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Building the Next Generation of Regional Geothermal Potential Maps: Examples from the Great Basin Region, Western USA

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ABSTRACT

Over the past decade research has greatly advanced our understanding of structurally controlled geothermal systems and the potential for "deep stratigraphic reservoirs" in the Great Basin region, western USA. For example, studies have shown that structurally controlled geothermal systems are associated with specific structural settings, such as terminations of major normal faults, accommodation zones, pull-aparts in strike-slip faults, displacement transfer zones, or step-overs in range-front faults. However, we know that not every structure (e.g., termination of a major normal fault or step-over in a range-front fault) hosts an active geothermal system. Recent research has also shown that regional strain rate model as determined from GPS geodesy, the composition of that strain (extensional versus shear or compressive strain), recency of Quaternary faulting, and slip and dilation tendency of faults correlate positively with the distribution of both high and low-temperature, structurally controlled geothermal systems within the Great Basin. Combining these strain data and fault slip history data sets with existing temperature gradient data, heat flow data, spring temperatures, fluid geothermometry, and geophysical data provides an effective platform for evaluating the geothermal potential of respective structural plays.

Recent studies focused on deep stratigraphic reservoirs indicate the best conditions for economically viable development are associated with thick sedimentary basins with low-thermal-conductivity sedimentary cap rocks overlying permeable host rocks (e.g. carbonates) and co-located with areas of high heat flow. Some of the factors that contribute to the potential for deep stratigraphic reservoirs and conventional structurally controlled geothermal systems apply to both types of resources, and in some places the potential for these two types of resources overlap in space, suggesting the potential for hybrid reservoirs (structurally controlled deep stratigraphic reservoirs). Effective and complete evaluation of geothermal potential in the Great Basin should include parameters that cover both types of resources.

In this study, two areas with a combined area of 26,000 km^2 were evaluated for geothermal resource potential, equating to <4% of the total 680,000 km^2 size of the Great Basin region. Within these two study areas, 73 potential structural targets and 8 potential deep sedimentary target areas were identified. Four of the 73 potential structural target areas are associated with known thermal anomalies. All 73 structural target areas were ranked according to multiple data sets using baseline metrics derived from the Great Basin region to evaluate their relative potential to host blind geothermal resources.

1. INTRODUCTION

Geothermal potential maps can provide estimates of potential regional resource capacity to guide both governmental and private industry exploration and development. The first comprehensive geothermal potential maps to incorporate probabilistic spatial correlation of multiple data sets for the Great Basin region were accomplished by Coolbaugh and others (2002, 2005, 2007) using thermal data, gravity and topographic data, crustal strain data, slip rates and orientations of Quaternary faults, and earthquake seismicity. These studies accounted for the key defining baseline attributes of Great Basin geothermal systems that were available at that time including: 1) That most geothermal activity in this region is amagmatic and related to regionally elevated heat flow associated with thin, extended crust (Sass et al., 1971; Koenig and McNitt, 1983; Lachenbruch and Sass, 1978; Wisian et al., 1999; Blackwell and Richards, 2004; Kennedy and van Soest, 2007), 2) That most geothermal systems are associated with high-angle normal faults (Benoit et al., 1982; Blackwell et al., 1999; Johnson and Hulen, 2002; Coolbaugh et al., 2002; Wannamaker, 2003; Waibel et al., 2003; Faulds et al., 2010), 3) A large proportion of systems are blind (Ball et al., 1979; Coolbaugh et al., 2007; Faulds and Hinz, this volume), and 4) Regions with greater extensional strain rate correlate favorably with the distribution of geothermal activity (Blewitt et al., 2002, 2003; Bell and Ramelli, 2007; Faulds et al., 2012). Subsequent to these assessments, recent and on-going studies have indicated that the majority of known geothermal systems in this region are not associated with just any high-angle normal faults, but are associated with specific structural settings (e.g., fault terminations or fault step-overs; Curewitz and Karson, 1997; Faulds et al., 2006, 2011; Faulds and Hinz, this volume). Additionally, a new type of potential geothermal resource in the western United States termed "deep stratigraphic reservoirs" or "hot sedimentary aquifers" has been identified (e.g., Allis et al., 2011).

This paper presents the results of two regional assessments of geothermal potential in the Great Basin, at White Pine County (WPC) in eastern Nevada, and at the Desert National Wildlife Range (DNWR) in southern Nevada (Fig. 1). In each of these areas, potential structural and stratigraphic target areas were identified and ranked for geothermal potential based on multiple parameters. These results and methods are further discussed in the context of applying these methods to the rest of the Great Basin and other regions around the world.

