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DIRECT RATE MEASUREMENTS OF ERUPTION PLUMES AT AUGUSTINE VOLCANO:
A PROBLEM OF SCALING AND UNCONTROLLED VARIABLESWilliam I. Rose¹, Grant Heiken², Kenneth Wohletz², Dean Eppler², Sumner Barr²,
Theresa Miller³, Raymond L. Chuan⁴, and Robert B. Symonds¹

Abstract. The March-April 1986 eruption of Augustine Volcano, Alaska, provided an opportunity to directly measure the flux of gas, aerosol, and ash particles during explosive eruption. Most previous direct measurements of volcanic emission rates are on plumes from fuming volcanoes or on very small eruption clouds. Direct measurements during explosive activity are needed to understand the scale relationships between passive degassing or small eruption plumes and highly explosive events. Conditions on April 3, 1986 were ideal: high winds, clear visibility, moderate activity. Three measurements were made: 1) an airborne correlation spectrometer (Cospec) provided mass flux rates of SO₂; 2) treated filter samples chemically characterized the plume and 3) a quartz crystal microcascade impactor provided particle size distribution. Atmospheric conditions on April 3 caused the development of a lee wave plume, which allowed us to constrain a model of plume dispersion leading to a forecast map of concentrations of SO₂ at greater distances from the vent. On April 3, 1986, the emission rate of SO₂ at Augustine was 24,000 t/d, one of the largest direct volcanic rate measurements yet recorded with a Cospec. The results, coupled with analytical results from samples simultaneously collected on filters, allow us to estimate HCl emissions at 10,000 t/d and ash eruption rate at 1.5×10^6 t/d. Based on other data, this ash eruption rate is about 1/50 of the maximum rate during the March-April activity. Filter samples show that the gas:aerosol proportions for sulfur and chlorine are about 10:1 and 4:1, respectively. By contrast, measurements of Augustine's plume, together with ground-based gas sampling in July 1986 when the volcano was in a post-eruptive fuming state, are 380 t/d SO₂ and approximately 8000 t/d HCl with no ash emission. The observations of large Cl releases at Augustine support the Cl abundance conclusions of Johnston (1980) based on study of melt inclusions in the 1976 lavas. The results reinforce the need for more measurements during eruptions and for better understanding of scaling of volcanic emissions of various eruptive components.

Introduction

Augustine Volcano (59.37°N, 153.42°W) is a symmetrical andesitic island volcano, located in lower Cook Inlet, 375 km SSW of Anchorage, Alaska (Figure 1). Augustine's summit (1200 m) is marked by a complex lava dome, while the flanks surrounding the volcano consist of a debris apron formed by pyroclastic flows. Recorded historic activity consists of six explosive Peléean eruptions that were often followed by lava extrusions. These

occurred in 1812, 1883, 1935, 1963-1964, 1976, and 1986 [Kienle and Swanson, 1985; Yount et al., 1987]. Because of the proximity of Augustine Volcano to the major north Pacific air routes, eruptive activity poses potential hazards to air traffic; previous eruptions have resulted in serious encounters [Kienle and Shaw, 1979; Rose, 1986].

Volcanological research at Augustine during and following the 1976 eruption focused on the transport and dispersal of the 1976 plume [Kienle and Shaw, 1979], the petrology of lavas [Johnston, 1978], the unusually chloride-rich nature of its volatiles [Johnston, 1980], aircraft sampling of eruption clouds [Hobbs et al., 1977], and the seismicity of the volcano [D. J. Lalla, Ph. D. thesis, in preparation, 1980]. Seismic monitoring of Augustine detected weeks of precursory seismic activity before the 1986 eruption [Kienle, 1986].

Studies of gas emission rates at active volcanoes have emphasized the use of the correlation spectrometer (Cospec) for SO₂ emission studies [Stoiber and Jepson, 1973; Casadevall et al., 1981]. The Cospec is very versatile for measurements during quiescent periods, and our understanding of rates and emission patterns during repose now includes direct measurements at more than 50 different fuming volcanoes. Notable problems in using the Cospec during eruptions are the opacity of cloud and the hazard of access by aircraft. Therefore direct data collected during eruptive periods (high emission rates) are still rare.

Estimates of the global volcanic degassing rates differ because of uncertainty in the estimates of degassing during large eruptions [Berresheim and Jaeschke, 1983; Stoiber et al., 1987]. Indirect estimates of eruptive degassing [Leavitt, 1982; Devine et al., 1984] may be criticized [Rose et al., 1981, 1983] because they are based on poorly-constrained erupted magma volumes and do not reflect contributions from intrusive magma. Krueger [1983, 1985] demonstrated the use of the total ozone mapping spectrometer (TOMS) as a synoptic satellite sensor of SO₂ released during eruptions. The quantitative potential of such remotely-sensed data can be augmented by simultaneous ground-based measurements. Direct measurements of emission rates of other gas species (CO₂, H₂O) are rare [Harris et al., 1981], but the Cospec data, together with other sampling methods, have now been applied to estimate the emission rates of other gases, ash, aerosols, and volatile metal species [Casadevall et al., 1984; Chuan et al., 1986; Rose et al., 1986; Lepel et al., 1978]. The objectives of this study were to make direct measurements of the SO₂ emission rates during explosive eruption of Augustine Volcano and to simultaneously collect other data that would allow evaluation of the emission rates of other gases and volcanic ash and aerosol particles of various sizes. A principal aim of the work is to determine how to scale from low-level activity which is easily observed and measured to large-scale explosive eruptions which are often unapproachable. We can thus estimate more accurately the relative and absolute amounts of material added to the atmosphere. We also hope that the direct flux measurements of this eruption can provide a calibration for weather-satellite detectors of ash clouds and sulfur dioxide. When calibrated, the synoptic satellite measurements will allow hazards to be quickly

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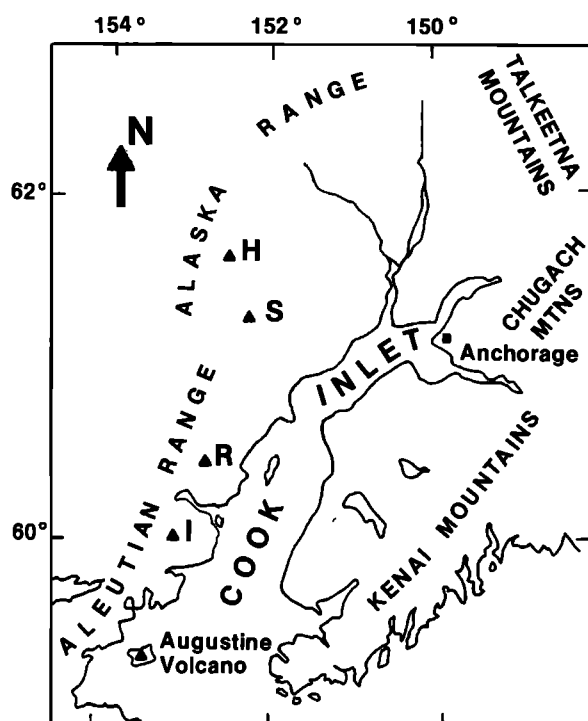


Fig. 1. Location map of Augustine Volcano and other volcanoes of the Cook Inlet area. I, Iliamna; R, Redoubt; S, Spurr; and H, Hayes (modified from Yount et al. [1987]).

characterized, tracked, and forecast on a worldwide basis. This paper focuses on the source characteristics, while a companion paper (G. Heiken et al., manuscript in preparation, 1988.) will address the dispersal and fallout patterns of the eruption clouds.

Methods

Measurements of SO_2 fluxes were made with a correlation spectrometer (Barringer Cospec-V) by an aircraft survey method [Casadevall et al., 1981]. The instrument's telescope, directed upward, detects absorption of ultraviolet skylight as the plane traverses under the plume, perpendicular to its dispersal axis. Such measurements give a quantitative cross section of the SO_2 burden, which is multiplied by the wind speed to give the emission rate. The aircraft contained a LORAN navigation device for wind speed determinations. Because the wind speed, our largest source of error, was well measured, we estimate that our individual flux measurements are accurate to about $\pm 15\%$ of the rates reported. We monitored the automatic gain control of the instrument to verify that opacity did not reach critical levels.

