FINAL PHASE 1 RESEARCH REPORT

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*The Prime Recipient certifies that the information provided in this report is accurate and complete as of the date shown.

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EXECUTIVE SUMMARY

Geothermal energy is an attractive sustainable energy source. Project developers need confirmation of the resource base to warrant their time and financial resources. The hydrocarbon industry has addressed exploration and development complexities through use of a technique referred to as Play Fairway Analysis (PFA). The PFA technique assigns risk metrics that communicate the favorability of potential hydrocarbon bearing reservoirs in order to enable prudent allocation of exploration and development resources.

The purpose of this Department of Energy funded effort is to apply the PFA approach to geothermal exploration and development, thus providing a technique for Geothermal Play Fairway Analysis (GPFA). This project focuses on four risk factors of concern for direct-use geothermal plays in the Appalachian Basin (AB) portions of New York, Pennsylvania, and West Virginia (Figure 1). These risk factors are 1) thermal resource quality, 2) natural reservoir quality, 3) induced seismicity, and 4) utilization opportunities (Figure 2). This research expands upon and updates methodologies used in previous assessments of the potential for geothermal fields and utilization in the Appalachian Basin, and also introduces novel approaches and metrics for quantification of geothermal reservoir productivity in sedimentary basins. Unique to this project are several methodologies for combining the risk factors into a single commensurate objective that communicates the estimated overall favorability of geothermal development. Uncertainty in the risk estimation is also quantified. Based on these metrics, geothermal plays in the Appalachian Basin were identified as potentially viable for a variety of direct-use-heat applications. The methodologies developed in this project may be applied in other sedimentary basins as a foundation for low temperature (50-150 °C), direct use geothermal resource, risk, and uncertainty assessment. Through our identification of plays, this project reveals the potential for widespread assessment of low-temperature geothermal energy from sedimentary basins as an alternative to current heating sources that are unsustainable.

There is an important distinction in this Geothermal Play Fairway Analysis project as compared to hydrothermal projects: this Appalachian Basin analysis is focused on the direct use of the heat, rather than on electrical production. Lindal (1973) illuminated numerous industrial and other low-temperature applications of geothermal energy for which this analysis can be useful. The major relationship to electricity is that direct-use applications reduce the electricity requirements for a region. Even though all of the geothermal resources in the Appalachian Basin are low grade, the high population and high heating demand across New York, Pennsylvania, and West Virginia translate into economic advantages if geothermal direct-use heating replaces electricity-based heating. The advantage is derived from the high efficiency of extracting heat from geothermal fluids rather than converting the fluids to electricity (Tester et al., 2015).

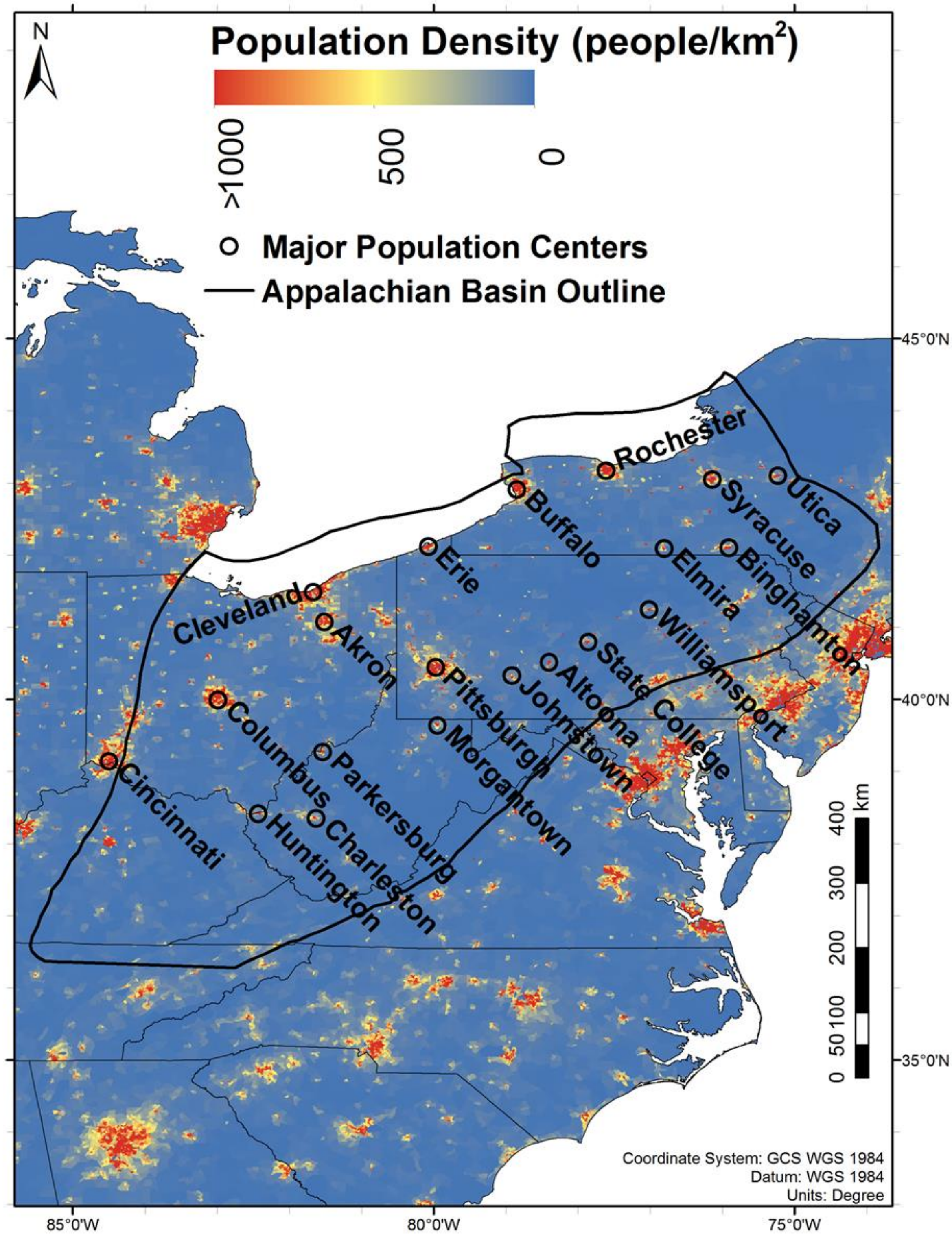

Figure 1: Population density (U.S. Census Bureau, 2010) within the Appalachian Basin region (Shumaker, 1996) highlighting the larger cities.

The Geothermal Play Fairway Analysis of the Appalachian Basin is valuable for several reasons:

1. The Appalachian Basin is a sedimentary basin with a history of substantial hydrocarbon drilling activity, thereby increasing our ability to access existing knowledge about the subsurface thermal field and reservoirs. GPFA techniques developed here could be applied in other sedimentary basins with ample publicly available hydrocarbon drilling records around the U.S., such as the Williston Basin, Sacramento Basin, San Joaquin Basin, Gulf Coast Basin, Black Warrior Basin, Denver Basin, Anadarko Basin, Illinois Basin, Michigan Basin and others.

2. The Appalachian Basin, like most of the U.S. east of the Rocky Mountains, is considered a 'low temperature' geothermal area. Some low temperature geothermal areas are suitable for direct-use applications (e.g., district heating, greenhouses, aquaculture, and industrial processes, such as pasteurization) or coproduction, but not for electricity generation alone. Because low-temperature geothermal resources are more common than high grade in the U.S., this project is important beyond its regional footprint for the development of direct use low-temperature geothermal projects across the U.S.

3. Several major population centers located within the Appalachian Basin concentrate the demand for heat in small areas. These include Pittsburgh, PA; Williamsport, PA; State College, PA; Morgantown, WV; Charleston, WV; Buffalo, NY; Syracuse, NY; and Rochester, NY (Figure 1).

4. Space heating and cooling of homes is the #1 use of the residential consumption of produced electrical energy in the U.S. (U.S. Energy Information Administration, 2015). This project explores the possibility that communities in the Appalachian Basin may be able to employ geothermal district heating to relieve the growing stress on the electric power grid.

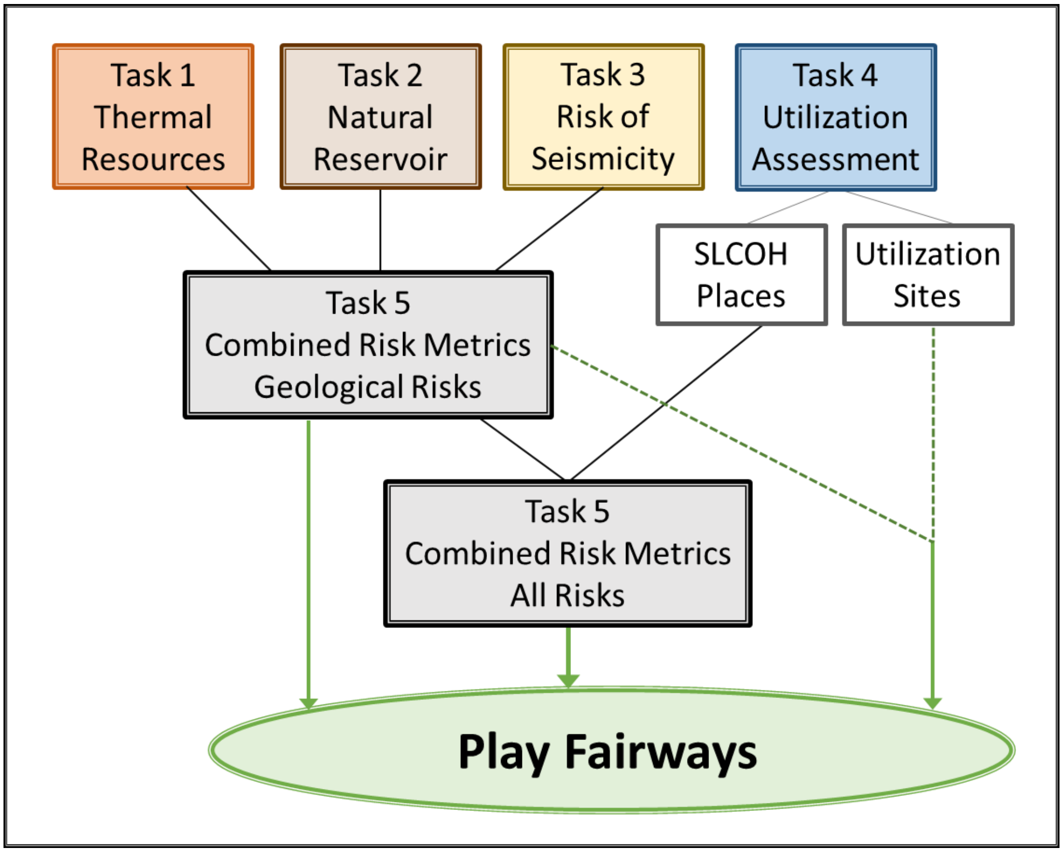

Figure 2: Appalachian Basin Geothermal Play Fairway Analysis Process. Each of four key risk factors studied in the context of favorability and uncertainty were combined using Play Fairway Metrics (PFM) to create final Play maps and overall basin risk.

Data Sources and Project Flow

The team began by characterizing the constraints to developing a geothermal project that must be managed in an integrated fashion. These constraints were treated as four categories of risk: 1) Thermal Resource Quality, 2) Natural Reservoir Quality, 3) Risk of Seismic Activity, and 4) Utilization Viability. Each risk was quantified, as was the uncertainty associated with the resultant risk value. These four risk factors were then combined (Figure 2) into a single metric that was used to determine the most favorable fairways within the Appalachian Basin.

To conduct a quantitative analysis, we utilized data collected as part of previous national and state research efforts, as well as data from the National Geothermal Data System; the Midwest Regional Carbon Sequestration Partnership; New York, Pennsylvania and West Virginia State geologic, oil and gas well data provided by the State Geological Surveys and by their oil and gas regulatory bodies; NOAA Climate data; NEIC and EarthScope (TA) seismicity data; regional-scale magnetic map; regional-scale gravity map; US Census Bureau population data; and Energy Information Agency power consumption data.

Thermal Resource Quality

Appalachian Basin temperature data from oil and gas bottom-hole temperatures (BHTs) are abundant (Figure 3), but of low quality. This project generated a new set of BHT corrections appropriate for this basin. At the location of each well, the corrected BHT was combined with generalized thermal conductivity stratigraphy to estimate the local geotherm using a 1-D heat conduction model. Analyses of local spatial outliers were performed on the geotherms, followed by a spatially stratified ordinary Kriging regression that predicted properties of the thermal field and its lateral variations. A sensitivity analysis on the input variables to the heat conduction model revealed that BHTs are the most critical input variable for quantifying properties of the thermal field. Overall, these methods resulted in higher quality results and a more robust evaluation of the uncertainty than previous studies.

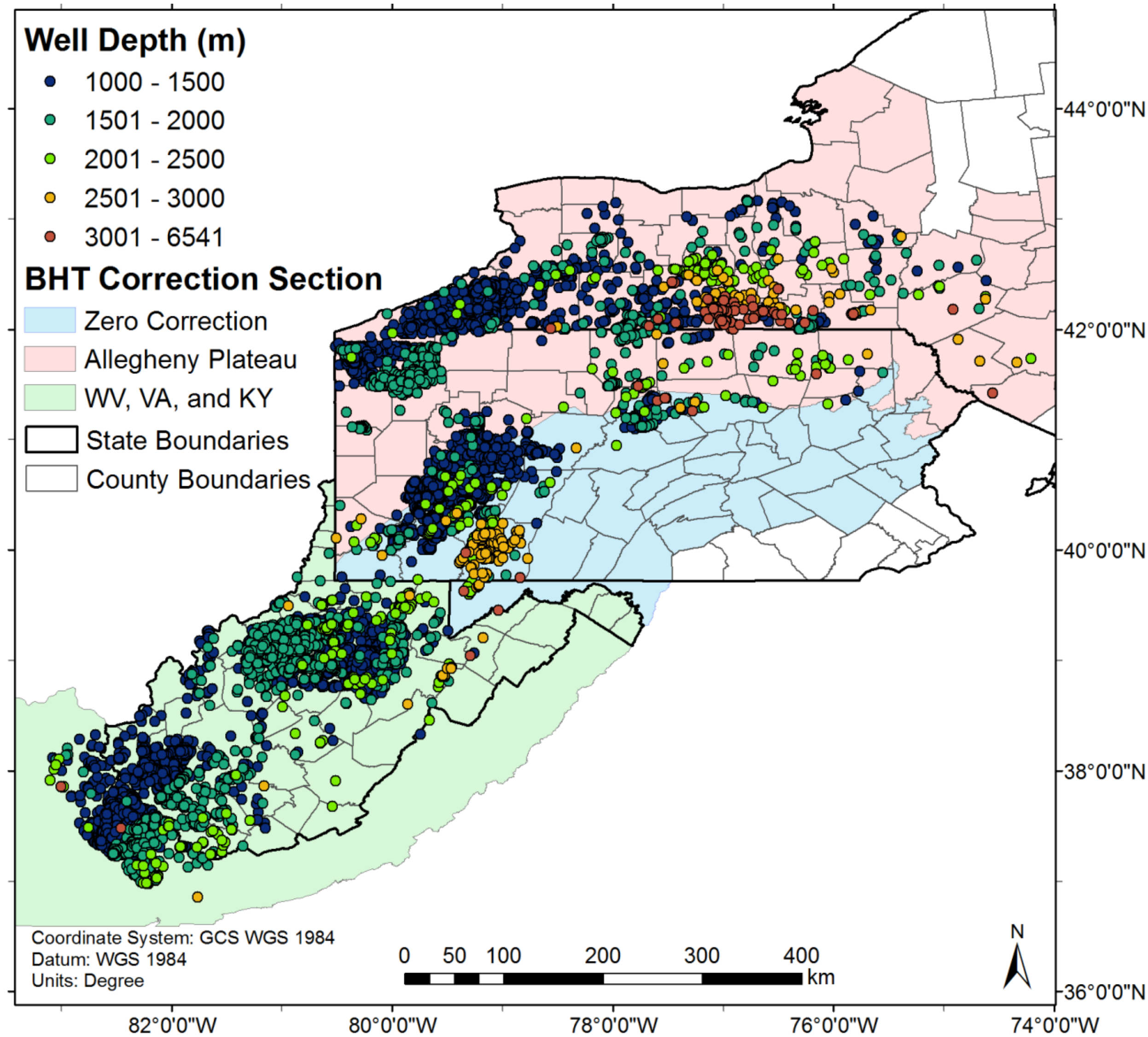

Figure 3: Well locations colored by depth of the BHT measurement, and BHT correction regions used in this project. County and state outlines are shown. For quality reasons, only those BHT measurements at depths greater than 1000 m were retained for analysis.

Natural Reservoir Quality

The Appalachian Basin's conventional hydrocarbon fields and its unconventional shale reservoirs have been extensively studied (Engelder, Lash, & Uzcátegui, 2009; Nelson, 2009). In the second task, Natural Reservoir Quality analysis, we examined the suitability of rocks to function as natural reservoirs, which necessitate sufficient water flow rates between injection wells and production wells to harvest heat within the reservoir. This procedure included additional independent methods to predict permeability using information from carbon sequestration studies and porosity data, both overlapped with oil and gas exploration and production datasets. Some of the most vital data are very scarce in public records: permeability values, pressure data, and production data. The oil and gas reservoir property records are spatially biased toward those locations with profitable amounts of hydrocarbons in the rock pore spaces. This bias ought *not* be shared by this project's search for *water* in pore spaces, although the existing data cause persistence of this bias. The spatial bias and the lack of permeability and/or flow data impose a severe limit on the completeness of the reservoir assessment that was possible in Phase 1. The locations of the natural reservoirs and lateral variations in reservoir properties reported here must be considered with the understanding that there exist potential errors that are not quantified due to lack of data and because our data base focused on oil/gas rather than on formations with water. Indeed, more data could identify additional reservoirs.

Seismicity

With the extent of ongoing induced earthquake activity in several states (Oklahoma, Texas, Kansas, Ohio) and the potential for similar activity in portions of the Appalachian Basin, it is expected that the public will require an informed risk assessment in advance of undertaking a new type of energy extraction work in the subsurface. To anticipate this concern, we examined the options for a regional analysis to identify sub-regions that may be more or less at risk for slip along planes of weakness in the rocks. Acknowledging that data for such a task are insufficient, we utilized what was available: records of seismic activity, regional estimates of the orientations of principal stress directions, and locations and orientations of zones identified on gravity and magnetic data as sites of lateral change in rock properties at depths down to several kilometers below Earth's surface. Analysis of those data sets highlight areas within the basement that have higher or lower sensitivities to fluid pressure changes. With these data, we created a first approximation of spatially variable risks for induced earthquakes.

Utilization Opportunities

Economically viable projects for low-temperature direct-use geothermal heat must be located near the field where the hot water is extracted to limit thermal losses and excessive pumping costs. Therefore, for the Utilization risk factor we worked principally with population density as a regionally known variable. For this economic analysis, we employed a previously developed model by Beckers et al. (2014), GEOPHIRES (GEOthermal energy for Production of Heat and Electricity ["IR"] Economically Simulated), with variations to capture the surface costs associated with delivering heat from a wellhead to final consumers through a district heating system. The Utilization maps do not include the costs of producing the hot water at the well head, because the below-ground costs are directly coupled to the spatial variability of the heat resource and the reservoir properties, which are factors treated under the Thermal Resource risk and Natural Reservoir risks. The result of the district heating analysis is provided as a surface levelized cost of heat (SLCOH). Because we have now identified potential plays, the cost of heat delivery for individual locations within the plays, including all of the components needed to compute a true levelized cost of heat, should be calculated during a follow-up study. In addition to district heating, we located institutions and businesses that utilize large amounts of thermal energy at low temperatures across the three-state study area. These represent additional utilization opportunities for the region that should be investigated in more detail in future studies.

Combined Risk Metric

The final task developed and assigned a Combined Risk solution to incorporate each of the four project risk factors using a set of Play Fairway Metrics (PFMs). This task identified the most favorable locations within the study area to examine with additional scrutiny. The four individual risk factors were assigned favorability ratings from 0 – 5, with 0 unfavorable (red), 3 moderately favorable (yellow) and 5 favorable (green) (Figure 4). Several techniques were used to compute the combined risk metric at each location using a grid resolution of 1 km^2. These methods included using the sum of individual risk factor favorability ratings, the product of individual favorability ratings, or the minimum (least favorable) value of the four risk favorability ratings. There is value in considering the outcomes of each of these methods:

1. The summation approach highlights areas that appear favorable overall, but does not inform a decision maker if any given risk factor is unfavorable at a location.
2. The minimum value approach highlights the most unfavorable rating of the four risk factors, but does not inform a decision maker of how much more favorable are other risk factors.
3. The product approach highlights those few areas that are favorable in all four risk factors, but highly down-weights those areas that are even slightly less favorable.

Overall the summation approach rapidly identifies areas for which additional study to reduce risk related to any one of the risk factors is most warranted. The minimum value approach highlights the fact that there is no place where the existing results warrant immediate investment in commercialization.

While it is almost impossible for analysts to say which method is best, the information conveyed by these methods is useful for the decision maker to consider in assessing their site, or when comparing sites for development. Where all three PFM methods are favorable, these sites are most robust as potential plays; however, uncertainty in each metric should also be considered while making a decision. Each individual risk is accompanied by a map of the uncertainty, which was then included as part of the final PFM.

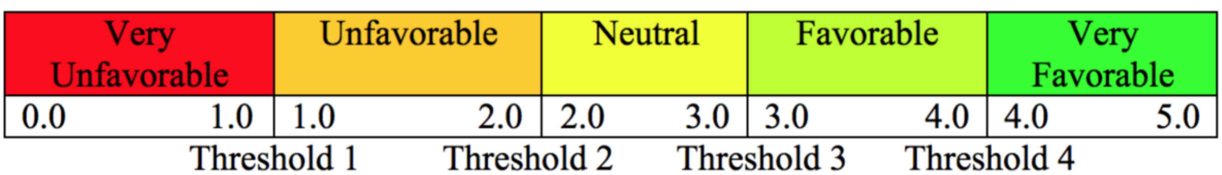

Figure 4: Individual Risk Factor maps and the combined Play Fairway Metric maps are expressed as a five-point scale (shown here) and a similar three-point scale.

The set of PFMs that combine all four risk factors highlight the spatial lay-out of existing population centers. Areas of low population density are matched by low favorability ratings, irrespective of their geological resources.

The geologic risk factors (thermal, reservoir, and seismic), when combined into a set of PFMs, emphasize the fixed natural-system properties that must be accommodated by engineering designs for well fields and for utilization scenarios. The advantage of the 3-factor geology-only PFMs is that they identify areas that a stakeholder group would find suitable for creation of a new industrial, commercial, or residential activity that utilizes the geothermal heat. These geology-only-PFMs express the fact that the Geothermal Play Fairway team cannot anticipate all possible thermal utilization scenarios that may interest a particular future user group. This natural resource information can be combined in future studies with not only direct costs but also indirect benefits, such as reduced use of fossil fuels, regulatory considerations, or tax incentives, to develop more comprehensive descriptions of the spatial variation of costs and benefits.

There are five Play Fairways that we recommend be of highest priority for further investigation (Figure 5). The Corning-Ithaca Play Fairway (mostly in New York) includes locations with especially favorable overall scores and small degrees of uncertainty, and warrants investigation to better determine the full costs of heat delivery as well as to determine the spatial extent of the high quality reservoirs. The Morgantown-Clarksburg Play Fairway (West Virginia), the Meadville–Jamestown Play Fairway (mostly in

Pennsylvania) and the Charleston Play Fairway (West Virginia) also have favorable scores for most of the four risk factors, and deserve more in-depth analysis than was within the scope of this Phase 1 project. The Pittsburgh Play Fairway is a region of very few deep wells and therefore scant data for the subsurface depths at which the temperature exceeds 50 °C. Given the large utilization potential near the city of Pittsburgh, we recommend a more focused study of the deepest wells in order to better evaluate the potential for deep natural reservoirs.

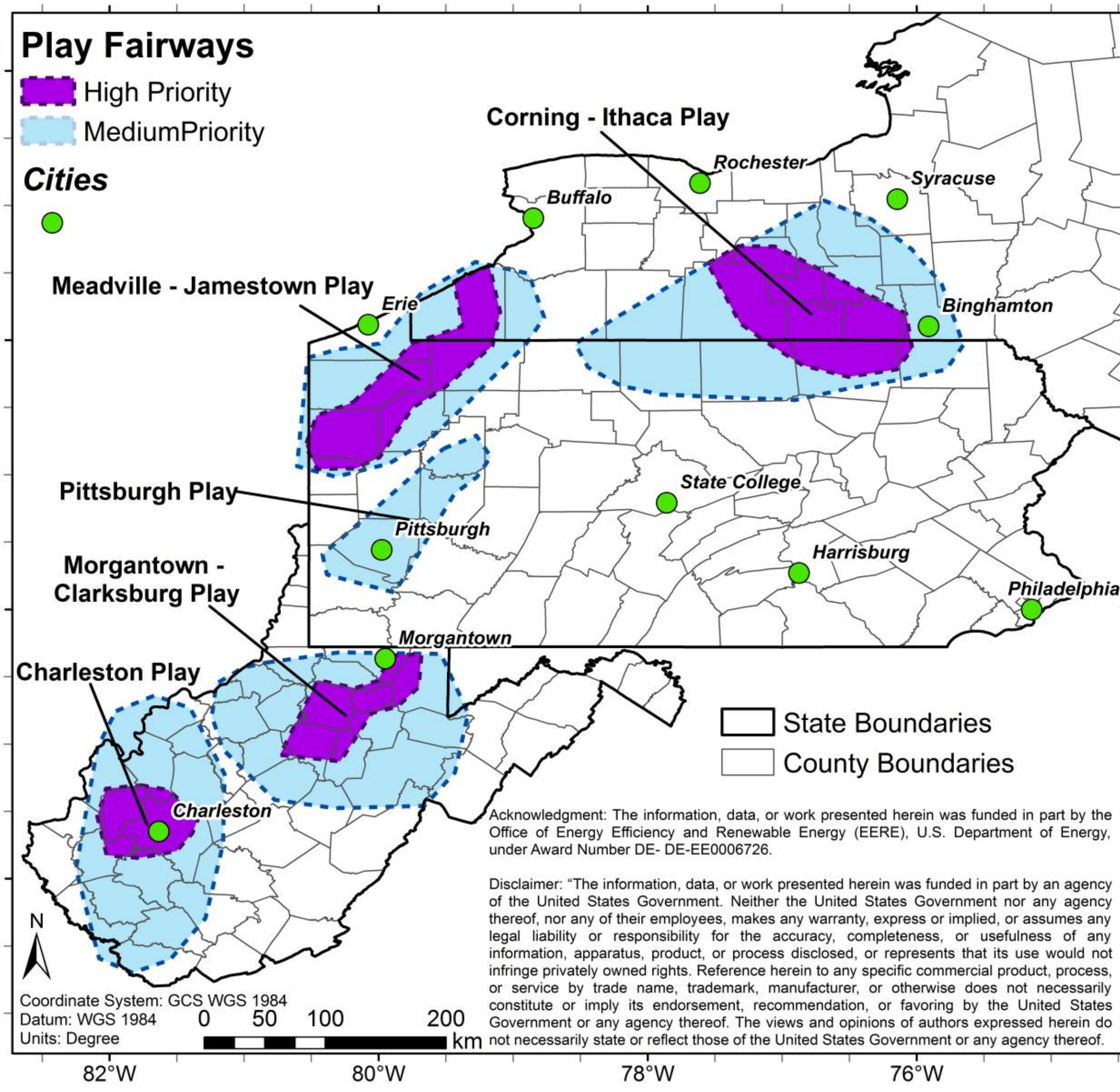

Figure 5: The most favorable Play Fairways within the Appalachian Basin based on this project synthesis of all Risk Factors as of Phase 1. Play fairways are named for one or more population centers within them. All but the Pittsburgh Play Fairway are subdivided into an inner fairway (high priority) and outer fairway (medium priority) regions, based on the combined risk analysis.

SUMMARY OF PROJECT ACTIVITIES

Original Project Hypotheses

Given the characteristic stable-continent heat flows associated with the Appalachian Basin (Blackwell & Richards, Geothermal Map of North America; Explanation of Resources and Applications, 2004), the **resource is presumed to be suitable for lower temperature, direct-use geothermal applications**. The extensive hydrocarbon extraction in the vicinity (most recently the large Marcellus Shale Play) affords prolific bottom-hole temperature (BHT) data, as well as oil and gas production data, useful in determining other key geothermal reservoir characteristics, such porosity and permeability. These **oil and gas industry data will be useful in modeling the sedimentary basin's suitability** for lower temperature, direct-use type geothermal applications in terms of reservoir characteristics. Because project viability includes other factors, including risk of seismicity, population distribution, and demand for heat, these and other criteria will also be incorporated into an **economic viability model, used to inform the next step of project development**.

This report is organized into the following sections:

- <u>Summary of Project Activities</u>: original project hypotheses, approaches used, problems encountered, departure from planned methodology, and impact on project results.
- <u>Methodology</u>: underlying scientific theory and key assumptions, steps in the workflow, summary of the strengths and limitations of the process, mathematics used (including formulas and calculation methods), potential sources of error, software used, and results of tests to demonstrate satisfactory model performance.
- <u>Discussion of Results</u>: primary conclusions, comparison of actual accomplishments with original goals and objectives, risk factor and related error/uncertainty maps, and final favorability maps.
- <u>Recommendations for Further Analysis Phase</u>: objectives and outcomes, description of planned activities (SOPO tasks), partners identified and roles, timeline, preliminary budget information, and anticipated permitting requirements.
- Catalog of Supporting Files: a list of datasets used including the source(s), limitations on rights, and any operations performed on the data to prepare them for use), custom code/scripts/configuration files used to process data, GIS databases, risk factor maps and final favorability maps (as images and in georeferenced format). This section also includes a series of '<u>Project Memos</u>' detailing major project tasks and methods, which will be useful for other researchers.
- <u>References</u>: Major works cited in this paper. The Catalog of Supporting Files contains more detailed documents with additional references provided.

Approaches Used

The Statement of Project Objectives (SOPO) outlines the Phase 1 Project Plan as a series of seven Tasks, each with several subtasks, as summarized below. Tasks 1-5 comprise the primary research activities in Phase 1 and Tasks 6-7 are related to project management and outreach (Figure 2). Specific research details, equations, and methods are provided within the Catalog of Supporting Files section of this report. The plan was followed very closely, with only minor adjustments needed, as described in the next section, Accomplishments and Challenges. The following is the condensed list of our original major SOPO Tasks and a description of each one. For the full detailed list that includes all the subtasks, milestones, deliverables, see the Catalog of Supporting Files document, <u>SOPOTasksMilestones.pdf</u>.

1. **<u>Task 1.0 Thermal Resource Quality Assessment</u>**: The purpose of this task and its several subtasks are to research and assemble the available thermal data in the published literature as well as thermal data available from non-published sources, to establish the data infrastructure for the project, and to carry out the assessment of the first of the proposed Risk Factors (RF1), Thermal Resource Quality.

