The rate of sedimentation from turbulent suspension: an experimental model with application to pyroclastic density currents and discussion on the grain-size dependence of flow runout

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Abstract

Large-scale experiments generating ground-hugging multiphase flows were carried out with the aim of modelling the rate of sedimentation S_r of pyroclastic density currents. The current was initiated by the impact on the ground of a dense gas-particle fountain issuing from a vertical conduit. On impact, a thick massive deposit was formed. The grain size of the massive deposit is almost identical to that of the mixture feeding the fountain, suggesting that similar layers formed at the impact of a natural volcanic fountain should be representative of the parent grain-size distribution of the eruption. The flow evolved laterally into a turbulent suspension current that sedimented a thin, tractive layer. A good correlation was found between the ratio transported/sedimented load and the normalized Rouse number P_n^* of the turbulent current. A model of the sedimentation rate was developed, which shows a relationship between grain size and flow runout. A current fed with coarser particles have a higher sedimentation rate, a larger grain-size selectivity and runs shorter than a current fed with finer particles. Application of the model to pyroclastic deposits of Vesuvius and Campi Flegrei of Southern Italy resulted in sedimentation rates falling inside the range of experiments and allowed defining the duration of pyroclastic density currents τ_{dep}, which add important information on the hazard of such dangerous flows. The model could be possibly extended, in the future, to other Geological density currents as, for example, turbidity currents.

Keywords: Pyroclastic density currents, sedimentation rate, turbulent suspension, experiments

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1. Introduction

The formation of sedimentary deposits is in many cases regulated by the passage of turbulent currents carrying a substantial particle load. Common examples are rivers, turbidity currents and pyroclastic density currents (Gladstone et al., 1998; Kneller and Buckee, 2000). The flow carries solid particles by three main modes (Rouse, 1939; Middleton and Southard, 1984): bedload, suspension and wash load. Bedload concerns the material moved by traction on the ground; wash load concerns particles so fine that are intimately coupled to fluid turbulence and are carried away by the current. Suspension refers to particles that are sustained by fluid turbulence and settle when their terminal velocity is lower than the current shear velocity. The suspension load is thought to represent about 90-95% of the total particulate material in the current. It is the rate of sedimentation from turbulent suspension that feeds the sediment layer, allows aggradation of deposit thickness and regulates the current runout. In the time-space evolution of a flow, particles, after transportation in suspension, eventually settle to the ground and form the bedload that, upon some tractional movement, comes to rest and forms the final deposit (Branney and Kokelaar, 2002; Sulpizio and Dellino, 2008; Sulpizio et al., 2014; Dufek, 2016). The structural configuration of the layer is acquired by the last movement of the sediment in the bedload, which leads to the formation of asymmetrical structures such as ripples, sand waves and cross lamination.

The flow of pyroclastic density currents moves in contact with the ground due to its higher density with respect to the surrounding atmosphere. The loss of particles from sedimentation, combined with fluid entrainment from the atmosphere, results in a reduction of concentration, with a consequent lowering of fluid density. It is related to the fact that the flow is composed of gas and particles and behaves as a "pseudofluid" which density is given by $\rho_f = \rho_s C + \rho_g (C-1)$, where ρ_s is particle density, ρ_f is fluid density, ρ_g is gas density and C is particle volumetric concentration (all symbols are defined in Table 1). It is known that pyroclastic density currents, as results from the density reduction due to sedimentation, at some point stop moving laterally and start lofting from the ground in the form of a buoyant phoenix cloud (Neri and Macedonio, 1996; Sparks et al., 1997; Branney and

Kokelaar, 2002; Andrews and Manga, 2011, 2012), aided by buoyancy resulting from entrainment and thermal expansion of atmosphere.

The ability of a turbulent current to transport a particle in suspension is a function of the particle Rouse number $P_n = w_t/ku_*$ (Rouse, 1939), where u_* is the current shear velocity, which is related to the turbulent shear stress (Pope, 2000; Schlichting and Gersten, 2000), k is Von Karman constant = 0.4 and w_t is particle terminal velocity

$$w_t = \sqrt{\frac{4Dg(\rho_s - \rho_f)}{3C_d\rho_f}} \quad (1)$$

where D is particle size, g is gravity acceleration, C_d is particle drag coefficient. Particles with P_n lower than 2.5 are carried in suspension by turbulence, meaning that they are suspended until u_* doesn't drop to values lower than w_t (Middleton and Southard, 1984; Valentine, 1987; Branney and Kokelaar, 2002; Dellino et al., 2008).