Measurements of other components were made by direct plume sampling. Air was brought into the aircraft through two aluminum sampling probes which entered at a gentle angle through holes in the aircraft window. The aluminum tubes were lined with flexible plastic tubing of the proper size to fit snugly over the expansion cones which were connected to the top of the filter packs. This arrangement allowed two filter packs to sample simultaneously. The first filter pack contained a series of four base-treated ($1\text{ M } ^7\text{LiOH}$) Whatman filters to collect SO_2 , HCl , and other acidic gases and was preceded by a fluoropore filter to collect particles. The second filter pack contained a series of four charcoal filters preceded by a

fluoropore particle filter. Half of each sample was prepared for instrumental neutron activation analysis (INAA). The remaining half filters were archived; in the case of the base treated filters, one fourth of the filter was used to analyze for water soluble SO_4^{2-} and SO_3^{2-} by ion chromatography.

Particle measurements were made with a four-stage cascade impactor with quartz crystal microbalance impactor plates [Chuan, 1975], which separates airborne particles into four aerodynamic size groups. The mass of particles in each size group was determined and the particles were individually studied with scanning electron microscopy (SEM) and X ray energy spectroscopy (XES).

Results of Measurements on April 3, 1986

For successful Cospec measurements during an explosive eruption, the plume must have a favorable geometry (ideally a regular lateral dispersion) and it must be sufficiently transparent so that absorption can be well measured. On April 3, 1986, the combination of clear atmospheric conditions, moderate activity and very high winds (45 knots or 23.1 m/s), precluded opacity and allowed absorption measurements. Traverses under the plume at low altitude (155 m) about 12 km downwind of the crater were possible because of the WNW direction of the winds and the lee wave geometry, which raised the plume above the sea surface (Figure 2a).

Contemporaneous Landsat (Figure 2b) and weather-satellite imagery is available for comparative study. Results of the Cospec survey are given in Table 1. The mean SO_2 emission rate, 24,000 t/d, is one of the highest ever measured although it is probably small compared with explosive eruptions; other examples are listed in Table 2.

Filter samples collected by flying a longitudinal traverse along the edge of the eruption plume for 56 min allowed chemical characterization of the eruption cloud (Table 3). The gas collected on treated filters and particles collected on fluoropore filters were analyzed for 19 elements. The gas:particle proportions of S and Cl are about 10:1 and 4:1, respectively. The proportion of gaseous S:Cl:Br is about 290:250:1. Many of the elements (Al, Ca, Ti, Mn, Sc, and V) reflect the ash of the plume, being detected mainly in the particle filters and being present in the same proportions as the Augustine dacite [Yount et al., 1987]. Figure 3 plots enrichment factors calculated for each element based on analyses of dacitic ash samples from Augustine. Although it is possible that the bulk composition of the plume particles could differ from the ash by processes of atmospheric fractionation (e. g., selective fallout of denser components), this was not observed. The plots show that most of the analyzed elements are present in essentially the same proportions found in the ash samples. Cl, Br and S (the latter is not plotted) are substantially enriched in the aircraft samples. Because these elements are also most enriched in the filters that trap gases, we interpret this to reflect volatile transport during eruption, by mechanisms similar to those described at volcanic fumaroles [Stoiber and Rose, 1974; Symonds et al., 1987b] and in plumes from fuming volcanoes [Rose et al., 1982, 1986; Casadevall et al., 1984; Chuan et al., 1986] and small eruption clouds [Rose et al., 1980]. A few of the cation species detected in the aircraft samples (Zn, Sb, Cr) may reflect enrichments due to volatile transport, but such enrichments are very slight and contrast strikingly with the large enrichments of many cations detected in plumes from fuming volcanoes [Lepel et al., 1978; Phelan et al., 1982; Zoller et al., 1983]. The small enrichments we observed are probably due to the large ash flux which masks significant volatile enrichment in the erupted gas.



Fig. 2a

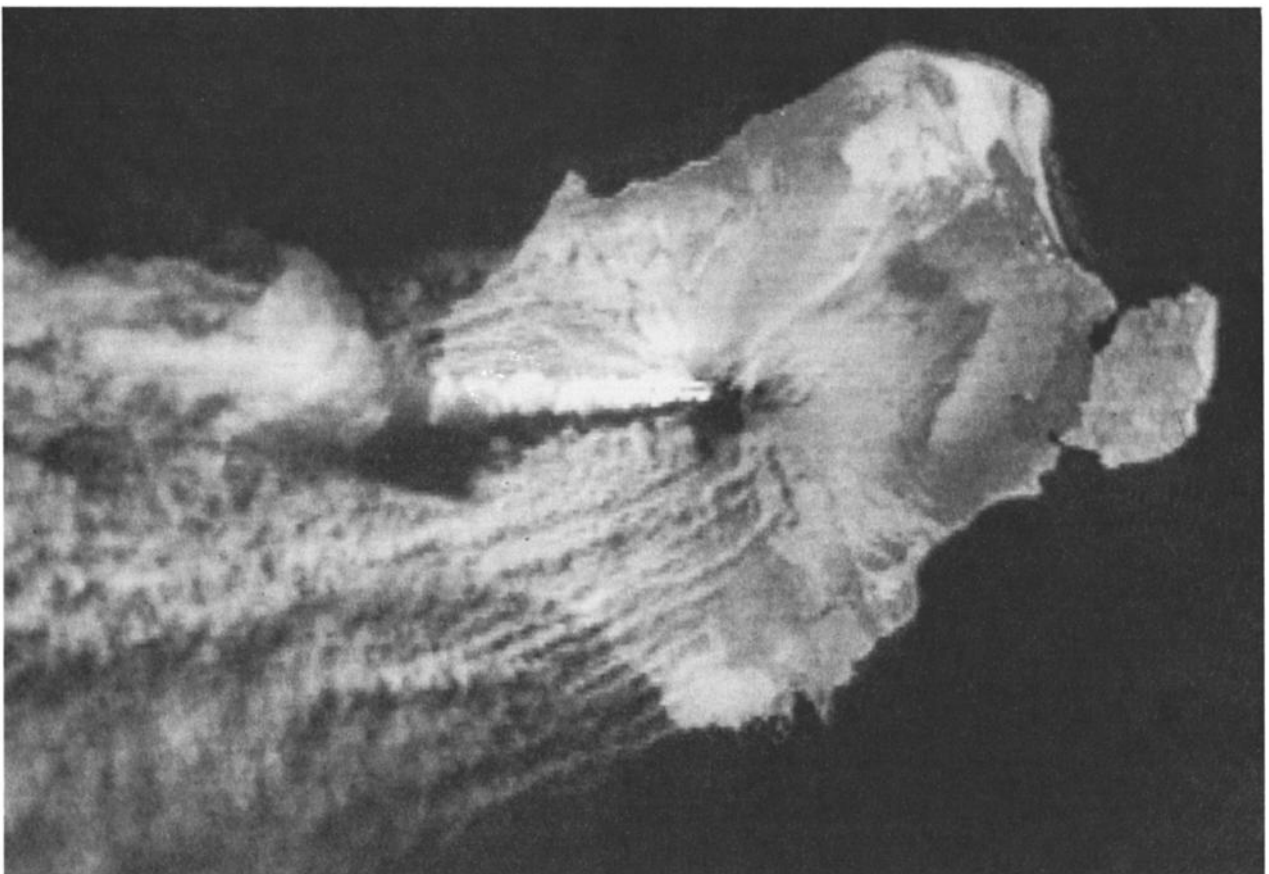


Fig. 2b

Fig. 2. Photographs of Augustine Volcano, 3 April 1986. (a) view from aircraft at 1100 am AST, showing the lee wave dispersion of the eruption plume. (b) Landsat image taken at 1319 AST. Only the SE corner of the image is shown.

TABLE 1. SO₂ Flux From Augustine Volcano Determined by Aircraft Survey With Corretion Spectrometer, April 3, 1986

Traverse Number	Plume Width, km	Time, AST	t/d
2	18.6	1141	19,700
3	20.5	1153	28,400
4	18.1	1205	20,400
5	17.6	1213	24,500
6	18.1	1224	26,100
Mean		24,000 rounded	

Clear visibility, winds 250⁰ at 45 knots (Loran) (22.5 m/s), air speed 155 knots (77.5 m/s).

Highest flux of SO₂ yet measured with Cospec, Kilauea East Rift Zone eruption measurements suggest 18,000 and 27,000 t/d during eruptions [Greenland et al., 1985]; previous Augustine activity in 1976 estimated with different method was 86,000 t/d [Stith et al., 1978].

Observations on previous two days (April 1 and 2, 1986) suggest that the rate of SO₂ emission during the main part of the activity (March 27 to April 2) was higher than the April 3 rate. On April 2, the altitude interval of 5000 to 15,000 ft between Anchorage and Mount Augustine contained about 200 ppm m of SO₂. Although the mass is not well constrained, we estimate it to represent about 70,000 t of SO₂.

