Geothermal Play Fairway Analysis of the Sou Hills, Northern Nevada: A Major Quaternary Accommodation Zone in the Great Basin Region

James E. Faulds[1], Andrew J. Sadowski[1*], Mark F. Coolbaugh[1], and Drew L. Siler[2]

[1]Great Basin Center for Geothermal Energy, Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada 89557
[*]Now at Washington Geological Survey, Ellensburg, Washington 98926
[2]U.S. Geological Survey, Moffett Field, California 94035

Keywords

Play Fairway Analysis, Nevada, Great Basin, Structural Controls, Accommodation Zone, Permeability

ABSTRACT

To facilitate discovery and development of blind geothermal systems in the Great Basin region, as well as assessment of known systems with surface hot springs, a play fairway approach was developed to evaluate and integrate multiple geologic and geophysical parameters for permeability and heat. Phase 1 of the project produced a geothermal potential map of 96,000 km^2 of Nevada. This analysis yielded 24 highly favorable locations with particularly high fairway scores, from which five promising sites were selected for detailed studies. The Sou Hills was chosen as a detailed study area due to a complex structural setting, plethora of Quaternary normal faults, and relatively high rates of both regional strain and slip on Quaternary faults.

Our analysis of the Sou Hills utilized: 1) detailed geologic mapping of ~60 km^2, 2) reconnaissance mapping of >200 km^2, 3) analysis of Quaternary faults, 4) detailed logging of cuttings from four, previously drilled wells (~2,000 m) and integration of ~5,500 m of existing logs from nine other wells, 5) a new gravity survey (355 stations), 6) LiDAR acquisition for 290 km^2, 7) a shallow temperature survey (82 stations), 8) interpretation of seven seismic reflection profiles, 9) slip and dilation tendency analyses, and 10) geochemical analyses of 23 water samples. Integration of these datasets shows that the Sou Hills occupies a major accommodation zone between oppositely dipping Quaternary normal fault systems. As such, the area is characterized by multiple, closely-spaced, west- and east-dipping Quaternary normal faults, many of which are favorably oriented for slip and dilation in the current stress regime. Seismic reflection and gravity data show an extensional anticline in northernmost Dixie Valley directly south of the Sou Hills. The anticline marks a zone of multiple intersecting, oppositely dipping normal faults and represents a particularly favorable site for potentially hosting a geothermal system.

1. Introduction

The Great Basin region of the western U.S. is a large geothermal province with >1200 MWe of installed nameplate capacity from ~28 geothermal systems. 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. Most of the geothermal systems in the region are amagmatic and not associated with middle to upper crustal magma chambers (Faulds et al., 2004). The geothermal wealth of this region can be attributed to its active extensional to transtensional setting and attendant crustal thinning, 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 west across the region 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 a fundamental, first-order control on geothermal activity, with nearly all geothermal systems located proximal to Quaternary faults (Bell and Ramelli, 2009).

Most geothermal systems in this region, especially those ≥130°C, reside along normal faults in complex interaction zones, such as fault terminations, fault intersections, step-overs or relay ramps, accommodation zones, displacement transfer zones at the ends of strike-slip faults, and releasing bends or pull-aparts in strike-slip faults (Curewitz and Karson; Faulds et al., 2006, 2013; Faulds and Hinz, 2015; Fig. 1). Geothermal systems generally do not occupy the main segments of faults. These fault interaction zones contain higher fault and fracture densities, more permeable fault breccia in lieu of impermeable clay gouge, and typically correspond to critically stressed areas (Faulds and Hinz, 2015; Siler et al., 2018). These characteristics lead to enhanced permeability and long-term fluid flow (e.g., Micklethwaite and Cox, 2004).

Although geothermal production has been trending upward in recent years (Muntean et al., 2019), studies indicate far greater potential for conventional hydrothermal systems in the region (Williams et al., 2009; U.S. Department of Energy, 2019), but most of these resources are blind or hidden (Coolbaugh et al., 2007). Because most systems in the region are controlled by Quaternary normal faults, they generally reside near the margins of actively subsiding basins. Thus, upwelling fluids along faults commonly flow into permeable subsurface sediments in the basin and do not emanate directly along the trace of the fault. Outflow from these upwellings may surface kilometers away from the deeper source or remain hidden with no surface manifestations (Richards and Blackwell, 2002). Thus, techniques are needed both to identify the structural settings enhancing permeability and to determine which favorable settings actually harbor subsurface hydrothermal fluid flow. The recent discovery in central Nevada of the robust geothermal system at McGinness Hills (Nordquist and Delwiche, 2013), a hidden system producing ~150 MWe (Muntean et al., 2019), suggests that many such systems are yet to be discovered in the region. The technical challenge is developing methodologies to locate such systems with minimal risk.

2. Geothermal Play Fairway Analysis

Geothermal play fairway analysis is a concept adapted from the petroleum industry (Doust, 2010) that aims to improve the efficiency and success rate of geothermal exploration and drilling. It involves integration of geologic, geophysical, and geochemical parameters indicative of geothermal activity. The concept was recently applied to evaluate known, undeveloped systems and potential hidden systems in various settings in the western U.S. (Faulds et al., 2015, 2016, 2018; Shervais et al., 2016; Forson et al., 2016; Lautze et al., 2017; Wannamaker et al., 2017; Siler et al., 2017).

In Nevada, we applied play fairway analysis to a large transect across the Great Basin region (Figure 1). In Phase 1 of this project, we developed a comprehensive, statistically based geothermal potential map for 96,000 km^2 of the region (Faulds et al., 2015, 2016). This project focused on fault-controlled geothermal play fairways due to the aforementioned 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, 2013; Hinz et al., 2011, 2014). Ten parameters were incorporated into the geothermal potential maps, including: 1) favorable structural settings, 2) location of Quaternary faults, 3) relative age of Quaternary faults, 3) slip rates on recent faults, 4) regional-scale strain rates, 5) slip and dilation tendency on Quaternary faults, 6) earthquake density, 7) horizontal gravity gradients, 8) temperature at 3 km depth, and 10) geochemistry from springs and wells. As described in detail by Faulds et al. (2015), these parameters were grouped into subsets to delineate rankings for local permeability, intermediate permeability, regional permeability, and temperature at 3 km depth, which collectively defined the play fairway (likely areas for geothermal fluid flow). 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 $\geq 130^{o}C$.

