Comment on “Particle aggregation in volcanic eruption columns”
by Graham Veitch and Andrew W. Woods

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0148-0227/04/2002JB002291$09.00

1. Introduction

[1] Ash dispersal from large explosive volcanic eruptions is very extensive and can be devastating for the environment, endangering people’s lives and property [e.g., Sparks et al., 1997]. In addition, volcanoes influence the global climate on timescales of years (see, e.g., Robock [2000] for a review). During the rise of a volcanic eruption column, a multitude of processes interact in a complex way and influence the effects of the eruption upon the environment. Some of these processes are incompletely understood, e.g., the effect of crosswinds [e.g., Bursik et al., 1992; Ernst et al., 1994], or the effect of ash aggregation on ash dispersal [Carey and Sigurdsson, 1982; Sparks et al., 1997]. Numerical models of ash dispersal help to estimate the atmospheric effects [e.g., Herzog et al., 2003; Textor et al., 2003] and to evaluate volcanic risks. However, these models are currently not comprehensive, and work on this issue is urgently needed. Therefore Veitch and Woods [2001] (hereinafter referred to as VW01) dealt with an important issue as it focuses on ash aggregation and its effect on ash dispersal.

[2] We have, however, concerns about the premises upon which the VW01 model of ash aggregation is developed, as well as upon which it is applied and evaluated against field data. The assumptions of steady state and uniform velocity profile at any given height (one-dimensional top hat description) are not sufficient to describe the processes in the eruption column, such as sedimentation followed by reentrainment, that are fundamental in the aggregation process. The lack of accounting of key cloud microphysical processes, especially the freezing process, leads to erroneous results. The approaches for the aggregation mechanism, as well as for the particle collision and sticking probabilities are not sufficiently explained by VW01, and they cannot be unambiguously inferred from descriptions of physical processes in the paper. The VW01 results are of unclear relevance to understanding ash aggregation in volcanic eruptions. The choice of the particularly dry 18 May 1980 Mount St. Helens eruption for comparison between model and field data is poorly suited for the validation of a wet aggregation model. Hence the good fit between data and predictions in VW01 is purely coincidental. Our arguments are highlighted in more detail below.

2. Eruption Column Dynamics

[3] The VW01 model of ash aggregation is an extension of the eruption column model of Woods [1988]. This model avoids the large demands on computer power, which would be necessary to solve the equation algorithm describing the dynamics and thermodynamics of an eruption column, by simplifying the geometry to one dimension (top hat). In addition, evolution in time is not taken into account. Instead, steady state is assumed. Steady state models are commonly considered to be suitable for quasi-steady eruption columns for which the eruption rate may vary gradually and in particular for so-called dry Plinian eruptions [Sparks et al., 1997]. Condensation of water from entrained moist air and magmatic water vapor is moderate and is thought to affect time-averaged flow properties only to a second order [Sparks et al., 1997]. In such dry Plinian eruption columns, ash aggregation is thought to be overwhelmingly dominated by the effect of electrostatic charging [Sorens, 1982; James et al., 2002]. However, this mechanism is not accounted for in the VW01 model. The formation of accretionary lapilli by the "wet aggregation process" as treated by the VW01 model is unlikely in a steady dry Plinian eruption, because it
relies on the availability of liquid water [Gilbert and Lane, 1994] and often also on aggregate freezing (A. J. Durant and G. G. J. Ernst, Formation of accretionary lapilli as volcanogenic hailstones submitted to Bulletin of Volcanology, 2003, hereinafter referred to as Durant and Ernst, submitted manuscript, 2003). Water-rich eruption columns however are known to be inherently unsteady, pulsating in intensity and alternating in eruption style between column and base surge development [e.g., Machado et al., 1962; Moore et al., 1966; Waters and Fisher, 1971; Kokelaar, 1983; Durant and Ernst, submitted manuscript, 2003]. These so-called phreatomagmatic eruptions cannot meaningfully be simulated with a steady model as used by VW01.

Another deficiency of using a steady model for the simulation of aggregate growth, as by VW01, is that such a model is by construction not able to reflect the unsteadiness and nonlinearity of the detailed aspects of microphysics. The model ignores the importance of particle recycling [Lane et al., 1993; Ernst et al., 1996], which increases the particle residence time, enhances particle concentration at the column edge [Carey et al., 1988] and leads to strongly time-dependent dynamic (and related microphysical) changes, e.g., fountain collapse alternating with stable plume columns [e.g., Carey et al., 1988; Veitch and Woods, 2000; Dartevelle et al., 2002]. In the VW01 model, aggregates only grow as one follows the motion of a volume parcel vertically in the column; particle concentration and size distribution are not evolving in time at each height level. This limitation of the VW01 model is a fundamental one as the efficiency of particle aggregation is strongly influenced by both particle concentration and size. In sum, we argue that the wet growth of ash aggregates cannot be satisfactorily resolved within the concept of a steady state, top hat model.

