

Fluid Geochemistry of the Surprise Valley Geothermal System

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ABSTRACT

Despite the prevalence of hot springs and the drilling of several test wells, the Surprise Valley geothermal system remains relatively undeveloped. One reason for this is that the source and flow-path of geothermal waters within the subsurface remains enigmatic. Our study aims to determine this through a comprehensive investigation of the geochemistry of the Surprise Valley fluids. Our approach divides the valley into five regions that we believe to be operationally distinctive in their channeling and mixing of waters. We compiled and analyzed relationships between all of the available major element and isotopic geochemical data on thermal waters from within these regions. Chemical data were modeled Geochemists Workbench®. Initial results support the theory that discrete recharge sources and mechanisms are operating throughout the valley. Our geochemical modeling suggests that the hottest waters within the system originate at around 170° C, and may be diluted by cold waters from multiple sources. We believe this study may be useful in the context of emergent geophysical work that is investigating structures controlling fluid flow within the valley.

INTRODUCTION

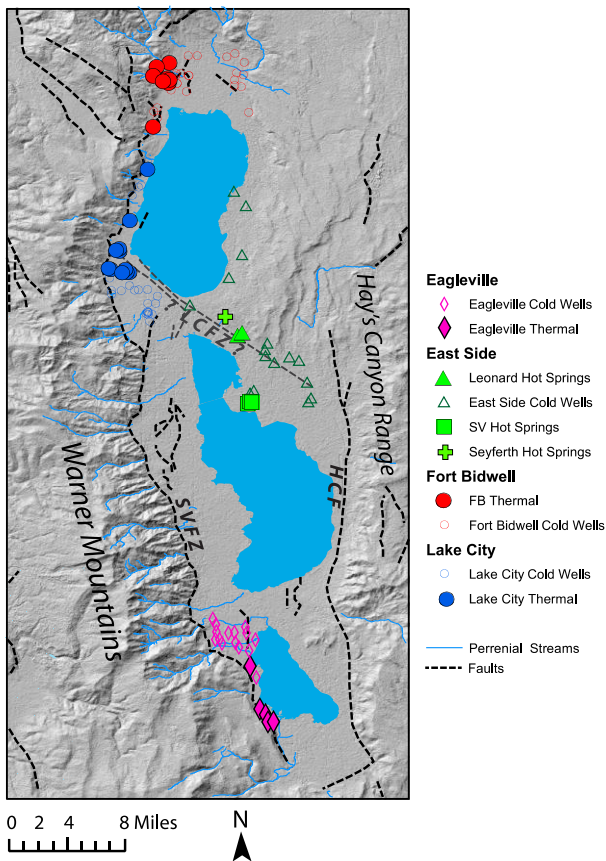


Figure 1: Map of the Surprise Valley geothermal region, showing water sample locations by region.

The Surprise Valley Geothermal System (SVGS) is a graben hosted, fluid-producing system bounded by the Surprise Valley Fault (SVF) to the west and Hays Canyon Fault (HCF) to the east. The Surprise Valley Graben transitions into a half-graben to the north of Seyferth and Leonards hot springs (Figure 1), where the HCF splays into a series of parallel, N-S trending normal faults (Hedel 1980, 1981, 1984, Bryant 1990, Egger 2010). The Surprise Valley Graben is a basin filled with alluvium and lake deposits interbedded with numerous volcanic flows, tuffs, and breccias (Benoit et al, 2005, Egger 2011). Drill logs show that stratigraphic thickness is highly variable throughout the graben, with basin fill ranging in thickness from less than 100 ft. to over the 6270 ft. in some areas (Benoit et al 2005). Surprise Valley contains three ephemeral alkali lakes: Upper, Middle, and Lower Alkali Lakes from north to south, respectively. The alkali lakes are remnants of the Pleistocene "Surprise Lake" hydrologic basin. The lake levels fluctuate annually due to a combination of snowmelt channeled by local streams, irrigation run-off, and evaporation during the summer months.

The source of recharge for thermal fluids in Surprise Valley also remains unknown, as do the pathways by which these fluids move in the subsurface and emerge as springs (Benoit et al 2005). It has not been established if various geothermal manifestations in the SVGS are interconnected and derive from a single reservoir, or if they derive from disconnected discrete sources. Drilling records indicate that thermal fluids on the western flank of Surprise Valley are hosted within the volcanic bedrock, and that fluid flow is controlled by fracture permeability within these units (Benoit, 2004, Benoit 2005). The inferred "Lake City Fault Zone" (LCFZ) (Hedel, 1980, 1981, 1984; Benoit et al., 2004; Egger et al., 2011) is a structure thought to run across the graben and connect the two range front faults (Figure

1), and has led to the proposition that the LCFZ controls west to east thermal fluid flow (Glen et al., 2008). Barring the emergence of hot springs at either end of the LCFZ, there is little evidence for the movement of fluids across this inferred conduit. A recent paper by Egger et al. (2014) presents geophysical data that questions the existence of a through going NW structure in the vicinity of the LCFZ. Potential recharge sources for SVGS fluids include precipitation from the Warner Mountains to the west, alkali lake waters within the graben, precipitation from the Hays Canyon Range to the East, and Pleistocene/Early Holocene groundwater within the Surprise Valley Graben. Surface expressions of geothermal fluids in Surprise Valley are concentrated along the eastern and western margins of the graben. In this study, we divide the SVGS into 5 sub-regions, based on geography and fluid chemistry. They are the Fort Bidwell, Lake City, Seyferth/Leonards, Surprise Valley, and Eagleville regions. The Fort Bidwell, Lake City, and Eagleville regions lie along the western side of Surprise Valley, where thermal waters surface within .5 to 1 km of the Surprise Valley Range Fault. Seyferth/Leonards and Surprise Valley hot springs emerge in the eastern portion of the graben, in the region where the HCF splays into a series of normal faults.

