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Discovery of a Blind Geothermal System in Southern Gabbs Valley, Western Nevada, through Application of the Play Fairway Analysis at Multiple Scales

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ABSTRACT

The Great Basin region is capable of generating much greater amounts of geothermal energy than currently produced. Most geothermal resources in this region are blind, and thus 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 to identify promising areas for new development. In the Nevada play fairway project, geologic, geochemical, and geophysical parameters were initially synthesized to produce a new geothermal potential map of 96,000 km^2. Southern Gabbs Valley in western Nevada is a particularly promising site selected for detailed study. It contains favorable structural settings, including Quaternary fault intersections and a displacement transfer zone. Geologic, geophysical, and geochemical techniques were employed to define the most likely sites for high permeability and select targets for temperature-gradient holes. Permeability models were revised to reflect results of detailed analyses and generate new detailed play fairway maps. The most promising site lies in an area of multiple fault intersections in a broader displacement transfer zone directly north of the Petrified Springs dextral fault, as revealed by gravity, magnetic, and MT data. A 2-m temperature anomaly and warm temperature gradient wells (~120^{o}C at ~150 m depth) confirm the presence of a geothermal system and provide initial validation of the play fairway methodology. The system is blind, with no surface hot springs, fumaroles, or paleo-geothermal deposits. Lessons learned in the detailed studies include: 1) initially identified sites commonly include multiple favorable settings at a finer scale; 2) promising sites in Cenozoic basins cannot be recognized without detailed geophysical surveys; and 3) play fairway analysis is critical at multiple scales.

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 (>130^{o}C) 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 represent a world-class geothermal province with over 670 MW of current capacity produced from ~25 operating power plants. Studies indicate far greater potential for conventional geothermal systems in the region (e.g. Williams et al., 2007, 2009).

Most of the geothermal systems in the Great Basin region, especially the relatively high-temperature systems (>130^{o}C), 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; Siler et al., 2018). These fault interaction zones typically contain higher densities of favorably oriented faults, 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.

Most geothermal systems in the Great Basin are controlled by Quaternary normal faults within the fault interaction zones, which commonly reside within or 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 holds promise of yielding significant new discoveries. This paper describes the results of the play fairway analysis as applied to southern Gabbs Valley in western Nevada and how our approach was modified as analyses initiated at the regional scale subsequently focused, at a finer scale, on individual geothermal systems and potential drilling targets.

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 to east across central Nevada in order to capture both 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 recent faults, 4) regional-scale strain rates, 5) slip and dilation tendency on faults, 6) earthquake density, 7) gravity gradients, 8) temperature at 3 km depth, and 9) geochemistry from springs and wells.