Because we measured the relative amounts of elements and specifically measured sulfur dioxide gas, we can calculate estimates of the flux rate of 18 elements by multiplying a ratio (the abundance of each element in the plume divided by the abundance of gaseous S) by the flux

rate of S as SO₂ observed by the Cospec. The proportion of S to Cl in the plume is about 1.2 and the calculated eruptive flux of HCl is therefore 10,000 t/d. This result supports the conclusions of Johnston [1980] who showed that Augustine releases proportionally large amounts of Cl when compared with other volcanoes (see Table 4 for data from other volcanoes). Volcanoes in a convergent plate boundary setting erupt magmas with higher water and Cl contents [Anderson, 1974].

The mass proportions of silicate materials in the plume can be calculated from the concentrations of Sc, Al, Ca, and Ti in the filter samples (Table 3) because these elements are present in the same proportions as they are in Augustine dacite ash (Table 5). From this data we estimate an ash:SO₂ proportion of about 70:1 and an ash emission rate on April 3 of about 1.5×10^6 t/d.

The size distribution of eruption cloud particles (Figure 4) was directly determined with the particle cascade sampler, and the morphology and composition of individual particles were studied in the laboratory using SEM and XES (Figure 5 and Table 6). Results confirm the presence of dacitic ash as a dominant component. Many of the largest particles are shards with a high Si content. There are also numerous Al- and Si-rich, tabular and elongate particles which are probably feldspar. S and Cl are present in barely detectable concentrations, usually as surface coatings of silicate grains. Data from Yount et al [1987] show that the ashes which fell from March 28 to April 3, 1986 contain an average of 0.08% S and 0.11% Cl. The proportions of soluble S and Cl on Augustine ash is also about 1:1. Some halite is observable, either sea salt or volcanic sublimate [see also Rose et al., 1986]. A notable abundance of Fe-rich particles (probably Fe oxide) is mainly associated with aggregates of particles. The SEM observations are consistent with the filter results, showing that the particulate material in the cloud is predominately dacite ash with Fe-rich particles, halite, and some particulate acid. The low amounts of S and Cl observed during the XES study are consistent with the high gas:aerosol proportions for S and Cl indicated by the

TABLE 2. Estimates and Direct Measurements of SO₂ Emission Rates During Volcanic Activity

Volcano	Date	SO ₂ Emission Rate, t/d	Reference
Kilauea	1983-1984	$1-3 \times 10^4$	1
Augustine	April 3, 1986	2.4×10^4	this paper
Augustine	Feb. 13, 1976	8.6×10^4	2
Fuego	1974	2×10^6	3
Mount St. Helens	May 1980	6×10^6	4

¹Greenland et al. [1985]. Based on several measurements during the episodes of the East Rift Zone sequence of 1983-1986. Some of these measurements were probably underestimating the flux because the Cospec signal was saturated.

²Hobbs et al. [1977]. Based on measurements of SO₂ concentrations inside an eruption cloud, measurements of the duration of the explosion, and assumptions about its expansion with time.

³Rose et al. [1981]. An indirect estimate, based on diverse data collected from samples of erupted rocks (melt inclusions, adsorbed volatiles), study of ashes, aerosols, and gases collected within small eruption clouds from the same volcano during low-level activity and various untested assumptions.

⁴Millan et al. [1985]. A very long range Cospec determination made in Toronto as the Mount St. Helens plume traversed North America on June 20-22, 1980, and based on assumptions about the plume geometry.

TABLE 3. Concentrations of Elements (in micrograms m^{-3}) on Filters Collected on April 3, 1986, During 56 Minutes of Flying Inside the Augustine Eruption Plume

Element	Base-Treated Filters		Charcoal Filters	
	Aerosol	Gas	Aerosol	Gas
Na	922		724	
K	325		256	
Cl	29.8	138	30.0	120
Mn	14.3	0.732	10.3	
Ba	23.0		15.3	13.2
Mg	206		210	
Al	1760	1.92	1240	
Ca	764		588	724
Ti	72.4		44.0	
V	2.54	0.00432	1.67	
Ga	0.476		0.386	
As	0.0656		0.0732	
Br		0.552	0.058	5.23
Sb	0.00964	0.0325	0.0160	0.030
La	0.440	0.0778	0.348	
Sm	0.106	0.0008	0.0876	
Yb	0.0808	0.0490	0.0544	0.0440
Lu	0.00996		0.00992	
W			0.48	0.0686
Sc	0.334	0.001	0.254	0.002
Cr	1.05	0.476	0.664	0.492
Fe	984	0.940	736	11.2
Co	0.330	0.099	0.248	
Zn	1.18		0.998	1.87
Rb	0.624		0.464	
Cs	0.0186			
Ce	0.976		0.768	0.0822
Eu	0.0292		0.0306	
Tb	0.0256		0.0212	
Hf	0.166		0.144	0.021
Ta	0.0128			
Pa	0.118		0.0968	0.0034
Ag		0.0114		
Sr				20.3
S	17.1	159	16.6	*

*Only particulate sulfur could be determined.

filter samples. Thus the high proportion of volcanic ash dilutes the aerosol S and Cl to low concentrations.

Meteorology and Plume Dispersion Modeling

Having measured the emission rate and using appropriate weather data, it is possible to model dispersion. We wanted to accomplish this to allow for ground-truth calibrations with satellites. Although only raw imagery from the weather satellites is presently available, we feel that detailed examination could develop a quantitative satellite monitoring ability for both SO_2 and volcanic ash. It is especially important to calibrate the concentrations of ash and SO_2 with the satellite data, and dispersion modeling provides a way to convert ground-based measurements to a larger-scale plume/concentration map.

The eruption of April 3, 1986, occurred under a northwesterly airflow on the backside of a dissipating low-pressure system in the Gulf of Alaska. The pressure gradient was reasonably strong, giving rise to a vigorous west-northwesterly wind of 7-10 m/s in the lowest

kilometer of the atmosphere and increasing to 20 m/s at the 500 mbar (6 km) level.

The 1000 mbar (surface) pressure map and the 500 mb map at 0140 Alaska Standard Time (AST), April 3, are shown in Figure 6. The sequence of positions of the low-pressure center at 12 hour intervals is shown in the 1000-mbar map. The low traveled east-northeastward at an average speed of 8 m/s over the previous 72 hours. During the course of the period, winds in Cook Inlet evolved from southerly in advance of the storm through easterly, northerly, and becoming northwesterly at the 1400 AST map time.

The plume transport is governed by the winds in the volume of atmosphere occupied by the plume. In order to estimate this factor, we need to know the plume altitude, since the winds vary quite dramatically with height. The April 3 plume was sheared off at approximately the top of the volcano itself, 1227 m (Figure 2). Should it be considered an elevated plume at 1-1.5 km above the sea surface?

Figure 2 shows a distinct train of vertical oscillations (waves) in the plume as it travels downwind. In order to understand the plume transport we explored the conditions under which such waves are expected to develop.

Linear theories describing the important properties of mountain waves were developed in the 1940's [Lyra, 1943; Queney, 1948; Scorer, 1949]. For real, finite-sized obstacles in the boundary layer of frictional fluids, nonlinear analyses as described by Long [1955] or laboratory simulations have also been applied. For our purposes it is enough to recognize that air displaced vertically over an obstacle in a stable atmosphere will encounter a buoyant restoring force and will oscillate at the Brunt-Vaisala frequency:

$$N = \left[\frac{g}{\theta} \frac{\partial \theta}{\partial z} \right]^{1/2}$$

where θ is the potential temperature, g is the acceleration of gravity, and z is the vertical dimension. If

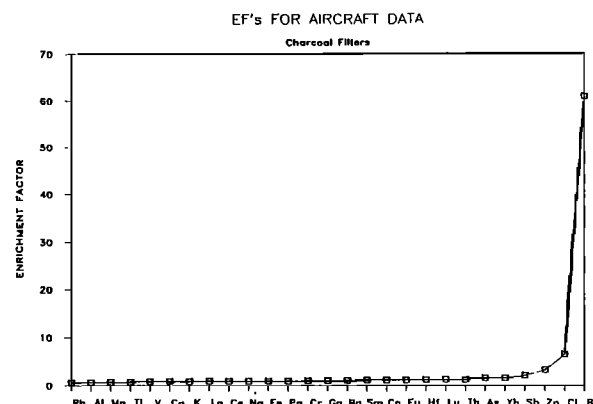


Fig. 3. Calculated enrichment factors (EF) or the charcoal sample pack collected on April 3, 1986. Enrichment factors are calculated for each element based on the ratio of that elements concentration to the Scandium concentration divided by the same ratio for Augustine dacite, as determined from the analyses of airfall ashes (Table 5). Except for Br, Cl, and a few very slight enrichments in other elements, the flat shape of this plot indicates that the eruption plume of April 3 was dominated by dacite ash, and the large enrichments of certain metals detected in volcanic plumes are absent (see text for discussion).

