FINAL PHASE 1 RESEARCH REPORT

CATALOG OF SUPPORTING FILES

Supporting documentation for GPFA-AB Phase 1 consists of a series of Research Memos, numerous National Geothermal Data System Submissions, and project management documents correlating to the Phase 1 Statement of Project Objectives (SOPO). The text of the research memos and the SOPO documents contain hyperlinks to separate files included with this report, whereas the data submissions are a catalog listing.

Statement of Project Objective Task Milestones

The project tasks and milestones are available by clicking the link to the PDF file name: 0_GPFA-AB_SOPOTasksMilestones.pdf

Research Memos

Written memos were utilized throughout the Appalachian Basin Geothermal Play Fairway Analysis Phase I project. These served a dual purpose:

1. Solicitation of feedback and input in determination of assumptions, selection of methodology, etc. among the team members, particularly for project elements that required reflection and refinement, such as how best to correct Bottom Hole Temperatures (BHT) or what thermal conductivity values to assign to lithological strata.
2. Providing insight to other researchers wishing to expand on this research, in the Appalachian Basin or elsewhere, after the conclusion of the project.

Depending upon the subject, some memos are a brief description and justification of choices made; whereas others delve into more analysis and are the result of several authors editing over a period of weeks. For example, the Memo describing the BHT Corrections goes into detail about the statistical analysis of different approaches tried and why the formula selected was appropriate for this data set. (The third quarter report contained watermarked draft versions of nine memos.) This Phase 1 Final Report contains 18 memos. In several cases, these memos will accompany a Tier 2 Data Submission as explanation of the data and methods utilized:

Research Memos (the numbered list below are hyperlinks to the descriptions and file links for each memo):

1. Methodologies for GPFA-AB
2. BHT Corrections in GPFA-AB
3. Anadarko Basin Thermal Conductivities in GPFA-AB
4. Assignment of Conductivity Stratigraphy for Individual Wells using COSUNA Methodology in GPFA-AB
5. Tests of Simplified Conductivity Stratigraphy by Monte Carlo Analysis in GPFA-AB
6. Thermal Outlier Assessment in GPFA-AB
7. Thermal Resource Thresholds in GPFA-AB
8. Thermal Model Methods and Well Database Organization in GPFA-AB
9. Exploratory Data Analysis and Interpolation Methodology for Thermal Field Estimation

10. Selection of Four Counties in Each State with the Best Thermal Resources
11. Natural Reservoirs Methodology in GPFA-AB
12. Natural Reservoirs Database Inputs in GPFA-AB
13. Identifying Potentially Activatable Faults in GPFA-AB
14. Seismic Risk Map Creation Methods in GPFA-AB
15. Utilization Analysis in GPFA-AB
16. Risk Analysis in GPFA-AB
17. Combining Risk Factors in GPFA-AB
18. Permits for Geothermal District Heating Project in GPFA-AB

Methodologies for GPFA-AB

Phase 1 of the project consisted of a series of 7 tasks, the first 5 of which justify detailed explanation of the methods. Tasks one through four evaluated 4 criteria in the context of risk: thermal resources, natural reservoir quality, seismicity, and utilization. The fifth task combined these risk elements into a series of combined risk maps in order to identify geothermal play fairways. This document describes the methodology for each of these five major tasks, making some references to additional research memos contained within this section.

Methodologies for GPFA-AB filename: 1_GPFA-AB_Phase1Methodology.pdf

BHT Corrections in GPFA-AB

Determination of heat flow is a crucial element in estimating geothermal resource potential. Geothermal gradient is one of the key components in calculating heat flow. The oil and gas industry activity within the Appalachian Basin is a wealth of temperature at depth data, as 'raw' or uncorrected Bottom Hole Temperature (BHT) values are routinely collected during the oil and gas drilling and/or extraction process. However, BHT can differ from true *in-situ* rock values due to drilling disturbances, circulation of fluids, and other human induced factors. Additionally, extreme terrain variations as seen in mountainous areas can impact accurate determination of geothermal gradient. For these reasons, BHT values are generally 'corrected' to approximate an equilibrium temperature-depth profile. Over the years, several approaches to BHT corrections have been used in heat flow determinations and geothermal resource estimations. This memo describes the BHT correction methodology used in this GPFA-AB project.

