The role of gravitational instabilities in deposition of volcanic ash

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ABSTRACT

Volcanic ash is a significant hazard for areas close to volcanoes and for aviation. Gravitational instabilities forming at the bottom of spreading volcanic clouds have been observed in many explosive eruptions. Here we present the first quantitative description of the dynamics of such instabilities, and correlate this with the characteristics of the fall deposit from observations of the 4 May 2010 Eyjafjallajökull (Iceland) eruption. Gravitational instabilities initially took the form of downward-propagating fingers that formed continuously at the base of the cloud, and appeared to be advected passively at the crosswind speed. Measurements of finger propagation are consistent with initial conditions inferred from previous studies of ash cloud dynamics. Dedicated laboratory analogue experiments confirmed that finger downward propagation significantly exceeded the settling speed of individual particles, demonstrating that gravitational instabilities provide a possible mechanism for enhanced sedimentation of fine ash. Our observations challenge the view that aggregation is the primary explanation of proximal fine ash sedimentation, and give direct support for the role of gravitational instabilities in providing regions of high particle concentration that can promote aggregation.

INTRODUCTION

Sedimentation of volcanic ash can significantly affect inhabited areas located close to active volcanoes, and the dispersal of the finest fraction can represent a hazard to aviation (Blong, 2000). The numerical description of particle dispersal during volcanic eruptions strongly depends on our understanding of the sedimentation of fine ash (<63 µm). Paradoxically, enhanced deposition of fine ash is often observed very close to the volcanic source (e.g., Brazier et al., 1983; Durant and Rose, 2009). A widely used interpretation of these deposits is that the fine ash fell as aggregated particles, but there is often no indication of aggregates in the deposits.

Vertical gravitational instabilities, called also convective instabilities and similar in appearance to virga, have been widely observed in volcanic eruptions, e.g., Soufrière Hills volcano, Montserrat, in 1997 (Bonadonna et al., 2002), and Ruapehu, New Zealand, in 1996 (Bonadonna et al., 2005). Ash accumulates at the base of volcanic clouds, and this region can become denser than the underlying atmosphere, leading to the formation of gravitational instabilities that propagate downward as fingers (Carazzo and Jellinek, 2012). These instabilities have been observed over a wide range of atmospheric conditions, suggesting that their formation is not strongly inhibited by crosswind conditions, and have been attributed to bursting of mammatus clouds (Schultz et al., 2006), ash-hydrometer forms of virga (Durant et al., 2009), and ash veils (Hobbs et al., 1991). However, their origin and triggering mechanism are still uncertain.

If the buoyant-velocity scale of the instability is greater than the settling speed of individual particles, ash is transported downward at the finger velocity. These instabilities therefore have the potential to cause premature sedimentation of fine ash during explosive volcanic eruptions and offer an alternative to particle aggregation. In addition, the high concentration of fine ash within individual fingers may promote aggregation (e.g., Carazzo and Jellinek, 2012). As a result, gravitational instabilities and particle aggregation are expected to be closely linked.

The convection dynamics due to the formation of fingers from a particle-rich layer of density ρ_1 initially overlying a particle-free layer of density ρ_2 have been investigated experimentally and theoretically (e.g., Hoyal et al., 1999b). A number of studies have focused on the initial propagation of the fingers (Hoyal et al., 1999b; Carazzo and Jellinek, 2012), and predicted their vertical velocity as a single unstable mode resulting from convection at a critical Rayleigh number of 1000 (following Turner, 1979).

