses. Additionally, in the future, technological advances will allow Pennsylvania to develop even more of its subsurface geothermal resources, including in locations and at depths that are neither possible nor cost-effective today.

Online Data Exploration with GeoMap

*Much of the data presented in this analysis is available online through **GeoMap**, an interactive, open-source, and free platform on which individual users can explore and manipulate a variety of geothermal maps and relevant data, including temperature, depth, sources of energy demand, power plants, and more.*

OVERVIEW OF PENNSYLVANIA'S SUBSURFACE

The U.S. Energy Information Administration estimates that in 2022, Pennsylvanians' primary energy consumption hit 3,737 trillion British thermal units (Btu).[4] Pennsylvania's upper 6.2 miles (10 km) of subsurface likely holds 18,000 times that much energy. [5]

The following section serves as a guide for those who are not geothermal experts, offering summary temperature-depth maps of Pennsylvania's geothermal heat resources and a brief review of subsurface rock characteristics. Subsequent sections of this chapter provide more technical, specialized analyses geared more towards experts.

Subsurface Temperature

Drilling is a significant contributor to the overall cost of developing a geothermal project and, thus, to its economic viability.[6] Whether based on directly measured or modeled data, understanding the depths required to reach a given subsurface temperature helps to illuminate subsurface geothermal potential and the different applications that may be feasible at a given site.

Temperature at 1 Kilometer

Figure 2.2 shows those portions of Pennsylvania that are 95°F or below at a depth of 3,281 feet underground (below 35°C at 1 km). Figure 2.3 maps locations that have temperatures above 95°F at 3,281 feet deep. As explained later in this section, the areas in Figure 2.2 are likely limited to using geothermal for climate control of residential and commercial buildings. The hotter locations in Figure 2.3 start to lend themselves to an increasingly broad range of direct geothermal uses, such as greenhouse heating and low-temperature industrial processes. At the 1 kilometer depth, Pennsylvania's subsurface temperatures appear to peak at 152°F (67°C) in McKeon County near the New York border.[7]

A Caveat About Data

Analysis of Pennsylvania's subsurface temperature is based on two very different types of data sources: **direct temperature measurements** and **geological models**. As shown in Figure 2.1, direct measurements are mostly available in the Commonwealth's north and west where significant oil and gas activity has created ample subsurface data. In the rest of the Commonwealth, analysis of subsurface temperatures relies on regional geological computer models to estimate temperatures. This chapter primarily focuses on the directly measurable areas in the north and west, which have verifiable observational data. Future exploration in the rest of the Commonwealth, including drilling exploration wells, would greatly benefit Pennsylvania and broaden geothermal opportunities.

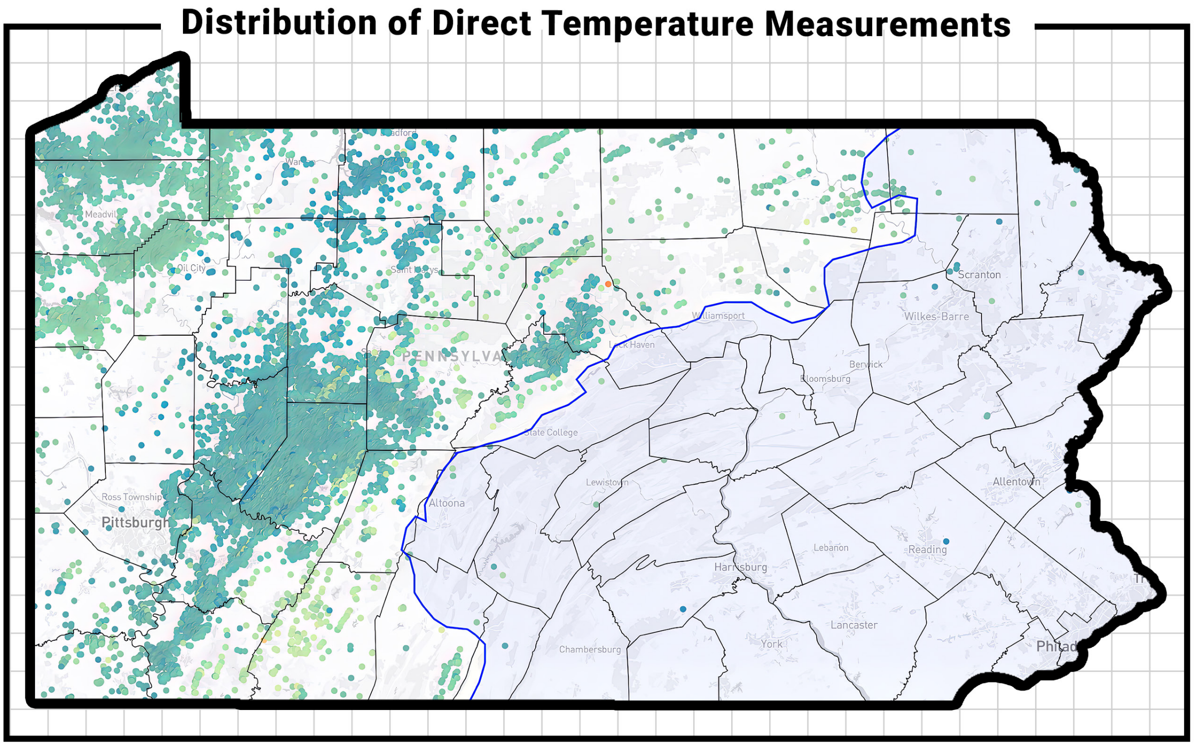

Distribution of Direct Temperature Measurements

Figure 2.1: Dots represent well locations where subsurface temperatures were directly measured. The area shaded in blue shows the parts of the Commonwealth that lack sufficient direct measurements and require the use of geological models to estimate temperature. Source: GeoMap

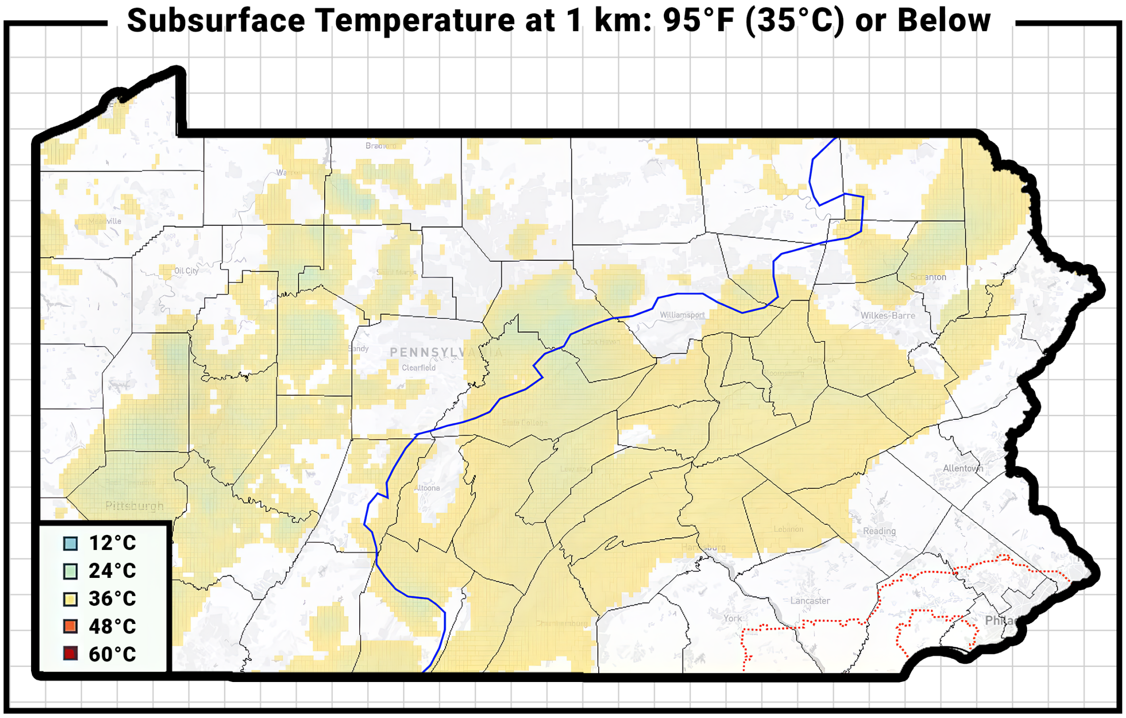


Figure 2.2: Based on available corrected temperature data. The legend provides reference colors on a sliding scale of gradients. The parts of Pennsylvania east of the blue line lack sufficient direct measurements and require the use of geological models to estimate temperature. The red dotted line around Philadelphia shows areas which geological modeling indicates are likely hotter at shallower depths than surrounding areas. Source: GeoMap

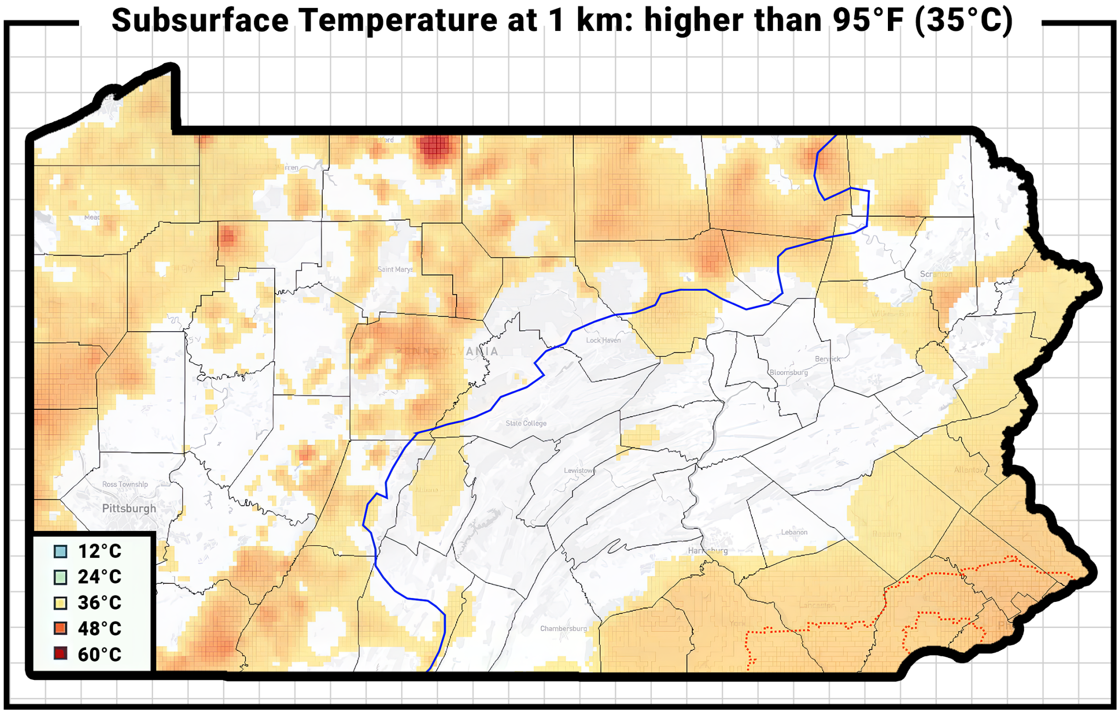


Figure 2.3: Based on available corrected temperature data. The legend provides reference colors on a sliding scale of gradients. Blue and red dotted lines have the same meaning as in Figure 2.2. Source: GeoMap

Depth to a Given Temperature

Subsurface temperatures generally increase the deeper you go. In other words, the farther a well is drilled, the hotter the rock, and the more options there are for geothermal applications. Figure 2.4 shows the depths needed to reach 212°F (100°C) in Pennsylvania. Electricity generation becomes possible at this temperature using technologies such as low-efficiency Organic Rankine Cycle (ORC) turbines. However, geothermal at this temperature is more thermally efficient (less energy is wasted) when used directly for industrial purposes (see *Chapter 3: Geothermal Direct-Use Opportunities*).

At a temperature of 300°F (150°C), you can efficiently generate electricity. As indicated in Figure 2.5, available temperature measurements show two locations in Pennsylvania that can reach 300°F at depths of less than 10,000 feet (3 km): the northeast corner of McKean County and the northwest corner of Forest County. This is shallower than some Marcellus shale gas wells. Many additional locations across the Commonwealth reach 300°F at depths of approximately 13,000 feet (3.9 km). These might be beyond the sedimentary rocks and into the older basement rock (see box on next page). These depths, too, are easily reached using existing oil and gas technology.

Note: While Figure 2.3 used red to show hotter, more favorable areas at 1km, Figures 2.4. and 2.5 now use red to display areas requiring greater depth to reach the specified temperatures. Green areas are shallower, more favorable locations (see legends).

