Interaction of Aircraft and Explosive Eruption Clouds: A Volcanologist's Perspective

William I. Rose*
Michigan Technological University, Houghton, Michigan

Eruption clouds contain a variety of solid, liquid, and gaseous materials. Silicate glass particles with melting temperatures of 800–1200°C are often the dominant solid material, and can cause significant problems in turbine aircraft engines. Plinian eruptions propel silicate glasses to altitudes of up to 60 km, and are then dispersed over large areas by prevailing winds. The basic characteristics of these clouds are described, and suggestions about how to avoid aircraft mishaps are listed.

Introduction

IN the past 13 years, there have been more than 20 incidents of aircraft suddenly encountering volcanic clouds. It is clear from these incidents that turbine aircraft can be seriously affected, and also that airborne radar systems and other existing instruments have not given warning of the encounter. In this paper, a basic description of volcanic clouds will be given, with an eye toward aircraft interactions. In an effort to apply the volcanology, and as a response to the concern of aircraft operators, some recommendations will be made to mitigate aircraft interactions.

Eruption clouds are very complex, and are influenced by numerous natural variables. Few have been studied at all and very few in any detail. They are short-lived phenomena that occur in widely separated areas. Long periods of inactivity usually prevail at volcanoes between eruptions, and much of what we know is based on study done after the eruption. Each eruption studied in real time has shown some unique characteristics. We have too few examples and too much inconsistency in the study methods used by the different scientists to be very good at generalizing characteristics.

An Eruption Classification Applied to Aerospace Operations

It is artificial to rigidly classify natural phenomena like eruptions. Table 1 is a simplified attempt to describe some end-member-type eruptions. There are major differences in the end-member types, but any single eruption often cannot be simply assigned to any end member. Eruptions may be intermediate between the idealized end members or may exhibit several types of activity throughout an eruptive cycle. Based on the critical variables listed in Table 1, and the record of aircraft encounters with eruption clouds, *plinian eruptions* are probably the most important type of activity to characterize. These eruptions are highly energetic, being characterized by vigorous vertical ejection, powered by the explosive release of gas which was dissolved in the magma under high pressure prior to eruption. Other types of eruptions are possibly less important to consider because they occur much less frequently (Katmaiian), release mainly gases to the atmosphere and not much silicate material (Hawaiian, strombolian), or are characterized by explosions that release lesser volumes of silicate material with less violent and dispersed consequences (vulcanian, surtseyan).

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*Professor of Petrology, Department of Geology and Geological Engineering.

Plinian Eruptions

Figure 1 is a simplified profile of a plinian eruption cloud. Three parts of the cloud can be identified. The *gas thrust* is the dense, high-velocity, vertical column region immediately above the vent. The *convective thrust* is a more slowly moving "buoyant" cloud above the gas-thrust region. The *drifting cloud* is by far the largest portion of the eruption cloud, which represents material that is no longer rising, but is being carried by winds. Table 2 gives some of the characteristics of these portions of the cloud. Several points are important in the context of aerospace operations.

1) The volume of the drifting cloud region is so much greater than the others that it has significance even though the concentrations and sizes of particles are generally much lower than the other parts.

2) The height of the gas-thrust region is usually a small fraction (approximately 10%) of the total column height (usually less than 5 km), and it has a very limited horizontal extent as well. But conditions within the gas thrust are very bad. Thus it is a statistically unlikely, but devastating, target for aircraft.

3) The convective thrust region is turbulent, often moderately large in scale, and has significant particle concentrations. It is also a serious hazard to aircraft in many eruptions.

4) The position of both the gas thrust and convective thrust is directly above the vent. Therefore, encounters with both regions can be prevented when the source volcano is known by a geographic coordinate window centered on the vent.

5) The maximum altitude of the convective thrust can be monitored by some radar systems (see Table 9) which can provide additional help.

6) The location of the drifting cloud is predictable from meteorological conditions, particularly if winds at a variety of altitudes are measured regularly. Dense eruption clouds can also be tracked by some radar systems and mapped by some satellite systems.

