Geothermal Play Fairway Analysis Best Practices

Hannah Pauling, Nicole Taverna, Whitney Trainor-Guitton, Erik Witter, Amanda Kolker, Ian Warren,* Jody Robins,* and Greg Rhodes*

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** former employees*

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List of Acronyms

AHP	analytical hierarchy process
CRS	common risk segment
DOE	U.S. Department of Energy
EA	environmental assessment
EBK	empirical Bayesian kriging
FOA	funding opportunity announcement
FONSI	finding of no significant impact
GDR	Geothermal Data Repository
GeoRePORT	Geothermal Resource Portfolio Optimization and Reporting Tool
GIS	geographic information system
GRRM	Geothermal Resource Reporting Metric
GTO	Geothermal Technologies Office
IDW	inverse distance weighted
MT	magnetotellurics
NREL	National Renewable Energy Laboratory
PFA	play fairway analysis
PI	principal investigator
USGS	U.S. Geological Survey
VOI	value of information

Executive Summary

Play fairway analysis (PFA) is a methodology that can improve success rates for geothermal exploration drilling, thus reducing the costs of geothermal projects while facilitating development in new areas[1]. It was originally developed for the oil and gas industry, but has been adapted for discovering geothermal resources over the last decade. The geothermal PFA methodology involves systematically screening a set geographic area for promising qualities typically related to the presence of heat, permeability, and fluid. Successful application of PFA can identify hidden hydrothermal systems.

From 2014 to 2021 the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) supported the development of PFA for geothermal resources through awards to 11 research teams across the country. The goal of these projects was to advance and adapt PFA for geothermal exploration to produce regional-scale maps that reduce exploration uncertainty.

Figure ES-1. Regions evaluated by DOE-GTO's PFA projects

Map from GTO[2]

This report is an outcome of the NREL-led PFA Retrospective project, which compiled, synthesized, analyzed the results of GTO's geothermal PFA program. Ultimately, we find that these projects greatly advanced approaches to geothermal exploration and resulted in extensive new data and new discoveries of unrecognized geothermal systems. We used the results to distill best practices in this report and to provide guidance for future applications of geothermal PFA. The report is organized as follows:

Section 1 presents PFA concepts and summarizes the DOE-funded projects at three different phases.

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[1] https://www.energy.gov/eere/geothermal/play-fairway-analysis

[2] https://www.energy.gov/eere/geothermal/articles/play-fairway-analysis-phase-ii-selections

- In Phase I, the 11 teams reviewed existing data on their study areas, which spanned the country and included diverse geologic and tectonic settings.
- In Phase II, six teams collected additional data for their sites.
- In Phase III, five teams were chosen to test the PFA models via exploratory drilling campaigns. Four teams completed targeting and drilling of temperature gradient wells at seven plays and discovered anomalously high temperatures and gradients at four of them.

Section 2 details the data and techniques used by the teams, visually reviews project progress, and discusses outcomes of the Phase III drilling work. Section 3 evaluates project outcomes to inform PFA best practices and recommendations. Key PFA methodology best practices are summarized here in Table ES-1; additional recommendations for improving drilling and overall project outcomes can be found in Section 3.

Table ES-1. NREL-Recommended PFA Methodology Best Practices

Evidence Layer Combination Method	Components Investigated (Common Risk Segment Maps Produced)	Transformation Method(s)	Weighting Approach	Confidence Quantification
Voter-veto method or weights of evidence	Heat, fluid,* permeability, and sometimes seal**	Density function (simple or kernel) or interpolation (empirical Bayesian kriging), depending on the nature of the data set in question. Sometimes Euclidean distance analysis is of value prior to density/interpolation functions.	Expert opinions in combination with analytical hierarchy process, or if sufficient training data exists, a more statistical weighting approach such as weights of evidence	Stochastic kriging (modeling confidence as separate from favorability)

*Fluid not required in areas where $P_{Fluid}(X) = 1$, i.e. Hawaii

**Seal requirement dependent on geothermal system type

While the 11 sites applied PFA methodologies in individualized ways, general best practices were derived and the drilling outcomes showed that PFA is well-suited for geothermal exploration, providing an intersection between data-driven and expert-driven approaches. The temperature gradient wells drilled in Phase III projects serve as important validation of the PFA methodologies. We believe the impact of this work—identification of previously undiscovered geothermal sites, as well as collection and analysis of 435,000 mi^2 of geologic data and over 100 publications and presentations—will continue to grow, with many prospective areas already identified for additional exploration and analysis.

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1 Background

Geothermal play fairway analysis (PFA) is a method of systematically evaluating potential locations for hidden hydrothermal resources, meaning those that do not show surface expression (GTO n.d.). The term “play fairway analysis” comes from the goal of the methodology—to evaluate the likelihood of a combination of unique geophysical, geologic, structural, or stratigraphic elements (the “play”) within a region to determine areas (“fairways”) where geothermal resources are projected to exist.

PFA was originally developed for oil and gas exploration, and was designed to assess whether the components necessary to form an economic hydrocarbon accumulation are present in a given stratigraphic and structural setting. PFA focuses on evidence for the presence or absence of source rock, reservoir rock, and trap, for which a variety of data types can be used to evaluate directly or indirectly. When adapted for geothermal exploration, a geothermal play may typically be defined as a tectonic and geological setting that includes a heat source, geothermal fluid, reservoir permeability and storage, and a reservoir seal (Doughty et al. 2018). Though extending beyond the original concept of PFA, non-geological components might also be included in a geothermal PFA that relate to development potential, e.g., land status, proximity to transmission, or environmental constraints.

The U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) released a funding opportunity announcement (FOA) in 2014 to collect data in unexplored or underexplored regions, generate geothermal favorability maps, and quantify uncertainty. Eleven projects were selected for Phase I, and the projects were competitively down-selected to six total projects for Phase II. Of these projects, five were selected for Phase III and four of these projects completed temperature gradient drilling.

1.1 Overview of PFA Concepts

PFA assembles data sets that are relevant for assessing the potential for the occurrence of a subsurface resource. In hydrocarbons exploration, PFA typically focuses on the occurrence of source rocks, reservoir rocks, traps, and seals—meaning, the components necessary for an accumulation of hydrocarbons. When applied to geothermal resources, DOE-funded PFA projects focus on identifying heat, permeability/reservoir, seal, and fluid components that enable the formation of a hydrothermal resource. Because geothermal PFA is based on the favorable intersections of these components rather than the presence of surface manifestations, it is especially useful for identifying blind, or hidden, resources. Importantly, the focus on potential for hydrothermal resources means the PFA methodologies that were developed may only be partly applicable or miss key components of geothermal resources more suited for enhanced geothermal systems or low-temperature geothermal. A wide variety of data sets help inform the potential for heat, permeability, and fluid, and these, on a project-by-project basis, vary in quantity, quality, and data density. The general process steps for PFA are shown in Figure 1 (Garchar et al. 2016).

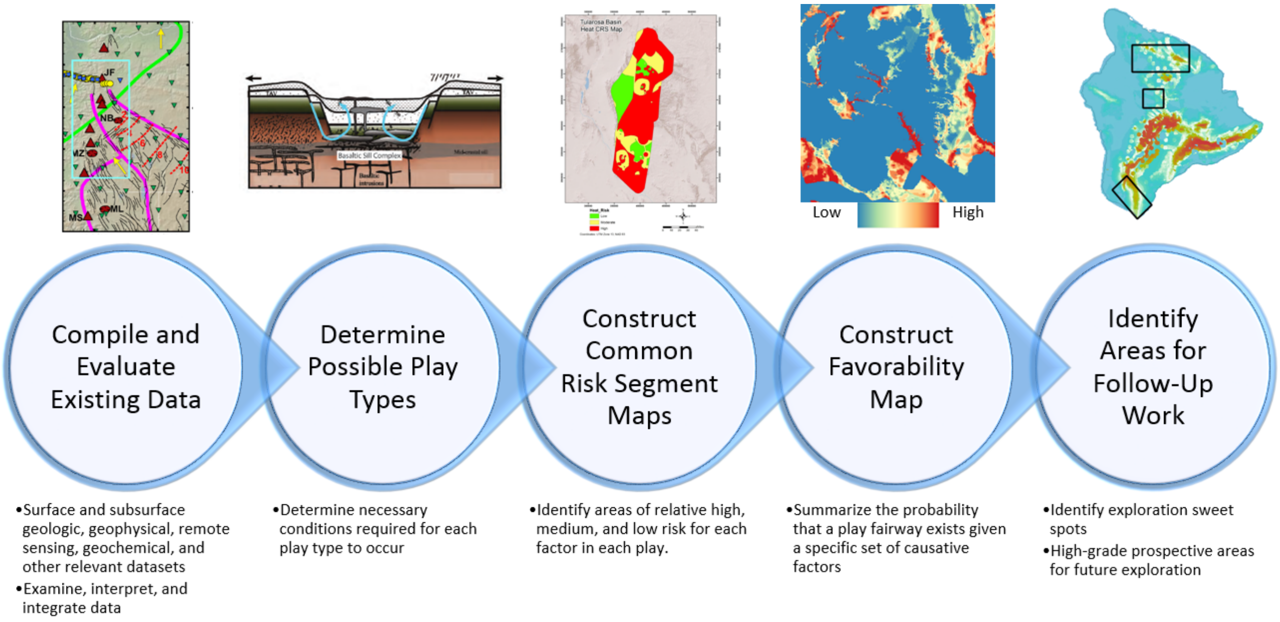


Figure 1. Flow chart showing the general steps of PFA

These general steps were expanded and refined during the DOE PFA projects. This expanded methodology is discussed in Section 2.1.

Figure from Garchar et al. (2016)

An important component of developing a PFA methodology and understanding what data inform it (and how they inform it) is the identification of geothermal conceptual models. During Phase I of the DOE PFA projects, a diverse set of geologic and tectonic settings were evaluated. The project teams evaluated relevant data sets within conceptual model frameworks, and performed probability and uncertainty analyses typically involving varying strategies for weighting data and for input of expert opinion. Phase I activities utilized existing data only, with a focus on data integration, GIS data organization and synthesis, uncertainty quantification, ranking/grading processes, and data gap identification. In Phase II, teams collected additional exploration data to fill data gaps, refine PFA methodologies, and identify plays within each fairway. Phase III primarily focused on targeting and drilling temperature gradient wells at select prospects to validate the methodologies developed in Phases I and II.

1.2 Overview of Projects

1.2.1 DOE PFA Projects: Phase I

In total, DOE selected 11 Phase I awardees, who identified 96 areas for follow-up studies. This represented the first pass at identifying plays within the identified fairways. Table 1 lists Phase I study areas and the areas of interest selected for preliminary Geothermal Resource Reporting Metric (GRRM) analysis (see Section 2.2.1; GRRM analysis is the predecessor to the GeoRePORT metric).

Table 1. Phase I Study Areas

Study Area	Awardee	Select Area of Interest for GRRM Analysis	Selected for Phase II?	Selected for Phase III?
Aleutians and Cascades	ATLAS Geosciences, Inc.	Sugarloaf	No	No
Appalachian Basin	Cornell University	Corning-Ithaca	No	No
Cascades	University of Utah – Energy and Geoscience Institute	Near Mt Jefferson (to N and E)	No	No
Eastern Great Basin	University of Utah – Energy and Geoscience Institute	Cinder Knoll	Yes	Yes
Hawaii	University of Hawaii	State of Hawaii	Yes	Yes
Modoc Plateau	University of California Davis	Bonham Ranch	No	No
Nevada Great Basin	Nevada Bureau of Mines and Geology	Crescent Valley	Yes	Yes
Rio Grande Rift	Los Alamos National Lab	Rincon	No	No
Snake River Plain	Utah State University	Camas Prairie: Mount Bennett Hills (B-1)	Yes	Yes
Tularosa Basin	Ruby Mountain Inc.	McGregor Range	Yes	No
Washington State	Washington Department of Geology and Earth Resources	Mt Baker, Mt St Helens, Wind River Valley	Yes	Yes

In Phase I, awardees defined the types of geothermal plays in the study areas. A typical definition included a combination of heat, permeability, and fluid. Some projects included play categories or other factors such as land access.

Favorability maps were developed for each study area to show the range of favorability and highlight areas of interest for Phase II or other follow-up work. These maps were displayed in various ways, including graduated color scales and solid-filled polygons or points of graduated color (Figure 2).

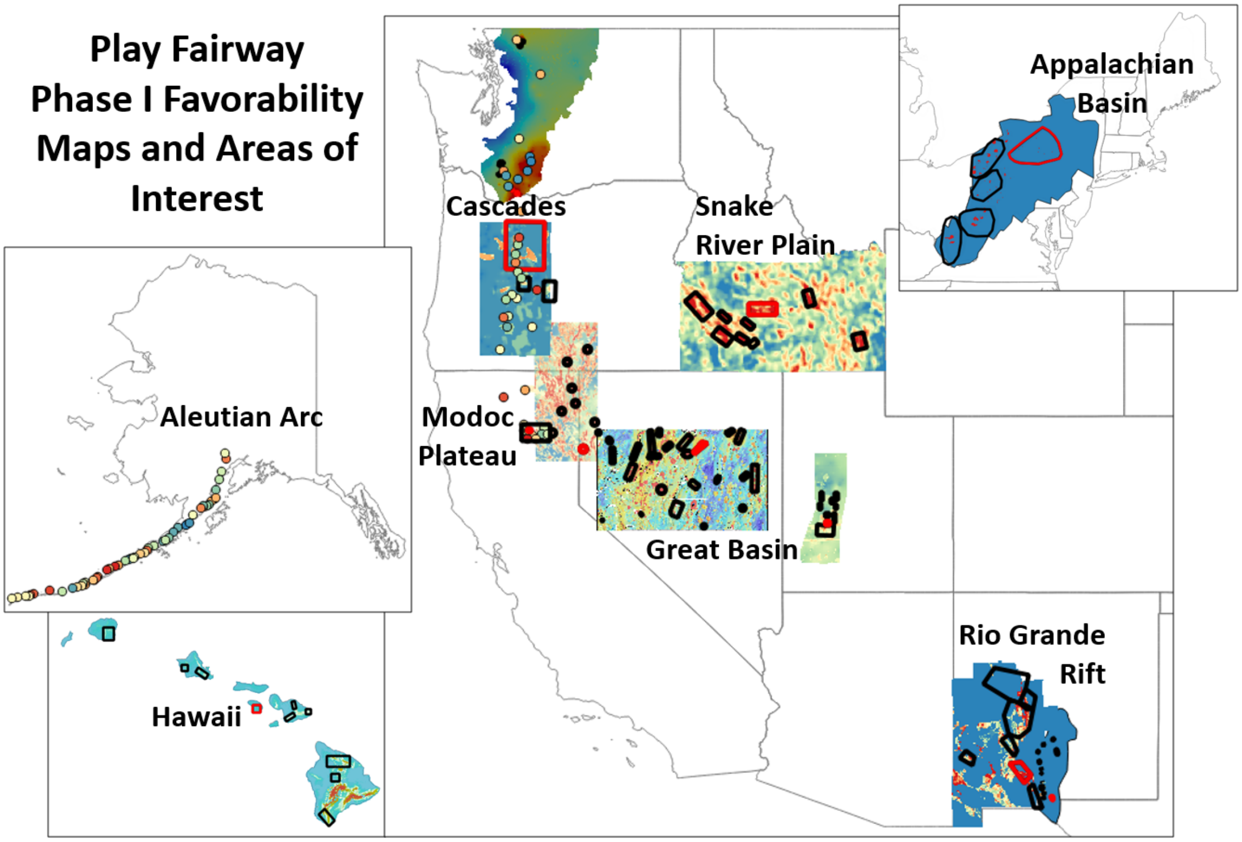


Figure 2. Summary favorability maps from Phase I with standardized color scheme

Garchar et al. (2016)

Sections 1.2.1.1 through 1.2.1.11 summarize the 11 Phase I projects. For more information on data inputs and combinations, see Appendix B for a table summarizing PFA project approaches, and Appendix C for PFA methodology flowcharts. Table 2 summarizes the data layers used by each Phase I project.

Table 2. Existing Phase I Data Layers

Project	Existing Data Layers				
	Permeability	**Heat**	**Fluid**	**Cap Rock/ Reservoir Quality**	**Marketability/ Risk of Seismic Activity**
Aleutians & Cascades	Tectonic setting Structural setting Fault slip rates Quaternary fault density Dilation potential Kinematically linked vents	Eruption volumes Recency of volcanism Composition of volcanism	pH and salinity Water table depth Scaling potential Non-condensable gases	Permissive lithology Degree breached	-
Appalachian Basin	-	Bottom-hole temperatures Equilibrium temperatures Mantle heat flow Surface temperature Thermal conductivity Radiogenic heat generation Sediment thickness Gravity/magnetic provinces of similarity	-	Formation top Formation thickness Reservoir average depth Reservoir pressure Porosity Reservoir area Reservoir net thickness	Building heat demand Roads Energy consumption Economic factors County population divisions Orientation of primary stress Magnetics Gravity Earthquakes
Cascades	Quaternary fault density Zones of critical stress Magnetotelluric (MT) conductivity	Heat flow MT conductivity Quaternary volcanic intrusions Fluid geochemistry (Si, Na/K, Cl, Mg)	-	-	-

Project	Existing Data Layers				
	Permeability	Heat	Fluid	Cap Rock/ Reservoir Quality	Marketability/ Risk of Seismic Activity
Eastern Great Basin	Quaternary fault density Zones of critical stress MT conductivity	Heat flow MT conductivity Quaternary volcanic intrusions Fluid geochemistry (Si, Na/K, Cl, Mg)	-	-	-
Hawaii	Rift zone Faults Geodetic strain Seismicity Gravity	Water well temperatures MT resistivity Cl/Mg ratio Caldera Gravity SiO_2 Vents Dikes Place names	MT resistivity Groundwater level elevation Groundwater recharge rate	-	-
Modoc Plateau	Fault length Fault age Dilation tendency Slip tendency Number of favorable settings Strain rate Total seismic moment	Age and type of volcanism Smoothed heat flow Maximum measured temperature Maximum measured heat flow Maximum measured temperature gradient Geothermometry	-	-	Land status Distance to existing high voltage transmission Population density
Nevada Great Basin	*Local:* Structural setting Quaternary fault recency Quaternary fault slip/dilation tendency	Temperature at 3 km	-	-	-

Project	Existing Data Layers				
	Permeability	**Heat**	**Fluid**	**Cap Rock/ Reservoir Quality**	**Marketability/ Risk of Seismic Activity**
	Quaternary fault slip rate *Intermediate:* Fault traces *Regional:* Horizontal gravity gradient Geodetic strain rate Quaternary slip rate Fault recency Slip/dilation tendency Earthquake density				
Rio Grande Rift	Known faults Inferred faults Earthquakes Subcrops	Heat flow Lithium Boron Basement temperature	Water table gradient Discharge zones	-	-
Snake River Plain	Quaternary faults Mid gravity gradient maximum Deep gravity gradient maximum Magnetic gradient maximum	Volcanic vents Heat flow Groundwater temperature Geothermometry temperatures Helium concentrations	-	Aquifer cap distributions Lake sediment distributions	-
Tularosa Basin	Quaternary faults Zones of critical stress	Temperature gradients Quartz geothermometry Heat flow	Point of diversion	-	-
Washington State	Slip tendency Dilation tendency Maximum shear strain	Temperature gradients Quaternary volcanic vents Quaternary intrusive rocks	-	-	-

Project	Existing Data Layers				
	Permeability	Heat	Fluid	Cap Rock/ Reservoir Quality	Marketability/ Risk of Seismic Activity
	Dilational strain at the surface Modeled fault displacement distribution Displacement gradient Shear Tensile fracture density	Spring temperature Reservoir temperature inferred from geothermometry			

1.2.1.1 Aleutians and Cascades

The Aleutians and Cascades PFA project focused on ranking individual volcanic centers within the Cascade and Aleutian arcs by their potential to host electricity-grade geothermal systems. The project developed PFA models by describing key geologic factors indicative of productive geothermal systems in a global training set that included 74 volcanic centers with current power production. In Phase I, the project team compiled data from existing databases and published sources, then used the data to evaluate trends and correlations. Data types were assigned data-driven and expert-driven weighting factors, which were included in evaluation of 100 volcanic centers in the Cascade and Aleutian arcs based on global data sets and known arc-hosted geothermal systems.

1.2.1.2 Appalachian Basin

Phase I of the Appalachian Basin PFA project identified direct-use geothermal plays in the Appalachian Basin portions of New York, Pennsylvania, and West Virginia, and is distinct because the analysis focused on the direct use of the heat rather than electricity production. The Appalachian Basin is a sedimentary basin with a history of hydrocarbon drilling activity, which increases subsurface data availability. This project, while unique among the other PFA projects, is a valuable case study for other low-temperature sedimentary basins in the United States.

1.2.1.3 Cascades

Central Cascadia represents a unique region for geothermal exploration because the Basin and Range extension is superimposed upon subduction arc magmatism. In Phase I of the Cascades PFA project, the team integrated data to create conceptual models of volcanic-hosted geothermal resources and identify upwellings of geothermal fluids that are suitable for electricity generation, direct-use, or enhanced geothermal systems. Rankings were established through a multi-criteria decision-making procedure, and the final favorability map identified promising areas in the Mt. Jefferson area, especially to the north and east into the Warm Springs region. The project also used a land access/infrastructure overlay to exclude wilderness areas.

1.2.1.4 Eastern Great Basin

In the Eastern Great Basin extensional tectonic regime of western Utah, the Basin and Range extension with volcanism (N-S trend) is superimposed upon pre-existing E-W plutonic belts and broad-scale structural lineaments. Western Utah also has a low velocity structure that has been interpreted to be a mantle melting signature. Unlike many other regions, existing data are relatively abundant in this region due to a history of geothermal exploration and the presence of three electricity-producing power plants. In Phase I of the Eastern Great Basin PFA project, statistical approaches to defining risk combined with conceptual models of the area led to the identification of several areas for follow-up studies, including the Cove Fort transverse zone and the Twin Peaks-Meadow zone. Like the Cascades project, the Eastern Great Basin project also used a land access/infrastructure overlay to exclude wilderness areas.

1.2.1.5 Hawaii

As the location of the only oceanic hotspot in the United States, the Hawaii PFA project is unique. A statewide geothermal assessment in 1983 found a potential resource on all islands. Limited recent data and few deep wells in existence on Hawaii posed challenges to the PFA project. For example, one existing well, the Saddle Road well on Hawaii Island, encountered temperatures of 140°C at a depth of ~1.7 km. However, there were no other data in the area to indicate these elevated temperatures, and the location was not previously recognized as a geothermal area of interest. Phase I of the Hawaii PFA project identified and compiled data sets collected since the statewide assessment, and each data set was assessed for its quality, reliability, and relevance. The combined data sets were used to develop a statewide map of geothermal prospects (nearly all of which were "blind" resources without surface expressions) and a gap analysis was performed to analyze which data types would improve reliability.

1.2.1.6 Modoc Plateau

The Modoc Plateau encompasses parts of northeastern California, southern Oregon, and northwestern Nevada. It lies at the intersection of the Basin and Range province and the Cascade volcanic arc. The western portion of the region contains geothermal systems with evidence of magmatic heat associated with Cascade arc magmatism, while the eastern portion contains fault-controlled systems with heat derived from high crustal heat flow, which is common in the Basin and Range area. During Phase I of the Modoc Plateau PFA Project, a wide variety of existing data were integrated to evaluate resource potential and exploration risk. "Fuzzy logic" was used to integrate expert opinion into each data set, and results identified several geothermal prospects. The project also identified low-risk areas with sufficient data coverage, quality, and consistency, as well as the degree to which the two play types (Cascade arc, Basin and Range) apply to each prospect.

1.2.1.7 Nevada Great Basin

Phase I of the Nevada Great Basin project analyzed 240,000 km^2 of the Great Basin region extending from west-central to east-central Nevada. The Great Basin is one of the largest geothermal provinces on Earth due to its high geothermal gradient and strain rates. Most geothermal systems in the region are amagmatic and associated with Quaternary faults that ruptured in the last 100 ka, but significant thinning of the crust and lithosphere have induced a high geothermal gradient throughout the region. However, many resources in the region are blind (lacking surface expressions), and it has proven difficult to locate areas with sufficient permeability. Gaps in data added to these difficulties. Specifically, only about 20% of the area had undergone detailed geologic mapping; LiDAR data were scarce; and gravity, MT, magnetic and reflection seismic data were lacking. Phase I of the Nevada Great Basin PFA project focused on a multidisciplinary geologic and geophysical analysis aimed at better defining geothermal play fairways. Results were compared against 34 benchmark systems in the region, all with temperatures ≥130°C. The project focused on fault-controlled geothermal play fairways, as faults are the primary control for geothermal systems in the region.

1.2.1.8 Rio Grande Rift

For the Rio Grande Rift PFA project, the team produced ArcGIS layers for each data type and combined them to create maps (structural analysis, slope, geothermometry, thermal, etc.), which were then used to rank prospects. The method developed by the project team was tested on the well-understood Socorro-La Jencia Basin geothermal system, and then it identified two additional prospects (one along the Comanche fault in the Lucero Uplift, another along the Gila River near Cliff-Riverside). Forward models of the Acoma Basin region were also developed to compute steady-state boron concentrations for 625 potential geothermal upflow zones, and the most likely upflow zone was east of the Comanche fault near the Lucero uplift.

1.2.1.9 Snake River Plain

The Snake River Plain (SRP) is a region with some of the highest heat flow values in North America. The Yellowstone hotspot feeds a magma system that underlies southern Idaho and has produced basaltic volcanism as young as 2,000 years old. Phase I covered a very large area (~150,000 km^2) and represents a new conceptual model for geothermal systems that includes aspects of volcano-hosted systems and Basin and Range systems. Phase I of the PFA project cataloged the critical parameters of exploitable hydrothermal systems and established risk matrices to evaluate those parameters in terms of both probability of success and level of knowledge. These matrices informed a GIS-based approach to process a range of different data types with distinct characteristics and confidence values. Data layers were processed with either density functions or interpolations to produce evidence layers.

1.2.1.10 Tularosa Basin

Phase I of the Tularosa Basin PFA project tested two distinct geothermal exploration methodologies for the basin within south central New Mexico and far west Texas. Geothermal plays were identified with both methods, and the results were compared to rank and evaluate potential plays. The first method was a deterministic method, and the second method was a stochastic (weights of evidence) method. The deterministic method identified eight plays, including a known resource at McGregor Range. The weights of evidence method required training data representing known geothermal systems to statistically evaluate the relationships of the input data types. This method identified ten plays, six of which were also identified with the deterministic method (including the known resource at McGregor Range). Four of the twelve identified plays were considered to be medium to high priority, based on proximity to control data and certainty analyses.

1.2.1.11 Washington State

In Washington state, a previous statewide assessment performed in 2014 revealed areas with elevated heat and permeability that were in areas reasonable for development. This assessment identified three plays: Mount Baker, Mount St. Helens, and Wind River Valley. These three sites represent two play types: 1) magmatic systems penetrated by faults on or near active stratovolcanoes (Mount Baker, Mount St. Helens) and 2) geothermal fluid circulation supported by active faulting (Wind River Valley). Phase I of the Washington state PFA project went beyond the existing statewide model by improving assessments of the heat and permeability needed for commercial geothermal operations. Challenges inherent in geothermal work in Washington are the presence of a rain curtain that depresses shallow temperatures, steep terrain that makes conducting field work more challenging, abundant tree cover, and a paucity of historical geologic data available for PFA evaluation.

1.2.2 DOE PFA Projects: Phase II

After the completion of Phase I activities, the PFA projects were evaluated by GTO based on technical strength of the methodology, utility of the methods for potential application at other sites, quantification of project risk, and commercial viability of identified plays. Down-selection of Phase I projects resulted in six projects advancing to Phase II. Following Phase I, which focused on using existing data, Phase II provided funding for new data collection at the highest priority areas as identified by their respective PFA scores identified in Phase I fairways. The variety of new data collections refined understanding of individual plays, which could advance to temperature gradient drilling in Phase III (Table 2).

Table 3. New Data Sets Acquired During Phase II

Project	New Data Collected During Phase II
Eastern Great Basin	Geochemistry Geologic mapping Gravity Magnetotellurics (MT) Passive seismic
Hawaii	Gravity Groundwater sampling MT
Nevada Great Basin	Geologic mapping Fault analysis (slip rates, recency, kinematics) Gravity LiDAR Seismic reflection (data collected in 1970s and 1980s, rights to interpret purchased for Phase II) 2-m temperature surveys Water chemistry
Snake River Plain	Field mapping and sampling Gravity Magnetics MT Seismic reflection Water chemistry
Tularosa Basin	Geologic mapping Geothermometry Gravity MT Temperature logging in existing wells Water chemistry 2-m temperature surveys
Washington State	Electrical resistivity Geochronology Geologic mapping Gravity LiDAR (flown in 2015 as part of USGS 3DEP program) MT Passive seismic

Sections 1.2.2.1 through 1.2.2.6 summarize each Phase II PFA project.

