PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

GFI™: Deep Closed-Loop GeoHeat™ Feasibility Assessment Workflow

Maria Fernanda Gonzalez, Ghazal Izadi and Hani Ibrahim

2479 East Bayshore Road, Suite 210, Palo Alto, CA 94303

mgonzalez@geothermicsolution.com

Keywords: Deep Closed Loop Systems Geological characterization, Heat-in-Place Assessment, Geothermal Resource, sedimentary basins, volcanic systems, blind systems, brownfield, greenfield, decision-making, chance of success, targeting, uncertainty quantification slim-hole drilling.

ABSTRACT

The GeoHeat™ deep closed-loop technology is designed for producing reliable geothermal energy anywhere. With the shortest time for the first Mega Watt, the minimum environmental impact, no corrosion, no scaling, and no seismicity risks, it is the most reliable and sustainable option in the market for large-scale, long-term energy production.

The GeoHeat™ harvesting technology incorporates a multidisciplinary workflow for assessing its feasibility under the various scenarios of geological, thermal, and mechanical information. This entails uncertainty quantification and an engineered strategy to maximize energy production and the rates of returns on investments. This integrated approach includes visualization and mapping as key s for effective communication between the internal and external stakeholders involved in the projects, warranting not only informed but also unbiased decision-making along the strategy for all the geological and development scenarios: Greenfields, blind systems, unexplored volcanic, metamorphic, plutonic, sedimentary basins, and their basement rocks, along with hydrothermally developed systems.

A generalized workflow for geologically delimiting the targets and estimating their GeoHeat™ feasibility through mapping is presented here. Each developmental stage and resource type will use an adaptation of this workflow for confirmation of the geothermal resource in place and the sustainability of the heat harvesting in time. The GeoHeat™ feasibility index then provides the developer with an integrated and fit-for-purpose indicator from the techno-economical perspective. This index accounts for the different resource de-risking methods, from integrating massive amounts of information to adding new datasets, through slim-hole drilling and geophysical surveying.

Two case studies of the workflow application, within two different data maturity scenarios, serve as an illustration for common intraplate settings where conventional geothermal systems are not easy to find, making GeoHeat™ the best alternative for renewable energy production. The workflow helps both during preliminary screening and decision-making process but also a quantitative feasibility index estimation for focused exploration (e.g., Slim-hole drilling, extra geophysical surveying) and development program inputs.

1. INTRODUCTION

Conventional geothermal systems are exploited through typically large diameter wellbores with high-flow capacity, under natural, pressure-driven flow from initial production state until decline and de-commissioning. Typical geothermal fields require an aggressive make-up drilling strategy (i.e., drilling of production wells inside an already confirmed reservoir to maintain fluid production in a certain level).

As conventional geothermal wells also take great advantage of pressure maintenance through re-injection, they often have adverse effects on the neighboring communities such as increased seismicity. Other adverse effects are those related to toxic gases emissions, such as sulfur and carbon dioxides, and noise. Additional to these environmental effects, corrosion or scaling problems may exist due to high in-situ fluid acidity or mineral solubility destabilization, commonly challenging the economic value of the projects. Fluid availability and sufficient rock formation permeability are requirements for conventional systems economical flow rates, also becoming a limiting factor for the success of both exploration and make-up drilling programs.

Closed-loop geothermal systems (CLGS) overcome many of the conventional hydrothermal environmental and economic adversities, by not extracting fluid from the rock, but only heat. This is done by solid-liquid heat conduction from the rock formation to the wellbore's open section filled with a circulating fluid of ideally non-reactive characteristics, bringing-up the mined heat by convection from depth to the wellhead, where it is passed through surface heat exchangers and converted to electric or thermal power.

One of the main challenges of conventional CLGS is sustaining the rate of thermal conduction from the rock formation to the wellbore, which is mainly controlled by:

1. The contact area between the hot rock and the well's fluid interface,

2. The thermal conductivity of the involved media in the heat transfer process,
3. The temperature difference between the rock and the wellbore face.
4. The size of the space between the two endpoints of the heat transferring process, in this case the rock and the wellbore's face.

As sedimentary rocks are typically thermal insulators, the thermal conduction process is slower than in crystalline igneous rocks, posing an even greater challenge for conventional CLGS. This is how the GeoHeat™ technology comes into place as a unique potentiator, enhancer and accelerator of the heat transferring process, through enhanced rock's thermal conductivity.

With the GeoHeat™ technology, the area of contact between the enhanced-conductivity media and the well's face is also increased. Furthermore, in comparison to engineered geothermal (EGS) and conventional hydrothermal systems, there is no long-term seismicity scaling, corrosion, nor gas emissions, making the environmental footprint as minimal as possible for any energy system. The technology can be operationally optimized in terms of rates of heat extraction and uses a non-problematic working fluid in terms of both, thermodynamics, and chemistry. Likewise, pressure maintenance is not needed nor injection wells, further increasing the attractiveness of the geothermal areas when GeoHeat™ harvesters are installed instead of legacy technology.

This article provides a preliminary report on the methods being developed for the GeoHeat™ application feasibility assessment. They are illustrated with two examples on a regional scale. These methods ultimately have evolved into a generalized indexed methodology called the GeoHeat™ Feasibility Index (GFI™). The methodology intends to systematically address the multidisciplinary nature of the approaches required for accurate risk and opportunity rankings within the GeoHeat™ probable areas (GPA), inside any Area of Interest (AOI).

2. IMPROVED GEOTHERMAL FEASIBILITY EVALUATION THROUGH GEOHEAT™ INDICES

The GeoHeat™ technology is a coaxial CLGS that provides enhanced capabilities with respect to both conventional geothermal wells and other existing CLGS. This due to the enhancement of the thermal properties of the rock provided in the installation, increasing the heat transfer rates and area of harvesting in a controlled, engineered manner through a comprehensive monitoring system that helps optimize the rate of heat extraction, so it does not drastically decay in time. It thus provides long-term energy production without compromising the sustainability of the geothermal resource, allowing to scale-up the harvesters for long-term baseload energy provision. Added to this, the top-notch drilling and completion technologies, from petroleum and conventional geothermal, are adapted for its installation in any kind of rock, from soft sedimentary to hard igneous and metamorphic, decreasing the cost per foot and amplifying the applicability of geothermal to anywhere, and not only magma-driven hot-spots. Furthermore, the working fluid is kept in a single phase by maintaining a fixed pressure at the wellhead, and a constant flow rate, to harvest the heat, and pure water can be used.