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) 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, d) distance from an electrical transmission corridor, and e) degree of previous exploration (Faulds et al., 2017a,b). From west to east across the region, the five sites chosen for detailed studies include: 1) northern Granite Springs Valley, 2) southeastern Gabbs Valley, 3) Sou Hills, 4) Crescent Valley, and 5) Steptoe Valley (Figure 1).

Detailed results of these studies have previously been reported for Gabbs Valley, Crescent Valley, and Granite Springs Valley (Craig et al., 2017; Craig, 2018; McConville et al., 2017; McConville, 2018; Faulds et al., 2018, 2019). Multiple collocated features suggestive of geothermal activity and high temperatures in thermal gradient holes drilled in Phase 3 of this project (e.g., 124°C at 150 m depth) indicate discovery of a hidden geothermal system in southeastern Gabbs Valley (Craig, 2018; Faulds et al., 2018). Several features, including anomalous temperatures in thermal gradient wells (95°C at 150 m depth), are also suggestive of a geothermal system in northern Granite Springs Valley. The detailed studies at Crescent Valley (McConville, 2018), Sou Hills (Sadowski et al., 2017), and Steptoe Valley (Hinz et al., this volume) have also yielded promising results. The purpose of this paper is to describe some of the detailed results and major implications of the Sou Hills study.

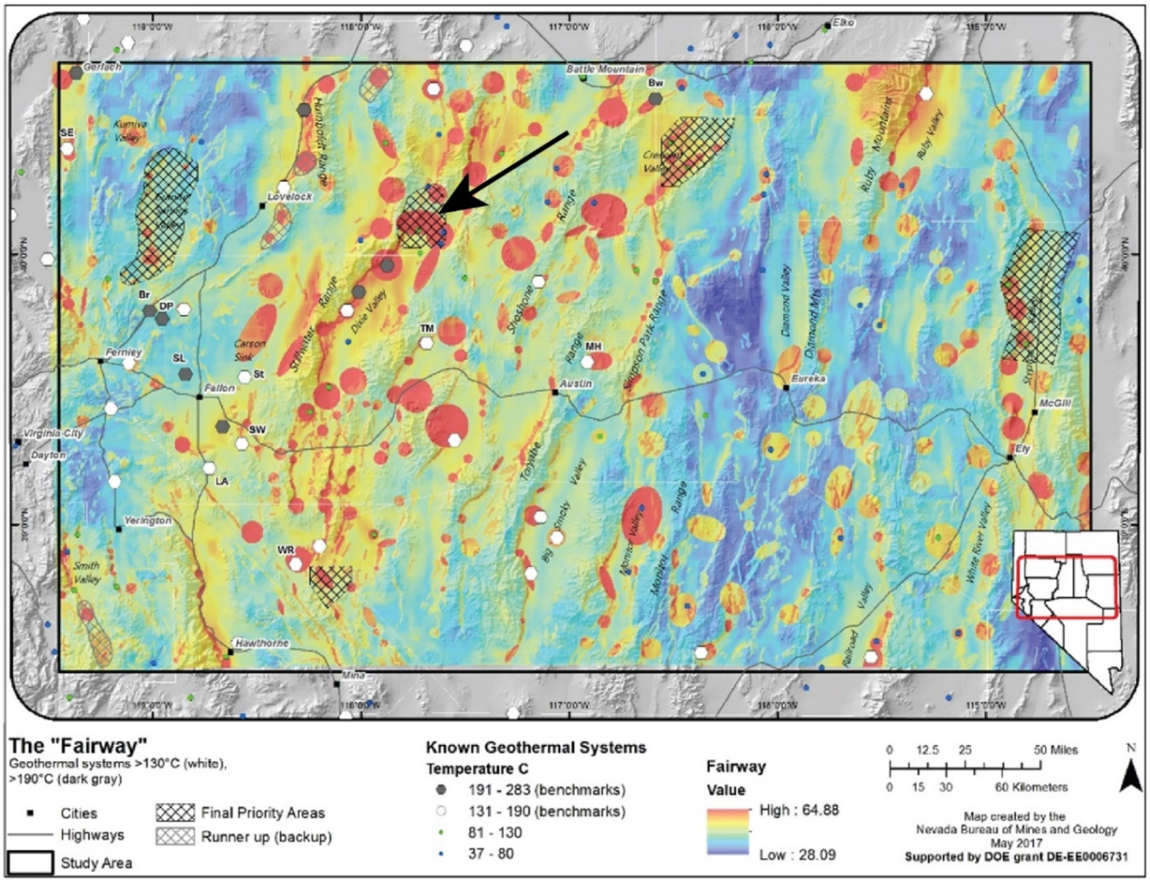

Figure 1: Detailed studies in the Nevada play fairway project shown by black hachures overlain on the play fairway map. Runner-up areas are shown by light gray hachures. From west to east, detailed study areas are Granite Springs Valley, SE Gabbs Valley, Sou Hills (black arrow), Crescent Valley, and Steptoe Valley. Abbreviations for other geothermal areas shown on map: Br, Bradys; Bw, Beowawe; DP, Desert Peak; LA, Lee-Allen Hot Springs; MH, McGinness Hills; SE, San Emidio; SL, Soda Lake; St, Stillwater; TM, Tungsten Mountain; SW, Salt Wells; WR, Don Campbell-Wild Rose.