Equation (1) gives a good estimation of particle settling velocity if particle volumetric concentration does not exceed a few percent, which is the case of the suspension currents considered in this paper. The particle volumetric concentration (hence density) is stratified within the current. The maximum volumetric concentration of particles that can be transported in suspension, i.e. the maximum current capacity, is a function of the Rouse number of the particulate mixture taken in suspension P_{nsusp}. It is regulated by the Rouse concentration profile over current height y

$$C_{tot} = C_0 \frac{1}{H_T - y_0} \int_{y_0}^{H_T} \left(\frac{H_T - y_0}{y_0} \frac{y}{H_{T-y}} \right)^{P_{nsusp}} dy \quad (2)$$

where C_{tot} is the total concentration of the current, H_T is current total thickness and C_0 is a value of known concentration at a specific height y_0, which is assumed to be the value of concentration at maximum packing in contact with the ground (0.75 in this paper). From (2) it can be inferred that a current carrying a finer mixture (lower P_{nsusp}) can transport, at maximum capacity, a higher concentration than one having the same shear velocity, but carrying coarser particles (higher P_{nsusp}).

The solid load constituting a suspension current, especially in the case of pyroclastic density currents, is made up of a mixture of different components (lithics, glassy fragments and crystals) with different size, density and shape, thus different terminal velocity. The Rouse number of the solid material in the current must be expressed as the average of the particulate mixture,

$P_{n_{avg}} = \sum_{i=1}^{n} P_{ni}\, C_i / C_{tot}$ (3)

with the subscript *i* referring to the i_{th} particle-size class and *n* being the number of size classes. The ratio between $P_{n_{avg}}$ of the material in the current and P_{nsusp} is here defined as the normalized Rouse number P_n* of the current. When it is higher than 1, a current has a particle volumetric concentration in excess of its maximum capacity, e.g. it is over-saturated of particles, which favours sedimentation. When it is lower than 1, a current has a particle volumetric concentration lower than its maximum capacity, e.g. it is under-saturated, and could potentially include additional sediment that is being eroded from the substrate. Very coarse particles, namely those with P_n higher than 5, settle from suspension without being much influenced in their trajectory by turbulence.

Particles in a pyroclastic density current often come from the fountaining of an eruption column and generally are over-saturated with particles. In fact, pyroclastic density currents leave continuous deposits on the ground, meaning that during most of the runout they are in sedimentation mode. The sedimentation rate $S_r = w_t \rho_s \gamma$ is a measure of the mass of particles sedimenting with time per unit area, where γ is the proportion of particles settling from suspension. It is convenient to express the sedimentation rate by means of the sum of the contribution of each size class in the mixture $S_r = \sum_{i=1}^{n} S_{ri}$ where $S_{ri} = w_{ti} \rho_{si} \gamma_i$, where S_{ri} is the sedimentation rate of the i_{th} size class, w_{ti} is the terminal velocity of the i_{th} size class, ρ_{si} is the density of the i_{th} size class and γ_i is the proportion of particles of the i_{th} size class settling from suspension.

The grain-size distribution of a deposit is generally represented by a histogram expressed in ϕ units $\phi = -\log_2 d$, with d particle diameter in millimetres. It represents the distribution of the weight fraction ϕ_i of each size class in the deposit, with $\sum_{i=1}^{n} \phi_i$ summing to 1 (or 100%). In the case of deposits formed by sedimentation from turbulent suspension, it is here assumed that the grain-size distribution represents also the proportion of the sedimentation rate of each size class. Thanks to this assumption, the values of γ_i can be easily calculated once the total sedimentation rate S_r, the terminal velocity w_{ti} and density of each size class ρ_{si} are known.

The growth of deposit thickness with time at a location, i.e. the layer aggradation rate, is given by $A_r = S_r/\rho_{dep}$ where A_r is the aggradation rate and ρ_{dep} is deposit density, measured in the field as $0.6\rho_s$ in this study. Depositional time τ_{dep} is given by $\tau_{dep} = \frac{H_{dep}}{A_r}$ where H_{dep} is deposit thickness. If deposit density and thickness are measured in the field, and the rate of sedimentation can be modelled, it is possible to reconstruct the depositional time, which to a good approximation represents the time it took for the current to pass that particular location. The depositional time is an important indicator of the potential impact that a pyroclastic density current can have on human health, since it quantifies the residence time of hot volcanic ash that can be inhaled by people potentially exposed to these dangerous flows (Horwell and Baxter, 2006). Even a very low volumetric concentration of ash in suspension is unbreathable, and is one of the main causes of mortality of pyroclastic density currents. A model of the sedimentation rate from suspension could greatly help assessing the hazard of pyroclastic density currents. Unfortunately, up to now, no such model exists. In fact, in the computational fluid dynamic simulations of pyroclastic density currents, the effect of sedimentation is generally not included.

This paper describes experiments carried out for developing a model of the sedimentation rate based on data derived from deposits. The model highlights the grain-size dependence of flow runout. Application to natural deposits leads to calculation of the depositional time of natural currents, which helps assessing the hazard to human health.

2. Experiments and laboratory investigation

The experiments were carried out with the apparatus described in detail in Dellino et al., 2007; 2010a; and 2010b, which allowed the reproduction of various regimes of explosive eruptions (Dellino et al., 2014). In this paper, only the results of experiments generating substantial density currents are considered (Dellino et al., 2010b). The particulate material used in the experiments comes from deposits of Vesuvius and Campi Flegrei volcanoes in Southern Italy, and covers an ample range of size, density and particle shape. For each run, up to 350 kg of particles were used. The grain size of two compositions, representing the coarse (from Vesuvius) and fine (from Campi Flegrei) end members, are shown on fig.1. The coarser composition, ranging from lapilli to fine ash (fig. 1a), is made of dense lithic, vesicular glass and crystal components, while the finer one, mostly fine ash (fig. 1b), is made almost exclusively of glass fragments.

