PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2019
SGP-TR-214

Vectoring into Potential Blind Geothermal Systems in the Granite Springs Valley Area, Western Nevada: Application of the Play Fairway Analysis at Multiple Scales

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Keywords: Geothermal exploration, Nevada, Granite Springs Valley, play fairway analysis, structural controls, direct evidence

ABSTRACT

The Great Basin region of the western USA is capable of generating much greater amounts of geothermal energy than currently produced. Most geothermal resources in this region are blind, and thus the favorable characteristics for geothermal activity must be synthesized and methodologies developed to discover new commercial-grade systems. The geothermal play fairway concept involves integration of multiple parameters indicative of geothermal activity as a means of identifying promising areas for new development. In the Nevada play fairway project, nine geologic, geochemical, and geophysical parameters were initially synthesized to produce a new geothermal potential map of 96,000 km^2. Granite Springs Valley in western Nevada is a particularly promising site selected for detailed study. It contains several favorable structural settings, including terminations of major Quaternary normal faults and fault intersections. Geologic, geophysical, and geochemical techniques were employed to define the most likely sites for high permeability and select drilling targets for temperature-gradient holes. Local and intermediate permeability models were revised to reflect results of detailed analyses and generate new detailed play fairway maps of the area. The most promising site lies in the northeastern part of the basin directly east of Adobe Flat, where the horse-tailing termination of a major normal fault (as revealed by new gravity data), opaline sinter deposits, warm shallow wells, and a low-resistivity anomaly are collocated. Geothermometry suggests a blind system with temperatures as high as ~130°C in this area. Four new temperature-gradient holes document temperatures of ~80°C at ~150 m depth. Lessons learned in the detailed studies of this project include: 1) initially identified sites commonly include multiple favorable settings at a finer scale; 2) promising sites in Cenozoic basins cannot be well defined without detailed geophysical surveys; and 3) play fairway analysis is critical at multiple scales, providing a means to select regional prospects as well as vectoring into drilling targets at individual sites.

1. INTRODUCTION

The geothermal play fairway concept involves integration of multiple parameters indicative of geothermal activity as a means of identifying the most promising areas for new geothermal development (e.g., Faulds et al., 2016a,b; Shervais et al., 2016; Forson et al., 2016; Lautze et al., 2016; Wannamaker et al., 2017; Craig et al., 2017; McConville et al., 2017). This includes the evaluation of the relative favorability of known, undeveloped geothermal systems, as well as assessing the probability of a particular area for hosting a heretofore undiscovered, blind relatively high-temperature (>130ºC) system capable of generating electricity.

We have applied the play fairway methodology across a broad swath (96,000 km^2) of the Great Basin of Nevada, a well-exposed extensional to transtensional, active tectonic setting within the Basin and Range province of western North America (Figure 1). The Great Basin region of Nevada and adjacent parts of neighboring states is a world-class geothermal province with ~720 MW of current capacity produced from ~25 operating power plants. Studies indicate far greater potential for conventional hydrothermal systems in the region (e.g. Williams et al., 2007, 2009).

Most of the geothermal systems (>85%) in the Great Basin region, especially the relatively high-temperature systems (>130ºC), reside in interaction zones along Quaternary faults, such as fault terminations, fault intersections, fault step-overs or relay ramps, accommodation zones, and displacement transfer zones, as opposed to the main segments of range-front faults (Curewitz and Karson, 1997; Faulds et al., 2006, 2011; Faulds and Hinz, 2015). These fault interaction zones typically contain higher densities of faults, with at least a subset favorable for dilatency, which enhance permeability and thus provide conduits for geothermal fluids. Most of the geothermal systems in the region are amagmatic and not associated with middle to upper crustal magma chambers.

Because most geothermal systems in the Great Basin are controlled by Quaternary normal faults, they generally reside near the margins of basins. Consequently, upwelling fluids along the faults commonly flow into permeable sediments in the subsurface and do not daylight directly along the fault. Outflow from these upwellings may therefore surface many kilometers away from the deeper source or remain entirely "blind" with no surface hot springs or steam vents (Richards and Blackwell, 2002; Coolbaugh et al., 2007). Thus, techniques are needed both to identify the major structural settings that enhance permeability and to determine which areas may currently channel hydrothermal fluids. The recent discovery in central Nevada of the robust geothermal system at McGinness Hills, a blind field that currently produces ~88 MW (Nordquist and Delwiche, 2013), suggests that many systems are yet to be discovered in the region. Application of the play fairway methodology therefore holds promise of yielding significant results. This paper describes the results of the play fairway analysis as applied to the Granite Springs Valley area in western Nevada and how we modified our approach as analyses initiated at the regional scale subsequently focused on individual geothermal systems and potential drilling targets.