    <u>Task 1 Deliverable</u>: Deliver an improved region-wide map of depths to 80 °C isotherm and a county map for four counties per state, as well as a Green-Yellow-Red-ranked thermal resource map for the region and for the four counties per state, as derived from all the considerations described in Task 1, including lithologies, updated conductivity, and updated basement heat flux model, etc. as well as the supporting data according to the Data Management Plan and thermal models for the New York (NY), Pennsylvania (PA) and West Virginia (WV) region of the Appalachian Basin.

2. **<u>Task 2.0 Natural Reservoir Quality</u>**: The purpose of this task is to develop the supporting database to evaluate and map the distribution of potential geothermal reservoirs. The result will be Ranking Maps and supporting data for natural reservoirs in a majority of the Appalachian Basin of WV, NY and PA.

    <u>Task 2 Deliverable</u>: Deliver reservoir quality maps, supporting data and related models for the NY, PA and WV region of the Appalachian Basin incorporating information such as reservoir quality and variability, porosity, permeability, and hydraulic conductivity.

3. **<u>Task 3.0 Risk of Seismicity</u>**: The purpose of this task is to review seismicity (excluding enhanced geothermal systems –EGS) as a Risk Factor and identify regions with enhanced likelihood for inducing unintended seismic activity during preparation of a reservoir, or during the course of geothermal heat production. The result of the task will be maps for the study area in the Appalachian Basin in NY, PA and WV of potential faults and of faults that are active.

    <u>Task 3 Deliverable</u>: Deliver risk map, supporting data according to the Data Management Plan, and related models, for the NY, PA and WV region of the Appalachian Basin for induced or reactivated seismicity, incorporating fault positions and seismicity activity.

4. **<u>Task 4.0 Utilization Variability</u>**: The purpose of this task is to identify regions in the Appalachian Basin with the capacity to utilize low-grade geothermal heat and the related variability of demand. The result of the task will be utilization maps for the region of the Appalachian Basin in NY, PA and WV and estimates of Levelized Cost of Heat for a small set of communities.

    <u>Task 4 Deliverable</u>: Deliver maps for spatial variability of population and heat demand, and a ranked map for utilization using supporting data according to the Data management Plan, for the NY, PA and WV region of the Appalachian Basin. Deliver estimated Levelized Cost of Heat (LCOH) for two communities in each state.

5. **<u>Task 5.0 Risk Matrix Analysis</u>**: The purpose of this task is to merge the risk segment maps described above to produce an overall risk map. This will be the compilation of factors and the most favorable combinations of multiple risk factors from the Risk Factors evaluated in Tasks 1-4. A risk matrix will be applied to combine the four sets of risk factors and will identify up to six "most promising Play Fairways" within the Appalachian Basin in NY, PA and WV.

    <u>Task 5 Deliverable</u>: Deliver common risk assessment map, which delineates up to 6 Play Fairways within the NY, PA and WV region of the Appalachian Basin based upon the compilation of the spatial variability of the risk factors assessed in Tasks 1-4. The models and available supporting data, according to the Data Management Plan, will also be delivered.

6. **Task 6.0 Project Management and Reporting:** The three team leaders (Cornell, SMU, WVU) will interact bi-weekly to assure continued progress on the project. At each quarter's end, available team members will meet by conference call or in person to discuss project progress and needs. Quarterly project reviews will be held with DOE staff by phone or webinar to present project status and verify milestones. One quarterly review will be made in-person at the Geothermal Technology Office peer review (tentatively scheduled for spring 2015 in Denver).

   Task 6 Deliverable A final report detailing all facets of the study and detailed suggestions for Phase II will be presented at the end of Phase 1. This report will be the basis for a competitive downselect process for Phase 2. The raw data collected and/or new data generated as part of the project will be uploaded to the NGDS at the end of the Phase I, following USGIN metadata guidelines.

7. **Task 7.0 Commercialization / Market Transformation:** Commercialization activities are to include 1) participation in a poster session at the Geothermal Resources Council (GRC) 2014 meeting, to lay out the project plans and objectives, and 2) a follow-up presentation summarizing project results (tentatively for GRC 2015).

Accomplishments and Challenges

The Geothermal Play Fairway Analysis - Appalachian Basin (GPFA-AB) project had few departures from the original SOPO. Southern Methodist University (SMU) and Cornell University team members are both experienced with large collections of data from oil and gas wells; Cornell and West Virginia University (WVU) are lead researchers for district heating models and wrote the code for GEOPHIRES (GEOthermal energy for Production of Heat and Electricity ["IR"] Economically Simulated (Beckers, 2015)); Cornell is experienced in analyzing datasets using statistical methodologies. The project accomplished all SOPO tasks and exceeded what was required. For instance, a set of BHT corrections specific to the Appalachian Basin region were developed, a detailed reservoir productivity index was created and the content model for Geologic Reservoirs was updated, innovative techniques were implemented for determining potential locations for induced seismicity that included stress orientations, a specialized list of site-specific industry locations of interest for utilization was created and Surface Levelized Cost of Heat was calculated for hundreds of Census Bureau Places, new methodologies for assigning and combining risk segment maps were developed, and detailed methodology 'memos' were written for future researchers to use in other Play Fairway Analysis projects (see Catalog of Supporting Files). Each of the Tasks are discussed next to highlight changes from the planned methodology.

The Geothermal Play Fairway Analysis - Appalachian Basin (GPFA-AB) project is built from the foundation of previous work efforts by Cornell, SMU, and WVU (Aguirre et al., 2013) (Blackwell et al., 2010). In addition to the initial team members, we included other faculty, staff, and students who were able to provide valuable expertise to the project. The Catalog of Supporting Files in this Phase 1 report provides a full explanation of the methods, assumptions, formulas and references. The data uploads to the National Geothermal Data System (NGDS) via the Geothermal Data Repository include not only a wealth of detailed information drawn from thousands of oil and gas wells in the region, but also provide summary maps indicating the risk factors evaluated in each of the Tasks undertaken and the composite of the four Task results.

Task 1 Thermal Resource Quality Assessment

Bottom-hole Temperatures

The foundation of our thermal resource assessment is bottom-hole temperature (BHT) data as control points of temperature at depth, and (American Association of Petroleum Geologists (AAPG), 1994) COSUNA lithology and thicknesses for subregions of the Appalachian Basin. BHT data were collected for New York, Pennsylvania, West Virginia, and a surrounding 50 km buffer into Maryland, Virginia, Kentucky, and Ohio. These BHTs, though prolific, are potentially subject to thermal disturbance from drilling activity that occurred when data were collected. Various BHT correction algorithms have been developed over the years to approximate equilibrium conditions (Förster & Merriam, 1995; Blackwell & Richards, Geothermal Map of North America; Explanation of Resources and Applications, 2004; Harrison, Luza, Prater, & Chueng, 1983). Through an extensive novel statistical evaluation of a small set of equilibrium well-log temperature measurements in the Appalachian Basin, a new set of BHT corrections appropriate for this basin were developed. A set of equilibrium temperature wells (29) and 44 additional wells that were judged to be reliable temperature logs (Whealton, 2015; see also BHT Correction Memo) were used to devise correction functions. The focus on sub-regions increased the possibility to discover relationships between geological characteristics and the temperature corrections. Once the correction functions were defined, the depth-BHT data for over 13,000 wells were corrected.

Thermal Conductivity Stratigraphy

In order to determine properties of the thermal field, knowledge of lithology, thermal conductivity, radiogenic heat production, and formation thickness are needed. Each of these parameters are unknown, and required assumptions backed by previous studies (Thermal Model Memo). Anadarko Basin thermal conductivity samples were used as representative to the Appalachian Basin because reliable data for Appalachian Basin rocks were not available, and because these basins reached similar burial depths. In order to capture the distribution of thermal conductivities that could be present, each formation in the Appalachian Basin was subject to a Monte Carlo analysis to determine the distribution of possible values in thermal conductivity (details are provided in the Catalog of Supporting Files within the memos). These formation values were used to determine the harmonic average thermal conductivity over the entire sedimentary column. Thermal conductivity measurements are associated with a 5-10% expected error (Gallardo & Blackwell, 1999), yet it is one aspect of the accuracy that can be readily improved, with reduced uncertainty, through collection in future studies of conductivity data specific to sites of interest.

Thermal Model

The corrected BHTs were used along with the thermal conductivity stratigraphy to estimate the geotherm at the location of each well using a 1-D heat conduction model developed for this project. This model improves upon and corrects equations previously published by Stutz et al. (2012) and Blackwell et al. (2007) (see Thermal Model Memo for details). These corrections are 1) the heat balance used to calculate the radiogenic heat production at the sediment-basement interface, 2) sediment thickness and sediment radiogenic heat production terms that were missing in the prior formulation for the temperature-at-depth for depths deeper than the well, 3) the calculation of surface heat flow relative to the radiogenic heat generation assumptions made, and 4) an explicit analytic solution to the governing Ordinary Differential Equations, thus freeing ourselves from the need to evaluate the results of the thermal model via approximate numerical techniques. In other words, input BHT values are exactly reproduced using this method. Previous formulations do not reproduce the BHTs.

The model for steady state 1-D heat conduction was written in the open source language Python 2.7.9. This updated thermal model allows for a rapid computation of the surface heat flow and the geotherm (i.e.

temperatures at depth) on a site-by-site basis (>13,300 sites for this project). Input variables include the ground surface temperature, corrected BHT, depth of BHT measurement, radiogenic heat production, mantle heat flow, thermal conductivity for related Correlation of Stratigraphic Units of North America (COSUNA) stratigraphy, and the total sediment thickness. A sensitivity analysis on the input variables to the heat conduction model was also performed and revealed that BHTs are a major source of uncertainty when quantifying properties of the thermal field. The Thermal Model Memo for this code has refined descriptions of the parameters, variables, and equations, thus making it easily adaptable. The code and full revision history are located on BitBucket (Horowitz et al., 2015).

Spatial Regression

These geotherms were subject to a spatial outlier analysis (see Outlier Memo); points that remained, acted as control points in a spatially stratified ordinary Kriging regression (e.g. Gaussian process regression) implemented in the 'gstat' package of R version 3.1.0 "Spring Dance". Lateral stratification was performed according to gravity and magnetic potential field edges at depth (from the Seismic Risk Factor analysis) that may affect properties of the thermal field (see Interpolation Memo for details). This spatially stratified regression captured the structure of local spatial correlation in the predicted properties of the thermal field (e.g. depth to 80 °C) better than previously published regional approaches (Aguirre, 2014); thereby improving the accuracy of the thermal resource assessment.

The results of this analysis are maps of the predicted mean and the standard error of the predicted mean for each thermal property. Figure 6 presents the depth to 80 °C resource map for the region.

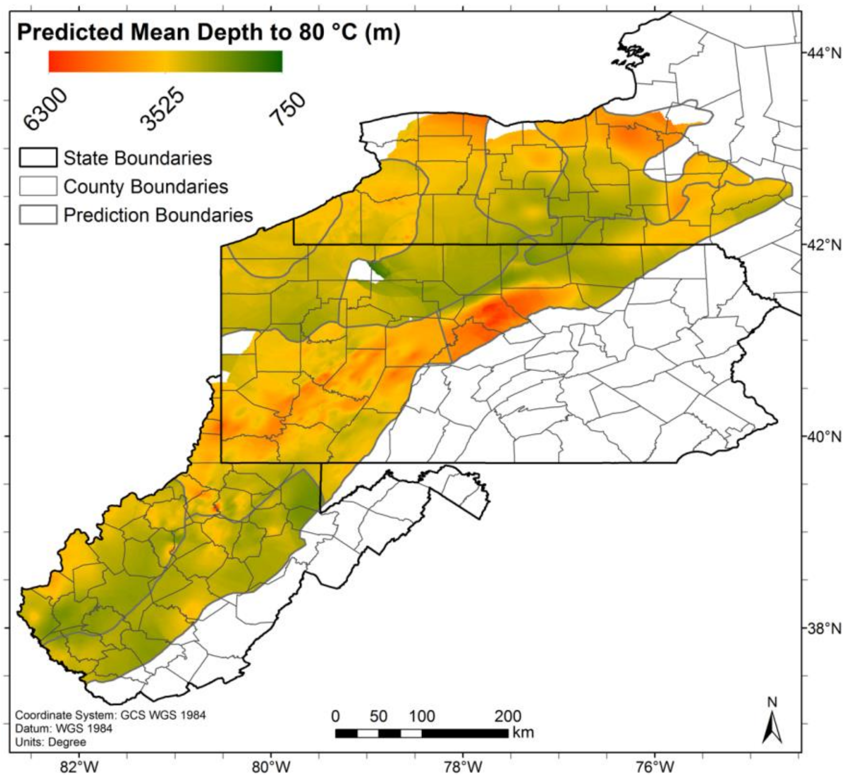

Figure 6: Predicted Mean Depth to 80 °C based upon thermal analysis. The sub-regions within the basin are boundaries for the spatially stratified Kriging interpolation of the thermal field properties.

Based on the map of Depth to 80 °C (Figure 6), along with some consideration of the reservoir availability and population centers, four of the most favorable counties in each state were selected and reviewed in greater detail (Figure 7). These twelve counties are shown in Figure 8 through Figure 17 as a set of 5 thermal resource maps paired with a cross section through each. The cross sections highlight the uncertainty and variability in the thermal resource through these counties.

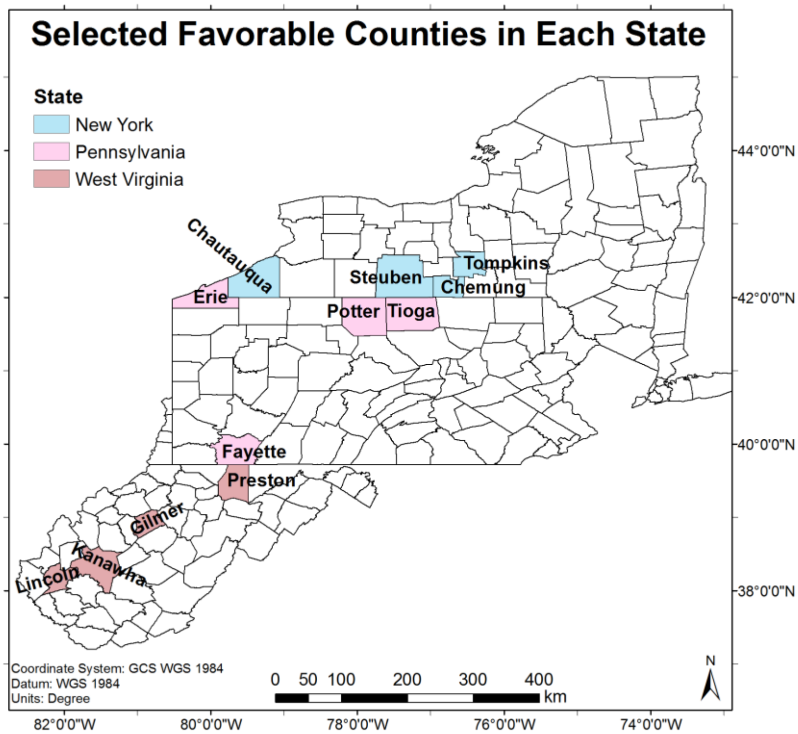

Figure 7: Counties selected for more detailed thermal maps based upon having favorable thermal properties, available reservoirs, and population centers.

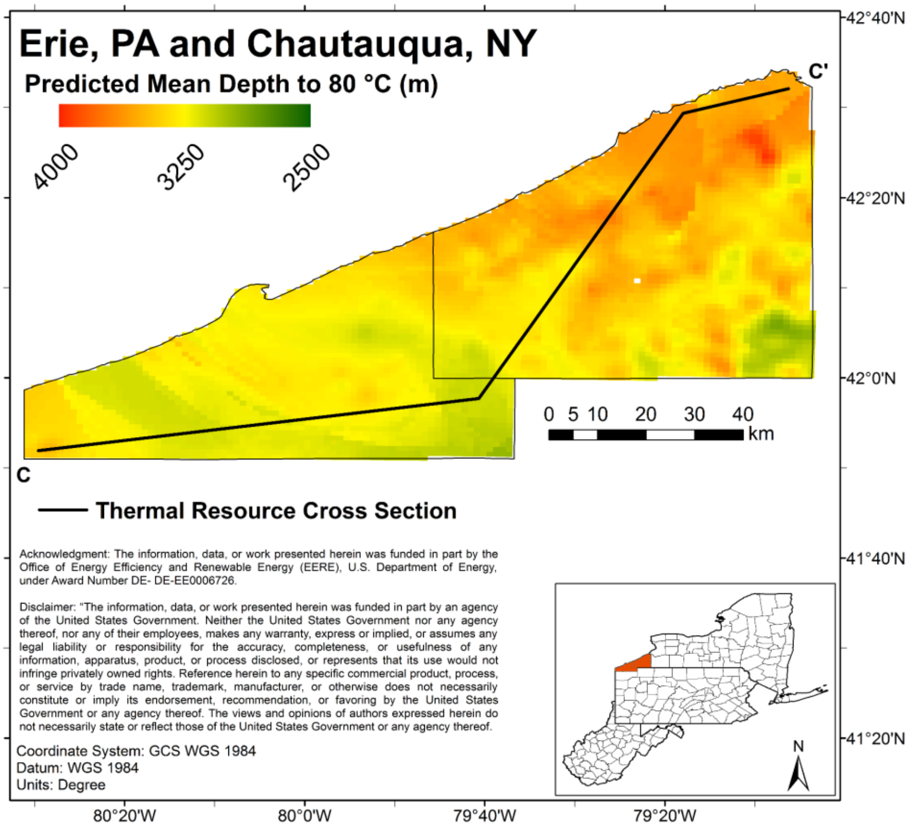

Figure 8: Erie, PA and Chautauqua, NY (Predicted Mean Depth to 80 °C [m]) with Cross Section.

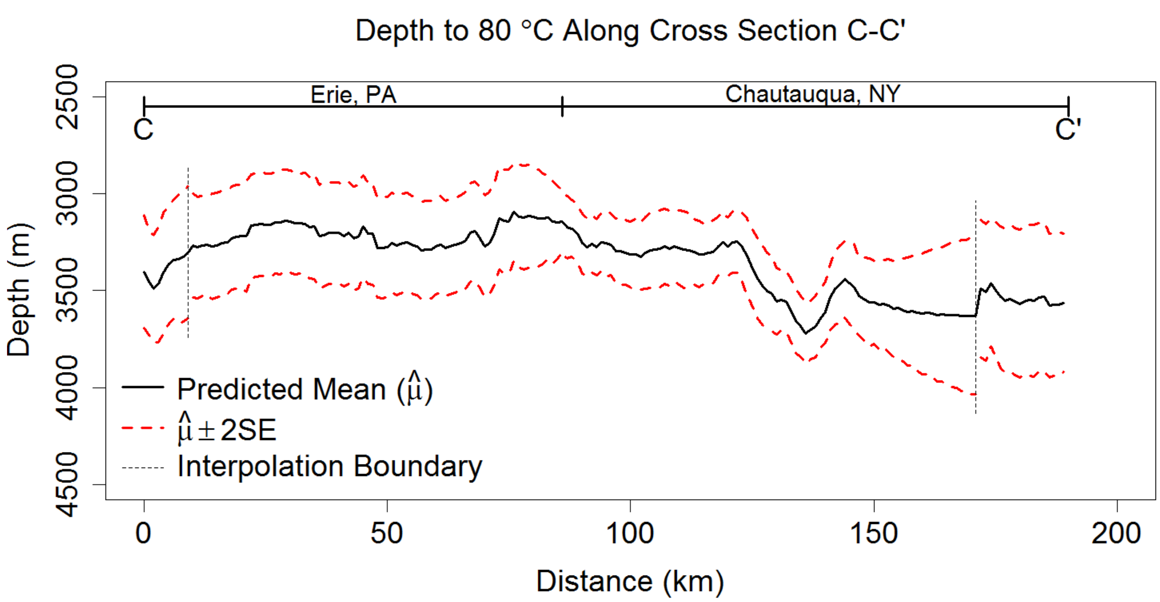

Figure 9: Variability and uncertainty in the predicted mean depth to 80 °C along cross section C-C'. Interpolation boundaries are marked by vertical dotted lines. Mean depths are significantly different when uncertainty bars do not overlap.

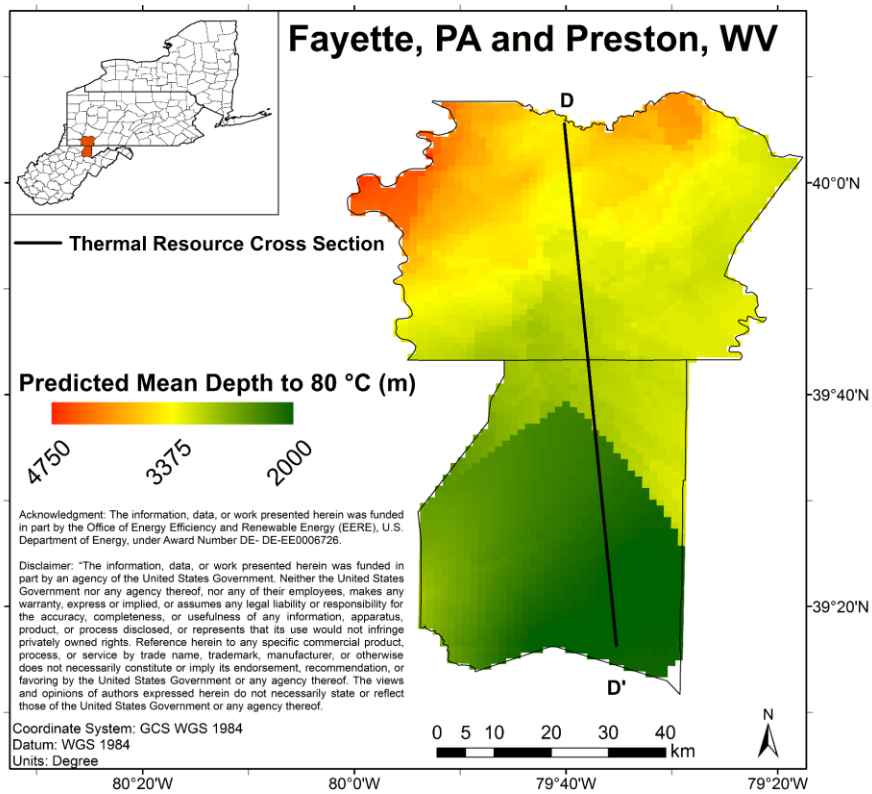

Figure 10: Fayette, PA and Preston, WV (Predicted Mean Depth to 80 °C [m]) With Cross Section.

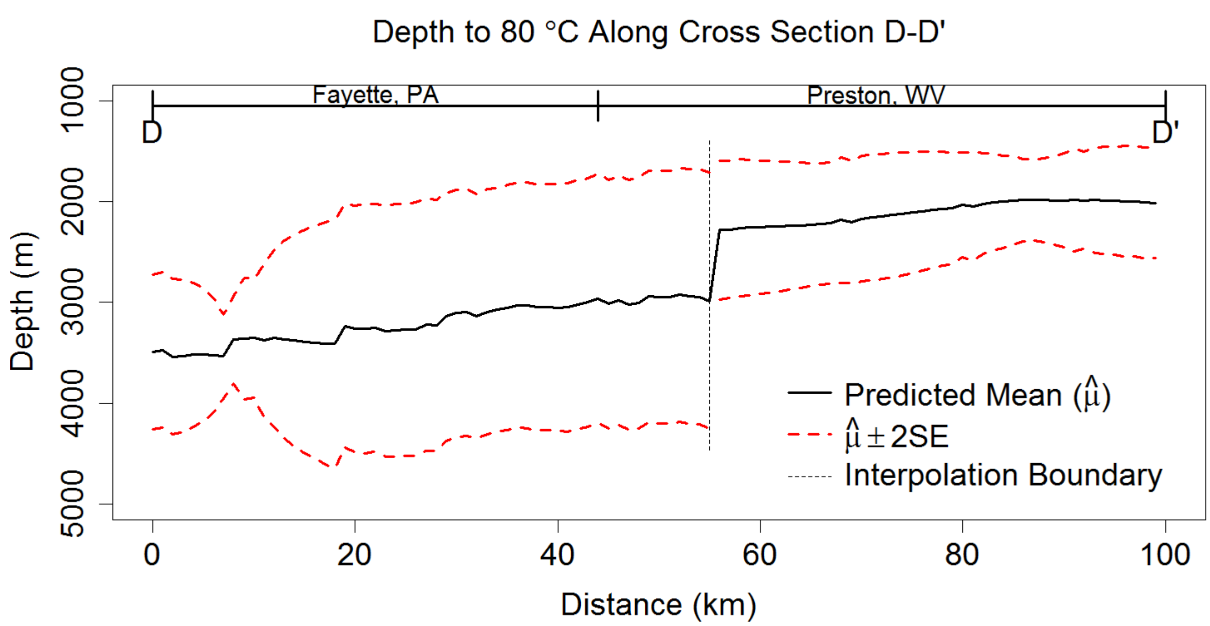

Figure 11: Variability and uncertainty in the predicted mean depth to 80 °C along cross section D-D'. Interpolation boundaries are marked by vertical dotted lines. Mean depths are significantly different when uncertainty bars do not overlap.

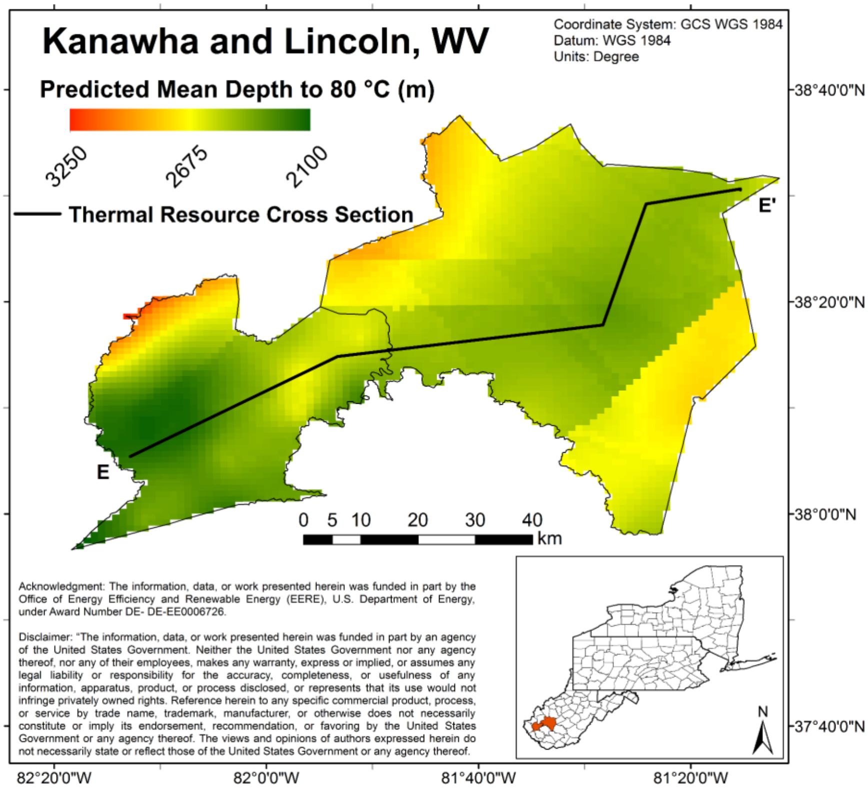

Figure 12: Kanawha and Lincoln, WV (Predicted Mean Depth to 80 °C [m]) With Cross Section.

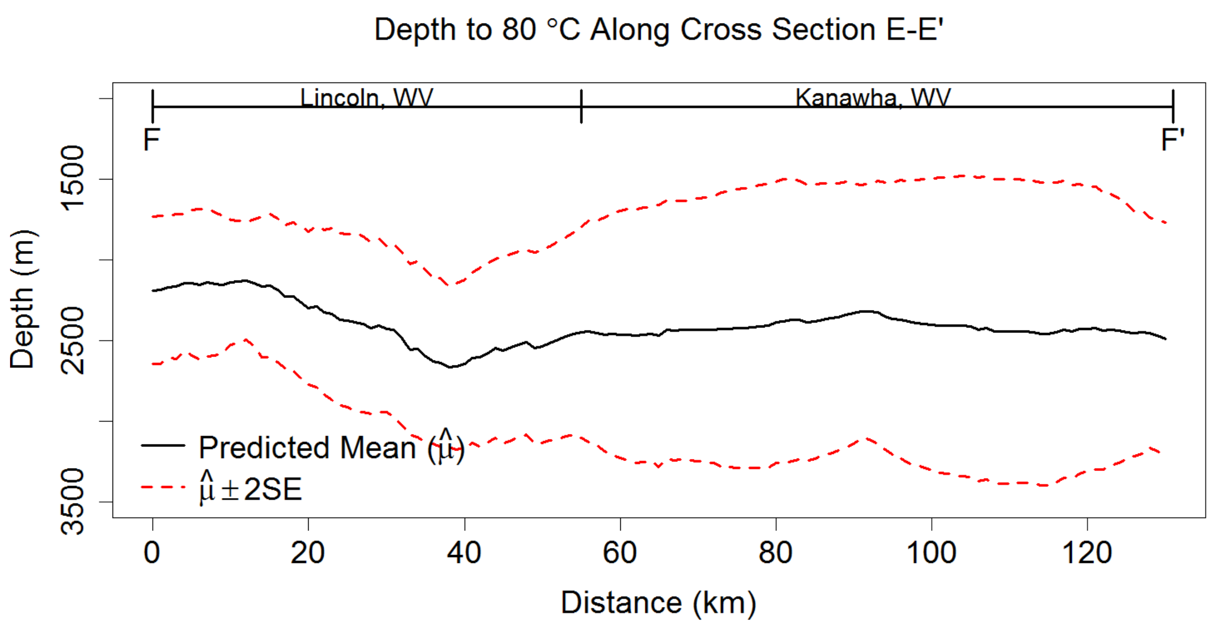

Figure 13: Variability and uncertainty in the predicted mean depth to 80 °C along cross section E-E'. Interpolation boundaries are marked by vertical dotted lines. Mean depths are significantly different when uncertainty bars do not overlap.

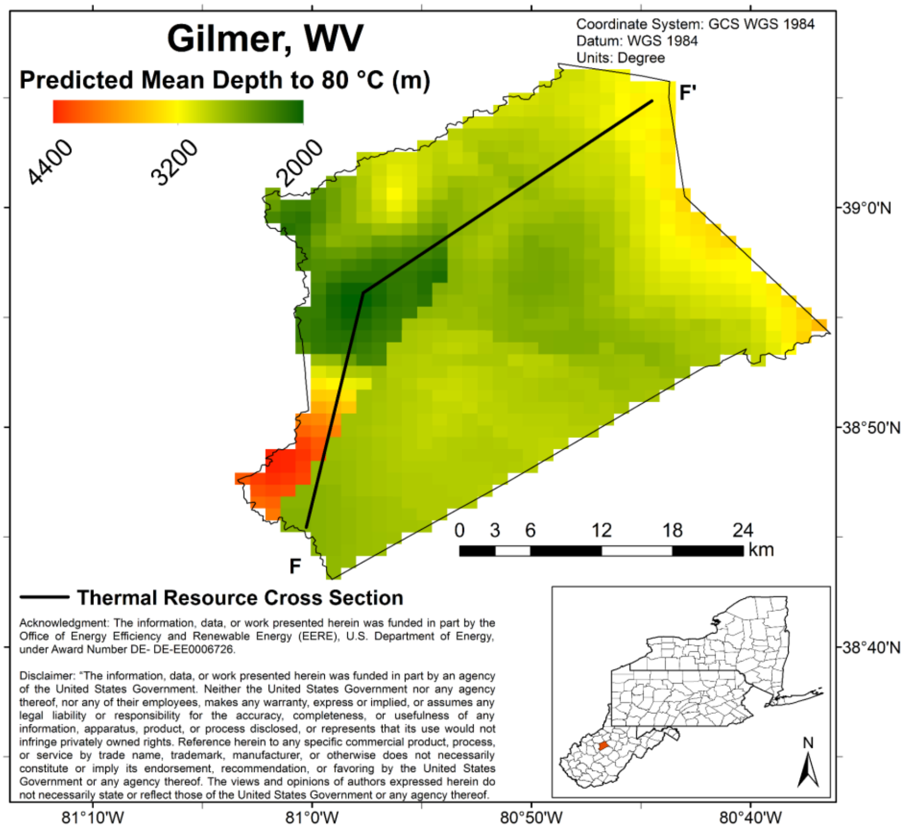

Figure 14: Gilmer, WV (Predicted Mean Depth to 80 °C [m]) With Cross Section.