Experiments were carried out at various temperatures, from ambient up to 300 °C. The effect of high temperature was that of reducing the density of the carrier fluid and forming a buoyant phoenix cloud at the end of runout (Dellino et al., 2010b). Additional details that emerged, by the experiments, on the effect of temperature on various regimes are deferred to Dellino et al. (2014). The experimental design (fig. 2) consists of 2 interconnected packs of 16 pressurized-gas bottles (the gas storage compartment); a high-pressure section consisting of 18 steel-reinforced rubber hoses each 30 m long; a rapid-compression section consisting of 18 steel-reinforced rubber hoses each 1.5 m long; and a low-pressure section consisting of a 3.2-m-long stainless-steel conduit with a 0.6-m internal diameter, mounted on a massive base plate. The gas bottles are coupled to the high-pressure section via two valves and a hub, in line with manometers that control the reservoir pressure and the pressure in the high-pressure section. High-speed solenoid valves connect the high-pressure section via a second hub to the rapid compression section. The short hoses are connected to eighteen blow nozzles in the base plate of the low-pressure section. The pyroclastic material is placed into the conduit and rests directly on the base plate. The experiment starts by opening the valves that connect the gas-storage compartment to the high-pressure section until the desired pressure is reached in the 30 m long hoses. The computer controlled opening of the solenoid valves connects the high-pressure section to the low-pressure section (via the rapid compression section) and allows a fast coupling of the pressurized gas with the pyroclastic material filling the conduit, which while mixing with the expanding gas, accelerates along the conduit. The two-phase mixture is finally expelled from the conduit in the form of a dense gas-particle fountain, reaching a maximum height over 10 m (fig. 3a). On hitting the ground, the fountain resembled the collapse of an eruptive column similar to that generating a natural pyroclastic density current.

Upon the impact of the fountain on the ground (fig. 3b), the normal stress of the fluid was transformed into tangential stress, which led to a flow that evolved laterally into a fully turbulent, gas-particle shear current, a few meters thick, moving at several m/s (fig. 3c). Deposits of measurable thickness (at least a few millimetres) formed on the ground upon the passage of the current. At the impact zone, where the lateral flow was not fully developed yet, a tens of centimetres thick, massive deposit, was formed (fig. 3d). It represents the excess of solid material that could not be transported into the lateral flow, and was emplaced “en masse” (Sulpizio et al., 2014; Roche, 2015). It is important to note that the grain-size distribution of the massive layer is very similar to that of the original particle load in the conduit. This happens both with the coarse and fine particle mixtures used in the experiments (fig. 4a and b). It reveals that there is not an effective grain-size selection between the particulate mixture issuing from the conduit and the material emplaced en masse at the impact on the ground. It means that the grain size of massive layers formed by similar collapses of dense volcanic fountains should be considered as representative of the parent particle population of natural eruptions. This deposit facies, which resembles a massive pyroclastic flow (Branney and Kokelaar, 2002), makes transition, laterally, into a thin structured layer, similarly to what is observed and documented in certain ignimbrites (Brown and Branney, 2013). The thin layer shows sedimentary structures such as ripples (fig. 3e), which are characterized by an asymmetrical distribution of particles. The finer load occurs at the foreset and the coarser load at the backset, suggesting a selective transportation of the bedload, which is typical of tractive processes occurring at the base of natural currents. These features are common among deposits formed by pyroclastic density currents, with the difference that natural layers have a much higher thickness and represent the aggradation of multiple tractional structures formed during the time integrated passage of the flow, which is much longer than that of experiments. The deposit thins out with increasing distance from the impact zone and has a fan shaped distribution covering, with a thickness ranging from a few millimetres to a few centimeters, an area of up to about 2000 m^2 (fig. 3f). The shear current was continuously fed from the fountain for several seconds. In that time period the deposit was formed by steady sedimentation of particles from suspension, and final bedload traction. When the fountain stopped feeding the current, the flow rapidly decelerated and only the finest particulate material of the upper part of the current continued moving as a wash load, for a long time (Supporting video). The wash load was spread well over the deposit fan-shaped area and formed a very thin, submillimetric, veil of ash.

The current runout was recorded by a network of pressure sensors and multiple high-definition digital video cameras (Dellino et al., 2007, 2010a, 2010b, 2014). For each experiment, thickness and speed of the current were recorded at multiple stations along runout, starting from the impact point and up to about 20 m of distance. The distance between successive stations was set at 1 m for runs spreading on a smaller area and at 2 meters for larger ones. Sediment samples were collected from each station. Sampling was done by collecting the sediment from a rectangular area on the ground, about 1 m^2, which allowed calculation of the mass per unit area of sediment deposited at each station. A total of 18 samples representing the total number of locations out of 6 experimental runs is considered in this paper, on which grain-size, density and particle shape analyses were carried on.

