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Formation of inversely graded basal layers in ignimbrites by progressive aggradation

F. Legros*, J. Martí

Institute of Earth Sciences Jaume Almera, CSIC, Lluís Solé i Sabarís s/n, 08028 Barcelona, Spain

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Abstract

A model for the formation of coarse-depleted, inversely graded basal layers in ignimbrites is presented. It is proposed that the deposit forms by progressive aggradation of sediment below the flow, and that the basal layer at any place is deposited from the leading part of the flow. Sinking of large lithics within the flow produces a normal grading, which is reversed in the basal deposit by the caterpillar-like motion of the flow. Large pumices rise to the top of the flow and migrate to the head, where many are pushed aside and accumulate in levées. Pumices, which deposit from the head are mostly re-entrained into the flow due to their buoyancy but, exceptionally, some may be trapped at the base of the aggrading deposit. We describe concentrations of large pumices in the basal layer of small-volume ignimbrites, which give support to this model. The model is an alternative to the traditional hypothesis which assumes that coarse-depleted, inversely graded basal layers in ignimbrites are the result of the upward migration of large particles out of the basal layer, in a flow which later freezes en masse. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Pyroclastic flows leave poorly-sorted, often massive deposits (called ignimbrites when pumice rich) that commonly have a coarse-depleted, inversely graded basal layer (Sparks et al., 1973; Sparks, 1976; Freundt and Schmincke, 1986; Palladino and Valentine, 1995; Druitt, 1998). Sparks et al. (1973) distinguished three layers in a typical section of pyroclastic flow deposit. Layer 1 is the deposit of the dilute surge that may precede the main flow, layer 2 is the deposit of the main flow, and layer 3 is an ash-fall deposit formed by settling of the fine ash left in suspension at the end of the flow pulse. Layers 1 and 3 are often absent and are not considered further in this paper. Sparks et al. (1973) further subdivided layer 2, which forms the pyroclastic-flow deposit sensu stricto, into layer 2a, the coarse-depleted, inversely graded basal layer, and layer 2b, the rest of the deposit. This paper is concerned with the formation of layer 2a, which hereafter will simply be called the basal layer. Basal layers in ignimbrites are typically a few centimetres to a few decimetres thick. They have the same grainsize characteristics as the rest of the deposit, except that they lack the coarsest particles (Sparks, 1976). Their contact with the overlying body of the deposit is gradational, through an inverse grading of coarse particles. Basal layers are generally well developed in pumice-rich deposits, thought to be the product of fluidised flows (types 2 and 3 after the

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* Corresponding author. Address: Facultad de Geologia, Universidad Nacional San Augustin, Av. Independencia, Arequipa, Peru.
E-mail address: f_legros@yahoo.com (F. Legros).

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terminology of Wilson (1980)) while they are absent or poorly developed in the deposits of block-and-ash, poorly fluidised, type-1 flows (e.g. Druitt, 1998).

The physics of pyroclastic flows is still too poorly understood to put strong constraints on the deposition processes. Two main models of deposition have been proposed, here referred to as the en masse freezing and the progressive aggradation models. In the en masse freezing model, the flow comes to halt abruptly over its entire depth. One may envisage two different cases. In one, the whole flow is deposited at the same time, as a single block. In the other, each vertical section is deposited instantaneously, but, laterally, the tail is deposited while the front is still moving. In the progressive aggradation model, the deposit builds up due to the continuous supply of material from the flow through a depositional boundary layer (Fisher, 1966; Branney and Kokelaar, 1992, 1997; Bryan et al., 1998; Freundt, 1999).

