Low-Temperature Geothermal Resources: Relevant Data and PFA Methods to Reduce Development Risk

Preprint

Estefanny Davalos-Elizondo, Amanda Kolker,
and Nicole Taverna

National Renewable Energy Laboratory

Presented at the 2023 Geothermal Rising Conference
Reno, Nevada
October 1-5, 2023

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Conference Paper
NREL/CP-5700-86889
October 2023

Contract No. DE-AC36-08GO28308

Low-Temperature Geothermal Resources: Relevant Data and PFA Methods to Reduce Development Risk

Preprint

Estefanny Davalos-Elizondo, Amanda Kolker,
and Nicole Taverna

National Renewable Energy Laboratory

Suggested Citation
Davalos-Elizondo, Estefanny, Amanda Kolker, and Nicole Taverna. 2023. *Low-Temperature Geothermal Resources: Relevant Data and PFA Methods to Reduce Development Risk: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-86889. https://www.nrel.gov/docs/fy24osti/86889.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5700-86889
October 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Geothermal Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Low-Temperature Geothermal Resources: Relevant Data and PFA Methods to Reduce Development Risk

Estefanny Davalos-Elizondo[1], Amanda Kolker[1], and Nicole Taverna[1]

[1]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, 80401, USA

Keywords

Play Fairway Analysis, Favorability Maps, Low-Temperature, Geothermal Heating and Cooling,

ABSTRACT

This project is part of a larger national effort focused on demonstrating the multi-faceted value of integrating low-temperature geothermal resources into national decarbonization strategies and community energy plans. Low-temperature geothermal resources are defined as reservoirs—natural or engineered—with temperatures < 150°C. While the focus in the NREL effort is on geothermal heating and cooling (GHC), resources at the upper end of this temperature range can also be used for small-scale power generation. However, low-temperature geothermal resources have not been studied as extensively as higher-temperature geothermal resources.

We identified three major classes of low-temperature geothermal play types: sedimentary basins, orogenic systems, and radiogenic systems. We developed workflows for evaluating the potential of these resources building off the Play Fairway Analysis (PFA) approach to de-risking geothermal exploration. This PFA-based approach to low-temperature geothermal resources includes: (1) identifying relevant data; (2) grouping and weighting of relevant datasets into PFA criteria (e.g., geological, risk, economic criteria); (3) developing favorability or common risk maps for low-temperature geothermal resources to identify potential locations for more focused data collection; and (4) estimating electric power generation and heating potential at those locations using the GeoRePORT Resource Size Assessment Tool. This project will facilitate future deployment of GHC by providing data, tools, and workflows applicable to low-temperature geothermal resources.

1. Introduction

Geothermal resource types likely to have temperatures >150°C at exploitable depths are better defined and characterized than lower temperature resource types. This is likely because geothermal resources >150°C have the potential to generate electric power economically, whereas the use case for geothermal resources <150°C is primarily for heating and cooling, or in some exceptional cases, smaller-scale electricity generation. Recent interest in geothermal heating and cooling (GHC)—driven by decarbonization goals and the increased cost and geopolitical implications of natural gas reliance—has highlighted the need to improve our understanding of low-temperature geothermal resources. In addition, enhanced geothermal systems (EGS) and other emerging technologies for exploiting petrothermal resources (heat is stored in hot dry rocks) have created the possibility of utilizing deep sedimentary basin systems for heat and power (Doughty et al., 2018). Through the application of EGS and advanced geothermal systems technologies, non-commercial reservoir conditions might be improved in the future for power generation (e.g., Denver Basin).

This paper focuses on improving the classification and typologies for geothermal resource types likely to supply heating and cooling through direct use. We do not address shallow subsurface conditions applicable to geothermal heat pump technology. This study suggests a classification approach that will allow better characterization of low-temperature geothermal play types (GPT). We discuss three classifications for low-temperature GPT: sedimentary basins, orogenic belts, and radiogenic play types.

Based on literature review of these geothermal plays, we identify relevant data to characterize each of the three GPT's. Lastly, we build off the PFA approach to de-risking geothermal exploration by developing custom workflows and data sources for each of the three GPT's. These workflows can be used to develop favorability maps for geothermal resources < 150°C, but it is important to note that PFA favorability maps should not be used for targeting geothermal wells directly. Rather, they should be used to identify prospective areas that would warrant more detailed investigations (Pauling et al., 2023).

2. Low-Temperature GPT

Geothermal systems have been classified in a variety of ways. In 2008, the U.S. Geological Survey (USGS) assessed the electric power generation potential of conventional geothermal resources in the United States, distinguishing between high-temperature (more than 150°C) and moderate-temperature (90 to 150°C; 194 to 302°F) geothermal technologies. Most publications (including Rybach, 1981; Nicholson, 1993; Moeck, 2014) make a distinction between "convective" and "conductive/static" types. The thermal regime of static or conductive type systems, which typically occur in low permeability environments such as deep aquifers or sedimentary basins, is only caused by conduction.

A geothermal play type can further be defined based on its tectonic and geological setting and can be classified by common characteristics shared by a play group (Moeck, 2014). Unlike higher-enthalpy GPT's, low-temperature GPT's are often conduction-dominated. Conduction-dominated systems host low- to-medium enthalpy resources because of the lack of faster convective fluid flow processes and related temporary fluid dynamics (Moeck, 2014). Conduction-dominated plays mainly occur in passive continental margins and intracontinental tectonically inactive areas and can be categorized into hydrothermal and petrothermal types (Moeck, 2014). The economic feasibility of conduction-dominated play types is linked to the local geothermal gradient or where overlying lithologies are thermally insulating (Beardsmore and Cull, 2001).

Moeck (2014) suggested a classification system of conduction-dominated GPT that includes "intracratonic basin" type, "orogenic basin" type, and "basement" type. In this study of low-temperature GPT, we use some principles from this classification. Our main departures from the Moeck classifications are as follows: (1) we reconsider "intracratonic basin" type resources as sedimentary basin resources, and expand this GPT beyond intracratonic settings, to include pericratonic, intercratonic, and oceanic basins as well; (2) we reconsider "basement" type resources as "radiogenic" resources and expand that GPT beyond Moeck's definition of these as petrothermal resources only. “Basement” and “radiogenic” GPT systems are poorly understood. Their existence is often explained simply by “deep circulation” of meteoric water along faults and fractures. While structures such as faults and fractures commonly control the upwelling of Radiogenic Geothermal Play Types (RGPTs), ‘deep circulation’ GPTs as exemplified by geothermal systems in Basin and Range are quite different with respect to heat source, tectonic setting, geologic features, and fluid chemical characteristics Kolker,2008).

2.1 Sedimentary Basin Geothermal Play Types (SBGPT)

To classify SBGPT, we used the classification suggested by Coleman and Cahan (2012) based on a simple geological setting scheme (see Table 1): (1) intracratonic basins are those created within the boundaries of a craton; (2) pericratonic, basins formed near or accreted to the margins of the craton; (3) intercratonic basins are those formed between cratons and extending onto oceanic crust; and (4) oceanic basins are those that developed independently of cratons, primarily on oceanic crust..

Table 1. Basin type classifications by Coleman and Cahan (2012) and GPT classifications by Moeck (2014).

Setting	**Basin type**	**Definition**	**Play Type by Moeck (2014)**	**Examples**
Intracratonic	Rift basins	Rifts formed within continental, resulting in a normal-faulting bounded basin	Convection- and/or conduction-dominated	Rio Grande Rift
	Transtensional basins	Basins with a substantial amount of strike-slip but net extensional.	Convection- and/or conduction dominated	Great Basin in the Basin and Range Province
	Aulacogens	Rift basins formed as the failed arm of a triple junction	Conduction-dominated	Anadarko Basin
	Sag basins	Basins formed in continental masses because of asthenospheric downwelling or isostatic equilibrium	Conduction-dominated	Michigan and Williston Basins
Pericratonic	Rift basins (proto-oceanic rifting)	Basins created between margins of continents leading the opening of an oceanic basin	Convection- and/or conduction-dominated	Nuwuk-Dinkum-Kaktovik Basin, Alaska
	Passive margin basins (including deltaic basins)	Basins developed over continental and transitional oceanic crust	Conduction-dominated	Gulf of Mexico and West Atlantic Basins
	Foreland basins and thrust belts	Basins formed adjacent to orogenic thrust belts and fault-bounded uplifts	Conduction-dominated	Appalachian and Mesozoic Rocky Mountain Basins
	Borderland basins	Basins created along the margins of a continent because of transtensional and transpressional faulting linked with oblique collision of tectonic plates	Convection- and/or conduction-dominated	California borderland, Santa Maria, and Los Angeles Basins
	Transtensional/ transpressional basins	Basins formed at the margins of continents, usually between plate boundaries	Convection- and/or conduction-dominated	Great Smoky Mountains Rift Basin

Setting	Basin type	Definition	Play Type by Moeck (2014)	Examples
Intercratonic	Passive margin basins (extending onto oceanic crust)	Basins developed between cratonic masses and extended onto transitional and oceanic crust	Conduction-dominated	Canada Basin
	Accreted back-arc basins	Basins formed because of trench roll-back beneath the landward side of a volcanic chain in a subduction zone	Conduction-dominated	Bristol Bay Basin in Alaska
	Accreted fore-arc basins	Basins developed in oceanic crust between the subduction zone and a related volcanic arc because of growth of an accretionary prism.	Conduction-dominated	Great Valley of California and Cook Inlet Basin of Alaska
Oceanic	Back-arc basins	Basins created on oceanic crust due to trench roll-back underneath the landward side of a volcanic chain (from the other side of the subduction zone)	Convective- and/or Conduction-dominated	Aleutian Basin in Alaska
	Fore-arc Basins	Basins formed on oceanic crust among the subduction zone and a related volcanic arc because of development and growth of an accretionary prism	Convection- and/or conduction-dominated	Western Washington-Oregon Basin

In the United States most of the basins currently located in the intracratonic part of the continent (blue in Fig. 1) show low temperature gradients (Fig. 2) and are thus expected to be conduction-dominated regardless of the classification of the basin.

