DISCOVERING NEW GEOTHERMAL SYSTEMS IN THE GREAT BASIN REGION, WESTERN USA: AN INTEGRATED APPROACH FOR ESTABLISHING GEOTHERMAL PLAY FAIRWAYS

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ABSTRACT

The Great Basin of the western USA is capable of producing much greater amounts of geothermal energy than the current ~670 MW from ~25 power plants. 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 (>130ºC). 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. These parameters were grouped into subsets and individually weighted to delineate rankings for heat and local, intermediate, and regional permeability, which collectively defined the play fairways.

From the regional map, 24 highly prospective areas, including known undeveloped systems and unknown potential blind systems, were identified for further analysis. Five particularly promising sites were then selected for detailed studies. Multiple techniques, including geologic mapping, Quaternary fault analysis, 2-m temperature surveys, gravity surveys, LiDAR, geochemical studies, seismic reflection analysis, and 3D modeling, were employed in these areas to define likely sites for high permeability and define highly prospective drilling targets. Local and intermediate permeability models were revised to reflect results of detailed analyses and generate new detailed play fairway maps. Lessons learned 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, providing a means to select regional prospects as well as vectoring into drilling targets at individual sites. Based on our detailed studies, several potential new, high temperature systems were discovered. However, TG drilling is needed to confirm commercial grade resources.

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., 2016;). 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. In the first phase of this project, we applied the play fairway methodology across a broad swath (96,000 km^2) of the Great Basin of Nevada in the western USA, a well-exposed extensional to transtensional, active tectonic setting. Phase II involved detailed studies of five highly prospective areas defined by the play fairway analysis in phase I (Fig. 1).

The Great Basin region of Nevada and adjacent parts of neighboring states is a world-class geothermal province with over 670 MW of current capacity at ~25 operating power plants. Although geothermal production has been trending slowly upward in recent years, all studies indicate far greater potential for conventional hydrothermal systems in the region (e.g. Williams et al., 2007, 2009). The Great Basin lies within the Basin and Range province of western North America, a broad region of crustal extension that has been active since the Miocene. The geothermal wealth of this region can be attributed to its active extensional to transtensional setting, including the diffusion of ~20% of the Pacific-North American dextral plate motion (~1 cm/year) along the Walker Lane into extension (Faulds et al., 2004). Accordingly, strain rates increase to the northwest across Nevada from much less than 1 mm/year near the Utah border to ~1 cm/year in the Walker Lane belt (Kreemer et al., 2012). As such, Quaternary normal faults abound across the Great Basin and provide the most fundamental, first-order control on geothermal activity, with nearly all geothermal systems located proximal to Quaternary faults (Bell and Ramelli, 2007).

Most of the geothermal systems (>85%), especially the relatively high-temperature systems (>130ºC), reside in fault interaction zones, 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, 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.

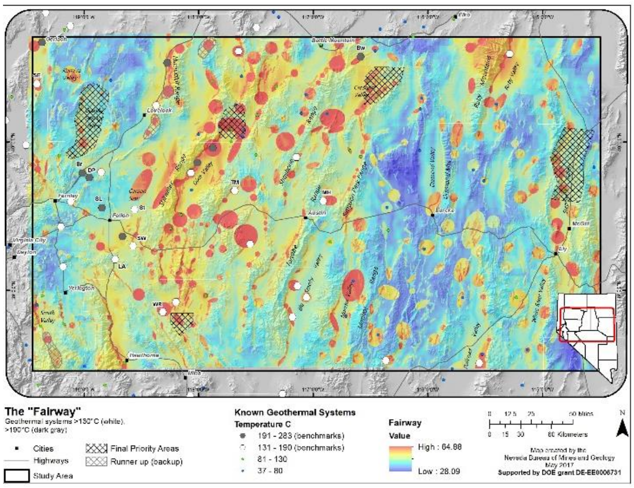

Figure 1: Final down-select areas for detailed studies in phase II shown by black hachures overlain on the play fairway map produced in phase I. Runner-up areas are shown by light gray hachures. From west to east across the northern tier, detailed study areas are Granite Springs Valley, Sou Hills, Crescent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

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 (Fig. 1; Faulds et al., 2015a,b, 2016a,b). This transect extended from west-central to eastern Nevada in order to capture the major aforementioned strain gradient across the region. Further, the transect incorporates a major transition in basements rocks 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 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.

