# Reports

## Mount St. Helens Ash from the 18 May 1980 Eruption: Chemical, Physical, Mineralogical, and Biological Properties

Abstract. *Samples of ash from the 18 May 1980 eruption of Mount St. Helens were collected from several locations in eastern Washington and Montana. The ash was subjected to a variety of analyses to determine its chemical, physical, mineralogical, and biological characteristics. Chemically, the ash samples were of dacitic composition. Particle size data showed bimodal distributions and differed considerably with location. However, all samples contained comparable amounts of particles less than 3.5 micrometers in diameter (respirable fraction). Mineralogically, the samples ranged from almost totally glassy to almost totally crystalline. Crystalline samples were dominated by plagioclase feldspar (andesine) and orthopyroxene (hypersthene), with smaller amounts of titanomagnetite and hornblende. All but one of the samples contained from less than 1 percent to 3 percent free crystalline silica (quartz, trydimite, or cristobalite) in both the bulk samples and 1 to 2 percent in the fractions smaller than 3.5 micrometers. The long-lived natural radionuclide content of the ash was comparable to that of crustal material; however, relatively large concentrations of short-lived radon daughters were present and polonium-210 content was inversely correlated with particle size. In vitro biological tests showed the ash to be nontoxic to alveolar macrophages, which are an important part of the lungs' natural clearance mechanism. On the basis of a substantial body of data that has shown a correlation between macrophage cytotoxicity and fibrogenicity of minerals, the ash is not predicted to be highly fibrogenic.*

On 18 May 1980, at 8:32 a.m., Pacific Daylight Time, a major pyroclastic eruption occurred from the Mount St. Helens volcano in Washington State. With an estimated volume of more than 4 km$^3$ (1 cubic mile), it was the largest eruption in North America since the eruption of Mount Katmai, Alaska, in 1912, and one of the five or six largest worldwide during the past century. This and subsequent eruptions resulted in deposition of volcanic ash on large areas of Washington and neighboring states and in the exposure of more than 1 million people to inhalation of the ash. To characterize the ash and assess the significance of any potential health hazards, we collected samples of the ash for analysis from various parts of eastern Washington and Montana beginning on the day of the eruption and continuing through the following week. Samples were obtained from Tieton Ranger Station, Ahtanum, Yakima, Richland, Ellensburg, Ritzville, Moses Lake, Spokane, Rosalia, and Pullman in Washington and from Missoula, Montana. These locations are shown in Fig. 1. Although two distinct layers of ash were noted in many locations, all samples reported here were thoroughly mixed before aliquots were taken. These materials were subjected to a variety of analyses including chemical, radiochemical, mineralogical, and physical characterization and an in vitro biological assay to determine the effects of the ash on pulmonary macrophages. The latter test gives an indication of toxicity of the ash to the macrophages, which are central to the body's natural clearance mechanism for removing small particles from the lung and are strongly implicated as part of the fibrogenic reaction associated with some mineral dusts. Results of these preliminary analyses are described in this report.

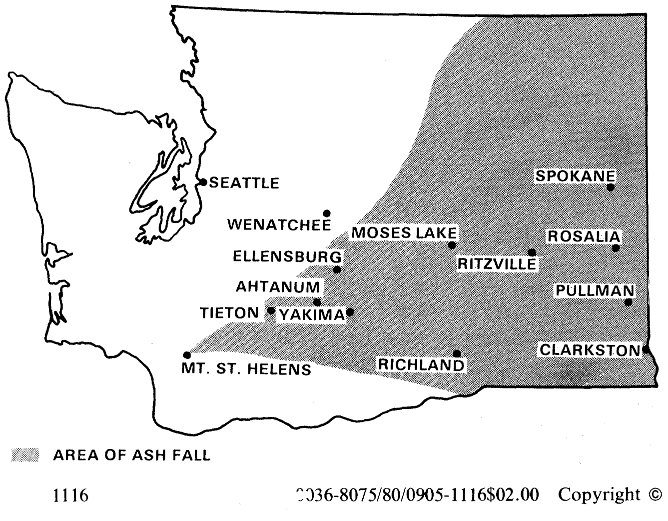

Fig. 1. Map of Washington State showing locations of collection of Mount St. Helens ash samples. Missoula is in Montana, approximately 645 km east of Mount St. Helens.

*Bulk chemical composition*. Nine samples of Mount St. Helens ash were subjected to extensive chemical analysis by a variety of techniques. Several different fusion procedures were used to dissolve the samples completely, including lithium metaborate, sodium carbonate, sodium peroxide, and potassium hydroxide fusion. Solutions were then analyzed by either d-c argon plasma emission or inductively coupled plasma methods. Samples were also analyzed by energy-dispersive x-ray fluorescence (XRF), using titanium, zirconium, and silver secondary target emissions. Where the results of all three methods could be compared, agreement was excellent. Data for the major elements are reported in Table 1. The ash that fell in the eastern Washington area varies somewhat in composition depending on its distance from the volcano. The average of nine samples matches a dacitic composition quite closely (*1*). Some general compositional trends are evident with increasing distance from the volcano. Silica tends to increase with distance, whereas iron, calcium, magnesium, titanium, and manganese decrease (see Table 1). Magnesium in particular varies by more than a factor of 3. Potassium and sodium are relatively constant and aluminum decreases only slightly.

Table 2 shows the trace element data for the same samples determined by carbonate fusion and energy-dispersive XRF. Mercury was measured by flameless atomic absorption. For comparison, typical trace element abundances in an andesitic rock (USGS-AGV-1) (*2*) are shown in the last column of Table 2. The volatile elements boron, sulfur, and chlorine are heavily enriched in the ash. Sulfur is enriched by at least two orders of magnitude. Similar enrichments were not observed in the bulk ash for arsenic, selenium, bromine, mercury, and lead. Another noteworthy feature of the trace element data is the Sr/Ba ratio, which decreases by about a factor of 3 with increasing distance from the volcano. This is probably related to the variable glass content of the ash sampled at different locations.

Table 3 gives data on airborne particulates collected from the volcanic plume 27 hours after the eruption. Although the explosive phase had ended, the volcano was still in full eruption at the time the sample was collected. This provided an excellent opportunity to search for expected enrichments in volatiles. The airborne particulates collected at that time had, on the average, about three to four times more sulfur than most of the ash collected at ground level. Chlorine and lead appear to be somewhat higher than in the ground-level samples. Arsenic is clearly enriched by at least an order of magnitude. Apart from these elements, the composition of this sample is similar to that of the ash samples collected at ground level.

*Leaching studies.* Leaching studies of the ash were conducted to determine what species would dissolve when the ash came in contact with water. Two sets of experiments were performed. In one, thick pastes of ash samples were made with equal weights of water to determine the *p*H and leachate species that would occur if the ash were barely wetted by a gentle rain (see Table 4). This mixture was stirred for about 10 minutes and allowed to stand for about 1 hour prior to analysis. In the second, water and ash were mixed 10:1 as indicated above to estimate the composition of the leachates if the ash fell into drinking water or stream water. These experiments showed no acidity; in fact, most of the ash samples increased the *p*H. Some chloride, nitrate, and sulfate were found in the leachates. Two different size fractions of one sample were tested and there was about three times as much

Table 1. Major element composition of Mount St. Helens ash. Values are percentages. Samples were analyzed by plasma emission spectroscopy; the uncertainty is 2 to 3 percent.

| Element (as oxide) | Tieton (98 km)* | Ahtanum (125 km) | Yakima (137 km) | Richland (224 km) | Moses Lake (240 km) | Spokane (378 km) | Rosalia (385 km) | Pullman (388 km) | Missoula (644 km) | Average | Dacite† |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ (not free silica) | 64.6 | 59.4 | 63.3 | 60.3 | 66.9 | 68.2 | 66.9 | 68.2 | 67.2 | 65.0 ± 3.3 | 63.6 |
| $Al_2O_3$ | 18.0 | 17.4 | 17.4 | 16.4 | 17.1 | 17.2 | 16.1 | 16.2 | 16.3 | 16.9 ± 0.7 | 16.7 |
| $Fe_2O_3$ | 5.24 | 6.64 | 5.59 | 5.61 | 4.99 | 4.22 | 3.69 | 3.56 | 3.76 | 4.81 ± 1.1 | 5.3 |
| CaO | 5.14 | 6.57 | 5.74 | 5.55 | 4.74 | 4.77 | 3.71 | 4.00 | 4.20 | 4.94 ± 0.92 | 5.5 |
| $Na_2O$ | 4.57 | 4.35 | 4.49 | 4.83 | 4.56 | 4.42 | 4.85 | 4.52 | 4.52 | 4.57 ± 0.17 | 4.0 |
| MgO | 2.70 | 4.10 | 2.80 | 2.77 | 1.84 | 1.61 | 1.28 | 1.33 | 1.48 | 2.21 ± 0.94 | 2.1 |
| $K_2O$ | 1.31 | 0.88 | 1.25 | 1.56 | 1.55 | 1.60 | 1.75 | 1.69 | 1.66 | 1.47 ± 0.28 | 1.4 |
| $TiO_2$ | 0.70 | 0.88 | 0.83 | 0.85 | 0.68 | 0.63 | 0.53 | 0.55 | 0.58 | 0.69 ± 0.13 | 0.60 |
| $P_2O_5$‡ | 0.23 | (0.37) | 0.33 | 0.46 | 0.32 | (0.37) | 0.39 | 0.48 | (0.37) | 0.37 ± 0.09 | 0.2 |
| MnO | 0.093 | 0.12 | 0.092 | 0.087 | 0.077 | 0.067 | 0.063 | 0.063 | 0.064 | 0.077 ± 0.020 | 0.076 |
| Weight loss on ignition‡ | 0.51 | (0.56) | 0.62 | (0.56) | 0.35 | (0.56) | 0.55 | (0.56) | 0.78 | 0.56 ± 0.16 | |
| Total | 103.1 | 101.3 | 100.4 | 99.0 | 103.1 | 103.7 | 100.1 | 101.1 | 100.8 | 101.6 | 99.5 |

