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The Nevada Geothermal Play Fairway Project: Exploring for Blind Geothermal Systems Through Integrated Geological, Geochemical, and Geophysical Analyses

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ABSTRACT

Most geothermal resources in the Great Basin region of the western USA are blind, and thus the discovery of new commercial-grade systems requires synthesis of favorable characteristics for geothermal activity. The geothermal play fairway concept involves integration of multiple parameters indicative of geothermal activity to identify promising areas for new development. In Phase 1 of the Nevada play fairway project, nine geologic, geochemical, and geophysical parameters were initially synthesized to produce a new detailed geothermal potential map of 96,000 km^2 from west-central to eastern Nevada. These parameters were grouped into subsets and individually weighted to delineate rankings for local permeability, intermediate permeability, regional permeability, and thermal potential, which collectively defined geothermal play fairways (i.e., most likely locations for significant geothermal fluid flow). This initial work was aimed at reducing the risks in regional exploration and therefore facilitating discovery of new commercial-grade systems in blind settings, as well as in areas with surface expressions of geothermal activity. Phase 2 of the project involved detailed analysis of some of the most promising areas identified in Phase 1. Twenty-four highly prospective areas, including both known undeveloped systems and previously undiscovered potential blind systems, were identified for further analysis. After reconnaissance of these areas, five of the most promising sites were selected for detailed studies. Multiple techniques were employed in the detailed studies, including geologic mapping, shallow temperature surveys, gravity surveys, LiDAR, geochemical studies, seismic reflection analysis, and 3D modeling. The goal of the detailed studies was to identify areas with the highest likelihood for high permeability and thermal fluids, such that drill sites could be targeted.

Phase 3 of the project involved more detailed geophysical analyses and temperature-gradient drilling in southeastern Gabbs Valley and northern Granite Springs Valley, deemed the two most promising sites, with the goal of providing preliminary validation of the play fairway methodology. In southeastern Gabbs Valley, the collocation of a favorable structural setting (displacement transfer zone and fault intersections), Quaternary faults, intersecting and terminating gravity gradients, magnetic low, shallow (2 m) temperature anomaly, low resistivity anomaly, and promising geothermometry from nearby water wells provided evidence for a blind system. Drilling of six temperature-gradient holes (TGH) defines an apparent geothermal system at this locality with temperatures as high as 124°C at 152 m. This system is blind, with no surface hot springs, fumaroles, or paleo-geothermal deposits. For northern Granite Springs Valley, a favorable structural setting (termination of a major Quaternary normal fault), terminating gravity gradient, magnetic gradient, newly discovered sinter deposits, nearby warm water wells, previously drilled TGHs, and promising geothermometry suggest a hidden system. Drilling of four TGHs yields temperatures of ~96°C at ~250 m, suggesting the presence of a geothermal system. Lessons learned in the course of this project include: 1) initially identified sites commonly include multiple favorable structural settings at a finer scale; 2) promising sites in Cenozoic basins cannot be recognized without detailed geophysical surveys; and 3) play fairway analysis should be updated as the exploration program vectors into the most promising sites and finer-scale data are acquired. This requires revision of initial predictions of permeability potential to reflect more detailed analyses and preparation of higher-resolution play fairway maps prior to selecting sites for drilling.

1. INTRODUCTION

Geothermal *play fairway analysis* is a concept adopted from the oil industry aimed at reducing the risks in geothermal exploration and drilling. The geothermal play fairway concept involves integration of multiple parameters indicative of geothermal activity to identify potential areas for new development (e.g., Faulds et al., 2016a,b, 2018; 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 evaluation of the favorability of known, undeveloped geothermal systems, as well as assessing the probability of a particular area for hosting a blind relatively high-temperature (>130°C) system capable of generating electricity. Blind systems have no surface manifestations of geothermal activity, such as hot springs or steam vents (e.g., Richards and Blackwell, 2002).

We have applied the play fairway methodology to 96,000 km^2 of the Great Basin region of Nevada, which encompasses an active extensional to transtensional setting within the Basin and Range province of western North America (Figure 1). The Great Basin region of Nevada and adjoining states currently has ~720 MW of capacity produced from ~25 operating power plants. However, studies indicate much greater potential for conventional hydrothermal systems in the region (e.g. Williams et al., 2007, 2009). Blind systems are thought to comprise more than 75% of the geothermal resources in this region (Coolbaugh et al., 2007).

Most geothermal systems (>85%) in the Great Basin region, especially the relatively high-temperature systems (>130°C), reside in four discrete types of favorable structural settings: 1) step-overs or relay ramps between overlapping normal faults; 2) fault tips or terminations, 3) fault intersections, and 4) accommodation zones, whereby oppositely dipping normal fault systems intermesh with multiple fault terminations and intersections (Faulds et al., 2011; Faulds and Hinz, 2015). In the transtensional western part of the

Great Basin region, pull-aparts and displacement transfer zones, involving the termination of individual strike-slip faults in arrays of normal faults, also host many geothermal systems. Nearly 40% of the known systems across the region are blind (Faulds and Hinz, 2015), but most of these blind systems were discovered accidentally through drilling of holes for agriculture or mineral exploration. These favorable structural settings contain high densities of relatively minor faults, which enhance permeability. The main segments of major normal faults are generally not conducive to geothermal activity due to thick zones of gouge that inhibit permeability and periodic release of stress in major earthquakes. Notably, most geothermal systems in the region are amagmatic and lack middle to upper crustal magma chambers as a heat source. Heat is generally provided by a high geothermal gradient associated with active regional extension and crustal thinning. It is also noteworthy that most of the geothermal systems in this region, especially the higher temperature systems (>130°C), are associated with Quaternary faults.

This paper describes the general methodology, phased approach, and both interim and final results of the Nevada play fairway analysis. More details on specific phases and individual study areas can be found in multiple earlier contributions (Faulds et al. 2015a,b, 2016a,b, 2017, 2018; McConville et al., 2017; Craig et al., 2017; McConville, 2018; Craig, 2018).