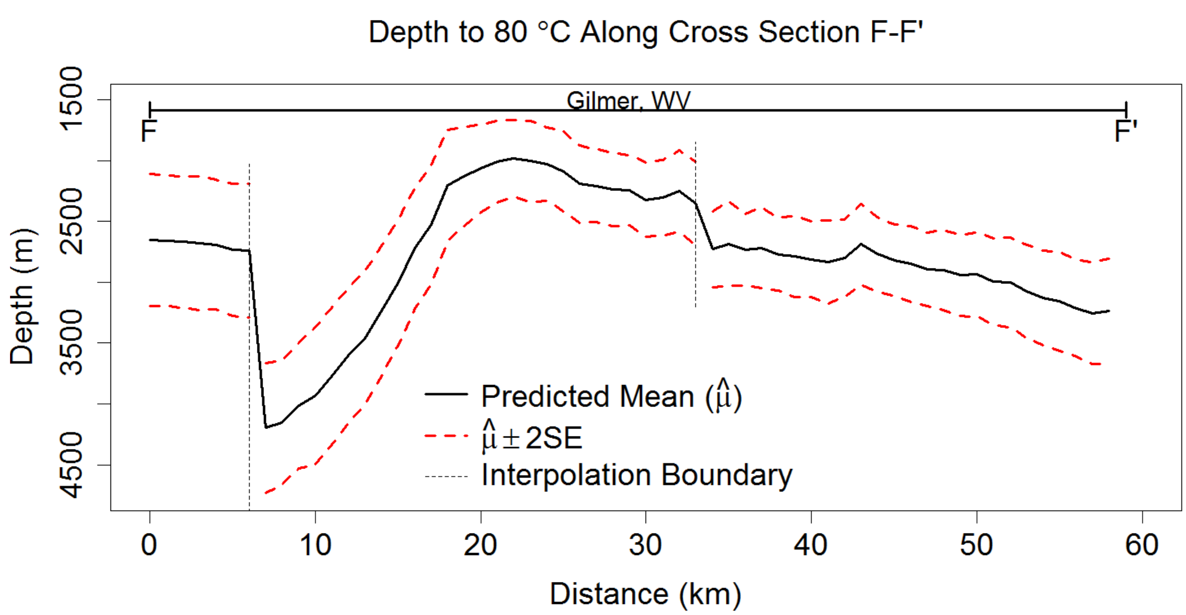

Figure 15: Variability and uncertainty in the predicted mean depth to 80 °C along cross section F-F'. Interpolation boundaries are marked by vertical dotted lines. Mean depths are significantly different when uncertainty bars do not overlap.

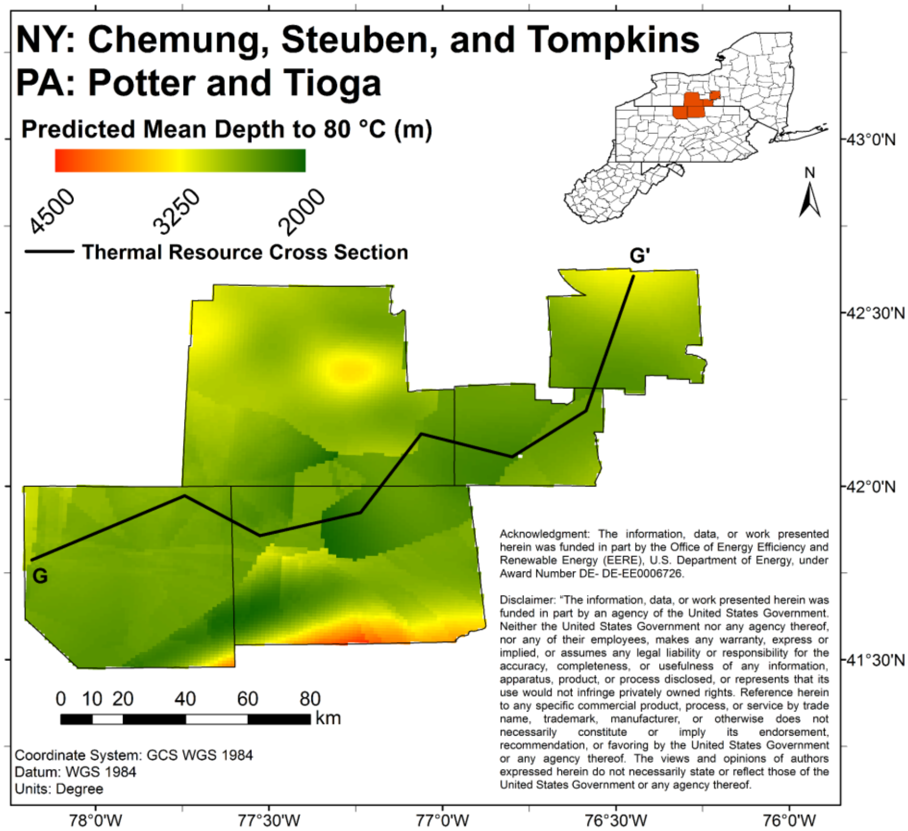

Figure 16: Predicted Mean Depth to 80 °C [m]) With Cross Section for Chemung, Steuben, and Tomkins counties of NY and Potter and Tioga counties of PA.

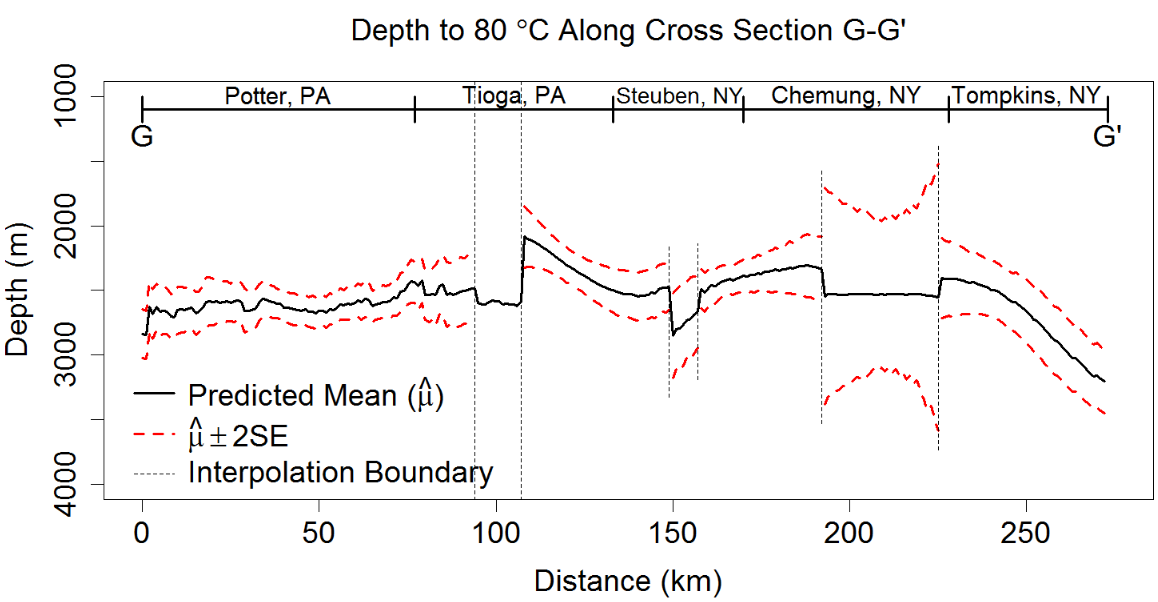

Figure 17: Variability and uncertainty in the predicted mean depth to 80 °C along cross section G-G'. Interpolation boundaries are marked by vertical dotted lines. Mean depths are significantly different when uncertainty bars do not overlap.

One approach to evaluate the confidence in the thermal analysis results is to compare the equilibrium temperature for the subset of 47 reliable wells with data as deep as 1.5 km to the predicted mean temperature at 1.5 km. Figure 18 reveals the number of standard errors difference between the recorded equilibrium temperature at or near 1.5 km and the predicted mean temperature at 1.5 km. Another approach was used to evaluate the results of the spatial regression. This approach was a "leave-one-out" cross validation. For the depth to 80 °C map in Figure 6, over 98% of the left-out wells had a calculated depth to 80 °C within 3 standard errors of the predicted mean at the location of the left-out point – a comforting result.

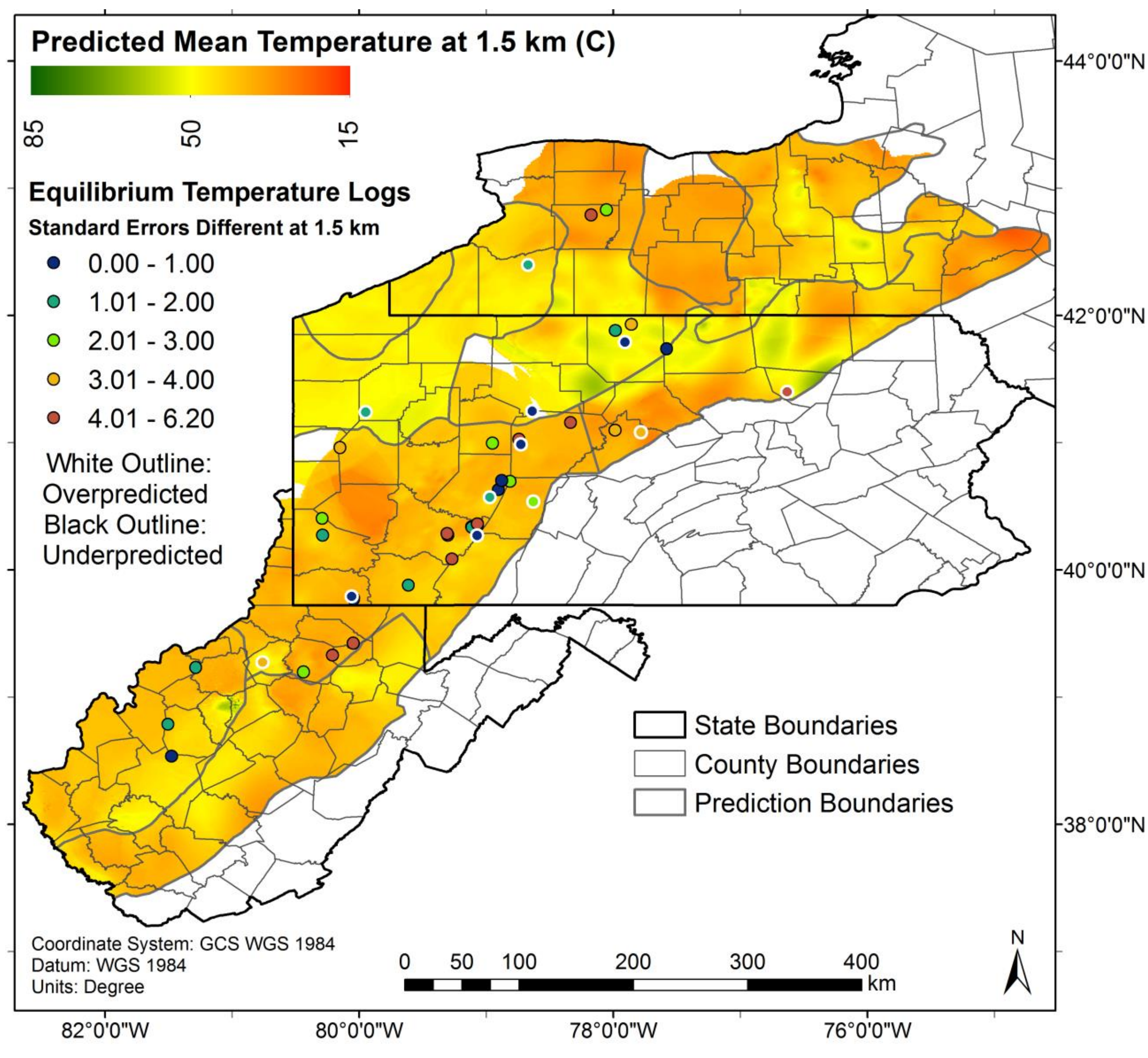

Figure 18: Wells considered equilibrium or having reliable temperature data are compared to predicted temperatures at 1.5 km depth. Colors of circles show differences in measured and predicted temperature at 1.5 km in terms of the number of standard errors that the equilibrium temperature was from the predicted mean.

Challenges

We are aware that to select a site and have it be colder than predicted is much more costly than it being hotter than expected. Thus, as we complete Phase 1 there continues to be an emphasis on the thermal risk factor associated with the BHT correction used and the confidence related to the BHT values as a foundational parameter in the thermal resource assessment. To improve on past projects' efforts, we did not use the Harrison Correction (1983), which only uses a depth-dependent temperature change. Instead, we devoted significant effort to developing a set of sub-region-specific corrections for the Allegheny Plateau and the Rome Trough (the portion in Pennsylvania). A separate correction was also developed for West Virginia. Use of temperature data held by oil and gas companies would permit improved accuracy.

At the project outset we evaluated the possibility of running thermal conductivity measurements on core, but this could not be accomplished within the available resource constraints due to mechanical failure of the WVU divided bar. Further studies to obtain thermal conductivity data for samples of rocks collected at depths of project interest are recommended.

Task 2 Natural Reservoir Quality

The natural reservoirs task required a number of simplifying assumptions due to data compilation issues across state borders and data availability limitations. Additional simplifying assumptions underpin the computation of a reservoir productivity index. All assumptions made are listed within the Natural Reservoirs Methodology Memo in the Catalog of Supporting Files.

This project has incorporated the available reservoir parameters (permeability, thickness, water viscosity, and area) in order to make a meaningful comparison of the potential flow rates from the reservoirs in a sedimentary basin. While not explicitly required in the SOPO, we developed a metric for quantifying reservoir favorability, built around the steady state Dupuit equation for dual-well dipole flow through porous media in a confined aquifer (Gringarten, 1978; Augustine, 2014). The metric, a Reservoir Productivity Index (RPI), reports volumetric flow rate per pressure drop (Liters per Megapascal seconds; L/MPa-s). A Monte Carlo simulation was used to calculate each reservoir's RPI, while taking into account the uncertainty on parameter values (e.g., reservoir permeability, thickness, depth, and area).

In order to meet the required flow rates without any additional stimulation or enhancements, we estimate that >10 L/MPa-s value for the reservoir productivity index is required. The majority of the reservoirs we have identified are below this value Figure 19. On a map, areas with dark green color indicate locations with this most suitable value of reservoir productivity index Figure 20)The spatial distribution of reservoirs of varying quality is partly expressed in Figure 20 although some regions have stacked reservoirs of differing qualities, and these are not well expressed on a single map.

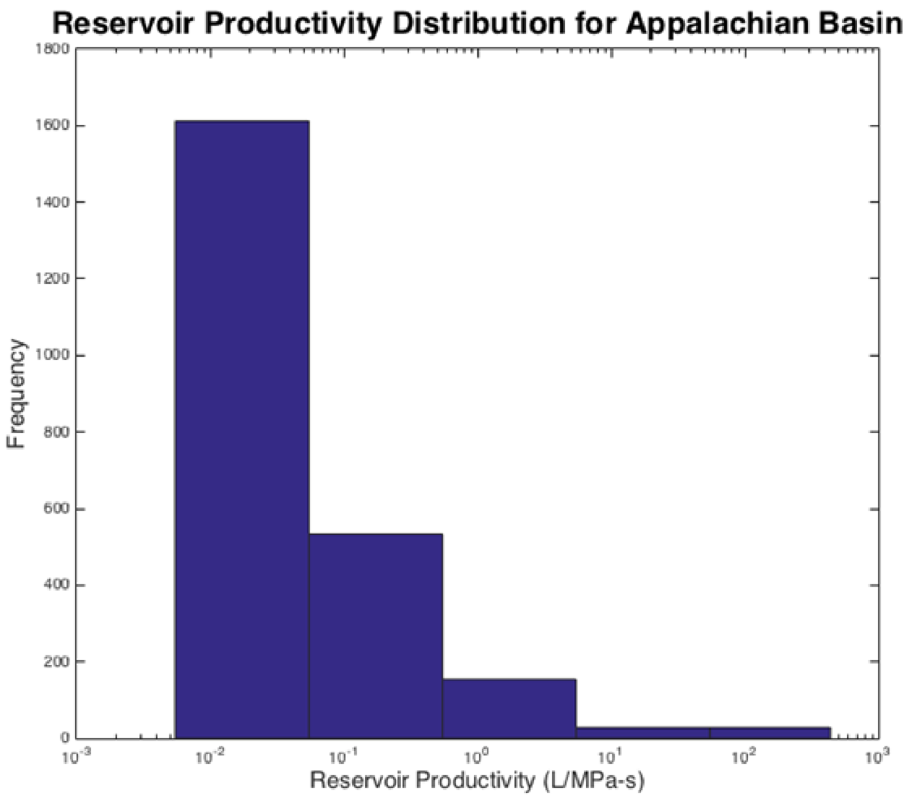

Figure 19: The distribution of reservoirs in the Appalachian Basin ranked by the determined Reservoir Productivity (logarithmic values of L/MPa-s).

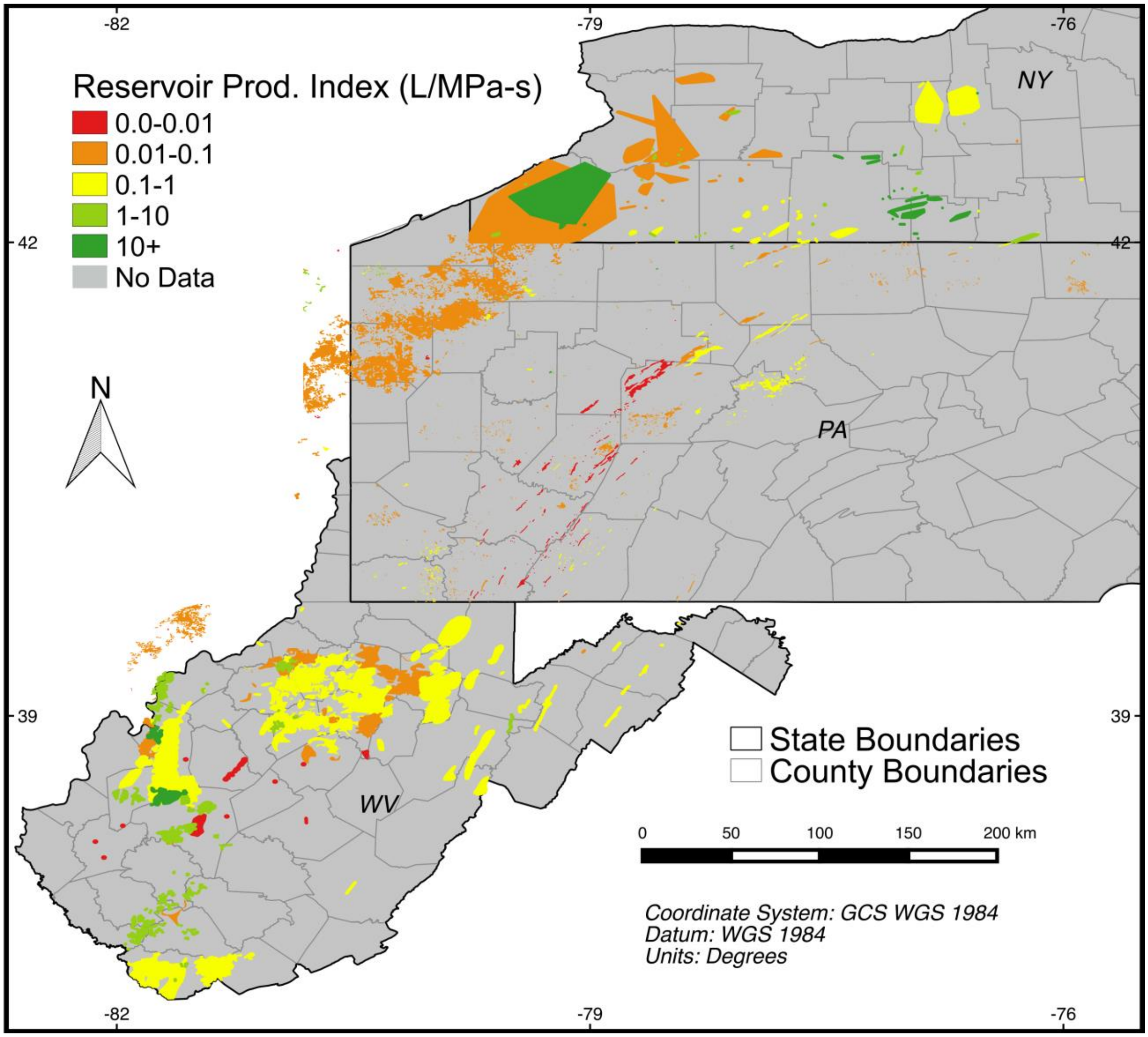

Figure 20: Distribution of reservoirs of varying degrees of favorability as measured by the Reservoir Productivity Index. The gray areas indicate regions without suitable data, because of the data bias toward oil and gas production. Within the gray areas there may exist high quality natural reservoirs, and undoubtedly there exist regions without suitable natural reservoirs. To discriminate those two cases in the areas without oil or gas fields requires analysis beyond the scope of Phase 1.

Challenges

The Natural Reservoir Analysis followed the SOPO tasks and methods as planned. Reliance on rock property information from the oil and gas industry imposed a location bias in the data sets. Suitable hot-water reservoirs may occur outside of the oil and gas fields, but to identify them will require time-intensive analyses of well records and the development of geological models of the controls on matrix permeability and fracture permeability.

In working with low-temperature geothermal resources, the potential reservoir flow rate is of utmost importance (Bedre & Anderson, 2012). The project team concludes that the knowledge available falls significantly short of what would be needed to predict at any given location whether a high enough fluid flux to support a district heating system can be extracted without stimulation. We recommend future studies to improve on the capacity to estimate flow potential by collecting data on production, injection, flow-back tests, and pressure tests in the most attractive prospective plays, to the extent that these data can be obtained from regulatory bodies, private companies, and data brokers.

This project analysis of natural reservoirs included more parameters than previously reported in the existing National Geothermal Data System (NGDS) content model for Geologic Reservoir Analysis, developed by the Texas Bureau of Economic Geology. One new parameter is "Reservoir Productivity Index" (RPI), a new metric adapted from the productivity index of a well, in units of L/MPa-s. Instead of simply adding a field called RPI to the existing content model for Geologic Reservoirs, we updated the entire content model and added flexibility for numerous types of analysis projects to provide relevant reservoir data. Researchers can now use the content model to report "*Reservoir Favorability*" and describe the units and methods associated in their analysis – in our case RPI in L/MPa-s. This is just one example of many such updates; the revised NGDS Geologic Reservoir Content Model is now available on USGIN (U.S. Geoscience Information Network, 2015) for others to use.

Task 3 Risk of Seismicity

The seismic risk factor analysis was initially aimed at determining whether a candidate location is near an active fault, and thereby potentially susceptible to induced seismicity from geothermal operations. Existing fault maps do not share the GPFA-AB boundaries or scale. Hence, their use leads to problems of uneven coverage, varying interpretation of faults vs. lineaments, and different mapping scales. For more uniformity across the GPFA-AB region, we use a Poisson wavelet analysis of gravity and magnetic fields, co-invented by Frank Horowitz (Hornby et al., 1999) and widely deployed in the mining industry since the late 1990s (e.g. GoldCorp, 2001).

Multiscale edge Poisson wavelet analyses of potential fields ("worms") have a physical interpretation as the locations of lateral boundaries in a source distribution that exactly generates the observed field – see the Seismic Hazards memo for more discussion. Clearly, not all "worms" are faults, and vice versa, thus only a subset might be active. As the basin is within an inter-plate region, deformation is very slow and return time for naturally occurring earthquakes is potentially >10,000 years. Also, only steeply dipping structures will be expressed by "worms".

To identify seismically active structures, we plotted both the "worms" and the earthquakes from the NEIC and EarthScope TA catalogs. "Worms" within a small distance of epicenters are tracked spatially. To within errors in location, this identifies structures that might be seismically active faults - which we categorize with higher risk than other structures. We called this strategy the "proximity technique" (Figure 21, Proximity Earthquakes).

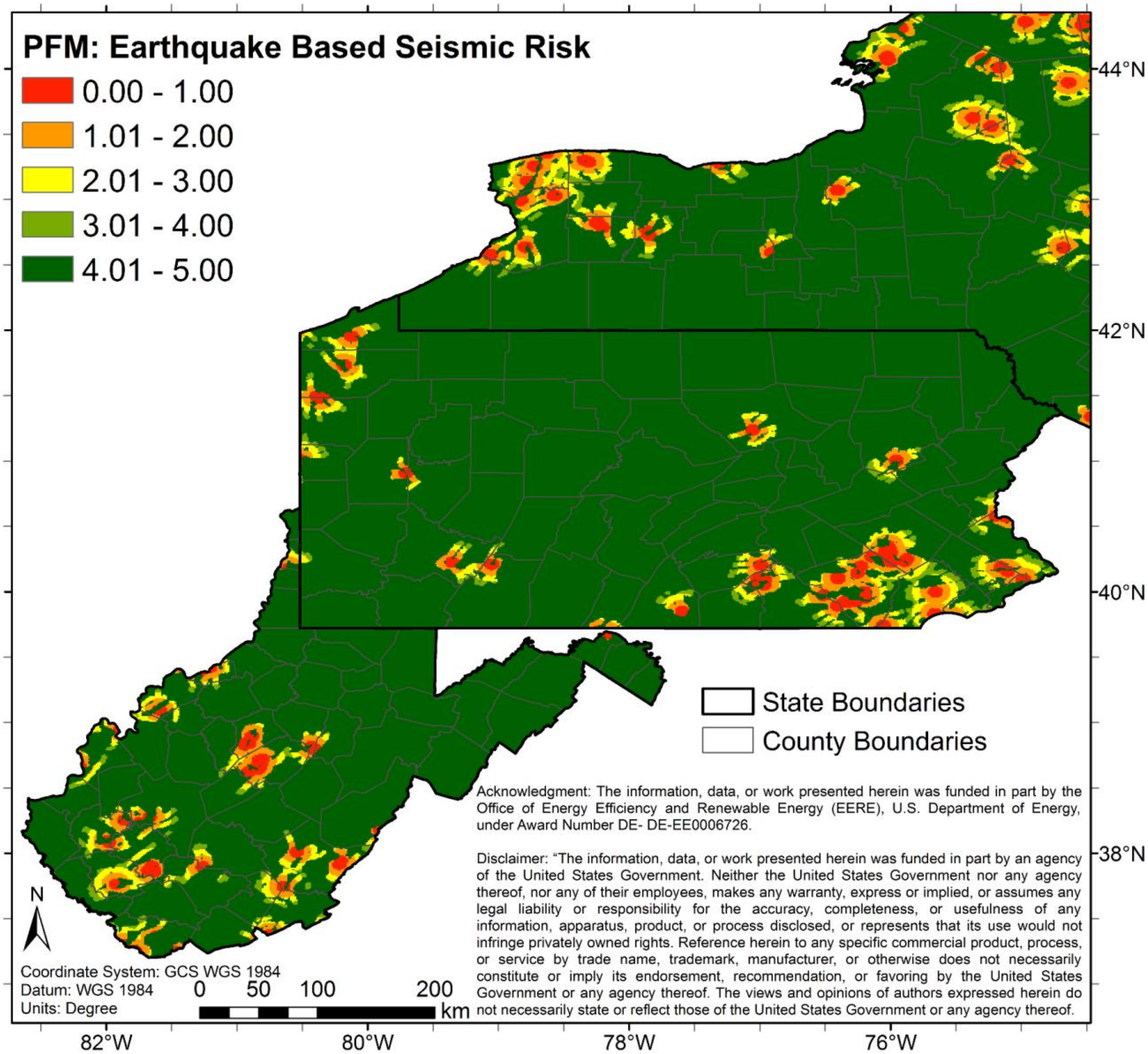

Figure 21: Map of risk of induced seismicity based on the proximity to a recorded seismic event and/or the co-occurrence of a "worm" and a nearby seismic event. Red indicates highest risk; green is lowest risk.

As the project progressed, after discussion with experts both within and outside of the team, we tried an additional approach. Plotting multiscale edge Poisson wavelet analysis lateral boundaries within World Stress Map σ_1 directions (see Catalog of Supporting Files for more information in the Identifying Potentially Activatable Faults Memo) yields an alternative qualitative approach to identifying reactivatable structures. Here, we use "worms" to identify structures with strikes favorably oriented for failure by Byerlee's law (Figure 22, Stress Orientation Hazard). While this might be a necessary criterion for fault activation (under an assumption of the validity of Byerlee's Law model) it *is not a sufficient criterion* - because we lack detailed information about stress magnitudes throughout the GPFA-AB region. This approach is termed a slip-tendency estimate.

Ultimately, we judged that the most useful representation of the total seismic risk resulted from the combined risk map formed by averaging the risk factor categories given by the proximity technique and the slip-tendency technique (Figure 23, Combined Seismic Risk).