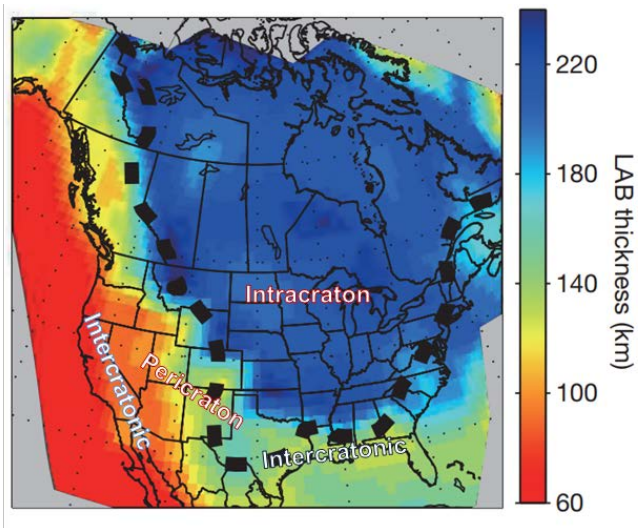

Fig. 1. Present lithospheric-asthenospheric boundary (LAB) thickness of North American continent from Yuan and Romanowicz (2010). A thick black dashed line indicates the borders of the craton.

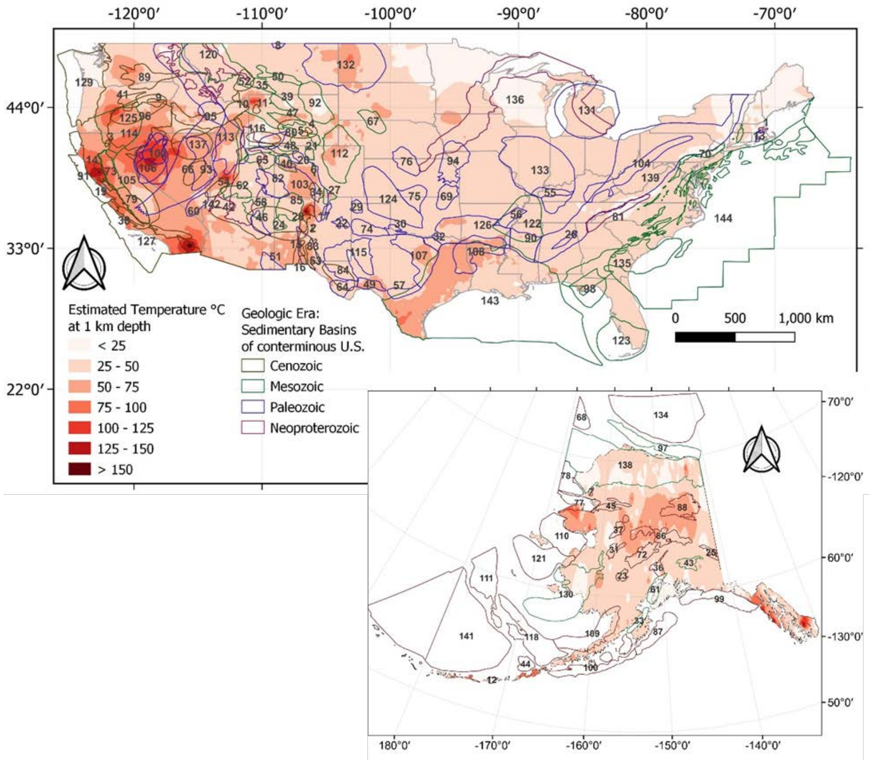

Fig. 2. The surface of sedimentary basins in the conterminous United States and Alaska by Coleman and Cahan (2012) overlapping the estimated temperature °C at 1 km map modified after Blackwell et al. (2011) and estimated temperature (°C) at 1 km map of Alaska modified after Batir et al. (2016).

2.2 Orogenic Belt Geothermal Play Types (OBGPT)

OBGPT can be divided into two different reservoir classifications: (1) a geothermal reservoir within an orogenic mountain belt (Fig. 3); and (2) sedimentary reservoirs within foreland basins adjacent to orogenic mountain belts (see Table 1). Due to obvious overlap between classification (2) and the sedimentary basins classifications presented above, this section focuses on classification (1).

OBGPT are rarely linked to large-scale hydrothermal systems but are instead the result of focalized deep circulation systems related to major deep fault in the crust (Moeck, 2014). The background geothermal gradient in OBGPT can be relatively low beneath high mountains (sometimes 15°–20°C/km compared to the continental average of 25-30°C/km) and increase beneath a foreland basin by about 30°–50°C/km (e.g., Hervey et al., 2014). The bulk-rock permeability of the host rock plays a major role in the creation of geothermal plays in mountain ranges. Particularly in locations of high topography, the permeability allows the meteoric water to infiltrate deeper. Active faults act as pathways of fluids that reach discharge spring areas (Moeck, 2014). The discharge of most of the meteoric water recharged in the mountains occurs in the valley (Fig. 3).

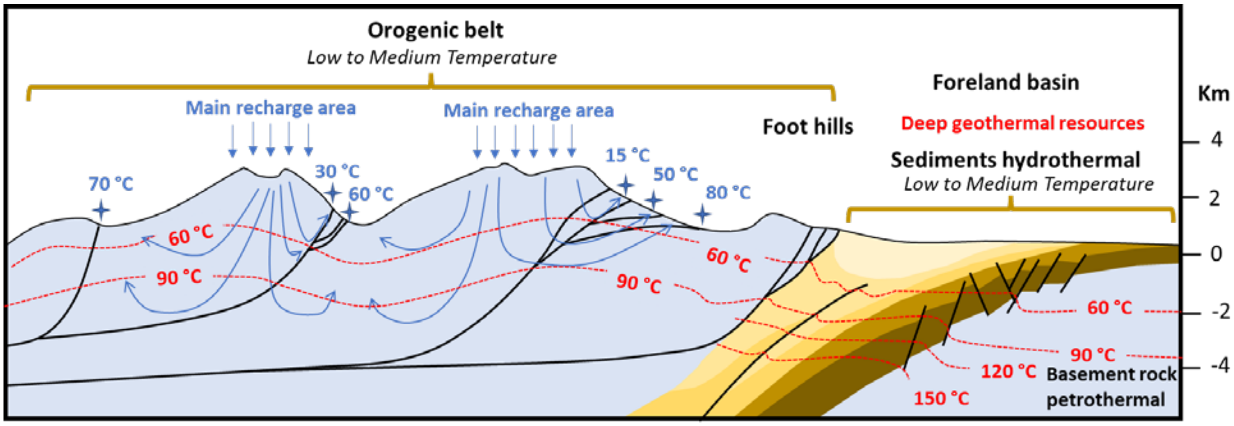

Fig. 3. OBGPT and related foreland basin. Modified from Moeck (2014).

2.3 *Radiogenic Geothermal Play Types (RGPT)*

RGPT's form in settings where the regional geothermal gradient is elevated due to higher concentrations of radioelements in crustal rocks, causing localized radiogenic heating. Radioactive heat production comes from the decay of long-half-life radioactive isotopes, such as K^{40}, U^{235}, U^{238}, and Th^{232}. The primary source of radioactive elements U, Th and K in earth's crust are felsic igneous rocks. High-grade metamorphism, metasomatism, partial melting, and fluid and melt migration are some of the processes that can transport ^{238}U, ^{232}Th, and ^{40}K to the middle and upper crustal levels (Taylor and McLennan, 1986).

Convective type hot springs systems occur in locations of higher natural radioactivity (see Hamza et al., 2005; Beitollahi et al., 2005; Brugger et al., 2005; Baranwal et al., 2006). Few studies, however, have found and described GPT's that are heated by radioactivity. This may be due to the recently feasible economic extraction of low-enthalpy fluids associated with radiogenic heat sources, as well as the rarity of active radiogenic hydrothermal systems in nature. Fossil hydrothermal activity has been observed in high heat-producing (HHP) granites, and it is possible that this activity was cyclical and rather short-term (Kolker, 2008).

We propose in this study that a RGPT is controlled by the presence of HHP rocks (such as granitoids) containing anomalous concentrations of radioelements that locally elevate the heat flow and the geothermal regime of the upper crust (McLaren et al., 2006; McLaren and Powell, 2014; Zhou et al., 2020). We further classify RGPT into three subgroups based on studied RGPT systems in particular locations (Fig. 4): (1) non-buried or exhumed HHP plutons (e.g., Chena, Alaska; Sierra de Cordoba, Argentina); (2) buried HHP plutons in sedimentary basins (e.g., Western Canada basin; Cooper Basin, Australia); and (3) sediments with high concentrations of radioactive elements eroded from HHP plutons (e.g., Karoo basins, Africa).

