

Use of GIS Geoprocessing to Select the Most Favorable Sites for Geothermal Exploration in Oregon

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ABSTRACT

In order to select the most favorable sites with a geothermal potential in Oregon, a GIS-based geoprocessing technique was employed. This technique consists of compiling several GIS layers of spatial repartition of elements in favor of the presence of a geothermal system.

The datasets that have been used in this analysis were grouped into two categories; the surface elements and the subsurface elements. The surface elements consider geologic and geochemical information, whereas the subsurface elements comprise thermal data obtained mostly from shallow drilling.

After completing the different steps of the analysis, no more than thirteen sites are anticipated to have a geothermal potential and were retained. For some of these sites, more advanced exploration data are available from past studies, which will be useful to confirm the efficiency of the geoprocessed selection technique.

1. Introduction

The goal of this study is to select the most favorable areas for future, more advanced and costly geothermal exploration work in Oregon, lower the risk but also to evaluate the accuracy of the use of a GIS-based technique to define these areas. This technique has been used a few times in the past to determine the most favorable geothermal areas in Iran and Japan (Noorallahi et al., 2007, Noorallahi et al., 2008).

After a description of the surface and subsurface elements considered in the study to lead to the most favorable areas, the methodology used to combine them using the software ArcGIS10 will be described. And finally, the results will be compared to existing results of site specific exploration data in the selected area, when available.

Note that this study will prioritize areas in Oregon which are the more likely to possess a geothermal resource in the subsurface, it doesn't consider development concerns such as access, distance from population or interconnection, lands rights, etc.

2. Background

To describe the geology of Oregon, five different geologic provinces have to be considered separately: The Basin and Range, the Cascade Range, the High Lava Plains, the Columbia Plateau and the Coast Range. Each of these provinces has its own geologic characteristics (Figure 1).

The Basin and Range constitutes the southeast part of Oregon and it consists largely of Paleozoic to Mesozoic metamorphic rocks and plutonic rocks, but is also covered with basaltic and rhyolitic rocks. The Basin and Range is also the province covering Nevada

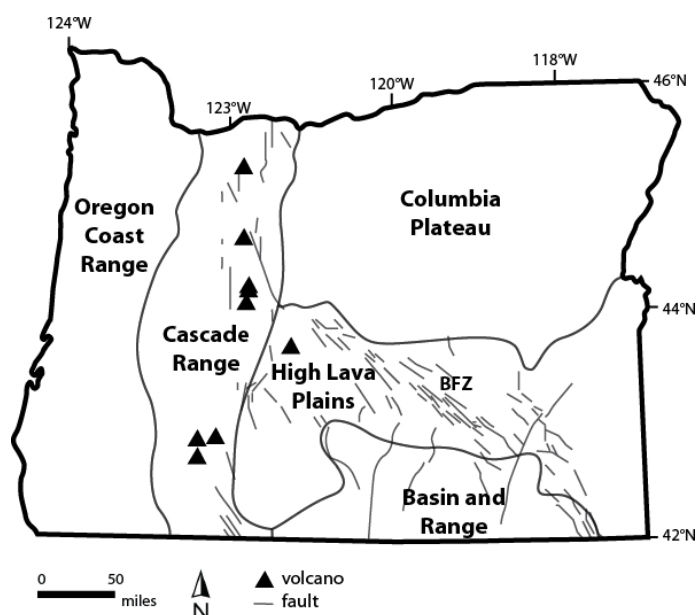


Figure 1. Physiographic provinces of Oregon and main morphological elements, BFZ: Brothers Fault Zone).

where several geothermal plants have been operating for decades. The typical Basin and Range structure involves an elongated basin, generally following a N-NW axis and a Range front type fault permitting fluid circulation to depth.

The Cascade Range is the most important morphologic feature of Oregon; it is a 1,200 km long volcanic arc that extends from southern British Columbia to northern California. The Cascade Range is separated into two distinct provinces: the Western Cascade Range; a deeply dissected uplifted block of Miocene and older tuffs and lava, and the High Cascade Range; a relatively undissected pile of chiefly post Miocene volcanic rocks (Priest et al., 1983).