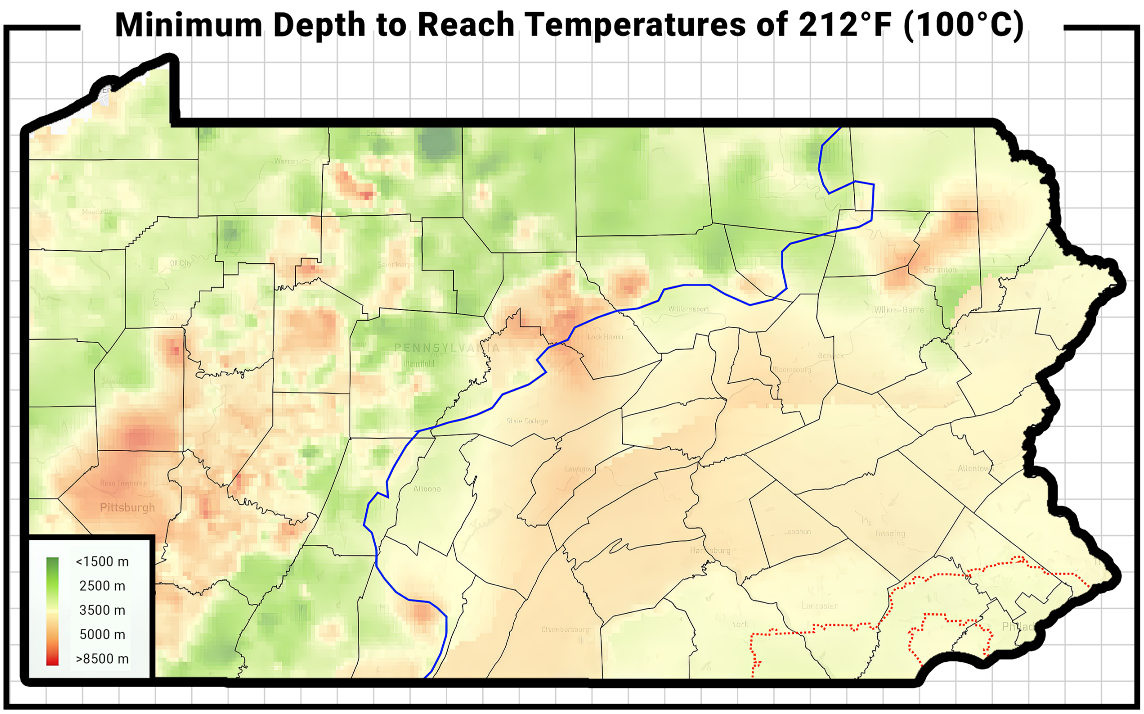


Figure 2.4: Based on available corrected temperature data. Blue and red dotted outlines have the same meaning as in Figure 2.2. Source: GeoMap

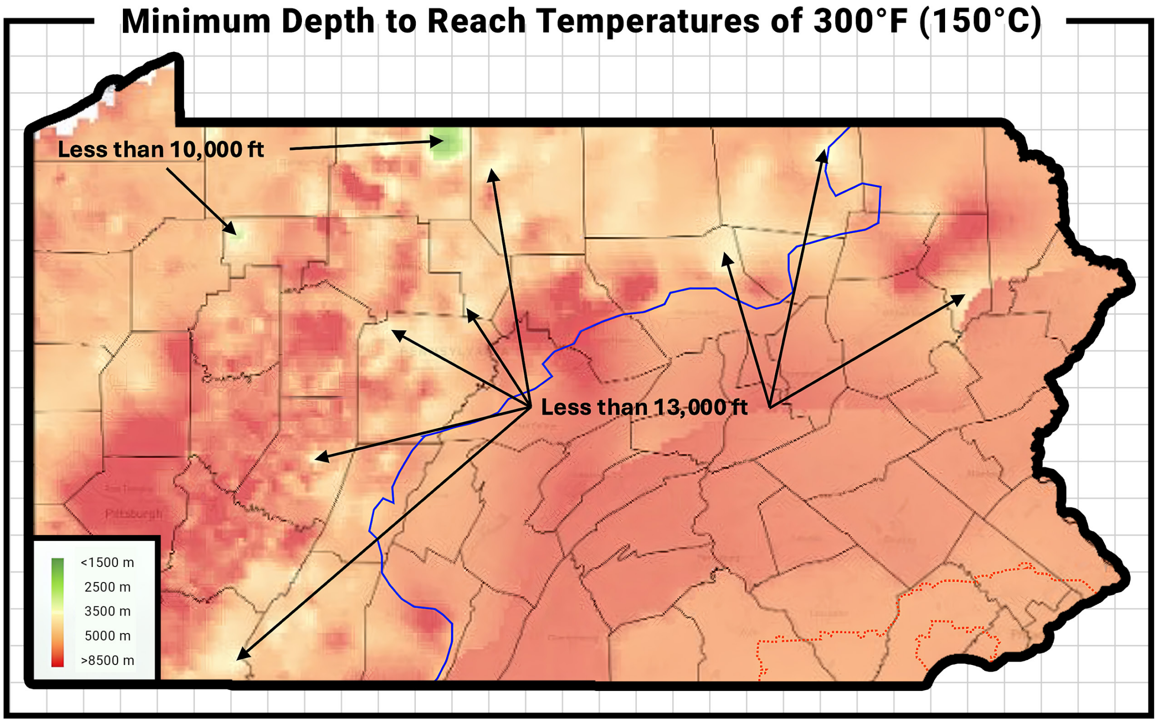


Figure 2.5: Based on available corrected temperature data. Arrows point to areas capable of reaching 300°F (150°C) at the indicated depths. Blue and red dotted lines have the same meaning as in Figure 2.2. Source: GeoMap

Sedimentary and Basement Rock

Sedimentary rocks form from the accumulation and compaction of mineral and organic particles, such as sand, silt, clay, and remains of plants and animals. These particles settle in layers over time, often in bodies of water like rivers, lakes, and oceans. Examples include sandstone, limestone, and shale.

In geology, the "basement" refers to the ancient, solid rock layer that lies beneath younger sedimentary rocks. Basement rock is typically made up of igneous and metamorphic rocks, which are much older and more stable than the sedimentary layers above. The basement rock forms the foundation of the Earth's crust and is deep underground.

Comparison of Historical Analysis: 2011 vs. 2024

In 2011, Southern Methodist University (SMU) in Texas published a project to characterize the geothermal potential of the entire continental United States. Figure 2.6 adopts a uniform color scale to allow for a comparison between the Pennsylvania portion of that historical analysis and the subsurface analysis developed for this report. The comparison shows how additional local data and more granular mapping can improve our understanding of the subsurface and reveal previously unidentified prospect areas. Differences in calculation methodologies and data availability mean the SMU maps are significantly smoothed, with the comparison maps showing much more localized variation, including higher highs and lower lows in close proximity.

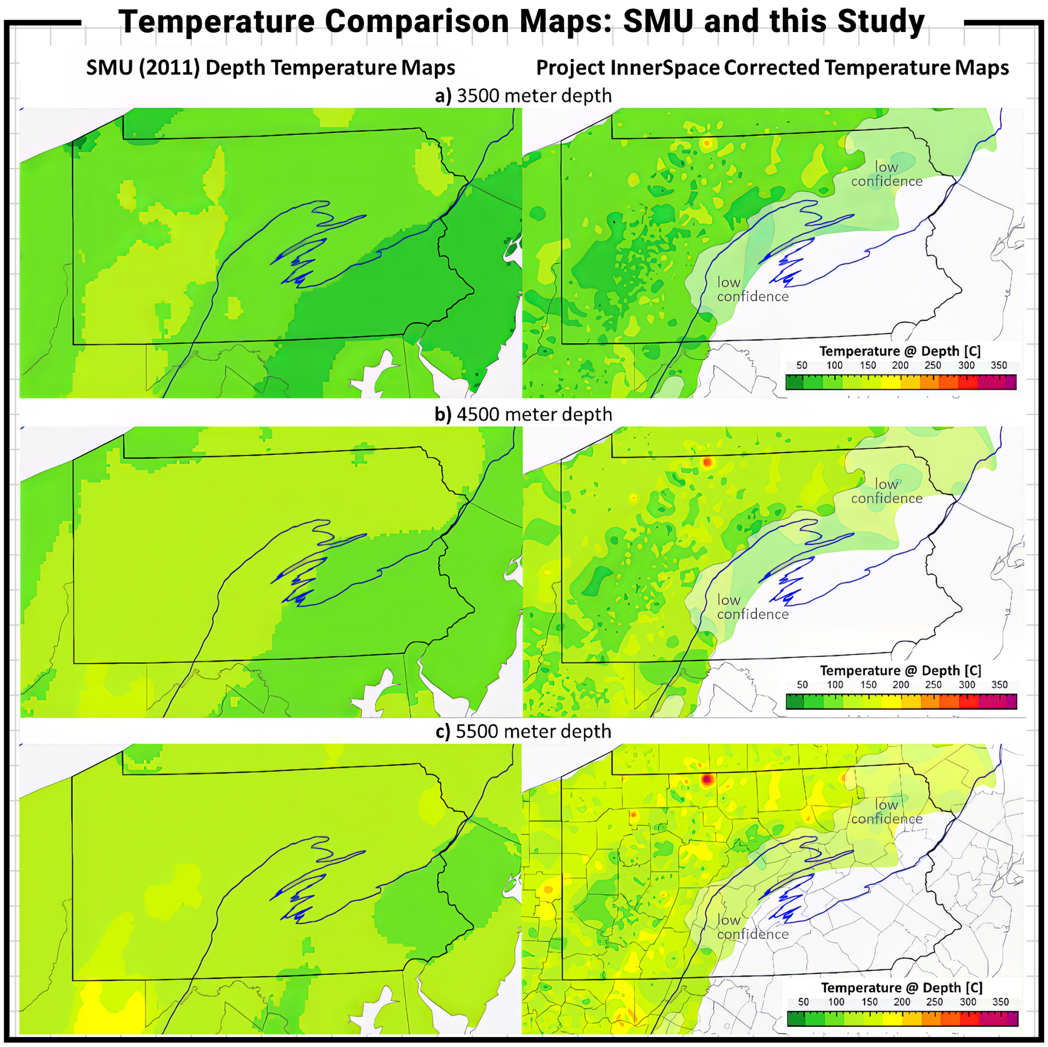


Figure 2.6: a) 3,500 meters depth, b) 4,500 meters depth, and c) 5,500 meters depth. The blue line indicates the eastern boundary of the Appalachian Basin. Low-confidence geologically modeled areas are covered by transparent white overlay. Source: Blackwell, D., Richards, M., Frone, Z., Ruzo, A., Dingwall, R., & Williams, M. (2011). Temperature-At-Depth Maps for the Conterminous US and Geothermal Resource Estimates. GRC Transactions, 35 (GRC1029452) and Project InnerSpace USA Temperature Dataset

Overview of Geothermal Applications Given Available Subsurface Temperatures

As suggested, given the temperatures and depths laid out in Figures 2.2 through 2.5, certain geothermal applications may be more feasible in some parts of Pennsylvania than others. Figure 2.7 uses a "weighted overlay analysis" to map the favorability of developing different geothermal technologies across the Commonwealth.

Dark green portions of the map are likely limited to using ground source heat pumps (GSHPs) for buildings, to provide heating and cooling. Lime green to yellow areas are still suitable for GSHPs but also offer opportunities to use geothermal directly for district heating and low-temperature industrial processes. Locations in orange into red may be suitable for electricity generation. This analysis attempts to identify the lowest-hanging fruit—the geothermal applications that can most easily be developed. Of course, as noted, drilling deeper will open up even more opportunities. But most importantly, Pennsylvania can use geothermal energy in some form everywhere across the Commonwealth.

Subsurface Fluid Flow

In addition to temperature, understanding the natural porosity or permeability of the subsurface helps determine what kind of engineering could help produce geothermal energy, and for what kind of application, in Pennsylvania. As explained in Chapter 1, all geothermal

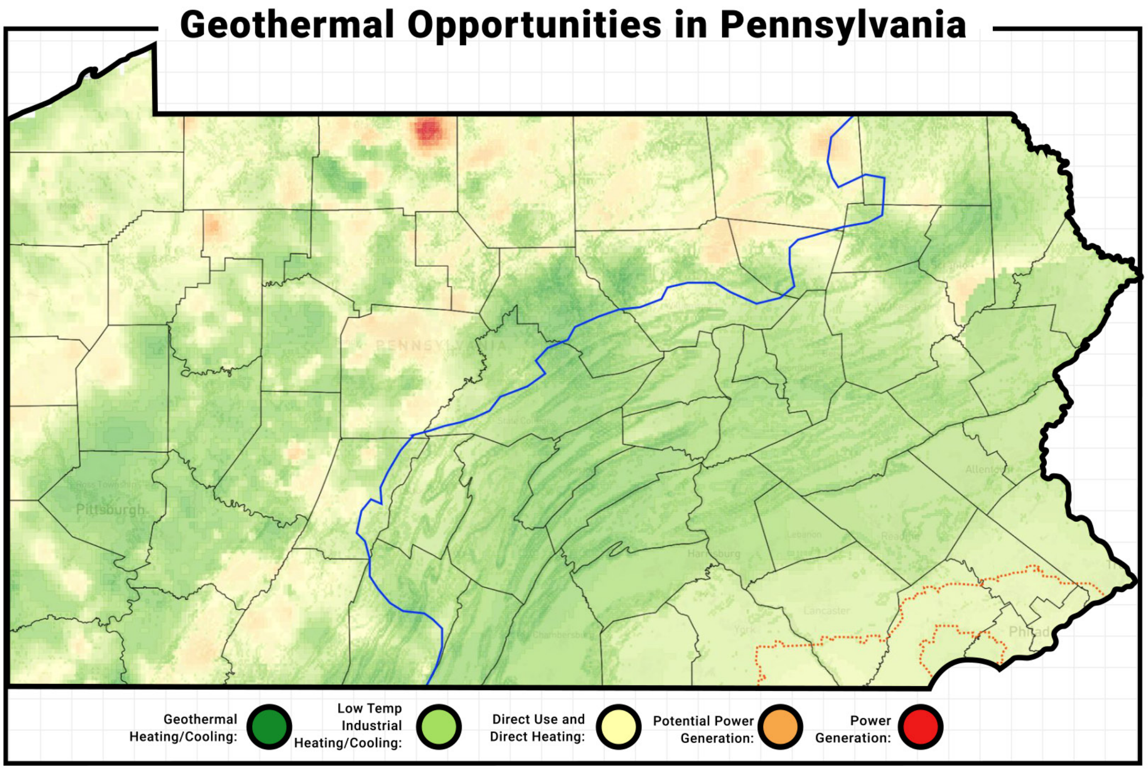


Figure 2.7: The map combines various factors: subsurface temperature, thermal gradient, seismic risk, proximity to convective features (flowing fluids), and the slope of the surface. Blue and red dotted lines have the same meaning as in Figure 2.2. Source: GeoMap

systems require heat in the form of hot rock, as well as some means for fluid to flow across the hot rock and extract thermal energy. Next-generation geothermal systems use engineering techniques to extract heat from rock formations that lack enough natural permeability or fluid content to generate electricity or provide direct heating. In engineered geothermal systems (EGS), reservoirs are created by artificially enhancing the permeability of the rock. In closed-loop advanced geothermal systems (AGS), sufficient wellbore surface area is created in a borehole network, at a sufficient depth (making the porosity or permeability of the surrounding rock irrelevant).

As explained in the expert analysis later in this chapter, Pennsylvania's subsurface is generally characterized by low porosity and permeability values. This means some form of engineered fluid flow, like hydraulic fracturing, or a closed-loop system will likely be needed to effectively use the Commonwealth's geothermal resources.

FURTHER ANALYSIS OF REGIONAL GEOLOGY AND GEOTHERMAL POTENTIAL

The remainder of this chapter provides a more in-depth and technical review of the data and methodologies used to develop the above temperature maps, and introduces additional favorability related analyses, such as geothermal gradients, formation structure, and rock property data. This information will be valuable when attempting to identify drill-ready geothermal development sites.