Branney (1991) first made the hypotheses that certain characteristics of the deposit of the Whorneyside eruption (Lake District, northwest England) could have been related to dense short-lived instabilities. Carazzo and Jellinek (2012, 2013) presented a detailed analysis of the conditions for formation of gravitational instabilities in volcanic clouds, built on the consideration of the dynamics of particle sedimentation and of finger formation following Turner (1979) and Hoyal et al. (1999a). Carazzo and Jellinek (2012, 2013) also developed a model for the concentration of particles suspended in the clouds, comparing these with concentrations derived from satellite measurements, and predicted the expected spatial variability in the deposit architecture that fingers can produce; they concluded that gravitational instabilities promote premature sedimentation of fine ash via higher localized ash concentration within fingers, increasing the efficiency of particle aggregation. However, none of these studies included direct correlations between observations of finger instabilities during an eruption and the related deposit features.

For the first time, we characterize the dynamics of gravitational instabilities from analysis of video imagery from the 2010 eruption of Eyjafjallajökull (Iceland) and field observations of the associated tephra accumulation in combination with insights from dedicated laboratory analogue experiments.

FIELD OBSERVATIONS

The second phase of the 2010 Eyjafjallajökull eruption lasted for more than a month (14 April–24 May) and produced a long-lasting ash-rich plume (e.g., Gudmundsson et al., 2012). We analyzed the propagation of fingers recorded using high-resolution video (Fig. 1; Fig. DR1 in the GSA Data Repository[1]) taken on 4 May 2010 (12:49:21 GMT) at a position 7.7 km south of the vent (0568182E, 7047683N). The measured average plume height of ~4 km asl (above sea level) is in good agreement with the range 3.6–5.5 km asl measured by the C-band weather radar of the Icelandic Meteorological Office between 6 a.m. and 6 p.m. local time on that same day (Ripepe et al., 2013). We observed that new fingers continuously formed at the base of the ash cloud from ~1.4 km from the vent, with an average width of 168 ± 26 m and spacing of 180 ± 60 m (Fig. DR2). Values have been averaged among all the fingers observed across the entire field of view at each minute of the video. Fingers propagated vertically at a speed of 1 ± 0.5 m/s and horizontally at 8.5 ± 0.8 m/s (average of 5 fingers), compared with a cloud horizontal velocity of 7.9 ± 1.3 m/s, and a typical wind speed at the ash cloud base of 11 ± 0.5 m/s at 12:00 h (European Centre for Medium-Range Weather Forecasts ERA-40 reanalysis interpolated at 0.25° resolution above the volcano). The similarity between these average horizontal velocities made us infer that the fingers were being advected downwind with little shear against the background atmospheric flow, and their vertical velocity (consistent with plausible conditions for finger formation) was unaffected by horizontal advection.

[1]GSA Data Repository item 2015075, images of the Eyafjallajökull eruptive plume; finger width and spacing data; grain-size distribution plots; description of the experimental method and scaling; and detailed experimental results, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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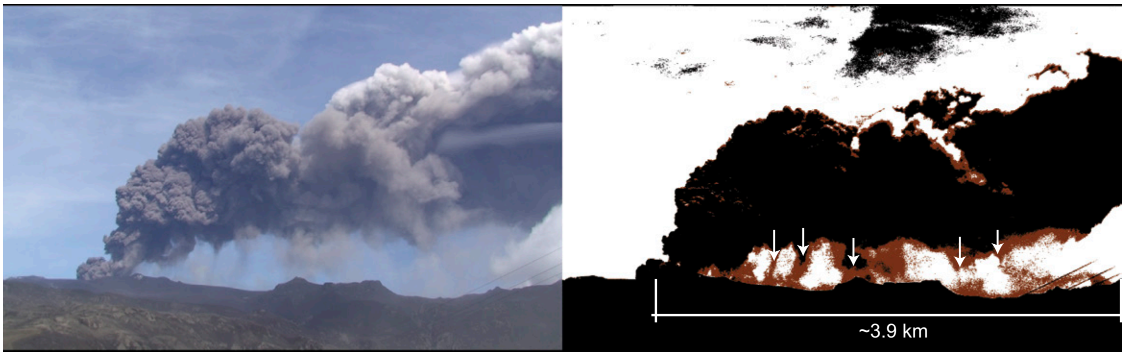

Figure 1. Original and processed snapshot of the video of the Eyjafjallajökull (Iceland) plume as observed on 4 May 2010. White arrows indicate finger position.

