Chemical Changes of Lakes Within the Mount St. Helens Blast Zone

Abstract. *Differences in the dissolved chemistry of lakes devastated by the 18 May 1980 eruption of Mount St. Helens are attributable to location relative to the lateral blast trajectory of the eruption and to the emplacement of mineral deposits. Elemental enrichment ratios of pre- and posteruption measurements for Spirit Lake and comparisons of the chemical concentrations and elemental ratios for lakes inside and outside the blast zone reflect the influences of the dissolution of magmatic and lithic deposits. The* p*H changes were minor because of buffering by carbonic acid and reactions involving mineral alteration, dissolved organics, and biological processes.*

The 18 May 1980 eruption of Mount St. Helens drastically altered the dissolved chemical composition of lakes in the blast zone. We report here the impact of this eruption on lake surface waters based on elemental enrichment, on a comparison of lake chemistries inside and outside the blast zone, and on variations in blast deposits. The degree of alteration of a lake's chemistry was a function of location relative to the blast trajectory of the eruption, emplacement and alteration of mineral deposits, terrestrial organics in deposits and waters, and biological processes.

On 30 June 1980 we sampled 12 lakes inside the blast zone (deposit areas S, B, and M) and four lakes outside the blast zone (area U) (Fig. 1). The blast zone (radius of 16 to 28 km northwest and northeast of the crater) was produced by a lateral high-speed eruption. Mudflows and debris avalanches inundated the Toutle River valley, destroyed forests and soils, and formed new lakes by damming East Castle, West Castle, South Coldwater, and North Coldwater creeks on the North Fork of the Toutle River. Massive debris and pyroclastic loadings to Spirit Lake (8 km northeast of the crater) raised the lake level ~ 40 m and increased the surface area by ~ 30 percent. Lake watersheds to the north of Coldwater Creek and Mount Margaret were characterized by denuded vegetation, snapped trees, heavy ashfall, and heat effects. Portions of the deposits were hot when emplaced as a result of hydrothermal-magmatic explosions (~ 500°C) that occurred during the eruption (*1–3*).

The dissolved chemistry of Spirit Lake showed a 22-fold increase in total alkalinity and a posteruption *p*H of 6.21 versus a preeruption *p*H (April 1980) of 7.35 (SA, Table 1). Dissolved manganese (815 times), iron (193 times), phosphate (248 times), sulfate (157 times), and chloride (85 times) showed the largest enrichment in comparison to SA values. Considerable enrichment also was evident for potassium (40 times), sodium (34 times), calcium (31 times), magnesium (28 times), phosphorus (33 times), silicate (14 times), and ammonia (13 times). Significant increases in metal concentrations other than iron and manganese were exhibited by aluminum (30 times), copper (17 times), zinc (4 times), lead (2 times), and antimony (2 times). These enrichment values are in agreement with other measurements of major cations, sulfate, chloride, and various trace elements in Spirit Lake (*3*).

The chemical composition of the other 15 lakes inside and outside the blast zone showed a gradient of concentrations (Table 1). The area U lakes (Merrill, McBride, June, and Blue) had *p*H values ranging from 6.73 to 7.46 and an average alkalinity of 243 μeq/liter. Merrill, McBride, and Blue lakes had concentrations of major cations, metals, primary nutrients (phosphorus and nitrogen), sulfate, and chloride comparable to those of preeruption Spirit Lake and other lakes near Mount St. Helens (*4*).