Geologic Overview

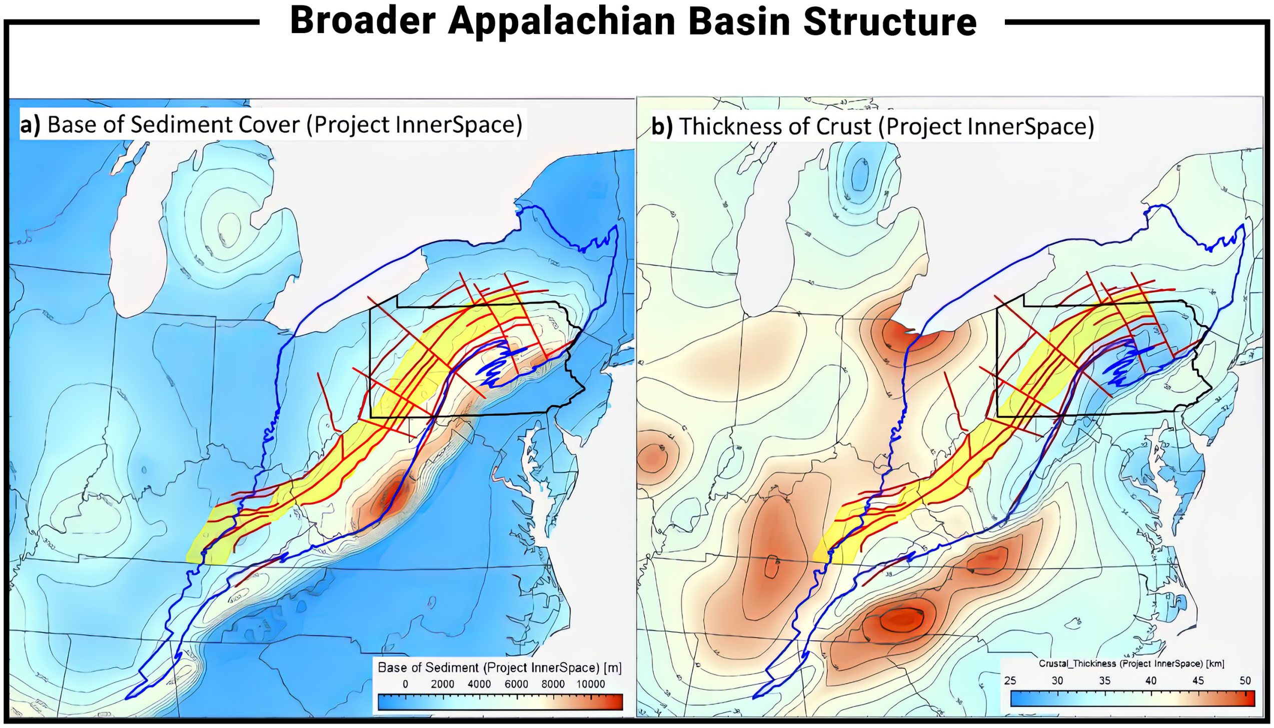
Key Structural Features of the Greater Appalachian Basin Region

> The Greater Appalachian Basin is a prominent geological province in the eastern United States, extending from New York to Alabama and west across the Appalachian Plateau. The basin's history includes significant mountain-forming tectonic events, when the Earth's crust folded, uplifted, and eroded over millions of years. The result is today referred to as the Appalachian Mountain Range.
>
> The Appalachian Basin contains a thick series of sedimentary rock layers.[8] (See Figure 2.A.1 in the Appendix of this chapter.) The estimated total thickness of all the combined sedimentary layers is a crucial factor in geothermal exploration. It serves as a key indicator for determining drill depth—information that significantly impacts project economics, the choice of extraction techniques, and subsurface temperatures (since sedimentary layers can insulate heat that might otherwise radiate from the inner layers of the Earth's crust and mantle). As shown in Figure 2.8a, the thickness of the Appalachian sediments varies significantly across the broader basin, from 0 to greater than 10 kilometers, with the thickest portion between Virginia and West Virginia along the western edge of the Appalachian Mountains. Across much of the East Coast, including in the greater Philadelphia area, there is no sedimentary cover, and the basement rock is exposed at the land surface (sea level is denoted by "0" in Figure 2.8a).

While thick sediment can insulate advective heatflow from the mantle (contributing to lower overall subsurface temperatures), thicker crust that is enriched with radioactive elements can generate radiogenic heat, contributing to higher heatflow at shallow depths (1-5km). As shown in Figure 2.8b, the Earth's crust below the Appalachian Basin is thin, relative to the surrounding areas, particularly to the east of the overall basin. This likely contributes to Pennsylvania's lower subsurface temperatures.

Structure and Composition of Pennsylvania's Geologic Layers

As if looking at a cliff face, Figure 2.9 shows a vertical cross-section of Pennsylvania's subsurface rock, subdividing the sedimentary fill into layers. This cross-section is heavily simplified compared to Figure 2.A.1, but its selection of depth horizons provides a representative depth distribution of Pennsylvania rock layers.[9] Notice that the available horizons or structural depth surfaces, extending diagonally from the northwest (A) to the southeast (A), are primarily confined to the western and northwestern Appalachian Basin regions of the Commonwealth. The same is evident in the overhead view of structural depth surfaces in Figure 2.10.


Broader Appalachian Basin Structure

a) Base of Sediment Cover (Project InnerSpace)

b) Thickness of Crust (Project InnerSpace)

Figure 2.8: (a) Sedimentary thickness and (b) Total crustal thickness maps. The Greater Appalachian Basin is outlined in blue. Red lines indicate major fault lineaments in the lower Paleozoic Utica section. The yellow shaded area represents the approximate extent of the Rome Trough, a major fault zone. Major faults and fault zones highlight areas of geological weakness, which can reach deep into the basement. Faults act as fluid conduits and can be associated with hydrothermal activity, since deep faults can provide pathways for hot fluid to flow to shallower depths. (Sea level is denoted by "0.") Source: GeoMap and Holdt, M. and White, N.

With a general understanding of the rock layers underlying Pennsylvania, it is now possible to begin to associate measured temperatures with their corresponding structural depth surface, a critical piece of any geothermal site-specific assessment.

Subsurface Temperatures

Measured Temperature Data

Oil and gas companies measure the temperature at the bottom of each well they drill. The geothermal evaluation in this chapter combines and incorporates numerous publicly available temperature datasets (see Table 2.A.1 in this chapter's Appendix), resulting in the locations, temperature measurements, and associated depths of tens of thousands of Pennsylvania wells. As previously highlighted, the greatest concentration of Pennsylvania temperature data is in the western and northwestern parts of the Commonwealth. *The eastern and southeastern parts of Pennsylvania lack "deep" well temperature data and aren't covered by this part of the analysis.*

That said, the temperatures that oil and gas companies measure do not always reflect the actual temperatures of the subsurface rock. Deep oil and gas wells are usually drilled with fluids that temporarily cool the surrounding rock, reducing the measured temperature of the rock in the immediate vicinity of the borehole. Mathematical correction methods are applied to estimate the

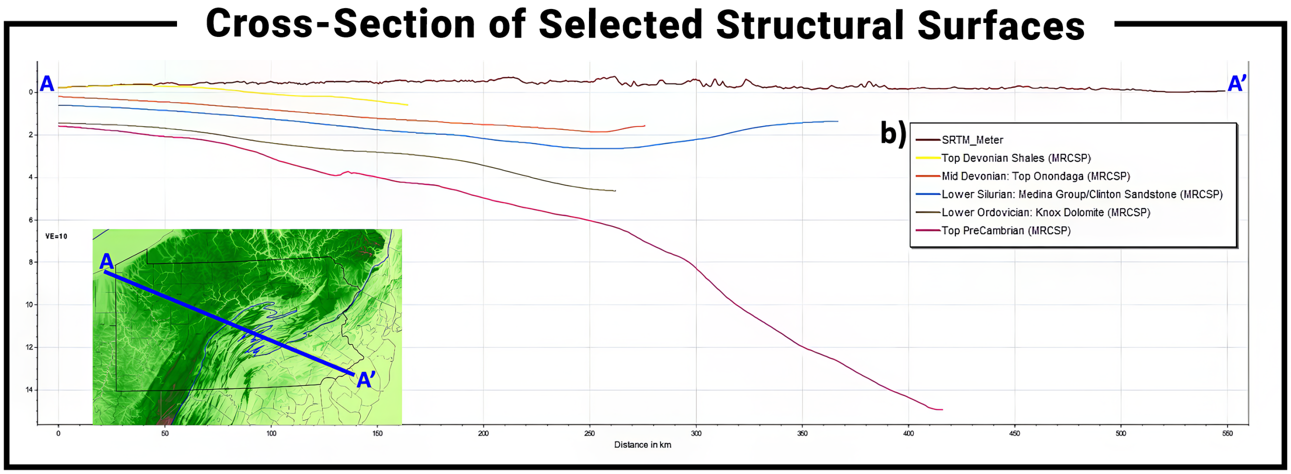


Figure 2.9: Subset of structural and stratigraphic depth surfaces providing a "representative" depth distribution of surfaces that do not intersect. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 8.)

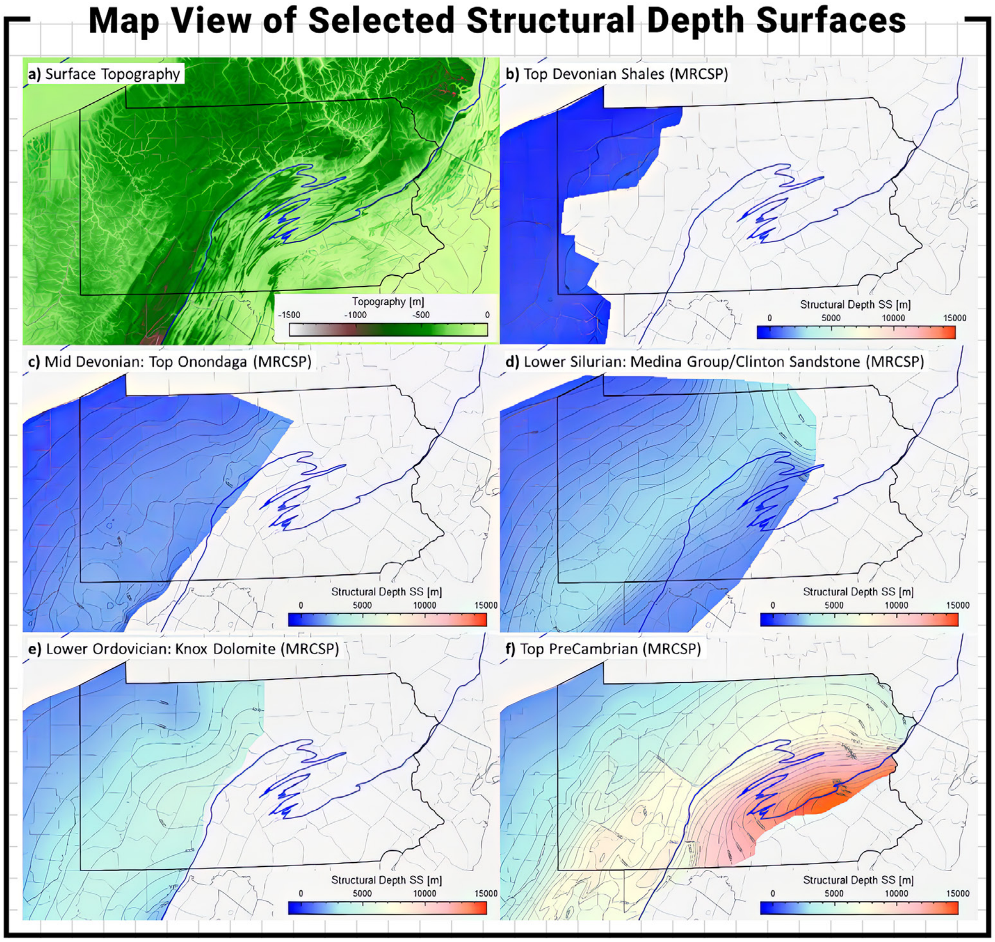


Figure 2.10: Limited data mean the extent of each map layer above may not reflect the actual area of each structural surface. The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp

original equilibrium temperature of the "undisturbed rock"—the temperature that could reasonably be accessed for a given geothermal application. Many of the public datasets used in this study (Table 2.A.1) included corrected temperature data. The available "corrected" temperatures for Pennsylvania wells are generally about 18 to 20 percent higher than "raw" temperature measurements.[10] (The difference in individual wells can be higher or lower.) Figure 2.11 maps the locations and plots the depths of corrected Pennsylvania temperature data used in this analysis.

Temperature-Depth Maps of Selected Geologic Layers

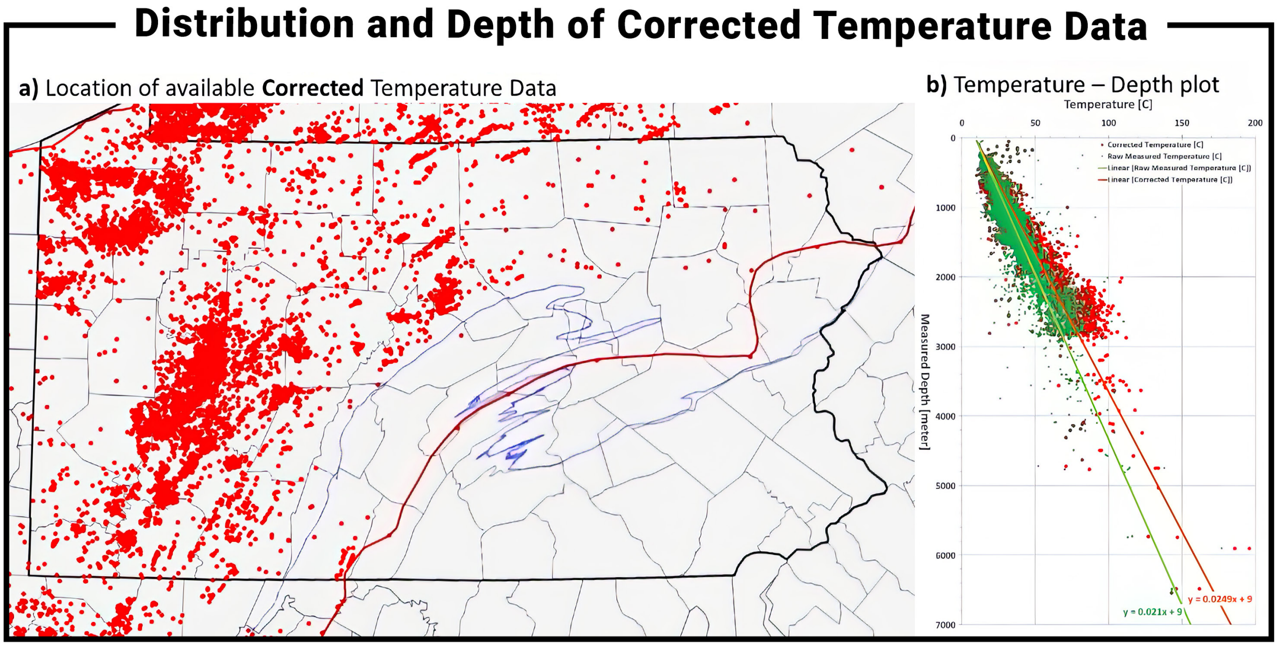
Figure 2.12 maps temperature data to the selected structural depth surfaces.[11] Further research is needed to gather additional stratigraphic and depth data to extend, update, and correct the existing suite of structural surfaces.[12]

Geothermal Gradient

The standard evaluation of the geothermal potential of an area includes the calculation of the geothermal gradient, a measure of the increase of the rock temperature with depth:

$$\text{Geothermal Gradient} = \frac{(\text{Subsurface Temperature} - \text{Surface Temperature})}{\text{Measurement Depth}}$$

Figure 2.13 shows regional geothermal gradient maps with and without temperature measurement locations. As indicated in turquoise, green, and yellow, the western part of Pennsylvania has two bands of slightly increased geothermal gradient separated by a zone of lower gradient in blue. Similarly, a slightly increased thermal gradient is found along Pennsylvania's border with New York.



