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Vertical segregations in flows of angular rock fragments: Experimental simulations of the agitation gradient within dense geophysical flows

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ABSTRACT

In this paper, we illustrate laboratory experiments whose purpose is to study the vertical segregations that are commonly observed in deposits of dense geophysical flows (such as pyroclastic flows and rock avalanches). In these experiments, we use rock cuboids with 5 mm long edges as matrix and rock cuboids with 2 cm long edges as segregating clasts. A rotating disk is used to apply frictional stresses at the base of the granular masses. In our experiments, segregating cuboids with density smaller than or equal to that of the matrix particles rise whereas segregating cuboids with density larger than that of the matrix particles sink. The granular flows are imaged through the glass container of the experimental apparatus by a high-speed video camera at 2000 fps. By means of particle image velocimetry analysis of the movies, we study the vertical gradient of particle agitation that exists within the granular flows where agitation increases downward because of the interaction with the subsurface asperities. The high-speed movies show that it is the particle agitation within the flows that exerts an upward force and that, when this force is larger than the weight of the segregating clast, the clast rises whereas, when it is smaller, the clast sinks. The most important result in our set of experiments is that the threshold which separates the values of density of the segregating clasts that segregate upward and the values of density of the segregating clasts that segregate downward is larger than the density of the matrix particles. This explains the upward segregation of dense lithics that is frequently observed in deposits of geophysical flows. This upward segregation is due to the fact that the resultant of the collisions exerted by the matrix particles is a force strong enough to push upward also dense and heavy fragments.

1. Introduction

The purpose of the laboratory experiments described in this paper is to study the vertical segregation of particles that are surrounded by a matrix of ungraded finer particles. This vertical segregation is common in deposits of dense geophysical flows (Fisher and Schmincke, 1984; Cas and Wright, 1988). It is called coarse-tail grading because it is a grading that affects only the coarser portion of the grain size distribution of a deposit whose matrix particles are equally present from the base to the top of the bed (Fig. 1a). In other words, coarse-tail grading is characterized by a critical diameter beneath which grading is absent (Sparks, 1976). Grading is called normal when the clasts segregate downward and inverse (or reverse) when the clasts segregate upward. In pyroclastic flow deposits, lighter pumice clasts are usually reversely graded, whereas both reverse and normal gradings of dense lithic clasts are possible (Fisher and Schmincke, 1984; Cas and Wright, 1988). Our experiments suggest that the preservation of these vertical gradings in the deposits requires a deposition en masse of the flows.

A mechanism that is often mentioned to explain vertical grading is kinetic sieving (e.g., Gray and Thornton, 2005). In kinetic sieving (known also as percolation of fines), finer fragments fall through the empty spaces that are present between coarser fragments. This phenomenon generates deposits where all clasts are inversely graded and where the coarser fragments at the top are not surrounded by finer fragments because all finer fragments have moved to the bottom (Fig. 1b). Convincing examples of reverse grading that is due to kinetic sieving can be found, for example, in cinder cones. However, the problem with kinetic sieving is that it is unable to explain the downward segregation of coarser clasts, and, also, it does not refer to the segregation of clasts that are completely surrounded by a matrix of ungraded finer particles.

It is intuitive to expect that lighter clasts move upward and that denser clasts move downward because of our familiarity with the effects of the static pressure field in water where the Archimedes' principle operates. Thus, it is no surprise that in pumice flows, the lighter pumice fragments segregate upward and the denser lithics segregate downward (Fisher and Schmincke, 1984; Cas and Wright, 1988). However, in geophysical flows, dense lithics can also segregate upward as illustrated by Fig. 2 (Cagnoli et al., 1994; Saucedo et al., 2002, 2004) and this demonstrates that the behaviour of granular flows and that of

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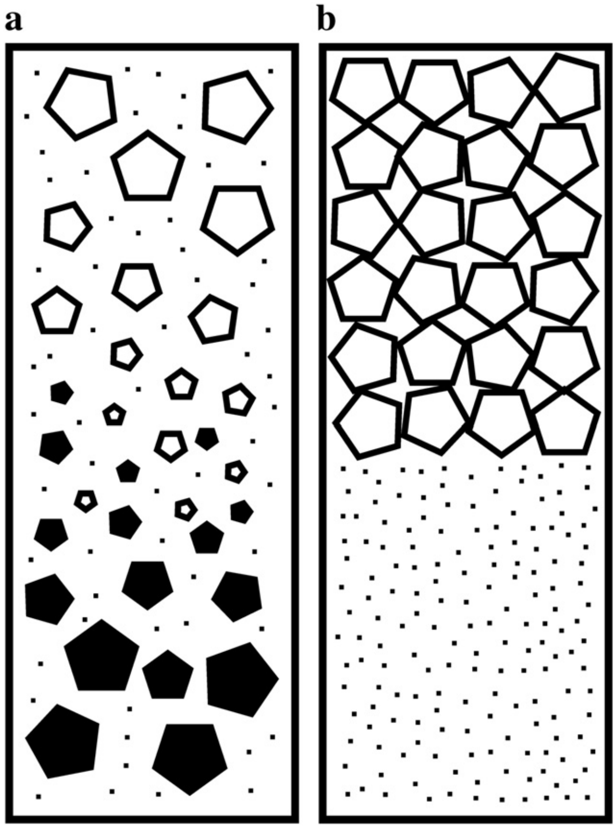

Fig. 1. (a) Coarse-tail grading where the white clasts are reversely graded and the black clasts are normally graded. (b) Grading due to kinetic sieving where the fine particles percolates through the gaps between the coarser ones.

fluids are completely different. For example, when a fluid is stirred, it becomes more homogeneous, whereas stirred granular material unmixes.

