

Particle sizes of andesitic ash fallout from vertical eruptions and co-pyroclastic flow clouds, Volcán de Colima, Mexico

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ABSTRACT

We report particle-size distributions for andesitic ash fall from vertical eruptions and clouds above block-and-ash flows at Volcán de Colima, Mexico, during 2004–2006. We analyzed 17 samples using laser diffraction: 11 from vertical eruptions and 6 from block-and-ash flows (co-pyroclastic flow ash). Vertical eruptions produce well-sorted fall deposits, whereas co-pyroclastic fall deposits are poorly sorted, with high proportions of very fine grained ash (<30 μm). Statistical analysis shows particle-size distributions of vertical eruptions are more leptokurtic (peaked) than co-pyroclastic samples. Deconvolution of grain-size histograms shows that co-pyroclastic samples have at least one subpopulation with a mode of 8.3–8.7 φ (2.4–3.1 μm). Estimates of the number of particles in different size ranges show that co-pyroclastic samples contain much greater numbers of very fine particles than vertical eruption samples. Our results provide no direct evidence that milling or comminution produces hazardous fine ash particles in pyroclastic flows, but are consistent with that interpretation.

INTRODUCTION

Fine ash can travel thousands of kilometers from a volcano (Rose and Chesner, 1987). Even when particle aggregation or meteorological events occur, the smallest particles take the longest time to settle out of the atmosphere. Volcanic ash hazards range from aircraft damage to physiological effects, and are the main reason volcanoes threaten at least 500 million people (USGS, 2000; Pickrell, 2003). Fine ash, used herein, refers to pyroclasts <250 μm in diameter (Fisher, 1961; Bonadonna et al., 1998; White and Houghton, 2006). We use the term “very fine ash” for particles with diameters of <30 μm (see also Rose and Durant, 2009). Very fine ash is particularly hazardous because humans and animals can ingest and inhale particles with diameters ≤10 μm, which cause severe health problems (Blong, 1984; Horwell et al., 2003; Stokstad, 2003; Horwell and Baxter, 2006).

Most eruptions produce fine ash. The size of particles produced reflects eruption style and fragmentation energy (Walker, 1981; Sigurdsson et al., 1982). In many eruptions, bursting of overpressured gas bubbles (Sparks, 1978) creates pyroclasts with diameters similar to the size of gas bubbles in the magma. Fine ash can also form from hydro-magmatic fracturing when water enters a vent (Wohletz et al., 1989), or from the milling of particles that occurs inside volcanic conduits and within pyroclastic flows (Freundt and Schmincke, 1992; Darteville et al., 2002; Zimanowski et al., 2003). Fine particles produced by milling inside pyroclastic flows are elutriated when hot gas escapes the flow to rise buoyantly, forming a cloud that can pro-

duce co-pyroclastic flow fallout (Freundt and Schmincke, 1992).

When pyroclastic flows accompany an explosive eruption, ash falls out from both vertical rising plumes and clouds above density currents moving away from the vent (co-pyroclastic). Therefore, it is reasonable to expect that eruptions with pyroclastic flows will produce greater amounts of fine ash than eruptions not associated with pyroclastic flows. The largest quantities of fine ash are associated with ignimbrite-forming eruptions (Walker, 1981; Dellino et al., 2004; Baines and Sparks, 2005).

The purpose of this study was to test the hypothesis that ash elutriated from a pyroclastic flow can be differentiated from ash derived from vertical plume fallout using size-distribution data. To test this hypothesis, the size distributions of a suite of ash samples from a single andesitic volcano, Volcán de Colima, Mexico, were analyzed. The results support the hypothesis and may ultimately be useful in improving volcanic hazard forecasting and identifying whether individual ash-fall deposits originated from a vertical plume or a co-pyroclastic cloud.

Background

Volcán de Colima, part of the Colima Volcanic Complex (Luhr and Carmichael, 1982), is an andesitic stratovolcano that produces vertical eruptions and block-and-ash flows (Allan, 1986; Saucedo et al., 2002; Saucedo et al., 2004). Colima has had >52 significant eruptions and >29 major explosive eruptions since A.D. 1560 (Bretón-Gonzales et al., 2002), and is the most active volcano in Mexico. Catastrophic (Plinian to sub-Plinian) eruptions occur in a cycle of ~100 years (Bretón-Gonzales et al., 2002). The

samples described here reflect dome extrusion accompanied by weak vertical eruptions, lava extrusion, and block and ash flows. Colima’s ashes and lavas are andesites with 57%–61% silica (Luhr and Carmichael, 1982). In andesitic ash, silica-rich phases including feldspar, glass, and microcrystalline silica tend to be preferentially fragmented; mafic phenocrysts resist breakage (Horwell et al., 2001). The bulk composition of particles described in this paper is andesitic, but they are variably enriched in lower-density components (feldspar, silicic glass, and perhaps microcrystalline silica).