Physically, the en masse freezing model relies on the assumption that pyroclastic flows behave as Bingham flows (Johnson, 1970; Sparks, 1976). The upper part of a Bingham flow develops a rigid 'plug', the thickness of which depends on the slope and the yield strength of the flow. When the driving stress at the base of the flow becomes less than its yield strength, the plug extends down to the ground and the flow freezes en masse. The existence of yield strength in pyroclastic flows has been hypothesised because of the presence of steep levées and lobate fronts in the deposits. However, levées might form by progressive accumulation of large clasts at flow margins and their height would only indicate their own minimum strength, not the strength of the flow (e.g., Kokelaar and Branney, 1996). Yield strengths have also been measured in fresh pyroclastic-flow deposits (Wilson and Head, 1981) but they provide only upper bounds for the possible yield strength in the parent flows. For these and other reasons, the Bingham-flow model is no longer very popular. Some authors now think that rapid freezing might occur in another way, from the base up and the front back, due to interparticle friction, as observed in some experimental granular avalanches on the laboratory scale (Druitt, 1998). However, it is not clear whether such avalanches are good analogues of pyroclastic flows. In particular, it is well known that dry granular avalanches have 'mobility' H/L ratios of about 0.5 (H and L are, respectively, the fall height and the horizontal displacement of the centre of mass), while pyroclastic flows generally are much more mobile. This has convinced many workers that pyroclastic flows are not simple granular flows and that the interstitial gas plays an important role in enhancing their mobility. Processes such as fluidisation (Wilson, 1980) or hindered settling (Druitt, 1995) have been postulated, based on field evidence such as gas escape pipes and the presence of layers of crystal-depleted, elutriated fine ash associated with crystal-enriched ignimbrites (Sparks and Walker, 1977). Recently, it has been shown experimentally that fluidisation does enhance the mobility of granular flows (Takahashi and Tsujimoto, 2000). The extent to which fluidisation and hindered settling are effective in natural pyroclastic flows and how they would influence deposition is still poorly known. Nevertheless, experiments on sedimentation of static, poorly-sorted, concentrated suspensions show that hindered settling deposition occurs by progressive aggradation from the bottom up (Druitt, 1995, 1998) and the deposits from fluidised experimental granular flows also form by progressive aggradation (Takahashi and Tsujimoto, 2000).

There are several lines of evidence that support the idea that extensive ignimbrite sheets form by progressive aggradation. Their range as well as their thickness and lateral grainsize variations are successfully predicted by models that assume deposition by progressive aggradation from dilute turbulent suspensions (Bursik and Woods, 1996; Dade and Huppert, 1996; Freundt and Bursik, 1998). Some ignimbrites show vertical variations in chemical composition (Branney and Kokelaar, 1992, 1997) or in the abundance, type or size of lithic clasts (Bryan et al., 1998), which are thought to reflect temporal changes in the material supplied to the depositional boundary layer of the flow. Moreover, many large ignimbrites have an estimated duration of emplacement much longer than the time estimated for the pyroclastic flow to travel from the vent to the distal edge of the deposit, which implies that the lower part of the ignimbrite was already deposited when the upper part was not erupted yet, a fact inconsistent with the formation of ignimbrite by en masse freezing.

The emplacement of small-volume, valley-ponded ignimbrites is more controversial. The typical accumulation of large pumice clasts at the top of these ignimbrites suggests that their parent flows are dense, at least during the depositional stage. Several authors have explained the inverse grading of pumices in ignimbrite by their flotation in a dense pyroclastic flow which later freezes en masse (Sparks et al., 1973; Sparks, 1976; Freundt and Schmincke, 1986; Cole and Scarpati, 1993; Palladino and Valentine, 1995). However, concentration of large pumices at the top of ignimbrites does not imply deposition by en masse freezing. Ignimbrites formed by progressive aggradation from dense or density-stratified flows may also have large pumice clasts concentrated at their top, provided the pumices can rise within the dense basal part of the flow more rapidly than the rising deposit boundary, or that they have already been segregated before deposition starts, or that they simply cannot enter the dense basal part of the flow.

Coarse-depleted, inversely graded basal layers in ignimbrites have been hypothesised by many authors to form by upward segregation of the large particles carried in the boundary layer due to a dispersive pressure force directed away from the boundary (Sparks et al., 1973; Sparks, 1976; Freundt and Schmincke, 1986; Palladino and Valentine, 1995). The traditional model is that this occurs within flows that move and stop en masse, so that the inverse grading developed at the base of the flow is preserved in the deposit. The formation of inversely graded basal layers owing to dispersive pressure forces is apparently inconsistent with a model of deposition by progressive aggradation of material at the base of the flow as in this model, the basal boundary layer, where dispersive pressure forces are hypothesised to be important due to strong shearing, progressively shifts upward during deposition. As a result, large particles should be continuously removed from the rising basal layer and would finally concentrate at the top of the deposit. The interpretation of inversely graded basal layers is therefore a crucial issue for understanding the mode of deposition of pyroclastic flows. Any physical modelling of pyroclastic flows needs a good knowledge of how they lose mass and momentum, so understanding the deposition processes is important for improving dynamical flow models.