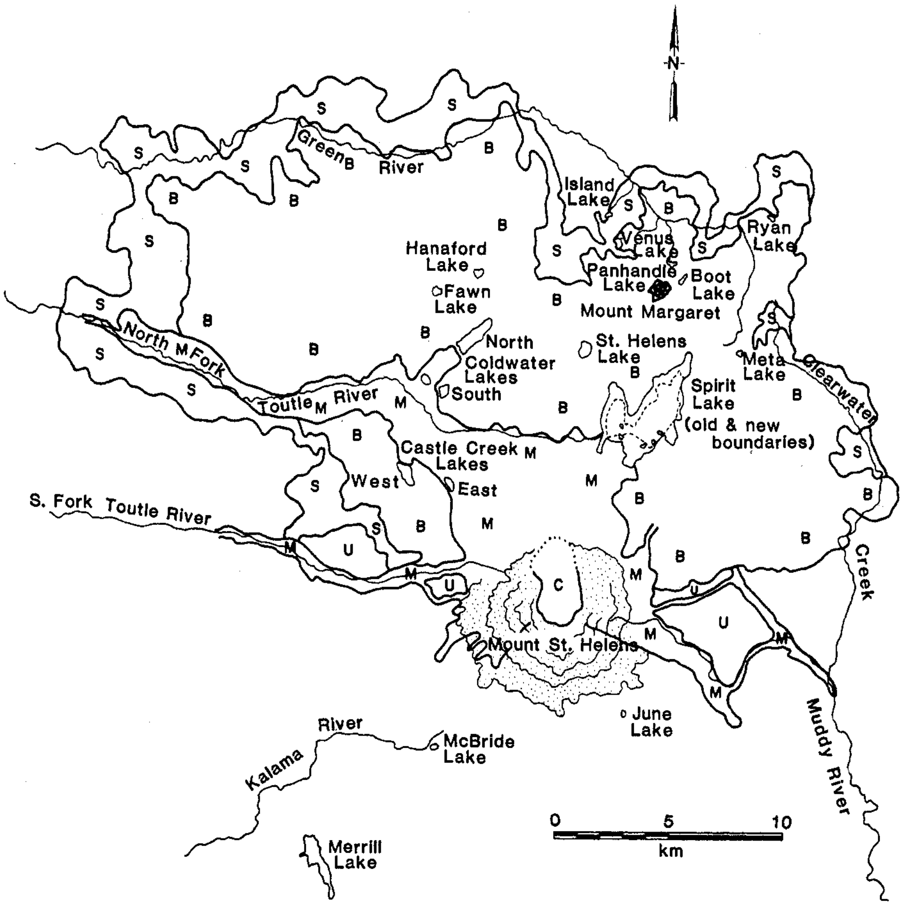

Fig. 1. Deposit areas and lakes within and immediately outside the Mount St. Helens 18 May 1980 blast zone. Deposit areas include the following: *U*, morphologically unaffected region with light ashfall, outside the blast zone; *S*, area of scorched vegetation at the edge of the blast zone; *B*, blowdown-timber area inside the blast zone; *M*, region of mudflows, debris avalanche, hot blast emplacements of volcanic and organic matter in the Toutle River and adjacent drainages, and pyroclastic flows near Spirit Lake. Magmatic and lithic minerals were the major components in the blast deposits (*3*). The magmatic component was composed of glass, plagioclase, magnetite, and a ferromagnesian silicate assemblage consisting primarily of hypersthene and hornblende. These minerals were common to pyroclastic flows and debris avalanches of area M deposits. The lithic component contained abundant plagioclase and other minerals common to magmatic materials as well as altered glass, smectite, chlorite, mica, cristobalite, tridymite, and quartz. Lithic minerals were characteristic of air-fall tephra deposits, mudflows, and debris avalanches. Portions of all deposit areas received some air-fall pumice as well as lithic tephra. The dashed line in Spirit Lake indicates the preeruption shoreline.

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Table 1. Dissolved chemical characteristics (Millipore filterable, 0.45 μm) and physical features of lakes near Mount St. Helens. Samples were taken 0.25 m below the water surface on 30 June 1980. Deposit areas U, B, S, and M are as shown in Fig. 1; areas BS and MB represent areas having features of more than one area; SA represents 4 April 1980 samples from Spirit Lake. ND, not detectable. The elements Se, Be, Ag, Cd, Co, Ni, and Hg were measured but not detectable. Enrichment factors for ND were estimated on the basis of a detection limit of 0.10 μ*M*.

