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The Geochemistry of Waters from Springs, Wells, and Snowpack On and Adjacent to Medicine Lake Volcano, Northern California

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ABSTRACT

Chemical analyses of waters from cold springs and wells of the Medicine Lake volcano and surrounding region indicate small chloride anomalies that may be due to water-rock interaction or limited mixing with high-temperature geothermal fluids. The Fall River Springs (FRS) with a combined discharge of ~37 m^3/s, show a negative correlation between chloride (Cl) and temperature, implying that the Cl is not derived from a high-temperature geothermal fluid. The high discharge from the FRS indicates recharge over a large geographic region. Chemical and isotopic variations in the FRS show that they contain a mixture of three distinct waters. The isotopic composition of recharge on and adjacent to the volcano are estimated from the isotopic composition of snow and precipitation amounts adjusted for evapotranspiration. Enough recharge of the required isotopic composition (-100 ‰ δD) is available from a combination of the Medicine Lake caldera, the Fall River basin and the Long Bell basin to support the slightly warmer components of the FRS (32 m^3/s). The cold-dilute part of the FRS (~5 m^3/s) may recharge in the Bear Creek basin or at lower elevations in the Fall River basin.

Introduction

Medicine Lake volcano is a large shield volcano consisting of basaltic and rhyolitic rock of Pleistocene and Holocene age located in northern California, about 50 km NE of Mt. Shasta (Donnelly-Nolan, 1988). Recent geothermal exploration and potential development at Medicine Lake volcano has spurred renewed interest in the hydrology of the region, especially the source(s) of recharge to the large-discharge (~37 m^3/s) Fall River Springs (FRS), and any possible connections between the geothermal reservoir and the shallow groundwater system (BLM *et al.*, 1999). In this report, we characterize the chemical and isotope composition of water from springs and wells from Medicine Lake volcano and the surrounding area. Because springs and shallow wells are relatively rare in the area, we also collected 37 snow cores (April 1998) to determine the effect of altitude, latitude, and longitude on δD and $\delta^{18}O$ in precipitation so that we could better constrain the possible source regions of recharge to the FRS. An additional set (49 snow cores) was collected in April 1999. These data provide information on annual variability of δD and $\delta^{18}O$ in snow and additional constraints on our modeling of the sources of recharge to the FRS. Our purpose in this study is to identify possible leakage from the geothermal system beneath Medicine Lake volcano into the shallow groundwater system and to determine if precipitation on Medicine Lake volcano can support discharge from the FRS.

Regional Hydrogeology

Medicine Lake volcano covers an area of about 2000 km^2, has erupted 17 times in the Holocene, and notwithstanding its relatively low elevation (peak is ~2300 m) has erupted more material (~600 km^3) than any other active volcano in the Cascade Range (Donnelly-Nolan, 1990). The volcano is crowned by a Pleistocene-aged caldera that is 10 km x 6 km and contains several small lakes including Medicine Lake (Figure 1). The volcano overlies older basalts and tuffs of Pliocene and Miocene age (Anderson, 1941) that have been disrupted by Basin and Range faulting. Most faults trend N-S or within 30° of north (Donnelly-Nolan, 1990).

Due to the preponderance of young, porous basalts on the volcano, there are very few perennial streams in the region. Almost all precipitation falls as snow and recharge enters the groundwater system during the spring thaw. Although springs are rare in the region, the largest spring group in the state, the FRS, emerge at an elevation of ~1000 m, near the southern edge of Medicine Lake volcano about 55 km south of Medicine Lake caldera (Figure 1). The FRS (Figure 2) are large discharge springs that combine to form the Fall River and its tributaries, Spring Creek, Tule River, Little Tule River, Lava Creek, Ja She Creek and Big Lake (Waring, 1915). The complex of springs is about 13 km across. The enormous discharge from the FRS (~37 m^3/s; 1300 cfs) accounts for ~20% of the water in Shasta Lake and clearly represents output from a large recharge area. The discharge rate of the FRS is not particularly well constrained. USGS data from the early part of the century indicates a discharge of about 40 m^3/s but data from the 1980's and 90's

