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Geothermal Play Fairway Analysis of Potential Geothermal Resources in NE California, NW Nevada, and Southern Oregon: A Transition between Extension-Hosted and Volcanically-Hosted Geothermal Fields

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Play Fairway analysis is a powerful tool in the petroleum industry for reducing drilling risk. It relies on general models for sedimentary depositional systems (at the basin scale) and applies all available data to identify weighted combinations of characteristics that can be used to predict the locations where drilling is likely to lead to successful fossil fuel extraction.

This project represents an effort to apply the same approach to geothermal resource exploration and assessment. Geothermal systems do not have the same level of basin-wide coherence as oil- or gas-bearing formations, but rather are often controlled by very localized characteristics. However, all geothermal fields must include elements of a heat source, fluids, and a permeability structure that may vary systemically over a region. This is where Geothermal Play Fairway Analysis (GPFA) may be a valuable tool. To this end, we are applying GPFA to a region where both volcanically and extensionally hosted systems are known, and examine the nature of the transition between these different geothermal play types.

For this effort we have chosen a region that spans the boundary between volcanic systems and extensional systems (Figure 1) in northeastern California, northwestern Nevada and southern Oregon. Our approach in Phase I of this study is to utilize two "end member" locations: Medicine Lake Volcano (CA), which is a volcanic-hosted system (Cumming and Mackie, 2010), and the San Emidio geothermal field, which is controlled by extensional tectonics (Rhodes et al., 2010). The important GPFA characteristics of these two play types will be interpolated (in a general sense) to at least two

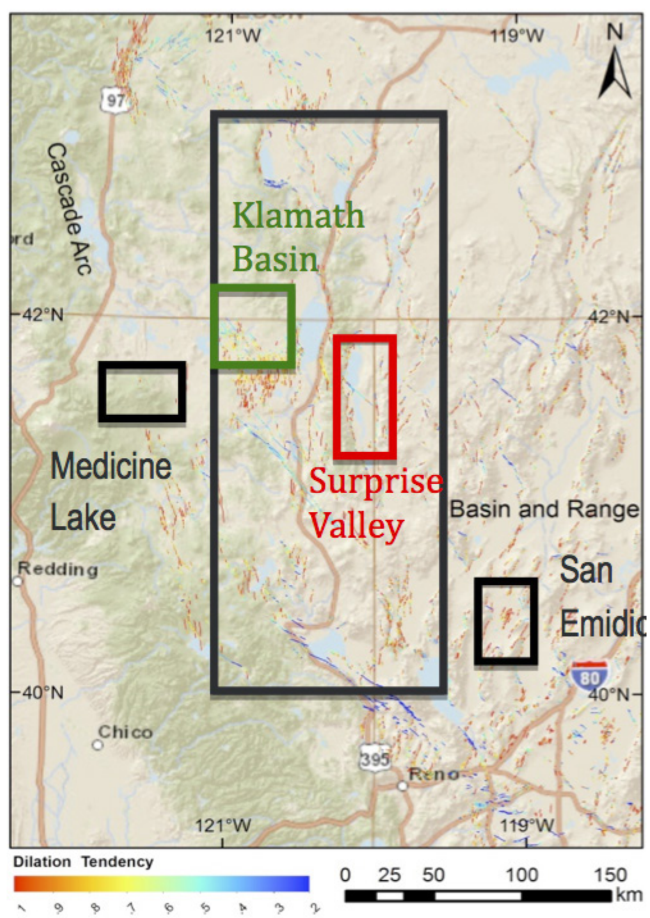

Figure 1. The Play Fairway region for our study (large rectangle). Our end-member sites are the Medicine Lake Volcano (Glass Mountain) and San Emidio geothermal sites (small black rectangles). The test sites within our region are the eastern Klamath basin (green rectangle) and Surprise Valley (red rectangle).

well characterized geothermal test areas in our transitional region (Surprise Valley and the Klamath Basin). If this approach is successful, we plan to apply this "interpolation" of play type characteristics to the entire study region.

