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Resource Evaluation Case Study for Surprise Valley, California

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ABSTRACT

Warner Mountain Energy (WME) sited, drilled, and flow tested an exploratory well (well WME-E1) in Surprise Valley, Modoc County, California which was successful in finding and characterizing a commercial grade geothermal resource. The resource is hosted in the Surprise Valley Known Geothermal Resource Area (KGRA) near the Surprise Valley Hot Springs resort (SVHS) which has great geothermal potential and has been studied for many years. Currently, the SVHS area utilizes shallow geothermal resources for space heating and balneology. Well WME-E1 was drilled into a deeper and hotter resource and was flow tested. A highly permeable and productive feedzone was encountered within fractures at ~2300 feet below ground surface (bgs). Downhole flowing temperature was 225 °F (liquid) and the maximum static downhole temperature was 230.5 °F. Reservoir permeability is extremely high. Under wide open flow, the well delivers 500 gpm of self-sustained artesian flow at a wellhead pressure of 1 psia. Data were analyzed and used to develop and calibrate a numerical model using TETRAD simulation software. Forecasts from the calibrated numerical model show that with additional wells, much higher levels of production are achievable and sustainable. This paper describes the analyses and simulation techniques used, their results and implications on the resource size and potential.

1. INTRODUCTION

Surprise Valley is in northeast California, eastern Modoc County, and east of Alturas. Locals refer to the area as the Tricorner Region because of the region's location at the intersection of California, Oregon, and Nevada state lines. The area is part of the Great Basin that extends across most of the northern half of Nevada. Most of the valley is over 4,000 feet above mean sea level and could be characterized as a high altitude desert valley. The Warner Mountains are located on the west side of the valley and the Hays Canyon Range is located on the east side of the valley. Communities in Surprise Valley include Eagleville, Cedarville, Lake City and Fort Bidwell. The project site, referred to as "Surprise Valley Hot Springs", is located five miles east of Cedarville and 20 miles east of Alturas in Modoc County, California.

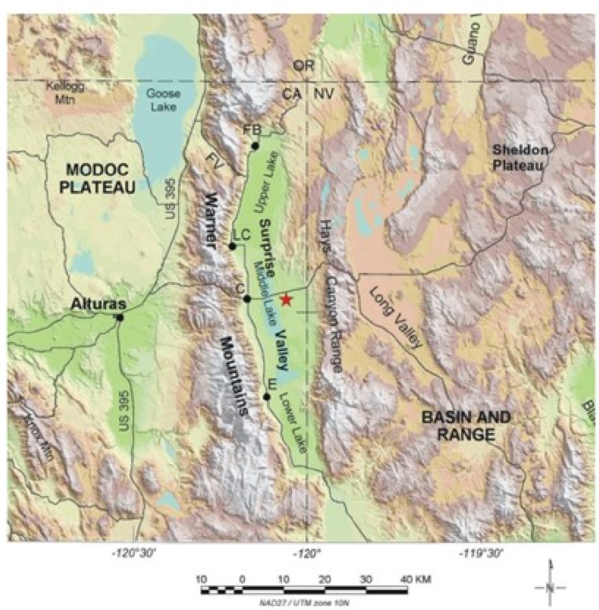


Figure 1: Surprise Valley area map, the red star denotes location of Surprise Valley Hot Springs

The study area is on about 800 acres of private land and includes the surficial property surrounding the Surprise Valley Hot Springs resort. The landowners hold geothermal rights. Figure 2 shows a Bureau of Land Management map of the general project location as located within Township 42 N, Range 17 E, Section 06, Modoc County, Mount Diablo Meridian; private lands are shown with a white background, public lands are shown with a gold background.

Figure 2: Surprise Valley project land map

In 2014, the California Energy Commission (Energy Commission) funded Modoc County to conduct geothermal exploration at the Surprise Valley site under grant GEO-14-003. This project included extensive geothermal exploration data collection, logistics, and analysis (two-meter probe temperature gradient survey; soil gas survey; shallow temperature probe augering; magnetotelluric survey; shallow seismic survey; geochemistry sampling and analysis; drilling of three temperature gradient wells and well logging). In addition, the project included an economic feasibility study.

Temperature gradient drilling results showed favorable and consistent results amongst all three wells and therefore warranted a further project to conduct targeted deeper drilling and well testing. Based on the results of the 2014 study, the Energy Commission funded Modoc County in 2016 under grant GEO-16-005 to conduct exploratory drilling to further investigate the geothermal resource characteristics of the Surprise Valley geothermal field. The purpose of this project was to drill a deep (nominally 3600 feet bgs) geothermal exploratory well to obtain further knowledge about subsurface temperature, geology, and fracturing at greater depths in the Surprise Valley geothermal field. Ultimately, the new data would provide the necessary data to estimate reservoir capacity and characteristics through well testing and reservoir modelling.

The exploratory well (WME-E1) was successfully drilled and completed to a depth of 3605 feet bgs. Mud logging, geophysical logging (temperature, caliper, natural gamma, acoustic borehole televiewer), static and dynamic pressure/temperature/spinner logging, short-term flow testing, brine and steam sample collection, and reservoir modeling tasks were performed. Geothermometry analyses indicate higher temperature potential than the temperature encountered in WME-E1, which could be the deep source for the currently drilled reservoir. Thus, deeper drilling is recommended because it could reveal a hotter, deeper reservoir and will facilitate characterization of the complex geological controls on the Surprise Valley geothermal system.

The numerical model quantitatively shows that the Surprise Valley geothermal field can sustainably support the well WME-E1 at its maximum artesian flow capacity in the long-term. Further, the numerical model shows that with additional production and reinjection wells, the resource can sustainably support much higher levels of production. The productivity index (which is directly related to permeability) of WME-E1 is among the highest seen in the geothermal industry. The reservoir supplying WME-E1 is an intermediate depth and highly productive system which makes it attractive for development. Well WME-E1 is capable of commercial grade electrical energy production at a relatively shallow depth of ~2300 feet bgs.

2. EXPLORATORY DRILLING

2.1 Drilling Operations

The drilling was initiated on May 15, 2019 and completed on June 8, 2019. Drilling activities proceeded uneventfully until fluid temperatures reached 140°F at which point a mud cooling system was installed. A minor lost circulation zone was encountered at a depth of 1835 to 1900 feet bgs, but circulation was regained. A second lost circulation zone was encountered at 2355 feet bgs with no success at regaining circulation after many attempts. Seven-inch casing was placed and cemented from the surface to 2325 feet inside of the 9 5/8" surface casing. Circulation was never regained, and blind drilling continued to total depth at 3605 feet bgs. The well, WME-E1, was completed with 5" liner, hung from 2276 to 3605 feet with slotted screen liner from 3261 to 3567 feet.