BHT Corrections in GPFA-AB filename: 2_GPFA-AB_BHTCorrections.pdf

Anadarko Basin Thermal Conductivities in GPFA-AB

One of the key components in calculating heat flow and temperatures at depth is the thermal conductivity of the rock layers. The thermal conductivity values of rocks within the Anadarko Basin have been studied in greater detail than many other sedimentary basins. While this GPFA is focused on the Appalachian Basin, values from the Anadarko Basin have been used as a proxy where measured values unavailable within the Appalachian Basin. This memo describes the results of a resampling of Anadarko Basin thermal conductivities from Carter et al. (1998). Methods for assigning specific thermal conductivity values to each Appalachian Basin formation are discussed in an appendix to the memo entitled Assignment of Conductivity Stratigraphy for Individual Wells using COSUNA Methodology in GPFA-AB. The thermal conductivity values for each formation will be provided as an NGDS data submission.

Anadarko Basin Thermal Conductivities in GPFA-AB filename:
3_GPFA-AB_AnadarkoBasinThermalConductivity.pdf

Assignment of Conductivity Stratigraphy for Individual Wells using COSUNA Methodology in GPFA-AB

In order to determine properties of the thermal field at depth, the thermal conductivity stratigraphy of the basin must be known everywhere. In practice, it is infeasible to know the conductivity stratigraphy everywhere, so approximations are needed. For this project, the Correlation of Stratigraphic Units of North America (COSUNA) stratigraphic columns, available from the American Association of Petroleum Geologists were used as approximations of the stratigraphy because 1) well specific stratigraphy is not available for every well, and 2) the time constraints of Phase 1 would not be conducive to implementing specific geology to each well. COSUNA provides information on stratigraphy for 'sections' throughout the continent, including approximate thicknesses of different rock types. A weighted average of thermal conductivity for the entire wellbore can be approximated by consulting COSUNA charts for the various rock types and thicknesses encountered within the well. This memo documents the approach, assumptions, limitations, advantages, etc. of the COSUNA methodology for assignment of thermal conductivity and formation thicknesses to each well.

Assignment of Conductivity Stratigraphy for Individual Wells using COSUNA Methodology in GPFA-AB filename: 4_GPFA-AB_ThermalConductivityStratigraphyCOSUNA.pdf

Tests of Simplified Conductivity Stratigraphy by Monte Carlo Analysis in GPFA-AB

The simplification of well geology using the COSUNA approximation is tested by using Monte Carlo analysis to examine the potential differences of the thermal model outcomes for the COSUNA simplification compared to a full analysis of each well. For 77 wells, thermal model outcomes of the conductivity stratigraphy based on well details are compared to thermal model outcomes for the same locations if the COSUNA approximation is used instead. This memo first describes the approach of selecting a smaller subset of wells from the large collection to better understand the Basin's characteristics. Criteria were established for well selection based on availability of better lithology detail, multiple temperature-depth readings at appropriate depths, spatial distribution throughout the region of interest, etc. against which to test the COSUNA-based thermal model. The memo then describes the Monte Carlo simulation parameters. The results of the analysis are that the differences between the COSUNA stratigraphy with Carter conductivities and the detailed stratigraphy are generally minor when compared over the whole region.

Tests of Simplified Conductivity Stratigraphy by Monte Carlo Analysis in GPFA-AB filename: 5_GPFA-AB_ConductivityStratigraphyMonteCarloAnalysis.pdf

Thermal Outlier Assessment in GPFA-AB

The project team must determine which algorithm should be used to identify outliers in the geospatial datasets. Outliers pose a problem for non-robust regression schemes because they would have high squared residuals. Many regression techniques seek to minimize the squared residuals, so an outlier can have undue influence on the results of the analysis. This memo outlines the recommended outlier detection algorithm and contains several appendices within it. Appendix 1 outlines the previous work on outlier algorithms for the NY and PA geothermal dataset. Appendix 2 illustrates the sensitivity of the final results to algorithm parameters over a reasonable range of values. Appendix 3 provides Monte Carlo type I error rates for different distributions with known shape (e.g. normal, student t, uniform). The type I errors were derived empirically using Monte Carlo simulation for sample size of 25. In addition to references, appendices for this memo include:

1. Appendix 1: Summary of Outlier Algorithms Used at Cornell
2. Appendix 2: Sensitivity Analysis of Recommended Algorithm
3. Appendix 3: Type I Error Rates

Thermal Outlier Assessment in GPFA-AB filename: 6_GPFA-AB_ThermalOutlierAssessment.pdf

Thermal Resource Thresholds in GPFA-AB

The thermal risk factor needs to have thresholds assigned for visualizing the map in the discrete play-fairway color scheme. These thresholds should be objectively defined to reflect actual acceptability of the resource at that threshold level. Using this method, the resulting risk factor maps will reflect the favorability of the site. This memo discusses how the risk thresholds were determined for the Thermal Risk Factor, and the methods are transferrable to other risk factors.

Thermal Resource Thresholds in GPFA-AB filename: 7_GPFA-AB_ThermalResourceThresholds.pdf

Thermal Model Methods and Well Database Organization in GPFA-AB

This memo describes the reorganization of the GPFA well database into a format with additional data fields that are necessary to run the thermal model. It also describes the methods, assumptions, and equations used in the thermal model. These methods were used for creating the 3rd quarter and final thermal maps for this project. This memo will accompany the Tier 2 Data submission for the Thermal Analysis task, including a Derivation of 1-D Conduction Heat Balance. The Tier 2 Thermal Analysis data upload will contain several attached files with this memo:

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

Thermal Model Methods and Well Database Organization in GPFA-AB filename: 8_GPFA-AB_ThermalModelMethods.pdf

Exploratory Data Analysis and Interpolation Methodology for Thermal Field Estimation

This memo describes the methods, including formulas and assumptions, used to interpolate the geotherm data at each well to create the thermal risk factor and uncertainty maps for the project. Included in this memo is an exploratory data analysis on wells after processing in the thermal model.

Exploratory Data Analysis and Interpolation Methodology for Thermal Field Estimation filename: 9_GPFA-AB_InterpolationThermalFieldEstimation.pdf

Selection of Four Counties in Each State with the Best Thermal Resources

This memo describes the methods used to select the four "best" counties in each state according to the thermal resource. This analysis complements the Play Fairway maps that are based on the combination of the other three risk factors with the thermal resource, but this analysis is specific to thermal attributes.

Selection of Four Counties in Each State with the Best Thermal Resources filename: 10_GPFA-AB_SelectBestThermalResourcesCounties.pdf

Natural Reservoirs Methodology in GPFA-AB

Task 2 for this project involves the mapping and characterization of natural reservoirs within the Appalachian Basin region of New York (NY), Pennsylvania (PA), and West Virginia (WV). The intention of this memo is to present the methods that have been used for the completion of this task's milestones. The reservoir data collection and compilation methods used for NY are different than those used for PA and WV, as will be described within. Reservoir analysis and uncertainty quantification methods are consistent across the tri-state region.

Natural Reservoirs Methodology in GPFA-AB filename:
11_GPFA-AB_NaturalReservoirsMethodology.pdf

Natural Reservoirs Database Inputs in GPFA-AB

This document is intended to augment the "Natural Reservoirs Methodology" document, by providing more details on the original and modified database inputs for New York, Pennsylvania and West Virginia. Additionally, all research and literature that affected decisions for the reservoir data input are recorded here. This especially includes data for geologic formations in the Appalachian Basin. This memo will accompany the Tier 2 Data submission for the Natural Reservoirs Quality Analysis task. The Tier 2 Thermal Analysis data upload will contain several attached files with this memo.