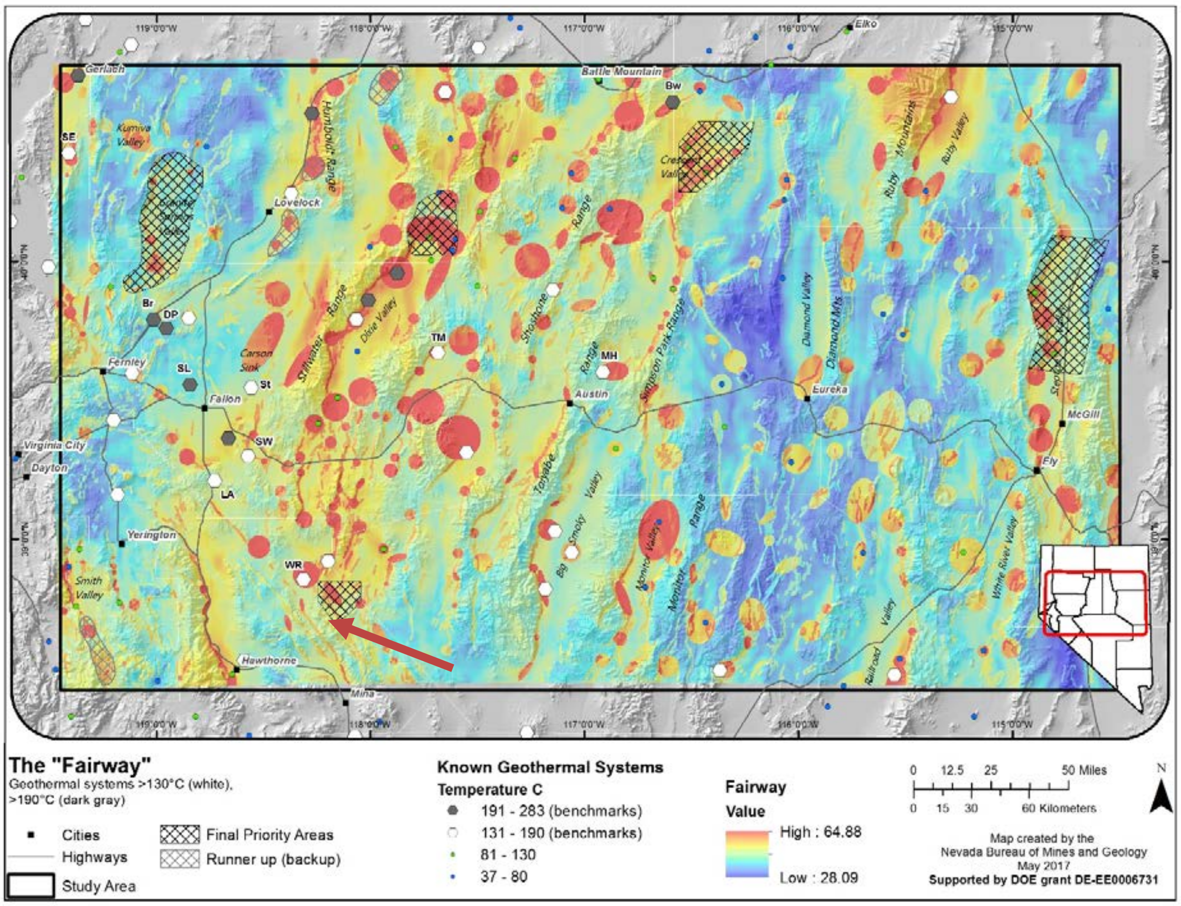

Figure 1: Final down-select areas for detailed studies in Phase II shown by black hachures overlain on the play fairway map produced in Phase I. Runner-up areas are shown by light gray hachures. From west to east across the northern tier, detailed study areas are Granite Springs Valley, Sou Hills, Crescent Valley, and Steptoe Valley. The lone area in the southern part is southern Gabbs Valley (red arrow). From north to south, runner-up areas are Dun Glen, Lovelock Meadows, southern west flank of the Humboldt Range, and Wellington. Abbreviations for known geothermal systems in the region: Br, Bradys; Bw, Beowawe; DP, Desert Peak; LA, Lee-Allen; MH, McGinness Hills; SE, San Emidio; SL, Soda Lake; St, Stillwater; SW, Salt Wells; TM, Tungsten Mountain; WR, Wild Rose-Don Campbell.

As described previously (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 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 development. Results compared favorably with 34 benchmarks, representing systems in the region with temperatures ≥130°C (Faulds et al., 2015b, 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 assessment on the basis of the play fairway 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, 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 (Figure 1), contains a highly segmented Quaternary range-front fault with multiple step-overs in an area of relatively low extensional strain.

As we examined each detailed study area more carefully, including southern Gabbs Valley, we concluded that all contain several favorable structural settings and thus multiple potential geothermal targets (Faulds et al., 2017a, b). 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 southern Gabbs Valley and how this process has permitted identifying the more promising locations for geothermal activity in this target-rich region. This work recently culminated with drilling of hot temperature-gradient wells in southern Gabbs Valley.

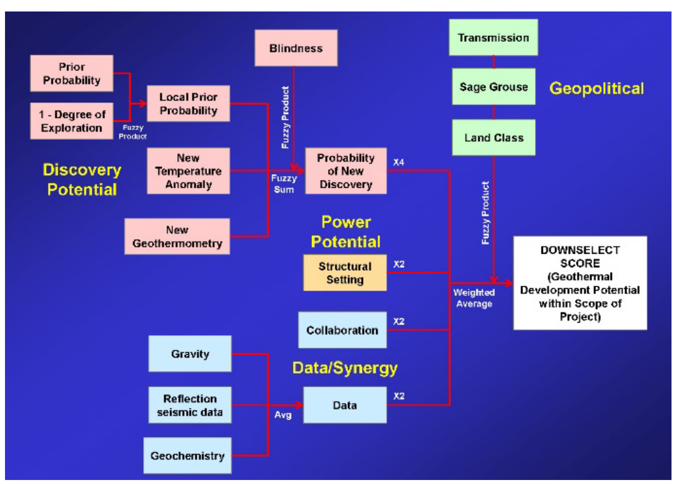

Figure 2: Flow chart showing down-selection process for selecting Phase II detailed study areas from prospective areas identified in Phase I. "Collaboration" refers to potential for industry collaboration.