3. Microphysics of Meteorological Clouds

As ash aggregation in the VW01 model takes place in a zone of liquid water within a narrow height interval (e.g., 6–10 km for a source discharge rate of $10^7$ kg/s). The existence of liquid water in the eruption column is inferred from the temperature and pressure fields calculated by their top hat plume model. The freezing level is set to 0°C. However, a huge body of observational, experimental and theoretical work by cloud scientists carried out over more than 50 years, showed that the overwhelming majority of pure water drops in clouds freeze in the range −10 to −35°C, depending on drop size, degrees of supercooling and supersaturation, and abundance of ice nucleation nuclei (i.e., aerosols which initiate the heterogeneous freezing process) [e.g., Langham and Mason, 1958; Rogers and Yau, 1989]. In typical deep convective clouds, supercooled water can exist down to −40°C [e.g., Pruppacher and Klett, 1997]. Furthermore, experimental data show that in the presence of volcanic ash ice or snow nucleates on ash at around −13°C [Rogers and Yau, 1989; Lacasse et al., 2003; Durant and Ernst, submitted manuscript, 2003]. In volcanic eruption columns, Tabazadeh and Turco [1993] argue that supercooled liquid solutions of HCl in water can exist down to −50°C. Clearly, the freezing temperature of cloud and rain droplets can be much lower than 0°C, as assumed in the VW01 model.

In addition, because of the assumption of horizontal homogeneity, the condensation of ice at the column edges cannot be considered and ice formation does not occur until unrealistic heights are reached. Once the freezing level is reached, all water is transferred to ice. VW01 do not account for the coexistence of ice and liquid water, but it occurs in real clouds [e.g., Pruppacher and Klett, 1997].

4. Aggregation Mechanism

The aggregation of particles of different sizes in turbulent flow, settling under gravity, can be governed by several mechanisms. Aggregation is quantitatively described by expressions for the collision kernels, which physically represents a second-order rate constant for the collision of two particles [see Pruppacher and Klett, 1997]. The relative importance of possible aggregation mechanisms is dependent on the turbulent kinetic energy and on the size of the particles considered. This is discussed hereafter to illustrate our doubts in the VW01 concept of aggregation.

Brownian aggregation is most important for very small particles with sizes ≤0.1 μm. It should not be relevant for volcanic ash which is dominantly ≥1 μm. Turbulent shear aggregation results from relative motions of particles carried in a turbulent flow field. The collection kernel $K_{TS}$ can be estimated as [Saffman and Turner, 1956]

$$K_{TS} \propto (r_i + r_j)^3 \varepsilon / \nu_v,$$

where $r$ is the particle radius of the colliding particles and $\varepsilon$, $\nu_v$ is the dissipation rate of turbulent kinetic energy per unit mass, and $\nu_v$ is the kinematic viscosity of air.

Turbulent inertial aggregation is due to the differential response of particles of different mass to local turbulent accelerations. For the kernel $K_{TI}$, Saffman and Turner [1956] gave the following proportionality:

$$K_{TI} \propto (r_i + r_j)^2 \left( r_i^2 - r_j^2 \right) \varepsilon / \nu_v^{1/2}.$$

These two kernels for turbulent aggregation are only strictly relevant in the Saffman-Turner limit, that is, for particles which are smaller than the Kolmogorov microscale length $\lambda_k$ and which have very small particle turbulent Stokes numbers $St$. These two quantities are discussed in detail below. Such small particles are contained within the smallest turbulent eddies and have well correlated velocities [e.g., Saffman and Turner, 1956].

