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LEACHING CHARACTERISTICS OF ASH FROM THE MAY 18, 1980, ERUPTION OF MOUNT ST. HELENS VOLCANO, WASHINGTON

by

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ABSTRACT

Leaching of freshly erupted air-fall ash, unaffected by rain, from the May 18, 1980, eruption of Mount St. Helens volcano, Washington, shows that Ca^{2+}, Na^{+}, Mg^{2+}, SO_4^{2-}, and Cl^{-} are the predominant chemical species released on first exposure of the ash to water. Extremely high correlation of Ca with SO_4 and Na with Cl in water leachates suggests the presence of $CaSO_4$ and NaCl salts on the ash. The amount of water soluble material on ash increases with distance from source and with the weight fraction of small (less than 63 micrometers) ash particles of high-surface area. This suggests that surface reactions such as adsorption are responsible for concentrating the soluble material. $CaSO_4$, NaCl, and other salts are probably formed as microscopic crystals in the high-temperature core of the eruption column and are then adsorbed by silicate ash particles.

The environmently important elements Zn, Cu, Cd, F, Pb, and Ba are released by a water leach in concentrations which could pose short-term hazards to some forms of aquatic life. However, calculated concentrations are based on a water-to-ash ratio of 4:1 or less, which is probably an underestimation of the regionally operative ratio. A subsequent leach of ash by warm alkaline solution shows dramatic increases in the amount of dissolved SiO_2, U, and V, which are probably caused by increased dissolution of the glassy component of ash. Glass dissolution by alkaline ground water is a mechanism for providing these three elements to sedimentary traps where they may co-accumulate as uraniferous silica or U-V minerals.

Leaching characteristics of ash from Mount St. Helens are comparable to characteristics of ash of similar composition from volcanoes in Guatemala. Ashes from each locality show similar ions predominating for a given leachate and similar fractions of a particular element in the ash removed on contact with the leach solution.

INTRODUCTION

Freshly erupted air-fall ash is commonly washed by rains that occur during or shortly after volcanic eruptions (Finch, 1930; Wilcox, 1959). This initial washing may release readily soluble ash components into the local ground- and surface-water system and may cause short-term, but potentially significant, changes in the local water chemistry. Transient elevated concentrations of some dissolved species may pose health hazards and/or represent the first step in transporting economically important elements to environments where they can be precipitated into deposits of commercial interest. After initial washing, prolonged exposure of ash to weathering may cause slow release of elements that are structurally incorporated within constituent minerals or in solid solution in glass. The cumulative effect of weathering-related processes may be of equal or greater importance than the initial washing for liberating elements of economic interest.

The explosive eruption of Mount St. Helens volcano, Washington, on May 18, 1980, produced an estimated 3.67×10^8 metric tons of ash (Sarna-Wojcicki et al., 1980). The ash fell in measurable quantities over a large area of Washington, northern Idaho, and western Montana. Personnel of the U.S. Geological Survey collected numerous ash samples before the ash was washed by rain. These samples provide an excellent opportunity to study the nature and amount of water-soluble material on volcanic ash and to determine the relationship between water-soluble material and other characteristics of the ash such as particle size and distance from source.

The existence of readily soluble material on freshly erupted volcanic ash has been documented by many researchers (Tovarova, 1958; Murata et al., 1966; Taylor and Stoiber, 1973; Rose et al., 1973, 1978; Rose, 1977). These authors found that the dominant consitutents in distilled-water rinses of fresh ash are Cl, SO_4, Na, Ca, K, Mg, and F. Other elements reported in smaller concentrations in the leachates include Mn, Zn, Cu, Ba, Se, Br, B, Al, Si, and Fe.

The formation of water-soluble material on volcanic ash is probably the result of a complex interaction between the ash particles and volatile constituents of the volcanic plume. Taylor and Stoiber (1973) concluded that the water-soluble material was originally in a gas phase and was deposited on the surface of ash particles during eruption. Much of the soluble material was probably transported in hot gas clouds composed of H_2O, SO_2, CO_2, HCl, and HF which contained small amounts of volatile compounds such as the halides of Na, K, Zn, Cu, Cd, and Pb (Krauskopf, 1969). The volatile halides condensed on ash particles during eruption and fallout as temperature and pressure decreased.

Another possibility is that droplets of condensed dilute acid (primarily H_2SO_4 formed by reaction of SO_2 and H_2O in the volcanic plume) attach to ash particles and leach soluble elements from the constituent minerals and glass (Rose, 1977). The resulting coatings of acid and leached elements are then available for subsequent mobilization by rain.

Ôskarsson (1980) proposed three temperature-dependent processes within an eruption cloud which affect the type and amount of soluble material on ash particles. At high temperatures in the eruption vent and the core of the eruption cloud, microscopic salt particles crystallize (primarily chlorides, fluorides, and sulfates of the alkali metals and calcium). An upper limit for the temperature of salt crystallization is set by the melting point of the salt being formed. For example, the melting point of NaCl is 801°C and that of $CaSO_4$ is 1,450°C (Handbook of Chemistry and Physics, 1967). At temperatures below 340°C, H_2SO_4 is stable and may condense as an aerosol. At temperatures between those for salt crystallization and H_2SO_4 formation, Oskarsson proposed that adsorption of HCl and HF gas onto the surface of solidified silicate material may be common.

In this study, freshly erupted ash, unaffected by rain, from the May 18, 1980, eruption of Mount St. Helens volcano, is subjected to three successive experimental leaches to attempt to model the behavior of various elements during initial ash-water interaction and subsequent weathering. The specific objectives of the investigation are:

(1) Through an initial water rinse, to determine the fraction of a given element which is present in a readily soluble form on the surface of the ash, and to evaluate the environmental and economic implications of the release of this material into the local ground- and surface-water system.

(2) Through a series of successive leaches, to model the relative leachability of elements during subsequent weathering of ash.

(3) To compare and contrast the results of (1) and (2) and to compare the overall results with those of parallel studies of compositionally similar active volcanoes of Central America.

SAMPLE DESCRIPTION

Nineteen samples of Mount St. Helens ash, fresh and unaffected by rain, were chosen for study. The samples were collected during May 18-21, 1980, at distances of approximately 100 to 800 km downwind from Mount St. Helens at localities in Washington, northern Idaho, and western Montana (Table 1 and Fig. 1). Sampling sites and collection procedures were chosen to minimize contamination of ash by soil or dust. Ash collection sites included plastic boat covers, vehicle hoods, and roofs of tall buildings. Samples were stored in sealed plastic bags or polyethylene bottles for shipment to Denver.

Tables 2 and 3 show the major, minor, and trace element composition of some of the samples used in the leaching experiments. These samples are field composites and as such contain ash from both the early and late stages of the eruption. Thus, no attempt is made to interpret chemical compositions of the ash samples or leachates as a function of time.

Zielinski and Sawyer (1981) studied the size and shape of ash particles in splits of the samples used for the leaching experiments. They found that the mean grain size for coarse-grained fractions (>63 micrometers) ranged from 183 to 93 micrometers and showed the expected inverse correlation with downwind distance from source. The mass fraction represented by particles greater than 63 micrometers diameter ranged from 86 to 6 weight percent and also decreased with distance. Mean diameter of ash particles of the 2 to 63 micrometer size fraction ranged from about 4 to 7 micrometers with no obvious relation to distance from source.

The morphology and composition of individual ash particles were studied by scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDXRA). It was observed that the surface area of particles varies greatly depending upon the degree of vesiculation and that there are a large number of small particles (less than 10 micrometers in diameter) adhering to larger particles. All the small particles analyzed by EDXRA were similar in composition to their hosts and are interpreted as surface dustings of very fine ash fragments.

EXPERIMENTAL METHODS

Each sample of volcanic material was subjected to three successive leach conditions of increasing severity. For the first leach, based on the method of Taylor and Stoiber (1973), five grams of sample were placed in a Teflon container and 20 ml of distilled-deionized water (pH = 5.0-5.5) pipetted onto the sample. The pH was measured approximately one minute after contact of ash and leach solution. The container was then covered with a Teflon cap and the contents gently agitated by a rocker-arm shaker for one hour at room temperature and pressure. The pH was again determined and the sample allowed to sit overnight. After a final pH measurement, the sample was filtered through a Millipore filter with a nominal pore size of 0.1 micrometer and the filtrate split into two portions of approximately equal volume. One portion was acidified to a pH of 2 or less with sub-boiling distilled nitric acid and submitted for cation analysis. The other portion of filtrate was untreated and submitted for anion analysis.