TABLE 4. Comparison of Some Measured and Estimated Rates of SO₂ and HCl Emission Rates at Various Volcanoes at Different Eruptive States

Volcano	Date	SO ₂ , t/d	HCl, t/d	Reference
<u>Non-eruptive Activity</u>				
White Island	Nov. 1983	1200	415	Rose et al. [1986]
Masaya	1979–1985	1275	830	Stoiber et al. [1986]
Augustine	July 24, 1986	380	8000	this paper
St. Helens	Sept. 16, 1981	250	300	Gerlach and Casadevall [1986]
<u>Eruptive Activity</u>				
Augustine	March to April 1986	375,000	160,000	Table 8
Fuego	Oct. 1974	2 × 10 ⁶	40,000	Rose et al. [1981]; see also footnote 3 in Table 2
St. Helens	May 1980	6 × 10 ⁶	?	Millan et al. [1985]; see also footnote 4 in Table 2

the parcel is transported downwind by a net velocity U while it is oscillating, it will describe a wave pattern with wavelength $\tau = 2\pi U/N$. An important dimensionless parameter that describes the ratio of inertial force to buoyant force, and therefore properties of vertically displaced flow in stable atmosphere, is the Froude number, $F = U/Nh$. U is the upstream wind speed and h the height of an obstacle. Hunt et al., [1978] present laboratory simulations of flows at a range of Froude numbers. At $F < 0.5$ the flow separates from the lee side of a circular hill. At $F > 1$ the lee wavelength is long compared with the obstacle dimension, and separation occurs. However, between those values the flow hugs the hill contour, as shown in Figure 7. Notice at $F = 0.8$ a second wave node is present at about one hill diameter downstream, similar to the pattern shown in Figure 2.

Meteorological data can be used to confirm similar Froude numbers. Analyzed large-scale meteorological data from the 2.5° resolution northern hemisphere grid were available, and we selected the grid point nearest in space and time to the Augustine eruption: 60°N, 152.5°W and 1500 AST on April 3. The temperature profile in the lowest 1500 m gives $N = 0.012\text{ s}^{-1}$, $U = 8.5\text{ m s}^{-1}$. With $h = 1227\text{ m}$, these values yield $F = 0.6$, equivalent to those shown between Figures 7a and 7b. The large-scale meteorological data are smoothed and not necessarily representative of the local conditions at the time of the photograph in Figure 2. The large-scale gridded wind speeds are lighter than were actually occurring at Augustine during the eruption. Wind speeds downwind of Augustine were measured by the LORAN aboard the aircraft at 22 m s^{-1} . How does this speed influence our estimate of the Froude number and the observed wavelength? The observed wavelength appears to be $8\text{ km} \pm 2\text{ km}$ from the aerial photographs. For comparison, $\tau = 2\pi U/N = 2\pi(22)/(0.012) = 11\text{ km}$, quite good agreement. The corresponding Froude number is 1.5. Thus we feel that our data and observations constrain a consistent model.

We note that the wave motion (Figure 2) undergoes some decay due to a turbulent mixing beyond the second

node. We estimate the effective source to be uniformly mixed between sea level and 1.2 km altitude. In that layer, the mean wind direction from the gridded analysis is from 297° with a directional shear of 8° between sea level and 1500 m. In addition to the lateral spread due to mixing within the shear from sea level to the top of the plume, we must consider horizontal growth due to horizontal turbulence processes. The empirical relationship derived by Heffter [1965] is remarkably simple and difficult to improve upon for mesoscale horizontal spread. We will adopt:

$$\sigma_y = 0.5 t \text{ (s)} \quad (1)$$

where σ_y is the lateral standard deviation of a quasi-gaussian concentration distribution. This adds another 5° to the lateral spread. With the lateral and vertical dimensions of the plume estimated out to 6 hours of travel, we have enough information to estimate air concentrations, provided that we have an estimate of source strength. Applying the gaussian plume dispersion formula for a plume mixed uniformly in the vertical from 0 to $L = 1200\text{ m}$:

$$C/Q = [1/\sqrt{(2\pi)\sigma_y LU}] \exp \{ -0.5[y/\sigma_y]^2 \} \quad (2)$$

Substituting for σ_y , L , and U into (1), we arrive at a simple expression for the axial concentration at a downwind distance, x :

$$C \text{ (kg m}^{-3}\text{)}/Q \text{ (kg s}^{-1}\text{)} = 6.6 \times 10^{-4} x^{-1} \text{ (m}^{-1}\text{)} \quad (3)$$

Since we introduced a dimensional empirical relationship for σ_y , we must be very careful to use mks units in applying (3). Using the estimated SO₂ emission of 24,000 t/d (280 kg s⁻¹):

$$C(\text{SO}_2) = [(280)(6.6 \times 10^{-4})]/(9 \times 10^4) = 2 \times 10^{-6} \text{ kg m}^{-3} \approx 1 \text{ ppm (by volume)}$$

TABLE 5. Bulk Chemistry of Ash Samples Using INAA

Element	Ash A	Ash K	Ash 1A
Na	30,600	30,500	31,300
Cl	1,087	919	1,090
K	12,200	9,560	12,700
Mn	426	580	630
Ba	864	521	626
Mg	12,500	28,300	---
Al	77,700	78,600	79,200
Ca	37,400	40,000	29,800
Ti	5,720	2,730	2,420
V	91.8	133	85.7
Ga	10.8	16.3	16.8
As	3.04	1.68	3.00
Br	5.17	3.36	4.18
Mo	4.49	---	---
Sb	1.12	5.06	1.18
La	15.0	13.1	16.6
Nd	17.9	13.5	14.3
Sm	3.80	3.61	3.41
Yb	2.79	2.64	2.83
Lu	0.376	0.362	0.360
W	1.23	---	---
Au	9.50 ppb	5.00 ppb	7.15 ppb
Np	1.88	1.45	2.08
Sc	11.3	18.9	12.2
Cr	23.0	51.1	29.9
Fe	32,400	50,100	34,200
Co	9.87	16.7	9.64
Zn	111	55.6	41.6
Sr	300	350	258
Rb	31.4	25.2	33.3
Ag	0.877	---	---
Sn	---	216	---
Cs	0.692	0.603	1.01
Ce	31.7	18.8	36.3
Eu	0.985	1.04	1.17
Tb	0.715	0.675	0.763
Hf	5.15	4.18	5.34
Ta	0.436	0.346	0.483
Hg	---	0.228	---
Pb	3.66	3.07	4.43

Concentrations are in ppm, unless otherwise noted. Locations of ash samples are ash A; a cumulative sample (March 27 to April 2) collected near Anchorage; ash K; collected on March 28 near Kenai; and ash 1A; a cumulative sample (March 27 to April 1) collected in the NE area of the Kenai Peninsula.

in the vicinity of the Barren Islands, 90 km downwind. Figure 8 shows the concentration isopleth for $C(\text{SO}_2) = 1 \times 10^{-6} \text{ kg m}^{-3}$. Our flux determination can also be used to estimate the maximum concentrations of silicate ash within the contours in Figure 8 at about 125 and $63 \times 10^{-6} \text{ kg/m}^3$. We expect that the application of this dispersion model can be used for calibration of satellites which detect volcanic plumes [Krueger, 1983; Matson, 1984] and detailed study of the relevant images has already begun.

Results of July 1986

In July 1986, more than two months after the explosive phases of activity, Symonds et al [1987a] sampled gases

and condensates at high-temperature vents on the summit of Augustine and again made an airborne Cospec rate measurement. The conditions at that time were typical of those that prevail following major eruptions when the vent is freely fuming and emitting gases, and there was some extrusion of lava, but little or no eruption of ash. The Cospec results are in Table 7. The SO_2 emission rate was 380 t/d, about 1.6% of the April value. Visual observations suggest that the ash content of the plume was low. The HCl flux of the plume in July can be estimated at 8000 t/d, based on gas sampling and the Cospec data. Thus the S/Cl ratio of the July plume (0.03) was lower than on April 3 (1.15). The July gas condensates also contained conspicuous enrichments of metals (Zn, Cu, B, Mo, Fe, Pb, Na, Al, Ca, As, Zr and V), which could not be detected, probably because they were masked by the large ash flux during the April eruption.

Bulk Chemistry of Ash

We analyzed bulk samples of ash that fell at locations from 60 to 200 km from the volcano within the period of March 28 until about April 3. Because of their wide dispersal, these samples represent materials erupted during the highest columns and probably also the highest eruption rates. Neutron-activation analyses of these samples are listed in Table 5, and we also compared XRF determinations of Yount et al [1987] on similar materials. All are compositionally similar and also closely resemble the 1976 pumices.

