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A METHOD FOR CHARACTERIZING VOLCANIC ASH FROM THE DECEMBER 15,1989, ERUPTION OF REDOUBT VOLCANO, ALASKA

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ABSTRACT

The development of an automated program for characterization of particles using a scanning electron microscope (SEM) with an energy dispersive X-ray detector (EDS) has greatly reduced the time required for analysis of particulate samples. The SEM system provides a digital representation of all particles scanned such that further measurement of the size, shape, and area are a product of image processing. The EDS and associated software provides information as to the particles' chemical composition. Data obtained from the SEM by this method are reduced by computer to obtain distribution graphs for size, density, shape, and mineralogy. These SEM results have been tested by comparisons with results obtained by traditional optical microscopy—the results obtained by optical microscopy support the SEM results and provide details concerning crystallinity and glass content.

This method was applied to the ash that damaged the engines from the Boeing 747-400 flight of December 15, 1989 (Brantley, 1990), which flew into the ash cloud from Redoubt Volcano. The sample was collected from the pitot-static system and had not been exposed to any engine parts that might have changed its characteristics. The sample analysis presented here demonstrates the capabilities and information obtainable from our automated SEM technique.

INTRODUCTION

Studies of volcanic ash particles can be used to understand problems associated with volcanic ash clouds such as aircraft engine damage, visibility, atmospheric dispersion, and deposition of ash (Heiken, this volume). By using several analytical techniques, particles can be characterized in terms of size, shape, mass, mineralogy, and chemical composition. These characteristics provide detailed information necessary to understand the nature of volcanic ash clouds.

METHODS OF STUDY

SAMPLE PREPARATION

Loose samples, such as the ash collected from the pitot-static system, can easily be prepared by traditional thin-section techniques. This involves mixing the ash with epoxy on a microscope slide and then polishing flat to a desired thickness. Both the SEM technique and optical microscopy techniques can use the same slide.

If the sample has been collected on filters, it is necessary to remove the particles from the filter medium. For ash collected on cotton or paper filters, the filters can be ashed in a low-temperature radio-frequency oven. The ashing destroys the filter material and leaves the particles unaltered. The particles then can be mixed with epoxy and made into a thin section.

SEM PARTICLE-ANALYSIS PROGRAM

The SEM uses a software program originally developed by L.J. Lee Group, Inc. for identification of airborne asbestos particles. It was modified to analyze volcanic ash particles. For each particle, the size, diameter, area, elemental composition and density are recorded. The location of each particle is also noted for easy return to a particular particle if detailed examination is needed.

TREATMENT OF DATA

The data is first transferred from the SEM into a spreadsheet from which various operations are performed. These operations characterize the particles as to their mineralogy, morphology, densities, and abundances. The spreadsheet and operations are done with BBN Software Products Corporation's RS-1 software program (G. Luedemann and G. Bayhurst, unpub. data, 1989).

Table 1. Mineral definitions used in this report.

[Numbers in definitions column indicate weight percent]

Mineral	Definitions
Quartz	Si ≥ 90
Calcite	Ca ≥ 90
Magnetite	Fe + Ti 2 90
Gypsum/anhydrite	Ca + S ≥ 90; Ca > 41; S > 29
Mica/clay	Ca + K + Al + Si ≥ 80; Fe > 4; K > 4; 23 < Si < 80
Feldspar	Ca + Na + K + Al + Si ≥ 80; Fe ≤ 4; Al + Si > 59; 30 < Si < 80
Amphibole	Fe + Mg + K + Ca + Al + Si ≤ 80; Fe > 5; K ≥ 3; 28 > Si > 80

Using the chemical analysis for each particle, the mineralogy is determined based on seven minerals or mineral classes. If the particle does not meet the criteria of the mineral definitions (table 1), it is labeled as "other." Because the SEM gives only chemical composition and not crystal structure, the glass content of the ash is not available by this method. The particles are then plotted according to the frequency of their mineral content.

The mean diameter, which is based on 16 measurements, is used to establish size frequencies. These size frequencies are calculated for both mineral type and overall bulk particles. The longest diameter measurement and the shortest measurement are ratioed without regard to mineralogy to provide an aspect ratio that gives an indication of shape. Digital image representation also allows computation of a shape factor given as the particle perimeter squared divided by the product of its area and 4 pi.