The procedure for the second leach experiment is the same as for the first, but the leachate was a dilute solution of hydrochloric acid (pH = 3.5-4.0).

The third and most severe leach is with 20 ml of a solution that is 0.05 $\underline{M}$ in both sodium carbonate and sodium bicarbonate. These two reagents

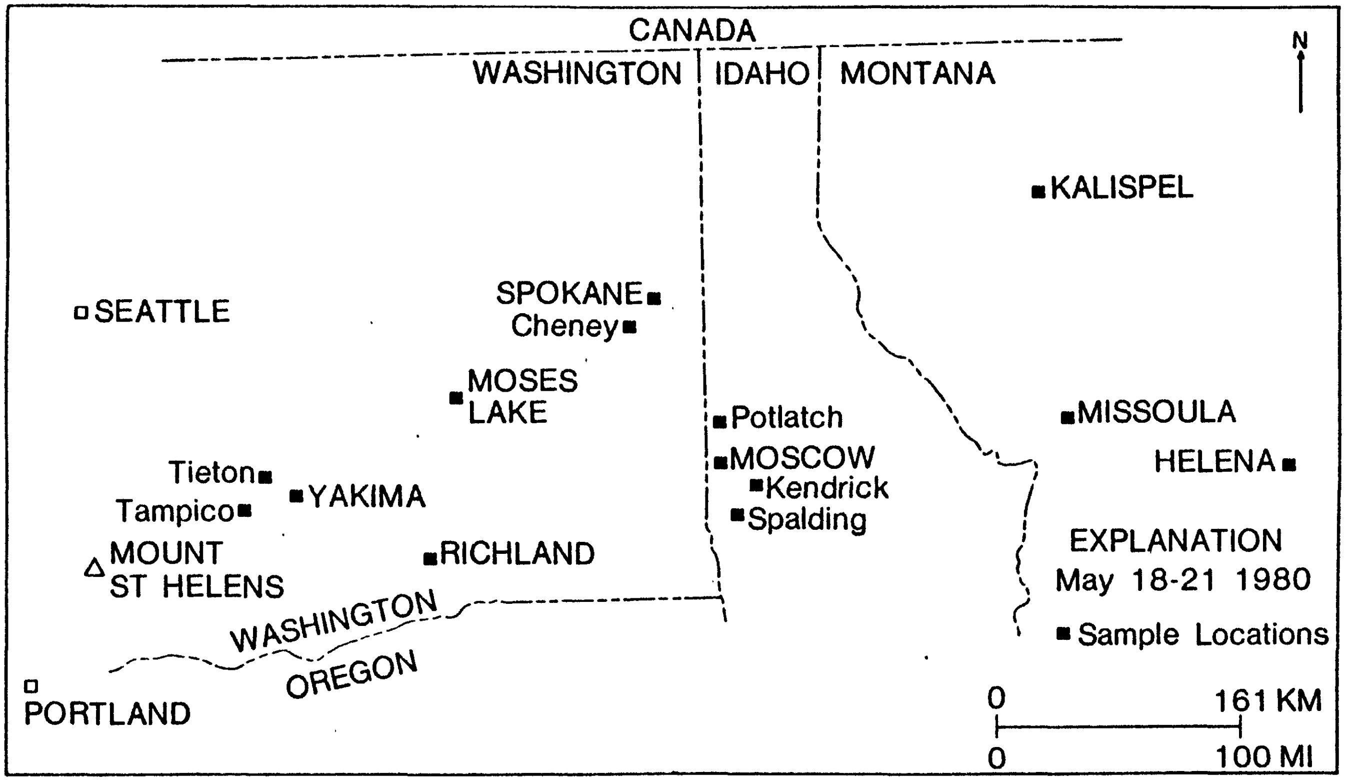

Fig. 1. Sample locations.

form a buffer solution at a pH of approximately 9.9. The leach solution and ash were sealed in a Teflon container and agitated inside an oven at 80°C for one week. The sample container was then weighed and, if weight loss by evaporation was less than 5%, the liquid was recovered and split as described above.

The acidified portion of each leachate was analyzed for Ba, Be, Ca, Cd, Co, Cu, Fe, Li, Mg, Mn, Mo, Na, Pb, SiO_2, Sr, V, and Zn by inductively coupled plasma emission spectrometry (Garbarino and Taylor, 1979), and for U by a fission-track technique (Smith et al., 1982). The unacidified portion of each water and acid leachate was analyzed for F, Cl, and SO_4 by ion chromatography (Fishman and Pyen, 1979). The carbonate-bicarbonate leachate was analyzed for F and Cl by specific-ion-electrode methods.

The liquid-to-solid ratio of 4:1 by weight was optimum for assuring that there was enough leachate to perform the necessary chemical analyses and at the same time assuring that most of the elements analyzed were present in detectable concentrations. A ratio of this magnitude was estimated to be realistic for Central America during the rainy season (Taylor and Stoiber, 1973). In a later section, this ratio is used as a model for calculations regarding likely concentration levels of contaminants of volcanic origin in ground and surface water near Mount St. Helens.

The first two leaching experiments are intended to mimic the interaction of ash with rain produced in the vicinity of an active eruption. The rain undoubtedly is slightly acidic because of its interaction with acidic gases (SO_2, HCl, etc.) emitted during the eruption. A similar acid precipitation is produced near smelters and coal-burning power plants which emit SO_2 and other gases into the atmosphere (Hutchinson and Whitby, 1977; Li and Landsberg, 1975). The third leach experiment is intended to simulate the effect of prolonged contact of volcanic ash with alkaline ground water present during ash diagenesis (Schoff and Moore, 1964; Harshman, 1972).

RESULTS AND DISCUSSION

Water Leach

The predominant species present in the water leachates of the ash are, in order of decreasing concentration, SO_4, Ca, Cl, Na, and Mg (Table 4). Anion and cation balances performed on the water leachates agreed, on average, within 12% with the cations consistently higher than the anions. Unanalyzed anions such as nitrate, reported as a significant component of water leachates by Taylor and Lichte (1980), are the likely cause of ion imbalance.

The pH of the water-leach solution (initially 5.0-5.5) increased an average of about 1 pH unit upon contact with ash (Table 5). This increase is probably caused by rapid exchange of dissolved hydrogen (as H_3O^+ ions) for alkali or alkaline earth ions at the surface of ash particles (Garrels and Howard, 1959; Luce et al., 1972; Petrovic et al., 1976). Two ash samples (7 and 10) caused a slight decrease in the pH of the water-leach solution. Both of these samples are from Tampico, Washington, which is the sample site nearest Mount St. Helens (124 km). Ash particles from the Tampico samples may have had relatively longer residence times in the condensation zone (Óskarsson, 1980) of the eruption column where sulfuric acid and halogen acid-water azeotropes condense as aerosols and may then be scavenged by ash particles (Rose, 1977).

Examination of the predominant species present in the water leachate suggests the dissolution of water-soluble salts of alkali and alkaline earth elements. A matrix of linear correlation coefficients calculated for the elemental concentrations in the water leachates (Table 6) showed the highest correlation (0.99) for the pairs Ca-SO_4 and Na-Cl suggesting the presence of these salts. Similarly high correlations between these pairs have been noted for Central American volcanic ash by Rose (1977). Scanning electron microscope study of these Central American ashes has provided direct evidence of $CaSO_4$ and NaCl on ash surfaces (Rose et al., 1973; Smith et al., 1982). The SEM-EDXRA measurements of Mount St. Helens ash described earlier failed to identify any crystals of these salts. However, the salts are probably present as very small particles scattered among much more abundant particles of fine silicate ash and are therefore difficult to find.

Other elements which have correlation of 0.90 or greater with SO_4 are Li, Mg, Na, and Sr. Those elements which have correlation of 0.90 or greater with Cl are Ca, Li, Mg, Mn, and Sr. The apparent association of a number of cations with a particular anion may indicate the formation of complex salts or numerous discrete sulfate and chloride mineral phases. SO_4 and Cl also correlate strongly with each other (r=0.91) indicating similarity in the occurrence of SO_4 and Cl species on the ash.

