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VOLCANIC ASH: WHAT IT IS AND HOW IT FORMS

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ABSTRACT

There are four basic eruption processes that produce volcanic ash: (1) decompression of rising magma, gas bubble growth, and fragmentation of the foamy magma in the volcanic vent *(magmatic)*, (2) explosive mixing of magma with ground or surface water *(hydrovolcanic)*, (3) fragmentation of country rock during rapid expansion of steam and/or hot water *(phreatic)*, and (4) breakup of lava fragments during rapid transport from the vent. Variations in eruption style and the characteristics of volcanic ashes produced during explosive eruptions depend on many factors, including magmatic temperature, gas content, viscosity and crystal content of the magma before eruption, the ratio of magma to ground or surface water, and physical properties of the rock enclosing the vent.

Volcanic ash is composed of rock and mineral fragments, and glass shards, which is less than 2 mm in diameter. Glass shard shapes and sizes depend upon size and shape of gas bubbles present within the magma immediately before eruption and the processes responsible for fragmentation of the magma. Shards range from slightly curved, thin glass plates, which were broken from large, thin-walled spherical bubble walls, to hollow needles broken from pumiceous melts containing gas bubbles stretched by magma flow within the volcanic vent. Pumice fragments make up the coarser-grained portions of the glass fraction. Particle sizes range from meters for large blocks expelled near the volcanic vent to nanometers for fine ash and aerosol droplets within well-dispersed eruption plumes.

INTRODUCTION

What is volcanic ash? The question is not a new one, and has been asked repeatedly since the time of Aristotle. Early scientists were able to do some remarkable studies of volcanic ashes and the eruptions that produced them, but were limited by scale. It has only been during the last few decades that we have had the laboratory equipment for characterization of the broad spectrum of volcanic ash types, down to a scale of tenths of micrometers. It has also only been during the last 20 years that we have had the ability to go beyond sampling ashfalls, with aircraft and balloons collecting *in-situ* samples from eruption plumes at elevations up to 20 km.

This brief paper will review the major volcanic ash types and the broad spectrum of explosive eruption types that have produced them.

Ash From a Recent Eruption That Affected Air Traffic—Augustine Volcano, Alaska The 1986 eruption of Augustine Volcano (Alaska) sent eruption plumes east and south that had considerable impact on airline traffic into Anchorage. The samples shown here were collected at Anchorage Airport, 280 km NE of the volcano; the airport was showered with ash for 9 days after the eruption began (Rose et al. 1988). Median grain size of the ash at Anchorage was around 30 μm (Fig. 1) and consisted of glass shards, glass from the lava dome, and mineral fragments (Fig. 2). As is the case for most moderate-size eruptions like this one, the glass shards are coated with acid condensates, and very fine grained dust, which consists of finer-grained ash; this bonding may occur because of static charge (Carey and Sigurdsson, 1982; Gilbert et al. 1991; Fig. 3). These ashes are typical of but one of hundreds of active or dormant stratovolcanoes characteristic of the Pacific Rim. However, volcanic ashes are very diverse in origin and composition, and this introduction has the purpose of providing a general view of explosive eruption processes and their products, which we have grouped under the category "volcanic ash."

EXPLOSIVE FRAGMENTATION OF SILICIC MAGMAS

Observations of fragmentation processes within explosive eruptions are limited. We can get reasonably close to only the smallest (and generally the most silica-poor and least explosive) eruptions of magma (molten rock). These eruption types are, however, of minimal interest for aviation safety, for they are small. Numerical models of magma fragmentation and the formation of volcanic ash are at best first approximations—at least until we find a way to emplace instruments that will survive within the throat of a volcano in full eruption.

Magmatic Eruptions. Explosivity is related mostly to overpressures within magma caused by gases coming out of solution as that magma nears the Earth's surface and encounters the atmospheric pressure (Fig. 4). Verhoogen (1951), in an analysis of gas bubble nucleation, growth and rise within magmas, concluded that volcanic ash formed when expanding bubbles within in the rising magma coalesced. That is most likely correct for lava fountains of low-viscosity magmas, but not for the formation of pumice and volcanic ash from magmas with more silica-rich compositions such as those of Redoubt and Pinatubo volcanoes; *pumice*, which is a silicate foam composed of glass, gas bubbles and minerals, would not exist if all bubbles in the magma had coalesced and disintegrated as Verhoogen had proposed. Rittmann (1936), a pioneer in volcanology, proposed that gases in the magma come out of solution as that magma rises through conduits to shallow depths; after the magma reaches the Earth's surface and an eruption begins, the highly viscous foam is disrupted by shock decompression before bubble coalescence can occur; this theory has been supported by shock tube analogiesby (Bennett, 1974), and computer experiments by several research groups in the U. S. and England (e.g., Wohletz et al 1984).