Distribution and Depth of Corrected Temperature Data

a) Location of available **Corrected** Temperature Data

b) Temperature – Depth plot

Figure 2.11: (a) The distribution of corrected temperature data across Pennsylvania (and beyond). The red line follows the limits of well locations and map gridding; no data areas fall below the red line. The blue line indicates the eastern boundary of the Appalachian Basin. (b) Temperature-depth plot showing the difference between the raw measured temperature data (green dots) and the provided and available corrected data (red dots).

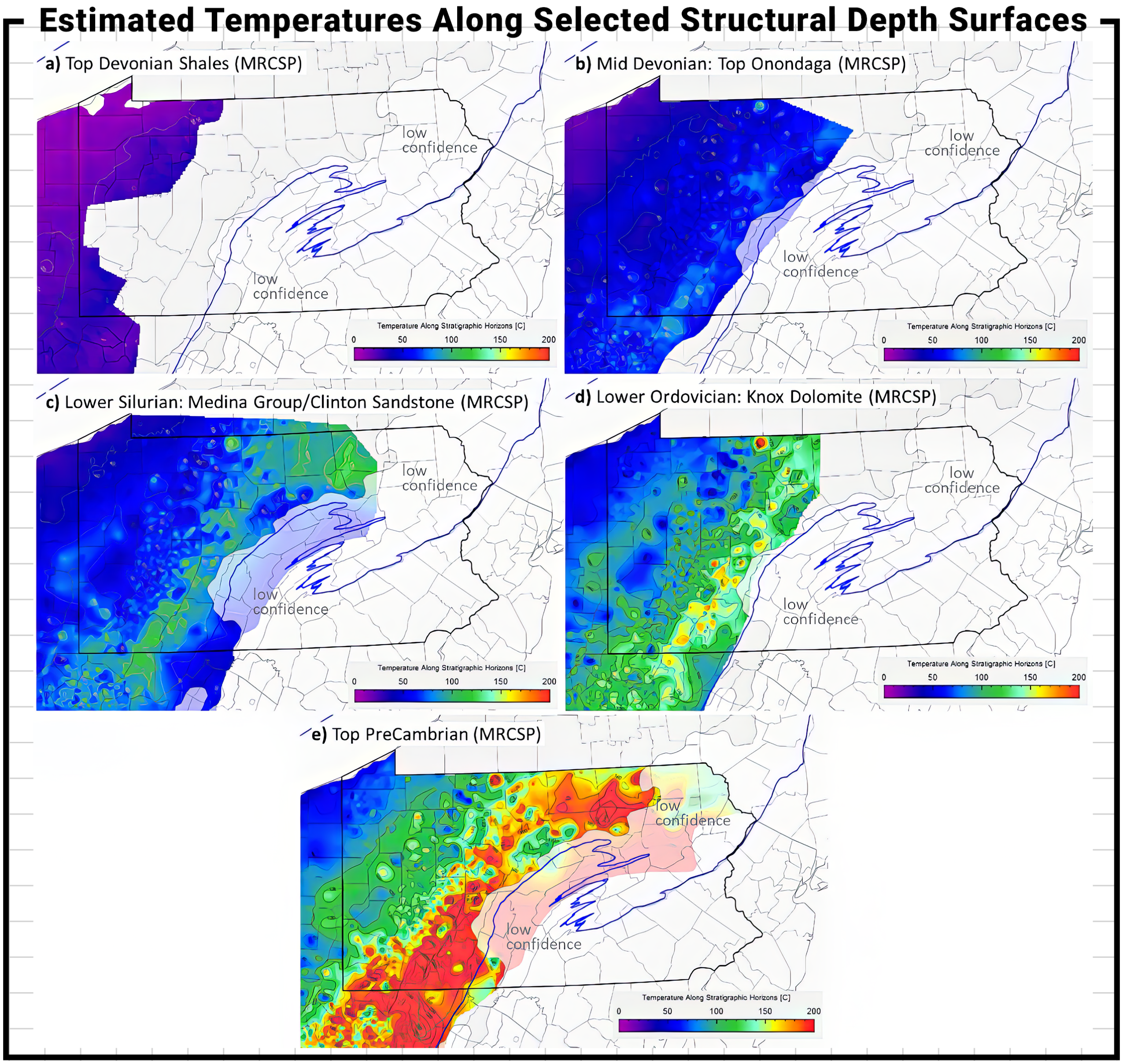


Figure 2.12: Based on available corrected temperature data. Low confidence areas are covered by transparent white overlay. The blue line indicates the eastern boundary of the Appalachian Basin. Source: Authors' analysis.

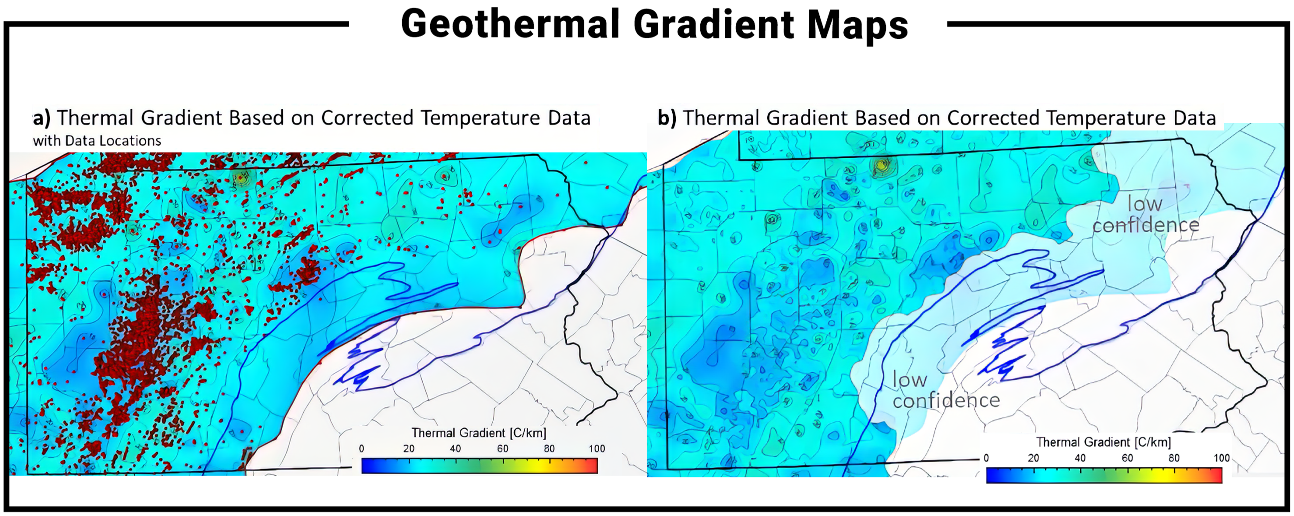


Figure 2.13: (a) with and (b) without data control points. The blue line represents the eastern limit of the Appalachian Basin. The red line represents the limit of the available corrected temperature data and mapping. Low confidence areas are covered by transparent white overlay. Source: Authors' analysis.

ANALYSIS OF AQUIFER PROPERTIES: LITHOLOGY, POROSITY, AND PERMEABILITY

We now turn from analysis of temperature, geothermal gradients, and formation structure to rock property data. The DOE report *Low-Temperature Geothermal Play Fairway Analysis - Appalachian Basin* (GPFA-AB) provides average bulk aquifer parameters for a number of Appalachian Basin sites in New York, Pennsylvania, and West Virginia, as shown in Figure 2.14.[13]

The most common aquifer intervals for Pennsylvania have been identified in Figure 2.15a. These aquifers consist of sandstone, limestone, and mudstone (Figure 2.15b). Porosity values for the key aquifer intervals are shown in Figure 2.15c and Figure 2.15d, ranging between roughly 3 percent and 13 percent, with a few higher values around 18 percent, as shown in figures 2.16a and 2.16c. The porosity value distribution appears to be bimodal, with maximums of around 7 percent and 11 percent. As shown in figures 2.16b and 2.16d, the aquifer permeabilities range from less than 0.001 millidarcies (mD) up to around 100 mD. Most of the permeabilities are around ±0.05 mD to ±1 mD.

Overall, the aquifer property data indicate low porosity and permeability values. These low values are related to the deep burial and strong compaction of the Appalachian Basin sediments, before their exhumation and erosion of some of the overburden. The low porosity and permeability values are unlikely to support the high fluid production rates necessary to economically implement some current conventional geothermal technologies. Aquifer stimulation such as hydraulic fracturing might be necessary for the required thermal fluid production rates, or the use of closed-loop systems.

Mapping the aquifer parameters on a formation-by-formation basis, as in figures 2.17, 2.18, and 2.19, can highlight the spatial distribution and parameter trends of potential geothermal aquifers, but based on the available data, no clear trends can be identified in the maps. Similarly, figures 2.20 and 2.21 do not show definitive depth trends in the porosity and permeability depth profiles.

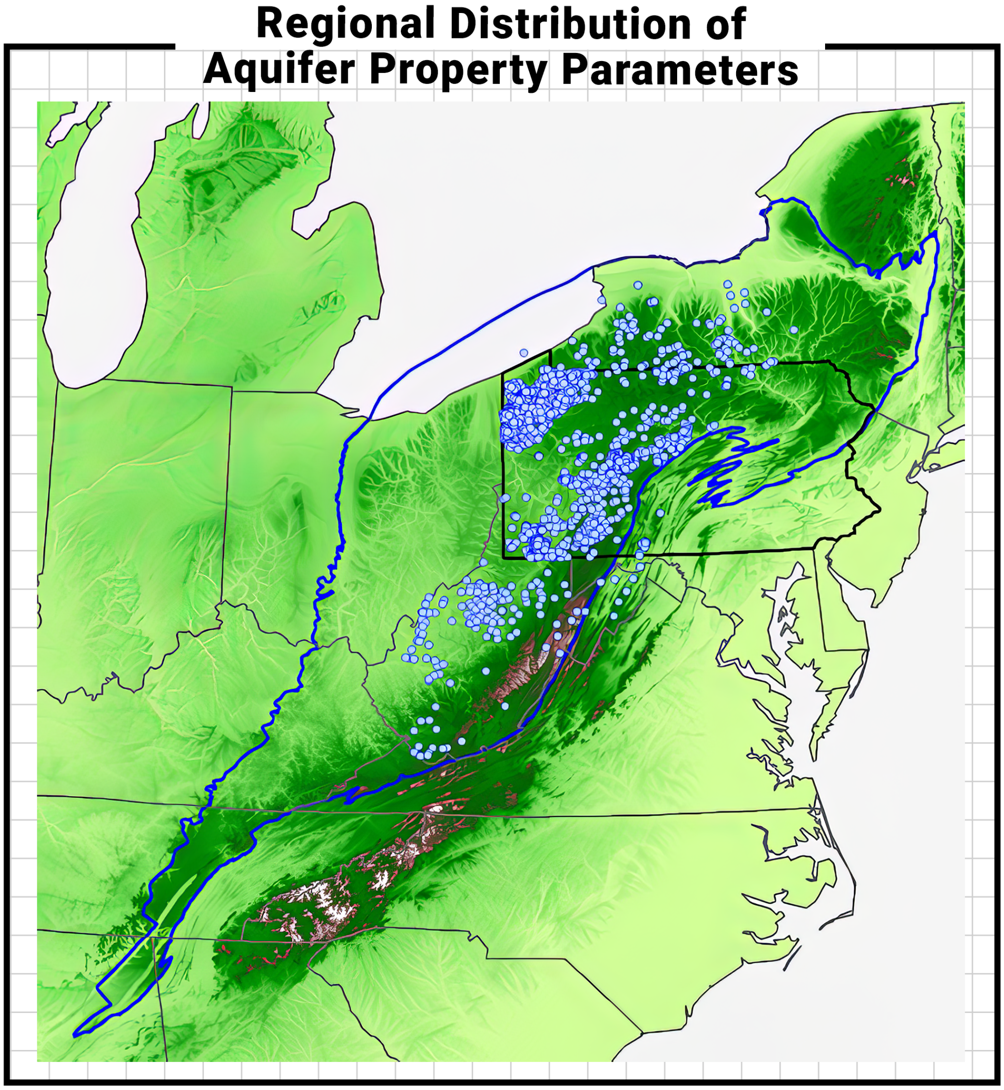


Figure 2.14: Map showing data points collected as part of the *Low-Temperature Geothermal Play Fairway Analysis - Appalachian Basin* study. Greater Appalachian Basin outlined in blue. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 12.)