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 (Fig. 2). Additionally, the fairway model was integrated with direct evidence of heat from wells 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 (Fig. 3). Fairway values range from a low of ~28 to near 65, with the 34 high-temperature (≥130°C) benchmarks yielding an average of 51.4.

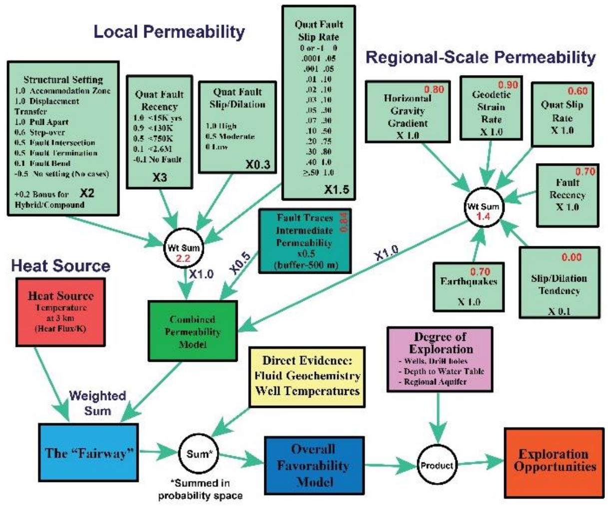

Figure 2: Nevada play fairway modeling workflow (Faulds et al., 2016a). Red numbers indicate relative weights determined from weights of evidence. Black numbers indicate expert driven weights used in the analysis. In all cases, the expert driven weights took into account the statistical analyses.

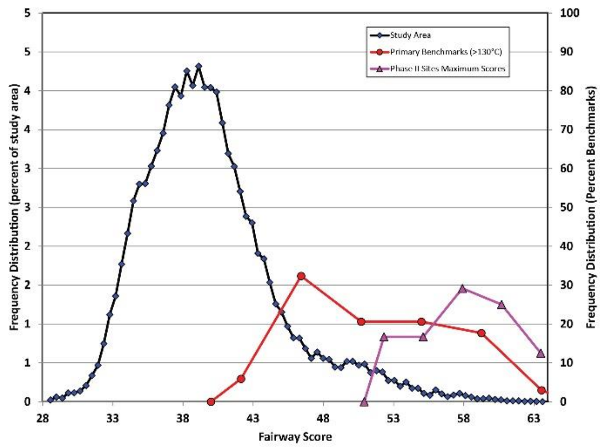

Figure 3: Distribution of play fairway scores for the primary benchmark (>130°C) systems (red) compared to scores for the study area as a whole (blue) and the maximum values within the 24 highly prospective sites selected for analysis in phase II (purple) (Faulds et al., 2016a).

2. DETAILED STUDY AREAS

Owing to the active extensional to transtensional tectonism and high heat flow in the Great Basin region, many sites in the broad study area (96,000 km^2) examined in phase I yielded high play fairway values. 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. Due to the plethora of favorable sites in the region, we were able to bias our final selections to include broad geographical distribution that incorporates 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 fault with multiple step-overs in an area of relatively low, purely extensional strain. Granite Springs Valley in northwest Nevada was selected based on distinct horse-tailing terminations of a Quaternary range-front fault. Sou Hills in northern Nevada incorporates a major accommodation zone between oppositely dipping Quaternary normal fault systems in the relatively high strain central Nevada seismic belt (e.g. Caskey et al., 1996). Crescent Valley in north-central Nevada contains a major highly segmented range-front normal fault with several discrete step-overs and fault intersections in an area of modest extensional strain. Each study area contains several favorable structural settings and thus multiple potential geothermal targets that were evaluated with respect to one another 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.

3. PLAY FAIRWAY ANALYSIS

Predictive play fairway maps were generated for each of the detailed study areas using the exploration data obtained during phase II studies (Faulds et al., 2017). 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, silica terrace mapping, and detailed temperature modeling) into the local permeability models.

Three main sets of predictive maps were generated. They are 1) play fairway maps, 2) play fairway error maps, and 3) direct evidence maps. Direct evidence maps are qualitative in nature, 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.

3.1 Model Methodologies

Modeling procedures for the five detailed study areas paralleled those of the phase I regional model (Faulds et al., 2015b). The regional-scale permeability and heat models of phase I remained unchanged, with the exception of the Steptoe Valley heat model, where additional data became available. 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. A number of adaptations and improvements were employed in the models to accommodate new types of data and additional structural attributes. These changes are briefly described below.