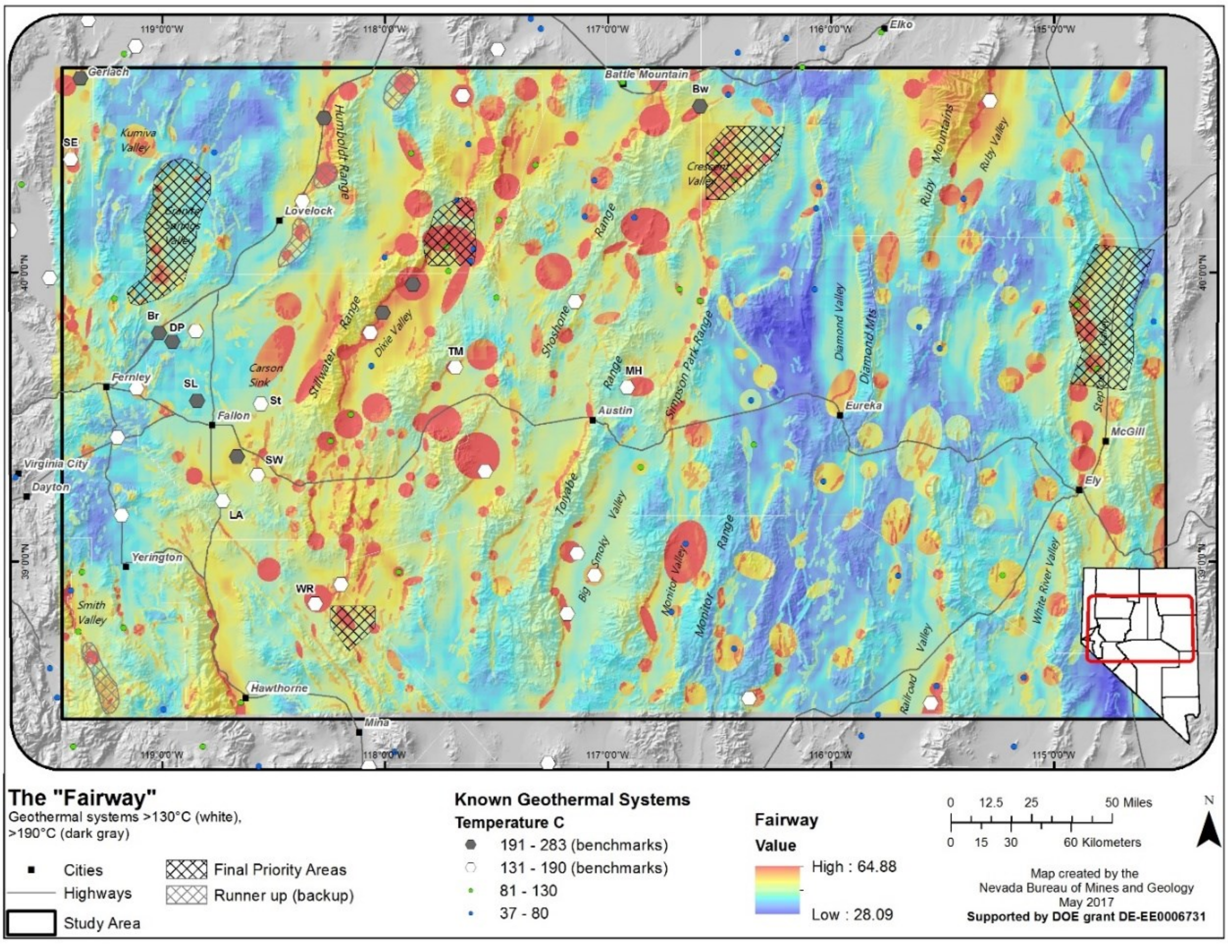

Figure 1: Geothermal play fairway map produced in Phase I, with final down-select areas for detailed studies shown by black hachures for Phase II. Runner-up areas are shown by light gray hachures. From west to east across the northern tier, detailed study areas are Granite Springs Valley, Sou Hills,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

2. NEVADA PLAY FAIRWAY PROJECT

The Nevada geothermal play fairway project utilized a phased approach, with three distinct phases funded by the U.S. Department of Energy. The first phase involved development of the play fairway methodology and production of a regional-scale geothermal potential map. The second phase included detailed studies of five particularly prospective areas identified in Phase I, as well as some refinement of the play fairway methodology. The third phase involved additional detailed analyses and temperature-gradient drilling at two of the most promising areas.

2.1 Phase I

Phase I focused on development of a statistically based geothermal potential map for 96,000 km^2 across the Great Basin region of Nevada (Figure 1; Faulds et al., 2015a,b, 2016a,b). This transect was selected to include regional strain gradients and changes in composition of the underlying basement from primarily Mesozoic crystalline rocks (granitic and metamorphic rocks) in the west to dominantly Paleozoic carbonates and sediments overlying Proterozoic gneisses and granites in the east. In addition, there were 34 known areas with temperatures ≥130°C, and these localities served as benchmarks or training sites that guided our analysis. Due to the strong control of Quaternary faults on geothermal systems in the region (Curewitz and Karson, 1997; Blackwell et al., 1999; Richards and Blackwell, 2002; Bell and Ramelli, 2007; Faulds et al., 2006, 2011, 2013; Hinz et al., 2011, 2013, 2014), our approach emphasized fault-controlled geothermal play fairways. Nine parameters were incorporated into the regional geothermal potential map, including: 1) structural settings, 2) age of recent faulting, 3) slip rates on Quaternary faults, 4) regional-scale strain rates based on GPS geodesy, 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 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 then combined to define the fairway (Figure 2). Many sites in the broad study area yielded high play fairway values.