MOTIVATION AND APPROACH

Several previous studies have reported geochemical and isotopic data for Surprise Valley hot springs fluids (Table 1), and some authors have interpreted these data by applying empirical and/or theoretical geothermometers to infer subsurface conditions (e.g. Sladek et al., 2004). In this paper, we examine mineral solubility modeled using fluid analyses and the Geochemist's Workbench program, and considered the results in the context of cation geothermometry, and stable isotopic data. This study aimed to compile and evaluate the complete record of geochemical data from thermal fluids throughout the valley. Our goals were to 1) resolve as much as possible from current data about the temperature in each geographic region of spring occurrence, and 2) to help inform the collection of future data in Surprise Valley by suggesting general hypotheses for fluid flow in each region.

Author	Sample Location	Notes
Waring, 1915	1	Chemical constituents, pH calculated from alkalinity.
White, 1955	2	pH, Cl, and specific conductance only.
Duffield and Fournier, 1974	1, 2, 3, 4, 5, 6	Chemical constituents, pH of samples not reported. Includes some non-thermal waters.
Reed, 1975*	1, 2, 3, 4, 5, 6	Chemical constituents; includes oxygen and hydrogen isotope data; and sulfate oxygen isotope data for Seyferth HS and Surprise Valley HS.
Bliss, 1983 (GEOTHERM Database)	1, 2, 3, 6	Chemical constituents, references ambiguous, although primarily from California Department of Water Resources sampling.
CADWR 1986	1, 2, 3, 4, 5, 6	Extensive CA Department of Water Resources dataset of chemical constituents primarily in non-thermal domestic and irrigation wells from 1956 to 1984 throughout Surprise Valley.
Elliot Allen Associates, 1986	1, 2	Chemical constituents.
Ingraham and Taylor, 1986	3, 5	Hot spring oxygen and hydrogen isotope data only.
Ingraham and Taylor, 1989		Extensive oxygen and hydrogen isotope dataset for non-thermal ground water, Alkali Lake water, and snow.
CARWQCB, 1990		Chemical constituents of Middle Alkali Lake, and Goose Lake.
Sladek et al., 2004	1, 2, 4, 6	Chemical constituents; oxygen, hydrogen, sulfur and carbon isotope data. Includes some non-thermal waters.
Barker et al., 2005	1	Chemical constituents, helium isotope data. pH of samples not reported.

1. Fort Bidwell
2. Lake City
3. Eagleville Area
4. Seyferth (Chicken) HS
5. Leonard HS
6. Surprise Valley Hotel (Cedar Jump) HS

*Reed (1975) data is also referenced by: Nehring et al (1979); Elliot Ellen Associates (1986); Mariner et al (1993)

Table 1: Fluid chemistry data sources.

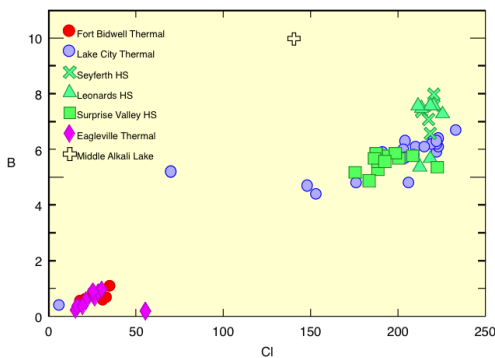
One technique we applied to infer subsurface temperature conditions was multiple mineral saturation state (Q/K) diagrams (Reed and Spycher, 1984). Many of the fluid analysis available in the published literature are incomplete, so we have made various assumptions to facilitate the modeling. In particular, dissolved aluminum concentrations are missing from many of the fluids precluding modeling of the saturation state of aluminosilicate phases that are likely to provide important solubility constraints on subsurface fluids. Based on the previously reported alteration minerals in Surprise Valley drill holes, the existing fluid geothermometry for Surprise Valley (which generally indicate subsurface temperatures <200°C), and the analogy to similar geothermal systems (Schiffman et al, 1984), we make the assumption that aluminum activity in the fluids is controlled by equilibrium with illite. For each modeled fluid, the temperature for illite equilibration was chosen by first determining the Q/K convergence temperature for a suite of non-Al bearing minerals (quartz, anhydrite, and fluorite) for each particular fluid analysis. The fluid was forced to be in equilibrium with illite at this temperature, and the process was repeated iteratively through trial and error until both Al-bearing and non-Al bearing minerals indicated Q/K convergence at a similar temperature. In a few instances, such as for Fort Bidwell fluids, Q/K convergence occurred below the Q/K=1 (saturation equilibrium) line, indicating dilution of the thermal fluid (Reed and Spycher, 1984; Pang and Reed, 1998). Another critical variable in mineral saturation calculations is the choice of pH input into the initial model. The pH measured at surface hot springs or in fluids sampled from geothermal wells can be strongly influenced by gas loss, particularly CO₂, especially if the fluids have boiled in the subsurface. In this study, we do not

attempt to correct the reported pH for CO₂ loss. CO₂ loss will increase in pH in the degassed fluids. In fact, most of the fluids we model are calculated to be supersaturated with calcite at the temperature of collection, and become increasingly supersaturated upon modeled temperature increase. Two observations suggest that CO₂ loss and the expected precipitation of calcite are not significantly changing the pH of the fluids measured at the surface. Observed hot springs show some bubbling of gasses, but vigorous degassing is not observed at Surprise Valley hot springs. More importantly, the Surprise Valley hot springs are not associated with travertine deposits, and most show no evidence of active carbonate precipitation. Therefore, while subsurface boiling could result in pH values that are somewhat elevated relative to subsurface conditions, we feel this effect is minor and therefore use the reported pH values to constrain our modeling.