By using the results from the chemical analysis, we can determine the mass of each particle by combining densities and diameters. The densities are based on values for oxides for each element in the particle such as SiO_2, Na_2O, and CaO. The masses are used in several ways. The mass for each particle can be plotted on a log cumulative mass versus log diameter to give mass accumulation curves. The mass distribution can also be expressed as a percent total versus phi (phi $= -\log_2$ x (diameter in mm)) and analyzed using the sequential fragmentation/transport (SFT) model of Wohletz and others (1989).

The final function of the software is to determine various statistical values for each sample. Our statistics summary contains the mean, standard deviation, minimum, and maximum for several parameters and automatically prints out a summary sheet.

To verify our programs, we prepared chemical-composition standards by grinding well-characterized mineral standards to a fine powder. The powders were then prepared in the exact same manner as the ash particles. To verify our sizing-routine software, we used National Institute of Standards and Technology (NIST) standards for particle size. The software program that identifies minerals from chemical analysis was also tested by using these composition standards, achieving 95 percent or better correct identification.

PETROGRAPHIC METHODS

Several hundred particles were examined and counted by standard petrographic methods on an optical microscope. This method allows us to determine not only the mineralogy of the particle but also if the particle is noncrystalline or glass. The importance of this is that the glass component of the volcanic cloud has a big influence on melting temperatures (Swanson and Beget, this volume).

RESULTS AND DISCUSSION

The mineralogy of the ash particles determined by chemical composition was about 70 percent feldspar. The other components were quartz, magnetite, mica or clay, calcite, and amphiboles (fig. 1). An occasional particle of gypsum or anhydrite was also observed. By using fairly large ranges for defining the minerals or mineral groups, only about 10 percent of the ash was unidentified. The majority of unidentified particles appear to be mixtures of mineral phases that were probably welded on glass fragments. This result suggests that about 10 percent of the sample is composed of lithic fragments.

The optical analysis gives another perspective of the mineralogy in that the glass component can be readily identified. The results from the optical analysis showed that the particles are mostly plagioclase feldspar (46.7 percent), with many of them being fractured. The glass component was second most abundant at 28.6 percent. The following were

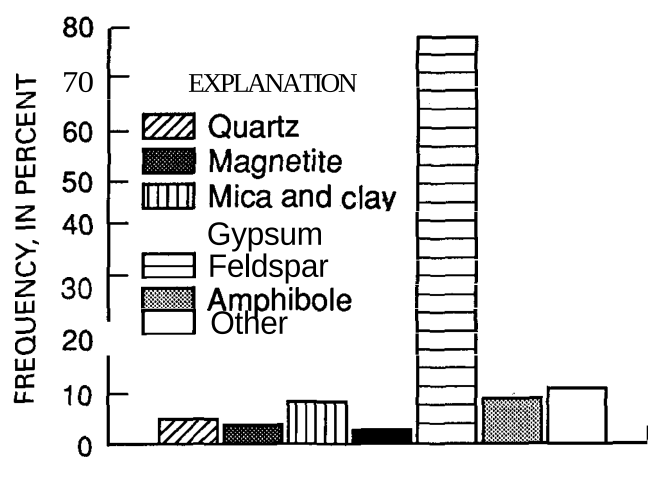

Figure 1. Mineralogy of ash particles from the December 15, 1989, eruption of Redoubt Volcano as determined by scanning electron microscopy.

Table 2. Bulk chemistry of glass from Redoubt volcanic ash from December 15, 1989, eruption.

Species	Weight percent
SiO_2	69.9
Al_2O_3	10.4
FeO	5.0
MgO	0.5
CaO	8.4
Na_2O	4.3
K_2O	0.1

minor components: pyroxene 2.8 percent, hornblendes 4.2 percent, opaque minerals 5.6 percent, altered rock 7.0 percent, and magnetite 5.2 percent. The petrographic name of this sample is a hornblende, two-pyroxene andesite.

If we assume that the glass component has nearly the same chemical composition as the crystalline minerals, then the results of the two methods are in good agreement. For example, if approximately 30 percent of the chemically defined feldspar particles are noncrystalline, then the percentage of crystalline feldspar would be approximately 49 percent.

