

Fate of volcanic ash: Aggregation and fallout

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While suspended in Earth's atmosphere, fine ash influences radiative transfer, weather, and climate (e.g., Newhall and Self, 1982). Sulfate aerosol, also in volcanic ash clouds, dominates atmospheric effects, having stratospheric residence times of months to years (Robock, 2000), so large eruptions may have widespread consequences (Robock et al., 2009). During the eruptions in Iceland (Eyjafjallajökull in 2010, and Grimsvötn in 2011), and Chile (Puyehue-Cordon Caulle in 2011), operational ash-cloud forecast models have over-estimated far-field atmospheric ash concentrations compared to aircraft and satellite observations (Schumann et al., 2011; Stohl et al., 2011). These models do not account for fine-ash (<63 μm) particle aggregation, which results in under-prediction of proximal fine-ash sedimentation and over-prediction of distal (hundreds to thousands of kilometers) fine-ash sedimentation. This oversight can result in the closure of airspace, that would otherwise be safe.

Very fine ash particles (<30 μm diameter) have terminal settling velocities of the order 10^{-1} to 10^{-3} m s^{-1} and would remain suspended for days or weeks as simple particles. However, volcanologists observe the very fine ash fraction mostly falling out in <1 day even for large ash eruptions injected at the level of the tropopause (Guo et al. 2004), thus fine-ash fallout involves more than the application of Stokes Law for single particle settling.

Although aggregation of ash is observed in deposits (Fig. 1) and is recognized as important (Gilbert and Lane, 1994), the understanding needed for ash-fall modeling has been elusive because it is challenging to observe ash fallout in situ. Aggregation mechanisms are inferred from the study of aggregates in deposits, which allows quantification of settling velocity and drag coefficients. Rapid fallout of fine ash in hours was also measured from satellite remote sensing during the Eyjafjallajökull eruption (Pavolonis, 2010). Taddeucci et al. (2011, p. 891 in this issue of *Geology*) present a significant breakthrough, and describe a variety of direct observations of aggregate formation using a high-speed imaging camera to observe the aggregation process in the field during the 2010 Eyjafjallajökull eruption.

In addition to the Iceland events that paralyzed air traffic in Europe and led to several sci-

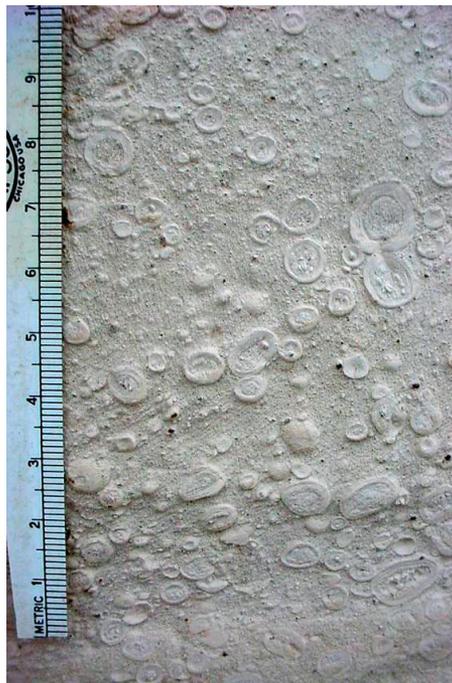


Figure 1. Detail from swept surface of ashfall deposit, Atitlan Caldera, Guatemala. Note the circular aggregates within a very fine grained deposit of volcanic ash. These are called accretionary lapilli, and are frequently seen in deposits. They are thought to represent hydrometeor/ash features, similar to hail, which fall from vertically developed volcanic clouds. Photo by A.J. Durant.

entific studies (e.g., Zehner, 2010; Bonadonna et al., 2011), additional relatively small-scale eruptions such as Okmok and Kasatochi in Alaska (Prata et al., 2010), and Chaitén (Carn et al., 2009) and most recently Puyehue-Cordon Caulle in Chile have also highlighted the fate and transport of ash. The Puyehue-Cordon Caulle eruption in June 2011 caused an ash veil that circumnavigated the Earth and persisted for weeks, and impacted aviation as far afield as Australia. Ash specialists assist Volcanic Ash Aviation Centers around the world with near real-time ash mitigation efforts (Prata and Tupper, 2009). Detection of ash via satellites maps distal, ash-bearing clouds, but hazard mitigation requires what ash levels are dangerous to aircraft (an industry engineering problem more than a scientific one).