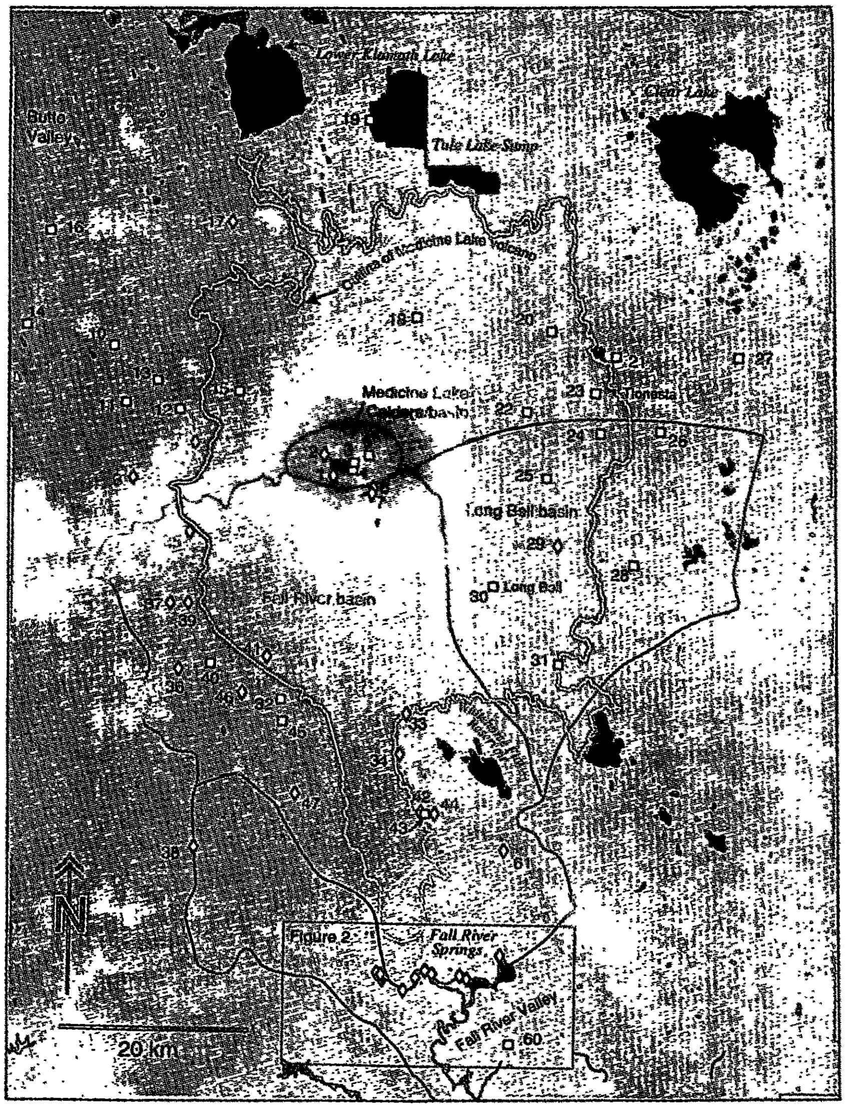

Figure 1. General topography and sample location map. Numbers correspond to samples in Table 1. Darker shading connotes higher elevation: the highest elevations near the caldera are ~2400 m, the lowest elevations in the southwest are ~500 m. Filled diamonds are springs. Filled squares are wells. Black regions are lakes. See Fig. 2 for the FRS area.

indicate 37 m³/s. For purposes of calculation we will use a discharge rate of 37 m³/s for the FRS. The springs emerge from Holocene basalt flows where they overlie Plio-Pleistocene lake sediments of the Fall River valley (Peterson and Martin, 1980). The topography slopes gently upward from the springs to Medicine Lake caldera and it appears that water recharged in the caldera and on the south side of the volcano could move southward to the FRS (Figure 1). However, water could also come from the Long Bell basin and perhaps even the Tule Lake area (Figure 1: not to be confused with the Tule and Little Tule Rivers of Figure 2).

Although the volcano hosts a geothermal system (BLM *et al.*, 1999), no leakage from the geothermal system beneath Medicine Lake volcano has been identified. Little Hot Spring in the Fall River valley is the nearest hot spring to Medicine Lake volcano but it is chemically and isotopically different from the thermal water of the Medicine Lake geothermal system. Little Hot Spring (#61 in Figure 1) discharges a Na-SO_4-Cl water similar to thermal springs in the Modoc Plateau to the east and the geothermal system at Klamath Falls, Oregon to the northwest (Mariner *et al.*, 1998). Water from Little Hot Spring is about 18‰ more depleted in δD than water from the Medicine Lake geothermal system (-113 vs. -95‰). A weak fumarole emerges within the caldera, but it is low in gas and most likely is related to residual heat from the last rhyolite eruption, about 900 years ago.

Methods and Procedures

Water temperatures and conductivities were determined with a combination conductivity/temperature probe. Sample pH was determined on site and corrected to two buffers having known pH-temperature dependence. Alkalinity was determined by acid titration as soon as possible after sample collection. The raw sample was filtered through a 0.45µm pore-size filter in the field. Filtered samples were stored in plastic bottles for later analysis. Samples for cations were acidified to a pH of 2 or less with concentrated nitric acid. Silica and cation concentrations were determined on an inductively coupled plasma emission spectrophotometer. Chloride and sulfate were determined on a computer controlled automated ion chromatograph.

Snow samples were collected by pushing a 1-inch diameter copper pipe (1998 samples) or standard snow coring set (1999) through the snow pack until solid ground was contacted. The snow was transferred to re-sealable plastic bags, melted overnight, and an aliquot of the water transferred to glass bottles with polyseal caps.

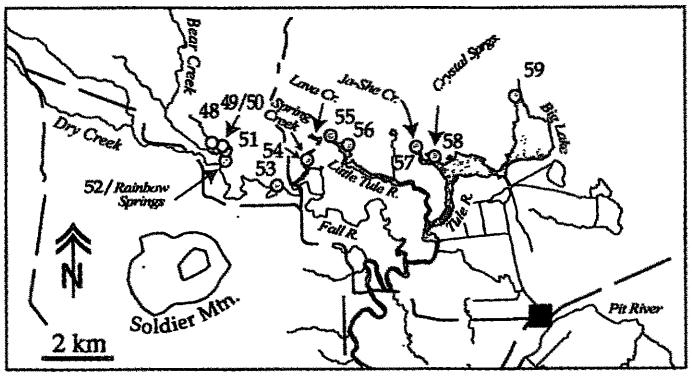

Figure 2. Map for the Fall/Tule river area showing sampled spring locations. Numbers correspond to samples in Table 1. Dashed lines are roads. The large square in the lower right corner is the town of McArthur.