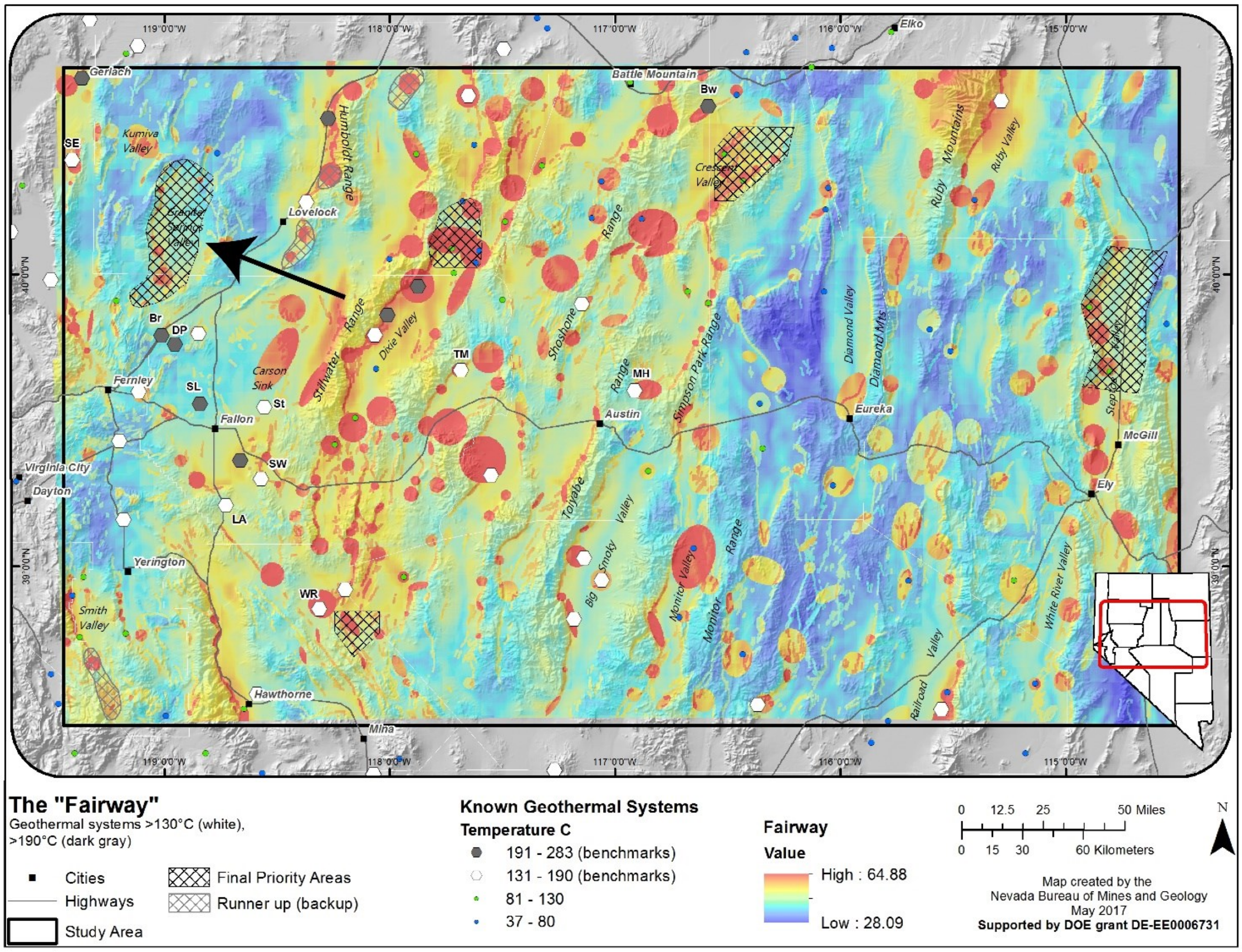

Figure 1: Final down-select areas for detailed studies in Phase II shown by black hachures overlain on the play fairway map produced in Phase I. Runner-up areas are shown by light gray hachures. From west to east across the northern tier, detailed study areas are Granite Springs Valley (denoted by black arrow), Sou Hills, Crescent Valley, and Steptoe Valley. The lone area in the southern part is southern Gabbs Valley. From north to south, runner-up areas are Dun Glen, Lovelock Meadows, southern west flank of the Humboldt Range, and Wellington.

2. NEVADA PLAY FAIRWAY ANALYSIS

In phase I of this project, we developed a comprehensive, statistically based geothermal potential map for 96,000 km^2 across the Great Basin of Nevada (Figure 1; Faulds et al., 2015a,b, 2016a,b). This transect extended from west-central to eastern Nevada in order to capture regional strain gradients and changes in the composition of the underlying basement from primarily Mesozoic crystalline rocks (granitic and metamorphic rocks) in the west to dominantly Paleozoic carbonates and sediments in the east. This project focused on fault-controlled geothermal play fairways due to the affiliation of most geothermal systems in the region with Quaternary faults (Curewitz and Karson, 1997; Blackwell et al., 1999; Richards and Blackwell, 2002; Faulds et al., 2006, 2010, 2011, 2013; Hinz et al., 2011, 2013, 2014). Nine parameters were incorporated into the regional geothermal potential maps, including: 1) structural settings, 2) age of recent faulting, 3) slip rates on Quaternary faults, 4) regional-scale strain rates, 5) slip and dilation tendency on Quaternary faults, 6) earthquake density, 7) gravity gradients, 8) temperature at 3 km depth, and 9) geochemistry from springs and wells.

As described in previous contributions (Faulds et al., 2015b, 2016a,b), these parameters were grouped into key subsets to define regional permeability, intermediate-scale permeability, local permeability, and regional heat, which were then combined to define the fairway (Figure 1). Additionally, the fairway model was integrated with direct evidence of heat from wells, springs, and geothermometers to delineate favorability for geothermal development. Results compared favorably against a group of 34 benchmark sites, representing systems in the region with temperatures ≥130°C (Faulds et al., 2016a, b).

Owing to the active extensional to transtensional tectonism and high heat flow, many sites in the broad study area (96,000 km^2) yielded high play fairway values. In Phase II of the project, we chose 24 of the most promising sites for reconnaissance level assessment on the basis of the play fairway and favorability values, land status, and proximity to an established electrical transmission corridor. We then down-selected to five sites for detailed studies through a semi-quantitative analysis involving consideration of a) available geological, geochemical, and geophysical data, b) new shallow temperature and geochemical data collected in this study, c) land status including % of area considered primary sage grouse habitat, d) distance from an electrical transmission corridor, and e) degree of previous exploration (Figure 2). Due to the abundance of favorable sites in the region, we were able to bias our final selections to include broad geographical distribution that incorporated variations in tectonic setting (transtensional vs. purely extensional), strain rates, composition of basement rocks, and types of favorable structural settings. For example, the southern Gabbs Valley study area in west-central Nevada occupies a displacement transfer zone in a region of relatively high strain at the transition between the Walker Lane dextral shear zone and the extensional Basin and Range province, whereas Steptoe Valley 250 km to the east in eastern Nevada, contains a highly segmented Quaternary range-front normal fault with multiple step-overs in an area of relatively low extensional strain. Granite Springs Valley in northwest Nevada was selected based on distinct horse-tailing terminations of Quaternary range-front faults.

