Geothermal Resources Council TRANSACTIONS, Vol. 18, October 1994

CONVECTIVE HEAT DISCHARGE OF WOOD RIVER GROUP OF SPRINGS IN THE VICINITY OF CRATER LAKE, OREGON

Manuel Nathenson[1], Robert H. Mariner[1], and J. Michael Thompson[2]

[1]U.S. Geological Survey, Menlo Park, California 94025
[2]U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington 98661

ABSTRACT

Data sets for spring and stream chemistry are combined to estimate convective heat discharge and discharge of anomalous amounts of sodium and chloride for the Wood River group of springs south of Crater Lake. The best estimate of heat discharge is 87 MW_t based on chloride inventory; this value is 3-5 times the heat input to Crater Lake itself. Anomalous discharges of sodium and chloride are also larger than into Crater Lake. Differences between the chemical and thermal characteristics of the discharge into Crater Lake and those from the Wood River group of springs suggest that the heat sources for the two systems may be different, although both ultimately related to the volcanic system.

INTRODUCTION

Nathenson (1990a) established that the Wood River group of springs south of Crater Lake (Figure 1) constitute a thermal anomaly based on comparisons of their temperatures to air, ground, and other spring temperatures and of their chemistry to the chemistry of other springs. Nathenson and Thompson (1990) discussed the similarity of the chemistry of the Wood River group of springs to the chemistry of Crater Lake water and concluded that both are probably produced by the same process. Collier, Dymond, and McManus (1991) demonstrated that the chemistry of Crater Lake water is largely determined by the input of thermal water at depth and that the convective heat discharge associated with this thermal water is 15-30 MW_t. Mariner and others (1990) inventoried the chloride flux from the Wood River group of springs but could not convert it to a convective heat discharge because they had no value for the ratio of heat to chloride. The purpose of this study is to combine the data sets of Nathenson (1990a), Mariner and others (1990), and Nathenson and Thompson (1990) to calculate the discharge of anomalous amounts of sodium and chloride and the convective heat discharge from the Wood River group of springs.

CHEMICAL AND THERMAL CHARACTERISTICS

The Wood River group of springs is located south of Crater Lake (circles on Figure 1) and is chemically and thermally anomalous compared to the Cedar springs group at the same elevation in the Wood River Valley (diamonds on Figure 1). The Wood River group takes its name from the Source of the Wood River, a large pool with numerous vents aligned along an ≈800-m long linear trending north-northwest, with a total flow of about 6700 L/s (Nathenson, 1990a). Temperatures of the Source of the Wood River (open circles in Figure 2) and the remainder of the Wood River group (closed circles in Figure 2) systematically increase with specific conductance, and this relationship indicates a mixing relationship between two waters: one that is warm and slightly saline with another that is cool and less saline. The different values for specific conductance and temperature measured for different vents of the Source of the Wood River shows that some of this mixing must be taking place locally. The Cedar Springs group is located mostly in the western part of the Wood River Valley (Figure 1) and is at approximately the same elevation as the Wood River group, except for Cedar Springs itself which is 200 m higher. Data for the Cedar springs group (diamonds on Figure 2) provide a perspective on typical values for conductance and temperature for springs with no thermal component and at a similar elevation to the Wood River group. Other springs for which temperatures are shown on Figure 2 (squares) are at higher elevations. Although data for the other springs on Figure 2 also show a relationship between conductance and temperature, plots of temperature and conductance versus elevation (Nathenson, 1990a, Figures 4 and 6) show that data for these springs correlate well with elevation, but the Wood River group has a broad range of conductance and temperature at nearly a single elevation.

Chemical data for the Wood River group are given in Table 1 for the spring samples from 1981-84 (Thompson and others, 1990) and the spring and stream samples from 1986-87 (Mariner and others, 1990). Plots of chemical data (Figures 3 and 4) illustrate that the water chemistry follows a mixing relationship, with the addition of Na, Cl, and SO_4 seeming to dominate the added constituents. Sensitivity over the range of variation is inadequate to establish if other constituents are increasing or remaining the same.

The average analysis for water from Crater Lake shown on Figure 4 has a reasonably similar chemistry to the Wood River group of springs, although there are small but significant differences. The ratio of SO_4/Cl is different, and sodium is lower and calcium higher in Crater Lake water for the same chloride concentration. Silica is lower in Crater Lake water, because it is consumed by diatoms (Nathenson, 1990b).