Isotope values were determined in USGS laboratories in Menlo Park, CA and Reston, VA.

Results

Cold spring and well waters in the area (Table 1, page 324) are dilute, neutral to slightly alkaline in pH (6.5 to 8.5), and have bicarbonate as the major anion. At higher elevations the waters are of a Ca-Mg-HCO_3 type, at lower elevations they tend to Na-Ca-Mg-HCO_3. This natural "softening" is likely due to exchange of Ca and Mg in the water for Na in the rock. A few wells near Tule Lake are not dilute; they have a large fraction of saline-lake water.

Cold spring and shallow well waters are as depleted as -106‰ δD and -14.7‰ $\delta^{18}O$ near and within the caldera and as enriched as -84‰ δD and -12.2‰ $\delta^{18}O$ at low elevations in the southwestern part of the study area (shown in Figure 1). Snow cores range from about -84‰ to -126‰ δD. Generally, snow cores, spring, and well waters become more depleted in δD and $\delta^{18}O$ northward and eastward from the southwest corner of the study area. Deuterium values of snow change slowly on the south side of Medicine Lake volcano and the ridge that extends WSW from it towards Mt. Shasta. North of the ridge and volcano, δD values quickly become as depleted as -120‰. At lower elevations both the 1998 and 1999 snow samples plot (Figure 3) on the global meteoric water line of Craig (1961). At higher elevations (more depleted values) the 1998 snow samples plot above the global meteoric water line, whereas some of the more northern and eastern 1999 snow samples plot below the line. Cold springs in the caldera generally plot slightly above the global meteoric water line (Figure 3). Water from wells in the Long Bell basin on the east side of the volcano plots to the right of the envelope defined by the 1998 and 1999 snow samples (Figure 3). This apparent oxygen shift could be due to a small amount of evaporation prior to recharge or an indication that precipitation in this basin has less deuterium excess. FRS waters plot between the values for the springs and wells in the caldera and the wells in the Long Bell basin, a hint that they may be mixtures of the two.

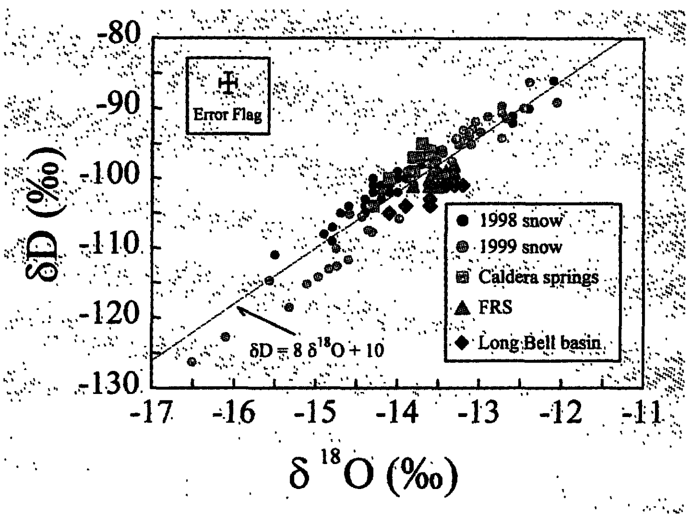

Figure 3. Deuterium versus $\delta^{18}O$ plot for springs from the caldera, wells in the Long Bell basin, the FRS, and the 1998 and 1999 snow samples. The solid line through the data is the global meteoric water line. Uncertainties: δD ± 1.5‰, $\delta^{18}O$ ± 0.1‰.

Discussion

Chloride in regional waters

Chloride is the most conservative "major" chemical constituent and is thus an excellent tracer for detecting the presence of small amounts of geothermal water. The geothermal system within Medicine Lake volcano is reported to have a chloride concentration of about 1,000 mg/L (BLM *et al.*, 1999). Therefore, any shallow well or spring water with an elevated chloride value might potentially have a component of thermal water. To determine whether a sample contains excess chloride, one must first determine what constitutes background chloride. Waters produced by melting snow from four sites on Medicine Lake volcano had between 0.15 and 0.2 mg of Cl/L. Crystal Spring (sample #1) and Schonchin Spring (sample #2) from high elevations on Medicine Lake volcano have chloride concentrations (Table 1) near that of melted snow. At lower elevations, higher chloride concentrations occur in most waters (0.5 to 10 mg/L) but this could indicate low-temperature water-rock reaction rather than a thermal water component. All volcanic rock contains at least ~200ppm chloride and even low-temperature water-rock reaction will release some of this chloride. In the study area, cold waters circulate to shallow depths and contact only young volcanic rock. These waters should thus have similar Na/Cl values unless additional chloride or sodium has been added from some other source (e.g., NaCl or $NaHCO_3$ waters). Figure 4 shows that many waters on and near Medicine Lake volcano have Na/Cl values of about 5. The well in Lava Beds