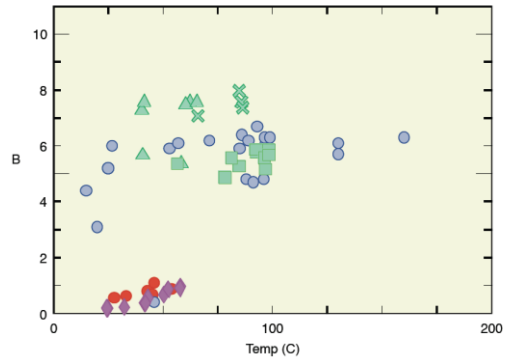
GEOCHEMICAL DATA

The first published geochemical data for thermal fluids in Surprise Valley appeared in a USGS Water Supply Paper (Waring, 1915). These were the only existing samples until 1955, when a mud volcano explosion occurred in the Lake City Area (White, 1955). To our knowledge, the data presented here (outlined in Table 1, compiled in Appendix 1) is a complete record of existing fluid geochemical data from the Surprise Valley.

B/Cl Ratio: Boron (B) and chloride (Cl) are both considered conservative elements in groundwater, and are thus commonly used proxies for determining the source of groundwaters. Hot water leaching of volcanoclastic rocks (such as those within Surprise Valley) contributes boron to hydrothermal fluids (Barker and Barker, 1985; Ellis and Mahon 1967). B and Cl concentrations in Surprise Valley vary widely, but generally lie along a trend of constant B/Cl ratio (Fig. 2a, 3a). B (and Cl) concentrations show a weak positive correlation with temperature, as well as clustering in discrete ratios by geographic region (Fig. 2b, 3b).

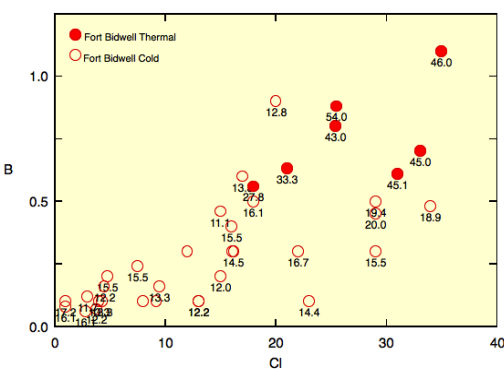


2a.

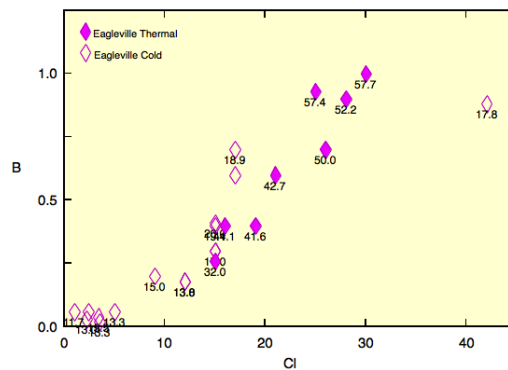


2b.

Figure 2 a: Boron (B, in mg/L) vs. Chloride (Cl, in mg/L) concentration plot for thermal fluids throughout Surprise Valley. Alkali lake compositions (CARWQCB, 1990) are plotted for reference. Values plot into discrete geographic regions. b: Boron concentrations (B, in mg/L) vs. measured temperature (°C). Eagleville and Ft. Bidwell waters have low B concentrations compared to waters from other regions in the valley of comparable measured temperature.



3a.



3b.

Figure 3: Boron concentrations (B, in mg/L) vs. Chloride (Cl, in mg/L) plot for Ft. Bidwell (a) and Eagleville (b), with measured T (°C) annotated. Thermal waters from both areas are enriched in B and Cl over cold waters.