As we examined each detailed study area more carefully, including Granite Springs Valley, we concluded that all contain several favorable structural settings and thus multiple potential geothermal targets. This required further assessment (i.e., a finer scale of play fairway analysis) within each study area to select the most highly prospective targets for drilling. Notably, the boundaries of all previously identified structural target areas were modified to reflect new details uncovered in Phase II. Here, we describe the application of these analyses to Granite Springs Valley and how this process has permitted vectoring into the more promising locations for geothermal activity within this target-rich region.

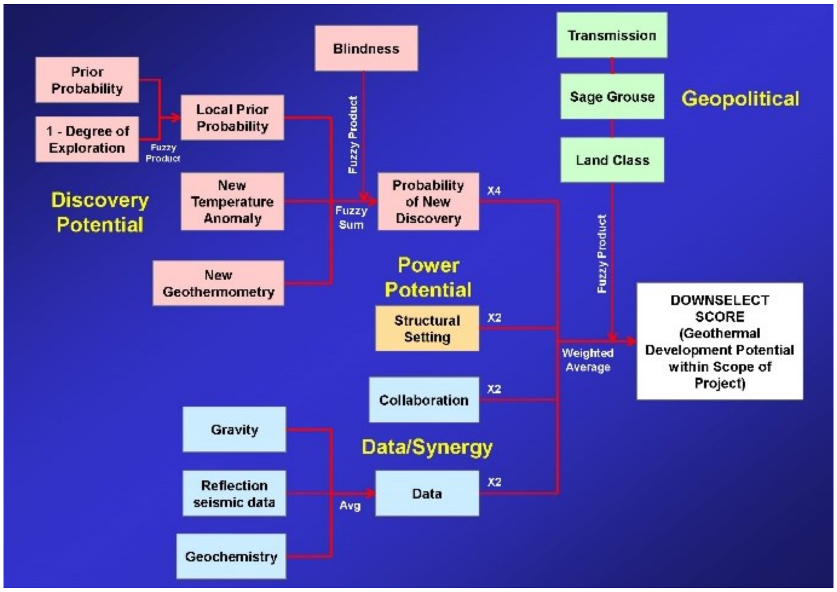

Figure 2: Flow chart illustrating down-selection process for determining Phase II detailed study areas from prospective geothermal areas identified in Phase I. Collaboration refers to the potential for industry collaboration at the site.

3. GRANITE SPRINGS VALLEY

3.1 Overview

The Granite Springs Valley study area lies in the Basin and Range province of northwestern Nevada (Figures 1 and 3). No hot springs or steam vents occur in the area, but favorable structural settings, including the terminations of a major range-front fault and a broad accommodation zone, resulted in high play fairway scores in Phase I. Our analysis in Phase II involved: 1) detailed mapping of Quaternary faults and ~50 km^2 of bedrock in the eastern Truckee Range, 2) reconnaissance mapping of >200 km^2 centered on Granite Springs Valley, 3) a new gravity survey totaling 415 stations, 5) acquisition of LiDAR for 215 km^2 in the southwestern part of Granite Springs Valley, 6) a shallow temperature survey (55 stations), 7) interpretation of 9 seismic reflection profiles (144 km), 8) slip and dilation tendency analysis, and 9) geochemical analyses of 34 water samples. Our new mapping was merged with existing maps of the area (e.g., Johnson, 1977; Whitehill, 2009; VanBuer, 2012).

The structural framework is dominated by a major east-dipping Quaternary normal fault (Sahwave fault with slip rates of ~0.1-0.3 mm/yr) on the western margin of Granite Springs Valley. Granite Springs Valley is a large west-tilted, ~2-km-deep half graben in the hanging wall of the Sahwave fault, as evidenced by seismic reflection data. This fault breaks into multiple splays as it terminates in the northwestern and southwestern parts of the basin. The east-dipping fault system gives way southward in the southern part of the basin to mainly west-dipping normal faults in a broad accommodation zone in the eastern Truckee Range (Figure 3E). A system of west-dipping Quaternary normal faults also extends southward from the west flank of the Seven Troughs Range and continues into the northeastern part of the basin, where it terminates directly east of Adobe Flat, as evidenced by a prominent north-northeast-trending gravity gradient and gravity high (Figure 3D). Isolated exposures of Oligocene tuff and shallow (~100 m) Mesozoic basement (based on well data) confirms this basement high.