3. Sou Hills

3.1 Geologic Framework and Results of Detailed Studies

The Sou Hills study area (Figure 1) in northern Nevada includes the northernmost part of Dixie Valley and a series of low ridges (the Sou Hills) that form an interbasinal topographic and structural high between Dixie Valley on the south and Pleasant Valley on the north (Figure 2). The Sou Hills lie within the central Nevada seismic belt, a portion of the Basin and Range province that has experienced relatively high rates of extension in the Quaternary (e.g., Caskey et al., 1996). Thermal areas in the Sou Hills reside at Seven Devils Hot Springs (57-76.7°C) and the McCoy Spring area (46°C). Our analysis of the area included: 1) new detailed mapping of ~60 km^2, 2) reconnaissance mapping of >200 km^2, 3) analysis of abundant Quaternary faults, 4) new detailed logging of cuttings from four previously drilled wells (~2,000 m) and integration of ~5,500 m of existing logs from nine other wells, 5) a new gravity survey totaling 355 stations, 6) acquisition of 290 km^2 of LiDAR, 7) a shallow temperature survey (82 stations), 8) interpretation of seven seismic reflection profiles, 9) slip and dilation tendency analysis, 10) geochemical analyses of 23 water samples, and 11) preliminary 3D modeling.

The structural framework of the Sou Hills is dominated by an accommodation zone (Fonseca, 1988) between a) the west-dipping Quaternary normal fault zone that bounds Pleasant Valley on the east and ruptured in 1915 in a M7.2 earthquake (Wallace, 1984), and b) the east-dipping Quaternary normal fault zone that bounds Dixie Valley on the west that has also experienced historic ruptures (Caskey et al., 1996). As such, the area is characterized by multiple, closely-spaced, west- and east-dipping normal faults. Legacy seismic reflection and newly acquired gravity data in this study indicate an extensional anticline in northernmost Dixie Valley directly south of the Sou Hills (Figures 2 and 3), as evidenced by the dips and offsets of prominent reflectors at the apparent base of basin-fill sediments. The fault-bounded anticline evident in the seismic reflection data is collocated with a broad NNW-trending gravity high that separates two major depocenters delineated by gravity lows in northernmost Dixie Valley (Figure 2B). The anticline marks a zone of multiple intersecting, oppositely dipping normal faults. Quaternary faults in the Sou Hills have ruptured in the past 15 to 130 ka and have slip rates ranging from 0.01 to 0.3 mm/yr. Potential host rocks for geothermal reservoirs in the area include highly fractured Tertiary volcanic rocks and Mesozoic granite along and proximal to faults.

The geologic and geophysical data indicate five discrete, favorable structural settings for geothermal activity in the Sou Hills area (Figure 2B). From north to south, these include: 1) a broad ~5 km wide step-over in the west-dipping Pleasant Valley fault zone; 2) a narrow ~1 km wide, step-over or relay ramp along a southern strand of the Pleasant Valley fault zone; 3) a small graben between oppositely dipping normal faults in the western part of the Sou Hills; 4) a major fault intersection between the east-dipping Dixie Valley range-front fault and an oblique-slip east-striking fault bounding Sou Hills on the south; and 5) the extensional anticline in northernmost Dixie Valley. NNE-striking normal faults have the highest slip and dilation tendency (e.g., Morris et al., 1996; Ferrill et al., 1999). Thus, many normal faults in the area are well oriented for slip and dilation, including faults in each of the favorable structural settings.

Past geothermal exploration in the Sou Hills includes several thermal gradient wells, but none showed any appreciable anomalies. However, nearly all wells were drilled outside the favorable structural settings (Figure 2B-C). One previously undocumented warm well (29^{o}C) was found in this study at the Sou Ranch in the axial part of the extensional anticline, but we could not obtain a sample due to a malfunctioning pivot pump.

Twenty-three geochemical water analyses for the area include 20 historical and 3 new samples from this study. Prior to this study, two areas were known thermal areas. Seven Devils is a cluster of ~7 northerly trending hot springs and associated travertine mounds in the southernmost Sou Hills directly north of the extensional anticline. McCoy Hot Spring lies in the southeast part of the area, possibly near the southern tip of a major strand of the Pleasant Valley fault zone. Relatively low subsurface temperatures of 85°C for Seven Devils and 55°C for McCoy are suggested by the chalcedony, Na-K-Ca, Mg-corr and K/Mg geothermometers. However, estimates by Spycher (personal communication, 2017) using GeoT multicomponent equilibria modeling (Spycher et al., 2016) suggest temperatures as high as 160°C in both systems, although considerable fluid reconstruction implies significant uncertainties. An additional sample was modeled for the Paris Well at the Draper Ranch in the northern part of the area. The chalcedony, Na-K-Ca, Mg-corr and K/Mg geothermometers indicated temperatures of 55-60°C, but GeoT analysis yielded 160°C with high uncertainty. Thus, previously known systems and the newly identified Draper Ranch area may have power-capable temperatures at depth.