Borehole heat exchangers were first introduced in the broad picture by Roland Horne (Horne, 1980), with an analysis on the design considerations of this system, where it was concluded that the optimum configuration is one which has the same velocity in the upward and downward flow. The first experiment addressed in the literature to prove the concept of a Coaxial Heat exchanger was performed in the HGP-A geothermal well, as published by Morita et al (Morita, Bollmeier, & Mizogami, 1992). These authors proposed these systems as heat extraction methods for low permeability geothermal reservoirs (hot wet rock), super hot rock adjacent to magma bodies and solidified magma bodies. During these experiments, the inlet temperatures were kept constant, the flow rates were kept constant at 80 l/min, and the outer/outlet temperatures were monitored. The observed maximum net thermal output was 373 kW, becoming 76 kW at the end of the experiment.

The GeoHeat™ technology projects to deliver megawatts-order energy production through the whole productive life of the harvester, with a 50 degrees celsius outlet temperature decrease in a 10 year production timeframe, when installed in hot dry rock formations at 300+ degrees celsius. The specific formation temperature of a project provides a basis that is used to delineate a feasibility index calculation for the technology, different to the conventional geothermal prospects, which need to rely on often-rare permeability descriptions and in-situ fluid availability.

In order to identify areas of higher prospectivity for geothermal energy, many government entities typically perform mapping of heat flow measurements or subsurface temperatures near to volcanic areas only, without the use of all the subsurface information available in other industries, especially mining boreholes or oil and gas wells. For the United States, the Geothermal Resource Favorability for Deep Enhanced Geothermal Systems (EGS) has been mapped by the National Renewable Energy Laboratory (NREL) in 2018 (Roberts, 2018), as seen on Figure 1.

GeoHeat™ targets subsurface prospects by integrating multiple sources of information and data, enlarging the conventional framework of geothermal prospectivity evaluation to not only volcanic but also sedimentary and metamorphic realms, and highlighting the importance of updating the current geothermal prospectivity maps to include all the technologies available to mine the heat. The workflow used to do this involves the calculation of two indices, one for risk, and one for uncertainty, which can be used to comparatively rank areas of potential application of the technology, as explained in the following section.

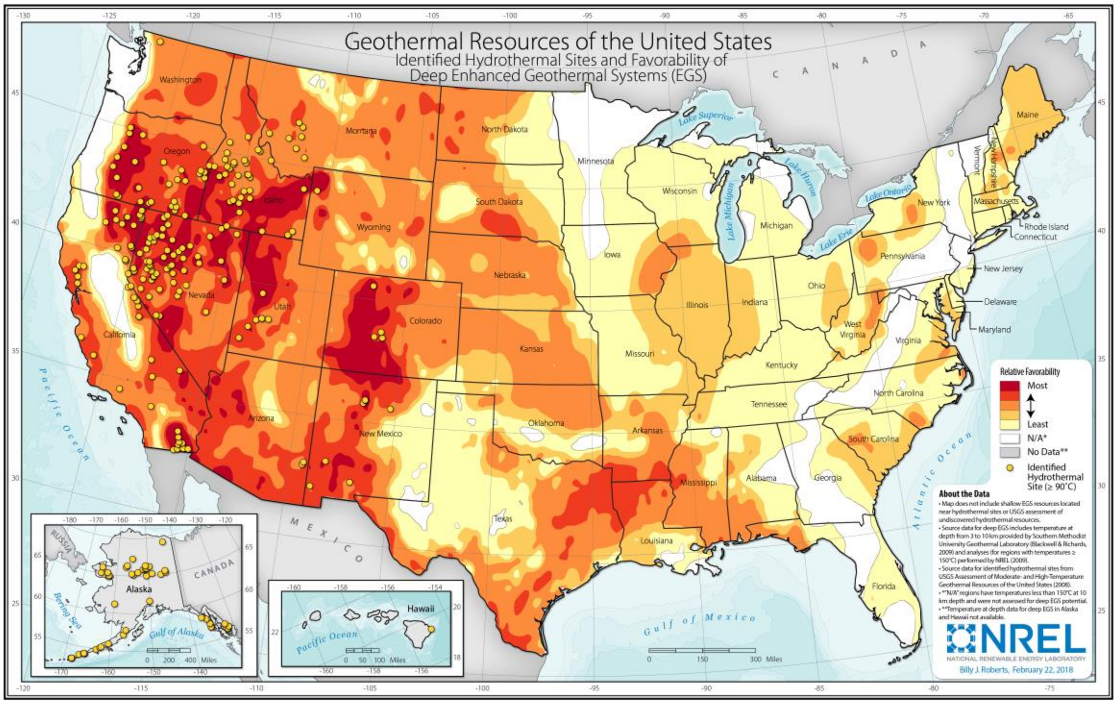


Figure 1. US Deep EGS Favourability and Hydrothermal sites map (Roberts, 2018).

2.1 GeoHeat™ Feasibility Index (GFI™) definition and workflow

The GFI™ aims to provide an integrative tool for technological risk analysis evaluation which includes, from an early project stage, the identification, characterization and ranking of prospects. This index is adaptable to the circumstances and scales of the projects for development, from greenfield or exploratory, to brownfield, data-mature or well-known areas. It encompasses, not only the rock's parameters and measurable properties driving success for the technology, from the resource in-place and engineering standpoints, but also economic factors. In the early stages of development/assessment, this index stands as a feasibility qualifier.

As the projects advance in information quality and quantity, the GFI™ turns into a Favorability Index, able to provide comparisons between targets in both two and three dimensions, from the geological, geomechanical, production and economic perspectives.

The GFI™ allows a distinct set of scenarios of development to exist as the project goes from warm sedimentary basins to super-hot volcanic areas. This, because the GeoHeat™ technology addresses geothermal extraction of a wide spectra, from challenging conventional geothermal environments to the non-conventional deep resources.