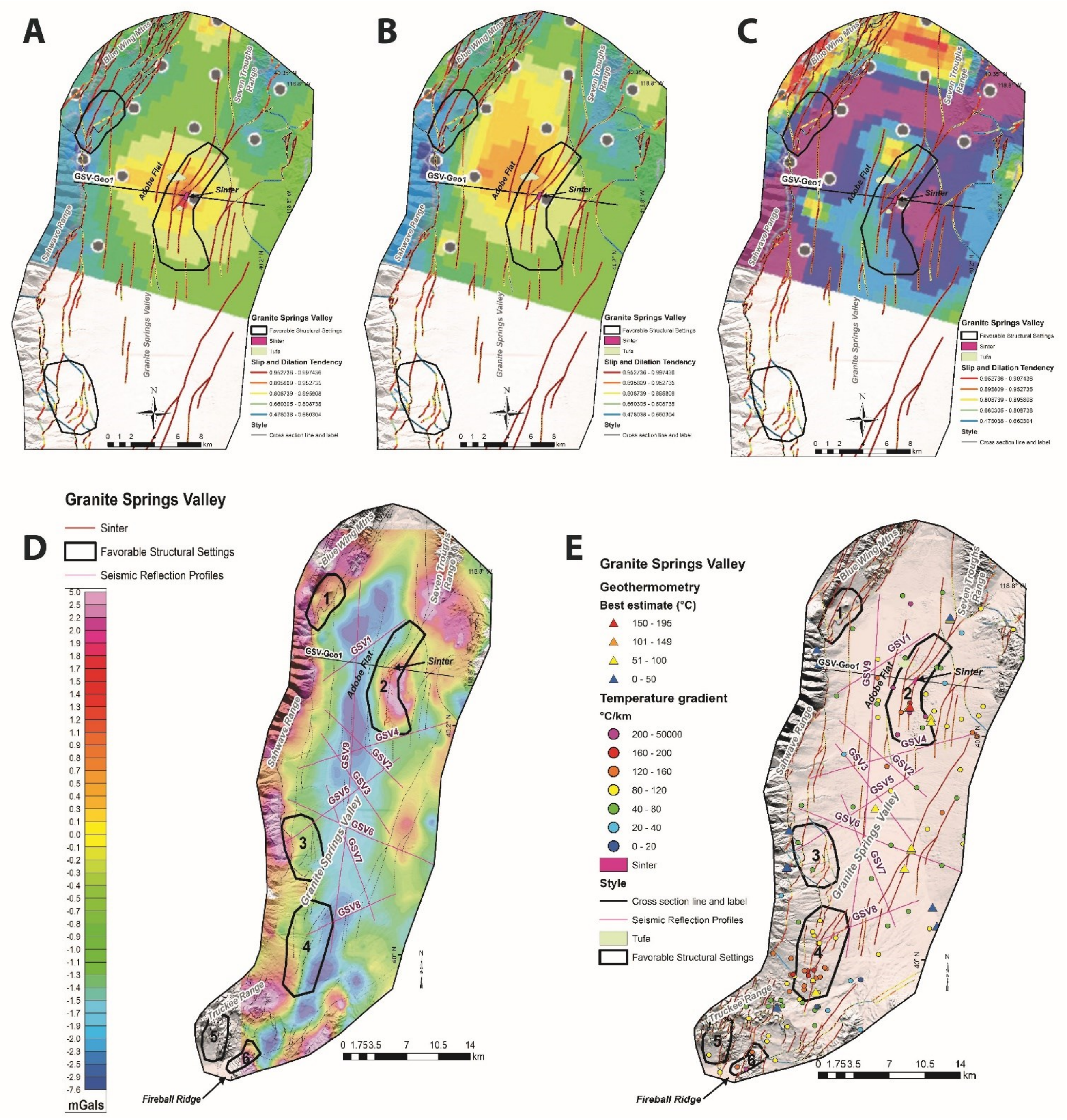

Figure 3: Granite Springs Valley study area. Favorable structural settings are outlined in black, with setting #2 the highest priority in this area. A. Slip and dilation tendency and MT data slice (Wannamaker, unpublished data) at 0.127 km; note the low resistivity co-located with the sinter deposit. B. Slip and dilation tendency with a low resistivity anomaly at 0.565 km. C. Low-resistivity anomaly at 4.77 km. D. Complete Bouguer gravity anomaly. E. TG and geothermometry data and location of seismic reflection profiles (purple lines) and geologic cross section. Cross section GSV-Geo1 shown in Figure 4.

3.2 Results of Phase II Detailed Studies

Geologic and geophysical data indicate six favorable structural settings conducive for geothermal activity in the study area (Figure 3D). From north to south, these include: 1) the horse-tailing northern termination of the Sahwave fault in the northwestern part of the basin; 2) the southern termination of the west-dipping normal fault zone extending south from the west flank of the Seven Troughs Range into the northeastern part of the basin directly east of Adobe Flat (Figures 3 and 4); 3) a major step-over in the Sahwave fault in the southwestern part of the basin; 4) the horse-tailing southern end of the Sahwave fault in the southwestern part of the basin; 5) the northern termination of a major west-dipping normal fault zone and fault intersections in the eastern Truckee Range; and 6) fault intersections along the north end of Fireball Ridge. Potential host rocks in these areas include highly fractured Mesozoic granite and Miocene volcanic rocks along and proximal to arrays of closely-spaced normal faults.

Notably, we discovered Quaternary opaline sinter, silicified sands, and travertine deposits at the favorable setting (#2 above) directly east of Adobe Flat (Figures 3D and 4). The opaline material occurs as matrix silica encompassing quartz sand grains. This area also corresponds to a low-resistivity anomaly extending from shallow levels (127 m) to >4 km depth (Figure 3A-C). The sinter suggests temperatures at depth >180˚C. Also, two hydrophreatic explosion craters are found in the horse-tailing termination of a west-dipping normal fault zone near its intersection with an east-striking fault in the eastern Truckee Range (#5 favorable setting above). North-northeast-striking normal faults have the highest slip and dilation tendency. Thus, many faults in the area are well oriented for slip and dilation, including the fault splays in the Adobe Flat area.

Past geothermal exploration included widespread temperature-gradient (TG) drilling (Figure 3E) in the 1970s-1980s generally to depths of <200 m. Previous exploration had focused on the north end of Fireball Ridge, the southwestern part of the basin, and Adobe Flat area (Desormier, 1985; Ormat, unpublished; Hulen, 2007; Benoit, 2008). However, no comprehensive analysis of potential geothermal resources had previously been conducted in the area.

Considering the lack of hot springs and fumaroles, previously drilled wells initially provided the only direct evidence of geothermal activity in the area. The most focused previous work was conducted in the Fireball Ridge area, where >20 TG wells defined an ENE-trending, ~5-km-long thermal anomaly (~10-14ºF/100 ft; Desormier, 1985). Slightly elevated thermal gradients also mark the southwest part of Granite Springs Valley. However, the Adobe Flat area contains the maximum thermal anomaly in the area, as defined by several TG holes (Benoit, 2008).

