Mount St. Helens 1980 and Mount Pelée 1902—Flow or surge?

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ABSTRACT

The far-reaching directed "blast" of Mount St. Helens and the devastating nuées ardentes of Mount Pelée produced deposits that in many places consist of three main layers: a basal gravelly or sandy layer 1, a massive or bedded ash layer 2, and a capping ash-cloud layer 3. These thin and in part landscape-mantling deposits are generally ascribed to pyroclastic surges, and the dune bedding seen in parts of layer 2 has reinforced this interpretation. There are several reasons, however, for preferring a pyroclastic-flow origin: (1) much of layer 2 is unequivocal pyroclastic flow; (2) the tripartite subdivision and landscape mantling habit is similar to that displayed by ignimbrites of the low-aspect-ratio type; (3) the deflation of a pyroclastic surge and the subsequent deposition of particulate material will tend not to conserve the fine ash and dust that are abundant in valley-ponded parts of layer 2 and cannot explain the observed tendency for layer 2 to show stronger fines depletion on ridges than in valley bottoms; and (4) the coarseness and the variance of grain size found within dune-bedded bed sets in Mount St. Helens layer 2 are like those of very weak pyroclastic surges, and the dune bedding most likely resulted from local minor turbulence (as could have been caused by surface roughness in a mountainous terrain littered with tree stumps and fallen trees) in a thin depositing pyroclastic flow. The directed blast and nuées ardentes at Mount St. Helens and Mount Pelée are interpreted to have been violently emplaced pyroclastic flows producing deposits of low-aspect-ratio type, the characteristics of which stem from an exceptionally high flow velocity.

INTRODUCTION

Among the most devastating volcanic events of the present century were the "directed blast" that leveled 600 km^2 of forest around Mount St. Helens on May 18, 1980, and the "nuées ardentes" of Mount Pelée that destroyed St. Pierre on May 8, 1902. There are close similarities between the two, except that one was incandescent and the other was cooler (though sufficiently hot to burn people and cause local charring of trees). Much has been published about each eruption, but we are uncertain about the exact nature of the destructive phenomena. Because of the suddenness and destructiveness of the phenomena, interpretations of them have been based partly on eyewitness accounts and analysis of damage done but mostly on subsequent studies of the pyroclastic deposits. Both are generally interpreted to have been pyroclastic surges (e.g., Fisher et al., 1980; Moore and Sisson, 1981; Fisher and Heiken, 1982), but here we present the alternative interpretation that both deposits were emplaced as pyroclastic flows.

We do not claim to present a definitive account of either eruption; our objective is to present an alternative viewpoint and to indicate some criteria that we think are important when deducing the nature of directed blasts and nuées ardentes from features shown by their deposits.

A pyroclastic surge is a highly expanded particulate system in which the continuous phase (gas) greatly predominates in volume. Particles are supported in suspension by turbulence; the highest particle concentrations occur near the ground surface where a bed load moves laterally by traction or saltation; only the finer fractions remain suspended in the inflated overriding cloud. Grain-size sorting thus occurs in the resultant deposits. In contrast, a pyroclastic flow is a highly concentrated particulate system that, when in motion, has a volume little greater than when it is at rest, and the particles are supported by fluidization and grain interactions. There are differences of opinion on whether all gradations occur between pyroclastic surges and flows or whether, as we suspect, a broad gap exists between them.

