Origin of the Mount Pinatubo climactic eruption cloud: Implications for volcanic hazards and atmospheric impacts

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ABSTRACT

Volcanic-ash clouds can be fed by an upward-directed eruption column (Plinian column) or by elutriation from extensive pyroclastic flows (coignimbrite cloud). There is considerable uncertainty about which mechanism is dominant in large-scale eruptions. Here we analyze in a novel way a comprehensive grain-size database for pyroclastic deposits. We demonstrate that the Mount Pinatubo climactic eruption deposits were substantially derived from coignimbrite clouds, and not only by a Plinian cloud, as generally thought. Coignimbrite ash-fall deposits are much richer in breathable <10 μm ash (5–25 wt%) than pure Plinian ash at most distances from the source volcano. We also show that coignimbrite ash clouds, as at Pinatubo, are expected to be more water rich than Plinian clouds, leading to removal of more HCl prior to stratospheric injection, thereby reducing their atmospheric impact.

Keywords: grain size, PM_{10}, specific surface area, Pinatubo, pyroclastic deposits, Plinian, coignimbrite, volcanic hazards.

INTRODUCTION

Volcanic-ash clouds are a significant hazard to aircraft (Rose et al., 1995; Casadevall et al., 1996; Sparks et al., 1997), involve chemical reactions (Hofmann and Solomon, 1989; Mankin et al., 1992; Tabazadeh and Turco, 1993), affect the global climate (Sparks et al., 1997), and pose potential health risks (Óskarsson, 1980; Mercado et al., 1996; Norton and Gunter, 1999; Baxter, 2000). Ash clouds can be fed by an upward-directed eruption column (Plinian column; Fig. 1A) or elutriated from extensive pyroclastic flows generated by fountain collapse (coignimbrite ash cloud; Fig. 1B) (Sparks et al., 1997). Knowledge of the ash-cloud origin is very important because the impacts on animal and human health, on the environment, and on aircraft safety may differ greatly. Coignimbrite ash clouds are much richer in breathable dust-size ash and can be substantially richer in water and ice than Plinian columns reaching the same height. As pyroclastic flows move downslope, they entrain moist tropospheric air and incorporate water by vaporizing streams, lakes, seawater, snow, or ice.

Evaluations of atmospheric impacts and health hazards of the Pinatubo ash cloud have previously assumed a dominant Plinian eruption-column origin. Here we demonstrate that the Pinatubo fall deposit is unusually fine grained for a Plinian deposit, and that all grain-size features can be reconciled with a major coignimbrite origin.

CLIMACTIC ERUPTION OF MOUNT PINATUBO

The Pinatubo climactic eruption on June 15, 1991, was one of the largest of the twentieth century. The eruption cloud reached 34 km in height (Koyaguchi and Tokuno, 1993), lasted more than ~6 h (Rosi et al., 2001), and released a bulk tephra volume (fall and flow) of 8.4–10.4 km^3 (Scott et al., 1996; Paladio-Melosantos et al., 1996), ~4.5 Mt of HCl, and ~20 Mt of SO_2 (Tabazadeh and Turco, 1993), caused by sulfur enrichment of the dacitic magma system (Bernard et al., 1991). The eruption has been widely studied, but the origin of the giant ash cloud remains unclear (Scott et al., 1996; Rosi et al., 2001). It is generally interpreted as a Plinian column (Fig. 1A) (Koyaguchi and Tokuno, 1993; Tabazadeh and Turco, 1993; Holasek et al., 1996;

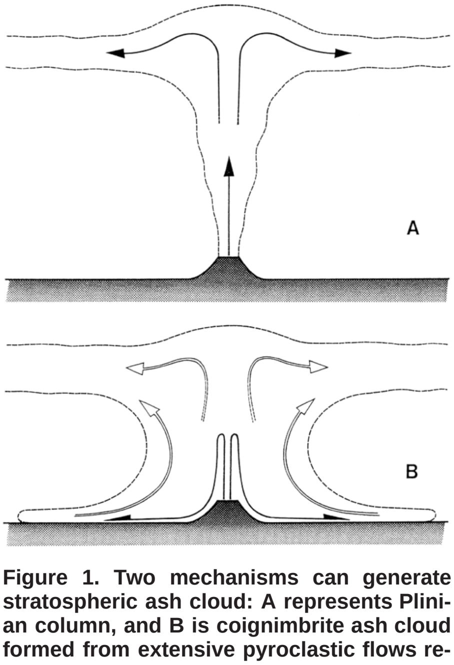

Figure 1. Two mechanisms can generate stratospheric ash cloud: A represents Plinian column, and B is coignimbrite ash cloud formed from extensive pyroclastic flows resulting from fountain collapse. When pyroclastic flows become buoyant and loft, they can generate stratospheric coignimbrite cloud. Plinian column tends to encompass very heterogeneous materials of various sizes, whereas coignimbrite plume is made of only small grains.