1.2.2.1 Eastern Great Basin

During Phase II of the Eastern Great Basin project, additional geological, geophysical, and geochemical data were acquired (Table 3) in areas initially identified in Phase I, including: 1) the Twin Peaks rhyolite field, 2) high heat flow areas north of the producing Cove Fort system, and 3) a geophysical structure beneath the Crater Knoll area. Regional MT profiling, which previously identified upwelling low resistivity structures at Dixie Valley and McGinness Hills, was also used with 108 new MT soundings acquired in Phase II. For acquisition, an ultra-remote reference in northwestern Nevada enabled noise cancellation against regional electromagnetic noise from DC transmission systems. The 3D resistivity model was computed with 294 total MT stations and confirmed the model derived from the sparser data set in Phase I with additional structural focus.

The previously modeled conductive anomalies at Twin Peaks, Crater Knoll, and Cove Fort were narrowed and refined. Arrays of ~50 Fairfield Nodal 3C 5Hz passive seismometers were deployed in separate networks for ~30 days each to test for the presence of earthquake swarms to support the concept that the MT geophysical structure represents upwelling heat and fluids that spatially correlate with seismic clusters and swarms. At Crater Knoll, 73 total events were identified, with almost all of them located to the east of the Crater Knoll array. Only five events were detected with the Twin Peak array, and the region appears to be mostly aseismic. Passive noble gas (3He) sensors were also used for a similar purpose. 40 passive He diffusion samplers were deployed over the three priority areas. The largest values were recorded at Twin Peaks, but almost all values were above the Great Basin background.

Geologic mapping performed in Phase II revealed numerous new faults and recovered siliceous opal sinter from several localities over the Twin Peaks rhyolite complex and Cove Creek Dome. Numerous faults were mapped or reinterpreted, including faults associated with the opal samples. All sample sites were associated with Quaternary faulting. New gravity data were acquired to identify subsurface faulting in areas with sparse outcrop. 138 new gravity stations were acquired during 2016 and 2017, mainly in the Twin Peaks and Crater Knoll areas. In the Crater Knoll area, a strong local gradient is coincident with the MT anomaly. Additionally, thermal gradient hole information originally acquired by Hunt Oil Company, Phillips Petroleum, Amax, and Unocal Corp for a total of ~170 wells was released to the PFA team during Phase II. Most of the holes are near Cove Fort, with a few near Twin Peaks and Crater Knoll. These data were used to augment statewide heat flow data and the Southern Methodist University and Utah Geological Survey’s heat flow databases for thermo-hydrological interpretation.

1.2.2.2 Hawaii

During Phase II, the Hawaii PFA project collected new data (Table 3) and produced 3D models of crustal stress due to topography. The new data were used to update the resource probability maps from Phase I. 62 groundwater samples were collected in 10 areas and were analyzed for temperature, major elements, trace elements, and isotopes. These samples reinforced Phase I data and identified anomalies on three islands: Oahu, Lanai, and Hawaii. Geochemical data provided further evidence for the presence of high crustal temperatures, and isotopic data were used to improve modeled groundwater flow trajectories on Lanai. MT and gravity surveys and geophysical inversions were performed in three target areas: Lanai, Mauna Kea (Hawaii Island),

and Haleakala Volcano's SW rift zone (Maui). 140 new gravity stations were acquired on Lanai and 73 new gravity stations were acquired southeast of Mauna Kea. A dense gravity survey at Haleakala Volcano's SW rift was previously performed by Ormat and acquired by the PFA team during Phase II. MT data were collected from 44 new sites on Lanai and eight on Maui. The team also performed new inversions of four pre-existing MT transects around Mauna Kea. The results of the gravity and MT inversions provided a basis for evaluating potential drilling targets and for establishing conceptual models about hydrologic and geothermal processes.

1.2.2.3 Nevada Great Basin

In Phase II of the Nevada Great Basin (NVGB) PFA project, new data were collected at five study areas (Table 3): Crescent Valley, southern Gabbs Valley, Granite Springs Valley, Sou Hills, and Steptoe Valley. Geologic studies were conducted at all sites, including 1) geologic mapping, 2) delineation of stratigraphy, 3) Quaternary fault analysis, 4) well logging of cuttings and core, and 5) regional stress assessment. A LiDAR survey plane was also flown at Granite Springs Valley and Sou Hills. LiDAR can help identify fault terminations, step-overs, and accommodation zones, which are recognized as favorable structural settings associated with geothermal activity. 30 new water samples were collected from springs and wells for geochemistry, measured temperature, and geothermometry. Shallow temperature surveys were conducted to assess possible upflow and outflow zones. Gravity surveys were carried out for all five areas to constrain the subsurface geometry of basins and faults. 1,559 new gravity stations were collected: 237 at Crescent Valley, 274 at southern Gabbs Valley, 415 at Granite Springs Valley, 355 at Sou Hills, and 278 at Steptoe Valley. The PFA team purchased the rights to interpret more than 540 km of seismic reflection data from Seismic Exchange, Inc. in Houston, Texas, for four of the five study areas. These data were originally acquired in the 1970s and 1980s and were used to constrain fault geometries, structural framework, and basin architecture. All of these data sets were incorporated into finer scale PFA, which allowed for selection of potential drilling targets.

1.2.2.4 Snake River Plain

New data were collected at two sites in the Snake River Plain during Phase II (Table 3). At the Camas Prairie, the target was a structurally controlled shallow resource inferred to be at 0.5–0.7 km depth. At Mountain Home Air Force Base (MH), the targeted blind resource was inferred to be much deeper at 1.5–2.3 km depth. Geologic mapping focused on structural mapping of the Pothole Fault system at Camas Prairie, and a wide range of volcanic vents were sampled. Approximately 56 km of active source seismic data were collected along county roads in Camas Prairie using an accelerated weight drop source and land streamer seismic system. The seismic data were used to image stratigraphy and faults, and to identify depth to bedrock beneath Camas Prairie. USGS collected data at 1,659 gravity stations and collected over 725 line-km of ground magnetic data during Phase II. Additionally, hundreds of rock property measurements were collected (including magnetic susceptibility, density, and magnetic remanence) on outcrops and samples to constrain potential field modeling. USGS also integrated water well logs into project analyses. In total, 102 MT stations were acquired during Phase II. 33 stations were acquired around the two deep drill holes (MH-1 and MH-2) at Mountain Home. The station array was designed to tie into the deep drill hole stratigraphy and to capture structures identified in previous high-resolution gravity surveys. Another 63 stations were acquired in Camas Prairie, covering the same area surveyed by the seismic, gravity and magnetic campaigns. Six stations were acquired along a profile crossing a previously identified gravity anomaly near the Bostic 1A deep drill hole. MT was used at all three locations to identify the presence and extent of a thick conductive layer corresponding to the known distribution of lacustrine sediments and possible alteration zones that are interpreted to represent a seal above a potential geothermal resource.

1.2.2.5 Tularosa Basin

Phase II of the Tularosa Basin PFA project collected new data (Table 3) at Fort Bliss, the Aerospace Data Facility-Southwest, and the White Sands Missile Range. Geologic mapping was performed to identify faults, dikes, and surficial geothermal features such as fossil sinters and hydrothermal alteration. Shallow groundwater samples were obtained for geochemical analyses, and 2-m temperature surveys were collected at the Aerospace Data Facility-Southwest and White Sands Missile Range sites. The high temperature anomaly identified at White Sands Missile Range follows a mapped Quaternary fault, and a patch of anomalous temperatures at Aerospace Data Facility-Southwest coincides with the hottest quartz geothermometer. Temperature logs were measured at four existing Aerospace Data Facility-Southwest wells and eight White Sands Missile Range wells. A gravity survey was performed and a total of 189 new gravity stations were acquired to investigate basin structure, fill thickness, and faults. An MT survey was performed at Fort Bliss to better characterize the area around validation well 56-5. 56 new MT stations were acquired, and the data show a northwest-trending conductor that may be related to hydrothermal alteration along a mapped Quaternary fault.

1.2.2.6 Washington State

Data collection was performed at three sites during Phase II of the Washington state PFA project (Table 3): Mount Baker, Mount St. Helens, and the Wind River Valley. LiDAR with 1-m resolution was flown in 2015 as part of the USGS 3DEP program and was made available to the PFA team at no cost to the project. 57 linear features at Mount Baker and 86 features at Wind River Valley were identified from LiDAR, several of which are along the strike from mapped faults. Many lineaments also correspond to strong geophysical gradients, suggesting that the geophysical boundaries may be controlled by active faults. 1:24,000-scale geologic mapping was completed, and abundant fractures were found in exposures along LiDAR lineaments. Geochronology was performed to determine the age of intrusive igneous rocks at Mount St. Helens and plutonic rocks at Wind River Valley. MT data were collected to identify regions of fluid content, hydrothermal alteration, major structures, and geologic features. Deeper conductive anomalies were found in areas with fault intersections, supporting the conceptual model of enhanced permeability near fault complexities. MT data were collected at 28 stations at Mount Baker and 56 stations at Mount St. Helens. Ground-based gravity and magnetic surveys were performed to constrain subsurface geology and fault locations. More than 93 km of magnetic data and 495 gravity stations were collected at Mount Baker, 481 gravity stations were collected at Mount St. Helens, and 604 gravity stations were collected at Wind River Valley. The gravity and magnetic data identified features that correspond well with mapped faults and LiDAR lineaments. Two 355-m-long electrical resistivity transects were collected at Mount Baker to improve characterization of shallow fault geometry and to check for conductive anomalies indicative of fluid pathways or clay caps. Four electrical resistivity transects were collected at Mount St. Helens. A passive seismic survey was performed at Mount St. Helens to define subsurface velocity structure and interpret large-scale geologic boundaries, faults, and regions of fluid-filled fractures. 20 broadband seismic stations were deployed and combined with 70 stations from the iMUSH experiment (Ulberg et al. 2020) and several permanent stations from the Pacific Northwest Seismic Network.

1.2.3 DOE PFA Projects: Phase III

After the completion of Phase II, the projects went through a down-selection process similar to the one conducted after Phase I. Of the six projects in Phase II, five were selected to advance to Phase III. The main goal of Phase III was to target and drill temperature gradient wells to validate PFA methodologies developed in Phases I and II. Additional data were collected during Phase III to improve well targeting.

1.2.3.1 Eastern Great Basin

In Phase III of the Eastern Great Basin PFA project, a deep thermal gradient hole was sited, and additional data were collected to refine drill hole targeting. New data included MT, gravity, structural geology, passive seismic, and He isotope profiling. The team planned to drill one or more holes at Cove Fort, where legacy temperature gradient holes showed high heat flow. However, high temperatures and potential for encountering H_2S led to cancellation of the drilling, as this was considered outside the experience base of the USGS Research Drilling Program.

1.2.3.2 Hawaii

Phase III of the Hawaii PFA project focused on two sites: Lanai and southeast Mauna Kea. Given the limited funding available, a decision was made to focus on deepening two previously drilled water wells on opposing sides of the Lanai Caldera. The wells were targeted based on their high geothermal favorability determined in Phase II, as well as the benefit of providing groundwater data. Preparation of Phase III drilling began with an Environmental Assessment, resulting in a system of mitigations to disruption of wildlife, and a Finding of No Significant Impact (FONSI). Video logs of both wells were provided by third parties, lending evidence that there were no unexpected blockages. Downhole deviation and gyroscopic surveys established that both wells were suitable for drilling to commence. Drilling was conducted on a 24-hour basis with excellent core recovery from 427 m to 1,057 m. Downhole temperature measurements were taken daily throughout the active drilling process. The well of primary focus in this project was allowed to equilibrate for 8 weeks before a downhole temperature survey was performed. The temperature at 900 m reached ~61°C, suggesting a temperature gradient of about 42°C per 1 km in this well. A major effort to obtain additional funding from state and industry partners resulted in $250,000 to conduct further fluid sampling. Groundwater samples were collected and analyzed from the Lanai wells and from wells around the state, including South Point Hawaii Island, East Rift Haleakalā, and Kauaʻi Island. Groundwater sampling included analysis of He isotopes, dissolved noble gases, major ions, and trace metals. These data reveal relevant geologic information that suggest the presence of geothermal resources outside the Big Island and are the basis for further studies and future exploration focus.

1.2.3.3 Nevada Great Basin

Phase III of the Nevada Great Basin PFA project involved additional geophysical surveys (gravity, magnetics, MT) and temperature gradient drilling at two sites: southern Gabbs Valley and northern Granite Springs Valley. The new geophysical work better defined the location of subsurface faults, areas of alteration, and areas of fluid flow. Six thermal gradient holes were drilled at southern Gabbs Valley, defining an apparent geothermal system with temperatures up to 124°C at 152 m. This is a blind system without surface expressions, but the site was targeted for drilling because of the co-location of 1) a favorable structural setting (fault intersections within displacement transfer zone), 2) Quaternary faults, 3) intersecting and terminating gravity gradients, 4) low magnetic readings, 5) shallow (2 m) temperature anomaly, 6) low resistivity anomaly, and 7) promising geothermometry from nearby wells. Six thermal gradient holes were drilled at Granite Springs Valley, suggesting the presence of a blind geothermal system with temperatures of ~96°C at ~150–250 m. The site was targeted for drilling because of 1) a favorable structural setting (termination of major Quaternary fault), 2) terminating gravity gradient, 3) magnetic gradient, 4) sinter deposits, 5) nearby warm water wells, 6) previously drilled thermal gradient holes, and 7) promising geothermometry. The isothermal gradients at this site suggest a convective heat source and upwelling, and the PFA team suspects that a major upwelling lies in the area proximal to sinter deposits (which imply subsurface temperature >180°C) and within a zone of complex faulting associated with the horse-tailing termination of a major normal fault.

1.2.3.4 Snake River Plain

During Phase III, the Snake River Plain PFA project team completed additional data collection and selected a site in Camas Prairie to drill a validation well. Data collection included the addition of 21 new MT stations, 293 new gravity stations, and two active source seismic surveys. The new MT stations were used to increase the detail of the 3D MT inversions, and the new seismic lines were used to document the precise locations and dips of faults near the planned test well. The gravity stations were added to provide detailed coverage in the area near the well. The validation well was drilled by the USGS Research Drilling Unit along a fault system that separates two distinct structural domains and offsets volcanic features. Two separate field campaigns in 2018 and 2019 included the collection of core, cuttings, and water samples. Geophysical well logs were collected, and a reservoir test was conducted. During the first field campaign, rotary drilling through basin fill sediments to bedrock was completed to 347-m depth, and further rotary drilling through bedrock was completed to 490-m depth. The second campaign consisted of diamond core drilling through bedrock that was completed to 618-m depth. Continuous core was collected during the second campaign. Wireline geophysical logs were collected in open holes for each stage of drilling, and a lithologic log was constructed from cuttings and core. Lithologic logs indicate that hydrothermal flow is associated with fracture permeability in basement granites, and hydrothermal alteration was common in both core and cuttings. Temperature logs indicate isothermal temperatures of ~80°C below ~300-m depth, and multicomponent geothermometry indicates equilibrium temperatures of ~124°C.

1.2.3.5 Washington State

Phase III of the Washington state PFA project validated the team’s modeling approach by drilling two thermal gradient holes and collecting core, image logs, temperature logs, and new geochemistry data. The drilling campaign was developed based on the new data collected during Phase II. The first drill hole is located near Little Park Creek, 11 km from the summit of Mount Baker, and is 448 m deep. 125 m of core was collected with image logs from ~53 m below ground to the bottom of the hole. Water samples were also collected for geothermometry. The equilibrated temperature gradient of 64°C/km at this drill hole is more than twice the regional average, indicating influence of the Mount Baker magmatic system. Geochemical analysis indicates a geothermal influence but may indicate mixing with groundwater or loss of SiO_2 due to precipitation and re-equilibration at shallow depths. Core and image log analysis indicates a history of permeability generation. The second drill hole is located along upper Schultz Creek, 16 km from Mount St. Helens. Core was collected from 143 m to the bottom of the hole at 321 m, and water samples were collected for geothermometry. The equilibrated temperature gradient of ~15°C/km at this drill hole is similar to regional values and does not indicate the presence of a heat anomaly. Geochemical analysis indicates a meteoric source with no geothermal component. The drill hole at Mount Baker is located in an area of high favorability and the drill hole at Mount St. Helens is located in an area of low favorability, so this is a positive validation of the modeling.

2 Retrospective Analysis

This report is part of the greater PFA Retrospective project, which involves synthesizing and analyzing the results of GTO's PFA program. This retrospective review is especially important considering that the 11 initial PFA projects varied dramatically in spatial extent, geologic setting, and technical approach. This diversity resulted in disparate methods, data products, and reporting, which limited comparisons between the projects. The PFA Retrospective project was intended to evaluate metrics for measuring and valuing exploration knowledge, determining the impact of the 11 PFA projects, assessing remaining data gaps and publicly available national exploration knowledge, and defining the typical characteristics of a geothermal play.

Following the 2020 Stanford Geothermal Workshop, the National Renewable Energy Laboratory (NREL) organized a PFA Retrospective Workshop at the USGS Menlo Park campus, with 37 attendees from academia, private industry, and government labs and agencies. Principal investigators (PIs) from each of the Phase III PFA projects (Snake River Plain, Eastern Great Basin, Hawaii, Nevada Great Basin, and Washington state) presented overviews and lessons learned from their projects. Other presentation topics included 1) PFA in oil and gas, 2) geothermal PFA in Argentina, 3) weights of evidence methods, 4) machine learning for PFA, 5) conceptual models and play types, and 6) geothermal PFA in Switzerland.

As part of the retrospective analysis, NREL compiled and analyzed publicly available geothermal exploration data sets for the western United States to identify and highlight data gaps in areas prospective for hosting geothermal resources (Rhodes et al. 2021). Results indicate that broad areas of the western United States lack sufficient geological and geophysical coverage necessary for regional resource exploration. The study directly informed the recent Geoscience Data Acquisition for Western Nevada (GeoDAWN) initiative, which united GTO with USGS, with input from NREL and the Nevada Bureau of Mines & Geology (NBMG), to assess U.S. needs for energy and critical minerals. The PFA Retrospective project was intended to enhance geothermal exploration practices and rate of discovery going forward and support future GTO-sponsored PFA and exploration programs.

This section details the data and methodology approaches used by the PFA teams. The following section, Section 3, uses this information to provide best practices and recommendations.

2.1 Exploration Data and Techniques Used in PFA

Though the PFA projects sometimes varied in terminology used, a uniform terminology is required for discussing the various GIS layers as data move through the assembly of common risk segment (CRS) maps. These terms apply to all data types and allow communication between various domain experts. Here, we define these layers as: 1) data layers, 2) evidence layers, 3) confidence layers, 4) CRS maps, and 5) the composite CRS map. These layers are based on the Snake River Plain PFA team's terminology and are defined as follows:

1. **Data layers** represent the raw data (prior to data processing). These data may include points, lines, or polygons, all of which must include geographical coordinates.

2. **Evidence layers** are created by applying geostatistical functions to data layers. Typically, these include application of either a density function, which calculates the occurrence of

objects within a given area, or a data interpolation function, which calculates intermediate values from a finite array of data points.

3. **Confidence layers** reflect data uncertainties, which are often assessed using a combination of approaches (e.g., fuzzy logic and kriging standard error).

4. **CRS maps** are the weighted sum of multiple confidence layers and evidence layers within a given play component, producing a CRS map for each characteristic observed in the project.

5. **Composite CRS** maps are the weighted product of multiple CRS maps, one each for play components (e.g., permeability, heat). Composite CRS maps highlight areas where the play components required for a viable geothermal resource are present.

We will discuss and further explain these PFA components throughout this section. Figure 3 outlines a generalized PFA methodology, which generalizes the components from each of the PFA projects and shows the relationship between components and PFA process steps.

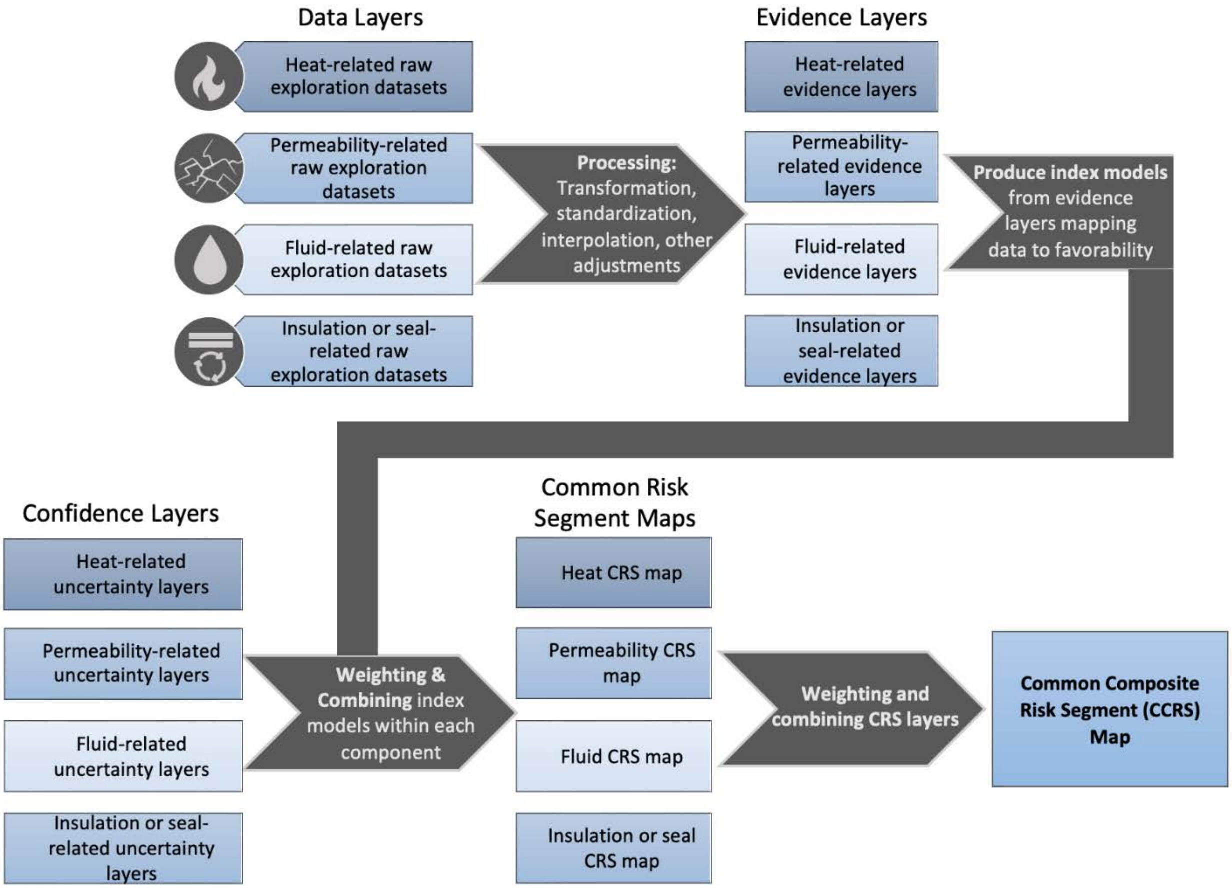


Figure 3. Flow chart outlining a generalized hydrothermal PFA methodology, combining portions of each project's approach

2.1.1 Regional PFA Using Existing Data

As discussed in Section 1.2.1, Phase I of the GTO-funded PFA projects consisted of using existing data as a means of narrowing in on plays of interest. As part of this, each project team first identified and acquired relevant existing data sets. The data sets were used to produce new or augment existing conceptual models. Initial regional-scale PFAs were then conducted to identify play-scale targets. Based on the play fairway models, conceptual models, and tectonic and geologic settings, project teams identified any additional data needs to describe plays of interest more adequately.

While this initial regional-scale PFA was in part a result of the funding structure, this type of approach is often carried out intentionally in practice as a way to identify more favorable plays within a study area. It is important to note that since the data sets used in this portion of the PFA process are often on a regional scale, the results of the regional-scale PFA are aimed at identifying plays that require further play-scale exploration data to plan temperature gradient drilling.

2.1.2 Data Acquisition

As described in Section 1.2.2, Phase II of the GTO-funded PFA projects involved collection of new data based on needs identified from PFA models, conceptual models, and tectonic and geologic settings. Phase III also involved data acquisition for some projects, in particular to address additional data needs identified by the play-scale models. The PFA process can be iterative, wherein additional data collection efforts may be carried out based on identified areas for improvement from the PFA modeling process. The data sets acquired in both Phases II and III included in-fill to improve resolution, expansion of data coverage to include new areas, and/or acquisition of new data sets to refine CRS and conceptual models.

Table 4 shows an overview of which data types were acquired and used in each PFA project, along with each project's final phase and tectonic setting. This table includes both previously acquired data used in Phase I and newly collected data from Phase II/III. The table also specifies which data are publicly available on the Geothermal Data Repository (GDR). Data sets not on the GDR may be publicly available elsewhere or may not have been released by the project team. Note that the amount of data used in each project was strongly correlated with the final phase to which a project was down-selected (e.g., a project that made it to Phase III included more data types than a project that ended after Phase I). Also, the tectonic setting is included because it plays a role in which exploration data sets provide the most value to the PFA. Table 3 in Section 1.2.2 shows only the data sets that were collected during Phase II.

Table 4. Data Sets Investigated for Use in PFA Projects

This table also specifies which data are publicly available on the Geothermal Data Repository (GDR) (large bold X's) versus not (small x's). These data sets not on the GDR may be publicly available elsewhere or may not have been released by the project team.

	Eastern Great Basin	**Hawaii**	**Nevada Great Basin**	**Snake River Plain**	**Washington State**	**Tularosa Basin**	**Aleutians & Cascades**	**Appalachian Basin**	**Cascades**	**Modoc Plateau**	**Rio Grande Rift**
Final Phase	**3**	**3**	**3**	**3**	**3**	**2**	**1**	**1**	**1**	**1**	**1**
Tectonic Setting	**Extensional/ Basin and Range**	**Hotspot island arc**	**Extensional / Basin and Range**	**Hotspot trace and backarc extension**	**Subduction-related continental arc**	**Rift zone**	**Subduction -related island arc**	**Deep Sedimentary Basin**	**Subduction -related continental arc**	**Subduction-related continental arc**	**Rift zone**
MT/AMT	x	**X**		**X**	x	**X**				**X**	
Strain rate/deformation		**X**	**X**		**X**	**X**	x			**X**	
Stress	**X**			x	x	**X**		x		**X**	
Gravity	**X**	**X**	**X**	x	**X**	**X**		**X**		**X**	**X**
Magnetics			**X**	x	**X**			**X**		x	**X**
Faults/fractures	**X**	**X**	**X**	x	**X**	**X**			**X**	**X**	
Dikes or rifts		**X**			x	**X**					
Volcanic vents		**X**		**X**	**X**		**X**				
Seismic	x		**X**	**X**	**X**					**X**	
Seismicity	**X**		**X**		**X**			**X**		**X**	
Heat flow	**X**			x	x	**X**		**X**	**X**	**X**	**X**
Geochemistry			x	x	x	**X**	**X**		**X**	**X**	**X**
Water chemistry		**X**	**X**	**X**	x	**X**					**X**
LiDAR	x		**X**		x						
Alteration mineralogy					x	**X**					
Geologic maps & models	x	**X**	**X**	x	x	**X**	**X**	**X**	**X**	**X**	**X**
Well data & logs		**X**	**X**	**X**	x					**X**	**X**
Downhole temperature		x	x	**X**	x	**X**		**X**			**X**
Geothermometry	**X**	x	x	x	x	**X**				**X**	**X**
Groundwater/ recharge data		**X**		x		**X**					**X**
Soil gas	x	**X**								x	
Land use/infrastructure		**X**		x	x				**X**	**X**	

2.1.3 Data Processing

Data processing transforms raw data to evidence layers, which provide information about each of the components being investigated. This process varies depending on the data set being observed, data density, and whether data are discrete or continuous. Discrete measurements require interpolation to create continuous evidence layers, whereas continuous data sets do not. Some data sets require transformation into more useful values that influence their impact on PFA, such as going from fault traces to distance from faults, calculating density and magnitude of seismic events, inverting gravitational acceleration data to density, or producing resistivity values from measurements of electric field. PFA also requires that data values be transformed to accurately represent their influence on CRSs that identify high favorability plays. CRSs, or play components, were developed in Phase I to describe favorability scaled to reflect data uncertainty or its complement confidence. In general, each project team developed CRSs by defining relationships between inputs that indicate high favorability. Details related to input types and combinations varied widely (Garchar et al. 2016).

2.1.4 Weighting Evidence Layers

Since evidence layers are not equally diagnostic and informative, the sum or product of the evidence layers is weighted to emphasize the layers that are thought to contribute most strongly to the CRS in question (e.g., heat, permeability, fluid, and/or insulation/seal). Weights can also help to balance layers with different data densities that may contribute equally to a particular CRS.

Within the DOE-funded PFA projects, weights were based on expert opinion, data confidence, and/or statistical models. While expert-opinion-based judgements can bring complex understanding regarding interactions between data types, they can also introduce bias that is amplified through interpretations of expert opinions. Quantitative approaches involving machine learning or based on statistical analyses rather than purely expert opinion can be applied to circumvent this and other disadvantages (Kolker et al. 2022). Some PFA projects initially used quantitative approaches to analysis, then slightly modified results based on expert opinions (e.g., Faulds et al. 2021).

