

## Chapter 25

# Pre- and Post-Eruptive Investigations of Gas and Water Samples from Mount St. Helens, Washington, 2002 to 2005

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### Abstract

Samples of gas and water from thermal springs in Loowit and Step canyons and creeks that drain the crater at Mount St. Helens have been collected since October 2004 to monitor the flux of dissolved magmatic volatiles in the hydrologic system. The changing composition of the waters highlights a trend that began as early as 1994 and includes decreasing  $\text{SO}_4$  and Cl concentrations and large increases in  $\text{HCO}_3$ . Geochemical models indicate that mineral sources and sinks are not the main controls on the changing water chemistry, and carbon and helium isotopes indicate that their sources in the gases and waters have remained unchanged during this time. The present-day molar ratios of C, S, and Cl in the springs approximate ratios measured in plume emissions in August 2005 and provide supporting evidence that changes in water chemistry most likely reflect changes in the release rates of sulfur gases, HCl, and  $\text{CO}_2$  from the magma and a varying degree of efficiency of gas scrubbing by the overlying water. Results from coupled chemical analyses and discharge measurements on the creeks yield an estimate of the dissolved flux of magmatic HCl,  $\text{SO}_2$ , and  $\text{CO}_2$  of around 5.2, 4.7, and 22 metric tons per day, respectively.

### Introduction

Airborne gas measurements were a valuable tool in tracking magmatic emissions for Mount St. Helens during the 1980–86 eruptive sequence, but flights eventually were suspended as emission rates dropped to low levels. Between September 1988 and September 2004, attempts to measure the

flux of magmatic volatiles at Mount St. Helens were restricted to analyses of gases and condensates from vents on the lava dome and thermal waters from springs in Loowit and Step canyons<sup>3</sup> in The Breach. Results from those analyses generally have shown a progressive decrease in magmatic volatile concentrations with time. Airborne gas-flux measurements over the crater at Mount St. Helens were resumed in September 2004 following the onset of seismic activity (Doukas and others, 2005). To date, those measurements have shown that plume  $\text{CO}_2$  and  $\text{SO}_2$  emission rates are much lower than emission rates during the 1980s eruptions (Gerlach and others, 2005, and this volume, chap. 26). Plume emission rates were one line of evidence that supported an early hypothesis that degassed magma was driving the current eruption.

To track the flux of dissolved magmatic volatiles in the hydrologic system during the current eruption, we established a surface-water sampling program on October 13, 2004. The first samples were collected on the Pumice Plain from two creeks that drain the crater. In mid-April 2005, as conditions nearer the crater stabilized, we expanded the monitoring network to include three locations in The Breach (fig. 1). These five sites were the main focus of our monitoring campaign during the first year after the 2004–5 eruption, but at times we also have collected samples from a warm spring on the west end of the Pumice Plain and from hot springs in Loowit and Step canyons in upper parts of The Breach. Thus far, our sample collection intervals have been irregular, but since October 2005 some continuous temperature and conductivity data have been collected by a probe installed near the top of Step creek.

In this report we present geochemical data from the monitoring sites; data from field campaigns in the crater and

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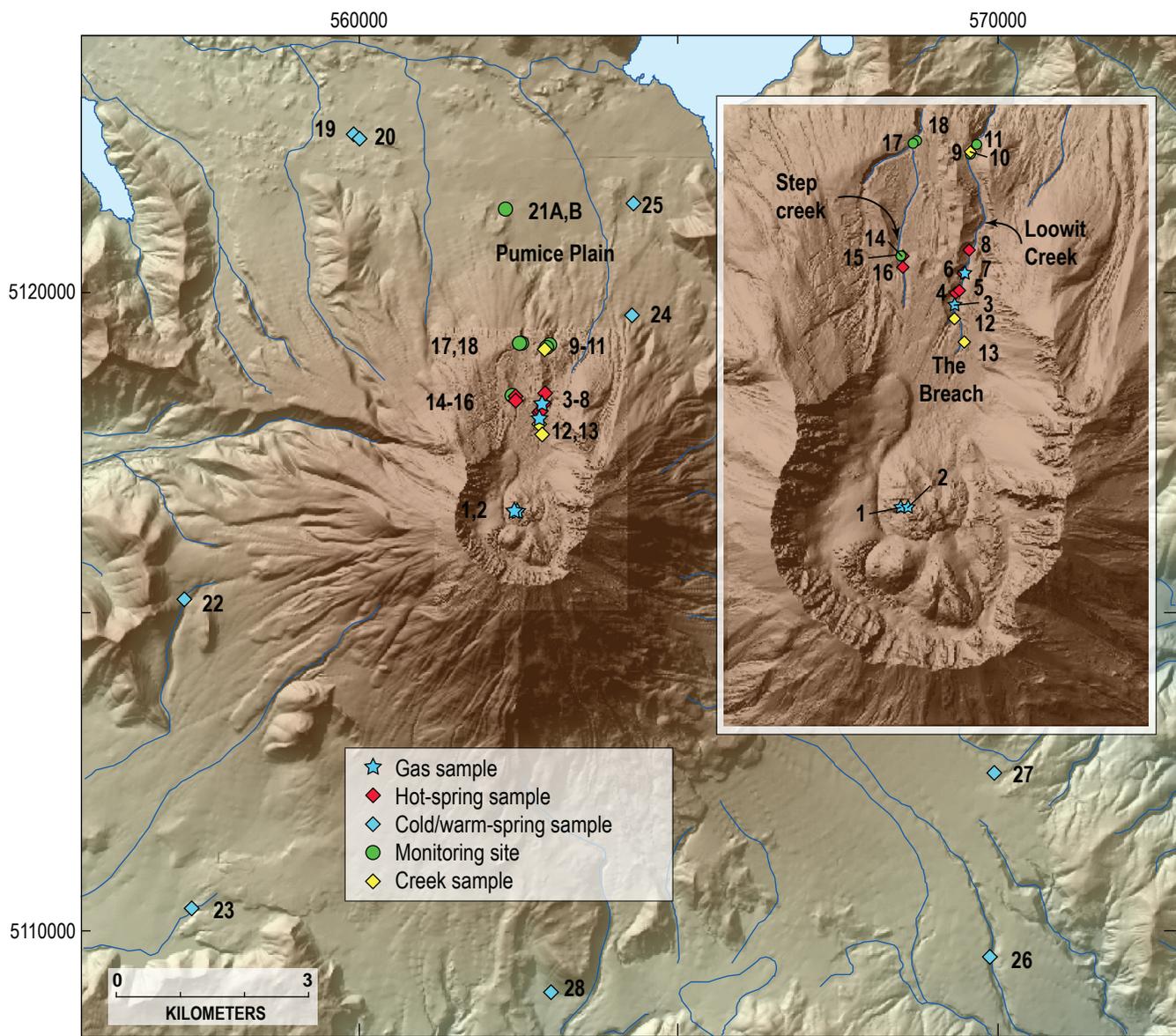
<sup>3</sup> Many geographic features in the Mount St. Helens area are referred to informally by Earth scientists. Capitalization of “canyon,” “creek,” or “spring” indicates names formally adopted and listed in the Geographic Names Information System, a database maintained by the U.S. Board on Geographic Names. Noncapitalized names are applied informally—eds.

The Breach in 2002 and 2005, which focused on the chemistry of crater gases and hot spring waters; and data from a survey of regional cold springs. We also include data from previous investigations of the geochemistry of the hot springs at Mount St. Helens in order to evaluate long-term changes in gas sources or fluxes and, ultimately, to determine how magmatic processes at an active volcano are reflected in the hydrothermal system. We have adopted the names of the Loowit canyon hot springs that were used by Shevenell and Goff (1993) but have adhered to the policies of the U.S. Board on Geographic Names regarding capitalization of formal and informal names. Additional chemical data not discussed in the paper can be found in appendix 1, which appears only in the digital versions

of this work (in the DVD that accompanies the printed volume and online at <http://pubs.usgs.gov/pp/1750>).

## Background

After the May 1980 eruption of Mount St. Helens, gas samples were collected from cracks and fumaroles near the dome in the fall of 1980 (Evans and others, 1981; Gerlach and Casadevall, 1986). Due to dome growth and collapse and extrusions of new lava, the gas-sampling locations varied during the subsequent years. Before our work in 2002, the last



**Figure 1.** Maps showing sample locations for this study, 2002–2005, Mount St. Helens, Washington. Numbers for sample sites correspond to numbers listed in table 1. Inset shows crater and The Breach sample locations in more detail. Datum for geographic grid and UTM coordinates referenced to WGS84, zone 10.

gas sample from the crater was collected in June 1998 from an 86°C vent on the southwest side of the 1980–86 lava dome on a flow called the September 1984 lobe, herein referred to more briefly as “September lobe.” The sampling site was formerly the hottest fumarole on the dome, but in 1998 it had cooled by 260–370°C relative to temperatures recorded in 1994–95 (Symonds and others, 2001).

Downcutting of avalanche deposits in The Breach of Mount St. Helens created Loowit and Step canyons, which drain to the north and represent the main discharge of surface water from the crater (fig. 1). Thermal springs were first observed discharging into Loowit Creek during the summer of 1983, and the first sample of spring water was collected in October 1983 (Thompson, 1990). Lower-temperature, low-discharge springs in Step canyon were discovered at a later date, and the first published analyses of the Step canyon springs are from 1988 (Shevenell and Goff, 1993). It has been estimated that more than 95 percent of the hot spring discharge from both canyons is provided by the springs in Loowit canyon (Shevenell and Goff, 1993). During the 1980s to mid-1990s, the hot springs in Loowit canyon were located in three areas along the length of the canyon. Each area contained clusters of hot springs of varying size and temperature. From south to north, the spring groups are called (1) Loowit source, (2) Loowit boulder basin, and (3) Loowit travertine. The name Loowit travertine is a misnomer that stems from the presence of gypsum-bearing precipitates on the rocks around the vent orifices (Shevenell and Goff, 1993). There are no names for the springs in Step canyon. The waters from both Loowit and Step canyons were sampled throughout the 1980s and 1990s, but because of the larger volume of thermal water, the Loowit canyon springs were sampled with the greatest frequency.

## Post-2000 Field Campaigns

### Gas and Water Samples from the Crater and The Breach

In August 2002 there were no fumaroles in the crater at Mount St. Helens, but diffuse steam was rising from several locations on the 1980–86 dome. We sampled gas at two locations from the strongest vents we could find on September lobe (fig. 1; table 1). Because of safety concerns we were unable to resample the sites in 2005. In August 2002 and July 2005 we also collected gases from bubbling hot springs in Loowit canyon. To our knowledge these are the first free-gas samples collected from springs in Loowit canyon.

Water samples were collected from the Loowit canyon hot springs in 2002 and 2005, and samples of the Step canyon springs were collected in July and October 2005. At springs with multiple orifices, our strategy was to choose the hottest spring for sample collection, and at times we also sampled water from a nearby spring. In 2002, the hottest vents at the Loowit boulder basin and Loowit travertine sites were along

the west bank of Loowit Creek. The outflow from the southernmost spring, which we assume to be the Loowit source spring, was from a single vent on a bench above the canyon floor. The water cascaded down the west canyon wall into Loowit Creek. In July 2005 there was no visible outflow from the Loowit source spring; instead, a new large spring issued from the base of a small fan that abuts the west wall of the canyon. Additional cooler waters discharged from an upper part of the fan and small vents along the west bank of the creek.

