PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Conceptual Models of Geothermal Resources in the Eastern Great Basin

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Keywords: Reservoir Geology, Conceptual Models, Geothermal Resources, Great Basin

ABSTRACT

Producing geothermal fields in the eastern Great Basin include Beowawe, Cove Fort-Sulphurdale, Dixie Valley, Jersey Valley, McGinness Hills, Raft River, Roosevelt Hot Springs, Thermo Hot Spring, and Tuscarora. In these, fault-fracture systems, typically associated with range fronts and basin margins, localize hydrothermal fluid flow that forms narrow plumes. Additional types of geothermal resources include hot sedimentary aquifers, which are inferred to exist in deep basins. Notable examples include the Steptoe and Elko basins, Nevada, and Pavant Butte, Utah. An EGS type resource for the FORGE laboratory has been identified in the north Milford Valley, Utah, where a broad area of conductive heat flow occurs within a very large volume of granitic and metamorphic rocks.

The geothermal resource at Beowawe appears to be a hybrid system where a strong connection exists between a deep hot carbonate aquifer, which could be laterally extensive, and a narrow fault fracture mesh, which controls hydrothermal upflow to the surface. This model is supported by the chemical composition of the produced fluid, which is dominated by aqueous bicarbonate despite producing from a siliciclastic rock formation, and the very large sinter sheet, which required more than 50 km^3 of hot water discharge to account for all the silica. The estimated reservoir volume is ~350 km^2, greatly exceeding the 1-5 km^3 that can be estimated from geothermal production and stored heat.

The different resource-types, fault-related, hot sedimentary aquifer, and EGS are distinguished by the geological setting in which they occur. They vary in size from <1 to >100 km^2, but the different types can be closely spaced. The diversity of geothermal resources seems to be a natural outcome of elevated heat flow across a broad region coupled with local controls on the storage and flow of hot fluids.

1. INTRODUCTION

There are a number of geothermal resources in the Great Basin due to the large area over which heat flow is anomalously high (e.g., Sass et al., 1971; Blackwell, 1983; Blackwell et al. 2011). Most known resources are hosted in recently active fault systems produced by regional extension that are commonly situated near or along range fronts and basin margins, where permeability and fluid flow are structurally-controlled (e.g., Sorey et al., 1982; Benoit and Butler 1983; Faulds and Hinz, 2015). However, these resources are unevenly distributed (e.g. Coolbaugh et al., 2005; Faulds et al., 2013). High strain rates associated with the Walker Lane may explain why a significant proportion occurs in the western Great Basin (Faulds et al., 2012), but in some resources, magmatic intrusions supply high-grade thermal energy (e.g., Benoit and Butler, 1983; Kennedy and van Soest, 2006, 2007; Simmons et al., 2015). That geothermal resources also develop in hot sedimentary aquifers has long been known (e.g., Sorey et al., 1982), but the case for their existence in the Great Basin is a recent advance (e.g., Allis et al, 2011, 2012, 2013, 2015; Allis, 2014). EGS type resources occur locally in southern Utah (Allis et al., 2016; Simmons et al., 2016) and at Raft River (Bradford et al. 2016).

In this paper, we emphasize that different types of geothermal resources (fault-related, hot sedimentary aquifer, and EGS) occur in the eastern Great Basin, sometimes in close proximity to one another. What sets this region apart from the western Great Basin is the occurrence of thick marine carbonate units within the Paleozoic stratigraphy, which exert a regional control on groundwater flow and as well as heat flow (Sass et al., 1971; Lachenbruch and Sass, 1978; Blackwell, 1983; Person et al., 2008; Heilwell and Brooks, 2011; Masbruch et al., 2012; Allis et al., 2015). Hydrothermal activity, regional heat flow, geology, energy production, and fluid chemistry are briefly reviewed and synthesized to construct a conceptual model of resources in terms of their setting, dimension, and geometry. In addition, we draw attention to the potential development of hybrid resource types.