*Distance from Mount St. Helens. †Data are from Nockolds (*1*). ‡Numbers in parentheses are taken from average of other samples.

Table 2. Trace element composition of Mount St. Helens ash. Values are parts per million. Estimated uncertainties are 2 to 5 percent for V, Cu, Sr, and Ba; 5 to 10 percent for Cr, Co, Ni, Zn, Ga, Rb, Y, Zr, Nb, and Hg; 10 to 30 percent for B, S, Cl, As, Mo, and Pb. Values for Se, Br, and Cd are upper limits.

| Element | Tieton (98 km)* | Ahtanum (125 km) | Yakima (137 km) | Richland (224 km) | Moses Lake (240 km) | Spokane (378 km) | Rosalia (385 km) | Pullman (388 km) | Missoula (644 km) | Average | USGS-AGV-1† |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | 16 | 27 | 31 | 34 | | | 22 | 36 | 41 | 30 ± 9 | 5 |
| S | 800 | 470 | 1300 | 1100 | 900 | 1400 | 340 | 430 | 910 | 840 ± 380 | <10 |
| Cl | 580 | 450 | 640 | 500 | 1000 | 900 | 720 | 620 | 570 | 663 ± 182 | 110 |
| V | 155 | 169 | 164 | 127 | | | 115 | 113 | 138 | 140 ± 23 | 125 |
| Cr | 15 | 16 | 27 | 31 | | | 11 | 8.6 | 12 | 17 ± 8 | 12.2 |
| Co | 19 | 28 | 22 | 19 | | | 15 | 14 | 15 | 19 ± 5 | 14.1 |
| Ni | 13 | 20 | 22 | 27 | | | 7 | 6 | 10 | 15 ± 8 | 18.5 |
| Cu | 33 | 25 | 35 | 41 | 34 | 41 | 35 | 33 | 38 | 36 ± 5 | 59.7 |
| Zn | 54 | 68 | 58 | 56 | 45 | 45 | 48 | 49 | 50 | 53 ± 7 | 84 |
| Ga | 18 | 20 | 18 | 8 | 18 | 19 | 16 | 18 | 17 | 18 ± 1.2 | 20.5 |
| As | 2 | < 2 | < 2 | 2.6 | 4 | 1.8 | 2.1 | 1.9 | 3 | ≈ 2.8 | 0.8 |
| Se | < 1 | < 1 | < 1 | 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | <0.14 |
| Br | < 1.5 | < 1 | < 1 | < 1 | 0.9 | 1.4 | 1 | 1.1 | 1.3 | ≈ 1 | 0.5 |
| Rb | 27 | 17 | 28 | 27 | 35 | 36 | 38 | 40 | 39 | 32 ± 8 | 67 |
| Sr | 500 | 670 | 510 | 510 | 390 | 400 | 350 | 360 | 410 | 460 ± 110 | 657 |
| Y | 10 | 10 | 11 | 12 | 12 | | 11 | 11 | 12 | 11 ± 8 | 21.3 |
| Zr | 120 | 82 | 130 | 160 | 150 | 400 | 150 | 160 | 160 | 170 ± 90 | 225 |
| Nb | 4.2 | 4.1 | 6.3 | 5.7 | 5.8 | | 4.8 | 6.1 | 5.7 | 5.3 ± 0.8 | 15 |
| Mo | 1.9 | 1.7 | 2.7 | 4.4 | 2.5 | | 3.0 | 2.1 | 4.4 | 2.8 ± 1.1 | 2.3 |
| Cd | <3 | <3 | <3 | <4 | | | <3 | <3 | <3 | <3 | 0.09 |
| Ba | 290 | 220 | 320 | | 360 | 380 | 380 | 380 | 390 | 340 ± 60 | 1208 |
| Hg | 0.0088 | | 0.0088 | 0.0070 | 0.013 | 0.011 | 0.0065 | | 0.013 | 0.0097 ± 0.0027 | 0.015 |
| Pb | 6.5 | 5.8 | 8.6 | 6 | 5.7 | 10 | 10 | 13 | 12 | 8.7 ± 2.9 | 35.1 |

*Distance from Mount St. Helens. †Data are from Flanagan (*2*).

Table 3. Composition of a particulate sample collected in the plume on 19 May 1980. The average ash composition is shown for comparison.

| Constituent | Particulate sample* | Average ash |
|---|---|---|
| | *Major elements (percent)* | |
| $SiO_2$* | ≡ 65.0 | 65.0 ± 3.3 |
| $Fe_2O_3$ | 6.7 ± 0.4 | 4.81 ± 1.1 |
| CaO | 3.0 ± 0.2 | 4.94 ± 0.92 |
| $K_2O$ | 2.0 ± 0.1 | 1.47 ± 0.28 |
| $TiO_2$ | 0.42 ± 0.03 | 0.69 ± 0.13 |
| MnO | 0.054 ± 0.004 | 0.077 ± 0.020 |
| | *Trace elements (ppm)* | |
| S | 3220 ± 800 | 940 ± 380 |
| Cl | 1190 ± 400 | 660 ± 180 |
| Ni | < 20 | 15 ± 8 |
| Cu | 61 ± 10 | 36 ± 5 |
| Zn | 34 ± 7 | 53 ± 7 |
| Ga | < 8 | 18 ± 1 |
| As | 22 ± 4 | ≈ 2.8 |
| Se | < 7 | < 1 |
| Br | < 8 | ≈ 1 |
| Rb | < 17 | 32 ± 8 |
| Sr | 285 ± 7 | 460 ± 110 |
| Zr | 142 ± 7 | 170 ± 90 |
| Pb | 36 ± 11 | 8.7 ± 2.9 |

*Collected on a traverse from 0 to 50 km from the volcano. All composition data for particulates are normalized to the average silica composition of nine ash samples in Table 1. Analysis was by energy-dispersive XRF.

leaching from the fine (< 75 μm) as compared to the coarse (> 75 μm) fraction.

Table 5 shows a partial chemical analysis of the leachates from nine samples. The $F^-$, $Cl^-$, $NO_3^-$, $SO_4^{2-}$, $NH_4^+$, and $Li^+$ were determined by ion chromatography. Mercury was determined by flameless atomic absorption and the remainder of the elements by d-c plasma emission spectroscopy. The cations and anions balance within 10 percent. A comparison of the data in Table 5 with the bulk chemical analysis data shows that for most samples about 20 to 30 percent of the sulfur and 30 to 50 percent of the chlorine is in readily leachable form. All samples have very small amounts of leachable boron and a variety of other trace elements, none of which appears to be a major source of concern. The sample from Missoula showed elevated levels of leachable zinc, corresponding to about 10 percent of the zinc in the sample. This was confirmed by a second experiment; however, the zinc may be of anthropogenic origin, since there are several smelters upwind from the site. In general, it appeared that samples high in $SO_4^{2-}$ and $NO_3^-$ also contained elevated levels of trace element cations such as iron, manganese, copper, magnesium, and sodium. If the samples did initially contain traces of sulfuric and nitric acids, upon wetting these acids must have reacted rapidly with the bulk of the ash, resulting in some minor leaching and an essentially neutral $p$H. Some such mechanism is necessary to resolve the apparent discrepancy between the neutral $p$H found in leaching experiments and the reports by many observers that the ash was mildly corrosive when it came in contact with metal surfaces.

None of the results of the chemical experiments carried out on the bulk ash to date seem to indicate any unusual hazard to biological systems. However, further measurements are needed to determine chemical properties of the respirable fraction.