7) The persistence of the drifting cloud[9] and the complexity of its trajectory[10] are both greater at stratospheric levels. Tropospheric material seems to fall out quickly, but stratospheric materials can last for months or years.[11]

Some Environmental Characteristics

Some of the conditions encountered by aircraft in eruption clouds are of particular interest.

1) Encounter of the drifting cloud at high altitudes can sometimes happen without much visual warning. The concentration of small particles can be significant—orders of magnitude above ambient—and still not be obviously visible.

2) Radio communications can be affected adversely within the drifting cloud.

3) The fine particles in the drifting cloud accumulate electrostatic charges; lightning is a frequent occurrence and can be a hazard.

4) The drifting cloud can become locally unstable with downward convecting cells. It also can cause rapid changes in weather conditions.

5) Significant abrasion of aircraft windows and surfaces can occur from slight contact with volcanic ash.

6) Ash particles can be very cohesive in eruption clouds. The material is often wet and can load on the body and wings.

Composition of Eruption Clouds

The eruption cloud is progressively highly diluted by the lower atmosphere. Factors of 10,000–100,000 times dilution are reached at the edge of convective thrust regions.[12] Because of dilution, the overall composition of the eruption is broadly similar to the atmosphere but contains variable amounts of silicate particles, liquid dilute acid aerosols, and various gases. The specific mixture is related to the magma source and the conditions near the vent. Table 3 is a list of the common materials in the eruption clouds. Most of the dilution is caused when air is injected at elevations similar to the vent. This air is warmer and more humid than air at higher levels, is heated in the column, and buoyed aloft. Much H_2O is moved aloft by dilution, which eventually results in formation of clouds and rainfall. Eruption clouds contain a complex mixture of the components contained in Table 3 and consist of magmatic components as well as accidental ones. The proportions of the different types of particles vary from eruption to eruption and from minute to minute during an eruption.

Silicate particles in the eruption cloud are perhaps the most critical materials to consider here because they are abrasive and sometimes melt inside aircraft engines. The particles that represent physical fragments of the magma itself are called "pyroclasts" (Fig. 2). Comprehensive descriptions of coarser ashes can be found in Ref. 13. The silicate materials consist of glass, mineral fragments from the magma, and accidental rock materials derived from the wall-rock near the magma. The proportions of these materials vary, but the proportions of glass are typically dominant and are even more dominant in the distal ash cloud after the mostly larger and denser mineral particles fall out of the moving cloud. The silicate glass is the portion of the magma with the lowest melting temperature, and because its melting endangers the aircraft engines it is the composition and

Table 1 Volcanic eruption types (idealized)

Type	Ref. no.	Character
Hawaiian	1	Extensive fissure vent eruptions of lavas and minor small, coarse spatter eruptions, magmatic gas released to the atmosphere, spatter mainly falls within 1 km of vent.
Strombolian	2,3	Small volume and often continuous coarse spatter eruptions, local (less than 1 km) spatter fallout, magmatic gas release.
Surtseyan	4,5	Eruptions caused by interactions of surface water with magma or hot rock above magma. Explosions sometimes violent, fine ash produced.
Vulcanian	6	A poorly understood eruptive type (which is also misnamed). Intermediate between strombolian and plinian and probably has a surface water influence, can have high columns and fine ash.
Plinian	7	Violent magmatic eruptions with high columns. Power of eruption comes from explosive escape of previously dissolved gases.
Katmaiian	8	Very large explosive eruptions in which the plinian column collapses to produce widespread pyroclastic flows. Caldera collapse associated and very large volumes erupted, not very frequent.