The distinctive shapes and physical properties of pumices are controlled by the history of gas bubble growth, presence or absence of phenocrysts as nucleation points (phenocrysts are those minerals that crystallized within the magma before eruption) and the type of fragmentation of the magma foam during eruption. There may be as many histories and size and shape distributions of gas bubbles within pumices as there are volcanic eruptions, but most are interpreted as having grown either continuously during shallow magma rise and eruption (i.e, one generation) or discontinuously, before and during eruption (i.e., two generations). A hypothetical example (Fig. 4—adapted here from Heiken and Wohletz, 1991) of pumice and ash formation during an explosive eruption of silica-rich magma, based on the gas bubble characteristics within pumice and volcanic ash particles goes like this:

> The example is one of a silica-rich magma (70 weight% SiO_2), which contains 2 to 3 weight% H_2O; bubble growth may begin at depths of 1 to 3 km below the Earth's surface, where the gas pressure exceeds lithostatic pressure (i.e., the pressure produced by the mass of rock overlying the magma body). If CO_2 is present, it may exsolve and form gas bubbles at even greater depths (Holloway, 1976). Uniform bubble nucleation may begin if the magma is homogeneous. If the magma contains abundant crystals (i.e, phenocrysts), nucleation and bubble growth on mineral surfaces may produce pumice fragments containing bubble clusters. Gas bubbles clustered around phenocrysts or other inclusions may coalesce and form large cavities within the magma foam.
>
> As rising magma approaches the Earth's surface, uniform bubble growth may create a foam consisting of evenly spaced bubbles (with the exception of larger bubble clusters around phenocrysts).

Isothermal expansion of these bubbles and surface tension of thinning bubble walls may increase the bulk viscosity of the magma considerably and give it a finite yield strength, making it more brittle. High viscosity prevents any significant buoyant bubble rise.

If bubble growth occurs at shallow depths, near the mouth of a vent, the pumice pyroclasts may contain nearly spherical vesicles. In this situation, there is no time before fragmentation for vesicles to be elongated by flow into tube-like shapes. The ashes produced in this type of eruption consist of arcuate, blocky, glassy shards.

After a vent or conduit is opened to the surface, the magma flow rate increases greatly. If this flow rate exceeds that of the rising bubbles, the gas bubbles are sheared by flow into long tubes or pita-bread-like shapes.

The more or less brittle mass of magma foam is disrupted by a large pressure differential at the magma/atmosphere interface. A shock wave moves ahead of the pumice and ash out of the vent, while an expansion wave propagates down into the inflated magma and allows its rapid decompression (Wohletz et al. 1984). An expansion wave disrupts the nearly solid foam, breaks it into particles, and accelerates the particles out of the vent. The explosive eruption process for silica-rich magmas is likely driven by this pressure differential and *not* by bubble coalescence.

Larger magnitude eruptions with high eruption columns, called Plinian eruptions, after the AD 79 eruption of Vesuvius described by the Roman Pliny the Younger, eject large pumice particles that fall out within tens of kilometers of the vent area. However, smaller ash particles produced by extremely energetic eruptions or those carried along with pyroclastic flows can be found far from their source. Some fine-grained ash deposits are made up mostly of the lighter glass shards, separated from denser mineral and rock grains by gravitational segregation within the eruption plume, or by the buoyant rise of gases from the eruption clouds.

Glass shards are pieces of bubble walls broken from the magma foam rising in the volcanic vent; the shard shapes depend upon bubble shapes and sizes within the magma foam and the eruption processes responsible for the fragmentation. Shards exhibit a wide range of physical characteristics, ranging from slightly curved, thin glass plates broken from large, thin-walled spherical gas bubbles, to hollow needles broken from pumiceous melts containing vesicles stretched by flow (Heiken and Wohletz, 1985). The example shown here is a glass shard sampled over central Wyoming, at an elevation of 18 km, 72 hours after the May 18, 1980 eruption of Mt. St. Helens (Fig. 6) .

Hydrovolcanic Eruptions. Where molten rock comes into contact with ground water or the shallow surface water in lakes, marshes, and littoral areas violent steam explosions can occur. Formation and collapse of steam films on melt surfaces causes deformation and fragmentation of the melt and propagation of strong stress waves that further fragment that melt. The rapid superheating of water results in far more explosive conditions than those that occur following only bubble growth and decompression. When an eruption is driven by both gas bubble growth and magmatic overpressures, and magma/water interactions, the Earth's most violent eruptions occur. These eruptions produce very fine-grained volcanic ash, made up mostly of bits broken from glass bubble walls. Hydrovolcanic deposits may have median grain sizes as low as 40 μm, and we now recognize that the very fine-grained components (<10 μm) of such eruptions stay in stratospheric suspensions long enough to be carried thousands of kilometers (Self and Sparks, 1978; Wilson, this volume).