2.1.5 Uncertainty Quantification

Uncertainty quantification was performed through evaluation of input data, risk factors, CRS maps, and favorability maps. Uncertainty of input data was evaluated based on spatial coverage, resolution, collection methods, recency of collection, presence of co-located data sets, scale of mapping, distance from station, sampling density, or kriging standard error. Data scarcity and reliability were analyzed with Bayesian analysis, fuzzy logic, multi-criteria decision-making, and expert knowledge. For some projects, data inputs were weighted based on reliability and completeness.

Typically, each data type was assigned its own confidence layer, commonly based on how the data were collected, density of data, and spatial distribution of data points, among other measures (e.g., data consistency, data vintage). For example, in the Snake River Plain project, heat flow and groundwater temperatures both have confidence layers derived from the standard error of their interpolated surface, derived by empirical Bayesian kriging (EBK), but their confidence layers are distinct because each has its own standard error surface. This standard error surface depends not only on the distribution of data (e.g., distance to its nearest neighbors), but also on the contrast in values between adjacent data points, with large contrasts increasing the standard error. Summaries of each project's PFA methodology and details are in Appendices B and C, including detailed methodologies with specific exploration methods and associated weights.

2.1.6 PFA Methodologies

Once all the previous steps have been completed, evidence layers and confidence layers can be combined into CRS maps for each CRS being evaluated (e.g., heat, permeability, fluid, and/or insulation/seal). Frequently, this was performed using a weighted sum, but some projects used novel approaches appropriate for their geologic and tectonic settings and data limitations. For example, the Hawaii PFA team combined evidence layers with expert knowledge to compute probabilities of the resource component qualities of interest using a generalized linear model (i.e., the voter-veto method). Table 5 shows a summary of all the teams' approaches to combining evidence layers into CRS maps.

Table 5. Summaries of Each Project's PFA Methodology

See Appendix B and Appendix C for more detailed methodologies with specific exploration methods and associated weights

Project	Evidence Layer Combination Method	Components Investigated (CRS Maps Produced)	Transformation Method(s)	Weighting Approach	Confidence
Eastern Great Basin	Weighted sum	Heat source, permeability	Probability kriging	Expert opinions combined with analytical hierarchy process (AHP)	Probability kriging
Hawaii	Generalized linear model ("voter-veto" method)	Heat, fluid, permeability		Expert opinion	Data quality and number of different data types at a given point
Nevada Great Basin	Weighted sum	Heat, local permeability, intermediate permeability, regional permeability, degree of exploration		Expert-guided fuzzy logic taking into account Bayesian weights of evidence and logistic regression	Error analyses of input data (expert-defined); favorability values compared to mean and error for anomaly confidence
Snake River Plain	Weighted sum	Heat, permeability, seal	Kernel density, simple density, interpolated EB* kriging	Expert opinion	Fuzzy logic

Project	Evidence Layer Combination Method	Components Investigated (CRS Maps Produced)	Transformation Method(s)	Weighting Approach	Confidence
Washington State	Weighted sum	Heat, permeability, fluid-filled fractures	Euclidian distance analysis, buffer polygons converted to weighted rasters; kriging interpolation for MSH*, IDW interpolation for WRV* and MB*	Expert opinions combined with AHP	Confidence analyses of input data (expert-defined) used to scale favorability
Tularosa Basin	Deterministic petroleum industry logic (union overlay and dissolve tools in ArcGIS) and Stochastic Weight of Evidence approach	Heat, fracture permeability, and groundwater	IDW* interpolation	Expert opinion	Weights of evidence and an additional more conservative probability kriging approach

* IDW = inverse distance weighted; EB = empirical Bayesian; MSH = Mount St. Helens; WRV = Wind River Valley; MB = Mount Baker

The CRS maps are combined into a final composite CRS. Composite CRS maps are the weighted sum or product of all the CRS maps, one each for the CRSs (play components) observed in the project (e.g., heat, permeability, fluid, and/or seal). The composite CRS highlights areas where all the critical elements required for a viable geothermal resource are present—in other words, a geothermal favorability map. An example of the weighted sum approach is seen in the Washington state PFA team's approach. Table 6 shows an example of the weights applied to each of the CRS maps in the Washington state PFA project to produce composite CRS maps.

Table 6. Weights Applied to Each CRS Map in the Washington State PFA Project

Model	MB	MSH-N	MSH-S	WRV
Heat	0.322	0.243	0.322	0.492
Permeability	0.344	0.351	0.344	0.388
Fluid-filled fractures	0.334	0.405	0.334	0.120

As an alternative, the Hawaii team computed a joint probability of the components' qualities of interest, assuming conditional independence (i.e., the veto equation).

2.1.7 Validation

Since geothermal PFA is generally an approach to identify plays and favorable areas to drill within plays based on limited or no direct subsurface data, there is uncertainty surrounding whether the identified subsurface target is "correct." Targeted temperature gradient drilling is designed to collect high-priority subsurface data in advance of drilling full-size production wells. Non-intrusive ways to validate PFA results include comparing to conceptual models and numerical reservoir models. These approaches are appropriate for advanced stage plays where sufficient data are available to inform conceptual and numerical reservoir models.

When PFA outputs become more certain, they support decisions to drill temperature gradient wells to confirm elevated temperature gradients, whether or not there is fluid present, and whether or not there is insulation/seal in the areas suggested by PFA outputs. Reservoir intersection and flow testing is required to confirm the presence of a geothermal resource and estimate its capacity; however, temperature gradient drilling is primarily meant to collect targeted, subsurface temperature data. During Phase III, four teams drilled small-diameter wells to validate PFA results by targeting anomalous temperatures and gradients. Table 7 describes a summary of the PFA-informed drilling outcomes from these four projects. Note that the Nevada Great Basin project also drilled 10 GeoProbe, or direct-push, holes in Granite Springs Valley, which is a lower cost and shallower-penetrating alternative to drilling temperature gradient wells. GeoProbe holes were all less than 50 m depth and were used to inform the locations for temperature gradient well drilling. Such shallow holes would not be applicable to locations with deeper geothermal resources, such as Hawaii and Washington state.

Table 7. Phase III PFA-Informed Drilling Outcomes, Including Depth, Temperature Gradient, Whether Fluid Was Encountered, and a Summary of the Well's Outcome

Project / Well	Depth	Temperature Gradient	Fluid Encountered?	Summary
Hawaii / Lanai 10	1,057 m	42°C/km	Yes	Deepened existing well. Temp gradient of 42°C/km is more than double Hawaii's background gradient. First well >1,000 m deep off of Hawaii Island to measure elevated temperatures.
Nevada Great Basin / Gabbs Valley 6 TG holes	152 m	190–400°C/km (outlier of 57°C/km)	No	Captured the peak of the thermal anomaly along a northeast-southwest transect, but the thermal anomaly is not constrained to the northwest or southeast of this transect.
Nevada Great Basin / Granite Springs Valley 6 TG holes	150–250 m	>220°C/km	No	Successfully identified multiple thermal anomalies in Granite Springs Valley. The temperature log profiles demonstrate convincing indications of hydrothermal fluid flow, but the precise locations of geothermal upflow are not well constrained.

Project / Well	Depth	Temperature Gradient	Fluid Encountered?	Summary
Snake River Plain / USU Camas-1	533 m	~70°C/km	Yes (artesian)	Reservoir test indicated modest flow rates at moderate temperatures (66.7°C)—lower than anticipated, but failed to reach target depth of 610+ m.
Washington State / MSH77-2	15.7 m	NA	No	Site abandoned due to lack of progress on 8th day of drilling.
Washington State / MSH17-24	318 m	~15°C/km	Yes (artesian)	Temp. gradient and heat flow are not higher than regional values. Drilling location negatively impacted by accessibility and logistics.
Washington State / MB76-31	448 m	~64°C/km	Yes (artesian)	Temp. gradient and heat flow are nearly double regional values, although less than those reported at previously drilled DNR83-3.

Another way to validate a PFA approach is through cross-validation, or applying a methodology developed using one area or set of training sites on a new area or a new set of training sites. This is similar to the concept of cross-validation in machine learning, in which an algorithm is tested on a set of test data points that were not included in the training data set, and therefore have never before been seen by the algorithm. Cross-validation is a good way to test the extensibility of an approach, making sure the method is not over-fitted to a single area or set of areas. The Snake River Plain team cross-validated their methodology by applying it to Phase II data from the Washington state PFA. Since both projects used different units, the outputs were not compared quantitatively, but instead a qualitative assessment was carried out, looking at similarities and differences between high favorability and low favorability areas identified by each PFA workflow. The Snake River Plain team observed quite a few similarities and a few differences, likely related to different interpolation approaches being used and limited data for some play components.

2.2 Using GeoRePORT To Track PFA Project Progress

To facilitate tracking progress from one phase of PFA to the next, project data were extracted from PFA project technical reports and input into NREL's Geothermal Resource Portfolio Optimization and Reporting Tool (GeoRePORT). GeoRePORT was developed by NREL and a large industry stakeholder group to help GTO track and measure the impact of its RDD&D funding on geothermal projects. GeoRePORT is designed to provide uniform assessment criteria for geothermal resource quality and project readiness as projects progress through exploration and development phases. GeoRePORT was developed to provide consistency among the user community in *reporting*; it is neither a prescription for conducting exploration and development, nor a scorecard or judgment on project feasibility.

The GeoRePORT tool provides two visualization outputs: one on the quality of the geothermal resource as it relates to the potential to extract heat (resource grade), and another on the progress of research and development efforts over the lifetime of the project (project readiness). ***Resource***

grade is depicted as a rose diagram with three quadrants: Geological, Technical, and Socio-economic. Each quadrant is composed of four attributes. The tool ranks each attribute based on user input on a scale of A (highest) through E. GeoRePORT also considers the activities conducted to assign grades for each attribute and what is known about the quality of the data collected. Geological attributes include temperature, volume, permeability, and fluid chemistry. For the geological attributes, activity and execution indices are developed to address uncertainty in the reported data (for full description of the geologic assessment protocol, see Rubin et al. 2022a). Technical attributes include logistics, drilling, power conversion, and reservoir management (Rubin et al. 2022b). Socio-economic attributes include land access, transmission, permitting, and market demand (Levine et al. 2022). The attribute grades seen in this report are a cumulative score, each one composed of several weighted sub-attributes. These sub-attributes are graded according to available data. Data that were not reported by PFA teams are left empty in GeoRePORT's resource grading but still affect the attribute grades. Uncertainties in technical and socio-economic attributes are addressed via activity indices.

Like resource grade, the GeoRePORT protocol breaks the concept of ***project readiness*** into ordered categories. These project readiness levels are not directly related to the grades and are an independent assessment of the project progress. As projects progress from one development phase to the next, they pass through activity thresholds, which are minimum activities required to qualify for the next category. By assessing the development activities of the project, users can report on incremental project progress. Like the resource grade, project progress will continually be updated throughout the project lifetime.

For the PFA retrospective, GeoRePORT was employed to track project progress between Phases I, II, and III, not to judge the quantity or quality of the data collected. For more information about the GeoRePORT spreadsheet tool and protocol for users, please visit: https://openei.org/wiki/GeoRePORT/Protocol.

In order to facilitate the task, an NREL team extracted data from PFA project publications (listed in Appendix A and on the Geothermal Data Repository: https://gdr.openei.org/pfa) and entered those data into the Excel-based GeoRePORT spreadsheet tool. Then, the PFA PIs were asked to review the completed spreadsheets for each project, input any missing data, and modify entries as needed. 41 spreadsheets were generated during this iterative NREL-led exercise. ***Importantly, the data inputted into the GeoRePORT sheets do not represent all available data and findings for study areas.*** They only represent what was reported by PFA teams in their final reports. Additionally, PFA projects were advised not to focus major resources on some of the attributes graded in GeoRePORT, such as land access, transmission, permitting, and market because these were not related to specific FOA goals. See Appendices B and C for more details on data input.

2.2.1 Pre-Phase I Results: Prior Work

NREL obtained prior work by DOE GTO using a previous version of GeoRePORT (Geothermal Resource Reporting Metric [GRRM]) that was used to evaluate PFA project data at the pre-award phase and to track PFA project progress between the pre-award phase and Phase I. For that effort, publicly available information from online sources (e.g., OpenEI, National Geothermal Data Repository, Geothermal Prospector) was entered into the GRRM (Young et al. 2015; Badgett et al. 2016; Garchar et al. 2016).

Summary Resource Grade Charts (Figure 4) were created with GRRM for each of the areas of interest identified in Table 1.

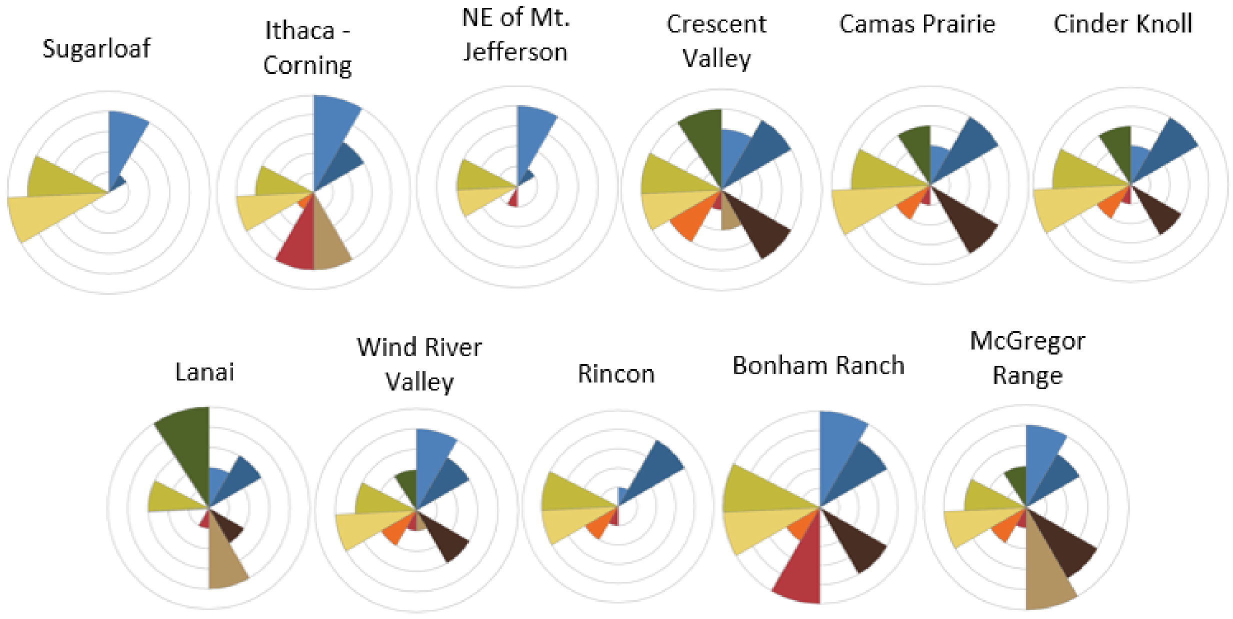


Figure 4. GRRM grades for selected areas of interest identified at the end of Phase I

From Garchar et al. (2016). See Table 1 to identify the corresponding Phase I projects.

2.2.2 GeoRePORT Analyses of Project Grade

Out of 11 total PFA Phase I projects, six were selected to continue into Phase II by DOE GTO. To avoid redundancy with the 2016 evaluation, this study focused on results from those six projects only. Of the six projects selected for Phase II, five were selected for Phase III (Tularosa Basin was not selected). Data entered into GeoRePORT were extracted from publications for the following PFA projects. A comprehensive list of publications is available in Appendix A.

- Eastern Great Basin, Utah – A.4
- Hawaii – A.5
- Nevada Great Basin – A.7
- Snake River Plain, Idaho – A.9
- Tularosa Basin, New Mexico – A.10
- Washington State – A.11

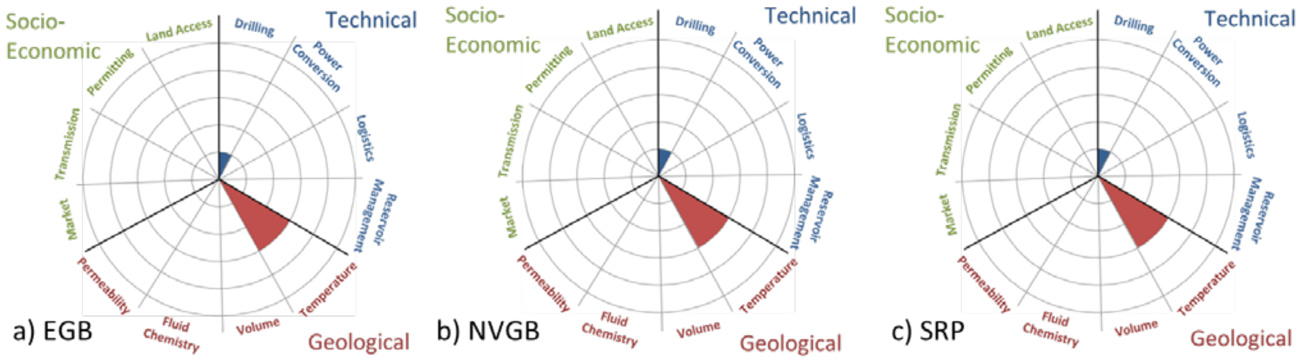
2.2.2.1 Phase I

The Phase I projects were similar in the type and amount of data collected. Data for 9 out of the 12 project sub-attributes reported in GeoRePORT were available in Phase I projects (Table 8), with the majority of projects reporting data on drilling, logistics, market, and resource temperature.

Table 8. Types of Data Reported for PFA Phase I Projects

GeoRePORT attribute	GeoRePORT sub-attribute	Projects reporting (out of 6)
Technical	Drilling	5
	Logistics	3
	Resource management	0
	Power conversion	0
Geologic	Temperature	5
	Permeability	2
	Volume	1
	Chemistry	1
Socio-Economic	Market	3
	Transmission	1
	Permitting	0
	Land Access	2

Summary GeoRePORT rose diagrams for the Phase I project grades are presented in Figure 5 and Figure 6. Three out of the six Phase I PFA projects were identical in the type of data collected. These three projects—Eastern Great Basin, Nevada Great Basin, and Snake River Plain—only reported data on drilling and resource temperature (Figure 5). The grades assigned to the data were also identical (E and C, respectively).



a) EGB b) NVGB c) SRP

Figure 5. GeoRePORT rose diagrams showing project grades for three of the six Phase I projects

a) Eastern Great Basin (EGB), b) Nevada Great Basin (NVGB), c) Snake River Plain (SRP)

The remaining three Phase I projects displayed more variability in terms of the type of data collected. These projects—Hawaii, Tularosa Basin, and Washington state—reported data on drilling, chemistry, permeability, volume, logistics, resource temperature, transmission, land access, and market as part of the Phase I PFA (Figure 6). Grades were also variable across these three Phase I projects. In Hawaii, only market data were reported for Lanai, which received a D grade. Mauna Kea also received a D grade for market data, as well as an E grade for logistics and a B grade for fluid chemistry. For Tularosa Basin, both sites received D grades for logistics.

White Sands Missile Range received a drilling grade of D, while Fort Bliss received a slightly higher C grade. At both sites, market and land access received E grades, temperature received D grades, and volume received A grades. Fort Bliss received an A grade for permeability, while White Sands Missile Range received a D grade. The three Washington state sites received E grades for market, transmission, and land access data. Drilling data was reported for Mount Baker and Mount St. Helens, receiving an E grade for both, but was not reported for the Wind River Valley. For Mount Baker, Mount St. Helens, and Wind River Valley, each site received logistics grades of D, D, and C, and permeability grades C, B, and A, respectively.

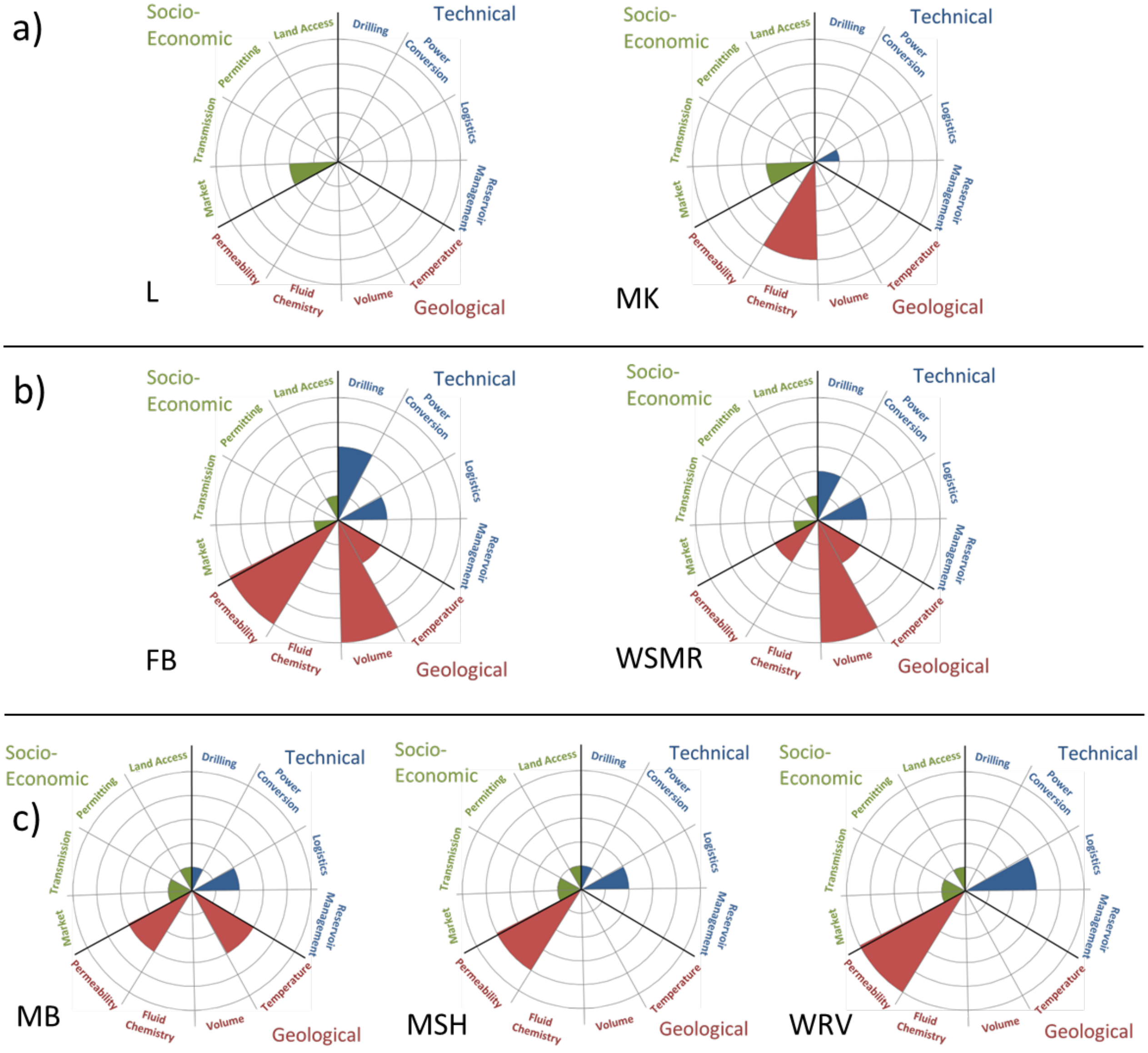


Figure 6. GeoRePORT rose diagrams showing project grades for the remaining three PFA Phase I projects

a) Hawaii (Lanai [L], Mauna Kea [MK]), b) Tularosa Basin (Fort Bliss [FB], White Sands Missile Range [WSMR]), c) Washington state (Mount Baker [MB], Mount St. Helens [MSH], Wind River Valley [WRV])

2.2.2.2 Phase II

Data for 10 out of the 12 project sub-attributes reported in GeoRePORT were available in the six Phase II projects (Table 9), with the majority of projects reporting data on drilling, resource temperature, and land access.

Table 9. Types of Data Reported for PFA Phase II Projects

GeoRePORT attribute	GeoRePORT sub-attribute	Projects reporting (out of 6)
Technical	Drilling	6
	Logistics	3
	Resource management	0
	Power conversion	0
Geologic	Temperature	6
	Permeability	3
	Volume	1
	Chemistry	1
Socio-Economic	Market	3
	Transmission	2
	Permitting	2
	Land access	5

Summary GeoRePORT rose diagrams for the Phase II project grades are presented in Figure 7 through Figure 12. The three Phase II sites in the Eastern Great Basin were identical in terms of the type of data collected. These three sites—Cove Fort, Crater Knoll, and Twin Peaks—only reported data on drilling and resource temperature, similar to Phase I (Figure 5). The grades assigned to the data were also identical (C and C, respectively). Since grade is based on the quality of the geothermal resource, not the number or quality of data sets, this means the collection of additional data sets in Phase II further confirmed the values shown by the data compiled in Phase I. Although Phase II data collection deepened the knowledge and understanding of each site, GeoRePORT does not have the granularity to track this kind of progress, especially during early exploration stages.

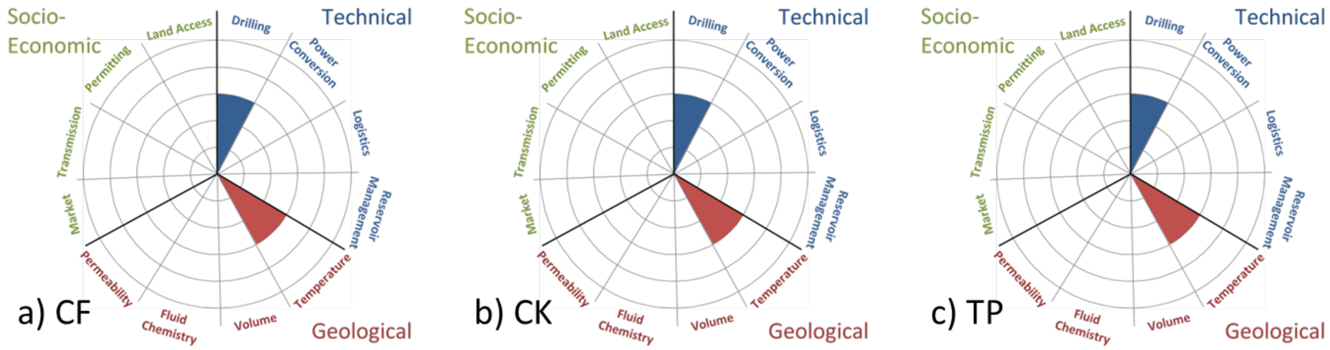


Figure 7. GeoRePORT rose diagrams showing project grades for the three PFA Phase II sites in the Eastern Great Basin

a) Cove Fort (CF), b) Crater Knoll (CK), c) Twin Peaks (TP)

For the most part, the type of data collected in the Phase II sites in the Nevada Great Basin was almost identical from one project to the next, though the grades varied somewhat (Figure 8). Four of the five sites—Crescent Valley, southern Gabbs Valley, Granite Springs Valley, and Sou Hills—only reported data in this phase on drilling and resource temperature, similar to the Eastern Great Basin (Figure 7). Due to the high number of pre-existing thermal gradient and exploration wells in Steptoe Valley, the site received higher drilling and logistics grades. Slip and dilation tendency analysis was undertaken at Steptoe Valley as part of the creation of a new 3D geologic map, so the site received a high permeability grade. Grades assigned to the data from Nevada Great Basin Phase II sites were E, E, D, E, and D for drilling, and all sites were assigned a C grade for resource temperature. Steptoe Valley was also assigned a B grade for permeability and a C grade for logistics. Similar to the Eastern Great Basin project, while significant new data were collected in Phase II, the GeoRePORT grades for the available data did not change significantly. New data may have provided a higher degree of certainty for expected resource temperature, but the expected temperature did not change, thus the grade remains the same. The drilling grade reflects the state of 10 sub-attributes, such as well depth, diameter, lithology, and pre-existing infrastructure. Phase II focused on data collection, so very little advancement in drilling grade from Phases I to II is to be expected.