METHODS

We analyzed 11 samples of fine ash deposited from vertical eruptions and six samples deposited from co-pyroclastic clouds. Samples were collected by Varley and his assistants (Table 1). Field notes included the time and date of collection and were used to separate samples into two categories: those collected following a vertical eruption and those collected from an area that was traversed by pyroclastic flows during the most recent event. Information about the type of volcanic activity was based on eyewitness accounts and seismic data. Samples of ash deposited from vertical eruptions were collected on the same day as the eruption. Samples of ash deposited from co-pyroclastic clouds were collected as late as one week after deposition, to ensure that the area was safe. Three of the co-pyroclastic samples (co-pf2, co-pf4, and co-pf6) were derived from the same flow but were collected at varying distances from the summit and the flow deposit. This pyroclastic flow was associated with one of the largest events of the explosive phase that began in January 2005 and continued through the remainder of the collection period.

The co-pyroclastic samples were deposited near the paths of pyroclastic flows. Based on observations (visual and stratigraphic), they are interpreted to have been deposited from dilute, elutriated pyroclastic flow clouds that rose <1 km from the ground. All of the samples in the co-pyroclastic category are assumed to be the product of pyroclastic flows, due to their deposition near pyroclastic flows active shortly before their collection. Although fine particles elutriated from pyroclastic flows may be hot and have high surface area, sometimes resulting in the

TABLE 1. LIST OF SAMPLES

Sample	Dates and time	Location	UTM E	UTM N	Distance (km)	Median	Mean	Mode	Skewness	Kurtosis	Sorting
vertical1	28 July 06 12:15	Playon thermal station	643915	2159309	1.64	3.106	3.082	3.631	0.052	2.530	1.167
vertical2	15 February 05 01:38	Playon campsite	644244	2160281	2.29	1.307	1.421	1.131	1.563	6.403	0.651
vertical3	15 February 05 12:36	Playon campsite	644244	2160281	2.29	1.616	1.663	1.631	1.050	5.409	0.618
vertical4	26 March 06 14:00	Playon campsite	644244	2160281	2.29	1.332	1.419	1.131	1.351	5.742	0.588
vertical5	22 January 06	Nevado Observatory	645107	2163954	5.81	1.864	1.869	1.881	0.451	4.296	0.571
vertical6	13 March 05	Los Mazos	654936	2165349	12.22	1.426	2.280	0.881	1.468	4.197	1.976
vertical7	27 July 05	El Remate	626425	2147524	21.46	3.285	3.594	2.381	0.912	3.541	1.469
vertical8	21 November 05 06:30	Colima Airport	644064	2134536	23.63	3.869	3.888	3.882	0.298	3.491	0.708
vertical9	27 July 05	La Caja	626137	2142347	24.66	3.850	4.249	2.631	0.774	2.835	1.826
vertical10	27 September 05	Between Colima and Minatitlan	618445	2140648	31.86	3.857	4.116	2.631	0.586	2.710	1.895
vertical11	27 September 05	Minatitlan	606963	2151218	38.73	1.957	2.465	1.881	1.651	5.203	1.516
co-pf1	14 May 04 (20 May)	North flank	644827	2159355	1.24	4.515	4.615	4.631	0.303	2.783	1.983
co-pf2	16 September 05 (19 September)	Monte Grande	644835	2155640	2.51	4.148	4.310	4.132	0.349	2.338	2.210
co-pf3	30 May 05 (1 June 05)	San Antonio	644516	2155627	2.57	5.418	5.613	4.882	0.482	2.697	1.673
co-pf4	16 September 05 (19 September)	San Antonio	644346	2155575	2.67	4.512	4.727	4.382	0.495	3.037	1.792
co-pf5	6 June 05 (14 June)	Monte Grande	644633	2153157	5.00	4.591	4.590	4.631	0.175	2.311	2.210
co-pf6	16 September 05 (17 September)	La Arena	649422	2155202	5.25	1.970	2.123	1.631	0.732	3.195	0.985