The High Lava Plains form a boundary between the Columbia Plateau to the north and the Basin and Range to the south. This province is marked by the Brothers Fault Zone, a northwest trending zone of normal and strike-slip faulting. The eruptive centers for both basaltic and rhyolitic volcanic rocks are concentrated in the zone of faults and in some nearby subsidiary faults (Stewart, 1978, Walker, 1977).

The Columbia Plateau, in the northeast part of the state, is a continental plateau covering parts of Washington, Oregon and Idaho. It includes the Columbia Basin to the north and the higher elevation Blue Mountains and lava plains to the south. Before the massive Miocene Columbia River basalt outflow, the plateau was subject to extension. Morphologically, the province is now a series of valleys and ridges due to reverse faulting and folding of the surficial basalt, but normal faulting is also common (Catching and Mooney, 1988).

The Oregon Coast Range is an uplifted belt along the Pacific coast, as the result of the plate convergence. It is composed of accreted oceanic sediments (Kelsey et al., 1996).

3. Surface Evidence Layers

In this first group of GIS layers, available surface information considered as evidence or as a parameter for a geothermal system to occur have been put together. The evidence is mostly geologic and geochemical: volcanoes and recent volcanic rocks, faults and geothermal manifestations (figure 2).

The geology plays an important role in the occurrence of geothermal systems. The presence of a heat source and paths for fluids is essential. Indeed, elements such as young volcanoes or recent volcanic rocks can lead to the presence of a heat source and the presence of faults and fractures is crucial to create paths for fluids.

Other elements could have been considered in this analysis, such as hydrothermal alteration zones, but these data are more site specific and are not available at the scale of the entire state.

3.1 Volcanoes, Calderas and Craters

The volcanic elements such as craters, calderas or active/young volcanoes are direct indicators for the existence of an underground heat source.

Oregon volcanoes are almost all related to the High Cascades and are composed primarily of upper Miocene to Quaternary volcanic rocks. A part of the arc is characterized by relatively high rates of Quaternary volcanic extrusion. The Cascade Range

also includes several silicic volcanic systems that are probably young enough and large enough to retain substantial amounts of heat. Among the most active central vent volcanoes are Mount Hood, Mount Jefferson, the Three Sisters, Broken Top, Crater Lake caldera or Newberry.

At the same time, in the High Lava Plains, the Newberry Caldera was formed. It has erupted several times in the Holocene, and as recently as 1,400 years ago (vulcan.wr.usgs.gov/Volcanoes/Newberry).

3.2 Quaternary Volcanic Rocks

Upper Pliocene and Quaternary volcanoes of the High Cascades have erupted lava flows and pyroclastic material that ranges in composition from basalt to dacite, with the exception of Mount Hood which has also erupted rhyolite.

Older volcanic rocks occur in the Western Cascades province in where volcanic activity started 40 million years ago and gradually decreased until Miocene. Most of the rocks are altered volcanic flows and pyroclastic rocks, and have been intensively eroded. These volcanic rocks don't constitute evidence in favor to the presence of a heat source and were not considered favorable in the analysis.

Other older volcanics can be found in the Basin and Range province in the southeast and in the north central and eastern part of Oregon; the Columbia River Basalts, these rocks erupted throughout fissures during Miocene. These older volcanic were not considered in the analysis due to their relative old age.

3.3 Faults

Faults are a primary target in drilling to encounter permeability; they constitute a key parameter in the presence of a geothermal system.

In Oregon, several major structures control the distribution of faults: the southeast part is part of the Basin and Range and is dominated by major range front faults, oriented north-south, with secondary E-W fault system. Several NW-SE major fault zones also cut through a large part of south Oregon, such as the Brothers fault zone. Only a few faults are present in the High Cascades Range due to the young age of the rocks (Figure 1).

3.4 Thermal Manifestations

More than 600 thermal features are identified in Oregon, mostly hot springs but also some fumarole fields on Mount Hood.

The fumaroles are direct indicators of active volcanism. It is assumed that the probability of occurrence of a geothermal resource is higher in an area with active hot springs than in any other area.