2.1.1 GFI Calculation workflow

At the exploratory stage, it is often common to have information such as the character of the geothermal resources and relevant-to-GeoHeat™ datasets contained in public repositories and literature, including surface thermal manifestation locations, basic quaternary lithology, outcropping structures with a non-detailed tectonic classification, regional stress regimes, petroleum, and geothermal wells' locations and non-stabilized bottom-hole temperatures or geothermal gradients. For this typical scenario of information availability, the GFI™ can be estimated by involving some or all of the steps below:

1. Gather information and load it into a Geodatabase focused on the project.
2. Define the scale of the analysis or Area of Interest (AOI) – State-wide, country-wide, city-wide, field-wide, etc.
3. Differentiate zones of differing dominant heat transferring mechanisms within the AOI i.e., Convection, conduction, or mixed types.
4. Generate temperature maps and polygons of interest per temperature range at different fixed depths.
5. Delimitate GeoHeat™ Probable Areas (GPA) according to the geological and thermal information.
6. Calculate the distribution of the heat resource within each GPA through industry-standard methods, such as the power density method or the volumetric method (Bixley., 2011).
7. Understand and study the possible sources of heat and their character (Kornprobst, 2003), to include their proportion per GPA relative to each other, and other relevant geological factors to heat extraction sustainability.
8. Define weighting factors for each thermal and geological factor and calculate the GFI per GPA and polygon.

9. Map the GFI™ and estimate the proportion of information availability and certainty index (GCEI) per GPA and classify the areas in exploration and development prone.
10. Define focus sub-areas for more detailed GFI™ calculations if an iterative development (i.e., exploration program) involving decreasing the uncertainty will be followed.

This process can be iterative and multi-scale, with each iteration aiming to increase the understanding, decreasing the risk and the uncertainty on the in-situ power predictions. It can drive, for instance, the definition of slim-hole and site locations, as seen on Figure 2.

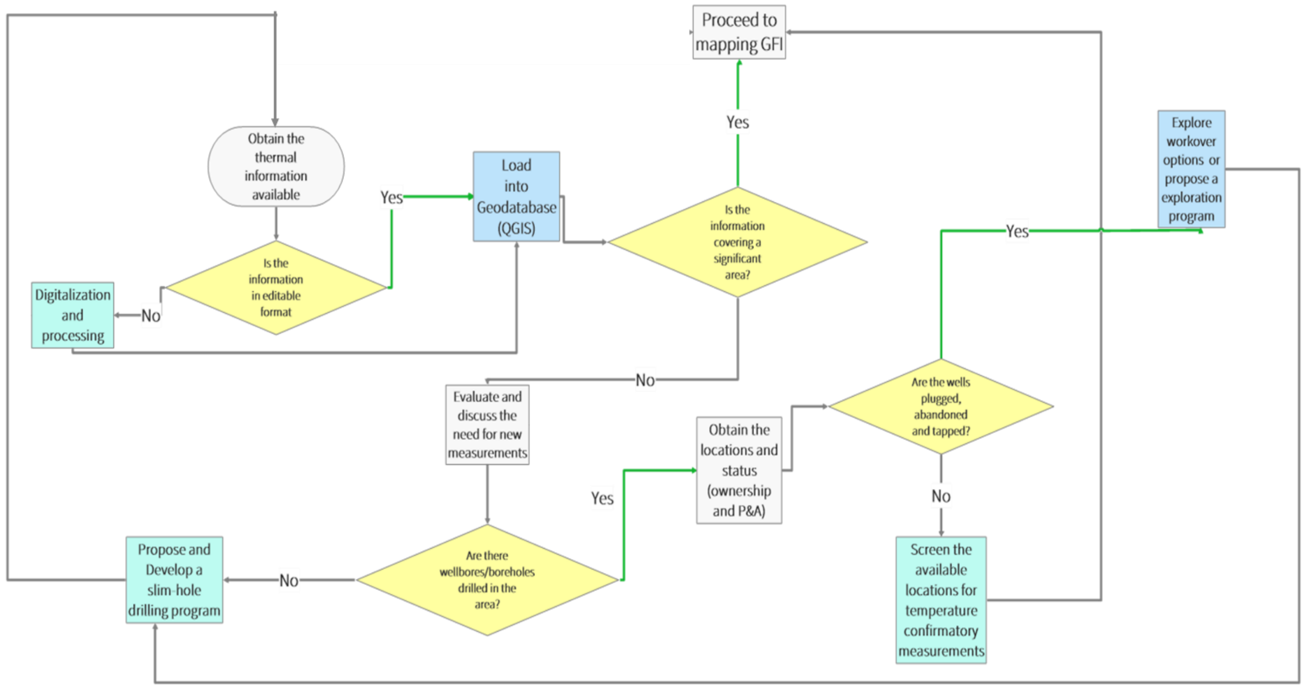


Figure 2: Generalized decision tree before the GFI calculation

<u>2.1.2 Minimum Datasets requirements and Assumptions</u>

The minimum datasets required for the GFI™ calculation are listed below:

1. Geographical limits (polygon) of the AOI and the location of conventional geothermal systems within them.
2. Geothermal gradients measurements and well locations and classifications.
3. Average surface temperatures.
4. Faults and their types, along with intrusion mappings.
5. Type of lithologies – sedimentary or igneous and available subclassifications– and potential heat sources locations.

The assumptions of the GFI ™ method are listed below and can be understood in terms of reliability though the Certainty Estimator Index (GCEI) calculation:

- The temperatures used for the thermal gradients' calculation, both at surface and depth, are representative or close to steady-state conditions (original, natural state).
- The thermal gradients calculated are representative of conduction-dominated conditions, holding a linear trend from shallower depths of around 1,000 m or more, depending on the system.
- Temperature datasets are evenly distributed in the AOIs and GPAs.
- The geological mapping being used is correct and reliable.

2.2 GFI Methodology

The methodology encompasses the different factors controlling the resource in place availability and the geological and physical properties controlling the success of the GeoHeat™ technology for sustainable energy production.

The generalized workflow is summarized in the following sections and on Figure 3.

2.2.1. Data acquisition, processing, and Geodatabase construction

This step includes the research of the general geological and geothermal background of the Area of interest (AOI), followed by the selection of GeoHeat™ Probable Areas (GPA), the temperature gradients calculation and extrapolation at different potential target depths, especially below the 2,000 m depths. This is done by data tables manipulation, cleaning and configuration in tools suited for that.

Secondly, the interpolation and mapping of the temperature is performed, producing raster files that are later vectorized and intersected with the GPA's, based on their temperature ranges to identify the areal locations and targets for GeoHeat™. These are ideally those above 300 degrees Celsius, at different depths of interest, all which are added to an estimation of the potential GeoHeat™ resource in place (GRIP) thicknesses. This threshold can vary depending on the ultimate application of the harvested heat.