Field observations suggest that particles transported in fingers reached the ground ~10 km downwind of the vent. Most particles deposited within 10 km of the vent have terminal velocities of >1 m/s, compared with terminal velocities <1 m/s for most particles deposited further from the vent (Fig. 2). In broad agreement with the prediction of Carazzo and Jellinek (2013), a terminal velocity of 1 m/s corresponds to an ash particle diameter of ~0.2 mm, representing ~0.02 wt%, 24 wt%, and 63 wt% of the deposit at locations 2, 10, and 20 km from vent, respectively (Fig. 2). Bonadonna et al. (2011) found that particles falling 2 km from vent did not aggregate, and the deposit was characterized by a unimodal grain-size distribution peaked at 0 ϕ, i.e., 1–2 mm. In contrast, the deposit ~10 km from vent is clearly bimodal with two modal peaks at ~1 ϕ and 6 ϕ, and was characterized by the occurrence of both coated particles and fragile ash clusters that broke on impact with ground. The deposit at 20 km from vent was mostly unimodal with a peak at ~3 ϕ and the presence of both coated particles and fragile ash clusters (see also Fig. DR3).

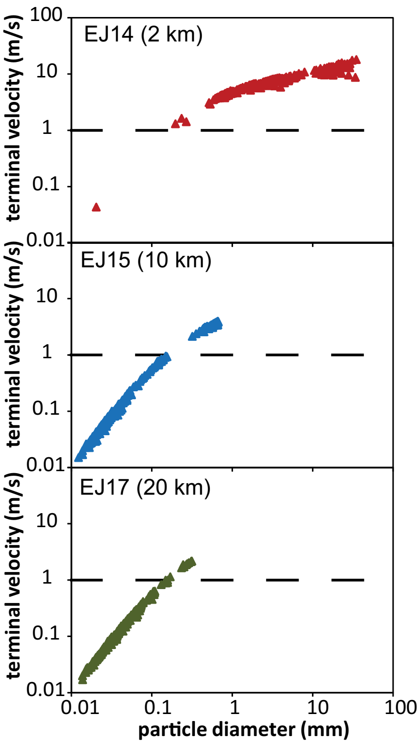

Figure 2. Particle terminal velocity derived with model of Ganser (1993) for samples collected at 2 km, 10 km, and 20 km from the vent. Finger average vertical velocity is also shown (1 m/s).

Observed fingers had average width and spacing of comparable dimensions, suggestive of an initially wave-like instability (Carazzo and Jellinek, 2012; Hoyal et al., 1999b), in which the finger spacing scales as twice the thickness of the destabilizing layer (e.g., Carazzo and Jellinek, 2012). We infer that this layer has a thickness of ~90 m.

Following Carazzo and Jellinek (2012), the finger instability velocity, v_f, resulting from destabilization of a particle boundary layer (PBL) at the base of an ash cloud can be written as:

$$v_f = g'^{\frac{2}{5}}\left(v_p \frac{1}{4}\pi\delta^2\right)^{\frac{1}{5}}, \qquad (1)$$

where v_p is the particle settling velocity, δ is the PBL thickness, and $g' = g\frac{\rho_{PBL}-\rho_a}{\rho_a}$ is the reduced gravity of the PBL, where g is the acceleration due to gravity and ρ_{PBL} and ρ_a are the densities of the PBL and atmosphere, respectively. We used field observations of v_f = 1.0 ± 0.5 m/s, $\delta \approx 90$ m, and v_p = ~1 m/s to infer that the PBL bulk density was 1.30–1.31 kg/m^3, corresponding to particle concentrations in the range 1×10^{-6} to 4×10^{-6} (density of air = 1.3 kg/m^3, density of Eyjafjallajökull ash = 1400–1700 kg/m^3; Bonadonna et al., 2011). These concentrations are consistent with those inferred for a destabilizing PBL from a range of ash cloud measurements and models (summarized by Carazzo and Jellinek, 2012), so we conclude that a finger vertical velocity of 1 m/s is consistent with the expected (and unmeasurable) initial conditions within the ash cloud and with the critical Rayleigh number convection mechanism invoked by Hoyal et al. (1999a, 1999b) and Carazzo and Jellinek (2012).