4. Subsurface Evidence Layers

The second group of evidence GIS layers favorable to the presence of a geothermal system consists of temperature data collected below the surface, primarily from temperature gradient holes. These measurements permit the determination of the temperature distribution and locate thermal anomalies at depth to provide information on subsurface heat sources.

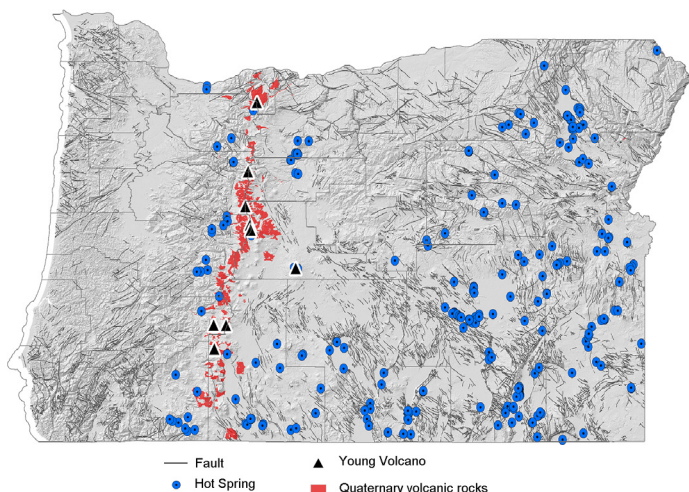


Figure 2. Surface evidence map.

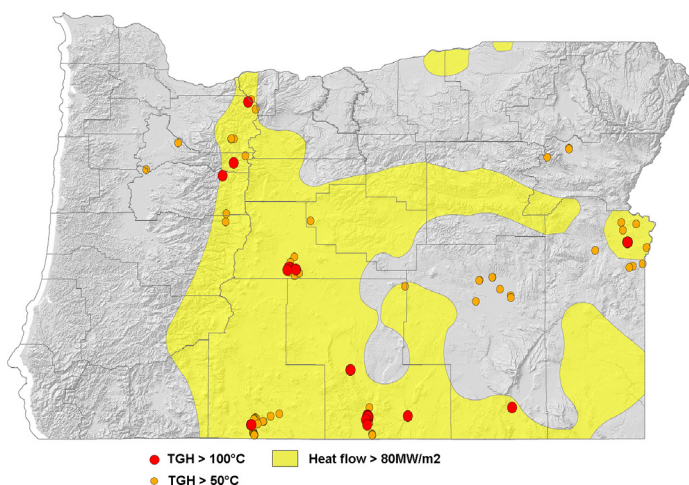


Figure 3. Subsurface evidence elements map.

Two GIS layers were considered in this group: the bottom hole temperatures and the heat flow (figure 3). Same as for the surface elements, geophysical data could have been incorporated in the analysis, but such data are not available at the state scale. They could be useful for a similar analysis at a smaller scale.

4.1 Bottom Hole Temperatures

Temperature measurements in shallow to intermediate depth gradient holes (<300 m) were obtained from the Oregon Department of Geology and Mineral Industries (DOGAMI), representing a total of about 1400 wells. Bottom hole temperatures ranged from 20 to 265°C. All these holes were divided in three categories: the holes below 50°C were removed from the database, and the remaining ones were separated in two groups: less than or greater than 50°C.

4.2 Heat Flow

Heat flow depicts the natural heat loss from the interior of the Earth to the surface (smu.edu/geothermal). In continental regions,

the average heat flow value is about 62mW/m², therefore, a heat flow above 80-100mW/m² can be considered as anomalous (Brott et al., 1976). The heat flow Q is calculated using the thermal gradient as well as the thermal properties of the rocks.

$$Q = K \frac{\partial T}{\partial z}$$

Where K is the thermal conductivity, and $\partial T/\partial z$ the geothermal gradient. The contour of the heat flow anomaly in Oregon used for the analysis was chosen as greater or equal to 80mW/m² according to the map published by Blackwell et al. (2011).