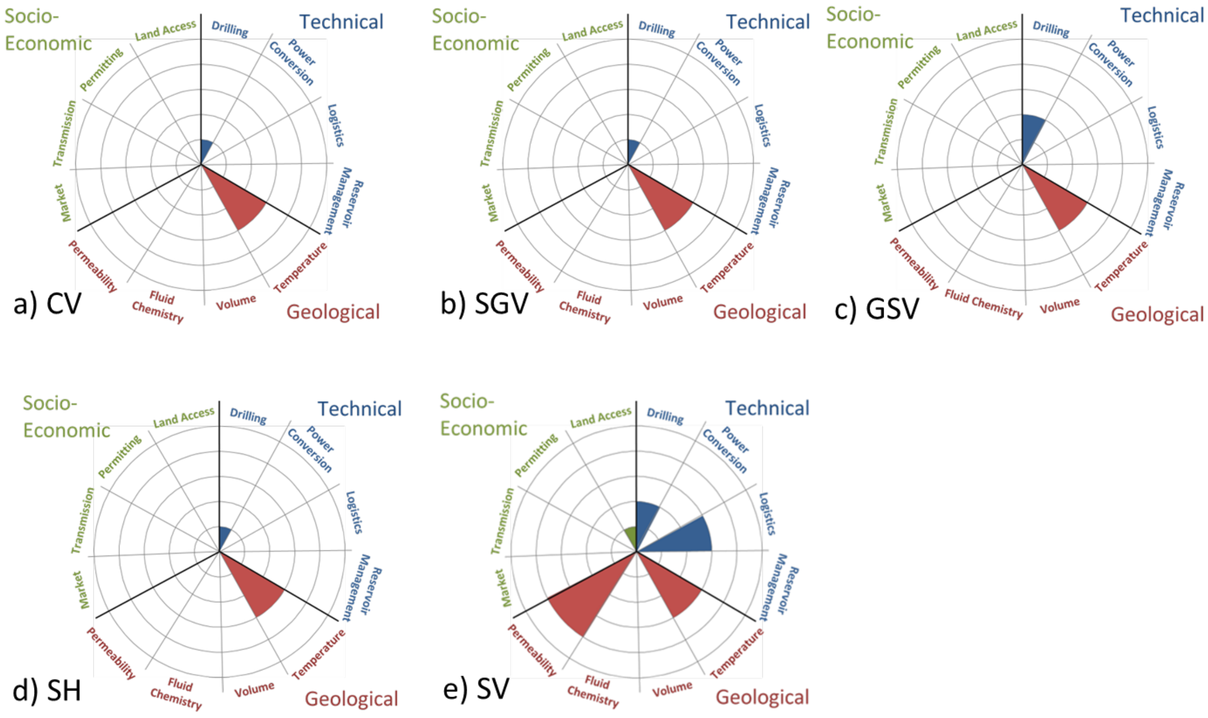


Figure 8. GeoRePORT rose diagrams showing project grades for the five Phase II sites in the Nevada Great Basin

a) Crescent Valley (CV), b) southern Gabbs Valley (SGV), c) Granite Springs Valley (GSV), d) Sou Hills (SH), e) Steptoe Valley (SV)

The type of data collected at the Phase II sites in Hawaii was very different between sites. While the Lanai project only reported data on land access and market, the Mauna Kea project reported data on land access, market, fluid chemistry, and resource temperature (Figure 9). Grades assigned to the data from Phase II are: D for market and C for land access at Lanai; E for drilling, D for market, C for land access, B for fluid chemistry, and B for resource temperature at Mauna Kea.

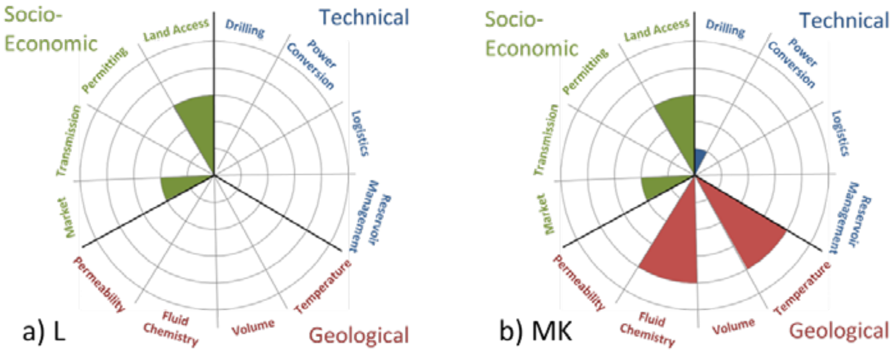


Figure 9. GeoRePORT rose diagrams showing project grades for the two Phase II sites in Hawaii

a) Lanai (L), b) Mauna Kea (MK)

The type of data collected at Phase II sites in the Snake River Plain differed slightly between sites. While the Mountain Home site only reported data on land access, drilling, and resource temperature, the Camas Prairie site did not report transmission data (Figure 10). Grades assigned to the data from Phase II were E and E for land access; D for transmission at Camas Prairie; E and C for drilling; and C and C for resource temperature.

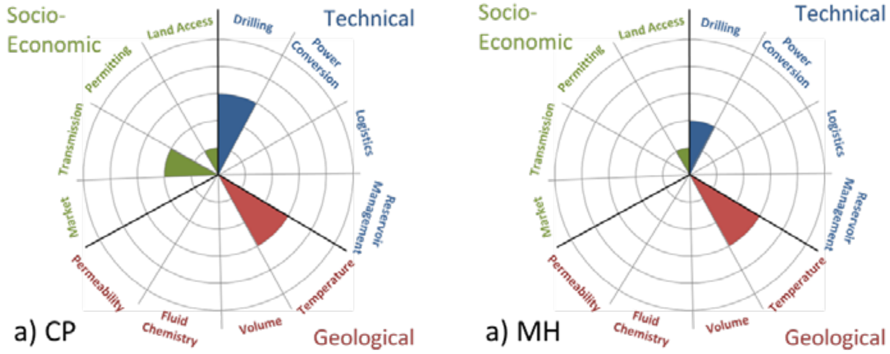


Figure 10. GeoRePORT rose diagrams showing project grades for the two Phase II sites in the Snake River Plain

a) Camas Prairie (CP), b) Mountain Home (MH)

The type of data collected in the three Phase II PFA sites in the Tularosa Basin differed substantially from one project to the next. The Fort Bliss site and the White Sands Missile Range site reported data on market, permitting, land access, drilling, and logistics, as well as resource temperature, permeability, and volume. The Aerospace Data Facility-Southwest site reported data on market, permitting, land access, logistics, and permeability (Figure 11). Grades assigned to the data from Phase II were D, B, and D for market; C, D, and D for permitting; E, C, and C for land access; C and D for drilling; D, D, and D for logistics; A, B, and B for permeability; A and A for volume; and D and D for temperature.

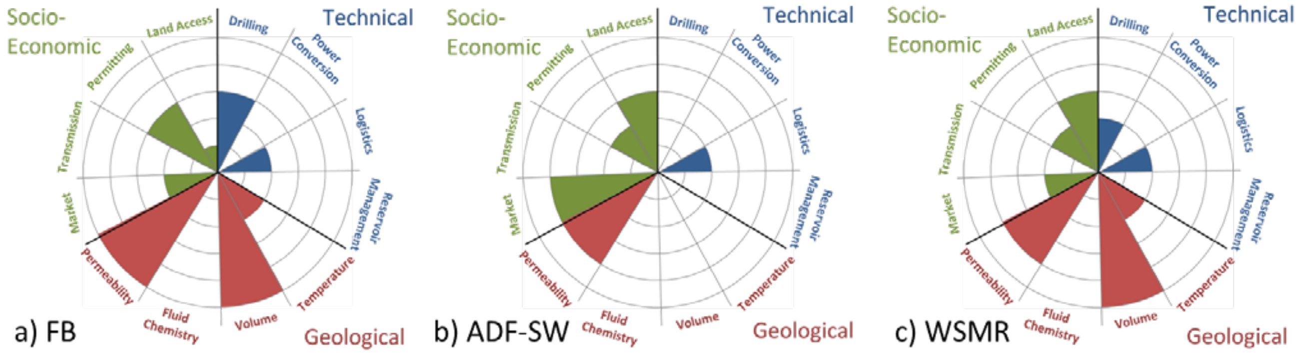


Figure 11. GeoRePORT rose diagrams showing project grades for the three Phase II sites in the Tularosa Basin

a) Fort Bliss (FB), b) Aerospace Data Facility-Southwest (ADF-SW), c) White Sands Missile Range (WSMR)

The type of data collected at the three Phase II sites in Washington state were quite similar from one project to the next, though the grades differed slightly. The Mount St. Helens and Wind

River Valley sites reported data on market, transmission, permitting, land access, drilling, and logistics, as well as resource temperature and permeability. The Mount Baker site reported data in all of these categories as well as resource volume (Figure 12). Grades assigned to the data from Phase II were: E, E, and E for market; E, E, and E for transmission; B, C, and C for permitting; C, C, and C for land access; D, D and D for drilling; D, D, and C for logistics; A, B, and A for permeability; C for volume; and C, D and B for temperature.

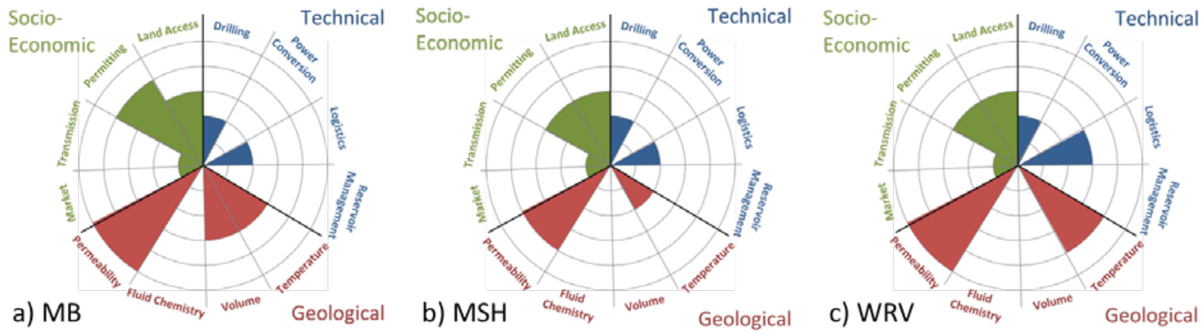


Figure 12. GeoRePORT rose diagrams showing project grades for the three Phase II sites in Washington state

a) Mount Baker (MB), b) Mount St. Helens (MSH), c) Wind River Valley (WRV)

2.2.2.3 Phase III

Data for 11 out of the 12 project sub-attributes reported in GeoRePORT were available in the five Phase III projects (Table 10). The only sub-attribute not assessed during Phase III was power conversion. The majority of projects reported data for drilling, logistics, temperature, permeability, permitting, and land access.

Table 10. Types of Data Reported for PFA Phase III Projects

GeoRePORT attribute	GeoRePORT sub-attribute	Projects reporting (out of 5)
Technical	Drilling	5
	Logistics	4
	Resource management	1
	Power conversion	0
Geologic	Temperature	5
	Permeability	4
	Volume	2
	Chemistry	2
Socio-Economic	Market	2
	Transmission	2
	Permitting	5
	Land access	5

Summary GeoRePORT rose diagrams for the Phase III project grades are presented in Figure 13 through Figure 16. The two Phase III sites in the Nevada Great collected the same types of data (Figure 13). Granite Springs Valley and southern Gabbs Valley both reported data on drilling, logistics, resource temperature, permeability, permitting and land access. While grades for the first five sub-attributes were identical (C, C, C, B, and A, respectively), southern Gabbs Valley was assigned a D grade for land access while Granite Springs Valley was assigned an E grade. These grades reflect only the reported data and are lower than may be expected because of missing data for some sub-attributes. For example, Granite Springs Valley had excellent land access, but data for only one of seven sub-attributes was reported, resulting in a low grade.

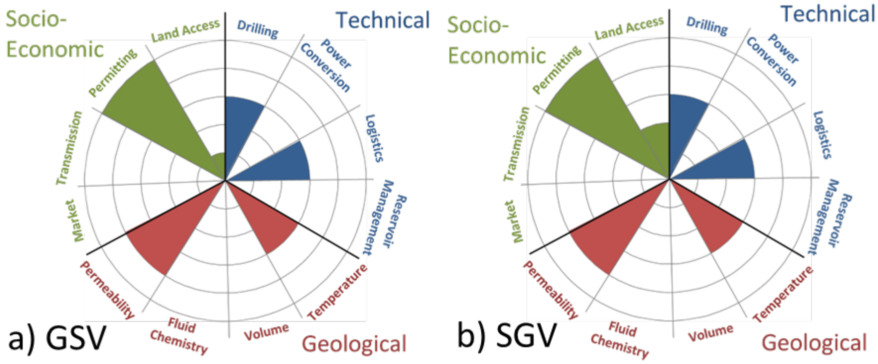


Figure 13. GeoRePORT rose diagrams showing project grades for the two Phase III sites in the Nevada Great Basin

a) Granite Springs Valley (GSV), b) southern Gabbs Valley (SGV)

The Eastern Great Basin and Snake River Plain projects both focused on a single site during Phase III—Cove Fort and Camas Prairie, respectively (Figure 14). Like the Nevada Great Basin sites, the Cove Fort site at Eastern Great Basin reported data on drilling, logistics, resource temperature, permeability, permitting and land access (grades C, C, C, B, A, and D, respectively—identical to the Nevada Great Basin's southern Gabbs Valley site. The Camas Prairie site at Snake River Plain varies from those previously mentioned both in terms of data collected and associated grades. The Camas Prairie site reported data on drilling, logistics, resource management, resource temperature, volume, permeability, transmission, permitting, and land access. The site was assigned C, D, E, D, C, B, D, D, and B grades, respectively.

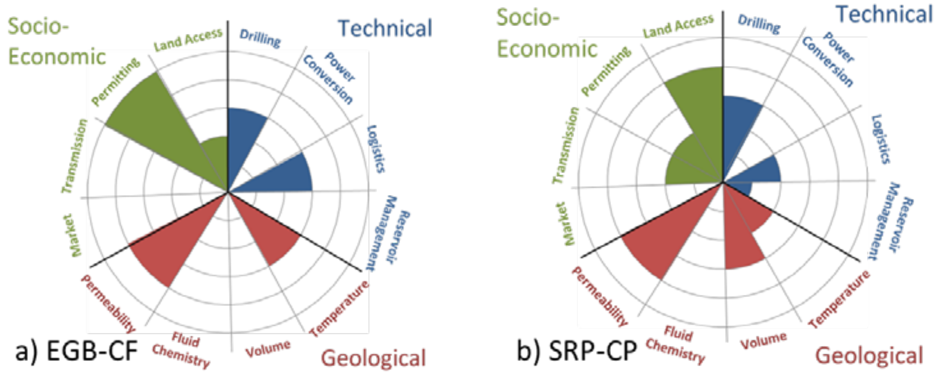


Figure 14. GeoRePORT rose diagrams showing project grades for the Phase III sites

a) Eastern Great Basin's Cove Fort (EGB-CF), b) Snake River Plain's Camas Prairie (SRP-CP)

The two Phase III sites in Hawaii varied widely, both between each other and the other Phase III projects. The Lanai site reported data on drilling, temperature, market, permitting, and land access (grades D, E, D, D, and C, respectively) while the Mauna Kea site reported data on drilling, temperature, fluid chemistry, market, and land access (grades E, B, B, D, and C, respectively).

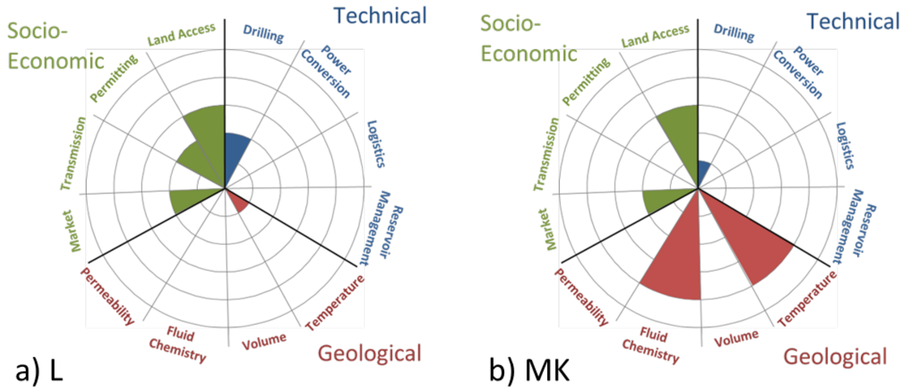


Figure 15. GeoRePORT rose diagrams showing project grades for the two Phase III sites in Hawaii

a) Lanai (L), b) Mauna Kea (MK)

Two Phase III sites in Washington state received the highest geological grades of the Phase III projects. Both sites reported data on drilling, logistics, temperature, fluid chemistry, permeability, market, transmission, permitting, and land access. Mount Baker was assigned grades of B, D, D, C, B, A, E, E, B, and C, respectively, while Mount St. Helens was assigned grades of B, D, E, A, A, E, E, C, and C, respectively. Mount Baker also reported volume data, for which it was assigned a C grade.

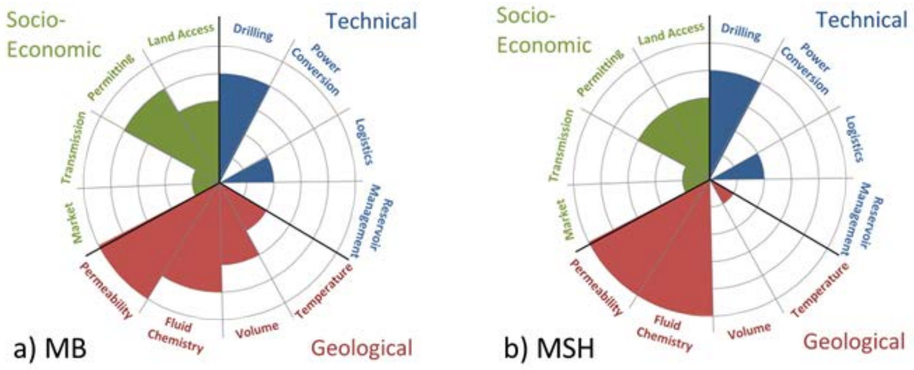


Figure 16. GeoRePORT rose diagrams showing project grades for the two Phase III sites in Washington state

a) Mount Baker (MB), b) Mount St. Helens (MSH)

2.2.3 Evaluation of PFA Project Progress

2.2.3.1 Project Progress: GeoRePORT Grades From Phase I to Phase III

To compare project progress across phases, this section presents GeoRePORT rose diagrams showing project grades from Phases I, II, and III for each project. Note that the figures only display the sites that were targeted for data collection and drilling in Phases II and III.

The Eastern Great Basin PFA project evolved from Phase I to Phase III, as shown in Figure 17. The Eastern Great Basin grades were the same for all three Phase II sites (Cove Fort, Crater Knoll, and Twin Peaks). The project focused on Cove Fort for Phase III, so it was the only site to have higher grades in Phase III. One important note is that the drilling grade at Cove Fort did not increase between Phase II and Phase III. The drilling campaign for the Eastern Great Basin project was cancelled last-minute because temperatures and possible H_2S encountered at the site were considered outside the experience base of the USGS Research Drilling Program. However, the project team still performed additional data collection and analysis in Phase III. The Cove Fort site added logistics, permeability, permitting, and land access data, while grades for drilling and temperature remained unchanged.

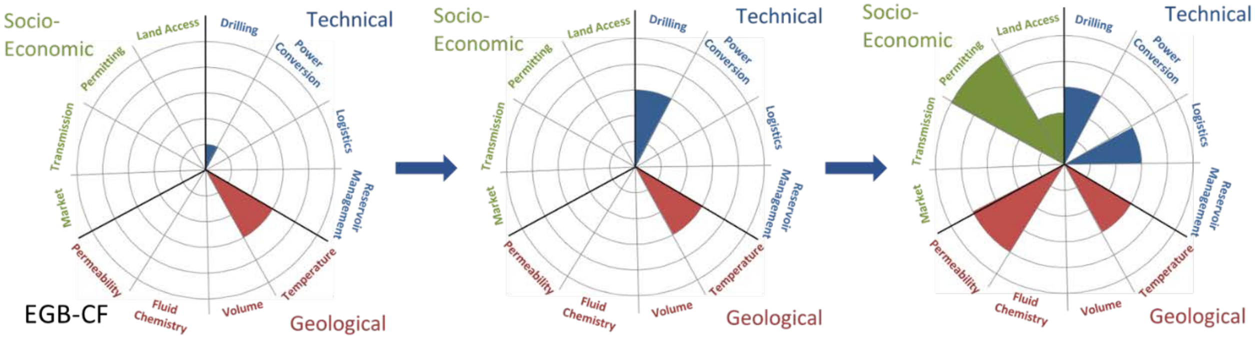


Figure 17. GeoRePORT rose diagrams showing attribute grades for Phases I, II, and III of the Eastern Great Basin Cove Fort site

Some of the Nevada Great Basin PFA site grades evolved from Phase I to Phase III, and some did not (Figure 18). The grades remained the same from Phase I to II for the Crescent Valley, Sou Hills, and southern Gabbs Valley sites. The assessment of drilling data was upgraded for the Granite Springs Valley site and the Steptoe Valley site in Phase II. Steptoe Valley also added logistics, permeability, and land access data in Phase II, and the temperature grade remained the same. In Phase III, both Granite Springs Valley and southern Gabbs Valley added logistics, permeability, permitting, and land access data. Drilling grades were upgraded for both sites, and temperature grades remained unchanged. Crescent Valley, Sou Hills, and Steptoe Valley were not included in the Phase III assessment.

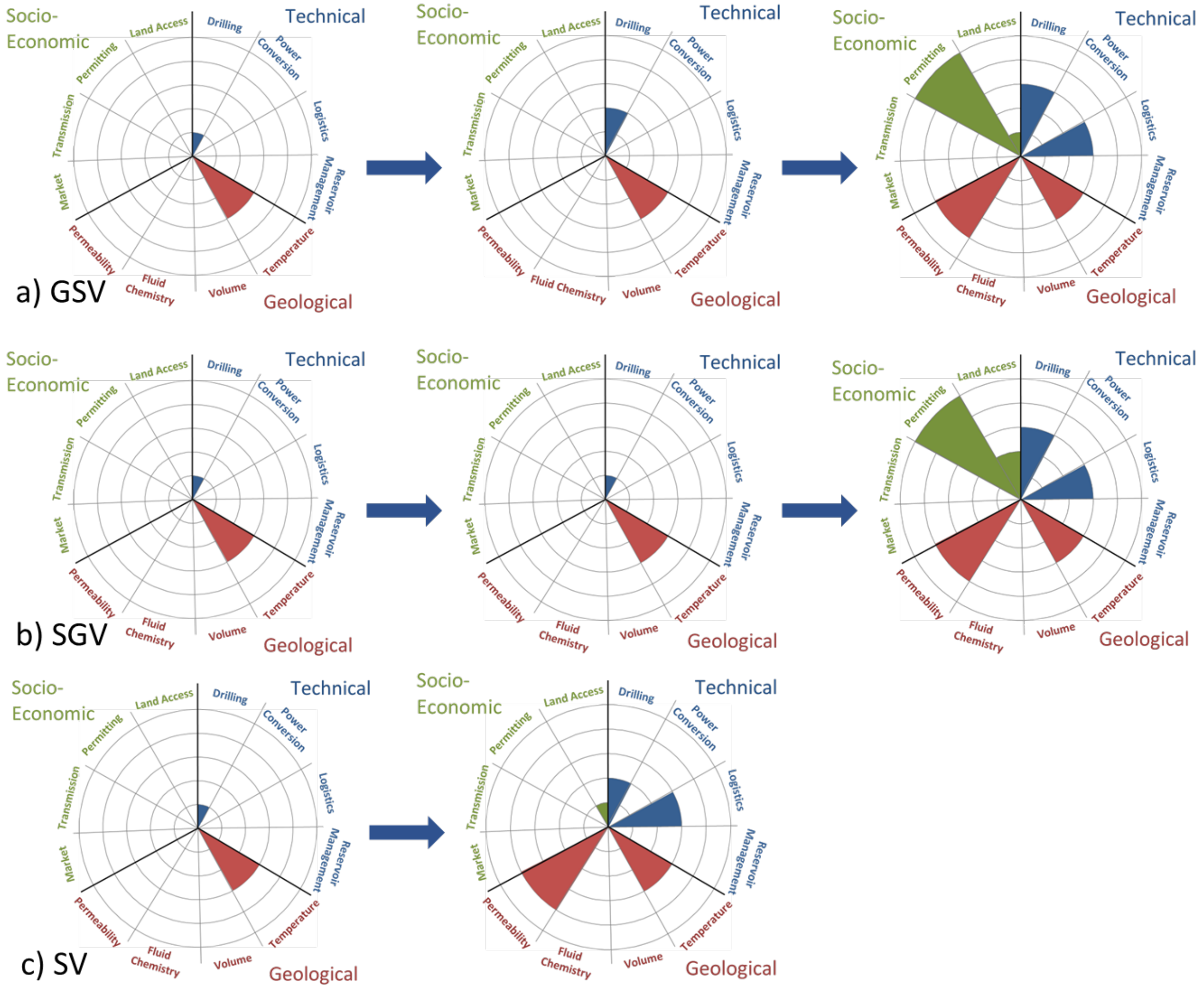


Figure 18. GeoRePORT rose diagrams showing attribute grades for Phases I, II and III of the Nevada Great Basin sites

a) Granite Springs Valley (GSV), b) southern Gabbs Valley (SGV), c) Steptoe Valley (SV)

Both Snake River Plain sites evolved between Phase I and Phase II, but only Camas Prairie was assessed in Phase III (Figure 19). The Mountain Home site upgraded its drilling data in Phase II of the Snake River Plain PFA and added permitting data. The resource temperature grade remained unchanged from Phase I. The Camas Prairie site upgraded its drilling data in Phase II and added transmission and permitting data. The resource temperature grade remained unchanged from Phase I. During Phase III, the Camas Prairie site added logistics, resource management, volume, permeability, and permitting data, and upgraded land access data. The temperature grade was downgraded, as the temperatures encountered during drilling were lower than those predicted by the data from Phases I and II.

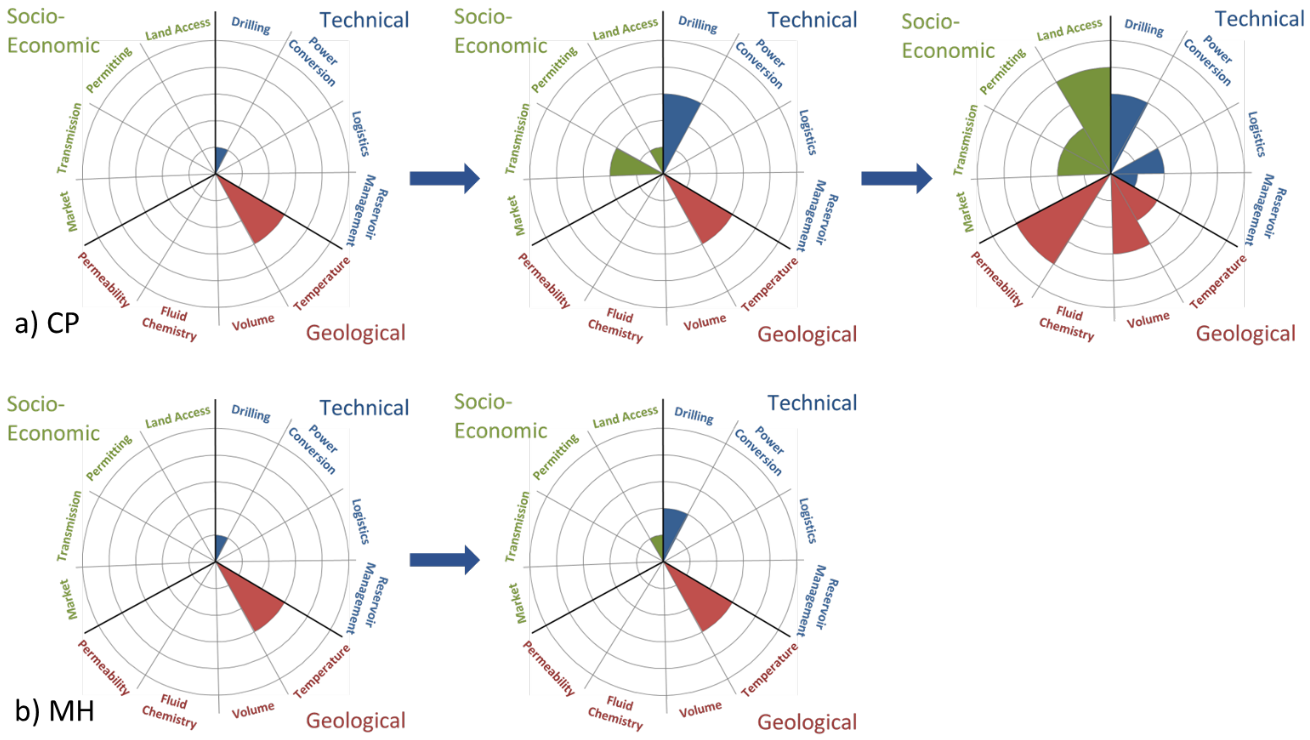


Figure 19. GeoRePORT rose diagrams showing attribute grades for Phases I, II, and III of the Snake River Plain sites

a) Camas Prairie (CP), b) Mountain Home (MH)

The Hawaii PFA project added land access data in Phase II for both sites. Phase II of the Mauna Kea project also added drilling and resource temperature data. The market grades for both sites, and fluid chemistry grade for Mauna Kea, remained unchanged from Phase I (Figure 20). In Phase III, the Lanai site added drilling, temperature, and permitting data, and market and land access grades remained unchanged. The grades for Mauna Kea did not change between Phase II and Phase III.