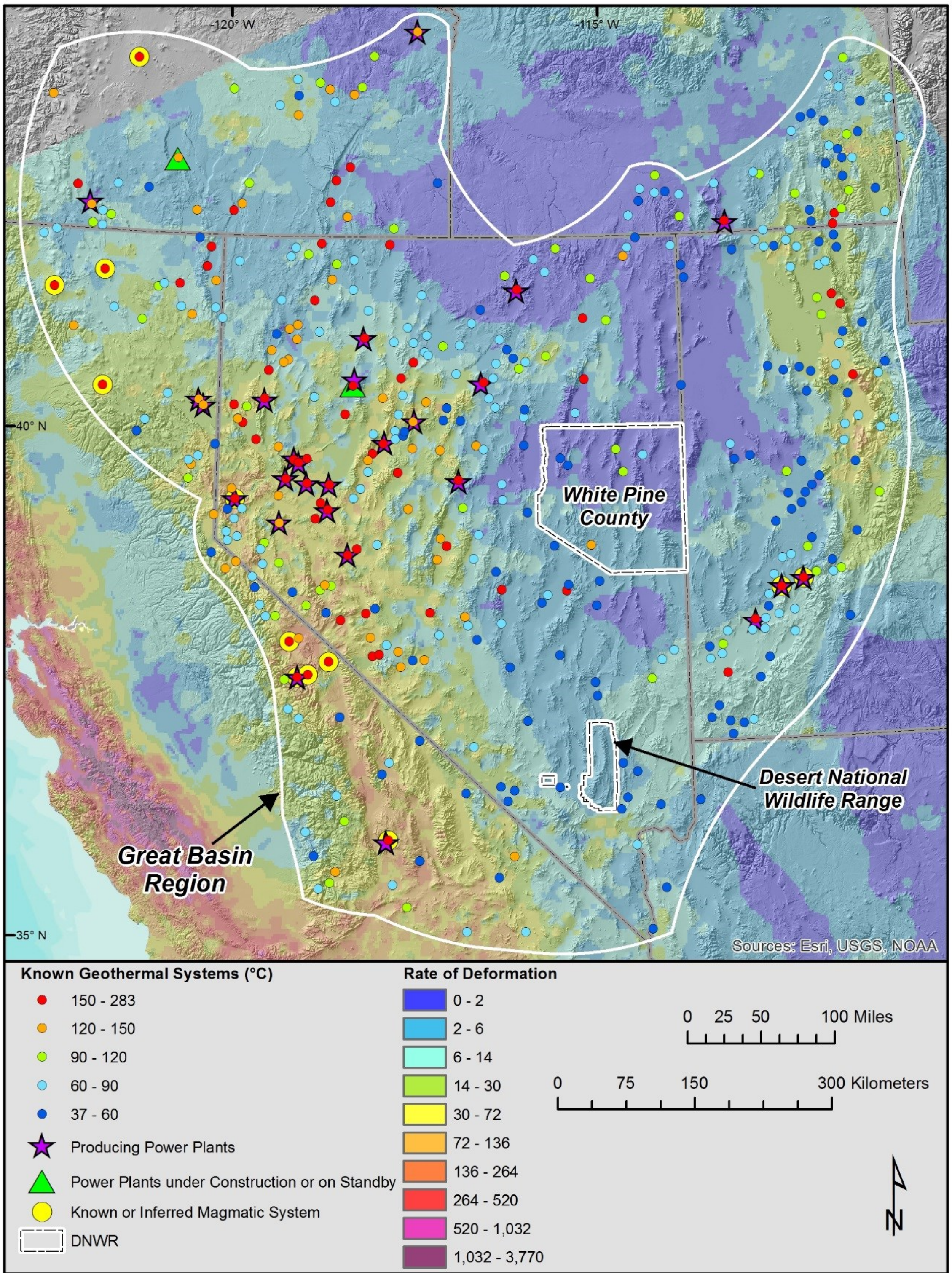

Figure 1: Geothermal systems and geothermal power plants in the Great Basin region plotted on a base map showing strain rates. Strain rates reflect the second invariant strain rate tensor model (10-9/yr; Kreemer et al., 2012). This figure was modified from Faulds and others (2012) and Faulds and Hinz, this volume.

2. BACKGROUND

Research has shown that most of the >400 known geothermal systems (≥37 °C) in the Great Basin region are associated with specific fault patterns or structural settings that are related to Cenozoic extension. These settings include terminations of major normal faults, accommodation zones (belts of intermeshing, oppositely dipping faults), step-overs in range-front faults, displacement transfer zones along strike-slip faults, pull-aparts along strike-slip faults, major bends in normal faults, and fault intersections (Faulds et al., 2006, 2011; Faulds and Hinz, this volume). In contrast, the central segments of major normal faults with maximum displacement contain relatively few geothermal systems. Not every one of these settings across the Great Basin region host geothermal systems, but they are the most likely place to prospect for blind, undiscovered geothermal systems (e.g., Anderson and Faulds, 2013).

Many deep sedimentary basins throughout the world have hot water aquifers that cover very large extents (e.g., Hurter and Schellschmidt, 2003; Porro et al., 2012; Barkaoui et al., 2014; Busby, 2014). Development of such aquifers for electricity generation has generally not been feasible due to the moderate temperatures (<150 °C) and/or cost-prohibitive depths at which these reservoirs/aquifers commonly occur. However, recent documentation shows that in western Utah and eastern Nevada, these aquifers could have higher than typical temperatures of 175 to 200°C at potentially economically extractible depths of 3 to 4 km (Allis et al., 2011, 2012; Anderson, 2013; Deo et al., 2013). The occurrence of such aquifers at such depths is made possible by the relatively high heat flow related to thin crust in parts of the western United States (Lachenbruch and Sass, 1978). Thick accumulations of sediments with low thermal conductivities in intermontane basins allow for high temperature gradients to develop where conductive heat flow is high (Allis et al., 2011, 2012, 2013). Preliminary modeling suggests that economic development of these deep aquifers is possible if sufficient permeabilities are present (Allis et al., 2013).

3. METHODS AND RESULTS

3.1 Potential Structurally Controlled Resources

White Pine County, covering 23,000 km^2 and the DNWR, covering 3,000 km^2 are located in the central and southern parts of the 680,000 km^2 Great Basin region, respectively (Fig. 1). There are six known structurally controlled geothermal systems in WPC with temperatures ranging from 42 to 123 °C and currently no geothermal power plants. In the DNWR there are no known geothermal systems. However, there are five low temperature systems within a surrounding radius of 25 km of the DNWR that range from 40 to 55°C, and thus the DNWR region is not absent of active geothermal activity.

Based on an evaluation of the Cenozoic extensional framework of each study area using geologic maps, publications, and fault databases (Stewart and Carlson, 1978; Stewart, 1998; Page et al., 2005, Jayko, 2007; USGS, 2010), we have identified 48 structural target areas in WPC (Table 2A, Fig. 2) and 25 structural target areas in the DNWR (Table 2B, Fig. 3). These structures include fault step-overs, accommodation zones, fault bends along range-front faults, fault intersections, terminations of major normal faults, and compound settings with two or more overlapping structural settings. All of these structures are related to normal and/or transverse faults associated with Cenozoic extensional structures. Four of these target areas in WPC are associated with known geothermal systems. The remaining 69 structural target areas may host blind undiscovered geothermal systems.