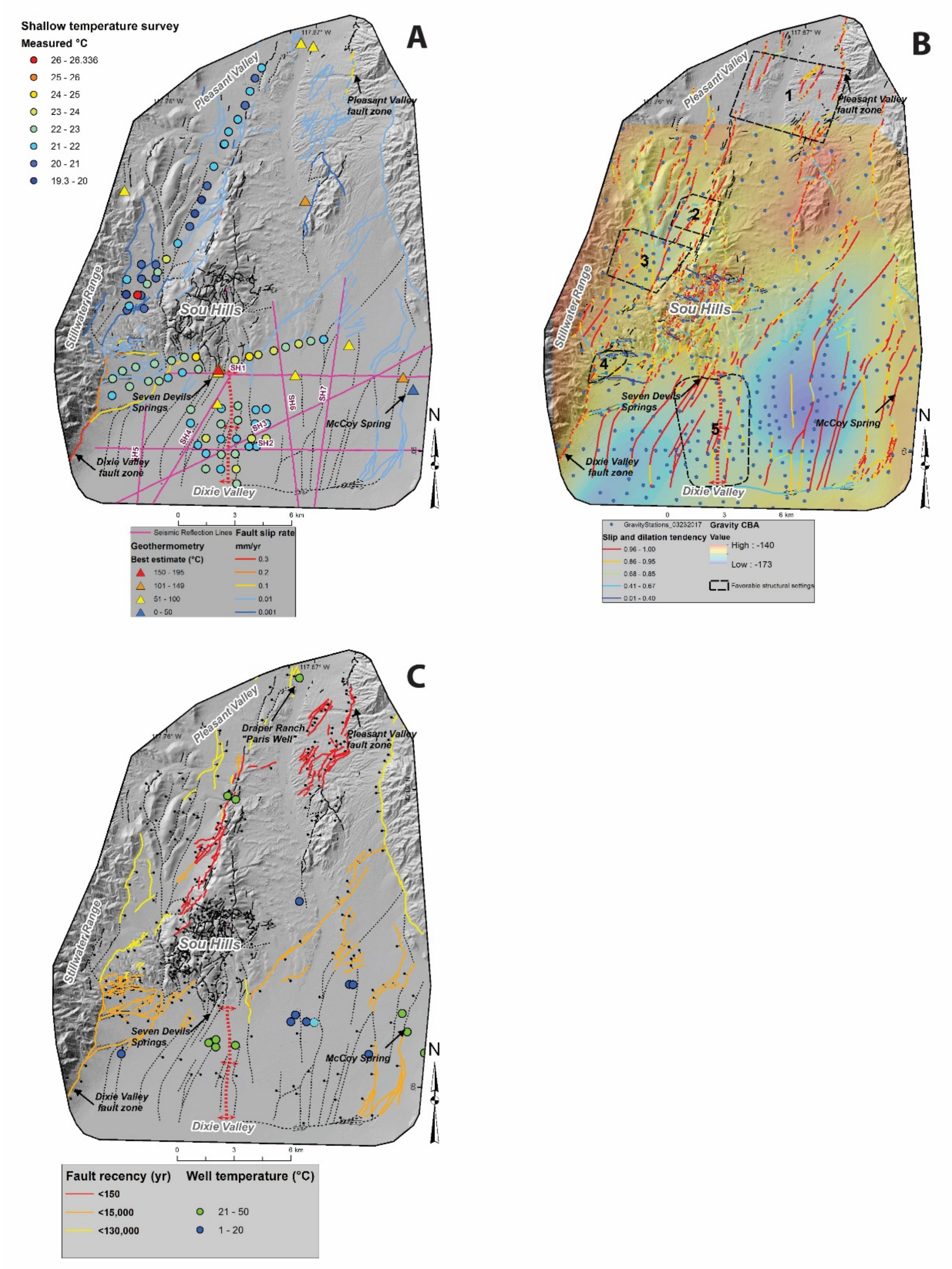

Figure 2: Sou Hills study area. A. Digital elevation model showing geothermometry, 2-m temperature survey, seismic reflection profiles (purple lines), and Quaternary fault slip rates. B. Complete Bouguer anomaly, gravity station locations (blue dots), slip and dilation tendency on Quaternary faults, and favorable structural settings outlined in black. Setting #5 received the highest play fairway score in this area. C. Age of Quaternary faults and well temperatures. Extensional anticline is marked by the N-trending dashed red line directly north of the Dixie Valley label in the southern part of the study area. Dotted and dashed black lines in northern Dixie Valley in A and C are faults inferred from seismic reflection data and geologic mapping. Bar-balls are shown on downthrown sides of faults in C.

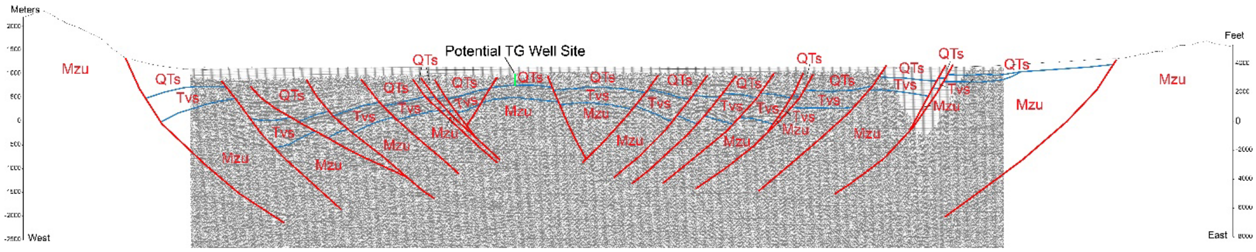

Figure 3: E-W-trending seismic reflection profile SH2 looking north and imaging anticlinal accommodation zone in the northernmost part of Dixie Valley. Location shown on Figure 2A. General area of proposed TG well sites shown by bright green line (see discussion in Section 3.2). Unit names: QTs, late Miocene to Quaternary basin-fill sediments; Tvs, Oligocene-Miocene volcanic and lesser sedimentary rocks; Mzu, Mesozoic basement rocks undivided, including Jurassic-Cretaceous plutons and Permian to Triassic metamorphic rocks. Horizontal scale is same as vertical scale in this depth-converted profile.

A total of 82 two-meter temperature stations were acquired in the area but did not reveal any appreciable thermal anomalies (Figure 2A). However, much higher than average winter precipitation in 2017 may have suppressed shallow thermal expression of geothermal upwellings. Further, relatively deep water tables in elevated parts of the Sou Hills may result in little expression of thermal anomalies at such shallow levels.

3.2 Local-Scale Play Fairway Analysis

Predictive play fairway maps were generated for the Sou Hills area using the exploration data obtained during the Phase 2 studies (Figure 4; Faulds et al., 2017a,b). These new data were integrated with the existing Phase 1 database. The general methodologies for producing regional predictive maps in Phase 1 (Faulds et al., 2015) were followed in building detailed predictive maps in Phase 2. Modifications to the methodology were made to accommodate the introduction of new data types (e.g., 2-m temperature measurements and paleo-geothermal features such as travertine) into the local permeability models.