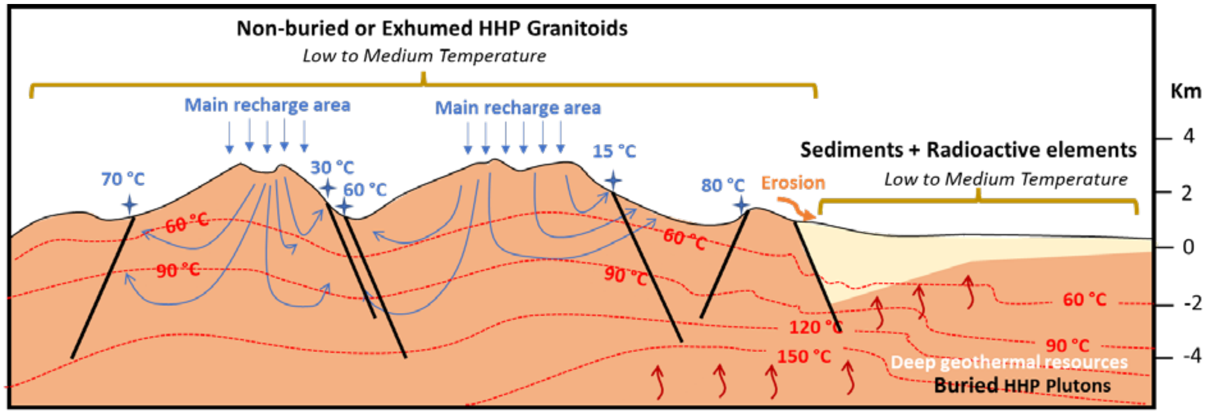

Fig. 4. RGPT and elated sedimentary basin. Three different RGPT: (1) Non-Buried or Exhumed HHP granitoids, (2) buried HHP plutons with a thermal insulation from sediments, and (3) sediment with high concentrations of radioactive elements eroded from nearly HHP plutons.

3. Data and Methods for Assessment of Low-Temperature GPT.

PFA methodologies were adopted in the geothermal industry from the oil and gas industry to de-risk exploration for hidden or blind subsurface resources (Pauling et al., 2023). The PFA technique defines localized areas that have high potential for hosting geothermal plays and eliminates large areas that have a higher potential for failure to reduce risk during the resource locating process.

The identification of potential areas for geothermal power and direct use is a geospatial multi-criteria decision problem (Greene et al., 2011). Based on literature review we suggest three essential criteria/risks for evaluation of low-temperature resources: **(1) geologic, (2) risk, and (3) economic criteria** (Fig. 5).

For the geologic criteria PFA for hydrothermal geothermal systems exploration involves identifying four or more “critical components”:

1. Heat (H)
2. Accessible fluids (F)
3. Permeability/porosity (P)
4. Caprock or seal (S)

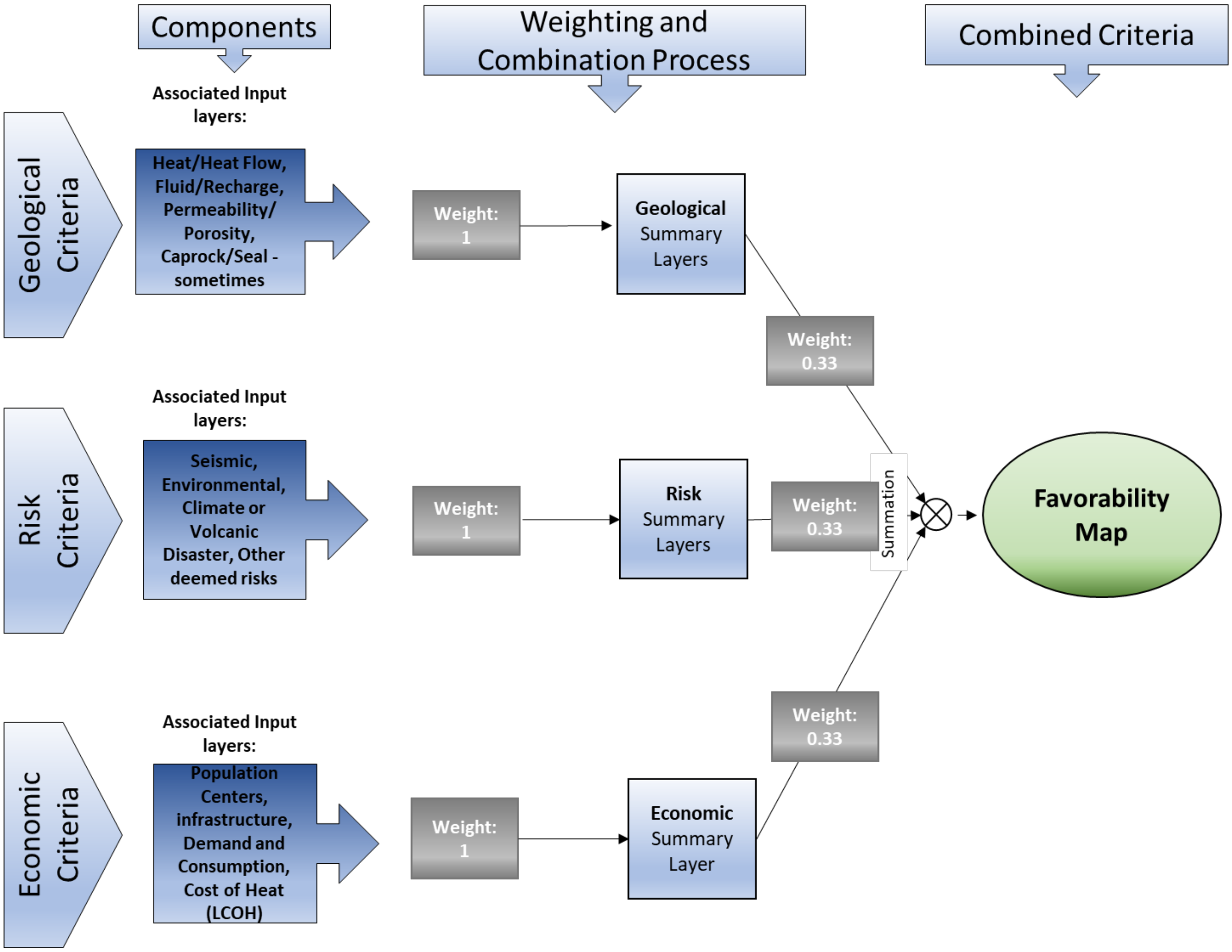

Fig. 5. Flowchart of mapping geothermal favorability. Geological, risk, and economic criteria are represented by input layers which can consist of several datasets.

3.1 Relevant Data and PFA Methods for SBGPT

The SBGPT relevant input data and methodologies (Fig. 6) are based on several various studies (i.e., Jordan et al., 2016; Palmer-Wilson et al., 2018; Williams and DeAngelo, 2008; and Mordensky et al., 2023). The key geologic controls are summarized in Table 2.

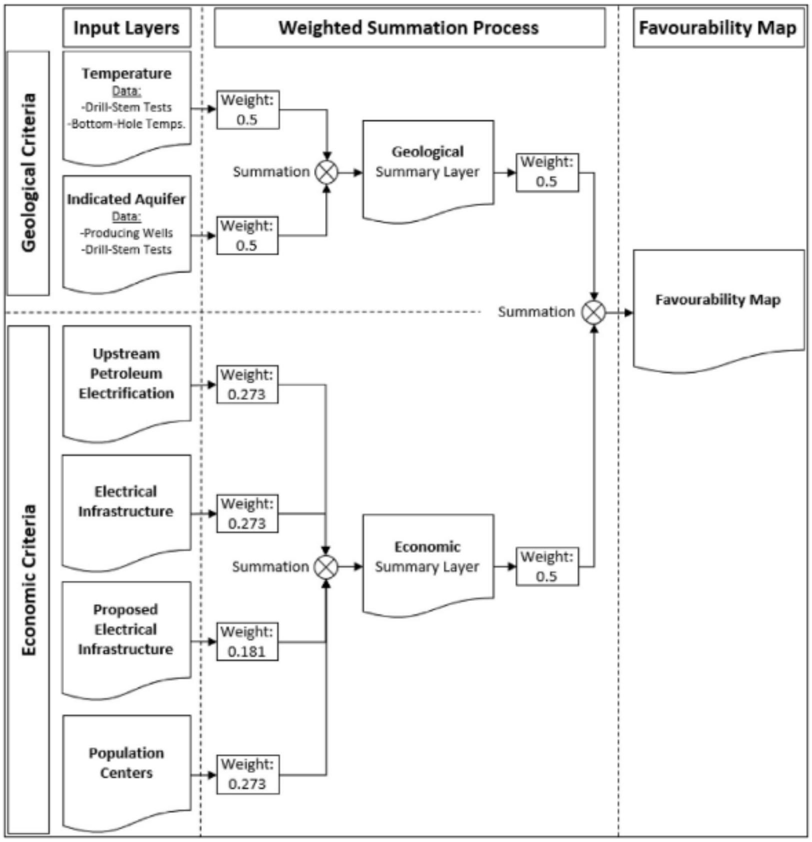

Fig. 6. Example PFA flowchart for determining SBGPT favorability, for geothermal systems in western Canadian sedimentary basin (Palmer-Wilson et al., 2018).

Table 2. Geothermal key controls of sedimentary basins.