Table 3 Composition of volcanic eruption clouds

Atmospheric material (N_2, O_2, etc.)
Essential or magmatic materials
Solid particles (for sizes, see Fig. 3)
Silicate glass pyroclasts (see Table 4)
Mineral pyroclasts (see Table 5)
Liquid particles (usually 0.1–10 μm)
Dilute acid aerosol particles
H_2O
Gases (see Table 6)
Accidental materials
Solid rock (generally coarser than essential solids)
Usually silicate, highly variable
Liquid (usually water)
Vapors and gases

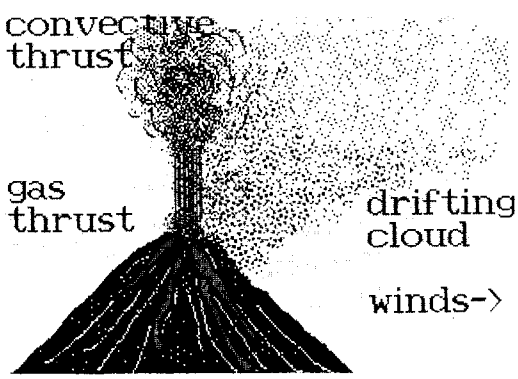

Fig. 1 Schematic sketch showing three parts of a plinian eruption cloud. See Table 2 and text for discussion.

Table 2 Estimates of some environmental characteristics of plinian eruption clouds

	Gas thrust	Convective thrust	Drifting cloud
Approx. particle concentration, g/m^3	1–1000+	0.05–10	0.004–4
Maximum diameter of particles, cm	100+	1	0.1
Vertical velocity, m/s	100	20–50	0
Temperature, °C	Ambient + 100+	Ambient + 10	Ambient
Area, km^2	1	10	100–1000+
Vertical dimensions, km	Vent altitude + 1–5 km	Vent altitude + 1–50 km	0–50 km

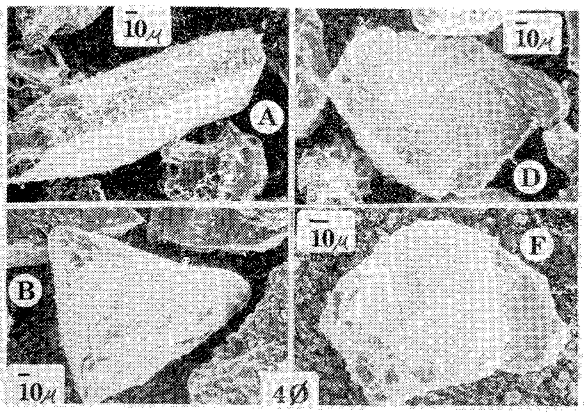

Fig. 2a Individual particles of the 100-μm split of May 18, 1980, Mount St. Helens ash, which fell at Spokane, identified by energy dispersive x-ray analysis. Most are crystal pyroclasts. A, a hornblende crystal, with a glass jacket. It is probably magmatic, and shows that crystals from the magma are also found in the material. B and D, fragmented plagioclase crystals; F, a titaniferous magnetite grain. Many vesicular glass particles occur in this size fraction also. From Ref. 29.

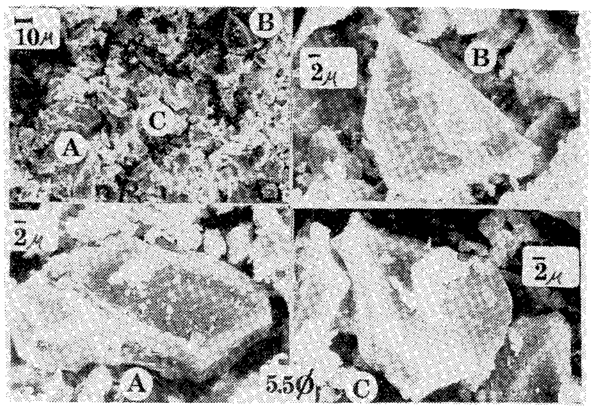

Fig. 2b SEM images of the 25-m split of the same Spokane ash. This material is chiefly glass pyroclasts. A and C, glasses with compositions of 70% SiO_2, 5% K_2O; B, a composite grain, with the left side glass and the right side titaniferous magnetite. The bulk composition of this size fraction reflects glass enrichment. From Ref. 29.

