Advancing Geophysical Techniques to Image a Stratigraphic Hydrothermal Resource

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Keywords

stratigraphic, sedimentary, basin, hydrothermal, geophysics, exploration, inversion, play fairway

ABSTRACT

Sedimentary-hosted geothermal energy systems are permeable structural, structural-stratigraphic, and/or stratigraphic horizons with sufficient temperature for direct use and/or electricity generation. Sedimentary-hosted (i.e., stratigraphic) geothermal reservoirs may be present in multiple locations across the central and eastern Great Basin of the USA, thereby constituting a potentially large base of untapped, economically accessible energy resources. Sandia National Laboratories has partnered with a multi-disciplinary group of collaborators to evaluate a stratigraphic system in Steptoe Valley, Nevada using both established and novel geophysical imaging techniques. The goal of this study is to inform an optimized strategy for subsequent exploration and development of this and analogous resources. Building from prior Nevada Play Fairway Analysis (PFA), this team is primarily 1) collecting additional geophysical data, 2) employing novel joint geophysical inversion/modeling techniques to update existing 3D geologic

models, and 3) integrating the geophysical results to produce a working, geologically constrained thermo-hydrological reservoir model. Prior PFA work highlights Steptoe Valley as a favorable resource basin that likely has both sedimentary and hydrothermal characteristics. However, there remains significant uncertainty on the nature and architecture of the resource(s) at depth, which increases the risk in exploratory drilling. Newly acquired gravity, magnetic, magnetotelluric, and controlled-source electromagnetic data, in conjunction with new and preceding geoscientific measurements and observations, are being integrated and evaluated in this study for efficacy in understanding stratigraphic geothermal resources and mitigating exploration risk. Furthermore, the influence of hydrothermal activity on sedimentary-hosted reservoirs in favorable structural settings (i.e., whether fault-controlled systems may locally enhance temperature and permeability in some deep stratigraphic reservoirs) will also be evaluated. This paper provides details and current updates on the course of this study in-progress.

1. Introduction

Sedimentary-hosted geothermal resources are characterized by permeable stratigraphic or structural-stratigraphic horizons hosted in areas with dominantly conductive thermal regimes and with temperatures that can be suitable for power production and/or direct use. Developed power-producing, sedimentary-hosted geothermal resources are present in half a dozen countries in Europe (e.g., Rühaak et al., 2010; Ćubrić, 2012; Vidal and Genter, 2018; Flechtner and Aubele, 2019). Potential resources that are broadly similar to the developed sedimentary-hosted resources in Europe have been identified in the USA; however, most have been minimally explored and development for energy production is still in a nascent stage (e.g., Allis et al., 2015; Hinz et al., 2015; Johnston et al., 2020).

Steptoe Valley has been identified to prospectively host a stratigraphic geothermal resource, with elevated temperatures initially documented during oil and gas well drilling (Allis, et al., 2011, 2012; Kirby, 2012; Allis and Moore, 2014; Gwynn et al., 2014). Steptoe Valley is in northeastern Nevada and is part of a region with multiple possible sedimentary-hosted resources (e.g., Allis et al., 2015; Hinz et al., 2015; Johnston et al., 2020). Based on available temperature data, the potential resources in this region have temperatures that range from 170 to 250°C at 3 to 4 km depth (Figure 1a; Allis and Moore, 2014). Each of the resource areas in this region are associated with thick sections of Paleozoic carbonates and clean Jurassic sandstones and limestones that are covered by approximately 2 to ≥3 km of low thermal conductivity Tertiary basin-infilling sediments (Figure 1b; Allis et al., 2012).

This applied research collaboration has been assembled to comprehensively assess the geothermal potential of Steptoe Valley by collecting additional geophysical data, employing novel joint inversion/modeling techniques to inform a 3D geologic map, and integrating the geophysical data to produce a geologically constrained thermal-hydrological working reservoir model. Acquisition of new gravity, magnetic, magnetotelluric (MT), and controlled-source electromagnetic (CSEM) data is underway, and the results will be integrated and evaluated for efficacy in understanding stratigraphic geothermal resources and mitigating exploration risk. We will combine the geophysical results with updated geochemical data and geological observations that are currently being assembled to broadly assess the potential influence of hydrothermal activity in favorable structural settings of the sedimentary-hosted reservoir. These datasets will be interpreted to develop one or more conceptual models for use in comparison with developed stratigraphic geothermal resources in Europe for guidance in completing updated power capacity estimates for northern Steptoe Valley. The following sections describe the geothermal resource potential based upon findings from previous research, a description of exploration methods being applied, a report on progress to-date, the planned characterization strategy, and the anticipated outlook/implications with respect to this ongoing study.