With our method, we are able to obtain bulk-chemistry compositions by simply averaging each chemical component. For example, the average SiO_2 composition from our Redoubt sample was 69.9 percent. Because of the high glass content, the overall bulk chemistry (table 2) showed a higher SiO_2 concentration than the magma erupted during this time (Nye and others, 1990). This result is, however, consistent with other studies of Redoubt volcanic ash (Swanson and Beget, 1991).

Our sizing routine showed that, for this sample, the majority of the particles were 20 µm or less (fig. 2). The different mineral types can show slight differences in size distribution from the overall distribution, but they still show that most of the particles are smaller than 20 µm (fig. 3). The information obtained from size distributions can provide insight as to the factors controlling the type of damage done to aircraft engines. For example, if the ash encountered had a large percentage of coarse particles, then increased damage from abrasion might be observed. If the ash is fine, it will melt more rapidly and contribute to the material adhering to turbine surfaces.

Aspect ratios can be used for several purposes. The morphology of the particle can be described in this way. Aspect ratios that are close to 1 indicate that the particle is approximately equant in shape. For example, the aspect ratio of the feldspar particles (and glass) showed that about in one-third of them were equant (fig. 4). Also, the average shape factor for the sample is 1.16, which characterizes nearly equidimensional, polygonal cross sections.

The mass distribution curve gives other important information about the nature of the volcanic ash. In our Redoubt sample, even though the small particles were the most numerous, they contributed only a small amount of the mass (fig. 5). Another way of looking at mass distribution is the phi plot (fig. 6). This plot shows that over 60 weight percent of the sample occurs between 62 µm (4.0 phi) and 125 µm (3.0 phi). The overall mean diameter is 78 pm.

SFT analysis shows that the size distribution is polymodal, which is likely a consequence of the various densities and shapes in crystals, glass, and lithics that determine the mass-to-size ratio. Furthermore, SFT analysis (fig. 7) shows a mean diameter of 3.68 phi (0.078 mm) and a standard deviation of 0.79 phi (+0.57 mm, -0.033 mm) and predicts this distribution by three subpopulations: (1) crystals (mode = 0.210 mm), (2) lithic fragments (mode = 0.099 mm), and (3)

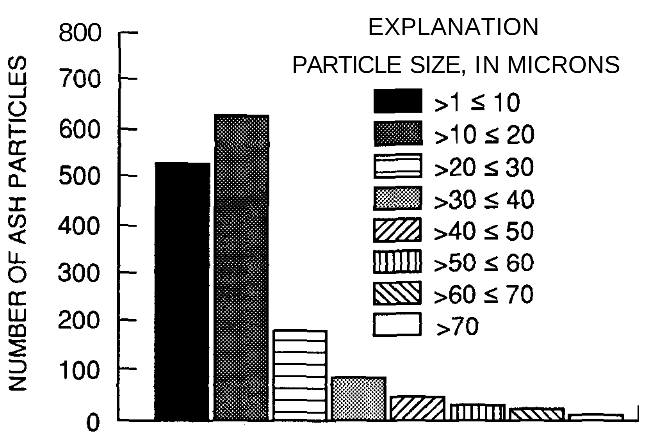

Figure 2. Size distribution of all minerals contained in ash from the December 15, 1989, eruption of Redoubt Volcano.

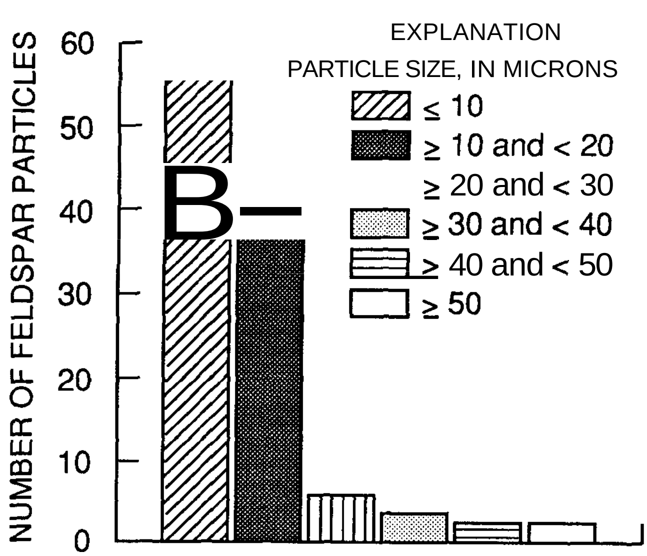

Figure 3. Size distribution of feldspar minerals from the December 15, 1989, eruption of Redoubt Volcano.