3. Southern Gabbs Valley

Southern Gabbs Valley lies in the Basin and Range province of western Nevada directly northeast of the Walker Lane (Figures 1 and 3). The Walker Lane is a strike-slip fault system, which accommodates ~20% of the dextral motion between the Pacific and North American plates (Hammond et al., 2009). Southern Gabbs Valley is a complex, tectonically active structural basin reflecting the transition between dextral shear along the Walker Lane and extension within the Basin and Range province. The recently active (<15 ka) Petrified Springs dextral fault (slip rate=1.4 mm/yr) within the Walker Lane splays into numerous north- to north-northeast-striking normal faults within the basin, effectively transferring dextral shear from the Walker Lane to WNW-directed extension in the Basin and Range. This produces a displacement transfer zone, which is a structurally favorable setting for hosting a geothermal system (e.g., Faulds et al., 2011; Faulds and Hinz, 2015). This favorable structural setting combined with relatively high regional strain rates and Quaternary faults with relatively high slip rates resulted in a high play fairway score for southern Gabbs Valley in the regional analysis completed in Phase 1 of this project (Figure 1). Displacement transfer systems with known, relatively high-temperatures include the 16 MW Don Campbell geothermal power plant (Orenstein and Delwiche, 2014) ~15 km northwest of southern Gabbs Valley. No hot springs, steam vents, or paleo-geothermal features (e.g., sinter or travertine) occur in the southern Gabbs Valley, and thus any geothermal system in this area can be considered “blind”. Although some geothermal exploration has occurred in northern Gabbs Valley ~15 km north of the study area (Payne et al., 2011), it is important to note that no previous exploration has taken place in southern Gabbs Valley. Thus, our initial play fairway analysis in Phase I pointed to a previously unidentified geothermal system in this area. We should stress that our initial reconnaissance of southern Gabbs Valley found no surface evidence of a geothermal system, but anomalously warm wells (32^{o}C) were identified in the area, which prompted more detailed investigations.

Similar to any exploration program (e.g., minerals or hydrocarbons), however, more detailed analyses were needed to vector into the most promising part of southern Gabbs Valley such that drilling targets could be selected with minimal risk. Analyses in subsequent phases of this project (Craig et al., 2017) therefore included: 1) new detailed mapping of >200 km^2, including Quaternary fault analysis aided by partial LiDAR coverage, 2) a 2-m temperature survey (124 stations), 3) geochemical analyses of 20 water samples, 4) new gravity surveys totaling 480 stations, 5) a new ground magnetic survey (300 line km), 6) slip and dilation tendency analyses of mapped and inferred faults, and 7) an MT study (24 stations). New mapping was merged with existing geologic maps of the area (e.g., Ekren and Byers, 1980, 1985, 1986; Payne, 2013). Earlier results and interpretations were reported by Craig et al. (2017). The geophysical surveys are discussed in greater detail in Earney et al. (2018). Geologic and geophysical data indicate five individual, favorable structural settings within southern Gabbs Valley (Figure 3A,B), including the aforementioned displacement transfer zone, individual fault intersections, and one small releasing bend. Potential host rocks for a geothermal reservoir include highly fractured Mesozoic basement rocks (granitoids and metasediments) and Miocene ash-flow tuffs along and proximal to faults. Slip and dilation tendency analyses indicate that north-northeast-striking normal faults have the highest slip and dilation tendency (Figure 3B). Thus, many faults are well oriented for slip and dilation.