For each of the 18 locations, by combining the processing of sensors and video camera recordings and laboratory analyses of the sediment samples, the following parameters were obtained:

- the shear velocity of the current u_*;
- the particle volumetric concentration of each size class C_i and the total particle volumetric concentration C_{tot};
- the Rouse number of each size class P_{ni} and the average Rouse number $P_{n_{avg}}$;
- the Rouse number at maximum suspension capacity P_{nsusp} and the normalized Rouse number P_n*;
- the proportion of particles of each size settling from suspension γ_i;

- the rate of sedimentation of each size class S_{ri} and the total sedimentation rate S_r;
- the settling velocity of each size class w_{ti};
- the density of each size class ρ_{si};
- the flow density ρ_f;
- the multicomponent grain-size distribution including the shape of particles;
- the particle mass flow rate PMFR.

In particular, the particulate mass flow rate at the impact zone was measured as the product of the area of impact, velocity of impact and density of the flow. The PMFR of each size class in the current was calculated, at each station, by subtracting the total mass of sediment deposited at all previous stations from the particulate mass flow rate at the impact, and using as the area crossed by the flow, the value measured by image analysis upon flow front passing from each station. The current density due to the particle load of each size class was calculated by dividing the mass flow rate of each size class by the average velocity of the current. The total mass and grain-size distribution of each component in the particulate mixture was measured in the laboratory before each run, as it was done also for the samples taken at each station. The mass of material transported in the current at successive stations was calculated by subtracting the mass of sediment deposited at previous stations from the total mass. The particle volumetric concentration of each size class of the current C_i was calculated by dividing the bulk density of the current by the particle density of each size class. The total sedimentation rate was calculated at each station by the mass of sediment per unit area divided by the time of sedimentation. The time of sedimentation was measured at each station starting from the arrival of the flow front and ending by the passage of the wash load. The total sedimentation rate was partitioned among size fractions according to the partitioning of the grain-size distribution. The proportion of particles settling from suspension γ_i of each size class was calculated by dividing the sedimentation rate of each size class by the settling velocity and particle density. For more details on the experimental methods, techniques and uncertainties, see the Supporting file A. The experiments covered an ample range of flow parameters. In particular, the sedimentation rate S_r was between 0.009

/ 1.17 kgm^{-2}s. It is in the same order of magnitude of the sedimentation rate obtained by means of lagrangian multiphase numerical simulations (Valentine et al., 2011; Doronzo et al., 2017). For the range of other experimental parameters see the summary Table 2.

3. The experimental model

The ratio between the particle volumetric concentration of each size class C_i and the proportion of particles of each size class settling from suspension γ_i of each experiment is well correlated with the Rouse number of each size class P_{ni}, as it should be expected in a turbulent suspension current where the attitude of particles to be transported (or sedimented) is a function of the balance between terminal velocity and shear velocity. On fig. 5, the different slopes in the regression equation of a current carrying coarser particles compared with one carrying finer ones demonstrates that flows having a different normalized Rouse number P_n* have also a different attitude toward sedimentation (or transportation), which depends on the excess of particle load (oversaturation) with respect to maximum current capacity. To take into account this factor, the ratio C_i/γ_i of all particle sizes and components of all samples was plotted against P_{ni}/P_n*. The equation of the regression line:

$$\frac{C_i}{\gamma_i} = \frac{P_{n_i}}{P_n^*} 10.065 + 0.1579 \quad (4)$$

well approximates data of all experiments (fig. 6).

The regression line of equation (4) can be used either to predict the proportion of each size class of particles settling from suspension γ_i if the Rouse number of each size class P_{ni}, the normalized Rouse number P_n* and the particle volumetric concentration of each size class C_i are known or to obtain C_i if P_{ni}, P_n* and γ_i are known. Unfortunately, it is difficult to estimate the values of C_i or γ_i of natural pyroclastic density currents. The particle parent population that issues from the volcanic conduit and feeds pyroclastic density currents is generally unknown. In fact, there is a strong geological evidence that it changes from volcano to volcano and from eruption to eruption, depending mostly on magma fragmentation processes. It is to expect that the relative proportions of the size fractions in the transported material should be different from the proportions of the material settling on the ground. In fact, the grain-size distribution will evolve as particles selectively sediment as a function of grain size and density. While it is reasonable to hypothesize a substantial grain-size difference, along runout, between the material transported at a certain location and the material deposited far away, the difference between the grain size transported at some point and that deposited at the same point should be smaller. Following this line, we tested whether the difference in grain size between the sediment sampled at a station and that of the particulate mixture transported in the current at the same station was small enough as to permit the use of the sediment size as a "first guess" of the transported material in equation (4) for reconstructing the sedimentation rate of the experiments. The relative proportions of the size fractions in the transported material at a station were obtained, as described in the previous paragraph, by subtracting the total mass of sediment deposited at all previous stations from the total mass. We made the test by using a goodness-of-fit formula based on the chi-square statistics: $100\% - \left(\sum_{i=1}^{n}\left(\frac{O_i - E_i}{E_i}\right)^2\right)$. O_i is the weight % of the transported material of the i_{th} size class (Observed value in Statistics), E_i is the weight % of the deposited material of the i_{th} size class (Expected value in Statistics). The components were summed together as to obtain, for each class, a weight not smaller than 5%, as it is suggested in Statistics when using percent data in the chi-square test (Davis, 2002). We obtained a fitting typically better than 90% (see Supporting file C and D for examples), which ensures that the grain-size distribution of the deposit can be used as a "first guess" of the grain-size distribution of the transported material, without too much error. The concentration of each component of each size class of the transported material was, then, reconstructed by means of the grain-size distribution of the deposit at each station by $c_{trans_i} = \frac{\phi_i/\rho_{s_i}}{\sum_{i=1}^{n}\phi_i/\rho_{s_i}} * C_{tot}$, where c_{trans_i} is the particle volumetric concentration of the i_{th} size class, $\frac{\phi_i/\rho_{s_i}}{\sum_{i=1}^{n}\phi_i/\rho_{s_i}}$ is the volume fraction occupied by the i_{th} size class, and C_{tot} is the total particle volumetric concentration of the current.