Figure 3. Summary of the GFI workflow for the geoscientific feasibility of the GeoHeat™ Technology

The potential outputs from this step are products from the Geodatabase, which can be delivered as maps or shape files with attributes:

a) GPA polygons.
b) GRIP polygons within the GPAs, for identification of subareas to further exploration through slim-hole drilling or existing wells workovers.
c) Volumetric Extension of the GRIP in terms of area and thickness estimations per GPA.

2.2.2. Calculation of GRIP per GPA and GFI

The GeoHeat™ resource-in-place (GRIP) estimation is based on the stored heat method (Grant & Bixley, 2011) and uses equation 1 for its calculation.

$$GRIP = A\ h\ \rho_t\ C_t\ (T_r - T_o) \qquad \text{(Equation 1)}$$

Where T_r is the resource temperature, T_o is the endpoint of the thermodynamic process utilizing the heated fluid, such as the power plant's rejection temperature, ρ_t is the density and C_t is the thermal conductivity of the wetted rock. *A* and *h* are the area and thickness of the target heat resource, respectively. The specific heat, $\rho_t C_t$, does not generally vary among different rocks (Grant, 2011).

As the GeoHeat™ technology significantly enhances the thermal conductivity of the rock, the recoverable heat is much larger than with conventional geothermal or closed-loop wells without thermal conductivity enhancement (TRE). The specific heat is a function of the porosity of the rock, and its pore fluid. However, in low porosity rocks, the dominating factor is the thermal conductivity of the matrix. The porosity and the fluid's saturation and phase are then only considered for the GFI™ calculation when this information is available and reliable.

After the GRIP or GRIP density (i.e., GRIP per unit area or volume) is calculated for each GPA, the additional geothermal feasibility controlling factors are accounted for, such as:

1. Petrological parameters such as metamorphism trends and type indicators per GPA.
2. Intrusions, as magmatically sourced rocks reaching shallow depths and thus having locally-heated the whole column of rock.
3. Surface manifestations, such as fumaroles or thermal springs, if conventional geothermal areas have not been identified yet by previous authors, which can provide valuable structural and convection-influenced areas/volumes of rock.
4. Extensional or transtensional tectonic settings metrics, such as normal active faults, ancient rifts overlapping, volcanic features with generally increased heat flow, typically ignored in sedimentary realms but potentially significant for GeoHeat™.
5. Geochemical datasets indicating the presence of corrosive fluids in the rocks, making more attractive the use of GeoHeat™.
6. Volume of rock types at target temperatures having adequate mechanical properties for Thermal Reach Enhanced (TRE) maximization, and thus, heat recovery factor improvement.

Once the geothermal feasibility factors are selected for the AOI, the GeoHeat Feasibility Index (GFI) is calculated per GPA *j* as the combination of both the GRIP, the main thermal indicator, and the relative abundance of the GeoHeat™ favourable *m* geological factors, as seen on equation 2. For this, weighting factors w_i are used for each GFI™ subcomponent *i*, which are refined as development advances.

$$GFI_j = w_i \frac{GRIP_j}{Maximum\ GRIP\ for\ all\ GPA} + w_{i+1} \frac{\sum_m GeoFactor_j}{Total\ Geofactor\ for\ all\ GPA} \qquad \textit{(Equation 2)}$$

After the GFI™ is estimated per GPA, the GeoHeat™ Certainty Estimator Index (GCEI) is calculated to address the inequalities of the main datasets used to quantify the GFI™, which could be the number of temperature locations per spatial unit, for example. Depending on the stage of the evaluation, the GCEI can vary from the relative number of temperature measurement locations per GPA or the relationship between measurement spacing and continuity of the mapped resource on an areal basis.

This GFI™ is often normalized, dividing the GFI_j by the maximum GFI™ among all the areas, to use it as a probability indicator of feasibility and ranking or comparison basis.

The potential outputs for this step are:

1. Inventory of Geological factors favourable to GeoHeat™.
2. GRIP per GPA.
3. GFI per GPA.
4. Map of GFI™ for the full AOI.
5. GCEI per GPA.

3. GFI™ APPLIED ON A REGIONAL SCALE AND SUPPORTING WORKFLOWS FOR DE-RISKING HEAT RESOURCE IN PLACE FOR GEOHEAT™

3.1 Case Study 1 – Mixed resource types of New Mexico

New Mexico is a geothermal state, having several mapped and historically used geothermal resources, especially above 2,000 meters depths and in the medium temperature ranges, distributed mainly in three out of the four physiographical provinces, as seen on Figure 4.

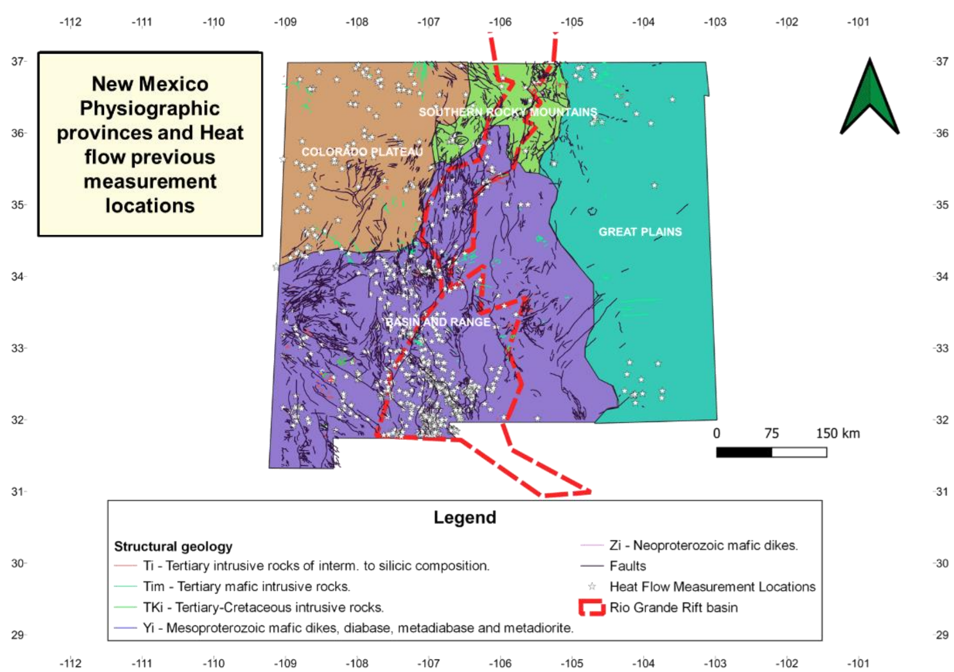


Figure 4. Physiographic provinces of New Mexico, overlapped by the main structures (fault lines and intrusions) mapped by the State's Geological Service, the Rio Grande Rift basin and Heat flow measurement locations

According to the information available online, such as in New Mexico Tech datasets, and the Bureau of Geology and Mineral Resources, seventeen areas were identified as GPAs within the state, in this case the AOI. Each one of these areas was characterized in area and predominant nature of the heat transferring mechanism occurring on them (i.e., conduction, convection or mixed), ultimately influencing the de-risking strategy that would be followed during exploration and development. These areas are mapped on Figure 5.