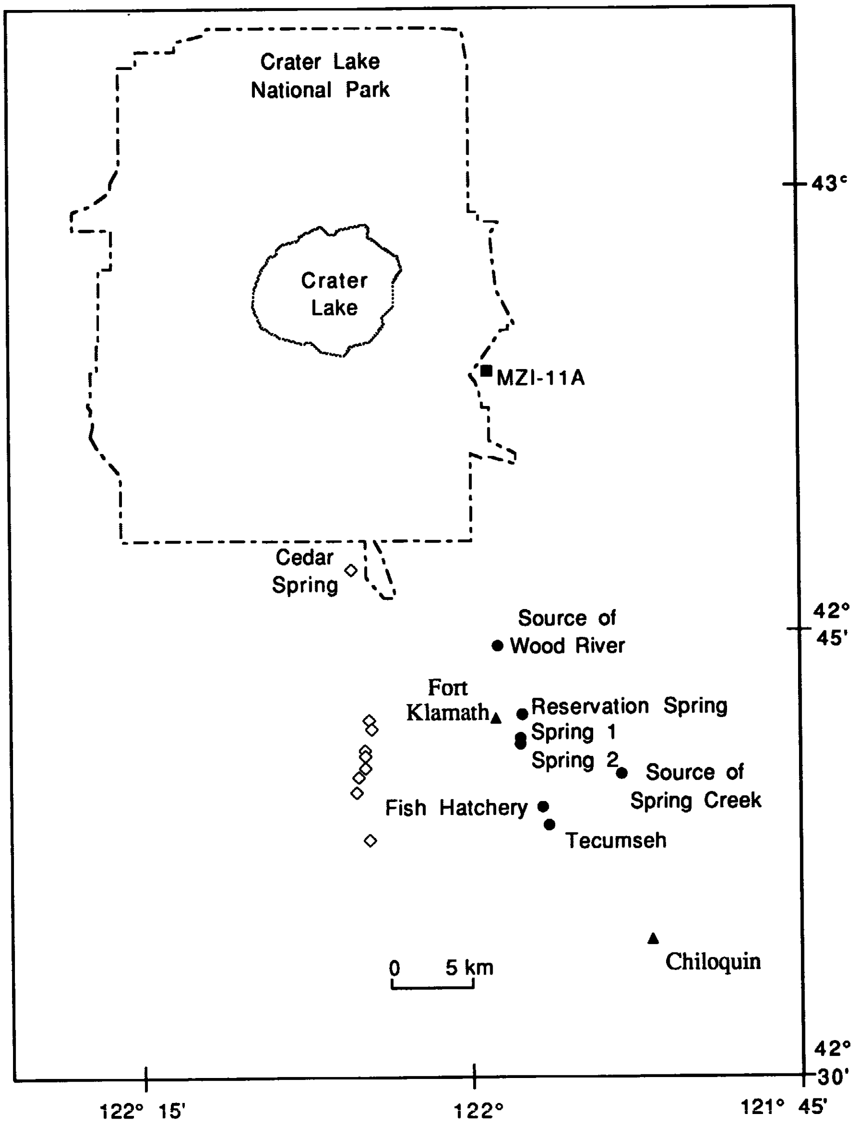

Figure 1. Map of Crater Lake and vicinity showing locations of the Wood River group of springs (circles), Cedar Springs group (diamonds), and geothermal exploration well MZI-11A. Outline of Crater Lake National Park, Crater Lake, and towns of Fort Klamath and Chiloquin are shown.

CONVECTIVE HEAT DISCHARGE USING SPECIFIC CONDUCTANCE

The fluxes of dissolved constituents and the convective heat discharge can be calculated by combining the data sets of Figure 2 and Table 1. The inverse of the slope of the line in Figure 2 provides a relation between temperature and specific conductance. The value of conductance above which the water is assumed to carry thermal energy above background can be visually estimated from Figure 2 as 70 µS/cm. Many of the samples collected in 1986-87 included integrated samples and detailed measurements of flow in order to perform a chemical inventory. Not all samples have measured specific conductances, but those that do have been used to calculate heat discharge (Table 2) using the relation:

$$H = \rho_w c_w \; Q\,(T - T_{ref})$$

$$= \rho_w c_w \; Q \frac{(T - T_{ref})}{(\kappa - \kappa_{ref})} (\kappa - \kappa_{ref}), \qquad (1)$$

where $\rho_w \, c_w$ are the density and specific heat of water, Q is the volumetric flow rate, $(T - T_{ref})/(\kappa - \kappa_{ref})$ is the inverse of the slope of the line in Figure 2, κ is the measured specific conductance, and κ_{ref} is the reference specific conductance of 70 µS/cm. Thus the slope comes from the data measured for springs, but the value of specific conductance comes from the integrated samples with associated flow measurements.