The thermal waters in Step canyon occur in clusters and line the banks of the headwaters of Step creek. In 2005 there were no high-discharge vents, and all of the waters issued from areas composed of low-discharge seeps. Intermittent degassing was observed at both of the sites in July, but no gas was visible in October 2005.

### Creeks and Regional Springs

The five sites that make up the monitoring network are along creeks that provide the major surface drainage from the crater at Mount St. Helens. The network includes two sites (LCBF and SCBF) on the Pumice Plain (fig. 1; table 1) and three sites (LCAF, EFSCAF, and WFSCAF) closer to the crater above the waterfalls on Loowit and Step creeks. The Pumice Plain sites are the most accessible and serve to monitor the surface drainage from locations just above the confluence of the two creeks. Of the higher-altitude sites, LCAF receives input from all of the hot springs in Loowit canyon and variable seasonal input of glacial meltwater; EFSCAF is on the east fork of Step creek, which is the fork that contains the Step canyon springs; and WFSCAF is a tributary to Step creek that drains the west wall of the crater. This channel (WFSCAF) carries seasonal runoff from the west arm of the Crater Glacier. We have not walked the length of this creek, but there are no obvious thermal waters that discharge to this drainage. In this report we also present water data from the probe locations (fig. 1; table 1) and three other locations on Loowit Creek, which were sampled in 2002 and 2005.

Several studies have used carbon and helium isotopes, together with water chemistry, to demonstrate that cold ground waters in volcanic regions can carry large amounts of dissolved magmatic carbon (Rose and Davisson, 1996; Chiodini and others, 2000; Evans and others, 2002). To investigate outflow of magmatic volatiles from the volcano to regional springs, we sampled eight mostly low-temperature springs in the area surrounding Mount St. Helens in July 2005. Kalama Spring, located southwest of Mount St. Helens, has the largest discharge of any spring in our sample set, followed by carbonate spring, a warm spring on the west end of the Pumice Plain (fig. 1; tables 1 and 2). Because the chemistry of carbonate spring has some similarities with the springs from The Breach, future discussion of this spring will be included with discussions of the hot springs. Of the seven other cold springs in this report, the most well-studied are Kalama, Willow, and Moss Springs, which have been sampled infrequently since

**Table 1.** Map number and location coordinates for samples collected during 2002–2005, Mount St. Helens, Washington.

[UTM coordinates and altitude are referenced to the WGS84 datum.]

Location	Map No.	Northing	Easting	Altitude (m)
<b>Old dome Mount St. Helens</b>				
September lobe, landing site	1	5116595	562436	2,122
September lobe, upper dome	2	5116600	562487	2,130
<b>Springs in Loowit canyon</b>				
2005 degassing spring	3	5118045	562819	1,664
Loowit source spring	4	5118136	562831	1,635
New spring on fan of Loowit canyon	5	5118157	562856	1,617
Loowit boulder basin spring	6	5118275	562882	1,604
Loowit boulder basin degassing spring	7	5118273	562891	1,604
Loowit travertine spring	8	5118442	562921	1,584
<b>Springs in Step canyon</b>				
Step canyon hottest spring	14	5118396	562453	1,644
Step canyon source spring	16	5118324	562453	1,645
<b>Monitoring network sites</b>				
Probe site, Loowit Creek above falls	9	5119128	562929	1,507
Loowit Creek above falls	11	5119198	562981	1,509
Probe site, east fork Step creek above falls	15	5118401	562446	1,617
West fork Step creek above falls	17	5119212	562519	1,512
East fork Step creek above falls	18	5119224	562546	1,512
Loowit Creek below falls	21A	5121306	562300	1,219
Step creek below falls	21B	5121306	562300	1,219
<b>Other creek locations</b>				
Lower Loowit Creek	10	5119150	562935	1,509
Upper Loowit Creek	12	5117947	562819	1,662
Upper Loowit Creek	13	5117784	562886	1,709
<b>Pumice Plain spring</b>				
Carbonate spring at gage	19	5122487	559926	935
Carbonate spring	20	5122421	560010	945
<b>Regional cold springs</b>				
Springs west of Cold Spring Creek	22	5115219	557268	1,132
Kalama Spring	23	5110368	557390	832
Spring on Loowit trail	24	5119654	564283	1,330
Willow spring	25	5121399	564292	1,125
Spring on Pine Creek	26	5109610	569886	731
Moss spring	27	5112493	569935	882
Spring west of Swift Creek	28	5109062	563021	756

the late 1980s. Four of the springs are unnamed and were identified on 24,000-scale quadrangle maps or were brought to our attention by Mike Clynne of the U.S. Geological Survey (USGS), who has mapped extensively in the area around Mount St. Helens. In the text that follows we refer to the regional springs by their associated map number (fig. 1; table 1). The eight springs we report on here are likely the largest on the margins of the volcano, although assuredly more cold springs are in the Mount St. Helens area.

## Field and Laboratory Methods

Water and gas samples were collected for a suite of chemical analyses using standard field and laboratory techniques. At all sites the water temperature and conductivity were measured in the field using portable meters. Spring-water samples collected for bulk chemistry were preserved in the field by filtering them through a 0.45- $\mu\text{m}$  filter into plastic bottles that were first rinsed with filtered water. Samples for cation analyses were preserved with high-purity nitric acid by dropwise addition to a  $\text{pH} < 2$ . Other nonfiltered (raw) spring-water samples were collected in glass bottles for alkalinity and  $\delta\text{D}$  and  $\delta^{18}\text{O}$  analyses and in preevacuated glass bottles for  $\delta^{13}\text{C}$  analysis of dissolved inorganic carbon (DIC), which consists of dissolved  $\text{CO}_2 + \text{HCO}_3 + \text{CO}_3$ . Depending on the sample size, waters collected for  $\delta^{13}\text{C}$ -DIC were acidified with 0.5 to 1.0 mL of high-purity hydrochloric acid to convert DIC to  $\text{CO}_2$ . Values for  $\delta^{13}\text{C}$ -DIC and  $^{14}\text{C}$ -DIC were determined on purified  $\text{CO}_2$  extracted from the water samples following methods described in Evans and others (2002).

Samples of creek waters from the monitoring sites typically were collected into prerinsed plastic bottles as raw waters. Filtering, sample preservation, and pH measurements were performed in the laboratory, at Menlo Park, Calif. Because samples from the monitoring sites were sometimes stored before they were received at the lab, we have not determined the bicarbonate concentrations of many of these water samples. A few samples of creek waters were collected for  $\delta^{13}\text{C}$  analysis of DIC as described above. Creek discharge rate was measured using a pygmy meter. Visual estimates of discharge are identified in table 2.

Anion and cation concentrations in water samples were determined using ion chromatography and inductively coupled argon plasma spectrometry at USGS laboratories in Menlo Park, Calif. Isotope analyses were performed at USGS laboratories in Menlo Park, Calif., and Reston, Va., and at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory, Calif. Isotope analyses were performed using techniques outlined in Epstein and Mayeda (1953), Coplen (1973), Vogel and others (1987), and Coplen and others (1991).

Gas samples for bulk composition and  $\delta^{13}\text{C}$ - $\text{CO}_2$  analyses were collected into preevacuated glass bottles through a hollow titanium rod (from gas vents) or a funnel fitted with

**Table 2.** Spring and creek temperature and discharge measurements 2003–2005, Mount St. Helens, Washington.

[Letters following discharge rate indicate field method: EV, width and depth measured, velocity estimated; E, visual estimate; M, measured. Some locations coded to specify sites: ps, probe site; LCAF, Loowit Creek above falls; LCBF, Loowit Creek below falls; EFSCAF, east fork Step creek above falls; WFSCAF, west fork Step creek above falls; SCBF, Step creek below falls; CARB gs, carbonate spring gage site.]

Location	Date	Temp. (°C)	Discharge (L/s)	Method
<b>Monitoring network sites</b>				
LCAF	08/20/03	27.0	323	M
LCAF	06/17/04	24.4	208	M
LCAF	08/12/04	27.3	320	M
LCAF	04/21/05	27.5	170	E
LCAF	07/26/05	29.1	397	M
LCAF	08/26/05	30.1	408	M
LCAF	10/11/05	30.0	267	M
LCAF ps	10/25/05	25.9	215	M
LCBF	09/28/04	18.1	249	M
LCBF	10/13/04	16.3	306	M
LCBF	10/20/04	10.2	230	E
LCBF	12/02/04	8.4	110	E
LCBF	02/10/05	11.5	110	E
LCBF	04/21/05	16.9	187	M
LCBF	07/26/05	22.5	399	M
LCBF	08/26/05	19.8	279	M
EFSCAF	08/12/04	30.0	80	E
EFSCAF	04/21/05	19.5	60	E
EFSCAF	07/26/05	26.6	45	M
EFSCAF	08/26/05	24.1	40	EV
EFSCAF	10/11/05	17.6	19	M
EFSCAF ps	10/25/05	25.4	27	M
WFSCAF	08/12/04	10.5	120	E
WFSCAF	04/21/05	4.2	<30	E
WFSCAF	07/26/05	10.5	142	M
WFSCAF	08/26/05	16.4	30	EV
WFSCAF	10/11/05	7.5	10	E
SCBF	09/28/04	16.3	95	M
SCBF	10/13/04	14.5	112	M
SCBF	10/20/04	9.1	10	E
SCBF	11/05/04	9.7	10	E
SCBF	12/02/04	4.1	20	E
SCBF	02/10/05	5.6	10	E
SCBF	04/21/05	10.0	3	E
SCBF	07/26/05	21.2	110	M
SCBF	08/26/05	19.2	49	M
<b>Pumice Plain spring</b>				
CARB gs	10/25/05	15.7	354	M
<b>Regional cold springs</b>				
Spring 22	07/29/05	4.4	11	M
Spring 23	07/29/05	4.7	818	M
Spring 24	07/30/05	3.0	16	M
Spring 25	07/30/05	5.4	44	M
Spring 26	07/31/05	7.2	137	M
Spring 27	07/31/05	6.3	82	M
Spring 28	07/31/05	5.2	29	M

Tygon tubing (from bubbling springs). Prior to sampling, the entire collection system was purged of atmospheric gases. Gas samples were analyzed for bulk composition at the USGS in Menlo Park, Calif., using gas chromatography methods reported in Evans and others (1981). Carbon dioxide for stable isotope analysis was separated from the bulk gas sample using standard cryogenic techniques on a vacuum line (Evans and others, 2002). The spring gas samples for  $^3\text{He}/^4\text{He}$  analysis were collected from the funnel and tubing apparatus into copper tubing that was then sealed at both ends with refrigeration clamps. The  $^3\text{He}/^4\text{He}$  determination was run at Lawrence Berkeley National Laboratory in Berkeley, California, following methods outlined by Kennedy and van Soest (2006). Helium isotope ratios are reported as  $R/R_A$  values, which represent the  $^3\text{He}/^4\text{He}$  ratio in the gas relative to the  $^3\text{He}/^4\text{He}$  ratio in air. Values for  $R/R_A > 1$  indicate that a percentage of the gas is derived from a mantle or magmatic source.