A mechanism that is put forward to explain the upward segregation of denser lithics is that one where Bagnold's dispersive force operates (Bagnold, 1954). Bagnold's force acts in a direction normal to that of shear and it is proportional to the square of the grain size so that larger fragments tend to move towards the zone of least shear strain, i.e. towards the free surface of the gravity flow. Resultants with opposite signs of Bagnold's dispersive force (which points upward) plus clast weight (which points downward) could explain the occurrence of normal and reverse grading. However, Bagnold's dispersive force is proportional to the square of the shear strain rate. This is a problem because recent studies have shown that the stresses at the base of geophysical flows do not seem to be a function of the shear strain rate (i.e., Iverson and Denlinger, 2001). For example, previous experiments (Cagnoli and Manga, 2004) have shown that granular flows generated on the rotating disk of the apparatus we use here (Fig. 3) have a tangential speed (when undisturbed by bursts, flow oscillations etc.) that is constant and independent from that of the disk as expected when the basal stresses do not depend on the shear strain rate. In this case, the adoption of Coulomb's law can be a simplification useful to overcome the complexity of the phenomena that occur at the base of granular flows (see also Cagnoli and Quareni, 2009). The purpose of the research described in this paper is to explain why, in geophysical flows, dense clasts can segregate upward.

Vertical segregation is only a portion of the journey that clasts can travel within a moving geophysical flow. Experiments and computer simulations have shown that the coarse fragments that segregate to the top are then transported to the flow front from where they can travel also to the flow margins and become part of the lateral levees (Johnson et al., 2012). The particles that segregate to the top move to the flow front because the horizontal components of particle velocities at the flow top are larger than at the base. A non-uniform occurrence along the flow front of coarse fragments with irregular shape (which, thus, generates more friction when in contact with the ground) seems responsible for the formation of the lobated flow fronts that are observed in pyroclastic flows (Pouliquen and Vallance, 1999).

The study of vertical segregation provides information to better understand the forces acting at the base of dense geophysical flows, because the agitation gradient that is responsible for the segregation is generated at the base where flows interact with the ground. The basal

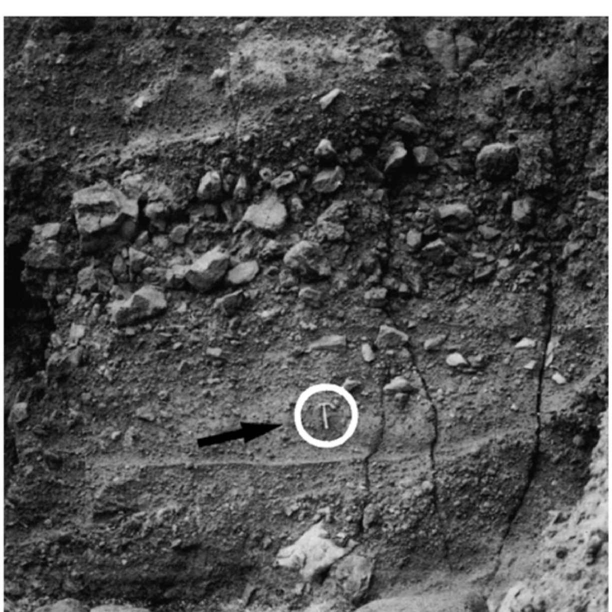

Fig. 2. Reverse coarse-tail grading of dense lithics in a block-and-ash flow deposit in Ustica Island, South Tyrrhenian Sea (Cagnoli et al., 1994). The arrow and the circle show the hammer for scale.

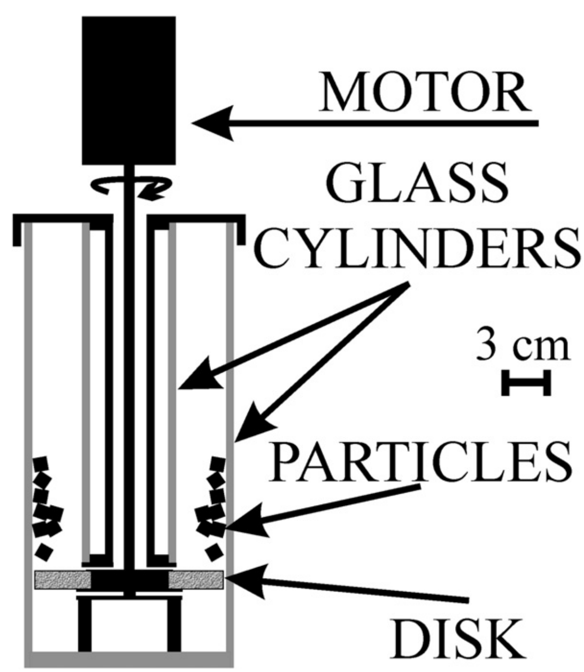

Fig. 3. Cross section of the experimental apparatus. This type of shear cell allows the vertical expansion of the granular flows during motion and it was first introduced by Cagnoli and Manga (2004, 2005).