SMALL-VOLUME EXPLOSIVE ERUPTIONS

The examples given so far are from the most explosive types of volcanic eruptions (Table 1). However, most of the Earth's subaerial volcanoes erupt less than 0.1 km^3 of volcanic ash and coarser ejecta. These eruptions have only a very small explosive component; e.g., basaltic fissure eruptions, which produce mostly lava flows, but have small ramparts composed of pyroclastic spatter. *Basalts* are silica-poor (SiO2<52 Weight% SiO_2) and Fe-rich magmas that comprise most of the Earth's volcanic rocks .

Vulcanian Eruptions. Among the smaller eruptions, *Vulcanian* eruptions are those characterized by intermittent explosions that deposit ashes composed of mostly older solidified lava particles (MacDonald 1972; Self et al.1979). These eruptions are most likely caused by overpressures developed within blocked vents. The eruption mechanism is not clear, but consists of alternating magmatic and hydrovolcanic processes. Sometimes the eruption will shift back and forth between *Vulcanian* and *Strombolian*, controlled by either a blocked or open vent. Vulcanian eruptions are associated with some cinder cones, craters in stratovolcanoes, and lava domes. Vulcanian eruptions can produce eruption clouds that rise several kilometers above the vent and small pyroclastic flows (Table 1). Because the original material is rich in water vapor, the pyroclastic flow deposits may grade into mudflows along the lower flanks of a volcano. At Ngauruhoe volcano in New Zealand, the cannon-like explosions and subsequent ash falls and pyroclastic flows are believed to have been caused by pulverization of a lava plug in the conduit by a combination of magma degassing and vaporization of ground water (Nairn and Self, 1978).

Strombolian Eruptions and Cinder Cones. Explosive bursts of solidified and partly solidified bombs, blocks, and ash movin in ballistic trajectories are known as *Strombolian* activity, named after Stromboli, a volcano in the Aeolian Islands, Italy. Well-documented Strombolian eruptions consists of weak to violent ejection of partly-fluid blobs. Nearly all of the ejecta falls ballistically around the vent, building a "cinder" or "scoria" cone (McGetchin et al 1974). Activity at cinder cones can rapidly switch between lava fountaining, Strombolian bursts, and Vulcanian eruptions.

Volcanic ash from Strombolian deposits range from irregular, smooth-skinned, bubbly droplets of glass to blocky, crystalline rock fragments with few gas bubbles. This spectrum of textural types is represented in all size categories, from large bombs several meters in diameter to scoria and fine ash.

Lava Fountains. Low-viscosity basaltic magmas erupt as lava fountains and as lava flows. The fountains range from a few m to over 1 km in height and deposit welded spatter (bombs and ash) as a circular or oval apron around a central vent or as ridges parallel to a fissure vent. A spray of low-viscosity ($<10^3$ poise) basaltic liquid is driven by expansion of magmatic gases.

Particles from lava fountains range in size from bombs a meter or more across to spheres a few μm in diameter. Coarser ejecta is deposited within a few hundred meters of the vent and finer ash, including filamentous Pele's hair (natural fiberglass), is swept downwind and deposited as ashfall. Nearly all fountaining is accompanied by lava flows.

Phreatic Eruptions Perturbations of a geothermal system by injection of new magma at depth, changes in ground-water level, or tectonic activity may cause explosive steam eruptions without the eruption of any molten particles. This type of activity is possible at many types of volcanoes and even in geothermal areas with no volcanic activity. Steam eruptions may occur with no subsequent activity, as was the case for Soufrière de Guadeloupe in 1976-1977 (Heiken and Wohletz, 1985), or be the precursors to a significant magmatic eruptions, such as those occurring at Mount St. Helens, 1980, and Pinatubo, 1991. The eruptions consist of intermittent or continuous explosive steam bursts and can form large craters.

Ejecta from steam eruptions are made up of hydrothermally altered or weathered rock fragments and mud.

CONCLUSIONS

In conclusion, there are four basic mechanisms of fragmentation in volcanic eruptions: (1) the decompression of rising magma, gas bubble growth, and subsequent fragmentation by an expansion wave (2) the explosive mixing of magma with ground or surface water, (3) fragmentation of country rock by rapid expansion of steam and superheated hot water, and (4) particle abrasion during transport by collision of grains with each other and the substrate. The fourth mechanism may be important during gravitational collapse of the volcano and subsequent avalanche, such as that which occurred during the 1980 eruption of Mount St. Helens (Siebert et al 1987). The variations of eruption style and the characteristics of volcanic ashes produced in explosive eruptions depend on factors such as the temperature, volatile content, viscosity and phenocryst content of magmas, the ratio of magma and meteoric water, and physical properties of rock enclosing the vent. The variations in physical and chemical properties of these ashes can be bewildering; there are as many variations as there are volcanoes, and as is described in the proceedings paper by Tom Simkin (this volume), there are a lot of volcanoes!

