Density and size segregation in deposits of pyroclastic flow

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[1] The main portion in the deposits of pyroclastic flow shows various characteristic features such as density and size segregation of large fragments in the vertical direction. To understand the mechanism which produces these features, we numerically study granular flows on an inclined rough surface with impurities that are different in density and size from the matrix particles. The simulation shows the occurrence of density and size segregation of large impurities, and the impurities finally concentrate at the top and the bottom. Based on these results, we discuss the mechanism of the segregation. It is found that the behavior of impurities is governed by gravity, buoyancy and the viscosity of the randomly moving matrix. *INDEX TERMS:* 8404 Volcanology: Ash deposits; 8414 Volcanology: Eruption mechanisms; 8450 Volcanology: Planetary volcanism (5480); 8499 Volcanology: General or miscellaneous. **Citation:** Mitani, N. K., H.-G. Matuttis, and T. Kadono (2004), Density and size segregation in deposits of pyroclastic flow, *Geophys. Res. Lett.*, *31*, L15606, doi:10.1029/2004GL020117.

1. Introduction

[2] Pyroclastic flows, commonly accompanying explosive volcanic eruptions, contain gas and grains of various sizes (10^{-6}–10^{1} m) and densities (500–3000 kg m^{-3}) which move down the flanks of volcanoes. The main portion in the deposits of pyroclastic flows has various features [*Sparks et al.*, 1973; *Sparks*, 1976; *Wilson*, 1980, 1984, 1985; *Palladino and Valentine*, 1995; *Druitt*, 1995, 1998; *Calder et al.*, 2000]. One of the characteristic features is that density and size segregation of large fragments in the vertical direction are often observed ("type 2" indicated in Figure 7b of *Wilson* [1980]); light pumice and dense rock fragments are enriched towards the top and the bottom, respectively, and the fragment size increases with height (reverse grading) for light pumice while it decreases (normal grading) for dense rock. Both gradings are often observed simultaneously. Another important feature is that, sometimes, pumice and rock fragments are concentrated at the top and the bottom, respectively, regardless of their size ("type 3" indicated in Figure 7c of *Wilson* [1980]).

[3] Much discussion in volcanology has been devoted to the mechanism which controls the grading. It was presumed that large fragments were dispersed in a fine-grained, fluidized matrix, and that the principal mechanisms of density and size segregation of rock fragments must be buoyancy and gravitational settling in the fluidized and the mobile matrix, respectively [*Sparks et al.*, 1973; *Sparks*, 1976; *Wilson*, 1980, 1984, 1985; *Druitt*, 1995, 1998]. Fluidization occurs when external forces are sufficiently large to support the weight of the matrix grains. As one possible mechanism for fluidization of the fine-grained matrix, the discharge of gas in upward direction had been proposed [*Sparks*, 1976; *Wilson*, 1980, 1984, 1985; *Roche et al.*, 2002; *Druitt et al.*, 2004]. It was also suggested that gas-fluidization is important for the reduction of friction [*Sparks*, 1976; *Wilson*, 1985; *Roche et al.*, 2002; *Druitt et al.*, 2004]. As the most probable source of gas with upward velocity, either diffusive release from pumice [*Sparks*, 1978] or break-up of pumice [*Wilson*, 1980] was proposed. Another mechanism proposed for fluidization of the matrix is sedimentation in aqueous systems [*Druitt*, 1995, 1998]; the displacement of water induced by the sedimentation of large and dense particles results in water streaming upward. Furthermore, it was demonstrated that the gas-particle suspension within a certain range of vertical gas velocity shows homogeneous fluidization like an aqueous suspension [*Druitt et al.*, 2004].

[4] On the other hand, there are theoretical [*Bagnold*, 1954; *Savage and Lun*, 1988], experimental [*Thomas*, 2000], and numerical [*Campbell and Brennen*, 1985a; *Campbell*, 1989; *Cleary and Campbell*, 1993; *Hirshfield and Rapaport*, 1997; *Straub*, 1997] results that the gravitational or initial kinetic energy can be converted into random motion of grains in granular flows on inclined rough surfaces. These indicate that fine particles become mobile also in the absence of gas or water, as long as the energy input in the particle systems is sufficient.

[5] In this paper, we apply this idea to pyroclastic flows and study the behavior of impurities which are different in density and size from those of the surrounding matrix particles on an inclined rough surface. In Section 2, the details of the numerical method and the results are shown. In Section 3, we discuss the mechanism for density and size segregation. Finally we summarize the results in Section 4.