MOUNT ST. HELENS

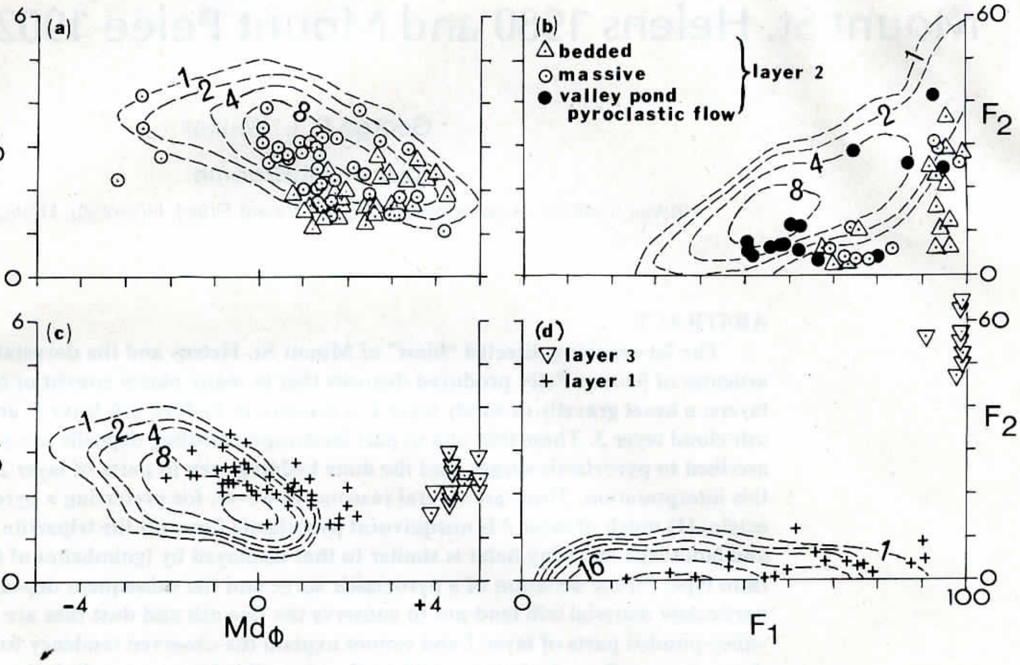
A well-defined tripartite subdivision of the Mount St. Helens "blast" deposit is found over much of its extent, and it is convenient to follow Waitt (1981) in designating these as layers 1, 2, and 3 in sequence upward. In the following, this layering is correlated with the tripartite subdivision of the "standard ignimbrite flow" of Sparks et al. (1973). The Mount St. Helens deposits are too poor in pumice to be termed ignimbrite, but we interpret them to have a pyroclastic flow origin, similar to a low-aspect-ratio ignimbrite.

Layer 1, the basal unit of Hoblitt et al. (1981) and Moore and Sisson (1981), is a relatively coarse and well-sorted gravelly or sandy layer that shows rapid and erratic lateral variations in thickness and grain size and gaps in its lateral continuity. The general outward decrease in its thickness and grain size have been well documented by Hoblitt et al. (1981) and Moore and Sisson (1981).

Layer 2 forms most of the thickness of the blast deposit and occurs as two distinct facies, one of which is massive and has the aspect of a pyroclastic flow deposit particularly where it occurs in valley ponds, and the other is stratified and shows dune bed forms. These two facies tend to be complementary.

Layer 3 is an extremely fine, mantling ash layer containing small accretionary lapilli and is accepted to be an ash-fall

Figure 1. Plot of grain-size data for May 18, 1980, Mount St. Helens "blast" deposit and valley-pond pyroclastic flows. (a) and (c): σ_ϕ (graphic standard deviation) vs. Md$_\phi$ (median diameter). (b) and (d): F2 (weight percent finer than 1/16 mm) vs. F1 (weight percent finer than 1 mm). Diagrams (a) and (b) show contoured fields for pyroclastic flow field (Walker, 1983); diagrams (c) and (d) show contoured fields for samples from fines-depleted facies of ignimbrite (Walker, 1983). Data points include those by Kuntz et al. (1981), Hoblitt et al. (1981), and Moore and Sisson (1981).



deposit resulting from the settling out of fines from an ash cloud after the passage or decay of the "blast."

SAMPLES AND THEIR INTERPRETATION

In 1981 and 1982 we collected and sieved 70 samples from layers 1 and 2 of the blast deposit of Mount St. Helens; data from these samples together with published analyses (Hoblitt et al., 1981; Kuntz et al., 1981) are plotted in Figs. 1, 2, and 3. We also collected suites of samples from individual beds in four dune-like bed sets of the stratified facies of layer 2 to study the variance within each bed set.

Many samples from the massive layer 2 lie within the field of pyroclastic flows on an Md$_\phi$/σ_ϕ diagram (Fig. 1a). This observation, combined with the homogeneity of the deposit, the valley-pond situations of many occurrences, and the common presence of gas-elutriation pipes where the deposit is thick, leave little doubt that these samples are from pyroclastic-flow deposits. Some of the samples lie well below the axis of the pyroclastic-flow field (Fig. 1a), however, which indicates that although the material may have a pyroclastic flow origin, more size sorting has occurred than in the average pyroclastic flow. On the fines-depletion plot (Fig. 1b), likewise, some samples plot well below the pyroclastic flow field, which indicates that a depletion in fines has occurred. Samples from the stratified facies of layer 2 on the Md$_\phi$/σ_ϕ plot (Fig. 1a) lie mostly within the pyroclastic flow field, though they plot below the axis of this field, indicating again that more size sorting has occurred than in the average pyroclastic flow. On the fines-depletion diagram (Fig. 1b), almost all plot well below the pyroclastic-flow field, indicating that significant loss of fines has occurred.