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FIGURE CAPTIONS

FIGURE 1. Grain size of volcanic ash from the April 2, 1986 eruption of Augustine Volcano (Alaska). The sample of ashfall was collected at the Anchorage Airport and sized by Horiba particle size analyzer.

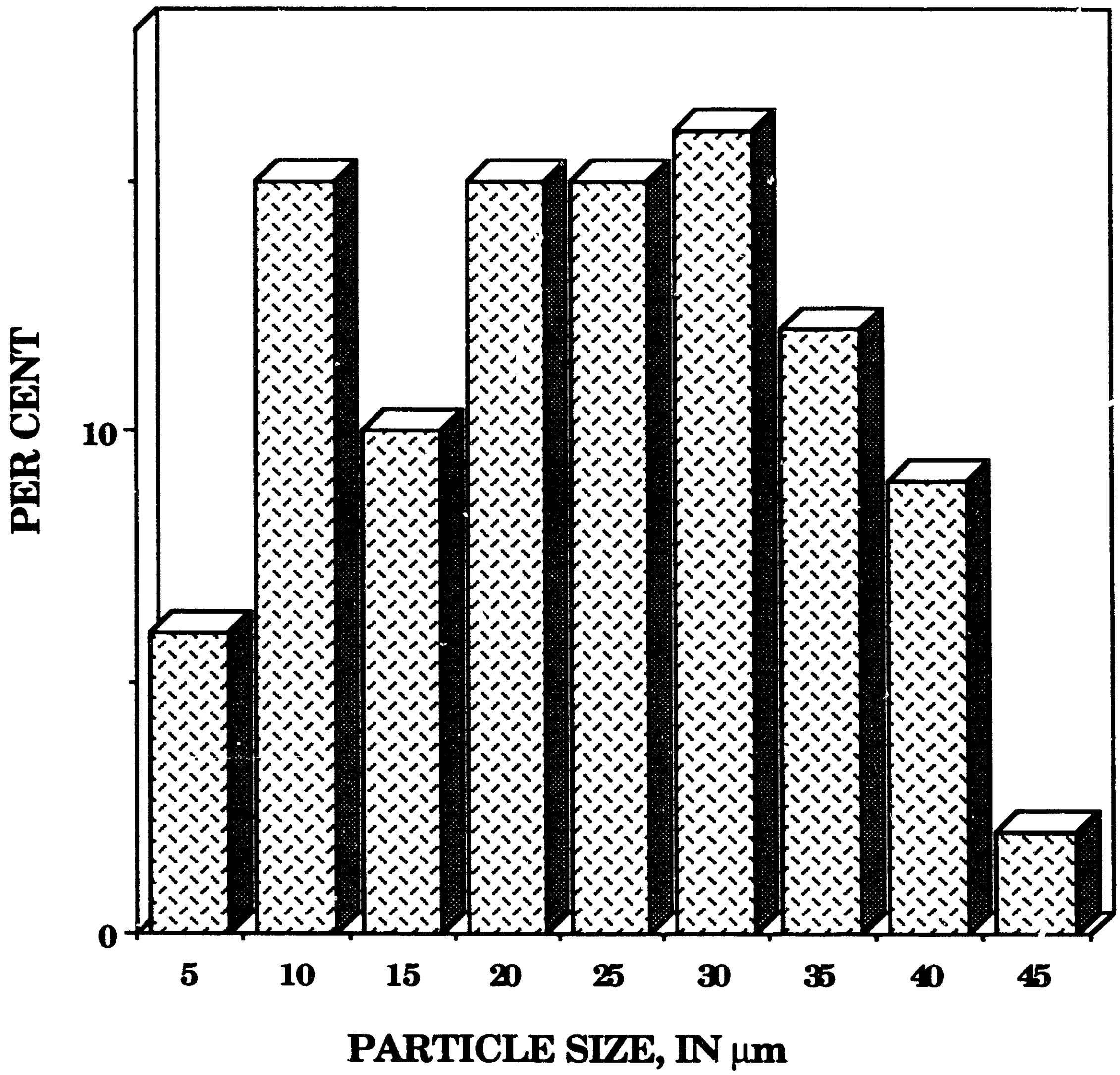
FIGURE 2. Particle types within ashfall collected at Anchorage Airport, March 28, 1986, from the Eruption of Augustine Volcano. (a) Grain count, showing percentage of particle types within this ash. The most common particle type from this eruption was glass shards, explosively broken from a foaming magma rising in the volcano. Other particles include individual minerals from the magma, bits of a lava that occupied the volcano's throat before eruption, and fragments from the claystone underlying the volcano. (b) Scanning electron micrograph, showing mostly equant but curved glass shards, which were broken from a quickly chilled magma foam; the curved surfaces are remnants of bubble walls.