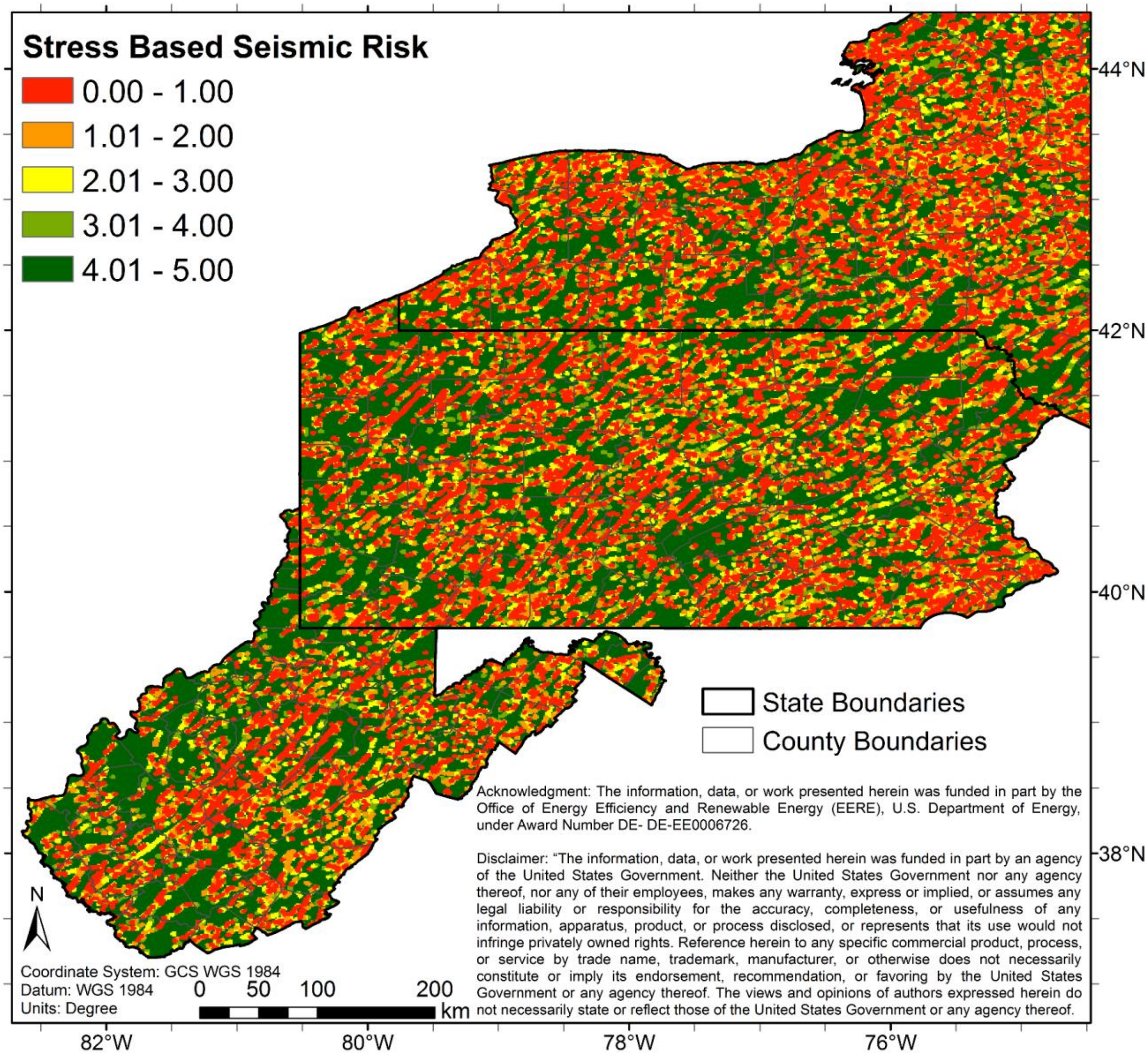

Figure 22: Map of the risk of induced seismicity estimated based on slip-tendency, as calculated by the premises of the locations of planes of weakness relative to the regional stress field. For this analysis, the "worms" are treated as if they are all planes of weakness, and Byerlee's Law criteria used.

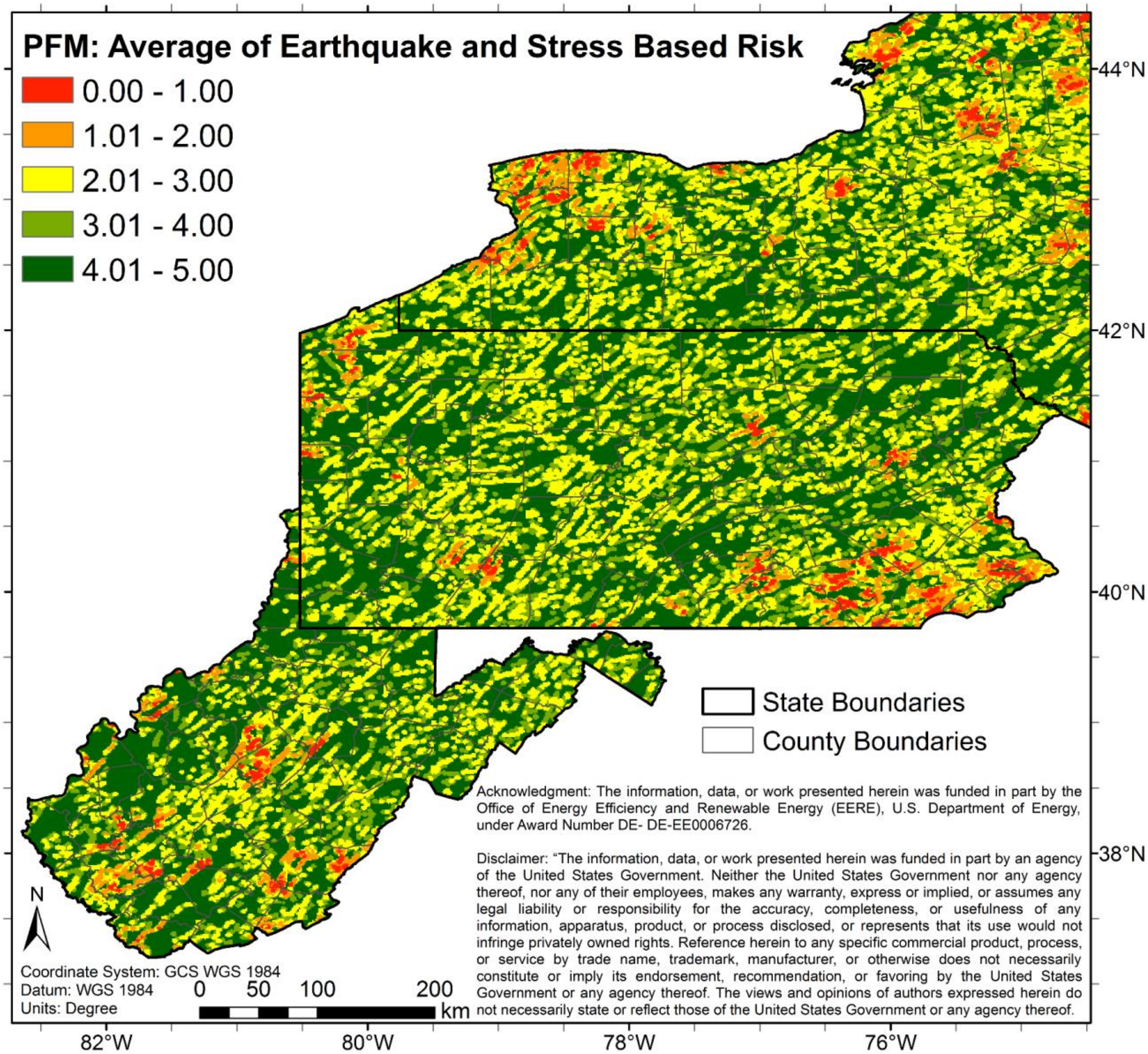

Figure 23: Preferred map of the spatial distribution of risk of induced seismicity, created by averaging the proximity and slip-tendency techniques.

In addition to the summary of the seismic risk method in the Catalog of Supporting Files, the reader should refer to (Seismic Risk Map Creation Methods Memo and the Identifying Potentially Activatable Faults Memo) for a complete discussion of these matters, including an overview of the wavelet theory, the earthquake catalog cleaning, and the computational techniques developed to estimate risks and their uncertainties at all points along the worms.

Challenges

The risk of induced seismic activity is now on many peoples' mind who live within the shale plays across the country. Those living in New York, Pennsylvania and West Virginia are no different. There is concern that the reinjection of water produced during oil and gas extraction will induce seismicity, and it is easy to imagine that a similar concern will be raised about the recirculation of water in a geothermal energy extraction project.

Initially the project had expected to use mapped faults that we anticipated would be available from the state agencies and the USGS. We found that there are extreme differences in the details and styles of surface fault maps within and between the states, making this dataset difficult to use for our basin-scale analysis. To make up for this data layer loss, we focused on generating a spatially consistent map of the gravity-field and magnetic-field variations (Hornby et al., 1999). This analysis located rock-property edges not only in the deeper levels of the sedimentary basin fill, but also in the basement beneath. In light of recent analyses that show that many of the induced earthquakes in Ohio, Oklahoma, Texas, and Kansas associated with oil and gas wells are related to deep basement faults, these new maps should be of value to the oil and gas industry, to geological carbon sequestration researchers and regulators, and to the geothermal industry.

The use of earthquake locations (from USGS/NEIC and the EarthScope Transportable Array (TA)) was chosen as the most direct indicator of areas of most concern. They are, except for in areas of active mining (both surface and deep). The NEIC catalog explicitly categorizes earthquake events, while the TA includes everything recorded and located by the array. The TA database added many more “apparent” earthquake locations, which we initially attributed to the higher sensitivity available from the TA’s closer station spacing than that found in the NEIC. Nevertheless, during our on-site visit to the State Geological Survey of West Virginia, they questioned the significance of numerous TA data located in areas of coal mining. Our experienced team members suggested filtering out TA events that occurred between 7 am and 6 pm, based on the fact that mine blasting is allowed only during daylight hours (Mining Safety and Health Administration, Title 30 CFR). The filtered results indeed nearly eliminated events located in the coal mining regions of West Virginia along with other suspicious locations (e.g., near quarries).

As evaluation of the potential for extraction of deep hot geothermal water advances in the Appalachian Basin, we recommend attention be given to experiences in the oil and gas industry. Lessons learned from their experience may inform successful approaches to avoid issues related to induced seismicity. Even within the single year duration of this project, induced seismicity emerged as a major hazard for the oil and gas industry and therefore the amount of research is escalating. It should be noted that the mapping of the Seismic Risk parameters presented here is at the regional scale. Nevertheless, it has been learned that the induced seismicity risk is highly dependent on the specific location. An early part of focused examination of any location-specific well field and utilization scenario should be to obtain relevant data with which to analyze the seismic background activity, fault locations and orientations, and state-of-stress.

Task 4 Utilization Assessment

The Utilization Assessment used US census data, EIA data and NOAA climate data to estimate the demand and surface costs associated with the delivering hot water to buildings via a single community district heating system, following methods detailed by (Reber et al., 2014). The cost estimates include pipes, pumps and heat exchangers, and the annual demand expectations rely on place-specific climate conditions. The surface levelized cost of heat (SLCOH), which includes costs associated with the surface operations of district heating, were calculated using a software tool, GEOPHIRES (Beckers et al., 2014) which permitted repetition of the analysis for many communities.

The Utilization effort included two broad types of data in Phase 1: 1) residential – community ‘Places’, and 2) site specific users with high heating demands such as universities, industrial users, government facilities, etc. Rather than using the 1500 population minimum as did Reber (2013), a population threshold of 4,000 residents per Place was applied for all three states, to focus on those Places with a sufficient number of users to justify the initial capital investment associated with a district heating system. A second effort was completed that determined >165 site-specific users of high heat loads such as paper mills, wood drying kilns, dairy processing (includes yogurt and milk pasteurization products), college and university campuses, and select military locations.

The GEOPHIRES program was designed to output Levelized Cost of Heat (LCOH). For Phase 1 the team used only the above-ground portion of the GEOPHIRES program. Thus the output is Surface LCOH (SLCOH) (Table 1) and cannot be compared to the usual LCOH of other projects as it does not include the site-specific below-ground costs of drilling and completion of wells, which will depend on flow rates and temperatures. Consequently, the full LCOH will be more expensive per MMBTU than what the Phase 1 products show. A 30-year lifetime for a geothermal field was assumed. In only showing the SLCOH we are able to differentiate the surface costs as distinct from the subsurface costs. For district heating systems already in place, they would not need most of the surface infrastructure. Additionally, using the surface components of GEOPHIRES enables those communities without installed district heating systems to consider the infrastructure costs of a system independent of the power supply (geothermal or natural gas).

Table 1: Distribution of Surface Levelized Cost of Heat (SLCOH) for Census Places with population ≥ 4, 000 within the Appalachian Basin for NY, PA and WV. Of 248 sites evaluated, 12 sites are omitted from this table because their SLCOH values exceeded 25 $/MMBTU.

State	Best Case (Green) \$5 – \$13.5/ MMBTU SLCOH	Good (Yellow) \$13.5 - \$16/ MMBTU SLCOH	Unfavorable (Red) \$16 - \$25/ MMBTU SLCOH
New York	43	21	29
Pennsylvania	57	37	17
West Virginia	22	9	1

The top sites for each of the three states based on the Place analysis methodology described above are listed in Tables 2 - Table 4.

Table 2: Top ten West Virginia Census Places with the lowest SLCOH. Only Places with population of 4,000 and above are included.

County	Census Place Name	Place Population	SLCOH ($/MMBTU)
Lewis County	Weston city	4110	7.0
Randolph County	Elkins city	7094	11.0
Upshur County	Buckhannon city	5639	11.1
Ohio County	Wheeling city	28,486	11.2
Wood County	Parkersburg city	31,492	11.2
Monongalia County	Morgantown city	29,660	11.3
Wetzel County	New Martinsville city	53,66	11.3
Hancock County	Weirton city	19,746	11.3
Marion County	Fairmont city	18,704	11.4
Kanawha County	Charleston city	51,400	11.4

Table 3: Top ten New York Census Places with the lowest SLCOH. Only Places with population of 4,000 and above are included.

County	Census Place Name	Place Population	SLCOH ($/MMBTU)
Cayuga County	Auburn city	27,687	10.2
Erie County	Buffalo city	261,310	11.0
Monroe County	Rochester city	210,565	11.2
Erie County	Kenmore village	15,423	11.2

Erie County	Lancaster village	10,352	11.3
Erie County	Eggertsville CDP	15,019	11.3
Erie County	Tonawanda CDP	58,144	11.6
Oswego County	Oswego city	18,142	11.7
Cattaraugus County	Olean city	14,452	11.7
Erie County	Cheektowaga CDP	75,178	11.8

Table 4: Top ten Pennsylvania Census Places with the lowest SLCOH. Only Places with population of 4,000 and above are included.

County	Census Place Name	Place Population	SLCOH ($/MMBTU)
Indiana County	Indiana borough	13,975	9.9
Warren County	Warren city	9710	11.0
Washington County	Washington city	9710	11.0
Allegheny County	Dormont borough	8593	11.2
Westmoreland County	Greensburg city	14,892	11.4
Westmoreland County	Latrobe city	8338	11.5
Erie County	Erie city	101,786	11.6
Blair County	Altoona city	46,320	11.7
Allegheny County	West View borough	6771	11.7
Allegheny County	Brentwood borough	9643	11.7

Challenges

For a utilization project focused on low-temperature geothermal applications, the temperatures are typically in the range of 50 to 120 °C. For these temperatures to be of value, utilization must occur close to the well field to avoid heat loss.

The Utilization Risk did not change the Reber et al. (2014) methodology; however only a subset of their methodology was most appropriate for the project and transferrable to other future phases of this project. The most significant challenge was to select between the slightly different methods to analyze the costs and benefits of utilization of geothermal fluids for district heating that had been developed in parallel by Cornell University and West Virginia students. Both groups had worked on related projects that expanded the details within the GEOPHIRES program (Reber, 2013; He, 2015). It was determined that the addition of new variables and updates to the MATLAB code would be simpler if Reber's work scheme was applied uniformly across the three-state study area. Reber's files for the still-current 2010 US Census were used, along with the census data for WV. As a result of this work, improvements to the methods and parameter names of Reber's code were made for ease of transferal to other users (see Catalog of Supporting Files for Utilization Analysis Memo).

Because the Utilization team removed the drilling expense component and the geotherm of a site from the analysis of costs of a direct-heating project, the value being mapped is not the Levelized Cost of Heat (LCOH) as originally planned as part of the SOPO, rather it is the Surface Levelized Cost of Heat (SLCOH). In the absence of drilling costs and their dependence on the site geotherm, the population density and climate-based heat demand became the variables of importance for the SLCOH. The impact on the Combined Risk of proximity of a community to a potential geothermal reservoir is expressed in the four-factor Combined Risk Maps.

This Census-based analysis seemed insufficient to express known and imagined cases of individual commercial, industrial, or large private entities who seek sustainable, low-carbon, high capacity, heating or cooling systems. Therefore an additional list was compiled for potential site locations for which further analysis of potential utilization needs is recommended. A further recommendation is that a full analysis of LCOH for several of those potential users be completed.

Task 5 Combined Risk Metric Analysis

The overall risk matrix analysis combined the four risk factors into an aggregate measure of the favorability of different locations, which we refer to as Play Fairway Metric (PFM). We explored several methods of combining the Task risk factors (discussed in more detail in Catalog of Supporting Files, Combining Risk Factors Memo); in the end we generally employed the sum of the four scaled risk factors (SRF), shown in equation 1. Each of the risk factors are scaled to a non-dimensional measure of favorability from their original measure. One critical issue is that we require co-location of the resource with utilization locations; however in practice we expect that the resource can be a small distance (approximately 10 km) away from the utilization center. Therefore, the risk factor for utilization in equation 1 shows that it is a function of the utilization distance, d. Using this method essentially buffered around the utilization locations. Many of the maps contained no data in some cells, for instance reservoirs are not known over the whole areal extent. Therefore only areas with all risk factors quantified at that cell (1 km^2 grid) were ranked in the final map.

$$PFM_{sum} = SRF_{seismic} + SRF_{thermal} + SRF_{reservoir} + SRF_{utilization}(d) \qquad \text{[EQ 1]}$$

In addition to simply calculating the PFM, we also approximated the uncertainty of the geologic risk factors (no utilization). For the summed PFM, the variance of the sum is simply the sum of the variances because we assumed that errors in the individual risk factors are uncorrelated. This gave both a mean and an uncertainty variance for each of the areas.

$$\mathrm{Var}(PFM_{sum}) = \mathrm{Var}(SRF_{seismic}) + \mathrm{Var}(SRF_{thermal}) + \mathrm{Var}(SRF_{reservoir}) \qquad \text{[EQ 2]}$$

Although the combined risk maps are useful, the ability to compare many locations at once on a site-by-site basis is also important. As an example of what is possible with the PFM analysis, we compared a small subset of potential sites to assess the individual Task Risk Factors that produced the final combined site PFM value for a site (Figure 24). At these same locations we computed more detailed measures of the uncertainty and generated boxplots that show the uncertainty in the individual risk factors for a site (Figure 25). This is type of additional review will enable decision makers to understand if some projects are more or less appealing based on the uncertainty associated with different risk factors and the potential importance of that uncertainty. Multiple decisions makers may have different attitudes towards uncertainty, and uncertainty may be more or less important for varying types of projects.

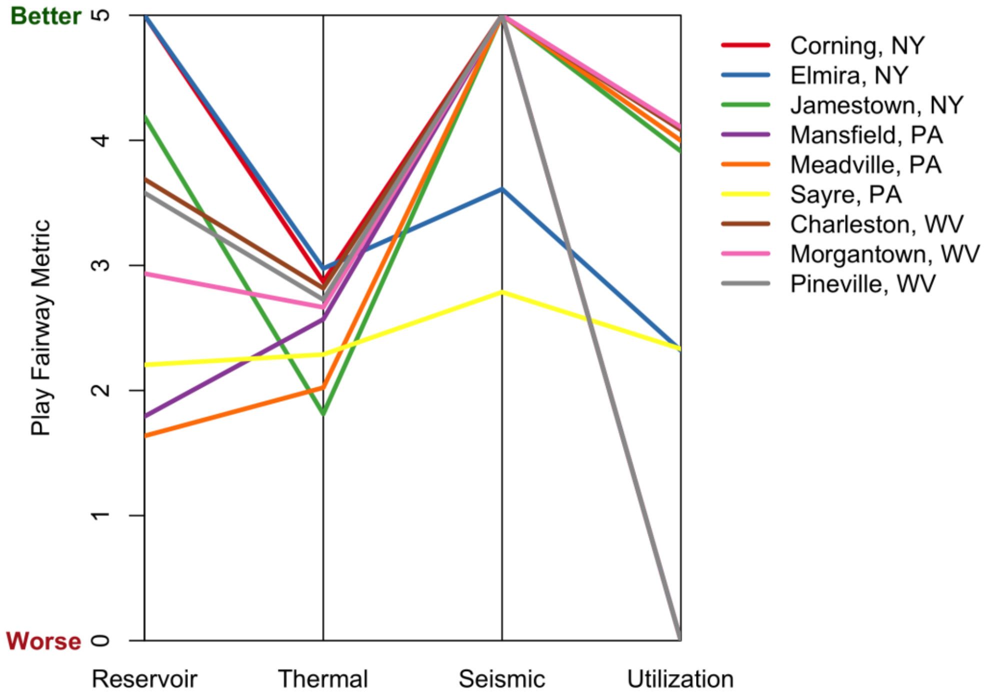

Figure 24: Example of a parallel axis plot for nine illustrative project locations. The plot emphasizes which sites tend to perform better on the metrics or if there are tradeoffs between objectives.

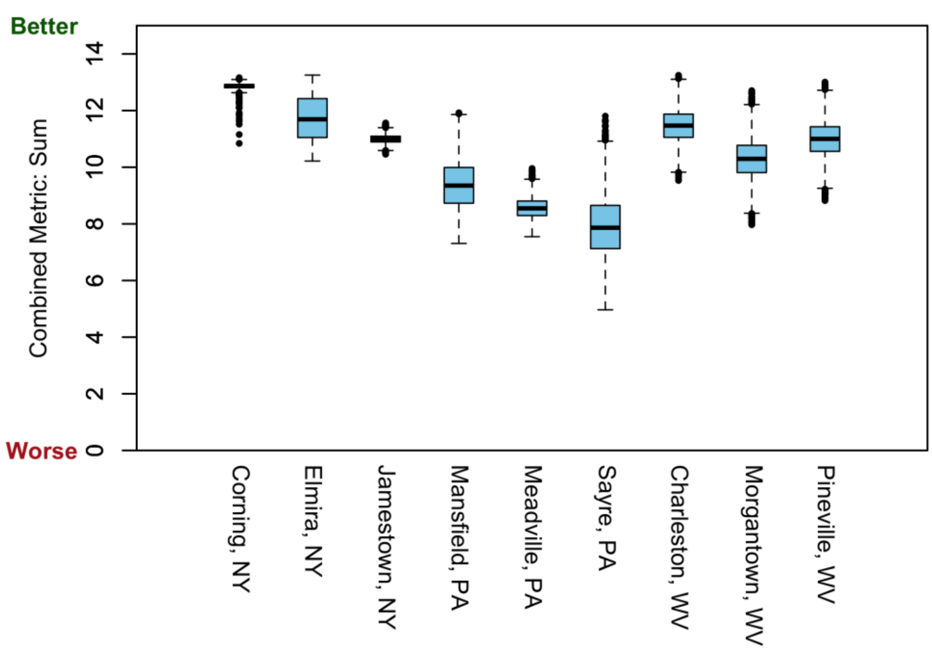

Figure 25: Boxplots of the estimated empirical distribution of favorability for the three geologic variables for nine illustrative project locations. The distribution at each site reports the results of a Monte Carlo simulation. The box is defined as between the 25th and 75th percentiles with a line at the median. The whiskers extend to

the most extreme observation that is within 1.5 times the interquartile range from the upper or lower quartile. Points outside the whiskers are plotted individually.

Challenges

Any attempt to combine different dimensions of a project, without a complete physical and economic analysis for a site, will involve critical approximations. A strength of the simple 4 risk factor analysis is that it provides several maps that could represent different ways a decision maker might consider combining the four risk factors. The values of each factor can also be represented spatially, which gives insight into where different factors are favorable. This allows identification of potentially favorable locations. Once a few especially attractive locations are identified, the decision maker can be presented additional site-specific information including the uncertainty distribution of the four risk factors and of the combined metric.

This analysis is limited in several ways. First, there are no existing geothermal district heating systems in the Appalachian Basin study area, and therefore no test cases against which to compare our combined risk metric. Second, the combined PFMs are only relative representations of favorability because there is no unified economic model, and the thresholds are not uniformly specified across risk factors. If there was information on the economic costs of seismic insurance, for instance, then this could be incorporated into a single model; but this is not feasible in a preliminary screening analysis. We have implied equal weighting, but some risk factors might have disproportionate impacts on the economics of a project.

Thresholds were not uniformly assigned from one risk factor to another. For instance, a value of 2 in thermal does not imply the same level of favorability (likelihood of success) as a value of 2 for seismic. The thresholds used in scaling are relative rankings. Thresholds are reasonable measures of general favorability, but they will cause the result to only represent relative favorability in the combined PFMs.

The uncertainty of the values were assigned to each risk factor based on professional judgment of the people who analyzed that risk factor. Therefore, our estimates of the uncertainty of the combined metric also represents the assessment of the developers as to the relative precision of different factors. The intent of the uncertainty analysis is to honestly represent the precision of the analysis as understood by those who performed the calculations, and to improve the characterization of the uncertainty associated with the recommendations to direct additional investigations.

Utility of the Methods for Application at other Sites

From the onset, the Geothermal Play Fairway Analysis – Appalachian Basin (GPFA-AB) team emphasized a detailed regional study with a premium on developing methods that were transferable to other areas of interest (see Catalog of Supporting Files). Geological examples include widely available datasets and a detailed description of methods. The Utilization effort focused on two categories of direct use that are widely applicable, first to residential and community users and second to high heat-demands users such as universities, industrial processes, government facilities, etc. The methods and assumptions are extensively described in a series of memos (listed in the Catalog of Supporting Files). Numerous Tier 1, 2 and 3 data are being submitted to the National Geothermal Data System (NGDS) via the Geothermal Data Repository, as described in the Catalog of Supporting Files.

Commercial Viability of the Play

Phase 1 results for the best Play Fairways in the Appalachian Basin enhance commercial viability by reducing risk of development. Additional study is vital to address the economic viability of geothermal district heating of any given location in the study area. Recommendations for work to assure commercialization is laid out in the Catalog of Supporting Files.

The Phase 1 analyses clearly indicate the presence of a low temperature geothermal resource. The thermal analysis indicates useful temperatures can be accessed at reasonable drilling depths (e.g., 80 °C can be reached between 1,000–3000 m depth in 30% of the Appalachian Basin (Figure 6). With some important local exceptions, the reservoir rock are of low inherent porosity and, by inference, permeability, at these depths. The reservoirs that have high possibility for natural productivity should be targets for immediate follow-up research. Elsewhere that the thermal resource quality and utilization opportunities align, the reservoirs either lacked data for characterization, or stimulation would be needed, as it has been for many decades of hydrocarbon extraction in the basin. While the available flow rate at depths of interest is not yet fully understood, the investment return analysis must consider the possibility of costs associated with both initial stimulation and ongoing circulation of fluids at relatively high flow rates to support a closed loop district heating system of sufficient scale to justify these costs.

While these costs are significant, the threshold for alternative energy sources in the study area is higher than the nation as a whole. The study area includes New York, with 2014 average retail price of electricity 156% of the national average. While Pennsylvania as a whole is just under the national average, both the residential and industrial sectors exceed the national average at 107% and 106% respectively. West Virginia actually pays less than the national average for electricity, but there are substantial environmental benefits associated with shifting a portion of West Virginia's electricity generation and consumption from coal (~80%) to cleaner alternatives. In this region, heating accounts for the primary electricity consumption. Because of this, district heating is proposed as the most economically justifiable use of the low temperature geothermal resources.

When analyzing the utilization risk factor, which is essentially the first stage of an economic analysis, the team considered scenarios that favor economic viability. For instance, because the up-front capital investment is significant, the utilization calculations intentionally excluded very small (population <4,000) municipalities that might otherwise be suitable in terms of the geological characteristics. Distance between resource (production wells) and consumers is also treated as an important economic factor, through both the impact on costs of piping and on heat loss. Many of the largest population centers within the study area are surrounded by suburban areas. Those suburbs have a large population and may be more suitable for siting a geothermal well field in a neighboring rural area within 10 km distance. Some potential consumers of the heat may have motivations beyond the cost of heat per BTU, such as independence from the utility grid, commitment to renewable energy, or atypical needs for heat such as an industrial or agricultural application. Our analysis does not quantify those benefits.

The primary environmental hurdle is believed to be seismic risk. This was addressed as one of the major factors in determining the viable plays. Other environmental factors, such as wetland protection, should be able to be addressed through proper engineering design, community education efforts, and permitting. The circulating geothermal fluids at the surface are presumed to be a closed loop system, with reinjection of all volumes produced, engineered to have casing in the upper portions of the wellbore within reach of fresh water aquifers and/or the water table. The target temperature of 80 °C would rarely be reached shallower than 1,000 m, which is likely deeper than drinking water aquifers. One environmental factor that has not been addressed during Phase 1 is the water needs associated with supplying necessary flow rates through the reservoir rock. Studies of water system risks related to high volume hydraulic fracturing have demonstrated that the availability of water in New York, Pennsylvania and West Virginia is not among the more important limiting environmental factors, though of course water supplies need to be planned and the extraction from certain streams avoided (Rahm and Riha, 2012; 2014).

An initial effort at understanding the permitting requirements was completed as shown in the Permitting Memo, but calls for further review as part of the well site selection work. Geothermal energy extraction regulations are not established in NY, PA and WV, except for geothermal heat pumps, creating limited levels of legislative clarity concerning the deeper geothermal resource. For example, in Pennsylvania and West Virginia it has not been designated if geothermal energy is a mineral right or a surface right. In New York, it is not legislatively designated as a mineral, but it is at least listed as a type of drilling under the oil and gas permitting section. As a future effort, it is recommended that test scenarios be worked through the permitting process of the deep geothermal wells with the appropriate agencies to educate them and then assist them in expanding their forms and the permitting process. Further details are given in the Catalog of Supporting Files.

Possible heat resource users (>165 sites) in addition to Census-identified "places" have been identified in the three states. For three cases, explicit interest in extraction of geothermal heat in the temperature range investigated in this study has been brought to the team's attention. For instance, the West Virginia National Guard is interested in pursuing alternative sources of onsite energy at military bases, motivated by the security associated with grid independence. The Cornell University community has adopted a Climate Action Plan, pledging to become carbon neutral by 2050, and there is interest in accelerating this to completion by 2035. West Virginia University is poised to upgrade an aged campus direct heating system, previously supplied by steam from a nearby coal-fired power plant under a contract that expires shortly, with a new heat source, and is considering geothermal energy among the options. More generally, the city of Pittsburg, Pennsylvania participated in the DOE August Direct Use Workshop and has undertaken many energy efficiency initiatives with programs like Sustainable Pittsburg and the 2030 District[1].

METHODOLOGY

The methodology applied to the Appalachian Basin Geothermal Play Fairway Analysis is described generally in this section, and more thoroughly in the Methodologies discussion found in the Catalog of Supporting Files. Additional details can be found in the 18 'Project Memos' found in the Catalog of Supporting Files of this report.

The overarching process involved evaluation of each risk factor, resulting in 4 risk segment maps and 3 maps of uncertainty (the Utilization map was assigned the same uncertainty value for the entire basin and thus not mapped) (Figure 26-Figure 31). Following this, the 4 risk factors were combined into a single favorability map. The Catalog of Supporting Files discusses the methodology for computing each of the four risk factors as well as the combination effort, touching on: a summary of the strengths and limitations of the process, mathematics used, potential sources of error, software used, and the results of any testing used to demonstrate satisfactory model performance. Hyperlinks to specific Memos are inserted within the Catalog of Supporting Files text for more information on mathematical formulas and calculation methods, potential sources of error, details on the software used (such as version and hardware requirements), and code verification/validation, sensitivity analyses, history matching with lab or field data, as appropriate.

