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# Cluster analysis as a tool for evaluating the exploration potential of Known Geothermal Resource Areas

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ABSTRACT

Although many Known Geothermal Resource Areas in Oregon and Idaho were identified during the 1970s and 1980s, few were subsequently developed commercially. Because of advances in power plant design and energy conversion efficiency since the 1980s, some previously identified KGRAs may now be economically viable prospects. Unfortunately, available characterization data vary widely in accuracy, precision, and granularity, making assessments problematic. Here we suggest a procedure for comparing test areas against proven resources using Principal Component Analysis and cluster identification. The result is a low-cost tool for evaluating potential exploration targets using uncertain or incomplete data.

## 1. Introduction

In the early 1970s, amidst a national energy crisis, the US Energy Research and Development Administration (which later became the United States Department of Energy, or USDOE) partnered with the United States Geological Survey (USGS) to identify and inventory the geothermal resources of the United States. As defined by the Geothermal Steam Act of 1970, a Known Geothermal Resource Area (KGRA) is an area where "…the prospects for extraction of geothermal steam or associated geothermal resources from an area are good enough to warrant expenditures of money for that purpose" (Godwin et al., 1971). The USDOE/USGS program of geothermal exploration identified a number of KGRAs, many of which are located in southern Idaho and eastern Oregon. Unfortunately, as the energy crisis eased during the 1980s, so did federal funding for geothermal exploration, and many of the identified KGRAs did not receive the follow-on studies that would have been required to evaluate their economic potential.

In the 40+ years since the Geothermal Steam Act of 1970, innovations in power plant design have increased the overall conversion efficiency of geothermal power developments. Although the average conversion efficiency of geothermal power plants is still the lowest of all thermal plants (Zarrouk and Moon (2014) cite an average conversion efficiency of 12%, on the basis of a worldwide review of published data), technological improvements such as double flash, triple flash, hybrid geopressure/geothermal, and binary plant designs have allowed an expansion of installed geothermal capacity to a worldwide total in 2015 of about 12,635 MWe (Bertani, 2015). In particular, binary plants, first introduced in the early 1980s, and the optimization of working fluids (e.g., ammonia, HCFC123, n-Pentane, PF5050) for a wide range of evaporation and condensation temperatures, enthalpy fluxes, and coolant velocities, have improved the performance of power plants and decreased the required resource temperatures, allowing economic development of resources that had previously not been considered viable (Hettiarachchi et al., 2007). Changes in legislation have also led to increased opportunities for geothermal development. The Energy Policy Act of 2005 amended the Geothermal Steam Act of 1970, modifying how royalties are calculated, how land is leased, and providing tax incentives and loan guarantees for certain types of energy resources in an effort to make geothermal (and other renewable resources) more competitive with fossil fuel electrical power generation.

As a result of the changing technological and economic landscape, KGRAs that were previously identified as not economically exploitable may now be commercially viable. Unfortunately, efforts to reevaluate data collected during earlier phases of exploration have been hampered by heterogeneous quality and granularity, as well as by site-to-site variations in observed parameters. To address these challenges, researchers at Lawrence Berkeley National Laboratory and Idaho National Laboratory, in collaboration with scientists at the University of Idaho, have been working to develop an approach to making between-area comparisons that can be used with incomplete and/or uncertain data.

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Here, we present one possible approach to such between-site comparisons. Our method applies Principal Component Analysis (PCA), Hierarchal Cluster Analysis (HCA), and *K*-Means Cluster Analysis (KMCA) to compare existing data from a group of candidate areas to data from multiple (high- and low-geothermal potential) control groups. The final result of the analysis is a dendrogram of related sites (see supplemental material S1 and S2) that can be used to help prioritize future exploration and characterization efforts.

## 2. Study area description

The KGRAs evaluated in this study are all located in either eastern Oregon or southern Idaho in the northwest region of the United States. With one exception,[1] the areas fall into one of two geological provinces: the Basin and Range province, or the Snake River Plain. We first present general background information on the geology and geothermal setting of these two provinces, followed by a brief description of the KGRAs included in our investigation.

### *2.1. The Basin and Range*

The Basin and Range province is an extensional terrain comprising a large number of horst and graben structures distributed across the western United States (Fig. 1). Thinning of the crust due to east–west extension allows for variable, but generally high, heat flow (from about 60 mW/m$^2$ to > 100 mW/m$^2$; Blackwell, 1983). Northwest–southeast oriented bulk regional extension in this area is generally manifested along northeast striking faults (Pezzopane and Weldon, 1993; Blewitt et al., 2003), and high-temperature geothermal systems are preferentially located along northeast-striking lineaments (Koenig and McNitt, 1983; Coolbaugh et al., 2003), or are associated with accommodation zones and other structurally favorable settings (Faulds et al., 2011, 2013). Geothermal activity in the region is generally assumed to derive from topographically-driven deep circulation of groundwater, although magmatic heat sources are likely responsible for a subset of areas (Koenig and McNitt, 1983). The high heat flow of the region, coupled with active extensional to transtensional faulting, creates a favorable environment for geothermal development. Apart from the large number of known and potential conventional geothermal resource areas in the US Basin and Range province, it is also believed that the region presents opportunities for "unconventional" (Engineered/Enhanced Geothermal Systems, or EGS) resources. A review of US geothermal potential cited the Great Basin (a subset of the US Basin and Range) as first in a list of high-grade EGS resources (Tester et al., 2006).

