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REPORT OF HYDROLOGIC INVESTIGATIONS IN THE THREE SISTERS AREA OF CENTRAL OREGON, SUMMER 2001.

By William C. Evans[1], Robert H. Mariner[1], Steven E. Ingebritsen[1], B. Mack Kennedy[2], Matthias C. van Soest[2], and Mark A. Huebner[1]

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Report of Hydrologic Investigations in the Three Sisters Area of Central Oregon, Summer 2001.

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ABSTRACT

An ongoing episode of crustal uplift centered in the Separation Creek drainage of the Three Sisters area, central Oregon Cascades, may result from a magmatic intrusion that began in 1998. An investigation of springs in this drainage in summer 2001 revealed slightly elevated water temperatures and chloride (Cl^-) concentrations of up to about 5°C and 20 milligrams per liter (mg/L), respectively, above background. The total discharge of anomalous Cl^- in Separation Creek was 9.2 grams per second, which in combination with the temperature-Cl^- relation in the springs results in a total advective heat discharge of 16 MW (megawatts). Comparison with similar findings obtained a decade earlier suggests that total Cl^- and heat discharges in the groundwater drainage are unaffected by the current uplift. However, the isotopic composition of the dissolved inorganic carbon (DIC) in the spring waters (delta carbon-13 ($\delta^{13}C$) = -9.03 to -11.6‰; carbon-14 (^{14}C) <25 pmC) combined with helium-3/helium-4 ($^3He/^4He$) ratios near 8 R_A and C/^3He ratios <10^{10} in two of the springs are indicative of a magmatic source. The high $^3He/^4He$ ratios indicate that the magmatic gas is derived from a relatively recent, if not ongoing, intrusion. The concentration of magmatic carbon is low, a few millimoles per liter (mmol/L) at most, with an average value of 1.53 mmol/L for all the springs sampled in the drainage. Combining this average with the late-summer water flow in Separation Creek suggests a discharge of 21 tonnes/day of magmatic carbon dioxide (CO_2). The presence of magmatic carbon in the shallow groundwater system, and the fact that DIC is uncorrelated with Cl^-, suggests that some magmatic gas could escape diffusely through the soils.

INTRODUCTION

Crustal uplift in the Three Sisters area was first detected by Wicks and others (2001) using InSAR imagery. That imagery reveals uplift over a broad circular region, with maximum rise at the center reaching 4-5 cm/yr. The uplift is centered several km west of the Cascades crest, at a location lacking young volcanic vents. However, discharge of thermal fluid in this area was recognized a decade prior to the onset of uplift on the basis of a Cl^- anomaly in Separation Creek, which drains the western flanks of South Sister (fig. 1).

In response to the detection of crustal uplift, USGS scientists conducted an investigation of springs and streams in the Separation Creek drainage, which includes the area of maximum uplift, from 8 to 16 July 2001. The main goal of the work was to check the water for geochemical anomalies that would reflect enhanced up-flow of either thermal water or magmatic gases, two processes that might accompany intrusion, especially at the shallow depth of 6-7 km proposed by Wicks and others (2001; 2002). This study was carried out in collaboration with noble-gas experts from the Lawrence Berkeley National Laboratory (LBNL).

BACKGROUND

Streams flowing over volcanic rocks of the Cascade Range normally have chloride concentrations within or near the range of average values in local precipitation (typically 0.2-0.7 mg/L), unless they have received some thermal fluid input. Reconnaissance sampling of lower Separation Creek on 11/17/89 revealed an anomalous Cl^- concentration of 1.6 mg/L (Ingebritsen and others, 1994, p. 33). Further sampling and stream gaging on 9/12/90 confirmed an anomalous Cl^- flux of about 10 g/s in Separation Creek (Ingebritsen and others, 1994, p. 59), comparable to that associated with hot springs of the Western Cascades, such as Breitenbush and the nearby McKenzie River group (fig. 1).

The anomalous Cl^- flux in Separation Creek was originally suspected to derive from input of thermal water similar to that discharging from the hot springs. The undiscovered hydrothermal source was thus expected to have a Cl^- concentration on the order of 10^3 mg/L and to occur at low elevation on Separation Creek, near the confluence with Horse Creek, because all of the known
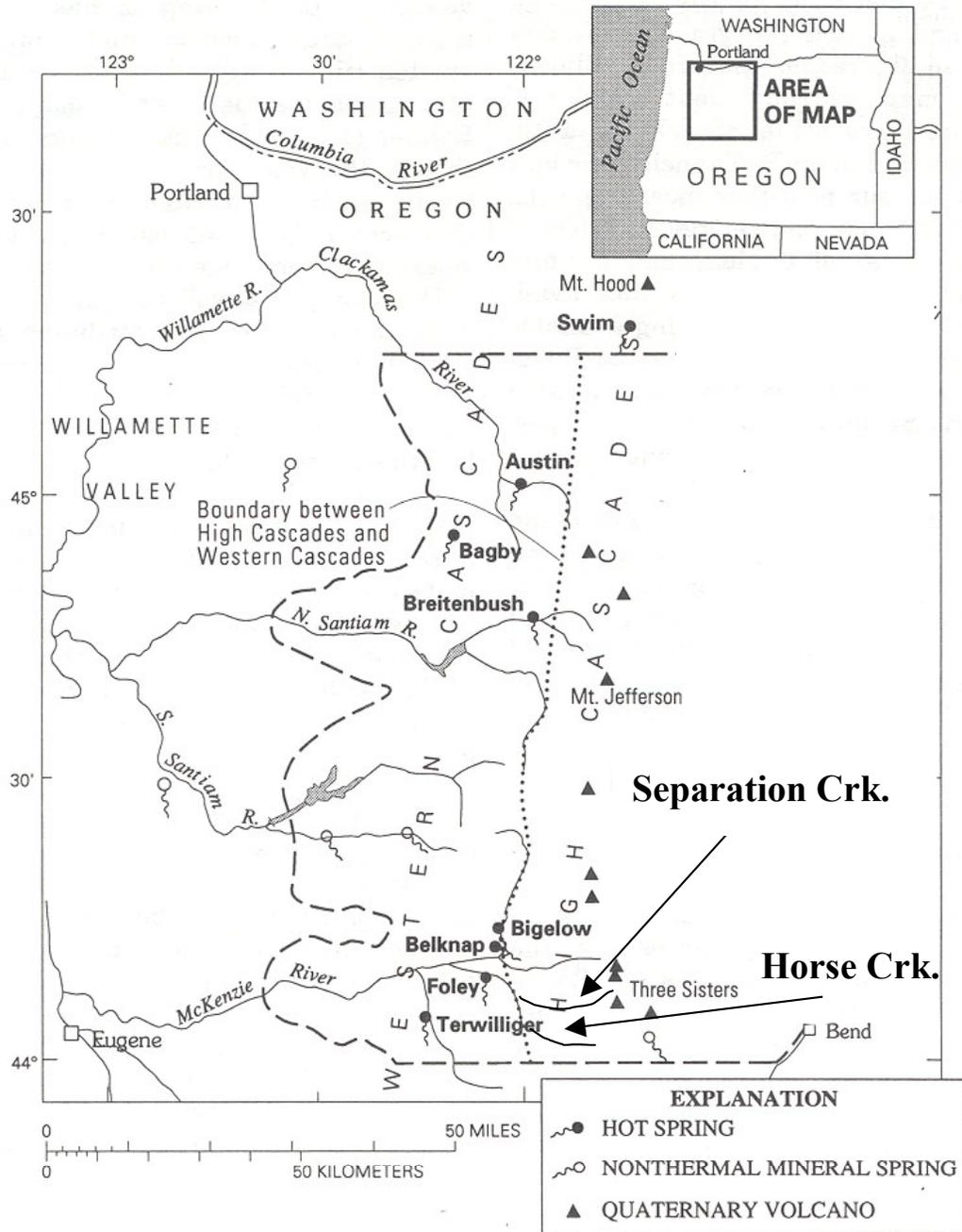
Figure 1. Map showing the volcanic peaks of the High Cascades, major drainages, and hot springs of the Western Cascades (*modified from Ingebritsen and others, 1994, to show Separation and Horse Creeks).*