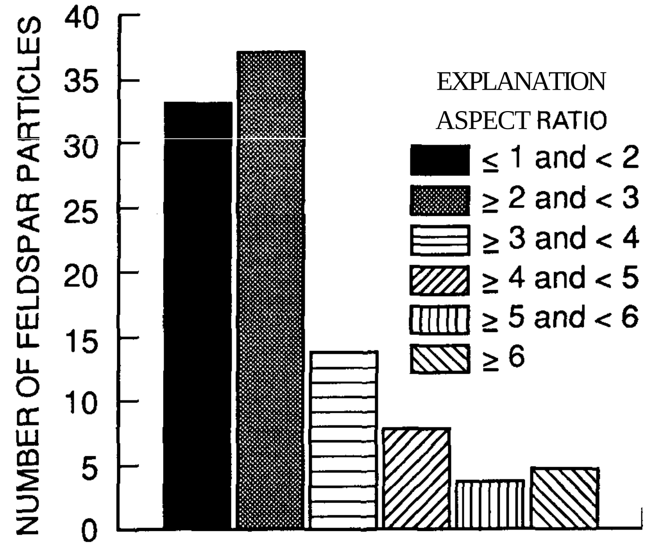

Figure 4. Aspect ratios of feldspar particles from the December 15, 1989, eruption of Redoubt Volcano. Aspect ratio is determined by dividing the longest diameter by the shortest diameter.

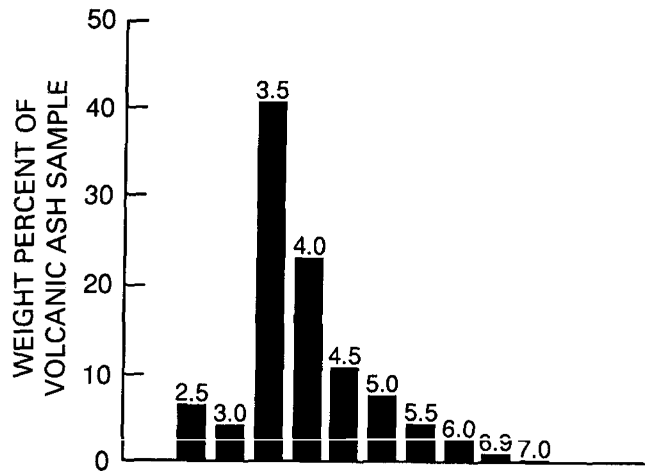

Figure 6. Phi size distribution plot of ash particles from the December 15, 1989, eruption of Redoubt Volcano. Phi = $-\log_2$ x (diameter in mm). Individual bars along x-axis are labeled with size in phi units.

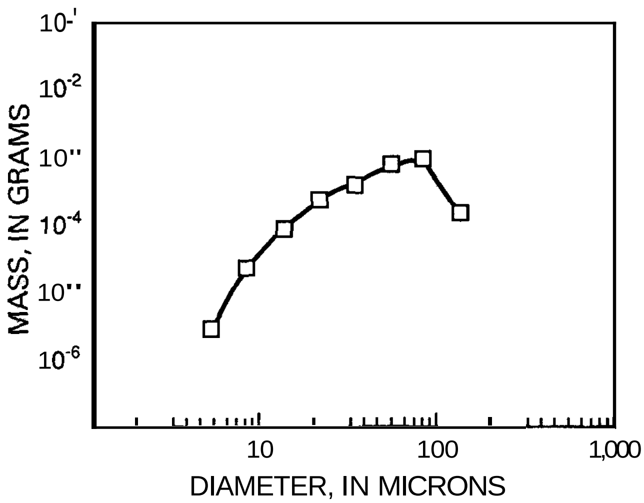

Figure 5. Mass distribution curve of ash particles found in ash from the December 15, 1989, eruption of Redoubt Volcano.

