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Slightly thermal springs and non-thermal springs at Mount Shasta, California: Chemistry and recharge elevations

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Abstract

Temperature measurements, isotopic contents, and dissolved constituents are presented for springs at Mount Shasta to understand slightly thermal springs in the Shasta Valley based on the characteristics of non-thermal springs. Non-thermal springs on Mount Shasta are generally cooler than mean annual air temperatures for their elevation. The specific conductance of non-thermal springs increases linearly with discharge temperature. Springs at higher and intermediate elevations on Mount Shasta have fairly limited circulation paths, whereas low-elevation springs have longer paths because of their higher-elevation recharge. Springs in the Shasta Valley are warmer than air temperatures for their elevation and contain significant amounts of chloride and sulfate, constituents often associated with volcanic hydrothermal systems. Data for the Shasta Valley springs generally define mixing trends for dissolved constituents and temperature. The isotopic composition of the Shasta Valley springs indicates that water fell as precipitation at a higher elevation than any of the non-thermal springs. It is possible that the Shasta Valley springs include a component of the outflow from a proposed 210°C hydrothermal system that boils to supply steam for the summit acid-sulfate spring. In order to categorize springs such as those in the Shasta Valley, we introduce the term *slightly thermal springs* for springs that do not meet the numerical criterion of 10°C above air temperature for thermal springs but have temperatures greater than non-thermal springs in the area and usually also have dissolved constituents normally found in thermal waters.

Keywords: Mount Shasta; springs; geothermal systems; stable isotopes

1. Introduction

Mount Shasta (elevation 4317 m) is a large (~500 km^3) stratovolcano near the southern end of the Cascades (Christiansen and Miller, 1989). It is built of four major cones ranging in age from younger than 250 ka for the Sargents Ridge cone, younger than 130 ka for the Misery Hill cone, and Holocene for the Shastina and the Hotlum cones. Lavas are predominantly silicic andesite with the latest eruptions within the central craters producing dacitic domes. The volcano hosts numerous springs (Fig. 1) with several large-volume springs emerging at lower elevations (Blodgett et al., 1988). The acid-sulfate spring at the summit is the only clear thermal manifestation

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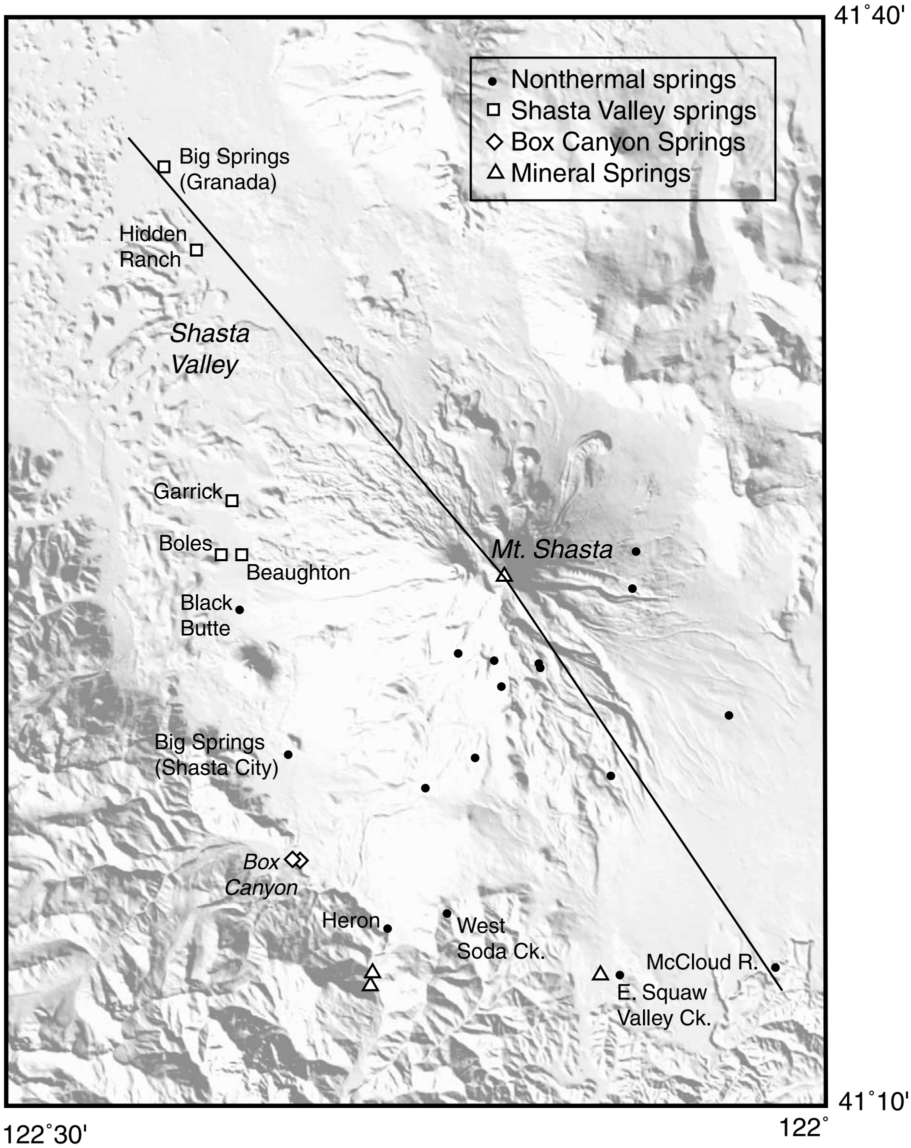

Fig. 1. Shaded relief map showing spring locations at Mount Shasta. Labeled springs discussed in text. Beaughton Creek Spring is part of Shasta Valley springs but is also a non-thermal spring. Line of section shown for Fig. 11.

of an underlying hydrothermal system, though Waring (1915) noted that Big Springs in the Shasta Valley 'yields a large flow of water that is noticeably above the normal temperature'. The purpose of this study is to use temperature measurements, isotopic contents, and dissolved constituents for springs on Mount Shasta and vicinity to show that there is an input of hydrothermal fluid into the slightly thermal springs in the Shasta Valley north of Mount Shasta. Thus there is a hydrothermal system at Mount Shasta, but its existence is masked by dilution of thermal water with cold ground water. These data are also used to show that springs high on Mount Shasta generally circulate to shallow depths, but that some springs at lower elevations have long circulation paths from higher elevations (Ingebritsen et al., 1992; Rose et al., 1996; James et al., 1999).

In studying the characteristics of springs, it is important to be clear on the terminology. A special class of springs known as *thermal springs* are ones 'whose water has a temperature appreciably above the mean annual temperature of the atmosphere in the vicinity of the spring' (Meinzer, 1923, p. 54). Meinzer does not define *appreciable*. Meinzer (p. 55) goes on to state that: '*Nonthermal springs* may be divided into (1) those whose waters have temperatures approximating the mean annual temperatures of the atmosphere in the localities in which they exist, and (2) those whose waters are appreciably colder.' The second group of non-thermal springs are *cold springs*. Waring (1965, p. 4) agrees with Meinzer that any spring that 'is noticeably above the mean annual temperature of the air at the same locality may be classed as thermal' but uses 15°F (8.3°C) above mean annual temperature of the air to define thermal springs in the United States. Reed (1983, p.2) in the U.S. Geological Survey's assessment of low-temperature geothermal resources of the United States uses a minimum temperature function that is 10°C above the mean annual temperature at the surface and increases with depth by 25°C/km to define low-temperature geothermal resources. In most situations, the question of using a numerical temperature criterion for thermal springs is not important, because measured temperatures are sufficiently anomalous. In the Cascade Range, however, large quantities of cold ground water mix with thermal water, making the magnitude of the temperature anomalies very small (e.g. Nathenson, 1990). To cover this situation, the term *slightly thermal springs* is introduced for springs that do not meet the numerical criterion of Reed (1983), but have temperatures greater than non-thermal springs in the area and usually also have dissolved constituents normally found in thermal waters. *Mineral springs* are ones whose water contains sufficient dissolved constituents (greater than about 500 mg/l total dissolved solids) to give it a definite (frequently unpleasant) taste.