Natural Reservoirs Database Inputs in GPFA-AB filename:
12_GPFA-AB_NaturalReservoirsDatabaseInputs.pdf

Identifying Potentially Activatable Faults in GPFA-AB

These analyses attempt to highlight the risk of induced seismicity related to a geothermal project. Absent a regionally complete map of deep faults, gravity and magnetic data are analyzed to extract a multi-scale-edge Poisson wavelet representation of the locations of rocks of laterally contrasting physical properties. Among these lateral rock property boundaries are a subset that are candidates for future fault slip, if fluid pressures change and if a plane of weakness is properly oriented in space. To narrow the focus of this analysis onto rock property boundaries of greater concern (e.g., faults with demonstrated propensity to slip), a second step was to identify the co-occurrence of rock-property-boundaries at depths of 3-4 km and seismic activity registered in earthquake catalogs or by EarthScope. One approach to exploring the likelihood that some of the faults in the region might be reactivated if subsurface pressures change is an analysis of tendency to slip, which is based on determination of the spatial orientation of a structure (plane of weakness) relative to the direction of the regional principal compressive stress. This method will produce interesting results that foster further investigation although at this stage the results will be of low reliability as indicators of the risk of induced seismicity. Collection of pertinent data during Phase 2 is vital to create more reliable risk results.

Identifying Potentially Activatable Faults in GPFA-AB filename:
13_GPFA-AB_IdentifyingPotentiallyActivatableFaults.pdf

Seismic Risk Map Creation Methods in GPFA-AB

This memo describes the methods used to process the seismic data gathered and generated for this project into a Risk of Seismicity. Detailed methodology used to convert the seismic risk data (i.e. distance to nearest earthquake, and angle to critical stress) into a two independent seismic risk maps is presented. This memo will accompany the Tier 2 Data submission.

Seismic Risk Map Creation Methods in GPFA-AB filename:
14_GPFA-AB_SeismicRiskMapCreationMethods.pdf

Utilization Analysis in GPFA-AB

Task four of Phase 1 of the project assesses the utilization demand for geothermal heat. This was done in two parallel efforts: 1) calculation of the Surface Levelized Cost of Heat (SLCOH) for Census Places exceeding a population threshold of 4,000 people and 2) identification of prospective users of geothermal heat, including larger commercial and/or industrial users. Intended to accompany the Tier 2 data submission which will include a number of files:

1) MATLAB code for interchange with GEOPHIRES
2) Result table for Census Places
3) Result table of Prospective Users
4) Shape file of Map showing Census Places and Prospective User locations

Utilization Analysis in GPFA-AB filename: 15_GPFA-AB_UtililzationAnalysisSCLOH.pdf

Risk Analysis in GPFA-AB

This memo builds upon the 1 April 2015 memo entitled "Combining Risk Factors." The relevant discussion from the previous memo is retained, when applicable. One difference here is an emphasis that map colors for 3-color or 5-color maps should be related to the *actual acceptability* of a location measured on that risk index at the scale of the analysis. They are not relative metrics providing just a comparison to other locations or projects, but absolute evaluations of project acceptability. This makes it reasonable to consider the minimum value across risk indices as a criterion for project acceptability. This memo outlines the required map data format for the individual risk factor maps, and the information that will be required. That includes thresholds used for scaling. The memo also describes some of the ways to represent uncertainty in the analyses and visualization tools that may be used in our final analyses. This memo summarizes some methods that we thought would be applicable to combining risk factors, but it does not represent the final methods used in the analysis. The next memo gives the final results and describes the methods used.

Risk Analysis in GPFA-AB filename: 16_GPFA-AB_RiskAnalysisAndRiskFactorDescriptions.pdf

Combining Risk Factors in GPFA-AB

This memo provides details and extended results related to the play fairway computations. The results include values used in converting each risk factor into the play fairway scale (scaled risk factor) and extended results on different methods of combining risk factors. The robustness of the different combination methods is briefly discussed. Calculations of uncertainty are discussed, including methods used to approximate the uncertainty in a scaled risk factor and a combined map. Detailed graphics for project locations are provided. The general principles of the combinations were outlined in the previous memo, but this document gives details on the computations and actual results from the analysis. Note: this is the lower resolution version of the file; a higher resolution version is available, but is >40MB.

Combining Risk Factors in GPFA-AB filename: 17_ GPFA-AB_CombiningRiskFactors.pdf

Permits for Geothermal District Heating Project in GPFA-AB

Permits will be required for any new drilling associated with a geothermal district heating project. This memo summarizes the anticipated permitting requirements and associated effort for subsequent phases of the project.

Permits for Geothermal District Heating Project in GPFA-AB filename: 18_GPFA-AB_PermittingGeothermalDistrictHeating.pdf

Available Data in Tier 1, 2 and 3 to GTDA:

This project will result in data submissions to the National Geothermal Data System (NGDS) via the Geothermal Data Repository (GDR) in all three supported Tiers. The SOPO tasks addressed by these submissions appears below each explanation as well.