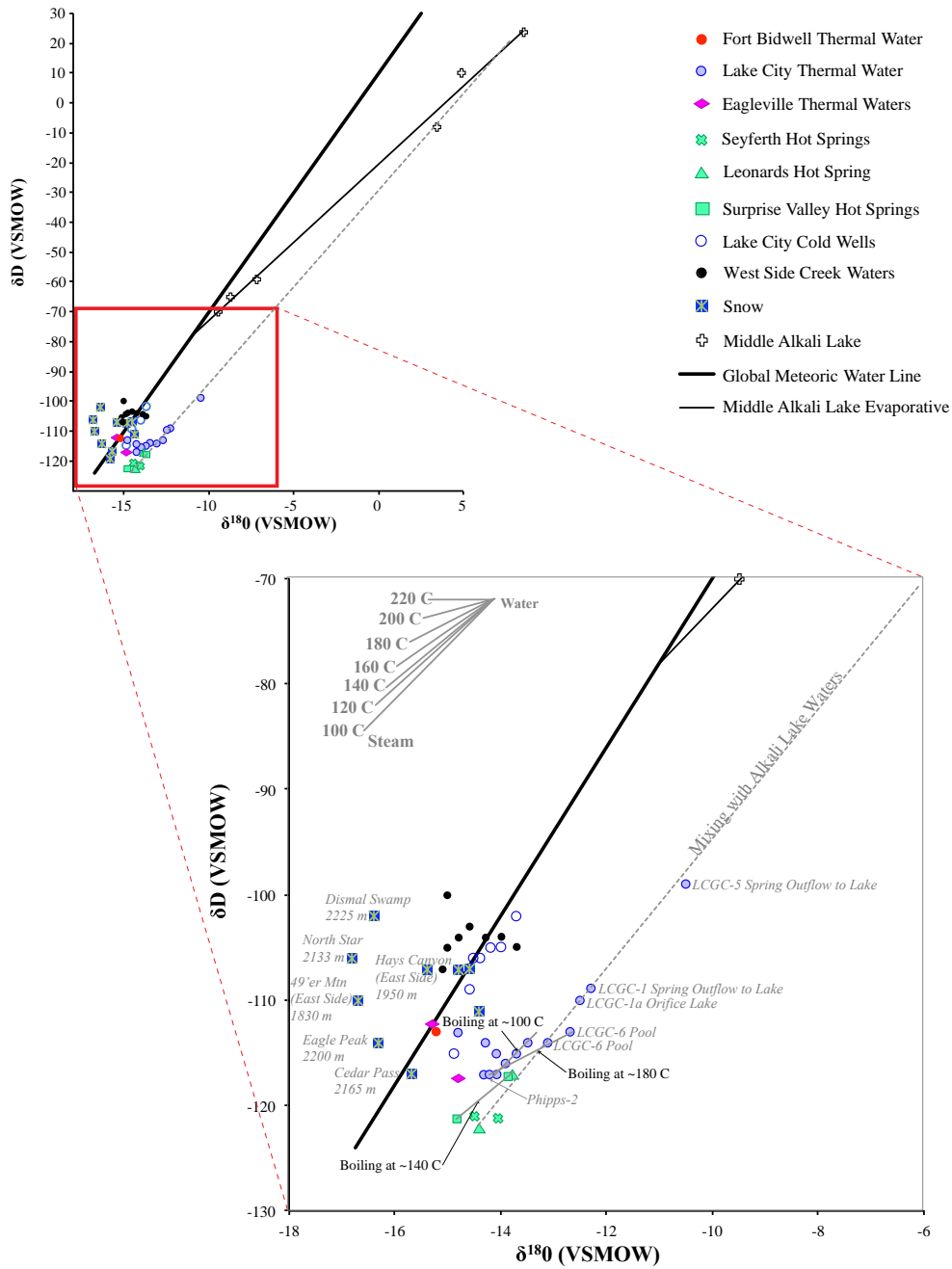


Figure 4: Stable isotope (oxygen-deuterium) plot for Surprise Valley waters. Due to the limited extent of data on meteoric water samples in the surprise valley region, thermal and freshwater samples are plotted with the global meteoric water line (Craig, 1961) as a best approximation of the local meteoric water line. Potential boiling or mixing scenarios to explain Surprise Valley geothermal fluid isotope data are indicated. Data sources outlined in Table 1.

Sample Name	Amorphous SiO ₂	α-Cristobalite	β-Cristobalite	Chalcedony Conductive	Quartz conductive	Quartz adiabatic	Na-K-Ca	Na-K-Ca Mg corrected
LCGC-17 (Seyferth HS)	28	99	50	125	150	130	129	129
Seyferth Hot Springs	21	91	43	116	142	123	129	129
Seyferth Hot Springs (Hot Springs)	24	94	45	119	145	118	128	128
Leonard Hot Springs (East)	21	91	43	116	142	147	124	124
Leonard Hot Springs (East)	23	94	45	118	144	121	126	126
Leonard Hot Springs (West)	-8	58	11	79	109	0	107	73
LCGC-18 (Surprise Valley HS)	23	93	44	118	144	0	96	96
Surprise Valley Mineral Well	16	86	37	110	137	0	96	96
Surprise Valley Mineral Well	19	89	41	114	140	172	98	98
Benmac HS	17	87	38	110	137	171	96	96
Unnamed HS SW of SV Mineral Wells	16	86	37	110	137	160	118	118
Cedarville Area (Spring)	109	188	138	223	237	0	83	83
Menlo Baths Hot Springs	-9	58	10	79	108	0	61	61
Menlo Baths Hot Springs	-12	54	7	74	104	0	64	64
Menlo Baths Hot Springs						160		
Unnamed spring near Squaw Baths Hot Springs	-23	42	-5	61	92	0	68	68
Unnamed spring SE of Squaw Baths	-25	39	-7	59	90	157	80	80
FB-1 (well)	11	80	32	104	131	127	181	172
FB-2 (well)	3	71	23	93	122	120	101	101
FB-3 (well)	33	105	56	131	155	148	118	118
Unnamed well west of Ft. Bidwell	14	83	35	107	134	130	180	180
Unnamed well (Fort Bidwell Indian Reservation)	7	75	27	98	126	123	179	179
Unnamed well east of Fandango Pass	1	69	21	91	120	118	124	124
Well 45N/16E-17M1	32	104	55	130	154	147	118	91
Unnamed spring north of Ft. Bidwell	4	72	25	95	123	121	174	57
LCGC #1 (Spring outflow to lake)							164	164
LCGC-2 (Boiling spring)	60	135	85	164	185	172	160	160
LCGC-2 (Boiling spring)	59	133	84	162	184	171	160	160
LCGC-3 (Seep)	47	120	71	148	171	160	161	159
LCGC-5 (Spring outflow to lake - dirty)							149	97
LCGC-6 (pool)	47	120	70	148	171	160	147	147
LCGC-7 (Cowbone)	43	116	66	143	166	157	163	163
LCGC-12 (Hot well)	47	120	70	147	170	160	176	168
LCGC-20 (County Road Weir)							158	84
Phipps-2 (Magma Energy exploration well)	49	123	73	150	173	162	137	137
Phipps #2 (Top of flow line)	85	161	111	194	211	192	193	193
Phipps #2 (Bottom of flow line)	87	163	113	196	213	194	193	193
Phipps #2 (Weir Box)	90	167	117	199	216	196	195	195
Well 44N/16E-6E2 (Unnamed Cedarville well)	-1	66	19	88	117	115	115	105
Lake City (Parman) Hot Springs	0	0	0	0	0	127	0	0
Unnamed spring (Lake City Mud Volcano)	56	130	80	159	181	0	160	160
Unnamed spring (Lake City Mud Volcano)	50	124	74	152	174	120	158	158
Unnamed spring (Lake City Mud Volcano)	46	119	70	147	170	148	157	156