Predictive maps were generated for play fairways and direct evidence (Figures 4 and 5). The play fairway and direct evidence maps provide complementary information. The fairway maps highlight areas of geothermal favorability based on fundamental underlying geologic and geophysical features, 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 sinter or travertine. 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. In Phase 1, the fairway and direct evidence maps were combined to produce overall “favorability” maps. This was not done in Phase 2. 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 (Figures 4 and 5) to facilitate visualization of one or more conceptual models of three-dimensional fluid flow.

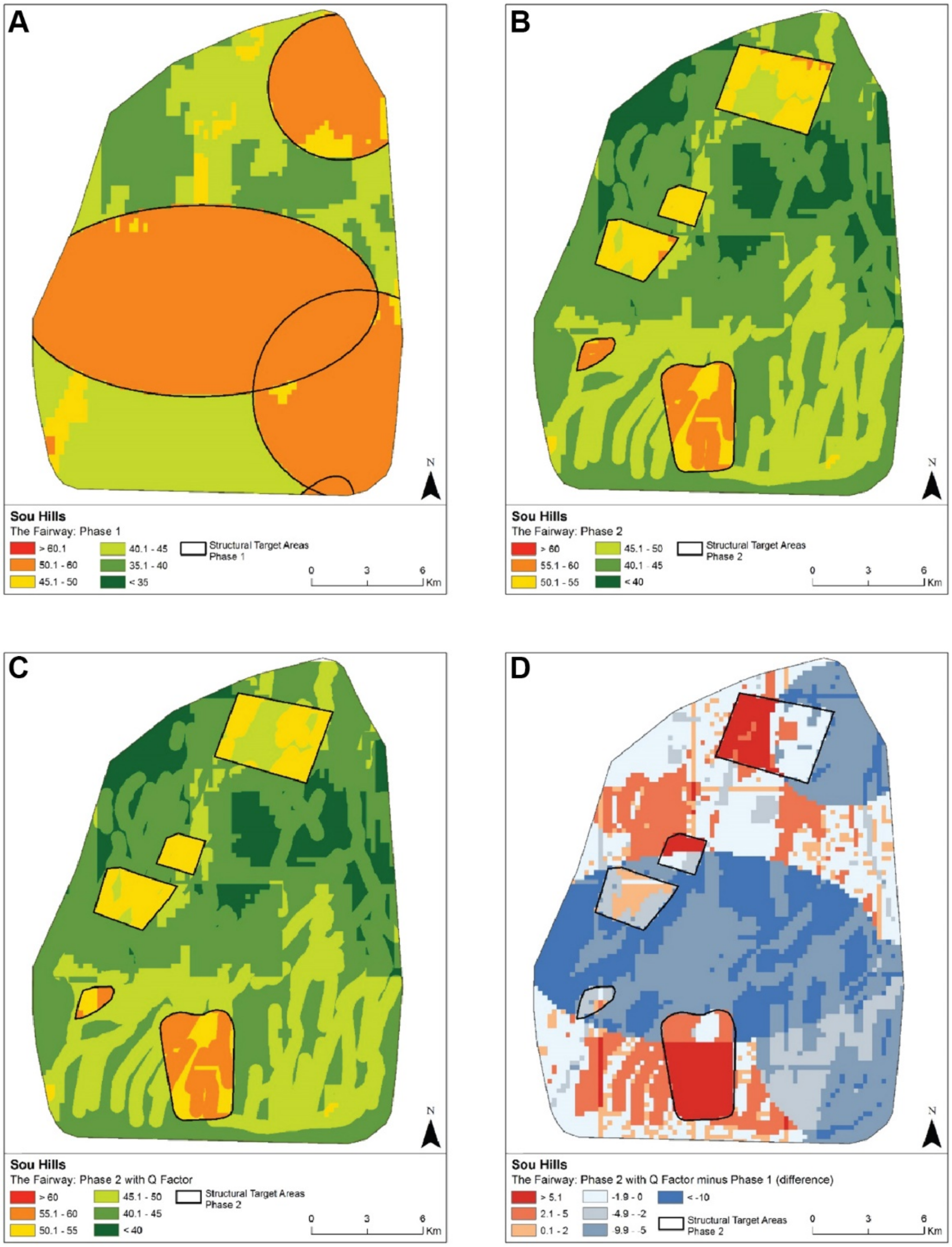

Figure 4: Comparison of Phase I and II fairway analysis for the Sou Hills. A. Phase 1 fairway results. B. Phase 2 fairway results calculated the same as in Phase 1. C. Fairway score from Phase 2 calculated with structural setting quality factor. D. Difference between the Phase 2 and Phase 1 fairway results with positive numbers equal to increase of fairway score from Phase 1 to Phase 2, and negative numbers equal to the decrease in fairway score from Phase 1 to Phase 2.

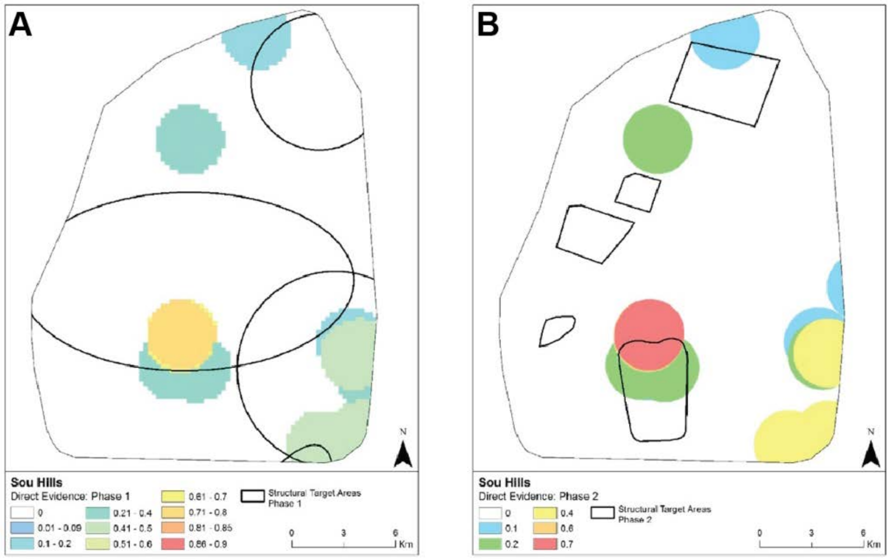

Figure 5: Comparison of Phase 1 and 2 direct evidence grid layers for the Sou Hills. A. Phase 1 direct evidence. B. Phase 2 direct evidence.