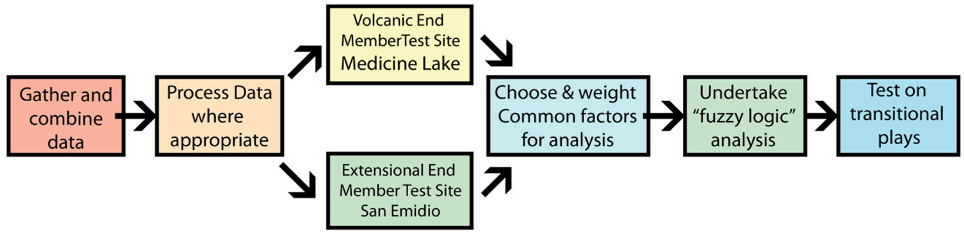

Figure 2. Work flow for Phase I of the play fairway analysis.

The project work flow (Figure 2) consists of gathering existing geological, geochemical, and geophysical data sets, reprocessing and/or reinterpreting some of those data sets, placing data sets in uniform computational environments (GIS and 3-D visualization) and determining a weighting algorithm of key attributes based on calibration with well characterized volcanic and extensional play types. The geological data include known faults, the distribution, composition, and ages of volcanic features, and the distribution of active thermal features. An example of one of these interpreted geologic data sets is the fault dilation analysis (Figure 3) conducted using the 3DStress software. The geochemical data include existing chemical analyses of surface springs and well waters. We have processed much of the water geochemistry for the area using the GeoT multicomponent geothermometry software as well as classical geothermometers (e.g., Cantwell and Fowler, 2014; Fowler et al., 2015) to estimate deep reservoir temperatures (Figure 4). Geophysical data compiled for this area include potential field exploration (gravity and magnetic surveys), some seismic and magnetotelluric surveys, seismicity (although there is relatively little), regional stress data, and heat flow data.

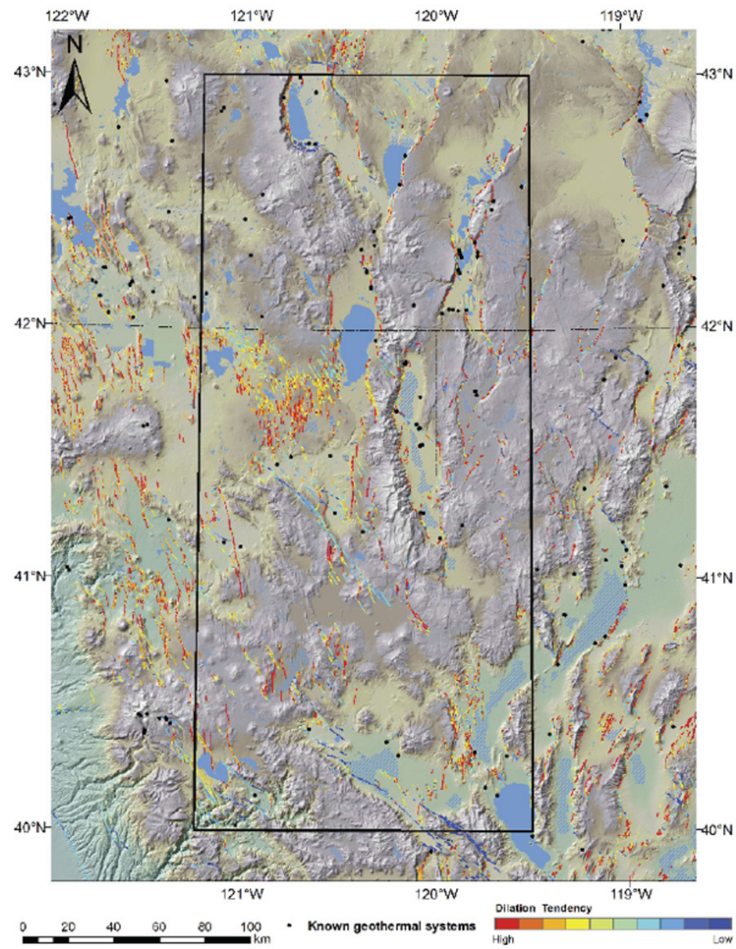

Figure 3. Slip dilation tendency analysis for mapped Quaternary faults. Black dots indicate the location of known geothermal features.