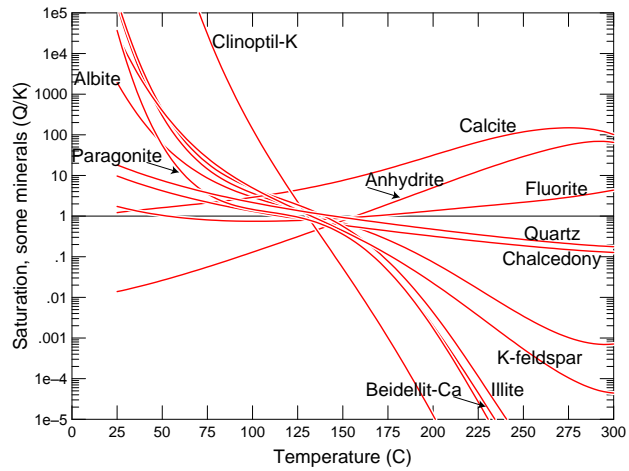
Table 2: Cation geothermometers: For this study we chose to calculate Na-K-Ca geothermometry temperatures (regular and Mg-corrected from Fournier, 1981) and SiO₂ geothermometry temperatures (Fournier and Potter, 1982). Calculations were carried out using the spreadsheet from Powell and Cumming (2010). Fluid analyses sourced from references in Table 1.

Sulfate-Oxygen Geothermometry

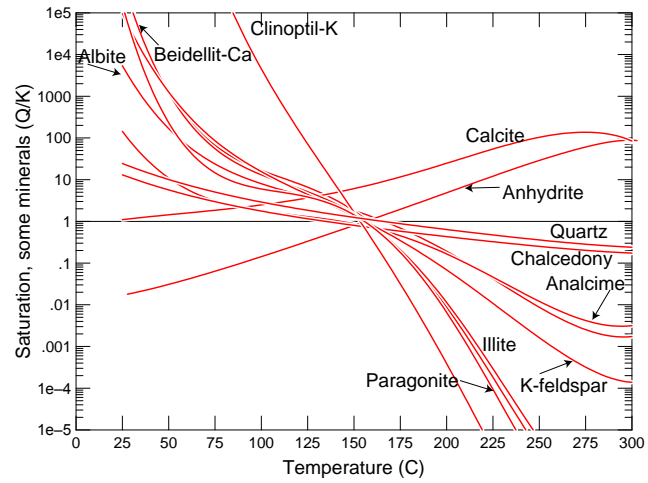
Sample	^{18}O H ₂ O Liquid	^{18}O (SO ₄ -H ₂ O) Liquid	Calculated T
Hot Springs Motel	-13.81	-5.11	200
Seyferth Hot Springs	-14.05	-5.62	205

Table 3: Sulfate-oxygen temperatures calculated using the method of Mizutani and Rafter (1969).Q/K Geothermometry

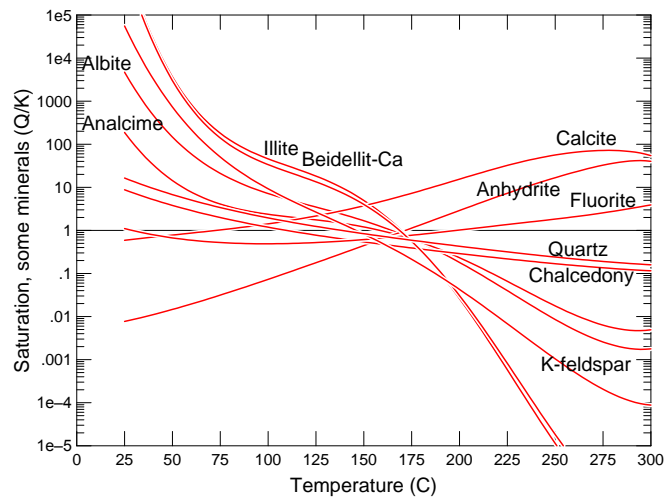
The use of saturation state (Q/K) diagrams has been shown to successfully predict geothermal fluid temperatures (Reed and Spycher, 1984). These saturation models utilize thermodynamic data on the activities of aqueous chemical species to determine the minerals with which a fluid could be in equilibrium across a range of temperatures. Results are plotted as the saturation state of minerals vs. fluid temperature. The point where several mineral saturation state lines intersect predicts the assemblage of minerals with which the fluid could have been equilibrated at the temperature of mineral saturation (Q/K=1). Major element analyses for waters from around Surprise Valley (Table 1) were input into the Geochemist's Workbench® program and analyzed in React® to determine the equilibration temperature. Fluids for which Al was not analyzed were assumed to be in equilibrium with illite at a variety of temperatures in order to calculate a likely value for the dissolved Al concentration of the fluid.