At least several questions remain unanswered.

(1) How and when is very fine ash created in eruptions? Some eruptions generate little or no very fine ash. More energetic silicic eruptions create more fines (Alidibirov and Dingwell, 1996), the interaction of magma and surface water creates fine ash (Wohletz, 1983), and milling or comminution may be important (Rose and Durant, 2009).

(2) What is the best way to initialize volcanic cloud dispersal and fallout model conditions (Mastin et al., 2009)? An integrated observation approach is required, as individual methodologies have limitations and no one technique can measure the characteristics of the full size range of volcanic ash. Stohl et al. (2011) combine satellite retrievals with an inversion model to improve eruption source parameter specification. Although insensitive to very fine ash, ground-based radar systems offer near real-time data on initial cloud characteristics and heights, if they are in range of the volcano (Marzano et al., 2010), and radar is a vital part of the most advanced ash mitigation efforts (Scollo et al., 2009).

(3) Is ash aggregation mainly driven by hydrometeor formation? And how do cloud microphysical processes (Textor et al., 2006) and especially ice (Rose et al., 1995; Durant et al., 2008) influence aggregate formation and fallout? There have been only a few very illuminating direct observations of aggregation in ash fallout (e.g., Sorem, 1982). Background atmospheric conditions, including the availability of atmospheric water for precipitation, are all highly relevant for aggregation models.

(4) How is electrical charging in volcanic clouds (Harrison et al., 2010) linked to aggregation? And to what extent does this process influence particle clustering and binding?

(5) Are ashy aggregates possibly falling at velocities greater than terminal velocity? As ash falls from the stratosphere to the ground through changing atmospheric conditions, many cloud processes could influence fallout: phase changes with latent heat, virga, collision-coalescence, Bergeron process, and presumably aggregate break-up (Kostinski and Shaw, 2009). The high-speed video provided by Taddeucci et al. directly observes aggregate break-up during ash fall.

The broadest area of future focus, which challenges volcanologists, is how does meteorology

influence formation and dispersal of volcanic clouds and the resulting ash aggregation and fallout? The first modeling study to address aggregation, and consider atmospheric influences, had success in reproducing observed fallout from the Mount St. Helens 1980 eruption (Folch et al., 2010; Costa et al., 2010). Without real-time meteorological data, ash cloud models lack a robust meteorological data linkage. Thus they reflect isolation from many potentially important phenomena such as turbulence (Bodenschatz et al., 2010), mammatus cloud processes (Schultz et al., 2006), or overseeding (Durant et al., 2008). Continued interaction between the meteorological and volcanological communities can lead to advances in understanding of the fundamentals of ash aggregation. Even without the effects of volcanic ash, atmospheric physicists are challenged by the understanding of the fundamentals of cloud formation (Feingold and Siebert, 2009). In summary, the use of high-speed imaging instruments for investigations of all clouds presents exciting possibilities.

Measurements reported by Taddeucci et al. were made on the ground, where environmental conditions (temperature, pressure, water phase stability, turbulence) differ from an ash cloud at upper tropospheric and/or lower stratospheric altitudes. It would be advantageous to use this technology from an aerial platform, such as used by Siebert et al. (2006). Laboratory applications could include high-speed imaging cameras in experimental cloud chambers that allow conditions of the high altitude and turbulent lower stratosphere to be produced, where ash fallout from large events often begins. A new multiphase turbulent reaction cloud chamber is currently being designed and fabricated at Michigan Technological University (R.A. Shaw, 2011, personal commun.), and taking motivation from the Taddeucci et al. study, it might be possible to observe volcanic ash aggregate formation in situ, under stratospheric conditions. Overall, this research field is having a surge of activity.

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Printed in USA