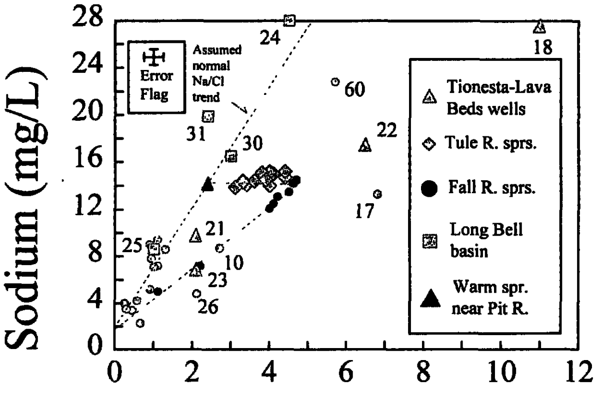

Figure 4. Sodium versus chloride plot for springs and wells. Springs with Na/Cl values near 5.2 are considered to be normal. Springs with Na/Cl values appreciably below 5.2 may have a high-chloride thermal component. The geothermal system beneath Medicine Lake volcano has a Na/Cl of 0.6. Many low chloride (normal Na/Cl) waters were not plotted to reduce clutter. Analytical values are ± 5%. Sample numbers are the same as Table 1.

National Monument (sample #18), Tionesta USFS well (sample #22), Tionesta Mtn. Store well (sample #23), and USFS well at Dry Lake Station (sample #21) form a geographic group (Tionesta-Lava Beds group: gray triangles in Figure 4) with anomalous chloride (Na/Cl <5). The McArthur city well (sample #60) and the FRS (samples #'s 48-59) also have anomalous chloride. The sample from the well at Tule Lake National Wildlife Refuge headquarters has a very high chloride concentration (109 mg/L; sample #19). However, this water also contains a large proportion of highly evaporated water probably from the adjacent Tule Lake sump.

If high-temperature, high-chloride (~1000 mg/L; BLM *et al.*, 1999) geothermal waters enter the shallow groundwater system, then they must constitute less than 1% of the latter, as the Cl concentrations of nearly all spring and well waters are less than 10 mg/L. Given the high temperature and chloride concentration of waters in the Medicine Lake geothermal system, mixing of this water with low-temperature waters should result in a positive correlation between temperature and chloride. Instead, temperature and chloride show a negative correlation for most of the FRS (Mariner *et al.*, 1998). Spring temperatures change in a systematic way across the FRS. Discharge temperatures are highest to the east (12.8°C in the spring at the north end of Big Lake) and lowest in the westernmost spring at the head of the Fall River (9.1°C). Chloride is lowest in the westernmost spring (1.1 mg/L) but increases rapidly downstream (Fig 2) to Rainbow Springs (4.6 mg/L). It remains high eastward to the headwaters of Lava Creek, and then decreases slowly to a value of 3.4 mg/L in the spring at the north end of Big Lake (the spring with the highest temperature). We interpret this distribution of chloride as due to mixing of three waters; a dilute end member (Type I), and two waters that are higher in Na but have differing Cl concentrations (Types II and III; see Figure 5). The dilute Type I water is cold and is most evident to the west. It originates at a low altitude and may represent local recharge. Many waters in the area have Na and Cl concentrations similar to the cold dilute end member (samples 33 and 47 in Table 1, for example). The stream from an unnamed hot spring on the Pit River (Mariner *et al.*, 1998) may represent the Type II end member (2.4 mg-Cl/L and 14.2 mg-Na/L). The extra heat in this slightly warm low-chloride water could be from circulation in the fault that bounds the eastern side of the Fall River valley. A well into the fault on the Wiley Ranch (sample #43) also has slightly warm low-chloride water. The slightly warm, higher chloride end member (Type III) is assumed to be at the intercept of the two mixing lines seen in Figure 5 (Figure 5, 4.7 mg-Cl/L and 14.2 mg-Na/L). Rainbow Spring (sample #52) and the unnamed spring on the Jacobsen Ranch (sample #53) approximate the Type III end member.

The proportions of Type I, II and III components in the FRS can be estimated by looking at the composition of water discharged from the Pit #1 Powerhouse (Table 1), as virtually the entire discharge of the Fall River system is diverted by penstock to this powerhouse. Solving for the proportions of Type I, II and III components indicates about 13%, 22% and 65%, respectively. This calculation is based on an October 1998 sample; therefore, the dilute Type I water, interpreted as locally derived and dominated by spring snowmelt, may be underestimated on an annual basis. These data combined with chemical and mean annual discharge data allow us to calculate the amount of excess chloride in the Type III fraction of the FRS. This part of the FRS carries about 55 gm-Cl/s more than expected. This is a large chloride anomaly. For comparison, the Morgan-Growler hot spring complex on the south side of Lassen Peak generates a 44 gm-Cl/s anomaly, as do the large discharge cold springs that feed into the Wood and Williamson rivers on the southeast side of Crater Lake National Park (Mariner *et al.*, 1990). Nevertheless, the source of this anomaly has not yet been identified.