5a

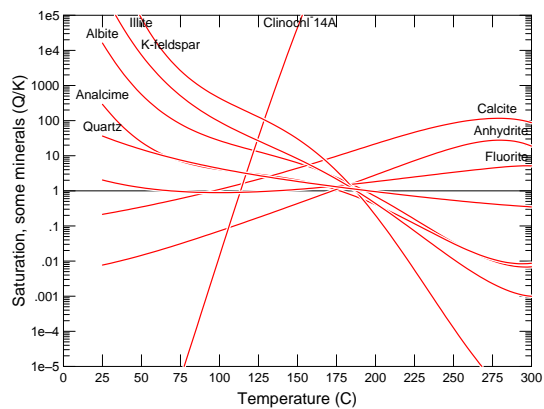


5b

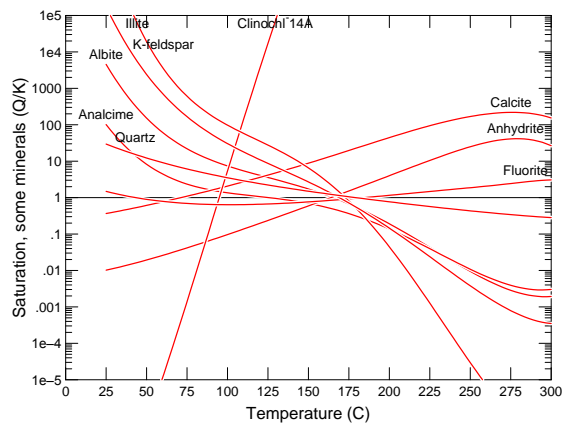


5c

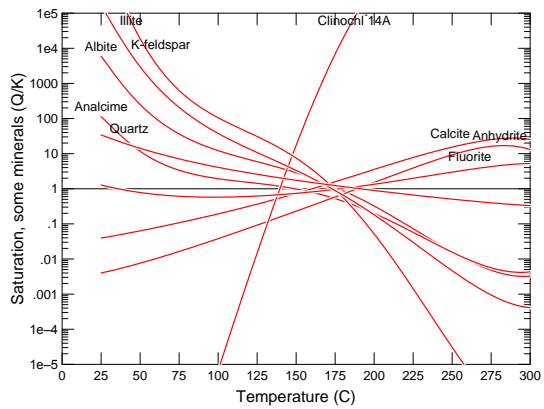
Figure 5: Q/K temperatures for Leonards (a) Seyferth (b) and Surprise Valley hot springs (c) Equilibrium of the fluids with illite at 145 C was assumed to estimate the aluminum concentration of the fluid.



6a



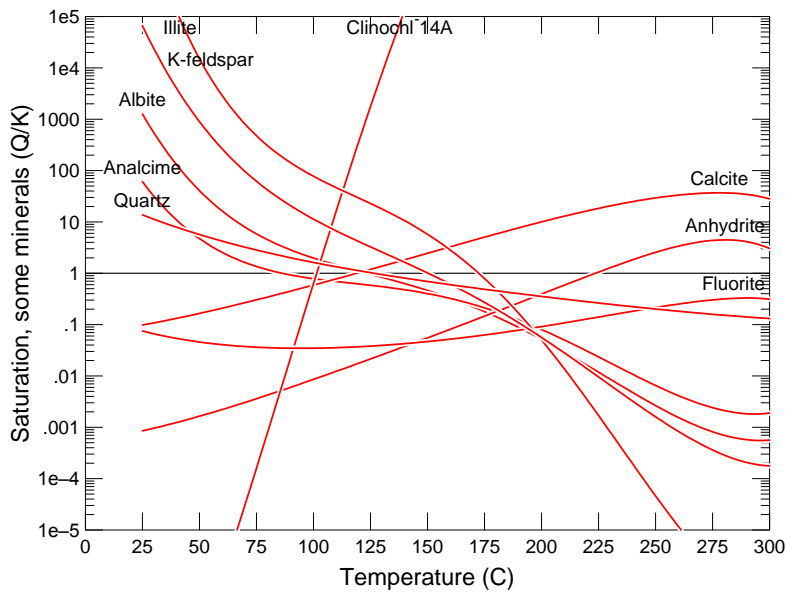
6b



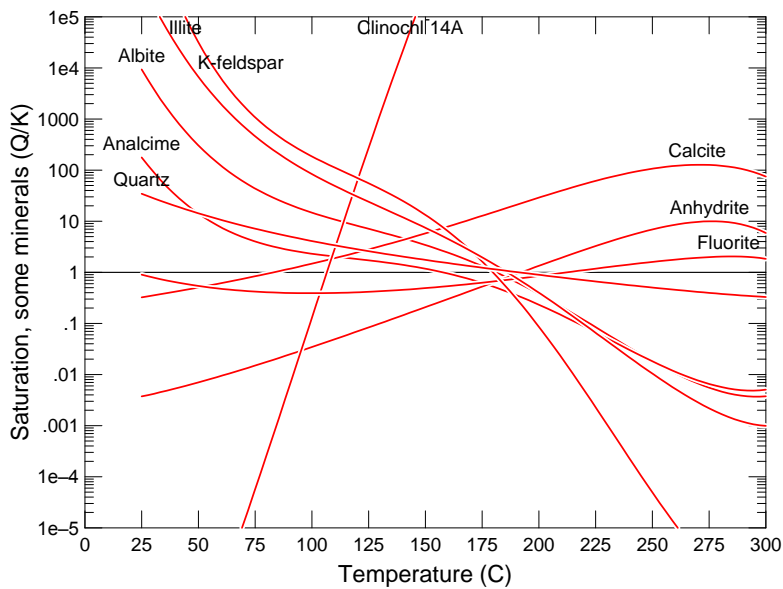
6c

Figure 6: Saturation diagrams for Lake City thermal fluids (a) LCGC 2, (b) LCGC 3, and (c) Lake City mud volcano. Equilibrium with illite at 165° was assumed for fluids (a) through (c) to estimate the Al content of the fluid

Fort Bidwell



7a



7b

Figure 7: Q/K plots for Fort Bidwell thermal water sample “Unnamed well on Ft. Bidwell Indian Reservation” (Reed, 1975). 7a shows poor Q/K convergence for water as sampled, 7b shows improved Q/K convergence at ~185° C after correcting for an assumed 60% dilution of the hydrothermal fluid with fresh water. Equilibrium of the fluids with illite at 150° C was assumed to estimate the aluminum content of the fluid.

DISCUSSION:

Despite differences in boron/chloride, stable isotope, and measured surface temperature values, Q/K geothermometry for fluids across Surprise Valley yields temperatures in the range of 160° to 185° C. Potential mineral assemblages which could be in equilibrium for most fluids include anhydrite, fluorite, albite, potassium feldspar, plus or minus zeolite and smectite minerals. The oversaturation of calcite in some fluids may be explained by degassing of CO₂ prior to the pH measurement. Some fluids show discrepancy between Q/K temperatures calculated in the Geochemist's Workbench[®] (Figures 5 through 7) compared to Na-K-Ca temperatures (Table 2). While Na-K-Ca geothermometers are considered relatively robust, this is an empirically based geothermometer and may not be applicable to all fluids. Reactions determining the concentration of these elements are often complex, and subject to influence by parameters such as CO₂ fugacity, which may or may not always correlate to temperature (Giggenbach, 1986). Reaction modeling assuming heterogeneous equilibrium calculations performed by software such as The Geochemists Workbench[®] can in some cases provide more reliable indication of temperature.