A key assumption central to the project is the understanding that this particular play fairway analysis is focused on low temperature and/or direct use applications. The Appalachian Basin, like much of the contiguous U.S., has relatively average continental heat flow (Blackwell and Richards, 2004),. While not hot enough for traditional hydrothermal power generation, the basin is expected to be warm enough for a reduction of power load through direct use applications such as district heating (Reber, 2013). Despite the

[1] http://www.pittsburghpa.gov/green/energyefficiency.htm

fact that these low-temperature systems can have a lower initial capital requirement than a large hydrothermal power plant, understanding where they will be most successful is critical.

The oil and gas industry has utilized Play Fairway Analysis as a means to site oil and gas well drilling in the most advantageous locale, within resource constraints. This project strives to use a similar approach. The four primary risk factors identified as critical to the success of a low-temperature geothermal project (e.g., quality of the thermal resource, potential for natural reservoir flow, induced seismic risk, and demand for the geothermal resource) are not considered to be a complete list of requirements. Indeed it is intended that a 'down select' based on these initial four criteria will allow later focus of more costly stages on only the most advantageous locations. This Geothermal Play Fairway project proposes identifying sub-regions worthy of the next stage activities (exploratory drilling and/or additional well logging, permitting due diligence, negotiation of project partnerships, funding avenues, etc.).

The project workflow consisted of a series of seven overlapping tasks, each with various subtasks, designed to analyze the play fairways. The first four tasks were specific to the four risk factors. Task 5 evaluated the combined risk, to identify candidates for continued Phase II activities. Task 6 encompasses project management and Task 7 provides for sharing Phase I plans and results.

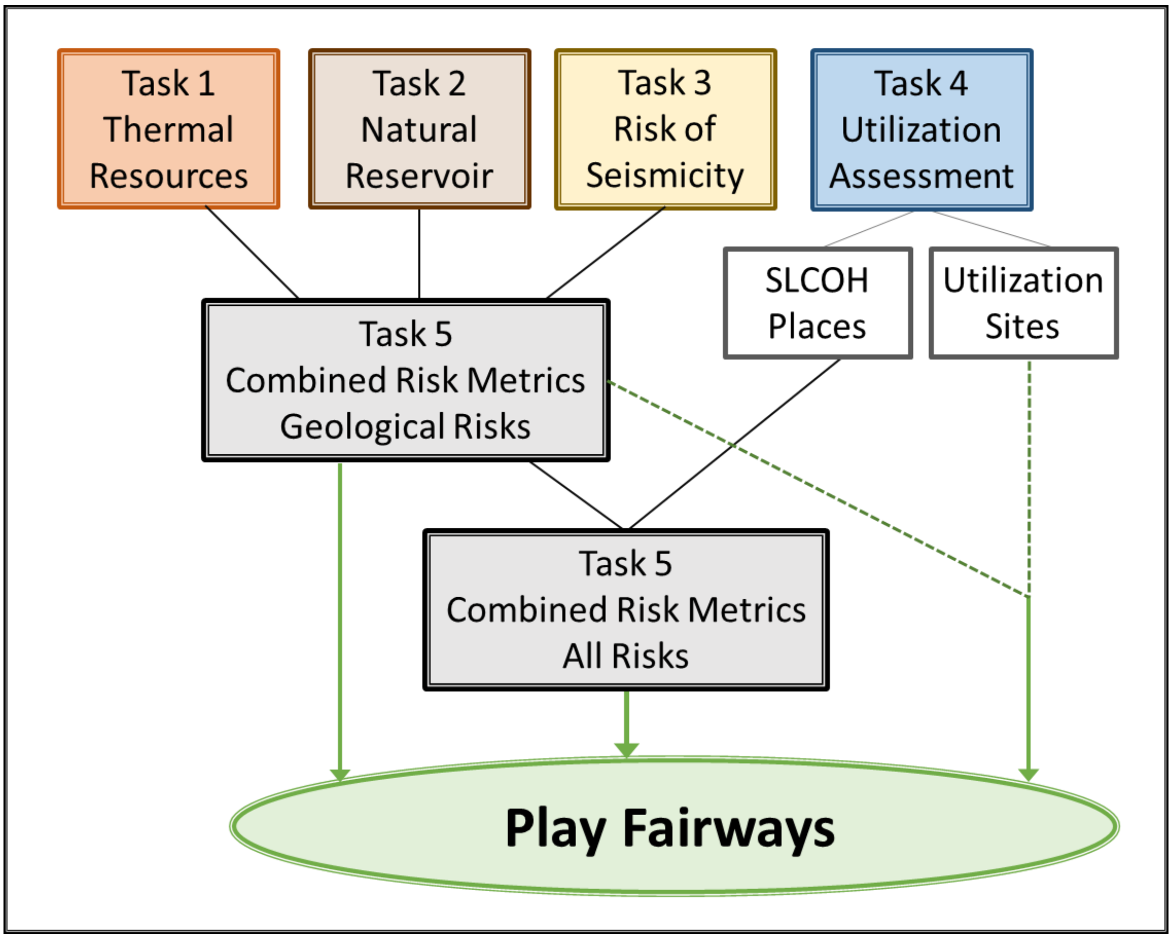

Figure 26: Appalachian Basin Geothermal Play Fairway Analysis Process. Each of four key risk factors studied in the context of favorability and uncertainty were combined using Play Fairway Metrics (PFM) to create final Play maps and overall basin risk.

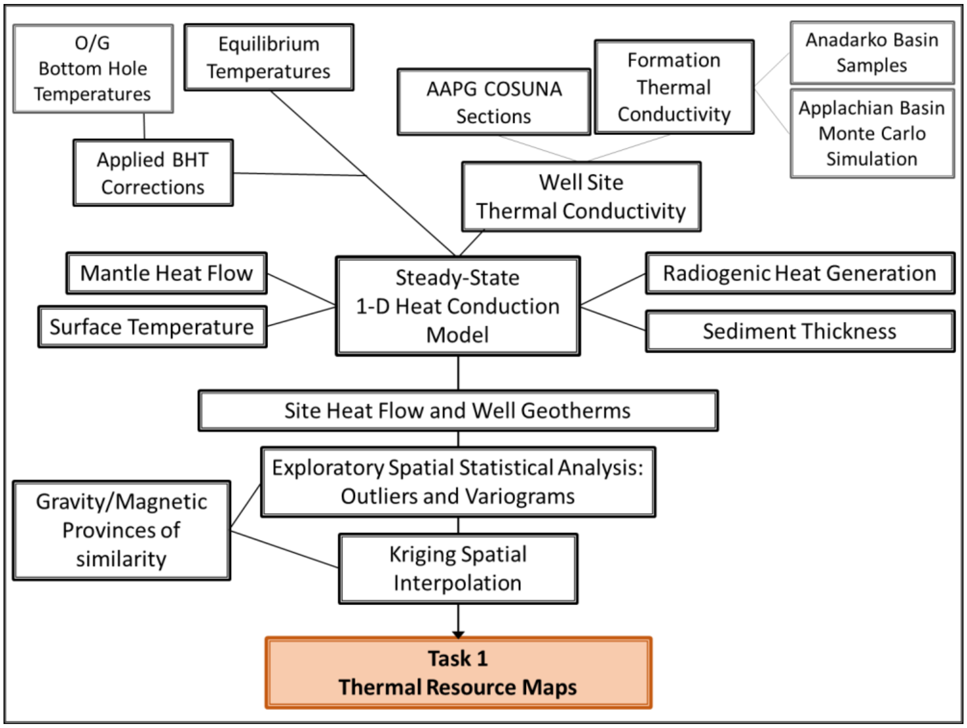

Figure 27: Flow chart for Task 1 Thermal Resources Risk showing primary data and overview of steps.

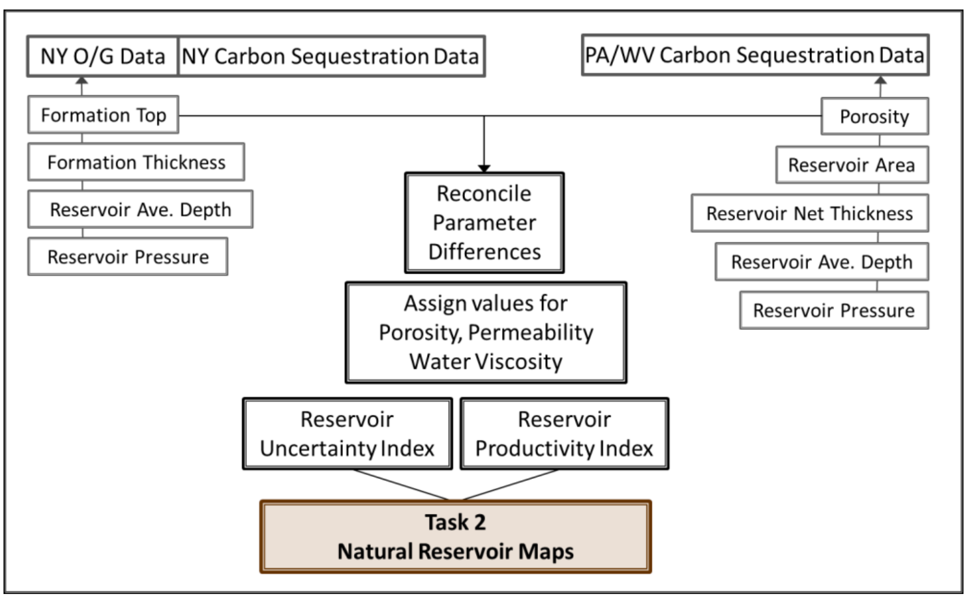

Figure 28: Flow chart for Task 2 Natural Reservoirs Risk showing primary data and overview of steps.

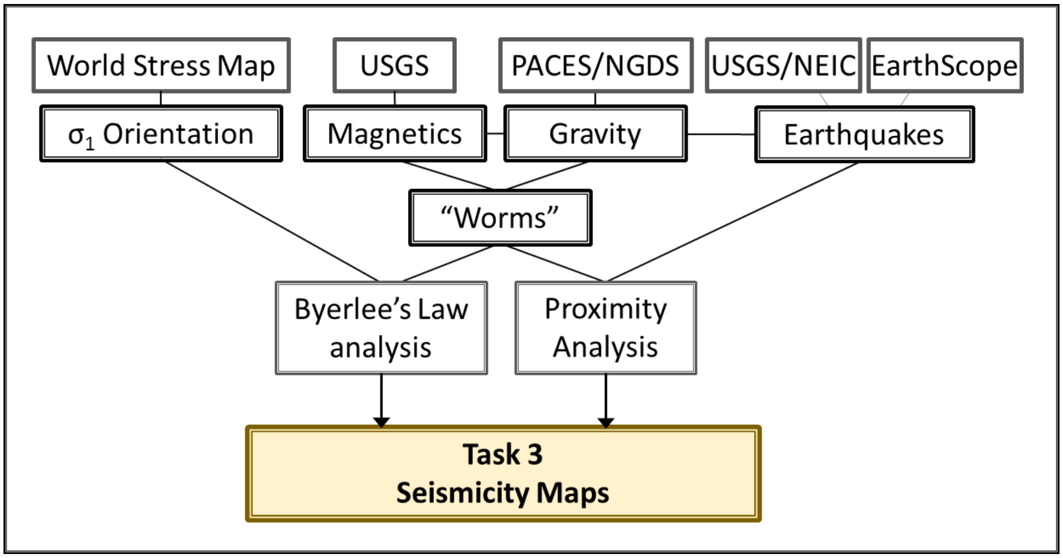

Figure 29: Flow chart for Task 3 Risk of Seismicity showing primary data and overview of steps.

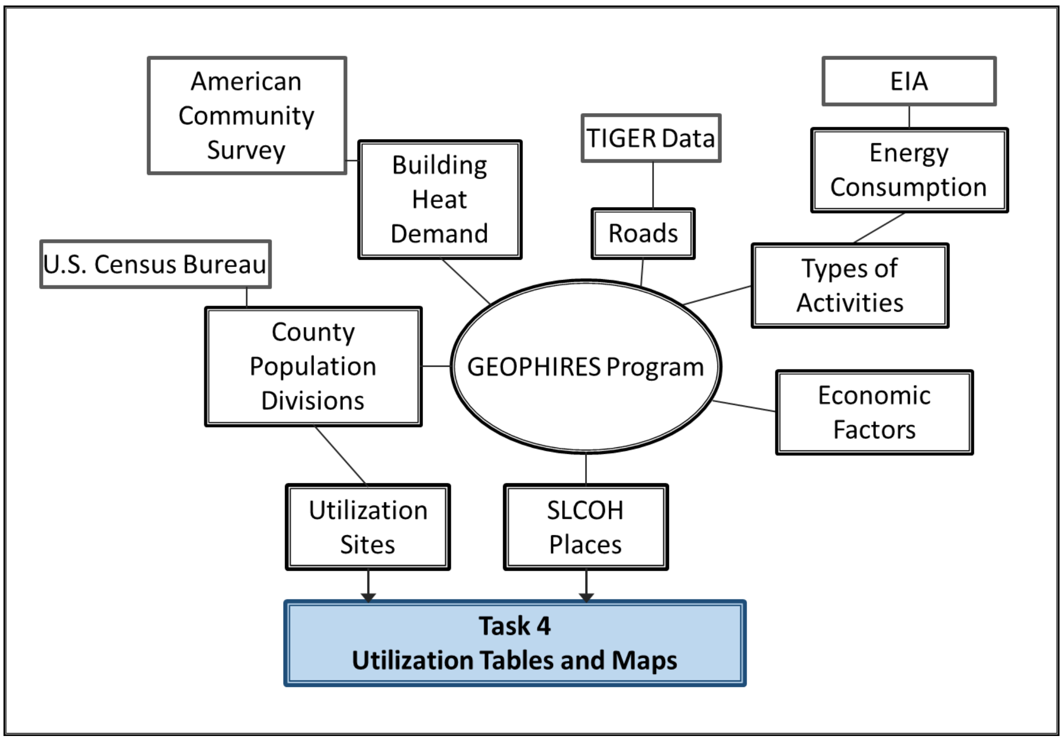

Figure 30: Flow chart for Task 4 Utilization Assessment showing primary data and overview of steps.

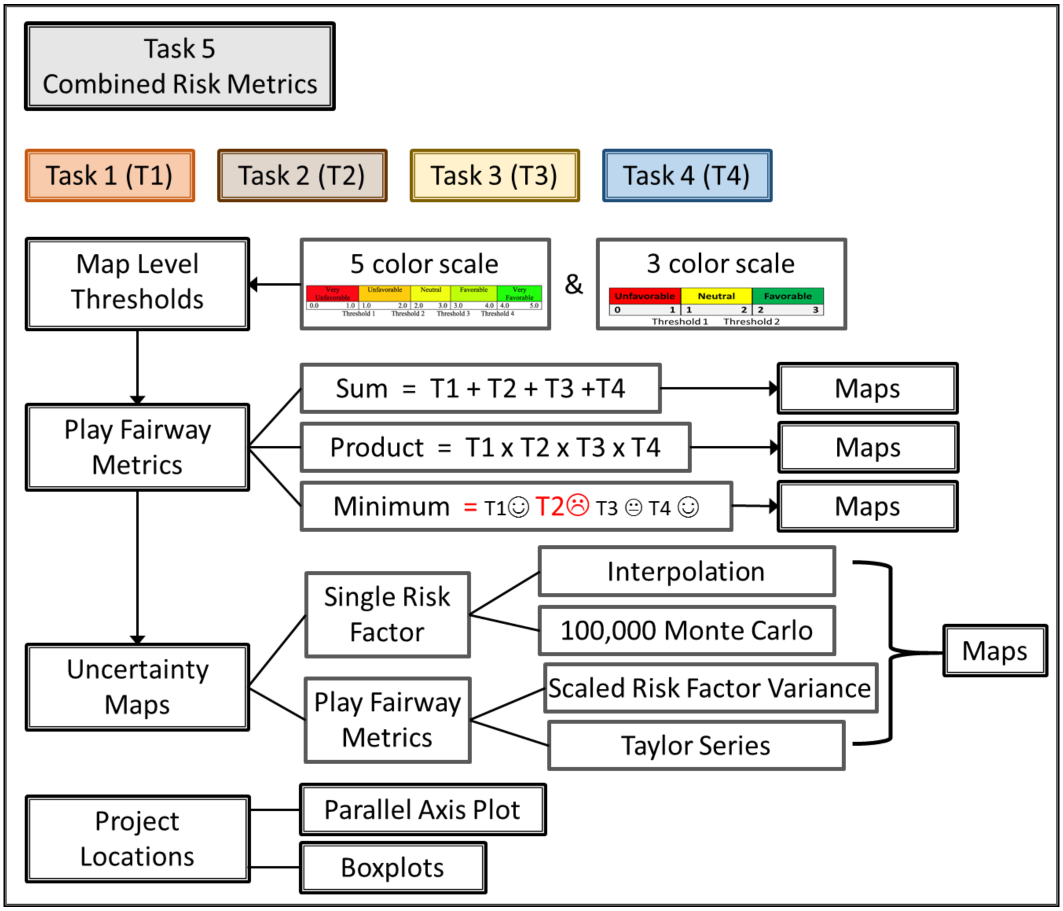

Figure 31: Flow chart for Task 5 Combining Risk Metrics showing an overview of main steps and methods for producing favorability maps.

DISCUSSION OF RESULTS

Phase 1 of the Appalachian Basin Geothermal Play Fairway Analysis project was a success, with original goals and objectives accomplished.

Primary Conclusions

Thermal Analysis

The thermal resource maps created as intermediate products of this project improve upon some previously published Appalachian Basin thermal resource maps, including, but not limited to Blackwell & Richards (2004), Frone & Blackwell (2010), Shope et al. (2012), Aguirre (2014) and Stutz et al. (2015). Results of the Phase 1 thermal analyses show that geothermal resources in the Appalachian Basin are indeed almost exclusively low temperature, which is in agreement with previous analyses.

The results indicate that rocks of temperatures of 80 °C can be reached across approximately 30% of the coverage area at depths routinely accessed between 1000-3000 m (Figure 6), with varying levels of certainty. In this same depth range, rocks of 100 °C are predicted to be accessible in over 15% of the project surface area (Figure 32). These depths are somewhat greater than the average depth of oil development and natural gas development wells in the US, which were 1500 m and 2000 m, respectively, in 2008[2].

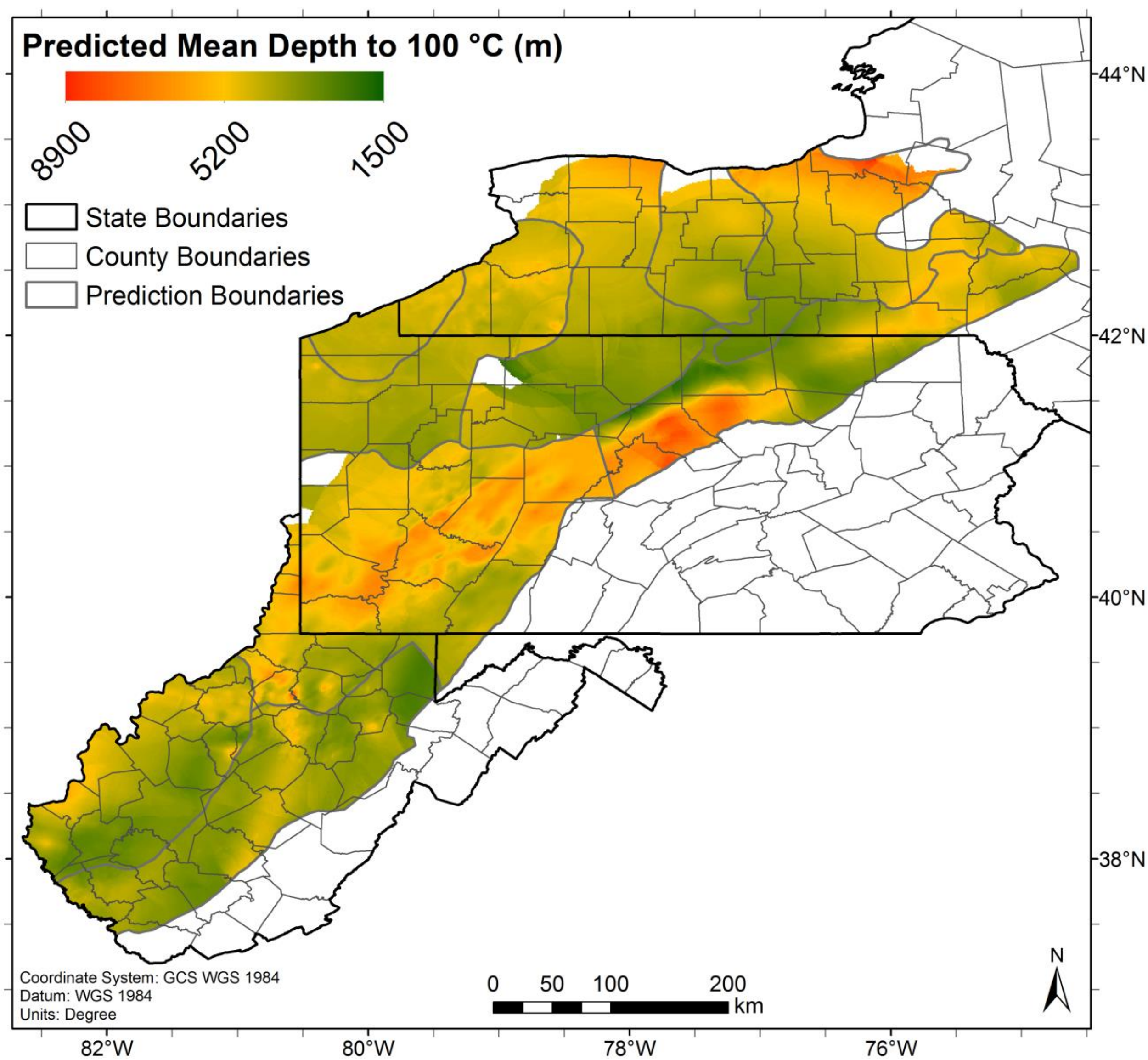

Figure 32: Predicted Mean Depth to 100 °C based upon thermal analysis.

The costs of geothermal energy development projects will be strongly dependent on the depth to temperatures needed for a given project, thus we consider it paramount to better validate the regional thermal models, to reduce the uncertainty on temperature predictions and, in turn, the uncertainties on project costs. A priority for future work should be to validate or modify the BHT corrections. Additionally, uncertainties in the predicted depths to temperatures needed for projects also result from the use of inaccurate thermal conductivities (e.g., Crowell, 2015). Future studies should measure Appalachian Basin conductivities, thereby increasing the accuracy of the predicted temperature values relative to the use of Anadarko Basin thermal conductivities. Additionally, a future priority should include collecting detailed

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[2] http://www.eia.gov/dnav/ng/hist/e_ertwo_xwdd_nus_fwa.htm;
http://www.eia.gov/dnav/ng/hist/e_ertwg_xwdd_nus_fwa.htm

thermal logs from shut-in or about-to-be-abandoned wells. These logs will provide ground-truth for our thermal models and their assumption of conduction-only heat flow — as well as constraints on the distribution of thermal conductivities actually encountered in the rocks.

Reservoir Favorability/Productivity Analysis

A new methodology and metric were developed to quantify the favorability of known hydrocarbon reservoirs to perform as low-temperature geothermal reservoirs. Either directly or indirectly, this productivity metric takes into account the depth, reservoir thickness, and permeability. A weakness of the method is that it uses an estimation of matrix permeability flow for all cases, including reservoirs dominated by fracture permeability.

The Phase 1 reservoir favorability analysis found that the reservoir productivity potential in the basin is highly variable (Figure 20), and the majority of the study area could not be ranked by reservoir productivity because of a lack of suitable data. While the majority of reservoirs are of low natural quality (< 1 L/[MPa-s]), a small subset has a productivity index >10 L/(MPa-s) (Figure 19), which may be sufficient flow to produce without reservoir stimulation. The favorable productivity index values correspond to the following formations:

- Trenton-Black River dolomite fields in southern NY and northern PA
- Lockport dolomite in northern PA
- Galway (aka Theresa, or Rose Run) in northwestern PA and western NY
- Oriskany Sandstone (updip pinchout formation) in all three states
- Newburg Sandstone in southwestern WV
- Onondaga Limestone Reefs in southern NY and northern PA
- Devonian Unconformity Play in southwestern PA.

A sensitivity analysis showed that the low productivity index for most reservoirs results from low permeability (see Catalog of Supporting Files, Methodology). Furthermore, the oil and gas industry has commonly employed stimulation for over 50 years in the study area, ranging from small degrees of stimulation in vertical wells up to high volume horizontal hydraulic fracturing. That history suggests that reservoir improvement by stimulation (hydraulic shearing of existing fractures to improve permeability and flow rate) should be given appropriate consideration in future studies.

We have drawn three major conclusions regarding the usefulness of the techniques employed for this risk factor. First, among the more than 2500 reservoirs analyzed, this technique successfully distinguished between low quality reservoirs and the best quality reservoirs. Second, state boundaries result in artificial differences in the perception of the extent of reservoirs. It is clear that the method in which reservoir polygons are reported by state geological surveys is inconsistent. This discrepancy was not addressed in Phase 1 and deserves additional work to achieve a uniform treatment. Third, reliance on oil/gas field data provides incomplete understanding of the regional distribution of and variations among natural reservoirs. There is a need for future evaluation of potential reservoirs that did not produce oil or gas ("saline water aquifers") to increase reservoir coverage. In total, because there is such incomplete coverage of reservoirs in our study area (Figure 20), and also because our reservoir uncertainty index was assigned based on data quality rather than reservoir heterogeneity, we recommend that the calculated uncertainty map play a small role in reservoir decision-making. High uncertainty could be due to poor reservoir quality, or it could be due to a lack of data to make an accurate prediction of reservoir quality. Regardless, if natural reservoirs are to be exploited for geothermal energy in the Appalachian Basin, additional work is recommended to develop a better way to understand and estimate variability within the reservoirs themselves, especially for naturally fractured reservoirs.

Part of the Phase 1 uncertainty regarding the fracture-dominated reservoir systems could be improved by the integration of more well test and production data, and by further integration of fracture-flow principles. A theoretical approach that considers the orientation of planes of weakness in the stress field predicts the orientations and locations of zones of dilatant strain, which should favor water flow through fracture systems. A regional prediction of the tendency toward dilation is straightforward to add to the analysis used to evaluate induced seismicity. If that theoretical analysis is completed, its results should be compared to the known locations of any of the fracture-dominated oil or gas reservoirs as a quality test.

Seismic Risk Analysis

Throughout the Appalachian Basin study region, based upon analysis of historical earthquake activity, of the locations of rock-property discontinuities that may be faults, and of the regional stress field, we highlighted areas at increased risk of induced seismicity (Figure 21–Figure 23). Earthquake activity over the last 50 years occurred sparsely across the three states of interest, and no seismic events of magnitude exceeding approximately ML 4.7 occurred. Within the Appalachian Basin in New York, the natural faults with a known slip history are almost entirely limited to the northern half of the Basin region (Figure 21), where the insulating sedimentary basin rocks are thin and therefore the geothermal heat opportunities are not favorable. In Pennsylvania, most of the sparse natural earthquakes occurred in the northwestern extreme of the state, where the largest recorded event is of ML 4.5. This cluster of seismic events occurs in general proximity to good natural reservoirs but only modest quality thermal resources. In West Virginia, natural earthquakes are more widespread in the southwestern half of the state, including the ML 4.7 event in the southernmost county (McDowell), but no natural earthquake activity has been recorded in the northeastern half of the state in the last 50 years (Figure 21). Although the thermally favorable areas of southwestern West Virginia are in relatively close proximity to clusters of natural earthquakes, the thermally favorable areas of the north-central part of the state are distant from known earthquakes.

Acknowledging that a 50 year earthquake record is insufficient for characterizing risk, the incorporation of a second theoretical means of risk analysis suggests much more widespread occurrence of localized zones of enhanced risk (Figure 22). To acknowledge the theoretical slip-tendency solution while placing greater confidence on the proximity-based solution, we recommend considering the average risk index (Figure 23) as the working hypothesis for risk of induced seismicity. However, the accuracy of this prediction is likely low, because neither the orientation nor the magnitudes of the local stress field are known.

To make major improvements on the regional-scale analysis of risk of induced seismicity would require a very large research undertaking. The data collection effort needed to determine which "worms" are indeed zones of weakness, to determine the local stress orientations, and to measure stress magnitudes is large. We recommend that a collaboration among seismologists and potential-field geophysicists be undertaken as a step towards validation of the Phase 1 approach with detailed real-world microseismicity.

Utilization Analysis

The distribution of Surface Levelized Cost of Heat (SLCOH) is highly skewed (Figure 33): very few census locations provided an estimated cost of less than \$10/MMBTU. Our results show that roughly 12% of Census Place have a SLCOH in the range of \$10/MMBTU to \$15/MMBTU, 6% ranged from \$15/MMBTU to \$20/MMBTU, and for the remaining approximately 80% such a means of heat delivery would cost much more.

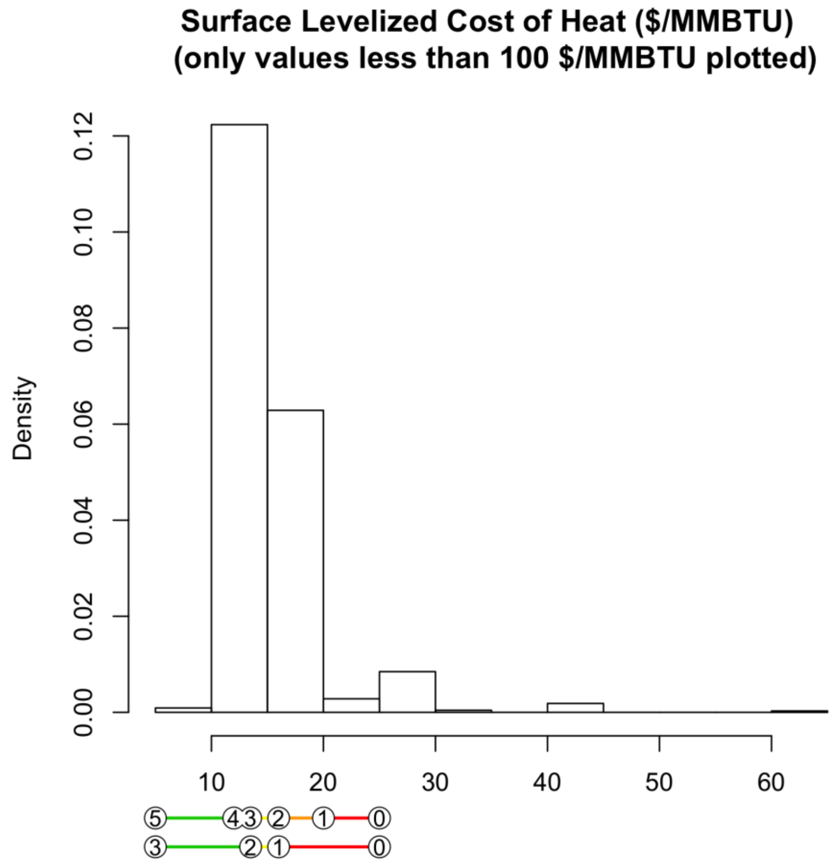

Figure 33: Frequency of Surface Levelized Cost of Heat among Census Places in the Appalachian Basin that have populations >4000. Of the two colored lines at bottom, the upper one shows the threshold SLCOH values corresponding to the five colors of the Figure 34 map.