Characteristic	Lakes outside blast zone				Lakes inside blast zone													
	U				B					BS		M	MB				SA
	Merrill	McBride	June	Blue	Hanaford	Fawn	St. Helens	Panhandle	Boot	Venus	Ryan	Debris flow pond*	West Castle*	East Castle*	South Coldwater*	Spirit	Spirit
Elevation (m)	474	862	985	1200	1260	1200	1405	1415	1415	1415	1018	740	740	972	740	1024	984
Distance from center of crater (km)	14	9	6	28	14	15	10	16	15	16	19	9	9	5	11	8	8
Alkalinity (μeq/liter)	126	146	563	136	461	367	110	99	195	24	409	187	4500	1910	1520	3010	139
*p*H	7.20	7.46	6.73	6.95	6.97	6.82	7.11	7.42	6.91	7.07	6.71	7.00	6.17	7.47	6.61	6.21	7.35
Dissolved constituents (μ*M*)†																	
Ca	54.14	90.32	101.30	76.35	1442.11	1564.37	324.35	499.00	608.78	146.46	693.61	521.46	2352.79	336.82	2270.45	1669.16	53.64
Mg	17.15	33.97	62.52	17.97	229.92	257.06	54.29	101.18	122.57	38.09	117.22	244.72	871.96	345.90	604.61	542.92	19.58
Na	160.95	121.80	382.80	113.10	2523.00	1892.25	478.50	665.55	735.15	256.65	765.60	1435.50	4872.00	408.90	3828.00	2923.20	87.00
K	7.67	19.18	40.15	15.34	613.68	281.27	63.93	135.52	97.17	28.13	148.31	186.66	1022.80	73.13	434.69	409.12	10.23
Mn	0.04	ND	0.16	0.62	16.64	20.75	5.50	6.41	8.30	2.08	12.85	5.92	98.28	1.17	60.97	81.54	ND
Fe	0.04	2.31	0.04	0.48	0.61	0.29	0.72	0.36	0.38	0.27	10.26	ND	281.19	6.86	3.15	19.34	ND
Cu	ND	ND	1.95	ND	0.39	1.34	ND	0.05	0.32	ND	0.43	ND	0.82	2.49	0.76	1.72	ND
Zn	ND	ND	0.81	ND	ND	0.03	0.09	0.03	0.06	ND	0.05	0.08	0.44	0.25	0.06	0.37	ND
Pb	ND	ND	0.43	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.09	ND	0.12	ND
As	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.05	ND	0.07	ND
Cr	0.01	0.02	< 0.01	ND	0.02	< 0.01	0.02	0.01	ND	ND	0.06	< 0.01	0.10	0.02	0.08	0.06	0.012
Sb	ND	ND	0.01	ND	ND	< 0.01	ND	ND	ND	ND	ND	ND	0.41	0.16	0.15	0.16	ND
Si	124.64	191.07	564.29	138.93	197.14	207.50	148.21	148.21	180.00	108.21	252.86	212.86	628.57	753.57	285.00	778.57	171.43
Al	3.90	1.67	0.37	1.12	1.86	0.93	2.23	1.49	1.67	1.12	3.72	0.74	37.15	0.37	1.86	11.15	0.37
P	0.16	0.65	1.13	0.07	1.13	1.36	0.87	1.16	1.23	0.97	1.13	1.39	5.68	2.52	2.52	7.61	0.23
PO_4-P	0.06	0.04	1.00	0.06	0.07	0.03	0.09	0.12	0.13	0.08	0.16	0.08	0.45	1.21	0.07	7.44	0.03
SiO_4	119.32	171.77	547.80	128.79	151.59	188.17	135.38	141.18	155.35	108.40	208.94	186.45	484.79	151.36	241.18	671.00	46.83
NO_3-N	0.06	0.15	2.64	0.15	0.08	0.59	0.07	0.14	0.16	0.14	0.14	0.18	2.08	1.10	0.18	0.14	0.06
NO_2-N	0.05	0.04	0.02	0.04	0.06	0.08	0.05	0.05	0.07	0.05	0.12	0.05	2.75	0.22	0.10	0.26	0.04
NH_3-N	0.16	0.17	1.61	0.14	0.27	3.04	0.18	0.16	0.27	0.21	0.54	0.21	3.43	4.40	0.77	0.93	0.07
SO_4	7.18	15.62		29.15	2029.95	1717.65	394.54	611.07	725.58	166.04	830.72	958.76	1249.20		3247.92	1301.25	8.28
Cl	33.85	126.24		78.99	2426.06	1805.40	409.05	846.30	902.72	200.29	761.67	959.14	4005.82		3244.15	2651.74	31.03