A plot of distance from source versus the concentration of water-leached cations, approximated by Ca+Na, gives a positive correlation (r=0.66) (Fig. 2). As expected, the relative abundance of fine ash, expressed as the mass fraction less than 63 micrometers in diameter, also increases with distance from source (Zielinski and Sawyer, 1981). The resulting positive correlation (r=0.57) of leached Ca+Na with the abundance of fine ash (Fig. 3) is compatable with the model of surface-related adsorption of water-soluble material.

The amount of material dissolved from the ash during the water leach can vary by an order of magnitude or more (Table 7) even though the ash is from a single volcanic event and fell to the ground over a short period of time. This large variation was previously reported for water leachates of ash from Central Americal volcanoes (Rose et al., 1973; Smith et al., 1982).

Other variables besides average grain size affect the amount of water-soluble material, as indicated by the intrasite variability of water-leached Ca+Na at a given distance from source. The sum of Ca+Na concentrations in water leachates of six ash samples collected near Spokane, Washington (404 km, Fig. 2) range from 48 to 310 mg/l. This range at a single site is a large fraction of the total range of leached Ca+Na from all sites (Fig. 2). Intra-site variability in the amount of water-soluble material is probably a complex function of sampling, glass/mineral fractionation during transport (Fruchter et al., 1980; Davis et al., 1981), and time-temperature history of individual ash particles within the continuously evolving regions of adsorption-condensation of the volcanic plume (Óskarsson, 1980).

Acid leach

The same species that predominate in the water leachates (SO_4, Ca, Cl, Na, Mg) also predominate in the acid leachates although their concentrations are roughly one-third that in the water leachates (Table 8). This similarity in suites of ions implies that the acid leach continues the process, begun by the water leach, of dissolving adsorbed salts. The acid leach may also attack acid-soluble sulfides and/or oxides, as evidenced by increased Fe concentration in a few samples.

The pH of the acid-leach solution (initially 3.4-3.5) increased an average of more than 2 pH units upon contact with ash (Table 5). As for the

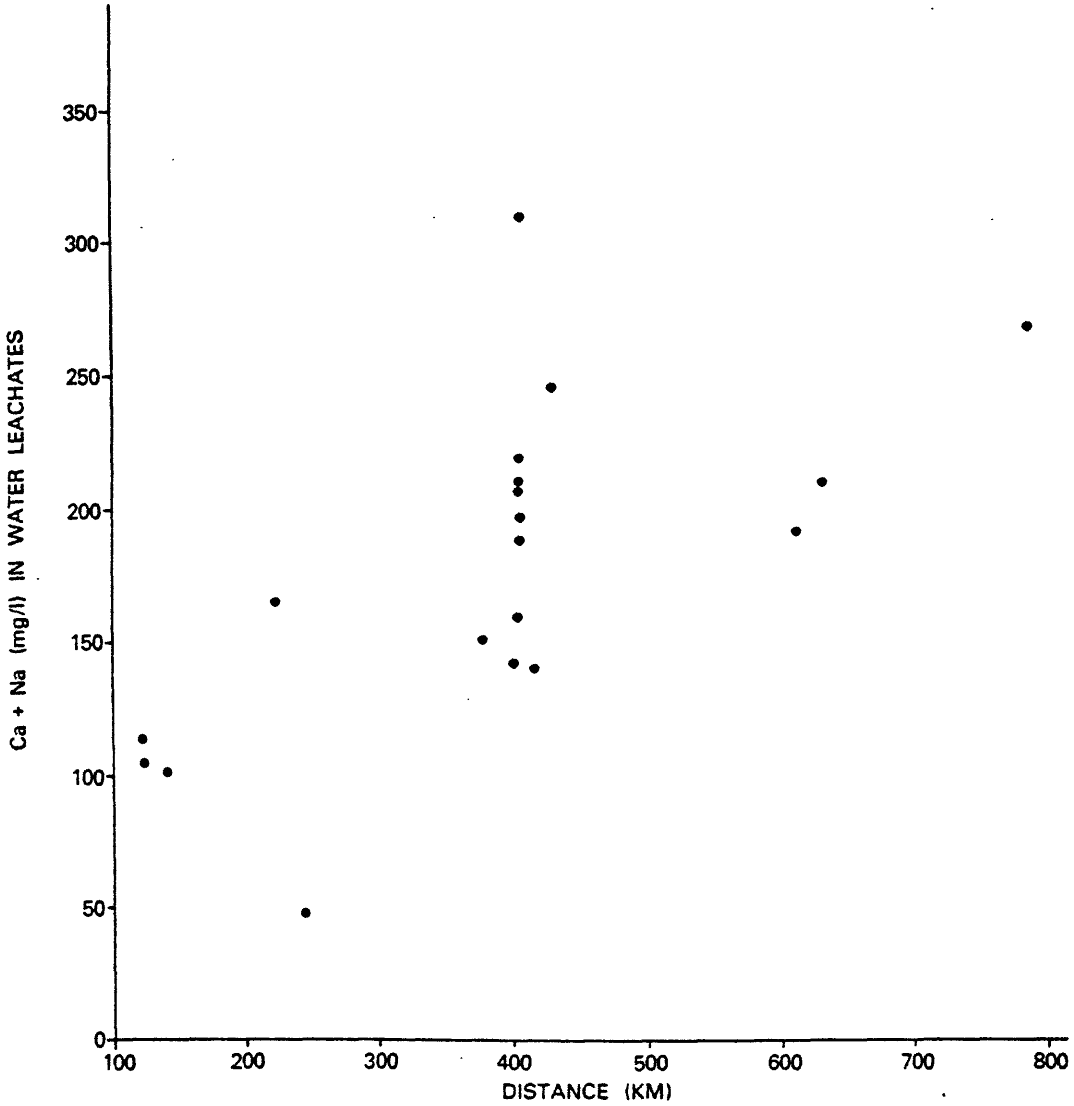

Fig. 2. Plot of concentration (mg/l) of Ca+Na in water leachates versus distance (km) of sample from Mount St. Helens.

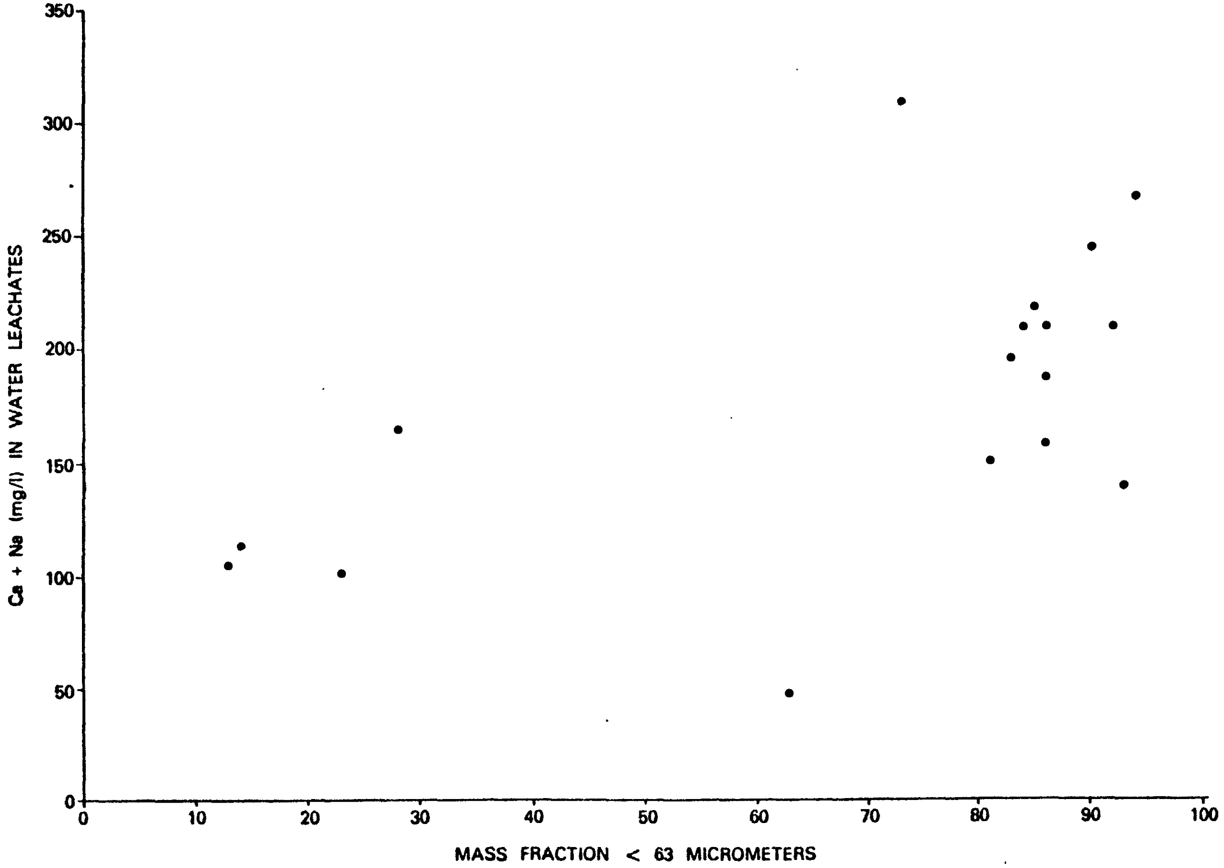

Fig. 3. Plot of concentration (mg/l) of Ca+Na in water leachates versus mass fraction of ash particles less than 63 micrometers in diameter.

water leach, the probable cause is exchange of dissolved hydrogen for alkali or alkaline earth ions on ash surfaces.