Western Cascades hot springs occur at the bottom of major stream valleys (fig. 1), between elevations of 460 and 760 m. Later sampling expeditions in 1990 and 1998 (Ingebritsen and others, 1994; Iverson, 1999) instead traced the source of Cl⁻ up Separation Creek and several of its tributaries to a large number of springs widely distributed through the drainage, at elevations ranging from 1050 to 1850 m. The most concentrated springs contained about 20 mg/L Cl⁻ and were only a few degrees above ambient temperature for the discharge elevation (Iverson, 1999). During these studies, much information was compiled on groundwater geochemistry, stream discharges, and dissolved loads, making Separation Creek an exceptionally well-characterized drainage compared to many in the Cascade Range. Anomalies resulting from the current episode of crustal uplift can be more easily distinguished from pre-existing conditions because of this large database (see Appendix for a compilation of data

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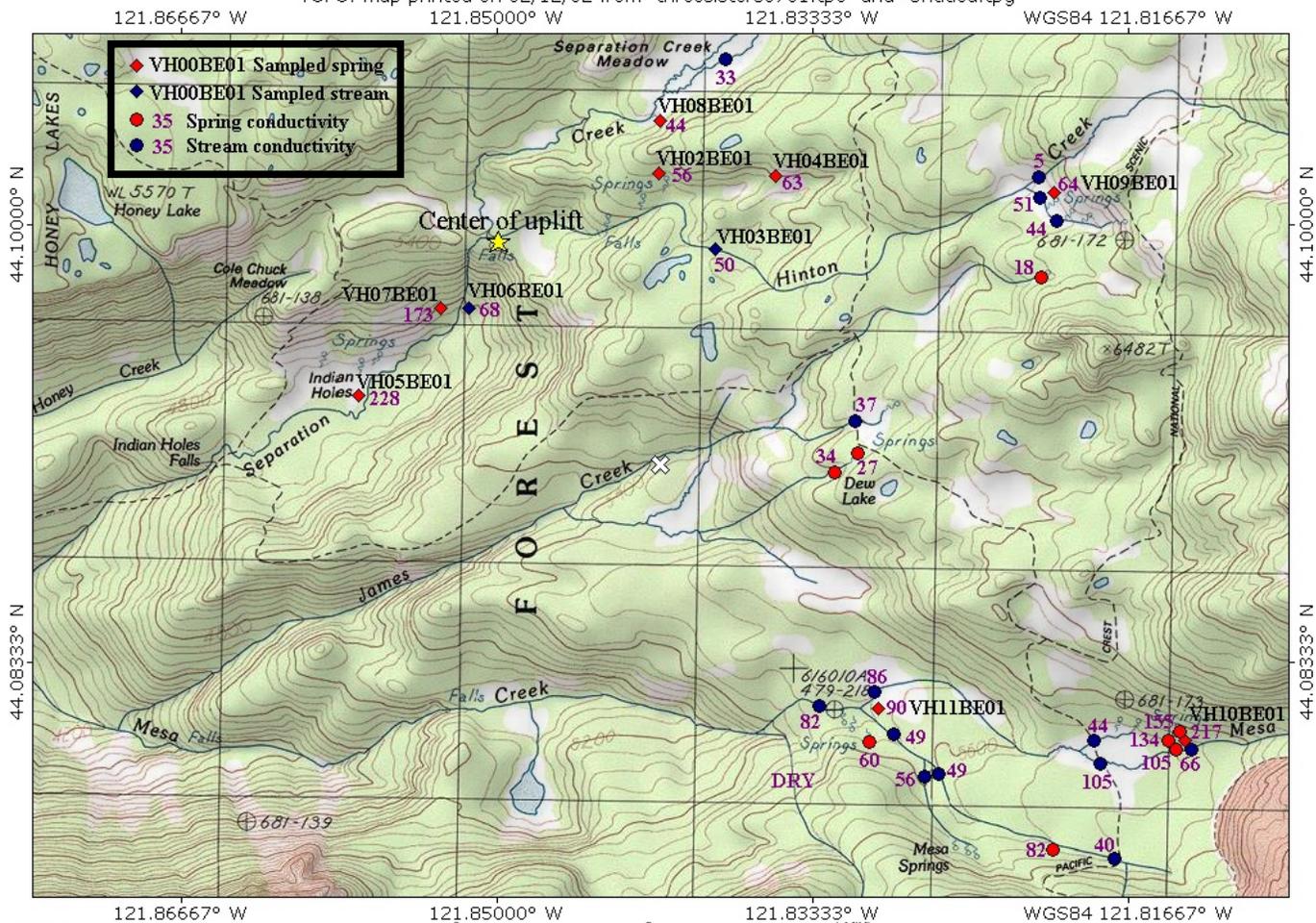
Figure 2a. Spring and stream locations with conductivity values in upper Separation Creek area, July 2001. Location of maximum uplift shown. See key for symbol explanation.
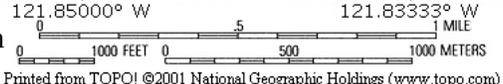
Figure 2b. Spring and stream locations with conductivity values in lower Separation Creek area, July 2001. See key on Fig. 2a for symbols.
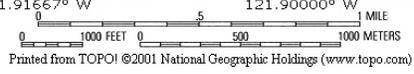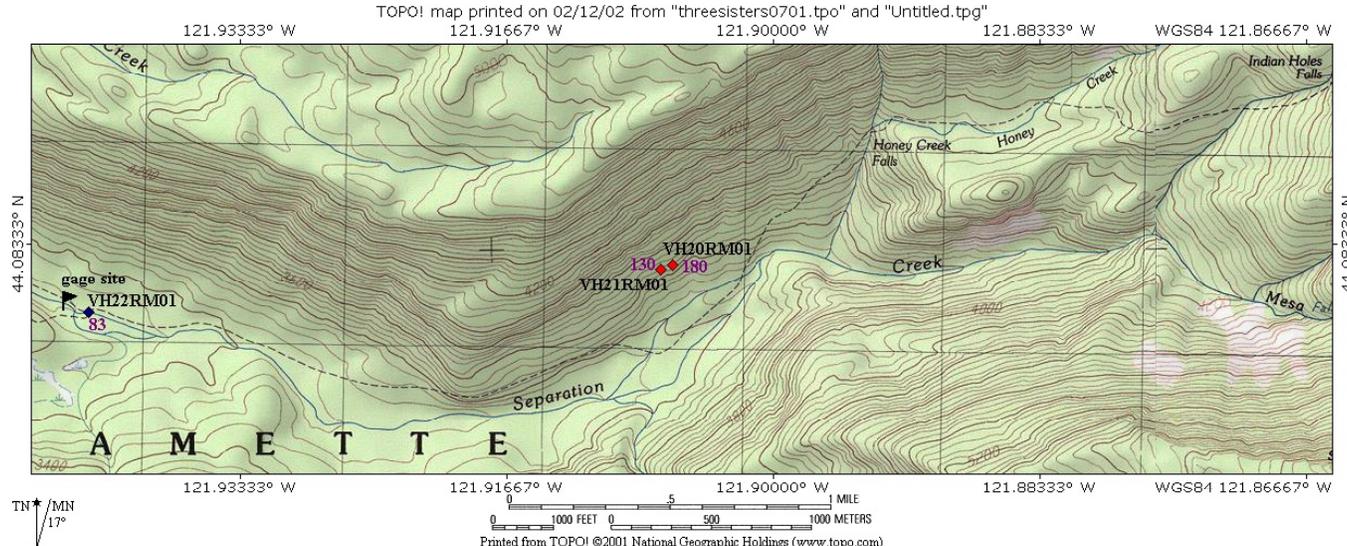
collected prior to 2001). However, some areas of the watershed remain to be sampled for geochemistry, even after the work described herein.