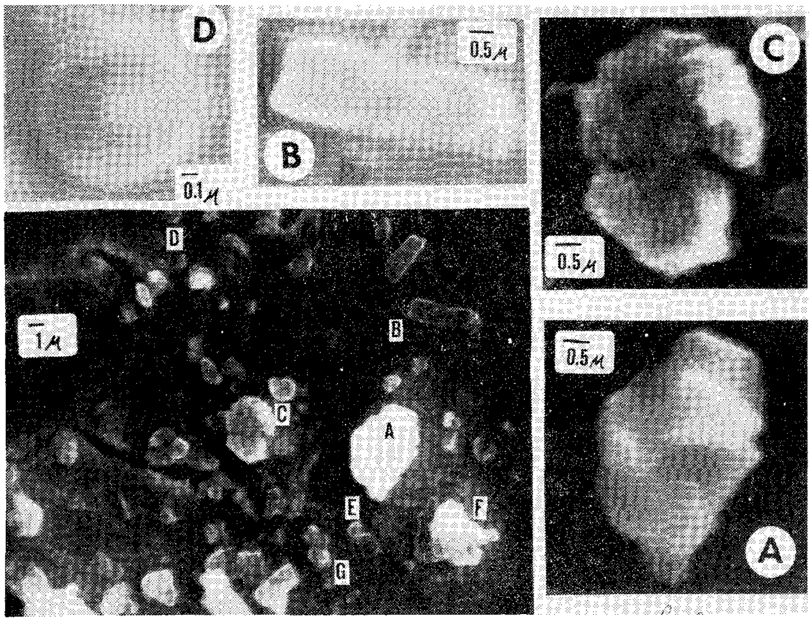

Fig. 2c Scanning electron microscope imagery of Santiaguito (Guatemala) eruption cloud particles of February 22, 1978, collected with conventional impactor. Lower left shows field of particles. A and F, angular particles with energy dispersive pattern of rhyolitic glass; B, tabular particle with energy dispersive x-ray analysis (EDXRA) pattern of $CaSO_4$ (hydrated?); C, angular particle with EDXRA pattern of plagioclase; D, E, and B, spherical particles with S peak in EDXRA pattern (probably H_2SO_4). From Ref. 12.

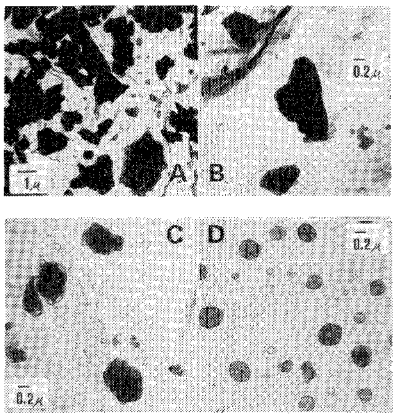

Fig. 2d Transmission electron micrographs of Santiaguito eruption cloud particles collected with conventional impactor. A, angular silicate particles and smaller droplets; B and C, silicate particles with droplets adhering and smaller discrete droplets; D, field of droplets. From Ref. 12.

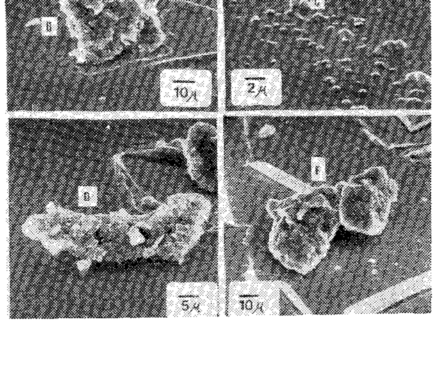

Fig. 2e SEM imagery of particles collected on stage 2 of the cascade for the February 28, 1978, sample from Santiaguito. The 50% cutoff for particles with a density of 2 g/cm^3 is 12 μm for this stage. A, silicate particle gives an energy dispersive x-ray pattern, which is a hybrid of plagioclase and the groundmass; B, small nonsilicate crystalline particle; C, droplets, possibly dilute sulfuric acid, because both B and C are much smaller than cutoff for the stage, they may have accumulated by splattering from the surfaces of larger particles such as A, D, or F; D, large aggregate of mainly silicate materials. EDXRA interpretation gives a groundmass pattern with excesses of Fe, Ti, K, Ca, and Cl. We suggest the aggregate contains magnetite, and salts such as $CaSO_4$ (hydrated?), and KCl; F, silicate particle with EDXRA pattern of goundmass. From Ref. 12.