To evaluate the resource potential of all 73 structural target areas identified in this study, we have assigned a relative geothermal potential rating (GPR) using the following three baseline parameters:

1. TYPE OF STRUCTURAL SETTING: The type of structural setting contributes to the relative geothermal potential of a structural target area. Recent research shows that structural settings with greater complexity (e.g., accommodation zones) have greater geothermal potential to host a viable geothermal resource than those with less structural complexity (e.g., fault termination). The relatively more complex structural settings may correspond to greater bulk permeability which can facilitate larger commercial reservoir volumes and provided more efficient conduits for conductive heat transfer through the crust to drive the geothermal system (Faulds et al., 2013; Faulds and Hinz, this volume; Siler et al., this volume).

   There are 31 geothermal systems that are either currently producing electricity (27) or have wells with successful flow tests (4) within the Great Basin region. These proven resources are associated with reservoirs that range from just over 100°C (e.g. Wabuska, NV) to >250°C (e.g. Roosevelt Hot Springs, UT) and are associated with multiple types of structural settings (3^{rd} column, Table 1). Currently, there are 152 known geothermal systems in the Great Basin region with measured or calculated reservoir temperatures ≥100°C and structural settings have been identified for 77% of these systems (2^{nd} column, Table 1). A

Table 1: Structural settings of geothermal systems and geothermal power plants in the Great Basin region.

Structural Setting	Great Basin Geothermal Systems ≥100°C (152 total)	Great Basin Geothermal Power Plants (31 total)*	Ratio**
Fault Termination	11%	13%	1.2
Fault Intersection	22%	16%	0.7
Step-over	21%	29%	1.4
Accommodation Zone	8%	23%	2.9
Displacement Transfer Zone	8%	16%	2.0
Pull-apart	3%	3%	1.0
Other Structure***	2%	0%	0
Primarily Magmatic	1%	0%	0
Undetermined	23%	0%	0
Total	**100%**	**100%**	
Compound Settings	18%	32%	1.8

*Includes 27 operating power plants, 1 under construction, and 3 successful flow tests

**Ratio equals % power plants with given structural setting divided by % geothermal systems with given structural setting

***Other structures include centers of major normal fault, antithetic normal fault, or fault bend number of geothermal areas are associated with two or more overlapping structural settings, forming a compound structural setting, and are tallied separately (final row, Table 1). Only the dominant structure of each compound structural setting is tallied in the first part of Table 1. The ratio of the percent power plants with given structural setting to the percent geothermal systems with given structural setting ranges from 2.9:1 to 0.7:1 (4^{th} column, Table 1). In this comparison, accommodation zones, displacement transfer zones, and compound structural settings are the most favorable structural settings to host productive geothermal resources. These results were used for weighting of structural target areas for the WPC and DNWR study areas, in which a relative geothermal potential rating value of "1" was assigned for compound settings, displacement transfer zones, and accommodation zones and a value of "0" was assigned for all others (Table 2).

2. AGE OF FAULTING: The majority of the high temperature systems (≥150°C) in the Great Basin Region are associated with faults active in the Holocene (Bell and Ramelli, 2007). Similarly, geodetically-derived strain rate models for the Great Basin correlate favorably with the regional density distribution of both high and low temperature geothermal systems (Faulds et al., 2012; Faulds and Hinz, this volume). For this study, the age of faulting was derived from review of aerial photo imagery, field reconnaissance, and the USGS Quaternary fault and fold database (USGS, 2010). Five different age categories were used pre-Quaternary (>1,600,000 yrs), Quaternary undistinguished (<1,600,000 yrs), Middle to Late Pleistocene (<750,000 yrs), Late Pleistocene (<130,000), and Latest Pleistocene to Holocene (<15,000 yrs). From oldest to youngest these were assigned relative geothermal potential rating values of 0, 1, 2, 3, and 4 (Table 2, Figs. 2A and 3A).

3. SLIP AND DILATION TENDENCY: Critically stressed fault strands are the most likely fault segments to act as fluid flow conduits (Barton et al., 1995; Sibson, 1994; Townend and Zoback, 2000). The tendency of a fault segment to slip or to dilate provides an indication of which sections of a fault zone within a geothermal system are most likely to transmit geothermal fluids (Morris et al., 1996; Ferrill, et al., 1999). Slip and dilation tendency values were obtained for each fault in the USGS Quaternary fault database (USGS, 2010) within WPC and the DNWR. The USGS database does not include dip of these faults and because most of these faults are normal faults, a dip of 70° was applied across the entire dataset. The resultant values are based on unit-less ratios of the resolved stresses applied to the fault plane by the measured ambient stress field (e.g., Heidbach et al., 2008). Values range from a maximum of 1, a fault plane ideally oriented to slip or dilate under ambient stress conditions, to zero, a fault plane with no potential to slip or dilate. Slip and dilation tendency analyses were measured separately for each fault segment and then summed with a range of zero to 2.00 possible (Figs. 2B and 3B). Each structural setting includes multiple individual faults of differing orientations relative to the regional stress field and each with specific slip and dilation tendency values, and therefore a qualitative assessment of the overall slip and dilation tendency of each structure as a whole. With respect to faults not associated with Quaternary scarps, key fault orientations were compared with the results of Quaternary faults of similar orientation located nearby. The resulting slip and dilation tendency analysis scores for the structural target areas in the WPC and DNWR study areas ranged from 0.30 up to 1.40. These scores were subdivided into even thirds of the range in scores whereby High = 1.40 to 1.05, Moderate = 1.04 to 0.68, and Low = 0.67 to 0.30. The corresponding relative geothermal potential rating values for slip and dilation tendency analysis were High = 3, Moderate = 2, and Low = 1 (Table 2, Figs. 2B and 3B).