SO_4 still correlates strongly with Ca, Mg, and Sr (r=0.98, 0.97, and 0.98, respectively). This probably indicates that Mg and Sr substitute for Ca in the $CaSO_4$ structure or form discrete sulfate minerals which also adhere to ash surfaces.

Carbonate-bicarbonate leach

SiO_2, Cl, and F consistently occur in the highest concentrations in the carbonate-bicarbonate leachate (Table 9). The pH of the leach solution did not change appreciably during contact with ash because of its large pH buffering capacity. This leach is assumed to preferentially attack volcanic glass because of the reported high solubility of amorphous silica at the measured pH (9.9) of the solution (Alexander et al., 1954; Krauskopf, 1956), the relative paucity of SiO_2 polymorphs (Fruchter et al., 1980), and the elevated concentrations of dissolved silica, the major constituent of glass. The leach simulates incipient dissolution of glassy components of volcanic ash caused by prolonged exposure of the glass to alkaline ground water. However, the results of this leach give no indication of the true mobility of dissolved ash components during weathering because the effect of the growth of secondary minerals such as clays or zeolites, with large adsorptive potential, is not considered.

The percentage of a given element removed from ash during each leach operation was calculated according to the following formula:

$$\%\ \text{Element Removed} = \frac{\mu\text{g element in leachate}}{\mu\text{g element in unleached ash}} \times 100.$$

The results of the calculations are summarized and shown graphically in Fig. 4. The elements in section A of the graph all show a smaller percentage removed by the carbonate-bicarbonate leach than by the water or acid leach. Those in section B all show larger percentages removed by the carbonate-bicarbonate leach than by the water or acid leach.

Figure 4 shows that the percent of SiO_2 removed from the ash by the carbonate-bicarbonate leach is roughly an order of magnitude greater than the percent removed by the water or acid leach. The only other elements that show a similar order of magnitude increase are U and V. Apparently these elements are also preferentially released by dissolution of volcanic glass. Other elements showing an increase in leachability of less than an order of magnitude over the water and acid leach include Li, Cu, and Mo.

Environmental and Economic Implications

Some of the elements removed during the first washing of a freshly erupted volcanic ash may have short-term detrimental effects on the water quality of small streams in the vicinity of the volcano. For example, such effects were caused by the 1970 eruption of Hekla in Iceland, where ingestion of contaminated water and vegetation caused lethal fluoride poisoning in sheep and other livestock (Thorarinsson, 1970). Of all the elements analyzed and found above blank in water leachates, only six (Cd, Pb, Cu, Zn, Ba, and F) are sufficiently harmful to have safe levels empirically established for various life forms. A comparison of these safe levels with average concentrations of the same elements in water leachates of Mount St. Helens ash shows that the safe levels are exceeded in some instances (Table 10).

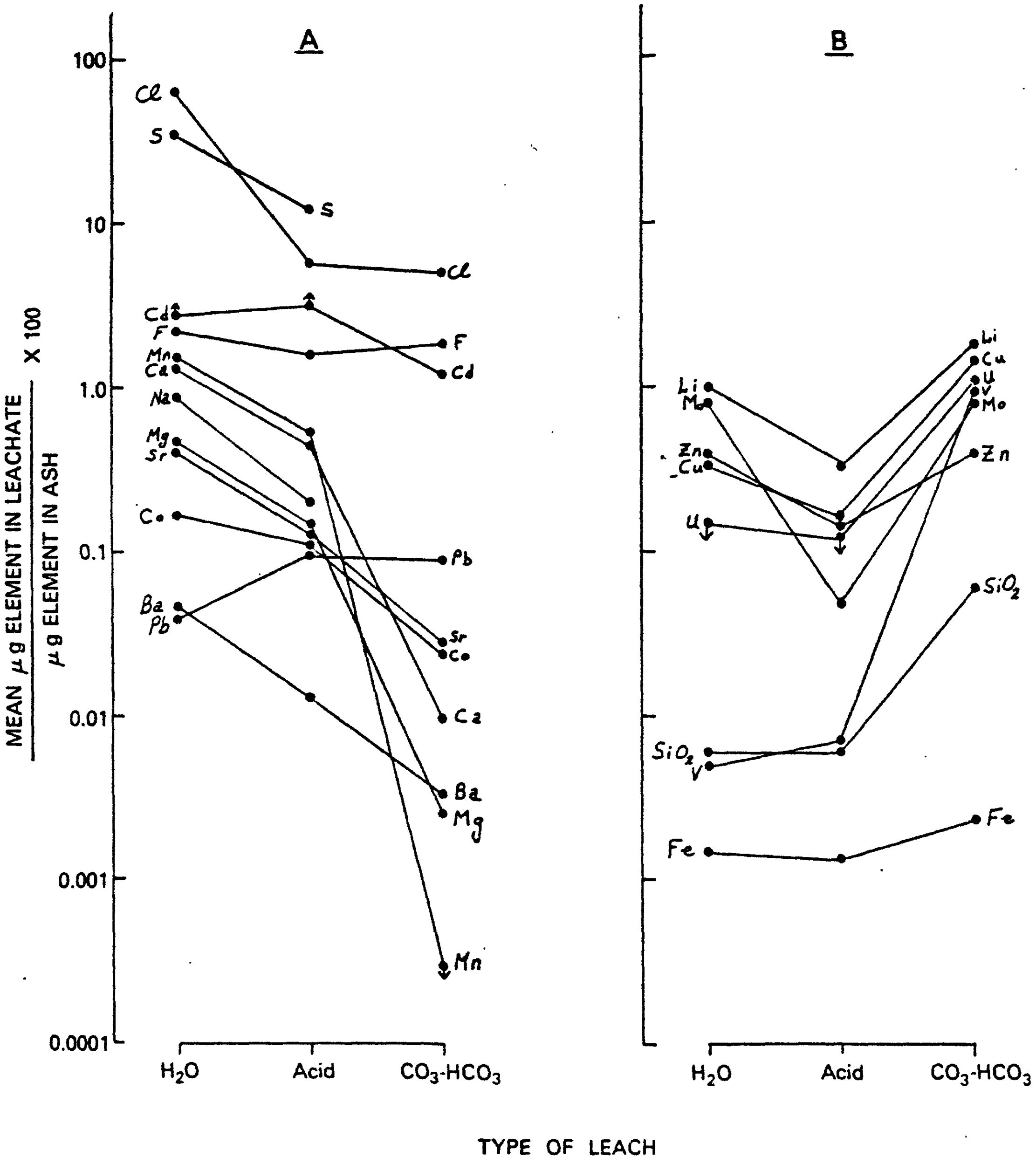

Fig. 4. Leachability of the measured elements as a function of leach type.

Any inference that streams near ash deposits might carry harmful concentrations of a certain element must be made with the understanding that the water-leachate data in Table 9 are based upon the experimental water/ash weight ratio of 4:1. Taking a hypothetical drainage basin with an area of 75 km^2 and assuming an uncompacted ash thickness of 3.5 cm and bulk density of 0.5 g/cm^3 [Sarna-Wojcicki et al. (1980) show this is realistic for the Moses Lake area, Washington], it is calculated that 7 cm (2.8 in) of rain per cm^2 would have to fall in the basin to give the experimental 4:1 water-to-ash weight ratio. The average annual precipitation for Washington in the area of significant ash fall ranges from 300 cm or more in the region adjacent to Mount St. Helens to 25 cm or less for south-central portions of the state (U.S. Geological Survey, 1966). Therefore, the 7 cm of rain needed for the hypothetical basin could reasonably be expected to fall within a short time of deposition of the ash. The operative water/ash weight ratio is obviously increased by dilution of surface runoff with surface and ground water originating in ash-poor areas. As a result, degradation of water quality is probably quite transient and generally restricted to small, first-order streams within drainage areas dominated by surficial ash fall.