Geological & tectonic settings			
Geothermal key controls	***Formation & evolution***	***Present time***	***Related PFA "critical component"***
Heat flow		**x**	**H**
Lithology/ stratigraphy	**x**		**H, F, P, S**
Fluid chemistry	**x**		**F, S**
Fluid dynamics		**x**	**F, S**
Basin geometry	**x**	**x**	**P**
Faults and fractures	**x**	**x**	**P**

Geological & tectonic settings			
Geothermal key controls	***Formation & evolution***	***Present time***	***Related PFA "critical component"***
Stress state		**x**	**P**
Permeability/porosity	**x**	**x**	**P**

Geological Criteria

The purpose of geological datasets is to evaluate the thermal regime and the distribution of potential natural reservoirs and properties, relevant to sedimentary geothermal viability.

Heat (H) Input Data:

1) Oil and gas bottom-hole temperature measurements (BHT) are abundant in sedimentary basins. BHTs should be corrected with equilibrium temperature logs (ETLs) appropriate for each basin (e.g., Harrison correction) to account for the cooling effect of drilling mud.

   Conterminous U.S. and Alaska BHT data (< 150°C) can be accessed via:

   (a) The American Association of Petroleum Geologists (AASG) U.S. dataset provides **BHT recorded** from log headers, and other information such as well logs, temperature measurements, etc. This dataset originated for the EGS Site Planning and Analysis project (Augustine, 2013). The dataset can be downloaded from the Geothermal Data Repository (GDR) at https://gdr.openei.org/submissions/252.

   (b) The Southern Methodist University (SMU) dataset consists of **corrected BHT data** from U.S. oil and gas wells including Alaska and Hawaii. Additionally, this dataset includes valuable information such as temperature gradient from the surface to the BHT depth (°C/km), thermal conductivity, and heat flow values (mW/m^2), and ETLs if available for the basin. The BHT datasets can be downloaded from http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm.

2) **Thermal conductivity** is based on a stratigraphic model for each basin. The thermal conductivity baseline datasets of the conterminous United States. and Alaska could be compiled for onshore sedimentary basins and include thermal conductivity values derived from lithological models from Correlation of Stratigraphic Units of North America (COSUNA). Thermal conductivity values derived from stratigraphic models have an expected error of 10%, while thermal conductivity measurements of rock samples have errors below 5% (Gallardo and Blackwell, 1999). This dataset can be downloaded from http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm

3) **Heat flow datasets** may be available in the region. The most recent heat flow map for Alaska and the conterminous United States- were updated by Batir et al. (2016) and Blackwell and Richards (2006), respectively. The dataset is available at the SMU repository at http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm

Accessible Fluid (F) Input Data:

1) Isolated hydrothermal systems of low temperature (<150°C) in the conterminous United States and Alaska can be identified from three different datasets:

   a) Berry et al. (1980) conducted an early compilation of **thermal springs** lists for the United States by the National Oceanic and Atmospheric Administration (NOAA). The report is available at https://www.ngdc.noaa.gov/hazard/data/publications/Kgrd-12.pdf.
   b) Mullane et al. (2016) compiled datasets from three USGS primary sources: Muffler (1979), Reed et al. (1982), and William et al. (2008). This database is available on the GDR: https://gdr.openei.org/submissions/842.
   c) Motyka et al. (1983) compiled and interpreted **hot springs** datasets for Alaska (108 hot springs and 3 wells) to inform the first Geothermal Resources of Alaska map by the Department of Natural Resources Geological and Geophysical Survey. The geothermal resource shapefile of the hot springs in Alaska is available to download at https://dggs.alaska.gov/pubs/pubs?reqtype=citation&ID=671.

2) Water production data from oil and gas wells can be used as a proxy for permeability, which is a key factor in resource assessment of natural geothermal reservoirs. Water production data provides information about the natural reservoir quality of rocks (i.e., their ability to maintain sufficient fluid flow rates between injection and production wells to mine heat from reservoir rocks).

   The baseline database of water production from oil and gas wells in the conterminous United States and Alaska identified by this study are:

   (a) U.S. Geological Survey (USGS) database of aggregated oil and natural gas drilling and **production history** of the United States. The USGS dataset provides an overview of the production history of all U.S. wells from 1817 to 2020. The USGS database was built from data compiled by IHS Markit, a commercial database. The production data is aggregated in 2- to 10-square-mile-increments that sum the total production of oil, gas, and water volumes. This data is expected to be released by USGS.

   (b) Alaska Oil and Gas Conservation Commission **produced water** data. The AOGCC is a public dataset that provides daily updates of oil and gas well history, production, and injection. The datasets consist of pre-2000 and post-2000 water volume production per well. It is available from: https://www.commerce.alaska.gov/web/aogcc/Data.aspx.

Caprock and Seal (S) Input Data:

3) Basin lithology–Stratigraphic column and reservoir properties could be obtained from published literature from a specific basin. When that is not available, seismic reflection and other geophysical methods can be used to determine basin stratigraphy.

   a) USGS released a **generalized lithology** for the conterminous United States. The data contains generalized lithology classes (rock types) as reassigned from the USGS state geologic map compilation for the conterminous United States (Schweitzer, 2011). Lithology was classified into 12 categories. Data is available at: https://www.sciencebase.gov/catalog/item/598b471de4b09fa1cb0eacfd

Permeability/Porosity (P) Input Data:

(a) Available **porosity and permeability** data can be identified from the USGS Open-File Report (Nelson and Kibler, 2003). This report records data from 70 datasets that include a total of 49 basins globally. The information can be obtained by searching the USGS Core Research Center catalog: http://my.usgs.gov/crcwc/.

(b) Quaternary fault slip-dilation tendency analysis identifies local permeability mostly in fault controlled geothermal systems. The datasets used for this analysis could be the same for identifying risk criteria below.

Risk Criteria

The purpose of the risk datasets is to evaluate seismicity as a risk factor and pinpoint areas that have a high chance of triggering seismic activity during reservoir construction or during geothermal heat production and utilization.

1) The USGS maintains the most complete database of global and national **earthquakes**: https://earthquake.usgs.gov/earthquakes/search/. Another earthquake catalog for Alaska is available at the Alaska Earthquake Center website: https://earthquake.alaska.edu/earthquakes.

2) Information about current **stress fields** (orientation and magnitudes) is key in understanding the susceptibility of faults to slip and/or dilation. The orientation and relative magnitudes of tectonic stresses in the conterminous United States, Alaska, and Hawaii can be derived from the World Stress Map Project (WSM; Heidbach et al., 2016). The WSM is a global compilation of crustal stress field magnitudes and directions maintained since 2009 at the Helmholtz Centre Potsdam German Research Centre for Geosciences. The WSM is an open-access public database: https://www.world-stress-map.org/download.

3) **Quaternary faults.** The USGS Quaternary fold and faults database (Machette et al., 2003) can be evaluated to determine relationships between active deformation in the upper crust

and location of geothermal systems, as well as seismic risk during exploitation and utilization of geothermal resources. Data on Quaternary faults can be downloaded from: https://www.usgs.gov/programs/earthquake-hazards/faults

Economic Criteria

Economic input data relevant to sedimentary geothermal viability include potential locations for commercial power sales or offtakes of heat for direct use, (e.g., regions with electrical infrastructure and population centers). Utilization viability input layers help identify regions with the capacity to utilize low-grade geothermal heat and estimated Levelized Cost of Heat (LCOH) for a set of communities.

1) **Roads and electrical infrastructure**. The roads dataset could be downloaded as a shapefile from the Topologically Integrated Geographic Encoding and Referencing dataset: https://tigerweb.geo.census.gov/tigerwebmain/TIGERweb_nation_based_files.html

2) Building **heat demand** and **energy consumption**. Thermal demand in the residential, commercial, and manufacturing sectors was updated by Oh and Beckers (2023) using the Energy Information Agency (EIA) end-use energy consumption and expenditure survey data. The energy consumption data can also be obtained from EIA power consumption data, available from: https://www.eia.gov/outlooks/aeo/tables_ref.php and http://www.eia.gov/consumption/manufacturing/.

3) **LCOH**. The cost estimates include pipes, pumps, and heat exchanger, and the annual demand expectations rely on place-specific climate conditions. **LCOH** can be calculated using the open-source GEOPHIRES tool (Beckers et al., 2014) which simulates techno-economic scenarios for geothermal direct use. The software can be found at: https://github.com/NREL/GEOPHIRES-v2.

4) **Population Centers** datasets can be obtained from U.S. Census Bureau population data that includes state, county, and place. A place is used to identify specific cities, towns, villages universities or any Census-Designated Places. This data is available from: https://data.census.gov/table?q=number+of+housing+units+by+county&tid=DECENNIALPL2020.H1.

3.2 Relevant Data and PFA Methods for OBGPT

The relevant input data and methodologies (Fig. 7) are based on different studies in OBGPT (e.g., Moeck, 2014; Wang et al., 2021) and the key controls are summarized in Table 3.