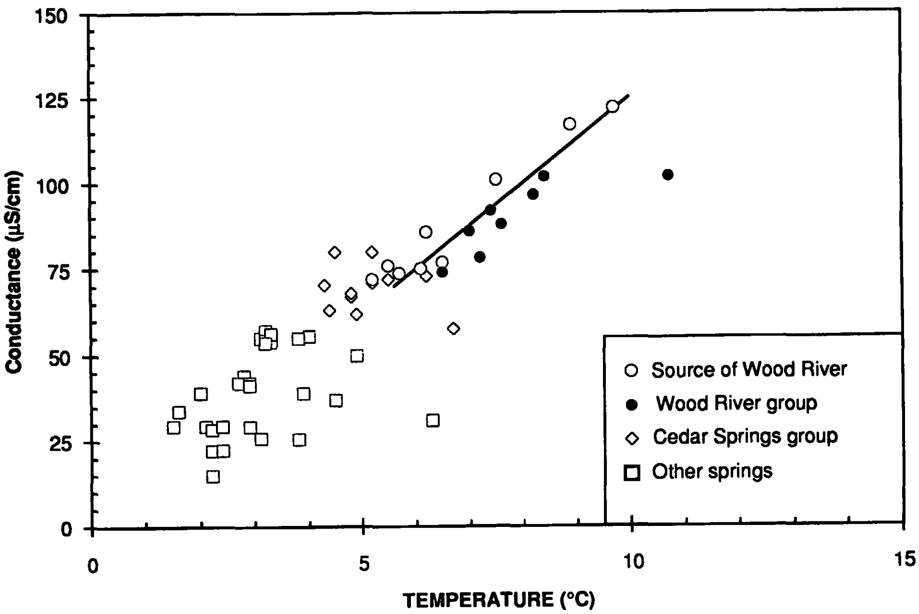

Figure 2. Specific conductance versus temperature for springs in the vicinity of Crater Lake (Nathenson, 1990a). Wood River group of springs separated into values for Source of Wood River and for remainder of group. Other springs (squares) are located north of the Wood River Valley, mostly within Crater Lake National Park (See Nathenson (1990a) for location map). Slope of line is 12.5 (µS/cm)/°C.

Table 1. Chemical data for water samples of the Wood River group and for Crater Lake. Samples for 1981-84 are from springs (Thompson and others, 1990). Samples for 1986-87 are from streams with significant spring input, streams directly associated with springs, and some springs (Mariner and others, 1990). Average for Crater Lake is from Nathenson (1990b). Specific conductance for sample JCL-81-10 is calculated using the model of Miller and others (1988), because measured values in 1981 are in error (Nathenson and Thompson, 1990). Bicarbonate concentrations (where noted) are calculated using anion/cation balance. Locations are given once for spring samples and not given for stream samples.

		Latitude		Longitude			Flow		SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Cond.	Temp.
Sample no.	Name	°	"	°	"	Date	L/s	pH	mg/L								µS/cm	°C
JCL-81-10	Source of Wood River	42	44.5	121	58.8	11 Aug 81		7.3	40	5.6	2.7	6.1	1.0	34	5	3.2	75*	9.5
JCL-84-4	Source of Wood River					3 Aug 84		6.7	46	2.1	2.4	6.6	1.9	47	1.8	2.8	50	12
JCL-84-2	Tecumseh Spring	42	38.5	121	56.5	3 Aug 84		7.9	34	7.5	1.8	12.5	1.4	58	3.4	4.9	95	11
JCL-84-3	Fish Hatchery Spring	42	39.1	121	56.8	3 Aug 84		7.9	36	8.0	2.4	15.6	1.9	53	6.2	8.4	126	11
JCL-84-5	Reservation Spring	42	42.2	121	57.7	3 Aug 84		7.6	40	15.7	1.9	10.8	2.1	50	4.6	5.8	103	8
JCL-84-6	Source of Spring Creek	42	40.2	121	53.2	3 Aug 84		7.5	41	3.2	1.8	8.5	1.3	46	2.4	3.3	60	6
GT481MC86	Williamson River at Chiloquin					18 Sep 86	11000					7.9				2.0		
GT485MC86	Wood River at Fort Klamath					18 Sep 86	9010					8.1				5.0		
GT51RM87	Source of Wood River					26 Aug 87		8.2	40	5.3	2.4	15	2.0	42	7.5	11	125	11
GT50RM87	Reservation Spring					26 Aug 87	1600	7.7	39	4.5	2.3	12	1.7	39	5.7	7.1	107	6.5
GT77RM87	Reservation Spring					23 Oct 87			41	4.6	2.3	13	1.5	43*	6.5	6.5	107	
GT83RM87	Unnamed Creek at Williamson River					23 Oct 87	178		35	4.6	3.0	11	1.3	50*	4.7	2.7	99	
GT52RM87	Spring Creek					26 Aug 87		7.8	40	4.0	2.6	8.8	1.4	39	3.1	2.1	83	6
GT80RM87	Spring Creek					24 Oct 87	7800		41	4.2	2.5	8.2	1.3	42*	3.2	1.7	82	
GT79RM87	Unnamed spring 1	42	41.4	121	57.8	23 Oct 87	700		43	4.7	2.7	9.9	1.3	45*	4.1	3.7	95	
GT78RM87	Unnamed spring 2	42	41.2	121	57.8	23 Oct 87	155		46	5.1	3.3	7.9	1.3	48*	2.8	2.3	91	
GT82RM87	Crooked Creek					24 Oct 87	1000		38	4.3	2.9	14	1.5	47*	6.3	7.3	115	
GT81RM87	Tecumseh Spring					24 Oct 87			38	4.5	2.7	11	1.2	46*	4.2	4.0	99	
Average	Crater Lake					1912-86			17.7	7.2	2.6	10.9	1.8	36.4	10.5	10.2		

* Calculated.