Note: UTM—Universal Transverse Mercator. Samples labeled “vertical” are assumed to be the product of fallout from a vertical eruption plume. Samples labeled “co-pf” are assumed to have been deposited from elutriation clouds associated with pyroclastic flows. The date and time of collection are indicated in the second column with actual collection date, if different, in parentheses. UTM coordinates for the sample collection sites (east and north) are in meters and are based on the WGS84 ellipsoid. Distance from the vent is horizontal measured distance from the vent to the sample collection site. Statistical results for each sample are in Φ (Krumbein and Pettijohn, 1938).

generation of phoenix clouds (Darteville et al., 2002; Rose et al., 2007), large phoenix clouds were not observed at Colima during times preceding collection of the co-pyroclastic samples. At least one of the co-pyroclastic samples (co-pf1) was collected near the margin of block-and-ash deposits and could be a surge deposit, but is grouped with co-pyroclastic samples because both co-pyroclastic ash deposits and surge deposits likely reflect milling during flow.

Two of the samples selected (co-pf6 and vertical1) are probably not representative of typical deposits in their respective categories. Sample co-pf6 is from an unprotected site in a ravine. The sample was collected one day after eruption, but was exposed to rain prior to collection. Sample vertical1 was deposited during the smallest eruption and was collected closer to the vent (1.64 km) than any other sample. Data for both of these samples are shown in Table 1, but were not used as the basis for any interpretations.

A Microtrac® Standard Range Analyzer 9210-1-10-1 laser particle-size analyzer was used to determine the diameter of particles at 0.25 Φ intervals within the range of 704–0.82 μm (0.5–10.5 Φ), which is a typical size range for the analysis of fine ash deposits (Cooper et al., 1984; Damm, 1990; Lindsay et al., 1998). Samples were sieved prior to Microtrac analysis to extract any particles >704 μm (0.5 Φ). Samples vertical3, co-pf3, co-pf4, co-pf5, and co-pf6 contained particles >704 μm (0.5 Φ), which represented 20%, 8.5%, 18.3%, 6.3%, and 12.3%, respectively, of each sample’s total mass. Scanning electron microscope photographs of samples were visually analyzed and it was determined that the shapes of grains did not

show any consistent variation related to mode of origin.

Grain-size distributions were analyzed using Gradistat (Blott and Pye, 2001) and Kware SFT (sequential fragmentation/transport) (Wohletz et al., 1989). We calculated the mean, median, main mode, sorting, skewness, and kurtosis for the entire portion of each sample finer than 704 μm (0.5 Φ) using the method of moments (Krumbein and Pettijohn, 1938) rather than using the Folk and Ward (1957) graphical method because the characteristics of each sample’s fine tail was of interest (Blott and Pye, 2001). Strictly speaking, lognormal statistics should only be used for samples that represent a single lognormal distribution. Sedimentologists commonly use the method of moments to characterize all types of samples, however, and this method was employed here to facilitate presentation and comparison of our results. Kware SFT was used to deconvolve each sample into a maximum of five separate lognormally distributed subpopulations.

RESULTS

Samples deposited from vertical eruptions and co-pyroclastic clouds (Table 1) show differences in mean, median, and modal diameters, and in sorting, skewness, and kurtosis. Vertical eruption samples have larger mean, median, and mode diameters than co-pyroclastic samples. Co-pyroclastic sample means are <53 μm (>4.25 Φ) with median and modal diameters <63 μm (>4.0 Φ). Vertical eruption samples are poorly to moderately well sorted, whereas co-pyroclastic samples are poorly to very poorly sorted. Nine of the 10 vertical eruption samples are fine to very fine skewed; the remaining sample is sym-

metrical. Two of the co-pyroclastic samples are fine skewed and three are symmetrical. Four vertical eruption samples are mesokurtic, and six are leptokurtic. Two co-pyroclastic samples are platykurtic and three are mesokurtic. Kurtosis differences show that the co-pyroclastic samples have a greater range in grain sizes than vertical eruption samples.

Means, main modes, and sorting of vertical eruption samples all tend to increase in Φ units (particle diameters decrease) with distance from the vent (Table 1), reflecting atmospheric fractionation (particle size decreases with atmospheric residence). Variation of these parameters with distance accounts, in part, for measured differences among vertical eruption samples. However, vertical eruption samples typically contain a smaller fraction (<45%) of particles finer than 63 μm (>4 Φ) than co-pyroclastic samples, regardless of their distance from the vent (Fig. 1).