*Plume sampling.* The airborne ash plume was sampled near Mount St. Helens on Monday, 19 May, with a Douglas DC-3 research aircraft equipped with meteorological, gas, and particle sampling equipment. Because of the possibility of damage to the aircraft engine due to the abrasiveness of the ash-laden plume, only the fringe of the plume could be sampled. Measurements were made for the gaseous species $H_2S$, $SO_2$, and $O_3$. Particulates were collected with a high-volume filter sampling system and a cascade impactor. An integrating nephelometer used to monitor suspended particle concentrations provided a means of detecting when the aircraft was in the plume. Mercury and radon were also sampled, using gold bead and evacuated Lucas tubes, respectively. No detectable amounts of mercury (< 10 ng/m$^3$) and radon (< 0.5 pCi/liter) were found. During several brief incursions into the plume fringe within 8 km downwind of the mountain, an $H_2S$ concentration of 0.4 ppm was observed and the odor of $H_2S$ was evident. We were not able to measure the $SO_2$ content of the plume, but were able to establish that within 50 km of the volcano, concentrations were less than 20 ppb in the plume fringe. Also, near our laboratory site 8 km north of Richland, which is about 200 km from the volcano, $H_2S$ and $SO_2$ concentrations were less than 100 and 39 ppb on the day after the eruption; in this area ashfall was about 1 to 2 mm. Ozone was also depleted in the plume—less than 20 ppb, compared to background values of 30 ppb east of Mount Adams and 65 ppb north of Richland.

*Radioactivity in the ash.* Three types of radioactivity measurements were made on the ash. The long-lived radioisotopes $^{232}$Th, $^{226}$Ra, and $^{40}$K were measured in samples from four locations (Table 6). These concentrations are comparable to or somewhat lower than the average radioactivities in crustal material.

In Table 7 we summarize the $^{210}$Po concentrations at four locations. It is interesting that the $^{210}$Po content increased with distance from the mountain during the eruption and that it increased with decreasing particle size, as shown by the data for the Moses Lake sample. The $^{210}$Po was apparently volatilized during the eruption and condensed on the ash particles in the eruption plume; this would be expected to result in higher concentrations on the smaller particles. The newly fallen ash contained rather high concentrations of the short-lived radon daughters $^{214}$Pb (27 minutes) and $^{214}$Bi (20 minutes) and the $^{214}$Bi daughter $^{214}$Po (164 μsec). In an ash sample collected at 12:15 p.m., 3 hours 43 minutes after the eruption, the concentrations of these radionuclides were 212, 274, and 274 pCi/g, respectively. These concentrations are comparable to those in uranium tailings material and are extremely high compared with the $^{226}$Ra content of the ash, which suggests that decay of $^{222}$Rn gas in the eruption plume was the source of these short-lived radionuclides.

Table 4. Water-soluble constituents in a 1:1 mixture (by weight) of distilled water and Mount St. Helens ash leachate.

| Sample location | $p$H* | Concentration (ppm) | | |
|---|---|---|---|---|
| | | $Cl^-$ | $NO_3^-$ | $SO_4^{2-}$ |
| Ahtanum | 6.85 | | | |
| Tieton | 6.78 | | | |
| Yakima | 6.57 | | | |
| Richland | | | | |
| < 75 μm† | 5.65 | 268 | 25 | 753 |
| > 75 μm† | 6.96 | 94 | 5 | 273 |
| Rosalia | 5.67 | | | |
| Pullman | 6.30 | | | |

*Initial $p$H of distilled $H_2O$ was 5.95. †Size fraction of particles.

We calculated the amount of radon in the plume, assuming that it was in equilibrium with these short-lived daughters, that the daughters attached themselves to the volcanic ash as they formed, and that all the ash that fell contained the amounts of the daughters indicated above. The amount of ash material ejected in the 18 May eruption has been estimated to be on the order of 4 km$^3$, which would be 8 × 10$^{15}$ g, based on a density of 2 g/cm$^3$. Assuming for simplicity that the deposited ash fell from the radon-containing plume 27 minutes before it was collected, we estimate that the ash in the plume had a $^{214}$Pb content of 424 pCi/g, corresponding to approximately 3 million curies of radon gas in the plume. The amount of radon actually ejected in the eruption was probably less than this, but if this were approximately the amount of $^{222}$Rn released, it would require that several hundred cubic kilometers of magma was purged of its gas during the violent eruption.

Another source for the daughters which has been suggested is scavenging of natural airborne radon daughters by the falling ash. Calculations based on an average radon flux from soil in eastern Washington of 1 pCi/m$^2$-sec indicate that if all the radon daughters in an equilibrated atmosphere above the soil were scavenged, this could approach the observed radioactivity in the ash. This explanation, however, would require scavenging coefficients of nearly 100 percent, far in excess of any that have been observed for precipitation. Irrespective of the radon source, the dose from the ash to persons resident in the fallout area would be small. The observed radon daughter concentration is in the range of those present in uranium mill tailings wastes, but they decay completely within a few hours. Other radioactivity injected into the atmosphere includes members of the natural uranium and thorium chains and $^{40}$K. Based on the 4-km$^3$ release, the $^{40}$K, $^{226}$Ra, and $^{232}$Th injected into the atmosphere are estimated at 61,000, 3200, and 680 Ci, respectively. If radioactive equilibrium is assumed, then 3200 Ci of each $^{226}$Ra daughter and 680 Ci of each $^{232}$Th daughter would likewise have been ejected from the mountain.

*Particle size distribution.* Size distribution was determined by two independent methods to obtain data for both weight and count-volume distributions. For the weight distribution, ash samples from nine geographic locations were dry-sieved into the size fractions > 150 $\mu$m, 75 to 150 $\mu$m, 45 to 75 $\mu$m, and < 45 $\mu$m by standard sieving methods. In addition, fine (< 20 $\mu$m) and respirable (< 3.5 $\mu$m) size fractions were obtained by aerodynamic particle fractionation techniques (*3*). The bulk sample was placed in a Wright dust feed cup, and an air stream of 10 liter/min and a vertical elutriator were used to separate the particles > 20 $\mu$m from those < 20 $\mu$m. Aerosol particles < 20 $\mu$m were electrically neutralized in a deionizer and then passed through an aerosol chamber; particles < 3.5 $\mu$m were separated from those < 20 $\mu$m with a cyclone device.

The percentages by weight of particles in the size fractions > 150 $\mu$m, 75 to 150 $\mu$m, 45 to 75 $\mu$m, 45 to 20 $\mu$m, 20 to 3.5 $\mu$m, and < 3.5 $\mu$m are shown in Fig. 2. These histograms show a bimodal distribution of particle sizes, suggesting that there are at least two different types of material, possibly old material blown out of the volcano by the eruption and fresh magmatic material. As expected, the mean particle size generally decreases with increasing distance from the volcano, reflecting aerodynamic settling of the coarse material near the source. At distances beyond 240 km, both types of material appear to be well mixed, peaking at the size fraction < 45 $\mu$m. The different size fractions show distinctly different colors. The material > 150 $\mu$m is medium gray and contains fragments of charred wood; the medium-size material, 150 to 45 $\mu$m, is dark; and the fraction < 45 $\mu$m is light gray. The relative amounts of material in the fine fractions, 3.5 to 20 $\mu$m and < 3.5 $\mu$m, are about equal, and range from about 1 to 3 percent of the ash by weight. It is also apparent from Fig. 2 that ash samples from all nine locations contained comparable amounts of the respirable fraction.

Size distribution as a function of particle count and volume was determined by quantitative image analysis, using a Quantimet-720 with a scanning electron microscope (SEM). We prepared SEM photomicrographs from specimens of ash deposited from an alcohol suspension onto a 0.05-$\mu$m Nuclepore filter. Several magnifications, ×60 to ×10,000, were used to include representative samples of all particle sizes present in ash from each location. Profile measurements were made with the Quantimet for particles shown on each micrograph, and equivalent circular diameters were calculated. Data from all micrographs were normalized to compensate for the different areas included at each magnification and were combined into a single distribution for each ash (Table 8).