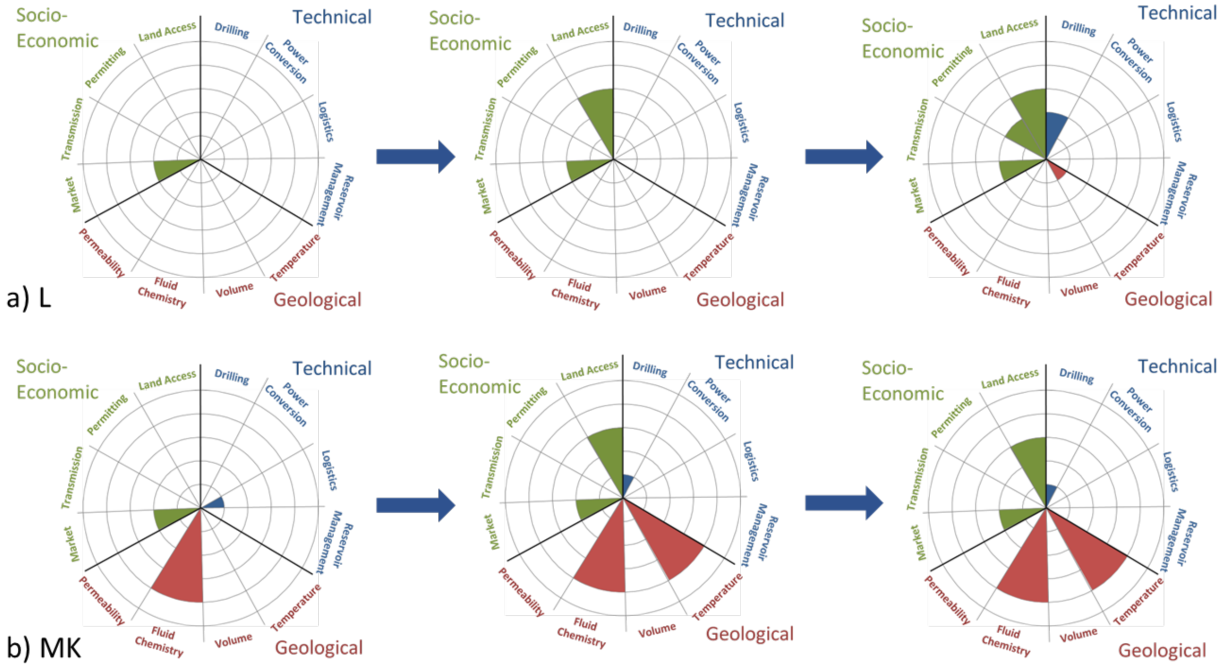


Figure 20. GeoRePORT rose diagrams showing attribute grades for Phases I, II, and III of the HI sites

a) Lanai (L), b) Mauna Kea (MK)

The Tularosa Basin PFA project added permitting data in Phase II for the Fort Bliss site and upgraded its market attribute. The White Sands Missile Range site also added permitting data and upgraded its market attribute along with its land access attribute in Phase II (Figure 21). The Tularosa Basin project was not selected to continue to Phase III, so only Phase I and Phase II rose diagrams are shown.

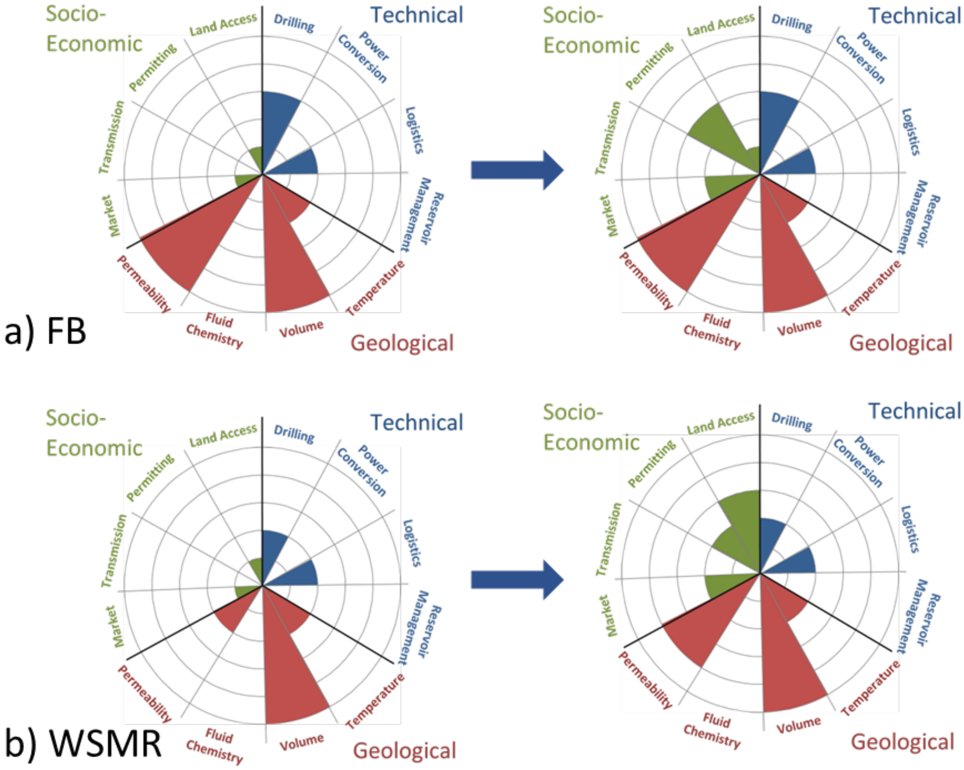


Figure 21. GeoRePORT rose diagrams showing attribute grades for Phases I and II of the Tularosa Basin sites

a) Fort Bliss (FB), b) White Sands Missile Range (WSMR)

The Washington state PFA project (Figure 22) added permitting and resource volume data for the Mount Baker site, and upgraded its land access, drilling, and permeability attributes in Phase II. The Mount St. Helens site added permitting and temperature data and upgraded its drilling and land access attributes in Phase II. The Wind River Valley project added permitting, drilling, and resource temperature data, and upgraded its land access attribute in Phase II, but was not assessed in Phase III. In Phase III, the Mount Baker site added fluid chemistry data and upgraded its drilling data. Temperature data was downgraded due to temperatures encountered while drilling. Logistics, volume, and all socio-economic grades remained unchanged. The Mount St. Helens site added fluid chemistry data and upgraded its drilling and permeability data in Phase III, while all socio-economic grades remained unchanged. Like the Mount Baker site, temperature data was downgraded.

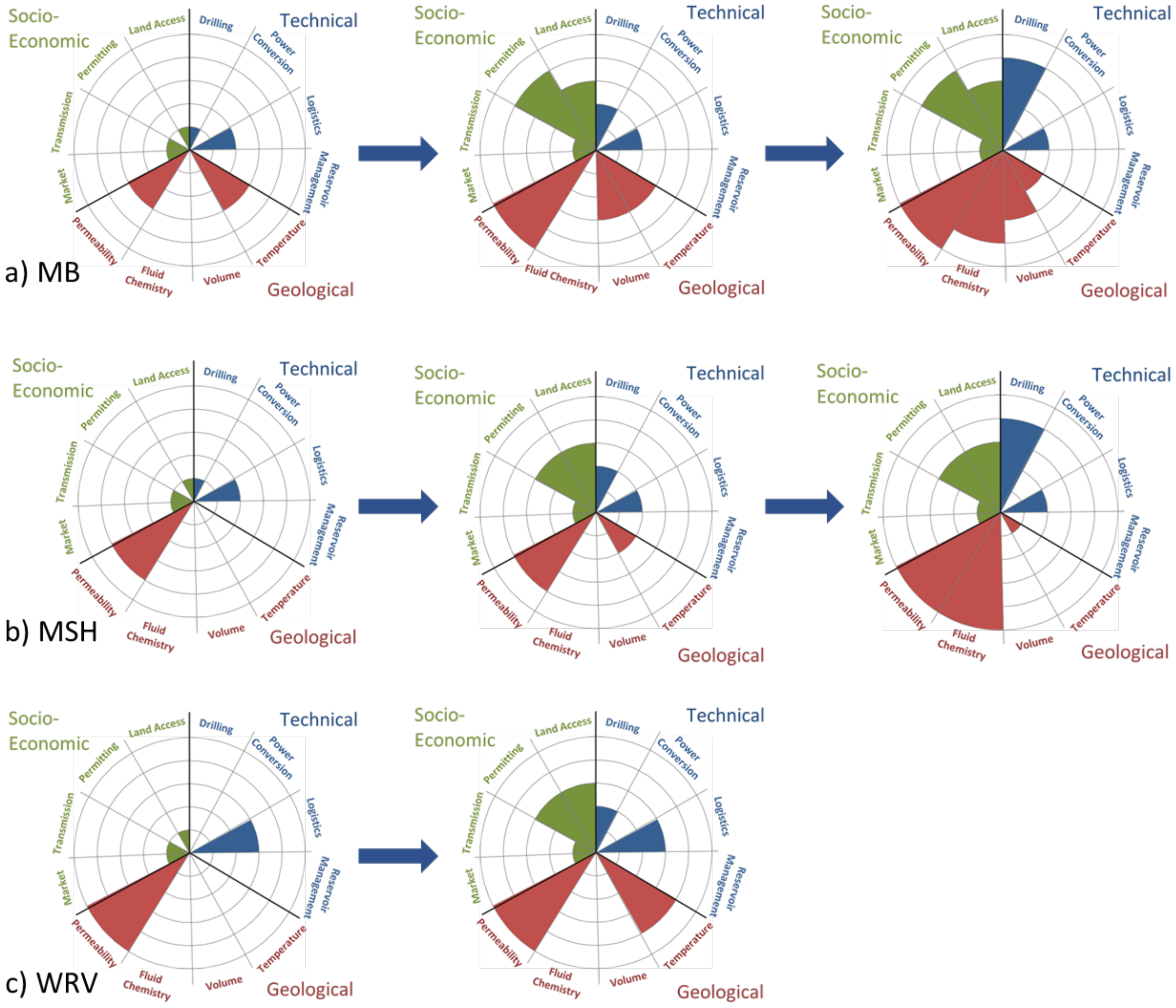


Figure 22. GeoRePORT rose diagrams showing attribute grades for Phases I, II, and III of the WA sites

a) Mount Baker (MB), b) Mount St. Helens (MSH), and c) Wind River Valley (WRV)

2.3 PFA Drilling: Outcomes

The drilling phase of any project requires a significant portion of the project funding, thus drilling optimization is crucial. Drilling best practice was evaluated based on an analysis of the PFA Phase III drilling operations with insight gained through interviews with GTO and project personnel (also see Table 7). The interviewees summarized operational successes and challenges, including the limitations of using the USGS or another single vendor for diverse well types (USGS was the drill contractor of choice to facilitate contracting and cost savings for drilling with DOE funds). While this decision eased logistical effort, a competitive selection likely would have yielded a vendor or vendors better equipped for the diversity and volume of drilling required. Communication and planning proved to be the largest barriers to productivity in many Phase III operations. Some of this miscommunication and nonproductive time may have been avoided by working with local drillers more familiar with specific site conditions, leading to greater consideration of regional drilling cost variations. Using this information, this section presents recommendations to improve project planning, operations, oversight, and communication.

2.3.1 Targeting

The culmination of multiple phases of PFA efforts helped identify locations for temperature gradient drilling within high favorability portions of identified plays. In addition to geologic, geochemical, and geophysical considerations, drilling targets selected by the PFA teams also had to be accessible and at locations that could be permitted for drilling.

2.3.2 Outcomes From Drilling in Hawaii

The Hawaii PFA project—especially given the unique challenges of permitting and supporting drilling operations on location in the Hawaiian islands—highlights components of a well-planned and executed temperature gradient drilling program. Much of the practice deployed by the Hawaii PFA team is applicable or can be adapted to temperature gradient drilling anywhere in the United States. The Hawaii PFA project recognized the need to obtain subsurface data from depths greater than typically drilled for temperature gradient data, so they leveraged drilling funding into deepening of an existing water well on Lanai. Though possibly not the ideal location on the rim rather than within the caldera, this strategy enabled them to drill to ~1,067 m below surface and to successfully measure a 40°–45°C/km gradient and bottomhole temperature of 66°C, obtain continuous core recovery from 427 m to completion, and conduct groundwater surveys and analyses. This temperature gradient is more than twice the background gradient in Hawaii, and the completed well is the deepest off Hawaii Island. The drilling planning began with preparation and submission of an Environmental Assessment, which was evaluated to determine that the project would have no significant impacts and could proceed (FONSI, Finding of No Significant Impact). Additionally, given the interest in Lanai's groundwater, uncertainty with respect to groundwater temperature, and small diameter of the deepened section of the well, the team was able to move forward efficiently by obtaining a simple well modification permit through the state's Commission on Water Resource Management. After drilling operations were approved and prior to their commencement, the well was evaluated with a downhole camera and a gyroscopic log to confirm the well was open and not damaged. Significant engagement with the local community before and during the project garnered local interest and support of the project and its goals.

2.3.2.1 Operational Successes

Successful elements of the Hawaii PFA temperature gradient drilling include the hiring of highly experienced personnel, skillful and comprehensive planning, and an effort to create and maintain strong relationships with local community and stakeholders. The project co-lead for the Hawaii PFA project provided valuable expertise in deep core drilling in Hawaii, pulling from his experience as project lead on four successful deep wells on Hawaii Island. A veteran drilling supervisor was hired, along with a Hawaii-based drill hand experienced in welding and machinery. An experienced lead drill core archivist provided valuable insight and expertise throughout the drilling process. Highly competent staff were hired to assist with the Environmental Assessment and procurement, which, along with support of the university's upper administration, resulted in a green light FONSI and reduced university overhead (24%) for project Phase III.

Additionally, an emphasis on the "two for one" benefit of providing information related to both fresh groundwater and geothermal potential favored the test well in the Phase III selection process (Lautze et al., 2021). Nonproductive time was reduced by ensuring nearly all equipment and supplies for drilling or to support drilling were on-site prior to the arrival of the crew and commencement of drilling operations. The preplacement of equipment was possible due to the PI's communication and relationship with the chief operating officer of Pulama Lanai, the land management company that covers 98% of Lanai Island. A dedicated effort to build a relationship with the landowner through Pulama Lanai began in Project Phase II and continued through Phase III to the present day. This effort included briefings on findings and possible plans, and answering questions of interest with respect to energy and water on Lanai. The local community was informed and engaged through community meetings prior to the project onset and a Drilling Open House during the drilling activity (Lautze et al. 2021). These relationships culminated in significant logistical support and contracting efficiency, and both in-kind and donation funds from the Lanai landowner (N. Lautze, personal communication, December 8, 2021).

2.3.2.2 Operational Challenges

The Hawaii PFA team faced several key challenges centered around temperature gradient drilling operations. Due to the isolated project location, the Hawaii PFA team was not required to use USGS drillers as transporting a USGS drill rig to the project would be much more expensive than using the drill rig owned by the University of Hawaii. However, the University of Hawaii drill rig used for the test well had been sitting idle between projects and required maintenance prior to drilling. Challenges during drilling began when the initially contracted drilling company was merged into another company during Phase III. Drilling was delayed when this company sent drill string that was not fit for use, despite assurances that any bad pipe joints had been removed from the shipment. Issues within the drill crew resulted in a firing, a reduction of operations to one 12-hour shift, and soon after, cessation of drilling (Lautze et al., 2021; N. Lautze, personal communication, December 8, 2021).

2.3.3 Outcomes From Drilling in Idaho, Nevada, and Washington

The projects drilled in the conterminous United States (Idaho, Nevada, Washington state) experienced similar operational successes and challenges. Notably, the USGS drill rigs and crews were initially contracted for each of these projects to facilitate cost savings. While this limited the opportunity to use drillers familiar with local conditions, projects benefited from the streamlined contracting and funding processes.

2.3.3.1 Operational Successes

Key elements of success in the projects drilled in Idaho, Nevada, and Washington include the hiring of experienced personnel to plan and manage drill projects, and rejection of high-risk projects. The selection of the USGS as the drilling contractor in each of these projects per DOE guidance allowed for unburdened pass-through of funds for drilling and made more funds available for the program (Steely et al. 2021; J. Shervais, personal communication, May 25, 2021). After the Washington project encountered delays in 2018 (detailed in following section), DOE was able to obtain extra funds to make up for the delay and limited progress. In the summer of 2019, a local driller returned to drill at Mount Baker, and core at Mount St. Helens.

The industry experience of the hired operational geologist was instrumental to the planning and operational success of the Nevada PFA temperature gradient drilling. In Utah, Phase III site analysis indicated hazardous drilling conditions that were beyond the scope of available funds, leading to cancellation of drilling. This was the correct decision as it considered crew safety and acknowledged that the drilling requirements were outside the experience of the drilling contractors (J. Faulds, personal communication, September 21, 2021; Wannamaker et al., 2020; S. Crawford, personal communication, May 27, 2021).

2.3.3.2 Operational Challenges

A variety of drilling challenges were encountered in the Idaho, Nevada, and Washington Phase III projects. The USGS rig crews were well-equipped to drill simple temperature gradient wells, although the scope of drilling was not always understood by the rig crews and non-24/7 operations likely contributed to some downhole issues. Some wells on each project were not typical temperature gradient wells, most notably due to their relatively deep completions (J. Faulds, personal communication, September 21, 2021; J. Shervais, personal communication, May 25, 2021; S. DeOreo, personal communication, June 25, 2021), which extended the scope of the project and led directly or indirectly to many of the logistical and operational challenges. For example, the drill team on the Washington PFA project did not see the drilling plan until several weeks after drilling had commenced, leading the drillers to arrive with equipment inappropriate to the site and drilling plan (Steely et al. 2021).

The rigs and crews faced many problems in logistics, operations, and communication. The following logistical problems contributed to various instances of nonproductive downtime: limited access to repair parts, downtime while waiting for rig crews to drive to nearby cities for parts, wrong bits sent to the rig, no backup bits on location, no lost circulation material on location, undertrained staff in use of the rig computer, and limited USGS drilling schedules due to weekends, holidays, and government shutdowns. The Nevada PFA drill rig was stacked before the beginning of operations, which resulted in breakdowns and maintenance issues while it was deployed to drill its first well (S. DeOreo, personal communication, June 25, 2021; J. Faulds, personal communication, September 21, 2021; J. Shervais, personal communication, May 25, 2021).

Drilling delays were compounded across projects due to the mutual reliance on a single drilling provider. The Washington PFA project experienced numerous challenges in drilling operations in 2018 at Mount St. Helens. This stemmed from the difficulty in finding appropriate drill sites due to steep topography, thick timber, and thick surficial (glacial and alluvial) deposits. The first drill site attempted at Mount St. Helens was a rare turnout along a forest road on a steep hillside. It was not appropriate for drilling as the turnout was buried with debris such as old cars, steel wires, and downed trees. The drill team at this site did not have the required equipment to drill through ash and sediment flows and shallow large boulders. These issues resulted in abandonment of the well at only 51 feet. After this initial failure, the rig and equipment moved to the second drill site at Mount St. Helens (17-24). The problems encountered here would have been common to any drill site near the study area: unconsolidated glacial and volcanic deposits, buried large boulders, and artesian water pressure. Delays at the Washington PFA project caused the Nevada and Idaho PFA projects to be pushed back into extreme weather. Project organization and operations suffered due to the absence of the rig supervisor throughout operations (Steely et al., 2021; S. Crawford, personal communication, May 27, 2021; S. DeOreo, personal communication, June 25, 2021; T. Cladouhos, personal communication, May 18, 2021; J. Faulds, personal communication, September 21, 2021; J. Shervais, personal communication, May 25, 2021).

The Idaho PFA experienced early project shutdown due to poor communication of their rig burn rate (J. Shervais, personal communication, May 25, 2021). The USGS was not prepared to handle challenges such as lost circulation and artesian water flows. More thorough planning and communication prior to the commencement of drilling would likely mitigate some of these problems. A stuck logging tool and core rod caused downtime and sunk costs in Idaho as well. In addition, some cost estimates were low due to insufficient local knowledge and data, and did not include contingency for unanticipated problems, a common practice in industry. The logistical and operational problems described above, in addition to inadequate financial planning, resulted in shallower or fewer wells than anticipated in the Idaho and Washington PFA projects. Projects that included personnel familiar with drilling operations (Nevada and Hawaii, Washington state in 2019) avoided problems as compared to projects without such support. Drilling serendipity always plays a role, but experience from planning through completion of drilling operations is invaluable for mitigating issues that cause downtime (J. Shervais, personal communication, May 25, 2021, J. Faulds, personal communication, September 21, 2021, S. DeOreo, personal communication, June 25, 2021; S. Crawford, personal communication, May 27, 2021; T. Cladouhos, personal communication, May 18, 2021).

3 Discussion and Recommendations

In this section, we take the project information presented in Section 2 and discuss best practices, recommendations, and takeaways related to data, methodologies, and drilling.

3.1 Data Discussion

Diverse data were used across a variety of geologic and tectonic environments to complete geothermal PFA (Appendices A and B). Data were selected and organized around defined CRSs, also referred to as play components. Of the projects reviewed, all selected data sets inform the risk for occurrence of heat and permeability. Some projects also considered seal and fluid components, and in later stages some projects incorporated infrastructure and development barrier components into PFA.

As noted previously, the structure of the funded projects dictated that Phase I focused on existing data sets. Generally, these data were used to identify, and in some cases confirm, fairways with geothermal potential. PFA with existing data enabled identification of potential plays for additional analysis and new data collections in Phase II. Though variable across projects and mainly owing to where they were located, projects varied quite dramatically in the types and density of data used in Phase I. Various data weighting schemes were employed (see below); however, only one project (Nevada Great Basin) was able to use formal Bayesian weights-of-evidence that relies on identification of training sites (i.e., positive labels). Rather than a final product, weights of evidence in this case served as an input into finalizing evidence layer weights. Other projects' areas of interest contain few or no training sites (e.g., geothermal power plants, hot springs) for input into weights of evidence, so despite weights of evidence being a method deployed by USGS for the formal assessment of mid to high enthalpy geothermal resources in the western United States (Williams et al. 2008), its use was limited by the scale and location of projects. Without formal weights of evidence analysis, training sites can still be used to constrain the combined data signals representative of high potential for geothermal occurrence (e.g., Raft River geothermal power plant in the Snake River Plain). Thus, the sophistication of methods was in some cases limited by availability of training sites. An important outcome from Phase I was meaningful PFA completed despite data availability challenges, showing how PFA can provide a framework for regional screening for identification of most prospective areas for further exploration. Regional-scale PFA across the funded projects demonstrate how risk and uncertainty analysis can be incorporated so that investment in new data collections is supported by available data relevant to understanding the potential for geothermal resource occurrence.

Selection and analysis of data were further refined with recognition of geothermal conceptual models likely to be appropriate for projects' geological and tectonic settings. Some projects developed new conceptual models during PFA (e.g., Snake River Plain basalt sill complex). The conceptual model frameworks refine what data are useful for evaluating heat, permeability, and other play components and the expected signals in existing and acquired data that validate a particular conceptual model component (e.g., location of upflow zone). Projects that progressed through Phase II with focus on specific plays and new data collections continually refined conceptual models and play-scale PFA to target temperature gradient wells in Phase III. PFA brings a formal workflow and risk and uncertainty analyses to what has heretofore been considered exploration best practice (e.g., Harvey et al. 2014), so that analysis and acquisition of data are further optimized toward discovery of new geothermal resources.

Geothermal play characteristics vary based on geologic setting. All PFA groups used heat and permeability as key indicators; others also included either seal or fluid as an important component. Many different parameters were used to assess permeability indirectly on a variety of scales (regional to local). Some of these inputs included structural discontinuities based on high gravity and/or magnetic gradients, the presence of Quaternary faults, seismicity, regional strain, faults with high slip or dilation tendencies, favorable fault configurations (such as accommodation zones, fault stepovers, fault terminations, pull-apart features, etc.), increased intensity of faulting, and the presence of surface thermal features. Heat indicators used by the teams varied quite a bit—these ranged from estimated temperatures at 3 km depth, heat flow maps, the abundance and size of young volcanic vents and their ages, the presence of structures identified using MT and/or gravity indicating magmatic upwelling or shallow intrusions, elevated $^{3}He/^{4}He$ values suggesting a significant mantle component to geothermal fluids, elevated groundwater temperatures, and elevated geothermometry temperatures from hot spring and/or thermal well water samples. Data coverage varied from restricted point source measurements to regionally extensive surveys. Fluid indicators used included MT, groundwater elevation, topographic elevation, and recharge. Cap/seal indicators were focused on lacustrine sediments and permissive lithology.

3.2 Methodology Discussion

Based on the structure of the funding, all projects began with existing data sets within defined areas of interest. Published information and team experience likely were important factors in selecting specific areas of interest. Thus, all projects began with similar, initial pre-PFA steps, namely selection of a study area, existing data, and a general conceptual model(s) appropriate for the selected geologic and tectonic setting. During Phase I, projects performed similar PFA activities focused on defining CRSs (or equivalent terminology, e.g., play components), identification of data sets that inform CRS, and organization of data into formats and scales compatible with combination of data into CRS maps. Projects performed PFA primarily using Geographic Information System (GIS) tools, including development of custom scripts to automate PFA.

Details of project methods are captured in workflow figures in Appendix C with further details of data processing in Appendix B. Typically, after identification of data to inform CRSs and transformation and scaling of those data, CRS maps (e.g., heat) were created by combining the data through various techniques, weighting strategies, and normalization strategies (e.g., Z-score). Commonly, data were weighted by expert opinion or more formal methods (e.g., analytical hierarchy process [AHP], weights of evidence), and weighted sums and products of the data formed the final CRS maps. Similarly, data were combined into final composite CRS maps with weighted sum and product strategies.

Various strategies were used to account for data uncertainty, or its complement confidence, so that uncertainty could be integrated into the final composite CRS for geothermal favorability. Table 5 shows projects' strategies for assigning confidence. Single data sets often had uncertainty assigned based on geospatial criteria (e.g., distance buffer around a fault), data-specific criteria, and typically with a component of expert opinion. Uncertainty can be evaluated for raw data, transformed data, CRS maps, and/or composite CRS maps. The variety of uncertainty evaluations across PFA projects are all valid approaches. For new PFA projects, these can serve as guidance with the most important aspect across these techniques being robust documentation of the process steps. The addition of uncertainty measures provides an important addition to composite CRS geothermal favorability maps by incorporating confidence into the decision-making. Focus on high favorability areas is refined to better assess risk so that areas with high confidence measures in the underlying data can be distinguished from those with low confidence measures.

Having a somewhat automated data processing system for developing the favorability maps greatly facilitated updating the maps with new data and for creating maps at different scales. Different play types often have different contributing geologic features. For example, most basin-and-range geothermal systems are not linked to active volcanism, whereas the Snake River Plain, Washington, and Hawaii fairways are associated with volcanic centers. A PFA methodology needs to be flexible enough to encompass all relevant data and turn off data inputs that might not be appropriate for certain regions. This would require having different data weighting schemes for different play types. Most teams utilized expert opinion to develop data weighting schemes, which could be validated using known geothermal areas. It would be helpful to develop data-driven weighting schemes that are validated against both known geothermal areas and areas devoid of geothermal resources. It might be helpful to conduct value-of-information assessment to identify which data inputs are most critical for PFA from a de-risking perspective to inform and prioritize additional data collection. Definition of sub-play types might potentially refine PFA (e.g., are there features that could be used to distinguish small vs. large geothermal systems in the Basin and Range?).

A number of challenges were identified by PIs at the 2020 PFA Retrospective Workshop regarding the development of PFA methodologies. The PFA process requires that an integrated and diverse team of experts perform a systematic process of data integration and statistical analysis, and this requires having someone on the team to help manage diverse geological, geophysical, and geochemical data collected. Many teams had difficulty deciding which data types were most appropriate for developing heat and permeability favorability maps, which may explain the diversity of data sets used. Quantifying uncertainty and determining how to weight each of the inputs was also a challenge—most groups relied on expert opinion, which is a subjective process. Interpolated data sets can emphasize or de-emphasize data-limited regions depending on sampling density. Biases caused by uneven data distribution and data sets may overemphasize certain inputs—this needs to be recognized and compensated. Also, future PFA projects should consider interdependence between data layers and identify whether different data sets are independent of one another, or if they are identifying the same play features resulting in such features being counted more than once in the favorability assessment. PFA is applicable at multiple scales; however, inputs and weighting must be adjusted accordingly.

3.2.1 Value of Information and Entropy Analysis

Two important questions underlying these retrospective analyses are which types of data are most ***insightful*** in revealing the geothermal flow regimes and/or how ***impactful*** are they on exploration decisions. These are both important concepts to quantify, but also very challenging to quantify given the diversity and complexity of both the geothermal systems and the data collected. As more PFA analysis reports are published, there will be more community consensus such as in the oil industry's realization that seismic data improves their drilling success by three-fold (Gray 2011).

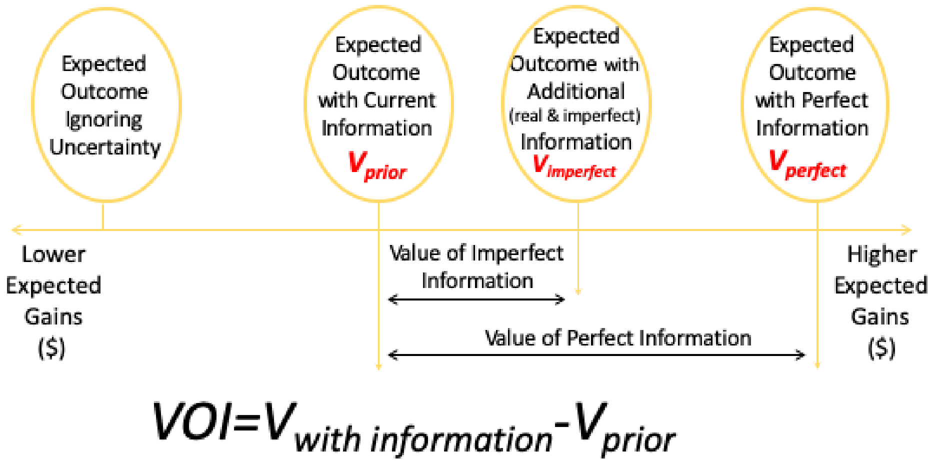


Figure 23. Visual depiction of value of information

The horizontal axis represents utility (e.g., the value unit, $). V_{prior} quantifies the average value with current understanding of risks.