The Kolmogorov microscale length $\lambda_k$ denotes the eddy size below which viscosity becomes important, i.e., in the so-called viscous subrange [e.g., Pruppacher and Klett, 1997]. It is given by

$$\lambda_k \approx \left( \frac{\nu_v}{ \varepsilon } \right)^{1/4}. \quad (3)$$

Air kinematic viscosity $\nu_v$ is of the order $10^{-5}$ m$^2$/s at ground level up to $10^{-4}$ m$^2$/s at 40 km elevation. The dissipation rate of turbulent kinetic energy per unit mass $\varepsilon$ is constrained by the parameters controlling the large-scale flow, the magnitude of velocity fluctuations $\Delta u$ and the size of the largest eddies $l$:

$$\varepsilon \approx \frac{\Delta u^3}{l}. \quad (4)$$
\[ \Delta u \] is of the order of about 10% of the mean upward speed as given by VW01 on the basis of the work by List [1982] and Papanicolaou and List [1988]. In a volcanic eruption column the typical upward speed varies with height and is of the order of 10 to some hundreds of meters per second. This leads to \( \Delta u \) values in the range of 1–50 m/s. The size of the largest eddies in a Plinian volcanic eruption column is some kilometers [Papantoniou and List, 1989; Ernst et al., 1996]. This results in \( \varepsilon \) values of order of 0.1—100 m²/s³. Hence the range of expected values for the Kolmogorov microscale length \( \lambda_K \) is of the order of hundreds of micrometers in a volcanic eruption column. This closely overlaps the size range of the most abundant volcanic ash particle sizes.

[11] The particle Stokes number is a measure of the relative importance of viscous and inertial motions for a particle. A particle in the limit \( St \to 0 \) closely follows fluid motion, whereas a particle in the limit \( St \to \infty \) moves completely independently of the small-scale flow. \( St \) represents the ratio of two timescales: the inertial response time of the particle, \( \tau_p \), and the characteristic timescale for turbulent motion of the fluid, which is in this case the Kolmogorov timescale \( T_K \):

\[
St = \frac{\tau_p}{T_K}, \quad \tau_p = \frac{2\rho_p r_p^2}{9\nu_0 \rho_a}, \quad T_i = \sqrt{\frac{\nu_0}{\varepsilon}},
\]

where \( \rho_p \) and \( \rho_a \) stand for the density of the particles and the surrounding air, respectively. The particle response time \( \tau_p \) for particles of the order of 1—100 \( \mu m \) in radius and a density of \( \rho_p \approx 2000 \text{ kg/m}^3 \) is in the order of \( 10^{-2} \) to \( 10^{-1} \) s.

For the Kolmogorov timescale \( T_K \) we get a range of \( 10^{-4} \) to \( 10^{-2} \) s using the values for the kinematic viscosity \( \nu_0 \) and the turbulent kinetic energy estimated above. This leads to a particle Stokes number \( St \) on the order of \( 10^{-3} \) for small volcanic particles in weakly turbulent parts of the plume to \( 10^{-2} \) for larger volcanic particles in high turbulence. Hence \( St \) varies over 6 orders of magnitude, it cannot be said a priori if particle motion will be dominated by viscous or inertial forces.

[12] In the limit of the kinetic theory, which applies for particles larger than \( \lambda_K \), and with \( St \gg 1 \), particles have a negligible velocity correlation. These larger particles move within and across the large-scale eddies and may collide at random. Abrahamsson [1975] approximated the kernel \( K_{RV} \) for this random velocity aggregation mechanism by

\[
K_{RV} \propto (r_i + r_j)^2 \left( v_i^2 + v_j^2 \right),
\]

where \( v \) is the mean particle velocity of the size fractions \( i \) and \( j \), which is related to the mean fluid velocity and to the particle sizes. This mechanism represents an inertial aggregation mechanism for large particles with uncorrelated velocities. A kernel accounting for the mean drift between particles of contrasting sizes was provided by Gourdel et al. [1998]:

\[
K_{RV,d} \propto (r_i + r_j)^2 \left| v_i - v_j \right| F(v_i, v_j, k_i, k_j),
\]

where \( F \) is a complicated function of the particle velocities \( v \) and their turbulent kinetic energies \( k \).

[13] The relative importance of the different turbulent aggregation mechanisms has been discussed by Park et al. [2002] for particles between 1 and 100 \( \mu m \) in radius and for turbulent intensity values \( \varepsilon \) in the range \( 10^{-2} \) to \( 10^{-3} \) m²/s³. The turbulent shear aggregation mechanism is only important for particles of equal size at low turbulence intensity, and for particles smaller than the Kolmogorov microscale [Kruis and Kusters, 1997], conditions which appear of little relevance to volcanic eruption columns. For particles of contrasting sizes the turbulent inertial aggregation mechanism is always at least 1 order of magnitude larger than the turbulent shear mechanism, especially at high turbulence intensities.