This paper proposes a model for the formation of coarse-depleted, inversely graded basal layers in ignimbrites, in which dispersive pressure forces do not play any role, and the deposit forms by progressive aggradation rather than by en masse freezing. In this paper, we are concerned with deposits from dense, high-concentration flows only, and do not consider further ignimbrites deposited by dilute flows.

2. Model

We consider a dense pyroclastic flow that is continuously depositing sediment along its base. At any location, the basal layer of the deposit will consist of the first material deposited, i.e. the material deposited from the head of the flow. In practice, the very head may sometimes be erosive, and deposition would then start from the leading portion of the flow just behind the head. Therefore, in order to explain the formation of a coarse-depleted basal layer, we just have to explain why the leading part of the flow lacks the coarse particles present in the rest of the flow. This requires only two assumptions. The first one is that particles are able to segregate vertically within the flow according to their size and density contrast with the matrix. The common concentration of large pumices at the top of ignimbrites is good evidence for this (Sparks et al., 1973). Such segregation also occurs in experimentally fluidised ignimbrite samples, with large lithics sinking to the bottom and large pumices rising to the top (Wilson, 1980). Clearly, grading in pyroclastic flow deposits can be the result of more complex processes, involving temporal variations in flow rate and sediment supply, and redistribution of locally eroded material. However, the concentration of large pumices at the top of many ignimbrites is hard to explain by a systematic increase in the proportion and size of pumices erupted at the end of an eruptive pulse. It is more easily explained by a segregation process operating within the flow, in which clast size and density are the most important parameters. Note that this implies no specific assumption about the exact nature of the segregation process. We therefore hypothesise that, within well-fluidised pyroclastic flows, heavy particles are normally graded, the largest being concentrated in the lower part and absent at the top of the flow, while light particles are inversely graded.

The second assumption for a model of formation of coarse-depleted basal layers by progressive aggradation is that the upper part of the flow is faster than the

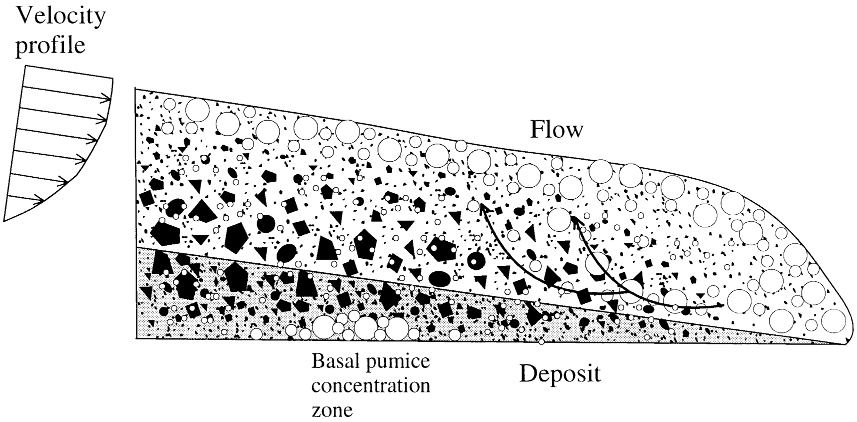

Fig. 1. Schematic representation of the formation of a coarse-depleted, inversely graded basal layer by progressive aggradation of an ignimbrite. Gravitational sinking of lithics (solid symbols) creates a normal grading in the flow, which is reversed in the deposit as a result of the velocity profile in the flow. Large pumices (white circles) are recirculated in the flow head (arrows) due to their large size and strong buoyancy. Some of them are locally trapped in the deposit and form a discontinuous basal pumice concentration zone.

lower part. As friction against the ground retards the flow at its bottom, this seems a reasonable hypothesis, whatever the exact form of the velocity profile, unless the whole flow moves as a rigid plug. Thus, the leading part of the flow is supplied with material from the upper part, hence with material lacking the coarsest heavy particles. This material is deposited first. In this manner, the normal grading of heavy particles developed in the flow is reversed in the basal layer of the deposit (Fig. 1).