## Results and Discussion

### Chemistry of the Hot Springs, 1983 to 2005

The chemistry and temperature of the Loowit canyon hot springs changed rapidly after the springs appeared in 1983 (Thompson, 1990; Shevenell and Goff, 1993, 1995). The highest water temperature recorded was 92.6°C from the Loowit travertine spring group in 1986, and by then, concentrations of many of the dissolved constituents in the Loowit springs had peaked (Shevenell and Goff, 1993). The subsequent declining temperatures and variable chemistry were attributed to a rapidly cooling hydrothermal system that had formed just after the 1980 eruption. Several important conclusions were reached by Shevenell and Goff (1993, 1995, 2000) and Goff and McMurtry (2000), including (1) that the Loowit canyon hot springs discharged mixtures of recent meteoric water and about 10 percent magmatic water, (2) that the underground residence time of the mixed water was too short to allow water-rock equilibration or reliable geothermometry, and (3) that  $\text{Cl}$ ,  $\text{SO}_4$ , and  $\text{HCO}_3$  in the springs were mainly derived from magmatic volatiles.

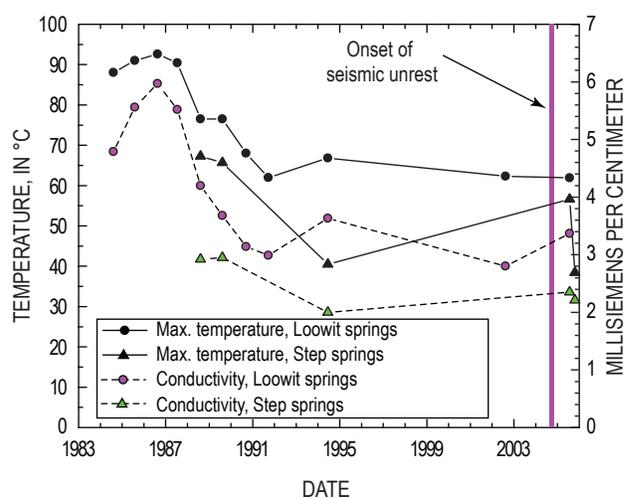
More recent samples show that the chemistry of the hot springs at Mount St. Helens is still changing (F. Goff and the USGS, unpub. data, 1984–94), although water temperatures since 1990 appear to have stabilized (fig. 2). The early trend in anions from  $\text{SO}_4$  toward  $\text{Cl}$  dominance stopped, and water samples from 1994, 2002, and 2005 show declines in both  $\text{SO}_4$  and  $\text{Cl}$  relative to  $\text{HCO}_3$  (table 3; fig. 3). The post-1989 data for the Step canyon springs follow a similar trend toward  $\text{HCO}_3$ -dominated water.

Overall, most elements in the Loowit springs show the effects of dilution by meteoric water over time (fig. 4). The plots in figure 4 may understate the dilution effects because of the increased focus on sampling the hottest springs in 2002 and 2005. Dilution effects also are seen in the  $\delta\text{D}$  and

$\delta^{18}\text{O}$  composition of the waters from 2002 and 2005, which plot on or near the world meteoric water line (table 4; fig. 5). Previous  $\delta^{18}\text{O}$  values of Loowit hot spring waters through 1994 were shifted by as much as 2 per mil to the right of the meteoric water line.

Simple dilution, however, does not fully explain all of the data. Concentrations of  $\text{Na}$  and  $\text{SO}_4$  have decreased since 1984, whereas  $\text{Cl}$  and  $\text{B}$  concentrations remained high throughout the mid- to late 1980s and declined in later years (fig. 4). Concentrations of  $\text{Mg}$  increased in the 2002 and 2005 samples, and  $\text{HCO}_3$  concentrations showed a large increase to concentrations higher than was recorded previously.

A clear response to the renewal of activity in 2004 has not yet been recognized in the hot springs. Just prior to the onset of seismicity in 2004, the discharge and water temperature at a spring in Loowit canyon appeared to be higher than normal (J.S. Pallister, USGS, oral commun., 2004), but no measurements were made. However, any possible temperature increase was short lived, as comparisons between the 2002 and 2005 samples from the hottest springs in Loowit canyon show little change in temperatures (table 3). Similarly, in July 2005 the temperature measured at the hottest spring in Step canyon was substantially higher than temperatures reported from 1994 (fig. 2), but three months later, in October, the temperature at the same location had declined 18°C, although the specific conductance had decreased only slightly. Because the flow from the Step canyon vents is low, this temperature decline is conceivably related to the change in surface air temperature and conductive cooling. The possible causes for rapid swings in temperature at the hot springs need further investigation, but at this point, it is difficult to attribute any temperature changes



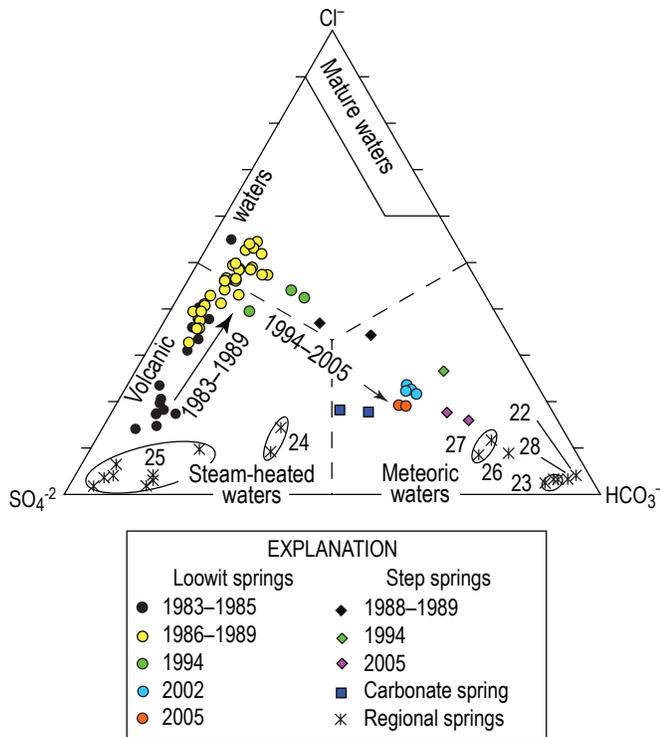
**Figure 2.** Change in maximum temperature and specific conductance of hot springs in The Breach of Mount St. Helens since 1984. Data from dates before 2002 are from Thompson (1990), Shevenell and Goff (1993), Goff and McMurtry (2000), and unpublished data from the U.S. Geological Survey.



**Table 3.** Water chemistry data from springs and creeks, 2002–2005, Mount St. Helens, Washington.—Continued

[Acidity (pH) and conductivity data in bold are from laboratory measurements, HCO<sub>3</sub> data in bold is determined on the basis of the measured amount of gas from the dissolved inorganic carbon extraction. Unless specified, all units are in parts per million. mS/cm, millisiemens per centimeter; --, no data. Additional chemical analyses are available in the digital appendix that accompanies electronic versions of this work.]

Sample No.	Date	Map No.	Temp. (°C)	pH	Cond (mS/cm)	B	Br	Ca	Cl	F	Fe	HCO <sub>3</sub>	K	Li	Mg	Na	SiO <sub>2</sub>	SO <sub>4</sub>
MSH-05-23	10/25/05	15	25.4	7.2	2.0	5.7	0.36	67	232	1.9	21	<b>787</b>	16	0.81	54	237	144	194
WFSCAF 042105	04/21/05	17	4.2	5.7	0.19	0.09	<0.003	12	47	2.2	0.0	--	0.90	0.01	6.0	6.5	19	6.5
WFSCAF 063005	06/30/05	17	6.6	5.7	0.09	--	0.01	--	20	3.2	--	--	--	--	--	--	--	2.5
MSH-05-10	07/26/05	17	10.5	5.8	0.06	0.03	<0.003	3.3	10	2.4	0.01	2.0	0.56	0.004	1.1	2.9	11	2.6
WFSCAF 082605	08/26/05	17	16.4	6.3	<b>0.05</b>	0.02	0.01	2.4	6	1.7	0.03	--	0.58	0.004	1.2	3.5	15	6.0
WFSCAF 101105	10/11/05	17	7.5	6.6	0.10	--	0.01	--	17	2.2	--	--	--	--	--	--	--	11
SCBF 101304	10/13/04	21B	14.5	8.5	0.79	--	0.100	--	84	0.9	--	--	--	--	--	--	--	84
SCBF 102004	10/20/04	21B	9.1	7.8	0.20	--	0.03	--	26	1.1	--	--	--	--	--	--	--	68
SCBF 120204	12/02/04	21B	4.1	8.5	1.0	2.6	0.14	31	94	1.3	0.10	--	8.6	0.39	24	135	65	118
SCBF 021005	02/10/05	21B	5.6	8.6	1.4	--	0.20	--	140	1.4	--	--	--	--	--	--	--	156
SCBF 063005	06/30/05	21B	14.5	7.9	0.34	--	0.06	--	48	3.0	--	--	--	--	--	--	--	28
MSH-05-13	07/26/05	21B	21.2	8.4	0.46	1.2	0.07	12	52	2.0	<0.04	--	5.6	0.20	13	69	44	44
SCBF 082605	08/26/05	21B	19.2	8.7	0.89	--	0.12	--	93	1.3	--	--	--	--	--	--	--	89
<b>Other Loowit Creek locations</b>																		
MSH-02-05	08/18/02	10	31.7	7.9	1.9	3.6	0.38	50	220	1.9	0.23	--	29	0.50	20	319	125	240
MSH-02-06	08/18/02	12	2.8	6.0	0.23	<0.02	0.004	23	1.3	1.4	0.62	92	3.4	0.03	6.3	12	39	39
MSH-05-01	07/26/05	13	7.7	<b>6.4</b>	0.08	0.04	0.010	7	16	2.3	0.02	4	0.54	0.005	2.0	3.3	17	2.0
<b>Pumice Plain spring</b>																		
CARB 081204	10/13/04	20	17.4	<b>7.8</b>	0.9	--	0.12	--	81	1.2	--	--	--	--	--	--	--	144
MSH-05-08	07/26/05	20	25.4	<b>7.3</b>	1.2	2.1	0.18	48	107	2.0	0.08	243	11	0.30	12	191	57	224
MSH-05-25	10/25/05	19	15.7	<b>7.4</b>	0.8	1.3	0.12	28	71	1.1	0.27	187	6.9	0.19	7.7	114	45	132
<b>Regional cold springs</b>																		
MSH-02-10	08/23/02	23	3.2	7.2	0.05	<0.02	0.003	3.5	1.0	0.1	0.01	25	0.73	0.004	1.2	4.6	22	1.9
MSH-05-15	07/29/05	22	4.4	5.7	0.04	0.004	<0.003	3.4	0.7	0.0	0.01	16	0.66	0.001	0.6	1.9	21	0.4
MSH-05-14	07/29/05	23	4.7	5.8	0.05	0.01	<0.003	3.6	1.1	0.1	0.01	28	0.74	0.006	1.2	4.9	24	1.9
MSH-05-17	07/30/05	24	3.0	8.2	0.08	0.01	<0.003	4.9	3.1	0.2	0.01	11	0.80	0.004	1.2	7.3	18	18
MSH-05-16	07/30/05	25	5.4	6.3	0.13	0.02	<0.003	13	1.4	0.2	<0.04	8	1.5	0.007	3.2	6.9	22	49
MSH-05-19	07/31/05	26	7.2	6.2	0.12	0.10	0.010	4.7	6.5	0.6	<0.04	54	1.8	0.048	2.6	18	43	8.5
MSH-05-18	07/31/05	27	6.3	6.5	0.09	0.08	<0.003	4.3	5.4	0.6	0.01	33	1.0	0.028	2.4	10	33	6.4
MSH-05-20	07/31/05	28	5.2	6.2	0.09	0.03	<0.003	7.0	2.1	0.2	<0.04	52	1.3	0.011	2.9	7.8	32	2.3



**Figure 3.** Ternary plot of anion proportion by mass for spring waters at or around Mount St. Helens, Washington (after Giggenbach, 1992). Arrows show change in major anions in Loowit springs since 1983 and Step springs since 1988. Data from dates before 2002 are from Thompson (1990), Shevenell and Goff (1993), Goff and McMurtry (2000), and unpublished data from the U.S. Geological Survey and Fraser Goff (University of New Mexico).