On the basis of the detailed analyses, several collocated features indicate a potential geothermal system in the south-central part of Gabbs Valley within the central part of the broader displacement transfer zone (Figure 3). These features include: 1) terminating and intersecting gravity gradients, suggesting a complex zone of intersecting northwest- and north-northeast-striking faults (Figures 3 and 4); 2) a 7 km^2 shallow (2 m) temperature anomaly with temperatures as high as 32°C, averaging 5°C above background; 3) a magnetic low possibly indicating altered rocks (Figure 3C); 4) favorably oriented faults in terms of slip and dilation tendency; and 5) a low resistivity anomaly. In addition, geothermometry from nearby wells (Figure 3A) suggests source temperatures of 130-140°C for a geothermal system in this area (Faulds et al., 2017).

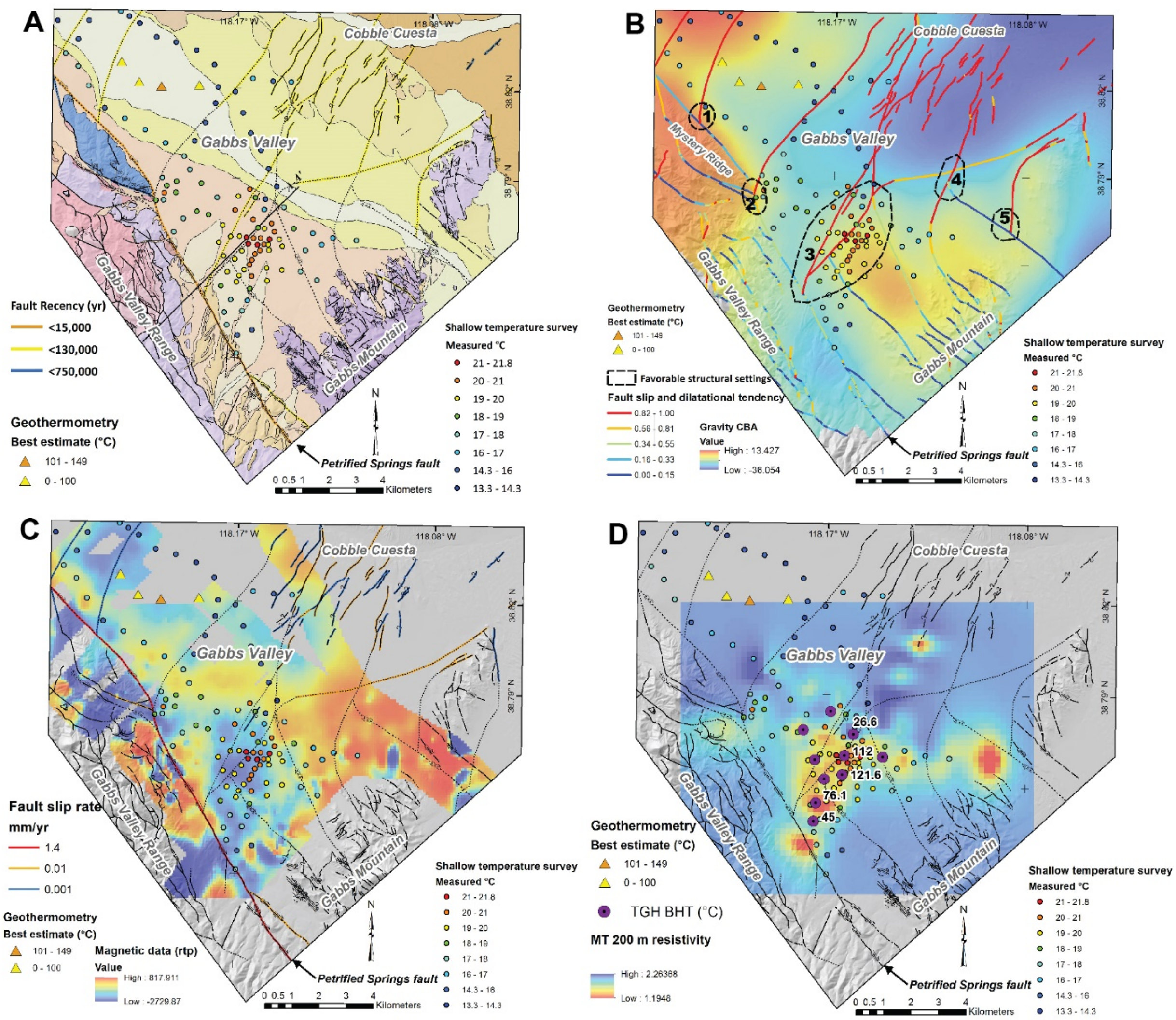

Figure 3: Southern Gabbs Valley study area. A. Geologic map showing age of Quaternary faults, geothermometry, and 2-m temperature data. Quaternary sediments are shown in yellow, white, and light orange; Tertiary volcanic units in lavender and pink; Mesozoic metasedimentary rocks are blue. Cross section A-A' shown in Figure 4. B. Slip and dilation tendency, complete Bouguer gravity, and favorable structural settings with geothermometry and 2-m temperature data. C. Ground magnetic data and fault slip data included with geothermometry and 2-m temperature data. Note collocation of magnetic low with shallow temperature anomaly. D. Magnetotelluric data (200 m depth slice), location of drilled or possible TG holes (not all will be drilled), and bottom-hole temperatures of TGHs (~152 m depth) with geothermometry and 2-m temperature data. Note collocation of low-resistivity anomaly with hot TGH's and shallow temperature anomaly.