PROCEDURES

Up-flow of thermal water brings dissolved salts into overlying shallow groundwater, increasing its conductivity and providing an easy means of detecting water that contains even a trace of thermal fluid. Conductivity was measured with a portable meter at many springs and streams. Other field measurements included temperature, dissolved oxygen, pH, and alkalinity. A few measurements of CO_2 in soil gas at 10 cm depth were made at selected locations by driving in a tube and connecting it to a pump and portable infrared sensor. Water samples were collected from springs with the highest conductivity within a given spring group and from a few springs with lower conductivity. All water samples were filtered on-site through 0.45 µm filters. One bottle was acidified to pH~2 with high-purity nitric acid for subsequent cation analysis by inductively coupled plasma mass spectrometry. A second bottle was left unacidified for subsequent anion analysis by ion chromatography.

Two of the springs with the warmest temperatures and highest conductivities produced streams of gas bubbles, which were collected in pre-evacuated Pyrex tubes. Separation Creek was gaged and sampled upstream from its confluence with Horse Creek by the USGS Oregon District during the week following the sampling. Samples were also collected from a non-thermal mineral (soda) spring located about 10 km southeast of the Separation Creek drainage (fig. 1), and noble gas samples were collected from several hot and soda springs at lower elevations in central Oregon.

RESULTS

Locations where conductivity was measured along with the results are shown in figure 2. Conductivities ranged from 5 to 228 µS/cm, with the lowest value measured in the upper reach of Hinton Creek, probably representing glacial melt-water. Iverson (1999), in the course of his USGS-sponsored senior honors thesis research, demonstrated that Cl⁻ exceeded background values in waters with conductivities ≥40 µS/cm (his fig. 1). Although it should be noted that HCO_3^- is the main anion responsible for conductivity in all waters sampled, the 40-µS/cm value can reasonably be used to distinguish waters with anomalous chloride from the regional background. Figure 2 shows that anomalous waters discharge throughout the area above 1050 m elevation but apparently not in upper James Creek or in Separation Creek above Separation Creek Meadows. The maximum conductivity (228 µS/cm) was found in the Indian Holes area, very close to the center of crustal uplift, but a value of 217 µS/cm was found in the upper Mesa Creek area, several km to the southeast.

Sites where additional analyses were performed are distinguished by diamond symbols in figure 2, and the

results are shown in table 1. Dissolved O_2 (oxygen) values are given both in mg/L and as percent of air-saturation at the temperature of the spring. Temperature anomalies are difficult to recognize in table 1 because of the large range in elevations and the fact that both springs and streams were sampled. Comparison with the regional temperature-elevation relation for cold springs given by Ingebritsen and others (1994) suggests that maximum anomalies are about 5°C in the springs (fig. 3). The anion results in table 1 show the change with elevation noted by Iverson (1999): Cl⁻ exceeds SO_4^{-2} (sulfate) in lower elevation springs, whereas SO_4^{-2} is dominant above 1600 m.

The gas collected from the two bubbling springs is dominated by an air-like component, as shown in table 2. Compared to atmospheric air, the gas is significantly enriched in He (helium), slightly enriched in CO_2, and depleted in O_2. The helium isotopes show a strong magmatic signature. Dissolved Inorganic Carbon (DIC) speciation and isotopes are shown in table 3. The few ^{14}C values available show that the DIC in those springs is dominated by dead carbon, whereas the $\delta^{13}C$ values of all the springs analyzed are heavier than expected for DIC in shallow groundwater.
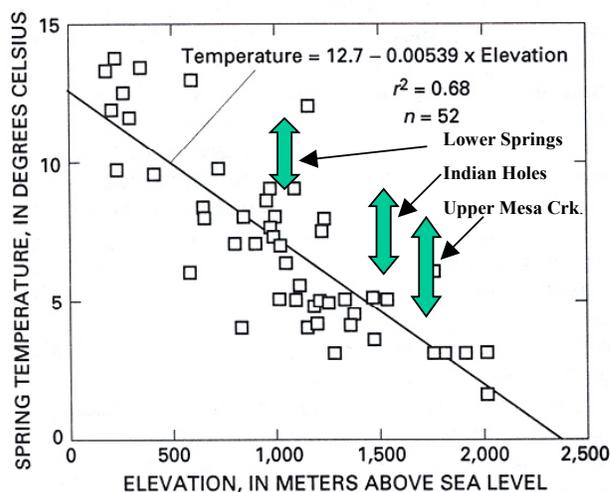
Figure 3. Temperature *vs.* elevation for three spring groups in the Separation Creek drainage (block arrows) compared to the regional data for springs with no Cl⁻ anomaly (open squares) and regression line from Ingebritsen and others (1994; their fig. 21). Block arrows include data from Appendix.

Comparisons with Past Data

The pattern of anomalous conductivities (fig. 2) is similar to that found in 1998 by Iverson (1999). For example, he found a low conductivity (14 µS/cm) in upper James Creek and conductivities up to 207 µS/cm in the Indian Holes area and up to 180 µS/cm in springs near the confluence of Separation, Honey, and Sphinx Creeks (near VH20RM01). In the upper Mesa Creek area (near VH10BE01) conductivities were anomalous in 1998 but less than 100 µS/cm. Several springs were found to have conductivities exceeding 100 µS/cm in 2001, suggesting

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Table 1. Locations where water analyses were performed (as shown on fig. 2) and results.

Sample #	Name	elev. m	t (°C)	cond. µS/cm	D.O. mg/L	O₂ Sat. %	pH	HCO₃ mg/L	Cl mg/L	SO₄ mg/L	Br mg/L	F mg/L	NO₃ mg/L	PO₄ mg/L	Trit. TU
VH02BE01	Unnamed spring	1746	2.9	56	10.3	93	6.05	27	1.54	2.1	0.005	0.06	0.01	0.025	
VH03BE01	Hinton Creek	1742	8.6	50					1.58	2.9	0.004	0.06	<0.01	0.018	
VH04BE01	Head of unnamed creek (rockfall)	1771	2.7	63	11.6	105									
VH05BE01	Indian Holes spring (lower meadow)	1483	7.8	228 - 197	8.6	86	8.04	85	20.5	6.8	0.056	0.22	<0.01	0.154	3.1
VH06BE01	Separation Creek	1525	6.8	68					2.1	2.1	0.006	0.08	<0.01	0.057	
VH07BE01	Indian Holes spring on hillside	1525	5.5	173	10.6	101	7.80	90	7.4	2.9	0.020	0.20	<0.01	0.21	7.0
VH08BE01	Spring near Separation Meadows	1737	2.8	44	10.5	94	6.43	27	0.85	1.03	0.003	0.06	<0.01	0.057	
VH09BE01	Unnamed spring	1855	2.8	64	10.2	92	5.60	29	2.2	4.1	0.006	0.06	<0.01	<0.01	
VH10BE01	Spring at upper end of Mesa Meadows	1755	7.8	217	5.5	56	8.03	93	7.0	18	0.021	0.36	<0.01	0.34	5.4
VH11BE01	Large discharge spring	1687	3.5	90			7.60	39	3.3	5.6	0.010	0.18	0.01	0.087	6.2
VH20RM01	Unnamed spring (low on Separation Creek)	1110	11.2	180			8.65	85	12.6	3.0	0.035	0.09	0.03	0.053	0.2
VH21RM01	Unnamed spring (low on Separation Creek)	1110	9.2	130				67	6.7	1.66	0.018	0.06	0.01	0.049	
VH22RM01	Separation Creek at foot bridge	957						44	3.0	1.62	0.003	0.07	<0.01	0.072	
VH23KL01	Separation Creek at gage site (0.1 km below br.)	952	7.4	83				36							
VH27BE01	Soda spring southeast of South Sister	1800					5.64	506	5.3	16.7	0.013	0.32	<0.01	<0.01	

Values for HCO₃ are alkalinity as bicarbonate. Anion analyses performed by Mark Huebner, tritium by Robert Michel, both USGS, Menlo Park, CA.