In contrast with heavy particles, light particles are inversely graded in the flow. The largest of them should therefore migrate to the flow head and form levées. This is consistent with the great accumulations of large pumices observed at the termination and in the lateral margins of small-volume ignimbrites (Wilson and Head, 1981; Sparks et al., 1997; Cole et al., 1998). Large pumices that deposit from the flow head and then are overrun by the rest of the flow should be easily re-entrained due to their strong buoyancy. They would migrate to the head again, by a process similar to the recirculation of large particles at the front of some experimental granular avalanches (Pouliquen et al., 1997). Exceptionally, some large pumices could be trapped in the basal aggrading deposit (Fig. 1). Such concentrations of large pumices at the base of ignimbrites have been observed and are described in the following section.

3. Field observations

Basal layers of ignimbrites were examined at Misti volcano (Peru). Misti is an active andesitic stratovolcano of the Central Volcanic Zone of the Andes. It has produced about 20 subplinian to plinian eruptions during the last 34,000 years (Legros, 2001). Most ignimbrites are observed in the valley walls on the southern pyroclastic apron. They have small volume (10^6–10^7 m^3) and thickness (1–10 m) and are confined in the 50–100 m deep paleovalleys. In some cases, the ignimbrite overlies a fall deposit in the valley, while no ignimbrite occurs over the same fall deposit out of the valley, which demonstrates that the pyroclastic flow was essentially channelled and had no significant dilute flow associated.

Several tens of ignimbrite vertical sections were examined. Most of them are lithic rich, but also contain a significant amount of pumices. Generally, they do not conform to the typical ignimbrite section of Sparks et al. (1973). In particular, they lack the basal lithic breccia (layer 2bL). Some deposits exhibit lithic and pumice concentration zones, which are laterally discontinuous at the scale of the outcrop. Sixteen vertical sections were submitted to a detailed granulometric study, the results of which will be presented elsewhere. The attention in this paper is restricted to basal layers.

Ignimbrites observed at Misti show different types

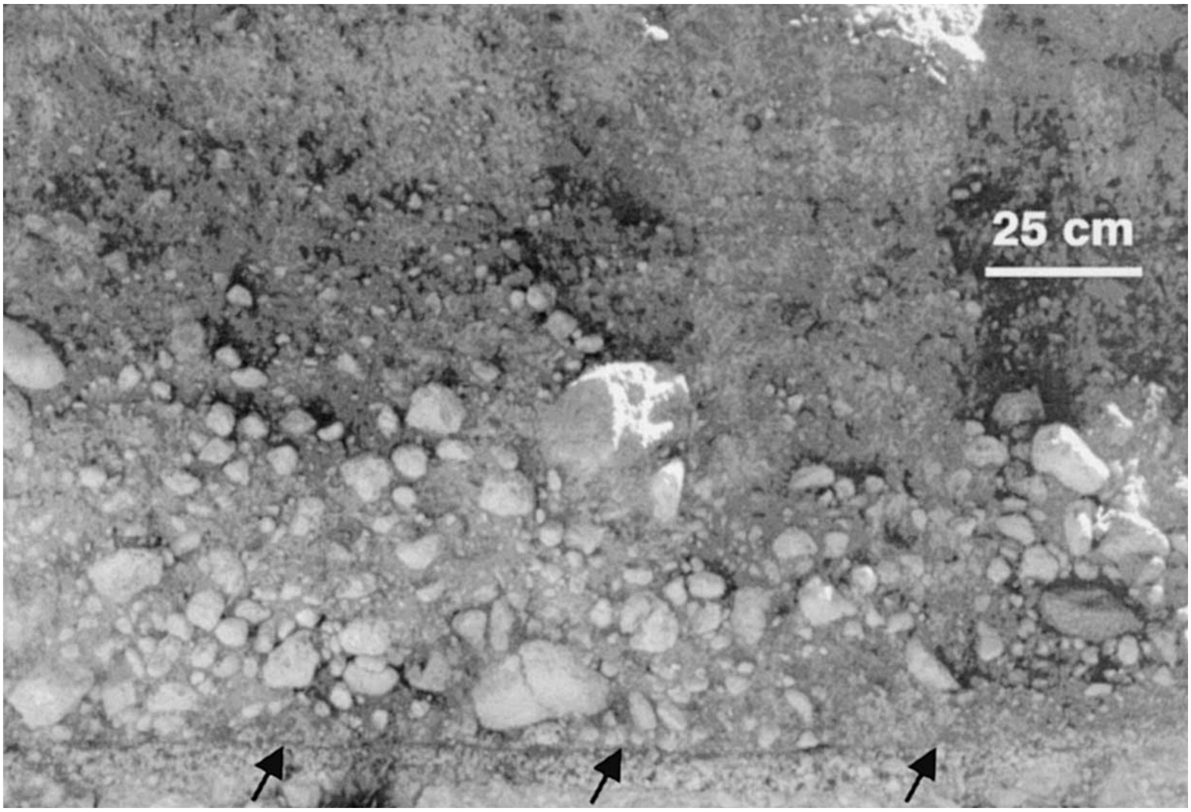

Fig. 2. Photograph of a clast-supported pumice concentration at the base of an ignimbrite at Misti volcano (arrows indicate the base of the deposit).