5. Geoprocessing

The GIS-based site selection technique was first introduced in the late 1990s when computer capacities started increasing, principally for city planning and economic market studies. It started then to be used in natural resources, such as in the mining industry to find new deposit areas. Geothermal potential site selection using GIS-based computerized techniques started in the mid 2000 in Japan (Noorollahi et al., 2007, Noorollahi et al., 2008).

The aim of such an approach is to compile a large amount of data together, too large for the human capacities, and observe their spatial relations.

In order to determine the most favorable areas for geothermal exploration in the Cascades in Oregon, all of the data previously cited were combined using a specific geoprocessing methodology, using the ArcGIS software of ESRI.

The methodology used consists of a sequence of simple operations which makes it easily reproducible in other areas. Three different spatial operation tools compose the data compilation analysis: ArcGIS Buffer, Union and Intersection tools.

The work using the closest methodology in the literature was completed in the Akita and Iwate prefectures in Japan by Noorollahi et al., (2007) and showed a good correlation with data of existing geothermal productive wells.

5.1 Principle

The methodology used is divided in three main steps (figure 4):

- Step 1: assign a buffer area around each element depending on its specific zone of influence,
- Step 2: combine data in each of the two groups, using the ArcGIS Union Tool to obtain two suitability maps,
- Step 3: combine the two suitability maps using the ArcGIS Intersection Tool to generate the geothermal favorability map.

The step 1 consists in extending the influence of a favorable area further than its actual surface extent. The goal of this process is to facilitate the connections between different elements and to establish a zone of influence for each element. On ArcGIS, the tool utilized to execute this operation is the ArcGIS Buffer Tool, with all output dissolved together.

The purpose of Step 2 is to combine all the evidence layers of each group of layers to obtain two different suitability maps: surface suitability and subsurface suitability. Thus the layers in the surface group (volcanoes, recent volcanism, faults and hot springs) were combine to create the surface evidences suitability map, and

the same process was used for the subsurface evidences suitability map.

The Union Tool in ArcGIS has been used to generate these maps, this tool calculates the geometric union. It avoids the loss of any prospective area not defined in all the layers of the group.

In Step 3, the two maps previously generated are being combined to obtain the geothermal favorability map. For this step the tool that will be used is the ArcGIS Intersection Tool. It will show the areas where both surface and subsurface suitabilities coincide the best.

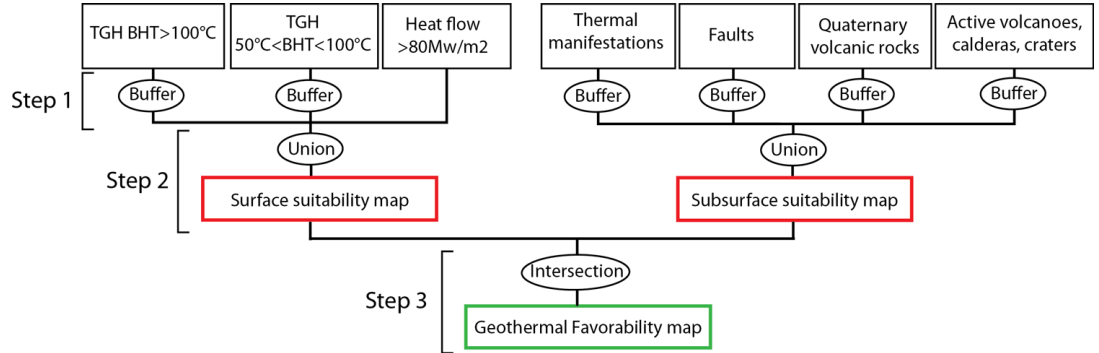


Figure 4. Flow chart of the methodology applied.

5.2 Buffer Creation

Adding a Buffer to a feature means creating a polygon around it to a specified distance, to enlarge its area of consideration.

The buffer size that has been created for each layer has been chosen mainly according to the results of Noorollahi et al (2007). In this study, 430 productive geothermal wells were used to complete a distance analysis. The results of this analysis are summarized in Table 1. For example, a hot spring is a point on the map and will be seen as a 4000 m radius circle after application of the ArcGIS Buffer Tool.