This total geothermal potential rating summed from these three input parameters is a unitless number, corresponding to the relative potential for a structural target area to host a blind, undiscovered geothermal system (Table 2, Fig. 4). In this analysis the minimum possible score is 1 and highest possible score is 8. In WPC, the four structural target areas with known thermal anomalies average 5.75, just above the average of 5.56. Nine structural target areas scored 7 or 8, and rank more favorably for hosting geothermal systems than the structural target areas associated with known geothermal systems. In the DNWR, the average score was 3.68, and only two of the 25 structural target areas ranked as high as 6. The lower overall favorability scores for the DNWR reflect older average ages of faulting and slightly lower average slip and dilation tendency ratings for many of the faults in that region.

Nearly half of the structural target areas identified in the DNWR were field-checked to look for evidence of geothermal activity, in the form of previously undiscovered active surface manifestations or paleo-manifestations such as alteration or fossil spring deposits. Silicified fault breccia was observed at two of the targets along fault intersection locations in the DNWR (Id Nos. 12, 16, Table 1B, Fig. 5). While no active springs were observed, the silica has an amorphous appearance suggesting a relatively recent, possibly Quaternary age, and clearly appears related to prior flow of hydrothermal fluids. Both of these locations scored a geothermal potential rating of 4, just above the 3.68 average for the DNWR.

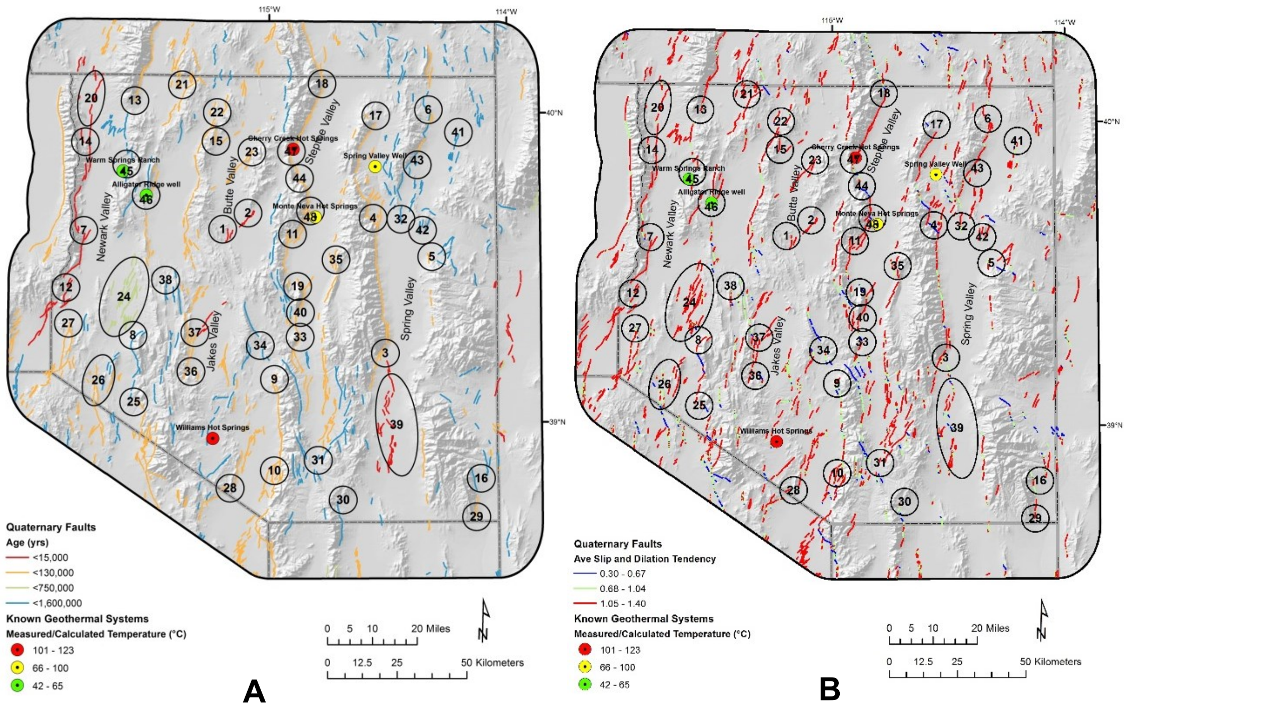

Figure 2: Shaded relief map of WPC with known geothermal systems, Quaternary faults (USGS, 2010), and potential structural settings that could host undiscovered blind geothermal systems (Table 1A). The size of the polygon depicts the general target area within which a blind resource may reside. Figure (A) shows the age of Quaternary fault activity and (B) shows the results of slip and dilation tendency analysis.