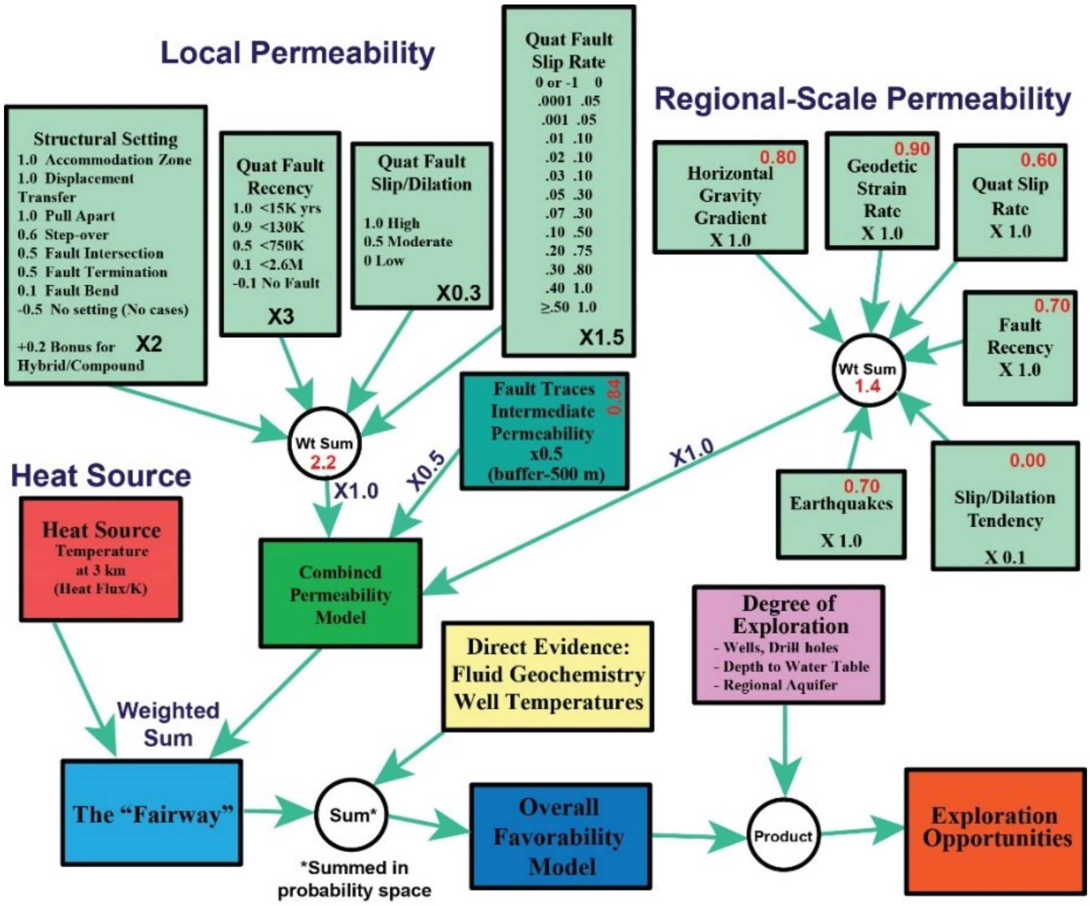

Figure 2: The Nevada play fairway modeling workflow. Red numbers indicate relative weights determined from weights of evidence. Black numbers indicate expert driven weights used in the analysis. In all cases, the expert driven weights took into account statistical analyses. We have generally focused on the fairway model (light blue box in lower left).

2.2 Phase II

Phase II of the project focused on detailed studies of five promising areas. Multiple techniques, including detailed geologic mapping, Quaternary fault analysis, shallow temperature surveys, detailed gravity surveys, LiDAR in three areas, geochemical analysis of water samples, seismic reflection analysis (where available), slip and dilation tendency analysis of Quaternary faults, and 3D modeling, were employed in the detailed studies. The goal of the detailed studies was to identify specific areas with the highest likelihood for high permeability and thermal fluids, such that individual drill sites could be selected. Due to the geothermal wealth of this region, there were dozens of areas that yielded high fairway values. Thus, a major challenge in the early stages of Phase II was determining which areas to down-select for detailed studies. We initially chose 24 of the most promising sites for reconnaissance level assessment based on 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 1) available geological, geochemical, and geophysical data, 2) new shallow temperature and geochemical data collected in this study, 3) land status including % of area considered primary sage grouse habitat (a threatened bird species), 4) distance from an electrical transmission corridor, and 5) degree of previous exploration (Figure 3).

Due to the abundance of favorable sites in the region, we elected to include in our final selections broad geographical distribution that incorporated variations in tectonic setting (transtensional vs. extensional), strain rates, composition of basement rocks, and types of favorable structural settings. Thus, the five detailed study areas essentially span the entire region from east to west. From west to east, areas chosen for detailed study were Granite Springs Valley, southeastern Gabbs Valley, Sou Hills, Crescent Valley, and Steptoe Valley (Figure 1). The Gabbs Valley study area occupies a displacement transfer zone in west-central Nevada in a region of relatively high strain at the transition between the Walker Lane dextral shear zone (cf., Stewart, 1988; Faulds and Henry, 2008) and extensional Basin and Range province. The Walker Lane accommodates ~20% of the dextral motion between the Pacific and North American plates (e.g., Hammond et al., 2009). In contrast, Steptoe Valley lies 250 km to the east in eastern Nevada in an area of relatively low extensional strain.

Notably, as we examined each area more carefully, we found that all contain several finer-scale, favorable structural settings and thus multiple potential geothermal targets. This required a revision of the play fairway analysis within each study area to select the most highly prospective targets for drilling (Faulds et al., 2017a,b, 2018; Craig, 2018; McConville, 2018). This process permitted vectoring into the more promising locations for geothermal activity within individual areas.