Table 1. Buffer size applied to the different elements (Noorollahi et al., 2007).

Feature	Distance (m)
Surface	
volcano	6000
recent volcanics	2000
faults	6000
hot springs	4000
Subsurface	
TGH 50°C < BHT < 100°C	2000
TGH BHT > 100°C	4000
Heat flow > 80 Mw/m²	N/A

No buffer was assigned to the layer of the heat flow, considering that this layer is already a spatial interpretation of data. Buffer sizes are given in table 1.

5.3 Suitability Maps

In order to create a unique suitability layer for each group, all the layers were combined using the ArcGIS Union Tool. This tool computed a geometric union of the input features, but keeps all the attributes of the original layers, creating a different polygon depending on how many of the input features exist at different locations.

In the surface GIS layers, the maximum layers that overlap are 4 and the minimum is the presence of only one of them. Thus, the surface suitability map ranked areas with values from 1 to 4.

For the subsurface layers, the wells were not considered as two categories but different buffer sizes were applied. If the buffer of a well >100°C cover the buffer of a well >50°C and <100°C, then the second one is not considered. Thus, the maximum value for subsurface suitability will be 2.

5.4 Generation of the Geothermal Favorability Map

To obtain the Geothermal Favorability Map of Oregon (figure 5), areas with the highest number of common layers from the surface and subsurface suitability map were defined by using the ArcGIS Intersection Tool. This tool computes a geometric intersection of the input features, or portions of features which overlap in both layers will be written to the output feature layer.

Moreover, with the combination of the ranking established in the previous suitability maps, a similar ranking will be established for the geothermal favorability map. The minimum favorability areas are where at least one layer of each group is represented, otherwise the intersection tool will not keep them in the output layer, and the minimum favorability will be 2.

The theoretical maximum favorability areas occur where no less than four layers of the surface group and two layers of the subsurface group overlap. The maximum observed favorability value is 6 at Newberry. The result shows four areas with high favorability value of 5. These areas are Mount Hood, Lakeview, Warner Valley, Alford Valley,

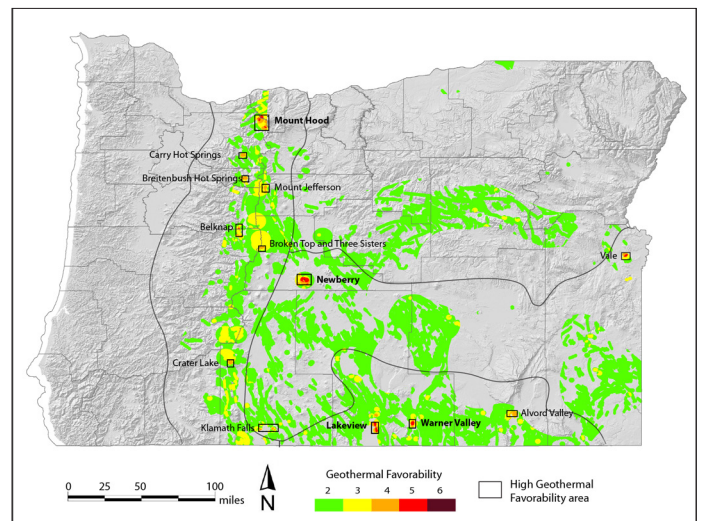


Figure 5. Geothermal favorability map for Oregon.

Warner Valley and Vale. Nine other areas also show relatively high favorability values as high as 4; these areas are: Carry Hot Springs, Breitenbush Hot Springs, Mount Jefferson (east flank), Belknap, the Broken Top and Three Sisters, Crater Lake, Klamath Falls and Alvord Valley.

6. Evaluation of the Results

This study has allowed isolating thirteen sites more likely to possess a geothermal potential in Oregon. This number of sites is reasonable considering that the full state of Oregon was considered. The selected sites are located in three provinces: the Cascade Range, the High Lava Plains and the Basin and Range.

Of the sites selected for geothermal exploration, 10 were previously referenced as Known Geothermal Resource Area (KGRA). The three others: Mount Jefferson, South Sister and Crater Lake, were however known as areas being underlain at shallow depth by thermal waters of sufficient temperature for direct heat applications.