Distribution of Aquifer Property Parameters by Type

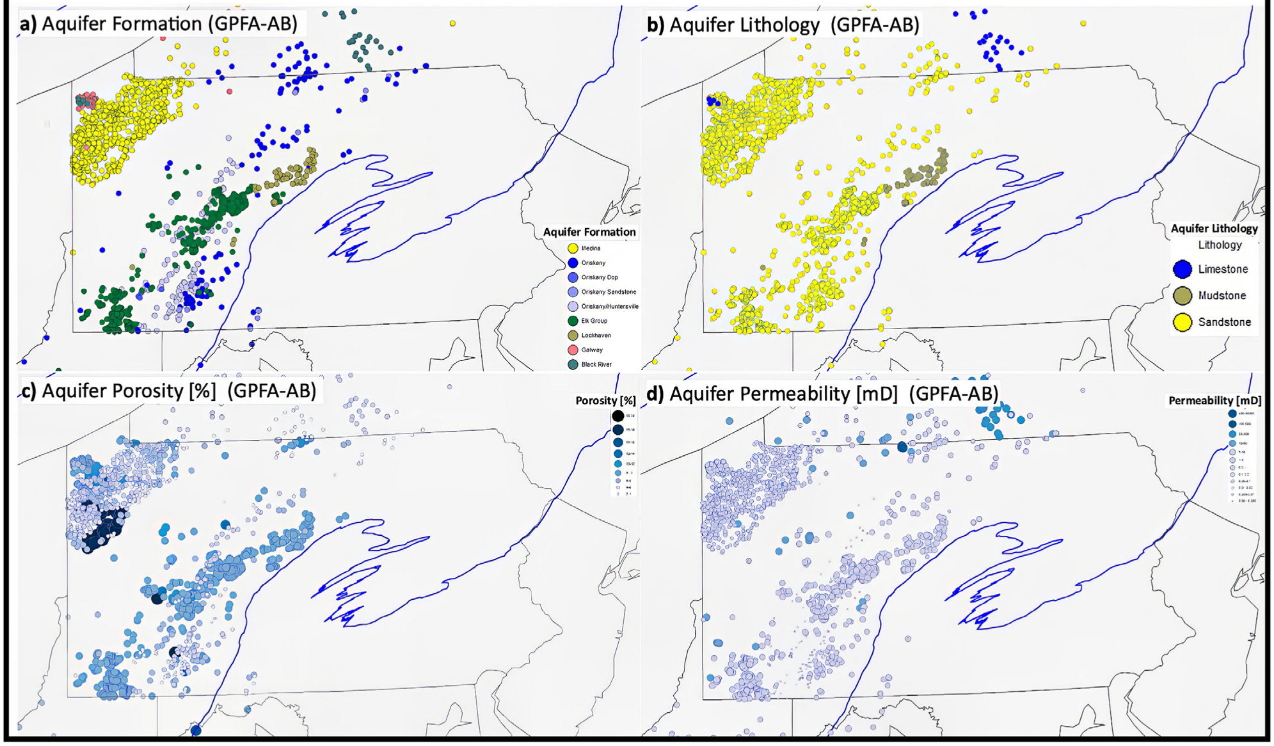
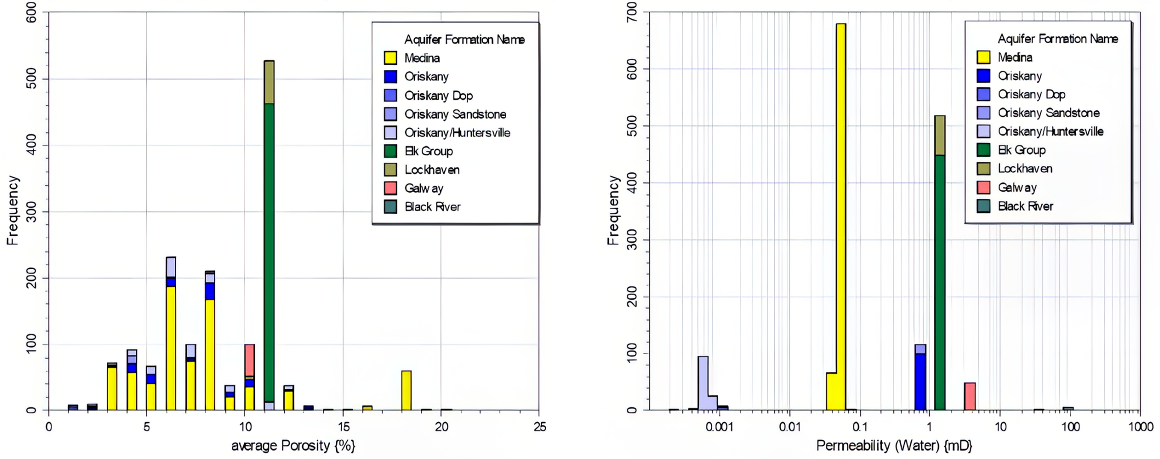


Figure 2.15: (a) Aquifer formation, (b) Aquifer lithology, (c) Aquifer porosity, (d) Aquifer permeability. The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

Histogram of Aquifer Parameters by Aquifer Formation and Lithology in Pennsylvania only

a) Aquifer Porosity Histogram: by Formation (GPFA-AB) **b)** Aquifer Permeability Histogram: by Formation (GPFA-AB)



c) Aquifer Porosity Histogram: by Lithology (GPFA-AB) **d)** Aquifer Permeability Histogram: by Lithology (GPFA-AB)

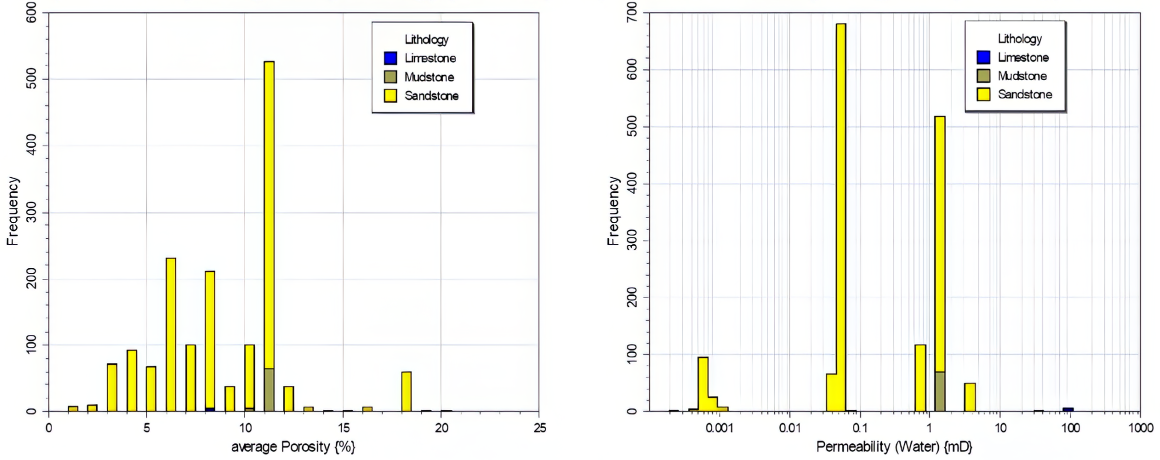


Figure 2.16: Pennsylvania only. (a) Porosity and (b) Permeability values. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

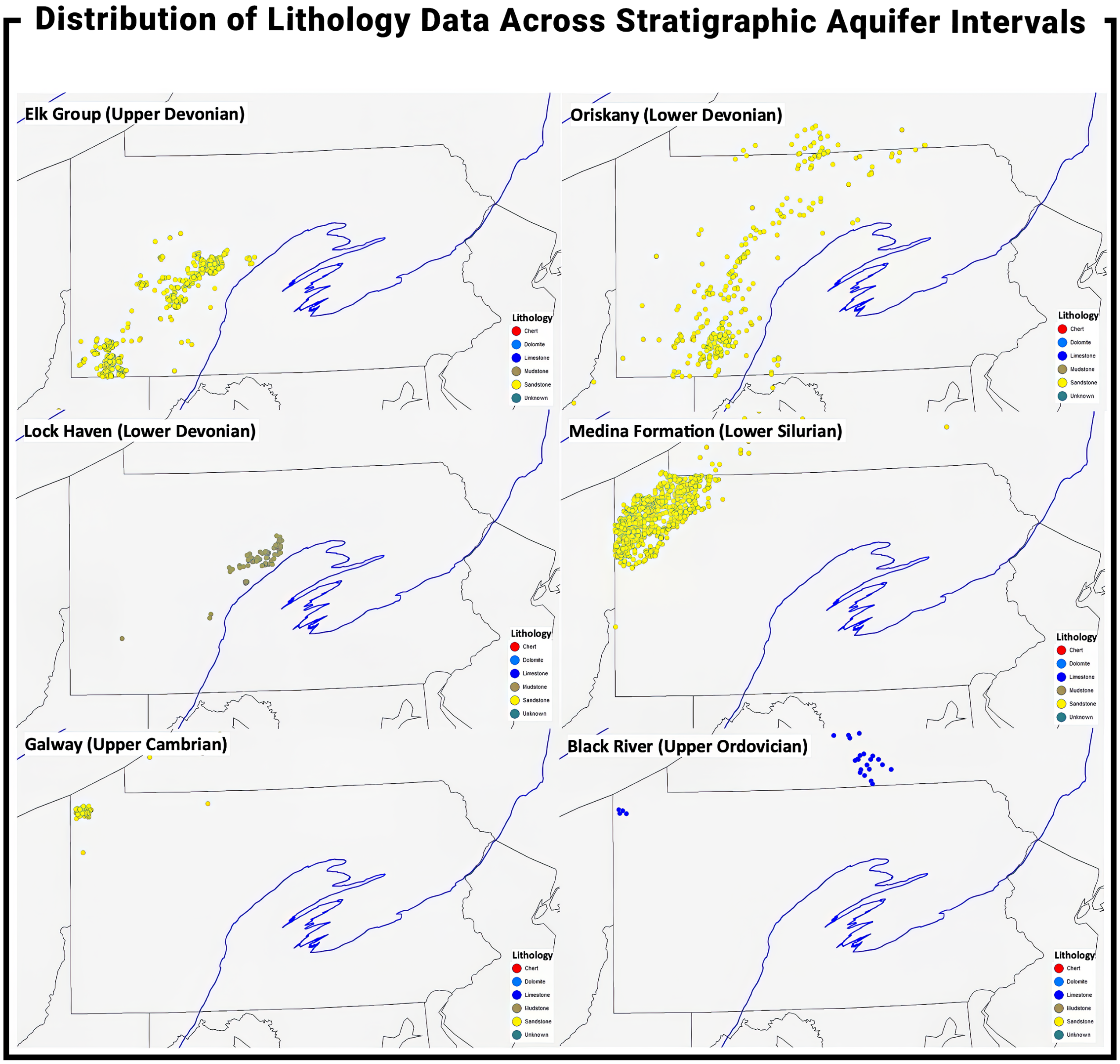
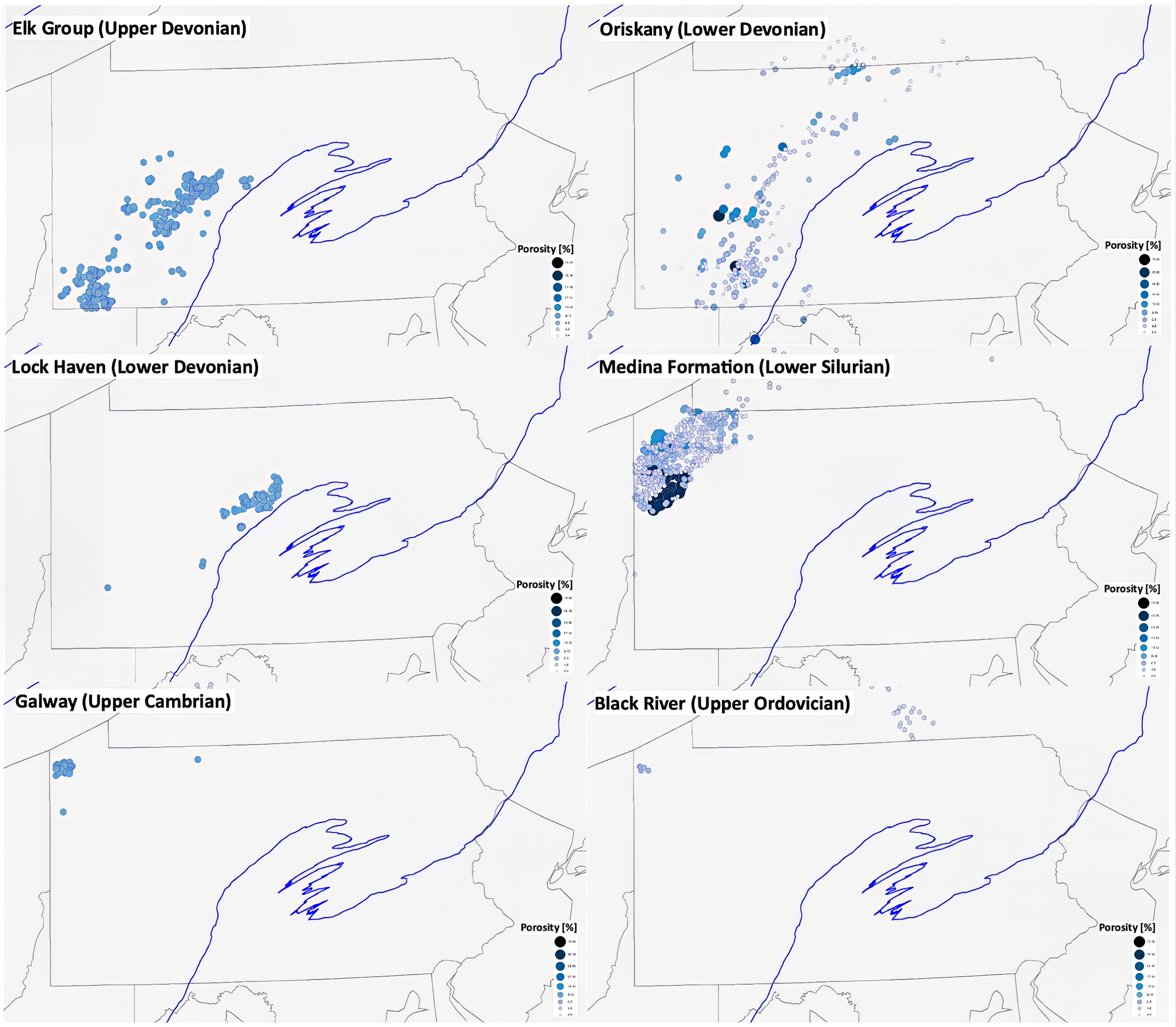


Figure 2.17: The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

Distribution of Porosity Data Across Stratigraphic Aquifer Intervals



Elk Group (Upper Devonian)

Oriskany (Lower Devonian)

Lock Haven (Lower Devonian)

Medina Formation (Lower Silurian)

Galway (Upper Cambrian)

Black River (Upper Ordovician)