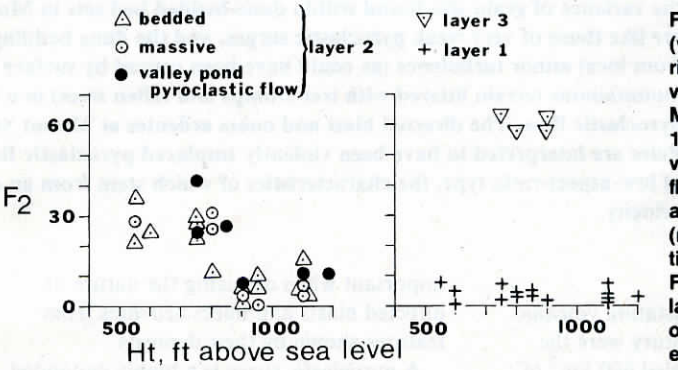


Figure 2. Plot of F2 (weight percent of material finer than 1/16 mm) vs. topographic height for Mount St. Helens May 18, 1980, layer 2 deposits and valley-pond pyroclastic flows (left), and layer 3 and layer 1 deposits (right). Note strong negative correlation between F2 and height shown by layer 2 deposits, and lack of any correlation in layers 1 and 3 deposits.

Samples that were collected from layer 2 show a strong inverse correlation between fines content and their topographic elevation (Fig. 2). Samples from lower hillslopes and valley-bottom pyroclastic flows generally have >20% of material finer than 1/16 mm, contrasting with the <10% in samples from ridge crests and upper hillslopes. This relationship is the converse of what would be anticipated if layer 3 had been formed by the deflation of a highly expanded pyroclastic surge, but it is consistent with a pyroclastic-flow model; i.e., the loss of fines is greatest where the flow is thinnest and where the surface of the land is roughest. It is apparent that parts of the flow which crossed the main ridges would have been thinner than parts that traveled in and were partly funneled by valleys. If the quantity of air ingested at a given flow velocity was constant, the quantity per unit volume ingested by the thin flow would have been greater than that taken in by the thick flow. Also, parts of the flow which crossed the ridges would have encountered on the whole the roughest topography, and ingestion of air would have been enhanced by the surface roughness. For both of these reasons, the quantity of air ingested and the amount of fines lost per unit flow-volume would have been greatest in the parts of the flow which surmounted the ridges.

In the bedded layer 2 deposit the variance in Md found among beds in the same bed set is 2.5 ϕ or less, which contrasts with the 3.0 to 5.6 typically shown by dry pyroclastic-surge bed sets (Walker, 1983). The coarsest Md$_\phi$ observed, -0.5, contrasts with the -0.5 to -3.3 of normal dry-surge deposits. These values show that if the bedded Mount St. Helens layer 2 deposits