melting temperatures of this glass that are perhaps most relevant to aircraft. Table 4 presents basic compositional and melting information on silicate glass of some recent eruptions. The geometry of typical glass pyroclasts is shown in Fig. 2b. Of particular interest are: 1) the sharp, irregular edges, which make the material highly abrasive at low temperature; 2) the high surface area and complex shapes of particles, which facilitate their mobility and remelting; and 3) the coating of acid material representing scavenged liquid acid aerosol particles, which can produce acid etching on some surfaces.

Mineral pyroclasts in eruption clouds are solids that have crystallized in the magma (Fig. 2a; Table 5). Most of the mineral pyroclasts are silicates, although nonsilicates do occur. In general, magmas contain several of the "common" mineral pyroclasts, but vary in the overall abundance and the size of mineral pyroclasts and exhibit diverse minor and trace mineral species (Table 5).

Injections of volcanic pyroclasts into the atmosphere can be detected and tracked by weather satellites, particularly if the conditions are clear of ordinary clouds during the eruption.[14,15] Such satellites offer hope for a global volcanic cloud monitoring system.

There are minor amounts of small (< 10 μm) solid sulfate, halide, and oxide particles in most eruption clouds and volcanic plumes.[16] These represent compounds that form from volatilized cations and anions in the eruptive gas.

Table 4 Some glassy pyroclast compositions and melting temperatures of recent eruptions

	Eruption			
	Fuego 1974	Mt. St. Helens 1980	El Chichón 1982	Galunggung 1982
SiO_2	52.3	71.4	68.0	61.3
Al_2O_3	18.7	14.6	15.9	7.1
FeO (total)	9.1	2.4	1.6	7.1
MgO	3.4	0.53	0.25	1.7
CaO	9.4	2.6	2.12	5.7
Na_2O	3.9	4.3	4.56	4.0
K_2O	0.8	2.00	5.05	1.5
TiO_2	1.2	0.37	0.29	1.3
F_2O_5	—	0.99	0.00	0.33
H_2O	—	—	—	—
Total	98.7	99.19	97.77	99.64
T, °C	1050	990	850–950	?
Reference no.	17	18	19	20

Liquid aerosol particles (Figs. 2c and 2d) are apparently always present in eruption clouds, and represent water droplets with dissolved acids (H_2SO_4, HCl, HF, H_2CO_3) which form as the eruption cloud enters the atmosphere.

The magmatic gases of eruption clouds are similarly diverse. Although highly diluted by the atmosphere, they often contain highly reactive species (Table 6). The eruptive release of SO_2 can be detected and measured by the TOMS instrument on the Nimbus 7 satellite,[21] and the path of the