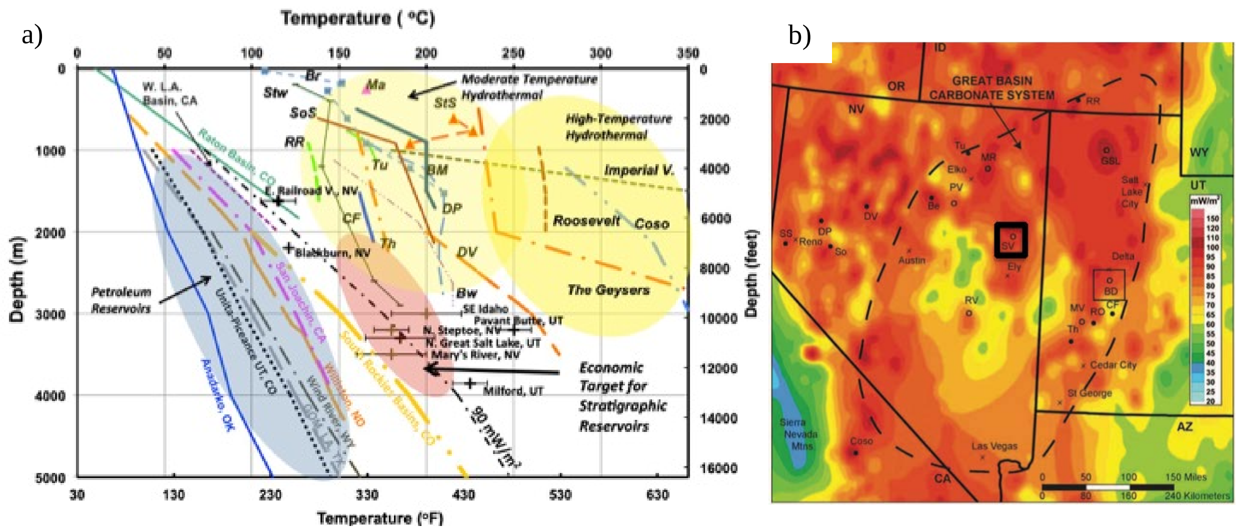

Figure 1: a) Figure from Allis and Moore (2014) of geothermal resource temperature regimes. b) Figure adapted from Allis et al. (2012), with location of Steptoe Valley outlined by a thick black box, of regional heat flow based on existing temperature data.

2. Geothermal Resource Potential

Steptoe Valley was highlighted for geothermal resource favorability throughout the course of the Nevada Play Fairway Analysis (PFA) studies (Figure 2a; Faulds et al., 2015; Faulds et al., 2016; Hinz et al. 2020). Northern Steptoe Valley has substantial potential as a sedimentary-hosted geothermal resource prospect; it also has surface thermal manifestations (e.g., hot springs) that are likely associated with deep circulation systems (Figure 2b; Hinz et al., 2020). Northern Steptoe Valley is associated with a combination of stratigraphy- and fault-controlled permeability. These permeability controls have important implications for understanding the natural state thermal regime of the basin, resource distribution, reservoir targeting, development strategies, and assessing power capacities.

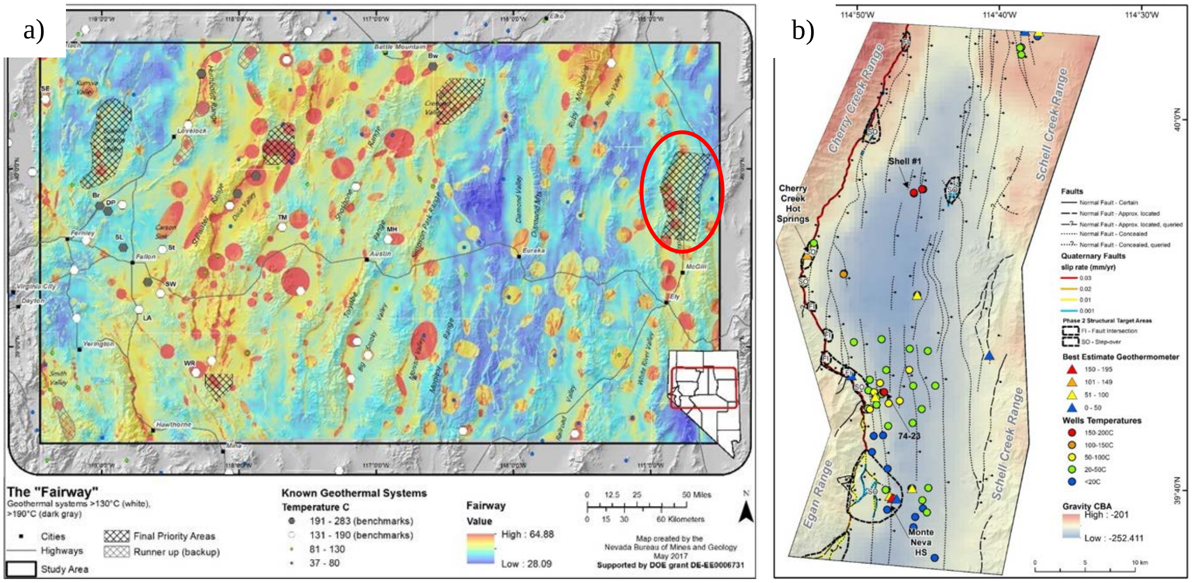

Figure 2: a) Nevada PFA favorability map of Faulds et al. (2015), with location of northern Steptoe Valley circled in red. b) Structural map of northern Steptoe Valley from Hinz et al. (2020).

2.1 Geologic Setting

Steptoe Valley is an elongate north-trending, late Cenozoic west-tilted half graben located directly north of Ely, Nevada (circled in red in Figure 2a; Faulds et al., 2015). Late Cenozoic extension was accommodated by a system of N- to NNE-striking, dominantly east-dipping normal faults. This includes a segmented range-front fault along the west side of the basin, as well as numerous synthetic and antithetic intrabasinal faults (Figure 2b; Hinz et al., 2020). Quaternary fault scarps mark the trace of the range-front fault system. In ascending stratigraphic order, major lithologic units in the area include up to 10 km of Paleozoic carbonate sections and lesser clastic sedimentary rocks; as much as 1 km of Oligocene-Miocene volcanic and lesser sedimentary rocks; and late Miocene to recent basin fill sediments locally approaching 3 km in thickness (Hinz et al., 2020). Two hot springs in the area (i.e., Monte Neva and Cherry Creek) are the only observed surficial geothermal features in Steptoe Valley and both are associated with normal fault step-overs (Figure 2b; Hinz et al., 2020). Monte Neva Hot Springs have the hottest surface discharge of fluids in the area at 79°C and also host a 0.3 km^2 travertine spring mound.