Discussion

We are interested in whether our data are representative of explosive eruptions. Because the most detailed direct measurements to date have been made either on non-eruptive plumes [Rose et al., 1986], on very small eruptions (much smaller than the 3 April activity at Augustine) [Rose et al., 1980] or at the extreme periphery of a large cloud [Hobbs et al., 1981], it is unclear whether the samples taken reflect conditions prevailing during the most intense eruptions when most material is released and when sampling is most difficult

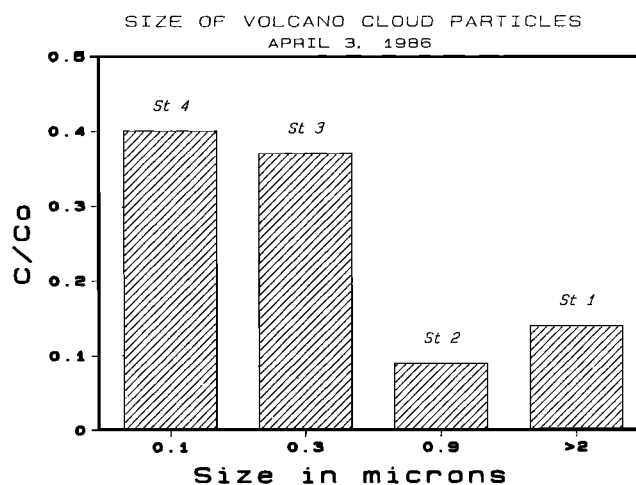


Fig. 4. The size distribution of particles that accumulated on the four stages of the Quartz Crystal microcascade sampler used on April 3, 1986. The size listed along the bottom of the figure is the 50% cutoff of isodynamically separated sizes [Chuan, 1975], assuming a density of 2 g/cm^3 . The proportion of the total mass C/C^0 is plotted on the y axis.

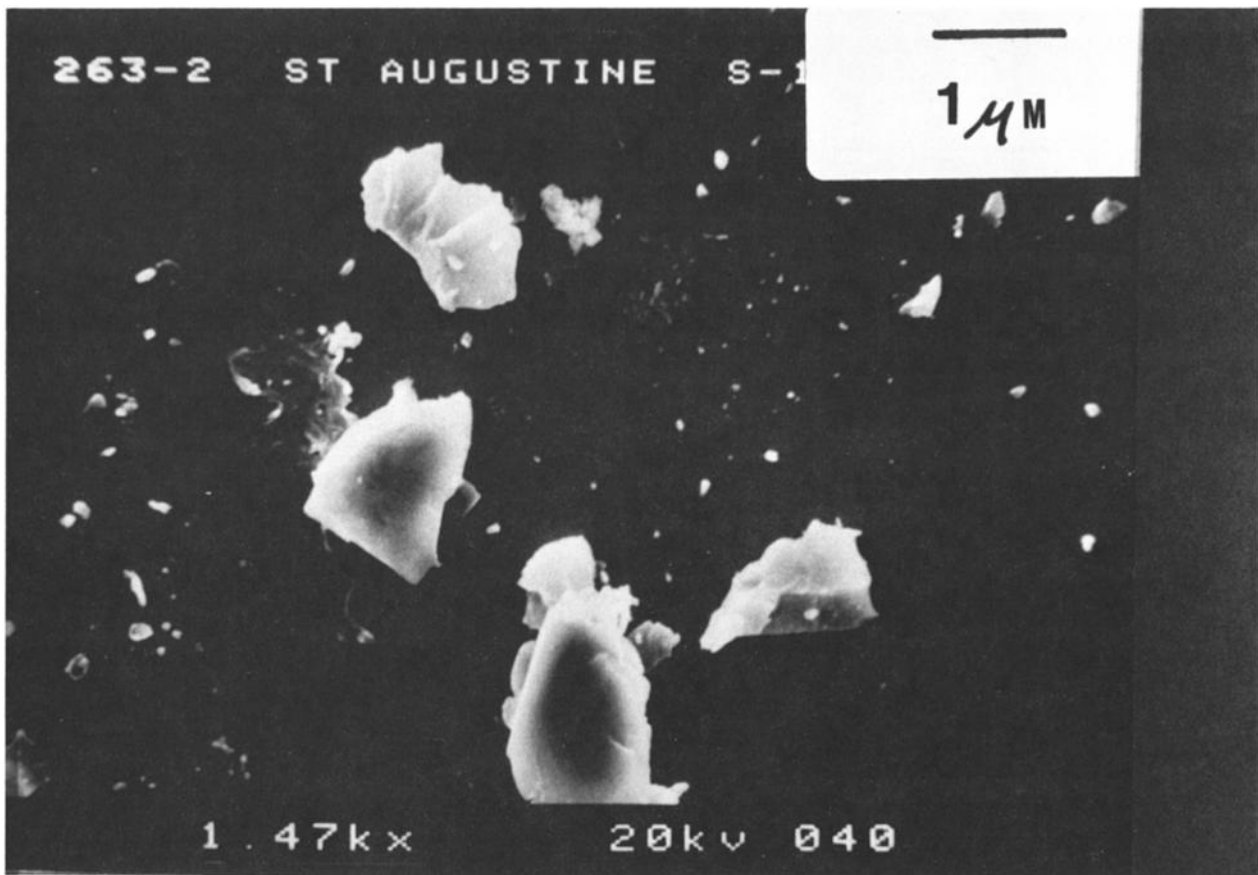


Fig. 5a

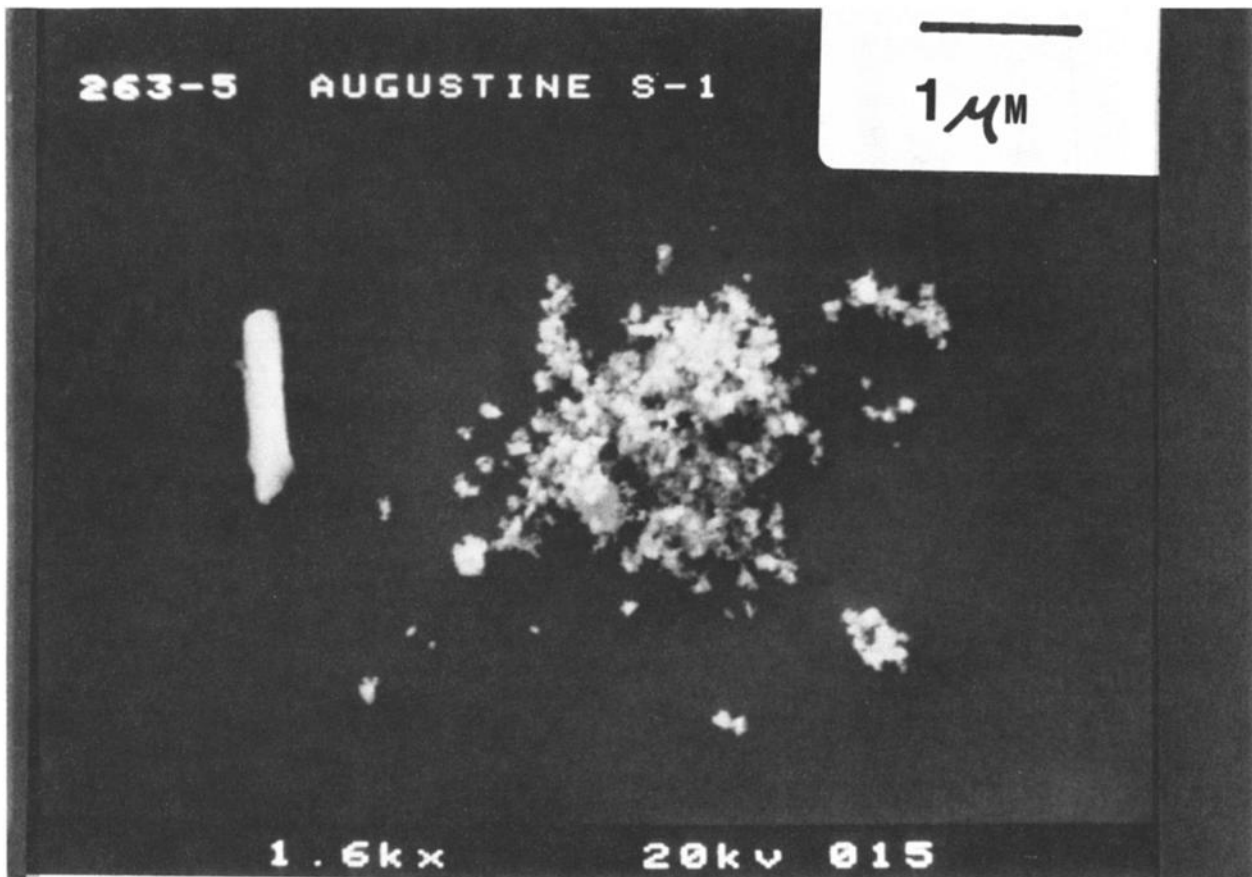


Fig. 5b

Fig. 5. Scanning electron microscope images of ash particles collected on the QCM at Augustine, April 3, 1986. (a) Some larger fragments of silicate material. (b,c, and d) Interpreted as aggregates which broke upon impact. See Table 6 for compositional information. S-1, stage 1; S-2, stage 2.