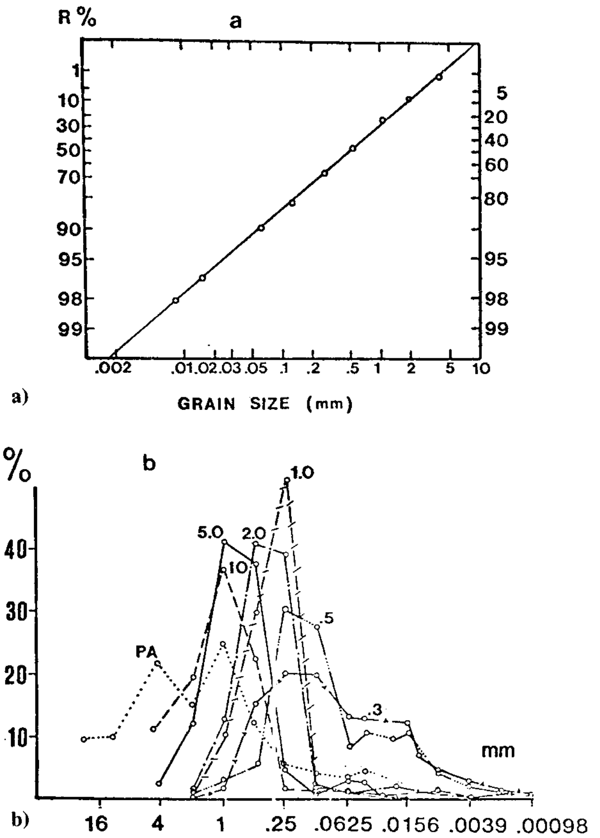

Fig. 3 a) Accumulated total size distribution of silicate particles in the October 14, 1974, plinian eruption of Fuego Volcano, Guatemala. Data taken from Ref. 22. b) Size distributions accumulated as fallout in various places. (PA refers to the near-source pyroclastic avalanches; 10, 5, 2, 1, 0.5, and 0.3 refer to the progressively more distal fall deposits of the eruption, which depict size distributions of 10, 5, 2, 1, 0.5, and 0.3 mm isopach regions of the ash blanket.[22])

Table 5 Mineral pyroclasts in volcanic ashes

Common	Occasional	Rare
$(Fe,Mg)_2SiO_4$ (olivine)	$ZrSiO_4$ (zircon)	$CaSO_4$ (annhydrite)
$Mg,Fe(SiO_3)_2$ (orthopyroxene)	$CaTiSiO_5$ (sphene)	$Mg_2Al_4Si_5O_{18}$ (cordierlte)
$Ca(Mg,Fe)(SiO_3)_2$ (clinopyroxene)	$NaAlSiO_4$ (nepheline)	
$(Na,Ca)Al_{1-2}Si_{2-3}O_8$ (plagioclase)	$KAlSi_2O_6$ (leucite)	$Na_8(AlSiO_4)_6(Cl,SO_4)$ (sodalite)
SiO_2 (quartz)	$KAlSi_3O_8$ (potash feldspar)	FeS_2 (pyrite)
Fe_3O_4 (magnetite)	$FeTiO_3$ (ilmenite)	+ others
$Na(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$ (amphibole)	+ others	—
$Ca_5(F,Cl)(PO_4)_3$ (apatite)	—	—
$K(Mg,Fe)_3(Al,Si)_4O_{10}(OH)_2$ (biotite)	—	—

drifting cloud can be tracked. The SO_2 signal does not by itself give a reliable measure of the volume of ash released, because the SO_2 and ash volumes in eruptions are not proportional (Table 7).

Particle Sizes in Eruption Clouds

There is little data available based on direct sampling of eruption clouds themselves,[12] and much more from studies of ash blankets after fallout.[17,22-25] At Mount St. Helens, an effort was made at correlating the grain size of fallout deposits with those in the cloud.[26,27]

Eruptions produce fragmental material with size distributions similar to those shown in Fig. 3. This "total" size distribution is not representative of any particular portion of the eruption except the gas thrust, because larger and denser particles fall out quickly and the life of the remaining particles depends most critically on their settling velocity in the atmosphere. Figure 3 shows how the particle size is typically influenced by the atmospheric fallout. Following an eruption, the vast majority of large particles (>20 μm) falls out quickly, mostly within 24 h. The most widely dispersed silicate particles in eruptions are the ones we know the least about, because they form inconspicuous deposits and are not well preserved in the geologic record.[30] We do not know how much of this material there was, even in very well-studied eruptions.[31] Although the concentrations of these small, highly dispersed materials are low, they can persist in the stratosphere for weeks or months after large eruptions.[32]

Table 6 Gases in eruption clouds

Order of relative abundance (most to least)	Relative order of release (first to last)
Major	
H_2O	CO_2,H_2
CO_2[a]	H_2O,SO_2
SO_2	HCl
Minor[b]	
HCl, A, CH_4	HF
H_2S, S_2, NH_3	
H_2, SO_3, CO	
HF, COS	

[a]Usually less than 99% of total. [b]Usually less than 1% of total.