Seyferth/Leonards and Surprise Valley Hot Springs

Geothermal features on the eastern side of Surprise Valley are concentrated at the Seyferth/Leonards and Surprise Valley Hot Springs areas.

Measured surface temperatures range from 65° to 85° C for Seyferth Hot Springs. Na-K-Ca geothermometers yield temperatures of 107°-129° C, quartz temperatures are ~140° C, and chalcedony are 118° C. The Na-K-Ca temperatures for Leonards (East) are 125° C, quartz geothermometry gives 140° C, and chalcedony gives 117° C, compared to the measured temperatures for this spring, which are 53-61°. Surprise Valley Hot Springs Na-K-Ca geothermometers yield temperatures of 96-98° C, very close to measured surface temperatures. Quartz temperatures are approximately 140° C and chalcedony 110° C. It would appear that both thermal springs emerge from a relatively undiluted hot aquifer. In contrast, the Q/K geothermometry for all of these springs are similar and are consistent with higher temperatures of roughly 165°C. These higher temperatures are closer to, but still below the temperatures inferred from the oxygen isotope composition of dissolved sulfate (Table 3)

Waters from the Seyferth/Leonards areas have the highest B/Cl ratio of any of the regions in the valley, and appear to be shifted vertically off of the valley-wide Cl/B trend towards higher values of B (Figure 1a). This signature, combined with the fact that that these waters are also relatively enriched in $\delta^{18}\text{O}$ (fig 3), suggests that, in relation to other waters in the valley, they are relatively undiluted thermal waters. Surprise Valley Waters cluster more closely to Lake City waters on the B vs. Cl plot than Seyferth Leonards, but more closely to Seyferth/Leonards on the D vs. ^{18}O plot. Interestingly, deuterium values for some of these samples are lighter than any of the Warner Mountain fresh water samples, or other thermal water samples. If there were a conduit such as the LCFZ channeling fluids from Lake City to the eastern side of the valley, one would expect the oxygen isotopes of the east side waters to be at least as enriched as those seen in Lake City and the Warner Mountains. If the isotopic analyses plotted in Figure 3 accurately represent range of values encountered in Warner Mountain precipitation, the thermal waters emerging on the east side of the valley must be recharged from somewhere else. Sampling to better constrain the Warner Mountain meteoric precipitation line, and further stable isotopic analysis of fresh water springs from the Hays Canyon Range (immediately adjacent to the Surprise Valley and Seyferth/Leonards areas, Figure 1) may reveal a separate recharge source for fluids on the east side.

Lake City

Springs in Lake City also appear to be tapping relatively undiluted thermal waters. Oxygen isotopic values for Lake city are consistent with Warner mountain snowmelt acting as a recharge source the springs in Lake City. The wide spread in isotopic values for Warner Mountain snow makes it difficult to discern the source of fluid recharge and the subsequent processes occurring in Lake City fluids. Here we have included boiling and mixing lines (Figure 3) as postulates for the spread in isotopic values, but they are by no means unique solutions. Until more freshwater isotopic values are obtained to tighten the local meteoric water line, it is impossible to decipher the effects of different recharge sources from boiling and mixing. Cl and B concentrations for Lake City waters are elevated relative to cold waters in the valley, and enriched in B relative to fluids of comparable surface temperature in Eagleville and Fort Bidwell. This further suggests that the Lake City thermal waters have equilibrated with hot rock at depth, and undergone little mixing with meteoric water upon their ascent. Saturation curve models for the Lake City Thermal waters (Figures 6a-d) converge on equilibration temperatures of ~170° C. The fact that the equilibrium curve convergence occurs on the Q/K saturation line suggests that no cold dilution of these waters has occurred. Additionally, the fact that Na-K-Ca geothermometry temperatures are close to quartz geothermometry temperatures provides further support for this. Na-K-Ca temperatures range from 150° to 176° C, and quartz temperatures range from 160° to 172°. The exception to this is the Phipps 2 well, with a measured temperature of ~170° C and Na-K-Ca and SiO₂ geothermometry temperatures of ~200°C (Table 1). While some minor component of dilution may be responsible for the discrepancy between Phipps 2 and other Lake City fluids, one would expect to see more evidence in the chemistry of the Lake City fluids, which is not the case. If the fluid seen in other wells is the same fluid that is encountered in Phipps 2, it is possible that the flow paths at depth are slow and fluids are re-equilibrating with minerals at lower temperatures. This is further supported by the ~200°C sulfate-oxygen isotope temperatures measured for the Seyferth and Leonard's Hot Springs (Table 3).

Two of the Lake City waters show indications of alkali lake mixing. LCGC 1 and LCGC 5 lie on a mixing line between the Lake City values and alkali lake isotopic values (Figure 3). LCGC 5 "dirty outflow to lake" (Sladek et al 2004) in particular displays evidence of mixing with alkali lake waters, with a more enriched ^{18}O signature (Figure 3), and a higher pH (8.3) than other Lake City waters (~7.5) This fluid also displays Na-K-Ca values that are significantly below the values expected for a typical Lake City water. Unfortunately, no SiO₂ analyses exist for this fluid, making it very difficult to calculate saturation for the phases of interest for Q/K modeling.