Modeling procedures for the detailed study areas in Phase 2, including Sou Hills, paralleled those of the Phase 1 regional model (Faulds et al., 2015). The regional-scale permeability and heat models of Phase 1 remained unchanged for the Sou Hills. In contrast, the local- and intermediate-scale permeability models were revised and updated to reflect results of the detailed geologic mapping and geophysical and geochemical surveys. As described in detail by Faulds et al. (2017), 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) presence of paleo-geothermal features, such as travertine and sinter/silica-cemented sands, 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 3) 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 Sou Hills has a similar overall score to that generated in the original Phase 1 model. The major difference between the detailed Phase 2 and the Phase 1 regional models is that locations of higher favorability are shown in much greater detail in the Phase 2 model (Figure 4). We note that fairway scores above ~45 indicate relatively high potential. The direct evidence map of the Sou Hills area is relatively similar to that derived in Phase 1 (Figure 5). However, the new geothermometry indicates higher direct evidence values for some areas, such as the Seven Devils Hot Springs.

For the Sou Hills area, we reviewed the Phase 2 results and ranked the area proximal to and directly south of the Seven Devils Hot Springs as the most promising local prospect (area #5 in Figure 2B). A potentially hidden, previously unknown upflow to this system may reside along the axial part of the anticlinal accommodation zone in this area, as evidenced by at least one warm well (29°C) and the nearby hot springs (Seven Devils) with apparent 160°C geothermometry. We therefore recommend additional and more detailed geophysical surveys (e.g., magnetics and magnetotelluric) for this area to better assess the potential for subsurface hydrothermal activity and ultimately select the most promising sites for thermal gradient wells. On the basis of available data, thermal gradient holes proximal to the axial part of the extensional anticline are probably the most pragmatic (Figures 3 and 6), although MT and magnetic data would provide additional important constraints. The major risk in this area is locating geothermal upflow in a relatively broad zone of structural complexity in a complex array of closely-spaced faults. However, the high temperature Geo-T geothermometry from the Seven Devils Hot Springs suggests a potential upwelling within the more structurally complex, axial part of the anticline.

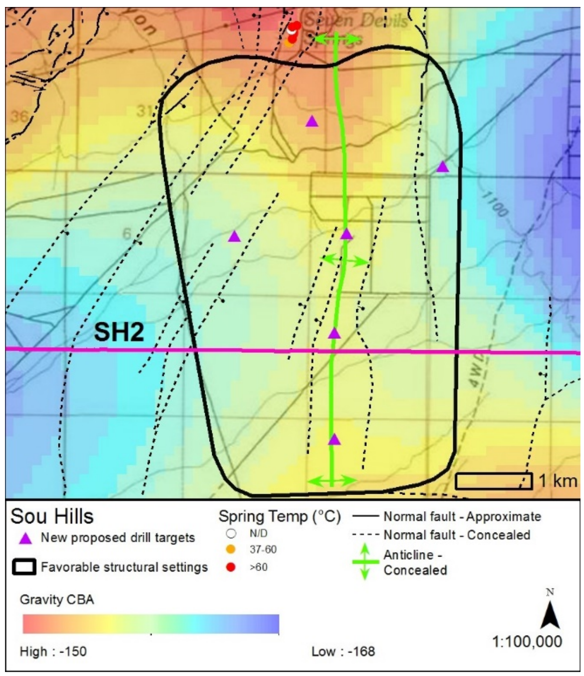

Figure 6: Proposed TG drilling sites for the Sou Hills in area #5 shown in Figure 2B. Purple line denotes the location of the seismic reflection profile (SH2) interpreted in Figure 3, with the full extent of the profile shown in Figure 2A.

4. Discussion

The progression from a regional- to local-scale analysis has resulted in several lessons learned for the geothermal play fairway concept. We note that differences between Phases 1 and 2 in the play fairway analysis are significant for the Sou Hills. New geological and geophysical data from the area permitted discovery of previously unrecognized individual, favorable structural settings within the broader accommodation zone, such as the extensional anticline in the vicinity of Seven Devils Hot Springs (Figures 2B and 6). These findings embody the importance of both the detailed studies and integration of multiple datasets in refining exploration targets. The Phase 1 regional analysis recognized relatively broad, favorable structural settings (Figure 1). As is typical in any regional exploration program, it is difficult in the early stages to understand the details of individual prospects and to select the most favorable targets for drilling. Upon more detailed analysis of individual areas in Phase 2, it became apparent that nearly all study areas contained multiple favorable structural settings (Faulds et al., 2018, 2019; Craig, 2018; McConville, 2018; Hinz et al., this volume). This presented the challenge of applying our play fairway methodology at a finer scale to effectively 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, our play fairway methodology is adaptable to the progression of an exploration program from a regional analysis to vectoring into the most promising local prospects.

5. Conclusions

The results of the play fairway analysis indicate that the Sou Hills is a promising geothermal prospect. Key evidence for this conclusion includes the presence of a major Quaternary accommodation zone, gravity and seismic reflection data indicating a structurally complex extensional anticline within the broader accommodation zone, high regional strain gradients, relatively high slip rates and Holocene to late Pleistocene activity on multiple faults, favorably oriented faults in the regional stress field, and geothermometry on area springs. The detailed geological and geophysical analyses in Phase 2 of this project identified several individual favorable structural settings within the broader accommodation zone. An extensional anticline in the south-central part of the study area appears to represent the most promising local prospect. Although potential targets for thermal gradient drilling were identified, we recommend additional geophysical surveys (e.g., MT and magnetics) prior to drilling to further reduce the exploration risk. Nonetheless, the results from this study demonstrate the broad applicability of the play fairway methodology at a variety of scales.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy (EERE) under the Geothermal Technologies Program and Play Fairway Analysis initiative (award number DE-EE0006731). We thank Nick Hinz, Alan Ramelli, Lisa Shevenell, Jason Craig, and Emma McConville for their many contributions to Phase 2 of this study. We also thank Dick Benoit for sharing his knowledge of the region. William Schermerhorn, Jacob DeAngelo, and Jim Lovekin provided thoughtful reviews that improved this paper.