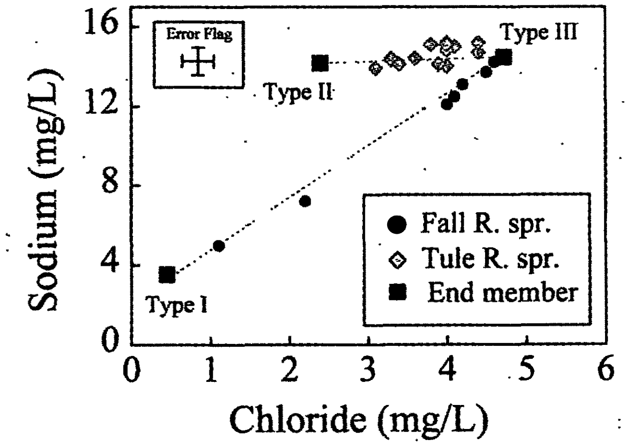

Figure 5. Sodium versus chloride plot for the FRS. Some scatter in data for the Tule River springs may be a function of samples being collected over a number of years and analyzed at different times. Fall River spring symbols include springs on Spring Cr. and Lava Cr. Tie lines represent mixing lines between components. Analytical values are ± 5%.

Isotopic Composition of the FRS and Regional Recharge

Isotopic compositions of the two slightly warm end members (II and III) can be estimated by looking at δD-Cl relations in springs that lack the Type I end member (i.e., Rainbow Springs, the spring on Ja She Creek, Crystal Spring, and the spring at north end of Big Lake). Data from Table 1 were used to calculate a least-squares line (eq. 1). From

$$\delta D = -1.73*Cl - 93.1 \qquad \text{(eq. 1)}$$

this equation, the Type II water (Cl = 2.4 mg/L) would have δD = -97‰ and the Type III water (Cl = 4.7 mg/L) would have δD = -101‰. Combining them in proportions derived from the Pit#1 outflow produces a weighted-average value of -100‰ (eq. 2). Therefore,

$$[(0.22)*(-97‰)+(0.65)*(-101‰)]/(0.22+0.65) = -100‰ \qquad \text{(eq. 2)}$$

about $1.0\text{x}10^9$ m^3/yr of -100‰ δD water would be needed to support the Type II and III components of the FRS (i.e., 87% of the ~37m^3/s annualized flow). The dilute Type I end member (about 13% of the total discharge or ~5m^3/s) is more enriched in deuterium (e.g., note effect on sample #48) than Types II and

III and may originate in the Bear Creek basin or the lower parts of the Fall River basin. Using the same δD vs Cl technique for the springs of the upper Fall River (only Type I and III waters), we find that Type I water must be about -93‰ δD.

To assess the likely volume of recharge available from precipitation on Medicine Lake volcano and its surroundings, we used the precipitation map of Rantz (1969). We also collected snow cores over two successive winters to determine the likely isotopic composition of recharge as a function of elevation and location. The 1998 snow cores, sampled around April 1, were obtained from an area too small to generalize the composition of precipitation over the Fall River and Long Bell basins. Thus, to estimate δD of precipitation, least squares methods were used to determine an equation that related δD of the snow to altitude, latitude, and longitude. This equation was then used to generalize over a broad geographic area. In contrast, the 1999 snow cores were obtained from a more regionally extensive area and could be contoured directly. For both years, the isotopic composition of recharge was calculated with EarthVision® software by inputting snow core data to create a grid with nodes spaced 1.4 km apart. With similar procedures, precipitation at each grid node was estimated based on the precipitation map of Rantz (1969). After the precipitation data were adjusted for evapotranspiration losses (0.3 m/yr. was assumed) the volume and average δD of recharge in each hydrologic basin (Figure 1) was calculated. Approximately 9.6×10^8 m^3/yr was calculated to be recharged in the Caldera, Fall River, and Long Bell basins, within 4% of that needed to account for the Type II and III components to the FRS. About 5% of that water could potentially come from the caldera itself, as the caldera makes up only a very small part of the likely recharge area to the Fall River Springs. Around 23% of the water would come from the Long Bell basin and the remaining 72% from the Fall River basin.

Using the 1998 snow core data, the mean δD value of the recharge water in the Caldera, Fall River, and Long Bell basins was calculated to be -97‰; though the 1999 value was calculated to be about -101‰. Snow collected in spring 1998 may have been more enriched in deuterium than normal due to the unusually warm-wet (El Niño type) winter. Over a period of years it is likely that the combined average δD of recharge to these three basins will be about -100‰. The FRS cannot be modeled by recharge from the Fall River and Caldera basins alone because the combined isotopic composition of precipitation to those basins was -95‰ δD in 1998 and -98‰ δD in 1999. A source of more deuterium-depleted water such as the Long Bell basin appears to be required. Our preliminary data, therefore, indicate that the volume, chemical, and isotopic composition of the Fall River Springs are consistent with recharge from the combined Medicine Lake caldera, Fall River, Long Bell, and Bear Creek basins.

Inter-basin flow from Tule Lake basin to the Fall River basin has been postulated (Macdonald, 1966). Although water table information is sparse for the Long Bell basin, it appears that water cannot move south from the Tule Lake basin into the Long Bell basin because of a potentiometric high located between Long Bell and Tionesta. However, waters from further south within the Long Bell basin are likely to flow south towards the FRS.