ANALOGUE EXPERIMENTS

Laboratory experiments were conducted to investigate the evolution of particle concentration in the mixing region that results from propagation of gravitational instabilities. The experimental configuration was similar to that of Hoyal et al. (1999b) with an aqueous suspension of spherical glass beads (D_{10} = 33 µm; D_{90} = 63 µm, where D is diameter) initially overlying a lower density sugar solution. The diffusivity of sugar is relatively low so that settling could be considered the main process causing gravitational instabilities. The tank was held isothermal, as thermal diffusion at the base of volcanic clouds is considered negligible (Schultz et al., 2008). This configuration with a fixed volume condition is a good representation of the observed Eyjafjallajökull eruption, because both plume and fingers are advected at the wind speed and, as a consequence, there is no net horizontal supply of buoyancy to the PBL in the downwind direction. The experiments consisted of removing the horizontal barrier that separates the two fluids and measuring how particle concentration varies in the tank. At the start of the experiment, the upper layer was either quiescent (no externally forced fluid motion, but with particles fully suspended by previous stirring, i.e., unmixed experiments), or continually mixed using a rotary stirrer; i.e., mixed experiments. The dynamic conditions in the experiments were similar to those for ash particles and finger instabilities in volcanic ash clouds, with scaling analysis following Carazzo and Jellinek (2012). Although it was not possible to reproduce volcanic ash cloud Reynolds numbers in the laboratory, as in nature suspensions were highly dilute, particle motions remained coupled to the fluid, and the dynamics were not viscously dominated (for full details on the experiments, see the Data Repository).

Following removal of the horizontal barrier to start the experiment, in the lower layer we observed a short-lived initial instability with fingers propagating downward at between 6×10^{-3} m/s and 8×10^{-3} m/s. This was rapidly followed by development of a convecting mixed region where no individual motions could be distinguished. According to Linden and Redondo (1991), the mixed layer propagates downward at a velocity of $v_f = 2(kAgh)^{1/2}$, where k is a dimensionless constant with a value determined in experiment by Linden and Redondo to be between 0.03 and 0.07, $A = (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$, the Atwood number, g is acceleration due to gravity, and t is the time elapsed since initiation of layer destabilization. For the experimental conditions, A = 0.001–0.0004, so the mixed layer propagated downward at a velocity of ~8 × 10^{-3} m/s.

The concentration evolutions were compared to mass balance models based on the assumption of either a quiescent or a turbulent upper layer and convective lower one (Hazen, 1904; Martin and Nokes, 1989; see also Hoyal et al., 1999b). We compared our upper layer data of unmixed and mixed experiments with models shown in Hoyal et al.'s equations 16 and 17 (1999b), respectively, and the lower layer of mixed experiments with the turbulent convective model of of Hoyal et al.'s equation 25 (1999b). For the unmixed lower layer, we derived a new quiescent-convective settling law:

$$c_{2q}(t) = c_1(0)\frac{v_p t}{h_2}\exp\left(\frac{v_p t}{h_2}\right) \text{for } t < \frac{h_1}{v_p}$$

$$c_{2q}(t) = c_1(0)\frac{h_1}{h_2}\exp\left(\frac{v_p t}{h_2}\right) \text{for } t > \frac{h_1}{v_p}, \qquad (2)$$

where c_2 and h_2 are the concentration and the thickness of the lower layer, and c_1 and h_1 are the concentration and the thickness of the upper layer. Subscript q indicates quiescent (but fully suspended) conditions, and t is the time since the start of sedimentation. In our derivation, the mass entering the lower layer is given by $c_1(0)$ $v_p tS$ until all the particles have left the upper layer at time $t = h_1/v_p$, where S is the area of the tank perpendicular to the flow direction.