2.2 Mud Logging and Geophysical Surveys

General lithology of the well included alluvium and lake sediments from 0 to 115 feet followed by alternating zones of andesite, welded tuff, and basalt from 115 feet to the area of lost circulation at 2355 feet. Drill cuttings were not obtained in the zone of lost circulation. However, several small chips of peridotite-serpentinite were retrieved from WME-E1 while raising a geophysical logging tool. Geophysical logging of WME-E1 was conducted immediately following drilling by Colog, Inc. and supervised by WME, Temple University (Nick Davatzes), and the U.S. Geological Survey (USGS) team. Geophysical data analyses indicate the presence of several prominent fault zones with a wide range of attitude, with the majority dipping 60°- 90° and a maximum horizontal compressive stress state that is slightly mis-aligned with the strike of regional faults and localized dike structures. This may indicate a local stress state associated with a step in a magnetic anomaly where WME-E1 is located.

Table 1: Well Lithology

Depth (ft. bgs)	Description
0-115	Gravel, clay, siltstone, sandstone, sand, and shale with quartz, calcite, pyrite, and hematite.
115-600	Andesite with quartz, calcite, pyrite, hematite, chlorite, and anhydrite. Fractures noted between 300-400 feet.
600-860	Welded tuff, clay, tuff, claystone, sandy clay, and claystone with minor quartz, pyrite, and chlorite.
860-1070	Basalt with minor quartz, calcite, pyrite, hematite, and chlorite. Fractures noted between 920-970.
1070-1170	Andesite with clay. Quartz, calcite pyrite, chlorite.
1170-1380	Basalt with quartz, calcite, minor pyrite, hematite, chlorite.
1380-1430	Tuff, basalt, lithic tuff. Opal
1430-1460	Basalt
1460-1900	Tuff, lithic tuff, clay, rhyolite (1850-~1900). Fracture from ~1840-1900. Quartz, calcite, pyrite, hematite, chlorite, anhydrite. Losing mud circulation at 1835-1900.
1900-2355	Basalt with quartz, calcite, pyrite, hematite, chlorite, trace anhydrite
2355-3605	Total loss of circulation. Drill blind to bottom hole. Four 4000-gallon water trucks running 24/7. Carbon dioxide gas present in varying levels. Drilling ceased at 3605.

2.3 Geothermometry

Geothermometry estimates of reservoir (or deep source) temperatures are presented in Table 2. For a point of reference, previous geothermometry estimates from WME temperature gradient well #2 ("WME-TG2") and the Surprise Valley Hot Spring (SVHS) well are presented. The maximum measured downhole temperature in WME-E1 is 230.5 °F; maximum temperature in WME-TG2 is 215 °F; and maximum temperature in SVHS well is 217 °F. The Na-K-Ca and Na-K-Ca Mg geothermometry values are lower than measured temperatures in the wells but are similar to measured spring temperatures located near the wells. The Na/K (Fournier, 1979) and chalcedony conductive geothermometers result in equilibrium temperatures similar to measured downhole temperatures in all three wells.

2.4 Well WME-E1 temperature

Geothermometry from WME-E1 water chemistry indicates reservoir temperatures ranging from 194 °F to 289 °F. Temperature logging of WME-E1 after 60 days (August 8, 2019) of static stabilization showed a maximum temperature of 230.5 °F at a depth of 2000 to 2100 feet bgs. Flow testing data showed that WME-E1 is an artesian geothermal well with a stable (and unassisted) flow rate of ~500 gpm of liquid water at 225 °F inflowing in its 5" liner from a prolific feedzone hosted in fractures at ~2300 feet bgs. The flowing pressure drawdown was negligible indicating very high productivity consistent with the total loss of circulation at that depth. The range of geothermometer estimates of reservoir temperature extends to higher temperatures than encountered by WME-E1. Therefore, there is the potential for a higher temperature reservoir in a geothermal system deeper than WME-E1 (greater than 3600 feet bgs).

Table 2: Geothermometer Estimates

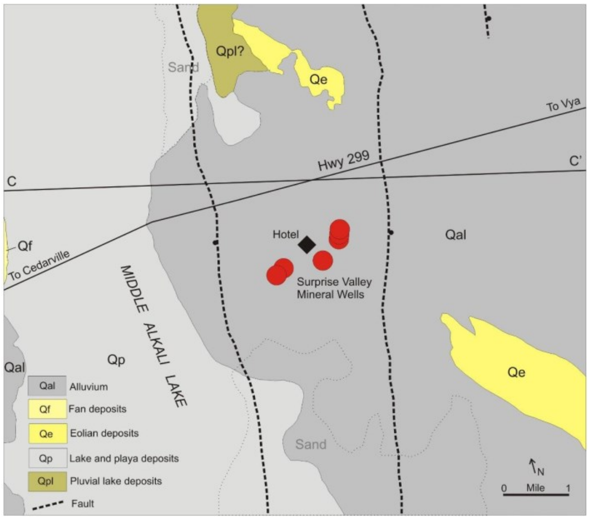
Geothermometer	Units	WME-E1 (3600 ft)	WME TG2 (929 ft)	SVHS Well (~200 ft)
Chalcedony conductive (Fournier, 1977)	°F	241	241	226
Quartz conductive (Fournier and Potter, 1982)	°F	289	275	275
Quartz adiabatic (Fournier, 1977)	°F	279	266	268
Na-K-Ca (Fournier and Truesdell, 1973)	°F	194	196	198
Na-K-Ca Mg corr (Fournier, 1978)	°F	194	196	198
Na/K (Fournier, 1979)	°F	243	225	226
Na/K (Giggenbach, 1988)	°F	280	262	264
K/Mg (Giggenbach, 1986)	°F	241	226	268

3. CONCEPTUAL MODEL

3.1 Geology

Geology and geothermal possibilities of the Surprise Valley has been studied since the 1970's with a substantial increase of research in the past decade. Recent research groups have included the University of California; University of Nevada, Reno; National Space and Aeronautics Administration (NASA); Stanford University; University of Central Washington; Carnegie-Mellon University; and the United States Geological Survey (USGS). Detailed geochemical and geophysical studies have been conducted, largely focusing on the west side of the valley to better understand how and where geothermal fluids flow through the subsurface (and create geothermal reservoirs) and which faults may affect the flowpaths of these fluids. Results of these studies indicate the potential for large-scale geothermal development exists in Surprise Valley. Scientists have identified some major fault structures and have estimated that the geothermal reservoir temperature throughout Surprise Valley is about 347 °F. Deep exploration wells have been drilled on the west side of the valley with the intent to develop a large-scale geothermal power plant. Out of 304 hot springs in the State, this project site, Surprise Valley Hot Springs, is listed as the third hottest at 208 °F with a total flow of about 3,000 gallons per minute. A 160-ft temperature gradient well at the Surprise Valley Hot Springs resort measured 217 °F.