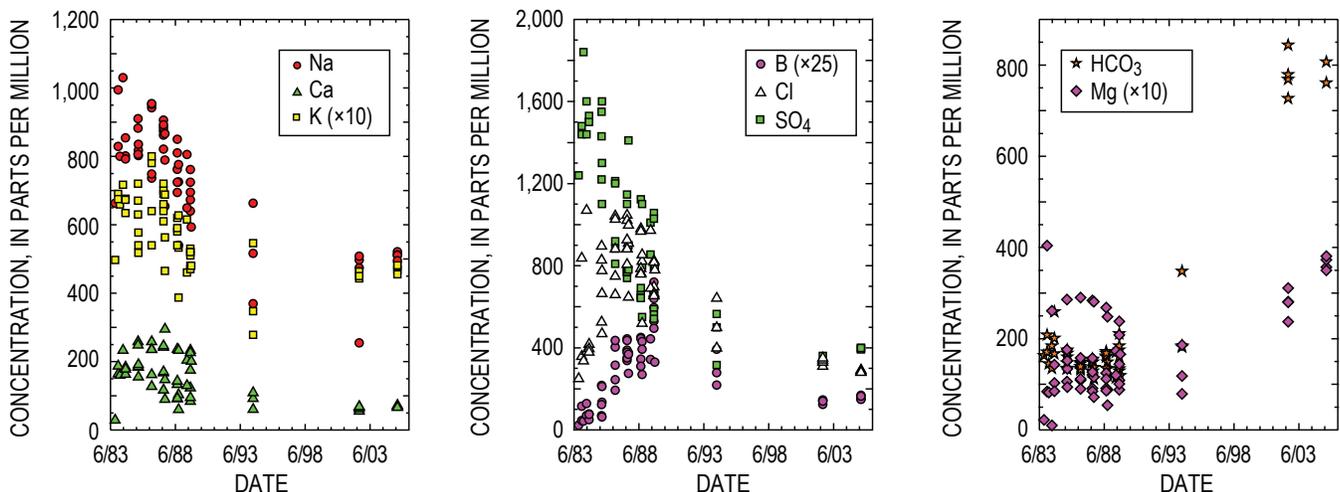
or the minor differences in the chemistry of the Loowit springs between 2002 and 2005 (table 3) to the current eruption.

### Chemistry of the Regional Springs

All of the regional springs have temperatures <8°C and conductivities <150 μS/cm but can be divided into three groups based on variations in major anion concentrations (fig. 3; table 3). One group is defined by relatively high SO<sub>4</sub> concentrations, and the other groups are characterized as HCO<sub>3</sub>-dominated waters but are subdivided on the basis of Cl concentrations.

The SO<sub>4</sub> waters consist of springs 24 and 25, which are north of Mount St. Helens on the eastern border of the Pumice Plain (fig. 1). Spring 25 has higher SO<sub>4</sub> concentrations than spring 24, and samples collected since 1988 show that anion compositions have been variable (fig. 3). In the late 1980s, SO<sub>4</sub>-rich warm springs occurred in the cooling pyroclastic deposits of the Pumice Plain. Shevenell and Goff (1995) noted that these springs were not “steam-heated” waters, which are characteristically SO<sub>4</sub> rich, but instead probably were leaching SO<sub>4</sub> from CaSO<sub>4</sub> alteration minerals or from encrustations around the vents of short-lived fumaroles on the pyroclastic flows. Springs 24 and 25 are likely to be cold, dilute examples of this type of water.

The HCO<sub>3</sub>-rich waters consist of springs 22, 23, and 28, which are solely HCO<sub>3</sub> waters, and springs 26 and 27, which have slightly elevated Cl in comparison with the other three springs (fig. 3; table 3). Springs 26 and 27 are southeast of Mount St. Helens and are of interest because (1) their anion chemistry lies along the dilution trend defined by the hot springs and (2) their <sup>14</sup>C values are greatly reduced relative to modern carbon (table 4), as discussed in more detail below. The elevated Cl in these springs may provide evidence for



**Figure 4.** Chemistry of Loowit springs waters from 1983 to 2005, Mount St. Helens, Washington. Data from dates before 2002 are from Thompson (1990), Shevenell and Goff (1993), Goff and McMurtry (2000), and unpublished data (Fraser Goff, University of New Mexico).

some leakage of Loowit-type water through the southeastern wall of the crater.

## Gas Transfer from Magma into Water

Gases released from magma can be variably dissolved into overlying cold water or released to a brine phase (Fournier, 1986) that can then mix with cold water. The resulting fluid is acidic, hot, and highly reactive with the surrounding rock. Mineral dissolution converts the acidic gas

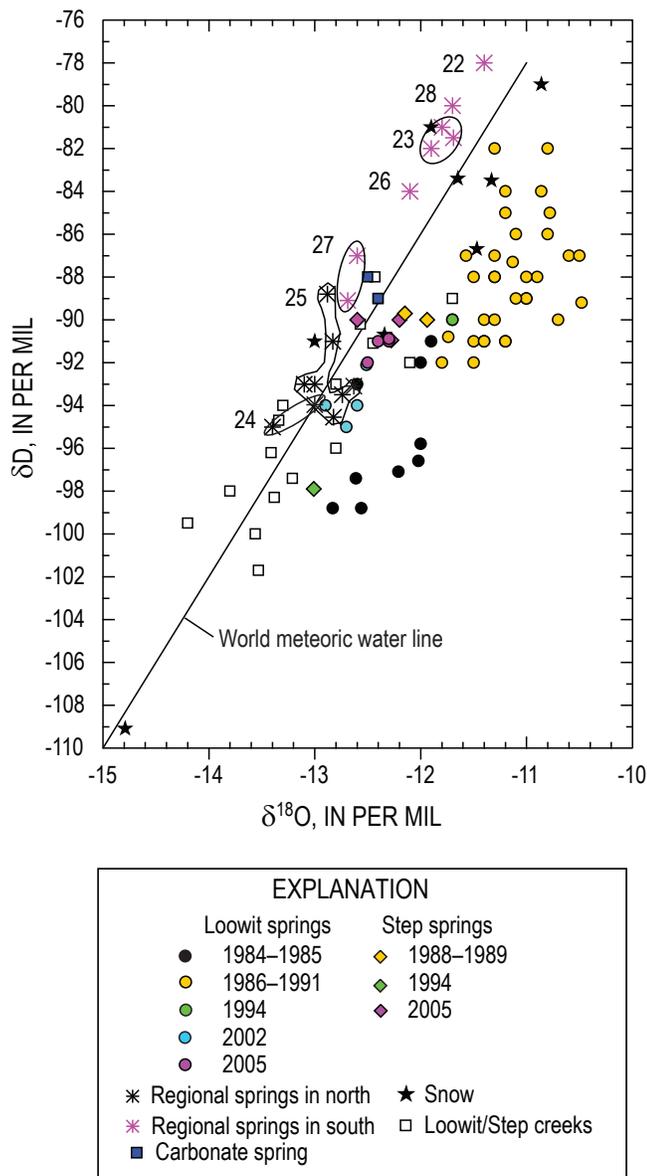
species  $\text{H}_2\text{S}$ ,  $\text{SO}_2$ ,  $\text{HCl}$ , and  $\text{CO}_2$  into the anions  $\text{SO}_4$ ,  $\text{Cl}$ , and  $\text{HCO}_3$ . The concentration of these anions in the spring waters can be related back to magmatic degassing only if the effects of variable gas solution and mineral dissolution/precipitation are constrained. Some constraints can be derived from the water chemistry.

Many metallic ions (such as Ca) are not transported in volatile form (Symonds and others, 1993), requiring that the major source of the cations in the springs be water-rock interaction. This process could ultimately remove  $\text{SO}_4$  and  $\text{HCO}_3$  from solution via precipitation. Attempts at geothermometry by Shevenell and Goff (1993; 1995) yielded maximum temperatures between  $120^\circ\text{C}$  and  $175^\circ\text{C}$  for the Loowit waters. For an assumed temperature of  $150^\circ\text{C}$ , calculations using SOLMNEQ88 (Kharaka and others, 1988) indicate saturation with anhydrite for waters collected in the 1980s but undersaturation for samples from 2002 and 2005. From the 1980s through 2005, Ca, Na, K, and  $\text{SO}_4$  in the spring waters all show similar patterns of decline that are consistent with dilution (fig. 4), so there is no evidence that anhydrite was ever a significant control on  $\text{SO}_4$  concentrations. Samples from all collection years are saturated with calcite at all temperatures above the discharge temperature. Calcite formation/dissolution may exert some influence on Ca and  $\text{HCO}_3$ . However, the large increase in  $\text{HCO}_3$  after the 1980s cannot be attributed to calcite dissolution, which would also produce both higher Ca concentrations and higher pH values. Ca and pH have in fact dropped during this time (table 3).

Shevenell and Goff (2000) argued that halite formation in the magmatic fluid component was probably not a significant sink for Cl. Although Br and Cl concentrations in the springs have declined steadily over the years, it is noteworthy that for the past two decades the ratios of these two components have remained at a remarkably constant value around 0.002 (1984–2005, 44 samples,  $\pm 0.001$ ). The Step canyon springs and carbonate spring have lower concentrations of Br and Cl than the Loowit springs but fall along the same trend (fig. 6). The constant Cl/Br ratio shows that halite was never a major control on Cl in fluid sources to the hot springs.

In contrast, fumarole condensates have shown a large range in Cl/Br (fig. 6), possibly indicating that deposition of metal halides in the vent throats (Keith and others, 1981; Edmonds and others, this volume, chap. 27) can be a significant control on fumarolic Cl/Br ratios. The Cl/Br ratio in the springs, which lies within the range of the fumarolic condensates, may better represent the HCl/HBr ratio in gases released from magma. Additional Cl and Br could be leached from the volcanic rocks. Reported Br and Cl ratios in seven samples of andesite and dacite from the crater, The Breach, and Pumice Plain are variable, ranging between 0.002 and 0.01 (table 1 of Shevenell and Goff, 1993). However, the  $\text{SO}_4$ -rich nature of the transient hot springs in the Pumice Plain (Shevenell and Goff, 1995) indicates that rock leaching is not a major source of halides.

Overall, the data indicate that mineral sources and sinks for  $\text{SO}_4$ , Cl, and  $\text{HCO}_3$  are not the main controls on the anions



**Figure 5.** Stable-isotope composition of Loowit springs since 1980s, Mount St. Helens, Washington. Data from dates before 2002 are from Thompson (1990), Shevenell and Goff (1993, 1995), Goff and McMurtry (2000), and unpublished data from the U.S. Geological Survey.