[14] For particles of different sizes settling under gravity at contrasting fall velocities, gravitational aggregation becomes significant [e.g., Pruppacher and Klett, 1975]. The gravitational aggregation kernel \( K_G \) is

\[
K_G \propto (r_i + r_j)^2 (\Delta w),
\]

where \( \Delta w \) is the difference in the particle fall velocities.

This mechanism is known to become dominant in atmospheric clouds as soon as some particles are larger than a few microns in radius. The relative importance of the gravitational and turbulent inertial aggregation mechanisms can be estimated from a comparison between the turbulent acceleration \( \alpha \) and the gravitational acceleration \( g \approx 9.81 \text{ m/s}^2 \) [Saffman and Turner, 1956]. For particles with \( St \ll 1 \) the following expression holds for the turbulent acceleration [Pruppacher and Klett, 1977]:

\[
\alpha_K = \frac{\nu_0^2}{\lambda_K} = \frac{\varepsilon^{1/4}}{\nu^{7/4}};
\]

we find that \( g \leq \alpha_K \) for \( \varepsilon \geq 0.1 \text{ m²/s³} \). Hence, for particles with \( St \ll 1 \) (i.e., particle sizes smaller than about 10 \( \mu m \)), gravitational capture can be neglected in most regions of eruption columns which are, characteristically, intensely turbulent. Gravitational capture must, however, be considered at the eruption column margins, where turbulence is less vigorous.

[15] For larger particles with \( St \gg 1 \) (i.e., particle sizes larger than about 10 \( \mu m \)), we consider the turbulent acceleration of particles moving in eddies with a size \( \lambda_m \), which is intermediate between the Kolmogorov microscale and the size of the largest eddies. The turbulent acceleration of these eddies \( \alpha_m \) is given as [Pruppacher and Klett, 1997]:

\[
\alpha_m = \frac{\nu_0^2}{\lambda_m} = \left( \frac{\varepsilon \lambda_m}{\lambda_m} \right)^{2/3}.
\]

With the range of \( \varepsilon \) given above and for representative eddy sizes \( \lambda_m \) of 10, 100, and 1000 m, we find that the gravitational is larger than turbulent acceleration for all \( \varepsilon < 295 \) 100 m²/s³. Hence, for particles larger than about 10 \( \mu m \), gravitational capture should be the dominant aggregation mechanism in most regions of the eruption column. Since there should always be some larger particles, which would nonlinearly grow at the expense of the smaller ones, gravitational capture should be the most significant aggregation mechanism in volcanic eruption columns.
(neglecting electrostatic forces for the moment). In addition, the efficiency of gravitational aggregation can be strongly enhanced in flows with strong turbulence [e.g., Pinsky and Khain, 1997; Pruppacher and Klett, 1997]. This superposition of purely turbulent and gravitational aggregation mechanism is considered by introducing a collision efficiency $E$ in the equation for the gravitational kernel in cloud microphysics, as highlighted below.

16. The above discussion illustrates that it cannot be known a priori which aggregation mechanism(s) will dominate. VW01, however, do not describe or discuss which aggregation process they consider the dominant one in their model. They give for the aggregation kernel $K_{ijw}$ a proportionality to the quadratic sum of the particle radii and to a collision velocity $w_p$:

$$K_{ijw} \propto (r_i + r_j)^2 w_p. \quad (11)$$

The collision velocity has a single value at a given height level and is depends only on the mean intensity of turbulent fluctuations, which in turn are controlled by the mean upward speed at that height. We agree that the collision velocity can be related to the intensity of turbulent fluctuations, especially in such strongly turbulent volcanic plumes. However, the effect of having contrasting masses, inertia, and fall velocities cannot be neglected, since it dominates the aggregation mechanism as demonstrated above. Hence the equation for the aggregation kernel in VW01 (their equation (4)) seems not to reflect any aggregation mechanism that would be relevant for particle growth in volcanic eruption columns. The solution of the aggregation equation (equation (6) of VW01) is performed using the well-known method of Berry and Reinhard [1974] by discretizing the equation on a logarithmic scale grid. It appears that VW01 use a constant collision velocity because it facilitates the solution of the aggregation equation. However, convenient this may be for mathematical treatment, our analysis suggests that this approach to aggregation modeling has no meaningful physical basis.