of basal layers. Often, there is no particular basal layer: the lowermost portion contains the same sizes and abundance of large clasts as the rest of the ignimbrite. Coarse-depleted, inversely graded basal layers similar to those described by Sparks et al. (1973) are also common. Some of them can be followed over the whole length of the outcrop while others pinch out laterally. A third type of basal layer consists of concentrations of large pumice clasts, similar to the pumice concentration zones usually observed at the top of ignimbrites (Fig. 2). Basal pumice concentration zones contain large (>10 cm), rounded, sometimes clast-supported pumices. They have a limited horizontal extent of no more than a few metres and are a few decimetres thick. They are strongly depleted in large lithics and are in gradual contact with the overlying deposit. Large pumices also occur as isolated clasts in some basal layers.

The size of the three largest lithics and the three largest pumices was measured in both the basal layer and the overlying deposit in 14 sections. Clasts were picked up from equal areas of outcrops (in general, ~1 m^2) in the basal layer and the overlying deposit, excluding the upper pumice concentration zone. Table 1 shows the ratio of maximum clast size (average of the three largest clasts) in the deposit to maximum clast size in the basal layer, for both lithics and pumices. A size ratio greater than 1 indicates inverse coarse-tail grading and a size ratio smaller than 1 indicates normal coarse-tail grading. In sections 1–4, where the basal part of the deposit show no visible granulometric difference from the overlying deposit, the basal layer was arbitrarily taken as the 10 lowermost centimetres of the deposit. Table 1 shows that there is no significant grading at the base of these deposits (size ratio ~1), neither for lithics nor for

Table 1
Ratio between the average size of the three largest clasts in the deposit (layer 2b, not including the pumice-rich top zone) and the average size of the three largest clasts in the basal layer, for 14 sections in ignimbrites from Misti. Sections 1–4 have no distinguishable basal layer, sections 5–11 have classical coarse-depleted, inversely graded basal layers and sections 12–14 have basal pumice concentrations

Section number	Pumice size ratio	Lithic size ratio
1	0.9	1.7
2	1.6	0.7
3	0.8	1.3
4	1.5	1.2
5	1.2	2.3
6	0.8	4.1
7	1.9	5
8	1.5	3.4
9	0.8	4.6
10	0.9	5.1
11	1.4	2.9
12	7.9	0.1
13	10.2	0.2
14	8.9	0.1

pumices, which confirms the visual impression of absence of a distinguishable basal layer. In sections 5–11, where a coarse-depleted, inversely graded basal layer is present, the gradational contact between the basal layer and the overlying deposit made the choice of a boundary somewhat arbitrary. Clasts were picked up in the lower part of the basal layer, where there was a visible granulometric difference from the overlying deposit. Table 1 shows that lithics are strongly inversely graded (size ratio $\gg 1$) while pumices are essentially ungraded (size ratio ~ 1) at the base of these deposits. This can be explained by the fact that large pumices generally concentrate at the top of the deposit. The inverse grading of the basal layer is therefore an inverse grading of lithics only, while pumices are inversely graded near the top of the section, not at the base (Fig. 3). In contrast, Sparks (1976) suggested that the size of both the maximum lithic and pumice clasts increase upward in basal layers, but no data were presented in support of this statement. The discrepancy might come from the fact that the results in Table 1 are for clasts taken from equal areas in the basal layer and the overlying deposit and do not consider the upper, pumice-enriched part of the deposit. In contrast, the visual impression that one may have in front of an outcrop is influenced by the presence of large pumices at the top of the deposit and by the fact that, for a given length of outcrop, the area of the basal layer is much smaller than that of the overlying deposit, and so the basal layer is less likely to contain large clasts.