The springs are located on a rather flat area which is covered by Quaternary (Holocene) alluvium (Qal) comprised of unconsolidated sedimentary deposits associated with modern sediments. This widespread unit overlies the Quaternary eolian deposits (Qe) (Holocene) which are comprised of eolian sand dunes, mostly stabilized as indicated by vegetation growth. Quaternary lake and playa (Qp) deposits (Holocene) which are evaporites and clay deposits in ephemeral lakes. The oldest unit in the area is Quaternary pluvial lake deposits. (Qpl) (Pleistocene) denotes the lake sediments deposited in Pleistocene Lake Surprise. These are primarily fine-grained sediments, often tuffaceous, but also include minor gravels and waterlain tuffs. The north-south trending faults are interpreted as rather deep-seated faults, however, they do not have significant vertical offsets along the cross-section. The westerly situated fault is interpreted to be west-dipping and cuts the Surprise Valley Fault at depth. The other fault, located easterly, is interpreted to dip to the east.



Red dots show the springs and wells. *Credit: Egger and Miller, 2011.*

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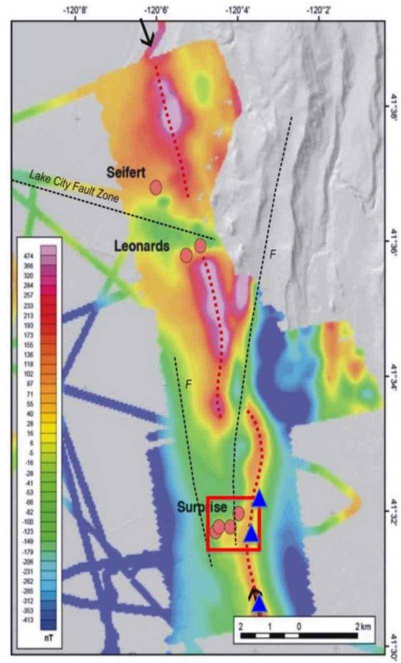

The red rectangle indicates the study area at Surprise Valley Hot Springs (SVHS, labeled Surprise on the figure). The orange circles denote the locations of hot springs. The red dotted lines and the black arrows indicate the linear magnetic anomaly that may play a role in hydrothermal system. The blue triangles are the locations of basalt outcrops observed in the area. Note that the hot springs lie along the magnetic anomaly, but also along the faults (F) that bound the eastern border of the valley. *Credit: Glen et al., 2013.*

Figure 3: Surprise Valley geologic maps showing interpreted fault locations and geophysical anomalies

3.2 Temperature Probe Survey

From May to October 2015 WME installed 123 soil temperature probes in the study area. Sixteen sites were surveyed in May, fifty-nine sites were surveyed in June, twenty-eight sites were surveyed in September, and twenty sites were surveyed in October. 25 shows locations of SV- and WME-subsets of soil probes and the results of the survey in October 2015. The highest measured temperatures were found adjacent to the hot springs. The warmest temperatures (>80 °F) trend northeast while the heat anomaly in the 70 °F range also extends in the same direction to the west of the 80 °F anomaly (26). These anomalies are consistent with the data obtained from aeromagnetic survey (Ponce et al., 2009) and field observations of basalt outcrops that altogether support a model where basalts and associated faulting, provide conduits for geothermal fluids.

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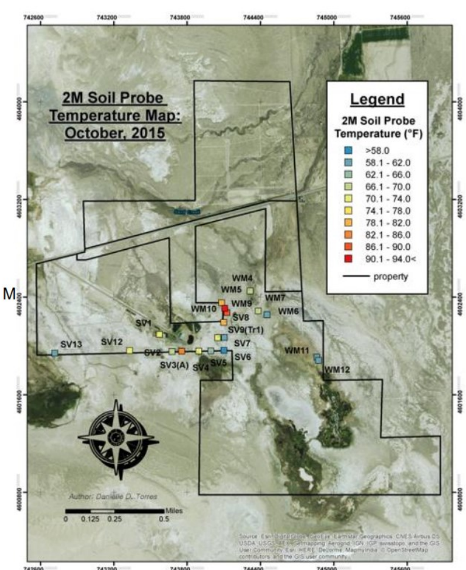
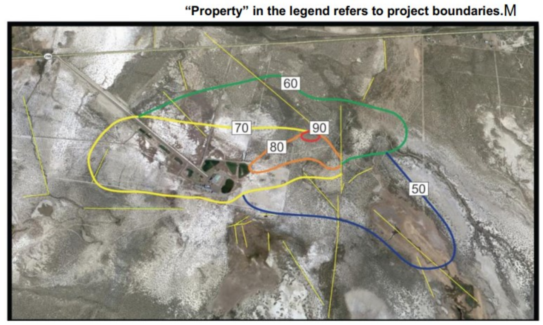


“Property” in the legend refers to project boundaries.M



Colors and respective numbers represent boundaries of the areas with the same average soil probe temperature (°F).

Figure 4: Surprise Valley 2-m temperature probe data

4. FLOW TESTING

The goal of flow testing well WME-E1 was to gather data needed for reservoir engineering analyses of the production responses of both the well and the reservoir. During the flow tests, the well was subjected to periods of static, dynamic, and transient conditions. The results of these analyses were used to quantify the well's production performance, to provide input parameters, calibration criteria and for the development of a numerical simulation model of the Surprise Valley geothermal reservoir. Once developed, the numerical simulation model provides a tool for making quantitative, long-term predictions of the resource's pressure and temperature response to production scenarios. The testing comprised of two flow periods and a long static period on WME-E1. First, a clean-out flow in June 2019 using air-lift without downhole surveys. Second, a flow test in July 2019 under self-flowing, artesian conditions (without air lift) with a dynamic downhole PTS survey. Third, after 60 days of stabilization, static downhole PT survey was taken in August 2019.

4.1 Clean Out Flow June 2019

The drilling of well WME-E1 was completed in early-June 2019. With the drilling rig still on the hole, WME-E1 was flowed on June 8, 2019. While flowing, the well was entered with open ended drill pipe to 1000 feet bgs. Air was pumped into the well via the drill pipe with the driller's air compressor to perform an air lift, which induces stronger flow. The wellhead was configured with a wellhead T which was connected to a flowline. The flowline discharged wide-open into an atmospheric flash vessel from which steam discharges vertically from three pipes while the liquid phase discharged horizontally. The liquid from the flash vessel flowed into a square-notch weir box, allowing the liquid flow to be metered through standard weir-flow equations. The configuration is shown in Figure 5, the photo taken while the well was undergoing air lift.