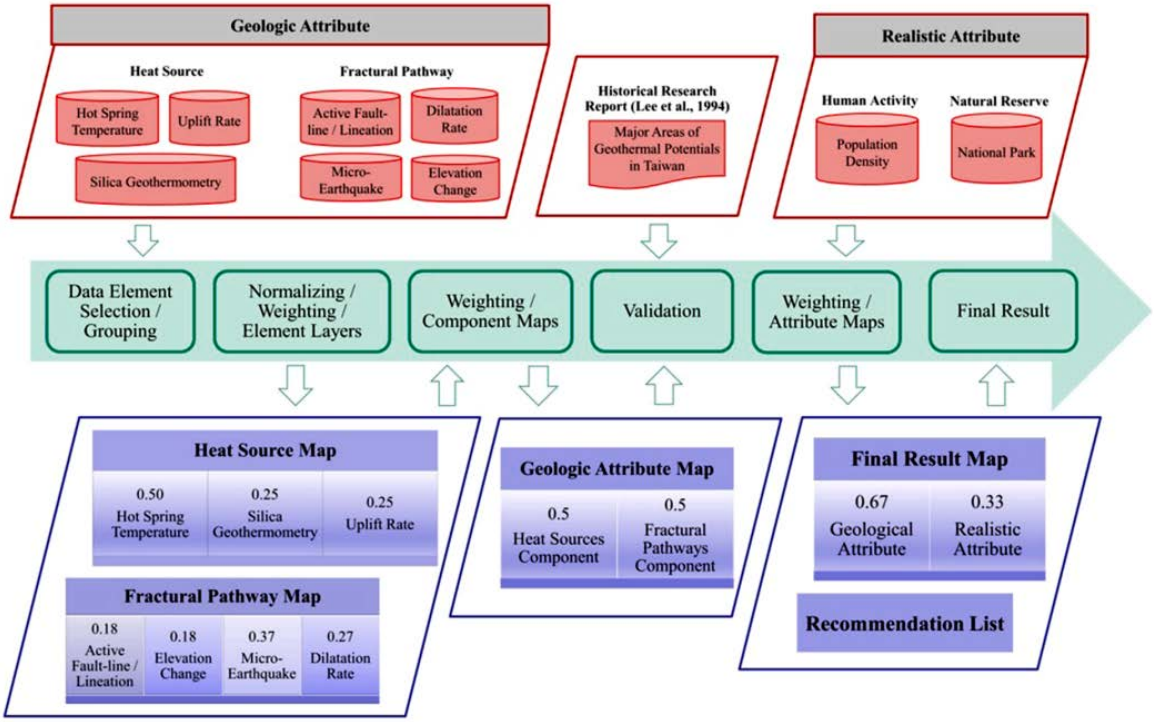

Fig.7. Example PFA flowchart for determining OBGPT favorability, for geothermal systems in Taiwan (Wang et al., 2021).

Table 3. Geothermal key controls of OBGPT.

Geological & tectonic settings			
Geothermal key controls	***Formation & evolution***	***Present time***	***Related PFA: critical component***
Heat flow		**x**	**H**
Fluid chemistry	**x**		**F, S**
Fluid dynamics		**x**	**F**
Faults and fractures	**x**	**x**	**P**
Stress state		**x**	**P**

Geological Criteria

Heat (H) Input Data:

1) The geothermal potential of each region is highly dependent on the heat discharge values related to the Earth's heat flow. Heat flow maps are extremely useful for identifying areas of high geothermal potential in a particular region or country (Blackwell et al., 2006).

    a) **Heat flow** datasets if available in the region. The most recent heat flow map for the conterminous United States and Alaska was updated by Blackwell and Richards (2006) and Batir et al. (2016), respectively. The dataset is available at the SMU repository at http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm

2) Uplift rate data could be used for active orogenic belts, which can be calculated through Global Positioning System (GPS) record (e.g., Blume and Sheehan, 2003) and implicitly reflect the altered temperature gradients from the flat line by diagenesis (Pollack and Chapman, 1977).

    a) **GPS data** provided by the University of Nevada, Reno Nevada Geodetic Laboratory. The selected data set is provided as north, east, and up components for more than 15 700 GPS sites in the IGS08 reference framework, with its origin in the center of mass of the total Earth system. This dataset can be found at: http://geodesy.unr.edu/

    b) A **new global GPS** dataset for testing and improving modelled glacial isostatic adjustment (GIA) uplift rates was generated from 4000 GPS vertical velocities as observational estimates of global GIA. The Global Mass GPS data set is available at: https://doi.pangaea.de/10.1594/PANGAEA.889923

Accessible Fluid (F)

1) Hot Springs and geothermometers of low-temperature (< 150°C) geothermal resources in the conterminous United States and Alaska can be identified from different datasets with geothermometer estimations.

    a) Mullane et al. (2016) compiled datasets from three USGS primary sources: Muffler (1979), Reed et al. (1982), and William et al. (2008). This database is available on the GDR: https://gdr.openei.org/submissions/842. Reed et al. (1982) identified 42 delineated areas related to conduction-dominated systems.

Permeability/porosity (P):

The Quaternary fault map, dilation-tendency analysis map, micro-earthquake locations, elevation patterns and lineation from LiDAR images are all elements of the permeability of fracture pathways component (Wang et al., 2021). At the same time, they are potentially susceptible to induced seismicity during geothermal operations.

1) Active faults along earthquakes activities indicate the occurrence of abrupt rock movements and fracturing (e.g., Faults and Hinz, 2015; Siler et al., 2018).

    a) **Quaternary faults.** The USGS Quaternary fold and faults database (Machette et al., 2003) can be evaluated to determine relationships between active deformation in the upper crust and location of geothermal systems, as well as seismic risk during exploitation and utilization of geothermal resources https://www.usgs.gov/programs/earthquake-hazards/faults.

2) Local stress field magnitudes and orientations along with active faults geometry could be used to estimate slip and dilation tendency in active structures (e.g., Faults and Hinz, 2015; Siler et al., 2018)

    b) Information about current **stress fields** (orientation and magnitudes) is key in understanding the susceptibility of faults to slip and/or dilation. The orientation and relative magnitudes of tectonic stresses in the conterminous United States, Alaska, and Hawaii can be derived from the WSM (Heidbach et al., 2016). The WSM is a global compilation of crustal stress field magnitudes and directions maintained since 2009 at the Helmholtz Centre Potsdam German Research Centre for Geosciences. The WSM is an open-access public database: https://www.world-stress-map.org/download.

3) Micro-earthquakes at shallow depths may be associated with geothermal exploration activity and/or fractures stress release (Foulger, 1982; Simiyu, 2009)

    c) USGS maintains the most complete database of global and national **earthquakes**: https://earthquake.usgs.gov/earthquakes/search/. Another earthquake catalog for Alaska is available at the Alaska Earthquake Center website: https://earthquake.alaska.edu/earthquakes.

4) Higher dilation rate as calculated from GPS data shows higher odds for increasing permeability for subsurface pathways where tensional strain is occurring (Dixon, 1991; Hsu et al., 2009).

Risk Criteria

Environmental and seismic risk are important factors to consider. For example, a few orogenic belts are within national parks or preserved land protected by public regulations in which any industrial development is prohibited. Other types of environmental risk are landslide risk due to the active uplift rates in active orogenic belts.

1) The purpose of the risk datasets is to evaluate seismicity as a risk factor and pinpoint areas that have a high chance of triggering seismic activity during reservoir construction (e.g., EGS) or during geothermal heat production and utilization.

    a) **Quaternary fault slip-dilation tendency** analysis identifies local seismicity risk. The datasets used for this analysis are the same for identifying permeability/fractural pathways because active faults may serve as pathways for geothermal fluids and at the same time, they are potentially susceptible to induced seismicity during geothermal operations.

2) Environmental risk in OBGPT accounts for exclusion layers such as national parks or landslide risk areas.

    a) **National parks boundaries** data to use for display and general GIS analysis can be found in the National Park Service Data Store: https://irma.nps.gov/DataStore/Reference/Profile/2224545?lnv=True

    b) The USGS interactive map with **landslide data** includes contribution from local, state, and federal agencies and provides links to the original digital inventory files: https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=ae120962f459434b8c904b456c82669d

Economic Criteria

Economic input data relevant to OBGPT viability include potential locations for commercial power sales or offtakes of heat for direct use, (e.g., regions with electrical infrastructure and population centers). The utilization viability input layers identify regions with the capacity to utilize low-grade geothermal heat and estimated LCOH for a set of communities. The same datasets used for SBGPT can be used for OBGPT.

3.3 Relevant Data and PFA Methods for RGPT

The RGPT relevant input data and methodologies (Fig. 8) are based on different studies (e.g., Kolker, 2008; Lacasse et al., 2022) and key controls are summarized in Table 4.

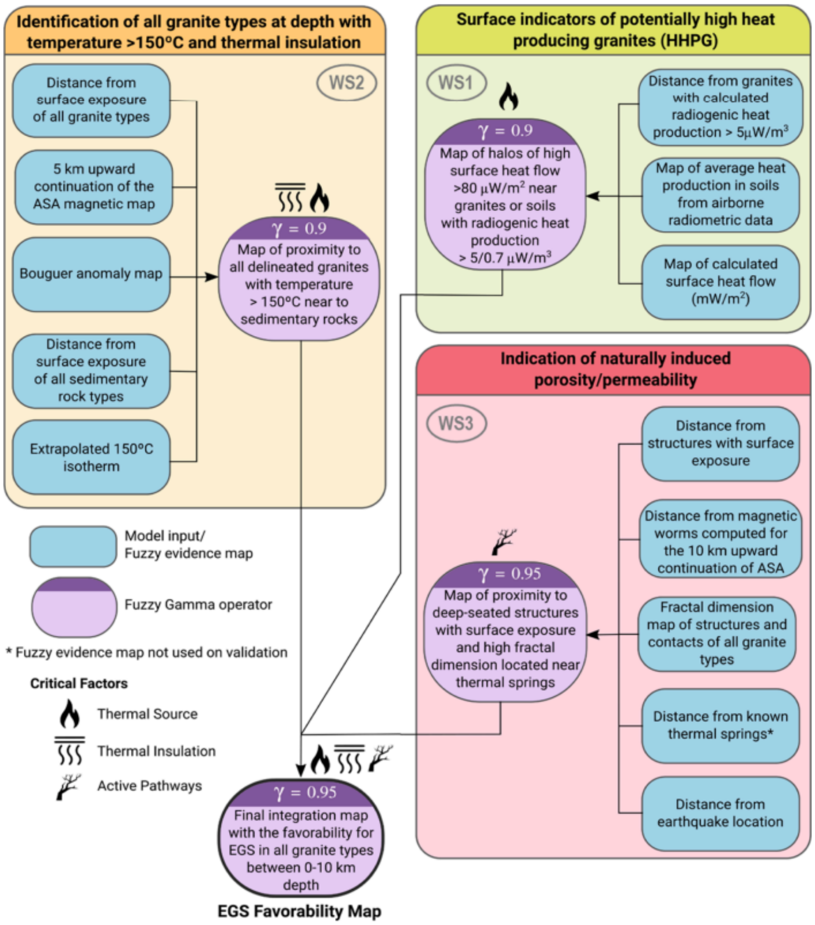

Fig. 8. Example PFA flowchart for determining favorability of RGPT for petrothermal or EGS favorability, from geothermal systems in Brazil (Lacasse et al., 2022).