The value of information metric (VOI) addresses the impactful aspect of data: How can it help improve the outcomes of decisions? VOI is a metric that was derived in the field of decision analysis; as such, it says information only has value when it can improve the outcomes of decisions. Many geothermal explorations have used MT to map out the clay cap, which formed due to hot water, thus MT can guide well placement (a spatial decision). However, VOI obliges us to statistically quantify how successful we would be at deciding where to drill the well both without and with new MT data. Figure 23 is a graphical representation of VOI with the main quantities: the prior value (V_{prior}) and the value with information ($V_{with\ information}$ either assuming perfect or imperfect information). These quantities represent average values, which use the statistics around the geothermal play at present (V_{prior}), and the statistics about the information (e.g., how frequently MT identifies a clay cap and how strongly that is associated with geothermal fluids). Figure 23 depicts a positive VOI, since values with information (both perfect and imperfect) are greater (to the right) of the prior value. The outcome of decisions must be measured in some utility or value metric, where monetary units are usually the most intuitive but not mandatory.

If we make a simplifying assumption that a geothermal exploration outcome is determined mostly by temperature (T), an example expression of V_{prior} could be:

$$V_{prior} = \max_{a} \left[\sum_{i=1}^{N} \Pr(T = t_i)\, v_a(T = t_i) \right] \quad a = drill, don't\ drill \qquad (1)$$

where the sum represents a weighted average (e.g., expected value) over the temperature bins (t_i), N is the number of temperature classes, and v_a represents the utility outcome ($) of the two decision actions a: to drill a thermal gradient hole or not. The weights for each temperature bin are expressed with the probability $Pr(.)$. The probability of the temperature classes occurring in the 3D subsurface represents the “odds” in the geothermal lottery given all the current information available to us today. The $\max_{a}$ operation identifies the action that results in the most successful outcome, given the likelihood of the temperatures **as we understand them currently**.

If the temperature statistics and economics show that on average an economic loss will occur when drilling, the action to not drill will be identified (e.g., the $\max_a$ operation). **The PFA studies outlined in this report have contributed to informing what these prior probabilities,** *Pr(.),* **should be, either for temperature classes as shown here or parameterized in other terms (location of faults, areas for power capacity modeling, etc.).**

Decision analysis and, consequently, VOI, require establishing a utility function related to the "value." The simplifying assumption above assumed the value may be proportional to temperature: hotter temperatures may result in better economic outcomes (e.g., power production). This value definition is used to quantify, in an average sense, the outcome of geothermal exploration decisions represented by $v_a(T = t_i)$. In this example, one may want to drill thermal gradient holes with the objective of finding hot temperatures, and a value definition tied to the temperature is logical. We present alternatives to this approach in the entropy subsection below.

The perfect information case posits that some information sources can precisely indicate the subsurface condition without errors (e.g., which temperature bins exist at particular locations). The same probabilities are used from V_{prior}, they are just switched in order, representing that each temperature condition will be revealed by the information, and therefore the ideal action (drill or not) will be performed for that temperature:

$$V_{with\,perfect\,information} = \sum_{i=1}^{N} \Pr(T = t_i) \left[\max_a v_a(T = t_i) \right] \quad a = drill, don't\ drill \tag{1}$$

In the earth sciences, assuming perfect information is usually unrealistic. However, it provides a useful upper bound on any kind of information, given the current economics and prior probabilities surrounding the geothermal exploration scenario. **Again, the PFA analyses provide more informed probabilities of the subsurface conditions, leading to more representative upper bounds of what new information may bring to a geothermal exploration decision.**

The value with imperfect information ($V_{imperfect}$ in Figure 23) "updates" the probabilities to account for how well a specific but *imperfect* data source can reveal the different subsurface conditions (e.g., temperature bins). $\tilde{T}_{2m}$ could represent 2-m temperature probe:

$$V_{with\,imperfect\,information} = \max_a \sum_{i=1}^{N} \Pr\left(T = t_i | \widetilde{T_{2m}} = t_i\right) [\ v_a(T = t_i)\ ] \quad a = drill, don't\ drill \tag{2}$$

Thus $\Pr\left(T = t_i | \widetilde{T_{2m}} = t_i\right)$ represents the statistical relationship between 2-m temperatures and deeper reservoir temperatures. In other words, this is the data reliability or data uncertainty.

$\mathrm{VOI}_{\mathrm{imperfect}}$ ($=\mathrm{V}_{\mathrm{with\ imperfect\ information}} - \mathrm{V}_{\mathrm{prior}}$) quantifies more realistically, on average, how the geothermal decision outcomes are improved if imperfect Data X (e.g., MT, seismic, 2-m temperature probes) are collected and used before the geothermal decision is taken (e.g., wells are drilled). If there is an increase in value with Data X, that means VOI is positive, and Data X has value. Only then is the cost of that data compared to the value. Again, if the value is greater than the cost of Data X ($\mathrm{VOI}_{\mathrm{Data\ X}} > \mathrm{Cost}_{\mathrm{Data\ X}}$), it is deemed a sound decision to purchase the data.

VOI vs. Information Cost

The purpose of VOI is to elucidate which information can improve the outcome of geothermal exploration decisions, thus identifying which data types should be considered for purchase. It is important to distinguish VOI from the cost of a data type. A common misconception is that VOI has an inherent relation to the cost of the information or that it will reduce the cost of a data type. The drilling difficulties described in Section 2.3 can be used to demonstrate this nuanced difference. The focus on reducing costs partially led to considering only one particular source for obtaining thermal gradient wells, which contributed to many pitfalls (e.g., failure to reach target depth, lack of drilling progress, accessibility and logistical issues). It can be argued, through a decision analysis lens, that ***the focus on a minimization or reduction of costs is the true problem***. Although a vendor may offer a certain data type at an economical price, do these data provide any clarity on the uncertainty that is making our geothermal exploration decisions difficult in a risky sense? Data X may cost half as much as Data Y, but has it improved our chances to drill to optimal depths, in the optimal location, in the expected challenging conditions, or at the optimal timeline? A paradigm shift must be made to focus on the ***value*** of the information and not its cost.

VOI addresses these questions by providing a framework for identifying which uncertainties are making the geothermal exploration decisions “hard” or risky, such as certain subsurface conditions. Then VOI forces decision makers to ask what type of information can reliably differentiate or distinguish between these different subsurface conditions. This analysis framework can be used to guide geothermal PFA projects when collecting data and evaluating risk. In the case of drilling, if the main uncertainty is limited to understanding the temperature at depths greater than 2 km, then only vendors that have a track record of being able to reach those depths in the possible drilling conditions would be considered. VOI reduces wasteful expenses by identifying the most relevant and reliable information for the decision. Lastly, the VOI that is calculated is used to compare against the cost of that information: If VOI is greater than the cost of the relevant and reliable data, it is deemed a sound decision to purchase the data.

Complexity of VOI Calculation

VOI can either be a back-of-the-envelope calculation, where rough probabilities are assigned, or it can use sophisticated uncertainty quantification methods such as a combination of geostatistics, Monte Carlo sampling, machine learning, 3D simulation (e.g., fluid flow, geophysics) as seen in Trainor-Guitton et al. (2011, 2014, *under review*) or Jreij et al. (2021). No matter which method is utilized along this spectrum, two sets of probabilities are needed: 1) the possible subsurface conditions (known as the prior probabilities in Bayes terminology) and 2) the information reliability, described above as the “track record” of the information source to reliably distinguish between the possible subsurface conditions.

This retrospective analysis outlines the reasons for and acknowledges that there is yet to be community consensus on the typical characteristics of a geothermal play (including different types of play), given the relative paucity of data and training sites compared to other subsurface resources. All these issues make it more challenging to estimate the reliability statistics of any given data source to identify geothermal resources consistently and accurately. However, these don’t preclude an execution of a meaningful VOI analysis. Prior probabilities can and should be informed and updated by expert opinion, and synthetic modeling can supplement information statistics. To emphasize that lack of data shouldn’t prevent the application of VOI, weights of evidence, used in several of the PFA projects, was originally developed as a medical diagnostic system using large patient databases to establish the relationships between symptoms and disease. For geothermal PFA, weights of evidence still provided useful outcomes despite not having rich data sets.

Weights of evidence is a log-linear version of the general Bayesian model and is normally applied where the evidence is binary. Therefore, the weights of evidence technique is designed to allow a large database to determine the proportions (or prior probabilities), whereas a more strictly Bayesian approach (captured in VOI) allows for more input from experts, which may be more appropriate in some geothermal scenarios. As more data become available, and more nuance is understood between different geothermal plays, nonbinary structure may be necessary as well.

Alternatives to the Value Metric

The value-based (or utility) approach may not be appropriate for assessing data worth for data exploration reasons. The purpose of data collection, such as drilling, could either be to find economic temperatures ***or*** to confirm and/or eliminate certain conceptual models. Therefore, a different approach is necessary to properly value “negative” results (e.g., low temperature or gradient), which may aid in ruling out conceptual models. One approach may be to use entropy

$$H = -\sum_{i=1}^{\mathrm{N}} \Pr(T = t_i) \log_2 \Pr(T = t_i) \tag{3}$$

which quantifies statistical disorder. Entropy will be greatest when the probabilities across all bins or categories (indexed by *i*) are even, thus as it approaches a uniform distribution. Entropy therefore needs a somewhat thorough probabilistic analysis to inform these probabilities. Entropy has been used as a method to help determine where more data should be collected in order to reduce uncertainty (disorder) at the geothermal prospect-scale (Trainor-Guitton et al. *under review*).

3.3 Recommendations

In this section we distill the discussion into recommend best practices across different aspects of the PFA workflow and specific methodologies utilized by all the projects.

3.3.1 Terminology Best Practices

In order to standardize the geothermal PFA process, a standardized terminology is needed. As such, we suggest adoption of a slightly modified version of the terminology outlined by the Snake River Plain PFA team, which defines five GIS map layers as 1) data layers, 2) evidence layers, 3) confidence layers, 4) CRS maps, and 5) the composite CRS map. These layers are described in more detail in Section 2.1. This set of terminology is comprehensive and best aligns with the methodology best practices outlined below.

3.3.2 Methodology Best Practices

Here we construct best practices based on similarities between the project methodologies (Table 5). The best practices are suggested for five main parts of the PFA process: 1) evidence layer combination method, 2) components investigated (or CRS maps produced), 3) transformation methods, 4) weighting approach, and 5) confidence quantification approach. This set of best practices naively assumes that similarities between decisions made are likely to represent best practices. It is important to acknowledge that where different decisions were made, they may have been made for a specific reason, and therefore may represent best practices for specific cases. The following subsections provide a more in-depth analysis of each component of each methodology and an additional set of best practices based on that analysis.

Table 11. Consensus-Based Methodology Best Practices

See Table 12 for more robust analysis-based recommendations

Evidence Layer Combination Method	Components Investigated (CRS Maps Produced)	Transformation Method(s)	Weighting Approach	Confidence Quantification
Weighted sum	Heat, fluid, permeability	None	Expert opinions	No consensus

Layer Combination Methods

Here we summarize the advantages and disadvantages of the different layer combination methods, including simple weighted sum, the voter-veto method, union overlay, weights of evidence, and fuzzy logic.

A simple weighted sum involves generating weights and applying them to intermediate rasters or index models of data sets. The products are then summed. This approach is simple, straightforward, and there is an existing tool to do this calculation in ArcGIS. Conversely, this approach does not eliminate areas where unfavorable conditions exist, and it can be less interpretable (i.e., produces a favorability index rather than a probability value).

The voter-veto method starts with a generalized linear model, which acts as a weighted sum, to calculate probability of meeting the criteria for a geothermal resource at each location on the map. It takes into account prior probabilities from experts in the absence of data. The voter equation allows each data type to influence the outcome depending on its weight. A simple weighted sum increases monotonically, but probabilities produced by the voter equation cannot increase above 1. For example, if there are already five separate positive indicators of a quality, then the sixth doesn’t add much additional information, which is taken into account in the voter equation. This approach vetoes areas where the probability of one of the components is zero because the probability of a resource is the sum of the probabilities of each of the components of a resource. In other words, this sum of probabilities is called the veto equation because the absence of any one quality will indicate the absence of a viable resource. Lautze et al. (2016) describe this approach in more detail. The advantage and disadvantage of this approach are that the prior probability and confidence weights must be defined a priori, but could be informed by either expert opinion or prior data observations. This technique handles missing data better than overlay approaches as described next. However, simply combining probabilities at the end may not account for data dependencies. There exist methods for combining probabilities beyond multiplying them together (Journel 2002).

Union overlay is an ArcGIS tool that overlays layers and removes areas where one of the criteria is not met. In other words, the union overlay calculates the geometric union of the feature classes and layers. The output feature class is composed of polygons representing the geometric union of all the inputs as well as the fields from all the input feature classes. Within this method, the union is followed by the ArcGIS dissolve, which aggregates features based on specific attributes. This deterministic approach has the benefit of a pre-existing tool in ArcGIS and it works well when there is a relatively even spatial distribution of all input data sets. However, this approach is tedious when there is an uneven spatial distribution of input data sets. It also bins favorability and measurement values into categories, and can produce unrealistic boundaries between high, moderate, and low favorability areas that are heavily biased by survey area boundaries.

Weights of evidence is an approach that examines multiple layers of evidence, calculates weights for each evidential layer based upon the spatial relationships of training points, which are located at known geothermal systems, and then produces a posterior probability raster surface and other related statistics. Weights of evidence is a ratio representation of a binary Bayes Law—e.g., geothermal either exists or does not. Moghaddam et al. (2013) found in their analysis that weights of evidence appears to be the superior probabilistic method, out of several tested, for geothermal exploration model development. This approach can include confidence modeling by default and weights (or significance values) for evidence layers. The main disadvantage to this approach is that it is challenging to apply when there is a lack of training sites, but there are workarounds.

Fuzzy logic formalizes reasoning in natural language using canonical if-then rules. For example, if a fault is long, young, and there is high fault stress, then it is favorable in terms of permeability. To apply this rule, boolean values for fault length, fault age, and fault stress are needed, and thus threshold values must be established to term each continuous variable into a categorical one. Zhang et al. (2016) describes this process in greater detail. This approach easily incorporates linguistic expert knowledge, makes it relatively easy to incorporate a variety of data types with varying levels of sparsity, and provides an uncertainty range. There are also existing tools with several coding languages (e.g., MATLAB, Python). However, it relies exclusively on expert knowledge, can be susceptible to human bias, and requires many decisions (i.e., fuzzy rules for each data type as it pertains to each component and membership functions for each variable).

As a best practice, we recommend the voter-veto method due to its ability to take into account prior probabilities, its interpretability, its use of the logistic link function to account for the fact that less is learned by each proceeding evidence layer that adds to the existing consensus, and its ability to “veto” areas where one criterion is not met. We encourage additional investigation into how this method compares to weights of evidence, which was highlighted by Moghaddam et al. (2013) as the superior probabilistic method for geothermal exploration model development.

Components Investigated (CRS Maps Produced)

Outcomes from the 2020 PFA Retrospective Workshop included discussions of the major play components and associated inputs among the projects. Those are summarized as:

- *Heat*: Well temperatures, regional heat flow, MT, chemistry and geothermometry, Quaternary volcanism, rifting, gravity anomalies
- *Permeability*: Rift zones, faults and ages, geodetic strain, slip and dilation, seismicity, gravity, magnetics, MT
- *Fluid*: MT, groundwater elevation, topographic elevation, recharge
- *Cap/Seal*: Lacustrine sediments.

Based on the workshop findings, we have a fairly good consensus on which components to require within a PFA. Generally, these should include heat, permeability, fluid, and sometimes seal (dependent on geothermal system type). A seal is of interest in convecting hydrothermal systems, wherein a seal is needed to contain the reservoir physically and thermodynamically. These systems often consist of permeable rock reservoirs rather than fault-dominated reservoirs.

Special cases do exist. For example, island plays like Hawaii may have groundwater everywhere at a reasonable depth ($P_{Fluid}(X) = 1$), so fluid may be left out in some studies. If for some reason $P_{Heat}(X) = 1$ or $P_{Permeability}(X) = 1$ or $P_{Seal}(X) = 1$, those may be left out as well, although these are less likely scenarios.

Transformation Method(s)

Transformation methods useful in PFA can generally be broken into three categories: 1) density functions, 2) distance functions, and 3) interpolation methods. Density functions calculate the occurrence of features (e.g., vents, fault segments) within a given area, and are sometimes normalized to put them on a scale from zero to one. This can be performed using simple density functions or kernel density functions.

Simple density functions quantify data density by counting all instances of a feature within a specified radius of each data point and dividing by the area of the search radius. This density value is then applied to the entire area. Kernel density functions quantify data density by first calculating the simple density. This density is then distributed from a maximum at the location of the data point, to zero at the perimeter of the search area using a quadratic function. Data points may be weighted using their properties prior to counting. For example, faults can be weighted by both dilation tendency and slip tendency.

Euclidean (or other) distance analysis calculates the distance to features to quantify proximity. This is an alternative to density for incorporating physical indicators of geothermal resources.

Interpolation functions are used to calculate intermediate values from a finite array of data points. Data interpolation can be carried out for point or line sources using a radial basis function, inverse distance weighting, or by kriging, depending on data density and desired result. The radial basis function, inverse distance weighting, and kriging are all exact interpolators, but kriging provides a kriging variance that uses the variogram (described in the following paragraph) to spatially increase the estimated error away from measured locations.

Probability kriging is a geostatistical method that relies on classes or bins of the original properties (e.g., temperature, permeability) and the concept of variograms to interpolate between data points. It is an extension of indicator kriging. Variograms model how dissimilarity, or covariance, increases with distance from an observation. Probability kriging uses thresholds to define the classes (defined as the indicator variables) and the original data to create probability maps. Compared to standard kriging methodologies, it allows spatial patterns within lower and higher magnitudes to be modeled. However, it requires variograms for each threshold defined, which can represent a lot of time and more uncertainty. This is available in ArcGIS and other open-source software (Remy et al. 2001).

Empirical Bayesian kriging (EBK) is a more iterative form of kriging that uses an intrinsic random function as the kriging model, which takes into account uncertainties in estimating the variogram. This can be used to estimate the value of a property at each point on a continuous surface. The standard errors of prediction may be more realistic for EBK than for other kriging methods, and the results from EBK on small data sets are more accurate than other kriging methods. Standard kriging methods use existing data locations to predict values at unknown locations, while EBK uses existing data as a starting point to estimate data values at all locations. EBK then uses those values to create a new set of starting values using an intrinsic random function through a series of iterations. Because of its iterative nature, EBK returns a more generalized interpolation and a more robust estimate of standard errors. It also takes into account uncertainties in estimating the semivariogram and assumes that the variable being mapped decreases in influence with distance from its sampled location. Because of this, EBK was the Snake River Plain team's preferred method for interpolation. However, EBK cannot use anisotropic variograms, where spatial correlations are different in different directions, which may be more appropriate for locations like the Basin and Range where more correlation is observed north-south versus east-west (Trainor-Guitton et al. 2020).

Inverse distance weighting estimates cell values by averaging the values of sample data points in the neighborhood of each processing cell. The closer a point is to the center of the cell being estimated, the more influence, or weight, it has in the averaging process. This approach is simple, and there is an existing tool for it in ArcGIS. It also assumes that the variable being mapped decreases in influence with distance from its sampled location, and the user can control the significance of known points on the interpolated values based on their distance from the output point. It is, however, limited by the assumption that the value at a specific point will be the average of the values at the nearby sample data points, and it can be challenging to determine what significance to apply to known points.

Radial basis functions are a series of exact interpolation techniques, meaning that the surface must go through each measured sample value. There are several different basis functions—each with a different shape and a slightly different resulting interpolation surface. Radial basis functions can predict values above the maximum and below the minimum measured values as in the cross-section below. In addition, they can be applied using the existing tool in ArcGIS. They are, however, overly simple, they assume a function to fit the variation in the data, and they do not account for uncertainty in measurements (i.e., the surface must go exactly through each measured sample value).

Best practices for transformation methods are heavily reliant on the type of data set in question. **That said, we recommend the use of density functions (simple or kernel) for quantifying the presence of features, and interpolation (kriging-based or other) for theoretically continuous data sets** (i.e., limited by observation spacing rather than the existence of a measurable property). Sometimes, it can be useful to apply Euclidean distance analysis to quantify proximity prior to application of density or interpolation functions. We leave this intentionally vague because we acknowledge that every data set has its own unique qualities and challenges that need to be recognized and compensated (e.g., biases caused by uneven data distribution and data sets that may have overemphasized certain inputs).

Weighting Approach

Most of the layer combination methods above require weights, significance levels, or feature importance values to be applied to the different evidence layers. This is most commonly done using expert opinions but can be done in a variety of other ways as well.

Expert opinion-based weights are produced by having those familiar with the play and the data sets in question rank the evidence layers. Then the ranks are converted into weights. This approach to weighting captures nuance and complex understanding of many factors. It is considered "trustworthy" and reflective of "what we know." Despite this, expert opinions can be biased, and it can be hard to account for "what we don't know." On top of that, expert opinion-based weights are semiquantitative at best, but usually qualitative, making it challenging to go from ranking to weighting.

Expert opinions can be combined with the analytical hierarchy process (AHP), which is a quantitative way to obtain consensus-based decisions through pairwise comparisons. This approach is frequently more organized than the traditional approach to combining expert opinions, and there exists a free tool online for applying AHP. The biggest disadvantage to this approach is that it requires pairwise comparisons, which do not account for more nuanced relationships between different data sets (i.e., gravity and magnetics are more valuable together than they are separately).

Bayesian weights of evidence and logistic regression are more statistically based alternative weighting approaches. Statistical approaches are data-driven, and therefore generally not biased by human opinions, meaning we can in theory learn what we do not already know. However, data can also contain their own bias given spatial coverage and their sparsity. Particularly, within weights of evidence, evidence layer weights are produced alongside favorability maps and confidence maps. According to the studies reviewed by Moghaddam et al. (2013), weights produced by weights of evidence align well with expert opinions. Statistical weighting approaches can be improved with more comprehensive training data set, i.e., as data collection continues or increases.

The 2020 PFA Retrospective Workshop identified weighting of input data as a challenging portion of the PFA process, which is often influenced by human bias. Therefore, additional research is warranted in this area. Taverna et al. (*in preparation*) will compare expert and statistical weighting approaches to determine how different approaches impact PFA results, but findings are yet to be published at the time of writing this report. **With this in mind, we recommend statistical or data-driven weighting approaches when sufficient training data exist, and expert opinion weighting approaches otherwise.**

Confidence

Within a PFA, it is important to quantify uncertainty, or its inverse, confidence. This is because there is always uncertainty when inferring subsurface conditions from data. For example, in geophysical data, uncertainty often comes from interpolation methods, non-unique solutions to inversions, survey setup and field conditions, and sparse measurements. Where possible, uncertainty is mitigated, but it is never zero unless true validation is possible (i.e., drilling into the reservoir).

The simplest option is expert-defined confidence analyses of input data. This approach uses expert confidence analysis to produce confidence maps, wherein the map probably begins as a set of confidence values at observation locations, and then can optionally incorporate some sort of interpolation/kriging or other spatial statistic method to produce a mapped confidence surface. Favorability values can also be compared to the mean and error of the favorability surface within an area for producing anomaly confidence. When interpolation is not used to produce confidence maps, the confidence quantification process is greatly simplified, however, it can be detrimental to decision-making and interpretability to work without confidence maps. When interpolation is used to produce confidence maps, these maps may be used to scale favorability maps, easing decision-making and interpretability. However, as previously mentioned, expert-defined analyses have the potential for human bias, and there may not be much transparency into the process.

One can alternatively use the probability maps produced by stochastic kriging methods. This is a quantitative and interpretable approach (easy to interpret probabilities) where probabilities are analogous to favorability (i.e., only have to look at one map/no need to combine favorability and uncertainty maps into one map). Stochastic methods can provide a distribution of property values that must then be combined with other properties to have favorability. P10, P50, and P90 (percentiles) could be used for the favorability. Confidence from these probabilities could be calculated via entropy as described in Section 3.2.1.

Another approach is to analyze data quality and the number of different data types at a given point as used in the Hawaii PFA and described in Ito et al. (2017). This means accounting for confidence in the calculated probability such that the probability value increases with the number of different types of data and their quality where the quality of the data set is quantified and used as a mathematical parameter; that parameter is set to zero if the data are absent. Quality factors are weighted according to modified weights, which may be generated using expert discussions. This approach is advantageous because each probability or favorability value has an associated confidence—and they are separate. This means you can have high probability/favorability and low confidence, or any other combination. This approach is mathematically modeled, and rather simply. The downside to this approach is that it requires a modified set of weights describing data quality, which may be subjective depending on how the weights are generated.

Fuzzy logic was described previously but is also capable of producing confidence maps. This method can be combined with standard error maps from kriged/interpolated surfaces, or with confidence defined by the scale of mapping, distance from measurement stations, and sampling density for density functions. Fuzzy logic can eliminate areas where the standard error is too low by setting confidence to zero, is relatively easy to incorporate a variety of data types with varying levels of sparsity and provides an uncertainty range. However, it is heavily dependent on expert knowledge and therefore can be susceptible to human bias and it requires numerous decisions (i.e., fuzzy rules for each data type as it pertains to each component and membership functions for each variable).

Weights of evidence can also be used to quantify confidence. Within this approach, confidence maps are automatically produced alongside weights of evidence favorability maps. If desired, this can be done using the Spatial Data Modeler tool in ArcGIS (Sawatzky et al. 2009). This approach to confidence modeling is not very conservative, which means it is riskier in practice.

For best practices in confidence modeling, NREL recommends stochastic kriging, as it produces a distribution of property and their frequencies which can be interpreted as confidence maps. This is to maximize transparency into the reasons a potential drill site is being selected (e.g., high favorability with moderate confidence). To produce a single map that highlights the best drill site in terms of both favorability and confidence, the favorability maps may be scaled by the confidence maps. This is what V_{prior} in VOI does via the utility function (Section 3.2.1).

Table 12. NREL-Recommended Methodology Best Practices

Evidence Layer Combination Method	Components Investigated (CRS Maps Produced)	Transformation Method(s)	Weighting Approach	Confidence Quantification
Voter-veto method or weights of evidence	Heat, fluid,* permeability, and sometimes seal**	Density function (simple or kernel) or interpolation (EBK), depending on the nature of the data set in question. Sometimes Euclidean distance analysis is of value prior to density/interpolation functions.	Expert opinions in combination with AHP, or if sufficient training data exists, a more statistical weighting approach such as weights of evidence	Stochastic kriging (modeling confidence as separate from favorability)

*Fluid not required in areas where $P_{Fluid}(X) = 1$, i.e. Hawaii

**Seal requirement dependent on geothermal system type

Other Factors

Some projects considered other factors, such as degree of exploration (Nevada Great Basin) and infrastructure potential (Washington state). We acknowledge these factors as important for geothermal development but consider them separate from the recommended standard PFA methodology. This is because historically within the oil and gas sector, PFA has focused on the geological and structural components of a play, highlighting areas that warrant further exploration. Most of these other factors are likely to evolve over time, and therefore are considered part of the "further exploration" stage.

Main Takeaways Regarding Methodologies

We posit that PFA is well-suited for geothermal exploration given the current state of the geothermal industry because it provides an intersection between data-driven and expert-driven approaches. Data scientists would prefer to rely solely on data-driven methods. Although geothermal exploration is past the point of using purely expert-driven decision-making, it is not quite at the point of being able to make purely data-driven decisions for a handful of limitations: data availability, data quality, and incomplete understanding of the best methodologies to apply.

All of the approaches taken by the different project teams have unique advantages and disadvantages, meaning that it is challenging to confidently construct a set of best practices. However, we acknowledge that the PFA methodology would benefit from standardization, therefore we attempt to do just that.

3.3.3 Drilling Best Practices

The four completed PFA Phase III projects demonstrate that drilling operations can be optimized through explicit project definition and planning, improved communication at all stages of the drilling process, employment of experienced personnel, and comprehensive financial planning. The bidding process for drilling programs should include local geothermal or water well drillers. Local drilling knowledge was central to success in the Hawaii and Washington PFA projects. Local rig contractors should always be consulted, as they have the most relevant knowledge of drilling conditions and local equipment supply chains. The selected drilling contractors should be involved in the site selection and site preparation processes, ideally drawing on prior experience to inform decisions. Clear communication prior to the start of drilling is crucial. Project parameters should be completely defined to avoid project scope creep. Project teams and drillers must understand the drilling plan as well as the project goals and challenges. Teams need to understand what type of well is to be drilled and where they will drill before contracting a rig. Teams should consider requiring a pre-spud meeting for every well to ensure all parties have a clear understanding of the scope of the project. Pre-spud meetings should include leadership as well as personnel that will be on-site during drilling to establish coordination throughout the crew.