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Paladio-Melosantos et al., 1996). However, field observations indicate unusual features for a Plinian column deposit, e.g., equal volumes and simultaneous emplacement of pyroclastic flow and fall deposits (Scott et al., 1996; Paladio-Melosantos et al., 1996; Rosi et al., 2001). The flow deposits are depleted in fines (Scott et al., 1996), and the fall layer is thin, even close to source (Paladio-Melosantos et al., 1996; Sparks et al., 1997; Rosi et al., 2001). It has been surmised that the ash cloud may not have been Plinian, and that a coignimbrite origin should be evaluated further (Fig. 1B) (Scott et al., 1996; Sparks et al., 1997; Rosi et al., 2001). A coignimbrite origin is consistent with satellite observations. Multispectral digital data (Holasek et al., 1996; Volon, 1997), acquired with two AVHRR (Advanced Very High Resolution Radiometer) thermal infrared channels (T4 and T5), show that the volcanic cloud was indistinguishable from meteorological clouds (i.e., T4-T5 > 0) (Casadevall et al., 1996; Volon, 1997). The positive T4-T5 signatures in the semitransparent regions of the ash cloud are consistent with strong water enrichment and ash particles encased in ice, which prevents detection of their true silicate spectral infrared signature (Rose et al., 1995). Such a water enrichment is not expected for a Plinian column; e.g., a positive anomaly was not observed for the 1982 El Chichón Plinian columns, which also erupted into a wet tropical atmosphere.

STORY IN THE GRAINS

To evaluate the origin of the Pinatubo climactic ash cloud, we measured grain-size characteristics of our own samples collected around Mount Pinatubo (see Data Repository item[1]) and analyzed an integrated data set including Philippine Institute of Volcanology and Seismology (PHIVOLCS) and deep-sea ash data (Paladio-Melosantos et al., 1996; Wiesner et al., 1995). In grain-size analysis, the logarithm of grain ''diameter'' is traditionally used as the random variable (Krumbein, 1936). This logarithmic scale is named the phi scale, where $\phi = -\log_2 d/d_0$, d is the grain's linear dimension in mm, and d_0 is taken as 1 mm in order to make the number inside the logarithm dimensionless, hence to prevent erroneously transforming the phi values back to the metric scale (McManus, 1963). However, the direct use of ''d'' as the random variable is logical because it is related to our experience of directly measuring the grains in terms of metric-length units and is routinely used in engineering and aerosol science (e.g., Rhodes, 1999). This study is the first application of this approach to volcanic deposits. Hence we use first moment and standard deviation (both in meters) of the mass grain-size distribution. The standard deviation measures the dispersion of the grain-size distribution (i.e., metric sorting). We also calculate the bulk specific surface area (SSA), which is the total surface area of a set of grains to their total volume (in m^{-1}). SSA is proportional to the inverse of the Sauter mean diameter of the number grain-size distribution in the metric scale. SSA of a set of grains is sensitive to the bulk grain size (e.g., it decreases with increasing grain size) and is a first-order control on heat transfer and chemical exchange between ash and any gas within ash clouds (Óskarsson, 1980).

[1]GSA Data Repository item 2002071, Annex, Locations, sample information, and methods, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