The concentration evolutions (Fig. 3; Figs. DR6 and DR7) are adequately reproduced by the models, and although discrepancies were larger in the lower layer, they remained within systematic experimental uncertainty and the general trends were well predicted. The velocity of the fingers calculated according to Equation 1, i.e., 6–8 × 10^{-3} m/s, was in good agreement with experimental observations (see Table DR1) supporting the origin of the finger instability as critical Rayleigh number convection in the PBL as described by Turner (1979), Hoyal et al. (1999b), and Carazzo and Jellinek (2012).

DISCUSSION AND CONCLUSIONS

Convective instabilities have been recognized to have an important role in the enhanced sedimentation of volcanic fine ash because they act to increase the sedimentation rate of fine particles with settling velocity lower than the fingers (e.g., Carazzo and Jellinek, 2013). This would cause fine particles to fall closer to the vent than expected, and therefore produce unexpected features, such as bimodal grain-size distributions, poor deposit sorting, and multiple accumulation maxima. These observations have been made for tephra deposits and have been mostly attributed to aggregation processes of various

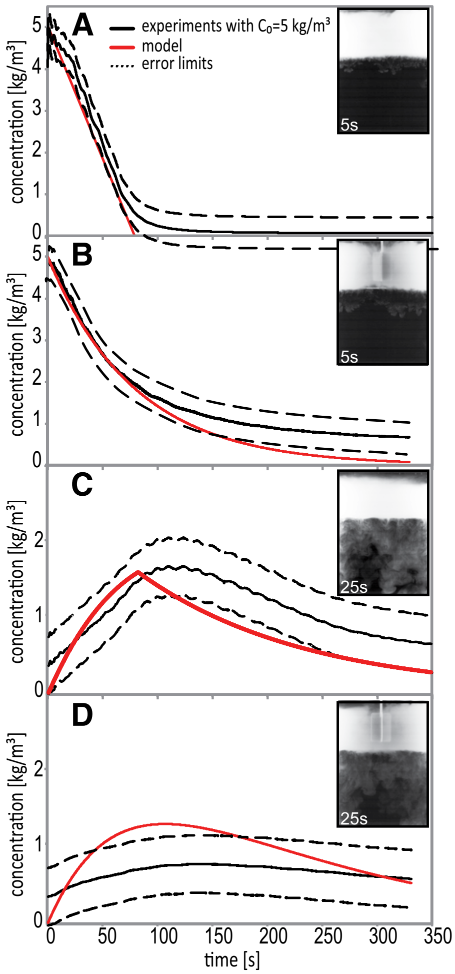

Figure 3. Experimental average particle concentration versus time compared with corresponding mass balance models of Hoyal et al. (1999b) and of Equation 2 (see text). A: Upper layer, unmixed. B: Upper layer, mixed. C: Lower layer, unmixed. D: Lower layer, mixed.

types (e.g., Brown et al., 2012, and references therein). The only type of aggregate likely to be preserved in tephra deposits is the accretionary lapilli, which are typically characterized by diameters between 2 mm and 15 mm (i.e., AP2, concentrically structured accretionary pellets, in the nomenclature of Brown et al., 2012). Particle clusters (both ash clusters, PC1, and coated particles, PC2), poorly structured pellets (AP1), and liquid pellets (AP3) have been commonly observed during fallout, but they typically break with impact with the ground. As a result, it is difficult to relate the aforementioned unexpected features exclusively to particle aggregation. In addition, higher concentration of fine ash in gravitational instabilities as compared with their parental eruption plumes and horizontal clouds could enhance particle aggregation (as proposed by Carazzo and Jellinek, 2013), and, therefore, their effect on particle deposition could be even more difficult to distinguish.

