

Using Fuzzy Logic to Identify Geothermal Resources and Quantify Exploration Risk through Play Fairway Analysis

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ABSTRACT

The objective of this work is to develop a methodology based on fuzzy logic to address the overarching theme of uncertainty quantification and reduction in identifying geothermal resources through Geothermal Play Fairway analysis. The study area includes regions from northeastern California, southern Oregon, and northwestern Nevada, bounded on the east by the Basin and Range extensional regime, and on the west by the Cascade (volcanic) Range. This is a region where geothermal resources are known to exist based on past exploration efforts, but their extent, risk and exploitability are poorly understood and understudied on both local and regional scales. Two main geothermal resource elements are investigated: permeability and heat. The available data used to explain these two elements are structural data (including fault length, age, stress, strain and seismicity) and heat source related measurements (including maximum heat flow data, maximum temperature data, maximum downhole temperature, smoothed heat flow, and geothermometry measurements). Fluid geochemistry data and some geophysical measurements (e.g., magnetotellurics data) are investigated, but not included in the assessment due to limited regional coverage.

To apply fuzzy logic for identifying blind geothermal resources, first, a set of fuzzy numbers and rules are formed based on data histograms and expert opinion. Then for each grid block (the study region was discretized into grid blocks with a size of 2×2 km), a fuzzy logic rule is applied to combine different data types to arrive at a favorability map and the uncertainty associated with the map. The final map is able to identify known geothermal resources and new areas with potential. The proposed methodology is generic and can be applied to other areas.

1. INTRODUCTION

Play Fairway Analysis (PFA) is a technique that has been used for oil and gas exploration to identify prospective resources for hydrocarbon extraction. The technique evaluates key elements required for the existence of such resources within a given geologic province. When it is used in geothermal exploration (e.g., Weathers et al., 2015), the key elements include: heat source, permeability, fluid to carry heat to surface, a reservoir unit, and cap rock. The objective of this study is to develop a method using play fairway concepts to identify geothermal resources. The method should be able to provide a probability map of geothermal resources as well as the uncertainty associated with such a map (i.e., to be used to quantify risk of failure). Our study area (Figure 1) includes regions from northeastern California, southern Oregon, and northwestern Nevada, bounded on the east by the Basin and Range extensional regime, and on the west by the Cascade (volcanic) Range. Two geothermal play type end-members, Medicine Lake (volcanic-hosted) and San Emidio (amagmatic extensional-hosted), are also included in our analysis. They are known geothermal systems that can be used to test our proposed method.

In this paper we use the fuzzy logic approach for data integration to construct geothermal potential map. Reasons why fuzzy logic is an appropriate technique for the GPFA include: 1. Fuzzy logic has the advantage of easily incorporating linguistic expert knowledge to identify geothermal resources or estimate properties; 2. There exist a variety of data types, but some types of data may be sparse. It is relatively easy to include all these data into resource evaluation using fuzzy logic; and 3. The result from fuzzy logic evaluation provides an uncertainty range, which can be used in the risk assessment of the evaluation. For this study, the fuzzy logic tool box from Matlab is used to perform such an evaluation.

We first briefly discuss the data that are available for GPFA for the study region. Then we focus on the development of fuzzy logic approach on data integration and probability map construction, followed by results and conclusion.

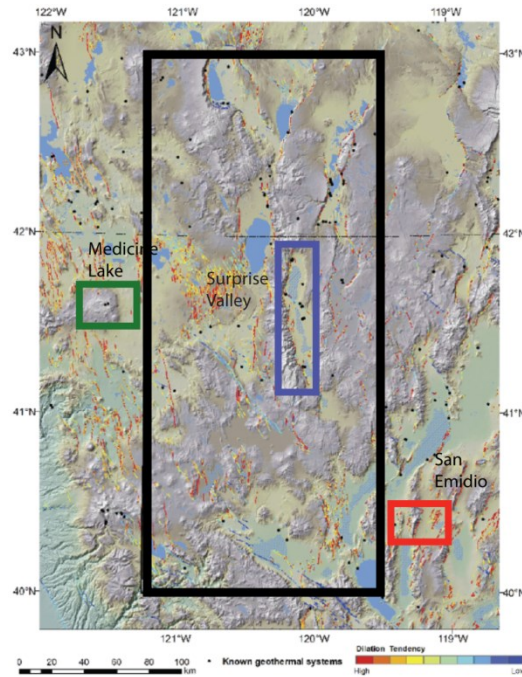


Figure 1: Study region (black rectangle) with two training sites Medicine Lake (green rectangle) and San Emidio (red rectangle). These are plotted on top of a relief map with estimates of dilation tendency of known faults, and known geothermal systems. The Oregon border is at 42°N, and the California border is just west of the eastern boundary of the Surprise Valley box (blue rectangle).