By means of the values of c_{trans_i}, and rearranging equation (4), the contribution of each particle size of each component in the sedimentation rate $\gamma_{proxy_i} = \frac{c_{trans_i}}{\left(\left(10.065 * P_{n_i}/P_n^*\right)+0.1579\right)}$ was obtained.

By means of γ_{proxy_i}, and using the values of settling velocity and particle density of each size class, the sedimentation rates were calculated and compared with the experimental values. The plot on fig. 7 shows the regression line approximating data points. Judging from the correlation coefficient, while some scatter is visible, the fitting is good. The slope of the regression line is, however, a little smaller than 1, suggesting that the calculated values are a little underestimated with respect to the experimental ones, which can be attributed to the approximation that was made by using the grain-size distribution of the deposit as a ”first guess” of the grain-size distribution of the transported material. The underestimation suggests that the grain size of the sediment must be a little coarser than that of the transported material, as it is expected from a current that settles, selectively, more of the coarser than of the finer particle load. We looked for correcting the underestimation and found the grain-size shift necessary to adjust the γ_{proxy_i} values. Details of the method are shown in the Supporting file B. By means of the application of the grain–size shift, the corrected proportions of the sedimentation rate of each size class are recalculated as: $\gamma_{true_i} = \gamma_{proxy_i} * 0.7 + \gamma_{proxy_{i+1}} * 0.3$, where γ_{true_i} is the correct value.

By means of the values of γ_{true_i} the sedimentation rates were recalculated and compared with the experimental ones, resulting in the regression of fig. 8, by which the final model equation of the sedimentation rate is obtained

$$S_r = \left(\sum_i^n \rho_{s_i} w_{t_i}\left(\frac{c_{trans_i}}{\left(\left(10.065 * P_{n_i}^*\right)+0.1579\right)} * 0{,}7 + \gamma_{poxy_{i+1}} * 0.3\right)\right) - 0{,}01 \quad (5)$$

By means of equation (5), the final fitting of fig. 9 is obtained, which shows, to a good approximation, a 1 to 1 ratio between measured and calculated sedimentation rates.

By rearranging terms, it is also possible to reconstruct the particle volumetric concentration of each size and component transported in the current, starting from the proportion in the deposit, by

$$c_{trans_{true_i}} = \left(\left(\gamma_{proxy_i} * 0.7\right) + \left(\gamma_{poxy_{i+1}} * 0.3\right)\right) * \left(\left(10.065 P^*_{n_i}\right) + 0.1579\right) \quad (6)$$

where $c_{transtrue_i}$ is the corrected concentration of the i_{th} size class in the current. By normalizing to 1 the sum of the values of $c_{transtrue_i}$ of all the size classes, the grain-size distribution of the particle mixture in the current is calculated.