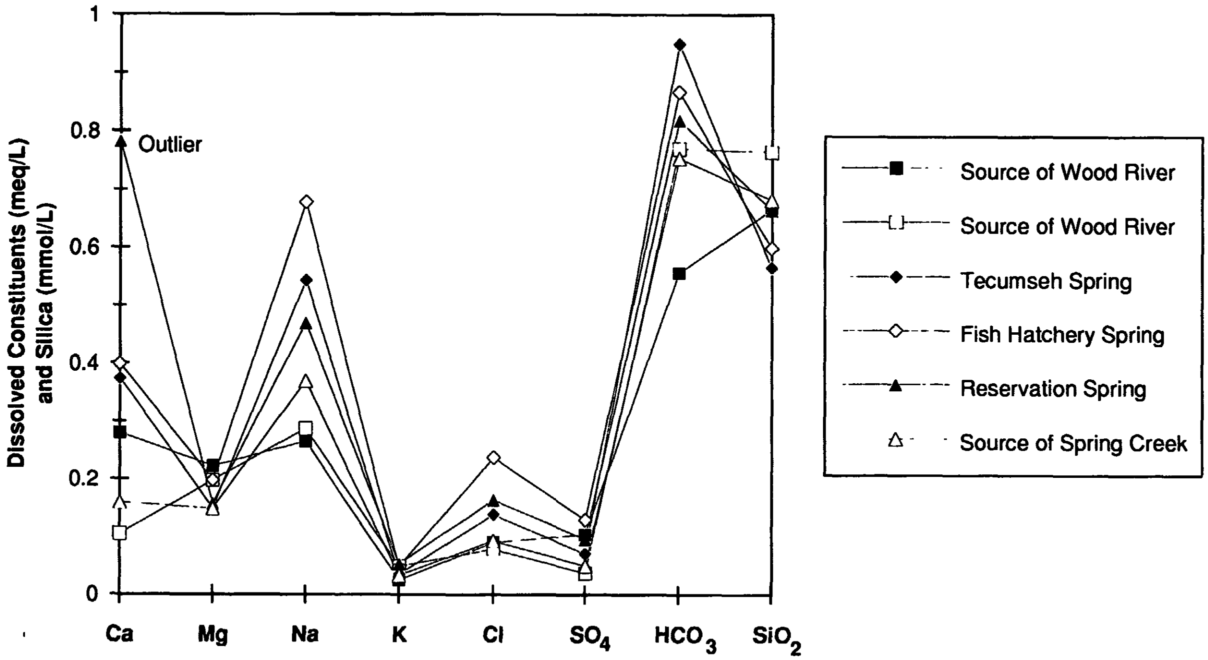

Figure 3. Modified Schoeller diagram for 1981-84 samples from Table 1.

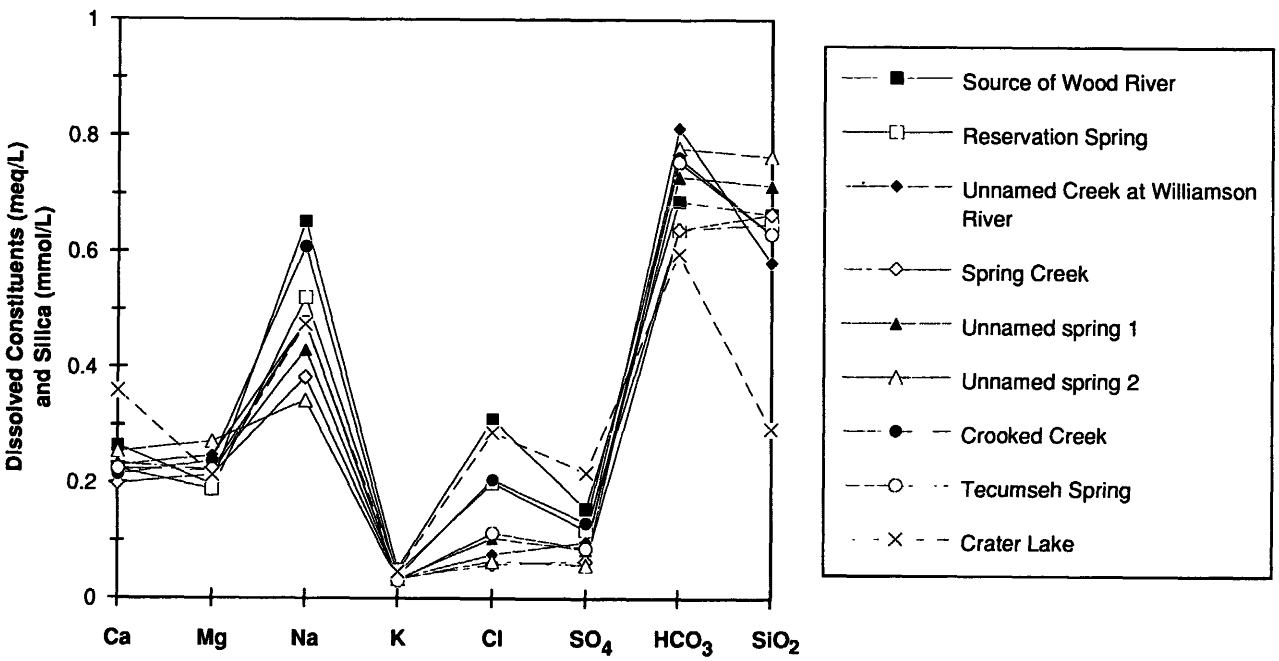

Figure 4. Modified Schoeller diagram for 1987 samples from Table 1.