Figure 2.18: The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

Distribution of Permeability Data Across Stratigraphic Aquifer Intervals

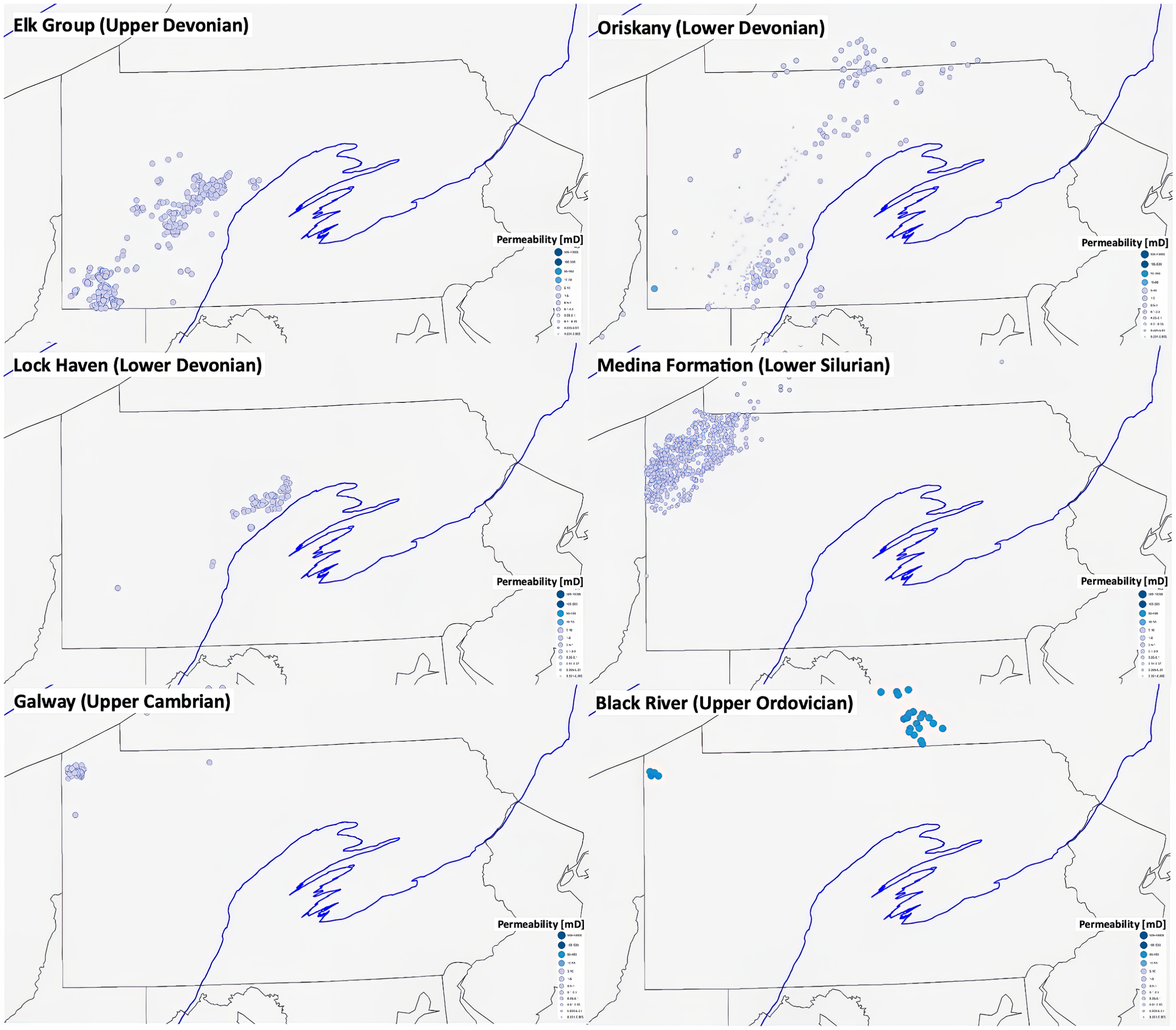


Figure 2.19: The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

Depth Profiles of Porosity and Permeability Colored by Formation Name (Pennsylvania only)

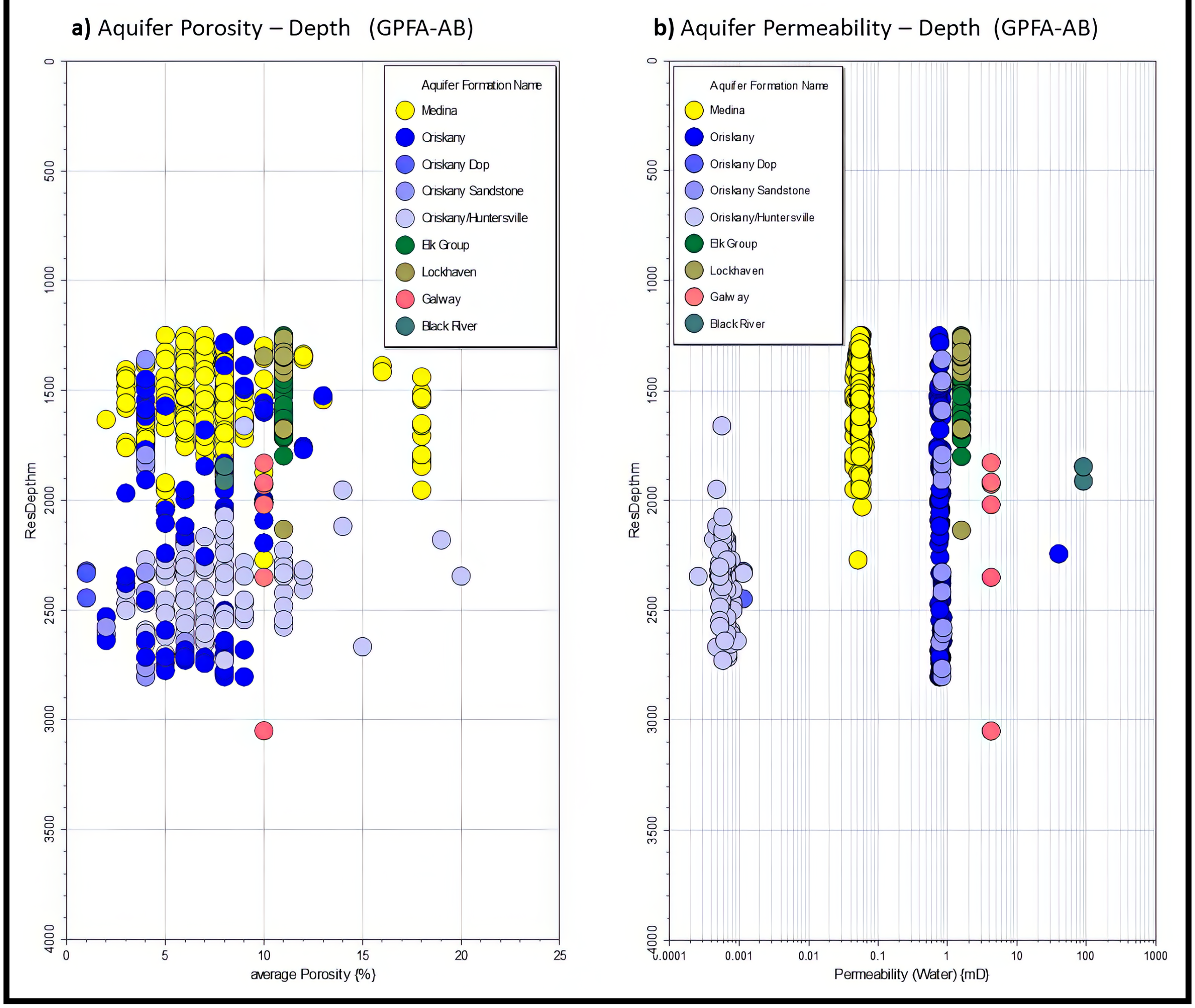
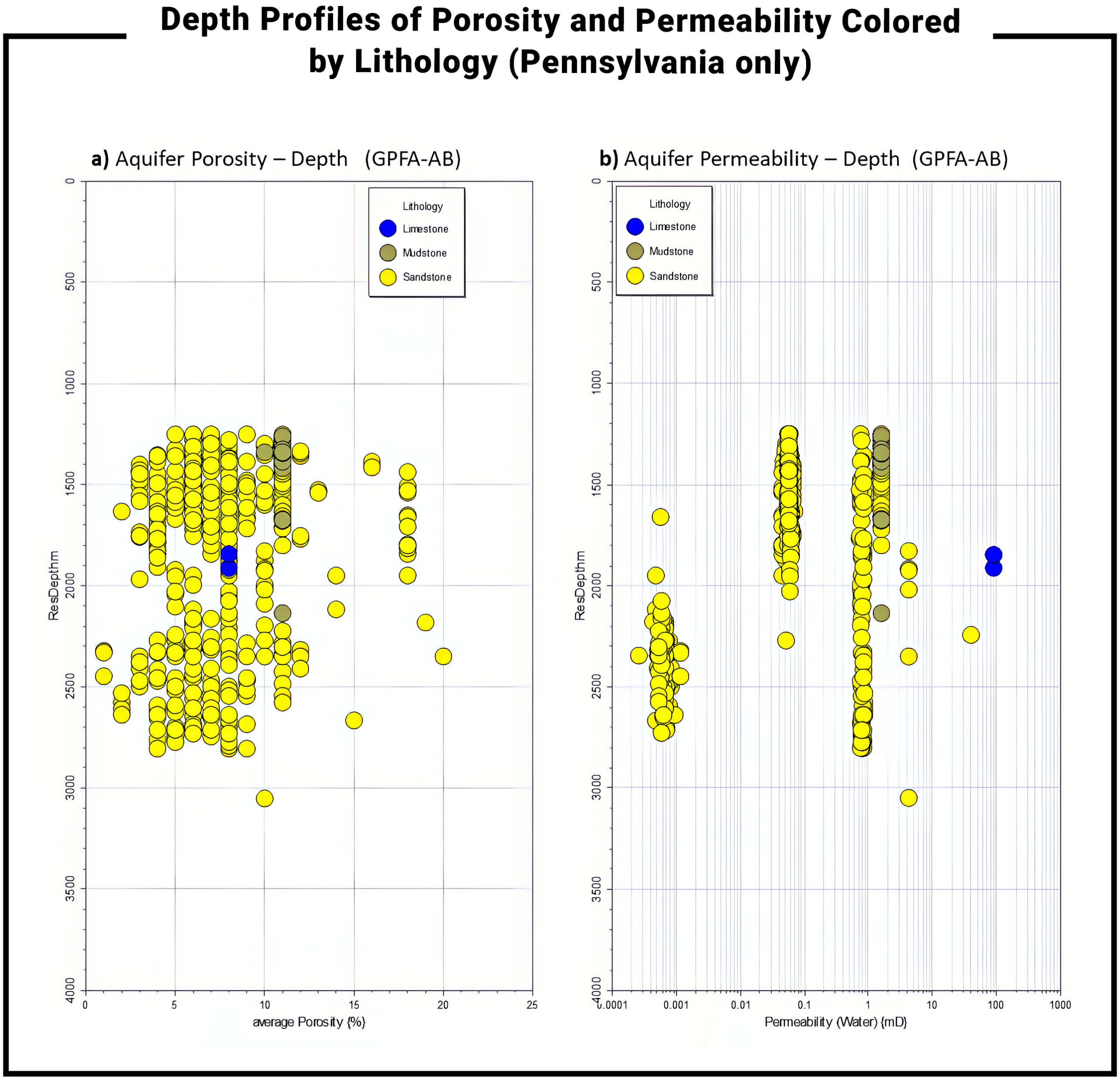


Figure 2.20: Pennsylvania only. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 12.)



Depth Profiles of Porosity and Permeability Colored by Lithology (Pennsylvania only)

a) Aquifer Porosity – Depth (GPFA-AB)

b) Aquifer Permeability – Depth (GPFA-AB)

Figure 2.21: Pennsylvania only. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 12.)

CHAPTER 2 APPENDIX

Information Referenced in Chapter

Calculating the Scale of Geothermal Drilling Required to Meet Pennsylvania Energy Demand

	Technology Year		2025	2030	
	Vertical Depth Constraint (feet)		**15,000**	**33,000**	
	Temperature Constraint		120 ºC	250 ºC	
Commercial Energy Demand	Met w/ 90 ºC Geothermal Heat	Annual Energy Consumption (GWh Thermal)	47,971		
		Output Per Well Pair (GWh Thermal)	55		
		Number of Wells to Meet Demand	**878**		
Industrial Thermal Energy Demand	Met w/ Geothermal Heat up to Specified Range	Annual Energy Consumption (GWh Thermal)	3,626	13,379	
		Output Per Well Pair (GWh Thermal)	57	49	
		Number of Wells to Meet Demand	**64**	**272**	
Geothermal Potential w/ 2025 Constraints	Sum of Wells		**942**		
	Years of Drilling		**1.19**		
Residential Energy Demand	Met w/ 80 ºC Geothermal Heat	Annual Energy Consumption (GWh Thermal)	64,161		
		Output Per Well Pair (GWh Thermal)	55		
		Number of Wells to Meet Demand	**1,174**		
Electricity Demand	Met w/ 250ºC Geothermal Heat	Annual Energy Consumption (GWh Electric)		394,267	
		Power Output Per Well Pair (GWh Electric)		75	
		Number of Wells to Meet Demand		**5,234**	
Geothermal Potential w/ Residential & 2030 Constraints	Sum of Wells		2,116	5,506	**Total Years**
	Years of Drilling		**2.68**	**6.97**	**9.65**

Table 2.A.1: Energy Consumption statistics assume demand remains at 2023 levels. 2030 calculations assume 2025 demand already satisfied. Years of drilling calculation assumes a rate of 790 geothermal wells drilled annually, which is the rate at which Pennsylvania's oil and gas industry drilled in 2022. Residential demand not included under 2025 Geothermal Potential due to geographic distribution of Pennsylvania residences. Some calculations appear erroneous due to rounded figures—outputs and conclusions are arithmetically accurate with decimal places. GWh = Gigawatt hours.