In the next section, we present data on air temperatures to define the background for comparison to spring temperatures at Mount Shasta. Data for ground temperatures from drill holes are used to show that ground and air temperatures are approximately the same in the vicinity of Mount Shasta. Temperature, specific conductance, and isotopic data are presented for springs to develop the characteristics of non-thermal and slightly thermal springs. The two following sections describe additional features of the slightly thermal springs in the Shasta Valley, of mineral springs in the area, and of the springs in Box Canyon.

2. Temperature, chemistry, and isotopes of springs

The definitions for thermal spring use mean annual air temperature, because there are abundant data available from weather stations. Fig. 2 shows the locations of weather stations in the vicinity of Mount Shasta with 30-yr records, and Fig. 3 shows a plot of the mean annual temperature versus elevation (National Oceanic and Atmo-

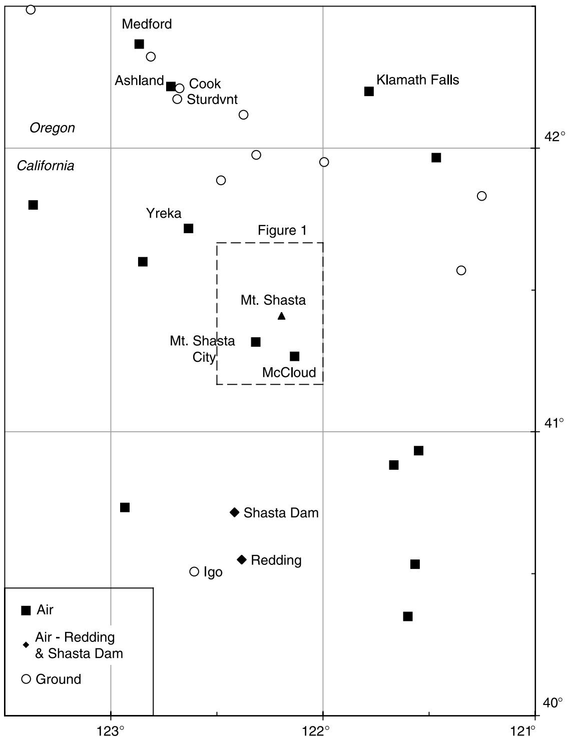

Fig. 2. Map of weather stations (National Oceanic and Atmospheric Administration, 1982a,b) and drill hole locations in the vicinity of Mount Shasta.

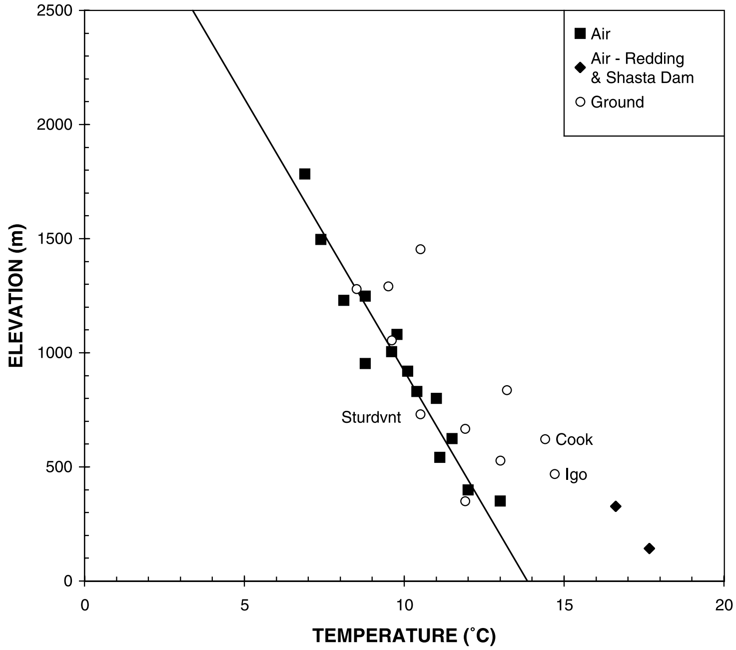

Fig. 3. Plot of air (National Oceanic and Atmospheric Administration, 1982a,b) and ground temperatures (Table 1) versus elevation for the sites in Fig. 2. Data for Redding and Shasta Dam weather stations are shown with different symbols and not included in the least-squares fit to the air temperatures.

spheric Administration, 1982a,b). The data for air temperatures define a good straight line except for data for weather stations at Redding and Shasta Dam. These two stations are located in the northern Sacramento Valley, and we assume that the normal lapse rate is different within the valley. The lapse rate for the decrease in air temperatures with elevation is 4.2°C/km, agreeing with the usual value for the variation in ground temperature of 4°C/km for wet climates as given by Delisle (1988).

Conceptually, a more appropriate quantity for

Table 1
Ground temperatures for drill holes in the vicinity of Mount Shasta obtained by projecting temperature as a function of depth to the surface

Name	Location ID no.	Latitude	Longitude	Elev. m	Temp. °C
Phoen-BL	T37S/R1W/27Cb	42°19.4′	122°48.7′	529	13.0
Cook	T39S/R1E/2Bc	42°12.7′	122°40.6′	622	14.4
Sturdvnt	T39S/R1E/15Cdb	42°10.4′	122°41.3′	731	10.5
Corral Creek	T40S/R4E/5Db	42°7.1′	122°22.5′	1055	9.6
Grants Pass	GRP	42°29.3′	123°22.7′	350	11.9
Igo, CA	Igo	40°30.5′	122°36.5′	470	14.7
Sheep Camp	MP08	41°34.2′	121°21′	1280	8.5
Clear Lake Hills	MP32	41°49.9′	121°15.1′	1455	10.5
Copco Lake	MP55	41°58.6′	122°18.9′	838	13.2
Klamath River #1	MP56	41°53.2′	122°28.9′	668	11.9
W&PR Dorris Obs.	MP60	41°57.1′	121°59.7′	1292	9.5

Data from Blackwell et al. (1982, 1986), Hull et al. (1978), and Mase et al. (1982).

comparison to spring temperatures is the average ground temperature at the surface (Nathenson, 1990). Average ground-temperature values can be calculated by projecting temperature versus depth data obtained in drill holes back to the surface. A search was made to find drill hole data for calculating average ground temperatures for the area of Fig. 2. Data from many drill holes indicate either hydrologic disturbances or near-surface disturbances that are not easily understood. Data from 11 drill holes were found to be easily used for extrapolation, and the results are given in Table 1 with locations shown in Fig. 2 and the results in Fig. 3 (Blackwell et al., 1982, 1986; Hull et al., 1978; Mase et al., 1982). The distribution of ground temperatures is generally similar to that for air temperatures (Fig. 3).

Some values for ground temperatures are higher than the air temperature data. The drill hole at Igo is located near Redding, and its higher temperature probably reflects the same warming in the Sacramento Valley as in the air-temperature data for Redding. The Cook drill hole is near Ashland, and the Sturdvnt drill hole is located nearby but has a projected ground-temperature value close to the air line. Thus, the difference in temperature for the Cook drill hole compared to the Sturdvnt drill hole seems to be a microclimate effect. The lapse rate for the ground-temperature data is −4.1°C/km, very close to that for the air-temperature data. The intercept for the ground-temperature data is 1.2°C higher than the intercept for the air-temperature data. Overall, comparing spring temperatures to air temperatures is similar to comparing to ground temperatures in this particular area, and the air line will be used to compare to spring temperatures, because it is based on more data with less scatter.