Project success was greatly impacted by hiring an experienced team with diverse skills. A program representative or on-site geologist with industry experience should be hired to supervise the rig and liaise with the project teams. This representative should also aid teams in the permitting and planning processes. GTO should ensure that project teams include a consultant with operational background to plan and supervise individual drilling projects if needed and if project funds allow. Drilling supervisors should ensure that drilling teams understand the scope of the project prior to and during drilling. Drilling rigs and crews should be fit to their specific purpose and well type to avoid nonproductive downtime. Clarity about which roles are required for a specific job should be established and decisions about which people will perform each role should be agreed upon. The data collection processes should be standardized during drilling. A specific data collection system or company should not be mandated, but required data types should be defined and mandated.

Comprehensive financial and logistical considerations are also crucial to project success. Housing expectations should be defined, especially for remote sites, allowing rig crews to stay on-site to save travel time. If 24-hour drilling operations are desired, this should be reflected in bids and cost estimates. Teams should consider including hard limits on overhead in project funding opportunity applications, specifically concerning funding that is subcontracted to drilling contractors. Pending DOE approval, teams could also consider including a mandated contingency fund for drilling cost estimates, thus reducing the impact of unanticipated problems. Changes to financial regulations may be required to allow for such contingency funds. Project teams should keep the option to replace the drilling contractor if initial results are not as expected. Finally, community acceptance and engagement must be considered. Strong relationships with stakeholders were seen to be very influential to the success of a project.

This review of project successes and challenges is solely to indicate areas for improvement and is in no way meant to undermine the work performed by each of the PFA teams. Indeed, these projects greatly advanced geothermal approaches to geothermal exploration and resulted in extensive new data and new discoveries of unrecognized geothermal systems. The lessons learned, data collected, and methodologies explored in these PFA projects form a robust base for future geothermal exploration.

3.4 Impact of PFA Projects

The geothermal PFA portfolio culminated in 11 total projects that collected and analyzed geologic data over about 435,000 mi^2 (1,127,000 km^2). Over 100 publications and presentations have been released in relation to this PFA effort (Appendix A). The impact of this work can be seen in the identification of previously undiscovered geothermal sites across the United States. The temperature gradient wells drilled in Phase III projects serve as validation of the PFA methodologies created. Some of these wells allowed for fluid sampling and geochemical analysis, and many prospective areas have been identified for additional exploration and analysis.

DOE-funded PFA projects demonstrated a variety of strategies for geothermal PFA in diverse geologic and tectonic environments. Through Phases I, II, and III, the projects demonstrated the potential of PFA from regional screening for geothermal favorability through drilling of temperature gradient wells. Results of Phase I and planning for Phase II demonstrated the potential for PFA to identify high-priority areas, data gaps, and along with conceptual models, the highest-value new data collections to advance plays. New data collection, evolution of conceptual models, and refined data processing and PFA methodologies enabled projects to identify highest-priority plays and locations within plays most likely for drill confirmation of anomalously high temperatures and gradients. Despite challenges executing some drilling programs—including suspension of drilling in the Eastern Great Basin—temperature gradient wells were completed safely, and downhole temperatures were measured. Regardless of results, safe completion of wells and temperature measurements define technical success. By statute in most jurisdictions, temperature gradient wells are not meant to intersect geothermal resources, and from a project assessment standpoint, negative results (low temperature and gradient) are equally useful as positive results (high temperature and gradient).

The projects that advanced to drilling achieved results in addition to technical successes. The well drilled on Lanai was located in a suboptimal location to allow drilling to greater depth by deepening an existing well, resulting in the deepest well away from geothermal drilling in the Kilauea Lower East Rift Zone of Hawaii Island. The Lanai well encountered temperature gradients more than twice background (42°C/km, 66°C at 1,057 m) and confirmed models of projected temperatures at depth (Lautze et al. in progress). Multiple plays in Nevada were drilled with indications of blind geothermal resources. In southern Gabbs Valley, six temperature-gradient holes defined a blind geothermal system with temperatures as high as 124°C at 152 m and a thermal anomaly extending 2 km north-south and 1 km east-west. At Granite Springs Valley, six new temperature gradient wells measured temperatures of up to ~96°C at ~240 m.

Drilling adjacent to the Snake River Plain at the Camas Prairie play intersected an ~80°C resource with chemistry indicative of a deeper 124°C geothermal resource. In Washington at the Mount Baker play, a temperature gradient of 63.6°C/km was measured, and based on measured thermal conductivity, heat flow is estimated to be 141–159 mW/m^2, nearly double the background heat flow (Blackwell et al. 1990).

Across Phase III projects, multiple priority areas for temperature gradient drilling were identified. Non-PFA factors affected choice of plays and locations for drilling. Importantly, the Hawaii, Idaho, and Washington teams were able to modify their temperature gradient drilling to more effectively advance identified high-priority plays, most notably by drilling deeper than typical for temperature gradient drilling. Had they not drilled deeper they may not have been able to validate their PFA results, thus serving as justification for not allocating equal amounts of funding and standardized thermal gradient hole approaches across varied settings. Temperature gradient drilling is much more effective if depths are not arbitrary but instead designed to collect the necessary subsurface data to inform decision-making based on local conditions and conceptual models. However, the higher cost of drilling deeper contrasts with the Nevada project's drilling of multiple temperature gradient wells at priority plays. While deeper temperature gradient wells can enable collection of required subsurface data or even be necessary given certain geologic settings and geothermal play types, multiple temperature gradient wells allow enhanced refinement of conceptual models, provide the opportunity to begin constraint of resource size, and better inform decision-making (e.g. Craig et al. 2021).

3.5 Future Directions

Although Phases II and III of the PFA projects saw the collection of a multitude of new data sets, many data gaps were identified by the data gap analysis performed by Rhodes et al. (2021) as part of this study. The majority of the western United States lacks 1) detailed geologic mapping (scale of 1:24,000 or larger), 2) publicly available aeromagnetic data coverage (minimum 400 m line-spacing resolution), and 3) publicly available gravity data. In addition, many of the areas identified as possessing relatively high hydrothermal favorability lack publicly available LiDAR data. As many of the PFA projects relied on these types of data, filling these data gaps and ensuring consistent spatial coverage are seen as essential to further reduce uncertainty in areas that have experienced relatively less exploration and that appear less favorable in PFA results simply because no useful data are available. The PFA Retrospective Workshop held following the 2020 Stanford Geothermal Workshop used the expertise of PFA project PIs as well as attendees from academia, private industry, and government labs and agencies to highlight ideal team competencies for PFA, major play components and associated inputs, project successes and validation methods, and project challenges and lessons learned. Additionally at the workshop, based on their respective experience, project PIs and other experts identified the lack of MT regional profiles, reflection seismic data (where possible), and improved heat flow measurements and analysis as major geothermal data gaps which could be employed in PFA and method validation and which have proven valuable to general geothermal exploration and characterization.

Spatially, the PFA projects covered a substantial portion of the western United States. Areas that were not examined but remain of interest for future studies include central and eastern Oregon, California (outside the Modoc region), and Nevada (outside the previously analyzed PFA region). The low-temperature methodology developed for the Appalachian Basin can be applied to and refined for sedimentary basins throughout the United States for geothermal PFA and for both low- and high-temperature resources. Having both deep and shallow data is important for resource assessment and the construction of conceptual models. Hidden systems often have some shallow signatures (e.g., elevated thermal gradients, silica sinters, surficial hydrothermal alteration), but obtaining high-quality deep signatures would require improved geophysical methods. Joint inversion of geophysical data may help reduce the ambiguity inherent in individual inversions. Additionally, novel techniques need to be developed and validated to improve characterization of the subsurface.

The application of machine learning to geothermal PFA is a concept that warrants further exploration. Machine learning approaches are being used for hydrocarbons PFA (e.g., Schnetzler and Alumbaugh 2017), but the challenge of working with a limited number of training sites has limited implementation for geothermal PFA. Geothermal PFA would also benefit from the development of an automated composite methodology that could be applied to multiple play types.

VOI approaches will also greatly benefit from more labeled geothermal data. As VOI is more ubiquitously applied, patterns of the type of data that best guides drilling decisions for the type of play will be better understood. Recommendations of specific data types for certain plays may be made as VOI (statistical) analyses are performed.

Anecdotally, the results of DOE-funded projects are being used by industry to prioritize exploration focus and refine exploration methodologies. Multiple geothermal PFA projects have been completed and are ongoing beyond those reviewed herein, including outside the United States (e.g., Lindsay et al. 2021). A primary focus of future work is to balance or test expert opinion with quantitative data observations. DOE has funded projects focused on machine-learning-driven PFA (e.g., Smith et al. 2021) and the U.S. Geological Survey is reexamining its 2008 hydrothermal resource assessment with machine learning techniques (Mordensky et al. 2023). An important component of future machine learning efforts needs to focus on the integration of conceptual model frameworks. PFA frameworks formalize the selection, processing, and interpretation of geothermal-exploration-relevant data; however, the conceptual models that provide frameworks for understanding data integration in a range of geology-geophysics-geochemistry scenarios are difficult to capture with methods focused on excluding expert decision. PFA is traditionally a 2D exercise, though 3D data are often integrated, most notably direct data from subsurface drilling and fluid chemistry or indirect geophysical inversions. At play scale and with targeting of wells, 3D models become essential, and these efforts should be distinguished from PFA, which has the primary goal of identifying high-priority plays. Conceptual model components are implicit in 3D geothermal play and drill targeting models, and this scale may be where machine learning methods are particularly effective.

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Appendix B. PFA Project Approaches

Table B-1. Summary of Each PFA Approach, Including Data Combination Method, Data Layers, Components Assessed, Transformations Applied Where Applicable, and Weights for Each Data Layer

Project and Data Combination Method	Data Layer	Component	Transformation (if applicable)	Weight
Hawaii Data combination method: Compute joint probability using "veto" equation	Well Temperature	Heat		9
	MT Resistivity	Heat		9
	Cl/Mg Ratio	Heat		8
	Caldera	Heat		7
	Rift Zone	Heat		6
	Gravity	Heat		6
	SiO_2	Heat		6
	Vents	Heat		4 to 5
	Dikes	Heat		4 to 5
	Place Names	Heat		3
	MT Resistivity	Fluid		9 to 10
	Groundwater Level Elevation	Fluid		9 to 10
	Groundwater Recharge Rate	Fluid		9
	Rift Zone	Permeability		8
	Faults	Permeability		8
	Geodetic Strain	Permeability		8
	Seismicity	Permeability		8
	Gravity	Permeability		6
Eastern Great Basin **Data** combination method: Weighted sum	Quaternary Volcanism	Heat Source		0.25
	Heat Flow	Heat Source		0.3
	Fluid Geochemistry	Heat Source		0.15
	MT	Heat Source		0.3
	Fault Density	Permeability		0.4
	Critical Stress	Permeability		0.4
	MT	Permeability		0.2
Nevada Great Basin Data combination method: Weighted sum	Structural Setting	Local Permeability		2
	Quaternary Fault Recency	Local Permeability		3
	Quaternary Fault Slip/Dilation Tendency	Local Permeability		0.3
	Quaternary Fault Slip Rate	Local Permeability		1.5
	Fault Traces	Intermediate Permeability		0.5
	Horizontal Gravity Gradient	Regional Permeability		1
	Geodetic Strain Rate	Regional Permeability		1

Project and Data Combination Method	Data Layer	Component	Transformation (if applicable)	Weight
	Quaternary Slip Rate	Regional Permeability		1
	Fault Recency	Regional Permeability		1
	Slip/Dilation Tendency	Regional Permeability		0.1
	Earthquakes	Regional Permeability		1
	Temperature at 3 km	Heat		1
	Fluid Geochemistry	Heat		1
	Well Temperatures	Heat		1
Snake River Plain Data combination method: Weighted sum	Quaternary faults (Dilation & Slip Tendency)	Permeability	Kernel Density	2
	Mid Gravity Gradient Maximum (Dilation & Slip Tendency)	Permeability	Kernel Density	5
	Deep Gravity Gradient Maximum (Dilation & Slip Tendency)	Permeability	Kernel Density	5
	Magnetic Gradient Maximum (Dilation & Slip Tendency)	Permeability	Kernel Density	4
	Dikes and Intrusions	Heat		8
	Volcanic Vents (Age/Size Weight)	Heat	Kernel Density	10
	Heat Flow	Heat	Interpolated, EB Kriging	10
	Groundwater Temperatures	Heat	Interpolated, EB Kriging	10
	rTest (Geothermometry) Temperatures	Heat	Interpolated, EB Kriging	0
	Helium Concentrations	Heat	Simple Density	2
	Aquifer Cap Distribution (Presence/Absence)	Seal	Polygon Sampled	
	Lake Sediment Distribution (Sediment type)	Seal	Polygon Sampled	
Washington State Data combination method: Weighted sum	Intrusive Rock Proximity	Heat	Euclidian distance analysis	AHP weights: MSH: 0.135, WRV: N/A, MB: 0.087
	Volcanic Vent Proximity	Heat	Euclidian distance analysis, buffer polygons converted to weighted rasters	AHP weights: MSH: 0.164, WRV: 0.129, MB: 0.168
	Thermal/Mineral Springs	Heat	Euclidian distance analysis, buffer polygons converted to weighted rasters	AHP weights: MSH: 0.124, WRV: 0.135, MB: 0.112
	Temperature Gradient	Heat	Kriging interpolation for MSH, IDW interpolation for WRV and MB	AHP weights: MSH: 0.519, WRV: 0.666, MB: 0.539
	Geothermometry proximity	Heat	Euclidian distance analysis, buffer polygons converted to weighted rasters	AHP weights: MSH: 0.057, WRV: 0.07, MB: 0.093
	Dilation Tendency	Permeability		AHP weights: MSH: 0.146, WRV: 0.23, MB: 0.244

Project and Data Combination Method	Data Layer	Component	Transformation (if applicable)	Weight
	Slip Tendency	Permeability		AHP weights: MSH: 0.149, WRV: 0.138, MB: 0.217
	Displacement Gradient	Permeability		AHP weights: MSH: 0.171, WRV: 0.117, MB: 0.068
	Displacement tendency	Permeability		AHP weights: MSH: 0.03, WRV: 0.05, MB: 0.052
	Maximum Coulomb Shear Stress (poly3D model)	Permeability		AHP weights: MSH: 0.206, WRV: 0.246, MB: 0.138
	sigma-3	Permeability		AHP weights: MSH: 0.065, WRV: 0.054, MB: 0.094
	Dilational Strain Rate	Permeability		AHP weights: MSH: 0.168, WRV: 0.113, MB: 0.113
	Maximum Shear Strain Rate	Permeability		AHP weights: MSH: 0.067, WRV: 0.053, MB: 0.074
Tularosa Basin Data combination method: Union overlay	Temperature Gradients	Heat	Interpolated IDW	
	Quartz Geothermometer	Heat	Interpolated IDW	
	Heat Flow	Heat		
	Quaternary faults	Fracture Permeability		
	Zones of critical stress	Fracture Permeability		
	Point of Diversion	Groundwater		
Aleutians & Cascades Data combination method: Components assigned probability value (0-1), then multiplied together	Eruption Volumes	Heat		
	Recency of Volcanism	Heat		
	Composition of Volcanism	Heat		
	Tectonic Setting	Permeability		1
	Structural Setting	Permeability		1
	Plate Angle of Obliqueness	Permeability		3
	Slip Rates	Permeability		3
	Quaternary Fault Density	Permeability		2
	Dilation Potential	Permeability		0.25
	pH, Salinity	Fluid		
	Water Table Depth	Fluid		
	Scaling Potential	Fluid		
	Non-Condensable Gases	Fluid		
	Permissive Lithology	Cap Rock		
	Degree Breached	Cap Rock		
Appalachian Basin	Bottom Hole Temperatures	Thermal Resource	Kriging Interpolation	
	Equilibrium Temperatures	Thermal Resource	Kriging Interpolation	
	Mantle Heat Flow	Thermal Resource	Kriging Interpolation	
	Surface Temperature	Thermal Resource	Kriging Interpolation	

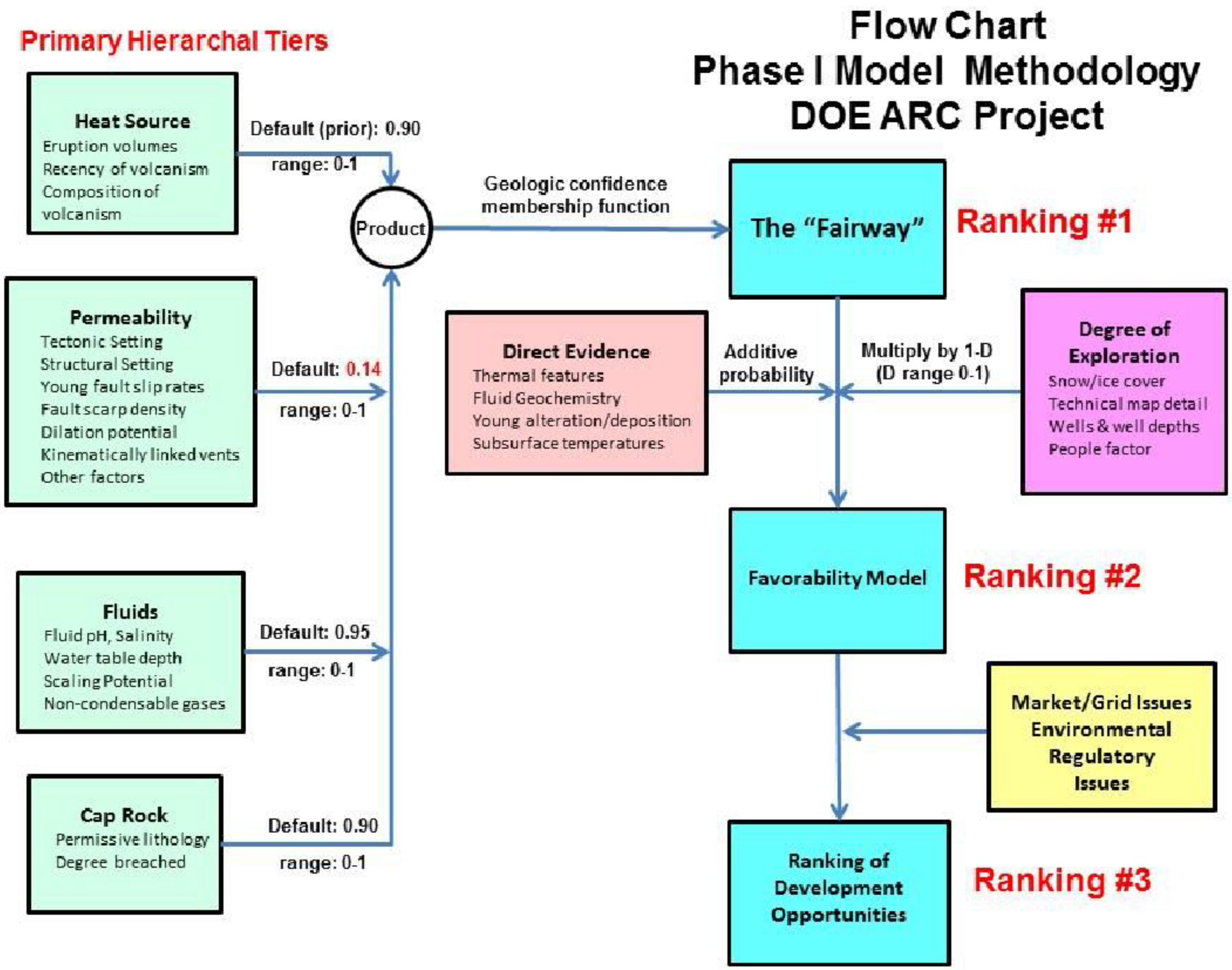
Project and Data Combination Method	Data Layer	Component	Transformation (if applicable)	Weight
Data combination method: Weighted sum	Thermal Conductivity	Thermal Resource	Kriging Interpolation	
	Radiogenic Heat Generation	Thermal Resource	Kriging Interpolation	
	Sediment Thickness	Thermal Resource	Kriging Interpolation	
	Gravity/Magnetic Provinces of Similarity	Thermal Resource	Kriging Interpolation	
	Formation Top	Natural Reservoir		
	Formation Thickness	Natural Reservoir		
	Reservoir Avg Depth	Natural Reservoir		
	Reservoir Pressure	Natural Reservoir		
	Porosity	Natural Reservoir		
	Reservoir Area	Natural Reservoir		
	Reservoir Net Thickness	Natural Reservoir		
	Orientation of primary stress	Seismicity		
	Magnetics	Seismicity		
	Gravity	Seismicity		
	Earthquakes	Seismicity		
	Building Heat Demand	Utilization		
	Roads	Utilization		
	Energy Consumption	Utilization		
	Economic Factors	Utilization		
	County Population Divisions	Utilization		
Cascades Data combination method: Weighted sum	Heat Flow	Heat Source	Probability kriging	0.15
	MT Conductivity	Heat Source, Permeability	Probability kriging	0.55 (heat) 0.35 (perm.)
	Quaternary Volcanic Intrusives	Heat Source	Probability kriging	0.3
	Fault Permeability	Permeability	Probability kriging	0.65
	Access and Infrastructure	Overlay		
Modoc Plateau Data Combination Method: “Fuzzy” numbers used to calculate overall potential for each cell	Fault Length	Permeability	Sum in cell	
	Fault Age	Permeability	Youngest in cell	
	Dilation Tendency	Permeability	Maximum in cell	
	Slip Tendency	Permeability	Maximum in cell	
	Number of Favorable Settings	Permeability	Picked w/ 2 km diameter circles	
	Strain Rate	Permeability	Mean in cell	
	Total Seismic Moment	Permeability	Sum in cell	
	Age and Type of Volcanism	Heat	Youngest/most felsic in cell	
	Smoothed Heat Flow	Heat	Mean in cell	
	Max. Measured Temperature	Heat	Maximum in cell/well depth	

Project and Data Combination Method	Data Layer	Component	Transformation (if applicable)	Weight
	Max. Measured Temperature Gradient	Heat	Maximum in cell	
	Geothermometry	Heat	Maximum calculated temperature in cell	
	Land Status	Marketability		
	Distance to existing high voltage transmission	Marketability		
	Population Density	Marketability		
Rio Grande Rift Data combination method: Weighted sum	Known Faults	Permeability		
	Inferred Faults	Permeability		
	Earthquakes	Permeability		
	Subcrops	Permeability		
	Heat Flow	Heat		
	Lithium	Heat		
	Boron	Heat		
	Basement Temperature	Fluid		
	Discharge Zones	Fluid		

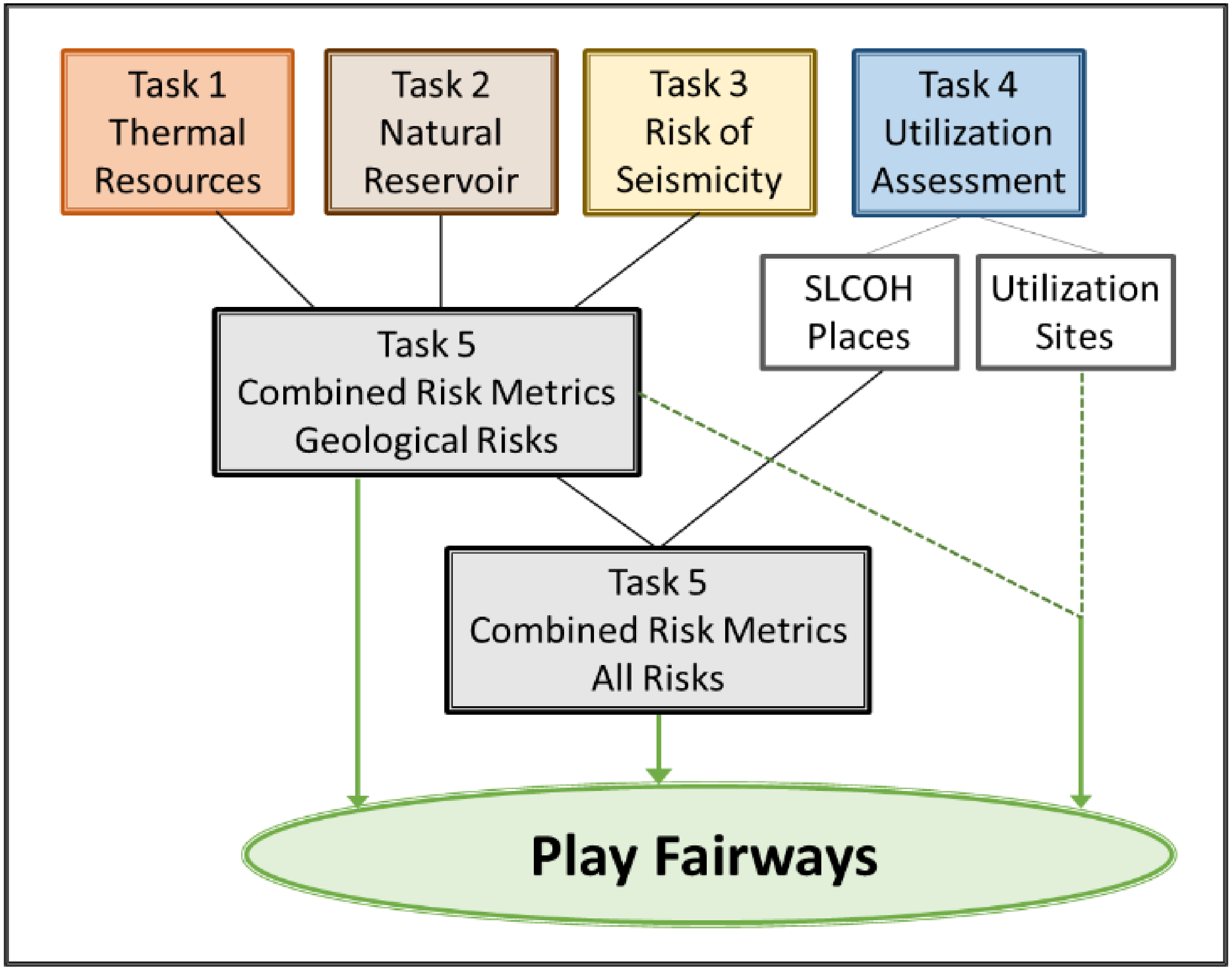
IDW = inverse distance weighted
MSH = Mount St. Helens
WRV = Wind River Valley
MB = Mount Baker