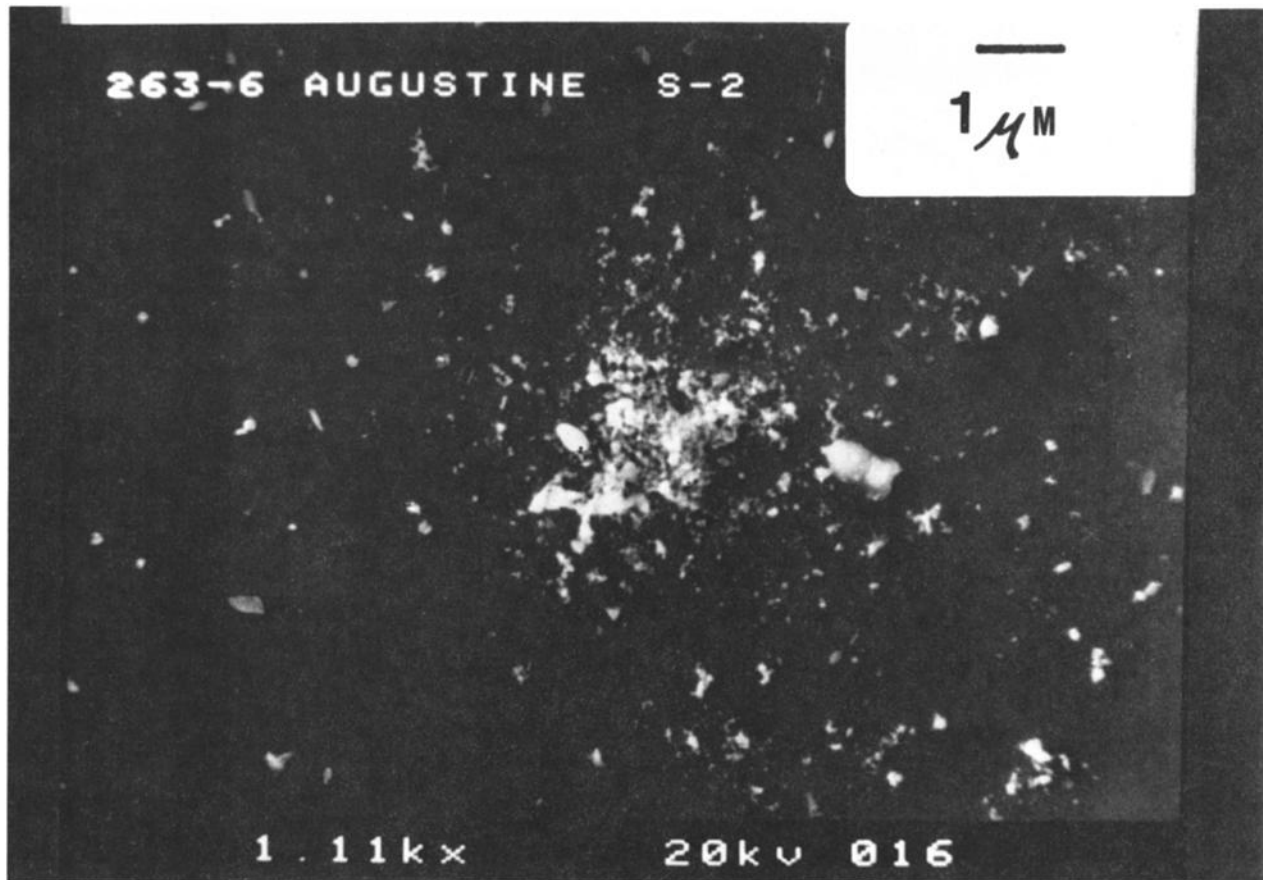


Fig. 5c

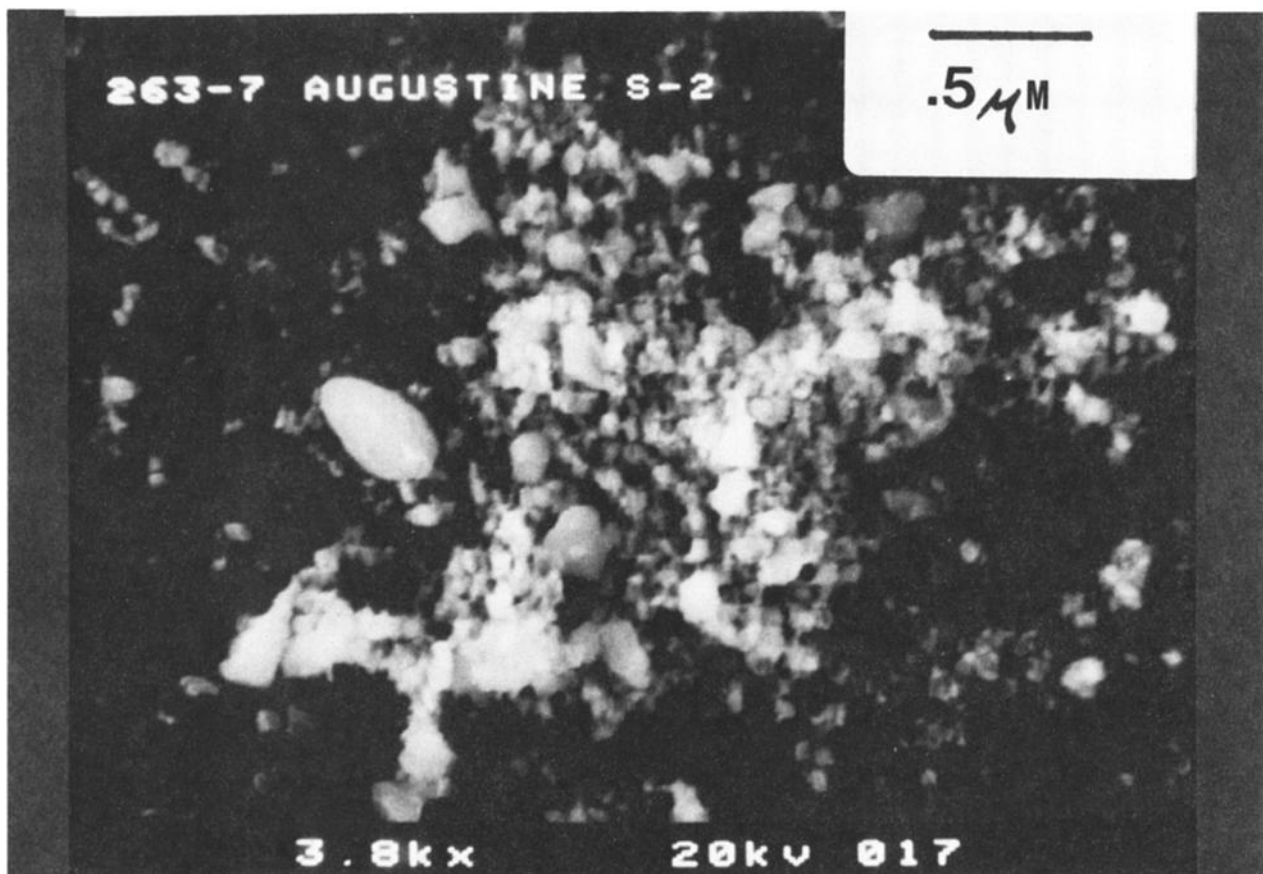


Fig. 5d

TABLE 6. Summary of SEM Observations of Eruption Cloud Particles Sampled in the Augustine Plume of April 3, 1986 With Quartz Crystal Microcascade

Stage	Nominal 50% Cutoffs, m	Observed Sizes, m	Comment
1	>2	15x25 to 2x2	Silicates (glass or lithics), with S and Cl
2	0.4-2	mostly 1-2, aggregates to >5	Silicates (glass xtals) with high Cl and S, NaCl, agg. rich in Fe
3	0.2-0.4	0.3-2	Silicates (shards, plag, amph)
4	0.05-0.2	0.1-2	Silicates with Cl, S

Particles were collected with the QCM during the same period as filter sampling, following the COSPEC traverses.