*Newly formed. †Analyses for As, Sb, Al, and Na were by atomic absorption spectrophotometry; SO_4 and Cl by ion chromatography (*16*); other metals by inductively coupled plasma emission spectrophotometry (*17*); PO_4-P, NO_3-N, NO_2-N, and NH_3-N after Strickland and Parsons (*18*); *p*H and alkalinity after Stumm and Morgan (*8*).

The area B lakes showing the lowest *p*H and the highest concentrations for total alkalinities, major cations, metals, primary nutrients, sulfate, and chloride were Hanaford and Fawn lakes (Table 1). Lakes of areas B and BS, the new debris flow pond, and East Castle Lake in the debris avalanche showed characteristics ranging between those of area U lakes and those for Hanaford and Fawn lakes. The other new lakes, South Coldwater and West Castle (area MB), had chemical properties similar to those of posteruption Spirit Lake. South Coldwater and West Castle lakes had the lowest *p*H values (6.61 and 6.17, respectively). These two lakes also had very high total alkalinities (1520 and 4500 μeq/liter, respectively) and major cation concentrations. The highest observed sulfate concentration was in South Coldwater Lake, and West Castle Lake had the highest concentrations of chloride, iron, and manganese.

The degree of chemical alteration for many lakes was determined by location relative to the blast cloud trajectories and the emplacement of deposits. June Lake, which lies 6 km from the crater but on the south slope outside the blast zone, had some chemical properties similar to those of blast zone lakes. Higher concentrations of major cations, silicate, and primary nutrients suggest possible contamination by erosional inputs from nearby mudflows (Fig. 1). Hanaford and Fawn lakes had higher chemical concentrations than other lakes in area B because of their exposed locations on the ridge above Coldwater Creek and apparent greater direct inputs from the lateral blast. Panhandle, Boot, Venus, and possibly St. Helens and Ryan lakes, appeared more shielded from the eruption by Mount Margaret and nearby mountains. Lakes in areas MB-M, primarily Spirit, West Castle, and Coldwater lakes, had high concentrations of most constituents because of their proximity to new mineral deposits.

Mineral alteration (chemical weathering and hydrothermal processes) occurred most rapidly in new deposits of warm pyroclastic flows, debris avalanches, and altered glass (*3*). The small mineral particle size (< 2 μm) and large surface area contributed to the high reactivity of such deposits (*5*). The relative order of abundance of dissolved constituents, $Cl > SO_4 > Na > Ca > Mg > K > SiO_4 > Mn > Fe$, in Spirit, West Castle, and Coldwater lakes suggests the possible solubility of elements in the new deposits. The apparent mobility of chloride, sulfate, sodium, and calcium implies their presence as soluble liquid and evaporative coatings on particles (*3, 6, 7*). The solubility of the major cations manganese and iron also is a function of different exchange sites and reactions on various mineral surfaces. The moderate mobility of silicate implies its occurrence in residue formed by the dissolution of surface layers of glass, feldspar, and ferromagnesian minerals (*2, 3*). High concentrations of manganese relative to iron probably reflect the slower oxidation and precipitation rates of manganese (*6, 8*).

The influence of the dissolution of mineral assemblages in deposit areas on lakes is shown by a comparison of the average molar ratio of sodium to silicate of 4.0 to 13.0 for blast zone lakes versus 0.9 for lakes in area U (Fig. 2A) and 1.9 for SA. Ratios of other major cations to silicate for the blast zone lakes were lower but showed the same patterns. Concurrently, the release of chloride and sulfate from coatings on particles and the presence of NaCl as the major soluble salt was indicated by an average K + Na/Cl ratio of about 1.0 as compared to a ratio of 3.0 for lakes of area U and for SA. The occurrence of less soluble salts, $CaSO_4$ and $MgSO_4$, was suggested by an average $Ca + Mg/SO_4$ ratio of 1.0 for the blast zone lakes versus a ratio of 8.0 for lakes of area U and for SA. The ratios for blast zone lakes were similar to those for water-soluble minerals in Mount St. Helens ash (*7*).