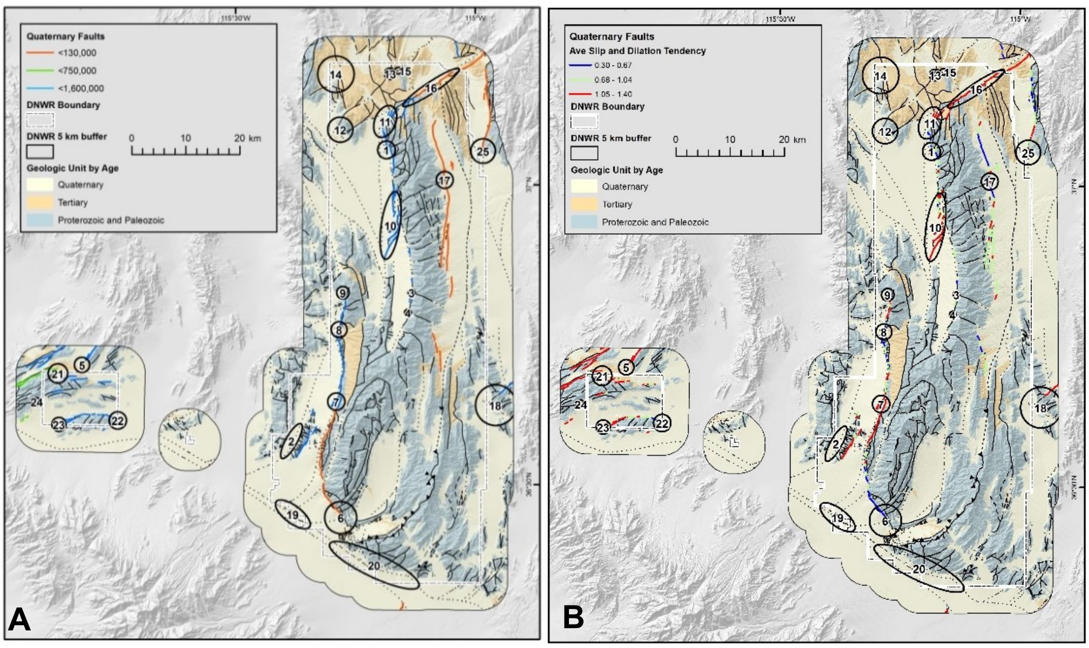

Figure 3: Shaded relief map of the DNWR showing simplified geologic units (Stewart and Carlson, 1978; Page et al., 2005; Jayko, 2007), Quaternary faults (USGS, 2010), and potential structural settings that could host undiscovered blind geothermal systems (Table 1B). Potential structural settings (targets) are depicted with a circle or oval that is larger than the typically 1 to 3 km² size of most producing geothermal reservoirs in the Great Basin region. The size of the polygon depicts the general target area within which a blind resource may reside. Figure (A) shows the age of Quaternary fault activity and (B) shows the results of slip and dilation tendency.

Table 2: Structures that may host undiscovered blind geothermal systems in WPC (2A; Fig. 2) and the DNWR (2B, Fig. 3). Geothermal Potential Rating (GPR) is a unitless semiquantitative ranking number defined in the text.

A) White Pine County								
Id No.	**Structure**		**Age of Faulting**		**Slip and Dilation Tendency**		**Thermal Anomaly**	**Total Geothermal Potential Rating**
	Structural Setting	**GPR (0-1)**	**Years**	**GPR (0-4)**	**Rating**	**GPR (1-3)**	**Y/N**	**(1 to 8 possible)**
1	Accommodation Zone	1	<15,000	4	High	3		8
2	Fault Termination	0	<15,000	4	High	3		7
3	Stepover	0	<15,000	4	High	3		7
4	Stepover	0	<130,000	3	High	3		6
5	Fault Termination	0	<130,000	3	Moderate	2		5
6	Stepover	0	<130,000	3	High	3		6
7	Stepover	0	<15,000	4	High	3		7
8	Fault Bend	0	<1,600,000	1	High	3		4
9	Fault Termination	0	<130,000	3	Moderate	2		5
10	Stepover	0	<130,000	3	High	3		6
11	Stepover	0	<130,000	3	High	3		6
12	Stepover	0	<15,000	2	High	3		5
13	Fault Termination	0	<130,000	3	High	3		6
14	Stepover	0	<15,000	2	High	3		5
15	Stepover	0	<130,000	3	High	3		6
16	Stepover	0	<1,600,000	1	Moderate	2		3
17	Fault Termination	0	<130,000	3	High	3		6
18	Fault Bend	0	<130,000	3	High	3		6
19	Compound F.I. and S-O	1	<130,000	3	High	3		7
20	Accommodation Zone	1	<15,000	2	High	3		6
21	Stepover	0	<130,000	3	High	3		6
22	Stepover	0	<130,000	3	High	3		6
23	Fault Intersection	0	<130,000	3	High	3		6
24	Accommodation Zone	1	<750,000	2	High	3		6
25	Stepover	0	<130,000	3	High	3		6
26	Accommodation Zone	1	<130,000	3	Moderate	2		6
27	Fault Termination	0	<130,000	3	Moderate	2		5
28	Stepover	0	<130,000	3	High	3		6
29	Fault Termination	0	<130,000	3	High	3		6
30	Fault Termination	0	<1,600,000	1	Moderate	2		3
31	Fault Termination	0	<1,600,000	1	High	3		4
32	Fault Termination	0	<1,600,000	1	Moderate	2		3
33	Fault Bend	0	<130,000	3	Moderate	2		5
34	Accommodation Zone	1	<1,600,000	1	Moderate	2		4
35	Compound F.T and A.Z.	1	<130,000	3	High	3		7
36	Fault Termination	0	<130,000	3	High	3		6
37	Fault Intersection	0	<15,000	4	High	3		7
38	Accommodation Zone	1	<1,600,000	1	Moderate	2		4
39	Accommodation Zone	1	<15,000	4	High	3		8
40	Accommodation Zone	1	<130,000	3	High	3		7
41	Fault Termination	0	<1,600,000	1	Moderate	2		3
42	Fault Termination	0	<1,600,000	1	High	3		4
43	Fault Intersection	0	<1,600,000	1	High	3		4
44	Stepover	0	<130,000	3	Moderate	2		5
45	Compound S-O and F.I.	1	<1,600,000	1	High	3	Yes	5
46	Fault Intersection	0	<130,000	3	High	3	Yes	6
47	Stepover	0	<130,000	3	High	3	Yes	6
48	Stepover	0	<130,000	3	High	3	Yes	6
							Average GPR for WPC	**5.56**

Table 3 continued.