2.2 Exploration History and Available Data

Hunt Oil Company drilled approximately 50 temperature gradient (TG) holes and two deep geothermal wells in the Steptoe basin during the 1970s. Two petroleum exploration wells, Shell #1 and 17-14, were also drilled by other companies in northern Steptoe Valley in the 1970s and 1980s. TG holes consistently yielded linear temperature increase with depth (i.e., a conductive temperature gradient) to depths of 600 m (Chovanec, 2003). Measured temperatures from the two exploration wells, in addition to other deep wells in Steptoe Valley, indicate a conductive temperature gradient at depths ranging from 1.5 to 3.5 km (Figure 3; Hinz et al., 2015). These measurements are consistent with a generalized conceptual model applicable to Steptoe Valley and stratigraphic reservoirs in the region, in which a thick section of low thermal conductivity basin fill acts as a thermal insulator which locally retains elevated temperatures from regionally high conductive heat flow at depth (e.g., Allis et al., 2011, Allis and Moore 2014, Hinz et al., 2020).

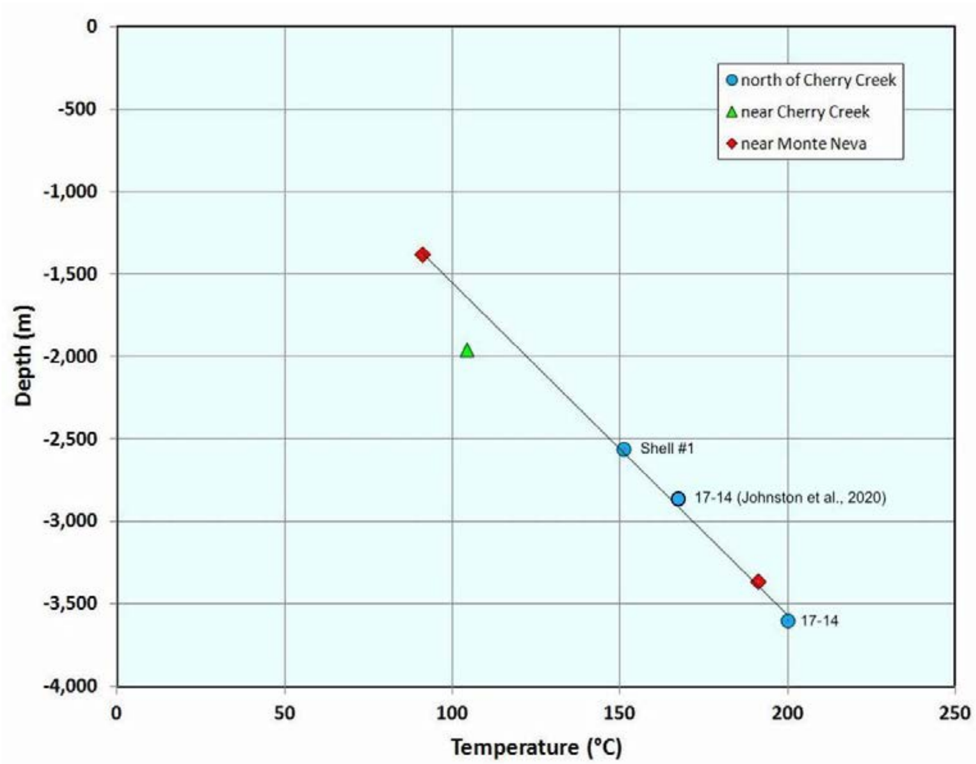

Figure 3: Bottomhole temperature plot adapted from Hinz et al. (2015) illustrating the linear/conductive temperature gradient measured from deep exploration wells in Steptoe Valley. Measurements from the Shell #1 and 17-14 wells from the northern Steptoe Valley study area are annotated. A shallower measurement from well 17-14, reported by Johnston et al. (2020), is also added/annotated on the figure and is consistent with the conductive temperature gradient.

Existing geoscience datasets include a Quaternary fault map of the basin, slip and dilation tendency analysis of Quaternary faults, logs and cuttings from the oil/gas and geothermal exploration wells, gravity data, legacy 2D seismic reflection profiles, depth to basement modeling along select profiles, fluid geochemistry from wells and springs, and thermal conductivity data. Moreover, lithologic logs from 25 wells, geologic map data, 16 cross sections including data from 14 seismic reflection profiles (e.g., Figure 4), and depth to basement modeled from gravity data were integrated into an initial 3D geologic map of Steptoe Valley. In addition, 40 samples of well cuttings from key stratigraphic units were analyzed for thermal conductivity. Existing temperature data, new thermal conductivity measurements, and the 3D geologic model were used to develop a new heat flow model for the northern Steptoe Valley area (Hinz et al., 2020).

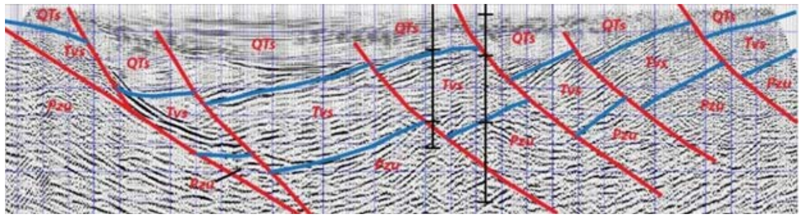

Figure 4: Interpreted seismic section from Hinz et al. (2020).