2. Numerical Calculations and Results

[6] We use a two-dimensional Discrete Element Method (DEM) with soft particle model that enables us to treat multi-body collisions [*Matuttis*, 1998]. The basis of the DEM simulations is the numerical integration of the equations of motion which describe the translation and rotation of the particles in the system [*Cundall and Strack*, 1979]. The number of matrix particles is 3953 and their diameter and the density are denoted by D_{m} and R_{m}, respectively. The number of impurities is 6 and their diameters D_{I} and

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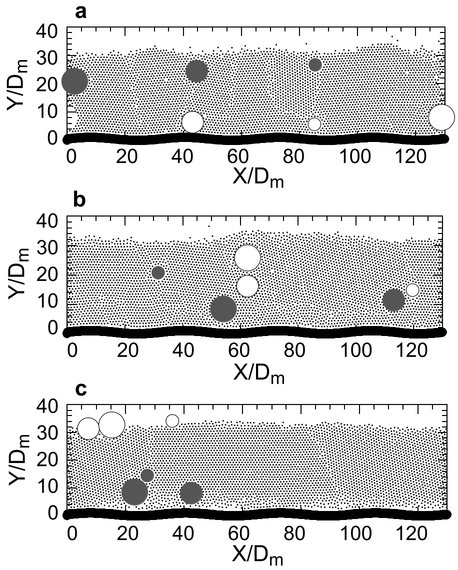

Figure 1. A snap shot at (a) $t' = t/\sqrt{D_m/g} = 0$, (b) $t' = 190$, and (c) $t' = 880$. The matrix particles are denoted by closed circles. The densities of the impurities R_I/R_m are 0.3 (open circles) and 1.7 (gray circles), respectively. The cases for D_I/D_m = 5, 7, and 9 are shown. The angle of the slope is set to be 10 degrees. Horizontal and vertical axes are normalized by D_m.

densities R_I are set to be 5, 7, and 9 times D_m and 0.3 and 1.7 times R_m, respectively. As the shape of the bottom, we choose a sine curve with an amplitude 0.5 times D_m and a wavelength 33 times D_m. After the vertical settling (*Y*-direction), the bottom surface is tilted (10 degrees). The system has periodic boundaries in *X*-direction; as a particle passes through the right boundary of the control volume, it re-enters through the left boundary with the same velocity and vertical position [*Campbell and Brennen*, 1985a, 1985b; *Campbell*, 1989; *Cleary and Campbell*, 1993; *Hirshfield and Rapaport*, 1997; *Straub*, 1997]. It should be noted that, though real pyroclastic flows contain particles in a large size range, we do not treat large size ratios between impurities and matrix particles because it is computationally infeasible due to computer time and storage requirements.

[7] Figures 1a–1c show the numerical result: (a) $t' = t/\sqrt{D_m/g} = 0$, (b) $t' = 190$, and (c) $t' = 880$, for time t and gravity constant g. The light and dense impurities are denoted by open circles and gray ones, respectively. The matrix particles are denoted by closed ones. After tilting, the matrix particles move most wildly near the bottom and the top. The middle region corresponds to the "plug flow region" where the shear velocity is almost zero. The light impurities rise and the dense ones sink. The largest impurities rise and sink fastest and they already reach the top and the bottom at $t' = 190$ while the smallest impurities move most slowly. If the slope ends at this time step, the grading is kept so that our result at $t' = 190$ corresponds to the observation that the reverse grading of pumice and the normal grading of rock can occur simultaneously ("type 2" in the work of *Wilson* [1980]). Furthermore, all light impurities have reached the top and all dense ones have reached the bottom of the flow bed at $t' = 880$; this corresponds to the observations that pumice and rock fragments can be concentrated at the top and the bottom of the flow bed regardless of the fragment size ("type 3" in the work of *Wilson* [1980]).

3. Discussion

[8] In Figure 2, the normalized position of the impurities Y_I/D_m averaged over our normalized time duration $t' = t/\sqrt{D_m/g}$ of 0.03 is plotted against normalized time. The cases for D_I/D_m = 5, 7 and 9, and R_I/R_m = 0.3 and 1.7 are shown. The position Y_I/D_m increases with time for particles with density R_I/R_m = 0.3 and decreases with time for those with density R_I/R_m = 1.7. This density segregation can be attributed to the balance between the gravitational force and the "buoyant" force caused by granular pressure which is the sum of stress components due to collisions and random motion [*Campbell and Brennen*, 1985b; *Shishodia and Wassgren*, 2001; *Huerta and Ruiz-Suarez*, 2004]. Figure 3 shows the granular pressure P normalized by $R_m g D_m$ at $t' = 500$. Here P is averaged over a horizontal control volume and over normalized time duration of 300. The granular pressure monotonously decreases with height and its negative gradient generates a buoyant force. Therefore, it is expected that since the light impurities are subjected to a force from the granular pressure which is larger than the gravitational force, they rise, and vice versa, dense impurities sink.