Thirty-four water analyses were utilized for evaluating the favorable structural settings in Granite Springs Valley. This included 11 historical, 15 new gray literature sources, and 8 new samples obtained in Phase II of this study. Most waters in the area are cool (<25°C), although 3 water wells in the northern part of the basin have reported bottom-hole temperatures between 30 and 41°C, and 3 TG wells in this same area have bottom-hole temperatures of 63.8, 73.7 and 89.7°C (well AV-ST-1) at 200, 260 and 550 m depth, respectively. The temperature at AV-ST-1 confirms the thermal anomaly in the Adobe Flat area, which is one of the larger thermal anomalies in Nevada not yet fully explored (Benoit, 2008). Most temperatures estimated with geothermometers are <100°C. However, one previous analysis from a water well proximal to AV-ST-1 has the highest geothermometer temperature (160°C from quartz) in the area. The high geothermal gradient (<140°C/km) and geothermometry together with the newly discovered Quaternary sinter deposits and silicified sands in the area warranted further investigation. However, 2-m temperature surveys during the spring of 2017 (55 stations) did not show any significant thermal anomalies, although the very wet winter of 2016/2017 may have suppressed temperatures.

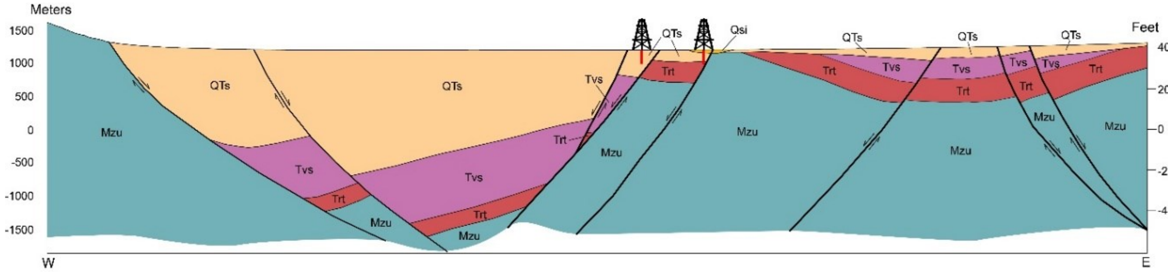

Figure 4: E-W cross section in northern Granite Springs Valley through Adobe Flat area, showing W-tilted half graben of the Granite Springs basin and W-dipping normal fault zone on the east side of basin that controls recent hydrothermal activity (sinter deposition). See Figure 3 for location (GSV-Geo-1). Possible drilling sites are shown by derricks. Qsi, silica sinter; QTs-late Miocene to Quaternary basin-fill sediments; Tvs, Miocene volcanic and sedimentary rocks; Trt, Oligocene ash-flow tuffs; Mzu, Mesozoic granitic and metamorphic rocks.

3.3 Refined Play Fairway Analysis – Vectoring into Most Promising Areas

Predictive play fairway maps were generated for the Granite Springs Valley area using the exploration data obtained during Phase II studies (Faulds et al., 2017a,b). These new data were integrated with the existing Phase I database. The general methodologies for producing regional predictive maps in Phase I (Faulds et al., 2015b) were followed in building detailed predictive maps in Phase II. Modifications to the methodology were made to accommodate the introduction of new data types (e.g., 2-m temperature measurements, sinter mapping, and MT data) into the local permeability models.

Three main sets of predictive maps were generated (Figures 5 and 6). They are 1) play fairway maps, 2) play fairway error maps, and 3) direct evidence maps. Direct evidence maps are qualitative, because probabilities are qualitatively assigned based on various types of evidence that consists principally of well and spring temperatures and geothermometers. Because of this qualitative aspect, direct evidence errors were not modeled in detail, but were assumed to equal a relative error of 25%, as was done in Phase I. Two-meter temperature data, which are considered a form of direct evidence, are an exception; these errors were modeled in detail to ensure statistical significance.

The play fairway and direct evidence maps provide complementary information. The fairway maps highlight areas of geothermal favorability based on fundamental underlying geologic, geophysical, and geochemical data, whereas the direct evidence maps highlight areas of favorability based on "direct observations" of geothermal features, such as temperature anomalies, fluid geothermometer temperatures, temperature gradients, or the presence of surface geothermal features, such as silica-cemented sands or sinter. In Phase I, the fairway and direct evidence maps were combined to produce overall "favorability" maps. This was not done in Phase II. Instead, it was found that because of the widely differing types of data employed in fairway and direct evidence maps, it was more informative to compare the results of both maps side by side to facilitate visualization of one or more conceptual models of three-dimensional fluid flow.

Modeling procedures for the detailed study areas in Phase II, including Granite Springs Valley, paralleled those of the Phase I regional model (Faulds et al., 2015b). The regional-scale permeability and heat models of Phase I remained unchanged for Granite Springs Valley. In contrast, the local- and intermediate-scale permeability models were revised and updated to reflect results of detailed geologic mapping and geophysical and geochemical surveys. As described in detail by Faulds et al. (2017b), several adaptations and improvements were employed in the models to accommodate new types of data and additional structural attributes. These changes included incorporation of 1) a structural settings quality factor used to model the strength or quality of structural settings; 2) magnetotelluric (MT) data (where present), whereby low-resistivity anomalies enhanced the structural quality factor by 0.1 due to their potential affiliation with clay caps and/or fluid flow at depth (e.g., Ussher, 2000; Cumming, 2009; Wannamaker et al., 2017); 3) presence of paleo-geothermal features, such as sinter/silica-cemented sands and explosion craters, which provides direct evidence of geothermal activity; based on known associations with active geothermal systems, probabilities of 0.5-0.6 were assigned to a 2-km buffer around such deposits; and 4) two-meter temperature anomalies utilizing established methods of assessing degrees above background (DAB) and potential errors (e.g., Sladek and Coolbaugh, 2013); a probability of occurrence of a 130°C geothermal system was assigned to the 2-m temperature anomaly as follows: a DAB of <2°C = 0 probability, 2-3°C = 0.15 probability, 3-4°C = 0.25 probability, 4-5°C=0.40 probability, and 5-6°C = 0.45 probability.