5. Collision efficiency

17. The collision efficiency is defined as the ratio of the actual collision cross section and the geometrical cross section. Hydrodynamic, electrostatic, and turbulent forces can modulate it. There still exist many uncertainties in the theoretical models for collision efficiencies. For charged particles in an electric field, for large particles of equal size in calm air, or for small particles in turbulent flow the collision efficiency can be enhanced. In turbulent flow the collision efficiency increases due to concentration inhomogeneities resulting from the differential response of drops of contrasting size to fluctuations in the turbulent velocity field, and due to inertia-induced relative velocities in turbulent air. Reviews of the recent theory are given by Pruppacher and Klett [1997], Pinsky and Khain [1997], Pinsky et al., [2000], Vaillancourt and Yau [2000], and Shaw [2003].

18. VW01 use the approach of Mason [1971], Klett and Davis [1973], and Beard and Ochs [1984] tabulated by Hall [1980] and the approach of Rogers and Yau [1989] based on Oseen flow for small particles and superposition of potential flow for larger ones. These collection efficiencies are obtained from theories, which are valid in calm air only. Hence they are in principle not consistent with the approach of VW01 where the relative particle velocities are determined by turbulence only. In addition, the collision efficiencies employed by VW01 are unlikely to be correct in a volcanic eruption column, where turbulence and electrostatic forces are likely to enhance particle collisions leading to collision efficiency values larger than one.

6. Sticking Efficiency

19. The sticking (or coalescence) efficiency is a complicated function of particle size, shape and surface conditions, relative velocity and other factors [e.g., Pruppacher and Klett, 1997]. VW01 assume that two ash particles can stick together with an efficiency dependent on the particle size only, as soon as liquid water is present in the eruption column. However, in reality, the relative mass mixing ratios of water and ash in volcanic clouds is often smaller than one, so that the amount of condensed water is not sufficient to completely moisten the ash particles. This is especially true for porous volcanic ash, where capillary forces may initially absorb the water inside the particle and not at its surface: such a particle may have a sticking efficiency like a completely dry particle. VW01 do not consider the influence of water availability on the particle surface, i.e., of the water mass mixing ratio.

20. The sticking between wet ash particles with Stokes number larger than one is parameterized by VW01 using experimental data from Gilbert and Lane [1994]. However, these data were obtained under atmospheric conditions, which do not scale to relevant environmental conditions. It is worth emphasizing that the Gilbert and Lane experiments failed to form spherical ash aggregates analogous to ash aggregates observed in the geological record. As a last resort, VW01 were forced to introduce a large poly styrene sphere to simulate how growth may proceed on it, i.e., in a situation where a large aggregate has already formed.

21. Aggregation of ice particles or of ash particles encased by ice is also neglected by VW01. However, it is clear from meteorological clouds that ice particles do grow to form larger snow or graupel particles [e.g., Pruppacher and Klett, 1997]. The coalescence of ice particles is most efficient close to the freezing temperature. Although it becomes rapidly less efficient with decreasing temperature, it cannot simply be ignored in volcanic eruption columns, where the temperature is below the freezing level in large regions and where ice frequently occurs [e.g., Rose et al., 1995; Mayberry et al., 2002; Lacasse et al., 2003].

7. Comparison With Mount St. Helens Data

22. VW01 compare their model predictions to a well-known ash fall data set for the 18 May 1980 eruption of Mount St. Helens (MSH) [Carey and Sigurdsson, 1982] and after adjusting several free parameters they obtain a good fit and use this in support of their modeling approach. However, the MSH fall event did not lead to deposition of aggregates, which could be associated with a substantial degree of wet aggregation. On the contrary, the MSH aggregates observed were described as archetypal examples.
of dry aggregates [Sorensen, 1982], which are held together primarily by electrostatic attraction and possibly also by geometrical interlocking as in snowflakes, leading to extreme porosities and a loosely bound, open framework structure [see also Schumacher, 1994; James et al., 2002]. The good fit between the VW01 model predictions and the MSH data appears coincidental and related to the adjustment of free parameters (e.g., the collision Stokes number). The validation of the wet aggregation model simulated in VW01 is of little relevance, because wet aggregation was not the dominant mechanism during the MSH eruption.

8. Conclusions

[23] The series of sensitivity experiments in the VW01 paper is misleading in giving the impression that the model assumptions have been validated against appropriate field data. Variations of the initial mass flux, temperature, and gas content, which is unrealistically low, do not mean much. In our view, the assumption of top hat geometry in the eruption column model is not suitable for the simulation of the wet aggregation process. The influence of varying the particle size distribution on the aggregation efficiency is of little interest: particle aggregation is not described according to sound first principles or parameterized in a way that would reflect any of the recent developments in cloud microphysics. The comparison with the Mount St. Helens eruption is inappropriate to validate the simulations. The experiments do not increase our understanding of ash particle aggregation in volcanic eruption columns. The model leads to erroneous results and should not be used for important applications such as aircraft safety or predictions of hazards on the ground.