The total amount of water-soluble material released during initial washing of Mount St. Helens air-fall ash is calculated (Table 11) assuming behavior similar to the experimental water leach and a mass of 3.67 x 10^8 metric tons of downwind material erupted (Sarna-Wojcicki et al., 1980). Table 10 shows that there are some economically important amounts of metals released from the ash on its first exposure to water. The fate of these dissolved metals after their liberation from the ash can vary considerably depending upon the degree of dispersion of dissolved species by local hydrologic flow regimes, the solubility of possible precipitates, and the distribution and abundance of adsorbents, reductants, etc. which act as traps for dissolved material.

Implications for evaluation of uranium source rocks

Silicic volcanic ash has been postulated as the primary source of uranium for sandstone-type sedimentary uranium deposits (Waters and Granger, 1953; Denson et al., 1959; Kittel, 1963; Love, 1970; Harshman, 1972; Adams et al., 1978). Henry and Tyner (1978) and Boberg (1981) speculate that a significant amount of uranium might be released upon the first exposure of a freshly deposited ash to rain and surface water. However, the study of Mount St. Helens ash, corroborating recent work on dacitic and basaltic ash from Guatemala and Iceland (Smith et al., 1982), indicates that very little uranium (less than 0.2% of the total uranium in the ash) is released on first exposure of ash to water. The 0.2% is an upper limit for leachable uranium based on a detection limit in solution of 0.5 µg/l which was never exceeded. The dacitic ash of Mount St. Helens contains approximately 1 ppm U (Table 3) compared to ashes of rhyolitic composition which average about 5 ppm U (Rogers and Adams, 1967). However, Smith et al. (1982) estimate that dacitic and rhyolitic ashes release similar percentages of contained uranium during an initial water rinse.

In contrast, significant amounts of uranium are leached from the volcanic glass component of ash during prolonged contact with alkaline solutions (Fig. 2). In nature, glass dissolution and associated release of uranium may begin within a rather short time of deposition of ash. Davies et al. (1979) report diagenesis of young (2,000 y) Guatemalan volcaniclastics as evidenced by formation of hematite, goethite, montmorillonite, and heulandite with concomitant reduction of permeability. Their diagenetic model proposes that unstable components (glass, pyroxene) are rapidly and selectively attacked under conditions of high fluxes of ground water. Thus, in evaluating uranium source rocks, a volcanic ash showing evidence of extensive dissolution and/or alteration of glass should be considered a better source of U than volcanics with abundant unaltered glass.

SiO_2 and V are also preferentially released by dissolution of volcanic glass as evidenced by an increase in leachability in the carbonate-bicarbonate leach similar to that for U. The release of SiO_2, U, and V from volcanic glass may partially explain the source of associated SiO_2 and U in uraniferous opal and chalcedony in tuffaceous sedimentary rocks (Davis and Hetland, 1956; Staatz and Bauer, 1951; Love, 1970; Lindsey, 1978; Zielinski, 1980) and associated U and V as uranyl vanadate minerals in the sedimentary U-V ores of the Colorado Plateau (Finch, 1967; Motica, 1968). It is interesting to note that Cu, Mo, and Li also show increased leachability in the carbonate-bicarbonate leach. These elements are also associated with sedimentary uranium deposits (Harshman, 1972; Lindsey et al., 1973).

Comparison with other ash-leaching experiments

An identical leaching study was previously undertaken using fresh ash from the Guatemalan volcanoes Fuego, Pacaya, and Santiaguito (Smith et al., 1982). The ashes are olivine-bearing high-Al basalts (Fuego and Pacaya) and hornblende-hypersthene dacite (Santiaguito). Figure 5 shows the average percent of various species removed by the water leaches of Mount St. Helens and Guatemalan ashes. In general, the values for Mount St. Helens fall within, or very close to, the range exhibited by the Guatemalan ashes. Except for Sr, the minor and trace elements show a much wider range in leachable fractions than do the major elements. Figure 6 is a similar comparison for the carbonate-bicarbonate leachates. The ash from Mount St. Helens is again observed to have leaching characteristics similar to ashes from the Guatemalan volcanoes.

CONCLUSIONS

An experimental leaching study of freshly erupted volcanic ash, unaffected by rain, from the May 18, 1980, eruption of Mount St. Helens volcano has led to the following conclusions:

(1) Ca^{2+}, Na^+, Mg^{2+}, SO_4^{2-}, and Cl^- are the predominant chemical species present in an initial water leachate and a successive dilute acid leachate of the ash. Correlation of Ca^{2+} with SO_4^{2-} and Na^+ with Cl^- suggests the presence of $CaSO_4$ and NaCl salts on the ash. These salts probably form as condensates in the high-temperature core of the eruption cloud and are then adsorbed by fine-grained silicate ash particles of high surface area. The large variation of amounts of soluble material on ash samples of similar grain size and distance from source may be indicative of varying residence times of ash particles in different thermal and chemical zones of the eruption cloud.

(2) If the water/ash weight ratio during the first washing of Mount St. Helens ash is 4:1 or lower, there is a possibility of sufficient concentrations of Cu and Zn in small streams to cause transient adverse effects to aquatic life. These marginally harmful concentrations are probably quickly reduced to safe levels by dilution with less contaminated ground water or surface water from outside the area of ash accumulation.