Table 2. Analyses of gas bubbles collected from springs.

vol-%	VH05BE01	VH10BE01	standard air
He	0.0095	0.0050	0.0005
H₂	<0.0002	<0.0002	<0.0002
Ar	0.989	1.018	0.934
O₂	16.93	11.30	20.95
N₂	81.24	86.19	78.08
CH₄	<0.0002	<0.0002	<0.0002
CO₂	0.1078	0.0879	0.0365
C₂H₆	<0.0002	<0.0002	<0.0002
H₂S	<0.0005	<0.0005	<0.0005
CO	<0.001	<0.001	<0.001
C₃H₈	<0.0005	<0.0005	<0.0005
C₄H₁₀	<0.0005	<0.0005	<0.0005
N₂/Ar	82.1	84.6	83.6
He/He(air)	19	10	1
O₂/O₂(air)	0.81	0.54	1
³He/⁴He (Rₐ)	7.4	8.6	1

Helium isotopic analyses by Mack Kennedy and Matthias van Soest at Lawrence Berkeley National Laboratory.

Table 3. Dissolved inorganic carbon and isotopic results.

Sample	HCO₃⁻ mmol/L	DIC mmol/L	δ¹³C-DIC per mil PDB	¹⁴C pmC	biogenic DIC mmol/L	abiogenic DIC mmol/L
VH02BE01	0.44	1.82				
VH05BE01	1.39	1.47	-11.49	22.2	0.28	1.19
VH07BE01	1.48	1.56	-9.72			
VH08BE01	0.44	1.16	-10.00			
VH09BE01	0.48	4.24	-9.30	5.85	0.22	4.02
VH10BE01	1.52	1.54	-9.03	10.3	0.14	1.40
VH11BE01	0.64	0.68	-11.43			
VH20RM01	1.39	1.40	-11.59			
VH21RM01	1.10					
VH22RM01	0.72					
VH27BE01	8.29	59.8	-9.84	1.11	0.58	59.20

Analyses of δ¹³C by L. D. White, USGS, Menlo Park, CA. Analyses of ¹⁴C by Tom Guilderson, Lawrence Livermore National Laboratory. Biogenic carbon was assumed to be 115 pmC.

that some change has occurred in the upper Mesa Creek area. The area near VH11BE01 was not visited in 1998.

The Cl$^-$ and SO$_4^{-2}$ values in 2001 (table 1) were also similar to those of Iverson (1999) for most spring areas. The exception is again the upper Mesa Creek area, where VH10BE01 has more than twice the Cl$^-$ and SO$_4^{-2}$ values found in any of the springs sampled here in 1998. In comparing present results to those of Iverson (1999), note that all anion analyses were performed in the same laboratory using the same instrument. Previous Cl$^-$ and SO$_4^{-2}$ values are given in the Appendix and are shown in map format at http://wwwrcamnl.wr.usgs.gov/volcwater/.

Spring temperatures we measured were also similar to those of Iverson, as was the tendency for temperature anomalies to correlate with Cl$^-$ within any given spring group (Iverson, 1999, his fig. 2).

Chloride/Bromide Ratios

Bromide, like chloride, is considered to be a conservative element in dilute groundwater. Water samples collected in 2001 were analyzed by a sensitive ion chromatography technique whereby Br$^-$ could be detected down to about 1 μg/L, sufficiently low that the Cl$^-$/Br$^-$ ratio could be determined for all of the samples. This ratio, shown in figure 4, is remarkably constant in the samples, including the mineralized soda spring southeast of the area. The only sample that plots significantly off the correlation line was collected from the lower reach of Separation Creek, and this probably reflects selective removal of trace levels of Br$^-$ by biologic or sorption processes (see Davis and others, 1998) in the channel during the long flow downstream. Excluding this point, the regression line has an R^2 of 0.997, and the average Cl$^-$/Br$^-$ mass ratio is 368.
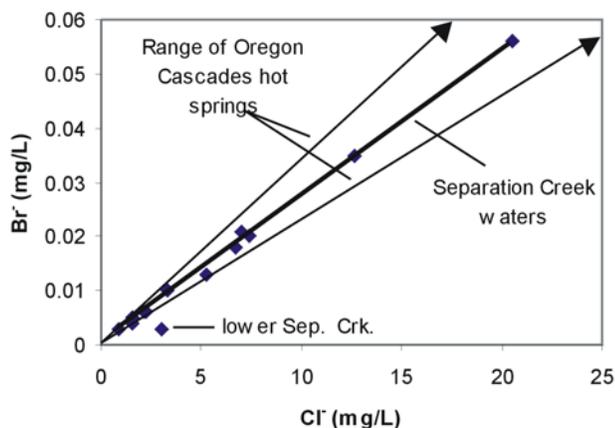
Figure 4. Bromide vs. chloride in Separation Creek waters compared to hot springs of the Oregon Cascades.

The strong correlation between Cl$^-$ and Br$^-$ suggests that they share a common source throughout the study area. The Cl$^-$/Br$^-$ ratio is within the range found in the hot springs in the Western Cascades (Mariner and others, 1989; R. H. Mariner, written communication).

Alkalinity and Dissolved Inorganic Carbon

Gaseous CO$_2$ has a moderate aqueous solubility at low temperatures. Cold groundwaters that encounter CO$_2$ rising from sources at depth can absorb large quantities of the gas. The high-TDS soda spring located about 10 km southeast of the study area is an example of a groundwater that has absorbed so much CO$_2$ that free gas bubbles exsolve vigorously out of solution at the spring vent.

Dissolved CO$_2$ is not a conservative component, however. It reacts with silicate minerals to form HCO$_3^-$, which accounts for nearly all the alkalinity in these waters. The concentration of HCO$_3^-$ in cold groundwater depends in part on the amount of CO$_2$ that dissolves into the water and on the time that elapses before the water discharges at a spring. If no CO$_2$ is lost from the groundwater and no carbonate minerals precipitate (or dissolve), then the molar DIC, which is the sum of the CO$_2$, HCO$_3^-$, and CO$_3^-$, is conserved during flow to the discharge point. These two conditions may be met for the dilute groundwaters in the study area, and so it is worthwhile to compare DIC and another conservative constituent, such as Cl$^-$.