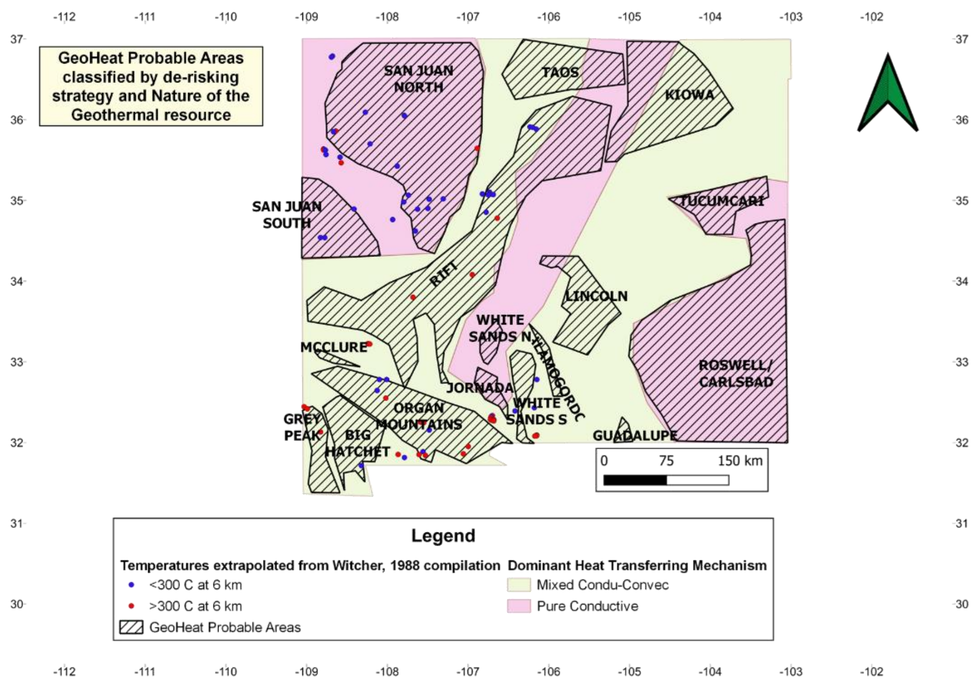


Figure 5. GPAs for New Mexico and their predominant heat transferring mechanism with some extrapolated temperature measurements at locations extracted from a report (Witcher, 1988)

Additional datasets for temperature and locations were added to the study, especially those related to heat flow measurements based on temperatures at depth (Gene Suemnicht, personal communication). Most of the datasets are rich for southwest New Mexico, where many of the conventional systems have been mapped and exploited for direct uses, such as green houses.

After the temperature datasets were compiled into one and extrapolated at different depths, they were imported to the geodatabase and 2D interpolated to generate temperature raster maps, later used with a threshold of Temperature above 300 degrees Celsius, as this is one of GeoHeat^{TM}'s target temperatures. Part of the results is shown on Figure 6, where the polygons of the GPAs are colored in green for two different depths: 3 and 6 km. These maps provide the knowledge of some of the resources, especially those within the areas of convective presence, may have more than 3,000 meters thickness, which is observed in the Southwest and the Rift GPAs.

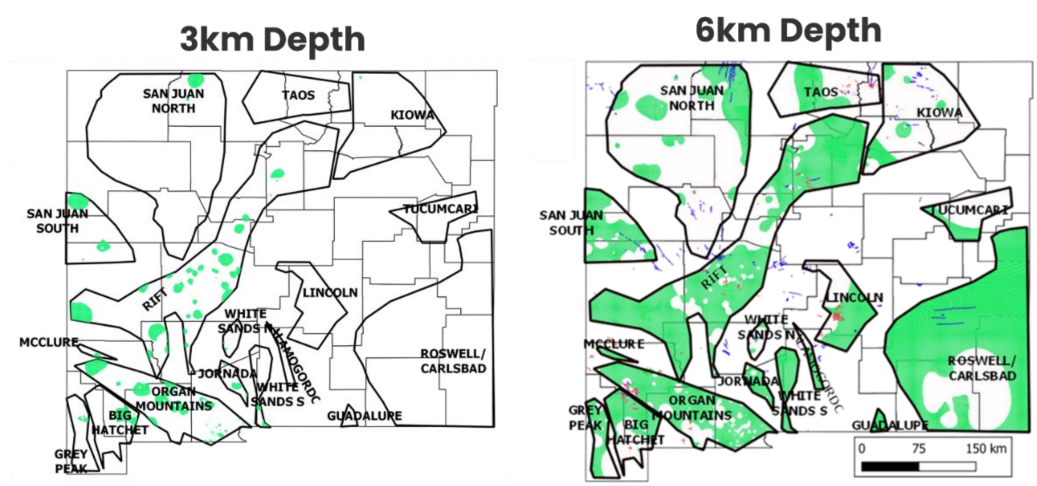
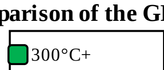


Figure 6. Comparison of the GRIP polygons for the GPAs in New Mexico at 3 and 6 km depths



For the case of 6 km depth, the GFI^{TM} was calculated and mapped as seen on Figure 7, it can be seen that feasibility increases due to the larger areas with temperatures above 300 Celsius, making GeoHeatTM and its deep, hard-rock drilling capabilities, optimal for targeting these unconventional geothermal targets. Some areas, however, posses significant amounts of temperature potential locations, such as Roswell/Carlsbad and Tucumcari, which could help confirm the reliability of the GFI as a lower uncertainty would be achieved.