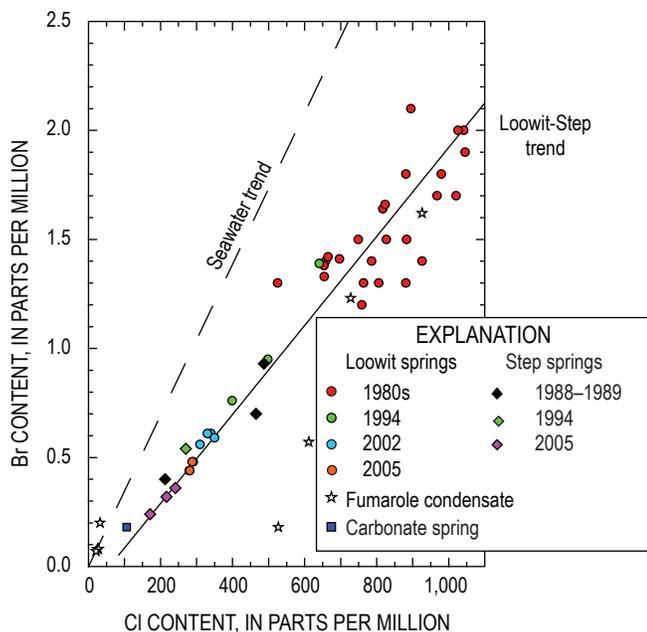
**Table 4.** Isotope values determined for water samples collected during 2002–2005, Mount St. Helens, Washington.

[DIC, dissolved inorganic carbon; --, no data.]

Sample No.	Date	Map No.	Temperature (°C)	$\delta D$ per mil	$\delta^{18}O$ per mil	$\delta^{13}C$ -DIC per mil	$^{14}C$ -DIC percent modern carbon
<b>Springs in Loowit canyon</b>							
MSH-02-01	08/16/02	4	58.9	-94	-12.9	-12.3	--
MSH-02-02	08/17/02	6	61.0	-95	-12.7	--	--
MSH-02-03	08/17/02	7	62.3	-94	-12.6	-12.2	--
MSH-02-04	08/18/02	8	57.6	-92	-12.5	-11.9	--
MSH-05-02	07/26/05	3	59.1	-91	-12.4	--	--
MSH-05-03	07/26/05	3	57.0	-92	-12.5	-12.1	--
MSH-05-04	07/26/05	5	61.9	-91	-12.3	-11.9	--
MSH-05-05	07/26/05	5	60.5	-91	-12.3	--	--
<b>Springs in Step canyon</b>							
MSH-05-06	07/26/05	16	45.1	-90	-12.6	-11.4	--
MSH-05-07	07/26/05	14	56.6	-91	-12.3	-10.9	--
MSH-05-22	10/25/05	14	38.4	-90	-12.2	--	--
<b>Monitoring network sites</b>							
MSH-05-23	10/25/05	15	25.4	-92	-12.1	-7.5	--
MSH-05-24	10/25/05	9	25.9	-89	-12.4	-8.1	--
<b>Other Loowit Creek locations</b>							
MSH-02-06	08/18/02	12	2.8	-98	-13.8	-11.2	--
MSH-05-01	07/26/05	13	7.7	-93	-12.8	--	--
<b>Pumice Plain spring</b>							
MSH-05-08	07/26/05	20	25.4	-89	-12.4	-11.5	5.5
MSH-05-25	10/25/05	19	15.7	-88	-12.5	--	--
<b>Regional cold springs</b>							
MSH-05-15	07/29/05	22	4.4	-78	-11.4	--	--
MSH-02-10	08/23/02	23	3.2	-82	-11.9	-14.2	93.8
MSH-05-14	07/29/05	23	4.7	-81	-11.8	-15.6	--
MSH-05-17	07/30/05	24	3.0	-95	-13.4	--	--
MSH-05-16	07/30/05	25	5.4	-93	-13.0	--	--
MSH-05-19	07/31/05	26	7.2	-84	-12.1	-16.5	50.0
MSH-05-18	07/31/05	27	6.3	-87	-12.6	-16.0	54.8
MSH-05-20	07/31/05	28	5.2	-80	-11.7	-15.9	53.1

in the hot springs. We conclude that the changing anion proportions shown in figure 3 reflect changes in the release rates of sulfur gases, HCl, and CO<sub>2</sub> from the magma and a varying degree of efficiency of gas scrubbing by the overlying water.

The 1983–89 trend in Loowit waters from SO<sub>4</sub> toward Cl (fig. 3) can be explained by the cessation in the supply of magma at the end of the 1980–86 dome-building eruptions. With declining output of sulfur gas from magma, less sulfur was available to be scrubbed into overlying meteoric water. The simultaneous increase in Cl can be attributed to crystallization of extruded and shallowly emplaced magma, with degassing of HCl or partitioning of Cl into an aqueous phase that then mixed with meteoric water. The ensuing trend toward HCO<sub>3</sub> dominance after 1989 (fig. 3) would logically be attributed to continuing declines in the supply of S and Cl as cooling and crystallization of the 1980–86 dome and shallow underlying magma progressed toward completion; CO<sub>2</sub>, due to its low solubility even at high pressure, continued to exsolve from magma at greater depths. This scheme does not explain the large increase in HCO<sub>3</sub> concentrations in Loowit springs (fig. 4; table 3). Coupled with the drop in pH, the rise in HCO<sub>3</sub> concentrations between 1989 and 2002 represents an order-of-magnitude jump in DIC, an event of particular interest because it could indicate the ascent of fresh, CO<sub>2</sub>-rich magma from depth beneath the chamber, leading up to the renewal of eruptive activity in 2004.



**Figure 6.** Trends in Br and Cl concentrations for 2002–2005 spring waters, compared with early data from springs and fumarole condensates from the 1980–86 dome at Mount St. Helens, Washington. One 1989 fumarole condensate sample that plots off the scale is not shown. Data from fumarole condensates and waters before 2002 are from Shevenell and Goff (1993, 2000), Goff and McMurtry (2000), and unpublished data (Fraser Goff, University of New Mexico).

However, the HCO<sub>3</sub> increase seems to have begun by 1994 (fig. 4), and carbon isotope data (discussed below) do not indicate CO<sub>2</sub> release from a new source of magma.

By 2002, the molar C:S:Cl ratio in Loowit waters had shifted from ~1:3:8 in the late 1980s to 10:1.4:3.6. This ratio is much closer to the 10:1.1:1.2 ratio measured in plume emissions by various techniques in 2005 (Gerlach and others, 2005; Edmonds and others, this volume, chap. 27). Our preferred explanation for the shift in the ratios is that for many years after dome emplacement in the 1980s, temperatures above boiling in the rocks of the 1980–86 dome prevented shallow waters from completely sealing off escape pathways for gas. Highly soluble HCl and SO<sub>2</sub> were effectively scrubbed by infiltrating water, but the CO<sub>2</sub> was still largely able to escape due to its much lower solubility. Once gas pathways were mostly blocked by liquid water, presumably after 1994, CO<sub>2</sub> scrubbing became efficient, and dissolved C:S:Cl ratios approached those of degassing magma. Note that the time-frame for these changes in chemistry is in fair agreement with the estimate that the 1980–86 dome would cool through its magnetization temperature in 18–36 years after emplacement (Dzurisin and others, 1990).

## Carbon and Helium Isotope Evidence on Magmatic End Members

### Gas from the Crater and The Breach

In spite of declining fumarole temperatures and the increasing amount of air in gases venting in the crater at Mount St. Helens, the carbon and helium isotopic compositions give evidence of a prolonged magmatic input. Gas collected in November 1980 from a >400°C fumarole near the dome provided the most representative δ<sup>13</sup>C–CO<sub>2</sub> value for the early magma at Mount St. Helens, –10.5 per mil (Evans and others, 1981; table 5). Over time the carbon isotope composition of CO<sub>2</sub> in fumarole gases shifted to lighter values (fig. 7A). The shift cannot be related to the increased air concentrations because the δ<sup>13</sup>C value of atmospheric CO<sub>2</sub> is around –7 per mil (Faure, 1986). Since 1994 CO<sub>2</sub> concentrations in gases from the 1980–86 dome have declined, but δ<sup>13</sup>C–CO<sub>2</sub> values have stabilized (fig. 7). In June 1994, gas from a 560°C fumarole and other lower temperature fumaroles on the dome contained about 32 percent CO<sub>2</sub> and had δ<sup>13</sup>C values between –11.7 and –12.0 per mil (Goff and McMurtry, 2000; F. Goff, unpub. data, 1994). In 1998, gas samples collected from an 86°C vent on September lobe contained 5 percent CO<sub>2</sub> with a δ<sup>13</sup>C value of –11.9 per mil (Symonds and others, 2003; table 5), and gas samples collected from vents on September lobe in 2002 had less than 3 percent CO<sub>2</sub> with δ<sup>13</sup>C values between –12.0 and –11.8 per mil (table 5).

Gas from the bubbling springs in 2002 and 2005 contained mostly CO<sub>2</sub> but also had considerable N<sub>2</sub> and Ar (table 5). The N<sub>2</sub>/Ar ratio in the gas falls between the ratios for air and air-saturated meteoric water, but low O<sub>2</sub> values show that

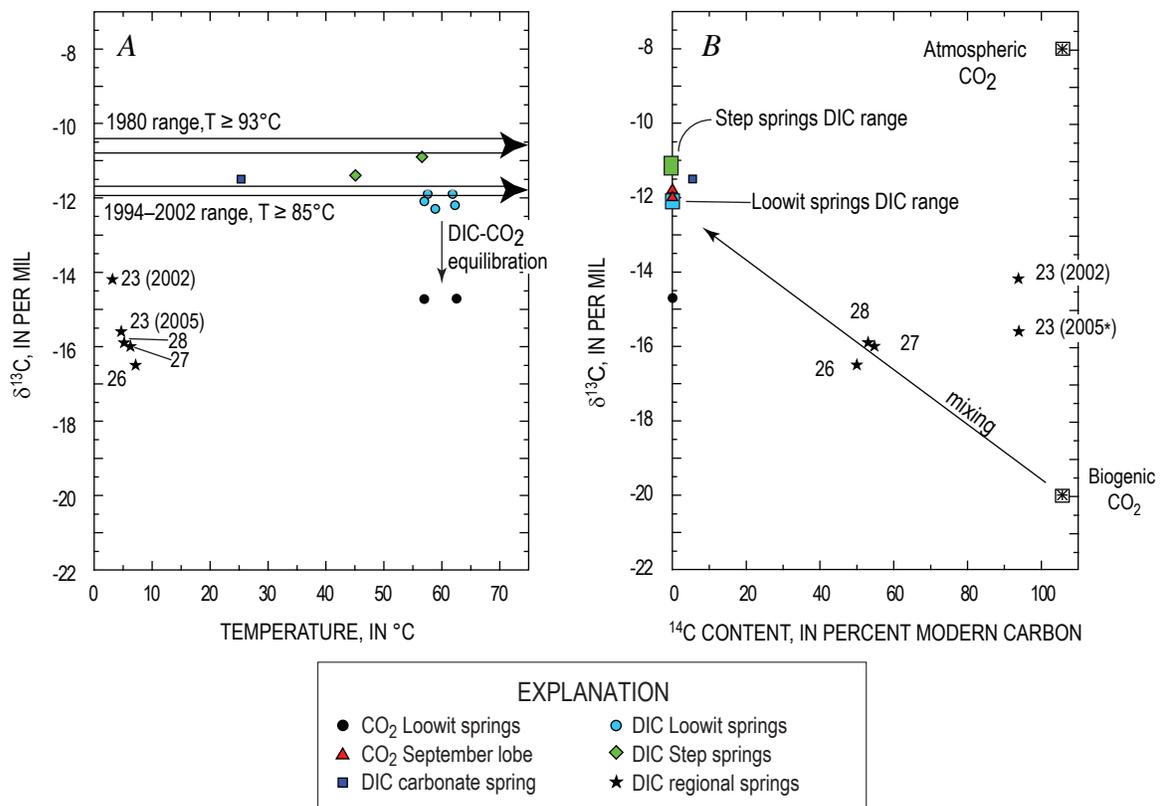
direct air contamination was not a factor. The  $R/R_A$  values for  $^3\text{He}/^4\text{He}$  ratios in the gas were 5.5 and 5.8, respectively, similar to a 1989 hot spring water sample that had a value of 5.7 (Goff and McMurtry, 2000). The  $\delta^{13}\text{C}$  value for the  $\text{CO}_2$  in both years was  $-14.7$  per mil, significantly lower than the isotopic composition of  $\text{CO}_2$  in the vent gases. Analysis of the 2002 bubbling gas indicates that it is essentially  $^{14}\text{C}$  dead, ruling out any significant biogenic  $\text{CO}_2$  source (table 5; figs. 7A, 7B). An important consideration is that equilibrium fractionation processes call for lower  $\delta^{13}\text{C}$  values in the gas-bubble  $\text{CO}_2$ , relative to the DIC, consisting of  $\text{HCO}_3$  and dissolved  $\text{CO}_2$ .