3. Applied Research Methods

The field campaign for northern Steptoe Valley is focused on geophysical surveys to image the subsurface stratigraphy and structural architecture of the subsurface. The photos in Figure 5 illustrate the applied, comprehensive approach to imaging and assessing the geothermal resource potential in northern Steptoe Valley. Ground gravity and airborne magnetic surveying are conducted first, followed by MT/CSEM surveying in a more focused part of the basin surrounding the two legacy petroleum exploration wells. The well data will calibrate the interpretation of the geophysical data and the geophysical imaging will provide insight on geologic layer shape/distribution around the wells. Targeted geologic mapping and geochemical surveying are also integral parts of the field study to provide context and constraint for developing and interpreting the geophysical results. New data collected from this study will be posted on the Geothermal Data Repository (https://gdr.openei.org/).

Figure 5: Pictures illustrating the field campaign for northern Steptoe Valley. Counterclockwise from top left: gravity surveying in Steptoe Valley conducted in FY22, an airborne magnetic vehicle, a schematic diagram of an MT receiver station, and spring sampling in Steptoe Valley performed in FY22.

The suite of planned surveys will provide information about different physical properties of the formations for the structural-stratigraphic model. Our plan includes joint modeling of gravity and magnetic data since these potential field data can be combined for a more robust interpretation (versus evaluating independently). Density and magnetic susceptibility information will be compiled from legacy and modern data to constrain modeling. These data will be processed and inverted jointly using codes under development at Pacific Northwest National Laboratory (PNNL) to create 3D subsurface geometry models and checked against local geologic data from wells and surface mapping. The resulting 3D models will be compared to other potential field inversion results to identify any geometric consistencies/inconsistencies. PNNL's joint inversion of MT/CSEM data is expected to combine the high-resolution imaging capability of CSEM (e.g., Darnet et al., 2020) and deep imaging capability of MT (e.g., Hardwick et al., 2015).

4. Progress Report

4.1 Gravity Surveying

A total of 260 new gravity stations from this study were added to 279 stations collected during the Nevada PFA study (Hinz et al., 2020). These 539 modern gravity stations were combined with 1,453 legacy gravity stations in the area to achieve better coverage in and around Steptoe Valley basin (Figure 6). Station spacing on valley transects is 500 m and later increased to 1 km for fill-in of other areas. Legacy gravity data was sourced from Pan-American Center for Earth and Environmental Studies (PACES). Field measurements were made using two Scintrex CG-5 gravimeters following the methods of Gettings et al. (2008); we used a 10-minute time series with reoccupations of local and regional bases. Elevation control on most of the stations is better than 0.1 m, which was achieved through post-processing of high-precision GPS data, resulting in a gravity accuracy of better than 0.03 mGal. The Complete Bouguer Gravity Anomaly (CBGA) was computed using a reduction density of 2.67 g/cm^3 and the formulas outlined by Hinze et al. (2005) followed by calculations of the horizontal gravity gradient.

The CBGA map shows that the dominant basin signal trends in a north-south orientation. This prominent, north-trending, -35 to -40 mGal gravity low is approximately 8 to 10 km wide and is bounded by gravity highs to the east and west. This gravity low is widest in the vicinity of the left stepover near Cherry Creek Hot Springs identified by Hinz et al. (2020) and contains the lowest CBGA value in the vicinity (-250 mGal). The gravity signal is asymmetrical, with the largest changes in the gravity field located on the west side of the valley as indicated by the increased horizontal gradient of the CBGA. These large gradients on the west side of the basin are interpreted as the gravity signature of steep changes in basement topography delineating the major east-dipping normal fault system along the western margin of Steptoe Valley (Hinz et al., 2020).