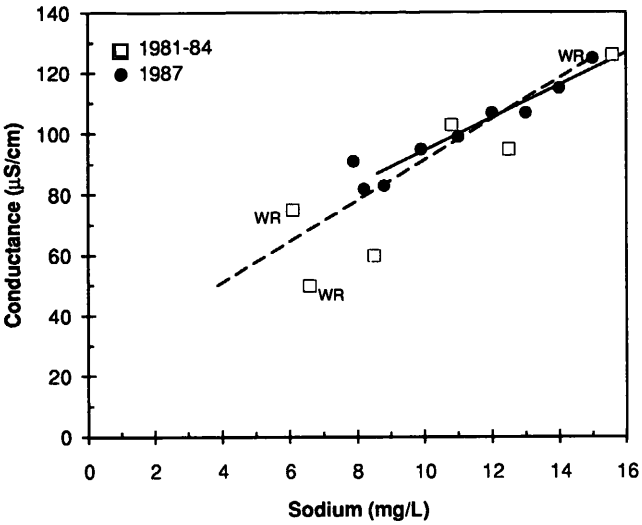

Figure 5. Specific conductance versus sodium for samples from Table 1. Data for samples from Wood River noted as WR. Solid line is least squares line that uses only 1987 data and has intercept of 40.8 µS/cm and slope of 5.4 (µS/cm)/(mg/L). Broken line is visual fit to Wood River data.

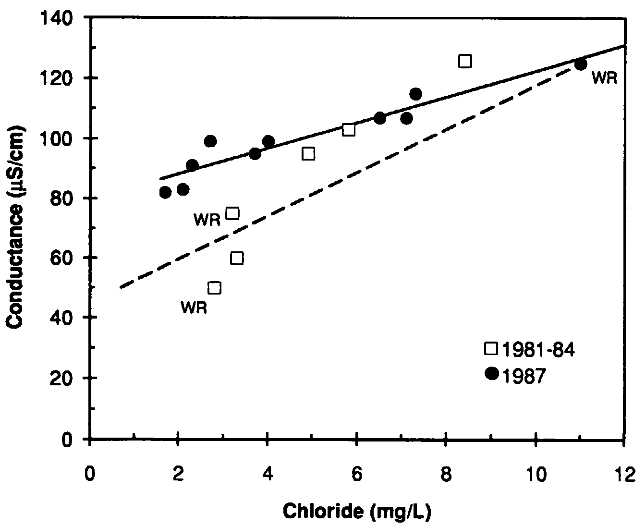

Figure 6. Specific conductance versus chloride for samples from Table 1. Data for samples from Wood River noted as WR. Solid line is least squares line that uses only 1987 data and has intercept of 79.5 µS/cm and slope of 4.3 (µS/cm)/(mg/L). Broken line is visual fit to Wood River data.

CONVECTIVE HEAT DISCHARGE USING SODIUM AND CHLORIDE

The inventory values for sodium and chloride are more complete than for specific conductance and can also be used to measure the heat discharge. The data for specific conductance versus sodium and chloride are shown in Figure 5 and 6 and for sodium versus chloride in Figure 7. The data for sodium versus chloride define a linear relation (solid line on Figure 7) except for some of the samples for the Wood River. The various samples for the Wood River are noted as WR in Figure 7. The most concentrated sample is the Source of the Wood River as sampled in August, 1987, and the values for this sample lie on the linear trend of other samples for the Wood River group. The sample for the Wood River at Fort Klamath (1986) and the two samples for the Source of the Wood River (1981 and 1984) define a different mixing line (broken line on Figure 7) from samples for the other members of the Wood River group.

A notable characteristic of the mixing line for the Wood River group of springs (solid line on Figure 7) is that the sodium concentration at zero chloride of 7.5 mg/L is higher than what has been measured for most dilute waters in the vicinity of Crater Lake of 3-4 mg/L (Nathenson and Thompson, 1990, Table 1). This observation implies greater water/rock interaction, which would most likely come from a relatively long circulation path. The similarity of values of deuterium and oxygen-18 isotopes of all the Wood River group samples to samples from springs located near or above the elevation of Crater Lake and the lack of variation of deuterium isotopes with

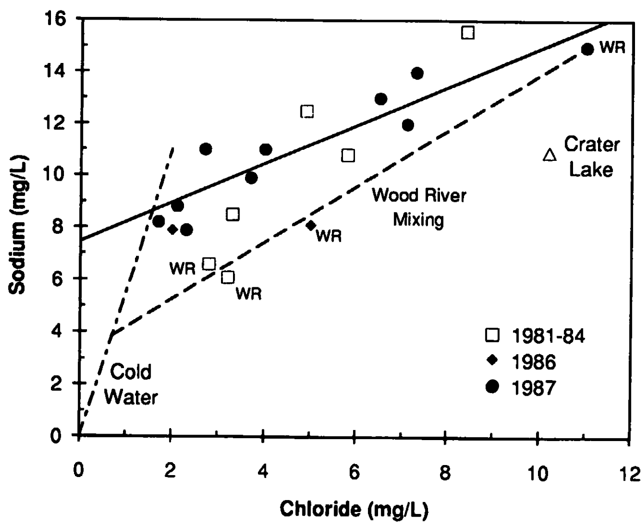

Figure 7. Sodium versus chloride for samples from Table 1. Data for samples from Wood River noted as WR. Solid line is least squares line that uses only 1987 data and has intercept of 7.5 mg/L and slope of 0.748. Broken line is visual fit to Wood River data. Line noted as Cold Water is from the empirical relation of Mariner and others (1990) for dilute water.

chloride concentration (Thompson and others, 1990) implies that both the thermal water and the diluting water are from a relatively high elevation. A reasonable interpretation is that the cold diluting water is recharged at a relatively high elevation and has a long circulation path before mixing with the thermal water to produce the range of compositions found for most of the Wood River group of springs. The different mixing line defined by the Wood River samples (Figure 7) then indicates local mixing with a more typical dilute water with a sodium concentration of around 4 mg/L. This local mixing is consistent with field measurements showing different values of conductance and temperature in different upwellings within the Source of the Wood River (Figure 2).