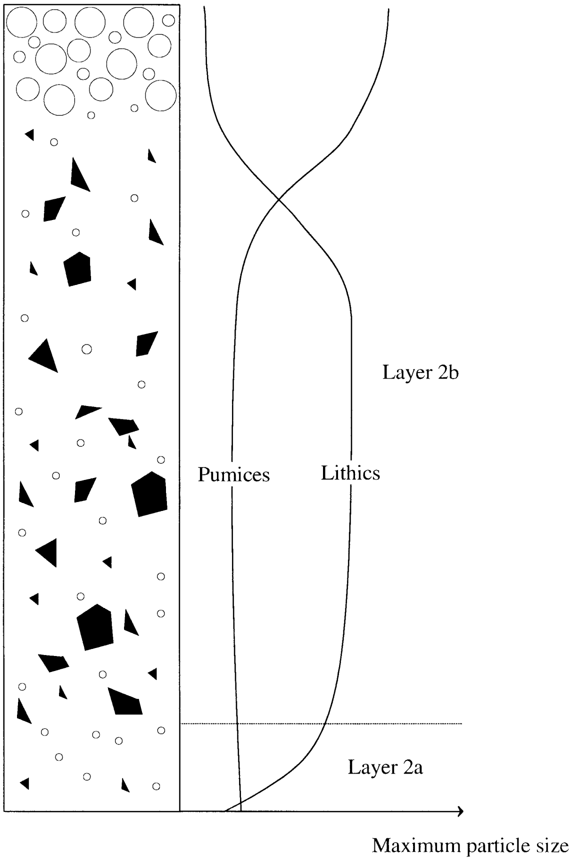

Fig. 3. Schematic size grading in a section of ignimbrite that contains a ‘classical’ coarse-depleted, inversely graded layer 2a. Note how inverse grading in layer 2a occurs only for lithics.

In sections 12–14, where the basal layer consists of a concentration of large pumice clasts, lithics are strongly inversely graded and pumices normally graded (Table 1). There are three main possibilities for the formation of these basal pumice concentrations: (1) they represent the pumice raft of a previous ignimbrite, remobilised and redeposited; (2) they represent the buried marginal or distal levées of a previous ignimbrite; (3) they are directly deposited by the head of the flow, as depicted in Fig. 1. At Misti, basal pumice concentrations occur even in deposits that do not overlie a previous ignimbrite, so the remobilisation and immediate deposition of a top pumice raft cannot be invoked. When they overlie a plinian fallout deposit, the pumices in the basal pumice concentration are much larger than those in the fallout deposit, so their presence cannot be explained by local erosion and redeposition. We did not find evidence for basal pumice concentrations to represent buried levées of a previous ignimbrite: the pumice concentration layers are discontinuous, their contact with the overlying ignimbrite is gradational, and we could never follow and correlate them laterally with previous deposits. We therefore propose that they may have been deposited by the pumice-rich head of the flow pulse which deposited the overlying ignimbrite (Fig. 1).

However, even if this interpretation were wrong and the large pumices were in fact derived from a previous ignimbrite, the important point regarding the model of ignimbrite deposition is that these large pumices have been preserved at the base of the deposit. If pyroclastic flows do not deposit sediment during transport, as hypothesised in the en masse freezing model, it is difficult to understand how large pumices lying over a flat surface could avoid being entrained by the dense flow passing over and around them, or how they could move in the basal layer for a significant time without rising through the flow, particularly as the strong ability of large pumices to segregate upwards in these flows is demonstrated by their concentration at the top of the deposits. Furthermore, if basal layers were due to dispersive pressure forces proportional to the square of the clast size, large pumices should be the first to be pushed upward. Preservation of large pumices at the base of ignimbrites suggests that deposition starts immediately after they enter the base of the flow, otherwise they would rapidly escape upward. This is more easily understood in a model of progressive aggradation, in which deposition at any place can start as soon as the flow arrives. Thus, while most large pumices are pushed by the flow head or rapidly re-entrained into the flow behind the head, some are trapped below the aggrading deposit and remain at the base of the ignimbrite. In a model of en masse freezing, we would have to argue that the flow has frozen immediately after the incorporation of the large pumices at its base. In this case, basal pumice concentrations could only be found near the margins of the deposit or close to a local source of pumices. We have found no evidence for this in the basal pumice concentrations observed at Misti.