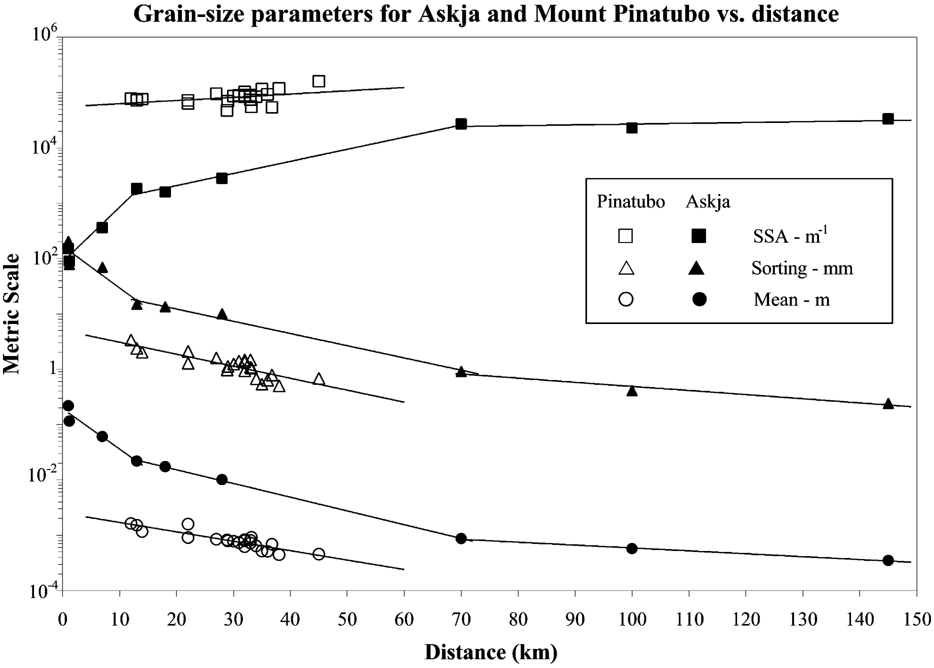

Figure 2. Variation of grain-size parameters with distance (km) from vent for Plinian Askja (closed symbols) and for coignimbrite Mount Pinatubo deposits (open symbols). For a given deposit, circles represent first moment (arithmetic metric mean, m), triangles represent standard deviation (metric sorting, mm), and squares represent bulk specific surface area (SSA, m^{-1}).

Figure 2 compares variations of mean, sorting, and SSA versus distance for the fall deposit from the unambiguously Plinian Askja D deposit, Iceland, 1875 deposits (Sparks et al., 1981), and the fall deposit from the Pinatubo climactic eruption ash cloud (layer C). Both Pinatubo and Askja are interpreted as eruptions of relatively similar intensity with respect to the duration of the eruption (~6 h), the wind velocity (~25 m/s), and altitude reached by the columns (~30 ± 4 km) (Sparks et al., 1981; Carey and Sparks, 1986; Rosi et al., 2001). Between 10 and 50 km from source, Pinatubo SSA values are about one to two orders of magnitude higher than those for Askja, while mean and sorting values are about an order of magnitude smaller than those for Askja. In the same distance range, SSA increases fivefold for Askja, whereas it does not even double for Pinatubo. Those contrasting trends appear exactly as expected by theory if Pinatubo and Askja were coignimbrite and Plinian falls respectively (Bonadonna et al., 1998). Moreover, the Askja deposits show no <10 μm ash (PM_{10}) for locations to 145 km, while Pinatubo shows a rapid enrichment in PM_{10}, ~5–11 wt% at 10–45 km increasing to 26 wt% at 250–600 km. Such high amounts of PM_{10} are only found ultradistally in Plinian fall deposits after extreme aerial sorting, e.g., ~28 wt% PM_{10} at ~1900 km for Askja falls. All the available data indicate that the Pinatubo giant ash cloud deposited dominantly homogeneous fine ash enriched in PM_{10} (mainly micrometer to millimeter size range, regardless of distance from the source), while the Askja Plinian cloud deposited coarser and more heterogeneous falls.

We also introduce two new grain-size parameters: (1) SSA/mean (in m^{-2}) and (2) mean/sorting (dimensionless). The first ratio distinguishes coarse-grained from fine-grained deposits (e.g., flow from surge deposits, proximal fall from distal fall deposits). The second ratio discriminates gravity-controlled flow and coignimbrite fall deposits from pure Plinian fall deposits. Using Figure 2 for a given deposit, the mean and sorting decay in a similar fashion with distance. Hence, to a first approximation, the mean/sorting ratio does not change much with distance from source, particularly proximally. In Figure 3, we show the grain-size ratios for 600 samples from many