Locations of springs sampled in this study are shown in Fig. 1. Anticipating the results, they have been grouped into non-thermal springs, Shasta Valley springs (four of which are slightly thermal), Box Canyon springs, and mineral springs (Table 2). Fig. 4 shows a plot of temperature versus elevation along with the air line from Fig. 3. At the higher elevations (above 2350 m), temperatures are close to the air line but are lower at intermediate elevations. The intermediate-elevation springs (1400–2100 m) probably meet the definition of cold springs, but they are not really different from the higher-elevation springs (see below). A least-squares line for the data from the higher- and intermediate-elevation springs is shown as a broken line in Fig. 4. The lower-elevation springs (below 1200 m) have a considerable spread in temperatures. The data for the five of the six springs shown as filled circles along with Beaughton Creek Spring shown as an open square form a group for the low-elevation springs that meet the definition of non-thermal springs, but these springs are warmer than the trend line from the springs at higher elevations. The springs from the Shasta Valley (except for Beaughton Creek Spring) are all slightly warmer than air temperature. The mineral springs have temperatures above and below air temperature for their elevation.

Additional perspective on the characteristics of springs can be obtained from a plot of specific conductance versus elevation (Fig. 5). The higher- and intermediate-elevation springs follow a single trend with elevation, whereas the lower-elevation springs have a higher specific conductance than the trend line, indicating that they are more concentrated. The Shasta Valley springs (other than Beaughton Creek) and the mineral springs have much higher conductances than can be shown on the plot. The temperature of West Soda Creek Spring is higher than air temperature (Fig. 4), but its specific conductance is on the same trend as the high- and intermediate-elevation springs (Fig. 5).

The consistent patterns of increasing temperature and specific conductance with decreasing elevation are brought together in a plot of temperature versus specific conductance (Fig. 6). Nearly all of the springs categorized as non-thermal (including Beaughton Creek Spring) follow a single relation of increasing conductivity with increasing temperature. The mechanism for this behavior is weathering of volcanic rock, with increased weathering related to higher temperatures (and increased carbon dioxide in the soil zone?) with decreasing elevation (Nathenson and Thompson, 1990). Although the data for lower-elevation non-thermal springs deviate from the higher-elevation

Table 2
Water chemistry and isotopic data for springs on and in the vicinity of Mount Shasta collected in August and September 1992

Sample no.	Name	Lat.	Long.	Elev. m	Flow l/s	Temp. °C	Field pH	Lab pH	SiO_2 mg/l	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	NO_3	B	Li	Cond. µS/cm	δD ‰	$\delta^{18}O$ ‰
	Non-thermal springs																						
JSa-92-21	McCloud River Sp.	41°13.8′	122°1.8′	939	5700	6.8	7.28	6.49	29.7	6.9	5.38	3.8	1.7	57	0.18	0.02	0.01	< 0.01	< 0.001	< 0.01	92	−96	−13.0
JSa-92-15	East Squaw Valley Ck. Sp.	41°13.6′	122°7.5′	933	42	7.1	6.51	6.10	40.0	5.5	3.14	3.9	3.0	44	1.85	1.24	0.01	1.80	0.06	< 0.01	82	−93	−13.0
JSa-92-14	West Soda Ck. Sp.	41°15.3′	122°13.8′	1170	2.4	10.1	6.65	6.34	14.4	3.8	0.90	2.4	0.3	15.9	2.5	0.05	0.03	< 0.01	0.05	< 0.01	37	−84	−12.1
JSa-92-26	Heron Spring	41°14.9′	122°16.0′	878	16	7.2	6.44	6.51	46.3	8.4	4.44	6.9	2.8	64	1.00	1.69	0.45	0.35	0.01	< 0.01	103	−96	−13.4
JSa-92-18	Widow Spring	41°20.8′	122°3.5′	1408	8.9	3.9	6.50	6.03	51.1	4.3	1.27	4.0	1.9	30.6	0.07	0.20	0.02	0.75	< 0.001	< 0.01	51	−90	−12.8
JSa-92-17	Intake Springs	41°19.1′	122°7.8′	1402	13	5.4	6.47	6.45	34.1	3.2	1.07	2.7	1.6	23.2	0.28	2.31[a]	0.65	0.05	0.03	< 0.01	37	−94	−13.1
JSa-92-9	McGinnis Springs	41°19.6′	122°12.8′	1768	0.8	4.5	5.96	5.53	30.9	4.1	0.34	2.5	1.2	23.3	0.10	0.11	0.05	< 0.01	< 0.001	< 0.01	34	−94	−13.3
JSa-92-8	Big Canyon Ck. Sp.	41°18.8′	122°14.6′	1512	20	4.4	6.48	5.83	32.2	4.6	0.89	2.4	1.5	27.7	0.20	0.12	0.26	< 0.01	< 0.001	< 0.01	43	−102	−13.8
JSa-92-22	Big Springs (Shasta City)	41°19.7′	122°19.6′	1097	420	6.8	6.71	6.70	53.4	3.7	3.18	7.9	1.7	47.6	0.42	0.45	0.07	0.20	< 0.001	0.01	81	−107	−14.5
JSa-92-19	South Brewer Ck. Sp.	41°25.3′	122°6.9′	2045	1.2	2.5	6.48	6.01	41.0	3.4	0.39	2.8	2.0	22.4	0.11	0.20	0.30	0.03	< 0.001	< 0.01	36	−102	−14.2
JSa-92-20	North Ash Ck. Sp.	41°24.3′	122°7.1′	2057	9.4	2.6	6.42	6.33	32.2	2.7	0.44	2.5	1.3	19.5	0.11	0.06	0.02	< 0.01	< 0.001	< 0.01	28	−105	−14.3
JSa-92-29	West Squaw Meadows Sp.	41°22.1′	122°10.4′	2408	0.2	2.9	6.71	5.76	8.7	1.3	0.06	0.8	0.4	7.0	0.09	0.01	0.01	< 0.01	0.01	< 0.01	10.4	−100	−13.9
JSa-92-30	Squaw Meadow Sp.	41°22.2′	122°10.5′	2499	20	1.7	6.94	5.85	14.2	1.5	0.17	1.1	0.7	9.9	0.13	0.01	0.01	< 0.01	< 0.001	< 0.01	14.7	−101	−14.0
JSa-92-5	Green Butte Sp.	41°22.3′	122°12.1′	2621	5.5	1.7	7.31	5.35	11.7	1.1	0.01	1.2	0.9	7.7	0.14	0.09	0.05	0.10	< 0.001	< 0.01	10	−103	−14.3
JSa-92-7	Alpine Lodge Sp.	41°22.5′	122°13.4′	2505	0.2	3.2	6.94	5.14	12.8	1.1	0.02	1.0	0.7	8.1	0.08	0.09	0.03	0.04	< 0.001	< 0.01	11	−104	−14.7
JSa-92-6	Panther Meadow Sp.	41°21.6′	122°11.8′	2353	2.4	2.9	7.36	5.32	15.5	1.0	< 0.01	1.0	0.8	8.0	0.12	0.05	0.01	0.02	< 0.001	< 0.01	13	−100	−14.1
JSa-92-3	Beaughton Ck. Sp.	41°25.2′	122°21.3′	1146	180	7.0	6.64	5.19	51.0	3.4	3.68	9.2	1.6	52	0.84	0.05	0.19	0.29	0.02	0.01	85	−106	−14.6
JSa-92-4	Black Butte Spring	41°23.7′	122°21.4′	1204	35	7.6	6.94	5.93	53.6	4.2	2.94	9.6	2.9	53	0.29	0.12	0.01	< 0.01	0.01	< 0.01	85	−103	−14.1
	Shasta Valley springs																						
JSa-92-2	Boles Ck. Sp.	41°25.2′	122°22.1′	1085	85	10.8	6.62	6.17	65.3	16.4	16.8	20.0	1.6	155	6.3	3.9	0.23	< 0.01	0.08	0.02	225	−110	−15.0
JSa-92-1	Garrick Ck. Sp.	41°26.7′	122°21.7′	1073	48	10.4	6.56	6.41	69.9	18.6	28.4	32.5	2.7	227	13.0	12.8	0.25	4.40	0.27	0.07	398	−111	−15.0
JSa-92-10	Big Springs (Granada)	41°35.9′	122°24.2′	795	560	11.6	6.32	6.27	63.0	11.7	29.0	32.9	3.2	214	4.2	20.1	0.17	1.80	0.35	0.04	394	−112	−15.4
JSa-92-11	Hidden Ranch Sp.	41°33.6′	122°23.0′	820	190	13.9	6.78	6.94	64.0	13.2	32.8	35.3	2.8	269	7.6	16.4	0.22	1.50	0.33	0.05	440	−102	−13.2
	Box Canyon springs																						
JSa-92-23	S-A in Box Canyon	41°16.8′	122°19.2′	963	85	8.2	7.33	7.22	52.0	14.5	13.2	6.0	2.6	127	0.94	4.10	0.56	0.24	0.01	< 0.01	211	−95	−13.0
JSa-92-24	S-C in Box Canyon	41°16.8′	122°19.5′	951	19	9.9	7.42	6.78	38.9	8.7	6.91	4.0	1.8	74	0.70	0.84	0.18	< 0.01	< 0.001	< 0.01	127	−95	−13.0
	Mineral springs																						
JSa-92-16	Soda springs	41°13.6′	122°8.2′	927	0.07	8.7	5.71	6.13	73.3	169	58.7	57.9	6.6	1020	0.12	28.1	0.11	0.11	1.42	0.06	1136	−91	−12.7
JSa-92-28	Cave Spring	41°13.7′	122°16.5′	732	0.11	11.5	5.83	6.25	80.5	132	80.3	426	21.4	1330	0.27	404	0.27	< 0.01	16.0	0.71	2430	−83	−11.1
JSa-92-27	Upper Soda Springs	41°13.3′	122°16.6′	719	0.13	12.2	5.97	6.23	82.7	97	70.4	374	19.8	1180	0.30	332	0.19	< 0.01	14.5	0.63	2210	−83	−11.3
	Acid-sulfate spring																						
Mt. Shasta Sulfur Springs		41°24.6′	122°11.7′	4249		74.0	–		240	72	41	43	10	–	2200	4.5	0.1	0.00	0.3	0.03			
Acid-sulfate spring		41°24.6′	122°11.7′	4249		80	2		–	47	36	43	11	–	2000	< 2	0.4						