6.1 Potential in the Cascade Range

More than half (7) of the selected sites are located in the Cascade Range and more precisely in the High Cascades where the active young volcanoes are located. However, only Mount Hood, and Belknap area show a favorability of 5 in a very small zone (<2km²). This can be explained by the lack of faults in the area, which is a major feature to consider for fluid circulation.

The most recent eruption of Mount Hood occurred about 200 years ago (Wise, 1969). The only surface manifestations of a hydrothermal system are summit fumaroles and areas of alteration surrounding the summit plug dome. Geothermal exploration in the vicinity of Mount Hood is still in its early stages, the deepest well (1800 m) reached a temperature of 120°C, giving a calculated geothermal gradient of about 60°C/km (Priest, 1982). The hydrothermal system has not yet been observed.

The Belknap Area is well known for direct geothermal use in pool and spas, located at the transition between High and Western Cascades. Geothermometer calculations from the hot spring waters estimates a possible reservoir temperature of 133°C, with potential circulation along the northwest trending faults (Priest and others, 1982).

None of the other areas have been subject to more detailed exploration work. No deep drilling data were found in the DO-GAMI database.

6.2 Potential in the High Lava Plains

Two important sites are located in the High Lava Plains; Newberry and Vale. Klamath Falls is located in a transition area called the Klamath Basin between different provinces.

Newberry has the highest geothermal favorability and is the only area showing a zone of geothermal favorability of 6, reflecting high geothermal potential. The resource has been explored for more than 30 years; in 1980, the well Newberry 2 recorded a temperature of 265°C at 942 m. Newberry is currently the site of a EGS demonstration project and deeper wells have been drilled for this purpose.

Klamath Falls is known for using geothermal heat in direct use all across the city. Well temperatures range from 38 to 110°C

and their depth from 27 to 610 m. The fluid produced is used to heat over 600 structures.

In Vale, geothermal fluids have been uniquely used for direct use and heating for a long period of time but power generation is planned to start soon. The geothermal field is being developed by US Geothermal. A 23 MWe binary power plant is currently under construction that will use 8 production wells and a series of injection wells. The maximum temperature measured in a well is 143°C, nearly as warm as the geothermometer estimates which indicated a likely reservoir temperature of about 154°C. The system has been determined as structurally controlled with upflow in a buried structure or along the faults (Wisian et al, 1996).

6.3 Potential in the Basin and Range

Three sites were selected for their geothermal favorability in the Basin and Range province of Oregon: Lakeview, Warner Valley and the Alvord Valley.

In Lakeview, geothermal fluids are currently used for a greenhouse, using two shallow wells at temperature of 104°C. Past exploration estimated the reservoir temperature at depth to be up to 157°C, based on the geothermometry.

The Warner Valley is known for the Crump Geyser; a well drilled in 1959 by Nevada Thermal Power Company that resulted in the formation of the geyser where temperature as high as 122°C were recorded at 10m depth. The area is currently under exploration by Nevada Geothermal Power (NGP), who completed a magnetic survey and plans to continue with shallow thermal wells and intermediate depth slim holes. NGP has received funds from the DOE and has entered into a joint venture with Ormat to develop a 30MW plant by 2013.

Three deep wells ranging from 640 to 770 m deep were drilled by Anadarko Company just south of the Borax Lake, in the south part of the Alvord Valley (these wells were not considered in the analysis since they are deeper than 300 m). The maximum recorded temperature in one of these wells was 163°C and the temperature surveys confirmed the occurrence of an active geothermal system.

7. Conclusion

This study has selected a reasonable number of sites showing characteristics in favor of the presence of a geothermal reservoir. Most of the sites were already known before as KGRAs.

However, for some of these sites, additional exploration data that were not included in the analysis on purpose, show that geothermal potential has been confirmed by deep well drilling or other surveys. These results show that the geoprocessing technique used gives accurate results and that the other sites that were not explored yet are worth being looked at.

This technique could be used in other areas as a first approach to select the best targets for exploration in a large area of interest.

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