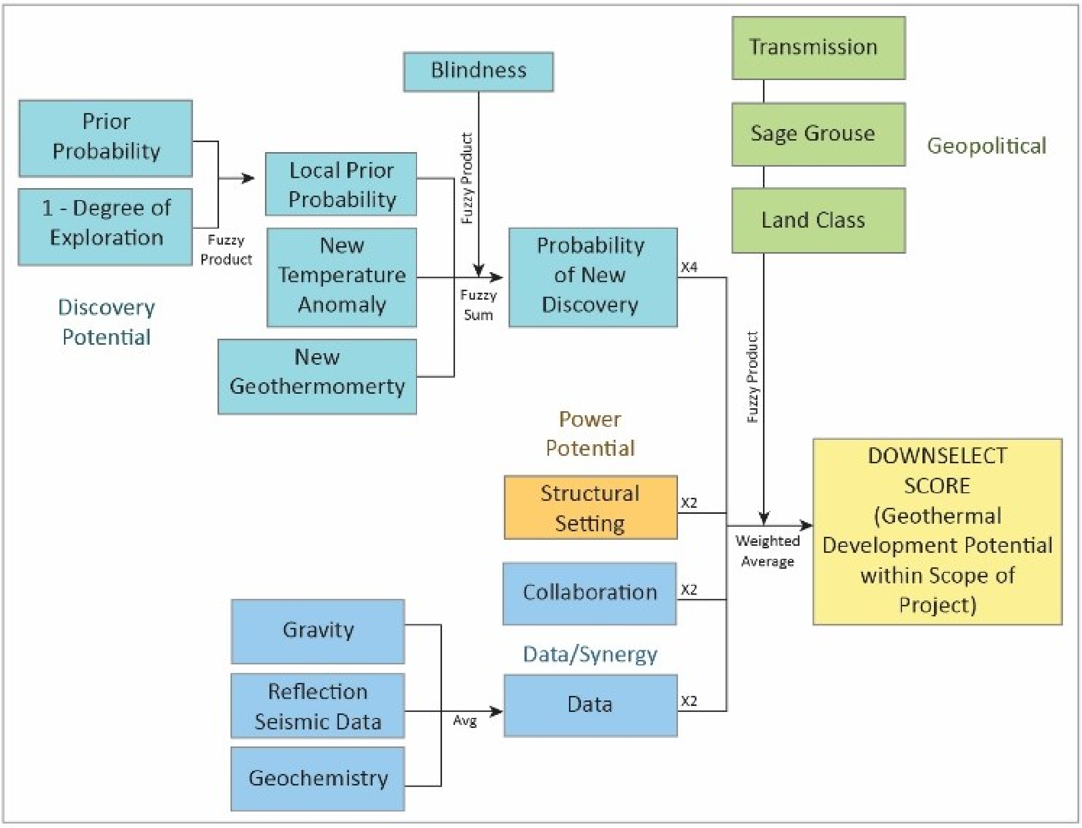

Figure 3: Flow chart showing down-selection process for selecting Phase II detailed study areas from prospective areas identified in Phase I. "Collaboration" refers to potential for industry collaboration.

2.3 Phase III

Phase III of the project involved more detailed geophysical analyses and temperature-gradient drilling in southeastern Gabbs Valley and northern Granite Springs Valley, deemed the two most promising sites. Southeastern Gabbs Valley occupies a broad displacement transfer zone proximal to a terminating dextral fault within the Walker Lane, and Granite Springs Valley contains several terminations of major Quaternary normal faults, fault step-overs, and a major accommodation zone. The primary goal of Phase III was to test the play fairway methodology with temperature-gradient drilling. The more detailed geophysical analyses included additional gravity and new magnetic and magnetotelluric (MT) surveys. The additional gravity work and new magnetic work better defined the probable location of subsurface faults. The magnetic and MT surveys helped to define possible areas of alteration and fluid flow in the subsurface.

In southeastern Gabbs Valley, multiple favorable structural settings were identified based on inferred fault intersections within the broader displacement transfer zone (Figure 4B). One area (#3 in Figure 4B) was particularly prospective based on the collocation of Quaternary faults, intersecting and terminating gravity gradients suggesting multiple fault intersections, magnetic low, shallow (2 m) temperature anomaly, low resistivity anomaly, and promising geothermometry from nearby water wells (Craig, 2018; Faulds et al., 2018; Figure 4). Drilling of six temperature-gradient holes defined an apparent geothermal system at this locality with temperatures as high as 124°C at 152 m (Figure 5), with the highest temperatures in the central part of the collocated geophysical and shallow temperature anomalies. 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 a north-south extent and probably at least 1 km wide from east to west. This system is completely blind, with no surface hot springs, fumaroles, or paleo-geothermal deposits.

For northern Granite Springs Valley, we chose the Adobe Flat area in northern Granite Springs Valley (area #2 in Figure 6) for more detailed analyses and subsequent drilling in Phase III due to a combination of geologic, geophysical, geochemical, and practical matters (e.g., land status and accessibility). This area contains a favorable structural setting (termination of a major Quaternary normal fault), terminating gravity gradient, magnetic gradient, newly discovered Quaternary sinter deposits, nearby warm water wells, nearby warm previously drilled temperature-gradient holes (Benoit, 2008), and promising geothermometry from water samples collected with geoprobe drilling suggest a hidden system (Figures 6 and 7A). The area is also easily accessible and resides on public land. Drilling of six new temperature-gradient holes yielded temperatures of up to ~96°C at ~240 m (Figures 7B and 8), suggesting the presence of a blind geothermal system. Well 42-2 has an essentially isothermal gradient from ~150 to 250 m, and well 54-2 shows an isothermal gradient from ~110 to 152 m (Figure 8). These isothermal gradients suggest a convective heat source and upwelling in that area, which is proximal to the largest, observed sinter deposits. The nearby 76-2 well has a conductive temperature gradient to 250 m depth, suggesting that it may be more distal to upwelling geothermal fluids. We therefore suspect that a major upwelling lies in the vicinity of wells 42-2 and 54-2 proximal to sinter deposits and within a zone of intersecting faults and a possible step-over within a broader horse-tailing fault termination. The sinter deposits imply subsurface temperature of more than 180°C.