Regional Stratigraphic Chart of the Appalachian Basin and the Greater Study Area

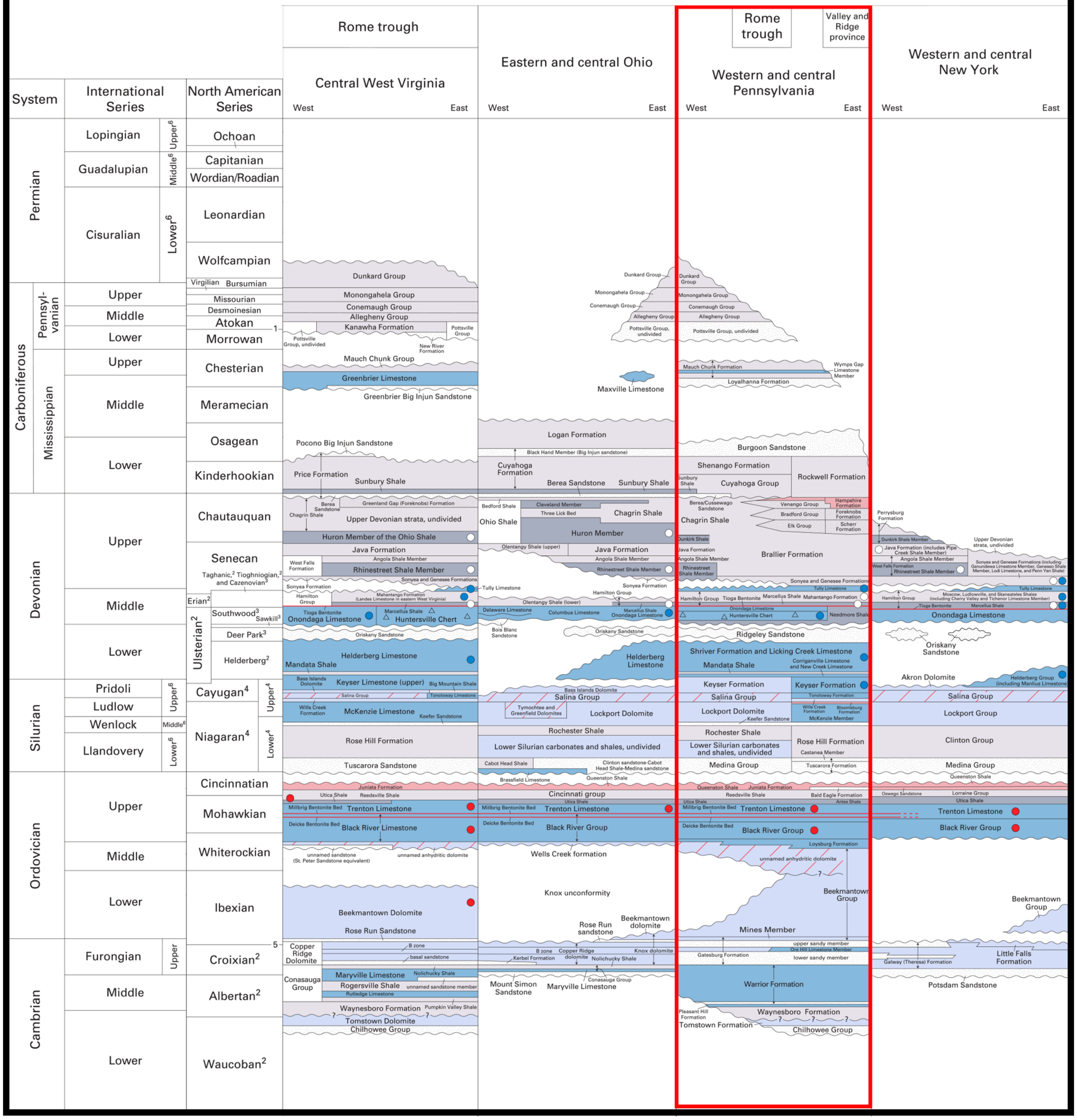


Figure 2.A.1: Source: Adapted from United States Geological Survey (USGS). (2008). SIM 3006. https://pubs.usgs.gov/sim/3006/SIM_3006_figures/SIM_3006_Fig4.pdf

Summary of Data Source Files and Source URL Links to Data of the Temperature Data Included in the Temperature Datasets

Data Source File	Data Source URL
..\001_DataSource_GDR_AASG_Geothermal_Boreholes\aasg_geothermal_boreholes.csv	https://gdr.openei.org/submissions/252
..\002_DataSource_SMU\core.surface_site_county_state_materialized_view.csv	http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?
..\002_DataSource_SMU\core.template_borehole_materialized.csv	http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?
..\002_DataSource_SMU\core.template_heatflow_materialized.csv	http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?
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..\003_DataSource_SMU_Geothermal_Boreholes\SMU_Geothermal_Boreholes.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\004_DataSource_AASG_GDS_Data\drillstemtests.csv	https://github.com/usgin-models/DrillStemTests
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..\005_DataSource_NREL_geothermal-prospector\GB_hot_spring_well_analyses.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\005_DataSource_NREL_geothermal-prospector\OIT_Colocated_Sites.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\005_DataSource_NREL_geothermal-prospector\OIT_Wells_Springs.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\005_DataSource_NREL_geothermal-prospector\USGS_Wells_Springs.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\006_DataSource_GDR_Low-Temperature Geothermal Geospatial Datasets An Example from Alaska\AASG_Geothermal_Boreholes.csv	https://gdr.openei.org/submissions/1518
..\006_DataSource_GDR_Low-Temperature Geothermal Geospatial Datasets An Example from Alaska\AASG_Low_Temperature .csv	https://gdr.openei.org/submissions/1518
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..\010_Stanford Thermal Earth Model for the Conterminous United State\Raw_BHT_aggregated_data.csv	https://gdr.openei.org/submissions/1592
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Table 2.A.2: Summary of data source files and source URL links of the temperature data included in the temprature datasets

SUPPLEMENTAL INFORMATION

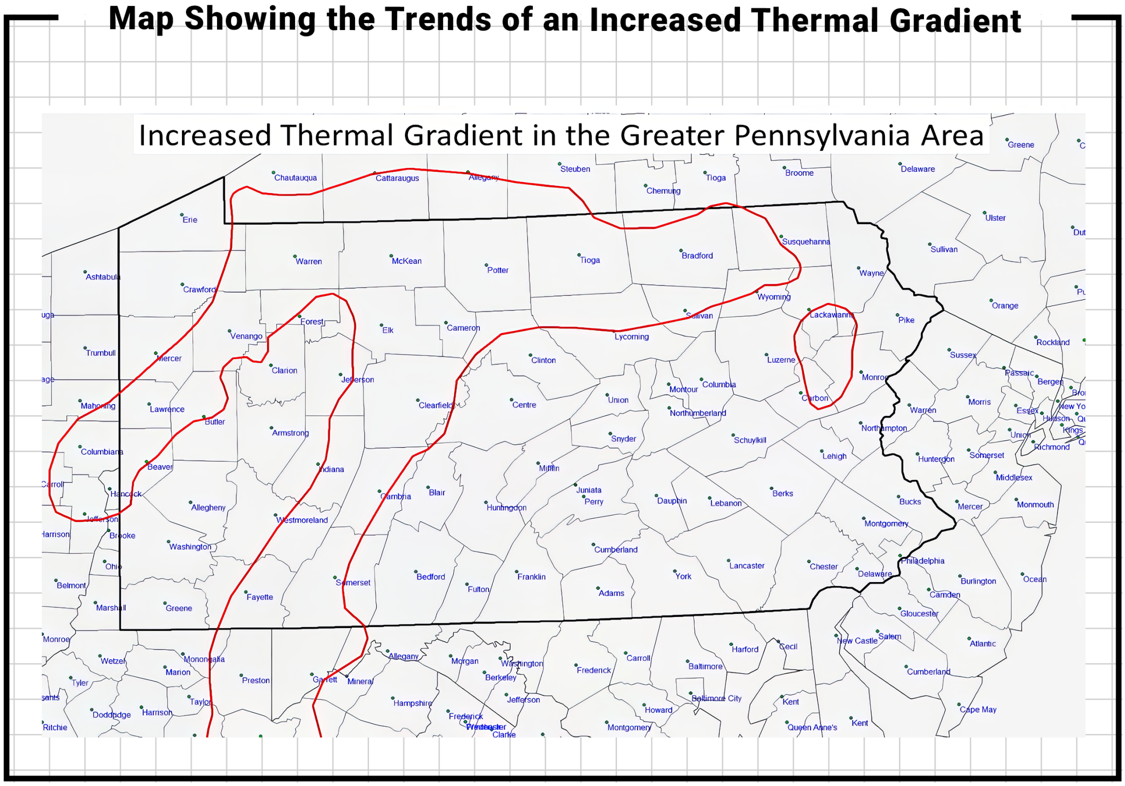


Figure 2.A.2: Map showing areas with increased thermal gradient, highlighted by red polygons. Source: Author analysis.

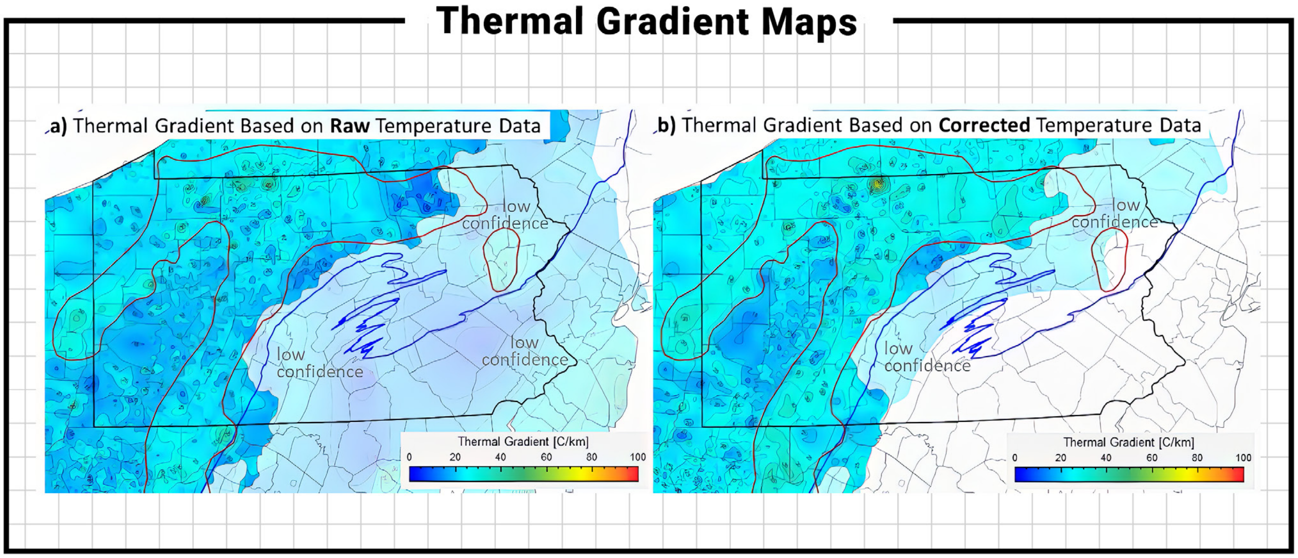
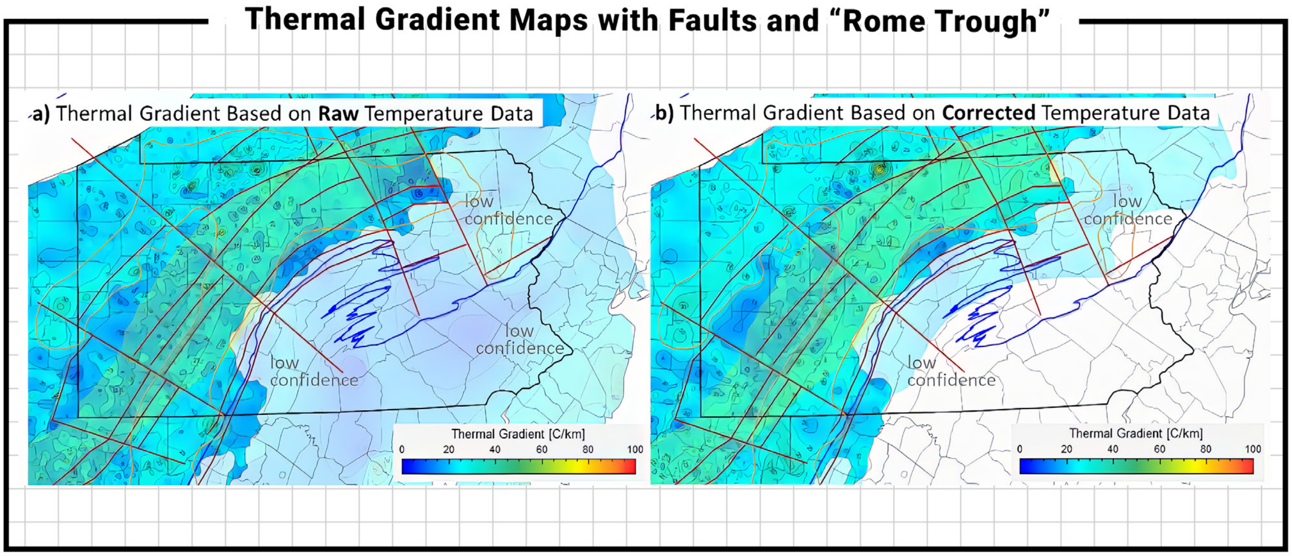


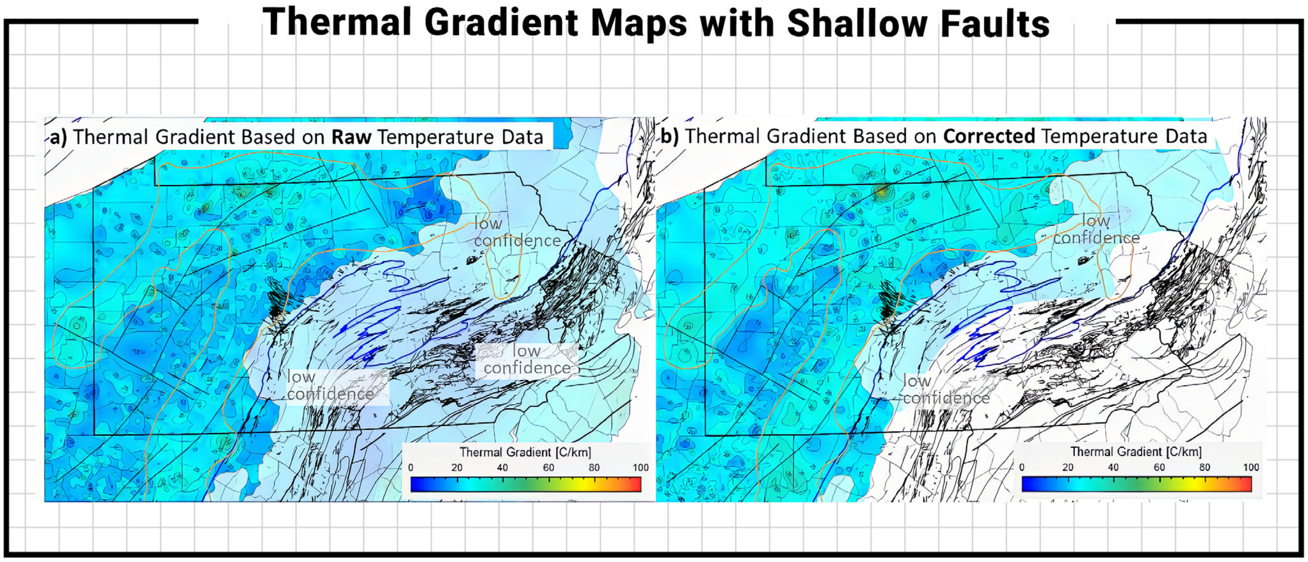
Figure 2.A.3: a) based on raw temperature data. b) based on available corrected temperature data. The blue line indicates the eastern boundary of the Appalachian Basin. Red polygon in both a and b outlines the areas of likely increased gradient based on corrected temperature data. Low confidence areas are covered by transparent white overlay. Source: Author analysis.