On fig. 10, examples of the comparison between the grain-size distribution of the transported material and that of the sediment material are shown. The sediment particulate mixture is a little bit coarser than the particle load transported in the current, as it is expected in a current that settles selectively more of the coarser than of the finer particle load. This happens when the coarse composition of Vesuvius is used in experiments (fig. 10a), where the weight % of the coarser size classes is constantly higher in the sedimented than in the transported material down to a size of 3 ϕ, then the behaviour is inverted for the finest class sizes. The difference is less obvious when the particulate mixture is composed of fine material (fig. 10b), as observed in the experiment with the composition of Campi Flegrei. In this case, in fact, the weight % of the coarser size classes is higher in the transported material down to 2.5 ϕ, then it is higher in the sedimented material from 2.5 and 5 ϕ, and finally it is again higher in the transported material, indicating a lack of a particular selectivity of grain size. An additional proof of the difference in selectivity between "coarse" and "fine" currents is shown on Fig.11 where a comparison between the grain-size evolution of deposits as a function of distance from the impact zone is shown for two experiments. In the "coarse" run a small but significant variation of grain size as a function of increasing distance is noticeable, while for the "fine" run the grain size is more or less the same at various distance. While the experiments do not represent the real scale of distance travelled by natural currents, the clear difference between currents carrying coarser vs fine pyroclasts suggests that pyroclastic density currents transporting mostly fine ash should show less grain-size variations along runout. The comparison of the sedimentation rate at two locations, which represent experiments fed with the coarse and fine end members, reveals some additional aspects of the grain-size dependence of runout of pyroclastic density currents. The relative data sets are included in the Excel worksheets of the Supporting file C and D for a detail analysis. Here we just discuss the fundamental results. While the flow characteristics, i.e. current velocity, are not much different, a big difference, between the coarse and fine cases, is in the ratio between the particle mass flow rate and the sedimentation rate. It is much smaller in the case of the experiment with the coarser material compared to the finer one (four times smaller, see Supporting file C and D). The coarser current has a much higher sedimentation rate than the finer one (tens of times, see Supporting file C and D). Summing up, finer currents can suspend a higher amount of particles (because of the lower *Pn*), emplace less material along runout, maintain a significant density difference with respect to the atmosphere, hence a higher mobility and a longer runout compared to coarser currents. As a consequence, fine pyroclastic density currents can run faster, longer and leave thin, widely spread deposits. This conclusion seems to be corroborated by the fact that some of the most widespread historical pyroclastic density currents known up to date, for example the 1.8 ka Taupo ignimbrite of New Zealand (Wilson et al., 1995; Dade and Huppert, 1996; Manville et al., 2009), show thin, fine-grained deposits, which grain size doesn't change much with travel distance.

4. Model application to natural pyroclastic deposits and scaling to experiments

The experimental model developed in this paper was applied to the deposits of pyroclastic density currents of the Mercato Plinian eruption at Vesuvius and of the Agnano Monte Spina Plinian eruption of Campi Flegrei in Southern Italy. Details on the eruptions and stratigraphy of deposits can be found in de Vita et al., 1999; Dellino et al., 2004; Mele et al., 2011, 2015. The layers considered in the present study were formed by the passage of density currents fed by the collapse of an eruption column and show, at the localities sampled in this study, a facies characterized by tractional structures (fig. 12a) and inclined lamination (fig. 12b), suggesting that transportation and sedimentation were from flows carrying a particulate load by turbulent suspension, and final tractional movement at the bedload.

The layers are 0.5 and 0.2 m thick for Mercato and Agnano Monte Spina, respectively. Deposit density is 1476 and 1295 kg/m^3 for Mercato and Agnano Monte Spina, respectively. They are composed of vesicular glass, dense lithics and crystals, which multicomponent grain size is shown on fig. 13 a and b, respectively. The density, shape and settling velocity of each size class of each component of the deposits were calculated using the same techniques of the experimental samples.

The flow parameters needed for the application of our sedimentation rate model were calculated by means of the software Pyflow (Dioguardi and Dellino, 2014), which is based on the models of Dellino et al. (2008) and Dioguardi and Mele (2015). The calculation used in the present paper utilizes the concept of hydraulic equivalence. If two components with different median size, density and shape, settle together, they are hydraulically equivalent and have the same settling velocity. By this assumption, the software equates the settling velocity of the two components and solves for the current shear velocity u_*, total concentration over flow height C_{tot} and Rouse number at maximum suspension capacity Pn_{susp}. The software finds a range of solutions that considers the variation of deposit particle characteristics. For the sake of simplicity, we restrict our analysis to the average solution, and give the uncertainty in terms of ± one standard deviation around the average.

By combining the particles data and flow parameters obtained by the software Pyflow: C_i, P_{ni}, $P_{n_{avg}}$ and P_n* were calculated, and by means of the combined use of eq. (4), (5) and (6) the sedimentation rate was obtained. In the Supporting file E and F, an Excel worksheet contains all the input data and results of the average solution, as to allow following step by step the calculations. The sedimentation rate is about $0.59^{+0.19}_{-0.22}$ and $0.38^{+.08}_{-.17}$ kg/m^{2}s for Mercato and Agnano Monte Spina, respectively. It falls inside the range of experiments, suggesting that the application of the model to natural deposits doesn't imply an unwarranted extrapolation of results outside the experimental range. By comparing data of file E and F and table 2 it is possible to judge how other important parameters scale between experiments and natural pyroclastic density currents. The shear velocity of the Mercato and Agnano Monte Spina pyroclastic density currents, while in the same order of magnitude of experiments, is about threefold. The thickness of natural currents is much larger than that of the experiments.