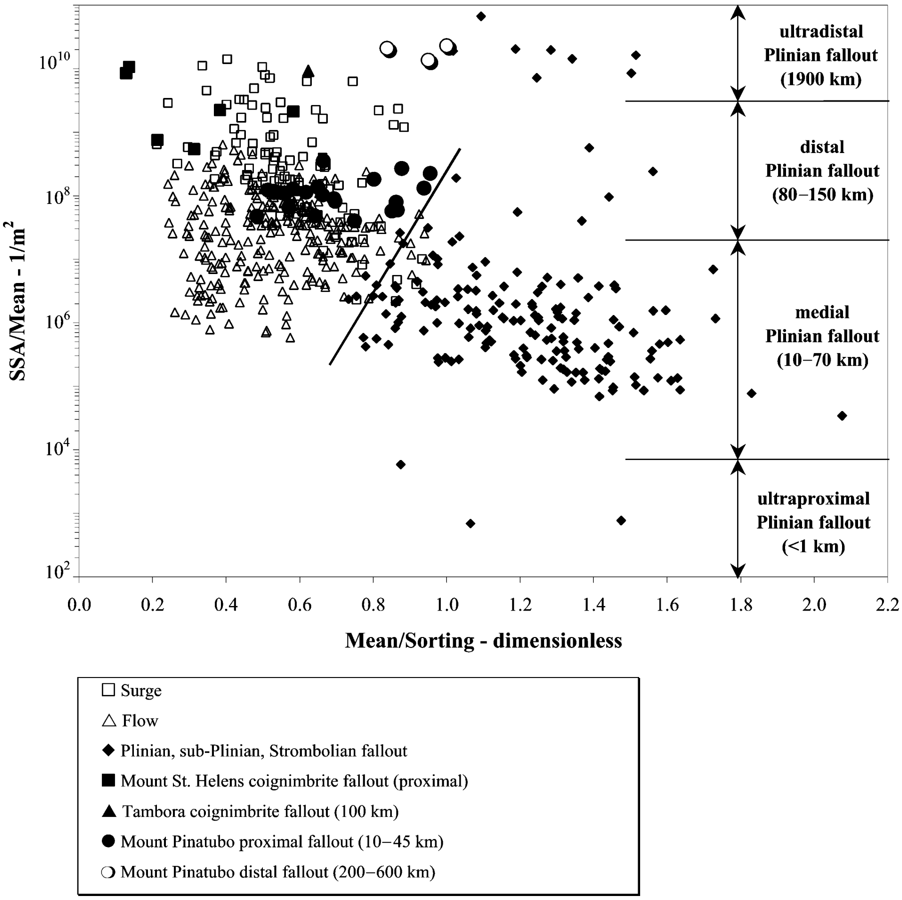

Figure 3. Grain-size ratios for 600 samples. Vertical axis is specific surface area over mean (SSA/mean, m^{-2}), and horizontal axis is mean over sorting (mean/sorting, dimensionless). Closed diamonds are for fall deposits from Plinian, sub-Plinian, or Strombolian clouds. Open triangles represent pyroclastic flow deposits, and open squares represent pyroclastic surge deposits. Black line, drawn from best visual fit, indicates boundary between pure Plinian fall domain (right side) and pyroclastic flow and surge domains (left side). As indicated, coignimbrite fall deposits from Mount St. Helens (closed squares), Tambora (closed triangle), and Pinatubo (circles) eruptions plot in flow-surge domain. Distance on right side only refers to Plinian deposits, and represents actual distance between deposits and volcano.

locations and eruptive styles (Plinian, sub-Plinian, Strombolian) representing the main types of pyroclastic activity (surge, flow, fall, and coignimbrite fall) (Murai, 1961; Kuntz et al., 1981; Sparks et al., 1981; Sigurdson and Carey, 1989; Lirer and Vinci, 1991; Wiesner et al., 1995; Paladio-Melosantos et al., 1996). Pyroclastic flow and surge deposits have a low mean/sorting ratio relative to Plinian fall deposits, enabling us to separate gravity current from Plinian fall deposits, regardless of the distance from source. As expected for Plinian falls, the SSA/mean ratio increases with distance from the volcano, while the mean/sorting ratio spans the same value range (i.e., ~0.8–2.1 at <100 km and ~1.0–1.6 at >100 km). Also plotted are the coignimbrite falls from the 1980 Mount St. Helens, and the 1815 Tambora eruptions (Kuntz et al., 1981; Sigurdson and Carey, 1989). Surge and coignimbrite fall deposits span the same range of mean/sorting values as dense pyroclastic flow (0.1 to ~1.0) because they are typically derived from them. Hence they are mainly distinguished from flows by contrasting SSA/mean ratios. Elutriation clouds (e.g., surge, coignimbrite clouds) contain mostly fine ash from their parent pyroclastic flows. Thus their SSA is much higher and their mean much lower than their parent pyroclastic flows. In Figure 3, Pinatubo fallouts clearly plot in the coignimbrite-surge-flow domain, and not in the Plinian fall domain. On the basis of all available data for Pinatubo, we conclude that the climactic-phase fall layer was substantially derived from an ash cloud fed by large pyroclastic flows, with a less important role for Plinian input than previously thought.