REFERENCES

Bell, J.W., and Ramelli, A.R., 2009, Active fault controls at high-temperature geothermal sites: Prospecting for new faults: Geothermal Resources Council Transactions, v. 33, p. 425–429.

Blackwell, D., Wisian K, Benoit D, Gollan B., 1999, Structure of the Dixie Valley Geothermal System, a “Typical” Basin and Range Geothermal system, From Thermal and Gravity Data: Geothermal Resources Council Transactions, v. 23, p. 525-531.

Caskey, S.J., Wesnousky, S.G, Zhang, P., and Slemmons, D.B., 1996, Surface faulting of the 1954 Fairview Peak (Ms 7.2) and Dixie Valley (Ms 6.8) earthquakes, central Nevada: Bulletin of the Seismological Society of America, v. 86, no. 3, p. 761-787.

Coolbaugh, M.F., Raines, G.L., and Zehner, R.E., 2007, Assessment of exploration bias in data-driven predictive models and the estimation of undiscovered resources: Natural Resources Research, v. 16, no. 2, p. 199-207.

Craig, J.W., 2018, Discovery and analysis of a blind geothermal system in southeastern Gabbs Valley, western Nevada [M.S. Thesis]: University of Nevada, Reno, 111 p.

Craig, J.W., Faulds, J.E., Shevenell, L. A., Hinz, N.H., 2017, Discovery and analysis of a potential blind geothermal system in southern Gabbs Valley, western Nevada: Geothermal Resources Council Transactions, v. 41, p. 2258-2264.

Curewitz, D. and Karson, J.A., 1997, Structural settings of hydrothermal outflow: fracture permeability maintained by fault propagation and interaction: Journal of Volcanology and Geothermal Research, v. 79, p. 149-168.

Doust, H., 2010, The exploration play: What do we mean by it?: American Association of Petroleum Geologists Bulletin, v. 94, p. 1657-1672.

Faulds, J.E., Coolbaugh, M., Henry C.D., and Blewitt, G., 2004, Why is Nevada in hot water? Relations between plate boundary motions, the Walker Lane, and geothermal activity in the northern Great Basin: Geological Society of America Abstracts with Programs, v. 36, no. 4, p. 27.

Faulds, J.E., Coolbaugh, M.F., Vice, G.S., and Edwards, M.L., 2006, Characterizing structural controls of geothermal fields in the northwestern Great Basin: A progress report: Geothermal Resources Council Transactions, v. 30, p. 69-76.

Faulds, J.E., Hinz, N.H., Dering, G.M., Drew, D.L., 2013, The hybrid model – the most accommodating structural setting for geothermal power generation in the Great Basin, western USA: Geothermal Resources Council Transactions, v. 37, p. 3-10.

Faulds, J.E., Hinz, N.H., Coolbaugh, M.F., Shevenell, L.A., Siler, D.L., dePolo, C.M., Hammond, W.C., Kreemer, C., Oppliger, G., Wannamaker, P.E., Queen, J.H., and Visser, C.F., 2015, Discovering blind geothermal systems in the Great Basin region: An integrated geologic and geophysical approach for establishing geothermal play fairways: Final report submitted to the Department of Energy (DE-EE0006731), 106 p.

Faulds, N.H., and Hinz, N.H., 2015, Favorable tectonic and structural settings of geothermal settings in the Great Basin Region, western USA: Proxies for discovering blind geothermal systems: Proceedings, World Geothermal Congress 2015, Melbourne, Australia, 6 p.

Faulds, J.E., Hinz, N.H., Coolbaugh, M.F., Siler, D.L., Shevenell, L.A., Queen, J.H., dePolo, C.M., Hammond, W.C., and Kreemer, C., 2016, Discovering geothermal systems in the Great Basin region: an integrated geologic, geochemical, and geophysical approach for establishing geothermal play fairways: Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, 15 p.

Faulds, J. E., Hinz, N.H., Coolbaugh, M. F., Shevenell, L. A., Sadowski, A.J., Shevenell, L.A., McConville, E., Craig, J., Sladek, C., and Siler D. L, 2017a, Progress report on the Nevada play fairway project: Integrated geological, geochemical, and geophysical analyses of possible new geothermal systems in the Great Basin region: Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 13-15, 2017, SGP-TR-212, 11 p.

Faulds, J.E., Hinz, N., Sadowski, A., McConville, E., Craig, J., Bourdeau-Hernikl, J., Shevenell, L., Coolbaugh, M., Siler, D., Hardwick, C., and Queen, J., 2017b, Discovering blind geothermal systems in the Great Basin region: An integrated geologic and geophysical approach for establishing geothermal play fairways, Phase 2 final report of U.S. Dept. of Energy Project DE-EE0006731 awarded to Nevada Bureau of Mines and Geology, University of Nevada, Reno, 39 p.

Faulds, J.E., Craig, J.W., Coolbaugh, M.F., Hinz, N.H., Glen, J.M., Deoreo, S., 2018, Searching for blind geothermal systems utilizing play fairway analysis, western Nevada: Geothermal Resources Council Bulletin, v. 47, p. 34-42.

Faulds, J.E., Hinz, N.H., Coolbaugh, M.F., Ramelli, A., Glen, J.M, Ayling, B.A., Wannamaker, P.E., Deoreo, S.B., Siler, D.L., and Craig, J.W., 2019, Vectoring into potential blind geothermal systems in the Granite Springs Valley area, western Nevada: Application of the play fairway analysis at multiple scales: Proceedings 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-214, p. 74-84.