Analysts: J.M. Thompson and L.D. White. Data for acid-sulfate spring from Poeschel et al. (1986) and Mariner et al. (1990).

[a] Chloride value probably too high based on data from other springs.

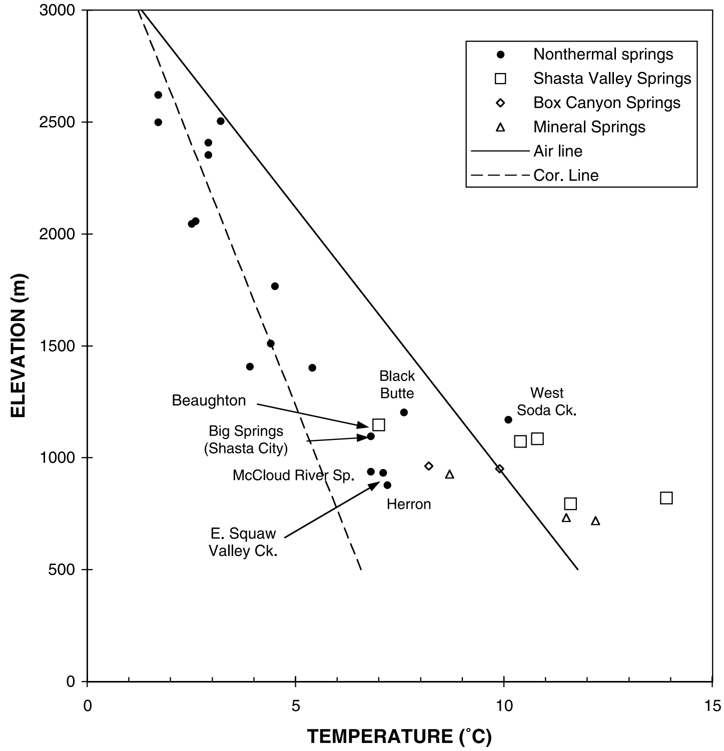

Fig. 4. Elevation versus temperature for springs around Mount Shasta. Air line is from Fig. 3. Correlation (Cor.) line is least squares line for the non-thermal springs above 1400 m in elevation using temperature as the dependent variable.

data on temperature and specific conductance versus elevation plots, the data for these springs on the temperature versus specific conductance plot are on the same trend, indicating that the process is the same. The data for West Soda Creek Spring are off the trend for non-thermal springs (Fig. 6), but its chemistry is generally consistent with its also being produced by weathering (Table 2). The springs in the Shasta Valley (other than Beaughton Creek) do not follow the same relation as the other springs and actually are mostly on a dilution line (see below).

The difference between the lower-elevation springs and the higher-elevation springs on temperature and specific conductance versus elevation plots is because the lower-elevation springs have a longer circulation path, as shown by the isotopic data. Fig. 7 shows deuterium versus oxygen-18 (reported as per mil deviations from VSMOW (Gonfiantini, 1978)) along with the global meteoric water line of Craig (1961). All the samples fall near the meteoric water line except for Hidden Ranch Spring. The data for Hidden Ranch Spring (Fig. 7) indicate that it is probably enriched by evaporation compared to the other slightly thermal springs in the Shasta Valley. The oxygen-18 data are plotted versus elevation in Fig. 8 (deuterium data show a similar behavior). The isotopic composition of precipitation decreases (more negative values) with increasing elevation (Dansgaard, 1964). Assuming that some springs are recharged at elevations only somewhat above their discharge elevations, the samples having the highest oxygen-18 values for a given elevation are used to define the line for local precipitation (fitted by eye) in Fig. 8 (Ingebritsen et al., 1992; Rose et al., 1996). The slope of the line is −0.14‰/100 m, somewhat less than the value of −0.23‰/km found by Rose et al. (1996) for the area north of Lassen Peak to the southeast of Mount Shasta and lower than the worldwide average of −0.2‰/100 m (Bowen and Wilkinson, 2002). The low-

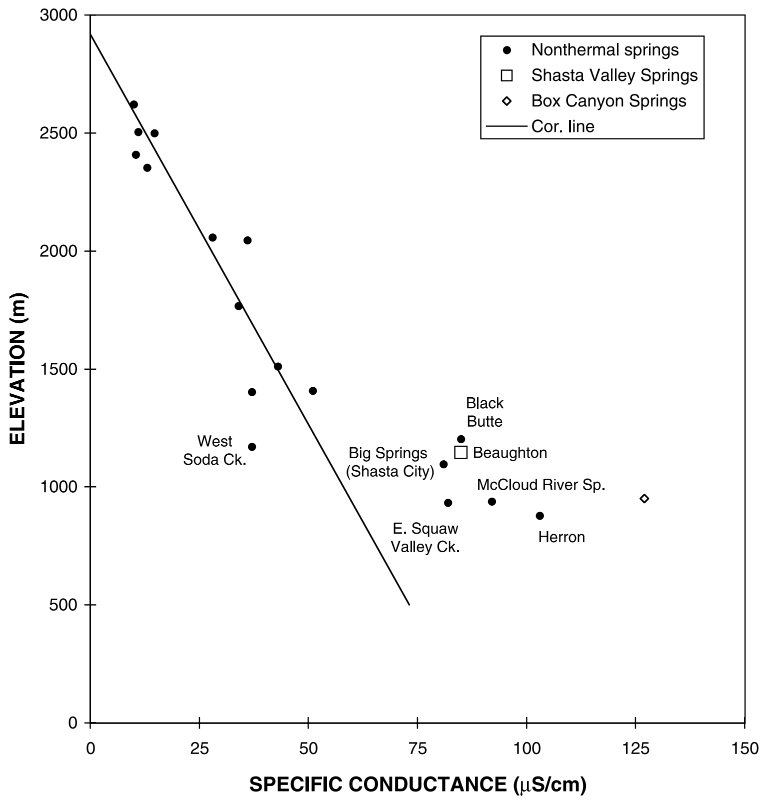

Fig. 5. Elevation versus specific conductance for springs around Mount Shasta. Correlation (Cor.) line is least-squares line for the non-thermal springs above 1400 m in elevation using conductance as the dependent variable. Mineral springs are not shown as their values are beyond the range of the plot.