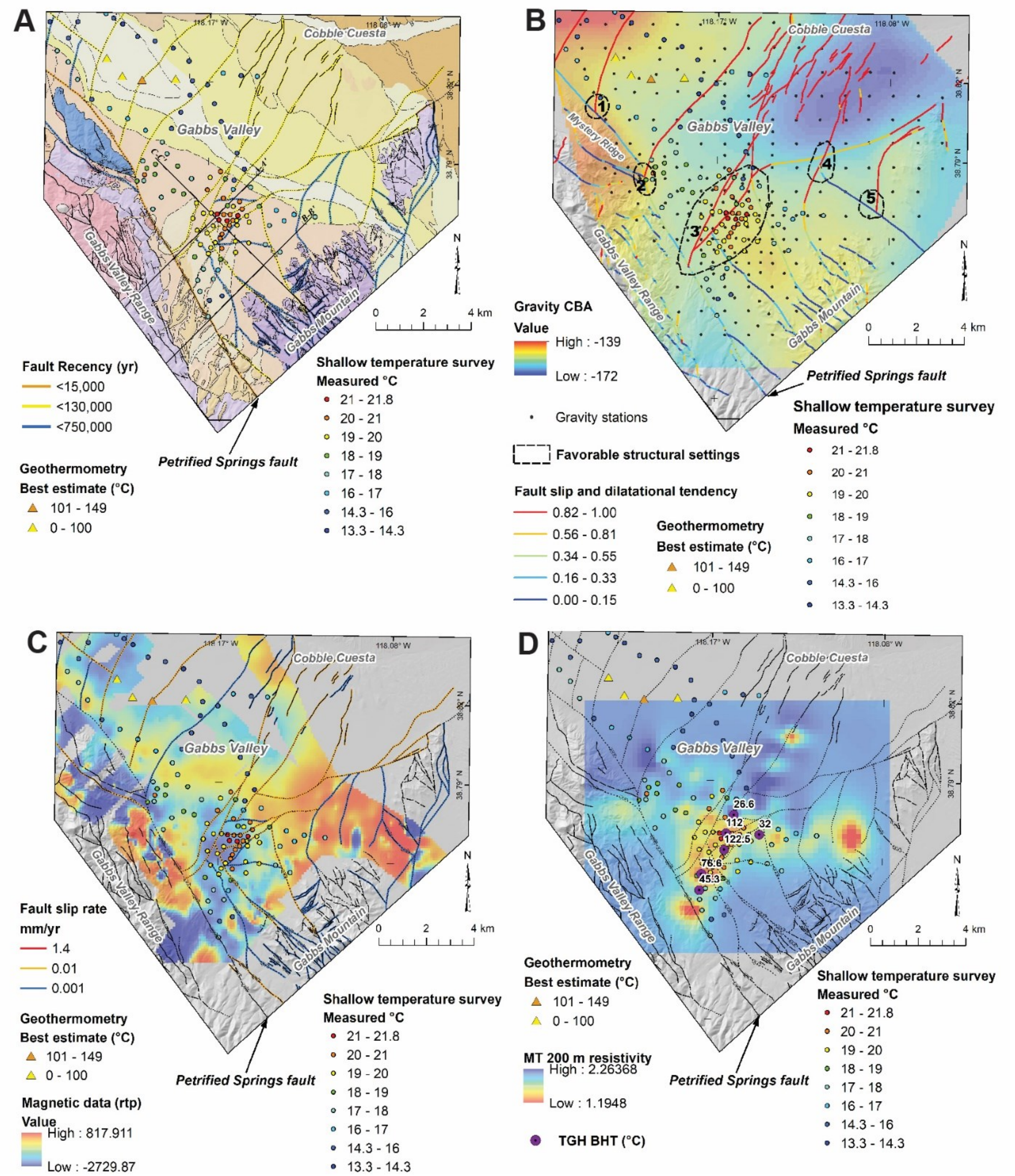

Figure 4: Southeastern Gabbs Valley. A. Geologic map showing Quaternary faults, geothermometry, and 2-m temperature data. Quaternary sediments are in yellow, white, and light orange; Tertiary volcanic units in lavender and pink; Mesozoic metasedimentary rocks are blue. B. Slip and dilation tendency, complete Bouguer gravity, and favorable structural settings with geothermometry and 2-m temperature data. C. Ground magnetic data and fault slip data with geothermometry and 2-m temperatures. Note collocated magnetic low and shallow temperature anomaly. D. MT data (200 m depth), temperature-gradient holes, and bottom-hole temperatures (as of June 2018) (~152 m depth). Note collocation of resistivity low with hot temperature-gradient holes and shallow temperature anomaly.