[9] Furthermore, in Figure 2, one sees that the larger the size of the impurities is, the larger is their speed for rising or sinking at $t' < 600$; this should account for the size grading. It is known that impurities are subjected to a granular viscous force from randomly moving matrix particles when the impurities move relative to matrix particles [*Zik et al.*, 1992], and that the viscous force is a function of the impurity size [*Albert et al.*, 1999; *Trujillo and Herrmann*, 2003]. Therefore, the dependence in the rising- and sinking-speeds on the size of the impurities is expected to be caused by the granular viscous force.

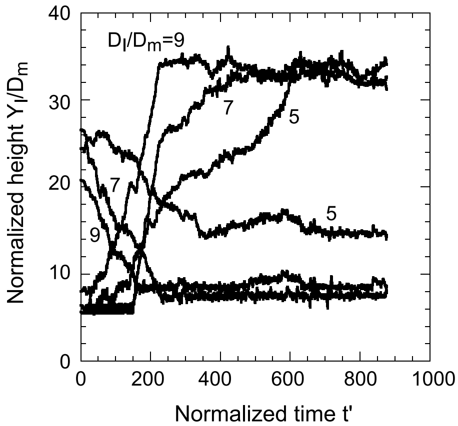

Figure 2. Numerical results of the position of the impurities averaged over normalized time duration of 0.03 against normalized time t'. The cases for D_I/D_m = 5, 7, and 9, and R_I/R_m = 0.3 and 1.7 are shown.

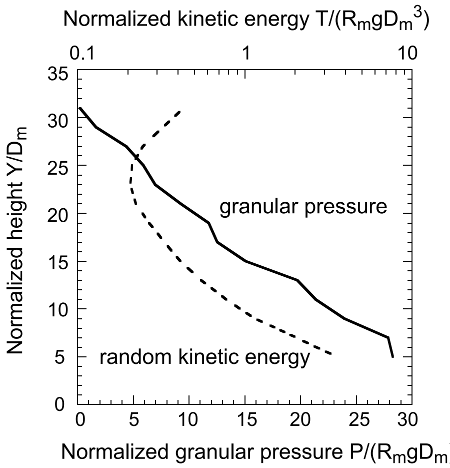

Figure 3. Numerical results for the bulk structure of matrix particles at $t' = 500$ averaged over a horizontal control volume and over normalized time duration of 300: normalized granular pressure and the kinetic energy of random motion per matrix particle.

[10] From the above consideration, we discuss the mechanism of density and size segregation in three dimensions. The impurities are subjected to a force by the pressure gradient F_P and the gravitational force F_g. In addition, they are subjected to the viscous force F_v from the randomly moving matrix, where F_v is proportional to the size of the impurity D_I and the relative velocity v_I between the impurity and the matrix [*Zik et al.*, 1992; *Albert et al.*, 1999; *Trujillo and Herrmann*, 2003]. Thus the behavior of the impurities is governed by $F_P \sim -(dP/dY)D_I^3$, $F_g \sim -R_I D_I^3 g$, and $F_v \sim -D_I v_I$, where the upward direction is taken to be positive. The force balance in the steady state can be expressed as

$$v_I \sim \left(-\frac{dP}{dY} - R_I g\right) D_I^2 \quad (1)$$

Equation (1) indicates that whether the impurity rises or sinks depends on whether the gravitational force is smaller or larger than the gradient of the granular pressure. Moreover, equation (1) indicates that the larger D_I is, the larger is the speed for rising or sinking. Thus the reverse grading of light pumice fragments and the normal grading of dense rock fragments as well as density segregation can be realized in granular flows simultaneously.

[11] Finally we discuss the mobility of the matrix particles, which is indicated by the behavior of impurities in Figures 1 and 2. Figure 3 also shows the kinetic energy of the random motion T per matrix particle (sometimes called granular temperature) normalized by $R_m g D_m^3$ averaged over a horizontal control volume. This indicates that the random motion near the bottom is violent and that even in the plug flow (middle) region, the random motion is sufficient for particles to be mobile in spite of the absence of shear velocity. This implies a flow of kinetic energy of the random motion induced on the free above surface and the rough bottom surface into the plug flow region [*Campbell and Brennen*, 1985a]. Therefore, the roughness of the bottom plays an important role in the fluidization of matrix particles.

4. Summary

[12] We performed a numerical simulation to explain the simultaneous occurrence of reverse grading of light pumice fragments and normal grading of dense rock fragments in the absence of gas and water. Our results suggest that the degree of size segregation increases with time, i.e., with the distance from the vent. After sufficient time, the impurities reach the top or the bottom of the granular bed regardless of their size, and only the density segregation prevails.

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