Summary

Small chloride anomalies occur in shallow wells on the north and northeast sides of Medicine Lake volcano and in the FRS but there is no evidence that the extra chloride is derived from the high-temperature geothermal system beneath the volcano. The FRS discharge a mixture of three waters. About 65% of the discharge is slightly warm, has chloride of 4.7 mg/L, and sodium of 14.2 mg/L (Type III). About 22% is also slightly warm, has chloride of 2.4 mg/L, and sodium of 14.2 mg/L (Type II). About 13% is cold, has chloride of 0.45 mg/L, and sodium of 3.4 mg/L (Type I). The Type II component is most common in the eastern springs. The Type I component is most common to the west. The weighted-average isotopic composition of Type II and III waters is about -100‰ δD. FRS waters plot between the Long Bell and Fall River basin waters on a diagram of δD vs. $\delta^{18}O$, consistent with derivation from both basins. Combined recharge to the Fall River, Caldera, and Long Bell basins adjusted for evapotranspiration, is calculated to be within 4% of the annual discharge of the Type II and III waters of the FRS. The isotopic composition of this combined recharge is somewhat difficult to assess because it is dependent on winter weather conditions (see also Friedman and Smith, 1971). The 1997-98 winter was warmer than normal and the average δD of recharge in the Caldera, Fall River basin, and Long Bell basin is calculated to have been about -97‰. The 1998-99 winter was colder than normal and the average δD of recharge is calculated to have been about -101‰ in the same basins. Over a period of years the mean recharge for these basins is likely to be close to -100‰ δD. We conclude that the high discharge from the FRS can be accounted for by precipitation on Medicine Lake volcano and its south and east flanks. However, this does not constitute proof that the waters discharged by the FRS originate on or adjacent to Medicine Lake volcano.

Acknowledgements

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Table 1. Chemical and isotopic data for selected springs and wells on and adjacent to Medicine Lake volcano [Chemical concentrations in mg/L; isotope concentrations in parts per'mil relative to Standard Mean Ocean Water (SMOW); - no data; ? – value questioned]