elevation springs plot significantly below the line for local precipitation in Fig. 8, indicating that the water fell as precipitation and probably recharged the ground-water system at higher elevations. For example, projection of a vertical line from the $\delta^{18}O$ value for Big Springs (Shasta City) intercepts the isotope–elevation line at an elevation of about 2800 m. Thus, most of the higher- and intermediate-elevation springs satisfy a model with a series of local circulation paths, but the low-elevation springs have long circulation paths with most of the water from precipitation at higher elevations (James et al., 1999).

This difference in circulation paths is confirmed by carbon isotope data in Rose and Davisson (1996). They found that alpine creeks at higher elevations on Mount Shasta have ^{14}C contents in bicarbonate of about 110 PMC (percent modern carbon), indicating a source that has modern carbon, and the $\delta^{13}C$ content indicates varying amounts of biogenic (soil zone) to atmospheric sources for the carbon. For Big Springs McCloud (either the same or a nearby spring to the McCloud River Spring sampled in this study), their ^{14}C value is 90 PMC, and the ^{14}C and $\delta^{13}C$ data indicate that the carbon in bicarbonate is a mixture between biogenic carbon with modern ^{14}C activity and carbon with a value similar to local soda springs with no ^{14}C activity. The difference in ^{14}C activity between the alpine creeks and Big Springs McCloud indicates that around 20% of the carbon in Big Springs McCloud is from a source with no ^{14}C activity. Rose and Davisson (1996) interpret the $\delta^{13}C$ values for local soda springs (−9.5‰ and −11.7‰ as scaled from their figure 1) to be the same as magmatic carbon,

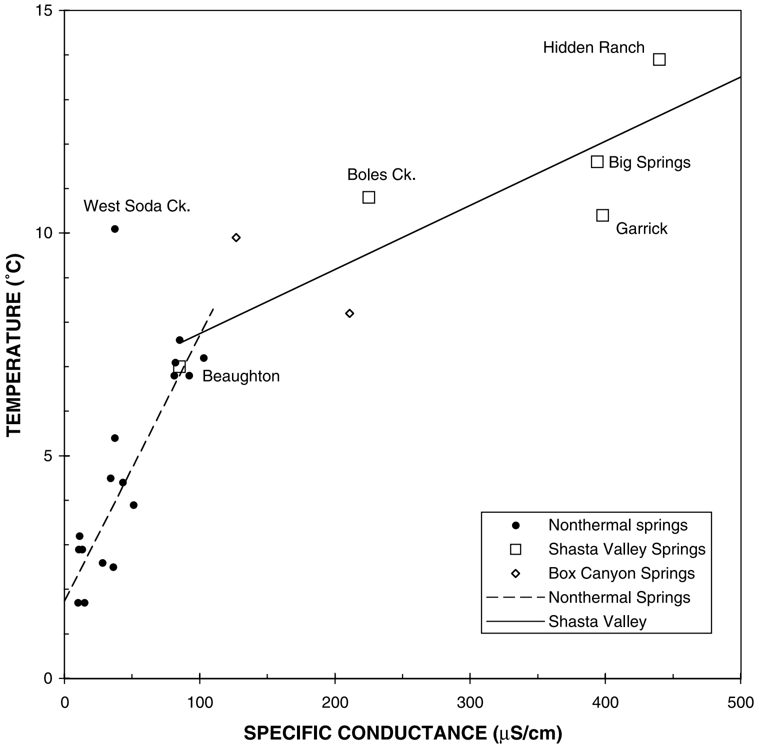

Fig. 6. Temperature versus specific conductance for springs around Mount Shasta. Correlation line for non-thermal springs includes all data for non-thermal springs except for West Soda Creek Spring. Correlation line for Shasta Valley springs includes Beaughton Creek Spring.

but it is not necessarily true that the source of the magmatic carbon in the soda springs is from the current magmatic system at Mount Shasta. In any case, the longer circulation path of the low-elevation springs allows carbon to be dissolved from a deeper source that is not biogenic or atmospheric in origin. This carbon with a magmatic signature has no associated sulfate or chloride (Jsa-92-21 McCloud River Spring, Table 2), and the carbon is being added without other gases normally associated with magmatic carbon dioxide. The dominant anion in the water of McCloud River Spring is bicarbonate, and the elevated specific conductance of the water from this and other low-elevation springs compared to the trend for the intermediate- and high-elevation springs (Fig. 5) indicates that more carbon dioxide was dissolved in the water while undergoing reaction with rock to produce more bicarbonate. This greater amount of carbon dioxide along with part of it being from a source with no modern ^{14}C activity supports the notion that water probably circulates to a significant depth within the volcano. The slightly anomalous temperature of this and other low-elevation springs compared to the trend for the intermediate- and high-elevation springs (Fig. 4) also supports the interpretation of a deeper circulation path, but the source of the thermal energy is most likely conductive heat transfer rather than any active process involving a hydrothermal system. Given the geometry of high-elevation recharge and flow within the volcanic edifice, the source of the carbon dioxide is likely to be degassing from the Mount Shasta magmatic/hydrothermal system with the gases associated with sulfur and chloride removed by gas scrubbing (Symonds et al., 2001).

Quantifying the amount and source of thermal energy added to the springs discharging at low elevation that started circulating at high eleva-

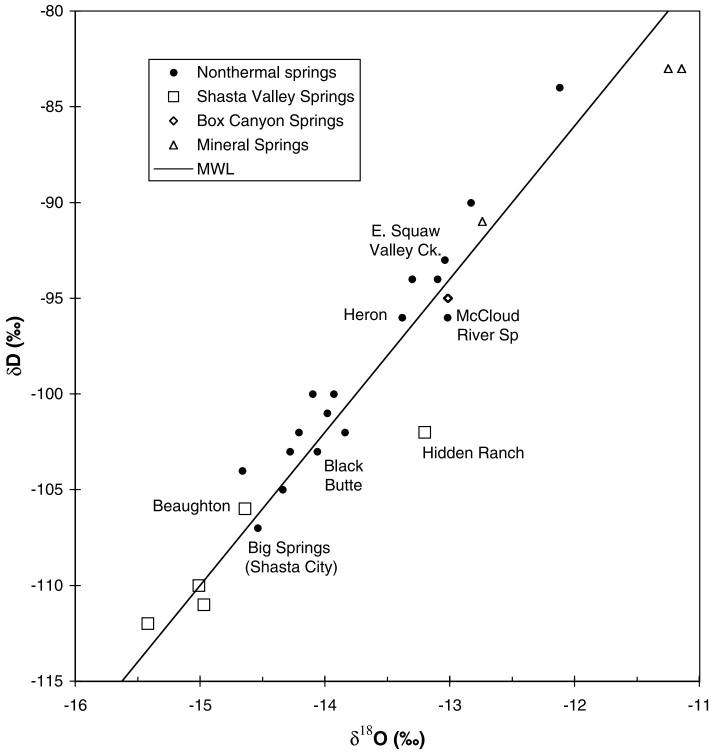

Fig. 7. Deuterium (δD) versus oxygen-18 ($\delta^{18}O$) for springs around Mount Shasta along with global meteoric water line of Craig (1961).