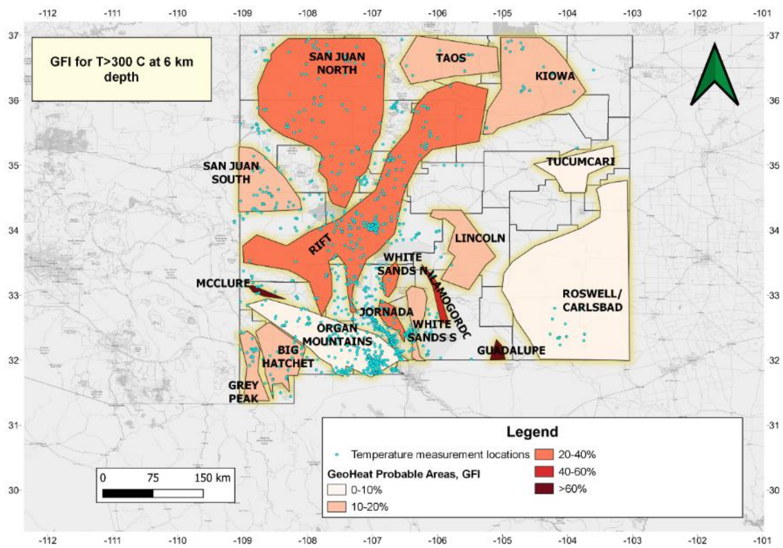


Figure 7. GFI™ for 6 km depths within New Mexico's GPAs

The GFI™ was thus calculated by assuming a constant temperature of 300 degrees C for all the polygons within the GPAs, and a constant Specific Heat of 2.5 MJ/m^3-K. The rejection temperature was assumed to be 15 degrees Celsius, and the weighting factors were both equal to 0.5, as shown in Equation 3.

$$GFI = \mathrm{w1} \times \frac{Heat\ Density}{Maximum\ Heat\ Density} + \mathrm{w2} \times \frac{No.of\ thermal\ features}{Total\ of\ thermal\ features\ in\ all\ areas} \qquad \textit{(Equation 3)}$$

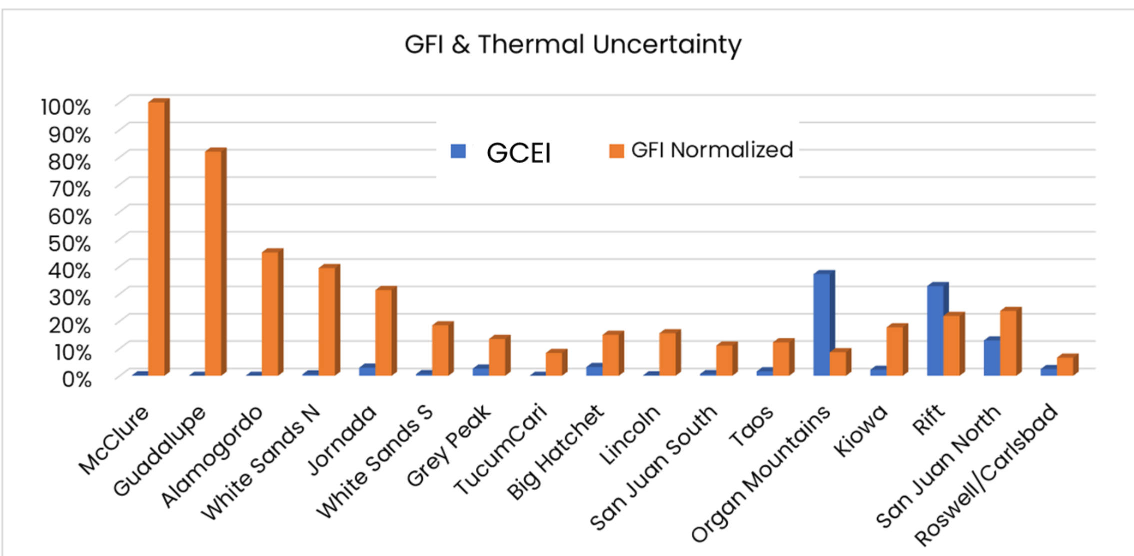


Figure 8. GFI™ and GCEI (Thermal) for New Mexico

In addition to the GFI™, which in this case is normalized, the GCEI was estimated as the percentage of certainty based on the relative abundance of temperature measurements per GPA, as shown on Figure 8. These two indicators accompany the projects as they progress in information acquisition and processing, helping optimize the well placement strategies through time, as a higher GFI and GCEI areas are the equivalents of higher opportunity and lower risks potential return on investments.

The imbalance between GFI and GCEI indicates areas that can be either improved in terms of information (low GCEI) or in geological and geothermal characteristics (low GFI). In this case, areas such as Rift and Organ Mountains can be compared more easily in terms of feasibility, as they have similar certainty levels, making the former one more attractive than the latter one. Areas such as McClure, show high feasibility but an extremely low certainty, indicating opportunities for information acquisition, processing, and input into this workflow. In the other hand, areas such as San Juan North, can be compared to Rift and Organ Mountains only if a bit more datasets are added.

The coupled evaluation of the GFI™ and the GCEI makes GPAs systematically comparable. As the GFI progresses in time, by adding more parameters later and datasets for higher GCEIs, some resources can turn into recoverable reserves while others will remain contingent, non-recoverable or non-commercial.

Derived from this analysis, additional opportunities were identified to de-risk the GRIP, not only in sedimentary dominated GPAs such as in the San Juan or Roswell/Carlsbad areas, but also in the NE of the state. This, due to the more than 100,000 oil and gas wells that have been drilled along the state that would serve the purpose to make additional stabilized temperature measurements without the need for drilling new holes. These opportunities are mapped on Figure 9.

Extra refinement of this evaluation could be done by considering higher temperatures inside the polygons, but a conservative approach was taken to delimitate the GFI™ based on the **minimum GRIP** for a representative range of target depths for the GeoHeat™ technology, specific for this project. The GFI™ can be calculated at shallower depths, where convection may have a larger input, but it has not been done in this evaluation.