FIGURE 3. The eruption plume from the 1986 eruption of Augustine Volcano was sampled by aircraft between major eruption phases. Even within plumes emanating from the volcano during relatively "quiet" phases there are numerous particles, albeit small ones. The sample was collected by Ray Chuan (Brunswick Corporation).

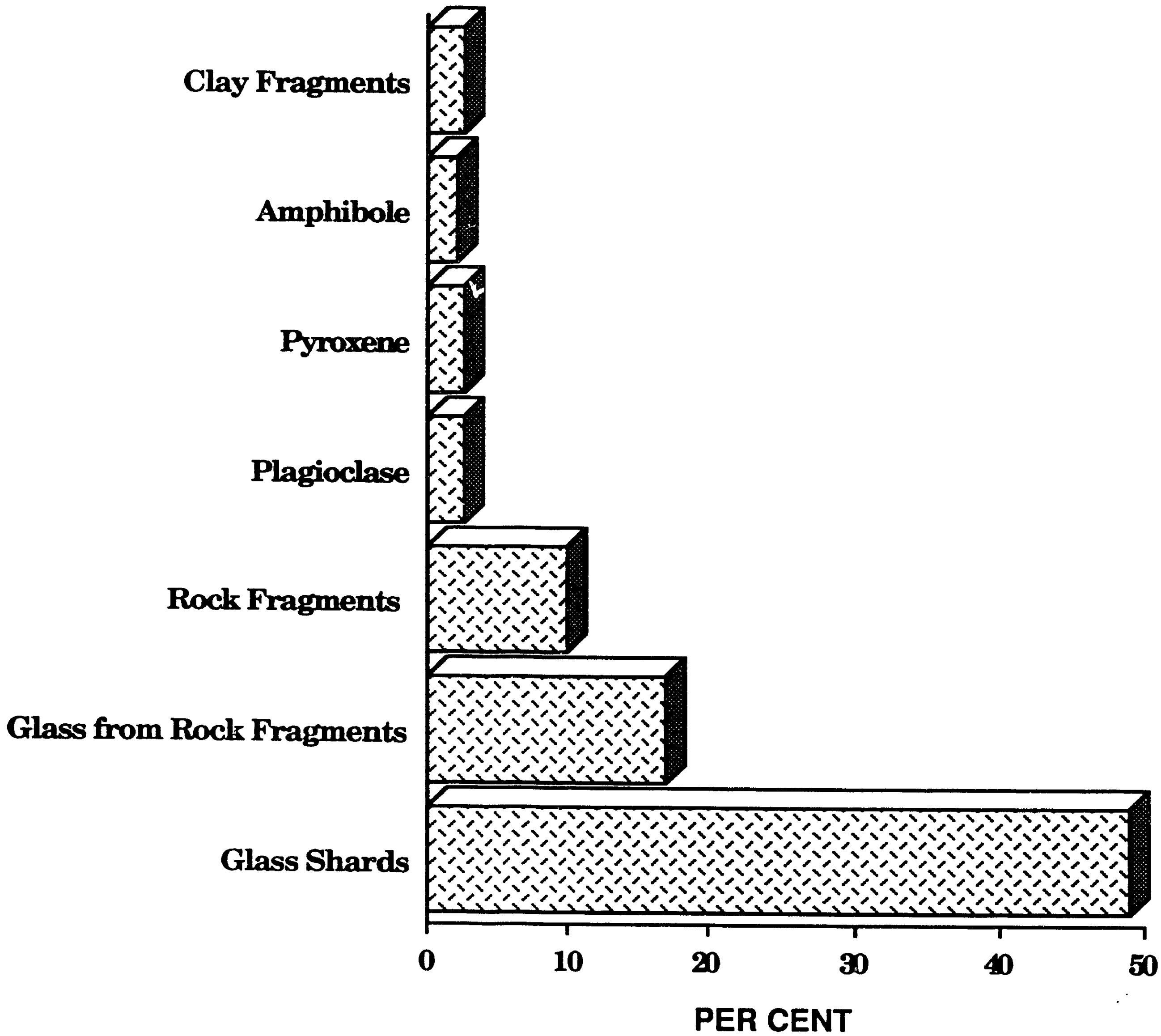
FIGURE 4. Schematic diagram of processes leading to the formation of volcanic ash within explosive volcanic eruptions. This diagram is based nearly entirely on inference and some experimental studies of the processes of gas exsolution and explosive decompression of a rising magma with a composition similar to that of the eruptions of Augustine Volcano. Scanning electron micrographs shown in the circles are about 300 µm in diameter. As magma rises to a depth where the pressure of gas in solution exceeds that of the overlying rock, some of that gas comes out of solution as small bubbles. As the pressure is lowered, those bubbles continue to grow. After the eruption begins, movement of the magma foam in the conduit may stretch the bubbles into elongate tapered tubes. A fragmentation surface between the pressurized magma foam and the ambient atmosphere tears the brittle foam apart and accelerates the pieces out of the conduit in the eruption column. These particles, of all sizes are carried out in eruption clouds and eventually fall to the