### Dissolved Inorganic Carbon in Spring Waters

The carbon isotope composition of DIC from the springs in Loowit and Step canyons and carbonate spring has a small range in values that is independent of water temperature (fig. 7A). The  $\delta^{13}\text{C}$ -DIC values in all these springs are similar to

the  $\delta^{13}\text{C}$  composition of fumarolic  $\text{CO}_2$  from recent years but are lower than the 1980 fumarolic  $\delta^{13}\text{C}$ - $\text{CO}_2$  values. The  $\delta^{13}\text{C}$ -DIC data thus provide additional evidence for a change in the  $\delta^{13}\text{C}$  of the  $\text{CO}_2$  released from the underlying magma. This carbon isotope shift to lower values since 1980 is most easily attributed to fractional loss of  $^{13}\text{C}$ -enriched  $\text{CO}_2$  during degassing of the magma (Gerlach and Taylor, 1990) and is a strong argument against the involvement of fresh magma. A new pulse of gas-rich magma from great depth would likely cause a return toward heavier  $\delta^{13}\text{C}$  values in gas vents and DIC, and a new pulse of basalt from mantle depths might bring an increase in  $^3\text{He}/^4\text{He}$  ratios.

The regional springs have much lower  $\text{HCO}_3$  concentrations than springs in the crater and The Breach and have lower  $\delta^{13}\text{C}$ -DIC values (tables 3, 4). The  $^{14}\text{C}$  content of the DIC in springs 26, 27, and 28 contains about 50 percent modern carbon, and the  $^{13}\text{C}$ - $^{14}\text{C}$  isotope values fall on a mixing line between typical biogenic carbon and magmatic carbon in the dome vents and hot springs (fig. 7B). Springs 26, 27, and 28



**Figure 7.** Water temperatures and carbon isotope compositions of dissolved inorganic carbon (DIC) and  $\text{CO}_2$  from vents and springs at and around Mount St. Helens, Washington 1980–2005. *A*,  $\delta^{13}\text{C}$ -DIC values for hot and cold springs from this study compared to  $\text{CO}_2$  gas collected from the 1980–86 dome. Horizontal arrows represent the range in  $\delta^{13}\text{C}$ - $\text{CO}_2$  values reported for 1980s dome gas samples from Evans (1981), Goff and McMurtry (2000), Symonds and others (2003), and this study. *B*, Comparison of  $\delta^{13}\text{C}$ -DIC and  $^{14}\text{C}$ -DIC values for some regional cold springs with values of DIC and  $\text{CO}_2$  from hot springs and atmospheric and biogenically derived  $\text{CO}_2$ .  $^{14}\text{C}$  values for DIC in Loowit and Step springs and  $\text{CO}_2$  from the September lobe are assumed to be zero. The 2005 analysis of sample 23, shown with asterisk, lacks a  $^{14}\text{C}$ -DIC value, so it is arbitrarily assigned the 2002 analytical value, for purposes of plotting the  $\delta^{13}\text{C}$  results.

**Table 5.** Chemical and isotopic results from gas analyses, 1980–2005, Mount St. Helens, Washington.[Concentrations are reported as volume percent; --, no data;  $R/R_A$ , the  $^3\text{He}/^4\text{He}$  ratio in the gas relative to the  $^3\text{He}/^4\text{He}$  ratio in air.]

Sample No.	Date	Map No.	Temp. (°C)	He	H <sub>2</sub>	Ar	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>	CO <sub>2</sub>	C <sub>2</sub> H <sub>6</sub>	H <sub>2</sub> S	CO	SO <sub>2</sub>	N <sub>2</sub> / Ar	$\delta^{13}\text{C}-\text{CO}_2$ (‰)	$^3\text{He}/^4\text{He}$ (R/R) <sub>A</sub>
<b>Dome gas, 1980s dome</b>																	
CQ244IB80 <sup>1</sup>	11/04/80	--	>400	<0.005	8.61	<0.02	0.03	1.6	<0.0002	86.6	<0.01	2.09	0.57	0.84	na	-10.5	--
981214 <sup>2</sup>	06/29/98	--	86	0.0005	0.0014	0.94	19.4	74.5	<0.0002	5.2	<0.0002	<0.0005	<0.001	--	79.1	-11.9	--
MSH-02-08 <sup>3</sup>	08/22/02	2	≥ 86	0.0005	0.0008	0.89	20.6	77.0	<0.0002	1.5	<0.0002	<0.0005	<0.001	--	86.2	-11.8	--
MSH-02-09 <sup>3</sup>	08/22/02	1	≥ 85	0.0006	0.0002	0.90	20.4	76.2	<0.0002	2.4	<0.0002	<0.0005	<0.001	--	84.4	-12.0	--
<b>Hot spring gas, spring in Loowit canyon</b>																	
MSH-02-03 <sup>4</sup>	08/17/02	7	62.3	0.0012	<0.0002	0.26	0.88	18.6	0.06	80.2	<0.0002	<0.0005	<0.001	--	72.4	-14.7	5.5
MSH-05-03	07/26/05	3	57.0	0.0019	0.0003	0.34	<0.0005	23.3	0.05	76.3	<0.0002	0.0026	<0.001	--	69.2	-14.7	5.8

<sup>1</sup> 1980 sample collected from crack near 1980 dome by W.C. Evans, from Evans and others (1981).<sup>2</sup> 1998 sample collected from September lobe by R. Symonds;  $^{13}\text{C}-\text{CO}_2$  from Symonds and others (2003).<sup>3</sup> Collected from September lobe.<sup>4</sup> Value for  $^{14}\text{C}-\text{CO}_2$  equals 0.07 (percent modern carbon).

may contain some magmatic carbon, and the Cl concentrations in springs 26 and 27 support this idea. The DIC in spring 23 contains 94 percent modern carbon, and two samples from different years had variable  $\delta^{13}\text{C}$  values that are higher than the other regional springs. The variation in the  $^{13}\text{C}$  composition may indicate that some  $\text{CO}_2$  degassing occurs from the water prior to its point of emergence. A small magmatic component in the spring is possible, but without additional study (for example, He isotopes), we cannot eliminate the possibility that the dead carbon in all four of these springs is derived from Tertiary-age hydrothermal carbonate in the volcanic rocks that underlie the edifice of Mount St. Helens (Evarts and others, 1987).

### Total Discharges of Water, Heat, and Magmatic Volatiles

#### Creek-Water Discharge

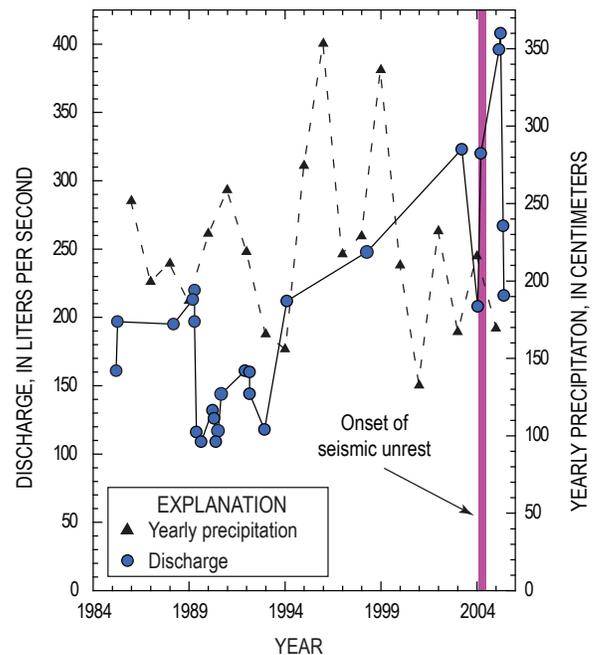
During the course of this investigation, the measured surface discharge from Loowit Creek was about three to six times greater than the discharge from Step creek (table 2). Maximum seasonal discharge at the monitoring sites occurred in the midsummer to fall months. There are no historical data on discharge at Step creek, but measurements at LCAF show that flow rates have increased since 1989 (fig. 8; tables 2 and 6). The increase does not reflect variations in annual precipitation and more likely results from increased input of meltwater as Crater Glacier grew from a persistent snow bank in the shadow of the crater rim to an area of about 1 km<sup>2</sup> by September 2001 (Schilling and others, 2004).

Since October 2004, the emplacement of the new lava dome at Mount St. Helens resulted in extensive deformation of Crater Glacier and a concomitant decrease in the volume of glacial ice, without any large change in the surface flows of the creeks, indicating that some meltwater may exit the crater from leakage through the crater floor (Major and others, 2005; Walder and others, 2007; Walder and others, this volume, chap. 13). A complete hydrologic budget to address this idea has yet to be developed for Mount St. Helens and, until such time, our multiple measurements of stream flow and chemistry for Loowit and Step creeks (table 7) offer the most comprehensive picture of discharge and dissolved fluxes from the crater area.

Two major contributors to conductivity in the creek waters are Cl and  $\text{SO}_4$  (fig. 9A). During the course of our investigation at both of the Loowit Creek monitoring sites, Cl/ $\text{SO}_4$  ratios were essentially constant and mimicked ratios in Loowit springs in 2005 (fig. 9B). In contrast, Step creek waters show large variations in Cl to  $\text{SO}_4$ , which can be attributed directly to changes in the chemistry and discharge of water from WFSCAF. Combining the average flows of Loowit Creek and the east fork of Step creek yields a total thermal water discharge of 335 L/s with an average Cl concentration of 180 mg/L (table 7). The creek waters are composed primarily of meteoric water from melting ice and snow plus water from the

**Table 6.** Discharge measurements and meter information for Loowit Creek above the falls, 1985–98, Mount St. Helens, Washington.