The particle size distributions by count and by weight are in general agree-

Table 5. Composition of water-soluble constituents in a 10:1 mixture of distilled water and Mount St. Helens ash. Concentrations are in milligrams per liter. Errors range from 5 to 30 percent, depending on level detected. Analysis was by ion chromatography and plasma emission spectroscopy.

| Element | Tieton (98 km)* | Ahtanum (125 km) | Yakima (137 km) | Richland (224 km) | Moses Lake (240 km) | Spokane (378 km) | Rosalia (385 km) | Pullman (388 km) | Missoula (644 km) |
|---|---|---|---|---|---|---|---|---|---|
| $F^-$ | 0.56 | 0.45 | 0.44 | 0.60 | 0.85 | 0.45 | 0.94 |  | 0.81 |
| $Cl^-$ | 17 | 33 | 10 | 26 | 24 | 33 | 33 |  | 27 |
| $NO_3^-$ | 1.1 | 1.2 | 0.90 | 5.1 | 1.9 | 1.2 | < 1 |  | 2.2 |
| $SO_4$ | 57 | 120 | 26 | 91 | 49 | 120 | 55 |  | 108 |
| $NH_4$ | 0.33 | 0.44 | 0.38 | 1.8 | 0.39 | 0.44 | 0.36 |  | 0.81 |
| Li |  |  |  | 0.018 |  |  |  |  |  |
| B | 0.040 | 0.067 | 0.022 | 0.023 | 0.031 | 0.063 | 0.044 | 0.042 | 0.045 |
| Na | 14 | 34 | 8.1 | 18 | 17 | 29 | 16 | 17 | 20 |
| Mg | 2.3 | 4.4 | 1.1 | 2.6 | 2.6 | 6.5 | 3.0 | 3.0 | 4.0 |
| Al | 0.030 | 0.069 | 0.015 | 2.25 | 0.054 | 0.063 | 0.12 | 0.082 | 0.18 |
| Si | 0.37 | 0.40 | 0.22 | 1.24 | 0.89 | 1.03 | 0.27 | 0.31 | 0.56 |
| K | 3.4 | 6.3 | 2.0 |  | 3.4 | 3.3 | 3.6 | 6.6 | 5.9 |
| Ca | 18 | 41 | 8.5 | 32 | 22 | 22 | 25 | 58 | 40 |
| V | < 0.05 | < 0.05 | < 0.05 | < 0.02 | < 0.05 | < 0.05 | < 0.05 | < 0.03 | < 0.04 |
| Cr | < 0.004 | < 0.004 | < 0.005 | < 0.005 | 0.010 | 0.045 | < 0.005 | < 0.006 | < 0.008 |
| Mn | 0.42 | 0.73 | 0.21 | 0.53 | 0.40 | 1.12 | 0.57 | 0.55 | 0.66 |
| Fe | < 0.007 | 0.023 | 0.007 | 1.76 | 0.085 | 0.057 | < 0.005 | < 0.005 | 0.047 |
| Co | < 0.006 | < 0.008 | < 0.005 | < 0.007 | < 0.008 | 0.008 | < 0.01 | < 0.01 | < 0.01 |
| Ni | 0.013 | 0.004 | < 0.006 | 0.021 | 0.027 | 0.085 | < 0.005 | < 0.003 | 0.009 |
| Cu | 0.005 | 0.011 | 0.006 | 0.017 | 0.006 | 0.018 | 0.023 | 0.015 | 0.051 |
| Zn | 0.014 | 0.047 | 0.013 | 0.044 | 0.060 | 0.17 | 0.030 | 0.035 | 0.47 |
| As | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 |
| Mo | < 0.005 | < 0.008 | < 0.005 | < 0.01 | < 0.005 | < 0.008 | < 0.005 | < 0.006 | < 0.006 |
| Cd | < 0.03 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.015 | < 0.02 |
| Hg |  |  |  | 0.00002 |  |  |  |  |  |
| Pb | < 0.03 | < 0.03 | < 0.02 | 0.014 | < 0.03 | < 0.03 | < 0.03 | < 0.03 | 0.012 |

*Distance from Mount St. Helens.

Table 6. Natural radionuclides in volcanic ash.

| Location | Distance (km) | Radionuclide concentration (pCi/g) | | |
|---|---|---|---|---|
| | | $^{232}$Th* | $^{226}$Ra† | $^{40}$K |
| Ahtanum | 125 | 0.067 ± 0.009 | 0.314 ± 0.022 | 6.06 ± 0.31 |
| Yakima | 137 | 0.069 ± 0.009 | 0.333 ± 0.022 | 6.42 ± 0.33 |
| Richland | 224 | 0.088 ± 0.006 | 0.376 ± 0.023 | 7.73 ± 0.39 |
| Spokane | 378 | 0.116 ± 0.015 | 0.552 ± 0.036 | 10.3 ± 0.52 |

*Based on measurement of the $^{232}$Th daughter $^{208}$Tl. †Based on measurement of the $^{226}$Ra daughter $^{214}$Bi in a sealed sample.

ment. While 90 percent or more of the particles counted were smaller than 10 μm, they account for only 10 percent or less of the total ash volume, and less than 0.3 percent of the volume was particles smaller than 2 μm.

*Ambient airborne particulates.* Size distributions of airborne particles were determined during the period 19 May through 1 June at two sites in the Hanford area, which is about 210 km east of Mount St. Helens. The measurements include both airborne material from the eruption and resuspended material. The Horn Rapids site is near the southwestern boundary of the Hanford area and the meteorological station site is 24 km northwest of the Horn Rapids site. Both sites received relatively low ash deposits—about 1 to 2 mm and 3 to 4 mm in depth, respectively. The principal deposition was farther north.

Ambient airborne solids were sampled with three different types of equipment.

1) A cyclone preseparator with a 6-μm 50 percent cutoff diameter, followed by a 20 by 25 cm$^2$ fiber glass filter, provided samples of nonrespirable and respirable particles, respectively. The sampling flow rate for this device was 1.1 m$^3$/min at a height of 1.2 m.

2) A 20 by 25 cm$^2$ filter was used for direct air sampling; some particle size separation by gravity settling occurs in the inlet before the filter (*4*). The sampling flow rate was 1.1 m$^3$/min at a height of 1.2 m.

3) A laser optical particle counter made continuous analyses of the aerosol size 0.9 m above the ground.

Concentrations of airborne solids are shown in Fig. 3 for both sampling sites. The horizontal bars indicate the sampling times. Meteorological data taken during the sampling period at the Hanford meteorological station are also recorded in Fig. 3. These meteorological data are summarized for time periods from midnight to midnight. Thus, in comparing mass loadings to meteorological data, there is a shift of about 1/2 day in time scale. The very substantial decrease in airborne solids on 27 May was associated with the heavy rainfall on 26 May.

Volume distributions of airborne ash as determined by the optical counter are shown in Fig. 4 as a function of particle diameter. The range in particle diameters during 22 to 30 May is shown by crosshatching. Also shown for comparison is the range observed at Hanford in 1975 during dust storms and clear days (*5*). The range for the volcanic ash overlies the earlier data, particularly for particle diameters between 0.3 and 1.0 μm. This is the range that can penetrate most deeply into the lung. For this range, the volcanic ash concentration before the heavy rain was comparable to those during the most severe dust storms at Hanford. In addition, the maximum concen-