In order to use the sodium and chloride inventory data to calculate anomalous discharge of solutes and heat, background values for sodium and chloride for dilute water must be chosen. One method would be to use values corresponding to the 70 µS/cm conductance of dilute water estimated from Figure 2; however, this conductance value is less than the minimum (79.5 µS/cm) of the projected line on the conductance versus chloride plot of Figure 6. Instead, we use the empirical relation developed by Mariner and others (1990) from central Oregon that the sodium concentration in dilute water is 5.5 times the chloride concentration, shown as a line marked cold water on Figure 7. In order to make allowance for uncertainties in measured sodium and chloride, the flux is calculated by passing a line through each sample value using the slope for the whole group of springs. The use of individual mixing lines makes it possible to deal with the points that are close to the cold water line and not to have the flux of one constituent be zero and the other positive.

To calculate the flux of anomalous sodium, we start with the relation satisfied by the cold water:

$$Na_I = 5.5\ Cl_I, \tag{2}$$

where the subscript I denotes the point where the mixing line and cold-water line intersect. The mixing line for the Wood River group can be written as

$$Na = Na_0 + 0.748\ Cl, \tag{3}$$

where Na_0 is the y-axis intercept that has to be calculated for each sample value. The mixing line for each sample value intercepts the cold-water line and passes through values for the sample:

$$Na_I = Na_0 + 0.748\ Cl_I \tag{4a}$$

$$Na_s = Na_0 + 0.748\ Cl_s, \tag{4b}$$

where the subscript s is for the sample. Equations (4a) and (4b) may be rearranged to:

$$Na_0 = Na_s - 0.748\ Cl_s \tag{5a}$$

$$= Na_I - 0.748\ Cl_I, \tag{5b}$$

$$= 5.5\ Cl_I - 0.748\ Cl_I, \tag{5c}$$

where equation (2) has been substituted in equation (5b) to obtain (5c). Combining equations (5a) and (5c), we obtain:

Table 2. Solute and heat discharge for Wood River group of springs. Sodium and chloride discharge are relative to background values based on empirical relation of Mariner and others (1990). Heat discharge is calculated for conductance above 70 µS/cm, for sodium and chloride above same value as for solute discharge, and slopes relating temperature, sodium, and chloride to conductance.

Name	Date	Flow L/s	Solute (mg/s) Na	Cl	Heat Discharge (MW_t) Cond.	Na	Cl
Williamson River at Chiloquin	18 Sep 86	11000	5400	7200	--	9.7	10.3
Wood River at Fort Klamath	18 Sep 86	3604*	25800	34500	--	47	50
Reservation Spring	26 Aug 87	1600	6800	9100	20	12.3	13.1
Unnamed Creek at Williamson River	23 Oct 87	178	110	140	1.7	0.2	0.2
Spring Creek	24 Oct 87	7800	1410	1890	31	2.5	2.7
Unnamed spring 1	23 Oct 87	700	1150	1540	5.9	2.1	2.2
Unnamed spring 2	23 Oct 87	155	120	160	1.1	0.2	0.2
Crooked Creek	24 Oct 87	1000	4100	5500	15.1	7.4	7.9
Total			44900	60000	--	81	87

* Flow of Wood River at Fort Klamath adjusted to fraction that has the same sodium and chloride concentration as most concentrated sample for Source of Wood River.

$$Cl_I = (Na_s - 0.748\ Cl_s)/(5.5 - 0.748). \qquad (6)$$

The anomalous sodium may then be expressed as

$$Na_s - Na_I = 0.748\ (Cl_s - Cl_I)$$
$$= 0.748\ (5.5\ Cl_s - Na_s)/(5.5 - 0.748), \qquad (7)$$

where the middle expression is obtained by subtracting equation (4a) from (4b), and equation (6) has been substituted for Cl_I to obtain the last expression The flux of anomalous sodium is

$$m_{Na} = Q\ (Na_s - Na_I), \qquad (8)$$

and a similar equation holds for chloride.

To calculate heat discharge, we use the slopes from the conductance and sodium relation (Figure 5) and from the conductance and temperature relation (Figure 2) in the formula

$$H = \rho_w c_w\ Q\ (T - T_{ref})$$
$$= \rho_w c_w\ m_{Na} \frac{(T - T_{ref})\ (\kappa - \kappa_{ref})}{(\kappa - \kappa_{ref})\ (Na - Na_{ref})}, \qquad (9)$$

where equation (8) has been used to substitute for Q. A similar relation holds for chloride. For the sample from the Wood River at Fort Klamath, we can either use the different slopes shown as broken lines on Figures 5 and 6 or convert the flow to an equivalent flow of water at the composition of the most concentrated sample from the Wood River and use the same relation as for the remainder of the Wood River group. Because the slopes in Figures 5 and 6 for the Wood River are not well determined (one of the conductivities is calculated rather than measured), we choose to use an equivalent flow.