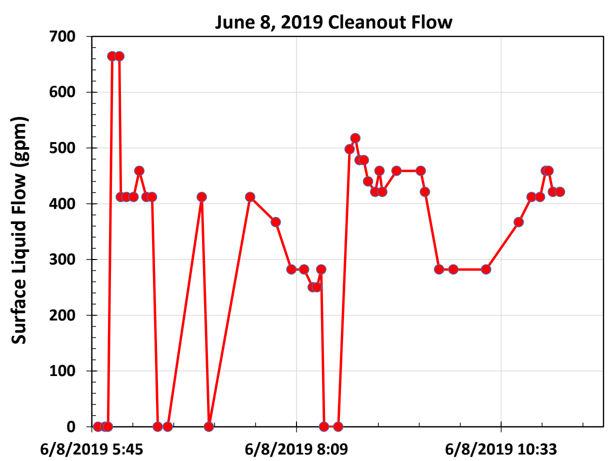


Figure 5: WME-E1 on June 8, 2019, during cleanout flow (with air lift)

A Geothermal Science, Inc. (GSI) reservoir engineer was on-site to guide the flow operations and manually collect data on the flow parameters. When the well was opened to flow, self-flow initiated immediately. The initial flow, as expected, was warm muddy water which cleared up and heated up over the course of two and a half hours. The well was then shut briefly to rig up the air compressor to drill pipe, and to initiate running into the hole with open-ended drill pipe. With drill pipe at 1000 feet bgs, the well was air lifted for one hour (starting at 8:15am) during which the flow rate increased to 450-500 gpm (see Figure 5). After the air lift, the well was producing nearly clear fluid which had heated up from 145 °F to 210 °F at the surface, reaching boiling point and visibly producing steam from the atmospheric flash vessel. The surface liquid flow rate during the cleanout flow is shown in Figure 5. WME-E1 flowed immediately on self-flow upon opening the flowline valve, and flow was maintained after the air lift was stopped, showing that the well is artesian. With air lift, the flow rate increased to 450-500 gpm, and fell to 290 gpm when air lift was stopped. Flow was restricted due to 1000 feet of drill pipe in the well. As the drill pipe was pulled from the well, the flow steadily increased to 410 gpm. Note that 10 feet of drill pipe remained in the well (through the wellhead) restricting flow, and the configuration did not allow downhole surveys in the flowing well.

4.2 WME-E1 Flow Test July 13, 2019

After the cleanout flow, the drilling rig was moved off site and well WME-E1 was left idle to allow time for further reservoir heatup, while planning and logistics were underway for a post-cleanout flow test. The flow test would be conducted fully open (with drill pipe removed) and the wellhead to be equipped to accommodate downhole surveys via a lubricator. The flow test data collection goals were to quantify wide-open flow, confirm self-sustaining flow, perform a multi-pass dynamic pressure-temperature-spinner (PTS) survey, run a static pressure-temperature (PT) survey 24 hours after end of flow (for pressure transient/recovery), and conduct an additional static PT survey 30 days after end of flow (temperature recovery August 10, 2019), to confirm full heatup.

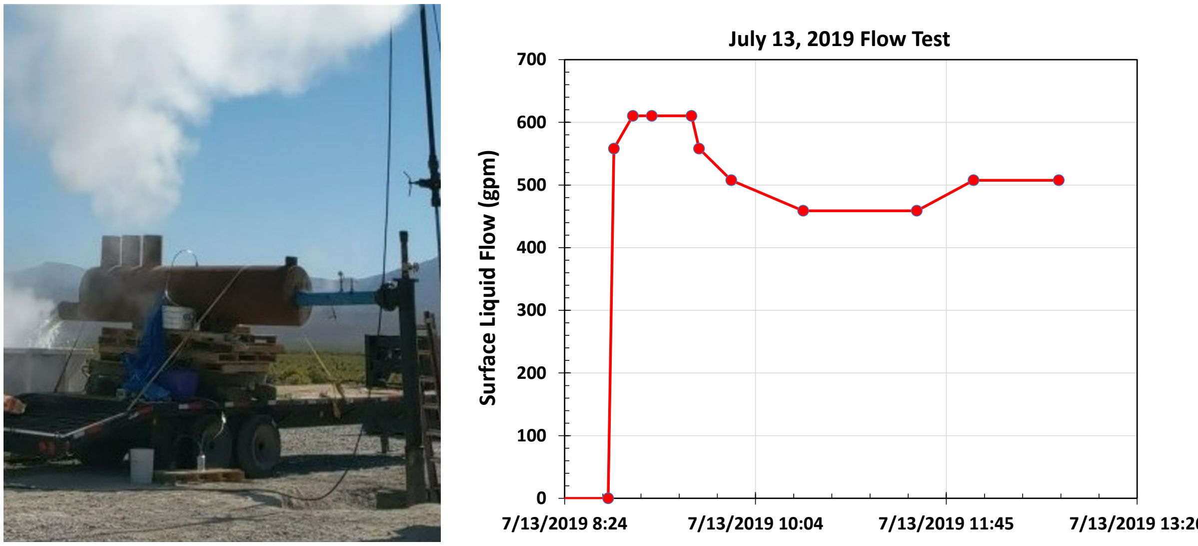


Figure 6: WME-E1 on July 13, 2019, during flow test (artesian flow)

The flow equipment and configuration for the July 13, 2019 flow test is shown in Figure 6. Some minor modifications were made to the flash vessel to accommodate both the absence of the drilling rig and to have the connections needed for the survey company to attach their equipment and enter the well. The flow test was conducted in accordance with the program above.

The flow test operations were carried out successfully and the results are summarized below. Well achieved stabilized wide-open flow of 500 gpm, see Figure 6, which was higher than the stabilized flow of 410 gpm achieved in the cleanout flow in June 2019. The increase in flow is due to the well being flowed without being restricted by drillpipe in the hole, and from the additional heatup of the well while static between flow periods.

Flowing Survey: wide-open flow at 500 gpm 225 °F water enters well at approximately 3200 feet (but is flowing down behind pipe from ~2300 feet). A high permeability, highly prolific reservoir was encountered at approximately 2300 feet containing liquid water at 225 °F to 230.5 °F (the zone at 2300 feet continued to heatup after the flow test and reached 230.5 °F by the August 10, 2019 static temperature survey). A less prolific reservoir zone was also encountered at 3280 feet which contributes less than 20% of the total flow and is approximately 222.8 °F liquid water. As shown in Figure 7 there was 8 psi of pressure drawdown for 500 gpm of surface flow (approximately 510 gpm of pre-flash liquid) making the productivity index (PI) ~65 gpm/psi, which is very high and ranks among the highest levels seen in the geothermal industry.