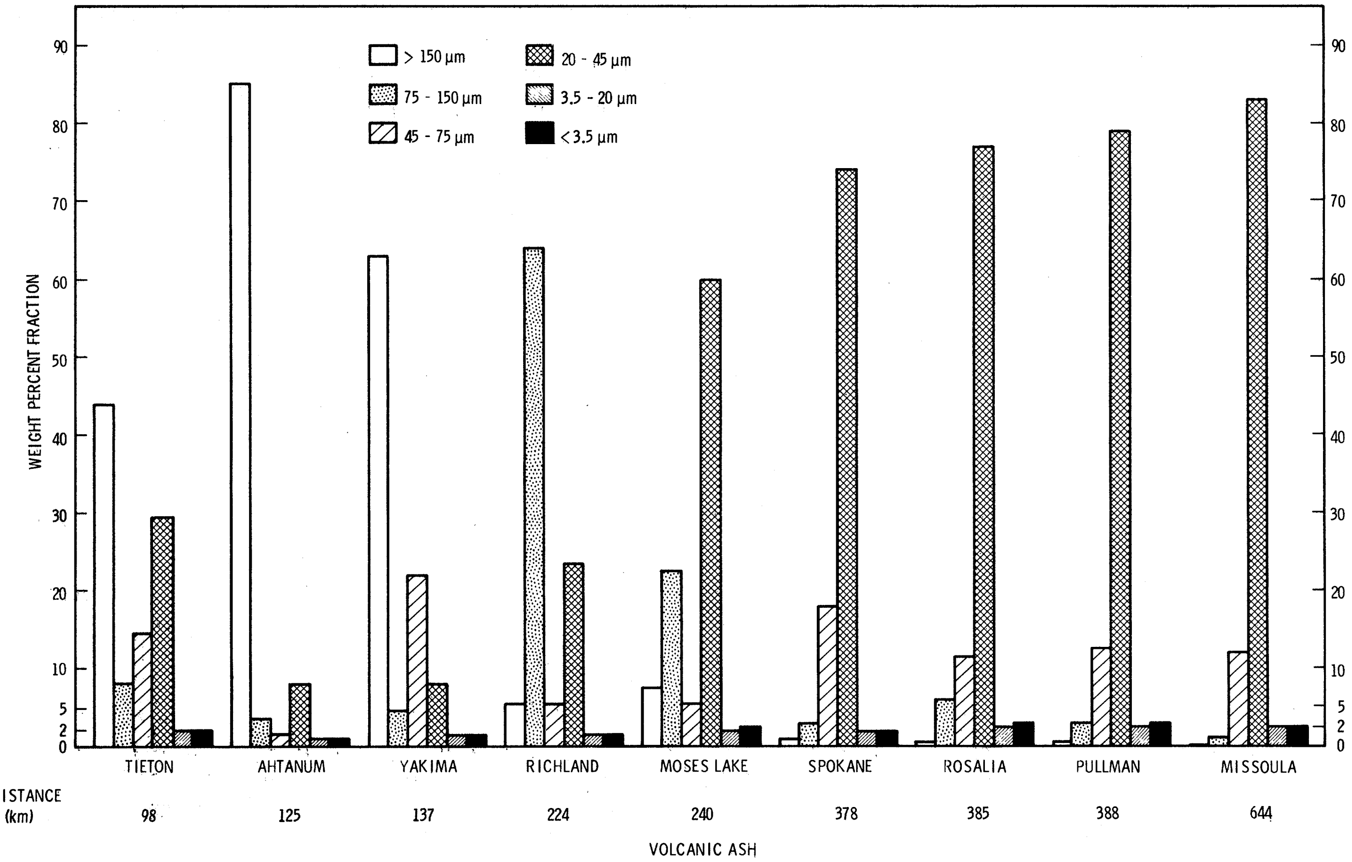

Fig. 2. Histograms of percentages by weight for size fractions of Mount St. Helens ash samples from various locations in eastern Washington and Montana following the eruption.

tration of particles 0.5 μm in diameter in the volcanic ash was about four times greater than reported for dust storms.

These measurements of airborne solids thus show a continuously higher mass loading of volcanic ash at the more northern of the two sites, a mass loading decreased two orders of magnitude after the 0.79-inch rainfall, and an increase as surfaces dried and resuspension occurred. Concentrations of particles 0.3 to 1.0 μm in diameter were comparable to or greater than concentrations in earlier dust storms.

These observations indicate that airborne mass loadings increase toward the north and hence toward areas of greater ash deposition. We do not know how to extrapolate this mass loading effect to areas of greater ash depth. We believe the effect of rainfall in the Hanford area is typical of what would be observed at other areas of the Northwest. Rain will certainly decrease airborne mass loading, but its long-term effect on resuspension is not known.

*Mineralogy.* The mineralogical composition of the ash samples was estimated by a combination of optical microscopy, SEM with energy-dispersive x-ray fluorescence (SEM/EDX), and x-ray diffraction (XRD) techniques. Pyroclastic debris collected in Richland contains, in order of decreasing abundance, plagioclase feldspar (andesine), orthopyroxene (hypersthene), titanium-bearing magnetite, glass, and trace amounts of other phases (hornblende and biotite). The samples from the eastern part of the area, including Spokane, Pullman, and Missoula are approximately 80 percent glass, with the remaining fraction consisting largely of feldspar with minor pyroxene.

X-ray diffraction methods precluded positive identification of cristobalite in the bulk sample because of superposition of plagioclase lines such as $d_{20\bar{1}}$. Plagioclase lines and orthopyroxene lines (such as $d_{121}$) interfered with the unequivocal identification of quartz. Estimates of quartz content using quartz-spiked samples and intensities of $d_{101}$ and $d_{100}$ yield values on the order of 1 to 2 ± 1.5 percent by weight in the bulk samples examined. Because of the errors inherent in this method and time limitations, a search for a suitable internal standard was not pursued.

Estimates of the amounts of crystalline silica phases with microbeam (SEM/EDX and microprobe) and optical methods were considered more reliable. Examination of several hundred grains by SEM/EDX generally indicated only 1 to 3 percent of the individual grains (4 percent in the Spokane sample) in which Si was the only element detected. These grains were mostly much smaller than average. This suggests that the number of discrete particles containing Si as the only detectable element is on the order of 1 to 3 percent.

Table 7. Concentration of $^{210}$Po in fallout ash samples and in particle size separates.

| Location | Distance (km) | $^{210}$Po (pCi/g) Leach method | $^{210}$Po (pCi/g) Dissolution method |
|---|---|---|---|
| Ahtanum | 125 | 0.16 | 0.35 |
| Richland | 224 | 0.27 | 0.56 |
| Rosalia | 385 | 0.47 | 0.84 |
| Moses Lake | 240 | | |
| > 150 μm | | 0.12 | |
| 75-150 μm | | 0.14 | |
| 45-75 μm | | 0.33 | |
| < 45 μm | | 0.55 | |
| < 3.5 μm | | 1.61 | |

Examination of 2- to 5-μm ultrathin sections of the Yakima ash sample indicated that a number of rock fragments are present. Some of the fragments, the largest of which are about 40 μm in diameter, are composed of feldspar and Si-only crystallites (<10 μm) in about equal proportions. It is not unusual for these aggregates to be encased in a glassy rind.

The presence of crystalline silica as components in rock fragments rather than as discrete phases may lead to conflicting results in crystalline silica determinations, depending on the analytical procedure used. Thus, a determination of crystalline silica by SEM/EDX where only individual grains are examined or by x-ray diffraction of poorly ground samples may yield different results than are obtained by other methods.

Accordingly, a selective dissolution technique, using phosphoric acid to remove phases other than crystalline silica, was employed (*6*). The residue collected on filter paper after the digestion step was generally greater than the amount of crystalline silica determined by instrumental methods. In terms of percent by weight of the total ash samples after the phosphoric acid dissolution, undissolved residue values ranged from 4 percent for samples from the eastern part of the region (Spokane and Moses Lake) to 10 percent for Yakima in the western region. Examination of the unashed residue by SEM/EDX, optical microscopy, and XRD, however, indicated that less than half of the residue was crystalline silica. Most of the

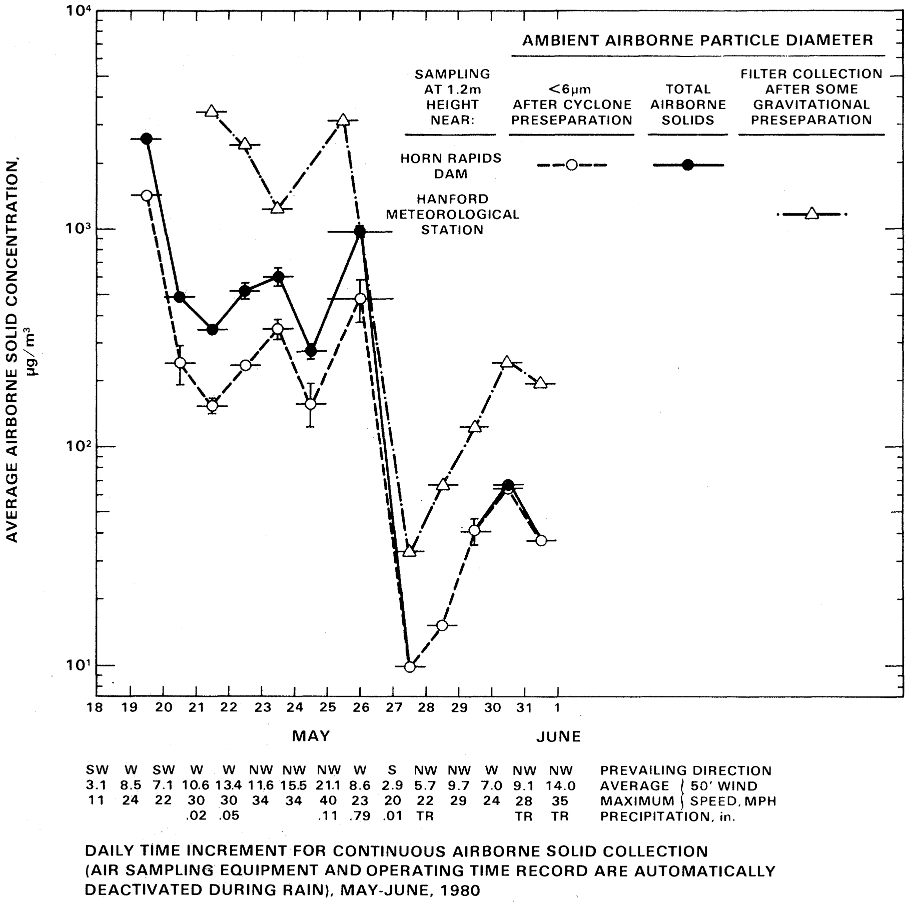

Fig. 3. Concentrations of airborne solids at two sites in eastern Washington following the eruption.