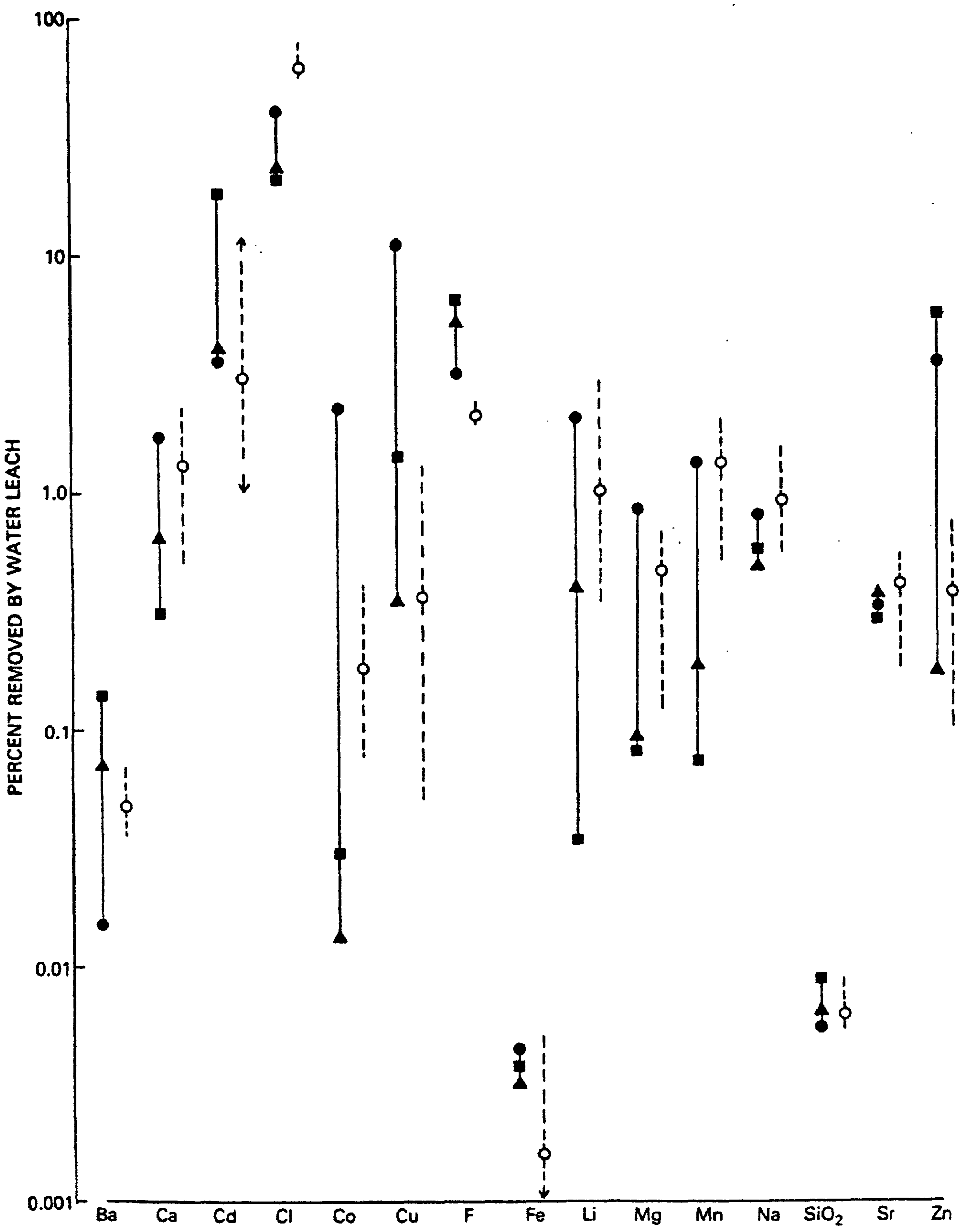

Fig. 5. Comparison of water-leach characteristics of Mount St. Helens ash (○) with Fuego (▲), Pacaya (■), and Santiaguito (●) volcanoes, Guatemala. Dashed lines on Mount St. Helens data points indicate approximate range of values for a particular chemical species. Data on Guatemalan volcanoes from Smith et al. (1982).

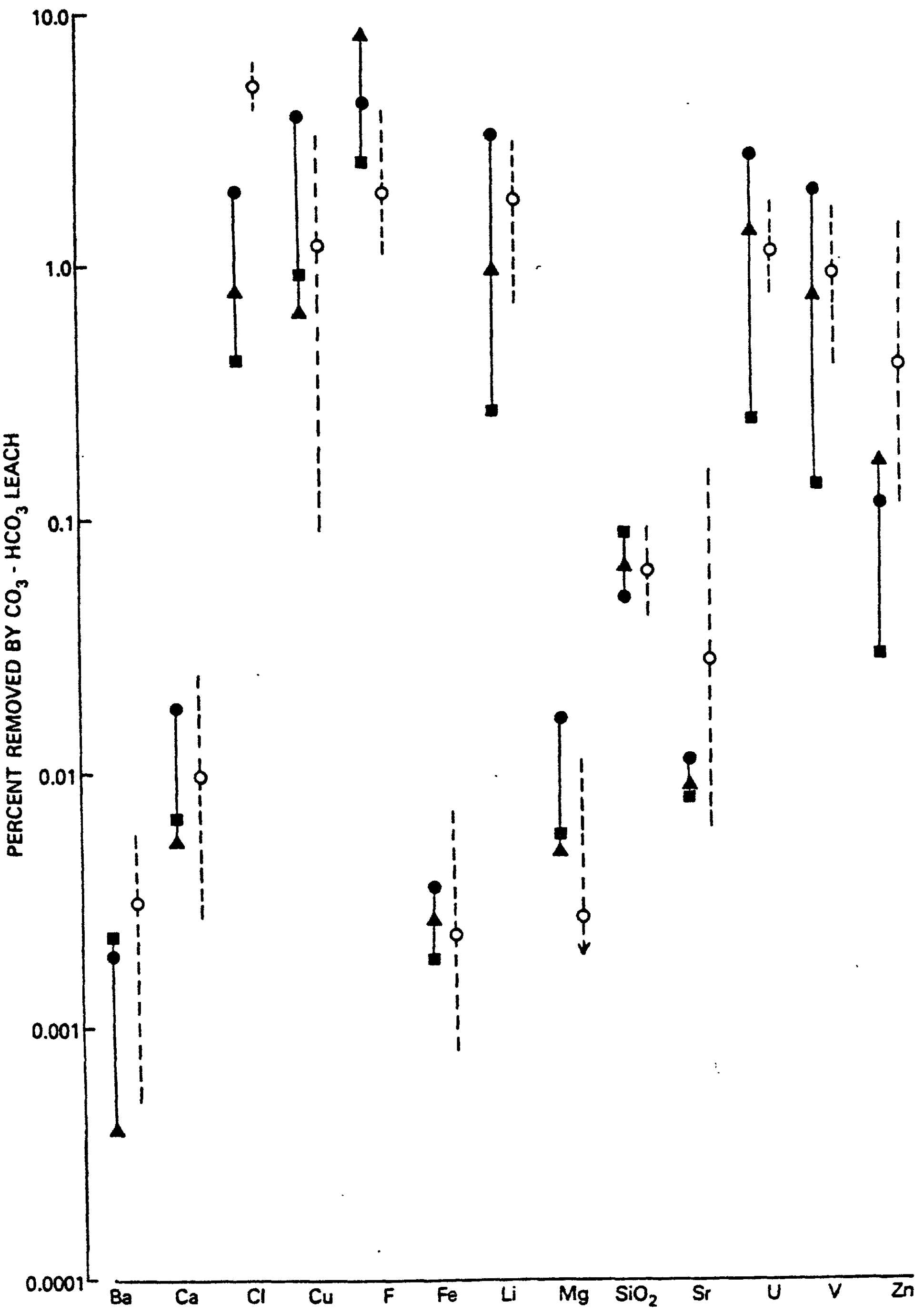

Fig. 6. Comparison of carbonate-bicarbonate leach characteristics of Mount St. Helens ash (○) with Fuego (▲), Pacaya (■), and Santiaguito (●) volcanoes, Guatemala. Dashed lines on Mount St. Helens data points indicate approximate range of values for a particular chemical species. Data on Guatemalan volcanoes from Smith et al. (1982).

(3) Leaching of ash by warm alkaline solutions chosen to preferentially attack volcnic glass indicates that of the analyzed elements, SiO_2, U, and V show the greatest increase in dissolved concentrations. This process may contribute to the association of V and SiO_2 with sedimentary U concentrations in or near tuffaceous rocks.

(4) Comparison of the results of this study with the results of identical leaching studies of Guatemalan ashes show similarity in the relative abundances and fractional amounts of ions removed by a given leachate.

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Table 1.--Sample Locations

Sample Number	Location	Approximate straight line distant from Mount St. Helens (km)
1	Spokane, WA	404
2	Spokane, WA	404
3	Spokane, WA	404
4	Spokane, WA	404
5	Moses Lake, WA	245
6	Helena, MT	783
7	Tampico, WA	124
8	Spokane, WA	404
9	Richland, WA	222
10	Tampico, WA	124
11	Kalispell, MT	610
12	Spalding, ID	400
13	Cheney, WA	378
14	Moscow, ID	402
15	Missoula, MT	630
16	Potlatch, ID	413
17	Kendrick, ID	428
18	Tieton, WA	141
19	Spokane, WA	404

Table 2.--Major element composition (wt. %) of selected ash samples[1]

	1	2	3	4	6	7	14	16	18
Major Element Oxides (wt. %)									
SiO_2	66.0	62.6	65.5	65.3	63.2	59.0	66.8	67.4	59.9
Al_2O_3	16.0	17.0	16.1	16.2	16.4	18.6	16.0	16.0	18.0
Fe_6O_3	3.87	4.98	3.95	4.12	4.05	6.39	3.68	3.65	6.25
MgO	1.4	2.1	1.5	1.6	1.59	3.56	1.30	1.24	3.22
CaO	4.14	5.33	4.23	4.38	4.48	6.72	3.93	3.84	6.22
Na_2O	4.1	3.9	4.1	4.1	4.46	4.31	4.62	4.68	4.29
K_2O	1.62	1.38	1.59	1.57	1.60	0.88	1.60	1.72	1.01
TiO_2	0.55	0.69	0.56	0.58	0.58	0.80	0.59	0.53	0.79
P_2O_5	0.2	0.2	0.2	0.2	0.16	0.17	0.14	0.14	0.16

[1] Samples analyzed by X-ray fluorescence spectrometry, relative accuracy ± 0.5% (Taggart et al., 1980).