tions presents some issues. Manga (1998) and James et al. (2000) propose calculating the thermal energy from the difference in discharge and recharge temperatures (using isotopes to determine recharge elevation) and then go on to assign the source of the thermal energy to geothermal heating. However, the temperature of the ground surface is determined by a balance between incoming solar energy and the outgoing ground radiation (Watson, 1975). If these radiative fluxes are out of balance, heat fluxes comparable to typical geothermal values can go into the ground. Given the increase in ground-surface temperature of 4.2°C/km from high to low elevations, temperature differences between the water flowing underground and the ground surface could result in warming the water from the heat flux into the ground needed to maintain equilibrium between incoming solar energy and the outgoing ground radiation. For example, for a heat flux into the ground of 30 mW/m^2 and a thermal conductivity for andesite of 3 W/(m K), the temperature differences between the surface and water flowing in the ground need only be 0.2, 1, 2, and 3°C at depths of 20, 100, 200, and 300 m. McCloud River Spring is cooler than air temperature at its discharge elevation by about 3°C, and it could be receiving significant thermal energy during its flow from high to low elevation. The addition of thermal energy to the ground surface from solar energy may explain the calculations of James et al. (2000) requiring the capture of all conductive heat flow in the recharge area to add the thermal energy necessary to obtain the measured temperature of the Metolius River. For most purposes, the calculation of thermal energy is more appropriately done using the temperature of the spring differenced from a reference temperature for springs at the same elevation that do not appear to be anomalous.

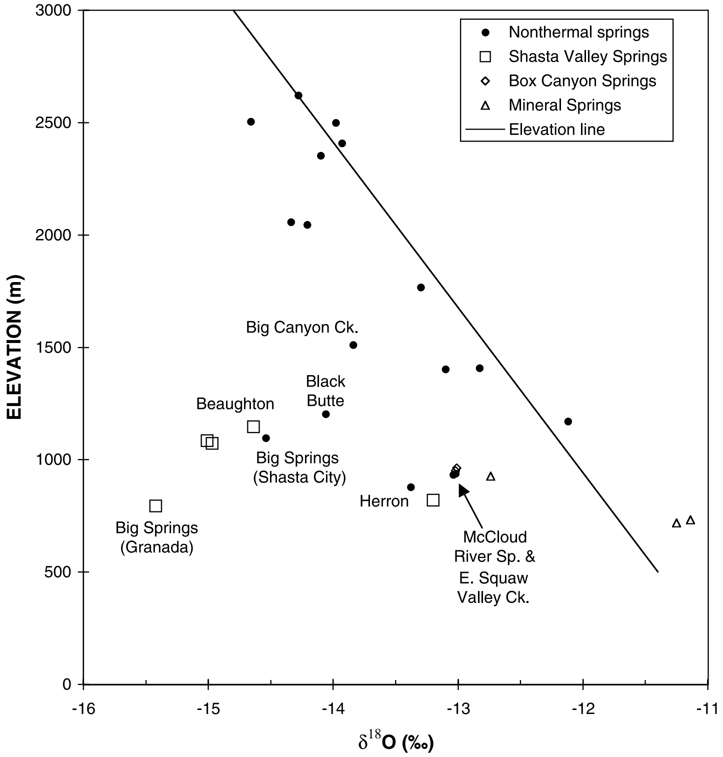

Fig. 8. Elevation versus oxygen-18 ($\delta^{18}O$) for springs around Mount Shasta. Elevation line picked to match highest values. Uncertainty in oxygen-18 is ± 0.2‰.

3. Shasta Valley springs

The Shasta Valley springs Garrick, Big Springs (Granada), Hidden Ranch, and Boles Creek have a clear signature of added constituents from a hydrothermal system. These springs have very similar chemistry, most of the differences being related to dilution as demonstrated in the plot of silica versus specific conductance (Fig. 9). The non-thermal springs (including Beaughton Creek Spring in the Shasta Valley) show a reasonably linear relation of increasing silica concentrations with increasing specific conductance that most likely reflects the degree of reaction with carbon dioxide, the major anion being bicarbonate. The Shasta Valley springs define a different trend in Fig. 9, indicating varying amounts of dilution by a low salinity water such as that in Beaughton Creek Spring. (The mixing relations are somewhat confused for sulfate and chloride, but this may be partly related to analytical uncertainties for these constituents.) Compared to the non-thermal springs, the Shasta Valley springs contain substantial amounts of bicarbonate, sulfate, and chloride (Table 2) indicating that the more saline component is likely to have involved a high-temperature reaction with volcanic rock and gases assuming that the circulation path does not go into older plutonic and metamorphic rock likely to exist under Mount Shasta. Weathering of volcanic rock does not add amounts of chloride or sulfate beyond that found in precipitation (e.g. Nathenson and Thompson, 1990). Amounts of magnesium in the Shasta Valley springs increase linearly with specific conductance (Table 2). Since thermal water normally has very small amounts of magnesium (Fournier and Potter, 1979), the increasing magnesium indicates that any more concentrated water supplying these springs would have had to undergo low-temperature reaction to add magnesium before being diluted. Dilution of the Shasta Valley springs by a low-salinity water

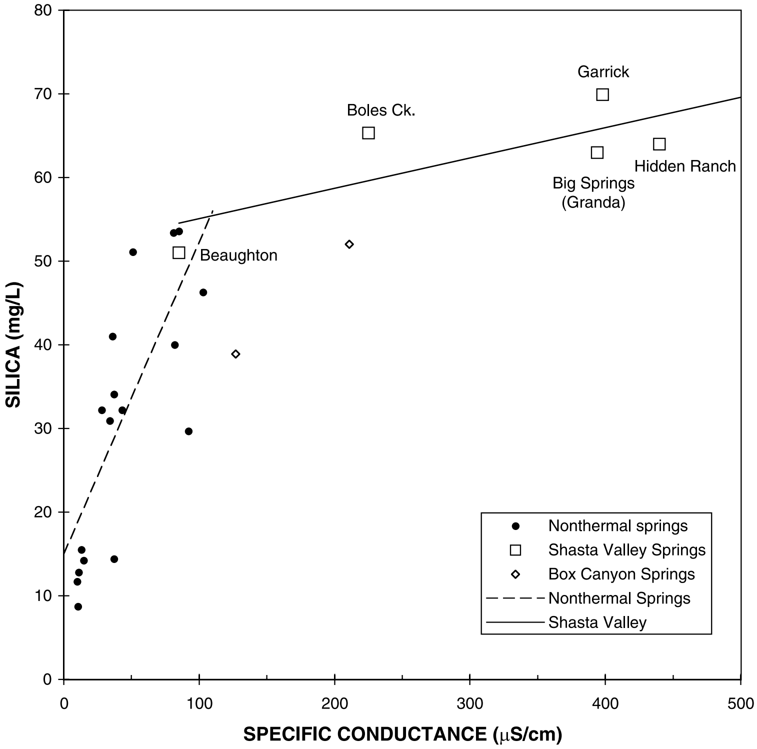

Fig. 9. Silica versus specific conductance for springs around Mount Shasta. Correlation line for non-thermal springs includes all data for non-thermal springs. Correlation line for Shasta Valley springs includes Beaughton Creek Spring.

is also supported by isotopic data. A good mixing line is defined by Beaughton Creek and three of the springs in a plot of oxygen-18 versus conductance (Fig. 10). The lowest value of oxygen-18 for the Shasta Valley springs is for Big Springs (Granada), and its value indicates a recharge elevation of over 3000 m (Fig. 8). Hidden Ranch is off trend in Fig. 10, but the isotope plot in Fig. 7 shows that isotopes of Hidden Ranch have been enriched by evaporation.