The fairway model of Granite Springs Valley has a similar overall score to that generated in the original Phase I model. The major difference between the detailed Phase II model and the Phase I regional model is that locations of higher favorability are shown in much greater detail in the Phase II model (Figure 5). An error analysis shows that all potential targets of interest have a statistically significant anomalous fairway score, as measured by the difference between the local score and the average score, divided by the estimated error (Faulds et al., 2017b). We note that fairway scores above ~45 indicate relatively high potential. The direct evidence map of the Granite Springs Valley area is also more detailed than in Phase I (Figure 6), because of the much greater availability of input data. Direct evidence in the form of surface silica deposits and anomalous well temperatures and geothermometry produce a coherent direct evidence pattern that is shifted northward relative to anomalous temperature gradient holes.

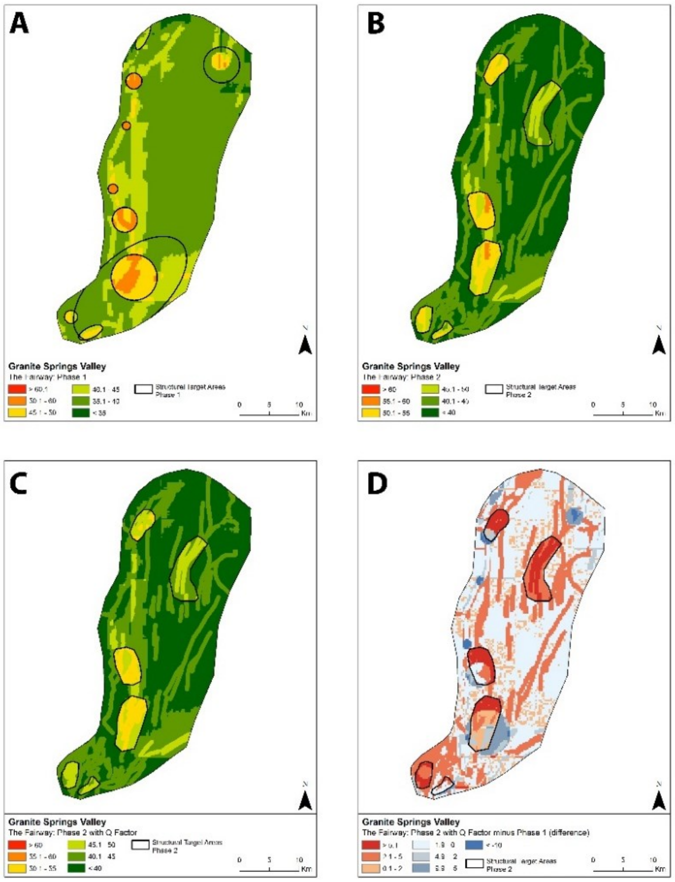

Figure 5: Comparison of Phase I and II fairway analysis for Granite Springs Valley. A. Phase I fairway results. B. Phase II fairway results calculated the same as in Phase 1. C. Fairway score from Phase II calculated with structural setting quality factor. D. Difference between the Phase II and Phase I fairway results with positive numbers equal to increase of fairway score from Phase I to Phase II, and negative numbers equal to decrease in fairway score from Phase I to Phase II.

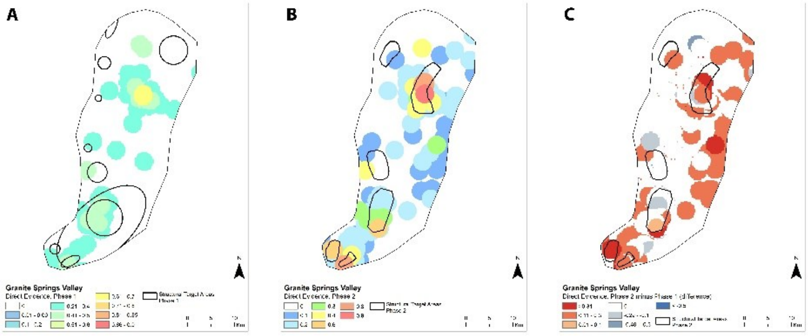

Figure 6: Comparison of Phase I and II direct evidence grid layers for Granite Springs Valley. A. Phase I direct evidence. B. Phase II direct evidence. C. Difference between the Phase II and Phase I direct evidence modeling grid layer with positive numbers equal to increase of fairway score from Phase I to II.

For the Granite Springs Valley area, we reviewed the Phase II results and ranked the Adobe Flat area as the most promising prospect due to the presence of opaline sinter, relatively high-temperature (albeit limited) geothermometry, good accessibility, and favorable land status. Although the phreatic explosion craters in the eastern Truckee Range reside in a favorable structural setting, the land status (checkerboard of private and public sections) and accessibility are less conducive to development. Further, no evidence (e.g., sinter) was found for a relatively high-temperature system in that area. Considering multiple factors, we selected the area directly east of Adobe Flat for additional detailed geophysical surveys and TG drilling for Phase III of this project.

3.4 Phase III Analyses and Drilling Results

More detailed geologic and geophysical investigations were conducted in Phase III of this project in the Adobe Flat area. More detailed geologic mapping by UNR revealed more widespread sinter and travertine deposits across a northerly trending 7 km2 area. Ground magnetic and more detailed gravity surveys by the USGS showed that the paleo-geothermal deposits were collocated with significant gravity and magnetic gradients (Figure 7B). These additional more detailed investigations guided subsequent selection of sites for drilling.