Table 3.--Minor and trace-element composition (ppm) of selected ash samples[1]

	1	2	3	4	6	7	14	16	18
Ba	410	350	420	370	344	222	344	390	218
Be	2.1	2.0	2.1	1.9	0.7	0.6	0.6	0.8	0.5
Cd	<10	<10	<10	<10	0.2	n.d.	<0.2	n.d.	0.3
Cl	850	850	830	830	n.d.	n.d.	n.d.	n.d.	n.d.
Co	9.4	14	9.4	9.7	9	17	8	9	15
Cr	10	21	12	13	15	13	3	4	11
Cu	44	55	44	42	42	32	37	40	33
F	300	300	300	300	n.d.	n.d.	n.d.	n.d.	n.d.
Li	23	18	22	21	28	21	29	33	23
Mn	540	660	560	510	501	799	453	498	733
Mo	<10	<10	<10	<10	2	<1	2	2	<1
Ni	11	19	12	13	14	15	8	6	13
Pb	17	18	18	18	19	<10	11	10	13
S	700	3,100	900	1,200	n.d.	n.d.	n.d.	n.d.	n.d.
Sc	<10	12	<10	<10	9	13	7	8	11
Sr	400	480	400	350	391	567	345	379	488
U	1.6	1.1	1.5	1.4	1.3	0.8	0.8	n.d.	0.6
V	63	98	63	61	61	101	52	57	100
Zn	54	70	76	81	56	92	53	59	71
Zr	140	160	150	160	116	74	131	150	83

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[1] Samples 1, 2, 3, and 4: Li - atomic absorption spectrometry, F - specific-ion-electrode method; Cl - titrimetric method; S - direct combustion; U - delayed neutron technique (Millard, 1976); all other elements by direct-reading quantitative emission spectrometry.

Samples 6, 7, 14, 16, and 18: analyses from Taylor and Lichte (1980) except for U (analyzed as above) on samples 6 and 7.

n.d. = not determined.

Table 4.--Concentration (mg/l) of chemical species in water leachates

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Ba	0.040	0.046	0.039	0.035	0.0025	0.031	0.040	0.055	0.037	0.037	0.048	0.022	0.037	0.037	0.034	0.048	0.047	0.022	0.060
Ca	110	200	120	130	27	180	62	140	110	67	120	95	90	98	140	79	170	56	130
Cd	0.0062	-	-	0.0053	-	-	-	0.0013	0.0063	-	0.0018	0.0023	-	-	0.0020	-	-	-	-
Cl	114	167	122	120	23	120	59	127	89	63	108	59	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co	0.0035	0.0033	0.0069	0.0057	-	0.0048	0.0048	0.0064	0.018	-	0.0041	-	0.0050	0.0081	0.0061	0.0071	-	-	0.010
Cu	0.010	-	0.016	0.021	0.011	0.025	0.044	0.040	0.11	0.039	0.056	0.054	0.018	0.12	0.048	0.022	0.085	0.017	0.037
F	1.7	1.5	1.6	1.4	3.0	2.0	1.5	1.9	1.4	1.5	2.4	2.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe	0.0039	0.0043	-	0.0016	0.0027	0.010	0.56	0.25	0.12	0.49	0.051	0.0046	0.0058	0.065	0.049	0.0076	0.11	0.0094	0.045
Li	0.056	0.13	0.064	0.065	0.0035	0.080	0.041	0.065	0.052	0.036	0.043	0.027	0.044	0.030	0.057	0.028	0.072	0.030	0.061
Mg	14	21	14	15	3.4	16	6.4	15	14	6.9	13	9.0	11	10	13	9.3	15	6.2	15
Mn	2.3	3.3	2.5	2.4	0.20	2.1	1.5	2.9	2.1	1.5	1.5	0.89	1.8	1.3	1.8	1.5	2.8	0.91	2.6
Mo	-	-	-	-	-	0.011	-	-	-	-	-	-	-	0.013	0.010	0.012	0.014	-	0.011
Na	78	110	77	80	21	88	43	79	55	47	73	48	61	61	70	61	76	46	80
Pb	-	-	-	-	-	-	-	-	-	-	-	-	-	0.011	0.014	-	-	-	0.018
SiO_2	10	10	10	8.9	9.4	14	8.8	11	9.2	8.2	9.9	8.6	11	8.9	11	8.7	12	8.0	13
SO_4	245	453	290	306	74	416	139	315	258	149	241	223	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sr	0.46	0.65	0.47	0.47	0.10	0.60	0.34	0.50	0.44	0.26	0.38	0.35	0.38	0.43	0.72	0.38	0.64	0.24	0.53
U	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
V	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0066	-	-	-	-	-
Zn	0.057	0.074	0.072	0.17	0.025	0.029	0.17	0.34	0.99	0.048	0.23	0.24	0.055	0.030	0.26	0.017	6.7	0.037	0.11

- = below reagent blank level.

n.d. = not determined.

Table 5.--pH values of water and acid leachates of Mount St. Helens ash

	pH after approximately 24 hours	
Sample	Water leachate	Acid leachate
1	6.3	5.8
2	6.4	6.2
3	6.2	5.7
4	6.4	5.8
5	7.0	6.3
6	6.4	6.0
7	4.7	4.6
8	5.0	n.d.
9	5.4	n.d.
10	4.7	n.d.
11	6.8	n.d.
12	6.8	n.d.
13	6.5	6.1
14	6.5	6.1
15	6.4	6.2
16	6.4	5.8
17	6.3	6.1
18	6.6	5.9
19	6.0	5.6

Table 6.--Correlation matrix for concentration (mg/l) of chemical species in water leachates[1]

	Ba	Ca	Cd	Cl	Co	Cu	F	Fe	Li	Mg	Mn	Na	SiO_2	SO_4	Sr	Zn
Ba	-	0.51	-0.23	0.72	-0.040	0.20	-0.61	0.19	0.51	0.61	0.75	0.65	0.36	0.50	0.56	0.19
Ca	-	-	-0.36	0.93	-0.20	0.22	-0.36	-0.27	0.92	0.95	0.83	0.92	0.62	0.99	0.90	0.31
Cd	-	-	-	0.045	0.41	0.044	-0.81	-0.34	0.24	0.34	0.26	-0.0012	-0.46	-0.041	-0.16	0.29
Cl	-	-	-	-	-0.22	-0.086	-0.49	-0.33	0.92	0.97	0.93	0.99	0.46	0.91	0.93	-0.027
Co	-	-	-	-	-	0.64	-0.37	0.035	-0.25	-0.061	-0.052	-0.38	-0.10	-0.18	-0.11	0.79
Cu	-	-	-	-	-	-	-0.23	0.14	0.029	0.27	0.073	-0.0071	-0.060	0.012	0.27	0.40
F	-	-	-	-	-	-	-	-0.39	-0.56	-0.46	-0.70	-0.020	0.14	-0.39	-0.54	-0.25
Fe	-	-	-	-	-	-	-	-	-0.11	-0.32	-0.0053	-0.30	-0.24	-0.43	-0.20	0.032
Li	-	-	-	-	-	-	-	-	-	0.91	0.89	0.91	-0.49	0.92	0.80	0.19
Mg	-	-	-	-	-	-	-	-	-	-	0.90	0.95	0.57	0.95	0.85	0.20
Mn	-	-	-	-	-	-	-	-	-	-	-	0.88	0.51	0.82	0.78	0.30
Na	-	-	-	-	-	-	-	-	-	-	-	-	0.55	0.91	0.83	0.11
SiO_2	-	-	-	-	-	-	-	-	-	-	-	-	-	0.62	0.63	0.28
SO_4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.96	0.0097
Sr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.34
Zn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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[1] Underlined numbers show statistically significant correlation at 0.01 level.