The flux of the solutes sodium and chloride and the resultant heat discharge are given in Table 2. The calculations of heat discharge from sodium and chloride flux differ by a fixed ratio and are not independent, but they are both tabulated to compare to other values.

DISCUSSION

The values of heat discharge calculated from conductance are generally larger than those calculated on the basis of sodium or chloride flux. The largest difference is for Spring Creek, where the conductance calculation yields 31 MW_t and the chloride calculation 2.7 MW_t. The reason for the smaller heat discharge value from the solute calculations is that the sodium and chloride values for Spring Creek (8.2 and 1.7 mg/L, respectively) are near the line for dilute water and carry very little anomalous dissolved constituents. The large heat discharge from the conductance calculation is due to the higher values of conductance in 1987 for temperatures that are probably the same as that measured in 1989. The conductance value for Spring Creek measured in 1989 was 74 µS/cm with a temperature of 6.5°C (Nathenson, 1990a). The October, 1987 value for the inventory was 82 µS/cm, with 83 µS/cm measured in August of the same year along with a temperature of 6°C. One interpretation is that there is a small but systematic difference in measured conductances between the 1989 and 1987 data. This difference is only really important for water samples that contain mostly dilute water, such as Spring Creek. For example, choosing a reference conductance of 81 µS/cm instead of 70 µS/cm yields conductance heat discharge of 3 MW_t for Spring Creek. The total heat discharge for the conductance inventory with the 70 µS/cm reference conductance is 75 MW_t compared to 26 MW_t for the same features using the chloride inventory. Increasing the reference conductance to 81 µS/cm decreases the heat discharge using the conductance inventory to 33 MW_t, close to the value from the chloride inventory for the same features.

The difference between the heat discharge calculated from conductance and that from sodium and chloride flux for Spring Creek would also be smaller if the heat discharge from the sodium and chloride flux were higher. The heat discharge from sodium and chloride flux would increase if the empirical relation between sodium and chloride involved a greater slope than what was found for central Oregon. For example, a slope of 12.5 (a value obtained from unpublished data of Nathenson for springs at Mount Shasta) increases the chloride heat discharge for Spring Creek to 12 MW_t from 2.7 MW_t. In general, the solute and heat discharges for other samples are not as sensitive as that for Spring Creek, but the uncertainty for the Spring Creek calculations does indicate the sensitivity for samples that contain mostly dilute water. The overall value for heat discharge of 81-87 MW_t is less sensitive to assumptions than values for specific features. Increasing the slope of the sodium/chloride relation for dilute water to 12.5 increases the heat discharge from the chloride inventory to 118 MW_t. The value of 87 MW_t may be a minimum, with the actual value as much as 50 % larger.

The heat discharge from the Wood River group of springs is large compared to the measurements of heat input to Crater Lake of 15-30 MW_t (Collier and others, 1991). Additional convective discharge is indicated by the drill hole data for MZI-11A east of Crater Lake (Figure 1) where a temperature of 107°C was found at a depth of 405 m (Blackwell and Steele, 1987). Thus most of the heat discharge appears to occur peripherally rather than into Crater Lake itself.

The ratio of temperature to solute can be obtained by combining the slopes of Figures 2 and 5 for sodium and is 0.43 °C/(mg-Na/L). For the thermal discharge into Crater Lake, the same ratio is 0.24 °C/(mg-Na/L) (Collier and others, 1991). This would appear to be a significant difference, and the difference implies that the thermal fluid feeding the Wood River group is different from that feeding Crater Lake. Surprisingly, the temperature per amount of solute is higher for the Wood River group. Thus more thermal energy is added per amount of solute, where just the opposite would be expected if there were significant conductive heat loss before the thermal fluid mixed to form the Wood River group of springs.

The discharge of dissolved constituents in Table 2 of 44,900 and 60,000 mg/s for sodium and chloride can be compared to values found for Crater Lake. Nathenson (1990b) calculated anomalous inputs of sodium and chloride to Crater Lake of 25,500 and 24,700 mg/s, respectively. Values for the average of the range reported by Collier and others (1991) for Crater Lake are 17,900 and 17,500 mg/s for sodium and chloride, respectively (the difference between the two calculations for Crater Lake is due to the use of different water balances for the lake). The ratio of the discharge of dissolved constituents at the Wood River group to the input to Crater Lake ranges from 1.8 to 3.4. As with heat discharge, the discharge of dissolved constituents at the Wood River group is significantly larger than at Crater Lake.

The ratio of sodium to chloride discharge for the Wood River group of springs is 0.75 versus 1.0 for Crater Lake. This difference indicates that the chemistry of the source thermal water for the two systems is probably different.