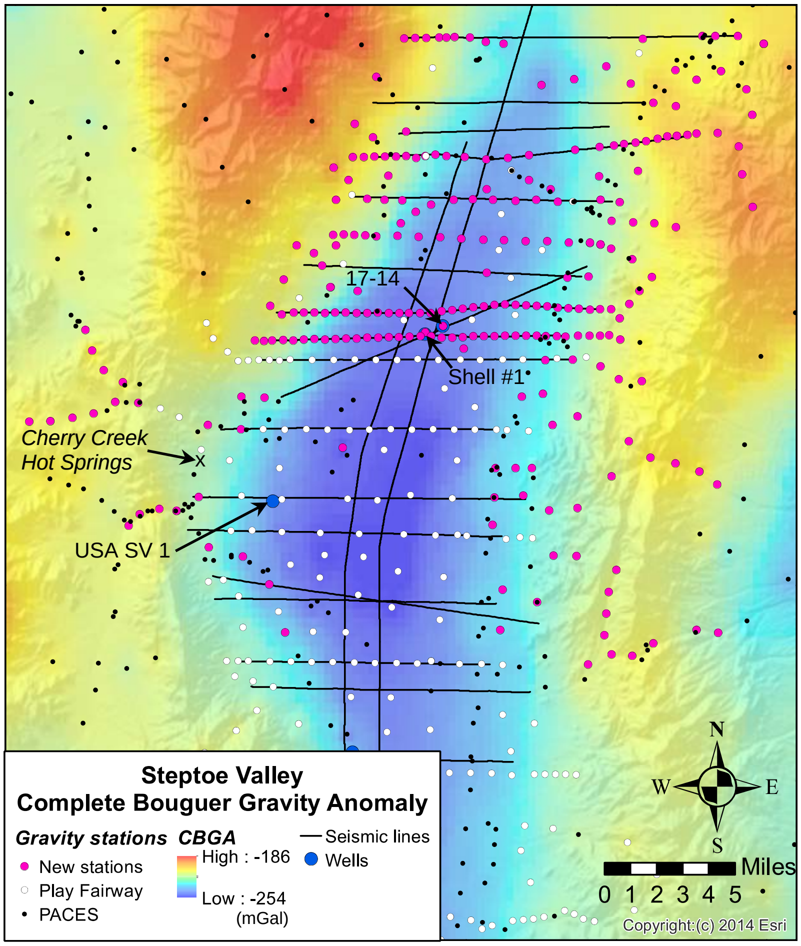

Figure 6: Preliminary CBGA color map of northern Steptoe Valley, with cooler colors (e.g., blue) delineating areas of basin sediment fill and warmer colors (e.g., red) indicating dense bedrock exposed in the surrounding mountain ranges. Gravity survey coverage is overlain with locations of new stations collected during this study (magenta circles), stations collected as part of Nevada PFA (white circles; Hinz et al., 2020), and stations from the PACES database (black dots). Locations of legacy seismic profiles (black lines) and exploration wells (blue circles, labeled with well names) are also shown.

4.2 Geochemical Sampling

Water samples were collected from 12 cold springs in northern Steptoe Valley in September 2021 (ST-1 – ST-12; Figure 7) to evaluate possible mixing relationships between the known thermal springs (e.g., Monte Neva hot springs and Cherry Creek springs) and to see if other chemical indicators of thermal fluids might be detectable in the cold springs. Detection of thermal fluids in these cold springs is not expected because developed stratigraphic geothermal systems in the world are typically not associated with surface manifestations (e.g., Rühaak et al., 2010; Ćubrić, 2012; Flechtner and Aubele, 2019). Given the abundant structural settings along this basin that are prospective for hosting deep circulation geothermal systems, however, these geochemical surveys provide guidance on the presence or absence of previously unknown deep circulation geothermal resources in this basin. Analysis of the fluids thus far indicate that all sampled cold springs have neutral pH, are relatively low salinity (conductivity < 600 µS/cm), and are calcium-magnesium-bicarbonate dominated (Figure 7b; Table 1).

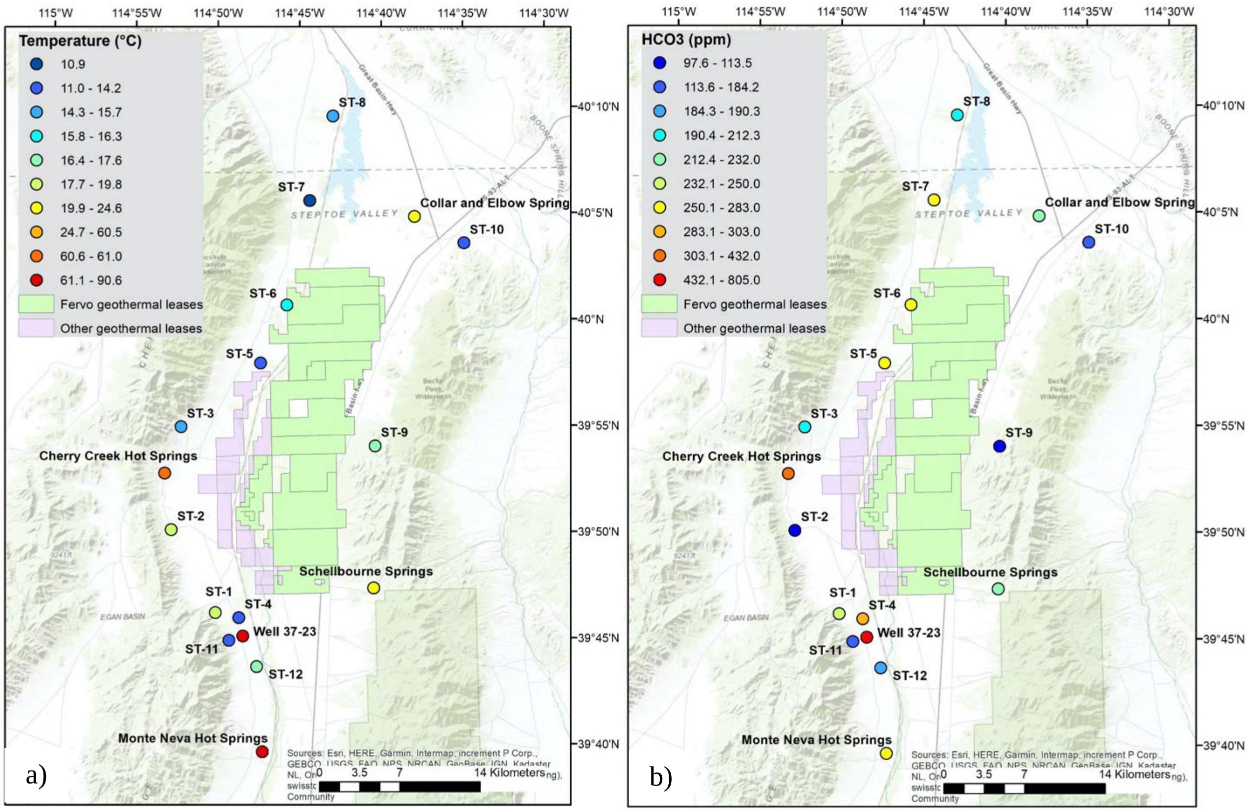

Figure 7: Locations of newly sampled springs (sample IDs preceded by 'ST') and other springs; a) measured temperatures and b) bicarbonate concentrations.