Drilling proceeded in two stages. Initially, we chose to conduct GeoProbe drilling in order to obtain waters samples for geothermometry. Once these water samples were analyzes, sites for TG drilling were selected. Four water samples were collected from GeoProbe holes (sites 8, 14, 15, and 20; Figure 7A) that were drilled to ~15 to 52 m depth in early July, 2018. Water samples were not collected from the GeoProbe hole at site 16, as no fluids were intersected (the GeoProbe intersected a hard, impenetrable layer at shallow depth). All fluid samples contained substantial suspended sediment load, and required double filtering: first using an electric vacuum-pump system with a 5 µm filter size, followed by hand-filtering through a 0.45 µm filter. At each site, three sub-samples were collected – one bottle for anion analyses (250 mL), one (250 mL) for cation analyses (acidified with HNO_3 to a pH of 2), and another (125 mL) for stable isotopes ($\delta^{18}O$ and δD).

The water samples provided important insights. Temperatures as high as 45°C were recorded in the GeoProbe holes at depths as shallow as 15 m. The four samples have TDS values ranging between ~780 mg/L (Site 14), up to a high of ~24,000 mg/L at Site 15. The samples are all alkali-chloride, equilibrated fluids. The only other sample with a similar composition that was collected previously is from a nearby warm water well. All other fluids previously reviewed and compiled in Phase 1 and 2 are dominantly bicarbonate fluids. For the four samples, the SiO_2 and cation geothermometry estimates are in reasonable agreement, at least for the Giggenbach Na/K geothermometer. The other Na/K estimates vary considerably, and most are substantially lower than the temperatures estimates from the Giggenbach equation. Given this variability (and the ongoing question about whether we even can or should be applying these cation geothermometers to Basin and Range geothermal systems, the SiO_2 results are considered to be more reliable. The highest estimated temperature is associated with Site 20 (126°C), followed by Site 14 (101 °C). This is consistent with the largest mapped areas of paleo-sinter deposition around Site 20. The four samples of fluids have stable isotope compositions that are similar to other samples collected from springs and wells in the area. A slight offset from the Global Meteoric Water Line likely reflects a combination of water-rock interaction and evaporation effects.

On the basis of the GeoProbe results, distribution of sinter, and geophysical data, six sites were chosen for TG drilling, primarily in the northern and southern parts of the 7 km long zone of sinter and travertine deposits. To date, four TG holes have been drilled. Three holes were drilled to 148-152 m depth, and yielded bottom-hole temperatures ranging from 75.9°C to 84°C. One TG hole was drilled to 250 m and yielded a bottom-hole temperature of 79.5°C (Figure 8). The warmest holes lie in the northern part of the area. Drilling of two additional TG holes is planned for winter 2019. These results are promising, with temperature gradients well above regional averages. The isothermal gradients in the lower parts of wells 54-2 and 71-2 in the northern part of the area are suggestive of convection and may indicate an upwelling of geothermal fluids in that area.

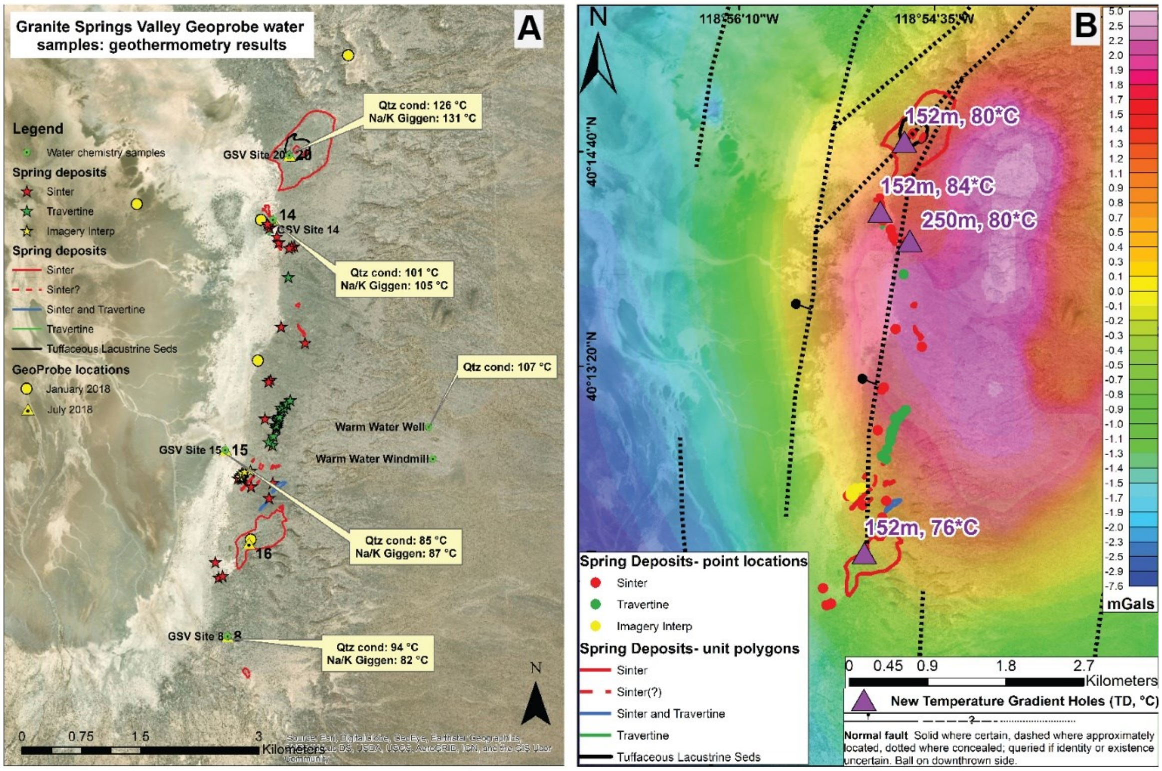

Figure 7: A. Locations of and geothermometry results from GeoProbe holes overlain on Google Earth image. B. Locations and bottom-hole temperatures of temperature-gradient wells overlain on isostatic residual gravity data. From south to north, wells numbers are 68-14, 76-2, 54-2, and 71-2. The distribution of sinter and travertine is also shown on both the GeoProbe and TG hole maps.