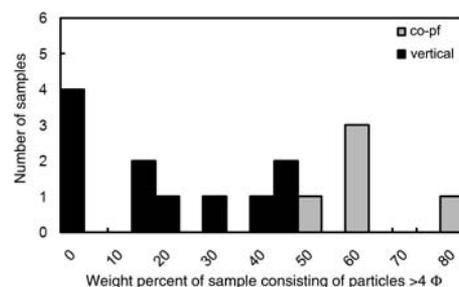


Figure 1. Histogram showing number of samples containing the indicated weight percents of particles <63 μm (>4 Φ) in size. Vertical eruption samples are black bars and co-pyroclastic flows are gray.

Deconvolution of samples into constitutive subpopulations highlights effects that could reflect comminution (Table 2). Only one vertical eruption sample (vertical10) has a subpopulation with a mode $<8 \mu\text{m}$ ($>7.0 \Phi$). In contrast, every co-pyroclastic sample has a subpopulation with a mode $<4 \mu\text{m}$ ($>8.0 \Phi$). This subpopulation is interpreted as the product of comminution in the pyroclastic flows (Wohletz et al., 1989; Freundt and Schmincke, 1992). All vertical eruption samples have at least two subpopulations with modes between 31 and 700 μm (0.5–5.0 Φ). The combined mass of these subpopulations composes $>75\%$ of each sample's total mass. In contrast, $>75\%$ of the mass of every co-pyroclastic sample is contained within subpopulations with modes $<63 \mu\text{m}$ ($>4.0 \Phi$) (Fig. 1). Each co-pyroclastic sample includes subpopulations with modes $>8.0 \Phi$ and is dominated by subpopulations with modes ranging from 4.0 to 5.5 Φ . In summary, we note that co-pyroclastic samples have much more conspicuous fine populations, consistent with effects of comminution, but not conclusive proof of any fine ash-producing mechanism.

of co-pyroclastic samples, with a main mode at 9.9 Φ . Samples vertical8 and co-pf1 are shown together to emphasize differences between the two ash types; note that the finest bin of the vertical eruption sample barely overlaps the coarsest bins of the co-pyroclastic sample. A histogram showing the main modes for every sample collected for this study, based on estimates of the numbers of particles (Fig. 2C), shows that modes for vertical eruption samples range from ~ 3.25 to 9.0 Φ , with four samples having modes in the interval 3.25–4.5 Φ , one having a mode between 6.0 and 6.5 Φ , and five having modes between 8.75 and 9.0 Φ . In contrast, co-pyroclastic samples have much finer primary modes, all located between 9.5 and 10.0 Φ .

DISCUSSION

Our results are based on samples from only one volcano, but it seems likely that milling in pyroclastic flows could be a mechanism for generating very fine ash at any volcano when pyroclastic flows occur. The higher proportion of very fine ash in co-pyroclastic samples documented here is similar to results from other

TABLE 2. LIST OF SAMPLE SUBPOPULATIONS

Sample	Subpop. 1	Subpop. 1 fraction	Subpop. 2	Subpop. 2 fraction	Subpop. 3	Subpop. 3 fraction	Subpop. 4	Subpop. 4 fraction
vertical1	3.36	0.77	1.61	0.23				
vertical2	1.17	0.96	3.14	0.04				
vertical3	1.51	0.98	3.72	0.02				
vertical4	1.21	0.97	3.19	0.03				
vertical5	1.93	0.74	1.19	0.26				
vertical6	0.84	0.57	4.64	0.28	1.82	0.15		
vertical7	3.97	0.54	2.32	0.41	6.4	0.05		
vertical8	3.82	0.95	2.59	0.05				
vertical9	2.66	0.49	4.58	0.28	6.61	0.23		
vertical10	4.84	0.58	2.35	0.38	8.51	0.04		
vertical11	1.87	0.57	1.14	0.22	4.73	0.19	6.26	0.01
co-pf1	4.51	0.73	1.68	0.15	7.74	0.09	8.67	0.03
co-pf2	4.18	0.61	1.52	0.22	8.33	0.09	6.39	0.08
co-pf3	5.13	0.91	8.69	0.09				
co-pf4	4.11	0.82	6.84	0.14	8.66	0.03	0.66	0.01
co-pf5	4.78	0.81	1.42	0.15	8.62	0.05		
co-pf6	1.73	0.88	3.57	0.12				

Note: Subpopulations (Subpop.) found via Kware SFT (sequential fragmentation/transport; Wohletz et al., 1989) are shown with their associated fractions of the sample. Subpopulations are presented in Φ (Krumbein and Pettijohn, 1938).