B) DESERT NATIONAL WILDLIFE RANGE									
Id No.	Structure		Age of Faulting		Slip and Dilation Tendency		Field Visit	Past Evid.	Total Geothermal Potential Rating (1 to 8 possible)
	Structural Setting	GPR (0-1)	Years	GPR (0-4)	Rating	GPR (1-3)	(X)	(Y)	
1	Stepover	0	<1,600,000	1	Low	1	X		2
2	Fault Intersection	0	>1,600,000	0	High	3	X		3
3	Fault Intersection	0	<1,600,000	1	Moderate	2			3
4	Fault Intersection	0	>1,600,000	0	Moderate	2			2
5	Fault Termination	0	<1,600,000	1	High	3			4
6	Compound F.T. and F.I.	1	<130,000	3	Moderate	2			6
7	Stepover	0	<1,600,000	1	High	3			4
8	Stepover	0	<1,600,000	1	Moderate	2			3
9	Fault Termination	0	<1,600,000	1	Moderate	2			3
10	Stepover	0	<130,000	3	High	3	X		6
11	Compound F.I. and F. B.	1	<1,600,000	1	Moderate	2	X		4
12	Fault Intersection	0	<1,600,000	1	High	3	X	Yes	4
13	Fault Intersection	0	>1,600,000	0	High	3	X		3
14	Fault Intersection	0	>1,600,000	0	High	3			3
15	Fault Intersection	0	<1,600,000	1	High	3	X		4
16	Fault Intersection	0	<1,600,000	1	High	3	X	Yes	4
17	Fault Intersection	0	<130,000	3	Moderate	2			5
18	Fault Intersection	0	<1,600,000	1	High	3			4
19	Fault Intersection	0	>1,600,000	0	High	3			3
20	Fault Intersection	0	>1,600,000	0	High	3			3
21	Compound F.T. and S-O	1	<750,000	2	High	3			6
22	Fault Termination	0	<1,600,000	1	Low	1			2
23	Fault Termination	0	<1,600,000	1	High	3			4
24	Stepover	0	<1,600,000	1	High	3			4
25	Fault Termination	0	<130,000	1	Moderate	2			3
								Average GPR for the DNWR	3.68

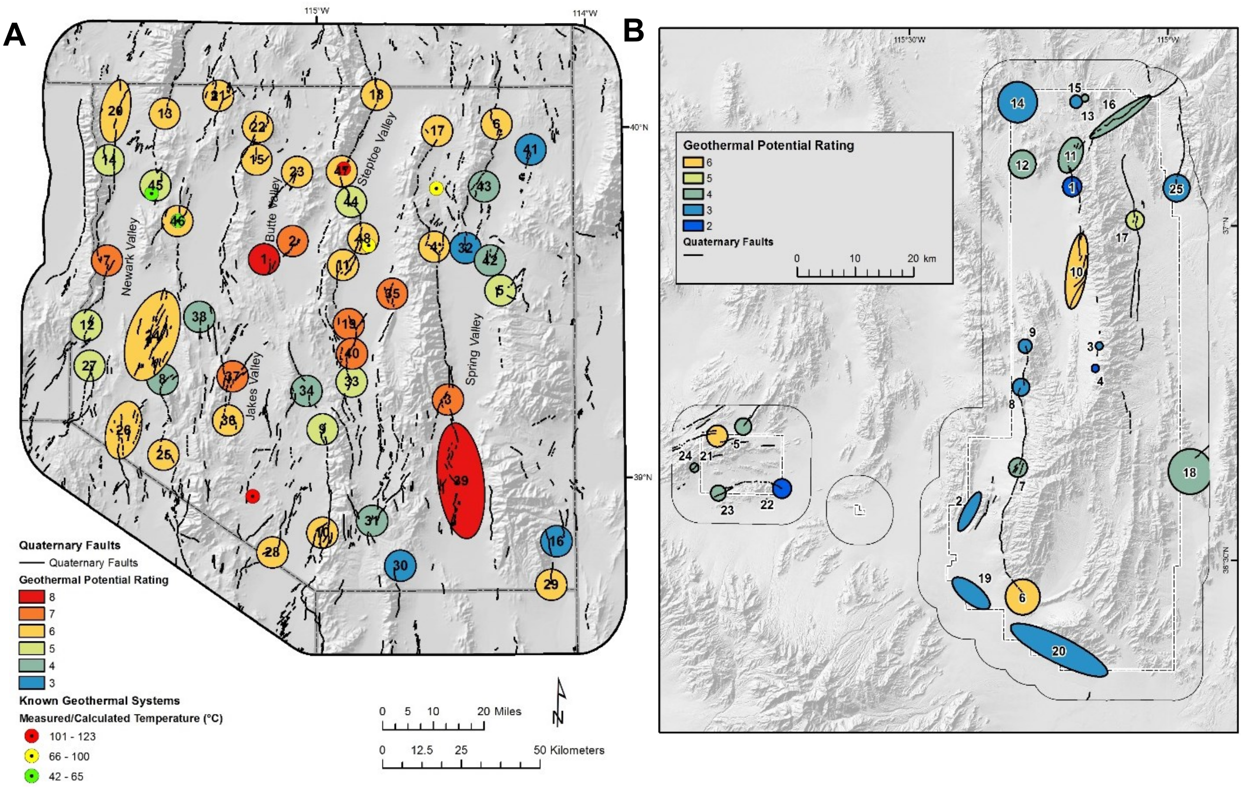

Figure 4: Geothermal potential rating (GPR) of the structural target areas identified in WPC (A) and the DNWR (B). GPR values correspond to Table 1.