Date	Discharge (L/s)	Meter type
08/15/85	161	Price AA meter
09/09/85	197	Price AA meter
08/09/88	195	Gurley meter
08/10/89	213	Gurley meter
09/14/89	220	Price AA meter
09/14/89	197	Price AA meter
10/16/89	116	Pygmy meter
01/17/90	109	Pygmy meter
08/24/90	132	Pygmy meter
09/20/90	126	Pygmy meter
10/23/90	109	Pygmy meter
12/07/90	117	Pygmy meter
02/08/91	144	Pygmy meter
05/01/92	161	Pygmy meter
07/28/92	160	Pygmy meter
07/28/92	144	Pygmy meter
05/05/93	118	Pygmy meter
07/07/94	212	Pygmy meter
09/01/98	248	Pygmy meter



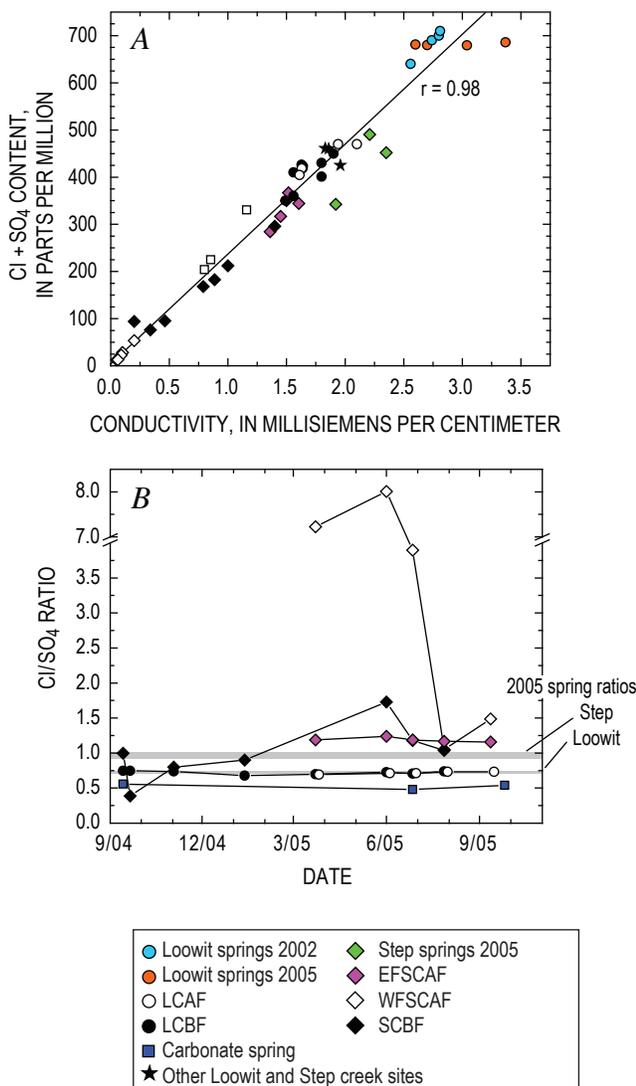
**Figure 8.** Discharge at site LCAF from 1985 to 2005 and yearly precipitation totals from the SNOTEL station at Spirit Lake, Mount St. Helens, Washington, from 1986 to 2005. Ticks on x axis correspond to month of June. Data from August 1988 and 1989 are from Shevenell (1990).

**Table 7.** Selected chemistry and discharge measurements for monitoring sites and some springs, 1988–2005, Mount St. Helens, Washington.

[CO<sub>2</sub> t/d, metric tons per day, calculated as CO<sub>2</sub> from measured HCO<sub>3</sub> flux; CO<sub>2</sub> mag., the corrected magmatic flux of CO<sub>2</sub> in metric tons per day based on measured spring pH values (see text); mS/cm, millisiemens per centimeter; ps, probe site; LCAF, Loowit Creek above falls; LCBF, Loowit Creek below falls; EFSCAF, east fork Step creek above falls; WFSCAF, west fork Step creek above falls; SCBF, Step creek below falls; CARB gs, carbonate spring gage site. Data from 1988 and 1989 are from Shevenell (1990). The <sup>14</sup>C data in bold were collected at a different time from the time the discharge was measured.]

Sample No.	Location	Date	Temp. (°C)	Conductivity (mS/cm)	Discharge (L/s)	<sup>14</sup> C (% modern carbon)	HCO <sub>3</sub> (mg/L)	CO <sub>2</sub> (t/d)	CO <sub>2</sub> (mag. t/d)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	Cl (t/d)	SO <sub>4</sub> (t/d)
<b>Monitoring network sites</b>													
MSH-05-11	LCAF	07/26/05	29.1	1.63	396		488	12.1	24	172	247	5.9	8.5
LCAF 082605	LCAF	08/26/05	30.1	1.61	408	--	--	--	--	169	236	5.9	8.3
LCAF 101105	LCAF	10/11/05	30.0	1.94	267	--	--	--	--	197	273	4.5	6.3
MSH-05-24	LCAF ps	10/25/05	25.9	1.83	215	--	533	7.1	14	193	268	3.6	5.0
LCBF 101304	LCBF	10/13/04	16.3	1.49	306	--	--	--	--	147	203	3.9	5.4
LCBF 042105	LCBF	04/21/05	16.9	1.87	187	--	--	--	--	180	270	2.9	4.4
MSH-05-12	LCBF	07/26/05	22.5	1.56	399	--	--	--	--	167	244	5.7	8.4
LCBF 082605	LCBF	08/26/05	19.8	1.63	279	--	--	--	--	178	249	4.3	6.0
<b>Average flux</b>									<b>19.0</b>			<b>4.6</b>	<b>6.5</b>
MSH-05-09	EFSCAF	07/26/05	26.6	1.45	45	--	535	1.5	3	172	145	0.7	0.6
EFSCAF 101105	EFSCAF	10/11/05	17.6	1.52	19	--	--	--	--	197	170	0.3	0.3
MSH-05-23	EFSCAF ps	10/25/05	25.4	1.96	27	--	787	1.3	2.6	232	194	0.5	0.5
<b>Average flux</b>									<b>2.8</b>			<b>0.5</b>	<b>0.4</b>
MSH-05-10	WFSCAF	07/26/05	10.5	0.06	142	--	12	0.1	0.1	10	3	0.1	0.03
SCBF 101304	SCBF	10/13/04	14.5	0.79	112	--	--	--	--	84	84	0.8	0.8
SCBF 082605	SCBF	08/26/05	19.2	0.89	49	--	--	--	--	93	89	0.4	0.4
MSH-05-13	SCBF	07/26/05	21.2	0.46	110	--	--	--	--	52	44	0.5	0.4
<b>Average flux</b>												<b>0.6</b>	<b>0.5</b>
<b>Pumice Plain spring</b>													
MSH-05-25	CARB gs	10/25/05	15.7	0.80	354	<b>5.5</b>	204	4.5	4.3	71	132	2.2	4.0
<b>Regional cold springs</b>													
MSH-05-14	#23	07/29/05	4.7	0.05	818	<b>93.8</b>	29	1.5	0.16	--	--	--	--
MSH-05-18 (nr)	#27	07/31/05	6.3	0.08	82	54.8	44	0.2	0.11	--	--	--	--
MSH-05-19	nr #26	07/31/05	7.2	0.12	137	50.0	94	0.8	0.42	--	--	--	--
MSH-05-20	#28	07/31/05	5.2	0.09	29	53.1	73	0.1	0.07	--	--	--	--
<b>Loowit Creek above falls, 1988 and 1989</b>													
SH-45	LCAF	08/09/88	41.0	3.36	195	--	87	1.1	1.1	600	567	10.1	9.6
SH-81	LCAF	08/10/89	41.6	3.02	213	--	88	1.2	1.2	549	507	10.1	9.3
<b>Average flux</b>									<b>1.1</b>			<b>10.1</b>	<b>9.4</b>

hot springs, and we can normalize the creek data to a source spring fluid with 280 mg/L by assuming that the meteoric water has no Cl (table 3). This calculation yields total water outputs of 215 L/s for the Loowit and Step springs. By using the density and enthalpy of water at 56°C, the heat output is ~50 MW. For perspective, a heat output of 50 MW would completely cool the 1980–86 dome in about 125 years.



**Figure 9.** Cl and SO<sub>4</sub> concentrations for Loowit spring waters since 2002 and the creek-monitoring sites since October 2004, Mount St. Helens, Washington. *A*, Cl and SO<sub>4</sub> are major anions controlling conductivity in creek waters. *B*, Temporal plot showing Cl/SO<sub>4</sub> ratios at the monitoring sites. Loowit Creek sites show no change during the first year after the start of the 2004–5 eruption. Sites SCBF and WFSCAF show change in Cl and SO<sub>4</sub> ratios. Gray bars represent range in Cl and SO<sub>4</sub> for Loowit canyon and Step canyon springs in 2005. The LCAF site plot is shifted slightly so data can be shown.

## Present-Day Flux of Magmatic Volatiles

Assuming that all of the dissolved carbon in the hot springs is derived from the underlying magma, we can couple the DIC concentration and the discharge to provide an estimate of the magmatic carbon flux. Table 7 shows six datasets for dates when a DIC sample was collected from a monitoring site concurrent with a discharge measurement. The largest flux measured was 12 metric tons per day (t/d), expressed as CO<sub>2</sub>, from LCAF in July 2005. On the same day, another 1.5 t/d (as CO<sub>2</sub>) discharged from EFSCAF. Measured pH values show that the DIC in Step and Loowit springs consists of approximately equal proportions of dissolved CO<sub>2</sub> and HCO<sub>3</sub>, but nearly all of the dissolved CO<sub>2</sub> is outgassed upstream of the monitoring sites. The total output of magmatic carbon from the springs would, therefore, be double the amounts noted above. We did not gage carbonate spring in July 2005, but in October 2005 its magmatic CO<sub>2</sub> flux was 4.3 t/d. That value is adjusted for a small modern, nonmagmatic carbon contribution indicated by the <sup>14</sup>C value using mass balance, assuming the modern DIC component contains 105 percent modern carbon (James and others, 1999). Any potential flux of magmatic CO<sub>2</sub> from WFSCAF or the regional springs is less than 1 t/d.

We also estimated Cl and SO<sub>4</sub> fluxes for the creeks using the same methods. Apart from carbonate spring, which may have some nonmagmatic sources of Cl and SO<sub>4</sub>, the data in table 7 show that the Loowit Creek sites are the main contributors of Cl and SO<sub>4</sub>. Together, the Loowit and Step creeks yield average Cl and SO<sub>4</sub> fluxes of 5.2 t/d (expressed as HCl) and 4.7 t/d (expressed as SO<sub>2</sub>) and, adjusting the DIC as discussed above, 22 t/d of CO<sub>2</sub>. These data provide a first look at the flux of magmatic components dissolved in the waters at Mount St. Helens. For comparison, HCl and SO<sub>2</sub> fluxes in plume emissions on August 31, 2005, were 14 and 22 t/d, respectively (Edmonds and others, this volume, chap. 27), whereas CO<sub>2</sub> in the crater-plume emissions during the course of the 2004–6 eruption were in hundreds of tons per day (Doukas and others, 2005; Gerlach and others, this volume, chap. 26), and CO<sub>2</sub> emissions from the plume coming off Loowit springs were 27 t/d on June 9, 2005 (Gerlach and others, this volume, chap. 26).

## Flux of Magmatic Volatiles 1988–1989

Estimates similar to those made for the 2004–5 data can be made for the flux of magmatic volatiles at LCAF in the late 1980s by using data from Shevenell (1990). Tables 2 and 7 show that the discharge at LCAF in August 1988 and 1989 was roughly 60 percent of the flow measured in the months of July and August 2003–5. In spite of lower discharges of creek water in the late 1980s, dissolved SO<sub>4</sub> and Cl fluxes were 1.4 and 2.2 times higher, respectively, than fluxes in 2004–5 (table 7). The dissolved magmatic CO<sub>2</sub> flux in 1988–89, however, was only 1.1 t/d, in comparison with 19 t/d from this study (table 7). Because the pH of the springs was about 7.2, we made no correction for outgassing of CO<sub>2</sub>.