<u>Structural Settings Quality Factor</u>: A quality factor was introduced into the algorithm used to model the strength or quality of structural settings. This factor, scaled from 0 to 1, allows for a gradational membership of structural settings; that is, the degree to which a structural setting warrants inclusion in a local permeability model. Without such a quality factor, artificially abrupt boundaries between "structural settings" and "almost structural settings" can occur.

<u>Magnetotelluric (MT) Data</u>: In hydrothermal systems, strong low resistivity anomalies may correspond to clay caps above geothermal systems, whereas less intense but broader low resistivity anomalies correlate with geothermal reservoirs in some cases (Ussher, 2000; Cumming, 2009). MT data were only available for northern Granite Springs Valley. Because MT data were not available for the other study areas, MT was not included as a distinct parameter in the model. Instead, where present, we used low-resistivity anomalies to enhance the structural quality factor by 0.1.

<u>Steptoe Valley Detailed Temperature Model</u>: A temperature slice at a depth of 1250 m below sea level (bsl) from a detailed temperature model of Steptoe Valley was produced in this study and used to replace the regional temperature model used in phase I. Temperatures at that level correspond closely to a 3 km depth below the floor of Steptoe Valley, which is the depth used in Phase I. Because the range of temperatures in the phase I regional temperature model and the 1250-m bsl UGS model are similar, the same weighting

parameters and methodologies used in phase I were also used in phase II to combine the heat model with the structural model to produce an overall play fairway model. The benefits of the new temperature model include a more accurate and detailed representation of temperatures, and an increased confidence in the model that results from significantly reduced errors (uncertainty). The availability of the temperature model also made it possible to produce more accurate estimates of temperature anomalies in wells, which are used for input into the direct evidence model. A temperature anomaly at a given depth in a well was calculated by subtracting the predicted temperature from the model from the observed.

Two-meter temperature anomalies: A 2-m temperature survey was used to identify a significant anomaly in the southern Gabbs Valley area. The temperature data were converted to "degrees above background" (DAB) (e.g. Sladek and Coolbaugh, 2013). Three sources of error in the anomaly are recognized, each with a magnitude of ~1°C. These errors derive from 1) errors in measurement of temperature and depth, 2) errors in estimating background temperature, and 3) variations in subsurface temperatures caused by differences in surface albedo, topographic slope aspect, ground moisture, and elevation. A statistical test of significance was created using an inverse-distance-weighted temperature anomaly map divided by the estimated error, which showed that the central part of the anomaly is statistically significant. Additional confidence is provided by the spatial continuity of the DAB pattern, which does not fit any other observed phenomena, lending further credence to a geothermal origin.

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. These probabilities were assigned based on experience with these surveys, taking into account that temperatures of geothermal fluids at depth are unknown.

Sinter/silica-cemented sands and explosion craters: A newly recognized area of silica-cemented sands and sinter in Granite Springs Valley provides direct evidence of geothermal activity. The opaline material occurs as matrix silica surrounded by quartz sand grains. Based on the known association of opaline terraces with active geothermal systems, we assigned a probability of 0.6 to a 2-km buffer around this silica deposit. Two craters believed to have formed from hydrothermal explosions occur in the southwest corner of the Granite Springs study area (eastern Truckee Range). These craters were modeled with a 0.5 probability of association with 130°+C geothermal activity. No carbonate rocks or other formations susceptible to dissolution are known in the subsurface in this area.

3.1 Model Results: Ranking and Down-selection of Final Areas for Drilling

The fairway models of the five detailed areas have scores similar to those in the original phase I model. The major difference between the detailed phase II models and the phase I regional model is that locations of higher favorability are more accurately shown in the phase II models and at a higher level of detail. Figure 4 shows an example from southern Gabbs Valley. 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., 2017). We note that fairway scores above ~45 indicate relatively high potential (Fig. 3).

Direct evidence maps are also more detailed than in phase I, because of the much greater availability of input data. This is most obvious at Gabbs Valley (Fig. 5), where very little direct evidence was available in phase I, and where phase II data strongly point to the existence of a previously unknown geothermal system. Similarly, at Granite Springs Valley Faulds et al., 2017), 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. In Steptoe Valley, a greater resolution of direct evidence in the form of temperature anomalies from springs and wells provides better resolution of possible outflow and/or upflow plumes related to known higher temperature springs and wells (Faulds et al., 2017).