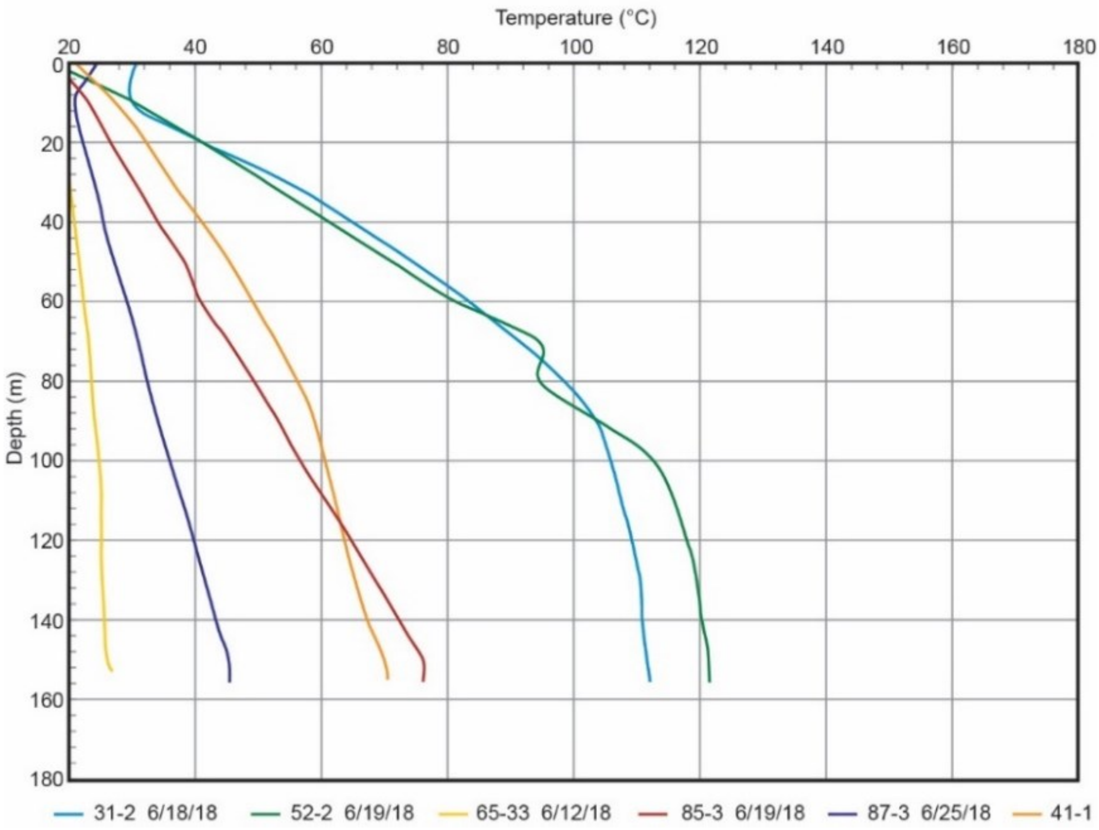

Figure 5: Data from temperature-gradient holes in southeastern Gabbs Valley. The two hot wells are collocated with the shallow temperature anomaly, intersecting and terminating gravity gradients, magnetic low, and low-resistivity anomaly.

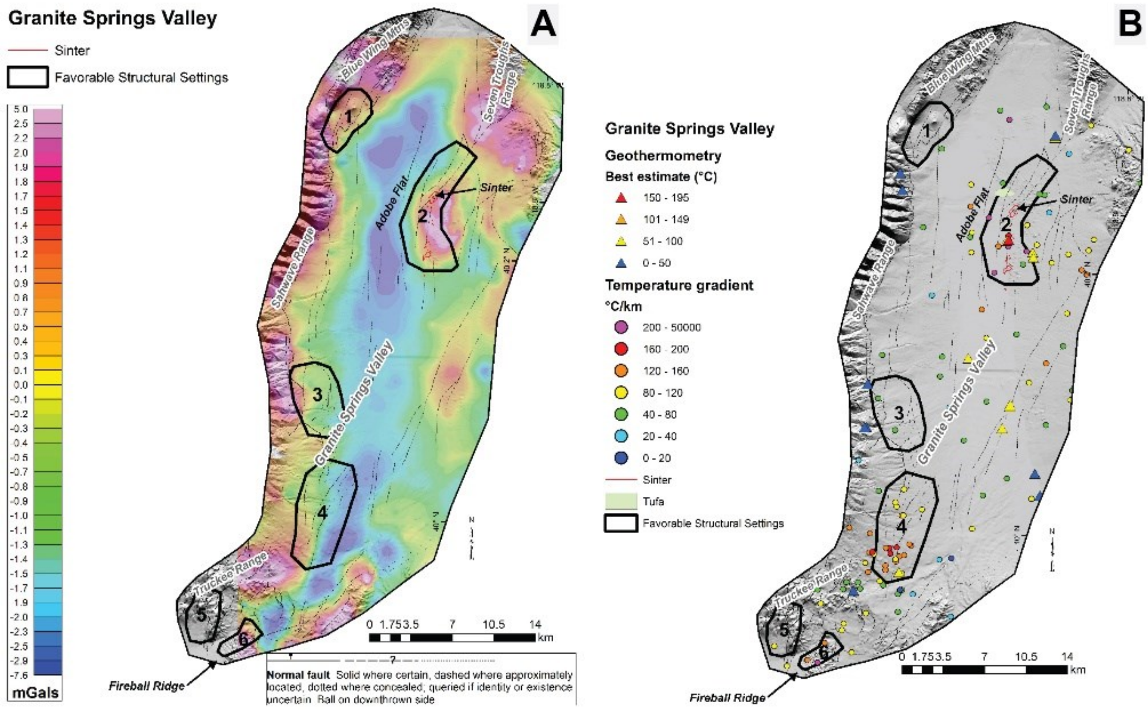

Figure 6: Granite Springs Valley study area. Favorable structural settings outlined in black, with #2 highest priority. A. Complete Bouguer gravity anomaly. B. Temperature-gradient wells drilled prior to this study and geothermometry data.