Table 8. Size distribution of Mount St. Helens ash by SEM image analysis (equivalent circular diameter).

| Location | Distance (km) | Observed particle diameter* (μm) |  | Calculated median diameter (μm) |  | Size distribution (%) |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | By count |  | By volume |  |
|  |  | Maximum | Minimum | By count | By volume | < 10 μm | < 2 μm | < 10 μm | < 2 μm |
| Tieton | 98 | 268 | 0.30 | 0.99 | 173 | 96 | 76 | 0.5 | < 0.1 |
| Ahtanum | 126 | 470 | 0.11 | 0.45 | 315 | 99 | 88 | 0.2 | < 0.1 |
| Yakima | 137 | 258 | 0.16 | 1.20 | 211 | 97 | 73 | 1.2 | < 0.1 |
| Ellensburg | 161 | 173 | 0.30 | 1.47 | 52 | 95 | 64 | 5.4 | 0.1 |
| Richland | 224 | 211 | 0.30 | 1.47 | 142 | 96 | 73 | 1.8 | 0.1 |
| Moses Lake | 240 | 53 | 0.05 | 0.25 | 29 | 97 | 83 | 9.0 | 0.1 |
| Ritzville | 322 | 53 | 0.11 | 0.54 | 29 | 98 | 83 | 10.2 | 0.3 |
| Rosalia | 385 | 95 | 0.30 | 1.20 | 78 | 94 | 61 | 1.9 | < 0.1 |
| Pullman | 388 | 116 | 0.11 | 0.45 | 95 | 99 | 88 | 3.6 | 0.2 |
| Missoula | 644 | 53 | 0.16 | 1.47 | 35 | 96 | 58 | 9.3 | 0.1 |

*Estimated relative uncertainty ± 25 percent.

crystalline silica present was quartz. Contaminants included gel-like Si-rich masses, glassy pumice fragments that apparently floated during digestion, minor opaques, phosphorus-rich agglomerates of needles, and an unidentified phase. An XRD trace of material obtained after ashing the phosphoric acid precipitate on filter paper at 950°C yielded better definition of quartz and cristobalite peaks plus an unknown phase. There is some evidence that some of the crystalline silica present after ashing was an artifact of the procedure, so our estimates of crystalline silica from the phosphoric acid procedures are based on the unashed samples.

Our experience indicates that some differences in the amount of crystalline silica determined could occur through comparison of results obtained by different procedures. Our estimates of the crystalline silica concentration based primarily on SEM/EDX and x-ray methods with as-received samples generally yield values less than 3 percent and in many cases less than 1 percent exclusive of rock fragments. Also, diffraction patterns of the < 3.5 μm fraction of ash collected on filters suggest less than 1 to 2 percent crystalline silica in this fraction. On the basis of the phosphoric acid digestion, these values range from less than 2 to as high as 5 percent for one Yakima sample which presumably includes the crystalline silica present in the rock fragments.

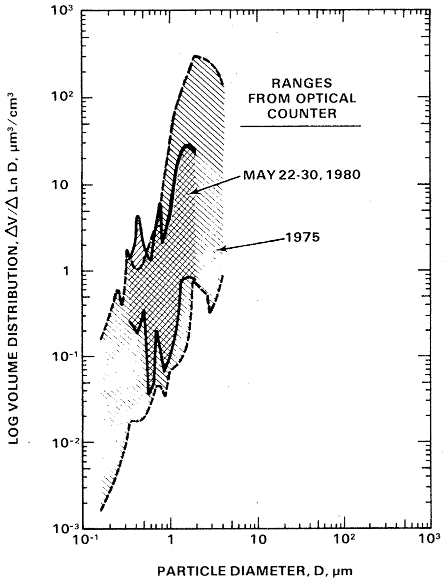

Fig. 4. Airborne particulate volume distributions at a site in eastern Washington following the eruption.

Consequently, on a mineralogical basis, there seems to be little indication that substantial amounts of free crystalline silica known to produce fibrogenic response in the lung are present in the samples received. This conclusion is, in part, supported by the data obtained from cultured rabbit alveolar macrophages in Table 9.

*Morphology*. The ash morphology was examined by methods similar to those described by Heiken (*7*). Ash particles deposited at locations between 98 and 644 km downwind from Mount St. Helens varied from 0.5-mm-diameter porous pumice to submicrometer fracture fragments of glasses, plagioclase, and titanium-bearing magnetite. The size distribution of these particles is shown in Table 8, and examples of particle morphology are shown in Figs. 5 and 6. Large, highly porous pumice particles (Fig. 5, A and B) were common in some ashfall within 98 km of Mount St. Helens, with particle sizes to 500 μm. The pumice particles shown appear to be mainly glassy aluminum silicates with varying amounts of iron, titanium, potassium, calcium, and sodium. One pumice particle (Fig. 5B) contains an embedded crystalline fragment of an iron silicate.

Only a few small pumice particles occur among the fine glass and mineral particles that comprise most of the ash deposited at distances of 242 km or farther (Fig. 5, C and D). The variation in ash characteristics with distance from Mount St. Helens, including the internal structure of some larger particles, is illustrated in the photomicrographs of polished sections (Fig. 6, A and B). In Fig. 6 most of the small bright components are titaniferous magnetite.

*Biological tests*. The elemental and mineralogical analysis of the ash suggests that it does not contain toxic levels of soluble materials. To rapidly estimate the potential of the ash to cause pulmonary injury, we made a preliminary assessment of the fibrogenicity of the ash by measuring its toxicity to alveolar macrophages in vitro. Several experimental studies have shown a general correlation between the ability of mineral dusts to cause fibrosis and their cytotoxicity to macrophages in vitro.

It has been shown that silica causes pulmonary fibrosis and is toxic to macrophages that phagocytize it (*8*). Further, the cytotoxicity of various forms of silica to macrophages is correlated with the ability of the dust to generate fibrosis in vivo. Studies with isolated macrophages have shown that the cytolytic effects can be attributed to increased permeability of cellular membranes, including those of lysosomes (*9*). In tissue culture experiments, soluble factors from silica-killed macrophages stimulated collagen synthesis by fibroblasts (*10*), a response that in the whole organ might result in undifferentiated collagen fiber accumulation. The action of silica on macrophages does not occur in the absence of particle-cell

Table 9. Viability of cultured rabbit alveolar macrophages exposed to particles of volcanic ash, polyvinyltoluene, soil, and fibrogenic quartz.

| Particle | Percentage of viable cells relative to controls* |  |
|---|---|---|
|  | Exp. 1 | Exp. 2 |
| Polyvinyltoluene | 96 ± 21 | 113 ± 29 |
| Fibrogenic silica | 42 ± 14 | 30 ± 8 |
| Tieton, ash | 79 ± 25 | 96 ± 31 |
| Ahtanum, ash | 87 ± 32 |  |
| Yakima, ash | 89 ± 23 | 91 ± 25 |
| Richland, ash | 94 ± 23 | 66 ± 31 |
| Ritzville, silt loam soil | 70 ± 27 | 32 ± 9 |
| Rosalia, ash | 91 ± 19 |  |
| Pullman, ash | 101 ± 26 | 111 ± 24 |
| Missoula, ash | 87 ± 22 |  |

*Values are means ± 1 standard deviation, $N = 5$; Exp., experiment.

contact, and thus seems to be a surface phenomenon, possibly involving hydrogen bonding between particles and membranes (*11, 12*).

Studies with macrophages in vitro cover a variety of mineral dusts (*13*), including asbestos (*14*). In general, the correlation between cytotoxicity to macrophages in vitro and fibrosis in vivo is well established. Asbestos is an exception, causing fibrosis in humans but little cell death to macrophages (*11*).

*Methods*. Male New Zealand White rabbits were killed by injection of Nembutal in the marginal ear vein, tracheas were cannulated, and lungs were lavaged with three washes of 0.15*M* NaCl at 37°C. The washes were pooled and centrifuged at 200*g* for 10 minutes. Cells were resuspended in culture medium, counted with a hemacytometer, and dispensed in 25-cm$^2$ plastic tissue culture flasks (Falcon) at $5 \times 10^6$ cells per flask. Culture medium consisted of RPMI 1640 (Gibco) supplemented with bovine serum albumin (0.4 percent), human transferrin (5 μg/ml), human insulin (5 μg/ml), penicillin (100 I.U./ml), streptomycin (100 μg/ml), and Fungizone (2.5 μg/ml). After overnight incubation, nonadherent cells were aspirated and discarded and 5 ml of fresh culture medium was added.