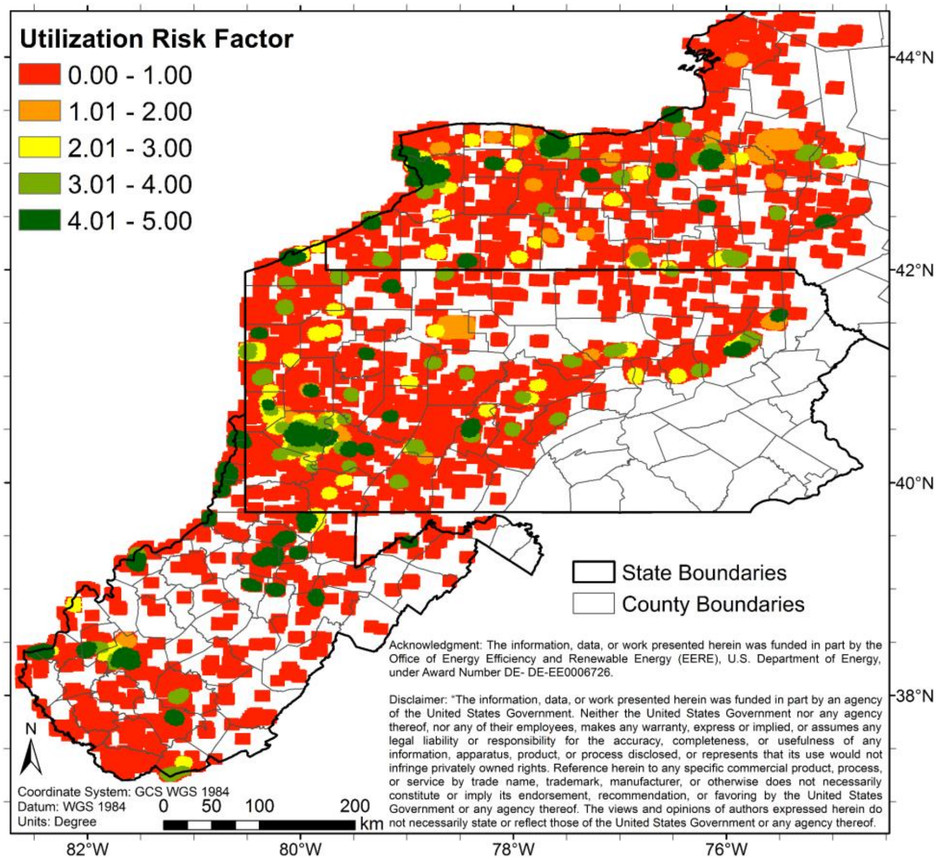

Figure 34: Utilization risk segment map (with 5-km radius buffers around Places). Green is favorable (lower SLCOH) and Red is higher SLCOH). See Figure 33 for the threshold SLCOH values between colors.

Some communities of favored low cost for such a system (Figure 34) occur in areas with moderate to favorable thermal resources, such as for the West Virginia cities of Elkins, Buckhannon, and Charleston (Table 2; Figure 6). In Pennsylvania, low SLCOH estimates overlap with moderate thermal resources for Warren city and Erie City (Table 4; Figure 6). In New York, the five high population areas with lowest SLCOH do not occur in thermally favored regions (Table 3; Figure 6), although some smaller cities in the southern tier of counties (i.e., Elmira) have reasonably favorable SLCOH (Figure 34) and very good thermal opportunity (Figure 6). Now that the distribution of resources in the subsurface has been newly established (temperature and reservoir resources), we recommend that a study be carried out to add the subsurface costs to the district heating surface costs for a few communities. The resultant LCOH for district heating systems will then be appropriate for discussion of alternative energy supply choices.

In addition to a risk factor analysis map based on census data, the team also identified more than 165 prospects for high value direct-use geothermal energy opportunities throughout the study area. These include industrial sites, university campuses, and federal facilities, among others. We recommend also that some of these sites be selected for estimation of surface and subsurface costs and LCOH analysis.

Combination of Risk Analysis

The four individual analyses were combined into final favorability maps using several techniques (sum, product, minimum values) (Figure 35–Figure 37). The various techniques emphasize differing properties of the choices that an institution might make, and thus for now all are retained. Using all 4 criteria, the summation method (Figure 35) indicates the most favorable counties within the study area are the West Virginia counties of Monongalia, Harrison, Lewis (dubbed the Morgantown–Clarksburg play), Putnam, and Kanawha (Charleston play), the Pennsylvania counties of Mercer, Crawford, Erie, and Warren, and adjacent Chautauqua county in New York (together, the Meadville–Jamestown play), and New York counties of, Chemung and Steuben plus adjacent Bradford county in Pennsylvania (Corning–Ithaca play).

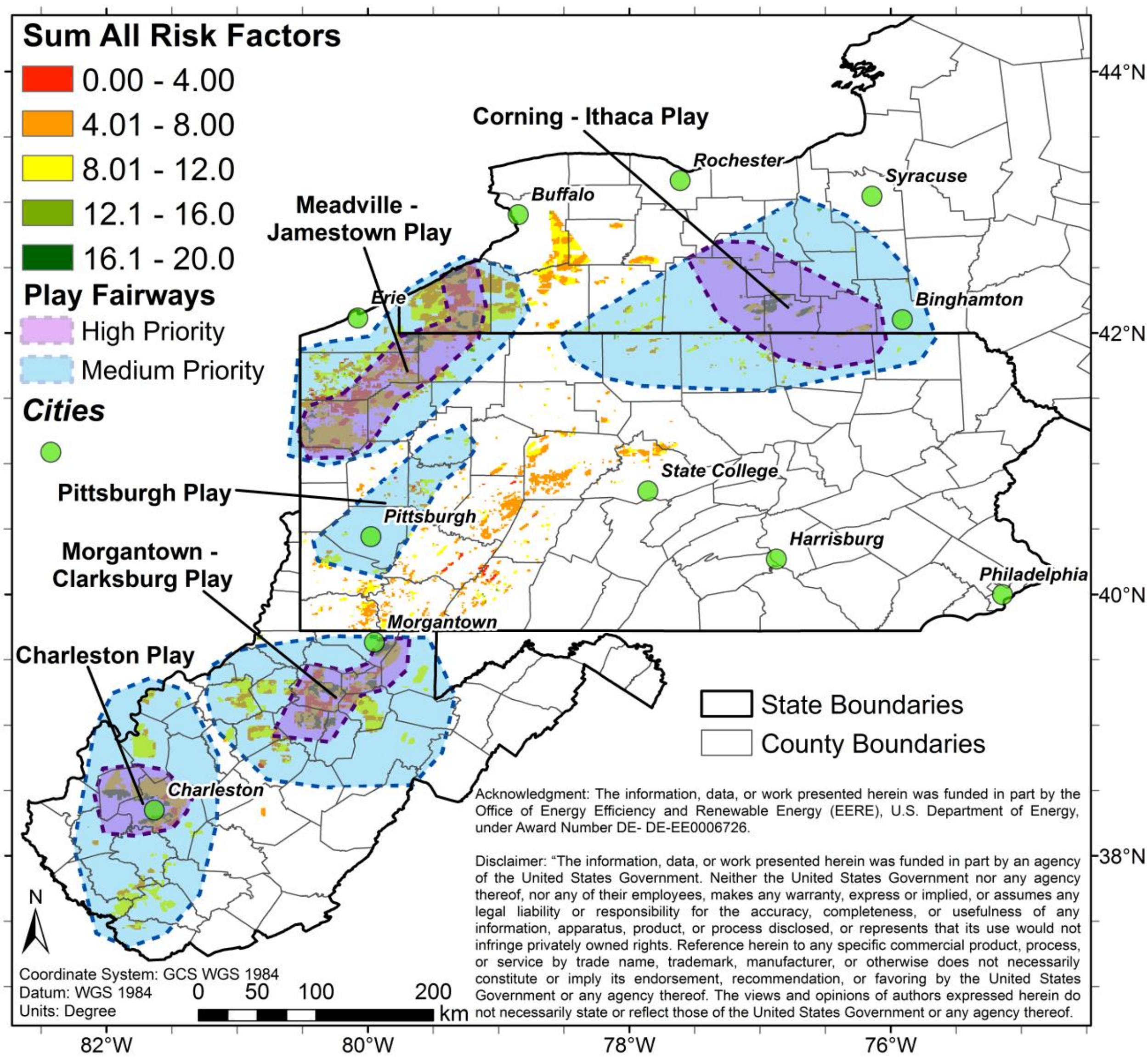

Figure 35: Favorability map for the combination of all four risk factors using a sum. Green-Favorable, Red-Unfavorable.

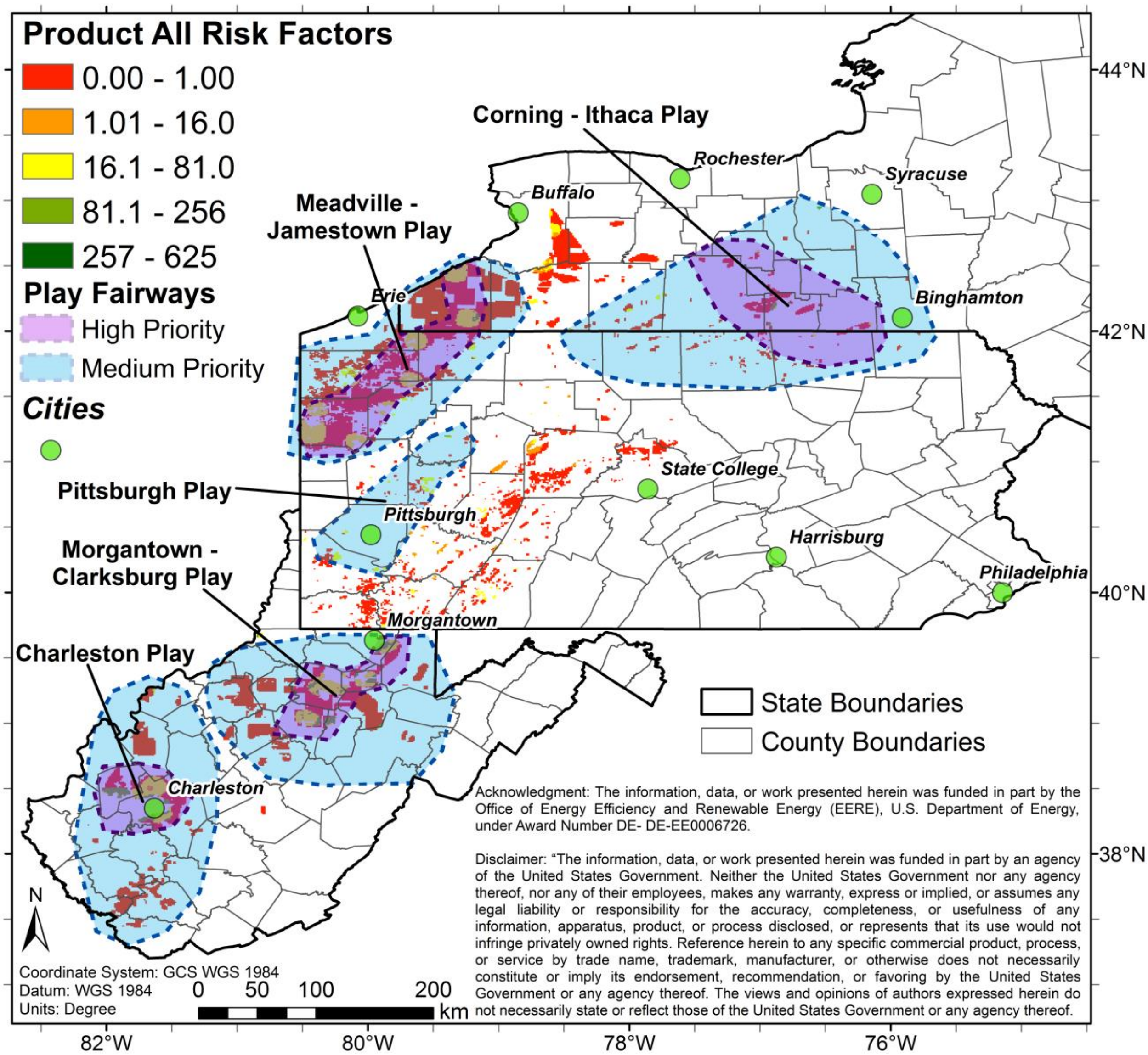

Figure 36: Favorability map for the combination of all four risk factors using the product. Green-Favorable, Red-Unfavorable.

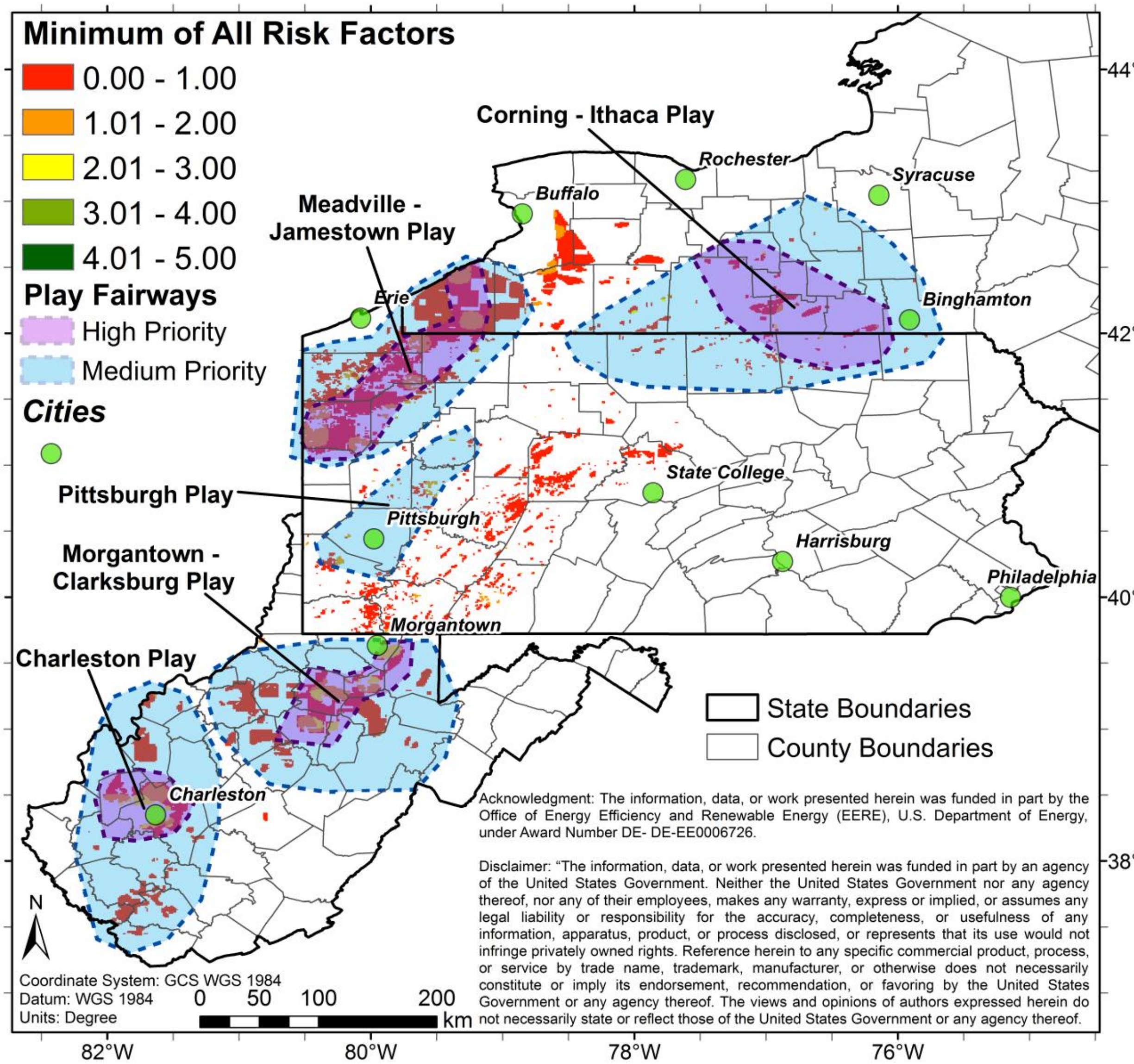

Figure 37: Favorability map for the combination of all four risk factors using the minimum value. Green-Favorable, Red-Unfavorable.

The maps presented above (Figures 35-37) are aimed at highlighting utilization opportunities for communities and municipalities based on population clusters. However, the long list of other prospects for geothermal direct-use identified (165+ across the 3 state area), independent of census data, points out that the utilization and the spatial variability in the cost of utilization are to a large degree functions of institutions. These factors contributing to the financial risk change through time and are spatially distributed. For example, a multi-year dynamic variability is true for regulations, carbon markets, community perceptions, and sites of employment or industry.

Therefore there is considerable value to examine the combined risks of the first three geological characteristics only (Figure 38-Figure 40). This second combined risk map set represents the geologically fixed features, against which the dynamic human factors can be compared either qualitatively or quantitatively. Relative to the three geologic characteristics, the most favorable counties illuminated by the summed combined risk are more widespread (Figure 38), especially in West Virginia. In West Virginia, these occur in the central-northern region (Monongalia, Preston, Taylor, Barbour, and Upshur), various clusters of counties in the western part of the state (Ritchie, Doddridge, Gilmer Calhoun; Jackson, Putnam, Kanawha) and in the far south (Mingo, Wyoming; Raleigh). Pennsylvania shows little area with collectively favorable geological factors, with small areas within counties in the far west (Crawford, Venango, Warren), center (Elk, Cameron, southwestern Potter), and northern tier (Tioga, Bradford, Susquehanna). New York's coverage of favorable geological factors by the summed method (Figure 38) is intermediate, revealing almost no strongly favorable areas in counties north of the southern tier. Along the southern tier, favorable areas are sparse in the west (Chautauqua County) and of increasing coverage from Allegany east through Chemung County.

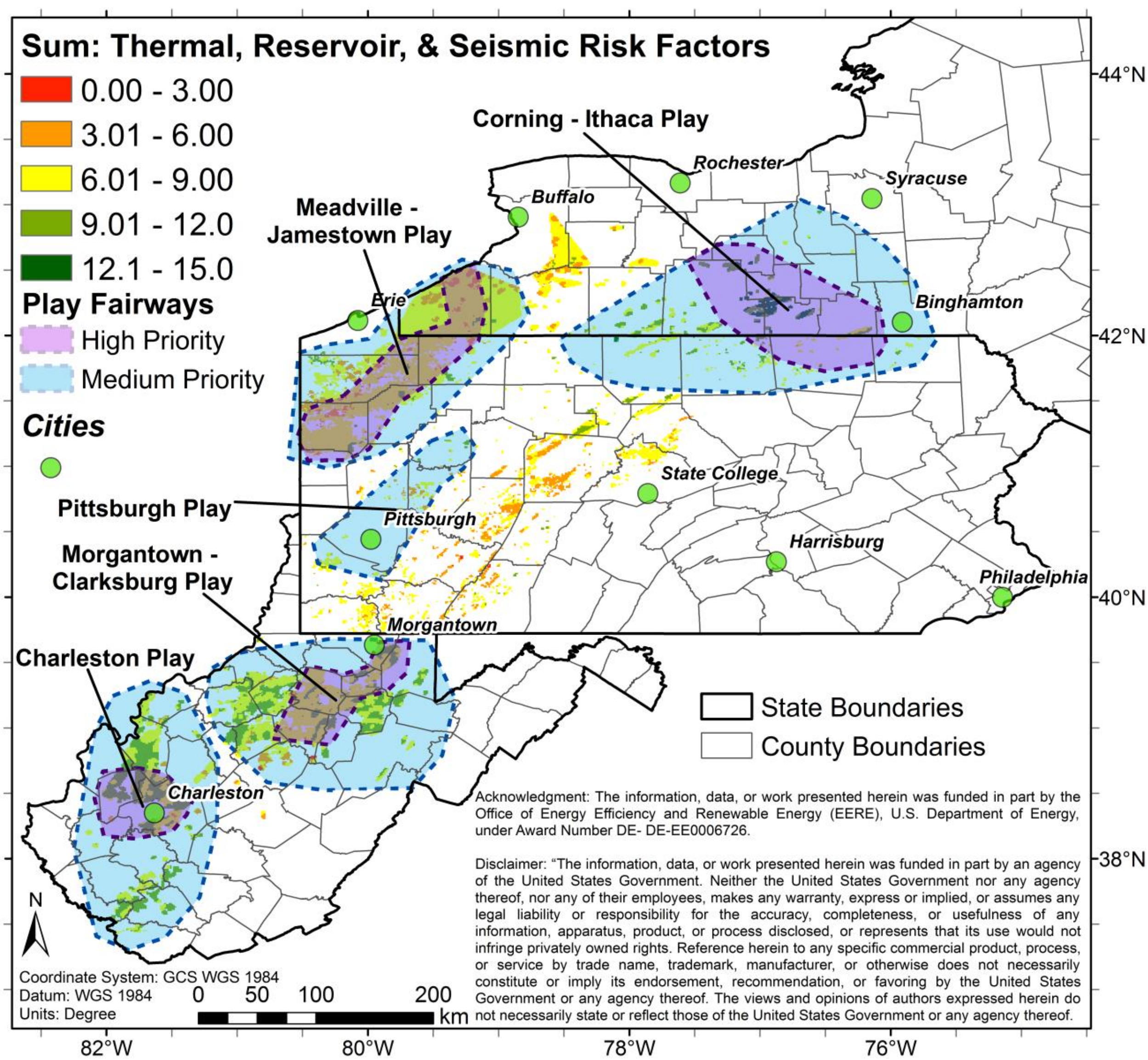

Figure 38: Favorability map for the combination of the first three geologic risk factors using a sum. Green-Favorable, Red-Unfavorable.

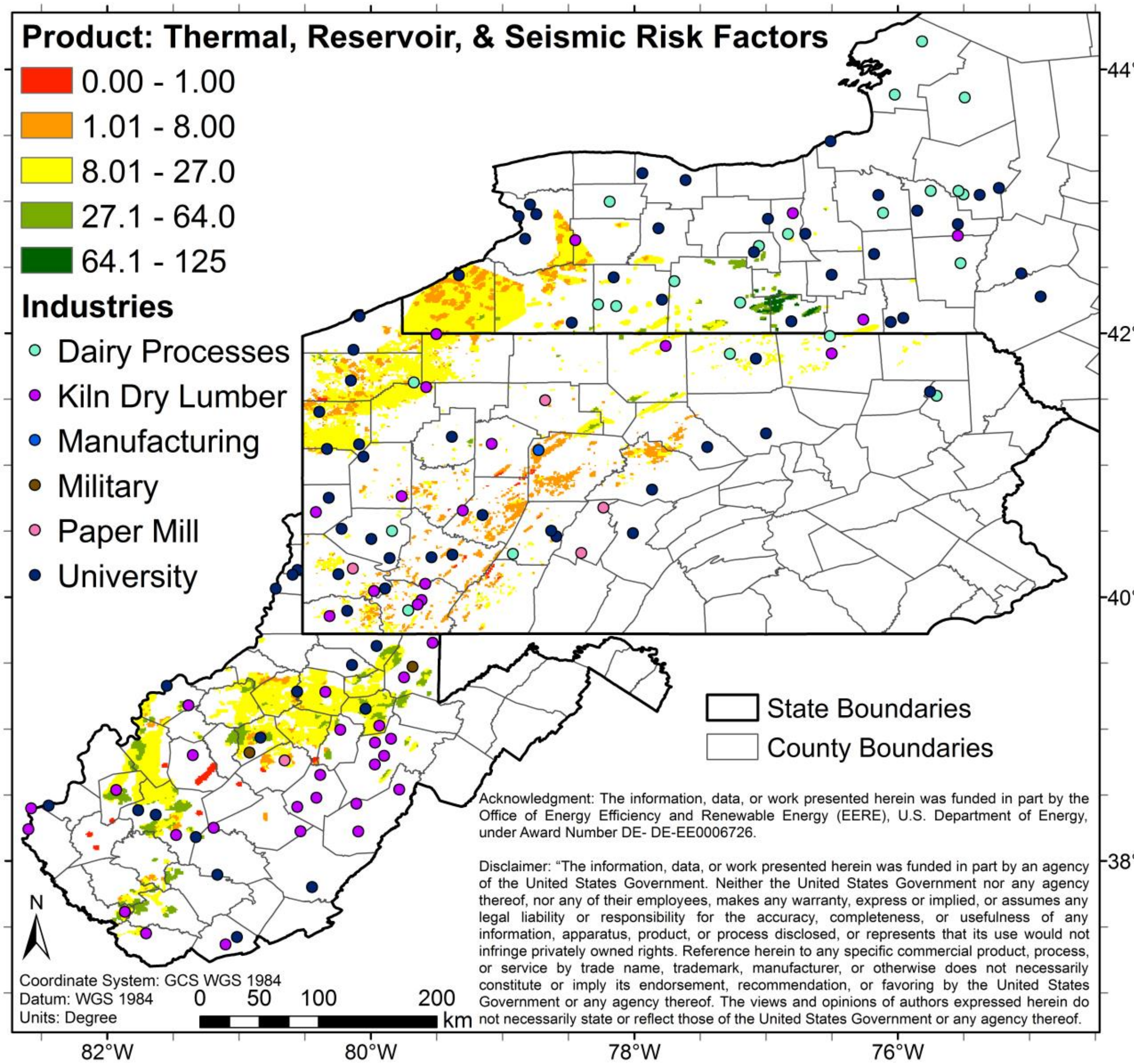

Figure 39: Favorability map for the combination of the first three geologic risk factors using the product, with the additional inclusion of the Utilization Individual Sites. Green-Favorable, Red-Unfavorable.

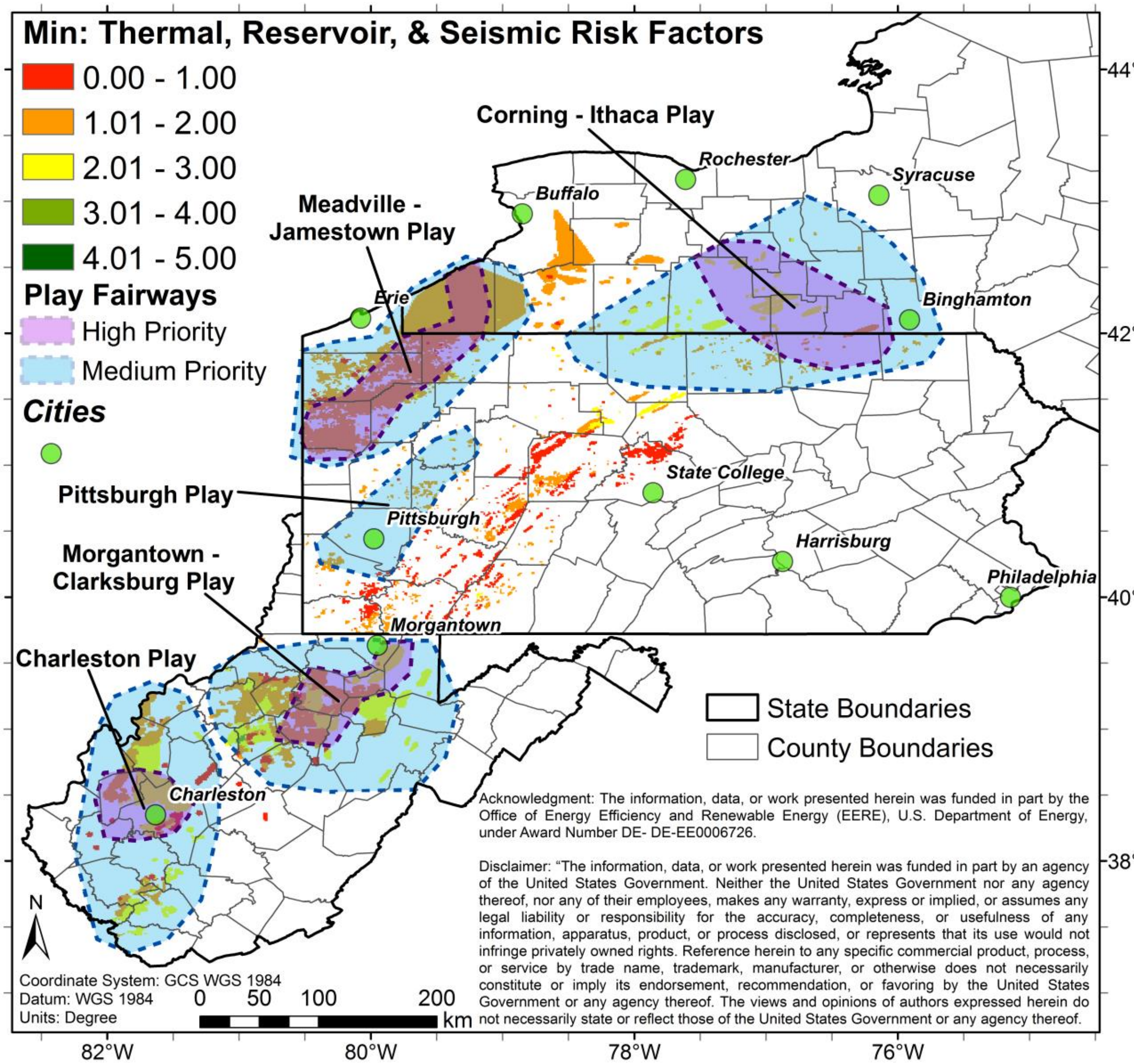

Figure 40: Favorability map for the combination of the first three geologic risk factors using the minimum. Green-Favorable, Red-Unfavorable.

The success of a geothermal energy extraction project that is based on circulation of water through naturally existing pore spaces, on which this study has focused, requires the co-occurrence of favorable rock temperature and favorable reservoir conditions at the same depth. To illustrate the spatial variability of the intersection of those two properties, Figure 41, Figure 42 and Figure 43 illustrate the temperature field at depths of 1.5 km, 2.5 km, and 3.5 km below the surface, respectively. On each of those maps, the documented oil and gas reservoirs are mapped that occur within vertical distances of 500 m above or below the reference depth of the temperature field.