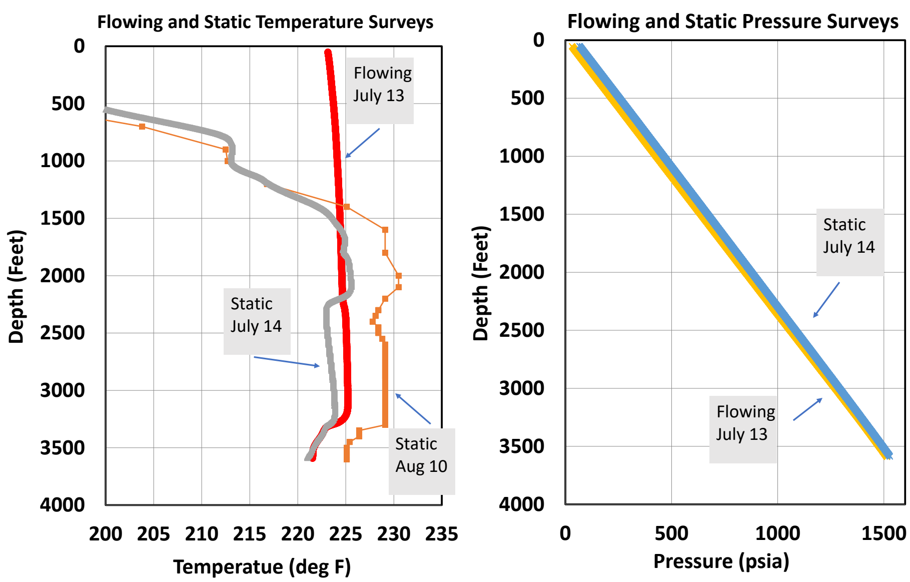


Figure 7: WME-E1 overlay of downhole Temperature and Pressure Surveys

5. NUMERICAL RESERVOIR SIMULATION

The primary objective of a reservoir study is to develop a means to make quantitative predictions of future reservoir conditions and production characteristics for various development options. At Surprise Valley, as with all geothermal reservoirs, the reservoir properties are known to vary within and around the reservoir in a three-dimensional manner. Presently, at Surprise Valley, because there is only one deep well, a numerical model had to be built using data collected and filling in data gaps by using analogy to other geothermal systems which are believed to be similar.

Reservoir simulation is a technique that allows these variations to be represented in a more rigorous way than other analysis techniques (Aziz and Settari, 1979). The simulation software can digitally represent the entire reservoir including the variations in rock properties described in the conceptual model, including flows into (deep source) and out of the geothermal system (surface discharges). The locations of existing and proposed wells, production flows, and reinjection flows are also represented digitally. The simulation software is used to predict the effects of different development options.

Over the past three decades, reservoir simulation has become the predominant method by which geothermal reservoirs are analyzed and predictions about the future state of a reservoir are made. The published literature contains hundreds of successful case studies of the application of geothermal simulation to geothermal reservoirs. The geothermal industry has accepted reservoir simulation as the best practice in analyzing geothermal reservoirs. The application of reservoir simulation at Surprise Valley is believed to be the best method in generating forecasts of future reservoir behavior.

The reservoir simulation software TETRAD has been selected and used for the numerical modeling of Surprise Valley. TETRAD is a three-dimensional, single or dual porosity, multi-phase, multi-component, thermal, finite-difference simulator (Vinsome and Shook, 1993). In the geothermal industry, TETRAD is widely used by operating companies, consulting firms, and research organizations. Additionally, a published research study by a U.S. based national laboratory concluded that TETRAD provides valid solutions to the complex equations in geothermal applications (Shook and Faulder, 1991).

5.1 Development of the numerical model grid

Figure 8 shows the extent of the Surprise Valley numerical model simulation grid domain within a topography map. The model covers an area of five-by-five miles and is centered on the surface location of well WME-E1. The model grid is aligned north to south (i.e. it is not rotated), making the grid in approximate alignment with the predominate fracture orientation in the region (generally north-south). Figure 8 also shows an aerial view of the numerical model grid with a satellite image of the region.

The area of the model was chosen by balancing two considerations. First, the model domain was made large enough to enclose an area such that modeling of the edges (boundary conditions) of the model would not have a significant effect on the model. Second, the model domain, and individual grid divisions, were made so that the number of cells was not so large that computational times became unreasonably large. The model contains 18 layers extending from ground surface +4500 feet RSL to a depth of -4920 feet RSL. Each layer contains 3,200 gridblocks. The ground surface was modeled as flat because the topography of the project area and its surrounding area is nearly flat. The complete simulation grid has 57,600 gridblocks. Figure 9 shows a three-dimensional view of the numerical model grid.