Atmospheric scientists commonly recalculate the grain-size distribution parameters based on the number of particles within each size class. The number of particles may be estimated assuming that particles are spherical, have diameters equal to the average for their size bin, and a density of 2.65 g/cm^3 (2650 kg/m^3 ; density of andesite). This highlights the abundance of fines in the co-pyroclastic samples (Figs. 2A and 2B). Sample vertical8 is typical of vertical eruption samples. It has main and secondary modes of 6.4 and 4.9 Φ , respectively. Sample co-pf1 is characteristic

volcanoes with different compositions and eruptive styles, including Pinatubo (Darteville et al., 2002), Soufrière Hills (Bonadonna et al., 2002), and Fuego (Rose et al., 2007). In large explosive eruptions (Volcanic Explosivity Index, VEI > 7), elutriated ash from pyroclastic flows is a significant or dominant contributor to stratospheric clouds, and the bulk of distal fallout from events like the Youngest Toba Tuff (Rose and Chesner, 1987) and the 11 Ma Bruneau-Jarbridge eruption of the Yellowstone hotspot (Rose et al., 2003) may be the result of pyroclastic flow com-

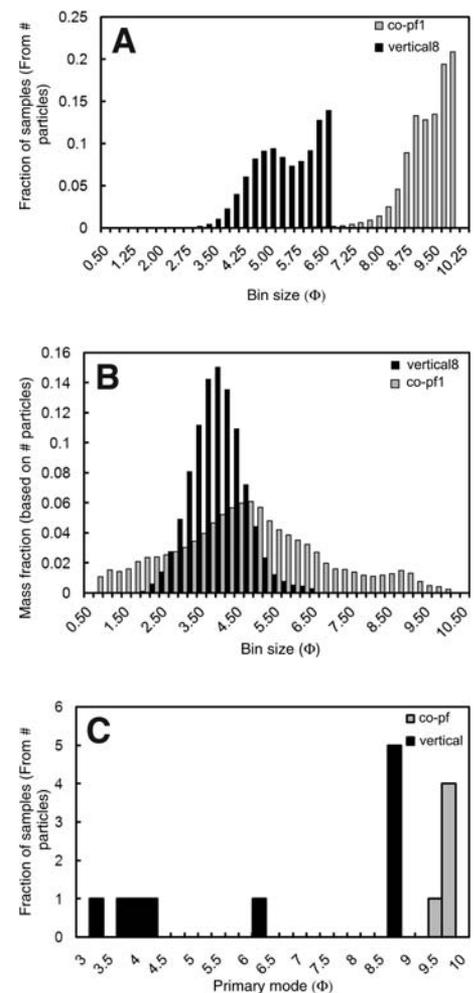


Figure 2. Comparison of size distributions. Vertical fall samples are black and co-pyroclastic flow samples are gray. A: Histogram showing size distributions based on estimated number of particles rather than mass for both vertical8 and co-pf1. Note that the finest particles in sample vertical8 are coarser than the coarsest particles of co-pf1. B: Mass-based size distributions for samples vertical8 and co-pf1. Note that size distributions calculated based on number of particles differ significantly from size distributions based on mass. C: Histogram of primary mode (based on estimated number of particles) for samples in Table 1, with exception of samples vertical1 and co-pf6.

minution. The finer-milled particles have lower terminal fall velocities than coarser particles and can be carried great distances prior to deposition. Thus, pyroclastic flow activity can lead to longer volcanic ash residence in the atmosphere and much more extensive remobilization after deposition, negatively influencing health over wide areas for relatively long time periods.

CONCLUSIONS

Andesitic ash falls at Colima resulting from vertical eruptions and block-and-ash flows from

2004 to 2006 show distinct grain-size distributions. Vertical eruptions produced well-sorted fall deposits, while co-pyroclastic ashes are poorly sorted and contain a high proportion of very fine ash. We conclude that the occurrence of pyroclastic flows at andesitic volcanoes increases hazards associated with very fine ash. Our data are consistent with the hypothesis that milling in pyroclastic flows is an important process in the generation of very fine ash. More data are needed to determine whether the results obtained here can be extrapolated to other sites with different magma compositions, volumes, and eruptive styles. Comparison of grain-size distributions based on estimated numbers of particles rather than mass is useful in the interpretation of samples containing very fine particles. While it exaggerates the proportions of fines, it enhances real differences in grain-size distributions that are difficult to document with other techniques.

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