ID# Name	t(°C)	pH	µS/cm	SiO_2	Ca^{++}	Mg^{++}	Na^+	K^+	Cl^-	$SO_4^=$	HCO_3^-	δD	$\delta^{18}O$	Coll. date	UTM Lat.	UTM Lng.
(1)Crystal Spring	2.6	6.71	46	31.8	4.9	1.6	2.4	0.7	0.24	0.27	38	-98	-13.8	7/31/97	4603128	616026
(2)Schonchin Spring	3.2	-	79	31.3	9.4	2.4	3.5	1.1	0.3	0.35	49	-96	-13.5	10/20/98	4605252	615080
	4.6	-	79	31.1	9.3	2.3	3.5	1.4	0.29	0.34	54	-96	-13.6	9/5/98		
	4.0	-	76	30.6	9.1	2.3	3.5	1.2	0.31	0.32	45	-97	-13.6	7/28/98		
(3)USFS well at Med. Lake	-	7.10at11°	58	26.2	6.8	2.0	2.1	0.4	0.24	0.60	31	-100	-14.1	7/30/97	4604457	618089
(4)private well – Med. Lake	5.1	7.74	61	24.3	8.0	1.5	2.1	0.7	0.54	0.27	35	-99	-13.8	11/18/97	4603715	617962
(5)USFS well in Arnica Sink	-	-	69	-	-	-	-	-	0.68	1.2	50	-101	-13.8	11/18/97	4605223	619605
(6)Paynes Springs – N	-	-	65	34.9	5.6	2.3	3.7	2.0	0.24	0.15	42	-97	-13.8	10/20/98	4601899	620077
	5.4	-	48	26.7	4.4	1.5	2.9	1.6	0.21	0.14	29	-98	-13.7	9/5/98		
	5.2	-	48	26.5	4.3	1.5	2.8	1.5	0.19	0.11	32	-97	-13.7	8/3/98		
(7)Paynes Springs – S	7.7	-	65	41.1	5.4	2.5	4.0	2.2	0.25	0.43	42	-96	-13.6	10/20/98	4601341	619947
	7.9	-	66	40.9	5.3	2.5	4.0	2.1	0.30	0.40	43	-96	-13.6	9/5/98		
	8.5	-	67	42.4	5.2	2.5	4.1	2.2	0.25	0.44	47	-96	-13.6	8/3/98		
(8)Baird Spring	-	-	-	-	-	-	-	-	-	-	-	-106	-14.4	7/8/79	4602646	595880
(9)Tamarack Spring	-	-	-	-	-	-	-	-	-	-	-	-102	-14.1	7/30/98	4606248	602083
(10)USFS – Cedar well	11.4	-	164	41.3	9.9	9.9	8.7	1.9	2.7	1.65	129	-105	-14.0	7/30/98	4615943	593760
(11)USFS – Honda well	8.9	-	93	36.5	6.8	5.5	3.8	1.5	0.81	0.53	53	-102	-13.5	7/30/98	4610224	595085
(12)USFS – Van Bremmer well	14.7	-	209	41.8	14.6	9.8	5.7	1.9	0.35	0.068	108	-104	-13.6	7/30/98	4609557	600509
(13)Schaffer well	11.7	-	109	38.0	7.0	5.0	8.2	1.8	1.16	0.68	72	-104	-14.3	7/30/98	4612487	598247
(14)USFS – Schaffer Cmgrnd.	18.2	-	123	37.0	10.2	6.9	4.9	2.1	0.61	0.90	75	-98	-13.1	7/30/98	4617870	584998
(15)Dock well	12.5	6.82	104	42.7	6.1	3.9	5.2	3.9	0.93	1.3	51	-96	-12.5	9/7/97	4611494	606451
(16)Red Rock Valley well	-	-	162	-	-	-	-	-	2.3	2.1	102	-101	-14.2	9/7/97	4627520	587238
(17)Unn. spr. – Willow Cr. Ranch	12.6	-	141	33.6	11.0	3.5	13.3	1.5	6.8	3.0	81	-102	-14.3	8/5/98	4628692	605503
(18)Lava Beds N.M. well	16.4	8.25	193	52.0	6.7	5.0	27.6	2.2	11	2.9	94	-106	-14.7	9/5/97	4619183	624226
(19)Tule Lake NWR hdqrts. well	18.7	8.01	1170	52.8	43.1	52.1	124.	16.4	109	79	459	-79	-8.6	9/5/97	4639273	619175
(20)USFS – well #42	25.5	-	430	42.4	19.8	15.9	52	10.5	10.2	5.1	258	-78	-8.3	7/29/98	4617951	637843
(21)USFS – Dry Lake Sta. well	13.3	-	195	30.9	15.8	10.4	9.8	2.1	2.1	2.2	114	-109	-14.1	7/28/98	4615489	644413
(22)USFS – Tionesta well	14.1	-	175	39.4	9.2	6.7	17.8	2.6	6.5	3.1	92	-105	-14.1	7/28/98	4609762	635500
(23)Tionesta Mtn. Store well	11.2	7.60	190	40.9	14.7	10.9	6.9	1.5	2.1	2.3	107	-103	-13.6	9/6/97	4611747	642405
(24)USFS – Timber Mtn. Ranch	26.3	-	191	34.0	10.2	2.5	28.	3.6	4.5	2.8	107	-102	-13.0	7/28/98	4607696	642963
(25)USFS – Sheep Camp well	15.3	-	173	37.2	12.7	10	8.6	2.8	1.0	1.0	114	-103	-13.6	7/29/98	4603137	637571
(26)Quarantine Station well	13.9	7.67	181	40.5	14.8	11.9	4.8	0.7	2.1	2.3	109	-104	-13.6	9/6/97	4607993	649010
(27)USFS – well	12.2	-	176	39.9	13.2	12.5	4.6	0.8	0.83	0.78	117	-101	-13.4	7/29/98	4615563	656764
(28)USFS – Mud Lake well	11.8	-	181	35.0	15.6	12.1	4.9	0.9	0.68	0.29	105	-99	-13.4	7/28/98	4594428	646507
(29)Quaking Aspen Spring	-	7.38	122	0.6	15.5	5.7	1.5	2.1	0.33	0.30	70	-31	+0.8	11/06/97	4596312	638815
(30)Long Bell Station well	14.7	-	199	38.3	11.8	9.3	16.5	3.1	3.1	1.8	81?	-101	-13.2	8/3/98	4592119	632352
(31)USFS – Lava Cmpgrd. well	18.0	-	186	38.9	10.7	6.6	19.9	3.8	2.4	1.0	115	-104	-13.9	8/3/98	4584285	639040