Due to the collocation of multiple features suggesting a blind geothermal system in southern Gabbs Valley, a temperature gradient drilling program was organized to 1) evaluate the presence of a system; 2) constrain its size; and 3) test the play fairway methodology. To date, five temperature-gradient holes (TGH) have been drilled in the area (Figure 3D). The holes are distributed across the north-south extent of the identified shallow thermal and geophysical (gravity, magnetic, and MT) anomalies and partially across the east-west extent. Bottom-hole temperatures from two holes in the central part of the identified shallow thermal and geophysical anomalies were 112^{o}C and 121.6^{o}C at ~152 m (500 ft) depth (Figures 3D and 5). Bottom-hole temperatures fall off rapidly to the north and more gradually to the south. At 150 m depth, the thermal anomaly is at least ~2 km long in its north-south extent and probably at least 1 km wide in the east-west direction. Additional drilling is needed to fully define the size of the system.

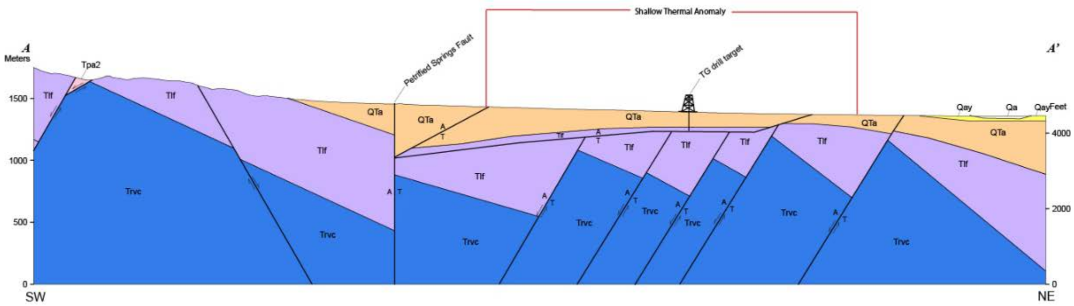

Figure 4: Cross section A-A' in southern Gabbs Valley (location in Figure 3A), showing complex fault intersection collocated with 2-m temperature anomaly and hot TG wells. Qay, Qs, QTA – late Miocene-Quaternary sediments; Tlf – Miocene volcanic rocks; Trvc – Triassic metasedimentary rocks.