1. HYDROTHERMAL ACTIVITY, HOT SEDIMENTARY BASINS, AND REGIONAL HEAT FLOW

Producing geothermal resources in the eastern Great Basin define localized zones of intense hydrothermal activity, and they occupy two separate corridors (Figure 1). The northwestern group, comprising Dixie Valley, McGinness Hills, Jersey Valley, Beowawe, Tuscarora, and Raft River, form a regional belt that extends southeast to northwest, which overlaps the Battle Mountain high heat flow zone (e.g., Lachenbruch and Sass, 1977, 1978; Blackwell, 1983). This trend is also referred to as the Humboldt geothermal belt, which extends southwest into the Walker Lane geothermal belt (Faulds et al., 2012). Evidence of modern magmatism is unknown, and high heat flow is related to crustal thinning along with inferred deep intrusions of magmas (e.g., Kennedy and van Soest, 2007; Siler et al, 2014). The southeastern group, comprising Roosevelt Hot Springs, Cove Fort-Sulphurdale and Thermo Hot Springs lie within the Sevier thermal anomaly (Mabey and Budding, 1987; Blackett, 2007; Wannamaker et al., 2016), which occupies the southern part of the Wasatch geothermal belt (Faulds et al., 2012). Both of these corridors are inscribed by high regional heat flow >90mW/m^2 (Blackwell et al., 2011), and all of the resources are related to fault-systems that control permeability and fluid flow. In the Sevier thermal anomaly, some of the regional heat flow also derives from intrusions of magmas, as inferred from the scattered young volcanic centers and high helium isotope ratios indicating leakage of mantle helium (e.g. Mabey and Budding, 1987; Blackett, 2007; Kennedy and van Soest, 2007; Simmons et al., 2015).

Hot sedimentary aquifers form another type of geothermal resource (e.g., Allis et al., 2011, 2012, 2013), and these resources hold potential for future development. High heat flows of 90-100 mW/m^2 occur in the Elko and North Steptoe basins where temperatures of 150-180°C occur at 3 km depth (Gwynn et al., 2014; Gwynn, 2015). Railroad Valley is an isolated thermal anomaly with heat flow of up to 105 mW/m^2 in the vicinity of the Bacon Flat and Grant Canyon (Hulen et al., 1994; Gwynn, 2015). At Pavant Butte, a single well has a bottom hole temperature of ~200°C at 2.2 km depth and the heat flow is estimated to be 140±20 mW/m^2 (Allis et al., 2015). The thermal structures and lateral extents of hot strata in these basins are unknown, but conceivably range from several tens to several hundreds of km^2 (Allis et al., 2015). Hydrological studies show that laterally extensive zones of strong permeability occur in lower Paleozoic carbonate units, and one area where promising reservoir rocks could occur is in northeast Nevada (Heilwell and Brooks, 2011; Masbruch et al., 2012; Allis, 2014). In southeast Nevada, good connectivity and the regional hydraulic gradient induce north to south groundwater flow, which flushes heat and depresses the regional heat flow to <90mW/m^2 (Sass et al., 1971; Masbruch et al., 2012).