Although the chemistry of the Shasta Valley springs is dominated by mixing, the exact relation is more complicated, as shown by the temperature versus specific conductance plot in Fig. 6. The data show a significant uncertainty in defining a mixing line between thermal energy and specific conductance. Some of this uncertainty may be caused by differences in flow path. Boles Creek and Garrick springs are near the city of Weed, whereas Hidden Ranch Spring is about 13 km north and Big Springs (Granada) a further 5 km north. The topographic gradient makes it unlikely that underground flow below Boles and Garrick feeds Hidden Ranch and Big Springs (Fig. 1), and there are probably multiple flows from Mount Shasta feeding the two discharge areas. Possible additional factors are the effect of evaporation on the temperature of Hidden Valley Spring and changes in the flow of Big Springs in response to irrigation (Mack, 1960, p. 43).

The maximum temperature of the more saline water feeding the Shasta Valley springs is not clear. The relation of silica to enthalpy at the discharge temperature for the Shasta Valley springs is not a well defined linear trend, and it is hard to justify using it with the silica geothermometer to estimate a reservoir temperature for these springs. The discharge of thermal energy of the four springs in the Shasta Valley above a 7°C reference value found in Beaughton Creek Spring is about 18 MW_t. This amount is larger than most thermal spring systems in the Cascades (Mariner

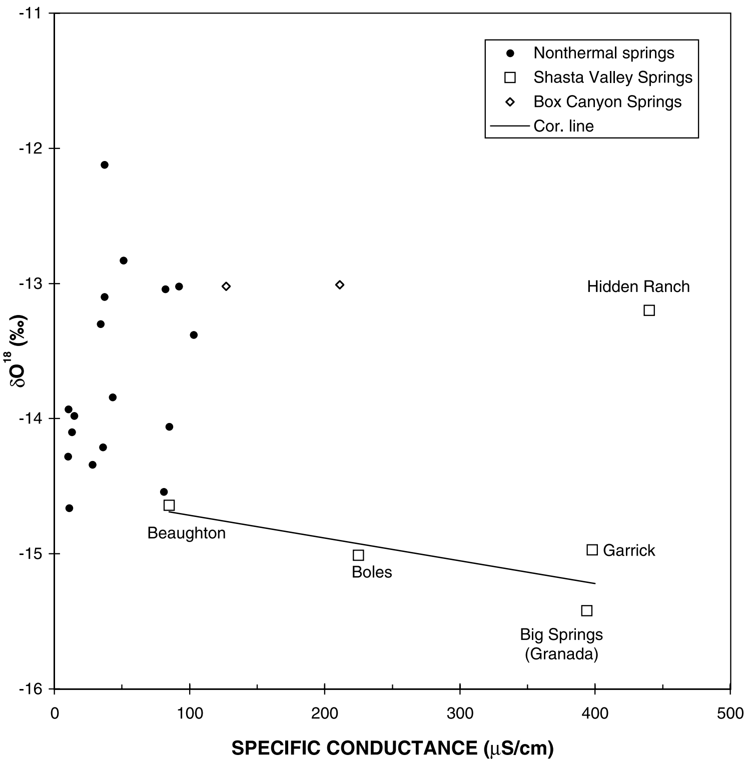

Fig. 10. Oxygen-18 versus specific conductance for springs around Mount Shasta. Correlation line does not include Hidden Ranch Spring.

et al., 1990) but only one fourth of the convective heat discharge of the Wood River group of springs south of Crater Lake (Nathenson et al., 1994). The actual discharge of thermal energy in the Shasta Valley is probably much larger, as a number of wells have the same chemistry as the springs (data in Mack, 1960) indicating that there is subsurface flow of thermal water that may not discharge in springs. In addition, measurements indicate that Big Springs Creek has water flowing into its streambed before it enters the Shasta River (Mack, 1960, pp. 58–59), and the added flow, if identical to that in Big Springs, could add another 20–30 MW_t.

Given the amount of thermal energy discharging in the Shasta Valley springs, it is possible that the spring at the summit of Mount Shasta is from the steam discharge from a hydrothermal system whose liquid discharge appears in the Shasta Valley. Analyses in Table 2 (Mariner et al., 1990; Poeschel et al., 1986) show that the summit spring is an acid-sulfate type water produced by steam and gases flowing into locally derived water and dissolving rock adjacent to the spring. This acid dissolution results in water chemistry that cannot be used to derive temperatures from geothermometers based on water chemistry. However, gases associated with the flow of steam can yield geothermometer temperatures. Table 3 gives a number of gas analyses for this spring along with temperatures from the D'Amore and Panichi (1980) gas geothermometer. The gas composition is quite constant through time, and the geothermometer temperatures are all around 210°C, indicating that the steam discharge is from a high-temperature hydrothermal system. The helium isotopic value referenced to air is 6.23 (Welhan et al., 1988), indicating a mantle component as the source of the helium in the gases associated with the steam. Because we have no sample of the

Table 3
Gas concentrations without water in mol% for samples from the spring near the summit of Mount Shasta

Date	Sample no. or desc.	Temp. °C	CO_2	H_2S	H_2	CH_4	N_2	O_2	He	Ar	T_{DP} °C
8/12/78	SG-78-2	73	82.1	0	1.06	0.14	14.0	3.31			
Recalculated analysis[a]			97.4		1.26	0.17	1.9	0			
1980	Residual gas[b]				19.4	21.7	58.7		0.0103	0.156	
Recalculated analysis[c]			95	0.3	0.91	1.02	2.76		0.00048	0.0073	
7/21/81	810721-2	83	94.7	0.194	1.12	0.753	2.91	0.329	< 0.0001	0.0186	208
7/21/81	810721-3	83	95.7	0.224	0.92	0.845	2.30	< 0.0001	< 0.0001	0.0105	204
7/29/84			94.01	0.22	1.28	1.10	2.67	0.08	< 0.005	< 0.01	210
8/16/91			96.65	0.24	1.14	0.992	2.17	0.040	0.0002	0.0030	208
8/23/94			95.34	0.30	1.17	0.967	2.15	0.0025	< 0.0002	0.0009	212
8/15/96	960815-1	82	95.01	0.391	1.142	1.105	2.34	0.0044	0.000560	0.00351	214
8/15/96	960815-2	82	95.04	0.342	1.155	1.128	2.33	0.0055	0.000342	0.00486	212

Sample for 1978 collected by Leigh Golden and analyzed by N. Nehring. 1980 data from Welhan et al. (1988). 1981 samples collected by T. Casadevall and analyzed by D.S. Sheppard (unpublished data, 1983). Samples for 1984, 1991, and 1994 from Mariner et al. (2003). Samples for 1996 from unpublished data from R. Symonds and C.J. Janik (1998). Geothermometer temperatures T_{DP} from D'Amore and Panichi (1980). Geothermometer uses concentrations of CO_2, H_2S, H_2, and CH_4.

[a] Analysis recalculated by using oxygen to remove air contamination.

[b] $^3He/^4He$ ratio R divided by that for air, $R/R_A = 6.23$.

[c] Analysis recalculated assuming representative values for carbon dioxide and hydrogen sulfide.

water phase from the hydrothermal system that boils to produce the gases feeding the spring at the summit of Mount Shasta, it is only possible to make an indirect case that this is the system that feeds the thermal component of the Shasta Valley springs.