Significant differences between phases I and II in the play fairway analysis are particularly strong for those study areas containing large late Cenozoic basins. New geophysical data in these areas afforded discovery of previously unrecognized intrabasinal, favorable structural settings, as exemplified in the Adobe Flat area of Granite Springs Valley and in the central part of southern Gabbs Valley (Fig. 4). 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 (Fig. 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 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 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.

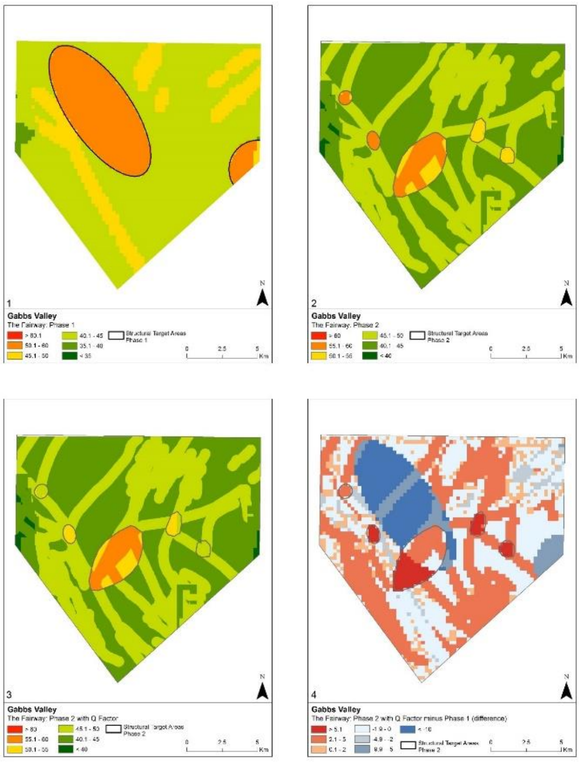

Figure 4: Comparison of phase I and II fairway analysis for southern Gabbs Valley. Phase I fairway results (1). Phase II fairway results calculated the same as in Phase 1 (2). Fairway score from Phase II calculated with structural setting quality factor (3). Difference between the phase II and phase I fairway results (4) 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.

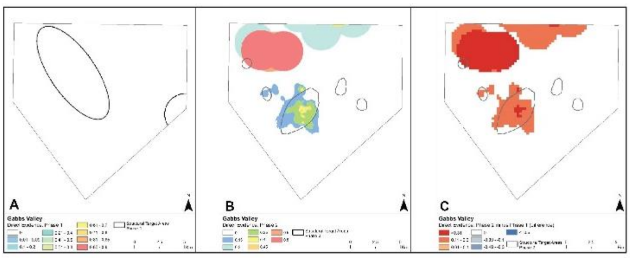

Figure 5: Comparison of phase I and II direct evidence grid layers for southern Gabbs Valley. Phase I direct evidence (A). Phase II direct evidence (B). Difference between the phase II and phase I direct evidence modeling grid layer (C) with positive numbers equal to increase of fairway score from phase I to phase II.

4. CONCLUSION

The results in phase II, including newly discovered hydrothermal features, shallow-temperature anomalies, and geothermometers indicative of commercial-grade temperatures of >130°C in all 5 study areas, have essentially validated our play fairway methodology. However, a critical test is whether our methodology can successfully target geothermal reservoirs with sufficient temperatures and volumes to support electrical generation. Therefore, the primary goal of phase III of this project is to complete the testing of our play fairway methodology through several closely integrated tasks that will characterize the temperature and geometry of each resource and provide a platform for evaluating commercial viability. These tasks include: 1) drilling TG holes to define the size of the thermal anomaly and identify possible up-flow zones; 2) collecting and analyzing new fluid samples directly associated with each resource to better define the reservoir temperature and provide direct context for the TG results; 3) collecting detailed potential field geophysics (gravity and magnetics) for building detailed 3D geologic models of each structural target area; 4) integrating potential field geophysics with existing phase II data and new drill data to build or update existing 3D geologic models; 5) collecting MT data to use with the 3D geologic model and temperature data to help build conceptual models of each reservoir and provide a clear road map for targeting deep geothermal wells by industry; and 6) integrating all data to develop conceptual models of the geothermal resources, identify and rank deep drilling targets, provide estimates of resource size, and present the phase III results in context of the play fairway analysis.

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