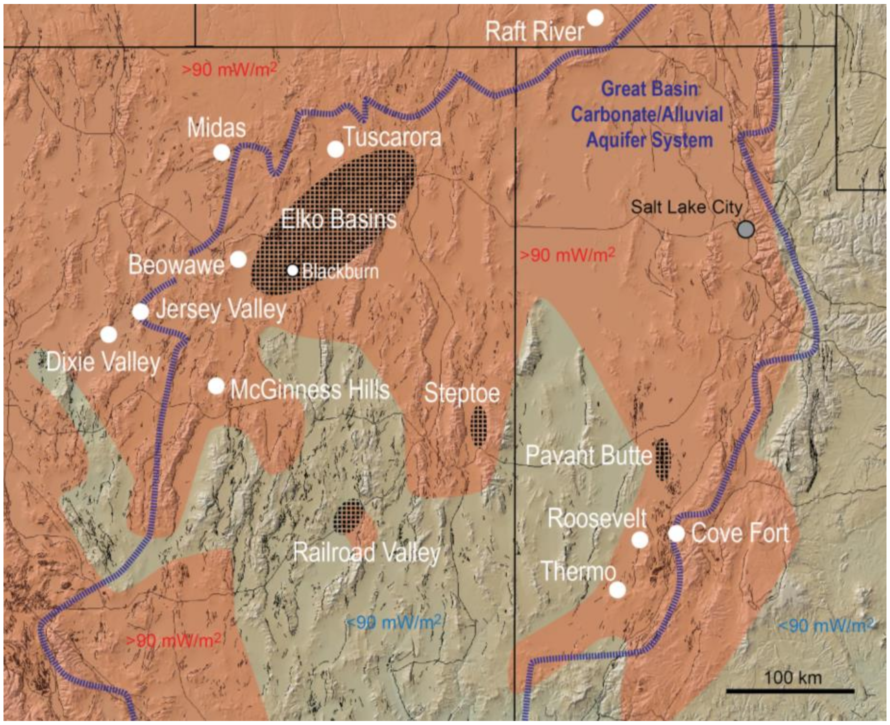
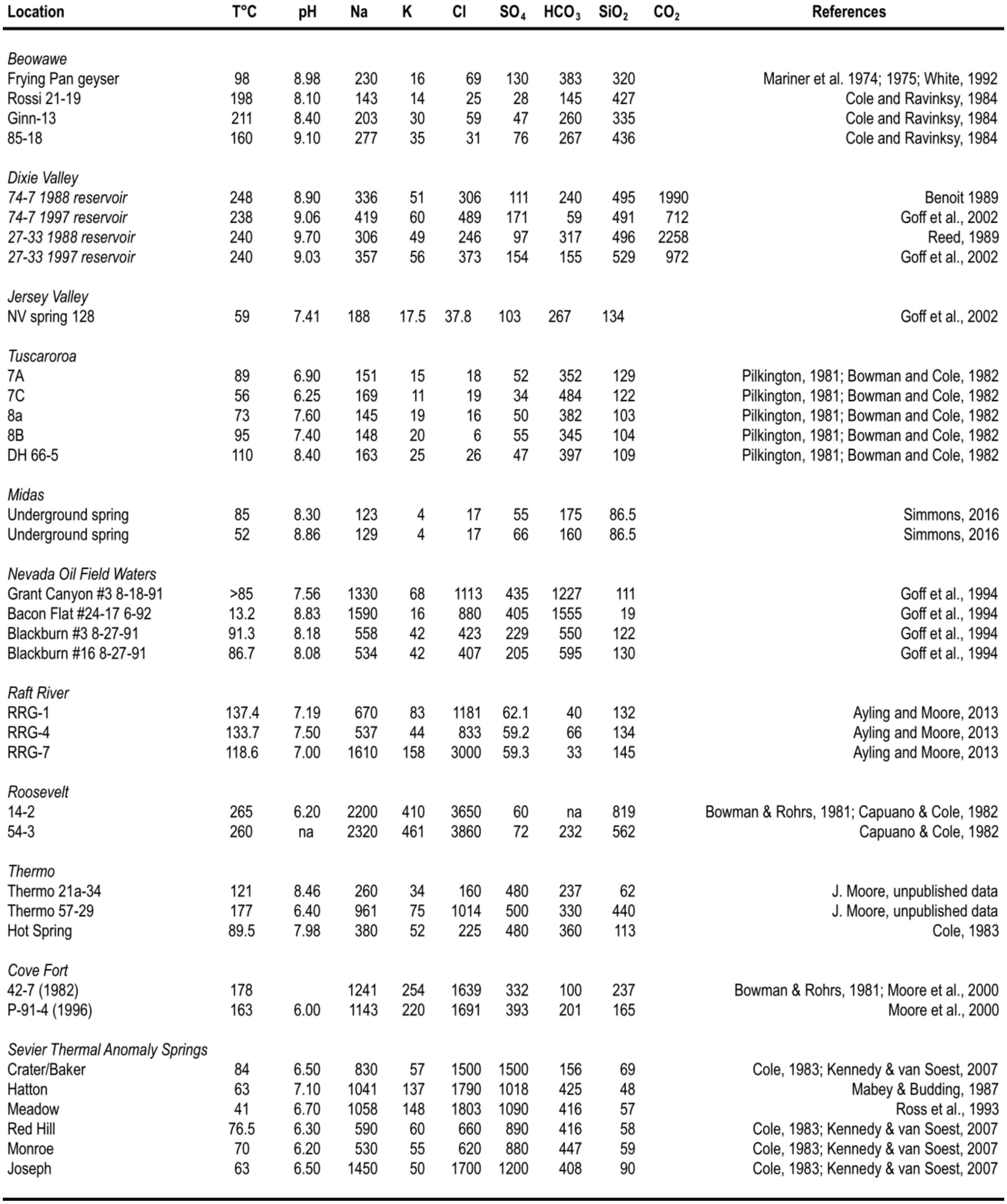


Figure 1: Map of northeast Nevada and western Utah, showing the locations of geothermal systems, hot basins (stipple pattern), the area of heat flow >90mW/m^2 in orange (Blackwell et al. 2011), and the limit of the Great Basin carbonate aquifer system (Heilwell and Brooks, 2011).

2. HYDROTHERMAL FLUID CHEMISTRY

The fluid chemistry from geothermal and petroleum wells plus a few springs are presented in Table 1. The data cover all the major geothermal resources, plus oil field waters from Blackburn (Elko Basins), Bacon Flat (Railroad Valley), and Grant Canyon (Railroad Valley). A trilinear graph showing the relative proportions of chloride, sulfate, and bicarbonate is presented in Figure 2, revealing provincial trends.