Table 4. Geothermal key controls of radiogenic GPT

	Geological & tectonic settings		
Geothermal key controls	***Intrusive event***	***Present time***	***Related PFA: critical component***
Magma type (pluton composition)	**x**		**H, F**
Radioelement concentration	**x**		**H**
Pluton volume	**x**	**x**	**H**
Fluid chemistry		**x**	**F, S**
Hydrothermal alteration		**x**	**F, P, S**
Faults and fractures	**x**	**x**	**P**
Stress state		**x**	**P**
Tectonic setting	**x**	**x**	**P**
Degree of sedimentary overburden		**x**	**H, S**

Geological Criteria

Table 5 summarizes the datasets that can address key unknowns related to the geological criteria components H, P, F, and sometimes S. However, the input layers and criteria should be selected depending on data availability for the study area and the nature of the GPT.

Important geological factors to consider in a PFA methodology for a RGPT area as recommended by Lacasse et al. (2022) include: (1) the existence of high heat producing granites (Heat Source); (2) identification of all granite types at depth with temperature >150°C and thermal insulation (caprock/seal: thermal insulation); and (3) indication of naturally induced porosity/permeability (fracture pathways).

Table 5. Critical components of a RGPT, key datasets, and qualitative assessment of relative uncertainty around the key datasets.

Component	Key Unknowns	Key Data Sets	Uncertainty
Heat (H)	• Rock types at depth • Volume of plutons at depth • High-heat-producing (HHP) plutons (K age) vs. "normal" (T age) • Role of magmatic heat from related intrusive event(s)	• U, Th concentration data (whole rock data and/or airborne radiometric data • Heat flow models • Fluid geothermometry • He isotopic data	High
Accessible Fluids (F)	• Presence of fluid • Degree of circulation or convection (dynamics) • Temperature and chemistry of reservoir fluids	• Hydrology data • Chemical composition of fluids (from hot springs or well samples) • Fluid geothermometry • Hydrothermal alteration data	Medium
Permeability (P)	• Key structures • Stress	• Stress data • Geophysical data (seismic, MT, magnetic and gravity) relevant to structure identification • Geologic maps/cross sections/models • Fault/fracture orientations relative to local stress field • Fracture data (size, aperture, orientation etc.)	High
Caprock or Seal (S)	• Quality and presence of caprock or seal • Degree of insulation from unconsolidated sediments	• Stratigraphy data from well logs or geologic models • Heat flow / basin models • Geophysical data (seismic)	Low to Medium

Heat (H) input Data:

1) U, Th concentration data and heat flow models: U and Th concentration data for RGBT plutons can be collected through several techniques, such as instrumental neutron activation analysis; atomic absorption; delayed neutron; gamma ray spectroscopy; and X-ray fluorescence. The following information is required to determine if radiogenic heat sources can fully explain the heat delivered to a particular RGPT system:

1) Heat generated by pluton (volume * heat production of plutons)
2) Heat required by geothermal fluids (volume of water * temperature differential)

a) **Radiogenic heat production** in content model format is accessible for Idaho, Montana, Minnesota, and Oregon. This dataset combines radiogenic heat measurements from several different submission files. It contains data from gamma ray spectrometry measurements conducted by the University of North Dakota, as well as any heat generation measurements from the heat flow determination by SMU, Cornell, and University of North Dakota. The dataset is available at the SMU repository at http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm

b) Data for **heat production in granitic rocks**: Global analysis based on a new data compilation GRANITE2017 were compiled data from original publications where information on rock type, heat generation and concentrations of radiogenic elements has been reported. The database is an electronic supplement to the article by Artemieva et al., (2017). The dataset is available at https://data.mendeley.com/datasets/yjjx5fvhvm/2.

c) **Heat flow** datasets may be available in the region. The most recent heat flow map for the conterminous United States and Alaska was updated by Blackwell and Richards (2006) and Batir et al. (2016), respectively. The dataset is available at the SMU repository at http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm

2) *Helium isotopic data:* Helium isotopes may be useful in distinguishing between magmatic, "deep circulation," or radiogenic type geothermal systems (Kolker, 2008). Helium isotopes provide unequivocal evidence for the presence of mantle-derived volatiles in geothermal systems, and therefore are an indication of heat source.

Helium derived from mantle sources but with no magmatic input (for instance, in deep circulation / crustal thinning settings) is also enriched in ^{3}He but characterized by lower ^{3}He/^{4}He ratios than helium derived from magmatic settings. Therefore, any value higher than 0.1 RA is considered to have a significant mantle He component (Ballentine et al., 2002). For example, fluids from the Dixie Valley, NV geothermal field range from 0.70 to 0.76 RA, indicating that 7.5% of the total helium is derived from the mantle (Kennedy and van Soest, 2007).

A summary of helium isotope signatures from the different types of geothermal systems is given in Table 6. Helium associated with crustal fluids that have experienced no mantle influence is dominated by radiogenic ^{4}He produced from radioactive decay of U and Th to Pb and is characterized by a ^{3}He/^{4}He ratio of ~0.02 RA.

Table 6. Compiled data from the literature on $^3He/^4He$ ratio (R) in geothermal fluids relative to the $^3He/^4He$ ratio in air (R_A).

Geothermal Play Type	He isotope signature (R/R_A)	Geologic origin of He
Radiogenic[a]	**0.02 – 0.04**	**Shallow crust**
Volcanic or Magmatic[b,d,e,f]	**2-16**	**Mantle**
Deep Circulation[b,c,e]	**~0.7 average**	**Deep crust and/or mantle**

Sources: (a) Brugger et al., 2005; (b) Kennedy and van Soest, 2005; (c) Kennedy and van Soest, 2007; (d) Christenson et al., 2002; (e) Ballentine et al., 2002; (f) Poreda et al., 1988.

a) The USGS released a dataset of **helium concentrations** in U.S. wells by Brennan et al. (2021). This dataset provides national scale location information for known, publicly available, data on helium gas concentrations, reported in mol%. The dataset is available at: https://www.sciencebase.gov/catalog/item/609e8fe1d34ea221ce3f39e6

Accessible Fluid (F)

a) **Hot springs** and **geothermometers** of low-temperature (<150°C) geothermal resources in the conterminous United States and Alaska. Mullane et al. (2016) compiled datasets from three USGS primary sources: Muffler (1979), Reed et al. (1982), and William et al. (2008). This database is available on the GDR: https://gdr.openei.org/submissions/842. Reed et al. (1982) identified 42 delineated areas related to conduction-dominated systems.

Permeability/Porosity (P)

The Quaternary fault map, dilation-tendency analysis map, micro-earthquake locations, elevation patterns and lineation from LiDAR images are elements that represent implications of the permeability of fracture pathways component (Wang et al., 2021) and at the same time, they are potentially susceptible to induced seismicity during geothermal operations. The same datasets described for permeability/porosity in OBGPT could be used for RGPT, see section 3.2.

Caprock/Seal (S: Thermal Insulation)

The proximity of an insulating sedimentary cover must be evaluated in RGPT. The occurrence of sediments in contact with the HHP granites, lithology, thickness, and thermal conductivity are important data to consider.

1) For basin lithology–stratigraphic column and reservoir properties could be obtained from published literature from a specific basin. When that is not available, seismic reflection and

other geophysical methods can be used to determine basin stratigraphy. The same dataset identified for SBGPT could be used for RGPT.

2) Thermal conductivity is based on a stratigraphic model for each basin.
    a) The **thermal conductivity** baseline datasets of the conterminous United States and Alaska could be compiled for onshore sedimentary basins and include thermal conductivity values derived from lithological models COSUNA. Thermal conductivity values derived from stratigraphic models have an expected error of 10%, while thermal conductivity measurements of rock samples have errors below 5% (Gallardo and Blackwell, 1999). This dataset can be downloaded from http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm

Risk Criteria

Environmental and seismic risk are important factors to consider. For example, a few areas are labelled as a national park, preserved land protected by public regulations that prohibit any industrial development. The risk criteria datasets for RGPT are similar to OBGPT and SBGPT; see section 3.1 and 3.2.

Economic Criteria

Economic input data relevant to RGPT viability include potential locations for commercial power sales or offtakes of heat for direct use, (e.g., regions with electrical infrastructure and population centers). The utilization viability input layers identify regions that can utilize low-grade geothermal heat and estimated LCOH for a set of communities. The same datasets used for SBGPT can be used for RGPT; see section 3.1.