Table 7.--Average chemical composition (mg/l) of leachates of Mount St. Helens ash

	H_2O leach		Acid leach		CO_3 leach	
Element	Mean	Range	Mean	Range	Mean	Range
Ba	0.038	0.0025-.060	0.010	0-.026	0.0017	0-.012
Ca	110	27-200	38	13-110	0.92	0.28-3.0
Cd	0.0013	0-.0063	0.0010	0-.0054	0.0020	0-.017
Cl	98	23-167	15	0-40	9.6	3.9-14
Co	0.0049	0-.018	0.0030	0-.012	0.0010	0-.0098
Cu	0.041	0-.12	0.019	0-.046	0.16	0.038-.40
F	1.8	1.4-3.0	1.3	1.1-1.7	1.2	0.62-3.5
Fe	0.094	0-.12	0.14	0-1.3	0.18	0.078-.48
Li	0.052	0.0035-.13	0.018	0.010-.028	0.12	0.035-.25
Mg	12	3.4-21	3.4	1.4-8.0	0.057	0-.60
Mn	1.9	0.20-3.3	0.74	0.23-1.7	0	
Mo	0.0037	0-.014	0.0006	0-.011	0.0062	0-.055
Na	66	21-110	16	8.0-24	n.d.	
Pb	0.0023	0-.018	0.0034	0-.044	0.0021	0-.015
SiO_2	10	8.0-14	11	8.1-14	93	55-130
SO_4	260	74-450	90	17-270	n.d.	
Sr	0.44	0.10-.72	0.13	0.050-.34	0.029	0.0070-.17
U	0		0		0.0037	0.0022-.0060
V	0.0003	0-.0066	0.0011	0-.011	0.18	0.095-.30
Zn	0.51	.017-6.7	0.14	0.0014-1.6	0.070	0.016-.25

0 = Element not found above reagent blank level in at least one sample.
n.d. = Not determined.

Table 8.--Concentration (mg/l) of chemical species in acid leachate

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Ba	0.0073	0.014	0.0090	0.012	-	0.0065	n.d.	0.020	0.0082	0.026	0.015	0.0070	0.0080	0.0054	n.d.	0.0093	0.0074	0.0050	0.015
Ca	25	110	27	46	13	60	n.d.	59	31	25	69	48	19	19	n.d.	15	34	14	30
Cd	0.0050	-	0.0025	0.0054	0.0012	-	n.d.	-	0.0017	-	-	0.0014	-	-	n.d.	-	-	-	-
Cl	9	17	11	12	-	10	-	12	5	30	40	31	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co	-	-	0.012	0.0038	-	-	n.d.	0.0061	0.0065	0.0050	-	-	-	-	n.d.	0.0047	0.0090	-	0.0041
Cu	0.014	-	0.023	0.019	-	0.014	n.d.	0.019	0.046	0.041	0.019	0.016	0.012	0.026	n.d.	0.019	0.039	-	0.016
F	1.5	1.3	1.1	1.3	1.1	1.3	1.2	1.7	1.1	1.3	1.5	1.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe	-	-	-	0.052	-	-	n.d.	0.38	0.23	1.3	-	-	0.38	-	n.d.	-	-	-	0.018
Li	0.012	0.028	0.023	0.018	0.010	0.017	n.d.	0.017	0.010	0.013	0.018	0.016	0.023	0.019	n.d.	0.018	0.025	0.018	0.025
Mg	2.7	8.0	3.2	4.4	1.4	4.3	n.d.	5.2	3.2	2.7	4.9	3.2	2.3	2.1	n.d.	2.0	3.1	1.4	3.6
Mn	0.66	1.7	0.68	0.96	0.23	0.77	n.d.	1.4	0.72	0.80	0.65	0.57	0.58	0.40	n.d.	0.45	0.69	0.38	0.94
Mo	-	-	0.011	-	-	-	n.d.	-	-	-	-	-	-	-	n.d.	-	-	-	-
Na	17	24	16	20	8.0	18	n.d.	21	9.6	10	18	13	15	15	n.d.	14	16	9.2	20
Pb	-	-	0.044	-	-	-	n.d.	-	-	-	-	-	-	-	n.d.	-	.014	-	-
SiO_2	11	13	10	10	9.4	12	n.d.	14	11	10	12	9.4	10	9.2	n.d.	8.6	12	8.1	14
SO_4	49	266	60	118	18	128	17	132	54	24	122	98	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sr	0.099	0.34	0.10	0.16	0.050	0.19	n.d.	0.21	0.12	0.10	0.19	0.16	0.080	0.085	n.d.	0.075	0.13	0.057	0.12
U	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
V	-	-	0.011	-	-	-	n.d.	-	-	-	-	-	-	-	n.d.	-	0.0071	-	-
Zn	0.031	0.026	0.018	0.049	0.023	0.010	n.d.	0.046	0.20	0.083	0.063	0.24	0.039	0.0014	n.d.	0.0085	1.6	0.0019	0.014

(-) = below reagent blank level.
(n.d.) = not determined.

Table 9.--Concentration (mg/l) of chemical species in carbonate-bicarbonate leachate

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Ba	0.0035	0.0048	0.0020	0.0020	-	0.0050	-	0.0005	-	-	0.012	0.0002	0.0002	-	0.0008	0.0005	-	-	-
Ca	0.50	0.98	0.70	0.58	0.45	1.1	0.45	0.62	.98	3.0	1.4	0.90	0.52	1.0	1.2	0.28	2.1	.30	0.40
Cd	-	-	-	0.0048	-	-	-	-	-	-	-	-	-	-	0.017	0.017	-	-	-
Cl	9.8	13	12	9.2	4.9	12	4.4	9.9	9.8	6.6	15	8.0	9.9	12	13	9.2	14	6.0	13
Co	-	0.0085	-	-	-	-	-	-	-	-	-	0.0098	-	-	-	-	-	-	-
Cu	0.10	0.25	0.13	0.098	0.072	0.19	0.062	0.095	.20	0.092	0.40	0.40	0.082	.30	0.21	0.060	.23	.038	0.095
F	0.87	3.0	0.92	0.97	0.87	3.5	0.62	0.95	.95	0.65	0.96	0.93	0.92	.93	0.97	0.88	2.5	.73	0.95
Fe	0.14	0.24	0.48	0.10	0.24	0.16	0.085	0.078	.12	0.10	0.12	0.15	0.12	.22	0.20	0.11	.32	.092	0.35
Li	0.13	0.035	0.12	0.11	0.15	0.12	0.050	0.078	0.060	0.038	0.12	0.13	0.15	0.22	0.13	0.25	0.14	0.068	0.15
Mg	-	0.15	0.062	-	-	-	0.12	-	-	0.60	-	0.050	-	-	-	0.095	.0078	-	-
Mn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mo	-	0.055	-	-	-	0.028	-	-	.035	-	-	-	-	-	-	-	-	-	-
Na	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	0.0090	0.014	0.015	-	-	-	0.0012	0.0008	-	-	-	-	-	-	-	-	-	-	-
SiO_2	110	62	100	88	110	75	78	82	55	85	100	88	130	110	78	130	75	82	120
SO_4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sr	0.014	0.016	0.014	0.013	0.012	0.019	0.0088	0.013	.010	0.025	0.020	0.014	0.014	.13	0.017	0.014	.17	.0070	.012
U	0.0030	0.0033	0.0034	0.0046	0.0030	0.0042	0.0035	0.0030	.0038	0.0022	0.0039	0.0033	0.0042	.0027	0.0041	0.0034	.0054	.0027	.0060
V	0.16	0.30	0.16	0.19	0.12	0.25	0.12	0.18	.21	0.11	0.23	0.16	0.17	.13	0.20	0.11	.24	.095	.20
Zn	0.016	0.098	0.12	0.035	0.065	0.035	0.030	0.035	.020	0.088	0.032	0.048	0.032	.22	0.12	0.019	.25	.032	.035

\- = below reagent blank level.
n.d. = not determined.

Table 10. Comparison of elemental concentrations in water leachates (this study) with reported safe levels for natural waters.

Element	Reported safe levels (mg/l)[1]			Average concentration (mg/l) in water leachates[2]
	Drinking water	Livestock	Aquatic life	
Cd	0.01	0.05	0.003	0.0013
Pb	0.05	0.1	0.03	0.0023
Cu	1.0		0.011	0.041
Zn	5.0		0.18	0.51
Ba	1.0			0.038
F	0.8	5.0		1.8

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[1] From Water Quality Criteria, 1972, and Gough et al., 1979.

[2] From Table 4, this study.

Table 11.--Estimated metric tons of material released by first water-rinse of ash deposited by the May 18, 1980, eruption of Mount St. Helens. The calculations were made assuming a mass of downwind material of 3.67×10^8 metric tons (Sarna-Wojcicki et al., 1980).

Substance released	Estimated metric tons
Ba	56
Ca	160,000
Cd	1.9
Cl	140,000
Co	7.2
Cu	60
F	2,600
Fe	140
Li	76
Mg	18,000
Mn	2,800
Mo	5.4
Na	97,000
Pb	3.4
SiO_2	15,000
SO_4	380,000
Sr	650
V	0.44
U	<0.73*
Zn	750

*Maximum possible value based upon the analytical detection limit.