Only a detailed comparative study of both tephra deposits and video imaging, as presented here for the 4 May 2010 eruptive event of Eyjafjallajökull, can show the relation between the two processes. Our results show how fingers started to reach ground level and thus deposit ash ~10 km from the vent, and transported particles with settling velocity of <1 m/s. At the same time particle aggregation started playing a significant role only beyond 10 km from vent, and particles with settling velocity <1 m/s mostly fell only after this distance (Bonadonna et al., 2011). In particular, the deposit 10 km from vent is characterized by a combination of particles with settling velocities both <1 m/s and >1 m/s. Individual fine ash particles found in the deposit >10 km from the vent could have been transported as aggregates that broke up on impact with the ground and that may have formed either within the gravitational instabilities or within the ash cloud. Alternatively, they could have been transported passively as individual particles within the gravitational instabilities at a greater downward velocity than their settling speed. Taddeucci et al. (2011) showed how aggregate settling velocity varied between 0.2 m/s and 4 m/s at a location ~7 km from vent for this eruption (but on a different day, 20 May 2010; plume height of 5 km asl and wind speed of 10 m/s). The sedimentation of PC1 with diameters between 50 µm and 600 µm, PC2 with diameters between 100 µm and 700 µm, and AP1 with diameters between 100 µm and 400 µm was observed (Bonadonna et al., 2011). Considering an aggregated density of PC1 of ~1500 kg/m³, PC2 of 2700 kg/m³, and AP1 of 1800 kg/m³ (assuming a porosity of ~0.4 from Gilbert and Lane, 1994, and pore density of 1 kg/m³ and 1000 kg/m³ for PC1 and AP1, respectively), resulting terminal velocities between 5 km and sea level determined with the model of Ganser (1993) are 0.1–4 m/s for PC1, 0.6–7 m/s for PC2, and 0.4–3 m/s for AP1, in agreement with Taddeucci et al. (2011). We can infer that the aggregates with terminal velocities <1 m/s could have formed either within the convective instabilities or in the volcanic cloud, whereas the aggregates with terminal velocities >1 m/s, whether they formed within the convective instabilities or in the cloud, must have eventually fallen independently of the fingers. In particular, we conclude that most PC2 sedimented independently of fingers due to their large sizes and densities, while PC1 and AP1 could either form in the cloud and sediment within the fingers or could directly form in the fingers.

Reduction of ash lifetime in the atmosphere due to fingers is comparable to that associated with aggregation, with a difference of 1–3 orders of magnitude with respect to individual particle settling velocity. Considering the height of the observed cloud base of ~2.2 km asl, sedimentation times of fine ash fallen within the gravitational instabilities, as aggregates (PC1, PC2, or AP1) and individual fine ash particles, are of

0.6 h, 0.2–0.1 h, and 2–61 h, respectively. The experimental observations show similar behavior and confirm that the particle sedimentation rate within fingers and the resulting convecting layer is 1 order of magnitude greater than for finest individual particles (measured finger and mixed layer velocity of ~$6–8 \times 10^{-3}$ m/s compared to 8×10^{-4} m/s for 33 μm particle terminal velocity).

In conclusion, this study provides direct evidence of the association of aggregation with convective instabilities. There is clear evidence that the formation of aggregates at Eyjafjallajökull started at the same location as the initiation of convective instabilities, and this may be associated with the higher particle concentration within the destabilizing layer at the base of the ash cloud. However, the formation of aggregates within the volcanic plume and/or cloud cannot be excluded. As a result, there is no single explanation for premature deposition of fine ash that is supported by the observations, and a range of distinctive origins is possible. Future analysis of fine ash deposition should include detailed study of the formation conditions and dynamics of gravitational instabilities.

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