Figure 5 shows a plot of HCO$_3^-$ and DIC against Cl$^-$. The HCO$_3^-$ concentration shows only a general correlation, and the DIC no correlation, with Cl$^-$. Both HCO$_3^-$ and DIC show only a weak correlation with SO$_4^{-2}$ as well. Although additional sampling is needed to fill in gaps in the plots, the existing data show that CO$_2$ source strength is not well linked with the thermal water up-flow, which transports the Cl$^-$.
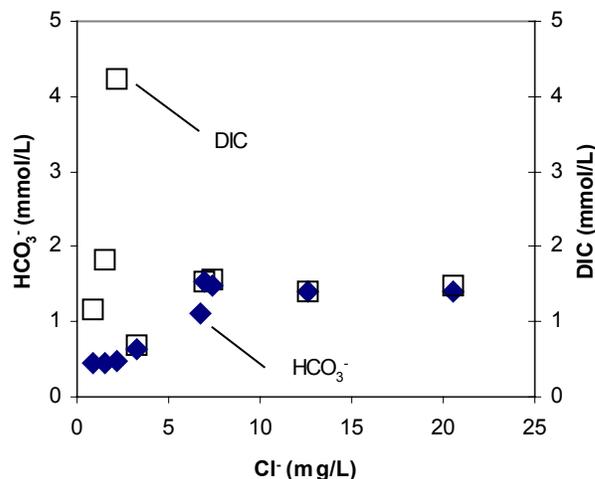
Figure 5. Bicarbonate (diamonds) and dissolved inorganic carbon (open squares) *vs.* chloride in springs of the Separation Creek drainage.

Carbon: Isotopes and Sources

The soil-gas CO$_2$ concentration measurements at 10 cm depth averaged 0.40% (range of 0.08% to 0.75%), fairly typical of well-drained soils in healthy forest and due to respiration by plant roots and soil microbes (see, e.g., Reardon and others, 1979; Fritz and others, 1985).

Groundwater that recharges through these soils dissolves some of this CO_2. To distinguish this shallow, biogenic component from any deep-seated component, isotopic analysis of the DIC is required. For the coniferous forest area here, the $\delta^{13}C$ value of soil CO_2 is expected to be near -20‰ (Reardon and others, 1979; Fritz and others, 1985; Evans and others, 2002). The heavy $\delta^{13}C$ values of the DIC in the springs (table 3) clearly reflect an input of deep-seated carbon, but until its $\delta^{13}C$ is known, the relative proportions of shallow and deep carbon cannot be calculated.

A few ^{14}C analyses were obtained to help resolve the issue. The residence time of most shallow groundwater in the upper Separation Creek drainage is probably <50 years, based on tritium values in table 1. This is short enough that radio-decay of ^{14}C within the aquifers can be ignored, and the DIC in springs that acquire CO_2 only from soil respiration processes should have modern ^{14}C values. Any depletion in ^{14}C from modern values results from addition of carbon from depth. The bomb-related spike and subsequent decline in atmospheric ^{14}C during the past 50 years is a slight complication because ^{14}C in soil CO_2 tracks the atmospheric values and also exceeds the defined "modern carbon". Assuming an average groundwater flow time of about a decade suggests that biologically produced DIC in these springs should have a ^{14}C of about 115% modern. On that basis, the ^{14}C values in table 3 can be used to break down the DIC into biogenic and abiogenic components. Clearly, most of the DIC in the samples is abiogenic, and very little error is introduced by the uncertainty in the assumed ^{14}C of the biogenic end member.

Figure 6 shows the $\delta^{13}C$ values plotted against the fraction of the DIC that is abiogenic. The three cold springs in the Separation Creek drainage correspond well
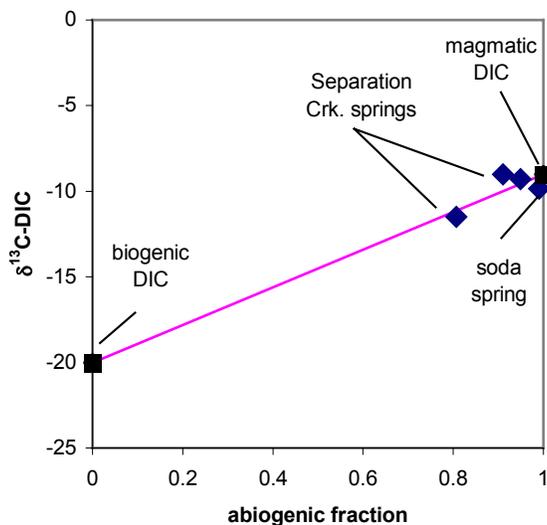

Figure 6. Carbon isotope plot of three springs in the Separation Creek drainage and the soda spring to the southeast. The mixing line assumes a $\delta^{13}C$ of -9‰ for magmatic carbon.

to a line that assumes a $\delta^{13}C$ of -20‰ for biogenic C and a $\delta^{13}C$ of -9‰ for the deep, abiogenic C. The -9‰ value is 2-3‰ lighter than both the average $\delta^{13}C$ value (-6.5‰) found (Sano and others, 1995) in mid-ocean ridge basalt (MORB) and the $\delta^{13}C$ of CO_2 gas from Newberry caldera (Carothers and others, 1987), southeast of Three Sisters. One possible source for the deep carbon is thermal breakdown of organic compounds in meta-sedimentary rocks buried deep beneath the Three Sisters volcanics. However, CO_2 from summit hot springs or fumaroles at many other Cascades volcanoes is similarly light isotopically. Mt. Hood, Mt. St. Helens, and Mt. Rainier to the north, and Mt. Shasta to the south of the Three Sisters area, all have $\delta^{13}C$ values between –9 and –12‰ (Evans and others, 1981; unpublished USGS data). At Mt. St. Helens, the light CO_2 was collected directly from erupted magma. Together with the helium isotopic data, the carbon isotopes suggest that the abiogenic component of the DIC derives from an up-flow of magmatic CO_2.

Based on the mixing line in figure 6, the $\delta^{13}C$ values in table 3 suggest that the DIC in all of the springs is dominated by a magmatic carbon component. The up-flow of magmatic CO_2 is apparently widespread through the area even though none of the springs contains a high concentration of DIC.

Gas Results

As noted by van Soest and others (2001), the $^3He/^4He$ ratios of 7.4 and 8.6 at Indian Holes and upper Mesa Creek, respectively, are among the highest in the Cascades. The magmatic origin of the helium is clear, but volatile species from depth otherwise constitute a minor fraction of the total gas phase. At the greater than neutral pH of both springs, most of the DIC is present as HCO_3^- and not CO_2.

The reason that bubbles form in these springs is that the waters are slightly warmer than background, in part through the small admixture of thermal fluid. Assuming that the waters recharged as snowmelt, they have warmed by nearly 8˚C prior to discharge. This temperature rise causes a 15-20% reduction in the solubilities of N_2, O_2, and Ar; and so the water, originally saturated with air gases at 0˚C, forms bubbles even though some of the dissolved O_2 has reacted away underground. The N_2/Ar ratio remains unchanged from the air value.

The composition of the gas bubbles can be used, along with the water temperature and ambient pressure, to calculate the concentrations of the various gases dissolved in the groundwater feeding the spring. The calculation assumes that the gas bubbles are in equilibrium with the water at the spring vent. Equilibrium is likely because probably <20% of the gas dissolved in these springs actually forms into bubbles. The good agreement between the $O_2/O_{2(air)}$ in the bubbles (table 2) and the percent-saturation measured in the water with the dissolved oxygen probe (table 1) further supports this assumption. For He, the calculated aquifer concentrations are 0.032 and 0.017 µmol/L for VH05BE01 and VH10BE01, respectively. Combining these concentrations with the $^3He/^4He$ ratios and DIC (table 3) gives $C/^3He$ ratios of 5 x 10^9 and 9 x 10^9,

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respectively, for the two springs. These low ratios, which are near the 2 x 10^9 value typically found in MORB (Sano and others, 1995), add further support for a magmatic carbon source.

DISCUSSION

Effects of Intrusion?