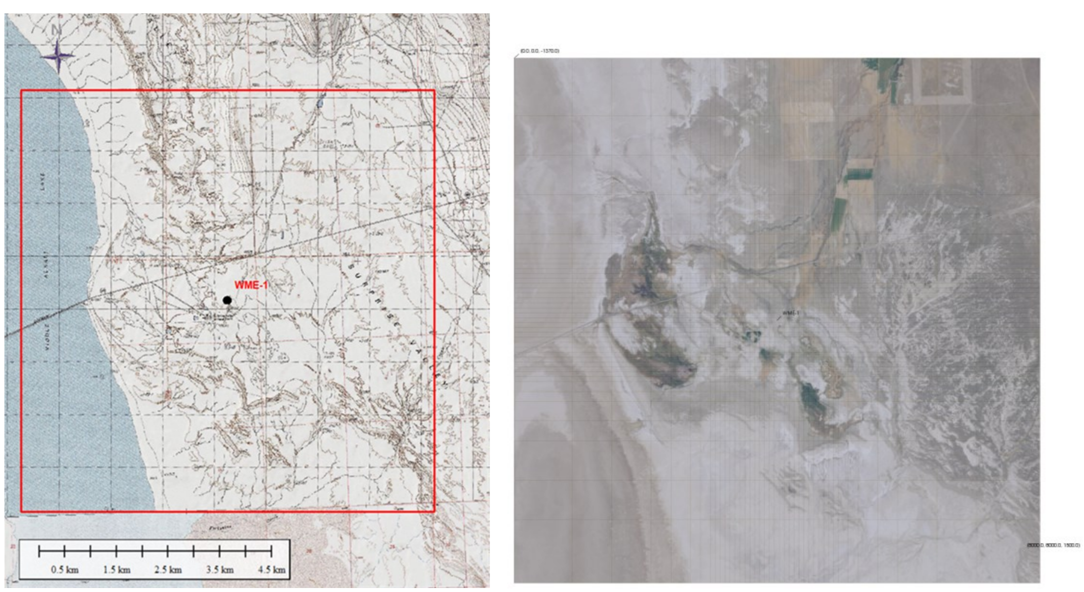


Figure 8: Extent of Numerical Model Grid

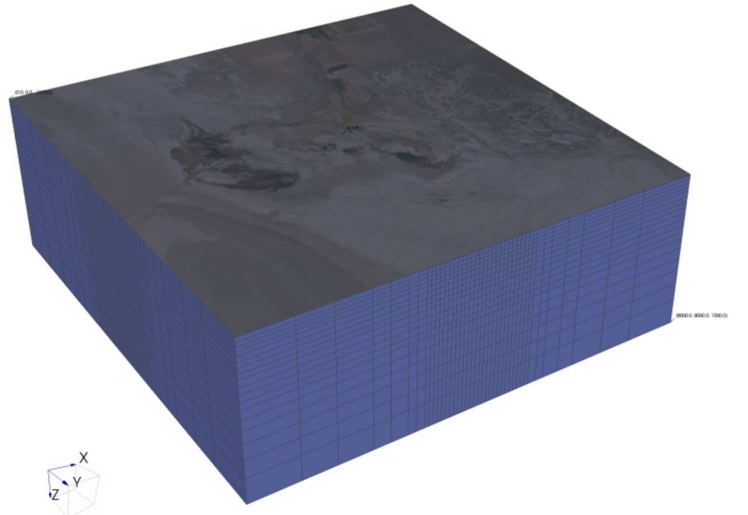


Figure 9: Three-Dimensional view of the numerical model simulation grid

5.2 Conceptual Model Converted to a Numerical Model

The starting point and fundamental basis for the Surprise Valley numerical model is a conceptual model of the overall geothermal resource. Because the flow within the reservoir is believed to be associated with faulting and/or open fractures, the reservoir rock is modeled using a dual porosity formulation. The concepts of single porosity and dual porosity have been described in the literature (Warren and Root 1963). In a single porosity, there is a single computational grid covering the space within the model. In dual porosity models, there are two computational grids covering the same space within the model. One computational grid represents the "fractures", which tend to have higher permeability, but limited capacity to store heat and fluid. The second computational grid covers the "matrix", which tends to have a higher capacity to store heat and fluids but has lower permeability. The third component of a dual porosity formulation is that there is a function that calculates the flow from the matrix blocks into the fracture blocks.

TETRAD contains a built-in option for implementing dual porosity, and that was used in the Surprise Valley reservoir model. Throughout the Surprise Valley model, the fracture domain is 1% of the total block volume and the matrix domain occupies the remaining 99%. The matrix permeability is a uniform 0.05 md across the entire grid, whereas the fractures have permeabilities up to 100,000 md. These ratios are calibrated to match the measured data at Surprise Valley. Listed below are brief summaries of each component of the conceptual model:

Primary Permeability: Distribution of primary permeable zones is related to the texture and mode of formation of the geological unit (e.g., low permeability mudstones or high permeability volcanics). Wells drilled thus far at Surprise Valley have not encountered geologic units with significant primary permeability, permeability is associated with faults or fracture zones.

Secondary Permeability: Distribution of secondary permeable zones is related to brittle faulting and fractures generated by earthquakes and/or regional strain. In the Surprise Valley region wells that contain significant permeability, it is related entirely to faulting and fracturing within a background rock of low primary permeability.

Deep Heat Inflow: The Surprise Valley resource is in an area of high regional heat flow and significant heat probably exists extensively at great depths within impermeable rocks. Local faulting at Surprise Valley provides a vertically permeable pathway for fluid migration to bring heated fluid to the ground surface convectively (active hot springs).

Discrete Fault: The Surprise Valley geothermal field consists primarily of a discrete fault zone. This fault is a discrete segment of permeability at depth which extends north and south. This fault was partially interpreted using well losses and measured production zones in addition to geophysical methods.

Permeability Distribution: A dual porosity formulation was used across the entire model, which means there is a permeability and porosity value for each of the two domains, fracture, and matrix. Taken together, overall permeability and porosity distribution in the model was changed iteratively to attain a match to the static and flowing temperature of WME-E1 and to the pressure response measured at WME-E1 during the July 13, 2019 flow test.

Boundary Conditions: The boundary conditions for the Surprise Velley numerical model are based on the natural state temperature profile of WME-E1, spring locations, geothermometry, and the geologic conceptual model. Based on these sources, GSI implemented an elongated hot upflow on the bottom of the model, extending along a north-south fault, which exists in a background of high background heat flow. The fluid outflows at the intersection of the fault system with the ground surface in the area of the hot springs southwest of well WME-E1.

Rock Type Distribution: Figure 10 is a west-east cross-section through the numerical model showing the distribution of materials used in the model.

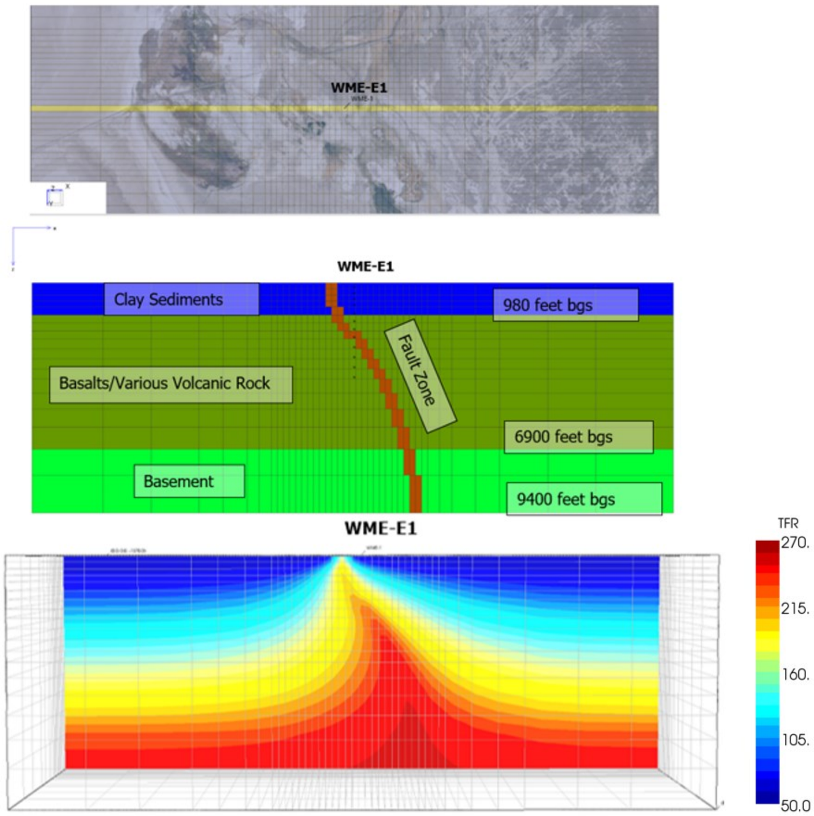


Figure 10: Cross-section through the numerical model grid showing rock types and simulated natural state temperature