IMPLICATIONS

Compared to Plinian clouds, coignimbrite clouds are richer in breathable fine ash, which poses a threat to human health (Mercado et al., 1996; Norton and Gunter, 1999; Baxter, 2000). Short-term exposure to PM_{10} ash during and after the Pinatubo eruptions was suggested as a possible initiating factor in acute respiratory infections (ARI) leading to chronic obstructive pulmonary diseases (such as pneumonia, bronchitis, bronchial asthma, and emphysema). After the Pinatubo eruptions, an average weekly mortality of 16 per 10 000 due to ARIs was documented in 1992 (Mercado et al., 1996). However, in the absence of continuous monitoring of airborne ash levels and their possible health effects, the deaths have been related to measles and pneumonia induced by poor nutritional status and health of victims (R.A. Mercado, P. Baxter, and C. Newhall, 2001, personal commun.). Today, 11 yr after the Pinatubo eruptions, the PM_{10} fraction of ash resuspended by winds and human activities remains a potential, yet unmonitored, health risk causing many respiratory problems (L. Yoshisaki, 2001, personal commun.). This may be aggravated by an average cristobalite content in the Pinatubo PM_{10} of ~2 wt% (measured by Rietveld X-ray diffraction), a level 20 times higher than the minimum level considered to be a potential health hazard (Smith, 1997).

Coignimbrite clouds are potentially richer in water than Plinian columns of similar intensity. From local atmospheric profiles taken by the U.S. Air Force on June 15, 1991, and from the Woods (1988) Plinian column model, we estimate the mass of tropospheric water entrained into the volcanic ash cloud as it rises to be ~42 Mt (assuming a 250 m vent radius at 2 km above sea level). This is small compared to the 500 Mt of magmatic water initially released by the eruption (Sparks et al., 1997). In contrast (S. Sparks, 2001, personal commun.), a rising coignimbrite ash cloud is expected to entrain 60 times more tropospheric water than a Plinian column (~2520 Mt, assuming a minimum averaged basal radius of 10 km for the coignimbrite source within a lower, moister atmosphere). As it rises, the water vapor condenses and freezes onto the fine ash, which masks their spectral infrared signature (Rose et al., 1995; Volon, 1997). This water enrichment in coignimbrite clouds for many of the largest eruptions prevents automatic detection of ash clouds using the infrared T4-T5 split window method. This is a cause for concern for aircraft safety during coignimbrite eruptions. For example, there were at least 16 aircraft encounters with the giant Pinatubo ash cloud (Casadevall et al., 1996).

The water enrichment also explains why the HCl emitted by Pinatubo was so efficiently scavenged (Mankin et al., 1992; Tabazadeh and Turco, 1993). El Chichón initially released 1.8 Mt of HCl, 60% less than Pinatubo (4.5 Mt) (Hofmann and Solomon, 1989; Tabazadeh and Turco, 1993). However, both eruptions injected equivalent amounts of HCl into the stratosphere (~0.04 Mt) (Hofmann and Solomon, 1989; Tabazadeh and Turco, 1993). Thus, in terms of stratospheric volcanic chlorine injections and their effect on ozone levels, coignimbrite ash clouds should have a smaller impact. Water droplets and ice also scavenge some of the SO_2 emitted, thereby reducing effects from SO_2-derived aerosols on ozone and temperature (Rose et al., 1995). However, higher stratospheric water injections can also lead to higher levels of OH radicals, which contribute to ozone destruction (Hofmann and Solomon, 1989). Models of atmosphere-climate impacts must account for these key differences between Plinian columns and coignimbrite ash clouds.

Since its introduction in the 1930s (Krumbein, 1936), the phi scale has been favored by geologists over the metric scale used in engineering. However, the metric scale has clear assets. First, it has a dimension, which makes metric grain-size statistics intuitive to interpret and easily usable by theoretical fluid-dynamic models. Second, it has a much larger variety of statistical parameters, opening promising new opportunities for the field of grain-size analysis in geology. Third, because of this, geologists can choose the best parameters depending on the nature of the grain-size frequency function, the measurement technique, and their objectives. Fourth, any combination (ratio) of grain-size parameters can be calculated to shed new light on genetic processes without losing any information and physical meaning; e.g., in volcanology, the mean/sorting ratio tends to constrain distance effects along one axis and potentially may be used for quantifying the proportions of ash from different end-member sources (Plinian and coignimbrite) within the deposit. In order to capture all the complexities of sedimentological processes, geologists should express their results in more than one manner (Krumbein, 1936).

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