Data for Nevada geothermal systems are restricted to Beowawe, Dixie Valley, and Tuscarora; in these thermal waters, bicarbonate is the predominant anion. Little isotopic data exist and so the source of the bicarbonate enrichment is unclear, but given the regional geology, interaction with Paleozoic carbonate units seems plausible. For example, deep exploration drilling at Tuscarora intersected 250 m of limestone and dolomite (4510-5300' depth) at the bottom of well 66-5 (Sibbet, 1982). At Beowawe, by contrast, drilling terminated in the Valmy formation, which is made of siliciclastic sedimentary rocks, and Paleozoic carbonate units are thought to be several km deeper (Zoback, 1979; John et al., 2003). At Dixie Valley, which lies outside the western boundary of the Great Basin carbonate-alluvial aquifer system, bicarbonate and CO_2 could have a magmatic source based on carbon isotopes and N_2-Ar-He data (Bergfield, 2001). The hottest spring water in Jersey Valley is dominated by bicarbonate as are the hot spring waters encountered at 300 m below the surface in the Midas gold mine. Nevada oil field waters from Blackburn and Railroad Valley are also bicarbonate-rich consistent with production from Paleozoic limestone and dolomite in these wells (Hulen et al., 1990; 1994; Goff et al., 1994).



Location	T°C	pH	Na	K	Cl	SO_4	HCO_3	SiO_2	CO_2	References
Beowawe										
Frying Pan geyser	98	8.98	230	16	69	130	383	320		Mariner et al. 1974; 1975; White, 1992
Rossi 21-19	198	8.10	143	14	25	28	145	427		Cole and Ravinksy, 1984
Ginn-13	211	8.40	203	30	59	47	260	335		Cole and Ravinksy, 1984
85-18	160	9.10	277	35	31	76	267	436		Cole and Ravinksy, 1984
Dixie Valley										
74-7 1988 reservoir	248	8.90	336	51	306	111	240	495	1990	Benoit 1989
74-7 1997 reservoir	238	9.06	419	60	489	171	59	491	712	Goff et al., 2002
27-33 1988 reservoir	240	9.70	306	49	246	97	317	496	2258	Reed, 1989
27-33 1997 reservoir	240	9.03	357	56	373	154	155	529	972	Goff et al., 2002
Jersey Valley										
NV spring 128	59	7.41	188	17.5	37.8	103	267	134		Goff et al., 2002
Tuscaroroa										
7A	89	6.90	151	15	18	52	352	129		Pilkington, 1981; Bowman and Cole, 1982
7C	56	6.25	169	11	19	34	484	122		Pilkington, 1981; Bowman and Cole, 1982
8a	73	7.60	145	19	16	50	382	103		Pilkington, 1981; Bowman and Cole, 1982
8B	95	7.40	148	20	6	55	345	104		Pilkington, 1981; Bowman and Cole, 1982
DH 66-5	110	8.40	163	25	26	47	397	109		Pilkington, 1981; Bowman and Cole, 1982
Midas										
Underground spring	85	8.30	123	4	17	55	175	86.5		Simmons, 2016
Underground spring	52	8.86	129	4	17	66	160	86.5		Simmons, 2016
Nevada Oil Field Waters										
Grant Canyon #3 8-18-91	>85	7.56	1330	68	1113	435	1227	111		Goff et al., 1994
Bacon Flat #24-17 6-92	13.2	8.83	1590	16	880	405	1555	19		Goff et al., 1994
Blackburn #3 8-27-91	91.3	8.18	558	42	423	229	550	122		Goff et al., 1994
Blackburn #16 8-27-91	86.7	8.08	534	42	407	205	595	130		Goff et al., 1994
Raft River										
RRG-1	137.4	7.19	670	83	1181	62.1	40	132		Ayling and Moore, 2013
RRG-4	133.7	7.50	537	44	833	59.2	66	134		Ayling and Moore, 2013
RRG-7	118.6	7.00	1610	158	3000	59.3	33	145		Ayling and Moore, 2013
Roosevelt										
14-2	265	6.20	2200	410	3650	60	na	819		Bowman & Rohrs, 1981; Capuano & Cole, 1982
54-3	260	na	2320	461	3860	72	232	562		Capuano & Cole, 1982
Thermo										
Thermo 21a-34	121	8.46	260	34	160	480	237	62		J. Moore, unpublished data
Thermo 57-29	177	6.40	961	75	1014	500	330	440		J. Moore, unpublished data
Hot Spring	89.5	7.98	380	52	225	480	360	113		Cole, 1983
Cove Fort										
42-7 (1982)	178		1241	254	1639	332	100	237		Bowman & Rohrs, 1981; Moore et al., 2000
P-91-4 (1996)	163	6.00	1143	220	1691	393	201	165		Moore et al., 2000
Sevier Thermal Anomaly Springs										
Crater/Baker	84	6.50	830	57	1500	1500	156	69		Cole, 1983; Kennedy & van Soest, 2007
Hatton	63	7.10	1041	137	1790	1018	425	48		Mabey & Budding, 1987
Meadow	41	6.70	1058	148	1803	1090	416	57		Ross et al., 1993
Red Hill	76.5	6.30	590	60	660	890	416	58		Cole, 1983; Kennedy & van Soest, 2007
Monroe	70	6.20	530	55	620	880	447	59		Cole, 1983; Kennedy & van Soest, 2007
Joseph	63	6.50	1450	50	1700	1200	408	90		Cole, 1983; Kennedy & van Soest, 2007