These datasets are being combined in a 3-D visualization environment and in ArcGIS for comparison and correlation (Figure 5). Parameters that are currently in our GIS system include the measured spring and well temperatures, calculated reservoir temperatures from geothermometry, presence of a favorable structural system, fault age, total length of faults per cell, slip and dilation tendency normalized to total fault length, earthquake magnitude, earthquake depth, seismic moment, total number of earthquakes, strain, age of youngest igneous activity, heat flow, total number of wells, well flow rate, well depth, and spring flow rate. Weighted key attributes of these data sets will be applied to test areas within the Modoc plateau that have undergone geothermal exploration, and then to the entire region of study to establish a series of risk elements and create composite risk element maps. The full set of geochemical, geophysical

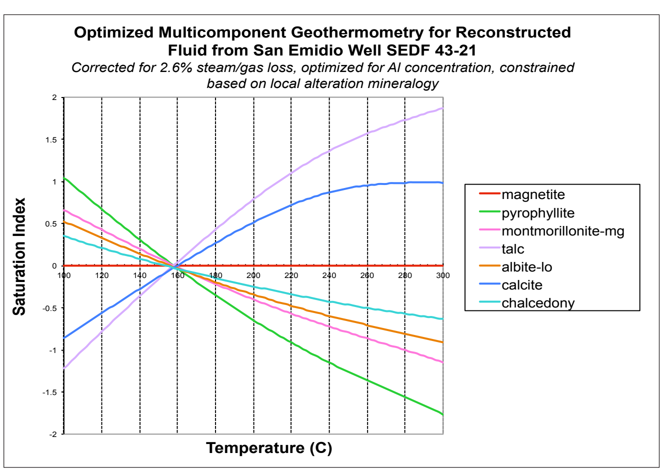

Figure 4. GeoT analysis of fluid chemistry from San Emidio well 43-21. Multicomponent geothermometry predicts a reservoir temperature of ~160°C.

and geological data from our two play type “end members” have been examined to identify defining characteristics for each site, and to develop a weighting scheme for those parameters that correlates best with geothermal favorability. For example, at Medicine Lake the presence of an impermeable argillaceous cap is an important hydrological feature (Figure 6), whereas the presence of complex faulting (terminations, offsets, etc.) is a key control of reservoir permeability at San Emidio. For both sites, the presence of faults in general is important.

Our test sites are Surprise Valley and the eastern Modoc basin (Figure 1). Surprise Valley has been the site of numerous exploration efforts (e.g., Woods, 1974; Barker et al., 2005; Benoit et al., 2005; LaFleur et al., 2010). The Surprise Valley region is interpreted as being mostly extensional (e.g., Faulds et al., 2005; Egger and Miller, 2011), and has a wide variety of geothermal features (e.g., Reed, 1975; Cantwell and Fowler, 2014; Fowler et al., 2015). However, the area also exhibits some features more typical of volcanic-hosted systems, such as elevated $^3He/^4He$ ratios. Initial studies have correlated the presence of thermal springs on the east side of the valley with structural features (Glen et al., 2013), and while cation and multicomponent geothermometry suggest reservoir temperatures in excess of 200°C at some locations, the highest temperature encountered to date is only 170°C (Sladek et al., 2004; Cantwell and Fowler, 2014; Fowler et al., 2015). For the Modoc basin there are relatively few geothermal features (Reed, 1975), but some cases of direct thermal water utilization have been reported.