Tier 1, Phase 1 Final Report and Associated Appendices

A PDF of this Phase 1 Final Report including associated appendices and memos will be uploaded as a Tier 1 data submission, after the removal of the section containing the cost estimates of Phase 2 recommendations.

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.

Tier 2, Thermal Quality Analysis Maps and Structured Data

This zipped folder includes the raw data (bottom-hole temperature data retrieved from the NGDS and from the state geological surveys) and calculated data, such as corrected BHT values, formation thermal conductivity values, heat flow values, and depth-to-temperature values. The submission also includes the applicable memos, describing the BHT correction methodology, outlier detection, thermal conductivity assignment, and thermal model calculations. The folder includes shape file(s) of all points, georeferenced rasters, and image files of heat flow and depth-to-temperature maps, and a 'read me' file describing the contents of the zipped folder.

Task 1.0 Thermal Resource Quality Assessment: 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 that 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.

Task 1 Deliverable: 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.

Tier 2, Natural Reservoir Quality Analysis Maps and Structured Data

This zipped folder includes the raw data (reservoir thicknesses, depth, water viscosity, and area) and interpolated data, including the newly developed Reservoir Productivity Index (RPI). The submission also includes the applicable memo, describing the RPI formulas assumptions and methodology. The folder includes shape file(s) of all points, PDFs of the reservoir quality and reservoir quality uncertainty map images, and a 'read me' file describing the contents of the zipped folder.

Task 2.0 Natural Reservoir Quality: The purpose of this task is to develop the supporting database, to evaluate, and to 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.

Task 2 Deliverable: 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.

Tier 2, Risk of Seismicity Analysis Maps and Structured Data

This zipped folder includes the raw data (historical record of earthquakes and fault data) and interpolated data, including the orientation as an indicator of fault reactivation. The submission also includes the applicable memo, describing the assumptions, equations, and the primary physics behind the analysis. The folder includes shape file(s) of all points, PDFs of the earthquake history and fault orientation seismicity map images, and a 'read me' file describing the contents of the zipped folder.

Task 3.0 Risk of Seismicity: 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 faults and of faults that are active.

Task 3 Deliverable: 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.

Tier 2, Utilization Variability Maps and Structured Data

This zipped folder includes the raw data (census bureau population data, EIA heat demand and power consumption, and the American Community Survey building size), and output sites with surface levelized cost of heat (SLCOH) for 248 Census Places. The submission also includes the applicable memo, describing the assumptions and modifications to the GEOPHIRES software. The MATLAB program used is included (executable as well as script). The folder includes shape file(s) of all points, PDFs of the SLCOH map image, and a 'read me' file describing the contents of the zipped folder.

Task 4.0 Utilization Variability: 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.

Task 4 Deliverable: 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 (SLCOH) for two communities in each state.

Tier 2, Combination of Risks Play Fairway Maps and Structured Data

This zipped folder includes the applicable memo, describing the methodology and assumptions and any modifications to the input data (such as combining the two seismicity risk elements into a single value). The folder includes a shape file of all points, georeferenced rasters, image files of combined risk maps using multiple approaches, and a 'read me' file describing the contents of the zipped folder.

Task 5.0 Risk Matrix Analysis: The purpose of this task is to merge the common risk segment maps described above, and to produce a common Risk segment 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.

Task 5 Deliverable: 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.

Tier 3, Geologic Reservoir in New Revised Content Model Format

The results of our Natural Reservoir Quality analysis is also being submitted as Tier 3 data submission utilizing a significantly reworded Geologic Reservoir content model. The previous content model for describing Geologic Reservoirs, originally developed by the Texas Bureau of Economic Geology was adapted to accommodate not only this team's new project analysis and metrics, but project data from other geothermal play fairway analysis projects beyond oil and gas extraction geographies.

Tier 3, Heat Flow Updates in Content Model Format

The new heat flow calculated values are being made available as a Tier 3 standardized data formatted submission. (Note: These will be submitted via the SMU Node of the NGDS at geothermal.smu.edu, rather than through the GDR).