4. Discussion

The model of formation of coarse-depleted, inversely graded basal layer by progressive aggradation from dense flows is an alternative to the traditional model which invokes clast segregation under the action of dispersive pressure forces followed by en masse deposition. The concept of dispersive pressure comes from the experiments by Bagnold (1954) in which a mixture of fluid and well-sorted, neutrally buoyant particles was sheared in an annular cell. Dispersive pressure in poorly sorted, possibly fluidised flows is poorly understood. The fine matrix is believed to have a damping effect that would drive the flow in a macroviscous regime, but no quantified model of this phenomenon is currently available for pyroclastic flows. Even in well-sorted sand avalanches, it is not clear whether dispersive pressure can explain the commonly observed inverse grading. Dispersive pressure increases with shear strain rate and solids concentration (Bagnold, 1954). However, dispersive pressure in a rapid granular flow can never exceed the static pressure of the overburden, as it would cause the flow to expand and the dispersive pressure to decrease to a level just sufficient to support the load of the flow (Savage and Hutter, 1989; Straub, 1997). Thus, the dispersive pressure gradient within a rapid granular flow is everywhere equal to the lithostatic pressure gradient, and it is unclear how it could push dense particles upward. Many authors now think that inverse grading in sand avalanches occurs by the sinking of small particles through the small voids that open and close in the agitated sand, a process known as kinetic sieving (Middleton, 1970; Savage and Lun, 1988; Pouliquen et al., 1997; Thomas, 2000).

A potential problem for the en masse deposition model is to explain how a dense, rapid, non-depositional flow can move over the ground without eroding. Although pyroclastic flows can indeed be erosive, it is also common that their deposits lie conformably over very erodible surfaces such as ash layers, without any trace of erosion. This probably requires a near-zero velocity at the base of the flow but it is unclear why such a no-slip boundary condition would not promote deposition. Preservation of erodible surfaces is more easily understood if deposition at any places starts as soon as the flow head arrives.

Pyroclastic-flow deposits can exhibit a variety of basal layer facies. In particular, ignimbrites, thought to be the products of fluidised pyroclastic flows, often have coarse-depleted basal layers, whereas block-and-ash-flow deposits, probably emplaced by poorly fluidised flows, generally have not (Druitt, 1998). If basal layers form by progressive aggradation, this means that the head of some pyroclastic flows is not depleted in coarse, heavy particles. Indeed, coarse lithics are probably not able to sink in poorly fluidised pyroclastic flows and may in contrast migrate upwards by kinetic sieving. Whether lithics tend to be removed from the top of the flow by gravitational sinking or to concentrate there by kinetic sieving will depend on several factors, such as particle concentration and the efficiency of fluidisation. Both situations are likely to occur in the wide spectrum of pyroclastic flows, which would be reflected by the presence or absence of a coarse-depleted basal layer in the deposit.

Coarse-depleted layers sometimes occur against the subvertical margins of troughs filled by ignimbrites. Such subvertical 'basal' layers suggest that deposition from the coarse-depleted leading edge of the flow occurs by consolidation of the granular mixture due to gas expulsion all along the solid boundary, including the subvertical walls. The aggrading subvertical deposit is prevented from collapsing due to the presence of the flow, of similar density, passing in the trough.

The model of basal layer formation presented here may not apply to all inversely graded basal layers. Another possibility is that basal inverse grading simply reflects the progressive increase in competence of a waxing flow (Kneller and Branney, 1995). This requires a short waxing stage followed by a longer stationary or waning stage, a likely scenario for short-lived pyroclastic flows. However, in contrast with dilute-suspension currents, the competence of dense pyroclastic flows is likely to be related mainly to particle concentration and fluidisation rather than to flow rate. For debris flows, Vallance (2000) proposes that an increasing dilution by water toward the head of the flow may be responsible for a decreasing competence. This would create a lateral grading in the flow, which by progressive accretion, would give rise to an inversely graded deposit. Downstream dilution of debris flows by water is a well-documented process but a similar process is unlikely in pyroclastic flows where the interstitial fluid is gas. Thus, for pyroclastic flows, the model of gravitational sinking of heavy clasts from an initially homogeneous flow described in this paper is more realistic.

Finally, it should be stressed that this model is concerned with the formation of only the basal layer of pyroclastic-flow deposits. It does not imply that the whole deposit forms by progressive aggradation. In particular, it cannot be ruled out that the final, pumice-rich, more permeable top part of the deposit might form by en masse freezing.

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