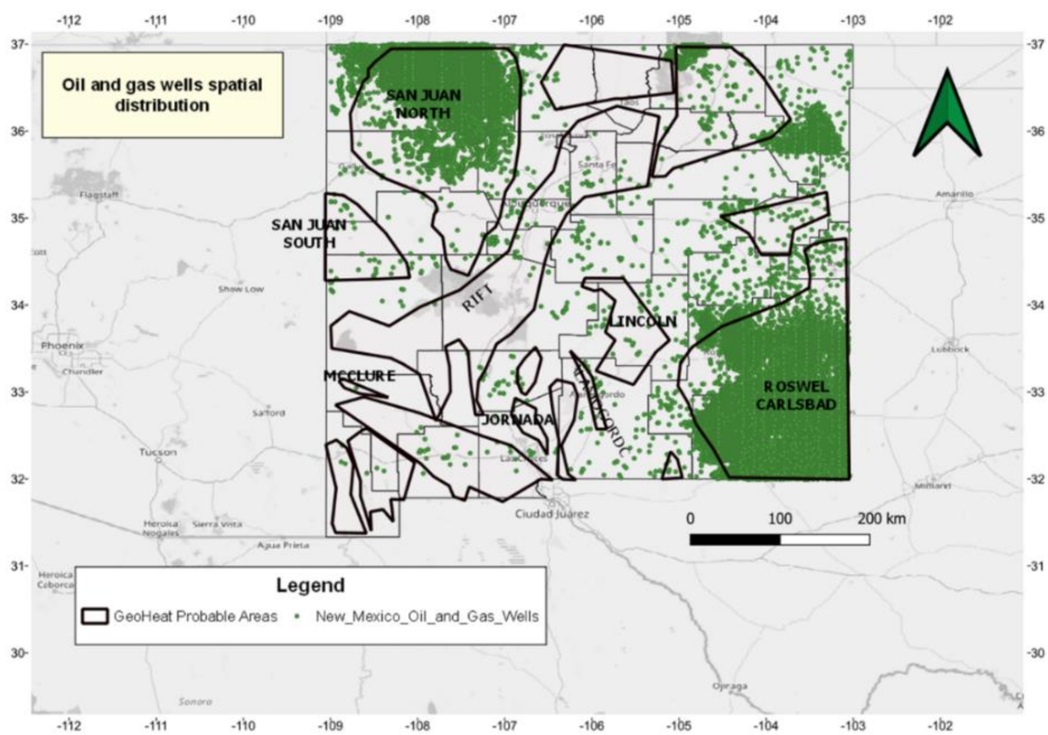


Figure 9. Locations of Oil and gas wells of New Mexico as potentially available for future temperature measurements in the context of the selected GPAs.

3.2 Case Study 2 – Sedimentary basins in Kentucky

The state of Kentucky has a large amount of public geological and well information, including:

- More than eleven thousand oil and gas wells with estimated temperature gradient.
- The locations of more than 10 thousand coal boreholes.
- The location of 13,500 abandoned oil and gas wells.
- Geological mappings of structures classified by type and dominant lithologies.
- The locations of 1400+ abandoned coal mines.
- Location and characterization of ancient rifts or extensional structural regimes.

The spatial distribution of the available information is shown on the Kentucky state maps in Figure 10. For this case, the GFI™ was not calculated, but the GPAs were delimited which, coupled with the geothermal gradients and feasible extrapolated temperatures at six-kilometer depths, helped on the selection of ten sites for confirmatory temperature measurements, as the preliminary steps to the GFI™ described on Figure 2 were followed. The GPAs were defined based on the thermal profiles from petroleum wells, the type of faults related to extensional events, the presence of ancient rifts and igneous intrusions outcropping, as no specialized subsurface data is currently available to define these at depth.

The result is an integrated map with the GPAs and selected locations for confirmatory temperature measurements under stabilized conditions, as seen on Figure 11.
For these wells, the preliminary temperature measurements available were used to estimate the depths at which 300 degrees Celsius temperatures would be found, as listed in Table 1.

As this is a sedimentary basin with no previous evaluated geothermal potential nor stabilized temperature measurements, the GFI™ was not calculated.

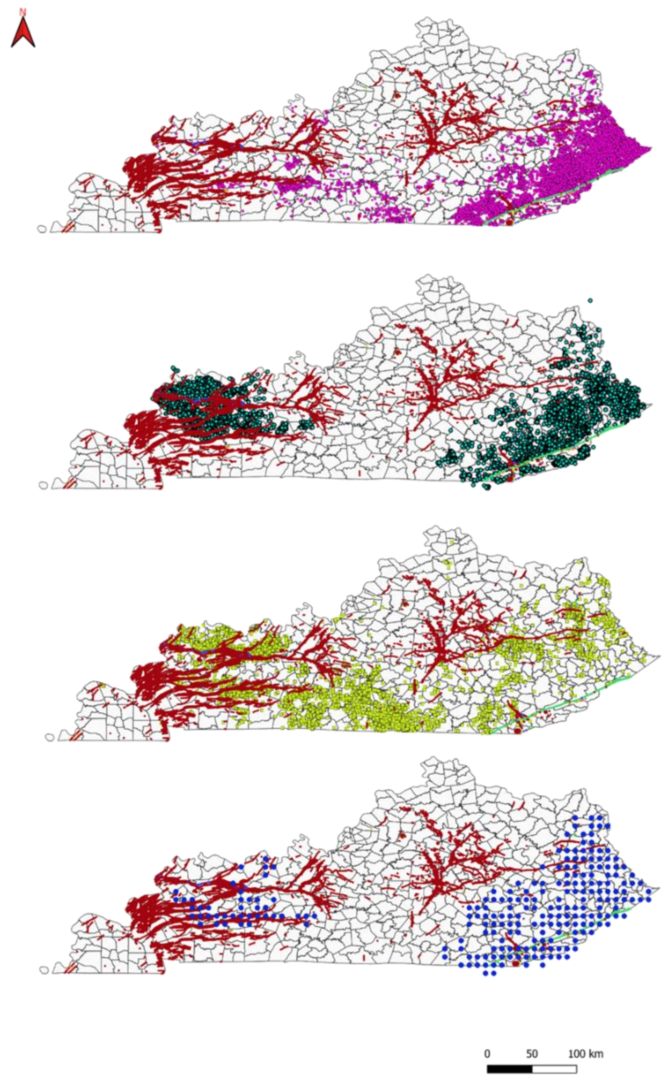


Figure 10. Geographical inventory of information available on wells and land mines' locations in Kentucky, overlying the main faults mapped at the surface by Kentucky Geological Service. In magenta, the oil and gas wells with thermal gradient calculation, in teal the core boreholes, in light green the abandoned oil and gas wells and in blue the locations of the mines. Red lines are normal faults and green are thrust faults.