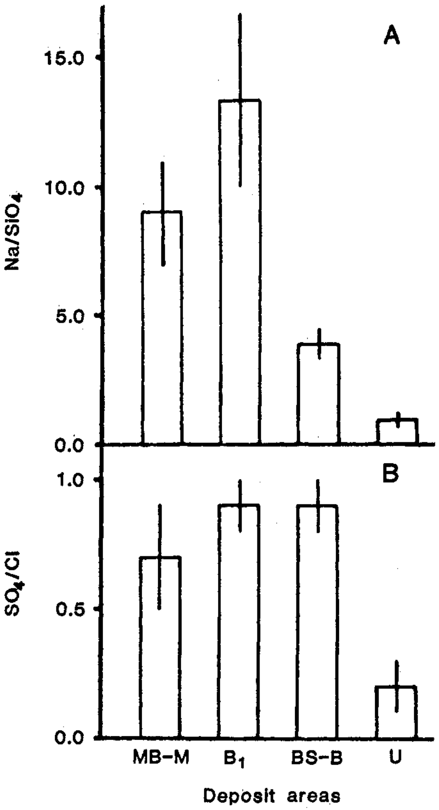

Fig. 2. Comparison of the average ratios of sodium to silicate (A) and sulfate to chloride (B) for lakes of the deposit areas in the Mount St. Helens blast zone with corresponding ratios for lakes outside the blast zone. Lines on the histograms represent standard errors. A dash between two areas below the histogram indicates an average of both areas. Deposit areas are as indicated in Fig. 1. Subareas include B_1 for exposed ridges (location of Hanaford and Fawn lakes) and BS and MB for overlapping areas.

Additional evidence of the influence of solutes from coated particles on the dissolved chemistry of the blast zone lakes was the high average ratios of sulfate to chloride of 0.9 in areas B_1, BS, and B and 0.7 in areas M-MB (Fig. 2B). Lower ratios of 0.3 for lakes of area U and for SA were similar to ratios of 0.4 for unaffected Cascade Mountain lakes ~ 200 km north of Mount St. Helens (*9*). However, the ratios of sulfate to chloride in the blast zone lakes were low in comparison to the ratios for soluble materials in ash from eruptions of several Central American volcanoes (*10, 11*) and Mount Baker (*12*), another recently active Cascade volcano. The low ratios for lakes may be attributable to lower emissions of sulfur- and chlorine-containing compounds from Mount St. Helens than from other volcanoes and limited acid sulfate alteration as minerals react with H_2SO_4 and HCl (*3, 7, 10, 11*).

The *p*H changes in most of these lakes were minor in comparison to other volcanically influenced lakes (*11–13*) because of apparent buffering by carbonic acid, neutralization due to abundant mineral particles acting as proton acceptors (*6, 8*), the limited acid sulfate alteration of minerals (*3*), and possibly the dissociation of dissolved humic substances (*14*). Much of the buffering capacity of the carbonic acid system was due to the continuous saturation of waters with CO_2 evolved from the biotic degradation of dissolved organic carbon (DOC). The occurrence of high concentrations of DOC and constituents such as iron, manganese, and sulfur in anoxic strata appeared to stimulate the development of dense bacterial populations that performed a variety of biological oxidation-reduction reactions (*15*). High DOC concentrations were caused by seepage from entrained forest particulates and distillates in deposits (*14*).

Continuing studies of chemical changes in these uniquely impacted lakes will provide new knowledge of the sequence of biogeochemical processes leading to the "recovery" of these ecosystems. However, we hypothesize that the initial phase of recovery to preeruption chemical conditions will require one to two decades primarily because of inputs to lakes rather than processes within lakes. Inputs dominate because they are controlled by rates of mineral alteration, degradation of entrained organics, and regrowth of vegetation in deposit areas.