Appendix C. PFA Methodology Flowcharts

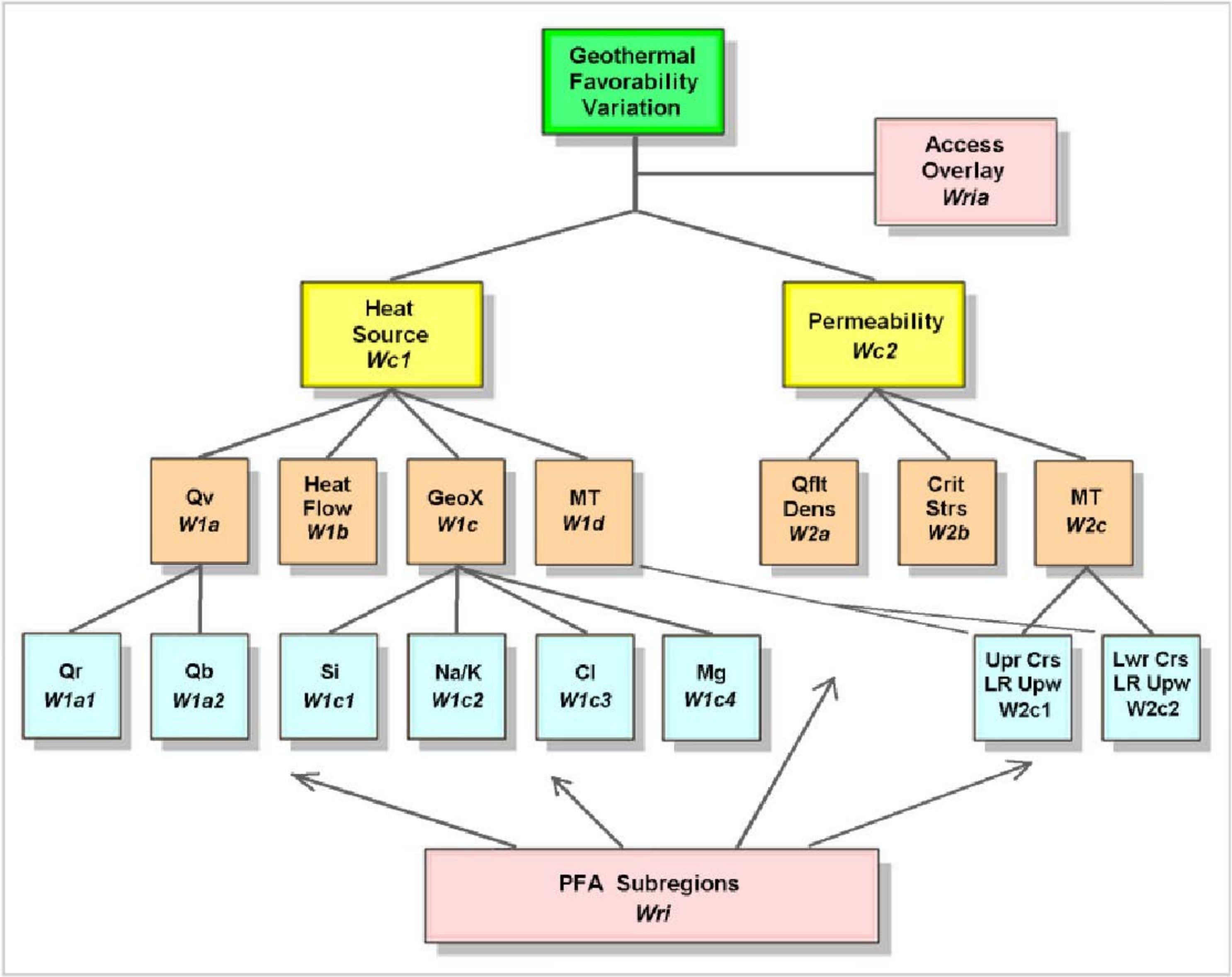
C.1 Aleutians & Cascades



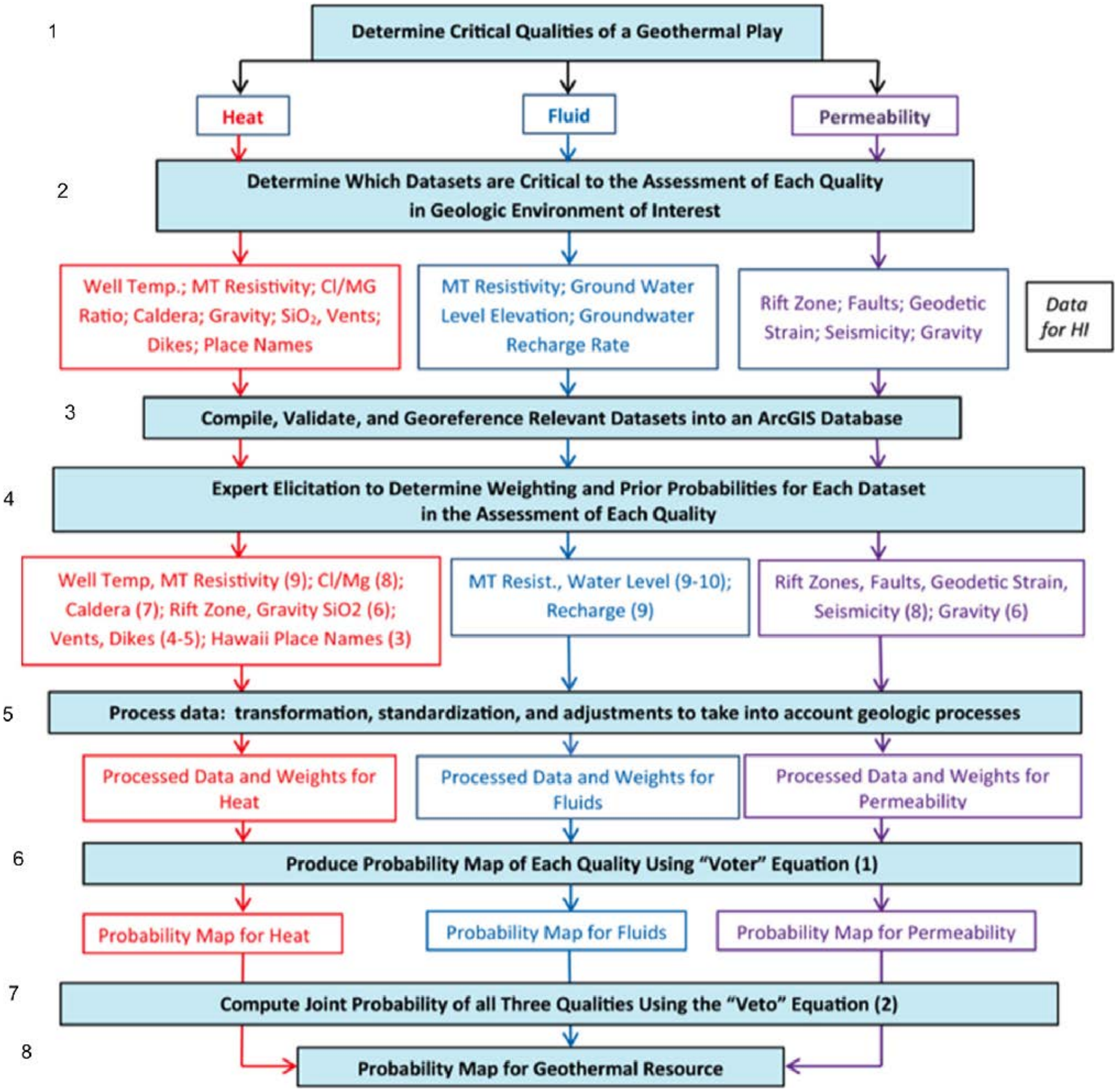
C.2 Appalachian Basin

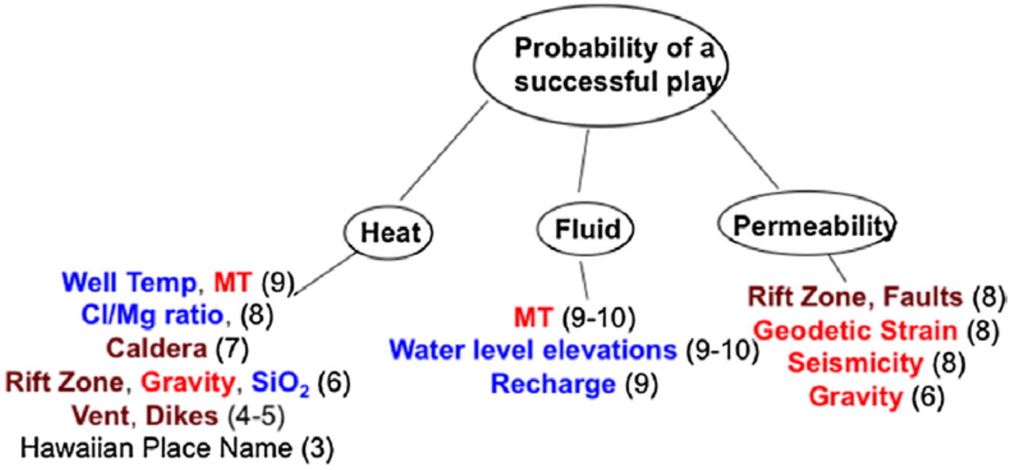


C.3 Cascades, Eastern Great Basin

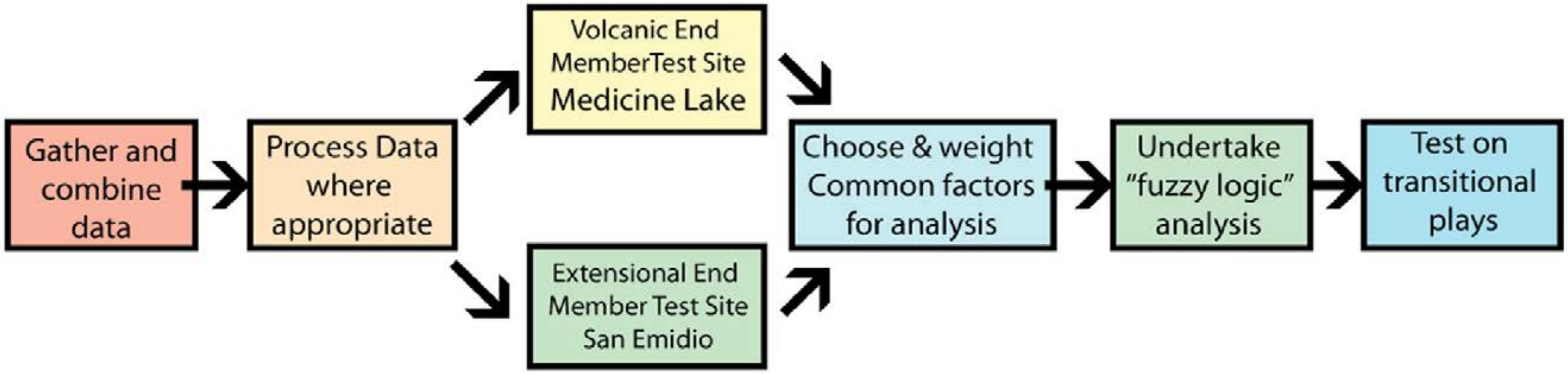


C.4 Hawaii

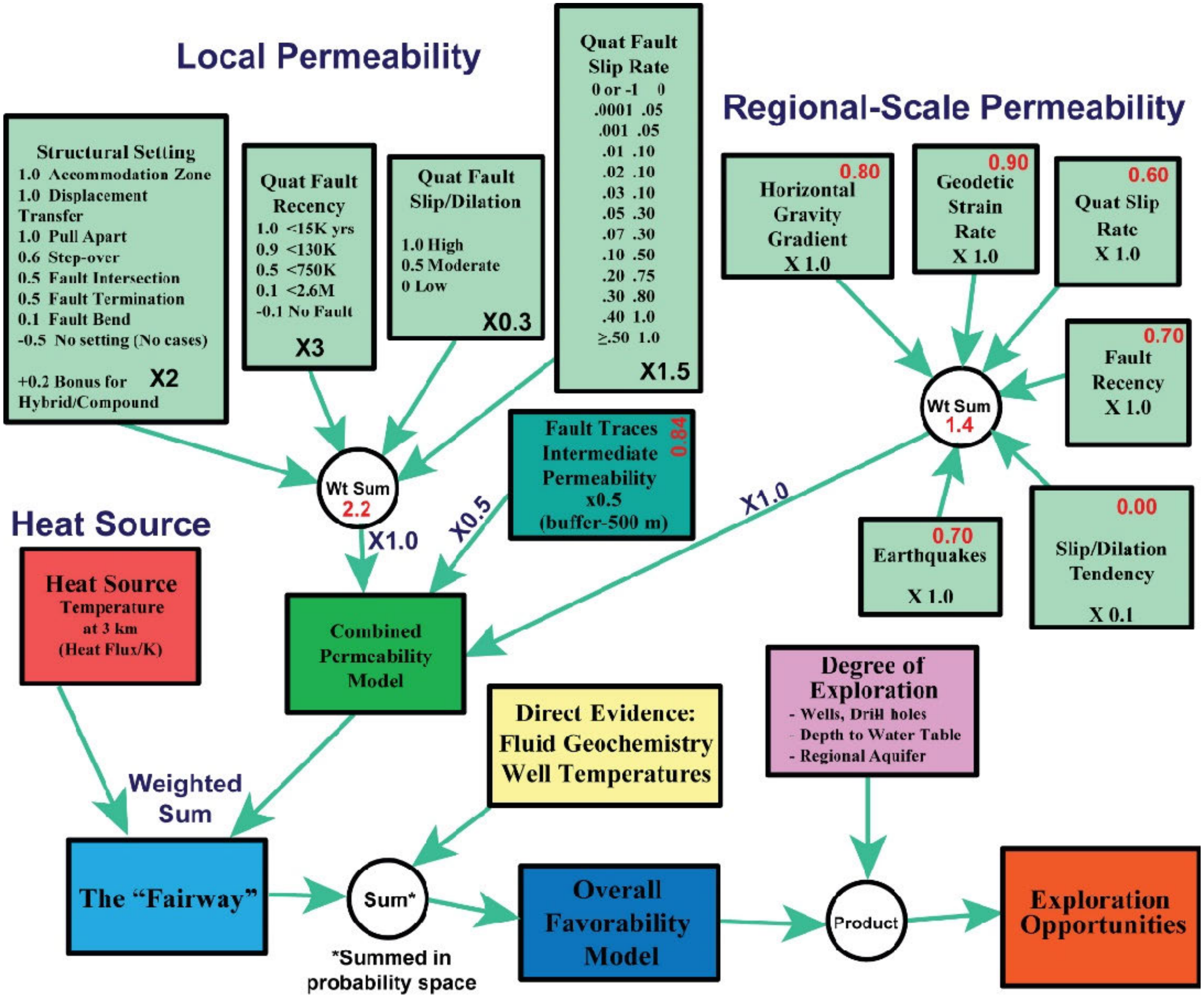

1
Determine Critical Qualities of a Geothermal Play
Heat
Fluid
Permeability
2
Determine Which Datasets are Critical to the Assessment of Each Quality in Geologic Environment of Interest
Well Temp.; MT Resistivity; Cl/MG Ratio; Caldera; Gravity; SiO₂, Vents; Dikes; Place Names
MT Resistivity; Ground Water Level Elevation; Groundwater Recharge Rate
Rift Zone; Faults; Geodetic Strain; Seismicity; Gravity
Data for HI
3
Compile, Validate, and Georeference Relevant Datasets into an ArcGIS Database
4
Expert Elicitation to Determine Weighting and Prior Probabilities for Each Dataset in the Assessment of Each Quality
Well Temp, MT Resistivity (9); Cl/Mg (8); Caldera (7); Rift Zone, Gravity SiO2 (6); Vents, Dikes (4-5); Hawaii Place Names (3)
MT Resist., Water Level (9-10); Recharge (9)
Rift Zones, Faults, Geodetic Strain, Seismicity (8); Gravity (6)
5
Process data: transformation, standardization, and adjustments to take into account geologic processes
Processed Data and Weights for Heat
Processed Data and Weights for Fluids
Processed Data and Weights for Permeability
6
Produce Probability Map of Each Quality Using "Voter" Equation (1)
Probability Map for Heat
Probability Map for Fluids
Probability Map for Permeability
7
Compute Joint Probability of all Three Qualities Using the "Veto" Equation (2)
8
Probability Map for Geothermal Resource


Probability of a successful play
Heat
Fluid
Permeability
Well Temp, MT (9)
Cl/Mg ratio, (8)
Caldera (7)
Rift Zone, Gravity, SiO₂ (6)
Vent, Dikes (4-5)
Hawaiian Place Name (3)
MT (9-10)
Water level elevations (9-10)
Recharge (9)
Rift Zone, Faults (8)
Geodetic Strain (8)
Seismicity (8)
Gravity (6)

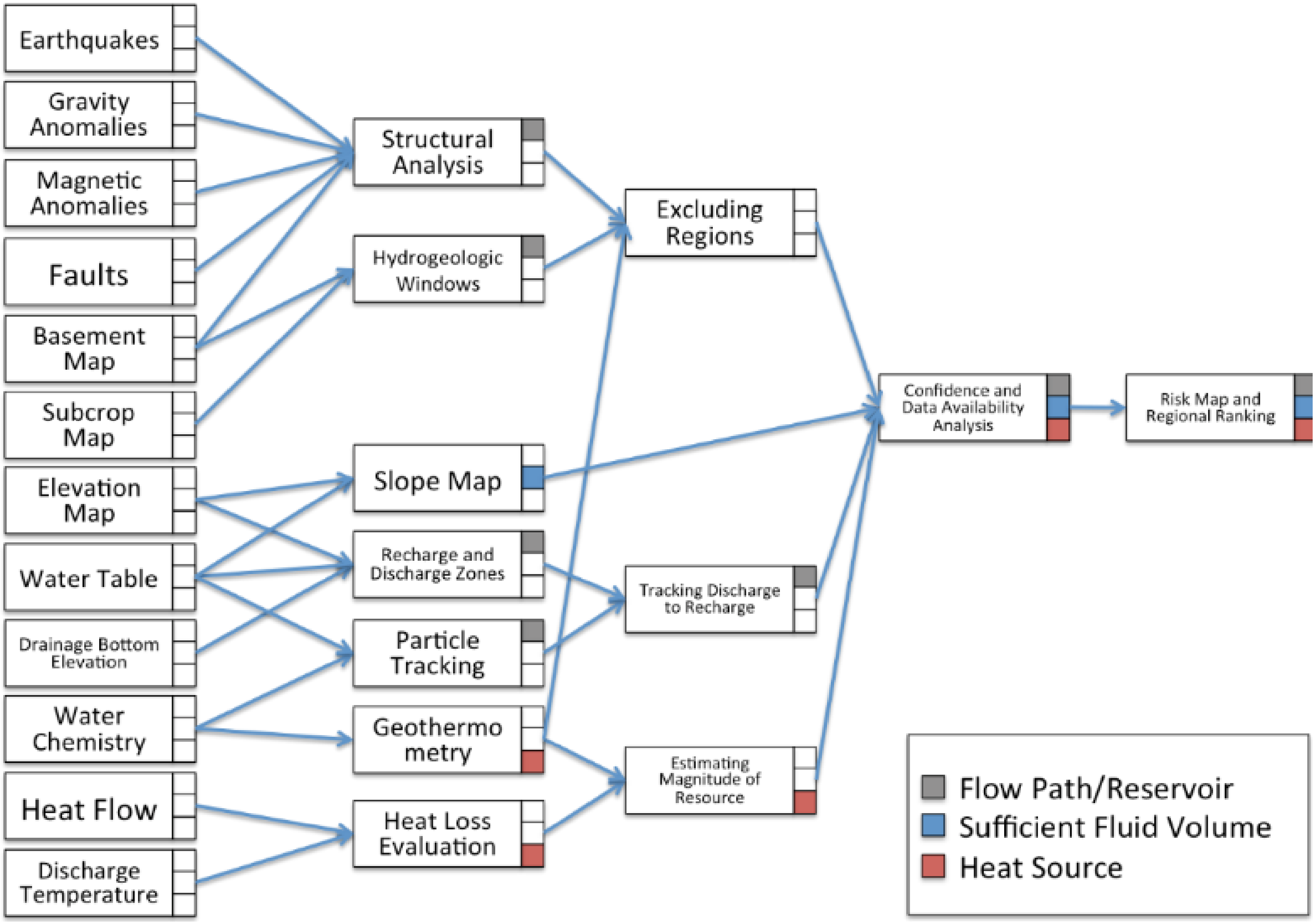
C.5 Modoc Plateau



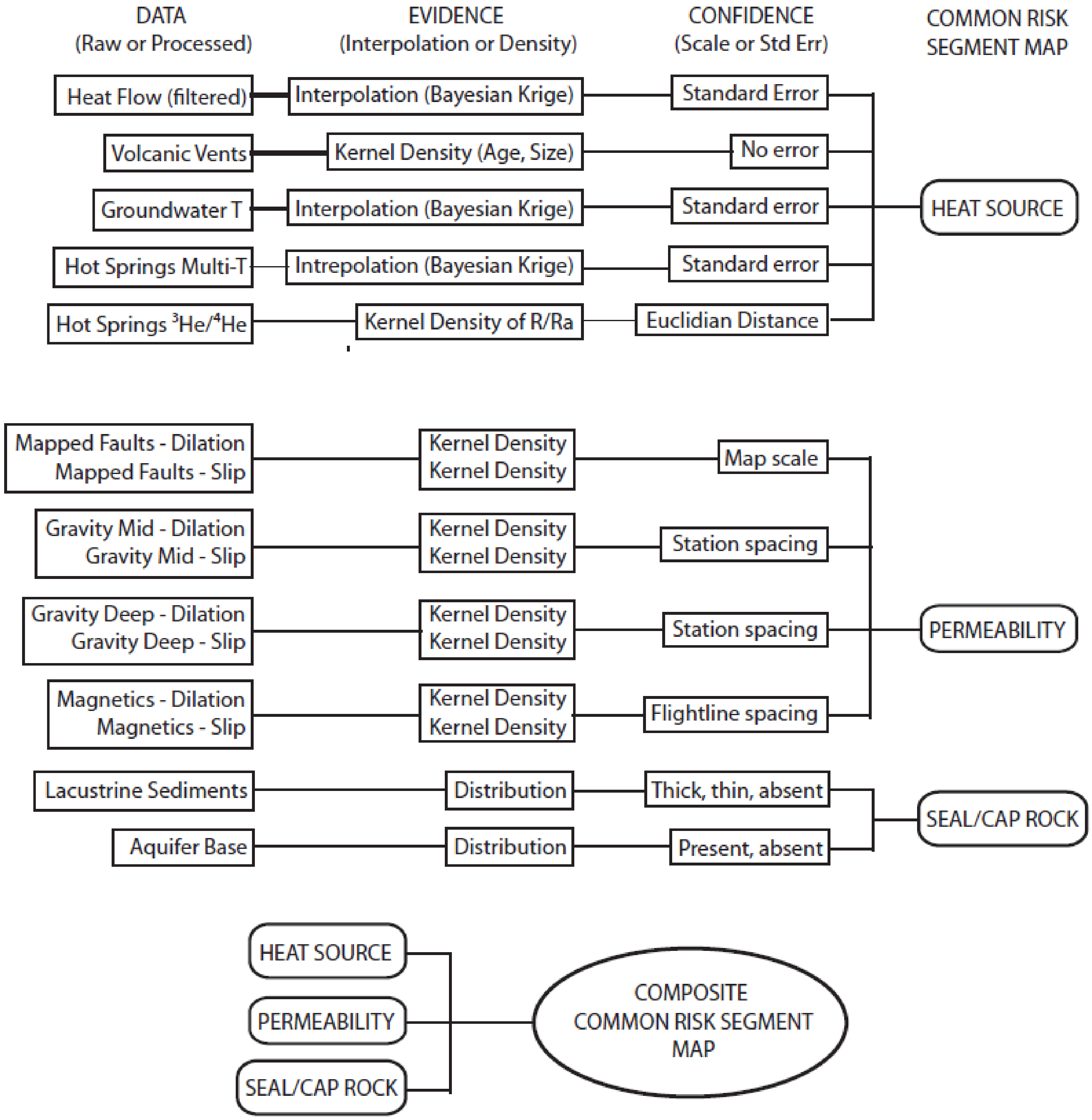
C.6 Nevada Great Basin



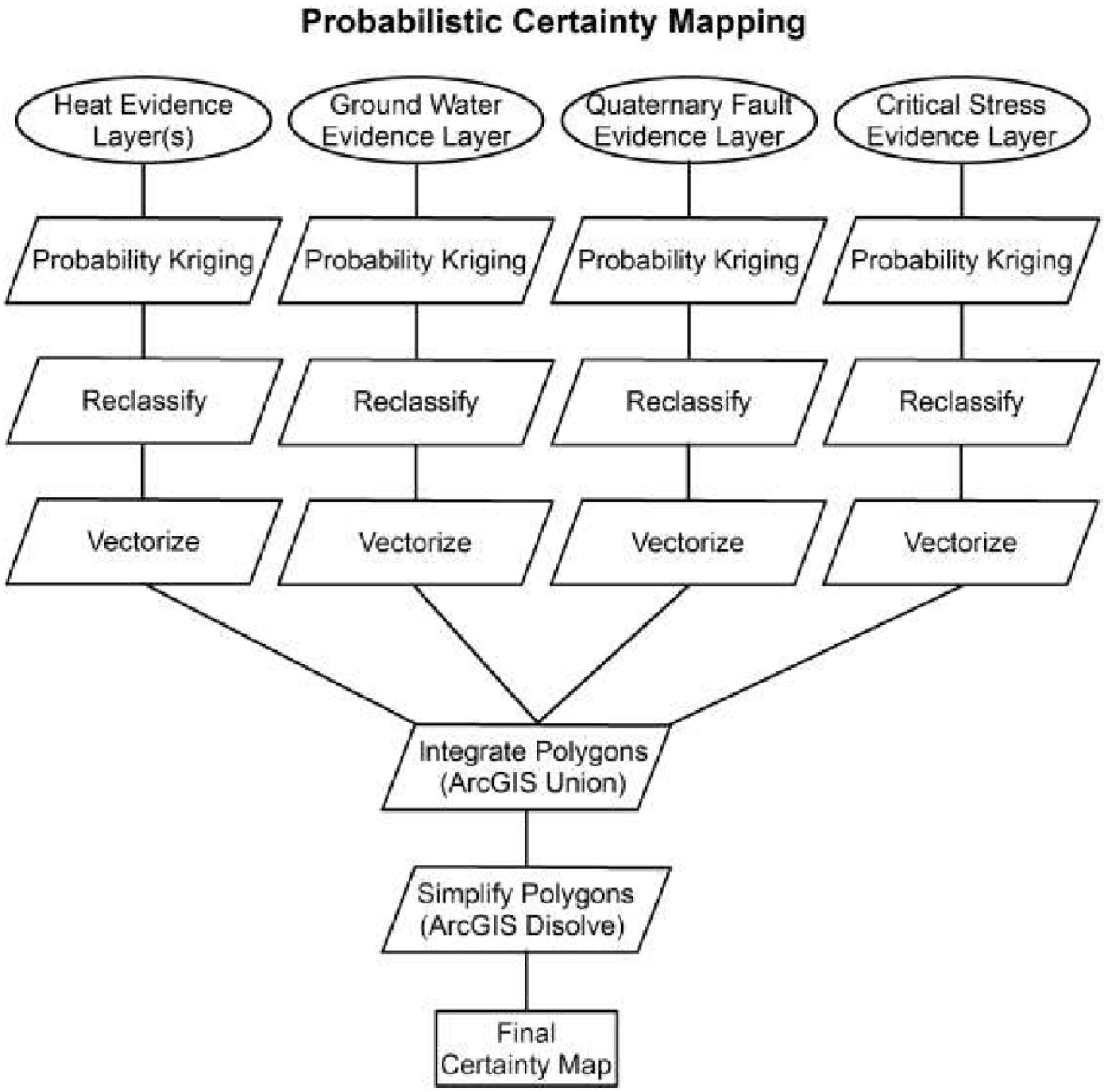
C.7 Rio Grande Rift



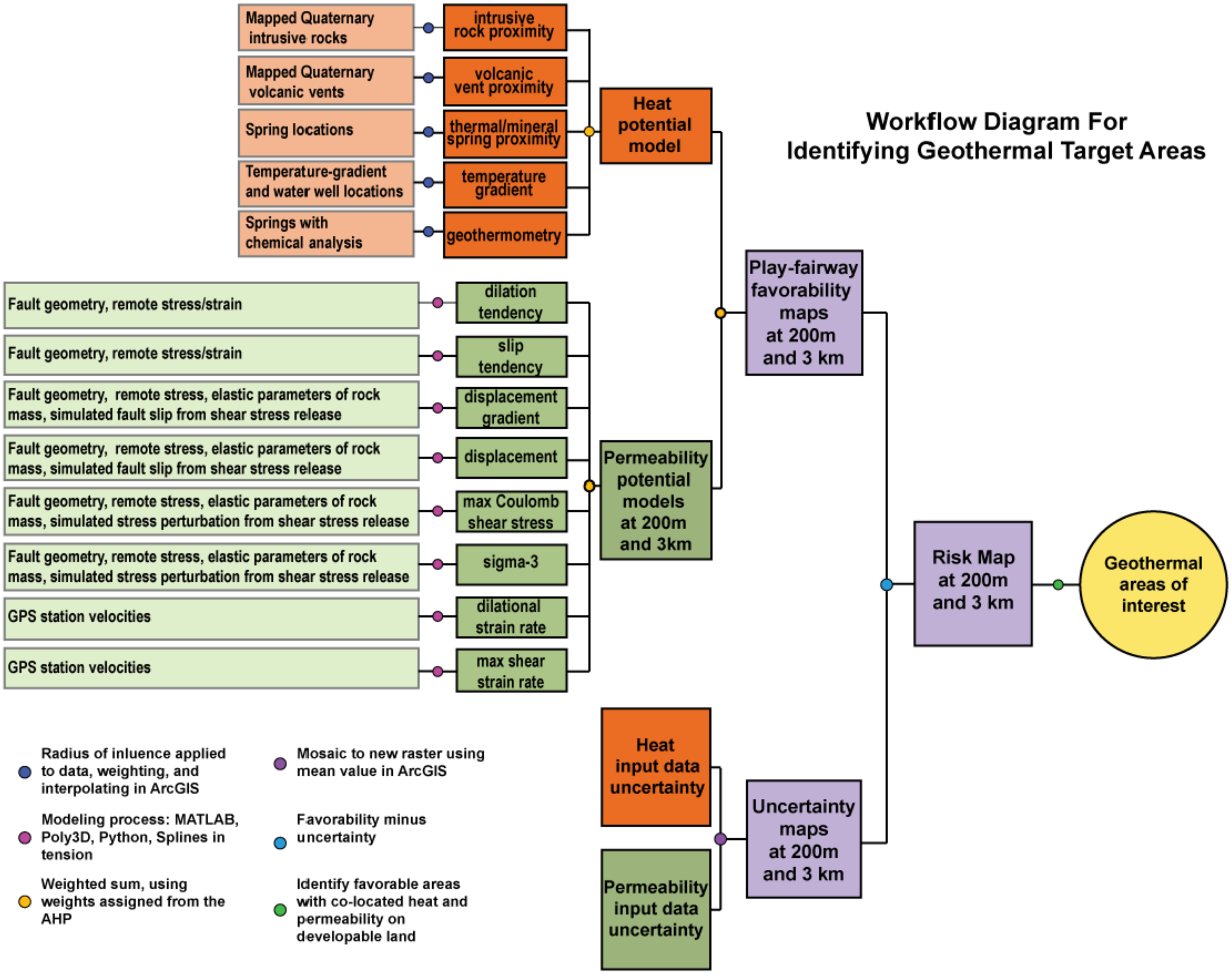
C.8 Snake River Plain



C.9 Tularosa Basin



C.10 Washington State



Workflow Diagram For Identifying Geothermal Target Areas