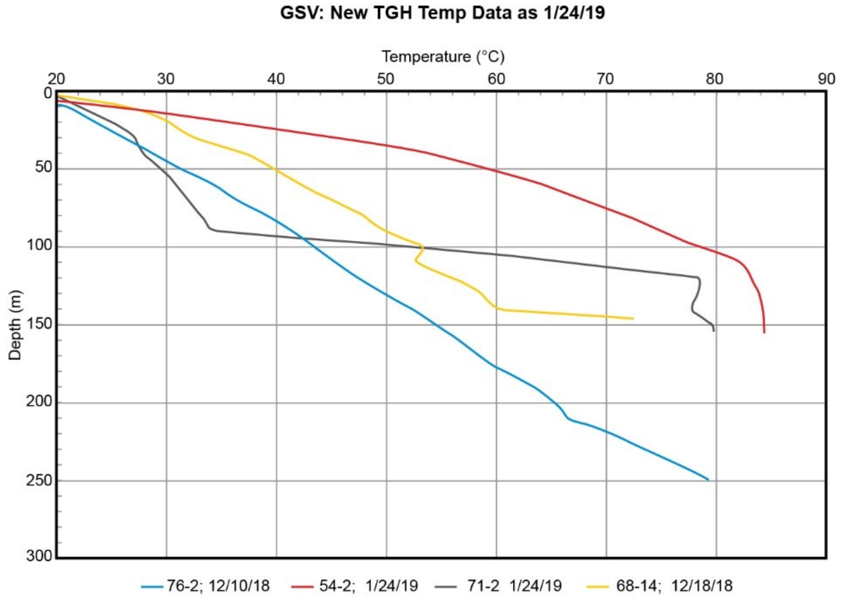

Figure 8: Temperature gradient data from four new TGHs drilled in 2018 in northern Granite Springs Valley. Locations of wells is shown in Figure 7.

4. DISCUSSION

The progression from a regional to local analysis in a major Cenozoic basin has resulted in several lessons learned for the geothermal play fairway concept. We note that differences between Phases I and II in the play fairway analysis are particularly strong for Granite Springs Valley due to its location in a large late Cenozoic basin. New geophysical data from the basin affords discovery of previously unrecognized intrabasinal, favorable structural settings, as exemplified in the Adobe Flat area (Figure 3). These findings epitomize the importance of the detailed studies in refining exploration targets in such areas. Considering that nearly half of the Great Basin region is covered by basins, this also demonstrates the broad applicability of such detailed studies as well as the large untapped potential for commercial-grade geothermal systems in many of these basins.

It is important to reiterate that a primary difference between Phase I and II of this project is that the regional analysis of Phase I recognized relatively broad, favorable structural settings or clusters of settings in particular areas (Figure 1). As is typical in any regional exploration program, it is difficult in the early stages to parse out the detailed characteristics of a particular area to select the most favorable targets for drilling. Upon more detailed analysis of individual areas in Phase II, it became apparent that nearly all study areas contained multiple favorable structural settings. This presented the immediate challenge of applying our play fairway methodology at a finer scale to efficiently model the geothermal potential of each of the favorable settings within a particular study area. The detailed geological, geochemical, and geophysical investigations afforded such an analysis. Ultimately, we utilized the play fairway score to compare multiple favorable settings in each of the study areas to one another and rank such areas to select the most promising sites for drilling. Thus, we found that our play fairway methodology to be very adaptable to the natural evolution of an exploration program as it progresses from a regional analysis and vectors into the most promising prospects that present the lowest risk for development.

Although the play fairway scores are a key factor in selecting the most promising sites for drilling, several other factors must also be considered for selecting sites for drilling, including presence or absence of direct evidence (e.g. thermal anomalies, hydrothermal deposits, and geothermometry), land status, and accessibility. Distance to existing electrical transmission corridors is also important for potential development, but all detailed study areas already satisfied the minimum criteria in this regard (i.e. within 20 km of such a corridor) based on our earlier down-select criteria.

We chose the Adobe Flat area in Granite Springs Valley for Phase III more detailed analyses and subsequent drilling due to a combination of geologic, geophysical, geochemical, and practical matters (e.g., land status and accessibility). The drilling results to date suggest the presence of an underlying geothermal systems but have yet to identify the site of a major geothermal upwelling. Additional TG drilling will be needed to further define the resource in this area.

5. CONCLUSIONS

The results in Phase II and III of the play fairway analysis, including newly discovered paleo-geothermal features, anomalously warm wells, good geothermometry, and both gravity and magnetic gradients suggest that the northeastern part of Granite Springs Valley directly east of Adobe Flat may contain a relatively high temperature blind geothermal system. Additional TG drilling and 3D modeling of the area is planned to further define the resource and provide initial estimates of its commercial viability. The positive results from both southeastern Gabbs Valley (Faulds et al., 2018) and northern Granite Springs Valley provide initial validation of our play fairway techniques and demonstrate the broad applicability of the methodology at a variety of scales.

6. ACKNOWLEDGMENTS

This project was funded by a Department of Energy grant awarded to Faulds (grant number DE-EE0006731) and a Department of Energy grant awarded to Wannamaker (DE-EE0005514). We thank Andrew Sadowski and Emma McConville for their many contributions to Phase II of this study. We also thank Dick Benoit for sharing his knowledge of the Granite Springs Valley area. Collaborations with the geothermal industry, including Ormat Nevada, Inc., were beneficial to this project.

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