At Raft River, the thermal waters are dominated by chloride, consistent with reservoir production from Precambrian basement rocks consisting of quartzite, schist, and quartz monzanite (Ayling and Moore, 2013). Differences in chloride concentration suggest the reservoir is compartmentalized by sub-vertical faults (Ayling and Moore, 2013).

Within the Sevier thermal anomaly, Roosevelt Hot Springs and Cove Fort-Sulphurdale waters plot in the chloride field, and these waters are thought to have interacted and equilibrated primarily with deep crystalline rocks (Simmons et al., 2015). Thermo Hot Spring waters, are different and straddle the chloride and sulfate fields, possibly as a result interactions with both deep crystalline and Paleozoic sedimentary rocks (Simmons et al., 2015) Although Paleozoic carbonate units host part of the reservoirs at Cove Fort-Sulphurdale and Thermo Hot Spring, they seem to have had relatively little influence on thermal water compositions when compared to the thermal waters in northeast Nevada. Sevier spring thermal waters straddle the chloride and sulfate fields, which may reflect inactions with Tertiary and Quaternary basin fill and evaporites (Simmons et al., 2015).

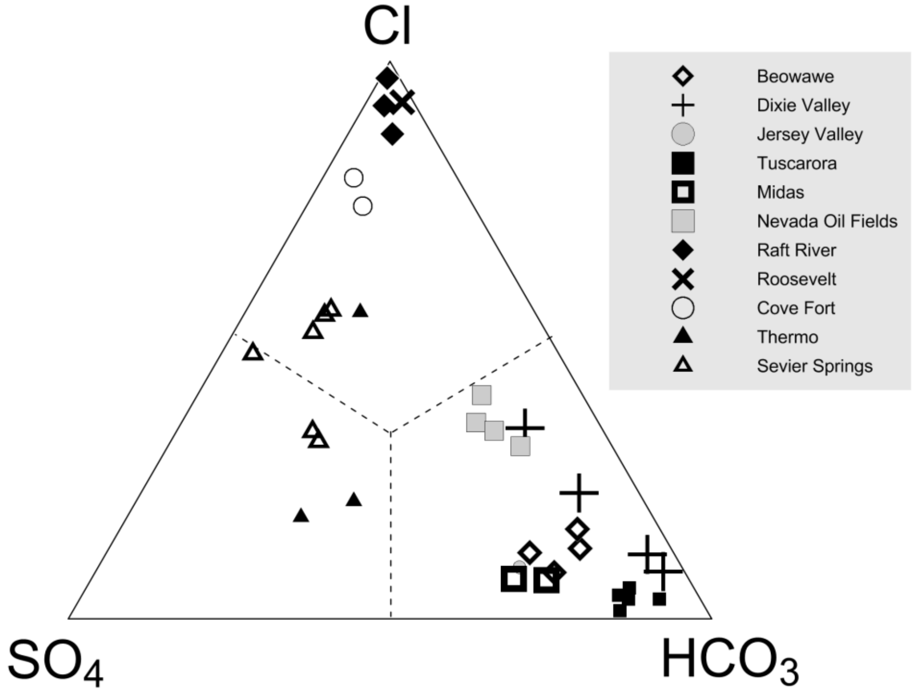


Figure 2: Trilinear graph of deep thermal water compositions with respect to Cl-HCO_3-SO_4.