3.4 PFA Techniques and Processes

A forthcoming report on PFA Best Practices (Pauling et al., 2023) identified a general geothermal PFA process: (1) selection of study area; (2) compilation of existing data and identification of data gaps; (3) definition of common risk segments and appropriate conceptual model framework(s); (4) measures of data confidence/uncertainty; (5) transformation and weighting of data to support combination into common risk segments; (6) combination of confidence and common risk segments; and (7) combination of confidence-scaled common risk segments into one or more common composite risk segment maps of geothermal favorability. That report also emphasizes the importance of adapting geothermal PFA to other geothermal resource types and explores refinement for more play types.

In summary, **data processing** transforms raw data into evidence layers that give information about the criteria to investigate. For example, discrete data tends to be interpolated to develop continuous layers, and some input data needs to be standardized and normalized to the same unit-scale to apply weighted summation methods or apply a machine learning algorithm (Burkov, 2019). Then, the evidence layers are each **weighted** to highlight the layers that are considered to contribute most significantly to the common risk segment of interest. The weights applied to evidence layers can be based on expert opinion, data confidence, and/or statistical models, or they can be generated through training and embedded into machine learning models (e.g., Mordensky et al., 2023). Other quantitative approaches, which attempt to reduce biases that are introduced using expert opinions include statistical methods (e.g., Palmer-Wilson et al., 2018; Kolker et al., 2022) and/or a combination of quantitative and expert opinions (Faulds et al., 2021). Afterward, data confidence is evaluated (**uncertainty quantification**) using different criteria such as kriging standard error, spatial coverage, collecting methods, availability of co-located datasets, scale of mapping, spatial resolution, etc. After evidence layers, confidence layers, and weights are produced, they may be united, using weighted sums or another layer combination technique, into common risk segment (CRS) maps, or individual **criteria favorability maps**, optionally **scaled by confidence,** for each criteria of interest. Lastly, a common composite risk segment (CCRS), or a **combined favorability map** (Fig. 9) can be created by further weighting and combining the CRS layers using geographic information systems, MATLAB, Python, or other tools.

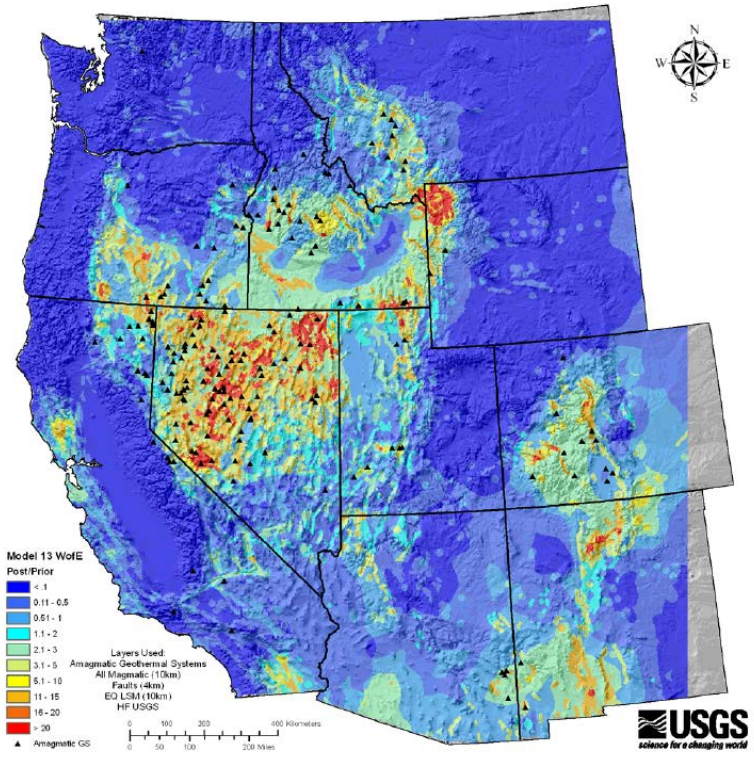

Fig. 9 Favorability map of a weights of evidence analysis results using a combination of faults, stress, earthquakes, and heat flow evidence layers produced by Williams and DeAngelo (2008).

As a final step of a geothermal resource favorability study, the **power and heat potential** of a geothermal reservoir can be estimated for regions of highest favorability using different tools such as the Geothermal Resource Portfolio Optimization Reporting Technique (GeoRePORT) Resource Size Assessment Tool developed by NREL (Rubin et al., 2022).

A generalized flow chart showing the proposed PFA methodology in this study, specific to assessment of low-temperature conduction or conductive-dominated GPT, is shown in Fig. 10.

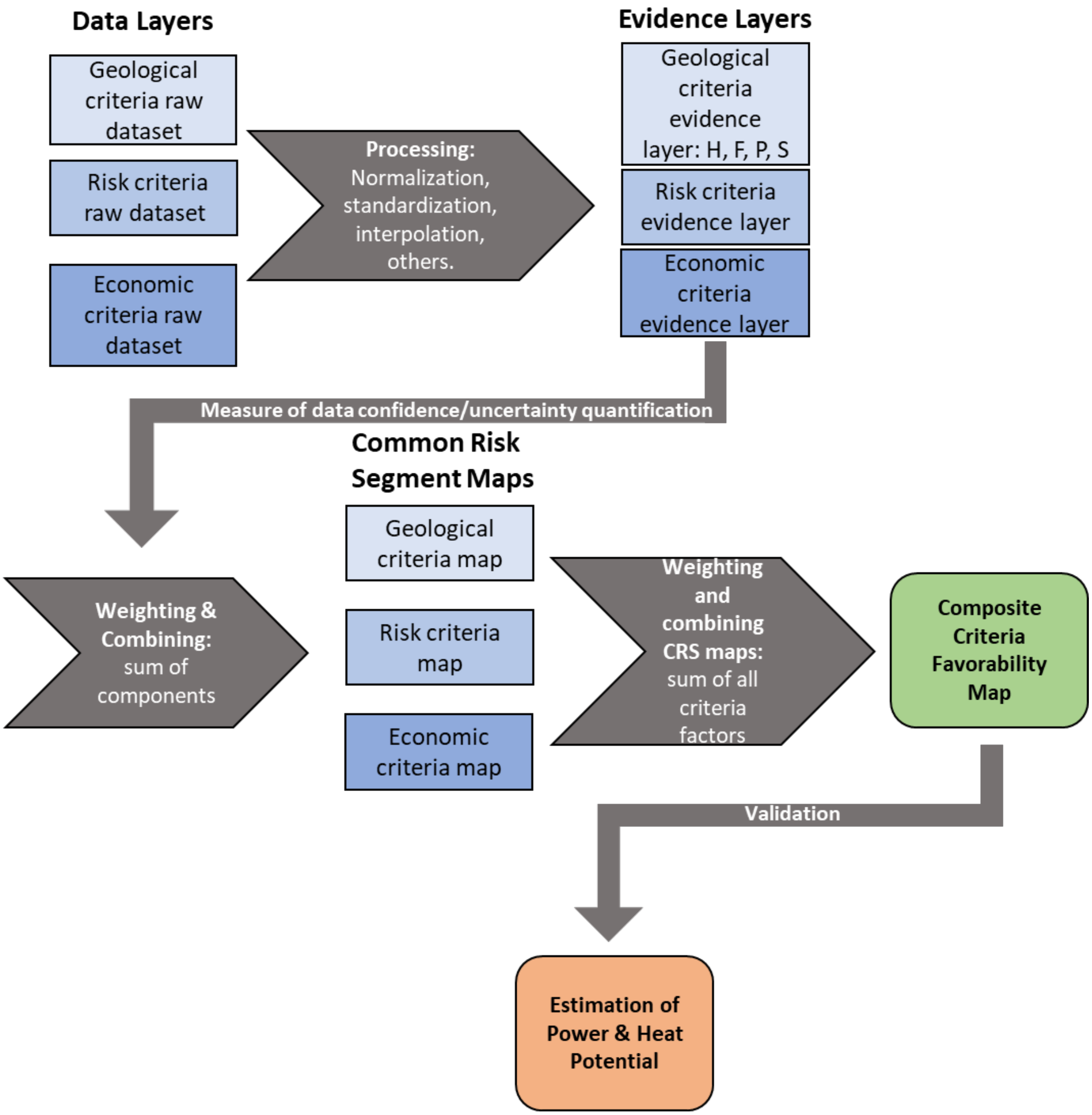

Fig. 10. Flow chart outlining a generalized methodology for low-temperature assessment resources.

Conclusions

This study classifies low-temperature geothermal resources by GPT. We redefined, updated, and characterized three major classes of low-temperature plays: SBGPT, OBGPT, and RGPT. This exercise should allow better characterization of low-temperature geothermal plays, which could facilitate favorability mapping for low-temperature geothermal resources. In the context of decarbonizing heating and cooling systems, such maps would meet a current need to understand where low-temperature geothermal resources are located close to demand.

The general PFA workflows suggested by this study for low-temperature resources are similar to other PFA methods suggested for high-temperature hydrothermal resources. However, there is an important distinction in this PFA approach, which is focused on low-temperature resources for applications such as GHC and geothermal direct use. For that reason, even though the geological criteria remain the most important in the PFA process, it is critical to include the risk and economic criteria, such as population centers and heat demand and consumption in order to represent important demand-side factors impacting the feasibility of geothermal direct use for heating and cooling, and other applications of low-temperature geothermal resources (such as small-scale combined-heat-and-power plants).