One of the main questions to address is whether there have been changes in the groundwater system of the Separation Creek drainage since 1998, when the surface uplift began (Wicks and others, 2002). As far as direct comparison is possible with the available temperature, conductivity, and chemistry data, no significant changes are apparent. Small but detectable changes seem to be restricted to the upper Mesa Creek area, where Cl$^-$ and SO$_4^{-2}$ values have increased. Both anions are proportionally increased from values reported by Iverson (1999), indicating that the deep fluid component has remained compositionally similar over the three-year period. The increased Cl$^-$ and SO$_4^{-2}$ concentrations could indicate that, in this part of the drainage, there is either a slight increase in up-flow of the deep fluid, or simply less dilution of the deep fluid by shallow groundwater because of the dry conditions in 2001.

For the entire drainage, the data suggest that any changes in the groundwater system have been small, even extending back to September 1990 when lower Separation Creek was gaged and sampled. Discharge and Cl$^-$ were 3.5 m^3/s and 3.3 mg/L, respectively, at that time, resulting in a total anomalous Cl$^-$ load of 10 g/s if the background Cl$^-$ concentration is assumed to be 0.5 mg/L. Discharge and Cl$^-$ were 3.6 m^3/s and 3.0 mg/L in July 2001, resulting in an anomalous Cl$^-$ load of 9.2 g/s, not significantly different from the 1990 result.

Some types of analyses, such as carbon speciation, were not previously performed in this area, making it difficult to evaluate temporal changes. Changes in HCO$_3^-$ can be ruled out because of the strong effect such changes would have on conductivity. Dissolved CO$_2$, however, does not contribute to conductivity and constitutes an important fraction of the DIC in some of the waters (fig. 5). Moreover, DIC does not appear to correlate with Cl$^-$, rendering a comparative approach speculative. Our carbon speciation measurements, and the carbon and helium isotopic work, serve as a basis for studying future changes.

Heat and Carbon Discharge

Although none of the springs in the drainage are more than ~5°C above the expected ambient value for a particular elevation, the total water flow from all of the springs is large enough that the advective heat transport is substantial. The general correlation between Cl$^-$ and temperature for springs in the drainage (fig. 7) allows advective heat transport to be calculated from the Cl$^-$
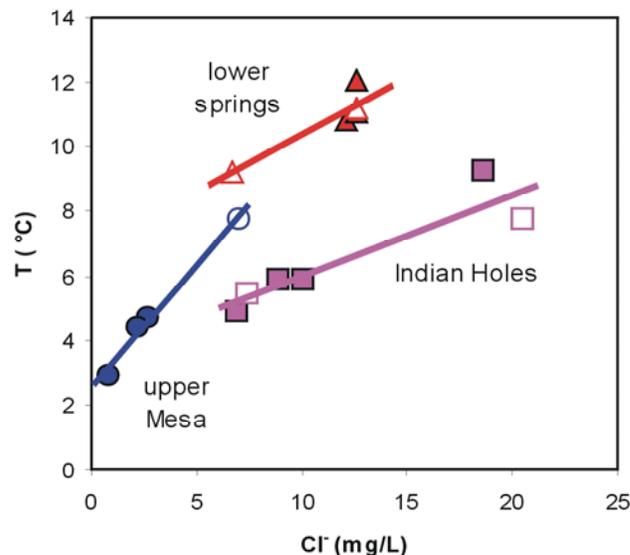

Figure 7. Temperature vs. chloride with regression lines for three spring areas in the Separation Creek drainage (solid symbols from Iverson (1999; his fig. 2); open symbols from table 1).

anomaly at the gaging site (3.0 – 0.5 = 2.5 mg/L) and the discharge (3.6 m^3/s). Figure 7 suggests a range of about 1.5 - 4 mg/L Cl$^-$ per °C above local ambient temperature for the different spring areas. Assuming the average value (2.5 mg/L/°C) gives a total advective heat transport of 16 MW with an uncertainty of about a factor of two. This is greater than the advected heat in many of the major hot spring systems in the Oregon Cascades (for example, the Breitenbush system). However, Ingebritsen and others (1994) hypothesized that the total heat advected by low-temperature groundwater systems of the central Oregon Cascades between 44° and 45°15' N latitude could be ~156 MW, ten times the amount in the Separation Creek drainage. This total represents an advective heat flow of ~1.1 MW/km-arc-length over 140 km. Manga (1998) documented a comparably large low-temperature advective heat flow of ~0.6 MW/km-arc-length south of South Sister, for the east side of the arc only.

The total discharge of magmatic carbon can also be calculated for the drainage. The 8 cold springs for which we have DIC data (table 3) show a range of 0.68 – 4.24 mmol/L with an average value of 1.72 mmol/L. The three that have ^{14}C analyses suggest that on average, 89% of the carbon is magmatic. Combining these values suggests an average magmatic DIC of 1.53 mmol/L. If all of the 3.6 m^3/s water at the gaging site reflected flow from such springs, the total magmatic carbon discharge through groundwater in the drainage would be 21 tonnes/day as CO$_2$.

The stream-discharge value of ~3.5 m^3/s – obtained both in 1990 and 2001 – is likely less than the mean annual stream flow, because both measurements were made under mid- to late-summer (low flow) conditions. Nevertheless,

8
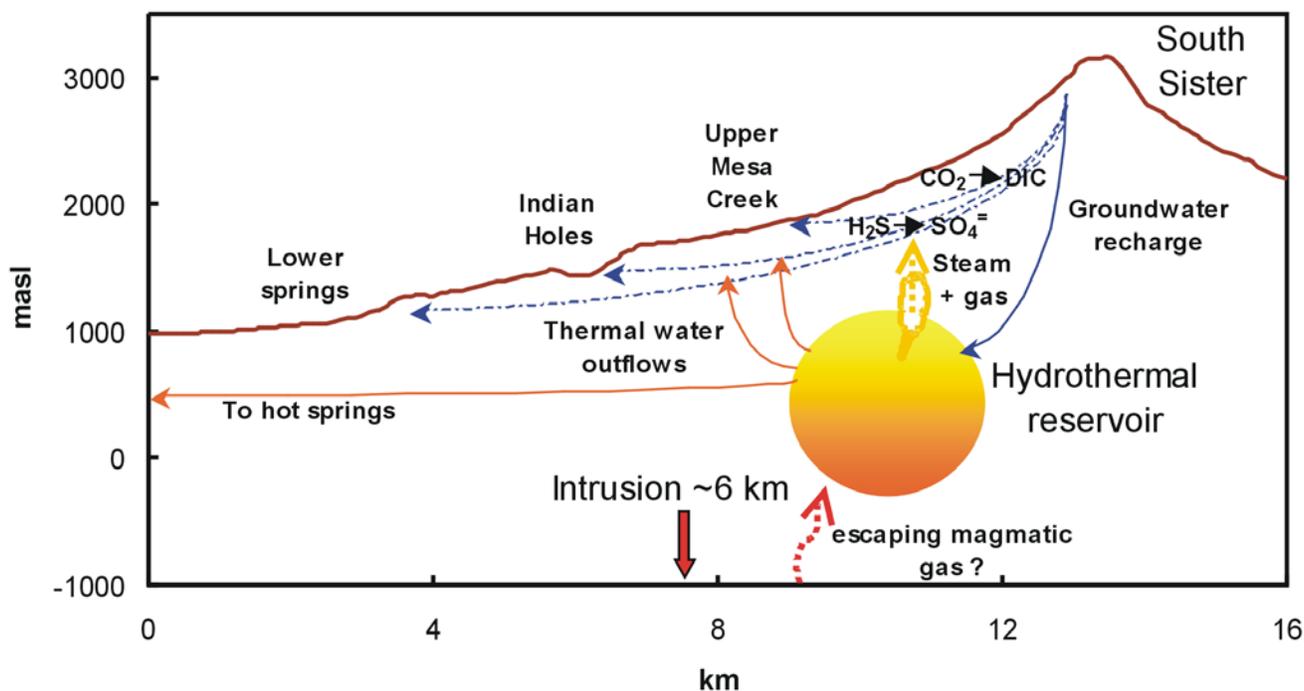
Figure 8. Conceptual model of the Separation Creek drainage (modified from Iverson, 1999). Up-flow of water from a hydrothermal reservoir beneath the western flank of South Sister feeds heat and Cl^- into the overlying groundwater system. Steam and gas from the reservoir affect the higher elevation groundwater. The H_2S oxidizes to SO_4^{-2}, while CO_2 is gradually and variably converted to HCO_3^- through reaction with silicate minerals.

a CO_2 discharge of 21 tonnes/day is likely to be a maximum estimate. One reason is that the spring with the lowest DIC, VH11BE01, had by far the largest discharge of all the springs sampled. In addition, the magmatic carbon discharge cannot be normalized to the Cl^- concentration at the gaging site, as was done for the heat transport, because DIC does not correlate with Cl^- in the springs (fig. 5). To the extent that some of the water flow at the gaging site does not result from spring input (Iverson, 1999) or may result from springs with no magmatic DIC, the 21 tonnes/day figure may overestimate the total discharge.