Table 7 SO_2 released in some eruptions

Eruption	Date	Magma volume, DRE km^3	Max. height, km	S gas released, g
Agung	1963	0.9	23	0.6×10^{13}
Fuego	1974	0.1	14	1.6×10^{12}
St. Helens	1980	0.3	27	2×10^{12}
El Chichón	1982	0.38	16+	1×10^{13}

This material is probably broadly similar to the larger proximal particles.

The following generalizations may apply for the particles most likely to occur in drifting cloud encounters with aircraft. Angular, sharp silicate glass pyroclasts with compositions similar to those listed in Table 4 are likely to be most abundant. The size of these particles at high altitudes will probably be mostly less than 50 μm and significant amounts could be less than 10 μm, because the larger particles will fall out before drifting very far or very long.

The size of various essential particles (Table 2) in eruption clouds is generally related to the particle composition. Larger particles are usually dominantly silicate, and smaller (< 10 μm) particles include the liquids and solid salts as well as silicates.[10] Particles also commonly form complex aggregates, which include silicate and nonsilicate components.[31,33] This process is important because it affects radar signals, produces higher reflectivity, and speeds the removal of ash, because larger particles fall faster. Unfortunately, we do not understand why this happens more efficiently in some eruptions than others.

In the preceding discussion of particles, no data on accidental materials were included. Usually in plinian eruptions these are not as important as the essential material. Exceptions to this occur in the initial stages of eruptions and in phreatic or phreatomagmatic (eruptions with a component of surface water/silicate melt interaction) explosions. Accidental materials are potentially extremely diverse, reflecting anything that is found in the vicinity of the volcano. Commonly they are silicate materials, not too different from the magnetic materials, and usually are large in size (>100 μm). The larger size can cause them to be selectively gravitationally removed quickly from eruption clouds.[29]

Timing and Scale of Plinian Eruptions

Table 8 shows some examples of the timing and scale of recent activity of the plinian variety. Eruptions of this type consist of clusters of very short-lived energetic eruptions separated by long reposes. The length of the clusters of eruptions is usually measured in weeks or months. The length of the eruptions themselves is typically measured in hours. The repose intervals range from years to centuries to millennia or more. Only a tiny fraction of the world's volcanoes that could produce a plinian eruption are monitored in a manner likely to allow reliable forecasting of activity. A much higher proportion of volcanoes do allow recognition of one or more premonitoring signals which would justify an alert status (recognition of a higher probability of eruption) but not a forecast of time or character of eruption. This type of alert status may be worthwhile for aircraft operations. The recent Galunggung activity was a case in point. During a period of nine months, Galunggung had about 50 plinian explosions; each explosion lasted only a few hours. Although the timing of the eruptions could not be forecast specifically, the recognition of the continuing likelihood of activity was clear

Table 8 Some data on recent plinian eruptions

	Fuego	Santa Maria	Mt. St. Helens	El Chichón	Galunggung
Year of eruption	1974	1902	1980	1982	1982
Repose preceding, yr	3	1000+	130	600	64
Volume of magma erupted, DRE km^3	0.1	8.5	0.26	0.38	0.1–1.0
Maximum height of convective thrust, km	14?	29–48	27	17	16+
Approximate area of largest measured isopach,[a] km^2	10,000	100,000	57,000	45,000	?
No. of eruptions in cluster	4	1	5	3	50?
Duration of eruptions, h	3–17	18?	1–9	2–6	1–6?
Duration of cluster, days	10	1.5	153	7	270
Reference no.	17	34	23,31	25	35

[a]An isopach is the line connecting points of similar ash fallout thickness.