[24] In general, numerical models can be extremely helpful for the investigation of processes, which are not accessible to direct observations, or which are not yet fully understood. Murray [2002, 2003] and Harry [2003] discuss the usefulness of numerical modeling as a geophysical research tool. Harry [2003] addresses the essential conditions, which have to be met by these models: “Simulations are based on quantitative descriptions of the relevant laws of physics as they are currently understood, empirical measurements of the physical properties involved, and the available field data.” This condition is not fulfilled in the VW01 model concept as highlighted above.

[25] Clearly, on the one hand, the problem of particle aggregation in volcanic or meteorological clouds is complex and much work is needed. There are very scarce constraints on several of the key parameters, even in the much simpler and more thoroughly examined case of strongly convective clouds. For example, information about the following parameters would be desirable: (1) in situ temperature data from eruption columns, (2) characteristics of turbulence (intensity and spatial distribution), (3) particle concentration, (4) chemical characterization and wettability of ash particles, (5) erupted and in situ size distributions of ash particles and aggregates, (6) coalescence efficiency of volcanic particles, and dry, wet, and icy ash aggregates, (7) collision efficiency of volcanic particles and aggregates in turbulent flow, (8) microphysical properties of hydrometeors and aggregates (e.g., shape, physical condition, hydrodynamic stability), and (9) in situ electrostatic field measurements in volcanic clouds and effects on particle aggregation. The results of simulations of a poorly constrained system, and any possible interpretation of them, are in their part, poorly constrained.

[26] On the other hand, however, Harry [2003] indicates that “…numerical simulations may…be a very important tool for determining which additional types of data are needed to better constrain the system. Alternatively, it may indicate that the system is sufficiently insensitive to certain parameters that they cannot be determined by even the most thorough observations of the system behavior.” Hence specific aspects of complex phenomena can be examined with numerical models even for a system with many unknown parameters in order to confine their sensitivity to certain parameters. These parameters can then be further investigated in the laboratory or possibly in the field.

We believe that the process of ash aggregation in volcanic eruption columns is one such problem.

[27] Yet the adaptability of a certain model configuration depends on the specific problem under consideration, and one must be careful to avoid developing models, which do not describe, in a physically sound way, at least one aspect of the complex natural phenomenon under study. The model assumptions must be discussed and their limitations established through comparisons with relevant field or laboratory data. The credibility of numerical simulations as a scientific method is in danger if model results are inadequately validated against such data. The exploration of factors leading to discrepancies between model predictions and data quite often results in the most important findings.

[28] Our analyses indicate that the VW01 model of ash aggregation is not based on sound first principles. A favorable comparison of the model predictions with irrelevant field data complete to illustrate that it is of little value in specifically and accurately describing the problem at hand and that it fails to provide new insights.

[29] In sum, no theoretical model of (either dry or wet) ash aggregation has been presented to date. The solution required here, must be an unsteady eruption column model including simplified but physically sound and fully justified principles of cloud microphysics. In the case of wet aggregation, comparison of model predictions must be against any of the following: Laboratory data, constraints from direct and from remote sensing observations of water-rich eruption columns [Rose et al., 1995, 2000; Lacasse et al., 2003] and from phreatomagmatic tuff deposits (i.e., more or less vesiculated layers containing accretionary lapilli (e.g., Durant and Ernst, submitted manuscript, 2003)). We propose to submit such a first numerical model of wet ash aggregation shortly.

[30] Acknowledgments. The work of C.T. was supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) program AFO2000, grant 06-056-0180, and by the Volkswagen Foundation under the project EVA. G.G.J.E. acknowledges support from the Nuffield Foundation (NAL Award) and from the Fondation Belge de la Vocation through the Golden Clover Prize; he also acknowledges support from NSF through Bill Rose (Processes in volcanic ashclouds NSF grant), which allowed him to develop this work with C.T. while visiting Michigan Tech in summer of 2002. G.G.J.E. is now supported by the Belgian NSF (FWO-Vlaanderen) at University of Ghent. We thank Francis Albarede and three anonymous reviewers for constructive and helpful suggestions that helped improve the manuscript.