CONCLUSIONS

The combination of the various data sets for the Wood River group of springs yields a convective heat discharge of at least 87 MW_t from the chloride inventory and a solute to temperature ratio of 0.43 °C/(mg-Na/L). Comparison of these results with the 15-30 MW_t and 0.24 °C/(mg-Na/L) obtained by Collier and others (1991) for Crater Lake provides important insights into the heat transfer characteristics of the volcanic system. Convective heat discharge from the summit of Mount Hood is 10 MW_t (Friedman and others, 1982), from the summit of Mount Rainier is 10.5 MW_t (Frank, 1985), and from Dorr Fumarole field and Sherman Crater of Mount Baker in 1972 before the increase in activity was 12 MW_t (Friedman and Frank, 1980). Thus the heat discharge into Crater Lake is larger than for these other volcanoes, but it is only a factor of 1.5 to 3 larger. Based on the similar magnitude of heat discharge into Crater Lake and that found in the summit fumaroles of other Cascade volcanoes, it may be that the mechanism for providing this heat is similar. The basic mechanism for summit fumaroles is heat input from magma in the conduits that fed recent eruptions rather than heat loss from the underlying magma chamber. Similarly, the heat input to Crater Lake could be from the conduits that fed eruptions within the caldera. The larger heat discharge and the higher ratio of heat to solutes at the Wood River group of springs, however, require a larger or younger heat source. The Wood River group of springs is located generally along a fault trending north-northwest that projects towards Crater Lake but cannot be followed under the cover of the young volcanic rocks of Mount Mazama and the climactic eruption (Kienle and others, 1981; Sherrod and Pickthorn, 1992). Based on the magnitude of the convective heat discharge from the Wood River group and the location of these springs along a fault that projects towards Crater Lake caldera, it seems likely that the heat source for this geothermal system is related to the volcanic system rather than gathering regional heat flow. The source of the heat could be either the underlying magma chamber or an intrusive body at shallower depth.

ACKNOWLEDGMENTS

Patrick Muffler and Michael Sorey provided helpful reviews.

REFERENCES CITED

Blackwell, D. D., and Steele, J. L., 1987, Geothermal data from deep holes in the Oregon Cascade Range: Geothermal Resources Council Transactions, v. 11, p. 317-322.

Collier, R. W., Dymond, Jack, and McManus, James, 1991, Studies of Hydrothermal Processes in Crater Lake, OR: College of Oceanography Report #90-7, Oregon State University, 317p.

Frank, D. G., 1985, Hydrothermal processes from Mount Rainier, Washington: PhD Dissertation, University of Washington, 196 p.

Friedman, J. D., and Frank, David, 1980, Infrared surveys, radiant flux, and total heat discharge at Mount Baker, Washington, between 1970 and 1975: U.S. Geological Survey Professional Paper 1022-D, 33 p.

Friedman, J. D., Williams, D. L., and Frank, David, 1982, Structural and heat flow implications of infrared anomalies at Mt. Hood, Oregon, 1972-1977: Journal of Geophysical Research, v. 87, p. 2793-2803.

Kienle, C. F., Nelson, C. A., and Lawrence, R. D., 1981, Faults and lineaments of the southern Cascades, Oregon: Oregon Department of Geology and Mineral Industries Special Paper 13, 23 p., 2 plates, scale 1:250,000.

Mariner, R. H., Presser, T. S., Evans, W. C., and Pringle, M. K. W., 1990, Discharge rates of fluid and heat by thermal springs of the Cascade Range, Washington, Oregon and northern California: Journal of Geophysical Research, v. 95, p. 19,517-19,531.

Miller, R. L., Bradford, W. L., and Peters, N. E., 1988, Specific conductance: Theoretical considerations and application to analytical quality control: U.S. Geological Survey Water-Supply Paper 2311, 16 p.

Nathenson, Manuel, 1990a, Temperatures of springs in the vicinity of Crater Lake, Oregon, in relation to air and ground temperatures: U.S. Geological Survey Open-File Report 90-671, 19 p.

Nathenson, Manuel, 1990b, Chemical balance for major elements in water in Crater Lake, Oregon, *in* Drake, E. T., Larson, G. L., Dymond, J., and Collier, R., eds., Crater Lake, An Ecosystem Study: Pacific Division, American Association for the Advancement of Science, San Francisco, p. 103-114.

Nathenson, Manuel, and Thompson, J. M., 1990 , Chemistry of Crater Lake, Oregon, and nearby springs in relation to weathering, *in* Drake, E. T., Larson, G. L., Dymond, J., and Collier, R., eds., Crater Lake, An Ecosystem Study: Pacific Division, American Association for the Advancement of Science, San Francisco, p. 115-126.

Sherrod, D. R., and Pickthorn, L. B. G., 1992, Geologic map of the west half of Klamath Falls 1° by 2° quadrangle, south-central Oregon: U.S. Geological Survey Miscellaneous Investigations Map I-2182, scale 1:250,000.

Thompson, J. M., Nathenson, Manuel, and White, L. D., 1990, Chemical and isotopic compositions of waters from Crater Lake, Oregon, and nearby vicinity, *in* Drake, E. T., Larson, G. L., Dymond, J., and Collier, R., eds., Crater Lake, An Ecosystem Study: Pacific Division, American Association for the Advancement of Science, San Francisco, p. 91-102.