ground, depending on the height of the eruption column, the strength of winds, and particle size and density.

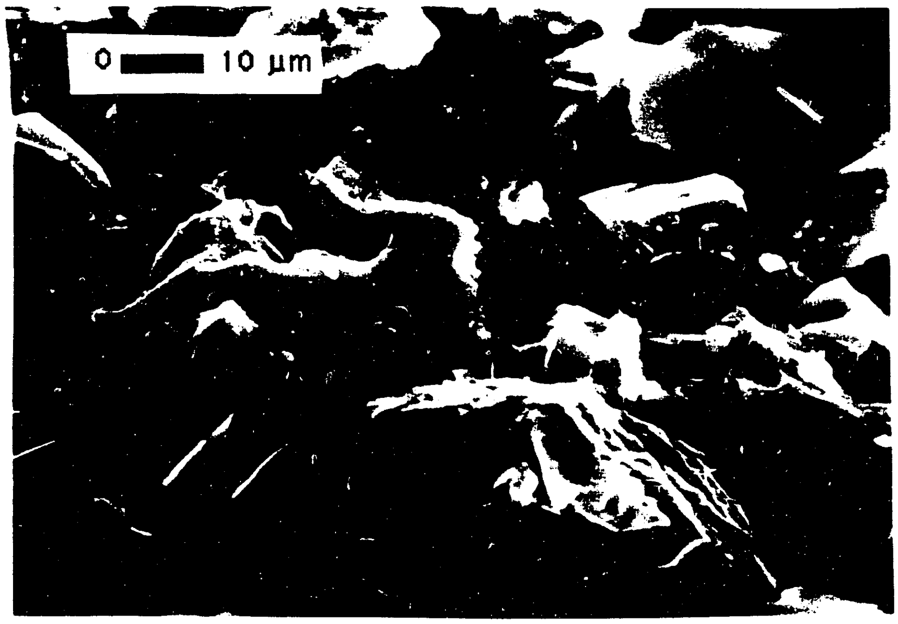
FIGURE 5. Ash from the May 18, 1980 eruption of Mount St. Helens, Washington. The 7-µm-long glass shard shown here is from a sample collected by high-altitude aircraft at an altitude of 18.3 km (60,000 feet) over south central Wyoming on May 21, 1980. This shard is from a sample with a median particle size of 1.5 µm.



