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A conceptual geochemical model of the geothermal system at Surprise Valley, CA

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ABSTRACT

Characterizing the geothermal system at Surprise Valley (SV), northeastern California, is important for determining the sustainability of the energy resource, and mitigating hazards associated with hydrothermal eruptions that last occurred in 1951. Previous geochemical studies of the area attempted to reconcile different hot spring compositions on the western and eastern sides of the valley using scenarios of dilution, equilibration at low temperatures, surface evaporation, and differences in rock type along flow paths. These models were primarily supported using classical geothermometry methods, and generally assumed that fluids in the Lake City mud volcano area on the western side of the valley best reflect the composition of a deep geothermal fluid. In this contribution, we address controls on hot spring compositions using a different suite of geochemical tools, including optimized multicomponent geochemistry (GeoT) models, hot spring fluid major and trace element measurements, mineralogical observations, and stable isotope measurements of hot spring fluids and precipitated carbonates. We synthesize the results into a conceptual geochemical model of the Surprise Valley geothermal system, and show that high-temperature (quartz, Na/K, Na/K/Ca) classical geothermometers fail to predict maximum subsurface temperatures because fluids re-equilibrated at progressively lower temperatures during outflow, including in the Lake City area. We propose a model where hot spring fluids originate as a mixture between a deep thermal brine and modern meteoric fluids, with a seasonally variable mixing ratio. The deep brine has deuterium values at least 3 to 4‰ lighter than any known groundwater or high-elevation snow previously measured in and adjacent to SV, suggesting it was recharged during the Pleistocene when meteoric fluids had lower deuterium values. The deuterium values and compositional characteristics of the deep brine have only been identified in thermal springs and groundwater samples collected in proximity to structures that transmit thermal fluids, suggesting the brine may be thermal in nature. On the western side of the valley at the Lake City mud volcano, the deep brine-meteoric water mixture subsequently boils in the shallow subsurface, precipitates calcite, and re-equilibrates at about 130 °C. On the eastern side of the valley, meteoric fluid mixes to a greater extent with the deep brine, cools conductively without boiling, and the composition is modified as dissolved elements are sequestered by secondary minerals that form along the cooling and outflow path at temperatures <130 °C. Re-equilibration of geothermal fluids at lower temperatures during outflow explains why subsurface temperature estimates based on classical geothermometry methods are highly variable, and fail to agree with temperature estimates based on dissolved sulfate-oxygen isotopes and results of classical and multicomponent geothermometry applied to reconstructed deep well fluids. The proposed model is compatible with the idea suggested by others that thermal fluids on the western and eastern side of the valley have a common source, and supports the hypothesis that low temperature re-equilibration during west to east flow is the major control on hot spring fluid compositions, rather than dilution, evaporation, or differences in rock type.

1. Introduction

Surprise Valley, northeastern California, is an active geothermal area located on the western edge of the Basin and Range extensional province and at the northern terminus of the Walker Lane dextral-slip belt (Egger et al., 2010). Hot and warm springs occur throughout the valley; the main locations are near Eagleville, Lake City, and Fort Bidwell on the

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western side; and at the Surprise Valley Hot Springs Resort (SVHS), Leonards hot spring, and Seyferth hot spring on the eastern side of the valley (Fig. 1). Geochemical studies related to energy exploration of the geothermal areas in Surprise Valley have been conducted periodically since the 1950s. The purpose of this study is revisit the conceptual geochemical model of the Surprise Valley geothermal system, taking advantage of the large body of historical data, advances in geochemical modeling software, and accessibility to high-resolution trace element analytical data.