### *2.2. The Snake River Plain*

The Snake River Plain (SRP) is a large igneous province that stretches some 640 km across southern Idaho, from the Idaho–Oregon border to the northwest corner of Wyoming (Fig. 1). The region is a shallow physiographic depression that cross-cuts pre-existing Basin and Range topography (Pierce and Morgan, 1992; Rodgers et al., 2002; Smith et al., 2009). The western part of the plain is a large tectonic graben filled with thick (1000s of meters) lacustrine deposits that are underlain by rhyolitic ignimbrites and basalt flows. In contrast, the Eastern Snake River Plain (ESRP) was formed by a string of large calderas associated with the migration of the North American Plate over the Yellowstone hot spot during the past 17 My (Pierce and Morgan, 1992). Up to 2 km of Holocene to early Pliocene basalts underlie the plain, which were erupted from shield volcanoes and NW-striking volcanic rifts. Beneath, and largely obscured by the basalts, are extensive rhyolitic ignimbrites and lava flows that are known from

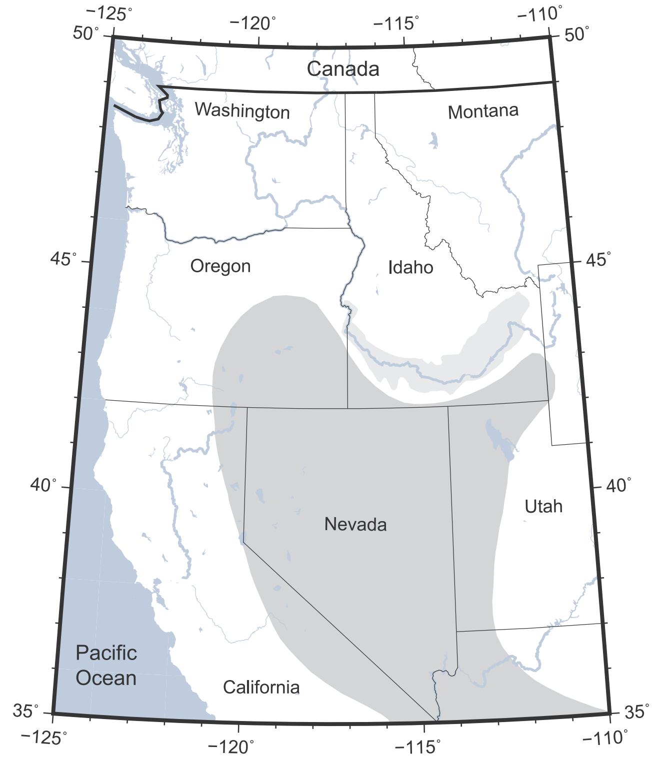


**Fig. 1.** Map of the western United States, showing the general area of the northern Basin and Range Province (darker shaded region) and the Snake River Plain (lighter shaded region) in southern Idaho. Note that some authors define the Basin and Range to include much of Idaho and, in some cases, as far north as eastern Washington.

boreholes and exposures along the margins of the plain (Morgan et al., 2008; Podgorney et al., 2013). The Snake River Plain represents one of the highest heat flow provinces in North America (Blackwell, 1989; Blackwell and Richards, 2004), and was listed second (behind the Great Basin) in a recent survey of high-grade EGS prospects in the US (Tester et al., 2006). Near-surface heat flow is suppressed by groundwater in the high permeability eastern Snake River Plain aquifer (McLing et al., 2016), but thermal gradients are high along the margins of the plain, and heat flow below the SRP aquifer is believed to be high as a result of the intrusion of mafic magmas in a mid-crustal sill complex (Blackwell, 1989; Shervais et al., 2006; Nielson et al., 2017).

### *2.3. KGRAs*

We examined 14 KGRAs or IHRAs (Identified Hydrothermal Resource Areas; Burkhardt et al., 1980) in southeast Oregon and southern Idaho. Three of these areas currently host geothermal power plants (Raft River, Neal Hot Springs, and Summer Lake/Paisley Hot Springs) for a combined electrical output of about 37 MWe, and these areas were used as a high-potential control group (i.e., high geothermal potential). In addition to the KGRAs/IHRAs, we also included groundwater samples from one area with no known geothermal potential to serve as a low-potential control group, for a total of 15 areas included in the analysis (Table 1). The low-potential control group samples were taken from shallow wells producing Ca-$HCO_3$-type waters from the Eastern Snake River Plain that differ markedly from the deeper, Na-$HCO_3$-type waters of thermal origin (McLing et al., 2002). Brief descriptions of the 14 thermal areas included in this study are given in the following paragraphs, and their approximate locations are shown in Fig. 2.

*Alvord Basin Geothermal Area*. The Alvord Basin is a north-northeast trending structural graben located in Harney County, southeast Oregon. The area is a KGRA comprising three groups of hot springs, with

[1] Vulcan Hot Springs KGRA is located in the Atlanta lobe of the Idaho batholith, somewhat off the margin of the western Snake River Plain near Cascade, Idaho.