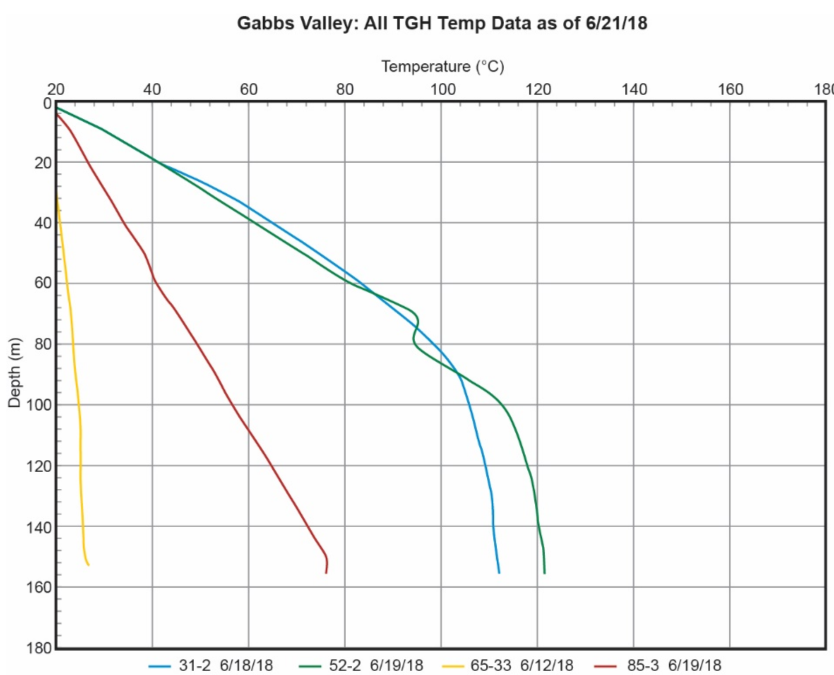

Figure 5: Data from TG holes in southern Gabbs Valley, as of June 21, 2018. The two hot wells are collocated with the shallow temperature anomaly, intersecting and terminating gravity gradients, magnetic low, and low-resistivity anomaly.

4. Discussion

Predictive play fairway maps were generated for the southern Gabbs 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 (Figures 6 and 7). 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 and MT data) into the local permeability models.

Three main sets of predictive maps were generated in this study. They are 1) play fairway maps, 2) play fairway error maps, and 3) direct evidence maps. Direct evidence maps are qualitative in nature, because qualitative values are 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 southern Gabbs 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 southern Gabbs 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 provide 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 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 southern Gabbs 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 6). 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 (not normalized) indicate relatively high potential. The direct evidence map of southern Gabbs Valley area is also more detailed than in Phase I (Figure 7), because of much greater availability of input data, including anomalous 2-m temperatures and geothermometry. We should note that these plots do not incorporate the recently acquired MT data nor the data from the TGH's.

Nonetheless, significant differences between Phases I and II in the play fairway analysis are particularly strong for southern Gabbs Valley (Figures 6 and 7) 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 and vectoring into the most promising setting based on complexity and collocation with other features (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 (Figures 3B and 6). 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 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 was very adaptable to the natural evolution of an exploration program as it progresses from a regional analysis and subsequently vectors into the most promising prospects that present the lowest risk for development.