Magmatic carbon discharges of this magnitude were postulated to exist on the western side of the Cascades by James and others (1999), who found similar discharges in several large spring systems east of the crest. Their data show that other, long-dormant central Oregon volcanoes support carbon discharges comparable to that in the Separation Creek drainage. There is thus no evidence that requires the magmatic carbon discharge in Separation Creek to be linked with the ongoing crustal uplift. Larger carbon discharges have been measured at Lassen Peak (>28 tonnes/day) and Mammoth Mountain (50 tonnes/day) in California (Sorey and others, 1998; Evans and others, 2002), both of which have shown unrest within the past 100 years.

New Data and the Conceptual Model

Data acquired over the past two decades link the low elevation hot springs of the western Cascades to outflows from hydrothermal systems beneath the Cascade crest, most likely at reservoir temperatures of 100-180°C (Mariner and others, 1990; Ingebritsen and others, 1994). Iverson (1999) applied this model to the Separation Creek drainage, suggesting that thermal water leakage from a hydrothermal reservoir at fairly high elevations on the western flank of South Sister accounted for the Cl^- anomaly in the lower elevation springs, and that sulfur-rich vapors boiling off this reservoir gave rise to the SO_4^{-2} anomaly in the higher elevation springs. Our new results support this model, shown in figure 8.

There is no evidence for vapor-phase transport of Cl^- as HCl. Vaporization of HCl from Cl^--containing thermal waters becomes significant at temperatures above 250°C (Truesdell and others, 1989), and drilling in nearby Newberry caldera (Sammel, 1983) has shown that hydrothermal systems might reach such temperatures in the Cascade volcanoes without giving rise to vigorous surface features such as boiling springs. However, vaporization of the halogens would likely fractionate Cl^- and Br^-. The uniform Cl^-/Br^- ratio in all the cold springs, and the fact that this ratio falls within the range for the

low-elevation hot springs (fig. 4), argues strongly that the Cl^- anomaly results from input of thermal liquid.

The lack of correlation between Cl^- and HCO_3^- or DIC (fig. 5) suggests that a gas/vapor zone rich in CO_2 does overlie the liquid reservoir, allowing CO_2 to dissolve into shallow groundwaters independently of any inputs of Cl^--rich thermal water. An extensive vapor zone would, in addition, allow any H_2S gas to oxidize to SO_4^{-2}, explaining the distinct patterns in each of the SO_4^{-2}, Cl^-, and DIC anomalies. This hypothesis would also predict that waters rich in sulfate should be, in part, steam-heated, a possible explanation for the steeper slope of the temperature-Cl^- relation in the upper Mesa Creek springs (fig. 7) relative to the other spring areas.

The reservoir may be the same one that feeds the low-elevation hot springs in the Western Cascades (as assumed in fig. 8) or may be a separate, adjacent or superjacent system. Additional geochemical constraints are needed to address this. We note that the temperature-Cl^- relations (fig. 7) for the Indian Holes and lower springs groups extrapolate to about 500-700 mg/L Cl^- at 180˚C, the maximum reservoir temperature estimated for the low-elevation hot-spring systems to the west (Mariner and others, 1990; Ingebritsen and others, 1994). If the hot springs, which contain ~1200-1350 mg/L Cl^-, are fed from this same reservoir, then additional Cl^- must be added along the outflow paths. Some interaction with sedimentary rocks may occur, explaining the CH_4, high-N_2/Ar ratios, and relatively lower $^3He/^4He$ ratios in the hot springs (R. H. Mariner, written communication).

Because CO_2 apparently reaches the shallowest levels of groundwater flow, the possibility exists that some of the CO_2 escapes directly to the atmosphere, particularly at higher elevations where the water table may be relatively deep. Diffuse efflux measurements in the upper Separation Creek drainage should therefore be continued. The obvious comparison is Mammoth Mountain in California, where several hundred tonnes per day of CO_2 diffuse out through the volcano's flanks (Sorey and others, 1998; Gerlach and others, 1999; Rogie and others, 2001), while ~50 tonnes/day are transported by cold groundwater (Evans and others, 2002). The main difference between the two cases is that many of the cold springs at Mammoth Mountain are nearly saturated with CO_2, which may be a necessary condition for diffuse emissions to occur.

The Need for Cold Spring Studies

In instances where volcanic unrest or intrusion is suspected, water sampling frequently focuses on hot springs as the obvious surface manifestation of volcanic heat. In the central Oregon Cascades, however, the hot springs are connected to the hydrothermal reservoir through long outflow paths that would likely retard recognition of any changes in reservoir conditions. In contrast, heat and gases released from intruding magma may cause a rapid increase in vapor flux from the top of the reservoir. Much or all of the rising steam and gas may be absorbed in cold groundwaters with much shorter subsurface residence times. Springs fed by cold groundwater systems on or near the volcanic edifice may

therefore be the first hydrologic features to respond to unrest.

Detailed sampling of cold groundwaters may also provide information about magmatic characteristics that are not obtainable by other means. The Separation Creek sampling suggests that magmatic carbon in the Three Sisters area has a $\delta^{13}C$ ratio of about –9‰, lighter than the global average for magmatic carbon but similar to several other volcanoes in the Cascades. The $C/^3He$ ratio in the area seems to be $<10^{10}$, fairly close to the MORB range. Although more sampling for helium isotopes is needed, a low $C/^3He$ ratio limits the amount of crustal or subducted carbon that might be involved. Recognition of these geochemical signatures may prove invaluable to future studies; for example, to identify the source of any diffuse CO_2 emissions. These ratios can sometimes be difficult to interpret at hot or highly mineralized soda springs because of extensive degassing in the vent areas or calcite precipitation in the aquifers.

CONCLUSIONS

Our investigation of springs and streams in the Separation Creek drainage reveals that the anomalous discharge of thermal fluid and heat is similar in magnitude to that obtained prior to the current episode of crustal uplift. The total discharge of anomalous Cl^- remains at ~10 g/s; the total advective heat anomaly at ~16 MW.

Up to about 20 tonnes/day of magmatic CO_2 are absorbed and transported by the cold groundwater as DIC. This amount is substantial, but apparently not atypical of central Oregon volcanoes (James and others, 1999), and discharges of this magnitude may be more common at dormant volcanoes than is currently recognized. If we assume that the CO_2 derives from magma with a density of 2.7 g/cm^3 and an initial CO_2 content of 0.65 wt-% (e.g., Gerlach and Graeber, 1985; Lowenstern, 2001), the discharge represents complete degassing of about 0.0005 km^3 of magma per year. Similarly, the 16-MW heat anomaly could be supplied by crystallization and cooling of about 0.0003 km^3 of magma per year, assuming the conditions given in Ingebritsen and Sanford (1998, p. 183). These figures may be representative of the long-term intrusion rate for the area rather than the current rate. Elastic models of the uplift invoke magma intrusion at a much higher rate of ~0.006 km^3/yr beginning in 1998 (Wicks and others, 2002).