4. Mineral springs and Box Canyon springs

The temperature versus elevation data for the non-thermal springs provide some context for characterizing mineral springs. The temperatures of the three mineral springs range from being near

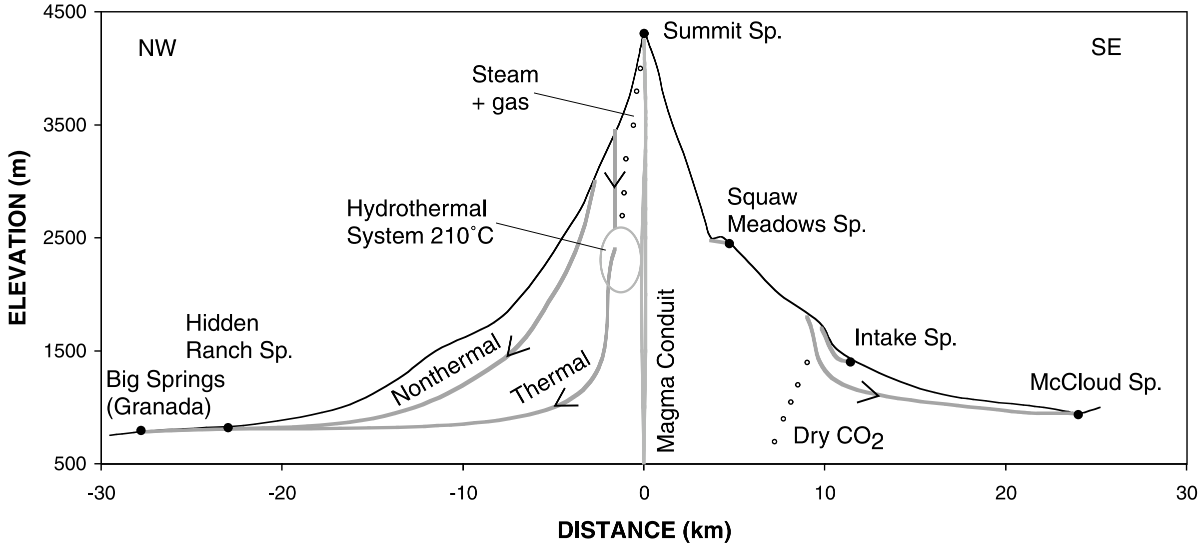

Fig. 11. Cross section from Fig. 1 showing topography with approximately 6:1 vertical exaggeration. Recharge elevations from isotope data. Shape of proposed hydrothermal system at true scale is thin and wide.

the group of low-elevation springs to just above the air line (Fig. 4). Cave Spring (11.5°C, specific conductance 2430 μS/cm, Table 2) discharges from a spring box just in front of the cave from which it takes its name. Inside the cave, there is an additional discharge of water with a conductivity of 106 μS/cm and a temperature of 10.3°C, and this difference indicates that Cave Spring does have slightly elevated temperature. Soda Springs has isotopic values that are on the meteoric water line, whereas Cave Spring and Upper Soda Springs may have a slight isotopic shift to values of oxygen-18 to the right of the meteoric water line (Fig. 7). The plot of isotopes versus elevations (Fig. 8) shows that Soda Springs is recharged by water a few hundred meters higher in elevation while the other springs seem to have very local recharge; however, the water supplying the mineral springs could be much older and follow a different meteoric water line than that supplying the non-thermal springs. All three springs have $\delta^{13}C$ contents of -12.0‰, similar to the values reported by Rose and Davisson (1996, Fig. 3) for mineral springs near Mount Shasta. Barnes et al. (1981) present data for Shasta Soda Spring, located about 2 km north of Cave Spring sampled by us. Shasta Soda Spring is more concentrated in dissolved constituents. The spring has a temperature of 13°C, slightly above the 12.2°C temperature of Upper Soda Spring, and this value does represent a slightly elevated temperature. The deuterium content for Shasta Soda Spring is about right for its elevation, but its oxygen-18 content is shifted by 1.7‰ to the right of the meteoric water line. That the water supplying Cave Spring, Upper Soda Springs, and Shasta Soda Spring appears to be from local recharge suggests that the carbon dioxide is flowing upwards locally, dissolving in water, and reacting with rock. The source of this carbon dioxide may not be related to the current magmatic system at Mount Shasta, because the mineral springs are at and beyond the edge of Mount Shasta's cone. The temperatures for Cave Spring, Upper Soda Springs and Shasta Soda Springs are above those for non-thermal springs and, along with their high dissolved solids contents, qualify them as slightly thermal springs; however, their dominant characteristic is their high mineral content rather than their slight excess in temperature.

The springs in Box Canyon are somewhat difficult to interpret. Spring C is similar in chemistry to other low-elevation springs, e.g. the McCloud River Spring (Table 2). However, its temperature of 9.9°C is higher than Spring A at 8.2°C that has substantially higher dissolved constituents. Spring C has a weir box and enters a pond from a culvert covered by rocks and may not be a natural spring. Spring A is close in temperature to those for other low-elevation springs, but its chemistry is anomalous compared to other low-elevation springs, with chloride, high bicarbonate, and high specific conductance (Fig. 6). However, its silica is not particularly high (Fig. 9) nor does it have much sulfate. Isotopes indicate that both springs were recharged from the same elevation, a few hundred meters above their outflow. Bertoldi (1973) reports data for three more springs further south in Box Canyon located below sewage-disposal ponds. His springs 2 and 3 also have chloride, high bicarbonate, and high specific conductance. The reported temperatures for his springs 1, 2, and 3 decrease with increasing specific conductance and are hard to interpret; however, all three springs have rather low flows. The silica concentration for his spring 3 is anomalous at 67 mg/l, but neither spring 2 nor spring 3 has anomalous silica. A reasonable model for the Box Canyon springs is that their chemistry is largely determined by the action of subsurface carbon dioxide dissolving volcanic rock in a manner similar to the soda springs but to a lesser degree, or that some of the constituents are from older altered volcanic rock (Bertoldi, 1973).

5. Conclusions

Non-thermal springs on Mount Shasta are generally cooler than mean annual air temperatures at the same elevation. The specific conductance (bicarbonate being the dominant anion) increases linearly with spring temperature. Springs at higher and intermediate elevations on Mount Shasta have fairly limited circulation paths, whereas low-elevation springs have longer (and probably deeper) paths because of their higher-elevation recharge (Fig. 11). That the low-elevation springs have longer circulation paths is shown by their slightly higher temperatures and higher specific conductances than would be indicated based on extrapolating the behavior of the high- and intermediate-elevation springs. The longer and probably deeper circulation paths of the low-elevation springs is confirmed by the presence of dissolved carbon with an isotopic signature similar to that from a magmatic system (Rose and Davisson, 1996). The slightly higher temperatures are most likely from conductive heat transfer, because there is no evidence for addition of other magmatic gases normally associated with magmatic carbon dioxide. The source of the heat transfer is probably a combination of geothermal and solar heating.

The Shasta Valley springs are warmer than air temperatures for their elevations and contain significantly more chloride and sulfate than non-thermal springs, constituents normally found in thermal water associated with volcanic systems. Data for the Shasta Valley springs generally define mixing trends for dissolved constituents and temperature, but the data have significant scatter. The differences between springs are probably caused by differences of many kilometers in their points of discharge. The concentration of magnesium increases with specific conductance in the Shasta Valley springs, indicating that the most concentrated water has substantial magnesium. Thermal water usually does not have much magnesium, and it is likely that the water feeding the Shasta Valley springs has undergone low-temperature reactions to add this magnesium. The deuterium and oxygen-18 values of the Shasta Valley springs are lower than of any of the non-thermal springs, indicating that water fell as precipitation at a higher elevation than any of the non-thermal springs (Fig. 11). Although it is quite possible that the Shasta Valley springs could represent the outflow from the 210°C hydrothermal system that boils to supply steam for the acid-sulfate spring on the summit of Mount Shasta (Fig. 11), there is no direct evidence for establishing a connection between these systems. In order to categorize springs such as those in the Shasta Valley, we introduce the term *slightly thermal springs* for springs that do not meet the numerical criterion of Reed (1983) but have temperatures higher than non-thermal springs in the area and usually also have dissolved constituents normally found in thermal waters.

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