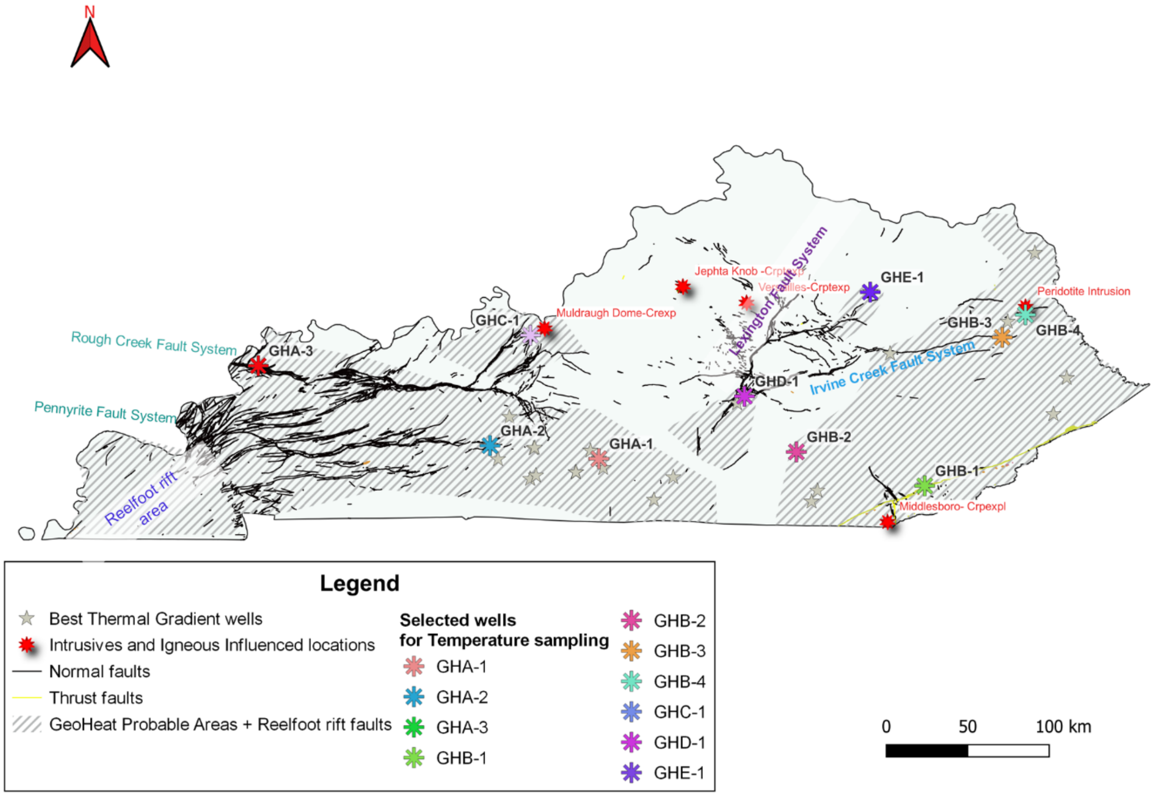


Figure 11. Integrated map of Kentucky with GPAs and wellbores selection for confirmatory measurements of temperature. Relevant geological features and structures are also shown, along with other potential high-temperatures

Table 1. Preliminary geothermal gradients and Estimated depths for GeoHeat™ Feasibility. The third letter of the well ID indicates the name of the GPA where it belongs. The lowest footage required to reach 300 C is highlighted in green while the largest one in red.

Well ID	Preliminary Thermal gradient (F/feet)	Depth for 300 C /572 F (feet)
GHA-1	0.0355	16,122
GHA-2	0.0304	18,816
GHA-3	0.0375	15,237
GHB-1	0.0324	17,660
GHB-2	0.0342	16,720
GHB-3	0.0335	17,098
GHB-4	0.0423	13,537
GHC-1	0.0342	16,727
GHD-1	0.0314	18,200
GHE-1	0.0500	11,440

Wells on Table 1 can thus be ranked in terms of depths needed for a specific target temperature. Additionally, as can be seen from this in-depth, integrated data review, geothermal "hot-spots" can be found within an area not commonly associated with geothermal opportunities. Detailed data evaluation is required to rank prospects from a techno-economic point of view. In this case, the 300°C isotherm can be found at depths between 11,440' and 18,816', which has significant ramifications for project economics. For instance, when comparing GHE-1 and GHA-2 depths for 300 Celsius, a significant increase on drilling footage difference (7,400 ft) can be used as feasibility indicator, making this workflow application essential for well and exploratory efforts placement.

4. CONCLUSIONS

A method for the evaluation of the feasibility in terms of risk and certainty for closed-loop technologies has been applied to GeoHeat™, based on preliminary and public information, for ranking areas of interest for the technology, in two different US states. This was done based on the integration of geological and geothermal data through geographical information systems.

This workflow indicated that the geothermal potential evaluation worldwide can be further improved if additional technologies are included in terms of their own favourable factors.

The GFI™ workflow is adaptable to any maturity state of the projects and can be iteratively improved as the data becomes richer, both in terms of scale and abundance, and as technological advances extend the depths, geology, and temperatures required for techno-economic feasibility.

The main goal of this workflow is to provide guidance for companies and governments on technology-focalized investments, in a comparative and objective manner. This will help on targeting green and brown-fields opportunities within existing geothermal systems or conduction-dominated hot-spots located in both sedimentary and igneous environments.

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APPENDIX – LIST OF ABBREVIATIONS

GFI = GeoHeat Feasibility/Favourability Index
GPA = GeoHeat Probable Area
GRIP = GeoHeat Resource in place, MW
rf = GeoHeat Recovery factor, fraction or percentage
AOI = Area of Interest
GCEI = GeoHeat Certainty Estimator Index
T = Temperature
r = GeoHeat reservoir conditions
o = thermodynamic endpoint to fluid utilization conditions
ρ_t *= Wetted in-situ rock density*
C = degrees Celsius or centigrade
C_t *= Thermal conductivity of the wetted in-situ rock or background thermal conductivity*
A = Area of the GeoHeat resource
H = Thickness of the GeoHeat resource
m = Geofactors index for GeoHeat favourability
w_i *= weight for GeoHeat Favourability factors*