Ferrill, D.A., Winterle, J., Wittmeyer, G., Sims, D., Colton, S., Armstrong, A., Horowitz, A.S., Meyers, W.B., and Simons, F.F., 1999, Stressed rock strains groundwater at Yucca Mountain, Nevada: GSA Today, v. 9, p. 2–9.

Fonseca, J., 1988, The Sou Hills: A barrier to faulting in the central Nevada seismic belt: Journal of Geophysical Research, v. 93, p. 475-489.

Forson, C., Czajkowski, J. L., Norman, D. K., Swyer, M. W., Cladouhos, T.T. and Davatzes N., 2016, Summary of phase 1 and plans for phase 2 of the Washington state geothermal play-fairway analysis: Geothermal Resources Council Transactions, v. 40, p. 541-550.

Hinz, N.H., Faulds, J.E. and Stroup, C., 2011, Stratigraphic and structural framework of the Reese River geothermal area, Lander County, Nevada: A new conceptual structural model: Geothermal Resources Council Transactions, v. 35, p. 827-832.

Hinz, N.H., Faulds, J.E., Coolbaugh, M.F., 2014, Association of fault terminations with fluid flow in the Salt Wells geothermal field, Nevada, USA: Geothermal Resources Council Transactions, v. 38, p. 3–10.

Kreemer, C., Hammond, W.C., Blewitt, G., Holland, A.A., and Bennett, R.A., 2012, A geodetic strain rate model for the Pacific-North American plate boundary, western USA: NBMG Map 178, scale 1:1.500,000, 1 sheet.

Lautze N.C., Thomas D., Hinz N., Ito G., Frazer N., Waller D., 2017, Play fairway analysis of geothermal resources across the State of Hawai'i: 1. Geological, geophysical, and geochemical datasets: Geothermics, v. 70, p. 376–392, doi: 10.1016/j.geothermics.2017.02.001.

McConville, E.G., 2018, Detailed analysis of geothermal potential in Crescent Valley, north-central Nevada [M.S. Thesis]: University of Nevada, Reno, 122 p.

McConville, E.G., Faulds, J.E., Hinz, N.H, Ramelli, A.R., Coolbaugh M.F., Shevenell L., Siler, D.L., Bourdeau-Hernikl, J., 2017, A play fairway approach to geothermal exploration in Crescent Valley, Nevada: Geothermal Resources Transactions, v. 41, p. 1213-1221.

Micklethwaite, S, and Cox, S.F., 2004, Fault-segment rupture, aftershock-zone fluid flow, and mineralization: Geology, v. 32, no. 9, p. 813-816.

Morris, A., Ferrill, D.A., and Henderson, D.B., 1996, Slip-tendency analysis and fault reactivation: Geology, v. 24, p. 275–278.

Muntean, J.L., Davis, A., and Ayling, B., 2019, The Nevada mineral industry 2018: Nevada Bureau of Mines and Geology Special Publication MI-2018, 222 p.

Nordquist, J., and Delwiche, B., 2013, The McGinness Hills geothermal project: Geothermal Resources Council Transactions, v. 37, p. 57-63.

Richards, M., and Blackwell, D., 2002, A difficult search: Why Basin and Range systems are hard to find: Geothermal Resources Council Bulletin, v. 31, p. 143-146.

Sadowski, A.J., Faulds, J.E., Coolbaugh, M.F., and Siler, D.L., 2017, Geothermal play fairway analysis of the Sou Hills, central Nevada: Geological Society of America Abstracts with Programs. Vol. 49, no. 6, doi: 10.1130/abs/2017AM-307789.

Shervais, J.S., Glen, J.M., Nielson, D., Garg, S., Dobson, P., Gasperikova, E., Sonnenthal, E., Visser, C., Liberty, L.M., DeAngelo, J., Siler, D., Varriale, J., and Evans, J.P., 2016, Geothermal play fairway analysis of the Snake River Plain: Phase 1, Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-209, 7 p.

Siler, D.L., Zhang, Y., Spycher, N.F., Dobson, P.F., McClain, J.S., Gasperikova, E., Zierenberg, R.A., Schiffman, P., Ferguson, C., Fowler, A., and Cantwell, C., 2017, Play-fairway analysis for geothermal resources and exploration risk in Modoc Plateau region: Geothermics, v. 69, p. 15-33.

Siler, D.L., Hinz, N.H., and Faulds, J.E., 2018, Stress concentrations at structural discontinuities in active fault zones in the western United States: Implications for permeability and fluid flow in geothermal fields: Geological Society of America Bulletin, v. 130, no. 7-8, p. 1273-1288; https://doi.org/10.1130/B31729.1.

Sladek, C., and Coolbaugh, M., 2013, Development of online map of 2 meter temperatures and methods for normalizing 2 meter temperature data for comparison and initial analysis: Geothermal Resources Council Transactions, v. 37, p. 333-336.

Spycher, N, L. Peiffer, S. Finsterle and E. Sonnenthal, 2016, GeoT user's guide: A computer program for multicomponent geothermometry and geochemical speciation , version 2.1: LBNL Report, Rev. 1, June 6, 2016, 42 p.

U.S. Department of Energy, 2019, GeoVision: Harnessing the heat beneath our feet, 218 p.

Wallace, R.E., 1984, Fault scarps formed during the earthquakes of October 2, 1915, in Pleasant Valley, Nevada, and some tectonic implications: U.S. Geological Survey Professional Paper 1274-A, 33 p.

Wannamaker. P.E., Moore, J.N., Pankow, K.L., Simmons, S.F., Nash, G.D., Maris, V., Trow, A., and Hardwick, C.L., 2017, Phase II of play fairway analysis for the eastern Great Basin extensional regime, Utah: status of indications: Geothermal Resources Council Transactions, v. 41, p. 2368-2382.

Williams, C.F., Reed, M.J., DeAngelo, J., and Galanis, S.P. Jr., 2009, Quantifying the undiscovered geothermal resources of the United States: Geothermal Resources Council Transactions, v. 33, p. 995-1002.