Fort Bidwell

When compared to other thermal fluids in Surprise Valley, Fort Bidwell waters have a relatively “non-thermal” signature based on low concentrations of B and Cl (Figures 1a, b) and stable isotopic data that plot near the GMWL (Figure 3). Two simple mechanisms for producing such a signature could be 1) cold meteoric water dilution of hot thermal fluid or 2) low temperature heating of cold meteoric waters with limited water rock reaction. Water rock interaction, which is enhanced by high temperatures, produces a shift in fluid oxygen isotope ratio toward heavier values characterizing the rocks. If a hot fluid bearing such a signature was diluted by cold meteoric water, this may have overprint the thermal signature by shifting the isotopic values back toward light, “meteoric” $\delta^{18}\text{O}$ values. Alternatively, this signature could be produced if meteoric water was being heated to temperatures too low to promote significant water-rock interaction. Like isotopic exchange, enrichment of B and Cl in thermal fluids is obtained by thermally enhanced water rock interaction.

Geothermometry values for Fort Bidwell suggest that there is a hot fluid at depth that is being diluted by cold water. When chemical geothermometry temperatures are calculated for Fort Bidwell, the temperatures for the silica polymorph geothermometers are consistently lower than the Na/K/Ca cation geothermometers (Table 1). Because the silica geothermometers are based on total silica concentration, and Na/K/Ca geothermometers are based on cation ratio, the Na/K/Ca geothermometers are less prone to producing erroneously low temperature values when dilution has occurred. The fact that the silica polymorph geothermometers give consistently lower values than the Na/K/Ca geothermometers suggests that cold-water dilution may have occurred as the thermal waters were surfacing near Fort Bidwell.

Cold water dilution can also be inferred from the Q/K plots for Fort Bidwell. When the saturation state for minerals in the Fort Bidwell fluid is calculated as a function of fluid temperature, a convergence of mineral saturation state is found at ~ 180 C. However, the mineral saturation indices cross point occurs below the saturation line (Figure 4a). This suggests that the fluid equilibrating with that mineral assemblage was diluted after equilibration. Multiple models were run with fluid compositions calculated by assuming variable degrees of dilution to look for convergence of mineral saturation state closer to the equilibrium condition. If we assume a 60% dilution of the deep fluid with pure (approximately meteoric) water and calculate the temperature dependence of the minerals in the undiluted fluid, the saturation indices cross at Q/K=1 (saturation equilibrium). The temperatures indicated by these models agree with the results of the silica geothermometers. Quartz crosses the equilibrium line at ~ 125 C in the model run for the original (diluted) sample (Figure 7a), as predicted by the quartz geothermometer for the “dilute” sample. The model run for the fluid prior to a 60% dilution indicates that quartz would be saturated at a significantly higher temperature (180° C), which is more consistent with the Na/K/Ca geothermometer, and more closely aligned with the other Surprise Valley systems.

Personal communication with farmers in the Fort Bidwell area has revealed that the Fort Bidwell thermal springs dry up seasonally in the summer. It is likely that seasonal snowmelt and rainfall from the adjacent Warner Mountains (particularly at elevations similar to Eagle Peak and Cedar Pass, based on stable isotopic data (Figure 3)) is supplying a significant volume of the fluid that is coming up in the springs. The Fandango Fault, (Figure 1) may provide a conduit for fluid infiltration. The details of this flow path may be resolved in the future through frequent sampling of Warner Mountain cold waters and Fort Bidwell thermal springs in order to correlate seasonal shifts in chemical composition and stable isotopic values.

Eagleville:

Similar to Fort Bidwell, B and Cl concentrations for Eagleville are lower than other thermal waters of comparable temperature from around the valley (Figure 1b). Na-K-Ca geothermometers in Eagleville predict temperatures between 61° and 80° C. These values are slightly warmer than the measured surface temperatures of samples (32° to 57° C). Quartz geothermometer temperatures for these waters are 104°-108° C, but temperature calculated assuming chalcedony controls silica at these lower temperatures inferred from the Na-K-Ca are similar (74°-79° C). Stable isotope data for Eagleville area are limited. One sample collected in 1983 from Menlo Bath’s hot spring could be interpreted to show oxygen isotope enrichment (Figure 3), but it differs from a sample collected in 1979, so the significance of these data are questionable. Q/K models do not converge for Eagleville samples. One other notable feature of the Eagleville fluids is their high pH (8.9). The low temperatures calculated for this area, as well as the higher pH, are both reasons to expect that the fluid may not have equilibrated with the rock/alteration minerals at depth, so it may not be surprising that our Q/K models do not show strong convergence.

CONCLUSION:

Waters in the Surprise Valley geothermal system are originating at a maximum of 200° C, with an average Q/K calculated temperature of ~ 175 ° C. Fluids emanating from Fort Bidwell and Eagleville, which are situated on the north and south peripheries of Surprise Valley, show strong chemical evidence for cold water dilution of thermal fluids (Fort Bidwell) and low temperature heating (Eagleville). Springs in these areas are likely being recharged and diluted by meteoric waters from the adjacent Warner Mountains Range, with the Surprise Valley range front fault as a probable conduit for this influx. Fluids emerging in the Lake City and Seyferth/Leonards/ Surprise Valley regions in the central West and East portions of the valley are the hottest and show little evidence for dilution. If there is flow of fluids between these two sub-regions, a west to east flow of fluid is not supported by current stable isotopic data. The geochemical and isotopic data that are presently available do require a subsurface hydrological connection between the Lake City and Seyferth/Leonards/ Surprise Valley hot springs systems along the inferred trace of the LCFZ. Further sampling of cold meteoric waters from the Hays Canyon and Warner Mountain Ranges for stable isotope analysis is necessary to constrain the recharge source and flow path for thermal fluids in the central portion of Surprise Valley. Additionally, seasonal sampling of alkali lake waters would be beneficial for constraining potential mixing relationship between Eagleville thermal fluids and alkali lake waters.

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