glass (mode = 0.041 mm). The dispersion values of these subpopulations are analogous to standard deviations for log-normal distributions. In addition, the dispersion values have physical significance: with increasing dispersion, subpopulation distributions are generally more peaked, which results from more evolved particle fragmentation and size sorting. The crystal subpopulation (1) has a dispersion value of 0.50, which reflects the tight distribution in size determined by growth kinetics. Positive dispersion values generally come about from particle aggregation or nucleation, whereas negative values arise from fragmentation and attrition. In contrast, the glass subpopulation (3) has a dispersion value of -0.51, which is a function of its fragmentation and transport history (dispersion values of -0.6 or greater are typical of fragmentation by water-magma interaction). The lithic subpopulation (2) has a dispersion value (0.15) that indicates some aggregation after its fragmentation.

The statistical summary (table 3) gives overall averages for many important parameters of the volcanic ash sample. This summary can be used to study the differences between different ashes or samples of the same ash.

Subpopulation size characteristics analyzed by the sequential fragmentation/transport (SFT) model of Wohletz and others (1989).

[See Wohletz and others (1989) for additional explanation]

Subpopulation	Mode phi (mm)	Dispersion	Fraction
Crystals	2.25 (0.210)	0.50	0.08
Lithic fragments	3.34 (0.099)	0.15	0.07
Glass	4.60 (0.041)	-0.51	0.21

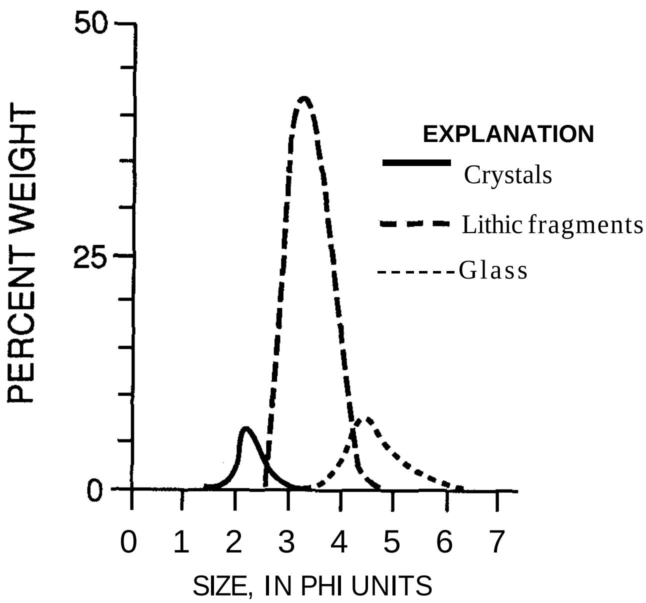

Figure 7. Subpopulation size characteristics of ash from the December 15, 1989, eruption of Redoubt Volcano.

CONCLUSIONS

To understand the nature of volcanic ash clouds, we must understand the nature of the particles that make up the cloud. By combining SEM and optical petrographic techniques with powerful software analysis and theories on particle transport, we obtain detailed information on the characteristics of the particles in volcanic ash clouds. The characteristics of the ash cloud will determine where it goes, how long it will stay in the atmosphere, how much damage it will cause to an aircraft, and its effects on the environment.

The volcanic ash ingested by the Boeing 747-400 that encountered the Redoubt ash cloud on December 15, 1989, has characteristics of material derived from eruption of andesitic magma by rapid release of high-pressure gases, perhaps by a hydrovolcanic mechanism. Optical microscope inspection revealed glass, blocky shards of minerals, and hydrothermally altered andesitic rock fragments. The chemical analysis derived from SEM analysis confirms the andesitic nature of the ash. Size analysis shows fragmentation characteristic of an evolved fragmentation process, such as is expected for a water-magma interaction. The shape analysis revealed dominantly low shape factors, characteristic of hydrovolcanic ash. Knowing the chemical composition and finding that a large fraction of particles have a glass structure, the melting-temperature range can be estimated.

Table 3. Statistical summary for Redoubt volcanic ash from December 15,1989, eruption.

	Average	Standard deviation	Maximum
Diameter (pm)	13.3	12.9	141.0
Aspect ratio	3.5	3.1	
Area (pm^2)	284.0	889.8	11,989.0
Density (g/cm^3)	2.42	0.79	6.6

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