ID# Name	t(°C)	pH	µS/cm	SiO_2	Ca^{++}	Mg^{++}	Na^+	K^+	Cl^-	$SO_4^=$	HCO_3^-	δD	$\delta^{18}O$	Coll. date	UTM Lat.	UTM Lng.
(32)USFS – Hunters Hill well	-	-	147	-	-	-	-	-	1.06	0.51	-	-95	-13.3	10/19/98	4580285	611095
(33)Indian Spring	5.2	-	-	20	7.3	4.9	2.9	1.3	0.60	-	62	-	-	—/—/94	4579011	623805
(34)Mayfield Spring	-	-	106	39.3	10.8	4.4	4.2	1.6	0.57	0.36	63	-93	-13.2	7/29/97	4574928	623177
(35)Lost Spring	11.9	6.68at17°	64	26.8	8.3	1.7	2.6	<0.1	0.13	0.04	39	-96	-13.5	7/29/97	4597173	601655
(36)Belnap Spring	-	-	47	22.2	4.0	2.2	2.0	.5	0.54	0.10	38	-91	-12.8	7/29/97	4583280	600736
(37)Bear Spring	-	-	76	28.9	6.7	4.3	2.4	<0.1	0.30	0.09	42	-96	-13.4	7/29/97	4589930	599808
(38)Cub Spring	-	-	25	15.3	2.0	1.1	1.1	.4	0.44	0.10	15	-84	-12.2	7/29/97	4565169	602524
(39)Harris Springs	8.8	-	64	23.7	4.8	3.0	2.3	1.0	0.66	0.04	47	-96	-13.3	8/3/98	4589955	601618
(40)Toad well	14.3	-	67	22.5	5.2	1.6	3.8	3.6	0.15	0.48	47	-95	-13.0	8/2/98	4583881	603933
(41)Lava Crack Spring	8.4	-	68	30.2	6.9	2.6	3.0	1.3	0.8	0.035	47	-96	-13.4	8/2/98	4584705	609634
(42)Unn. spr. – Wiley Ranch	14.7	-	193	47.3	18.2	8.7	9.0	4.1	0.9	0.26	133	-97	-13.4	6/24/98	4569043	625371
(43)USFS – Wiley Ranch well	19.4	-	178	46.6	19.0	9.7	9.4	4.4	1.1	0.64	128	-99	-13.5	7/28/98	4568865	625794
(44)Unn. spr. – Wiley Ranch	12.8	-	188	40.1	17.6	9.0	7.8	3.4	0.94	0.21	126	-97	-13.5	8/1/98	4568882	626771
(45)Hambone well	-	-	78	19.8	5.7	5.0	2.7	0.9	0.15	<0.02	56	-93	-12.8	6/25/98	4578067	611268
(46)Mud Lake Spring	-	-	-	-	-	-	-	-	-	-	-	-89	-12.2	6/26/98	4580967	607181
(47)Unn. spr. – Sand Flat	12.3	-	105	35.3	7.4	7.1	3.4	1.2	0.45	0.14	-	-92	-12.6	6/26/98	4570735	612663
(48)Unn. spr. #1 – Fall River	9.2	7.47	136	30.6	11.8	7.2	5.0	1.5	1.1	1.15	82	-94	-13.2	7/31/97	4552685	621174
(49)Unn. spr. #2 – Fall River	9.1	7.95	113	34.2	8.6	5.2	7.2	1.8	2.2	1.04	63	-99	-13.6	7/31/97	4552507	621597
(50)Unn. spr. #3 – Fall River	11.2	8.17	142	39.8	8.4	6.0	12.1	2.5	4.0	1.58	73	-101	-13.7	7/31/97	4552507	621597
(51)Unn. spr. #4 – Fall River	11.2	7.68	146	40.3	8.5	6.2	12.5	2.2	4.1	1.67	83	-101	-13.7	7/31/97	4552324	621740
(52)Rainbow Spr.	12.0	8.36	161	41.6	8.8	6.7	14.2	2.7	4.6	1.75	90	-101	-13.6	9/5/97	4551954	621746
(53)Unn. spr. – Jacobsen Ranch	12.2	-	148	37.4	8.4	5.8	14.5	2.3	4.7	1.60	82	-100	-13.6	8/1/98	4550879	623864
(54)Unn. spr. on Spring Cr.	12.2	7.41	157	40.1	8.7	6.3	13.7	2.7	4.5	1.63	86	-101	-13.8	11/4/97	4552196	625102
(55)Unn. spr. – Lava Cr.	11.6	7.59	152	40.4	8.7	6.3	13.1	2.5	4.2	1.54	83	-100	-13.6	11/4/97	4551953	626069
(56)Unn. spr. – Lava Cr.	11.9	-	-	-	-	-	-	-	-	-	-	-102	-13.5	—/—/81	4552595	626775
(57)Unn. spr. on	12.2	-	174	36.0	10.6	7.6	15.0	2.8	4.1	1.83	101	-101	-13.5	10/24/98	4552459	629576
Ja She Creek	12.1	-	173	36.0	10.5	7.5	15.0	2.9	4.1	1.76	101	-99	-13.4	7/31/98		
	12.2	-	172	35.8	10.4	7.5	14.8	2.8	4.0	1.72	108	-101	-13.5	6/23/98		
(58)Crystal Spring	12.6	-	176	35.4	10.9	7.6	15.2	2.9	4.0	1.83	106	-100	-13.4	10/22/98	4552101	630283
Adjumawi Lava Springs	12.4	-	177	35.2	10.9	7.7	15.1	2.7	4.0	1.74	113	-100	-13.3	7/31/98		
State Park	12.4	-	176	35.3	10.9	7.7	15.1	2.5	3.8	1.71	115	-99	-13.3	6/23/98		
(59)Unn. spr. at	12.8	-	181	34.3	11.7	8.4	14.4	2.8	3.3	1.54	113	-99	-13.5	10/22/98	4554567	633597
north end of	-	-	-	34.4	11.6	8.4	14.3	2.6	3.3	1.5	102?	-98	-13.2	7/31/98		
Big Lake	12.7	-	179	34.2	11.6	8.3	13.9	2.7	3.1	1.5	115	-99	-13.3	6/23/98		
(60)McArthur city well –	-	8.70	203	24.6	15.8	2.6	22.8	2.5	5.7	15.2	90	-100	-13.5	11/6/97	4545516	634603
Pit #1 outflow	-	-	160	32.2	10.1	7.0	12.9	2.8	3.7	1.47	94	-97	-13.3	10/21/98	4568516	626037
	-	-	-	31.7	10.0	7.0	12.9	2.5	3.6	1.53	93	-97	-13.4	9/5/98		
	-	-	-	31.7	9.9	7.0	14.7	2.8	3.5	1.47	104	-96	-13.2	8/4/98		
(61) Little Hot Spring	76	8.1 at46°C	-	80.0	48	0.3	235	5.4	120	390	53	-113	-14.1	6/6/83	4565307	633820

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