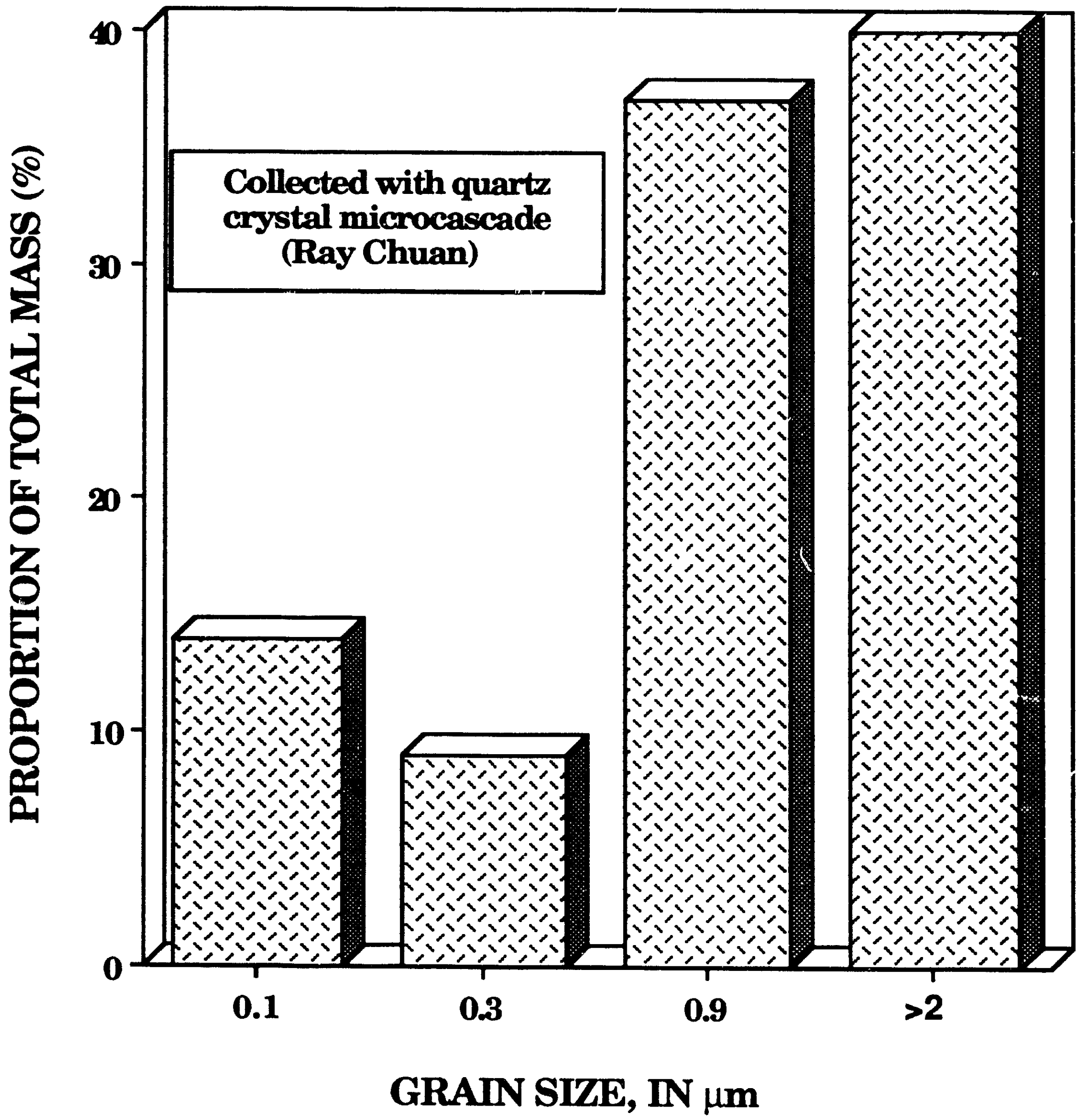
Heiken-Figure 1



Heiken, Fig. 2a

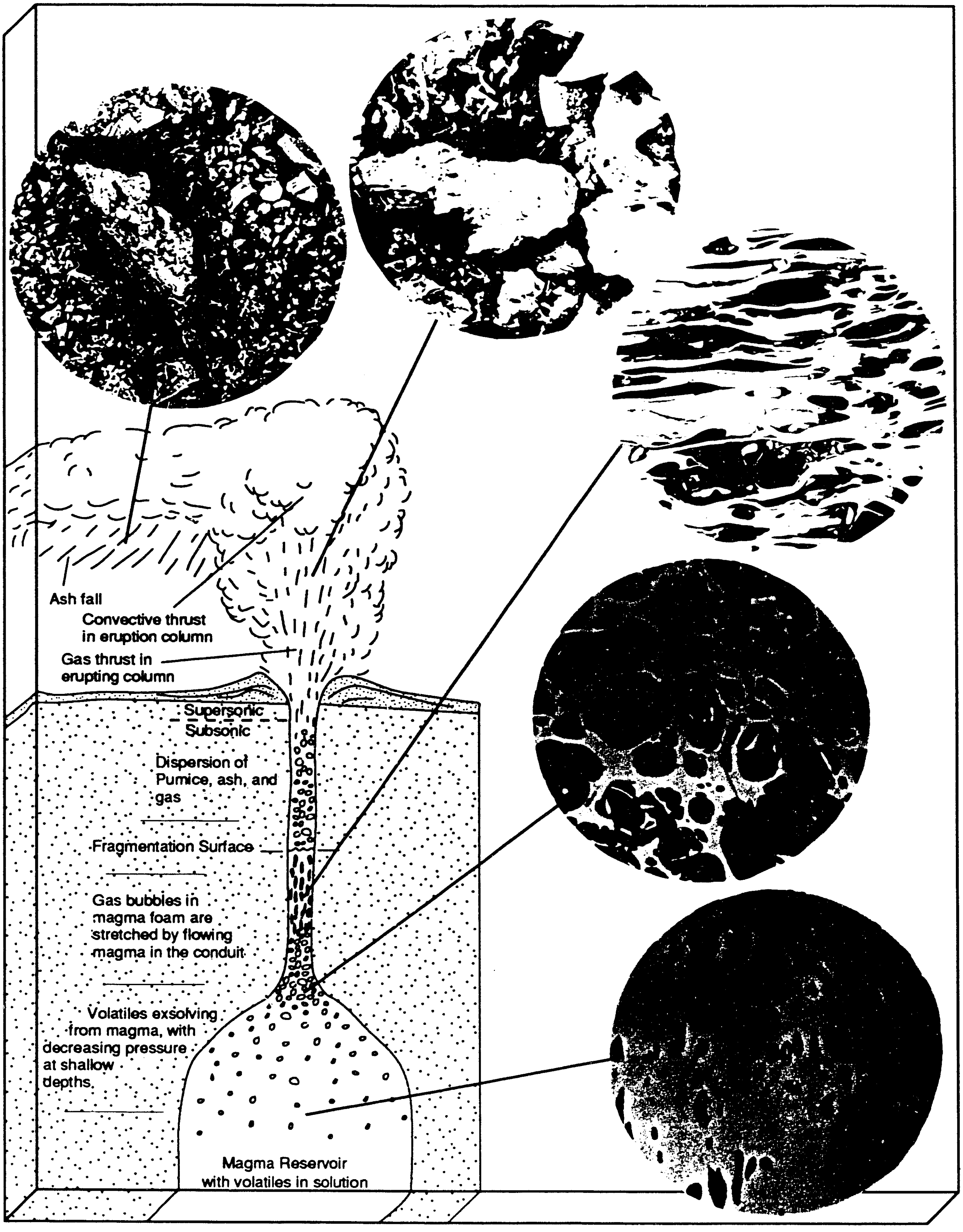


Heiken- Fig.2b



40
30
20
10
0
PROPORTION OF TOTAL MASS (%)
Collected with quartz crystal microcascade (Ray Chuan)
0.1
0.3
0.9
>2
GRAIN SIZE, IN μm

Heiken, Fig. 3



Ash fall
Convective thrust in eruption column
Gas thrust in erupting column
Supersonic
Subsonic
Dispersion of Pumice, ash, and gas
Fragmentation Surface
Gas bubbles in magma foam are stretched by flowing magma in the conduit
Volatiles exsolving from magma, with decreasing pressure at shallow depths
Magma Reservoir with volatiles in solution

Heiken - Fig. 5

TABLE 1

EXPLOSIVE ERUPTION TYPES AND THEIR PRODUCTS

Eruption Type	***Plinian***	***Plinian-Hydro-volcanic***	***Vulcanian***	***Strombolian***	***Hawaiian***	***Surtseyan (Hydrovolcanic)***
Heights of Eruption Columns	10 to 40 km (33,000 to 131,000 ft)	20 to 50 km (66,000 to 164,000 ft)	0.3 to 3.0 km (1,000 to 10,000 ft)	0.1 to 2.0 km (300 to 6,500 ft)	<0.1 to 0.5 km (<300 to 1,600 ft)	0.3 to 2 km (1000 to 6,500 ft)