Combining shear velocity and flow thickness and recalling that the velocity profile is a function of the shear velocity (see Supporting material A), it results that natural currents typically reach, with increasing height, a speed of tens of m/s, while in the experiments the maximum speed was a little bit lower than 10 m/s. The grain size of natural deposits is in the same range of experiments as it is also the particle volumetric concentration and the normalized Rouse number, P_n*. Summing up, while velocity and thickness of natural currents are larger than experiments, the experiments well preserve the scale of natural flows in their basal part, where sedimentation occurs, justifying the fact that the sedimentation rate of natural deposits is well inside the range of experiments. The tractional features of natural deposits are similar to the experimental ones, whereas the thickness of deposits is much larger in the natural case. Since the growth of deposit thickness with time is a function of the aggradation of the material sedimented from turbulent suspension, the larger thickness of natural deposits means a longer duration of the passage of natural pyroclastic density currents with respect to the experiments. For approximating the duration of the passage of the natural currents, first the aggradation rate A_r and finally the deposition time τ_{dep} were calculated, by recalling the definition given in the introduction section. A_r is $4^{+1.3}_{-1.5}$x10^{-4} and $2.9^{+.07}_{-.13}$x10^{-4} m/s for Mercato and Agnano Monte Spina, respectively, and τ_{dep} is 1240^{+765}_{-307} and 681^{+554}_{-125} s. It means that the passage of the currents, at the location where the deposits were sampled, lasted around 20 minutes in the case of Mercato and around 11 minutes in the case of Agnano Monte Spina. This is consistent with the observation of historical eruptions, where the flow lasted for several minutes to hours (e.g. Lube et al., 2007). During that time period the territory was engulfed with thick, expanded, fast and hazardous currents, loaded with unbreathable hot ash (Horwell and Baxter, 2006). It is important to take note of such information, when projecting for emergency plans and risk-reduction measures.

5. Discussion and future perspective

By means of large-scale experiments, a novel model of the sedimentation rate from turbulent suspension (Equation 5) was obtained. The sedimentation rate strongly influences the runout of pyroclastic density currents, depending on the grain-size of the particulate mixture. If the grain size of the current is coarser (coarse ash to lapilli), the flow sediments selectively the particulate load, making the particle mixture gradually finer along the runout. When, instead, the particulate mixture is finer (fine ash) there is less selective transportation, hence deposition. In this case, particles have a smaller Rouse number, which is the exponent of the concentration profile, resulting in an almost evenly distributed concentration of the sediment along flow height. In principle, fine particles should be transported in continuous suspension, but if the current is oversaturated (P_n*>1), a sedimentation rate must be anyway allowed, although it is very small (tens of times lower than the case with coarser particles, see Supporting file C and D). The settled fine ash remains attached to the ground and cannot be re-eroded from the substrate (Gladstone et al., 1998). In summary: fine-grained pyroclastic density currents, while leaving thin layers on the ground, travel further and possess a higher capacity of impact over the territory. The impact potential is related to the presence of unbreathable hot ash (Horwell and Baxter, 2006) and to the dynamic pressure of the flow $\frac{1}{2}\rho_f u^2$, which in extreme cases is able to destroy buildings (Valentine, 1998; Baxter et al., 2005; Neri et al., 2015). The distribution of these impact parameters along flow runout is strongly influenced by the sedimentation rate. We believe that the inclusion of the sedimentation rate in the numerical multiphase simulation codes, by means of equations (5) and (6), would improve the ability to predict the hazard of pyroclastic density currents on active volcanoes.

In order to effectively use our new model, it is important to have precise data on the physical characteristics of the particles present in a current. Unfortunately, there are no theoretical models giving a priori insights into the grain size, density and shape of the particulate mixture. Pyroclastic deposits are the only record of the passage of pyroclastic density currents, and a prerequisite work in the field is needed for getting information of the real particle population that feeds the flow. After a detailed facies analysis that includes measurements of thickness and density of deposits, samples collected from representative layers need to be processed in the laboratory for multicomponent grain-size analysis, including density and shape. On this regard, a word of caution must be spent on the conditions that permit a proper application. Since our model is based on the concepts of sedimentation from turbulent suspension and final traction at the bedload, a careful study of the deposit facies architecture is needed in order to ascertain that such conditions are met. The occurrence of asymmetrical bedforms, such as ripples and sand waves and of internal inclined lamination (see fig. 12) are features indicative of tractional processes at the bedload, which guarantee the application of the model presented in this paper. However, pyroclastic density currents do not always behave as turbulent suspensions, as it is the case of massive pyroclastic flows (Branney and Kokelaar, 2002), or also the case of massive deposits from pyroclastic density currents found in proximal locations, i.e. at the impact zone of the collapsing fountain (Sulpizio and Dellino, 2008; Sulpizio et al., 2014; Dufek, 2016). An example of a metric thick, massive, structureless deposit formed by the impact of the eruptive fountain feeding pyroclastic density currents of the Mercato eruption is shown, as an example, on Fig. 14. The layer does not show any feature suggesting a particle selective transportation in suspension or traction at the bedload. The model of sedimentation rate by turbulent suspension is not applicable to this layer. In fact, at the impact, the particle volumetric concentration was so high that particle-particle interaction played a stronger role than turbulent suspension upon deposition. Judging from the experiments described in the present paper, it seems that the particulate mixture issuing from the conduit and feeding the dense fountaining column did not undergo a grain size selection upon the impact on the ground from where the "en mass" deposition of the massive layer occurred. The grain size selection, in fact, started only after the development of the lateral turbulent suspension current. It implies that, if thick, massive, structureless layers are formed by the collapse of a natural eruptive column in the same way as in the experiments, their grain size, not having underwent a selective process, can be taken as representative of the parent grain-size population feeding the eruption. This outcome has important implication on the modelling of explosive volcanism, since the parent grain-size population is one of the main parameters used for initializing eruption simulations (Neri and Macedonio, 1996). Furthermore, concerning the modelling of grain size of pyroclastic density currents, equation (6) allows the reconstruction of the grain size of the material transported by turbulent suspension from the deposit or, vice-versa, the reconstruction of the sedimented material grain size starting from that of the transported material. This information can be used, in models, to predict the granulometric evolution of the particulate mixture during runout.