2. DATA COMPILATION AND PRE-PROCESSING

The data collected for the region studied are summarized in the following categories: 1. Geological (structural) data; 2. temperature/heat data; and 3. fluid chemistry data. The goal is to gain information on the key elements (i.e., permeability, heat source, fluid, reservoir unit and seal) by interpreting and integrating these data.

For the convenience of evaluation, the study area is discretized into 2 km by 2 km grid blocks, which results in a total of 12,960 grid blocks. The above mentioned data are intended to be used as proxies to evaluate the geothermal potential for each grid.

2.1 Geological data

We have considered four geological factors related to permeability: fault favorability (which includes fault age, length, and slip/dilation tendency), structural setting type, strain rate, and magnitude of earthquakes. These factors are used to evaluate permeability favorability for each grid block.

2.2 Temperature/heat data

In this category, we incorporate the following data: heat flow data, temperature gradient data, and temperature measurements.

There are two types of heat flow data. The first type is the maximum heat flow at USGS wellbore locations. The measurements are relatively reliable, but there are only 74 measurements among all the 12,960 grid blocks. The second type of heat flow data is a smoothed heat flow map generated by the USGS (Williams and DeAngelo, 2011) through smoothing, interpolation, and extrapolation processes. The advantage of this map is that the smoothed heat flow is available for each grid block, but the high and low values are smeared out and the interpolated or extrapolated data are not as reliable as the ones directly taken from the wells.

Temperature gradient data at some well locations provide similar information as heat flow. The measurements have the same problems as heat flow measurements at wells, i.e., the data are too sparse (only at 136 locations over the study area). A linear correlation is expected and found between the maximum heat flow and temperature gradient at the same locations. This relationship can be used to predict maximum heat flow at locations where temperature gradient data are available, but heat flow measurements are not.

Direct temperature measurements with known maximum well depths are available at 194 locations. We assume that these measurements were taken at the bottom of the well. So a similar measure to geothermal gradient – the temperature divided by well depth, is used in the evaluation of heat.

2.3 Fluid chemistry data

Water chemistry data were collected and compiled, but due to uneven distribution and sparsity of data, no reliable interpretation can be made. Therefore, most of them are not used in the probability map construction. The only type of data used is the calculated temperature from Na/K geothermometer, which is relatively reliable and contains 760 points. Currently we only have data to infer permeability and

heat favorabilities. Our focus is to develop the fuzzy logic data integration method and demonstrate the proposed method, creating not only a probability map for potential geothermal resources, but also providing an uncertainty range of the probabilities. We recognize a thorough and complete GPFA will require information on all essential elements mentioned previously. However, we can achieve our goal by demonstrating our proposed method with only permeability and heat. The method would work the same way if additional data were available.

3. USING FUZZY LOGIC FOR DATA INTEGRATION TO CONSTRUCT PROBABILITY MAP

The primary purpose of fuzzy logic is to formalize reasoning in natural language. A simple fuzzy if-then rule assumes the canonical form. For example, one of the many fuzzy rules to evaluate fault favorability for permeability can be formulated as:

If a fault at a location is **LONG**, and **YOUNG**, and the fault stress is **HIGH**, then the fault is **FAVORABLE** to permeability.

To be able to apply this rule, it is necessary to define fuzzy numbers for “LONG” or “YOUNG” fault, “HIGH” stress, and “FAVORABLE” to permeability. In fuzzy logic, they are defined using membership functions. These functions are discussed below for both permeability and heat attributes.

3.1 Evaluation of Permeability

Figure 2 shows how membership functions are defined for each fuzzy number representing variable “fault length”. X-axis is the logarithm of a fault length. Y-axis defines the membership. A “short” fault is defined for the logarithm (base10) of the fault length $-\log_{10}(L)$ between 0 and 3.5, the membership for a fault with $\log_{10}(L)$ between 0 and 3 to be “short” is 1, and a fault with $\log_{10}(L) \geq 3.5$ to be “short” is 0; “medium” defined for $3 \leq \log_{10}(L) \leq 4$; and “long” for $\log_{10}(L) \geq 4$. Based on these definitions, a degree of membership of each grid block in the fuzzy set will be calculated. For example, if a grid block with faults has $\log_{10}(L) = 3.25$, the membership that it is “short” is 0.5; the membership that it is “medium” is 0.5; and the membership that it is “long” is 0. For each type of data, the membership functions are defined based on the histograms of all the 12,960 data points.