Unlike most plume samples during inactive fuming, all stages in this sampling are dominated by silicates. The particles are very fine grained and poorly sorted. Acid droplets are not obvious, probably flooded and scavenged by the silicates. High by the silicates. High S and Cl in the samples account for several % by wt of the particles. Some of the Cl is probably NaCl, perhaps sea salt. The ash is actively aggregating before sampling, and many aggregates are preserved. Cores of aggregates are Fe-rich (magnetite?). Silicates include weathered lithics (larger), shards, plagioclase and, amphibole (or px?), in the proportion expected.

and dangerous. Although the new data represent much more energetic activity than has been measured well before, they nonetheless represent a relatively low eruption rate compared with the most intense episodes of the eruption. The ash eruption rate estimated above (1.5×10^6 t/d) is slightly higher than those of the weak eruptions of February 1976 which were sampled by Hobbs et al. [1977]. By contrast, the eruption rates during the peak of the 1976 eruption were probably in the range of 10^8 t/d or more, based on the volume (0.186 km^3 DRE, [Kienle and Swanson, 1985]) and its duration of about 3

days. The March-April 1986 eruption may have involved similar eruption rates, although it seems from the descriptions and data available that it was somewhat smaller in volume. The value 10^8 t/d is about 50 times the rate estimated on April 3, 1986, so it is clear that we need to consider how to scale the eruption cloud parameters by a large factor. Specifically we must evaluate whether the proportions of materials we measured are likely to apply at the peak of the eruption.

Table 8 compares plume characteristics at different stages of activity at Augustine, based on the eruption

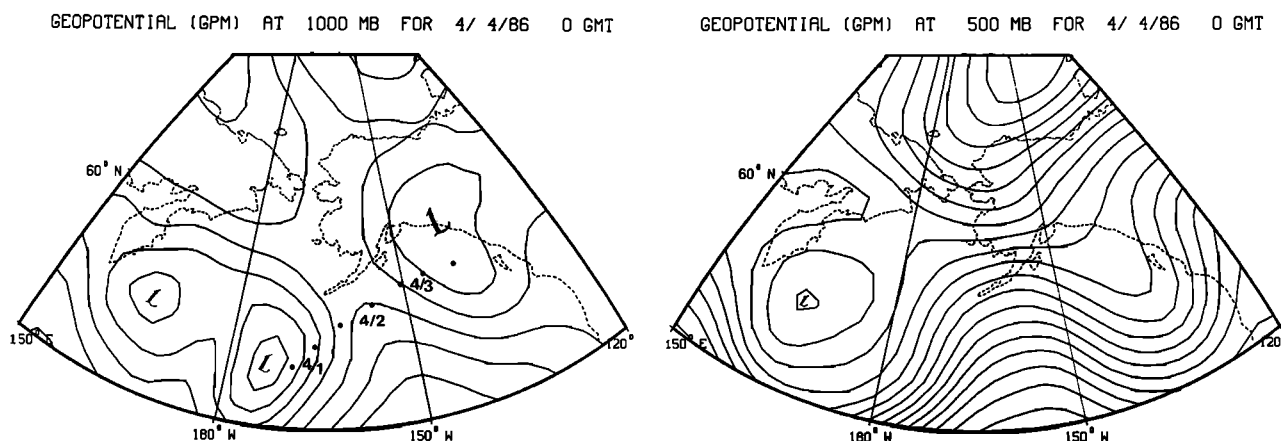


Fig. 6. Geopotential maps at 1000 mbar and 500 mbar for 1500 AST, April 3, 1986.

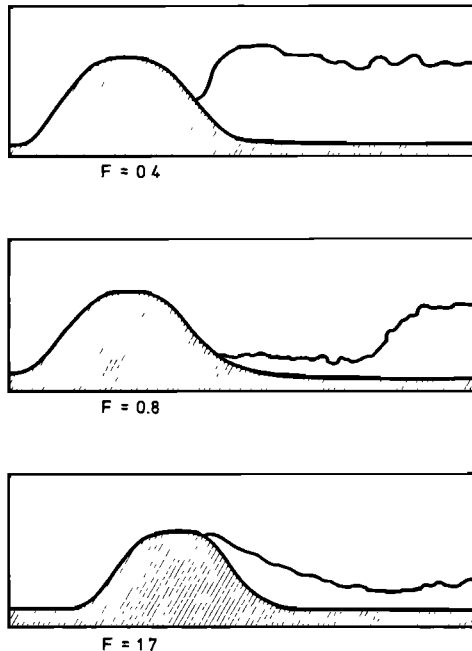


Fig. 7. Tracings from shadowgraphs of stratified flow in a water channel. The cross-hatched area is a cylindrically symmetrical obstacle. The irregular area downwind of the obstacle is a disturbed wake flow [from Hunt et al., 1978]. F is Froude number.

cloud samples, bulk ash analyses, and Cospec results. It includes estimates of some proportions of ash and gaseous components during the most explosive activity. To derive the final column of the table, three assumptions labeled and discussed below were made.

The gas/aerosol ratios for S and Cl that we measured are similar to results for other volcanoes [Lazrus et al., 1979; Kotra et al., 1983; Stoiber, et al., 1987]. The available data thus suggest that in eruption clouds and plumes, aerosol S and Cl make up about 1–10% and 5–20% of the S and Cl gas flux, respectively.

Assumption 1: We assume that these percentages are also representative of intense eruptive activity. If this is true, we can use ash leachate data to constrain the amounts of gas in eruption clouds when we lack direct measurements, by using a factor multiplier. During its open vent, fuming state, the volcano is not emitting ash but has a concentrated plume of H_2O , SO_2 , HCl , HF , and other gases, with a low S/Cl ratio (<0.1). During low-level activity, such as on April 3, the ash emission rate is moderate and the concentrations of SO_2 and HCl together amount to about 2% of the mass of ash being emitted.

Direct visual observation of the height of the eruption cloud shows that the intensity of activity we measured on April 3 was much lower than the peak activity between March 27 and April 2. In order to scale our measured data to the maximum eruption rates, seismic data were consulted. Magnitudes of explosion earthquakes during the 9 days varied over more than an order of magnitude (Figure 9), and the detail of that record is better defined than actual observations of the eruption column. The most intense explosions were about 50 times more energetic based on the magnitude of explosion earthquakes.

Assumption 2: We used a factor of 50 to scale up the ash flux from "low level" to "eruption peak" (Table 8). Wilson et al [1978] have shown that the column height (H)

during a pyroclastic eruption is roughly proportional to its eruption rate (Q) by an equation $H = 236.6 Q^{1/4}$. An eruption rate of 7.5×10^7 t/d of ash would approximately correspond to a column height of 8–10 km, a height observed on several occasions between March 27 and April 2 [Yount et al, 1987]. To scale the amounts of S and Cl during the peak of eruption, however, we will not use a factor of 50 because the ashes that fell at Homer, Kenai, and Anchorage contain less S and Cl than the samples acquired within the plume on April 3, and we believe that the proportions of gas to ash in the most explosive eruption clouds may be lower than the April 3 cloud.

Assumption 3: We assume instead that during the eruptive peak the SO_2 mass flux was 0.5% of the ash flux, which is a value consistent with results obtained from study of melt inclusions [Johnston, 1978], and that the S and Cl emission rate was only about 16 times the low-level rate. We estimate that SO_2 and HCl gas make up no more than about 1% of the mass of ash released in the most explosive part of the eruption, and that the S/Cl ratio of that mixture is >2 .