Table 1: Chemical and isotopic composition of new water samples.

Sample	Date	Temp °C	pH	Li ppm	Na ppm	K ppm	Ca ppm	Mg ppm	SiO2 ppm	B ppm	Cl ppm	F ppm	SO4 ppm	HCO3 ppm	Cond µS/cm	d18O ‰	dD ‰
ST-1	9/14/2021	19.0	7.33	0.0048	6.62	1.13	54.5	24.9	11.1	0.036	3.5	0.1	18.9	248	404	-16.28	-123.4
ST-2	9/14/2021	19.8	7.7	0.014	16.75	1.21	26.7	4.5	24.7	0.035	3.4	2.28	25.2	98	223	-15.9	-121.4
ST-3	9/14/2021	15.7	7.57	0.0141	11.4	2.68	89.4	28.4	11.5	0.05	4.5	0.24	151	212	596	-16.13	-124.1
ST-4	9/14/2021	14.2	7.47	0.0067	9	1.24	65.7	28.1	13.4	0.042	4.5	0.1	21.9	294	464	-16.2	-123.6
ST-5	9/15/2021	14.0	7.83	0.0161	7.16	1.59	60	23.5	15.9	0.036	2.2	0.1	10.6	273	415	-16.17	-122.8
ST-6	9/15/2021	16.3	7.57	0.0058	5.67	1.3	57	24.6	15.6	0.032	2.7	0.04	9.9	278	425	-16.73	-126.6
ST-7	9/15/2021	10.9	8.3	0.0056	9.49	1.29	62.2	24.2	14.4	0.043	4.8	0.11	20.8	283	449	-16.62	-126.8
ST-8	9/15/2021	15.5	7.74	0.005	9.75	1.56	42.2	20.4	27.6	0.03	3.2	0.07	11.2	212	342	-16.78	-127.1
ST-9	9/16/2021	17.6	7.58	0.0071	17.75	3.11	26.7	5.36	45.4	0.049	7.2	0.15	10.7	113	227	-15.73	-121.7
ST-10	9/16/2021	13.4	7.5	0.0099	21.4	2.9	50.9	8.84	38.0	0.083	19.8	0.25	23.5	179	384	-15.36	-120.6
ST-11	9/17/2021	13.4	7.26	0.0046	6.89	1.22	51.1	10.7	13.1	0.035	4.2	0.1	20.4	184	327	-15.58	-119.7
ST-12	9/17/2021	17.0	7.85	0.0066	10.05	1.32	38.4	15.75	14.9	0.038	5.6	0.08	11.1	190	320	-15.54	-119.4

Measured spring temperatures at the 12 sites range between 10 to 20°C. The water samples are chemically distinct from the Cherry Creek Hot Springs as well as a sample previously collected from the 37-23 geothermal exploration well (Figure 8; Hinz et al., 2020). However, the fluids generally align along a mixing trend for some solutes and share chemical characteristics associated with Monte Neva Hot Springs fluids. This may suggest a common formation process and/or depth of circulation in the basin (Figure 8). Further work will be conducted as this study progresses to evaluate potential fluid mixing relationships and how these relate to conceptual modeling of fluid flow in northern Steptoe Valley.

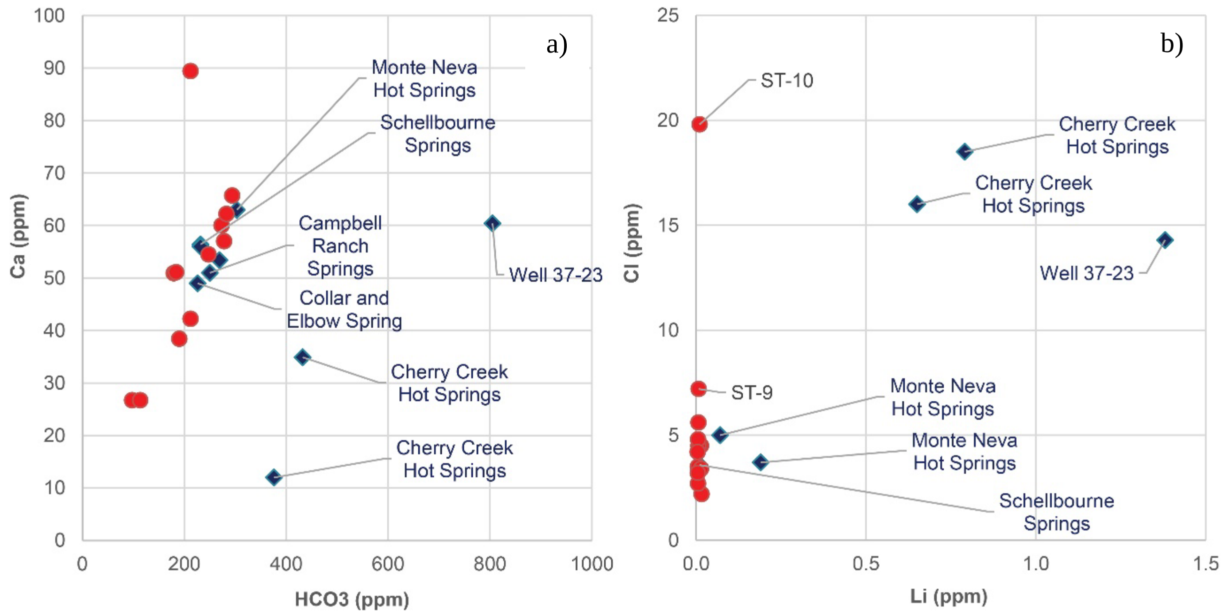

Figure 8: Cross plots of major element chemistry for water samples; a) Ca vs HCO3 and b) Cl vs Li. Red dots are from samples collected during this study and blue diamonds are from existing data.