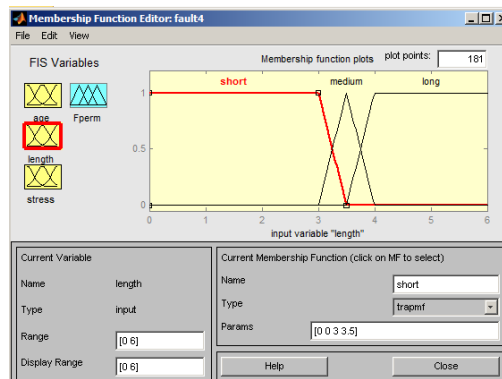


Figure 2. Membership functions for fuzzy numbers representing variable “fault length”.

Similarly, membership functions are defined for variables “fault age”, and “fault stress” (use average of slip and dilation tendency). The next step is to define a set of fuzzy rules to infer favorability of a fault to permeability. The rules in this project are derived based on expert-knowledge. An example of a rule is “If a fault at a location is **LONG**, and **YOUNG**, and the fault stress is **HIGH**, then the fault is **FAVORABLE** to permeability.”

A total of 33 rules are defined to infer fault favorability to permeability. For each grid block to be evaluated, usually multiple rules are applied. Rules are then combined using the standard inference method “mamdani”, provided by Matlab. The output is an aggregated membership function which, in the end, is usually “defuzzified” by some averaging processes (e.g., using the “centroid”).

A similar approach is used for the next step of evaluation, which includes setting type, seismicity, strain rate and fault favorability to create a permeability map.

3.2 Evaluation of Heat

The evaluation of heat is a little different than the evaluation of permeability for two reasons: 1. Only smoothed heat flow is available for all the grid blocks; all other types of data have much less spatial coverage; and 2. The quality of each type of data is clearly different (e.g., the smoothed heat flow is not the best for heat evaluation as the peak heat flow does not stand out due to the smoothing process, as the USGS heat flow map for the western United States was generated with a cap on the maximum heat flow value of 120 mW/m^2 to minimize the influence of anomalously high heat flow associated with hydrothermal systems (Williams and DeAngelo, 2011)). As a result, preferences are made for different types of data, with maximum heat flow/temperature gradient (the linear functional form obtained from Figure 6 is used to predict maximum heat flow at locations where it is not available but maximum temperature gradient is) most preferred. The membership function of each variable is defined based on the histogram data, which provide the range of the data.

3.3 Construction of Favorability Map

For each grid block, now there is a favorability score with upper and lower bounds for both permeability and heat. To construct the overall favorability map, we have defined five fuzzy numbers for permeability (see Figure 3a), similar five fuzzy numbers for heat and nine fuzzy numbers for the final favorability (see Figure 3b).

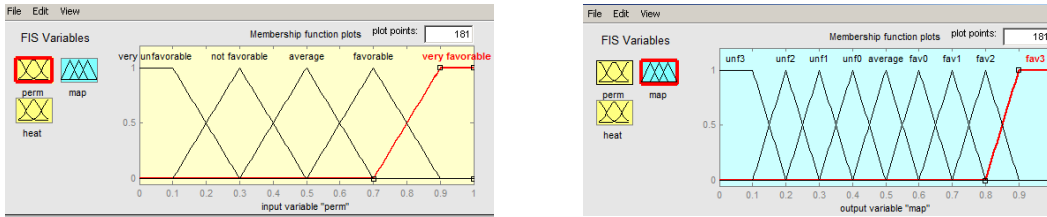


Figure 3. Fuzzy numbers used to define a. permeability favorability and b. overall favorability

4. RESULTS

Figure 4a shows the overall potential geothermal resource (mean). Medicine Lake and San Emidio clearly stand out. In addition, the Lakeview area in Oregon also appears as a prospective target, as it is known KGRA and the site of a new district heating project. These identified red spots confirm the validity of the used methodology: even though fuzzy rules are only generated from expert knowledge (i.e., no learning site data are used), the final evaluation is able to identify existing geothermal resources.

We also show in Figure 4b the upper bound of the favorability map, as the upper bound can identify the risk-high benefit regions. These are the regions where more data should be collected to further determine if more focused exploration activities should be carried out.