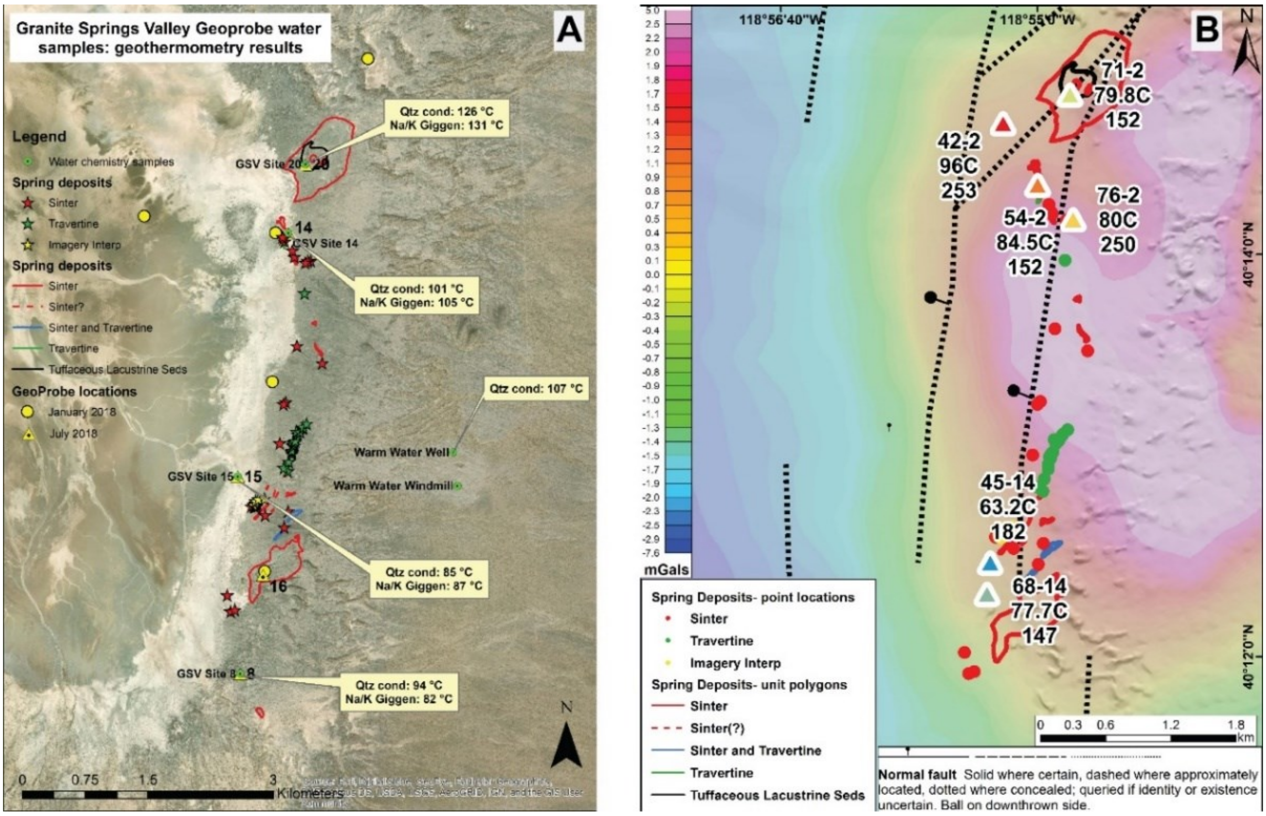

Figure 7: A. Locations of and geothermometry results from GeoProbe holes overlain on Google Earth image. B. Locations and bottom-hole temperatures of temperature-gradient wells overlain on isostatic residual gravity data and interpreted faults. Well locations are marked by triangles, with warmer colors indicating higher bottom-hole temperatures. From top to bottom, numbers adjacent to wells are well number, bottom-hole temperature, and depth in meters. The distribution of sinter and travertine is also shown in both A and B.

Predictive play fairway maps were generated for the Gabbs Valley and Granite Springs Valley areas using the exploration data obtained during Phase II and III studies (e.g., Faulds et al., 2017a,b). These new data were integrated with the existing Phase I database. Modeling procedures for the detailed study areas in Phase II, such as 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. 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 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; and 4) two-meter temperature anomalies utilizing established methods of assessing degrees above background (DAB) and potential errors (e.g., Sladek and Coolbaugh, 2013). Using Granite Springs Valley as an example, the fairway model 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 9).

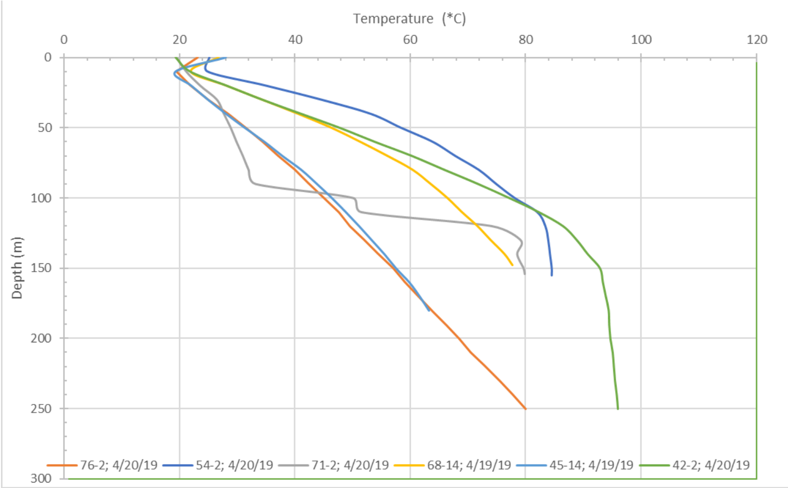

Figure 8: Temperature gradient data from six new temperature-gradient holes drilled in 2018-2019 in northern Granite Springs Valley. Locations of wells are shown in Figure 7B.