Ash, soil, and silica samples (positive control) were suspended in a 7.5-cm column of RPMI 1640. After a 2-minute settling, the top 4.5 cm was aspirated and an aliquot was weighed and dried to determine particle content. Examination of the aspirated fraction by light microscopy and electron microscopy revealed that 99 percent of the particles by count were less than 5 μm in diameter. Ritzville silt loam soil is an extensively characterized benchmark sample which does not appear to present any respiratory problems. Samples of this soil were placed in a vibrating gravity sieve containing nylon cloth with mesh sizes of 7, 20, or 140 μm. The fraction that passed through the 20-μm mesh was treated as described above. Polyvinyltoluene beads (2.02 μm; Dow Diagnostics) were diluted 1:5 with saline, autoclaved, and then diluted with RPMI 1640. Samples of each particle suspension were then added to culture flasks to give 1.25 mg per flask. After incubation for 22 to 24 hours, the cells remaining attached to the flask were released by addition of 0.5 ml of 50 m*M* adenosine triphosphate in 0.08*M* tris chloride (*p*H 7 to 7.5). After incubation for 20 to 45 minutes, the supernatant containing detached cells and particulates was aspirated and the flask was washed twice with 4 ml of medium 199 containing 10 percent rabbit serum. The supernatant and pooled washes were centrifuged at 200*g* for 5 minutes and the cell pellet was resuspended in 0.5 ml of RPMI 1640 culture medium. Trypan blue (0.5 ml of 0.4 percent in saline; Gibco) was added and the number of viable and nonviable macrophages counted.

The data in Table 9 suggest that the ash samples do not differ significantly in cytotoxicity from the nontoxic polyvinyltoluene particles. The ash samples also do not differ significantly from each other in any consistent manner. In contrast, fibrogenic quartz (positive control) is significantly more toxic than any of the ash samples. The cytotoxicity of the Ritzville silt loam may be due to leachable matter on the soil or a mineral fraction in the soil. The fraction of the soil investigated here represents an extremely small fraction (less than 0.1 percent) of the total, which could explain the absence of detectable respiratory problems associated with Ritzville soil under normal conditions. For comparison, 7 to 10 percent remains suspended after similar treatment of the ash samples.

These preliminary biological data indicate that the ash is not highly cytotoxic and thus, within the constraints of the model linking fibrogenicity to cytotoxicity, is not highly fibrogenic compared to fibrogenic silica. They are consistent with the mineralogical data indicating a very low content of some of the known fibrogenic forms of silicon dioxide and the presence of the weakly fibrogenic feldspar.

It is difficult to relate exposure levels in vitro to inhalation in vivo; therefore, caution should be exercised in extrapolating the data to human exposure. It has been shown (*9*) that prolonged exposure to elevated amounts of weakly cytotoxic (*14*), or in the case of asbestos noncytotoxic (*15*), particles may result in a fibrotic reaction. Feldspar, the major constituent of the ash, has been shown to be weakly fibrogenic compared to silica (*16*).

*Conclusions*. Although many of the

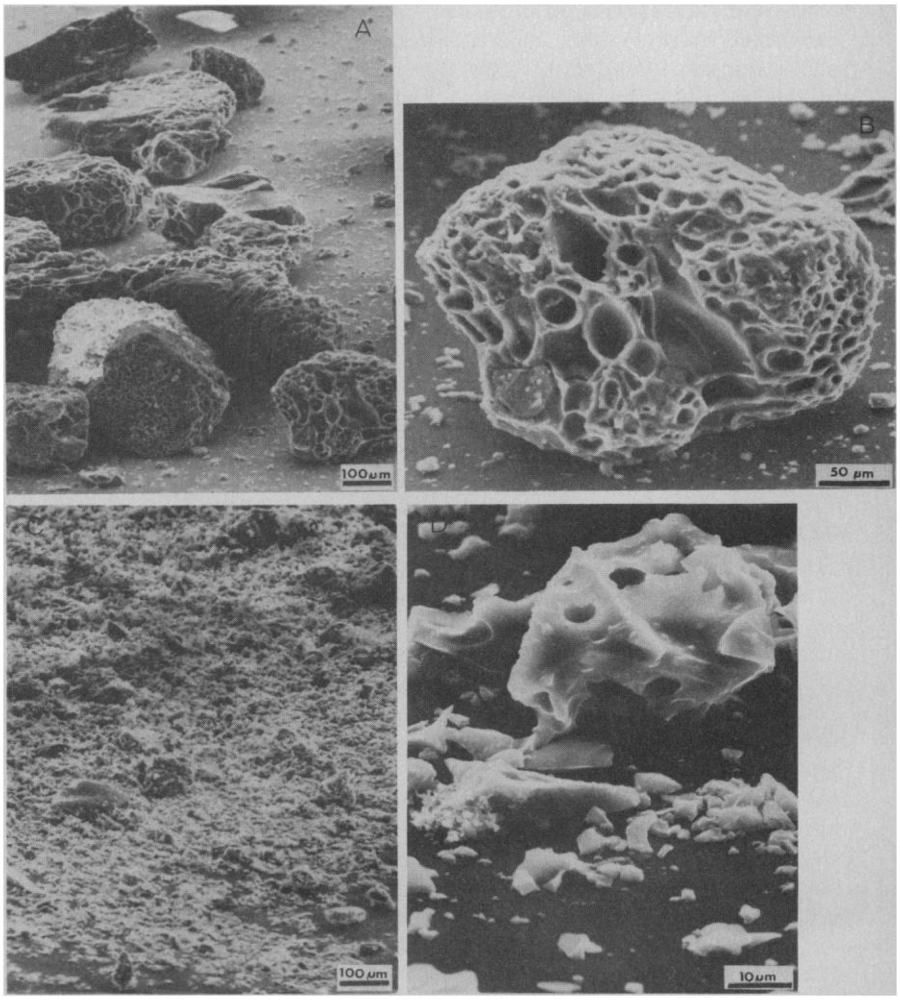

Fig. 5. Scanning electron micrographs of two representative types of as-received ash. (A and B) Silicate glass pumice from Ahtanum, 125 km from Mount St. Helens. (C and D) Glass and mineral fragments typical of ash collected at locations 250 km or farther from Mount St. Helens; the sample shown was from Ritzville, 320 km.

data presented here are preliminary, a number of conclusions can be drawn. The results and conclusions are listed below.

1) Chemically, the volcanic ash is dacitic in composition; silica (not free silica) ranged from 59 to 68 percent.

2) Particle size distributions vary with sampling location, with the finer ash deposited at greater distances from the volcano. At all distances, the weight fractions of respirable particles were comparable.

3) Distilled water leachates of the ash were essentially neutral to slightly acidic. Initial *p*H values were somewhat lower but increased and became stable in about 1/2 hour.

4) Major chemical species in the leachates were sulfate, chloride, calcium, and sodium. Fluoride ranged from 0.2 to 1 ppm. Toxic heavy metal cations were present in extremely low concentrations.

5) The only sulfur species detected in the airborne ash plume 27 hours after the first major eruption was $H_2S$. No mercury, arsenic, or radon was detected at that time in the gas phase.

6) Radioactivity measurements of the ash approximately 12 hours after the eruption showed concentrations of natural long-lived radionuclides similar to those in average crustal material. The $^{210}$Po concentration in the ash was inversely correlated with particle size, and radon daughter concentrations on newly fallen ash were more than 100 times what could be supported by the radium content of the ash. Because of the very short half-life (< 30 minutes) of these radon daughters, very little dose to living organisms resulted from these radionuclides.

7) Airborne particulate concentrations after the eruption remained very high at the Richland, Washington, monitoring sites, but were reduced two orders of magnitude by a heavy rain, and then increased as drying occurred.

8) Mineralogical analyses showed that the ash samples from various locations varied from largely glassy to largely crystalline. The major minerals in the crystalline samples were plagioclase feldspar (andesine) and orthopyroxene (hypersthene) with lesser amounts of titanomagnetites and hornblende. All but one of the samples contained from less than 1 percent to 3 percent (by weight) free crystalline silica (quartz, trydimite, or cristobalite). The size fractions less than 3.5 $\mu$m in each sample contained from less than 1 percent to 2 percent free crystalline silica.