5. CONCLUSION

In this study we use a fuzzy logic approach to integrate various types of data for identification of geothermal resources. The fuzzy logic approach has the advantage of formalized reasoning in natural language, which helps to apply expert opinion into modeling practice. Due to the large area studied, we have a range of locations; some hardly having any data, while other locations having multiple, repetitive information. Fuzzy logic can easily handle both of these situations and provide an uncertainty range based on how much/what information is available. For the study region, we identified three prospective target areas that have been proven to have geothermal potential, which provides confidence in the proposed method.

Even though we have not considered all the attributes needed for geothermal resources in this analysis, using permeability and heat attributes only is sufficient to demonstrate our proposed method. When available, additional attribute data can be easily included in the evaluation.

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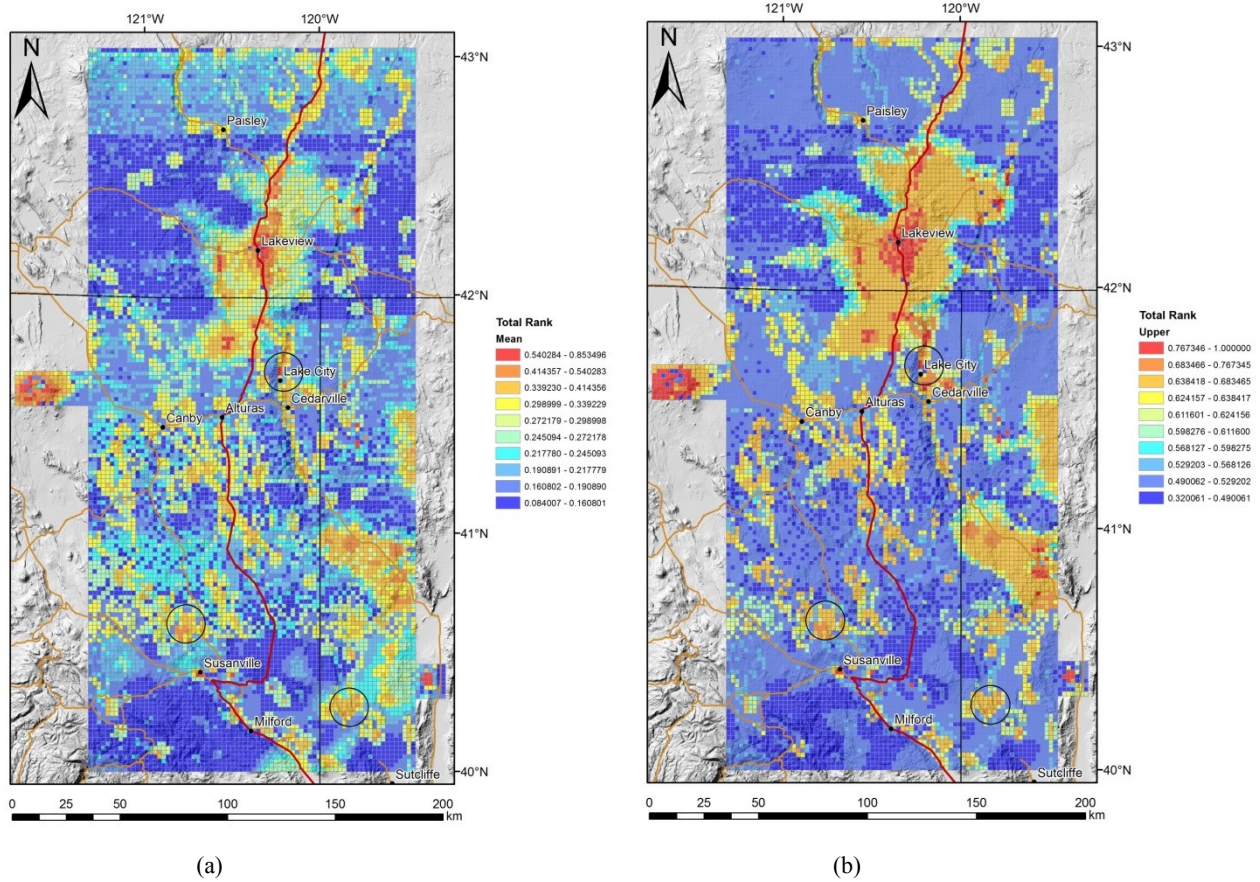


Figure 4. Computed overall favorability rank: (a) mean value and (b) the upper bound maps. Circled regions represent areas recommended for future study.

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