5.3 Natural State Model

In a natural state model, the boundary conditions are fixed, and the model is run for a period simulating geologic time. The model code is run until it comes to stable conditions where the pressures and temperatures do not change with additional simulation time. The goal is to represent the pre-production natural state of the reservoir with its initial distribution of temperature and pressure. Heterogeneity in the permeability structure causes the fluid to flow preferentially in certain regions. Changes to this permeability structure, the inflow conditions, outflow locations, and the constant temperature boundaries resulted in the match to natural state conditions. Figure 10 shows simulated natural state temperatures on a west-east cross-section. Figure 11 shows a direct match of measured static temperature at WME-E1 with simulated temperatures. The match between measured and simulated temperatures is good, which indicates the quality of the calibration of the model to be high, which adds confidence to forecasts made with the model.

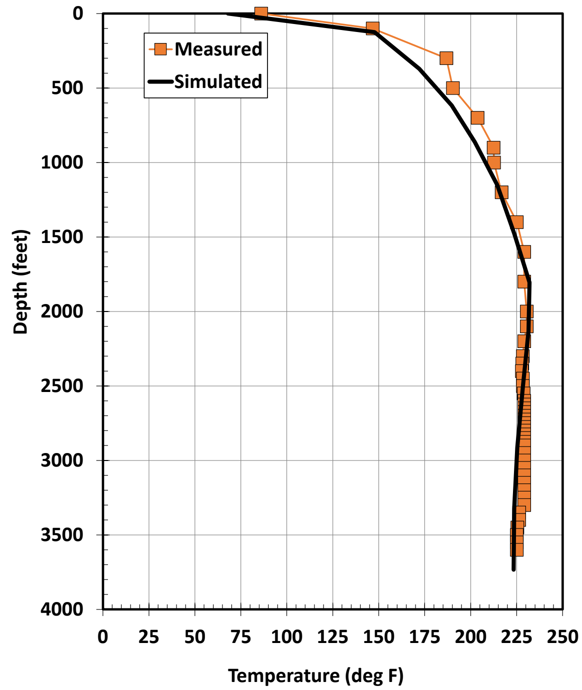


Figure 11: Well WME-E1 natural state temperature match

5.4 Production History Match

The Surprise Valley numerical model was calibrated to well measurements under pressure transient conditions. Specifically, the downhole flowing pressure during the end of the July 13, 2019 flow test and the static pressure recovery survey from July 14, 2019 was used to calibrate the model. Using the final model, a good match was obtained between measured and simulated data (see Figure 12). The following element of the calibration results are important for reservoir management because it increases confidence in the model's forecasts.

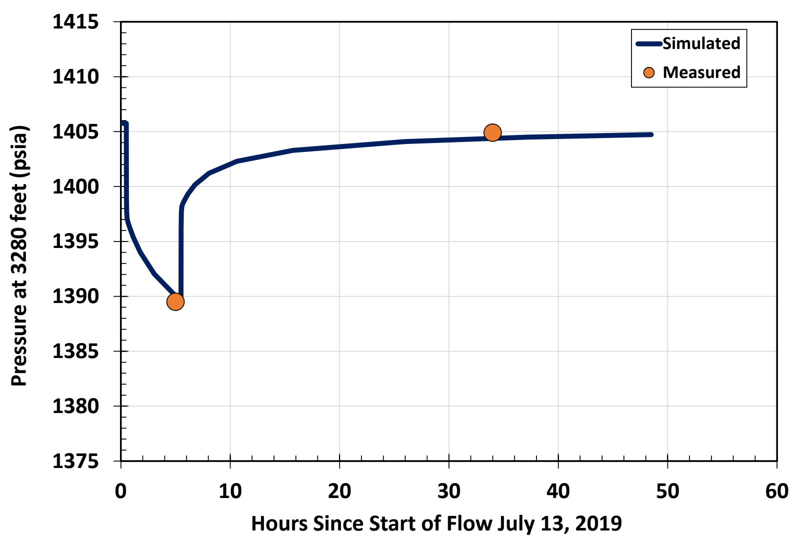


Figure 12: Well WME-E1 simulation match to flow test pressure transient

6. NUMERICAL SIMULATION FORECASTING

The calibrated model was used to make a forecast of the reservoir's response to long-term production of well WME-E1 at its maximum artesian flow capacity of 500 gpm of surface flow (post flash), equivalent to approximately 510 gpm of downhole pre-flash liquid. The following forecast scenario was simulated with the numerical model.

6.1 Production Scenario 1

Production: It was assumed that well WME-E1 is placed into commercial operation at its full artesian flow capacity of 500 gpm into a process that accepts 500 gpm inlet flow of a two-phase mixture of steam and water at the enthalpy equivalent to 225 °F liquid water (193.3 btu/lbm). The assumption is that the plant (or industrial process) does not "consume" and brine or vent any steam, rather the produced fluid is maintained in a closed system.

Injection: The outlet of the plant (or industrial process) then returns the full amount cooled to 70 °F. Due to shrinkage from cooling, the total volume to reinject is 475 gpm of brine at 70 °F. In the simulation, it was assumed that the 475 gpm of reinjection flows into one reinjection well. Because this well is hypothetical, assumptions were made to allow it to be included in the simulation. It was assumed that the single reinjection well would be located 3280 feet of lateral distance from WME-E1 and inject at a depth of 4000 feet (which is 1700 feet deeper than the production zone in well WME-E1). In the model, this configuration provided a reasonable balance between pressure support and cooling impact from the reinjected brine.

Results: Figure 13 shows the forecasted downhole pressure at WME-E1 for long-term production of 500 gpm. As shown, the model predicts an initial downhole pressure decline in WME-E1 of about 72 psi, followed by long-term stability with negligible further pressure drop. This represents favorable, sustainable production performance. Figure 14 shows the forecasted downhole flowing temperature at WME-E1 for long-term production of 500 gpm. The forecasted production temperature from the simulation shows a negligible long-term temperature decline. This is consistent with long-term sustainability of the resource.

6.2 Additional Scenarios

Scenario 1 was simulated as a test case forecast. However, the numerical model can be used to simulate many other Scenarios. A development plan could call for several (or many) new wells to be drilled. The common practice is to build an initial model, when the first well is drilled, as was done for the Surprise Valley numerical model. As each new well is drilled, the additional data collected is then used to refine the numerical model.