Approximate Area Affected by Ash Fallout (km^2); 1 km^2=0.38 mi^2	Hundreds to tens of thousands	Tens of thousands to hundreds of thousands	Tens to hundreds	0.05 to 5.0	<0.05 to 0.05	1.0 to 200.0
Percent Glass Shards and Pumice	~60 to 100%	~60 to 100%	~10 to 30%	~60 to 80%	~90 to 100%	~70 to 100%
Percent of Mineral Grains	~0 to 35%	~0 to 35%	~10 to 30%	~1 to 5%	~0 to 10%	~0 to 10%
Percent of Rock Fragments	0 to 30%	~0 to 40%	~70 to 90%	~20 to 40%	Traces	~5 to 30%
Types of Glass Particles	cm- to µm-size angular shards and pumice	mm- to µm-size angular shards and rare pumice	mm-size angular fragments and rare droplets	cm- to mm-size angular, blocky fragments	m- to mm-size droplets and pasty bombs	mm- to µm-size angular, blocky fragments
Potential Hazard to Aviation	High, over large regions	High, over large regions	High, locally; medium regionally	Low	Low	Medium, locally
Examples	Krakatau, Indonesia, 1883; Pinatubo, Philippines, 1991; Mt. St. Helens, USA, 1980	Taupo, New Zealand, ~150 AD	Fuego, Guatemala, 1966; Nguaruhoe, New Zealand, 1974	Stromboli, Italy (all of the time); Cerro Negro, Nicaragua, 1968	Kilauea Volcano, Hawaii (most of the time)	Surtsey, Iceland, 1963; Taal, Philippines, 1977

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