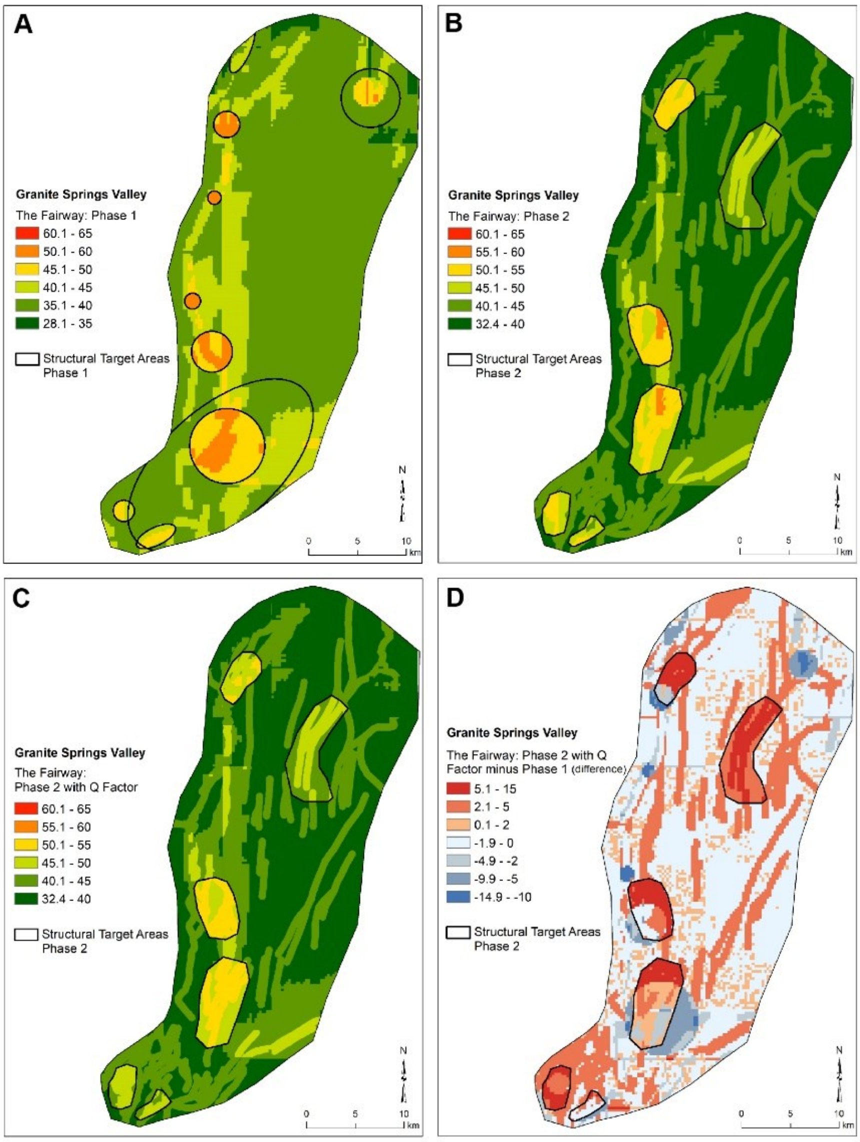

Figure 9: Comparison of Phase I and II fairway analysis for Granite Springs Valley. A. Phase I fairway results. B. Phase II fairway results calculated the same as in Phase 1. C. Fairway score from Phase II calculated with structural setting quality factor. D. Difference between the Phase II and Phase 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.

3. DISCUSSION

The discovery of two new blind geothermal systems provides initial validation of the play fairway methodology. This has significant implications both for reducing the risks in geothermal exploration and for facilitating major expansion of geothermal energy production in the Great Basin region and possibly elsewhere.

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). In a regional exploration program, it can be difficult to have enough detail in a particular area to select the most favorable targets for drilling. Once more detailed analysis of individual areas was conducted in Phase II, multiple favorable structural settings were recognized in each of the study areas. This required application of the play fairway methodology at a finer scale to evaluate geothermal potential of each of the favorable settings within a particular study area (Figure 9). The detailed geological, geochemical, and geophysical investigations in Phases II and III afforded such an analysis, and play fairway scores were employed to rank individual favorable settings in each of the study areas to select the most promising sites for drilling. The play fairway methodology was adaptable to the natural progression of an exploration program from regional analysis to selection of individual prospects for temperature-gradient drilling and potential development. It is particularly noteworthy that the progression from a regional to local analysis in major Cenozoic basins, such as Gabbs and Granite Springs Valleys, indicated multiple additional prospects, as geophysical data revealed the subsurface basin architecture and several additional favorable structural settings (Figures 4 and 6). Promising sites in many of these Cenozoic basins simply cannot be recognized without detailed geophysical surveys. We further note that basins make up about half of the Great Basin region and probably host huge amounts of untapped, conventional geothermal energy. Identification and ultimately development of these resources can clearly benefit from more detailed geophysical surveys coupled with play fairway analysis.

We should emphasize that our play fairway analysis applies to the tectonic setting and general conditions (e.g., quality of exposure, availability of certain datasets, etc.) of the Great Basin region, a broad well-exposed and reasonably well studied, extensional to transtensional active tectonic setting. Although available datasets are generally more robust in this region than in many parts of the world, critical data gaps do exist in much of the Great Basin, including MT data and detailed magnetic and gravity surveys. Clearly, the addition of such datasets at the local scale permitted vectoring into the most favorable sites and selection of successful drilling targets in our study. The play fairway methodology has broad applicability to other parts of the world, including other tectonic settings. However, the individual datasets employed in other regions, specific weighting of different parameters, and general algorithms can and should differ depending on the local conditions. Inclusion of machine learning techniques may also facilitate more expeditious application of play fairway methodologies to other regions.

CONCLUSIONS

Geothermal play fairway analysis involves integration of geological, geophysical, and geochemical parameters indicative of geothermal activity to discover new geothermal systems, especially blind systems with no surface hot springs or steam vents. In Phase I of the Nevada play fairway project, we incorporated nine parameters to develop a regional geothermal potential map of 96,000 km^2 of the Great Basin region in Nevada in the western USA (Figure 1). In Phase II of this project, we acquired detailed geologic, geophysical, and geochemical data to analyze five particularly promising areas identified on the initial geothermal potential map produced in Phase I. The play fairway analysis was adapted to a finer-scale to vector into favorable sites for drilling in the detailed study areas (Figures 4, 6, and 9). More detailed geophysical and geochemical surveys and temperature-gradient drilling were then conducted at two sites, southeastern Gabbs Valley and northern Granite Springs Valley, in Phase III of this project. Results from the temperature-gradient drilling, including bottom-hole temperature of 96 to 124°C and related geophysical anomalies, suggest that blind geothermal systems may exist at both sites, thus providing initial validation of the play fairway analysis technique. Although play fairway analysis is easily adaptable to any region or tectonic setting and therefore has broad applicability, the individual weightings of various parameters and general algorithms employed will likely differ in each area depending on local conditions and availability and robustness of datasets.

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