4.3 Upcoming Geophysics

A high-sensitivity aeromagnetic survey vehicle will be utilized to collect magnetic field data along critical transects in northern Steptoe Valley. This magnetic data will be combined with gravity data for joint inversion models along the existing seismic profile lines. MT/CSEM surveying shall also be conducted along select gravity, aeromagnetic, and/or seismic profiles (Figure 9). The legacy seismic profiles will also be reevaluated for interpretation.

5. Characterization Strategy and Implications

This study builds on the PFA results and utilizes a confluence of applied geoscientific methods to demonstrate the efficacy of advanced geophysical imaging, 3D geologic mapping, and conceptual resource modeling in characterizing stratigraphic geothermal resources. Implications both to and from analogous geothermal systems are also being evaluated.

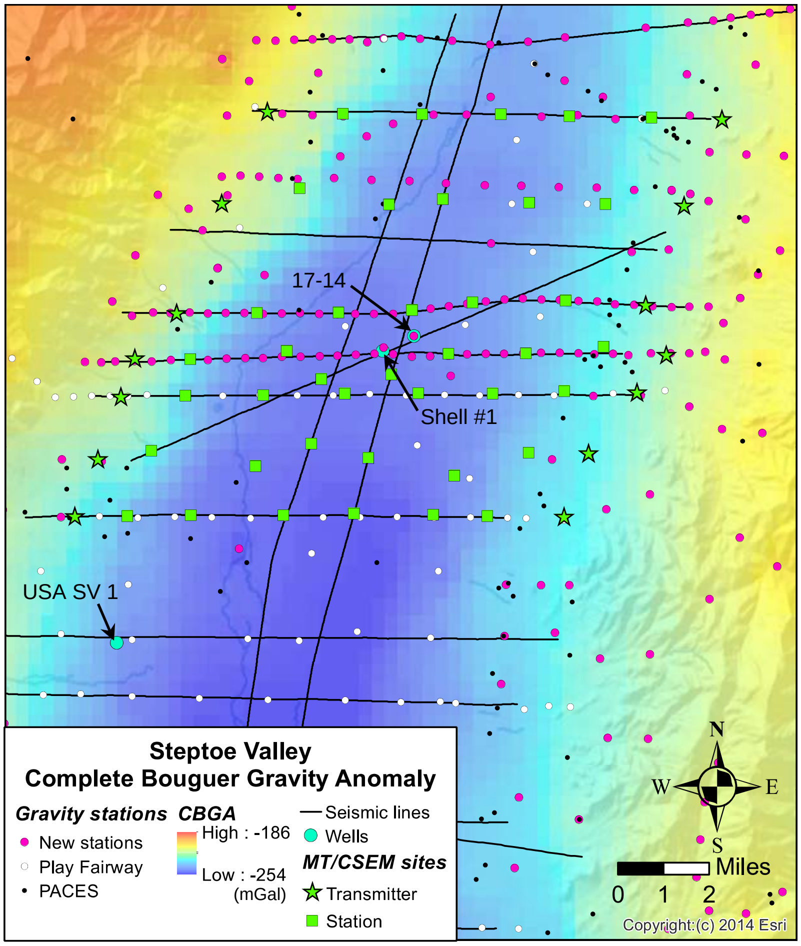

Figure 9: Planned locations of MT/CSEM transmitter and receiver locations plotted on the CBGA map adapted from Figure 6. Station spacing is approximately 2 km, though there are spacing irregularities designed around site access issues and to mitigate impacts from cultural features (i.e., artificially induced electromagnetic interference).

5.1 Geophysical Imaging

Jointly modeled gravity/magnetic datasets and MT/CSEM datasets, combined with re-interpreted legacy seismic data, are expected to provide robust imaging results to depths of 2 to 4 km in northern Steptoe Valley. The results will be calibrated for interpretation using lithologic logs of local wells and physical rock properties of local well data and analogous deep basins, as needed. Density-depth relationships for basin fill and rock density values will be taken from existing well logs and laboratory-measured physical rock properties of field samples and drill cuttings. Calibrated physical rock property values will then be used in subsequent 2D joint inversion models to develop a depth-to-basement map consistent with interpretation of existing seismic line profiles.

Regarding the electromagnetic techniques, we developed forward and inverse models using MT and CSEM methods at Steptoe Valley to explore depth sensitivities and survey design (Jaysaval et al., 2021). Modeling suggests that the MT method recovers resistivity structures of the shallow subsurface (i.e., the basin) based on generalized geological and geophysical parameters. MT is less robust at recovering the relatively conductive geothermal reservoir and in accurately resolving depth/thickness of the related geologic layers. On the other hand, the CSEM modeling indicates better resolution in the deeper subsurface, particularly in recovering the depth/thickness in resistivity structures, as well as resolving the relatively conductive geothermal reservoir 2 to 4 km deep. Based on this survey design analysis, MT and CSEM data will both be collected using a receiver grid spacing of approximately 2 km and CSEM transmitters on the east/west ends of the receiver grid (Figure 9). Inversion and interpretation of MT/CSEM data will be performed using a massively parallel 3D CSEM/MT modeling and inversion code (Jaysaval et al., 2021).