3. RESOURCE DIMENSIONS

To estimate minimum requirements for resource dimensions, we have used the histories of electricity generation for the three longest producing fields (Beowawe, Dixie Valley, and Roosevelt Hot Springs), assuming all produced energy is stored heat (Table 2; Grant and Bixley, 2011). We also assume the reservoir rock cools by 50°C (Delta T°K, Table 2) over the production period, which is possibly an over estimate. We assigned a reservoir porosity of 15% based on the rock types, but the results are not very sensitive to variations in this value. The calculations show that Dixie Valley, Roosevelt Hot Springs, and Beowawe require minimum reservoir volumes of 2.7, 1.4, and 0.9 km^3, respectively, assuming a recovery factor of 1. If the recovery factor is closer to 0.1 to 0.2 as is expected (e.g. Grant and Bixley, 2011), then the reservoir volumes are 5-10 times larger. From what can be estimated about reservoir sizes (Figure 3), sufficient stored heat possibly exists at <4 km to supply all the electricity generated so far based on well data and production histories.

For Beowawe, the large contiguous sinter sheet on the northern edge of the Malpais fault scarp provides further insight regarding the resource dimension. We estimate the sinter sheet to comprise a volume ~7.5 million m^3 (i.e., 1500x1000x5 m^3), and taking a measured bulk density of 1600 kg/m^3 (Rimstadt and Cole, 1983), the sinter contains ~1.2 E10 kg of silica. By contrast, Rimstadt and Cole (1983) estimated the sinter volume to be ~10 times larger, whereas Zoback (1979) estimated the silica sinter volume to be 2.4 times larger. We calculate that the total discharge of boiling water required to account for the mass of silica is ~4.4 E13 kg based on amorphous silica solubility over the temperature range of 95 to 15°C (Rimstadt and Cole, 1983). The total volume of hot water discharge is ~5.2 E10 m^3, requiring a reservoir volume of ~350 km^3 at 15% porosity and ~230°C. The reservoir volume is obviously much larger, if our estimate of silica volume is too small. Nevertheless, the history of boiling water discharge as represented by the silica sinter deposit suggests a vastly larger reservoir than indicated from the results in Table 2. Based on the thermal water composition and the permeability requirements, such a reservoir was possibly hosted by a deep Paleozoic carbonate unit (Zoback, 1979).

Table 2. Minimum reservoir volumes for Dixie Valley, Roosevelt and Beowawe based on stored heat and production histories.

	Dixie Valley	Roosevelt	Beowawe
Delta T°K	50	50	50
specific heat MJ/m^3°K	2.5	2.5	2.5
porosity fraction	0.15	0.05	0.15
Thermal energy/volume (MJ/km^3)	1.06E+11	1.19E+11	1.06E+11
Production field area km^2	2	2	<1
Production period	1988-2014	1984-2016	1985-2016
Electricity production (MW hrs)	14,300,000	6,900,000	4,000,000
Total electricity produced (MJ)	5.1E+10	2.5E+10	1.4E+10
Conversion efficiency (thermal to electrical)	15%	15%	15%
Total thermal energy produced (MJ)	3.4E+11	1.7E+11	9.6E+10
Stored heat (MJ/km^3)	1.06E+11	1.19E+11	1.06E+11
Minimum reservoir volume (km^3)	3.2	1.4	0.9
References	Benoit 2015 Blackwell et al. 2007	Allis and Larsen, 2012	Butler et al., 2001 Garg et al., 2007