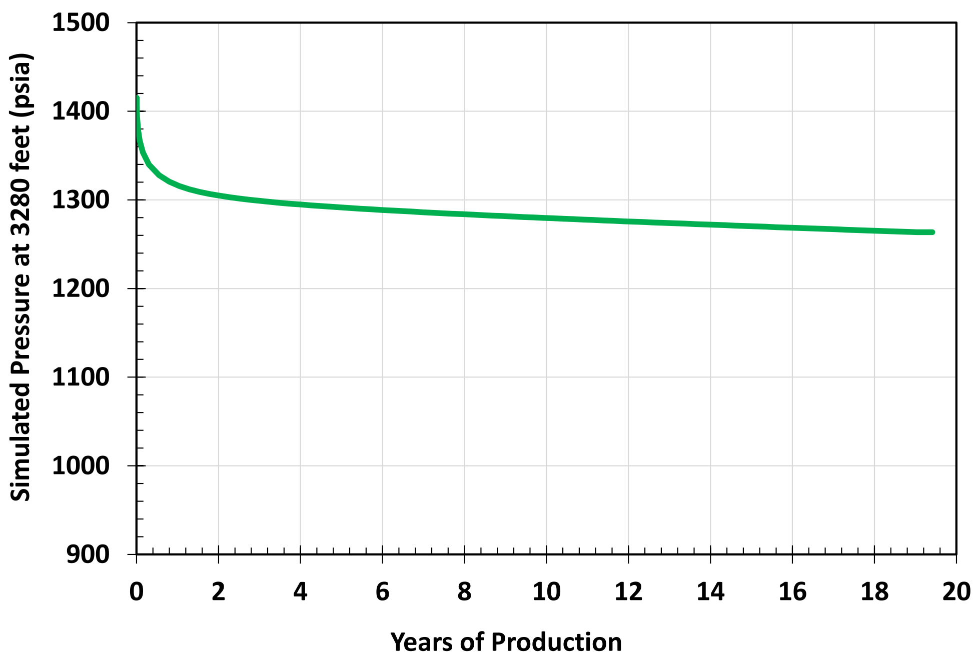


Figure 13: Scenario 1 (500 gpm), simulation forecast of downhole pressure in well WME-E1

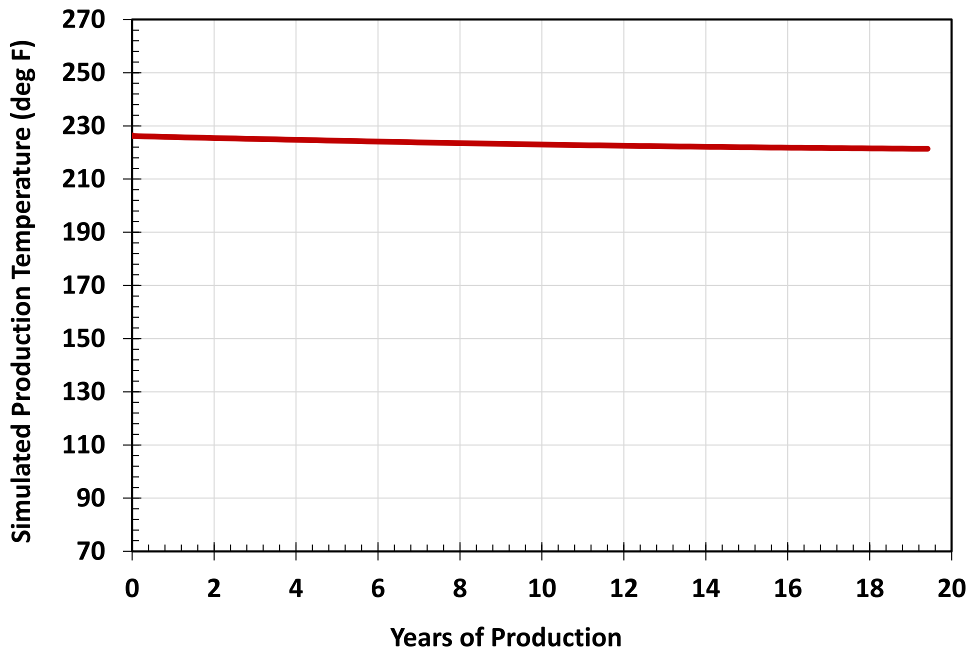


Figure 14: Scenario 1 (500 gpm), simulation forecast of downhole production temperature well WME-E1

6. CONCLUSIONS

An exploratory geothermal well was drilled on the east side of Surprise Valley to investigate the potential for electrical energy development. Public outreach activities such as public meetings, media releases, and newspaper articles helped to inform the community about the project.

Geophysical studies, based on borehole logging, reveal the presence of several prominent fault zones. The fault zones have a wide range of attitude, mostly dipping 60˚- 90˚, typical of Basin and Range structures. Fractures below ~ 2300 feet bgs are observed to be associated with increasing temperature gradient in WME-E1. WME-E1 is highly permeable and borehole logs confirm fractures are the primary control on hydrothermal flow. Fractures observed in WME-E1 at these depths are well-aligned with the stress state to accommodate normal faulting. Well aligned fractures are more likely to create a permeable zone. However, the preferred orientation of the fractures is slightly misaligned with the strike of the Surprise Valley Fault on the west side of the valley and localized dike structures. This can be an indicator of a recently active tectonic system and the fracture misalignment may be one of the key factors explaining why hydrothermal flow is present on the east side of the valley at the WME-E1 site.

Geothermometry based on water chemistry in WME-E1 indicate reservoir temperatures ranging from 194˚F to 289˚F. However, the measured flowing temperature (225˚F) and maximum borehole temperature (230.5°F) in WME-E1 are higher than some of the geothermometer estimates. WME-E1 flowed under artesian conditions at ~500 gpm in the 5" liner with no drawdown for six hours during flow testing. This result indicates a highly permeable system. Reservoir modeling indicates that Well WME-E1 can sustain an artesian flow over a long term (20 years or more) and the geothermal reservoir on the east side of Surprise Valley can sustainably support much higher levels of production with a strategically managed re-injection plan. Flow test results show the productivity index of WME-E1 is very high, among the highest level seen in the geothermal industry.

The reservoir supplying WME-E1 is a shallow and highly productive low temperature system which makes it attractive from a development point of view in terms of production and injection drilling costs. WME-E1 is capable of commercial grade electrical energy production at a relatively shallow depth of ~2300 feet bgs.

Geothermometry results indicate higher temperature potential. Deeper drilling could reveal a hotter, deeper reservoir and will facilitate characterization of the complex geological controls on the Surprise Valley geothermal system. A hotter resource will increase opportunities for Modoc County to exploit the resource for economic development.

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