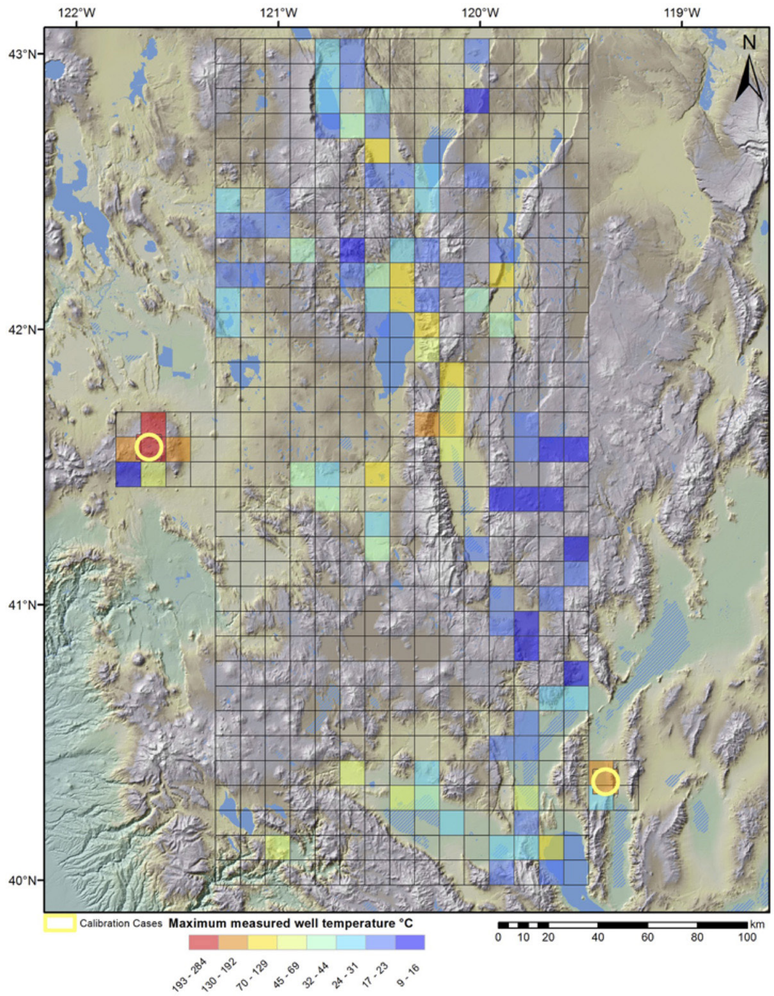

Figure 5. Example of integrated evaluation of data in our GPFA region using ArcGIS. Geothermal favorability is calculated for a 5 km grid spanning the GPFA region and the two calibration areas. Maximum measured well temperatures are shown.

One of the key elements in any GPFA is the weighting of characteristics (key attributes) that can best determine the potential for successful geothermal development; this type of weighting scheme has only recently been applied to geothermal exploration (e.g., Trumpy et al., 2015; Sadeghi and Khalajmasoumi, 2015). Presently we are attempting to weigh different resource parameters across the transition between our two play types of interest. In doing so we are developing maps that include the probability of geothermal resource and the uncertainty of that probability, representing the risk of false positive and false negative identification of the resource. Such an uncertainty is determined based on data source and availability. An alternative approach to be examined is the use of fuzzy logic in which the uncertainty of data can be carried over to the probability prediction.

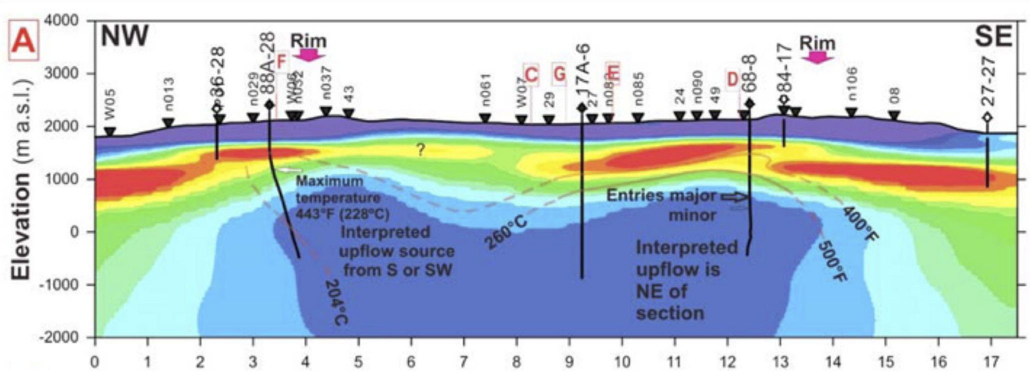

Figure 6. Cross section of the Glass Mountain geothermal system with 3D MT resistivity inversions, wells, isotherms and MT stations (from Cumming and Mackie, 2010).

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