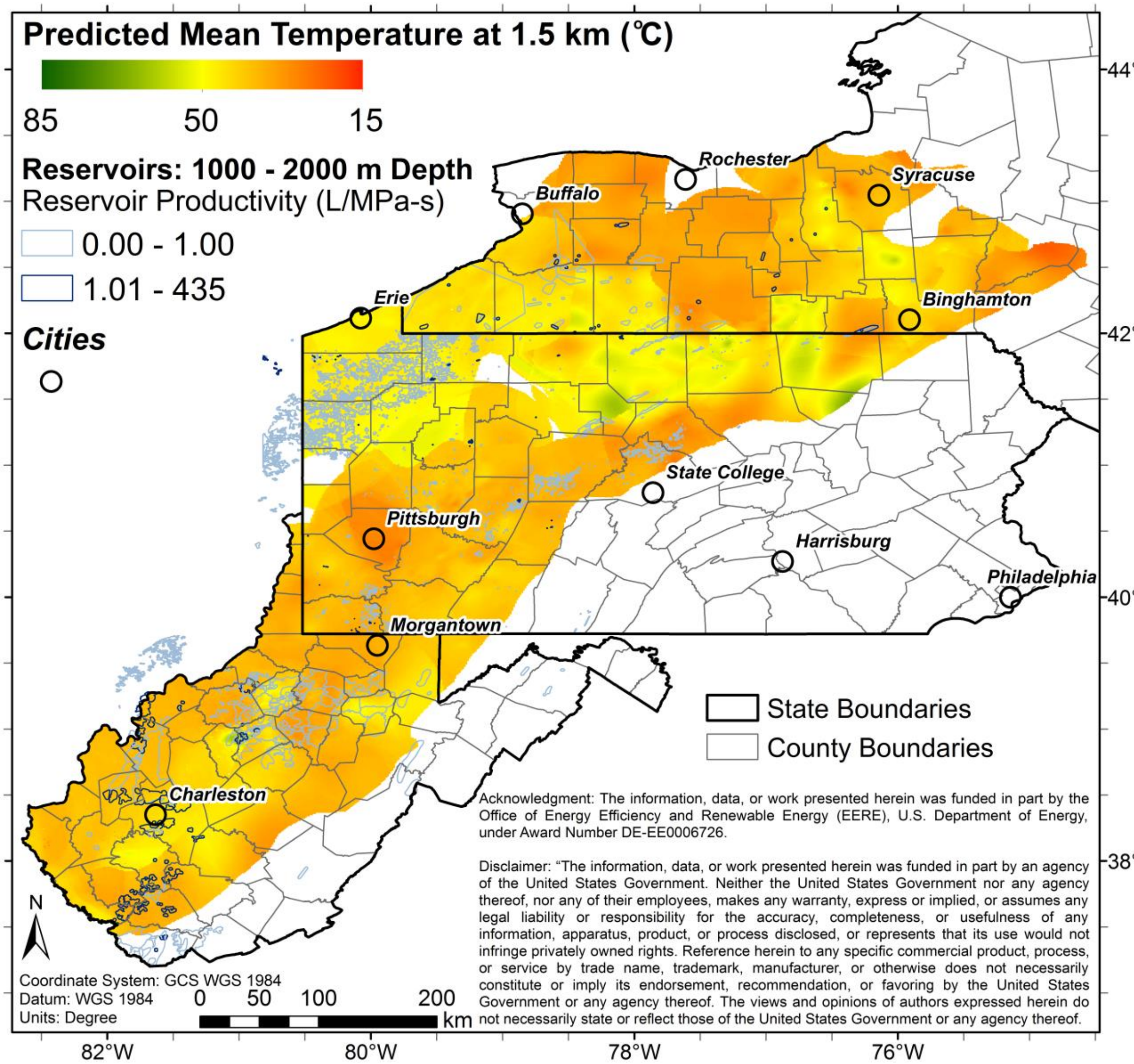

Figure 41. Map of the temperature predicted at a depth of 1.5 km depth below the local Earth surface throughout the study area. Superimposed are the locations of reservoir rocks in the range of depth below the surface of 1000–2000 m, based on oil or gas production. For those reservoirs, the reservoir quality is indicated by the color of the surrounding polygon: a black line indicates a reservoir quality index ≥ 1 L/MPa-s; a gray line indicates a reservoir with a lower quality index.

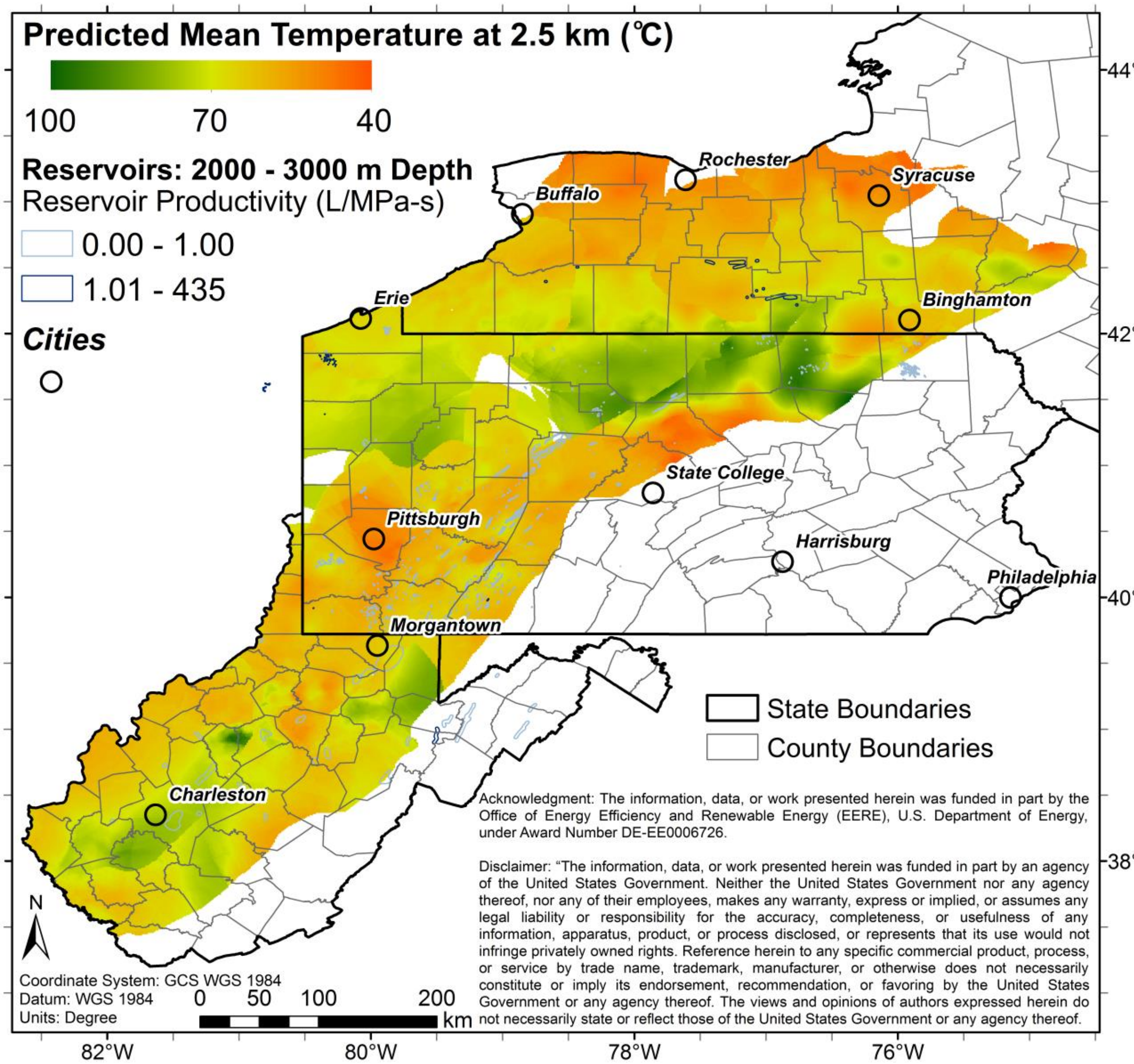

Figure 42. Map of the temperature predicted at a depth of 2.5 km depth below the local Earth surface throughout the study area. Superimposed are the locations of reservoir rocks in the range of depth below the surface of 2000–3000 m, based on oil or gas production. For those reservoirs, the reservoir quality is indicated by the color of the surrounding polygon: a black line indicates a reservoir quality index ≥ 1 L/MPa-s; a gray line indicates a reservoir with a lower quality index.

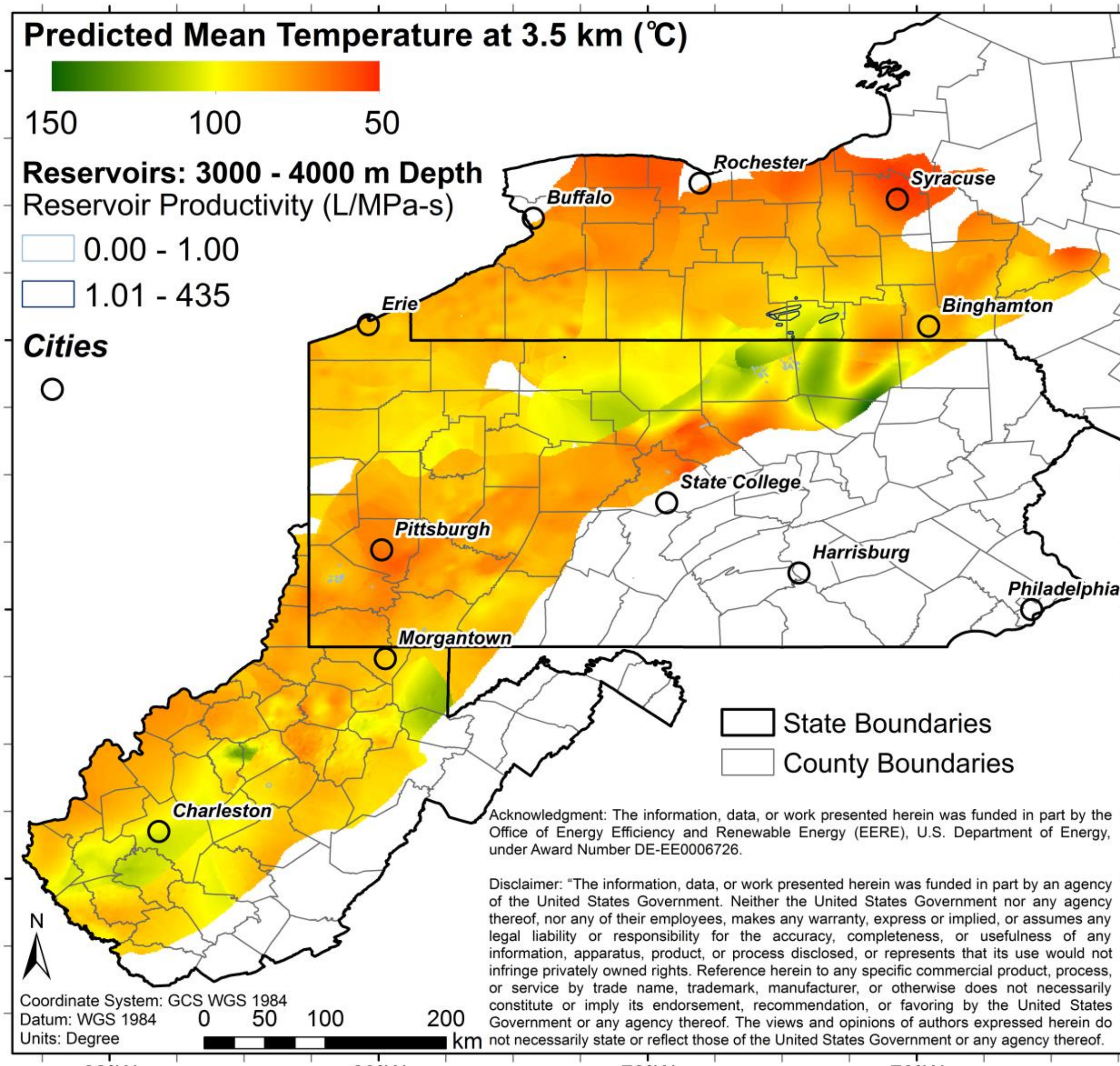

Figure 43. Map of the temperature predicted at a depth of 3.5 km depth below the local Earth surface throughout the study area. Superimposed are the locations of reservoir rocks in the range of depth below the surface of 3000–4000 m, based on oil or gas production. For those reservoirs, the reservoir quality is indicated by the color of the surrounding polygon: a black line indicates a reservoir quality index ≥ 1 L/MPa-s; a gray line indicates a reservoir with a lower quality index.

Consideration of a combined risk method that more strongly weights the geological weaknesses of the plays (Figure 39, product) reduces significantly the attractiveness of all but a handful of areas. The region favored by the summed method which changed least when analyzed by the product method is a three-county cluster in south-central New York (the border of Steuben with Yates and Schuyler counties, and Chemung County). There, favorable temperatures coincide with high potential from the Trenton-Black River reservoirs (Figure 43). These define a play fairway that is robust based on consistent PFM favorability (Corning–Ithaca Play Fairway,

Figure 40), and should be a high priority for further analysis. In West Virginia the total number of possible sites increased dramatically when the utilization constraint was lifted (compare Figure 36 to Figure 39, product), identifying high quality plays primarily in eastern Monongalia , western Preston, Taylor and Harrison counties in the north (Oriskany and Helderberg Group reservoirs; Morgantown–Clarksburg Play Fairway). and as patches in the southern counties of Kanawha, Putnam and Jackson (Charleston Play Fairway). In the Charleston Play Fairway the Oriskany stratigraphic reservoirs and Newburg Sandstone combine with favorable temperatures to create two types of play that warrant further investigation. A wide area in western Pennsylvania ((Mercer, Crawford, Venango and Warren counties) and southwestern New York (Chautauqua county) also has favorable scores for most of the four risk factors, garnering designation as the Meadville–Jamestown Play Fairway.

A region with a high population and thick insulating sedimentary rocks that is not highlighted by either combined risk analysis is the southwest Pennsylvania region around Pittsburgh. It is an example of a region with high use potential (Figure 34; Table 4's boroughs of West View, Brentwood, and Dormont are all near Pittsburgh) but there is little oil and gas well BHT data deeper than 1000 m (Figure 3) and few documented reservoir rocks (Figure 20). Based on the sparse geological information near Pittsburgh on which to base this project and the high degree of utilization opportunity, Pittsburgh is designated as a region worthy of farther consideration (Pittsburgh Play Fairway), which we designate as medium priority (**Error! Reference source not found.** to Figure 37). The outlines of this play respect the variability of Risk Matrix values of the areas around Pittsburgh (Figure 39), but are mostly influenced by usage (Figure 34).

Three of the institutions that we know are interested in investigating the feasibility of tapping deep sedimentary basin geothermal direct-use resources are located relatively near the better areas revealed by the combined geological risk analyses (Figure 39). In south-central New York, Cornell University.in Tompkins County is at the margin of the inner high priority region of the Corning–Ithaca Play Fairway. A lack of information about reservoirs is the primary shortcoming in Tompkins County. West Virginia University in Monongalia County and a West Virginia National Guard base in Preston County are within the Morgantown–Clarksburg Play Fairway.

Comparison of Actual Accomplishments with Original Goals and Objectives

Referring to the project major tasks and deliverables described under Approaches Used in this report, all goals and objectives were achieved. Deliverables exceed those required, going beyond the risk segment maps and the final favorability maps, to also include a series of research Memos documenting the details of the analysis by topic and even some sub-topic areas. Maps are provided immediately below and the Memos can be found within the Catalog of Supporting Files.

Risk Segment Maps

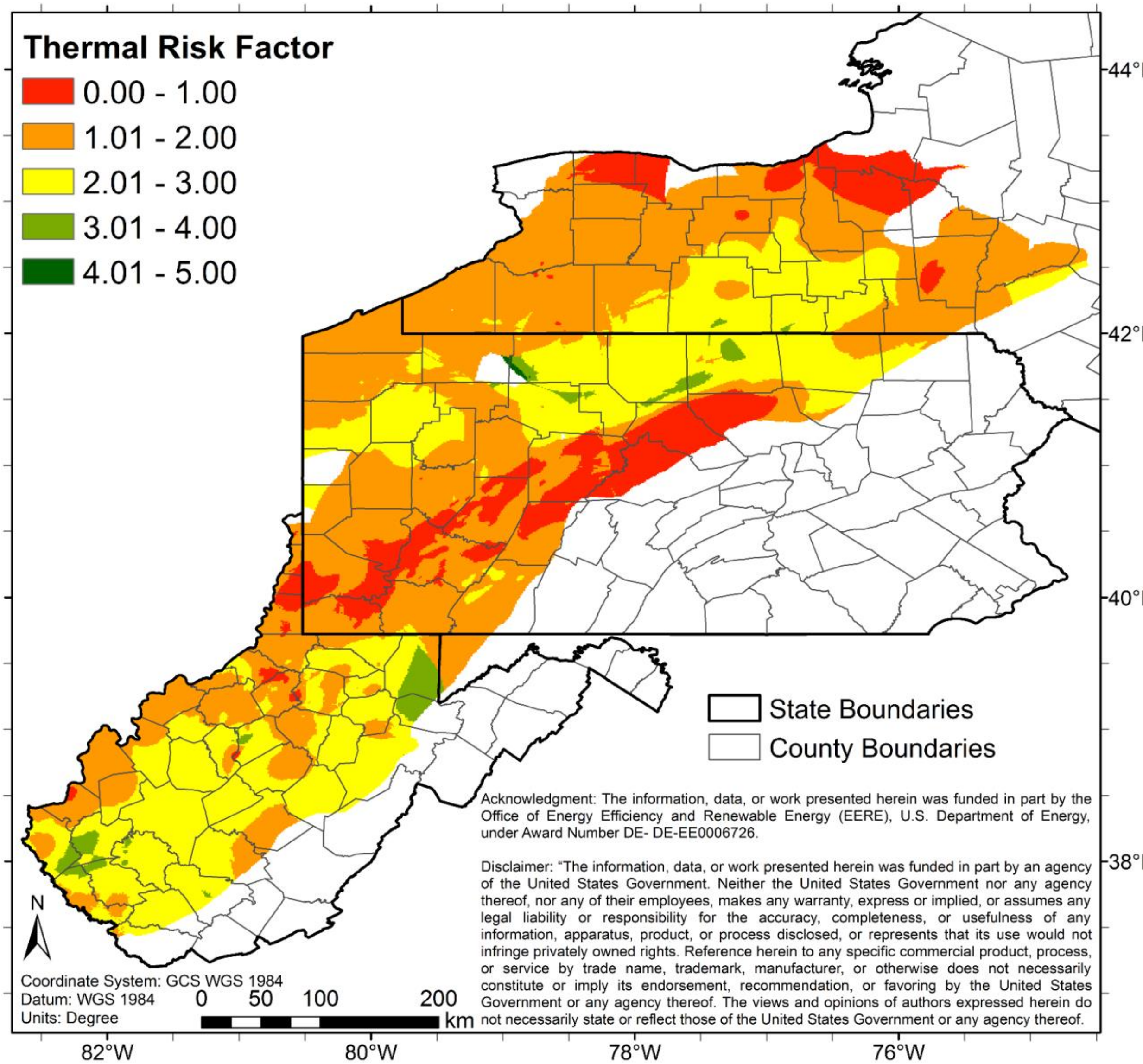

Figure 44: Play Fairway Metric risk segment map for the thermal resource with a five color scheme. Green-Favorable, Red-Unfavorable.

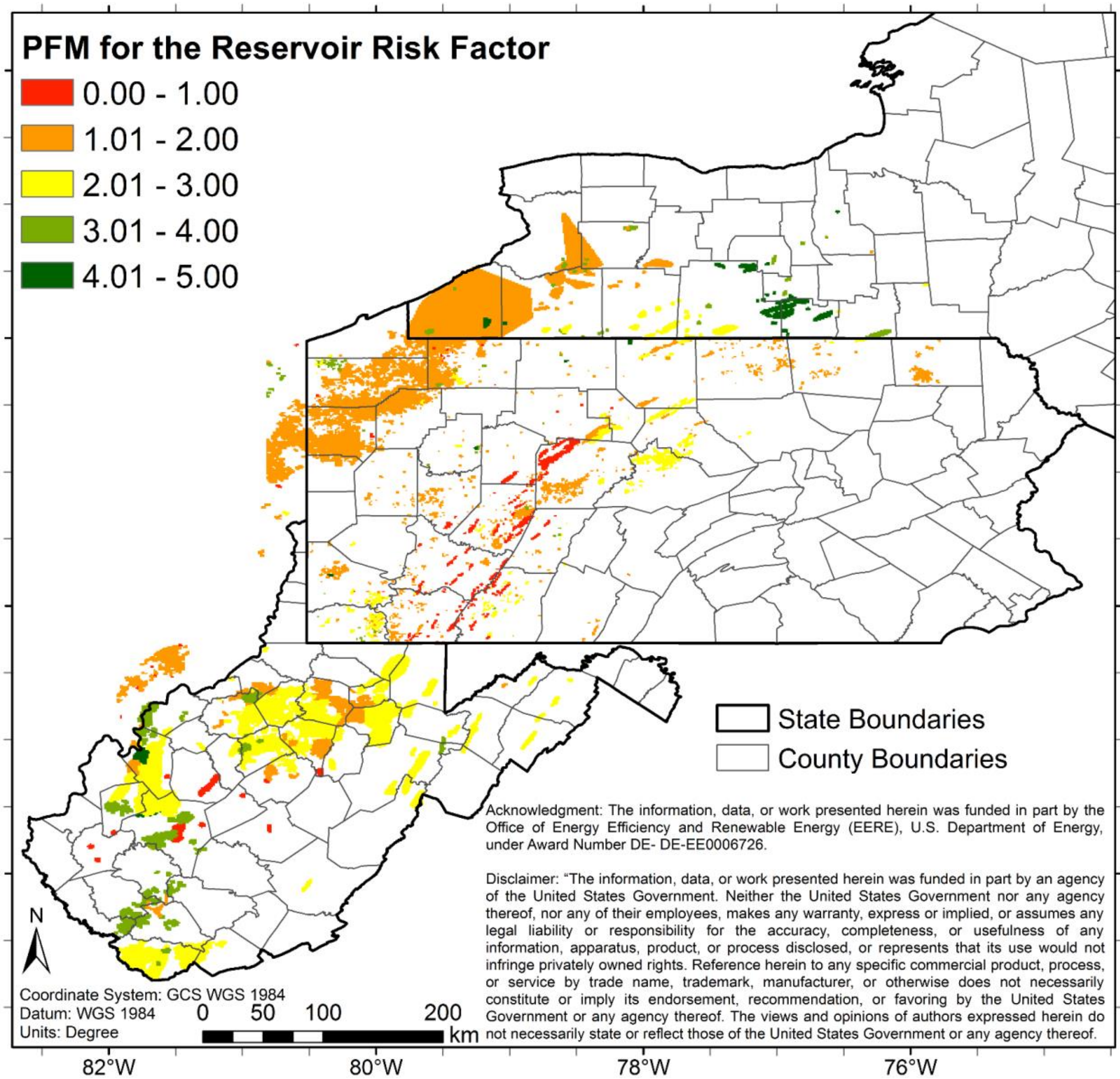

Figure 45: Play Fairway Metric risk segment map for the reservoir resource with a five color scheme. Green-Favorable, Red-Unfavorable.

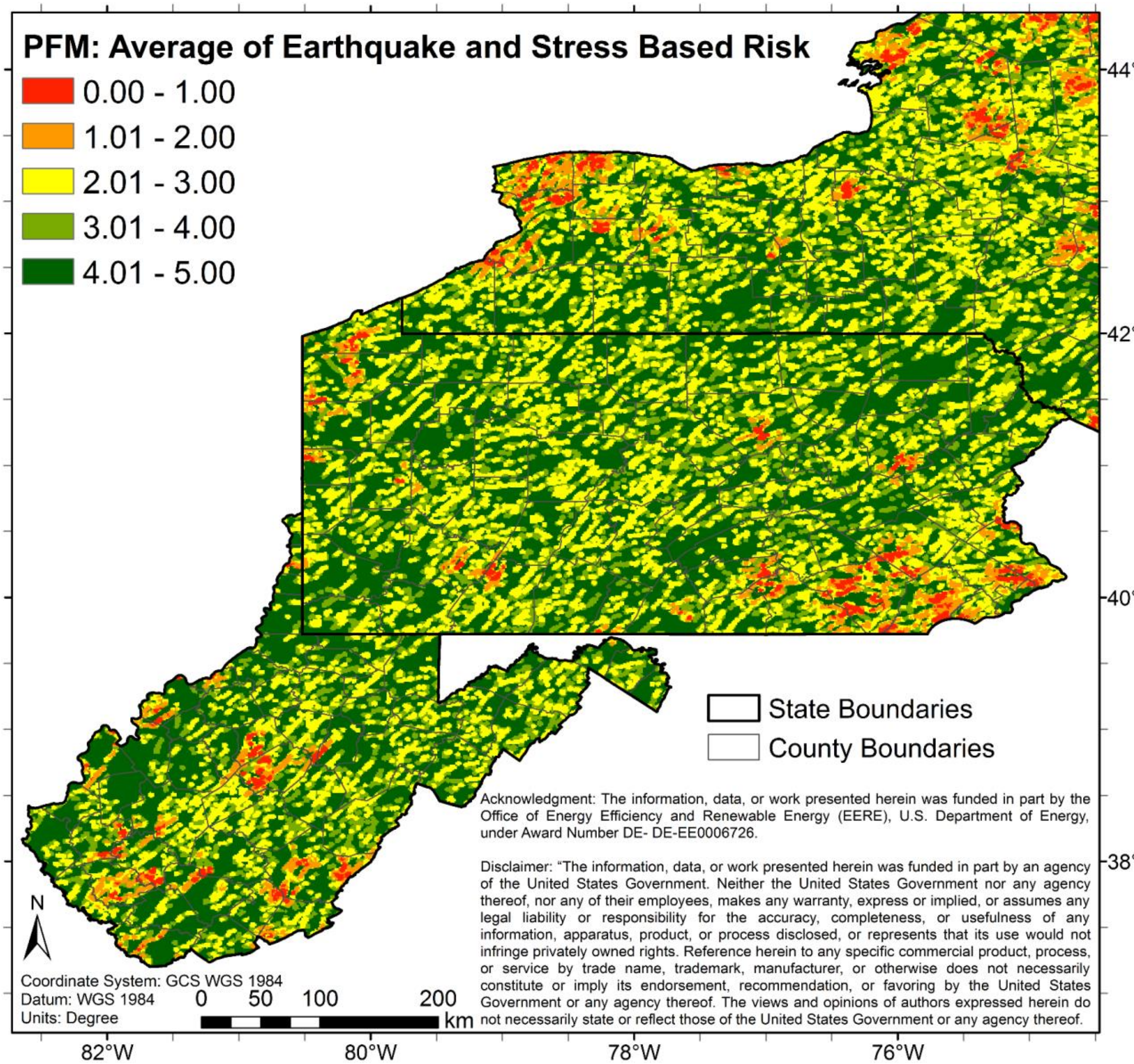

Figure 46: Play Fairway Metric risk segment map for the seismic resource with a five color scheme. Green-Favorable, Red-Unfavorable.

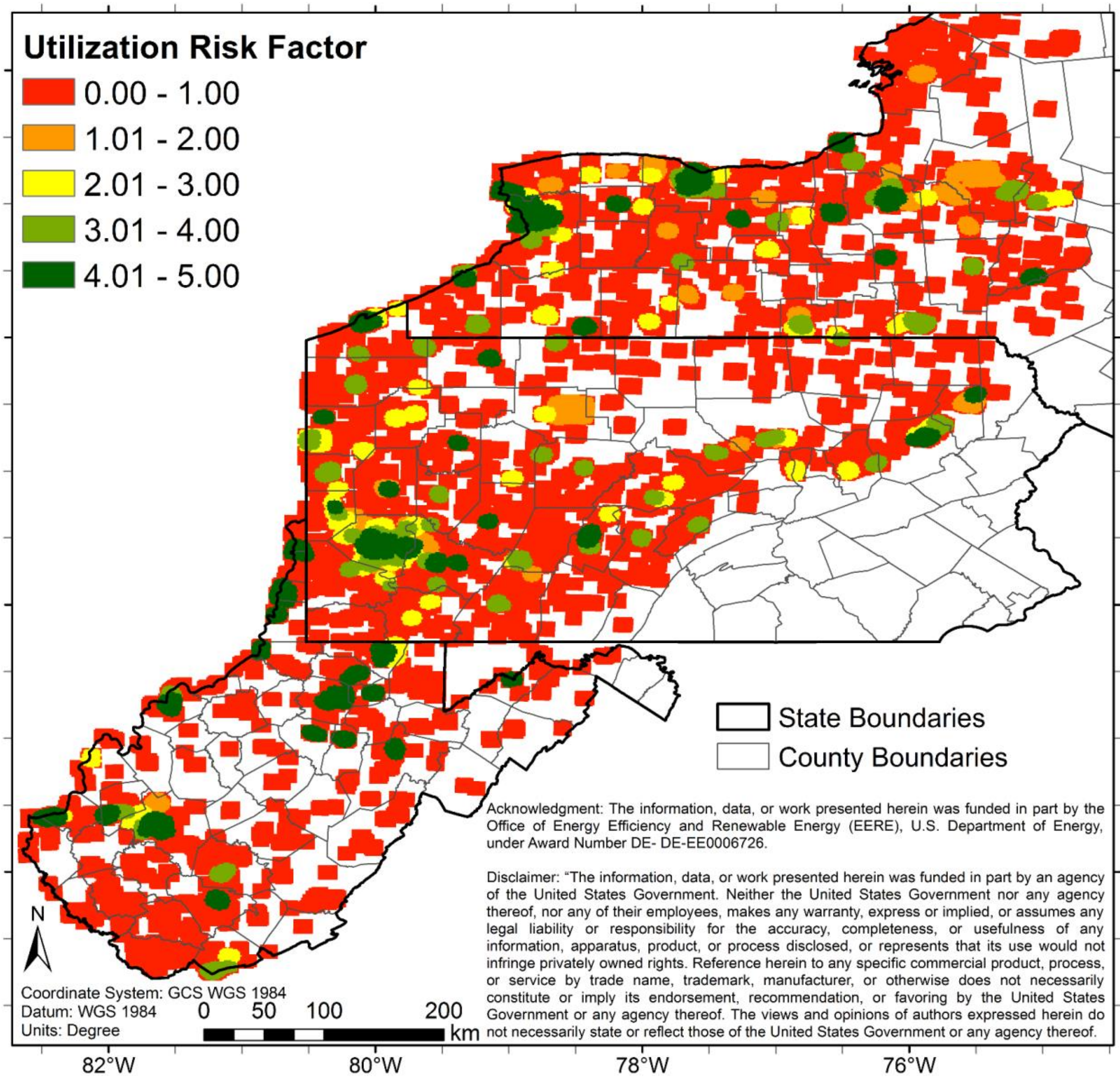

Figure 47: Play Fairway Metric risk segment map for the utilization of resource with a five color scheme. Green-Favorable, Red-Unfavorable. The utilization locations are buffered by 5 km and then the maximum is selected, which reflects a willingness to move the water small distances.

Uncertainties Corresponding to the Final Favorability Maps

In addition to the series of 6 Final Favorability Maps provided in Figure 35 through Figure 40, numerous maps depicting uncertainty (standard deviation) were plotted. These will be part of the Tier 2 uploads into the NGDS via the Geothermal Data Repository. Figure 45 below is a representative example of an uncertainty map for the final favorability map for the combination of the three geologic risk factors using the sum method of combination.