As first pointed out by Johnston [1980], Augustine's high Cl releases highlight interest in quantifying the natural flux of Cl to the atmosphere. A central point here is whether the high Cl content of the magma is of deep-seated origin or whether it is somehow related to influx of seawater through an underground aquifer. The location suggests the latter possibility, as does the interpretation of seismicity by D. J. Lalla (thesis in preparation, 1980). Johnston's work showed that the high Cl content was recorded in melt inclusions trapped within

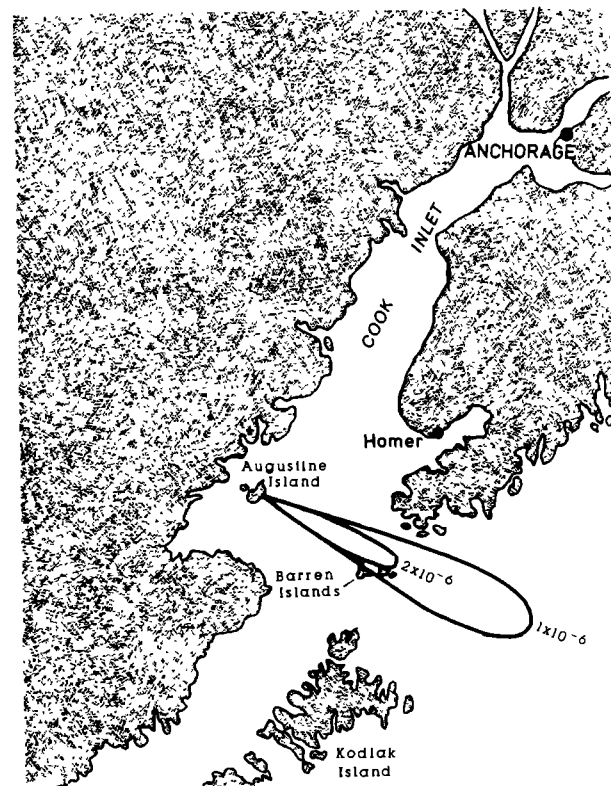


Fig. 8. Estimated concentration isopleths for $C = 1, 2 \times 10^{-6}$ kg/m³ of SO_2 emitted from Augustine, assuming a constant emission rate of 280 kg/s and the geopotential shown in Figure 6. Determined by plume dispersion model explained in text.

TABLE 7. Results of Aerial Cospec Survey at Augustine Volcano July 24, 1986

Traverse Number	Time, UT	Traverse Elevation, ft	Plume Width, km	Average, ppm m	Flux, t/d
3	1252	500	5.1	130	393
4	1257	500	5.4	99	315
5	1304	500	7.1	78	327
6	1310	500	5.1	125	375
7	1317	500	6.4	103	391
8	1324	500	6.8	103	414
9	1331	500	6.7	109	431

All measurements done flying perpendicular to the plume at 97-108 knots. The wind speed used in flux calculation was 5 knots. The reported winds for Anchorage (at 1135) were 240⁰ at 07 knots for 3000 ft and 240⁰ at 09 knots for 6000 ft. The measured winds (using the Loran C) in the Augustine area were 200 at 05 knots (at 1230) for 2000 ft and 220 at 04 knots (at 1405) for 3000 ft. The lack of turbulence during the measurements is consistent with wind speeds less than 7 knots.

phenocrysts of the dacite, showing that the Cl entered the system before crystallization was complete. This suggests that the Cl may come from a deeper source. Anderson's [1974, 1982] work demonstrated that many other convergent plate boundary volcanoes, including some rather far from the sea, also have high pre-eruption Cl. It is important to know how general high Cl releases are for explosive volcanoes, because of its possible role in the atmospheric ozone degradation.

Rose et al. [1983], Sigurdsson et al. [1985] and Woods et al. [1985] have presented data allowing minimum estimates of the Cl release of some recent explosive eruptions. Although Cl releases from basaltic volcanoes are sometimes very minor [Anderson, 1974], magmas of intermediate or high silica content release much larger amounts, often subequal to or exceeding the S releases regardless of their proximity to the sea. In view of the frequency of intermediate silica eruptions, we assert that volcanic contributions of Cl to the atmosphere may be of

significance with respect to the world industrial production of Cl-bearing compounds, a conclusion first suggested by Johnston [1980].

Another question raised by the high Cl content of the Augustine gases is the chloro- and fluorohydrocarbon releases and the releases of other halide species. We have no direct data on the amounts of these compounds, but mass action considerations suggest that such species should be much more abundant in gas mixtures rich in HCl. Because the enrichment of halogen-bearing gases in the stratosphere is possibly related to the ozone hole phenomenon and also to greenhouse warming, we need to know the magnitude of natural releases.

The low enrichments of cations observed in the Augustine eruption materials (Figure 3) should be considered by those who have suggested that the occurrence of both shocked minerals and enrichments of Ir and other elements in the K/T boundary materials are consistent with explosive volcanism [e.g. Carter et al.,

TABLE 8. Scaling Up Emission Rates During Eruptions, Data From St. Augustine Volcano, Alaska

	Fuming Vent*	Low Level Eruption†	Peak of Eruption‡
SO ₂ flux, t/d	380	24,000	375,000
HCl flux, t/d	8,000	10,000	160,000
Ash flux	0	1.5 x 10 ⁶	7.5 x 10 ⁷
SO ₂ /HCl	0.05	2.4	2.4?
SO ₂ /ash, %		1.5	0.5
S gas/aerosol	?	10	10
Cl gas/aerosol	?	4	4

*Data from July 24, 1986 [Symonds et al., 1987a,b].

†Data from April 3, 1986.

‡Scaling up assumptions applied to seismic data, ash fallout and observations, and theoretical considerations (see text).

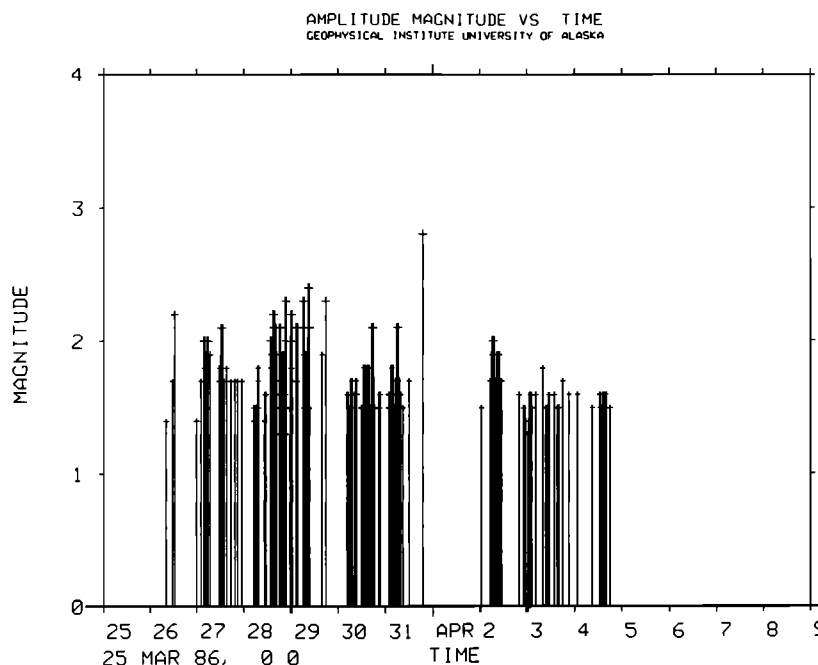


Fig. 9. Plot of explosion magnitudes as measured by seismic station OPT, 28 km north of Augustine (from J. Power and J. Davies, Geophysical Institute, University of Alaska, personal communication, 1987. Times are in GMT.

1986]. Even the very Cl-rich eruptive gases of Augustine do not produce large enrichments of cations because of the large ash volumes, which mask the gaseous component. Either low-level explosive degassing activity [Phelan et al., 1982] or effusive activity with little volcanic ash [Zoller et al., 1983] is a much better condition for highly enriched volcanic emissions than highly explosive eruptions. Thus the combination of highly dispersed ash and highly enriched volatile metals seems unlikely.

A logical extension of this study is to test our dispersion model (Figure 8) with satellite images. We know, for example, that some weather satellite images of the March 27 to April 4, 1986, period show plumes with about the same shape and extent. In the future we will attempt to calibrate the weather satellites and the TOMS/Nimbus 7 instrument, so that we can get a quantitative estimate of plume concentrations, for both ash and SO₂, directly from the satellite data. We hope that this Augustine research will be the first step toward that long-term goal.

Conclusions

1. The Augustine eruption released 1.5×10^6 t/d of ash, 24,000 t/d of SO₂, and 10,000 t/d of HCl on April 3, 1986 during low-level activity. Peak eruption rates, achieved (or exceeded?) several times during the 9-day eruption, are estimated at 7.5×10^7 t/d of ash, 375,000 t/d of SO₂, and 160,000 t/d of HCl.
2. The 1986 eruption of Augustine Volcano released proportionally large amounts of Cl, approximately equivalent to the S released and about 0.2 wt % of the magma volume. We do not know how many volcanoes release similarly high amounts of Cl to the atmosphere.
3. The relative proportion of gases to silicates in eruption clouds decreases sharply as the intensity of activity increases, and this relationship must be quantified to enable us to accurately estimate eruption rates of gases.
4. The gas/aerosol proportions of S and Cl in the

low-level Augustine eruption cloud were about 10:1 and 4:1, respectively.

5. Lee wave phenomena during eruptions or plume emissions allow constraints on dispersion models which may allow for more precise modeling. Such models are needed to calibrate satellites which detect ash and SO₂ clouds to allow ash cloud movement and fallout forecasts.

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