The sedimentation rate calculated for some pyroclastic density currents of Vesuvius and Campi Flegrei falls within the range of experimental data, which is a guarantee of good scalability of the model. Furthermore, the duration of the natural currents, as calculated by the model, is compatible with the observations of historical eruptions, making us confident that the model allows a reasonable reconstruction of the behaviour of natural currents. We expect that higher values of the sedimentation rate will result when the model is applied to more powerful eruptions than those studied in this paper, and a systematic investigation will allow acknowledging the true range that can be reached by pyroclastic density currents. Probably there is an upper limit over which massive deposition takes over suspension-sedimentation plus bedload-traction. Future investigations are required to determine this limit.

As a conclusive remark, we suggest that the model proposed in this paper, as it is based on the general laws that regulate the sedimentation of particulate material from turbulent suspension, can have applicability beyond the study of pyroclastic density currents, for example to other geological density currents such as turbidites.

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Caption of figures

Fig. 1. Grain-size distribution of the material used for experiments. A: multicomponent grain-size distribution of the coarse material coming from the Veusvius composition. The relative fractions of components are shown. The xx symbol means crystals. B: grain-size distribution of the fine glassy material coming from the Campi Flegrei composition.

Fig. 2. Skecth design of the experimental apparatus with description of the main parts. Modified after Dellino et al., 2017.

Fig. 3. Display mount showing phases of the experiment and associated deposits. A: formation of the dense gas-particle foutain at the conduit exit. B: Collapse of the fountain and impact on the ground. C: development of the fully turbulent current. D: Massive deposit formed at the impact area where the flow is not extablished yet. Deposit with tractional features of the type of ripples formed by the fully turbulent suspension current. E: Fan shape distribution of the deposits.

Fig. 4. Grain-size distribution of the massive layer formed at the impact of the experimental fountain. A: grain size of a “coarse” run. B: grain size of a “fine” run.

Fig. 5. Graph showing the correlation between the ratio of the particle volumetric concentration of the transported material, C_i, and the proportion of the material sedimented from turbulent suspension, γ_i of the particle size classes as a function of the Rouse number of the size class P_{ni}. For comparison, data from a coarse run and data from a fine run are represented, together with the respective correlation coefficient, regression equation and normalized Rouse number $Pn*$.

Fig. 6. Graph showing the correlation between the ratio of the particle volumetric concentration of the transported material, C_i, and the proportion of the material sedimented from turbulent suspension, γ_i of the particle size classes as a function of the ratio of Particle Rouse number of the size fraction P_{ni} and normalized Rouse number Pn*. Data of all the components and size classes of all experiments are included. The correlation coefficient and regression equation are inset.

Fig. 7. Graph showing the correlation between the measured sedimentation rate and the sedimentation rate calculated by means of γ_{proxy_i}. The regression equation and correlation coefficient are inset.

Fig. 8. Graph showing the correlation between the measured sedimentation rate and the sedimentation rate calculated by means of γ_{true_i}. The regression equation and correlation coefficient are inset.

Fig. 9. Graph showing the correlation between the measured sedimentation rate and the sedimentation rate calculated by means of equation (5). The regression equation and correlation coefficient are inset.

Fig. 10. Comparison between the grain-size distribution of the transported material and that of the sedimented material. A: Coarse composition coming from Vesuvius. B: fine composition coming from Campi Flegrei.

Fig. 11. Graph showing the variation of the median size of the grain-size distribution of samples as a function of distance from the impact location for an experimental run fed with corse material (dots) and one with fine material (triangles). D is maximum distance, d is distance from the impact.

Fig. 12. Photos showing the facies of deposits used for the application of the model of the sedimentation rate. A: layer of the Mercato eruption at Vesuvius showing tractional structures. B: layer of the Agnano Monte Spina eruption showing inclined laminae.

Fig. 13. Multicomponent grain-size distribution of layers used for the application of the model of the sedimentation rate. A: multicomponent grain-size distribution of the layer from the Mercato eruption at Vesuvius. B: multicomponent grain-size distribution of the layer from the Agnano Monte Spina eruption at Campi Flegrei.

Fig. 14. Photo showing a massive, structureless layer of the Mercato eruption formed at the impact of a collapsing eruptive fountain.