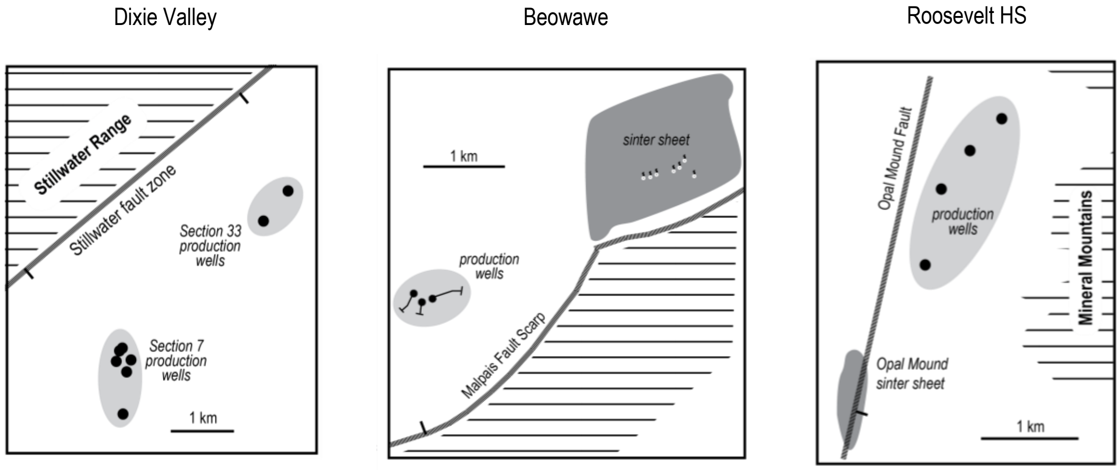


Figure 3: Sketch maps of Dixie Valley, Beowawe, and Roosevelt Hot Springs, showing plan dimensions of well fields and inferred subsurface reservoirs (medium grey pattern) with respect to major geological features. The horizontally lined areas represent topographic highs.

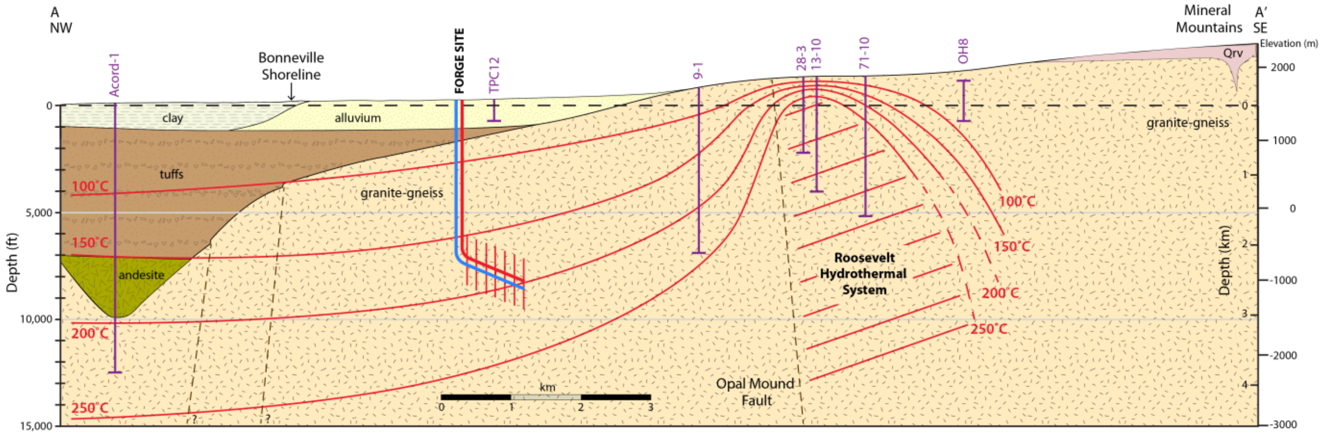


Figure 4: Cross section view of the Utah FORGE EGS site, showing the geology and thermal structure (Allis et al., 2016; Simmons et al., 2016).

4. FORGE UTAH-EGS

FORGE Utah site is being evaluated as a laboratory for EGS technologies (e.g. Allis et al., 2016), but the geothermal resource potential of the area was known by the early 1980s (Goff and Decker, 1983). FORGE Utah is situated 5 km west of the Roosevelt Hot Springs, on alluvial fan deposits (200-600 m thick) that overlie a large volume of hot crystalline basement rock (Figure 4). The site occurs within a region that is geologically complex and characterized by a history of extensional faulting, sporadic magmatism, and localized hydrothermal convection, which combined produced a zone of anomalously high heat flow covering ~100 km^2 (Allis et al, 2016; Gwynn et al., 2016; Simmons et al. 2016). Analysis of data from shallow and deep wells indicate that temperatures of 175-225°C exist 2-3.5 km depth in low porosity crystalline rock consisting of weakly fractured and jointed granodiorite and gneiss. Heat flow is dominated by conduction. A downward step change in pressure head from east to west across the Opal Mound fault indicates the FORGE site is isolated from hydrothermal fluid flow at Roosevelt Hot Springs.

5. SYNTHESIS

The main aim of this work is to advance a first order understanding of the geometries and dimensions of geothermal resources and to characterize the diverse settings in which they form (Figure 5). This is an ongoing project for which revisions and refinements are expected.