5.2 Geologic Mapping and Resource Modeling

A 3D geologic map of the northern part of Steptoe Valley was developed from previous work in Steptoe Valley (Figure 10; Hinz et al., 2020). Interpretation of 2D seismic reflection profiles, 2D geologic cross section, 2D forward models of potential field data will be integrated with surface geologic data to build the 3D structural and stratigraphic framework similar to established 3D geologic mapping methods (Siler et al., 2019). Key parameters of the structural and stratigraphic architecture that may relate to the sedimentary-hosted geothermal system will be constrained. These parameters will include geometry, lateral extent, depth, and volume of relatively intact (un-faulted) Paleozoic basement blocks. Geometry and location of faults and fault intersections that may contribute to secondary permeability, or alter primary permeability, will also be incorporated.

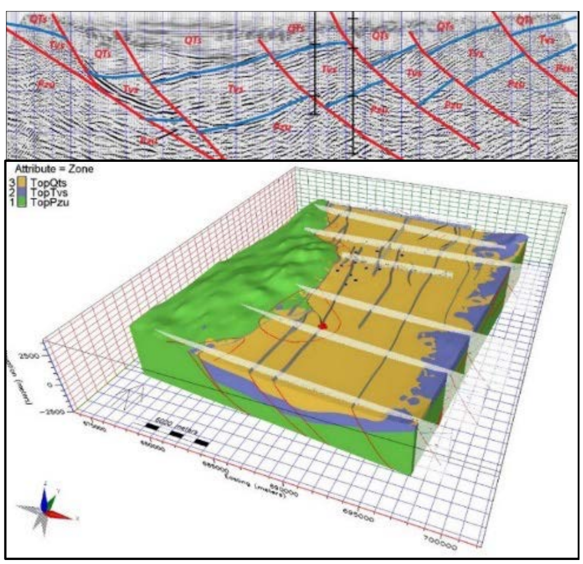

Figure 10: Interpreted seismic profiles used to constrain and develop a 3D geologic map of Steptoe Valley; figure adapted from Hinz et al. (2020).

The team’s combined expertise in reservoir engineering and geomechanics will be applied to further refine modeling and estimation of the northern Steptoe Valley stratigraphic resource. Applying a range of well spacing patterns and development scenarios will improve resource capacity and power density estimates. The approach employs 3D reservoir simulation that integrates detailed wellbore models, discrete fractures, flow/heat transfer in fractures and matrix rock, and mechanical deformation of fractures (e.g., McClure and Kang, 2017). Model inputs will consist of measured rock properties from this work and previous studies in conjunction with regional analogues.

5.3 Analogous Geothermal Systems, Conceptual Modeling, and Power Capacity Estimates

Data are being compiled and reviewed for developed analogue stratigraphic resources (e.g., Rühaak et al., 2010; Ćubrić, 2012; Vidal and Genter, 2018; Flechtner and Aubele, 2019) to guide selection of parameters for the power capacity estimates of Steptoe Valley. The next step will be conceptual modeling of the resource by integrating the geologic, geophysical, and geochemical data compiled in this study. The final step will be to complete a power capacity estimate for the sedimentary-hosted resource in Steptoe Valley using analogue-based power density and/or volumetric methods.

6. Summary and Outlook

A comprehensive geophysical imaging project, founded upon previous PFA studies and constrained by geological and geochemical information, is underway in northern Steptoe Valley. This site represents a potential archetype of sedimentary-hosted geothermal energy resources that are estimated to be prolific across the Great Basin and likely exist within other basins in similar stratigraphic/tectonic settings. Gravity and geochemical surveys are complete and preliminary results suggest the presence/mechanisms of structural controls that are common to Great Basin hydrothermal systems are also pertinent to the stratigraphic resource in northern Steptoe Valley. Additional work, including aeromagnetic and MT/CSEM surveying in the field and review of legacy seismic profiles, are being conducted to apply joint inversion and integrated interpretation techniques that are expected to provide robust imaging of the subsurface to depths of 2 to 4 km. Advanced techniques in 3D mapping, thermal-hydrological reservoir modeling, and geothermal resource estimation will leverage these geophysical results to assess the resource geometry and energy potential.

The completion of this project is intended to establish a decision point for follow-on work in northern Steptoe Valley. The next foreseeable and crucial step in exploration of the site is to calibrate the resulting geological/thermal-hydrological model with stratigraphic reservoir data from at least one new, targeted vertical well. This geophysical imaging and modeling project will provide a basis for optimal well targeting. From the sedimentary-hosted resource perspective, it will also be essential to identify and target a lateral horizon suitable for reservoir stimulation/production. Decisions on the specific design aspects of this well (e.g., location, depth, bottom-hole diameter, completion, drilling method) and logging/test protocol to measure reservoir parameters (e.g., core/cutting analyses, well logs, diagnostic fracture injection testing), balanced with non-technical considerations, will be informed by the completion of this study.

Acknowledgements

This material was based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of Technology Development, Geothermal Technologies Office under the FY2020 Hydrothermal Imaging Lab Call. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. Access to Public Lands was authorized in coordination with representatives of the United States Bureau of Land Management. The authors thank: Barbi Harmon and the team at Kautz Environmental Consultants, Inc. for assessing and ensuring compliance with respect to cultural resources, Chet Lide of Zonge International, Inc. for the guidance and consultation to conduct the electromagnetic surveying, and Kirsten Chojnicki of PNNL for researching and compiling fundamental background information needed for this project.

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