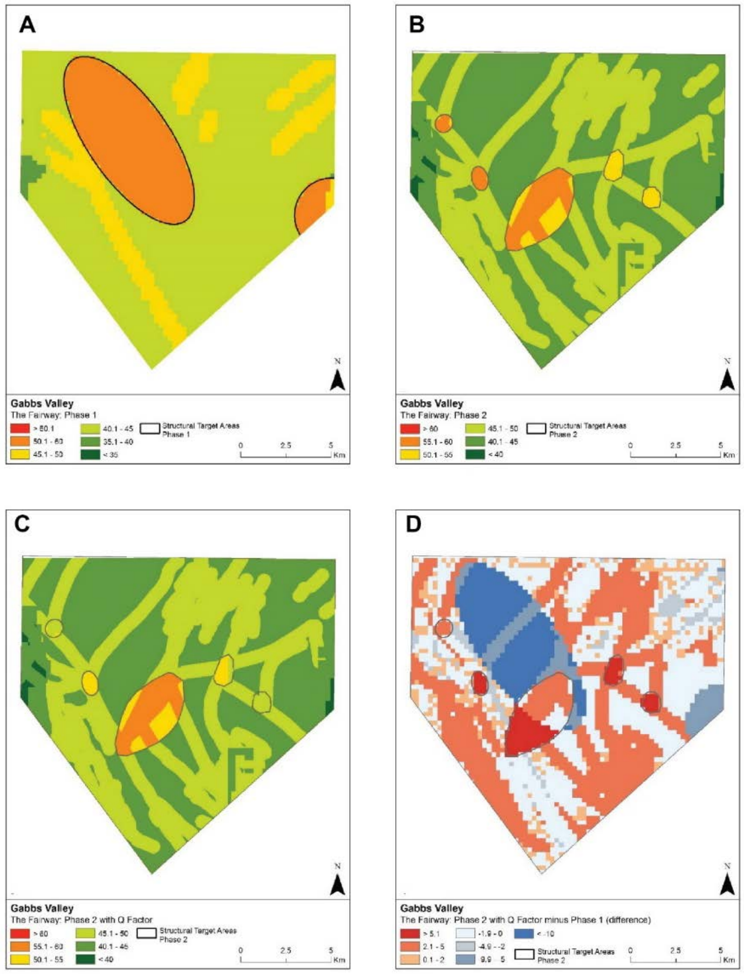

Figure 6: Comparison of Phase I and II fairway analysis for southern Gabbs Valley. A. Phase I fairway results. B. Phase II fairway results calculated the same as in Phase I. C. Fairway score from Phase II calculated with structural setting quality factor. D. Difference between the Phase II and Phase 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.

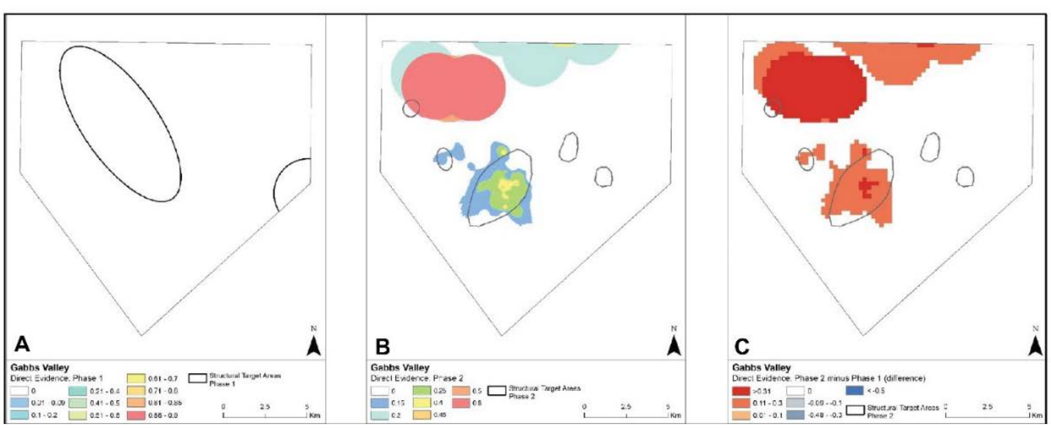

Figure 7: Comparison of Phase I and II direct evidence grid layers for southern Gabbs Valley. A. Phase I direct evidence. B. Phase II direct evidence. C. Difference between Phases I and II direct evidence modeling grid layer with positive numbers equal to increase of fairway score from Phase I to II.

5. Conclusions

Multiple features, including hot TGH wells, good geothermometry from nearby wells, intersecting and terminating gravity gradients, magnetic low, and low-resistivity anomaly, indicate that the south-central part of southern Gabbs Valley contains a relatively high temperature (>130^{o}C) blind geothermal system. Additional work is needed, however, to fully characterize the temperature and geometry of this resource and provide a platform for evaluating commercial viability. These tasks include: 1) collecting and analyzing fluid samples directly associated with the resource to better define the reservoir temperature and provide direct context for the TGH results; 2) integrating the detailed potential field geophysical (gravity and magnetics) and geologic data to build a detailed 3D geologic model; and 3) integrating all data to develop conceptual models of the geothermal resource and constrain its size.

The discovery in southern Gabbs Valley is particularly significant, as no previous geothermal exploration had been conducted in this area. These results provide preliminary validation of our methodology and suggest that broader applications of play fairway analysis will likely yield positive results. Not only are there many additional promising sites within the original 96,000 km^2 study area, but other parts of the Great Basin region abound in favorable geologic settings and could greatly benefit from play fairway analysis, especially considering that blind systems probably represent the bulk of the geothermal resources. Play fairway analysis provides a platform from which to conduct geothermal exploration at multiple scales and ultimately minimize the inherent risks in drilling and development. Although the details of play fairway analysis will differ between regions, depending on tectonic setting, available data, and other factors, the general methodology provides a roadmap for unleashing the vast untapped potential of conventional geothermal systems in the Great Basin and other regions.

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