This project should facilitate future deployment of geothermal direct use for heating and cooling by providing data, tools, and a workflow applicable to low-temperature geothermal resources. Future work could use relevant data identified in this study and apply the PFA workflows described to create favorability maps of low-temperature resources for various GPT in some regions of the United States. Future research could also identify data gaps where more research and data acquisition will enhance future favorability mapping efforts.

Acknowledgement

This work was authored by the NREL operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Geothermal Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

REFERENCES

Artemieva, I., Jakobsen, K., Thybo, H., Sørensen, N.K., and Nielsen, L.S.K. Data from "Heat production in granitic rocks: Global analysis based on a new data compilation GRANITE2017." Mendeley Data, V2 (2018). doi: 10.17632/yjjx5fvhvm.2.

Augustine, C. AASG Wells Data for the EGS Test Site Planning and Analysis Task (No. 252). USDOE Geothermal Data Repository; NREL, Golden, CO (2013).

Baranwal, V.C., Sharma, S.P., Sengupta, D., Sandilya, M.K., Bhaumi, B.K., Guin, R., and Saha, S.K., 2006. "Anewhigh background radiation area in the Geothermal region of Eastern Ghats Mobile Belt (EGMB) of Orissa, India". *Radiation Measurements*, 41, *pp*.602-610.

Batir, J.F., Blackwell, D.D., and Richards, M.C. “Heat flow and temperature-depth curves throughout Alaska: finding regions for future geothermal exploration.” *Journal of Geophysics and Engineering*, 13(3), (2016), 366-378.

Beckers, K.F., Lukawski, M.Z., Anderson, B.J., Moore, M.C. and Tester, J.W. “Levelized costs of electricity and direct-use heat from Enhanced Geothermal Systems.” *Journal of Renewable and Sustainable Energy*, 6(1), (2014), 013141.

Beitollahi, M.M., Ghiassi-Nejad, M., Esmaeli, A. and Dunker, R., 2005, July. “Radiological studies in the hot spring region of Mahallat, Central Iran”. *In Health Physics* (Vol. 89, No. 1, pp. S3-S3). 530 Walnut St, Philadelphia, Pa 19106-3261 USA: Lippincott Williams & Wilkins.

Berry, G.W., Grim, P.J. and Ikelman, J.A. “Thermal springs list for the United States; National Oceanic and Atmospheric Administration Key to Geophysical Records Documentation No. 12.” National Geophysical and Solar-Terrestrial Data Center, Boulder, Colorado; Cooperative Institute for Research in Environmental Sciences, University of Colorado/NOAA, Boulder, CO (1980).

Blackwell, D.D., Negraru, P.T., and Richards, M.C. “Assessment of the enhanced geothermal system resource base of the United States.” *Natural Resources Research*, 15, (2006), 283-308.

Brugger, J., Long, N., McPhail, D.C. and Plimer, I., 2005. “An active amagmatic hydrothermal system: the Paralana hot springs, Northern Flinders Ranges, South Australia”. *Chemical Geology*, 222(1-2), *pp*.35-64.

Burkov, A. The hundred-page machine learning book (Vol. 1, p. 32). Quebec City, QC, Canada (2019).

Coleman Jr, J.L. and Cahan, S.M. Preliminary catalog of the sedimentary basins of the United States. (2012).

Doughty, C., Dobson, P.F., Wall, A., McLing, T. and Weiss, C. “GeoVision analysis supporting task force report: exploration.” NREL, Golden, CO (2018).

Durrance, E.M., 1985. “Hydrothermal circulation and isostasy, with particular reference to the granites of southwest England”. In High heat production (HHP) granites, hydrothermal circulation and ore genesis. *Conference* (*pp*. 71-85).

Faulds, J.E., Hinz, N.H., Coolbaugh, M., Ayling, B., Glen, J., Craig, J.W., McConville, E., Siler, D., Queen, J., Witter, J. and Hardwick, C. Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways: All Phases (No. DOE-UNR-06731-01). Univ. of Nevada, Reno, NV (United States); ATLAS Geosciences, Inc., Reno, NV (United States); US Geological Survey, Menlo Park, CA (United States); Hi-Q Geophysical, Inc., Ponca City, OK (United States); Innovate Geothermal Ltd, Vancouver (Canada); Utah Geological Survey, Salt Lake City, UT (2021).

Gallardo, J. and Blackwell, D.D. “Thermal structure of the Anadarko Basin.” *AAPG Bulletin*, 83(2), (1999), 333-361.

Greene, R., Devillers, R., Luther, J.E. and Eddy, B.G. “GIS-based multiple-criteria decision analysis.” *Geography Compass*, 5(6), (2011), 412-432.

Hamza, V.M., Gomes, A.J.L. and Ferreira, L.E.T., 2005. “Status report on geothermal energy developments in Brazil”. *Natural Gas*, 14, *pp.*7-5.

Heidbach, O., Rajabi, M., Reiter, K., and Ziegler, M. WSM-World Stress Map Database Release (2016).

Jordan, T.E., Richards, M.C., Horowitz, F.G., Camp, E., Smith, J.D., Whealton, C.A., Stedinger, J.R., Hornbach, M.J., Frone, Z.S., Tester, J.W. and Anderson, B. "Low Temperature geothermal play fairway analysis for the Appalachian basin: phase 1 revised report (No. DE-EE0006726)." Cornell Univ., Ithaca, NY (2016).

Kolker, A.M., 2008. "Geologic setting of the Central Alaskan Hot Springs Belt: Implications for geothermal resource capacity and sustainable energy production". *University of Alaska Fairbanks.*

Machette, M.N., Haller, K.M., Dart, R.L. and Rhea, S.B. "Quaternary fold and fault database of the United States." USGS Open-File Report (2003). https://www.usgs.gov/programs/earthquake-hazards/faults? qtscience_support_page_related_con= 4# qt-science_support_page_related_con.

McLaren, S. and Powell, R., 2014. "Magmatism, orogeny and the origin of high-heat-producing granites in Australian Proterozoic terranes". *Journal of the Geological Society*, 171(2), *pp.*149-152.

McLaren, S. Sandiford, M., Powell, R., Neumann, N. and Woodhead, J., 2006. "Palaeozoic intraplate crustal anatexis in the Mount Painter Province, South Australia: timing, thermal budgets and the role of crustal heat production". *Journal of Petrology,* 47(12), *pp.*2281-2302.

Moeck, I.S. "Catalog of geothermal play types based on geologic controls." *Renewable and Sustainable Energy Reviews*, 37, (2014), 867-882.

Mordensky, S.P., Lipor, J.J., Deangelo, J., Burns, E.R., and Lindsey, C.R. "Predicting Geothermal Favorability in the Western United States by Using Machine Learning: Addressing Challenges and Developing Solutions." In *Proceedings: Forty Seventh Workshop on Geothermal Reservoir Engineering* (2022).

Motyka, R.J., Moorman, M.A. and Liss, S.A. "Geothermal Resources of Alaska: Miscellaneous Publication MP 8." (1983).

Nelson, P.H. and Kibler, J.E. "A catalog of porosity and permeability from core plugs in siliciclastic rocks," pp. 3-420. U.S. Department of the Interior, U.S. Geological Survey (2003).

Oh, H. and Beckers, K. "Geospatial Characterization of Low-Temperature Heating and Cooling Demand in the United States" NREL, Golden, CO, NREL/CP-5700-84708 (2023).

Palmer-Wilson, K., Banks, J., Walsh, W. and Robertson, B. "Sedimentary basin geothermal favourability mapping and power generation assessments." *Renewable Energy*, 127, (2018), 1087-1100.

Reed, M.J. "Assessment of low-temperature geothermal resources of the United States-1982 (No. USGS-CIRC-892)." USGS, Menlo Park, CA (1982).

Rubin, R., Kolker, A., Witter, E. and Levine, A. "GeoRePORT Protocol Volume VI: Resource Size Assessment Tool." NREL, Golden, CO, NREL/TP-5700-81820 (2022).

Rybach, L., 1981. "Geothermal systems, conductive heat flow, geothermal anomalies." *Geothermal Systems: Principles and Case Histories*, (1981), 3-36.

Siler, D.L., Hinz, N.H., and Faulds, J.E. “Stress concentrations at structural discontinuities in active fault zones in the western United States: Implications for permeability and fluid flow in geothermal fields.” *Bulletin*, 130(7-8), (2018), 1273-1288.

Taylor, S.R. and McLennan, S.M., 1986. “The chemical composition of the Archaean crust”. *Geological Society, London, Special Publications*, 24(1), *pp.*173-178.

Pauling, H., Taverna, N., Tranor-Guitton, W., Witter, E., Kolker, A., Warren, I., Robins, J., and Rhodes, G., 2023. Geothermal Play Fairway Analysis Best Practice. Renewable Energy Lab (NREL), Golden, CO (United States).Williams, C.F. and DeAngelo, J. “Mapping geothermal potential in the western United States.” *Geothermal Resources Council Transactions* 32, (2008), 181.

Wilmarth, M. and Stimac, J., 2015. “Power density in geothermal fields.” *Power,* 19, (2015), 25.

Yuan, H. and Romanowicz, B., 2010. “Lithospheric layering in the North American craton”. *Nature*, 466(7310), *pp.*1063-1068.

Zhou, Z.M., Ma, C.Q., Qi, S.H., Xi, Y.F. and Liu, W., 2020. “Late Mesozoic high-heat-producing (HHP) and high-temperature geothermal reservoir granitoids: The most significant geothermal mechanism in South China”. *Lithos,* 366, *p.*105568.