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Biological Responses of Lakes in the Mount St. Helens Blast Zone

Abstract. *Loadings of dissolved organics and suspended particulates from destroyed forests and volcanic debris produced by the 18 May 1980 eruption of Mount St. Helens altered the trophic structure of many blast zone lakes to the extent that anoxic conditions and chemoorganotrophic and chemolithotrophic microorganisms prevailed. High bacterial counts and high adenosine triphosphate concentrations were directly related to enhanced concentrations of dissolved organic carbon, and plankton chlorophyll a was inversely related to light extinction. The recovery of these lakes to the preeruption state appears dependent upon the oxidation of organics and the stabilization of watersheds.*

The 18 May 1980 volcanic eruption of Mount St. Helens devastated lakes and watersheds near the mountain. A major difference between lakes impacted by this eruption and previously studied volcanically influenced waters was that, in addition to volcanic material, many lakes within the Mount St. Helens blast zone received high loadings of organic matter (*1*, *2*). The eruption produced superheated magmatic gases, pyroclastic material, and steam which pyrolyzed and extracted organic matter from surrounding soils and forests (*2*–*4*). Virtually all fish, their food chains, and their habitats were destroyed. The lake chemistries were so altered that the trophic structure of many lakes appeared to be dominated by chemoorganotrophic and chemolithotrophic microorganisms in anoxic waters. This eruption offered a unique opportunity to study for the first time the unique and rapid evolution of the highly impacted lake ecosystems. We describe here the first step in that process for lakes inside and outside the immediate blast zone (radius of 16 to 28 km northwest and northeast of the crater).

The lakes were in four deposit areas: U, morphologically unaffected regions outside the blast zone; S, scorched areas on the edge of the blast zone; B, timber-blowdown areas within the blast zone; and M, regions of blast zone mudflows, debris avalanches, and pyroclastic flows (*2*). Spirit Lake, an area M lake (8 km north of the crater), was sampled both before (4 April 1980) and after the eruption. Our preeruption data from Spirit Lake are in agreement with the limited historical data available for lakes near Mount St. Helens (*5*) as well as with data from similar, subalpine Cascade Mountain lakes (*6*). Lake locations and additional chemical features of biological significance are given elsewhere (*2*).

In most respects, the posteruption condition of Spirit Lake was typical of the highly affected lakes (area M lakes). Inputs of organics, pyroclastic materials, and soil extracts resulted in a 33-fold increase in suspended particulate matter (SPM) and a 36-fold increase in the light extinction coefficient [Table 1 (*7*)]. The lake temperature increased to 34°C on 20 May 1980 (*8*) but cooled to a more normal but still somewhat elevated value of 22°C by 30 June. Although particulate organic carbon (POC) and particulate organic nitrogen (PON) showed, respectively, only moderate one- and twofold increases, dissolved organic carbon (DOC) was enriched 48-fold. The dramatic increase in DOC was accompanied by a 17-fold increase in living matter as measured by adenosine triphosphate (ATP). This increase was not attributable to algal growth because chlorophyll a concentrations decreased substantially after the blast. Furthermore, the ATP increase corresponded not only with higher DOC but with lower dissolved oxygen concentrations.

The physical and chemical characteristics of the unaffected lakes (Merrill, McBride, June, and Blue) (Table 2) were comparable to those of Spirit Lake prior to the eruption (Table 1). Merrill and June lakes had POC, PON, chlorophyll a, and ATP concentrations comparable to oligotrophic Findley Lake (*9*), a totally unaffected mountain lake about 200 km north of Mount St. Helens. McBride and Blue lakes had somewhat higher concentrations of POC, PON, chlorophyll a, and ATP because of more abundant phytoplankton and invertebrate communities (*10*).

As in Spirit Lake, almost all lakes within the blast zone had higher SPM concentrations, light extinction coefficients, and DOC, POC, and PON concentrations than lakes outside the blast zone (Table 2). The highest DOC and ATP concentrations were observed in the highly impacted organically enriched Ryan and Spirit lakes and in the newly formed East Castle, West Castle, and South Coldwater lakes. These high ATP