Most known resources are related to heat transfer by hydrothermal convection focused along fault-fracture systems (e.g. Benoit and Butler, 1983; Faulds and Hinz, 2015). For these systems, fault geometry and localized development of strong permeability are critical attributes (e.g., Faulds and Hinz, 2015). The depth of hydrothermal convective circulation is not well constrained, perhaps 8-10 km (Wisian and Blackwell, 2004), and probably limited by the depth to the brittle-ductile transition (Manning and Ingrebritsen, 1999). The cross-sectional area of the upflow zone is ~1-3 km^2 across (Figure 3), which is small compared to the dimensions of many producing resources in volcanic regions (5-50 km^2; e.g. Grant and Bixley, 2011). Multiple close-spaced hydrothermal plumes separated by distances of 1-5 km can develop, as documented in Dixie Valley (e.g., Blackwell et al. 2005). There is also the possibility that fluid upflow is inclined along the fault structure, not strictly vertical, which at Beowawe accounts for the separation (1.5 km) between the hot springs/sinter terrace and the production field (Butler et al. 2001; Garg et al., 2007). Finally, these hydrothermal systems may be concealed, and have little or no surface expression (e.g., McGinness Hills; Coolbaugh et al., 2006; Midas, Simmons, 2016), but they can have very high heat flows as is now clear for Cove Fort (Allis et al., 2017).

Not proven but highly probable is the existence of geothermal resources in hot sedimentary aquifers. Well profiles show temperatures of >150°C at 2-4 km depth (Allis et al., 2012, 2015b; Gwynn et al., 2014). Knowledge of the lateral extents of reservoirs, however, is poorly constrained. The evidence from Beowawe suggests that large volumes of hot water (>200°C) were stored in deep carbonate aquifers, and depending on thickness, might cover areas 10s to 100s km^2. From the predominance of bicarbonate in thermal waters, we infer that hot carbonate aquifers are a widespread regional feature that may be best developed in northeastern Nevada. They may also connect with fault-related hydrothermal systems to form a hybrid resource model as proposed for Beowawe.

EGS resources comprise significant volumes of hot crystalline rock with low permeability. They are not as common as hydrothermal systems and hot sedimentary aquifers at shallow depths, and considerable work is required to prove their viability. Nevertheless, well profiles at the Utah FORGE site in the north Milford Valley suggest the EGS-resource might cover several tens of km^2. Notably, the zone of high conductive heat flow is about 10 times larger in area than the reservoir associated with the Roosevelt Hot Springs.

In sum, three different resource-types are distinguished, which reflect the host rocks and geological setting in which they occur. They vary in size from <1 to >100 km^2 and have geometries that relate to fluid flow control by sub-vertical faults and horizontal aquifers. The diverse range of resource types seems to be a characteristic feature of the Great Basin, and a natural result of high heat flow across a broad region that is geologically complex and a product of the Phanerozoic record of sedimentation and deformation.

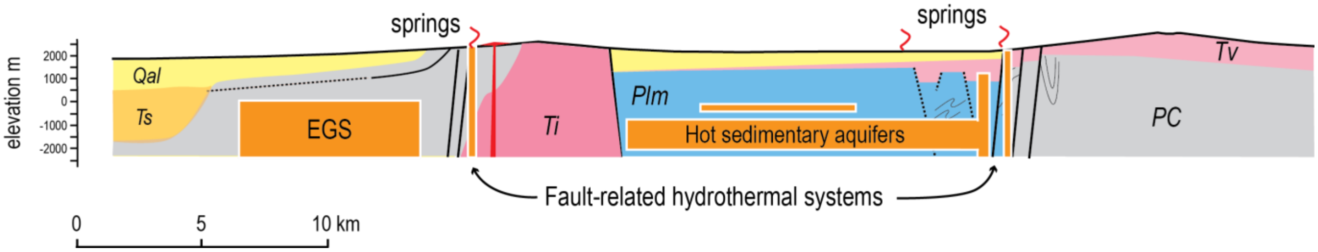


Figure 5: Schematic cross-section showing geothermal resources (orange) in the eastern Great Basin. Fault-related hydrothermal systems are localized along sub-vertical structures. Some have surface expression in the form of hot springs, and some are blind. They are shown to have a potential connection to hot sedimentary aquifers hosted by carbonate rocks. EGS resources occur in hot crystalline rocks that have low porosity. Abbreviations: PC=Precambrian gneiss-schist; Plm=Paleozoic limestone; PS=Paleozoic siliciclastic rock; Qal=Quaternary alluvium; Ti=Tertiary pluton; Tv=Tertiary volcanic rock.

ACKNOWLEDGEMENTS

Funding for this study was provided by DoE grants to investigate geothermal resources in hot sedimentary aquifers (Moore and Allis PIs), the Utah FORGE site (Moore, PI), and through play fairway analysis in southern Utah (Wannamaker PI).

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