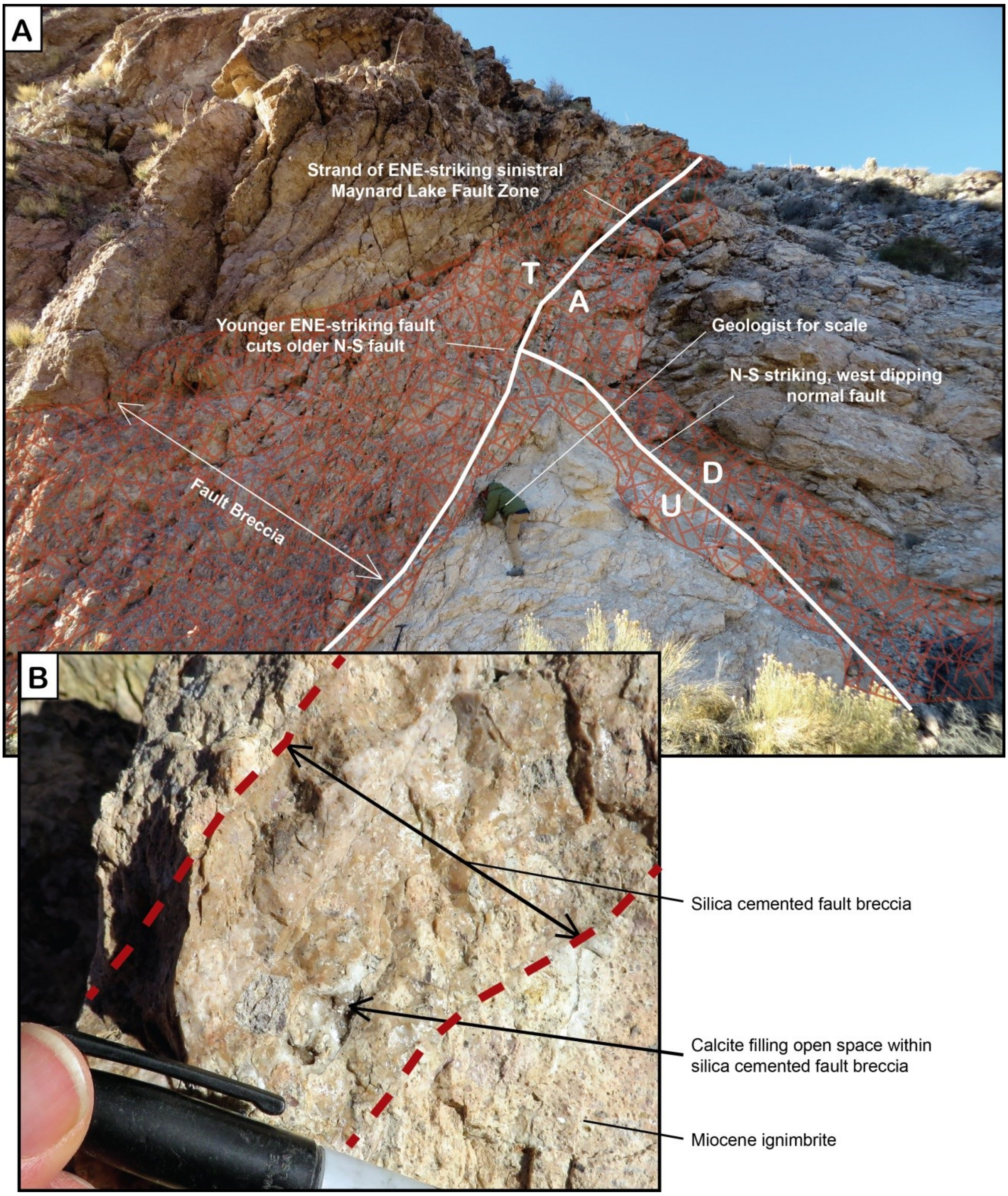

Figure 5: (A) Fault intersection between northeast-striking sinistral Maynard Lake fault zone and a north-south west-dipping normal fault zone from target No. 16 of DNWR (Table 1B, Figs., 3, 4). The north-striking normal fault is offset by the sinistral Maynard Lake fault zone. Silica and calcite veining and cementation of fault breccia noted in outcrop. Silica and calcite veins only present in Miocene volcanic rocks and not in the overlying Quaternary sediments. Fault strands only locally observed cutting the Miocene bedrock and not the Quaternary surficial deposits. This fault zone is associated with a scarp of probable late Pleistocene age several kilometers east of this location and is associated with a scarp of probable early Pleistocene age west of this location. The closest known Neogene magmatic centers to this outcrop are >30 km to the east. (B) Close up of hand-sample with silicified fault breccia.

3.2 Potential Deep Stratigraphic Reservoirs

Data compiled from oil and gas drilling and regional map relationships indicate that lower Paleozoic carbonate rocks underlie basin fill in many valleys in WPC and the DNWR, and that these carbonates commonly have primary lithologic permeabilities necessary to sustain the flow rates needed for power production (Allis et al., 2012; Kirby, 2012). Estimated depths of basin fill deposits reach >3 km-deep in 8 locations throughout WPC, based in part on modeling of regional gravity data (Fig. 5A; Jachens et al., 1996). Estimated depths of basin fill deposits do not reach more than 1 km within the DNWR (Fig 5B; Jachens et al., 1996), and thus the DNWR probably does not host any economic deep stratigraphic reservoirs.

There are 8 potential stratigraphic targets in WPC (defined where basin fill deposits exceed 3 km depth). Available data in these areas indicate that the northern Steptoe Valley provides the best environment for possible energy production from deep stratigraphic reservoirs (Allis et al., 2013). The Steptoe Valley has the highest upper crustal temperature gradient in WPC, based on temperature maps produced by Southern Methodist University (Fig. 5A; Coolbaugh et al., 2005). Estimated depths of basin fill deposits are also greatest for Steptoe Valley, based in part on modeling of regional gravity data (Fig. 5A; Jachens et al., 1996). Direct measurements of temperatures in several oil exploration wells and deep geothermal exploration holes confirm temperatures of approximately 190 to 200 °C at a depth of about 3.5 km (Allis et al., 2012; UNR digital data). In one well (Placid oil exploration well), a thick section of lost circulation was encountered at a depth of ~3 km, suggesting the possible presence of a significant thermal aquifer (Allis et al., 2012). Although Steptoe Valley has the best documented potential for deep stratigraphic aquifer development, insufficient data are present to adequately evaluate the potential of some of the target valleys of WPC.