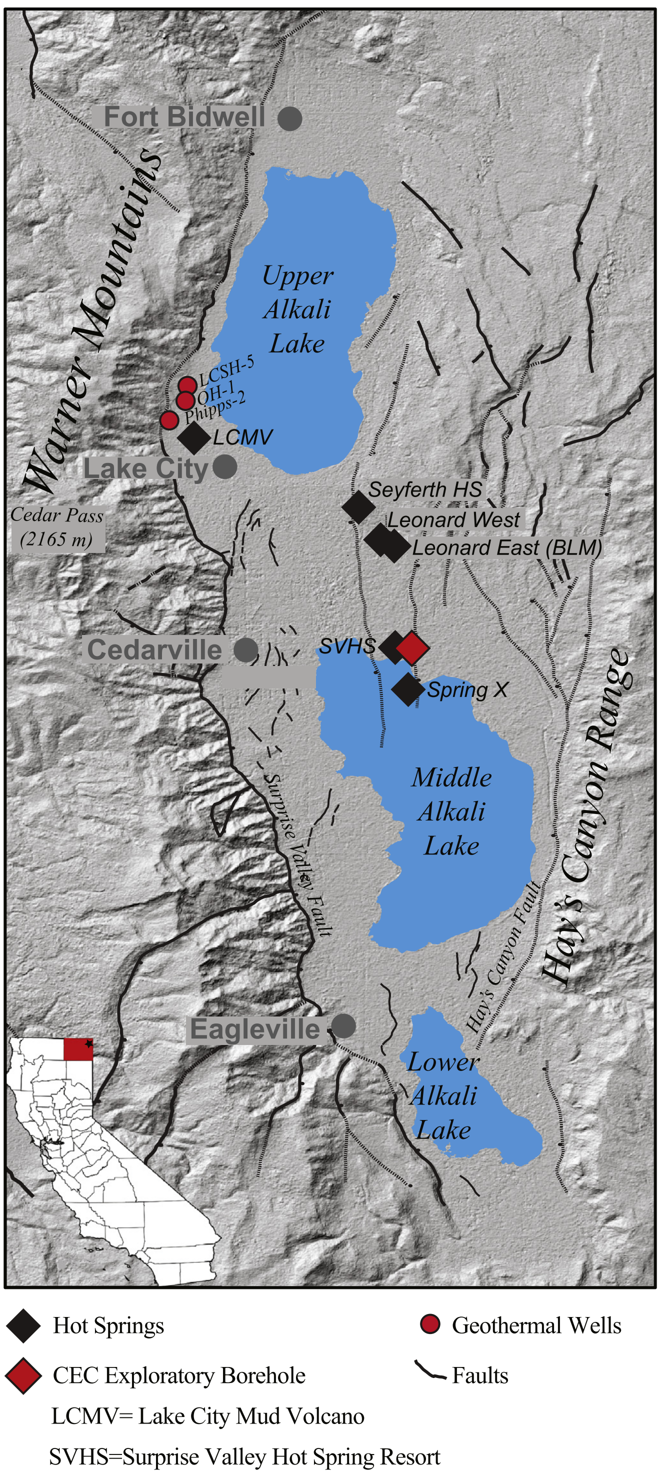

Fig. 1. Surprise Valley showing sampling locations. Spring E of SVHS (northern and southern) and Spring SW of SVHS (see Table 1) are located adjacent to SVHS.

1.1. Background

Direct use of the Surprise Valley geothermal resource began in the 1950s with construction of the SVHS, where boiling water from a 27 m deep well is still used to heat spas. Interest in the geothermal energy potential of Surprise Valley followed eruption of the Lake City mud volcano (LCMV) in March 1951 on the western side of the valley (White, 1955). Magma Energy, Inc. subsequently drilled three exploratory wells in the LCMV area between 1959 and 1962. Parman-1 reached 140 °C at 655 m, Parman-2 reached 125 °C at 600 m depth, and Parman-3 reached 92 m when a blowout destroyed the rig and expelled boiling water (Woods, 1974; Reed, 1975). Following designation of Lake City as a known geothermal resource area (KGRA) under the Geothermal Steam Act of 1970 (Godwin et al., 1971), six more deep test wells were drilled by Magma Energy, Inc., Gulf Oil Corporation, and American Thermal Resources between 1970 and 1974. This included the 1508 m deep Phipps-2 exploration well just to the northwest of LCMV, which achieved the maximum measured subsurface temperature in the valley of between 160 °C and 170 °C (Duffield and Fournier, 1974; Rigby and Zebal, 1981).

A lack of local demand for hot water and electricity led to a hiatus in Surprise Valley geothermal exploration (Rigby and Zebal, 1981) until the 2000s, when interest in the Surprise Valley geothermal resource renewed. A series of temperature gradient and core holes were drilled in the LCMV (Benoit et al., 2004; Benoit et al., 2005a; Benoit et al., 2005b) and Fort Bidwell (Barker et al., 2005; LaFleur et al., 2010) areas. During these efforts, holes OH-1 and LCSH-5 were drilled to the north of Phipps-2 and near the Surprise Valley Fault (SVF). OH-1 and LCSH-5 were drilled to 1047 m and 1441 m, respectively, and the wells both achieved maximum temperatures of approximately 160 °C during testing, comparable to the bottom hole temperature measured in Phipps-2 (Benoit et al., 2005b). In 2016, the California Energy Commission (CEC) funded drilling of three closely spaced temperature gradient holes on the eastern side of the valley near SVHS, including one for which water samples were collected. The results of water sampling from the CEC project are discussed herein.

In addition to exploration drilling, several geophysical and geologic studies have been conducted to evaluate geologic and structural controls on subsurface geothermal fluid flow in Surprise Valley using high-quality gravity, magnetic, and audio magnetotelluric measurements (Glen et al., 2008; Kell-Hills et al., 2009; Lerch et al., 2010; Glen et al., 2013; Hawkes et al., 2013; Egger et al., 2014; Athens et al., 2016; Tanner et al., 2016). These studies show a close association of hot springs with faults in Surprise Valley, and support the contention of Duffield and Fournier (1974) that thermal fluid flow is structurally controlled (Egger et al., 2014). A dominant structural control on thermal fluid flow appears to be the SVF, a major offset normal fault located along the eastern front of the Warner Mountains (Duffield and McKee, 1986; Egger et al., 2010). A number of authors (e.g. Glen et al., 2013) argued for the existence of a northwest striking "Lake City Fault" connecting the Lake City hydrothermal system with the system on the east side of the valley. Hawkes et al. (2013) argue against a major fault in this location based on audiomagnetic studies. Egger et al. (2014) also found little evidence for a distinct 'Lake City Fault', and instead proposed a model where small offset N—S trending and westward dipping normal faults intersect the SVF at depth and facilitate flow of thermal waters to the eastern side of the valley. Magnetotelluric surveys conducted by Tanner et al. (2016) recognized that hot spring locations fall off-axis of the westward dipping faults identified by Egger et al. (2014), and proposed that porous basalts within fault-tilted blocks provide a fluid pathway. Fowler et al. (2017) identified two distinct groundwater trends with a thermal signature using a statistical analysis of historical groundwater geochemical data. One subsurface trend is coincident with the SVF on the western side of the valley between Lake City and Fort Bidwell, and the other trend is located on the eastern side of the valley and is coincident with the trend of the small N—S trending westward dipping faults and porous basalts.