9) Preliminary results of an in vitro biological test with samples of the ash

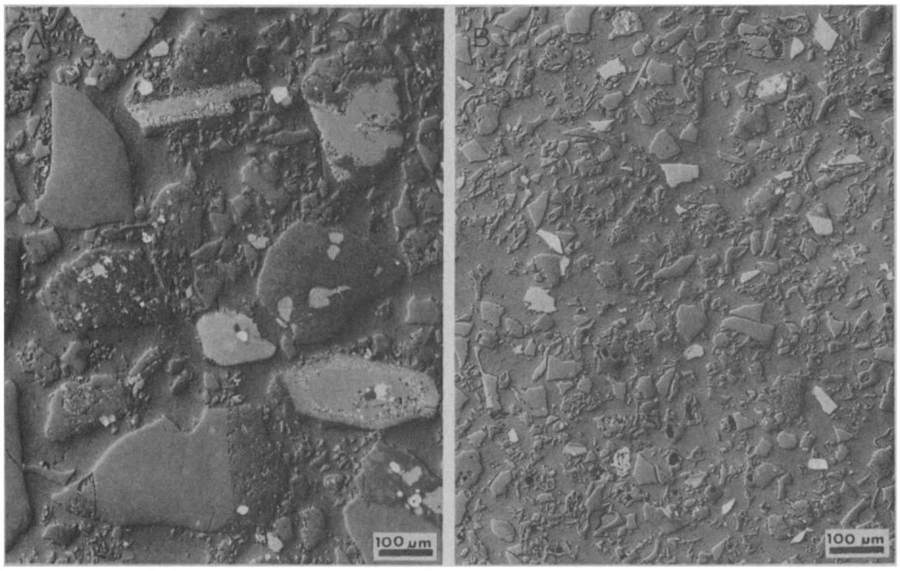

Fig. 6. Photomicrographs obtained with interference contrast illumination of polished sections of ash. (A) Yakima, 137 km from Mount St. Helens; (B) Missoula, 644 km.

Just 90 minutes after Mount St. Helens erupted on 18 May 1980, a NOAA Orbiting Weather Satellite transmitted data that were used to create the IBM computer-enhanced color picture shown on the cover. Researchers at IBM's scientific center (Palo Alto, California), studying image processing for future satellite applications, used their IBM System/370 computer, a scanner/plotter, related digital image processing equipment, and specially designed computer programs to convert the digital information from the satellite into this color image.

The volcano's purplish plume, which was 12 miles high and had spread 150 miles eastward, appears in the upper right third of the picture. By contrast, dominating the upper left of the picture is a massive Pacific storm—the same storm that eventually produced rain on the volcanic ash that blanketed the western states. In the upper right are the Canadian plains. The yellow that outlines the California coast represents Sunday morning fog and low clouds.

This picture (taken from an altitude of more than 500 miles) embraces an area of about 5 million square miles of the Pacific Ocean and North America, including the San Joaquin Valley of California, the Snake River area of Idaho, and the plains of Alberta and Saskatchewan, Canada. The plains are differentiated from the darker mountainous areas. Also visible are the Snake and Columbia rivers.

This color rendering was based on data furnished by the NOAA Field Service Station of the National Environmental Satellite Service, Redwood City, California. The data come from NOOA/6, a weather satellite whose sensors sweep the surface of the earth in a direction perpendicular to its line of flight, with a resolution of about 1/2 mile.

Among the instruments aboard NOAA/6 is one sensitive to radiation from three different wavelength bands of the electromagnetic spectrum. These bands correspond to visible light, radiation from the near infrared, and radiation from the thermal infrared regions of the electromagnetic spectrum. The image was produced with a series of computer programs that transform the raw digital data received from the satellite into an enhanced geometrically corrected form. One black-and-white transparency was produced for each of the three spectral bands (bands 1, 2, and 4). These transparencies were then sequentially contact-printed on the same piece of color paper.

The information collected by the satellite does not contain the three primary colors; thus the colors in this picture are not necessarily those which a human observer would see from the same vantage point in space.

showed low cytotoxicity to alveolar macrophages, which are an important part of the lungs' natural clearance mechanism. Since in vitro cytotoxicity and fibrogenicity of minerals appear to be correlated, it seems unlikely that the ash is highly fibrogenic.

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### References and Notes

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17. We thank L. P. Diediker of UNC Nuclear Industries, Richland, Wash., for the early measurements of radon daughters in the ash and R. M. Garcia and C. M. Smyser for their help in typing the manuscript and tables. Supported in part by Corporate Technical Development, Battelle Memorial Institute, and in part by the Office of Health and Environmental Research, Department of Energy, under contract DE-AC06-76RLO 1830.

18 June 1980

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# Composition of the Mount St. Helens Ashfall in the Moscow-Pullman Area on 18 May 1980

*Abstract.* Mineralogical and chemical analyses of the ashfall from Mount St. Helens on 18 May 1980 indicate that there were two distinct ashes. The early dark ash is composed principally of plagioclase and lithic fragments of plagioclase and glass with titanium-rich magnetite and some basaltic hornblende and orthopyroxene. The later pale ash, four-fifths by weight of the whole fallout, is 80 percent glass with plagioclase as the principal crystalline phase. Quartz and potassium feldspar are rare to absent in both ashes. Chemical analyses of nine ash fractions and of the glass in each type emphasize the differences between the two ash types and their chemical homogeneity.

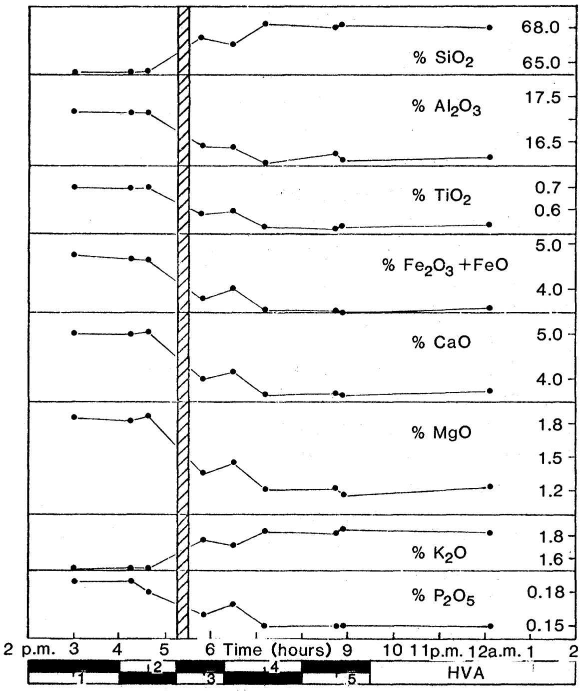
Moscow, Idaho, and Pullman, Washington, straddle the Idaho-Washington border about 400 km east-northeast of Mount St. Helens. Three explosions were heard in Pullman at 9:03 a.m. (P.D.T.) on Sunday, 18 May 1980, some 31 minutes after the eruption of Mount St. Helens is reported to have occurred.

Table 1. Percentages (by weight) of the major oxides in Mount St. Helens ash, 18 May 1980; column A, average of three XRF analyses of dark ash (samples HVA-1, HVA-2, and MSHA-1) (see Fig. 1); column B, average of two XRF analyses of mixed dark and pale ash (samples HVA-3 and MSHA-2); column C, average of four XRF analyses of pale ash (samples HVA-4, HVA-5, MSHA-3, and MSHA-4); column D, partial microprobe analysis of glass particles in the dark ash; and column E, microprobe analysis of the colorless glass particles in the pale ash (0.1 percent chlorine and no lead or sulfur were detected in this glass); N.A., not analyzed; N.D., not detected. Parentheses in column C indicate standard deviations.

| Oxide | A | B | C | D | E |
|---|---|---|---|---|---|
| $SiO_2$ | 64.21 | 66.98 | 68.20 (0.19) | 76.15 | 72.20 |
| $Al_2O_3$ | 17.20 | 16.41 | 16.15 (0.10) | 13.50 | 15.40 |
| $TiO_2$ | 0.70 | 0.59 | 0.53 (0.01) | N.A. | 0.45 |
| $Fe_2O_3$* | 2.21 | 1.84 | 1.66 (0.03) | 1.43† | 2.51† |
| FeO* | 2.53 | 2.11 | 1.90 (0.03) | | |
| MnO | 0.07 | 0.06 | 0.05 (0.005) | N.A. | 0.04 |
| CaO | 5.07 | 4.12 | 3.70 (0.04) | 1.22 | 2.48 |
| MgO | 1.85 | 1.41 | 1.22 (0.03) | N.A. | 0.98 |
| $K_2O$ | 1.52 | 1.75 | 1.85 (0.02) | 3.02 | 1.99 |
| $Na_2O$ | 4.47 | 4.59 | 4.57 (0.09) | 4.05 | 3.88 |
| $P_2O_5$ | 0.19 | 0.17 | 0.15 (0.00) | N.A. | N.D. |

*Total iron assigned as 44 percent $Fe_2O_3$ and 56 percent FeO. †Total iron shown as FeO.

Fig. 1. Change in the oxide percentages of major elements in the ash plotted against time on 18 May 1980. The period over which samples were collected is shown at the base of the figure. HVA samples were collected 5 km north of Pullman ($SW^1/_4$, $SE^1/_4$, section 18, T15N, R45E); MSHA samples were collected on the Washington State University campus ($SW^1/_4$, $NE^1/_2$, section 5, T14N, R45E). The ruled vertical zone indicates the period of abrupt change in the color and composition of the ash.



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