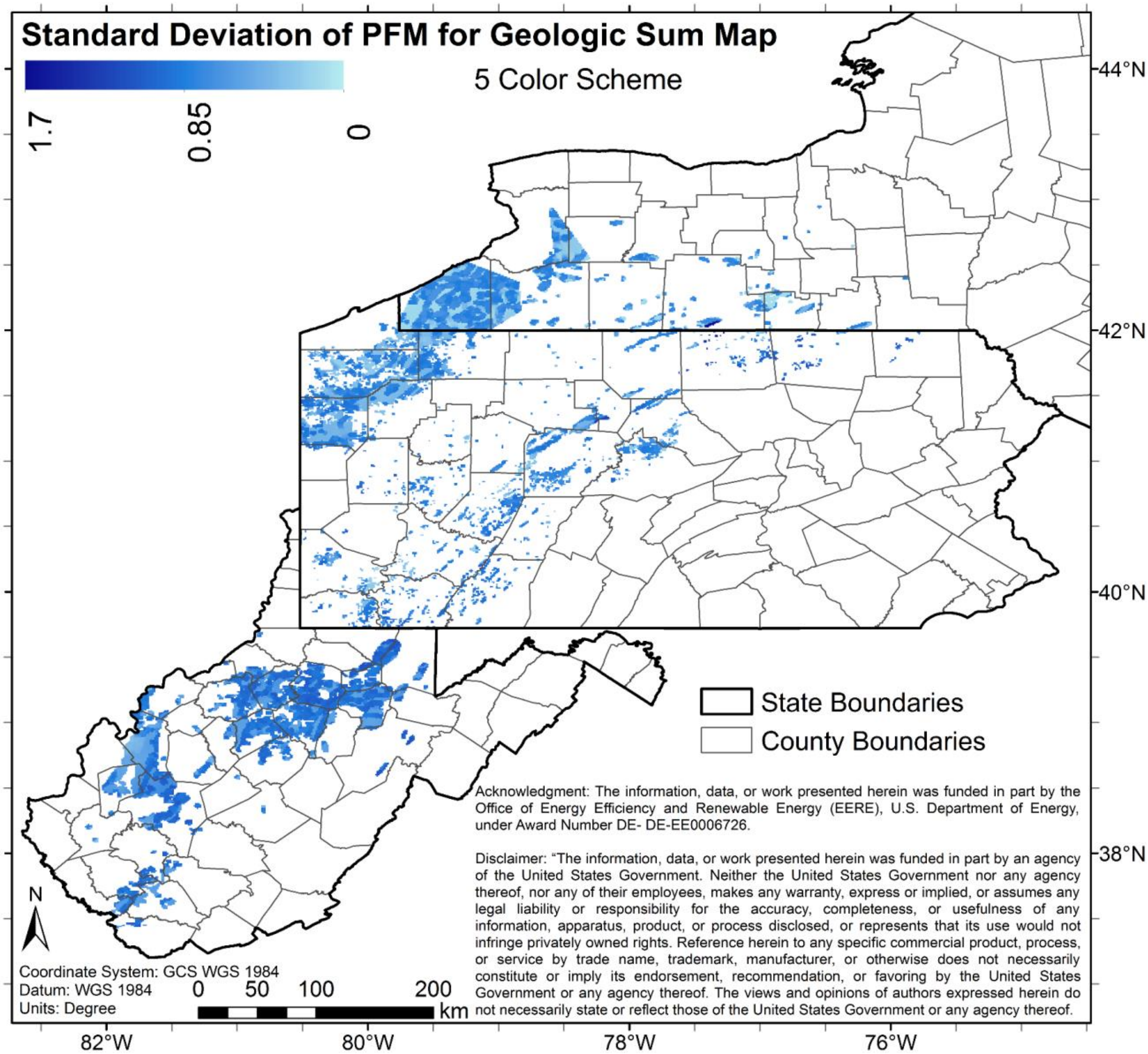

Figure 48: Uncertainty (standard deviation) of the favorability map for the combination of the geologic risk factors using a sum (Error! Reference source not found.**). Lighter colors are more certain and darker colors are less certain.**

RECOMMENDATIONS FOR FURTHER ANALYSIS

Description of Objectives and Outcomes of Recommended Studies

At the closure of this regional-scale Geothermal Play Fairway Analysis of the northern Appalachian Basin, the most significant technical uncertainties, starting with the largest unknowns, are 1) reservoir distribution and capacities; 2) validity of thermal resource maps, and 3) the holistic estimation of Levelized Cost of Heat for favorable geological situations. Furthermore, in preparation for developing an operational geothermal heat supply and usage system at any location within the study area, additional groundwork is needed that pertains to permitting and public awareness.

Description of Recommended Activities

An overview of the recommended activities for each of the identified priority Play Fairways may be found in Table 5: Summary of five play fairways and recommendations for next investigation steps. We explain briefly here the nature of follow-on studies that we recommend in order to verify our Phase 1 analyses as well as to advance the analysis of geothermal energy potential for a few select "prospect scale" locations.

Broadly speaking, we recommend refinement, validation, and extension of the following aspects of our Phase 1 work:

- Reservoir Productivity Maps. We recommend four sets of study to improve the predictions of reservoir productivity. The first and second types of study focus on improving the quality of results of the reservoir productivity index as presented in this report: 1) obtain more data on properties of known reservoirs, and 2) improve the Reservoir Productivity Index through incorporation of flow analysis. The third and fourth types of study focus on identifying geothermal reservoirs outside of oil and gas fields and on better differentiating fracture-permeability reservoirs from matrix-permeability reservoirs: 3) use sedimentary facies and structural geological approaches to identifying potential geothermal reservoirs, and 4) use the "worm analysis" of magnetic and gravity field data to locate dilational regions either directly from the "worm" orientation in stress fields or indirectly via mapping locations of structural complexity (e.g. magnetic and gravity worms intersecting). If "fractured reservoir potential" indices can be extracted from the analysis suggested in item 4, they should be validated against a few locations known from hydrocarbon production to be dominated by fracture permeability. Informed by the results of each of these four parts, the basin scale reservoir maps should be adjusted accordingly.

- Thermal Resource Maps. Because the accuracy of our Phase 1 result was limited by the availability of relatively few widely separated equilibrium temperature gradient determinations as well as by the need to assume thermal conductivity values that may or may not be appropriate, we recommend efforts to add more high quality data to the thermal analysis. First, we recommend acquisition of existing shut-in temperature data (as representative of an equilibrium value) from industrial partners. Second, we recommend that new equilibrium temperature profiles be logged in shut-in holes or those about to be abandoned. Those new equilibrium temperature data can serve the dual purposes of testing the accuracy of this study's thermal model, as well as perhaps enabling refinement of the BHT correction analyses. Additionally, thermal conductivity of relevant core samples should be measured. Results from detailed thermal logs as well as statistics from conductivity measurements should then be jointly inverted to establish local heat fluxes and a conductivity stratigraphy at those locations. All of these aspects should be incorporated into enhancing the regional thermal model.

- Seismicity Potential. The validity of the seismicity risk factor maps should be tested against newly acquired seismic monitoring results in PA and NY. Also, detailed analysis should be conducted of known induced seismicity (e.g., at the Dale brine mining site (Fletcher and Sykes [1977]) relative to our worm based seismic risk estimates for the purpose of ground-truthing those techniques in a real-world situation. Where higher resolution gravity and magnetic surveys may be acquired in the future, features within them that may be faults (e.g., the set of "worms") should be subject to the "orientation in stress field" analysis described in this report and accompanying methods memo.

- Structural Delineation at the Prospect Scale. For specific locations of interest for further examination of the geothermal development potential, geophysical studies are recommended to locate faults. These studies should include collection of high spatial resolution gravity and magnetics data, as well as purchase or acquisition of 2D seismic reflection lines along profiles that survey a variety of orientations. Where surface materials do not entirely obscure the sedimentary rocks, geological mapping of faults is equally recommended.

- Utilization LCOH Methods. Detailed scenarios for geothermal direct-use heating should be developed for interested communities or businesses. Alternatives for financing and potential tax benefits for the geothermal projects in these scenarios should be explored, and corresponding benefits and costs expressed by refinement of the GEOPHIRES computational model. GEOPHIRES should be used to estimate the Levelized Cost of Heat, inclusive of subsurface and surface parts, for those scenarios.

- Potential Basement Reservoirs. Our study focused on analyzing hot sedimentary type plays for the Appalachian Basin region. The analysis should be extended to basement rocks with an eye towards Enhanced Geothermal System (EGS) type projects. A recommended initial step is to describe expected basement lithologies, constrained by core/cuttings and outcrop where available. Additionally, basement fracture architectures (healed/open; spacing) should be estimated for these rocks.

- Planning for pilot boreholes or full geothermal well fields. Where a stakeholder group has significant interest in exploring the potential for geothermal direct-use heating, community education and efforts to secure necessary permits should be integral parts of their work. Outreach information must be developed and used within the communities surrounding prospect-scale locations. Additionally, permitting for well drilling and potential mitigation strategies must be planned. Other work should involve determining whether significant quantities of water – in addition to that naturally occurring in our reservoirs – will be required for a given prospect-scale locations and, if so, how to secure the rights to that water. If so, the responsible agencies, costs, etc. for that location must be evaluated.

Table 5: Summary of five play fairways and recommendations for next investigation steps.

Summary of five play fairways and recommendations for the next investigation steps. The minimum "depth to 80 °C" values are for the best location in the inner high priority fairway, and the city values are the best location within 10 km from the city. Also given for those locations is the range of depths corresponding to 95% confidence[2]. The reservoir units are the geological formations in or near the play fairway that are both relatively deep (to access higher temperature rocks), and with a high reservoir productivity index. Blank boxes indicate no recommended immediate action, pending further reservoir analysis and improved assessment of probability of reservoir success

Play Fairway (Name of major community)	Conditions in inner high priority play fairways (2015 Phase 1 analysis results)			Recommendations		
	Depth (m) to 80 °C	Uncertainties (m): 95% Confidence Range of Combined Errors	Reservoir Target Unit and Depth(s) Below Local Surface (m)	Geophysical data & analysis	Borehole data & analysis	Utilization scenarios & analysis
Charleston	Location of Minimum: 2200 Charleston: 2500	Location of Minimum: 950-3500 Charleston: 950-4100	Newburg Limestone (~1700) Oriskany Sandstone (~1400-1500)	Seismic for influence of the Rome Trough on thermal field and fracture networks	Use existing well logs to identify positions of deep formations that are known reservoirs in region, and evaluate by log data and models (facies, structure, and probability), the reservoir potential near Charleston. Log equilibrium temperature profile.	Define needs of a stakeholder district heating system and model the subsurface costs of delivering geothermal heat to meet their needs
Morgantown Clarksburg	Location of Minimum: 2300 Morgantown 2700 Clarksburg: 3380	Location of Minimum: 1000-3600 Morgantown: 1500-3900 Clarksburg: 2100-4700	Newburg Sandstone (~1500-2300) Brallier Formation (~1400)	Purchase or record gravity data & magnetics data and analyze for locations of faults	Log an existing well to obtain equilibrium temperature thermal profile and reservoir parameters	Define needs of WVU district heating system and model the subsurface costs of delivering geothermal heat to meet WVU needs; define needs of military base and model the subsurface costs of delivering geothermal heat to meet its needs

Pittsburgh	Location of Minimum: 2400 Pittsburgh: 3800	Location of Minimum: 1200-3600 Pittsburgh: 2100-5500	Formation associated with Devonian Unconformity (~1500)		For deep wells in neighboring counties, use existing well logs to identify positions of deep formations that are known reservoirs in region, and evaluate by log data and models (facies, structure and probability) their potential near Pittsburgh	Define needs of a stakeholder district heating system and model the subsurface costs of delivering geothermal heat to meet their needs
Meadville – Jamestown	Location of Minimum: 2700 Meadville: 3000 Jamestown: 2900	Location of Minimum: 1500–3900 Meadville: 1800-4200 Jamestown: 1700–4100	Galway Formation (~2000) Onondaga Limestone (~1300)		Use existing well logs to identify positions of deep formations that are known reservoirs in region, and evaluate by log data and models (facies, structure and probability), their potential near Meadville and Jamestown. Log equilibrium temperature profile.	Define needs of a stakeholder district heating system and model the subsurface costs of delivering geothermal heat to meet their needs
Corning – Ithaca	Location of Minimum: 2300 Corning: 2500 Ithaca: 2600	Location of Minimum: 1500–3100 Corning: 2100–2900 Ithaca: 2100–3100	Trenton-Black River (2800-3100)	Purchase or record seismic reflection data, gravity data, magnetic data, and analyze for additional T-BR reservoir locations as well as for fault locations	Log an existing well to obtain equilibrium temperature thermal profile and reservoir parameters	Define needs of Cornell University district heating system and model the subsurface costs of delivering geothermal heat to meet CU needs; define needs of Corning area office campuses and model the subsurface costs of delivering geothermal heat to meet their needs

[2] The uncertainty is based on two components. The first uncertainty component is the standard error on the thermal model depth estimate, derived from relations between standard error vs. BHT depth in 77 wells with detailed stratigraphy, then applied to the area of interest based on the dominant BHT depths in counties near the named location. The second uncertainty component is the kriging standard error of predicted mean at the named location due to spatial extrapolation of the well-specific predicted values of depth to 80 °C. These two components are treated as independent, permitting derivation of the combined uncertainty as the square root of the sum of the squares. The upper and lower bounds of 95% confidence are expressed by the best estimate of depth minus and plus, respectively, the combined uncertainty.

REFERENCES

Aguirre, G. A. (2014). *Geothermal Resource Assessment: A Case Study of Spatial Variability and Uncertainty Analysis for the State of New York and Pennsylvania.* Master's Thesis, Cornell University. Retrieved from http://hdl.handle.net/1813/38982.

Aguirre, G. A., Stedinger, J. R., & Tester, J. W. (2013). Geothermal Resource Assessment: A Case Study of Spatial Variabiality and Uncertainty Analysis for the State of New York and Pennslvania. *Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering.* Stanford: Stanford University. Retrieved from http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2013/Aguirre.pdf.

American Association of Petroleum Geologists (AAPG). (1985). Correlation of Stratigraphic Units of North America (COSUNA).

American Association of Petroleum Geologists (AAPG). (1994). CSDE, COSUNA, and Geothermal Survey Data_Rom.

Augustine, C. (2014). Analysis of Sedimentary Geothermal Systems Using an Analytical Reservoir Model. *Geothermal Resources Council Transactions.* Portland: Geothermal Resources Council.

Beckers, K. (2015). *GEOPHIRES Software Tool*. Retrieved from GEOthermal Energy for the Production of Heat and Electricity Economically Simulated: http://koenraadbeckers.net/geophires/index.php.

Beckers, K. F., Lukawski, M. Z., Anderson, B. J., Moore, M. C., & Tester, J. W. (2014). Levelized costs of electricity and direct-use heat from Enhanced Geothermal Systems. *Journal of Renewable and Sustainable Energy, Vol. 6, No. 1,* 013141.

Beckers, K. F., Lukawski, M. Z., Reber, T. J., Anderson, B. J., Moore, M. C., & Tester, J. W. (2013). Introducing GEOPHIRES V1.0: Software Package For Estimating Levelized Cost of Electricity and/or Heat from Enhanced Geothermal SystemsSYSTEMS. *Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering.* Standford: Standford University. Retrieved from http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2013/Beckers.pdf.

Bedre, M., & Anderson, B. (2012). Sensitivity analysis of low-temperature geothermal reservoirs: effect of reservoir parameters on the direct use of geothermal energy. *Geothermal Resources Council Transactions,* 1255-1262. Geothermal Resources Council.

Blackwell, D. D., & Richards, M. (2004). Geothermal Map of North America; Explanation of Resources and Applications. *Geothermal Resources Council Transactions, Vol. 28,* 317-320. Geothermal Resources Council.

Blackwell, D. D., Negraru, P., & Richards, M. (2007). Assessment of the enhanced geothermal system resource base of the United States. *Natural Resources Research, Vol. 15, No.* 4. doi:10.1007/s11053-007-9028-7.

Blackwell, D., & Richards, M. (Eds.). (2004). 2004 Geothermal Map of North America, Scale 1:6,500,000. American Association of Petroleum Geologists.

Blackwell, D., Richards, M., Batir, J., Frone, Z., & Park, J. (2010). New Geothermal Resource Map of the Northeastern US and Technique for Mapping Temperature-at-depth. *Geothermal Resources Council Transactions, Vol. 34,* 313-318. Geothermal Resources Council.

Blackwell, D., Richards, M., Frone, Z., Batir, J., Ruzo, A., Dingwall, R., & Williams, M. (2011). Termperature-At-Depth Maps for the Conterminous U.S. and Geothermal Resource Estimates. *Geothermal Resources Council Transactions, Vol. 35*, 1545-1550. Geothermal Resources Council.

Boschetti, F., Hornby, P., & Horowitz, F. (2001). Wavelet Based Inversion of Gravity Data. *Exploration Geophysics, Vol. 32, No. 1*, 48-55. doi:10.1071/EG01048.

Buescher, E. (. (2015). Green District Heating - Actual Developments of Deep Geothermal Energy in Germany. *Proceedings World Geothermal Conference 2015.* Melbourne, Australia: International Geothermal Association. Retrieved from http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/35000.pdf?.

Camp Dawson West Virginia Army National Guard. (2015). *About Camp Dawson*. Retrieved from Camp Dawson West Virginia Army National Guard: http://www.wv.ngb.army.mil/CampDawson/Form1.aspx?MP=MTc1&P=MTc1#Dawson.

Carter, L., Kelley, S., Blackwell, D., & Naeser, N. (1998). Heat flow and thermal history of the Anadarko basin, Oklahoma. *American Association of Petroleum Geologists Bulletin, Vol. 82*, 291-316.

Cho, J., Augustine, C., & Zerpa, L. (2015). Validation of a Numerical Reservoir Model of Sedimentary Geothermal Systems Using Analytical Models. *Stanford Geothermal Workshop Proceedings.* Stanford University.

Crowell, J., 2015, Quantifying How Errors in Thermal Conductivity Estimates Affect Geothermal Production Models: *Geothermal Resources Council Transactions*, 39th Annual Meeting, Reno, NV.

Engelder, T., Lash, G., & Uzcátegui, R. (2009). Joint sets that enhance production from Middle and Upper Devonian gas shales of the Appalachian Basin. *AAPG Bulletin*, *Vol. 93*, *No. 7*, 857-889.

Fletcher, J. B., & Sykes, L. R. (1977). Earthquakes related to hydraulic mining and natural seismic activity in western New York State. *Journal of Geophysical Research*, *Vol. 82, No. 26*, 3767-3780.

Förster, A., & Merriam, D. F. (1995). A Bottom-Hole Temperature Analysis in the American Midcontinent (Kansas): Implications to the Applicability of BHTs in Geothermal Studies. (pp. 777-782). Potsdam: International Geothermal Association.

Frone, Z. (2015). Heat Flow, Thermal Modeling and Whole Rock Geochemistry of Newberry Volcano, Oregon and Heat Flow Modeling of the Appalachian Basin, West Virginia. Southern Methodist University. ProQuest Dissertations Publishing.

Frone, Z., & Blackwell, D. (2010). Geothermal Map of the Northeastern United States and the West Virginia Thermal Anomaly. *Geothermal Resources Council Transactions, Vol. 34,* 339-343. Geothermal Resources Council.

Gallardo, J., & Blackwell, D. (1999). Thermal structure of the Anadarko Basin, Oklahoma. *American Association of Petroleum Geologists Bulletin, Vol. 83*, pp. 331-361.

Gerard, A., Genter, A., Kohl, T., Lutz, P., Rose, P., & Rummel, F. (2006). The Deep EGS (Enhanced Geothermal System) Project at Soultz-sous-Forets (Alsace, France). *Geothermics, Volume 35*, 473-483.

GoldCorp Inc. (2001, March 12). US$575,000 Goldcorp Challenge Awards world's first 6 million ounce internet gold rush yields high grade results! Toronto. Retrieved from http://www.infomine.com/index/pr/Pa065434.PDF.

Gringarten, A. (1978). Reservoir lifetime and heat recovery factor in geothermal aquifers used for urban heating. *Pure and Applied Geophysics, Vol. 117, No. 1-2*, 297-308.

Harrison III, W., Grammer, G., & Barnes, D. (2009). Reservoir characteristics of the Bass Islands dolomite in Otsego County, Michigan: Results for a saline reservoir CO2 sequestration demonstration . *Environmental Geosciences, Vol. 16, No. 3*, 139-151.

Harrison, W., Luza, K., Prater, M., & Chueng, P. (1983). Geothermal Resource Assessment of Oklahoma. *Special Publication 83-1, Oklahoma Geological Survey*.

He, X. (2015). *Feasibility and Supply Analysis of U.S. Geothermal District Heating and Cooling Systems.* West Virginia University, Benjamin M. Statler College of Engineering and Mineral Resources. Morgantown: Proquest LLC, UMI Dissertation Publishing. Retrieved from http://search.proquest.com/docview/1682034532. Abstract Available at http://gradworks.umi.com/37/01/3701975.html.

Hildenbrand, T. G., Briesacher, A., Flanagan, G., Hinze, W. J., Hittelman, A. M., Keller, G. R., Webring, M. (2002). *Rationale and Operational Plan to Upgrade the U.S. Gravity Database*. Retrieved from Gravity Database of the US: http://research.utep.edu/default.aspx?tabid=37229.

Hornby, P., Boschetti, F., & Horowitz, F. (1999, April). Analysis of potential field data in the wavelet domain. *Geophysical Journal International, Vol. 137, No.* 1. 175-196. doi:10.1046/j.1365-246x.1999.00788.x.

Hornby, P., Horowitz, F., & Boschetti, F. (2002). A Physical Interpretation of the Poisson Wavelet Transform of Potential Fields. *Proceedings, EGS XXV!! General Assembly.* Munich: European Geophysical Society. Retrieved from http://www.cosis.net/abstracts/EGS02/05568/EGS02-A-05568.pdf.

Horowitz, F., Smith, J., & Whealton, C. (2015). *One dimensional conductive geothermal Python code*. Retrieved from Online Git Repository: https://bitbucket.org/geothermalcode/jaredthermalconductivity.

Jordan, T., Camp, E., Smith, J., & Whealton, C., Horowitz, F., Stedinger, J., Tester, J., Richards, M., Hornbach, M., Frone, Z., Anderson, B., Xiaoning, H., Welcker, K., 2015, Low-Temperature Geothermal Energy Characterization by Play Fairway Analysis for the Appalachian Basin of New York, Pennsylvania and West Virginia: *Geothermal Resources Council Transactions.*

Lewis, J., McDowell, R., Avary, K., & Carter, K. (2009). Characterization of the Helderberg Group as a geologic seal for CO2 sequestration. *Environmental Geosciences, Vol. 16, No. 4*, 201-210.

Lienau, P., Lund, J., Rafferty, K., & Culver, G. (Augut 1994). *Reference Book on Geothermal Direct Use.* Klamath Falls, Oregon: GEo-Heat Center, Oregon Institute of Technology. Retrieved from http://www.oit.edu/docs/default-source/geoheat-center-documents/publications/direct-use/tp82.pdf?sfvrsn=2.

Lindal, B. (1973). Industrial and other applications of geothermal energy (except power production and district heating). Geothermal energy; review of research and development, (pp. 135-148). UNESCO.

Lugert, C., Smith, L., Nyahay, R., Bauer, S., & Ehgartner, B. (2006). *Systematic Technical Innovations Initiative Brine Disposal in the Northeast.* Albany, NY: New York State Energy Research and Development Authority.

Malinconico, L., & Moore, M. (2013). *Provisional Bouger Gravity Map of Pennsylvania.* Retrieved from AASG Geothermal Data Repository: http://repository.stategeothermaldata.org/repository/resource/a748ce233a25e3e0dd00c9865d0af3e5/.

Midwest Regional Carbon Sequestration Partnership. (2009). *Phase II Report.* Midwest Regional Carbon Sequestration Partnership. Retrieved from http://www.mrcsp.org/userdata/phase_II_reports/phase_ii_final_report_MRCSP.pdf.

Nelson, P. H. (2009). Pore-throat sizes in sandstones, tight sandstones, and shales. *AAPG Bulletin, Vol. 93, No. 3,* 329-340.

Obama, B.H. (2015). *Executive Order 13693 - Planning for Federal Sustainability in the Next Generation.* Washington, D.C.: U.S. Government Publishing Office. Retrieved 2015, from http://www.gpo.gov/fdsys/pkg/FR-2015-03-25/pdf/2015-07016.pdf

Rahm, B., & Riha, S. (2012). Toward strategic management of shale gas development: Regional, collective impacts on water resources. *Environmental Science & Policy, Vol. 17*, 12-23.

Rahm, B., & Riha, S. (2014). Evolving shale gas management: water resource risks, impacts, and lessons learned. *Environmental Science Processes and Impacts,* ***Vol.*** *16,* 1400-1412. doi:10.1039/c4m00018h.

Ravat, D., Finn, C., Hill, P., Kucks, R., Phillips, J., Blakely, R., Elawadi, E. (2009). *A Preliminary, Full Spectrum, Magnetic Anomaly Grid of the United States with Improved Long Wavelengths for Studying Continental Dynamics: A Website for Distribution of Data.* United States Geological Survey. Retrieved from http://pubs.usgs.gov/of/2009/1258.

Reber, T. (2013). Evaluating Opportunities For Enhanced Geothermal System-Based District Heating In New York And Pennsylvania. Cornell University. Ithaca, NY: Cornell University. Retrieved from http://hdl.handle.net/1813/34090 (restricted until 2018).

Reber, T. J., Beckers, K. F., & Tester, J. W. (2014). The transformative potential of geothermal heating in the U.S. Energy market: a regional study of New York and Pennsylvania. *Energy Policy, Vol. 70,* 30-44.

Roen, J., & Walker, B. (1996). The atlas of major Appalachian gas plays. *Publication V-25*.

Sanyal, S., & Butler, S. (2009). Geothermal Power From Wells in Non-Convective Sedimentary Formations - An Engineering Economic Analysis. *Geothermal Resources Council Transactions, Vol. 33,* 865-870. Geothermal Resources Council.

Shaalan, H. E. (2001). Generation of Electric Power. In *Handbook of Electric Power Calculations* (pp. 8.1-8.38). Retrieved from http://castlelab.princeton.edu/EnergyResources/GenerElectPower__Shalaan.pdf.

Shope, E. (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.* Master's Thesis, Cornell University. Retrieved from http://hdl.handle.net/1813/31206.

Shope, E. N., Reber, T., Stutz, G., Aguirre, G., Jordan, T., & Tester, J. (2012). Geothermal Resources Assessment: A Detailed Approach to Low-Grade Resources in the States of New York and Pennsylvania. *PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering. 37.* Stanford: Stanford University. Retrieved from https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2012/Shope.pdf.

Shumaker, R. (1996). Structural history of the Appalachian basin. In J. Roen, & B. Walker, *The Atlas of Major Appalachian Gas Plays: West Virginia Geological and Economic Survey Publication* (Vol. V-25, pp. 8-21).

Smith, L., Nyahay, R., & Slater, B. (2010). *Integrated Reservoir Characterization of the Subsurface Cambrian and Lower Ordovician Potsdam, Galway and Theresa Formations in New York.* New York State Energy Research and Development Authority (NYSERDA).

Social Security Administration. (2015). *Cost-Of-Living Adjustment, Prior Cost-of-Living Adjustments*. Retrieved from Official Social Security Website: http://www.ssa.gov/news/cola/facts.

Stutz, G. R. (2012). *Development, Analysis, and Application of a Well by Well Method for Estimating Surface Heat Flow for Regional Geothermal Resource Assessment.* Cornell Thesis, Cornell University. Retrieved from http://hdl.handle.net/1813/31037.

Stutz, G. R., Shope, E., Aguirre, G., Batir, J., Frone, Z., Williams, M., Jordan, T. E. (2015). Geothermal energy characterization in the Appalachian Basin of New York and Pennsylvania. *Geosphere, Vol 11, No. 5.* 1291-1304. doi:10.1130/GES00499.1.

Stutz, G., Williams, M., Frone, Z., Reber, T., Blackwell, D., Jordan, T., & Tester, J. (2012). A Well by Well Method for Estimating Surface Heat Flow for Regional Geothermal Resource Assessment. *Stanford Geothermal Workshop Proceedings.* Stanford University.

Tester, J., Joyce, W., Brown, L., Bland, B., Clark, A., Jordan, T., Anderson, B. (2010). Co-generation Opportunities for Lower Grade Geothermal Resources in the Northeast - A Case Study of the Cornell Site in Ithaca, NY. *GRC Transactions.* Vol. *34*, pp. 475-483. Geothermal Resources Council. Retrieved from http://pubs.geothermal-library.org/lib/grc/1028690.pdf.

Tester, J., Reber, T., Beckers, K., Lukawski, M., Camp, E., Aguirre, G. A., Horowitz, F. (2015). Integrating Geothermal Energy Use into Re-building American Infrastructure. *Proceedings World Geothermal Congress.* Melbourne, Australia: International Geothermal Association. Retrieved from http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/38000.pdf?.

The Coal Forum. (2015). *WV Leads SSEB in Rejecting 'Clean Power Plan'*. Retrieved from wvcoalforum.org: http://www.wvcoalforum.org/201510015019/recent-press/wv-leads-sseb-in-rejecting-clean-power-plan.html.

U.S. Census Bureau. (2000), Created 2003, Last Revised 2004, Accessed 2015). *U.S. Census Bureau*. Retrieved from Survey of Program Dynamics, Sampling Errors: http://www.census.gov/spd/sampling.html.

U.S. Census Bureau. (2010). *2010 census population & housing unit counts – Blocks*. Retrieved from https://www.census.gov/geo/maps-data/data/tiger-data.html.

U.S. Census Bureau. (2015). *U.S. Census Bureau*. Retrieved from State Quick Facts: http://quickfacts.census.gov/qfd/states/.

U.S. Energy Information Administration . (2015, October 1). *Frequently Asked Questions, Estimated U.S. residential electricity consumption by end use, 2014*. Retrieved from U.S. Energy Information Administration: http://www.eia.gov/tools/faqs/faq.cfm?id=96&t=3.

U.S. Environmental Protection Agency (EPA). (2015, October 1). *U.S. Environmental Protection Agency (EPA)*. Retrieved from Clean Power Plan for Existing Power Plants: http://www2.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants.

U.S. Environmental Protection Agency (EPA). (2015, August 3). *U.S. Environmental Protection Agency (EPA).* Retrieved from Clean Power Plan: State at a Glance, West Virginia: http://www3.epa.gov/airquality/cpptoolbox/west-virginia.pdf.

U.S. Geoscience Information Network. (2015, August 27). *USGIN Content Model Schemas Geologic Reservoir 1.0*. Retrieved from http://schemas.usgin.org/models/#geologicreservoir.

Walcott, C. (1896). *Cambrian Rock of Pennsylvania.* United States Geological Survey (USGS). Retrieved from http://pubs.usgs.gov/bul/0134/report.pdf.

West Virginia Geological & Economic Survey. (2006). *Trenton Black River Project Appalachian Basin*. Retrieved from Trenton-Black River Project Website: http://www.wvgs.wvnet.edu/www/tbr/.

Weston Solutions, Inc. (2014, June). *Engineering Evaluation/Cost Analysis Known Distance Range Munitions Response Site Berm Area.* Contract No. : W912DR-09-D-006, Delivery Order No.: 0008, West Chester, PA. Retrieved 9 2015, from West Virginia Army National Guard: http://www.wv.ngb.army.mil/CampDawson/Documents/kd_range_final.pdf.

Whealton, C. (2015). *Statistical Correction Of Temperature Data For New York And Pennsylvania Wells.* M.S. Thesis, Cornell University, Ithaca. Retrieved from https://ecommons.cornell.edu/handle/1813/40609?show=full.

Zoback, M. D., Barton, C. A., Brudy, M., Castillo, D. A., Finkbeiner, T., Grollimund, B. R., Wiprut, D. J. (2003). Determination of stress orientation and magnitude in deep wells. *International Journal of Rock Mechanics and Mining Sciences, Vol. 40, No. 7*, 1049-1076.