Thermal Gradient Maps with Faults and "Rome Trough"

a) Thermal Gradient Based on **Raw** Temperature Data

b) Thermal Gradient Based on **Corrected** Temperature Data

Figure 2.A.4: The yellow shaded area represents the approximate extent of the "Rome Trough." The red lines indicate major fault lineaments. The blue line indicates the eastern boundary of the Appalachian Basin. Orange polygons outline increased thermal gradient. Low confidence areas are covered by transparent white overlay. Source: Author analysis


Thermal Gradient Maps with Shallow Faults

a) Thermal Gradient Based on **Raw** Temperature Data

b) Thermal Gradient Based on **Corrected** Temperature Data

Figure 2.A.5: The irregular black lines represent shallow and major fault lines identified by Project InnerSpace. The blue line indicates the eastern boundary of the Appalachian Basin. Orange polygons outline increased thermal gradient. Low confidence areas are covered by transparent white overlay. Source: Author analysis

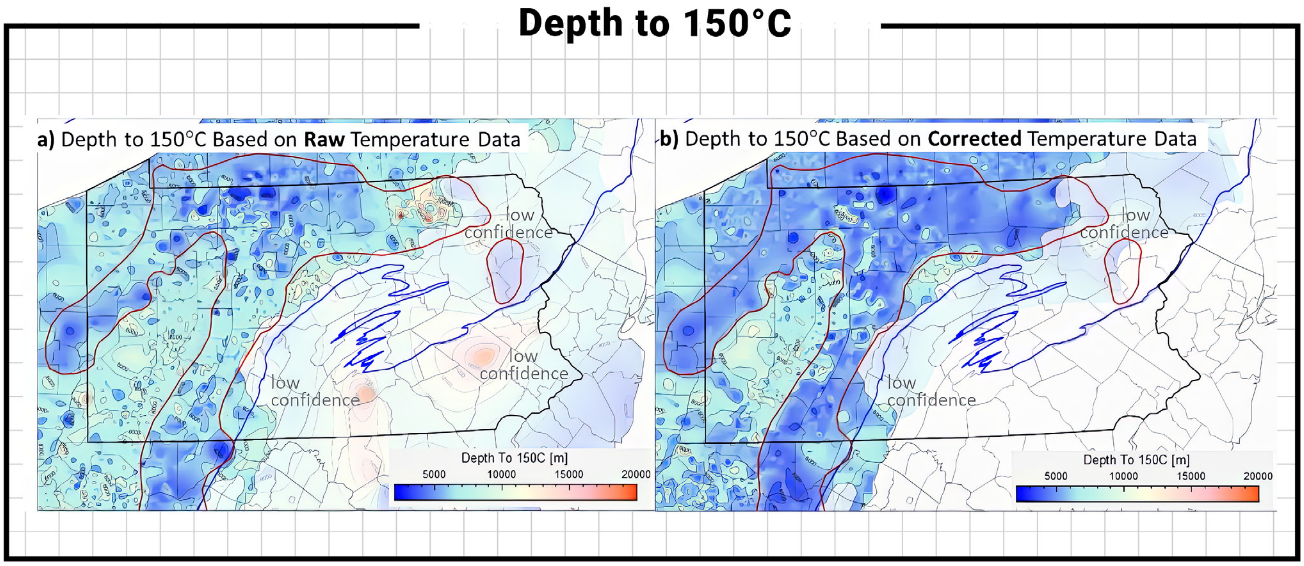


Figure 2.A.6: Based on a) raw temperature data and b) available corrected temperature data. The blue line indicates the eastern boundary of the Appalachian Basin. Red polygons outline increased thermal gradient. Low confidence areas are covered by transparent white overlay. Source: Author analysis.

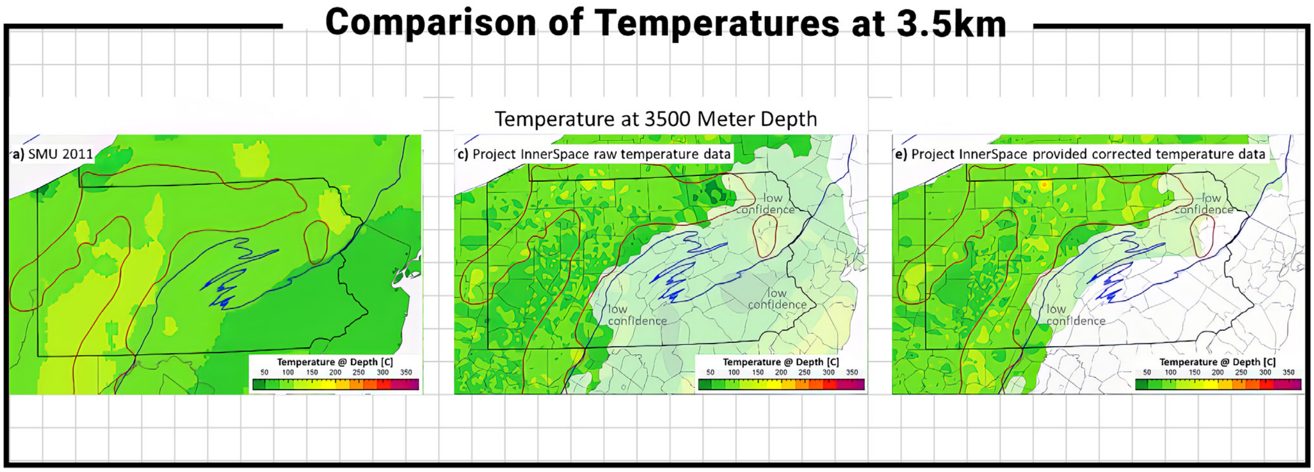


Figure 2.A.7: a) SMU 2011. c) InnerSpace raw temperature data. e) InnerSpace available corrected data. Red polygons highlight the areas of increased thermal gradient. The blue line shows the eastern boundary of the Appalachian Basin. Low confidence areas are covered by transparent white overlay. Source: https://www.smu.edu/dedman/academics/departments/earth-sciences/research/geothermallab/datamaps/temperaturemaps and authors' analysis.

Temperature Along the Available Structural Depth Surfaces

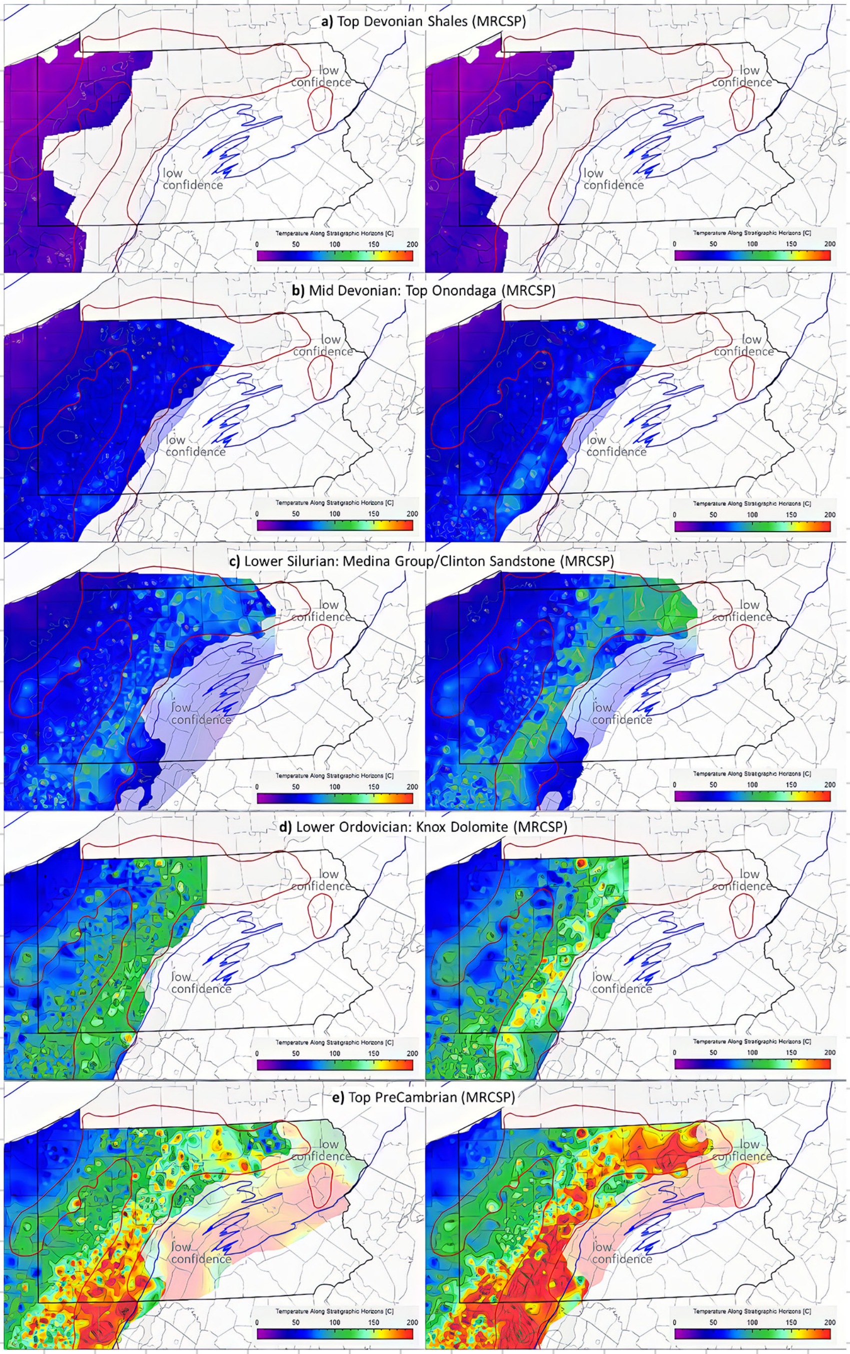


Figure 2.A.8: Left-hand side temperature values are based on raw temperature data. Right-hand maps are based on available corrected temperature data. The red polygons highlight the areas of increased thermal gradient. The blue line represents the eastern boundary of the Appalachian Basin. Low confidence areas are covered by transparent white overlay. Source: Author analysis

Gravity and Magnetics Maps

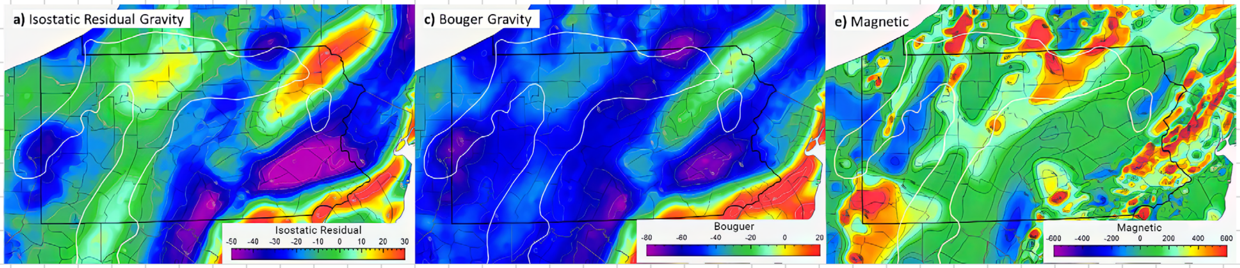


Figure 2.A.9: a) Isostatic Residual. b) Bouguer Gravity. c) Magnetic anomalies. Source: USGS. White polygons highlight the areas of increased thermal gradient.

CHAPTER REFERENCES

1. Cornell University. (2016). Appalachian Basin Play Fairway Analysis: Revised 2016 Combined Risk Factor Analysis [data set]. From https://dx.doi.org/10.15121/1495427.
2. Low-temperature processes are generally defined as those requiring temperatures of less than 300°F (150°C). See Chapter 2: "Geothermal Direct-Use Opportunities" for a more in-depth look at manufacturing and industrial applications.
3. International Energy Agency (2024). The Future of Geothermal Energy. From https://www.iea.org/reports/the-future-of-geothermal-energy.
4. U.S. Energy Information Administration. Pennsylvania State Profile and Energy Estimates. Last updated July 18, 2024. https://www.eia.gov/state/data.php?sid=PA#ConsumptionExpenditures
5. Tester, J. W., Anderson, B. J., Batchelor, A. S., Blackwell, D. D., DiPippo, R., Drake, E. M., ... & Veatch, R. J. (2006). The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology. Chapter 2, Appendix A, https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf
6. Robins, Jody C., Devon Kesseli, Erik Witter, and Greg Rhodes. 2022. 2022 GETEM Geothermal Drilling Cost Curve Update: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-82771. https://www.nrel.gov/docs/fy23osti/82771.pdf
7. Available data in this area consists of a cluster of shallow wells. A temperature of 152°F (67°C) represents an extrapolation of the shallower measurements. Further investigation will help confirm if the temperatures actually increase with depth and whether deep geothermal wells might provide additional geothermal opportunities.
8. This includes the Marcellus Shale, the key layer that supports the large majority of Pennsylvania's recent natural gas exploration and production—and which has made Pennsylvania one of the largest natural gas producing states.
9. The depth surfaces presented in this study are a subset of available surfaces in the Midwest Regional Carbon Sequestration Partnership (MRCSP) dataset. They were selected because they do not intersect. Intersecting surfaces reflect contradictions from poor data rather than physical reality.
10. Where they exist, "corrected temperature" measurements were calculated as part of the original studies from which this aggregate database drew. This study relied on the original datasets and did not apply its own correction method. Properly correcting temperature data is custom site-specific work and must be undertaken at a prospect scale.
11. The accuracy and utility of these depth stratigraphic maps are limited by the extent of the available structural surfaces and the considerable uncertainty associated with their geometry and depth values. See MRCSP for additional detail.
12. A complete and consistent (not crossing/intersecting) set of depth structure/stratigraphic horizons is desirable to be able to tie the calculated temperature values to the lithology and related rock properties of the associated stratigraphic depth interval.
13. Cornell University (2016). Improvements in 2016 to Natural Reservoir Analysis in Low-Temperature Geothermal Play Fairway Analysis for the Appalachian Basin [data set]. From https://dx.doi.org/10.15121/1422756.