## Conclusions

Data from springs and gas discharges in the crater are consistent with plume emission rates (Doukas and others, 2005; Gerlach and others, this volume, chap. 26) that indicate the current eruption is driven by degassed magma. From the early 1980s to 2002, gas vents on the 1980–86 dome grew weaker and more air-dominated, while magmatic Cl and SO<sub>4</sub> inputs to the Loowit springs declined, and the isotopic signal (D and <sup>18</sup>O) from magmatic water input disappeared. The large DIC increase in Loowit springs over time could indicate a pulse of new magma, but the δ<sup>13</sup>C signatures of the DIC and of CO<sub>2</sub> gas are consistent with degassing of residual magma emplaced in the 1980s. No significant changes in Loowit springs occurred between 2002 and 2005. However, we note that the time for water to flow from the new dome to the spring vents could exceed one year, the time between the onset of unrest and the latest water sampling, so some caution must be applied to interpretations of the Loowit data. Carbon and helium isotope data for gas from the new dome might be more compelling but are unavailable.

Hot or mineralized springs occur on many volcanoes that lack summit plumes or obvious fumaroles and, in these cases, may provide the only opportunity to look for magmatic gases released at depth. The similarity in C:S:Cl ratios of recent Loowit springs samples and the 2005 plume emissions strongly supports the idea that spring geochemistry can accurately reflect magmatic degassing under favorable conditions. In this context, it is important to continue tracking the chemistry of the Mount St. Helens springs during the next few years in a search for responses to the current eruption.

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## References Cited

- Chiodini, G., Frondini, F., Cardellini, C., Parello, F., and Peruzzi, L., 2000, Rates of diffuse carbon dioxide Earth degassing estimated from carbon balance of regional aquifers—the case of central Apennine, Italy: *Journal of Geophysical Research*, v. 105, no. B4, p. 8423–8434.
- Coplen, T.B., 1973, A double focusing, double collecting mass spectrometer for light stable isotope ratio analysis: *International Journal of Mass Spectrometry and Ion Physics*, v. 11, p. 37–40.
- Coplen, T.B., Wildman, J.D., and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibration technique for hydrogen isotope-ratio analysis: *Analytical Chemistry*, v. 63, p. 910–912.
- Doukas, M.P., McGee, K.A., and Gerlach, T.M., 2005, Airborne measurement of CO<sub>2</sub>, SO<sub>2</sub>, and H<sub>2</sub>S emissions rates during the 2004–2005 eruption of Mount St. Helens [abs.]: *Eos (American Geophysical Union Transactions)*, v. 86, no. 52, Fall Meet. Suppl., Abstract V53D-1590.
- Dzurisin, D., Denlinger, R.P., and Rosenbaum, J.G., 1990, Cooling rate and thermal structure determined from progressive magnetization of the dacite dome at Mount St. Helens, Washington: *Journal of Geophysical Research*, v. 95, no. B3, p. 2763–2780.
- Edmonds, M., McGee, K.A., and Doukas, M.P., 2008, Chlorine degassing during the lava dome-building eruption of Mount St. Helens, 2004–2005, chap. 27 of Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., *A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006*: U.S. Geological Survey Professional Paper 1750 (this volume).
- Epstein, S., and Mayeda, T., 1953, Variation of <sup>18</sup>O content of waters from natural sources: *Geochimica et Cosmochimica Acta*, v. 4, no. 5, p. 213–224.
- Evans, W.C., Banks, N.G., and White, L.D., 1981, Analyses of gas samples from the summit crater, in Lipman, P.W., and Mullineaux, D.R., eds., *The 1980 eruptions of Mount St. Helens*, Washington: U.S. Geological Survey Professional Paper 1250, p. 227–232.
- Evans, W.C., Sorey, M.L., Cook, A.C., Kennedy, B.M., Shuster, D.L., Colvard, E.M., White, L.D., and Huebner, M.A., 2002, Tracing and quantifying magmatic carbon discharge in cold groundwaters—Lessons learned from Mammoth Mountain, USA: *Journal of Volcanology and Geothermal Research*, v. 114, p. 291–312.
- Evarts, R.C., Ashley, R.P., and Smith, J.G., 1987, Geology of the Mount St. Helens area; record of discontinuous volcanic and plutonic activity in the Cascade arc of southern Washington: *Journal of Geophysical Research*, v. 92, no. B10, p. 10155–10169.
- Faure, G., 1986, *Principles of isotope geology*: New York, John Wiley, 589 p.
- Fournier, R.O., 1986, Conceptual models of brine evolution in magma-hydrothermal systems, chap. 55 of Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., *Volcanism in Hawaii*: U.S. Geological Survey Professional Paper 1350, v. 2, p. 1487–1506.
- Gerlach, T.M., and Casadevall, T.J., 1986, Fumarole emissions

- at Mount St. Helens volcano, June 1980 to October 1981; degassing of a magma-hydrothermal system: *Journal of Volcanology and Geothermal Research*, v. 28, nos. 1–2, p. 141–160, doi:10.1016/0377-0273(86)90009-0.
- Gerlach, T.M., and Taylor, B.E., 1990, Carbon isotope constraints on degassing of carbon dioxide from Kilauea Volcano: *Geochimica et Cosmochimica Acta*, v. 54, no. 7, p. 2051–2058.
- Gerlach, T.M., McGee, K.A., and Doukas, M.P., 2005, Emission rates, pre-eruption gas saturation and ascent degassing during the 2004–2005 eruption of Mount St. Helens [abs.]: *Eos (American Geophysical Union Transactions)*, v. 86, no. 52, Fall Meet. Suppl., Abstract V52B-07.
- Gerlach, T.M., McGee, K.A., and Doukas, M.P., 2008, Emission rates of CO<sub>2</sub>, SO<sub>2</sub>, and H<sub>2</sub>S, scrubbing, and preeruption excess volatiles at Mount St. Helens, 2004–2005, chap. 26 of Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., *A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006*: U.S. Geological Survey Professional Paper 1750 (this volume).
- Giggenbach, W.F., 1992, Chemical techniques in geothermal exploration, in D'Amore, F., ed., *Applications of geochemistry in geothermal reservoir development*: Rome, UNITAR/UNDP Guidebook, Center on Small Energy Resources, p. 119–144.
- Goff, F., and McMurtry, G.M., 2000, Tritium and stable isotopes of magmatic waters: *Journal of Volcanology and Geothermal Research*, v. 97, p. 347–396.
- James, E.R., Manga, M., and Rose, T.P., 1999, CO<sub>2</sub> degassing in the Oregon Cascades: *Geology*, v. 27, no. 9, p. 823–826.
- Keith, T.E.C., Casadevall, T.J., and Johnston, D.A., 1981, Fumarole encrustations; occurrence, mineralogy and chemistry, in Lipman, P.W., and Mullineaux, D.R., eds., *The 1980 eruptions of Mount St. Helens, Washington*: U.S. Geological Survey Professional Paper 1250, p. 239–250.
- Kennedy, B.M., and van Soest, M.C., 2006, A helium isotope perspective on the Dixie Valley, Nevada, hydrothermal system: *Geothermics*, v. 35, p. 26–43.
- Kharaka, Y.K., Gunter, W.D., Aggarwal, P.K., Perkins, E.H., and DeBraal, J.D., 1988, SOLMINEQ.88—A computer program for geochemical modeling of water-rock interactions: U.S. Geological Survey Water Resources Investigation Report 88–4227, 420 p.
- Major, J.J., Scott, W.E., Driedger, C., and Dzurisin, D., Mount St. Helens erupts again; activity from September 2004 through March 2005: U.S. Geological Survey Fact Sheet 2005–3036, 4 p.
- Rose, T.P., and Davisson, M.L., 1996, Radiocarbon in hydrologic systems containing dissolved magmatic carbon dioxide: *Science*, v. 273, p. 1367–1370.
- Schilling, S.P., Carrara, P.E., Thompson, R.A., and Iwatsubo, E.Y., 2004, Posteruption glacier development within the crater of Mount St. Helens, Washington, USA: *Quaternary Research*, v. 61, no. 3, p. 325–329.
- Shevenell, L., 1990, Chemical and isotopic investigation of the new hydrothermal system at Mount St. Helens, Washington, USA: Reno, University of Nevada, Ph.D. dissertation, 282 p.
- Shevenell, L., and Goff, F., 1993, Addition of magmatic volatiles into the hot spring waters of Loowit Canyon, Mount St. Helens, Washington, USA: *Bulletin of Volcanology*, v. 55, no. 7, p. 489–503, doi:10.1007/BF00304592.
- Shevenell, L., and Goff, F., 1995, Evolution of hydrothermal waters at Mount St. Helens, Washington, USA: *Journal of Volcanology and Geothermal Research*, v. 69, p. 73–94.
- Shevenell, L., and Goff, F., 2000, Temporal geochemical variations in volatile emissions from Mount St. Helens, USA, 1980–1994: *Journal of Volcanology and Geothermal Research*, v. 99, p. 123–138.
- Symonds, R.B., and Reed, M.H., 1993, Calculation of multi-component chemical equilibria in gas-solid-liquid systems; calculation methods, thermochemical data, and applications to studies of high-temperature volcanic gases with examples from Mount St. Helens: *American Journal of Science*, v. 293, no. 8, p. 758–864.
- Symonds, R.B., Gerlach, T.M., and Reed, M.H., 2001, Magmatic gas scrubbing—implications for volcano monitoring: *Journal of Volcanology and Geothermal Research*, v. 108, nos. 1–4, p. 303–341, doi:10.1016/S0377-0273(00)00292-4.
- Symonds, R.B., Poreda, R.J., Evans, W.C., Janik, C.J., and Ritchie, B.E., 2003, Mantle and crustal sources of carbon, nitrogen, and noble gases in Cascade-Range and Aleutian-Arc volcanic gases: U.S. Geological Survey Open-File Report 03–436, 26 p.
- Thompson, M.J., 1990, Chemical data from thermal and non-thermal springs in Mount St. Helens National Monument, Washington: U.S. Geological Survey Open-File Report 90-0690-A, 16 p.
- Vogel, J.S., Southon, J.R., and Nelson, D.E., 1987, Catalyst and binder effects in the use of filamentous graphite for AMS: *Nuclear Instruments and Methods in Physics Research*, v. B29, p. 50–56.
- Walder, J.S., LaHusen, R.G., Vallance, J.W., and Schilling, S.P., 2007, Emplacement of a silicic lava dome through a crater glacier—Mount St Helens, 2004–06: *Annals of Glaciology*, v. 45, p. 14–20.
- Walder, J.S., Schilling, S.P., Vallance, J.W., and LaHusen, R.G., 2008, Effects of lava-dome growth on the Crater Glacier of Mount St. Helens, Washington, chap. 13 of Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., *A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006*: U.S. Geological Survey Professional Paper 1750 (this volume).

## **Appendix 1. Trace-Element and Isotopic Data from Springs and Creeks in the Mount St. Helens Area, Washington, 2002–2005**

[This appendix appears only in the digital versions of this work—in the DVD-ROM that accompanies the printed volume and as a separate file accompanying this chapter on the Web at: <http://pubs.usgs.gov/pp/1750>. ]

This appendix is a spreadsheet of analytical data.