Table 9 Applications of radar systems to eruption clouds

Measurement	Applications
Maximum height of convective thrust as a function of time	Real-time eruption rate, aircraft routing
Maximum height of drifting cloud	Settling rates, grain sizes, forecasting, fallout, aircraft routing
Horizontal dimensions of drifting cloud	Forecasting fallout areas and times
Vertical dimensions of drifting cloud	Forecasting fallout durations
Movement of densest part of cloud	Aircraft routing
All of above measurements	Concentration of ash in cloud, potential mass of ash fallout

during the sequence. Alert status for aircraft is clearly justified for such situations and perhaps even in precursory situations at highly explosive volcanoes, such as Mount St. Helens and Santa Maria, where warnings of up to several months sometimes precede major eruptions.

The scale of eruptions varies markedly, and our understanding of them is restricted because we have not really experienced a large eruption in the aviation era. Geologically it is very probable that a large-scale event—on the scale of Santa Maria, Krakatoa, or Katmai—will occur at some point in the next 50 years.[36] We really do not know much about "scaling up" the effects of eruptions, particularly by several orders of magnitude. It is important to be aware that one or more very large eruptions are likely somewhere in the world during our lifetime.

Applications of Radar in Eruption Studies

Weather and Federal Aviation Administration radar systems can detect and monitor volcanic clouds; such studies have been shown to give valuable real-time data.[26,27] The types of data collected and the applications of the data are given in Table 9. The potential application of such data to aircraft hazard is obvious, but is restricted by the position of ground radar installations, which need to be close enough to the volcano (less than about 150 km) to provide useful real-time data. It is possible to tell with radar whether the eruption rate is increasing or decreasing in real time, something that is often impossible by other methods because visibility is so restricted. It is possible to estimate particle size and to map the convective thrust and the denser drift portions or eruptions in real time. More information on the potential of various radar systems for studies of volcanic clouds is needed. It would be potentially useful if military radar observations could be released for scientific study. A suitable radar for volcano cloud detection might be recognized, and basic scientific data would be made available. More data on the response of aircraft radar systems to volcanic clouds is also desirable.

Recommendations/Suggestions

As a volcanologist, the author has chosen to make some naive suggestions which he feels would help solve the problem of aircraft/eruption cloud encounters.

1) We should make a commitment to gaining some more "ground truth" at eruptions while they occur. Eruptions often happen in remote ground locations, where very little scientific work has been done. Because the phenomena are so complex and variable, more actual observations are needed during or immediately after eruptions. This would benefit in the short run by producing some data on the state of activity for day-to-day aircraft considerations, but also in the long run for understanding and application for later eruptions.

2) Application of satellite systems to eruptions, such as Nimbus 7/TOMS and weather satellites, should be maintained and strengthened.

3) Maps showing major air routes and the locations of potentially active volcanoes should be prepared and appropriately distributed. This requires both volcanological and aeronautical input. Volcanoes known to produce plinian activity should be specifically marked, and the coordinates of a 10-km square above them delineated.

4) A volcanologist/aircraft control group should discuss how and whether an alert status designation could be made for flight rules in the area immediately above volcanoes during high-probability periods.

5) A linkage of volcanological, meteorological, satellite, and air-traffic officials should be formalized for facilitation of rapid interaction when necessary. The location and movement of volcanic clouds could be part of standard meteorological reports in appropriate areas.

6) Busy airports in volcanically active areas are foci for many aircraft. Ground radar systems should be applied as much as feasible to nearby volcanoes. Perhaps the installation of radar systems should be considered at aircraft foci in volcanic regions where they do not exist already. Volcanologists could possibly provide some suggestions to radar operators on operation of radar to get the most helpful volcanological data. Perhaps a manual could be prepared.

7) Pilots should be encouraged to collect information on eruptions when they observe them. All data, such as height of eruption cloud, drift direction, radar reflections, etc., might be of value. A form should be distributed to pilots. It is important to be certain about the capability (or lack of capability) of aircraft radar systems to detect eruption clouds. A specific study of this question should be designed and completed.

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