Although none of the anomalous characteristics we observed are necessarily tied to the current uplift, the cold groundwater system is nevertheless strongly influenced by magmatic inputs, as evidenced by $^3He/^4He$ ratios near 8 R_A and $C/^3He$ ratios $\leq 10^{10}$ in two of the springs. A recent input of mantle basalt would normally be invoked to explain such ratios in a continental setting (see e.g., Kennedy and Truesdell, 1996). All of the analyzed springs contain magmatic carbon, in concentrations uncorrelated with Cl^-, suggesting that a shallow zone of gaseous CO_2 is widespread through parts of the area.

The new data support the conceptual model proposed by Iverson (1999), who called for a vapor zone to overlie a liquid hydrothermal reservoir on the western

flanks of South Sister. The cold springs in the Separation Creek drainage that contain a small component of thermal fluid are likely to be the first hydrologic features to change in response to intrusion and are clear candidates for future monitoring studies in this region.

ACKNOWLEDGEMENTS:

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APPENDIX

UTM N m	UTM W m	Elevation m	Date	Temp. deg. C	Na mg/L	Cl mg/L	SO$_4$ mg/L	Notes
Springs								
4885855	580217	740	3/28/1990		3.3	0.6		
4883640	592840	1730	Aug-98			1.95	3	JI-1 spring emerging from talus
4883560	592250	1730	Aug-98			1.96	3.3	JI-2 spring emerging from talus
4883510	592840	1720	Sep-98	3.8		2	3.3	JI-69 spring, taken above confluence
4883490	592630	1705	Aug-98			1.33	2.2	JI-3 spring orifice emerging from wooded hillside
4883490	592580	1705	Aug-98			1.21	2.1	JI-4 spring orifice emerging from wooded hillside
4883490	592750	1720	Sep-98	3		1.34	2.2	JI-71 spring, may be same as 70
4883476	594780	1910	8/12/1981	3	4.2	1	2	RHM sample
4883460	592700	1720	Sep-98	3.4		1.29	2.2	JI-70 spring 50 m down stream from 69
4883460	592300	1660	Sep-98	4.7		0.88	1.5	JI-75 spring/trib
4883440	592630	1695	Sep-98	3.1		1.19	2	JI-73 spring, may be same as 72
4883410	592580	1695	Sep-98	3.6		1.27	2.1	JI-72 spring
4883400	592490	1660	Sep-98	3.2		0.95	1.6	JI-74 spring
4883310	593230	1745	Sep-98	4.1		1.83	2.7	JI-68 spring, taken above confluence
4882866	591414	1500	9/11/1990		9.3	4.7		Indian Holes
4882860	591690	1485	Sep-98	4.9		6.9	2.7	JI-77 spring, small woodland, first of the Indian Holes
4882780	591610	1485	Sep-98	5.9		8.9	3.3	JI-78 spring, joins with 77 along with others
4882740	591550	1480	Sep-98	5.9		10	3.7	JI-79 spring system
4882680	591340	1480	Sep-98	9.3		18.6	6	JI-80 spring, lowermost of Indian Holes
4881490	588590	1090	Sep-98	7		3.9	1.9	JI-82 low-flow woodland spring
4881460	588650	1100	Sep-98	6.1		5.4	1.8	JI-81 low-flow woodland spring
4881410	587790	1080	Sep-98	10.8		12.1	3	JI-84 lower spring E at orifice
4481410	587730	1085	Sep-98	12.1		12.6	3	JI-85 lower spring, central, just below orifice, joins with 84?
4881410	587650	1105	Sep-98	11.1		12.6	3.1	JI-86 lower spring, W just below orifice at trail crossing
4881366	594875	1755	8/12/1981	3	5.2	<1.00	2	RHM sample
4881293	587687	1055	9/11/1990		24.3	12.4		
4881280	595060	1755	Sep-98	4.7		2.7	7.5	JI-63 N. Fork of Mesa Cr., easternmost spring
4881243	587557	1060	9/11/1990	10	24.4	12.4		Q = 26 L/s
4880620	586950	1005	Aug-98			1.01	0.4	JI-58 spring-fed tributary to Sep. Cr.
4876878	599108	1725	8/15/1987	3	2.6	0.2	<1.00	RHM ('81), LS ('87)
4876218	583600	1165	Sep-86		3			Cedar Swamp
Streams								
4886024	580048	705	3/28/1990		3.6	0.6		Louise Cr. above Sep. Cr.
4885940	580048	705	3/28/1990		5.8	2.2		Sep. Cr. above Louise Cr.
4885699	580120	715	3/28/1990		6.1	2.3		Sep. Cr. above Louise Cr.
4885072	580361	740	3/28/1990		6	2.3		Sep. Cr.
4883723	582000	915	3/28/1990		3.3	0.6		George Cr. at trail
4883667	594438	1840	Sep-98	3.6		1.97	3.2	JI-67 N. Fork Hinton Cr.
4883663	581675	790	3/28/1990		3.6	0.8		George Cr. at confluence with Sep. Cr.
4883554	581627	790	3/28/1990		5.7	2.3		Sep. Cr. above George Cr.
4883385	592050	1645	Sep-98	7		0.58	0.9	JI-76/12 Sep. Cr. above confluence with Hinton Cr.
4882974	593650	1780	Sep-98	6		0.26	0.5	JI-91 James Cr.
4882723	582265	815	3/28/1990		6.3	2.5		Sep. Cr.
4882482	582651	840	9/11/1990		7.3	3.1		Sep. Cr.
4882436	590950	1460	Aug-98			3.3	2.1	JI-19-21 Sep. Cr. above Indian Hole Falls
4882282	590588	1370	Aug-98			3.2	2.1	JI-22 Sep. Cr.
4882256	589500	1280	Sep-98	7.6		5.1	2	JI-89 Honey Cr.
4882154	589063	1270	Sep-98	7.5		5	1.9	JI-88 Honey Cr.
4882128	588650	1220	Sep-98	7.4		4.6	1.9	JI-87 Honey Cr., main channel just above fork and falls
4881819	583699	925	9/11/1990		4.1	0.6		Separation Lake tributary
4881590	589975	1205	Aug-98			2.9	2.3	JI-28-30 Sep. Cr. below confluence with Mesa Cr.
4881564	590150	1220	Aug-98			2.5	2.5	JI-25-27 Mesa Cr. above confluence with Sep. Cr.
4881526	589688	1135	Aug-98			2.9	2.3	JI-31 Sep. Cr.
4881513	588425	1075	Sep-98	7.8		4.6	1.8	JI-83 Honey Cr. above confluence with Sep. Cr.
4881436	589100	1095	Aug-98			3	2.2	JI-32 Sep. Cr., below two small woodland spring inputs
4881150	584747	950	9/11/1990		7.6	3.3		Sep. Cr. at trail bridge, Q = 3,560 L/s
4880795	594775	1745	Sep-98	9.2		0.68	0.4	JI-62 Middle Fork of Mesa Cr.
4880782	587400	1025	Aug-98			3.2	2	JI-50 Sep. Cr. above confluence with Sphinx Cr.
4880744	587250	1010	Aug-98			3.3	2	JI-55-57 Sep. Cr. below confluence with Sphinx Cr.
4880731	587425	1025	Aug-98			1.45	0.6	JI-52-54 Sphinx Cr. above confluence with Sep. Cr.

Pre-2001 data for selected springs and streams in the upper Separation Creek watershed.

JI = Justin Iverson; RHM = Robert Marine