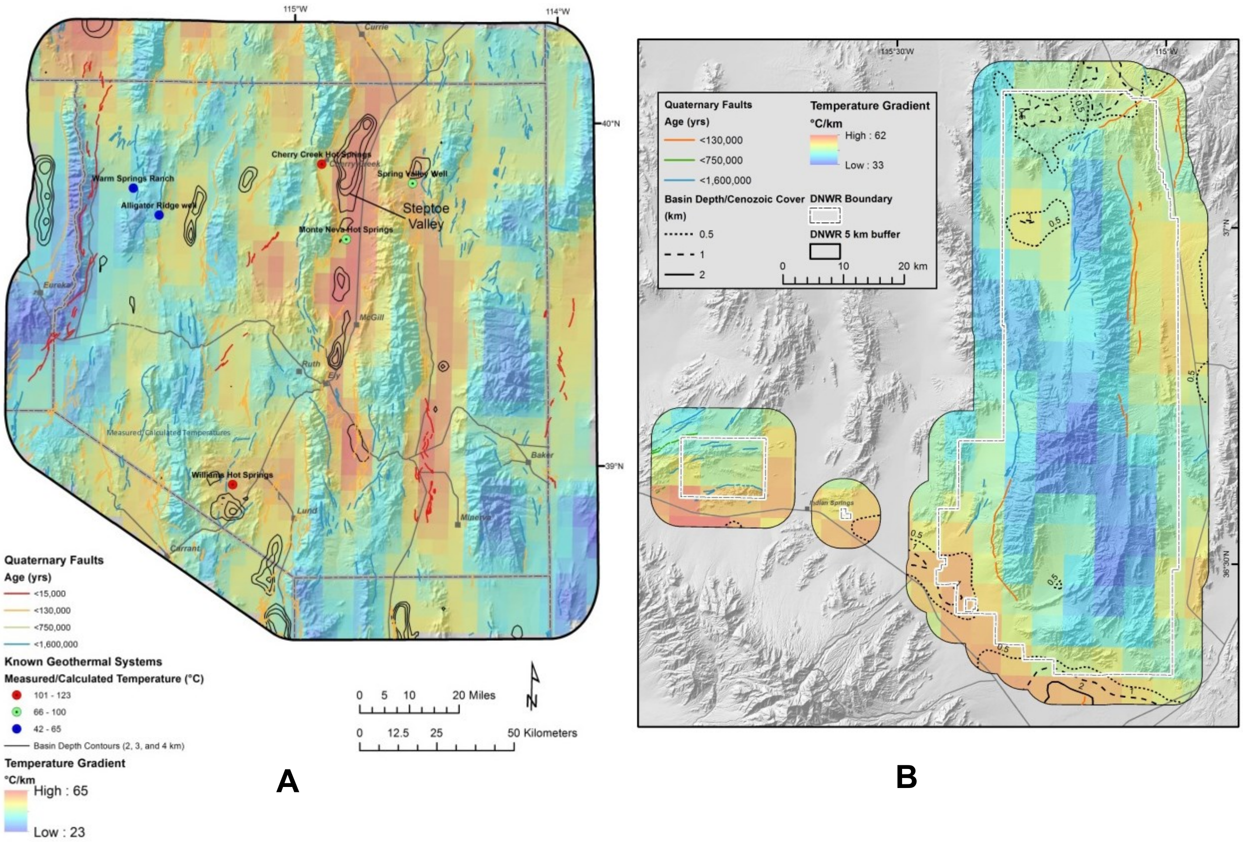

Figure 6: Shaded relief map of (A) WPC and (B) DNWR, with known structurally controlled geothermal systems and Quaternary faults (USGS, 2010). Upper crustal temperature gradient provided by Southern Methodist University (Coolbaugh et al., 2005). Estimated basin depth of poorly consolidated basin-fill sediments (black line contours) from Jachens and others (1996).

4. DISCUSSION

Assessments of WPC and the DNWR identified 73 structural targets, four of which are associated with known geothermal systems and 69 that could potentially host blind undiscovered structurally controlled geothermal systems. White Pine County contains 8 basins potentially capable of hosting deep sedimentary resources. These structural and sedimentary target areas were identified over a combined area of 26,000 km^2. Comparatively, the Great Basin region encompasses 680,000 km^2 and thus there are likely to be a large number of similarly definable targets that may host undiscovered geothermal resources across this entire region.

The potential of these structural targets identified in this study to host undiscovered blind geothermal resources were evaluated according to three data sets, including type of structural target, recency of faulting, and results of slip and dilation tendency analyses. As our modeling work continues, we anticipate including other data sets and developing tighter constraints on the relative baseline parameters for predicting the favorability, and incorporating those favorabilities into an overall ranking of geothermal potential. This will be accomplished through more rigorous analysis of data for known geothermal areas and will constrain the relative effectiveness of a given parameter at predicting geothermal potential. For example, one parameter may rank proportionately with whole integer values (0, 1, 2, 3) and another parameter that is not as strong at predicting favorability be scored an order of magnitude lower (0.1, 0.2, 0.3, 0.4). Specific values can be constrained through using multiple-valued logic statistical approaches (Coolbaugh et al., 2005, 2007; Carranza et al., 2008; Iovenitti et al., 2012; Poux and Suemnicht, 2012).

The targets with greatest potential can be prioritized for initial exploration to confirm if a blind resource is present using proven cost-effective exploration strategies and tools such as geochemical analyses, 2m temperature surveys, temperature gradient drilling, and geophysical surveys (e.g., Coolbaugh et al., 2006; Kratt et al., 2010; Hinz et al., 2013). While the development of deep stratigraphic resources is still largely theoretical, exploration of these resources can still benefit from predictive analyses. For these deep sedimentary basins, more detailed gravity data, temperature gradient data, deep drill-holes and seismic reflection surveys will be needed to more fully assess these potential resources. Integrative resource potential maps may also reveal key hybrid relationships between structural and deep stratigraphic resources that in turn will guide future exploration.

5. CONCLUSIONS

Recent advances in characterizing structurally controlled geothermal systems and the potential for viable deep stratigraphic resources have provided an opportunity to develop a new generation of geothermal potential maps. Such maps are built around identification of discrete structural or stratigraphic target areas that can then be evaluated against multiple data sets to evaluate their relative potential to host viable geothermal resources. Methods covered here provide a framework for broad analysis of the Great Basin region as whole as well as other areas around the world including settings with both amagmatic and magmatic geothermal resources. In areas where geothermal activity is magmatically mediated the same rigorous, multivariate statistical analyses to predict resource potential and guide exploration is likely to be useful as well. For any given geothermal region, baseline metrics can be developed from data covering known systems in that region, thus yielding region-specific geothermal potential criteria. Furthermore, these geothermal potential maps are not restricted to evaluating resources solely for power production, but may also be used for evaluating potential resources for low-temperature direct-use applications.

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