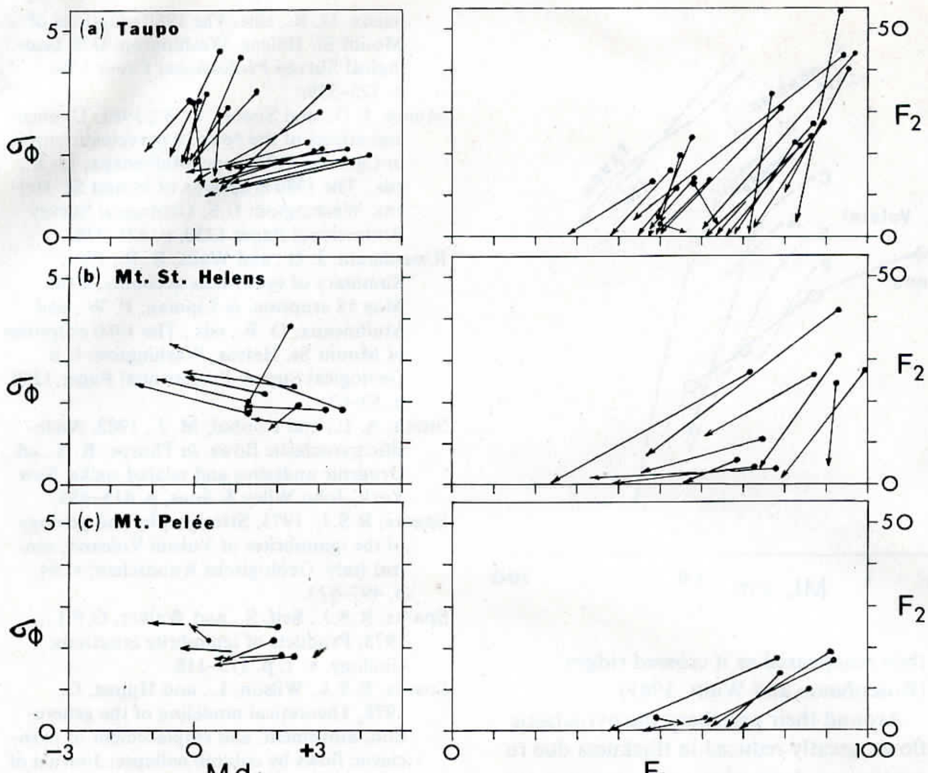


Figure 3. Left: plots of σ_ϕ (graphic standard deviation) vs. Md_ϕ (median grain size). Right: plots of F2 (weight percent finer than 1/16 mm) versus F1 (weight percent finer than 1 mm) for (a) Taupo ignimbrite, (b) Mount St. Helens May 18, 1980, "blast" deposit and valley-pond pyroclastic flows, and (c) Mount Pelée 1902 nuée ardente deposits. In each, dot relates to layer 2 sample, and head of arrow joined to dot indicates underlying layer 1 sample. Note general similarity in trends, although Mount St. Helens and Mount Pelée layer 2 deposits are significantly fines depleted compared with Taupo, which changes slope of tie lines in diagrams on left.

have a pyroclastic-surge origin, the surge was relatively weak. It is known, however, that the May 18 "blast" was exceptionally violent; the bedding in layer 2 must therefore have been generated by a weak secondary effect and not by the primary "blast." The best explanation seems to be that the bedding was generated by local turbulence within layer 2 of a thin depositing pyroclastic flow.

Layer 1 samples that we have analyzed are coarser and show stronger fines depletion than the associated layer 2 deposit (Fig. 3), and in both respects they resemble samples from the ground layer of ignimbrites. The grain-size features are consistent with the interpretation that layer 1 was generated by sedimentation of heavy particles, and the concomitant loss of fine material, in the fluidized head of a pyroclastic flow. At Mount St. Helens, pumice is subordinate in amount, and the density contrast between pumice and lithics is small; thus, segregation between layers 1 and 2 is negligible.

MOUNT PELÉE

Consider now the products of the 1902 eruption of Mount Pelée. Massive and extremely coarse pyroclastic-flow deposits ("block and ash flows") occupy the valley of the Rivière Blanche, and their pyroclastic-flow origin is not in doubt (Smith and Roobol, 1982; Fisher and Heiken, 1982). The origin of thin layers that mantle the topography over a wide area on either side of the Rivière Blanche and embrace the town of St. Pierre is, however, controversial. A tripartite division is seen, as was recognized by Fisher et al. (1980), and includes a gravelly or sandy layer 1 basal unit, a stratified or more or less massive middle unit layer 2, and a local capping fine ash layer 3 containing accretionary lapilli. At the northwest edge of St. Pierre two tripartite units are seen, related to nuées ardentes of May 8 and May 20, 1902. The top of the lower one has been baked to a pink color by the upper one. Grain-size characteristics are very similar to Mount St. Helens (Fig. 3), and a similar interpretation is offered. This interpretation differs from that proposed by Fisher et al. (1980) and Fisher and Heiken (1982), in which layer 1 is regarded as a pyroclastic-surge deposit.

A feature of Mount Pelée is the prevalence of similar-looking deposits among the earlier products of the volcano. They are found at several different stratigraphic levels and are best developed around the northeast and southeast sides of the volcano. Commonly, layer 1 is 50 cm or more thick and is full of carbonized vegetation, and layer 2 is commonly 1 m or more thick. In general, the thicker that layer 2 is, the more it comes to look like a pyroclastic flow. These deposits show that blasts, like those of 1902, are a normal and common accompaniment of volcanic activity on Mount Pelée.

DISCUSSION

Interpretation of deposits such as these described depends on four concepts: (1) The ability of fast-moving pyroclastic flows to surmount topographic obstacles and to deposit a veneer draping the landscape (Walker et al., 1981b). The thickness of veneer may bear little or no relationship to the depth of flow that deposited it. (2) The ability of some pyroclastic flows to generate a deposit (layer 1) that is strongly fines depleted. It is important to emphasize that layer 1 is the deposit from a pyroclastic flow and is very dissimilar in character from the main mass of the flow itself. (3) The requirement that a pyroclastic flow must have a high particle concentration in order to retain the gas and fine ash and dust needed to sustain fluidization. (4) The inability of a dry dilute pyroclastic surge to deflate (so as to generate either a deposit or a pyroclastic flow) without losing most of its fine ash and dust. Pyroclastic surges may readily be generated by the inflation of pyroclastic flows, but because of fines loss the reverse does not happen.

This last concept is important in view of the interpretation of isolated valley-pond pyroclastic-flow (layer 2) exposures on the far-from-vent side of mountain ridges, interpreted by Hoblitt et al. (1981) at Mount St. Helens to be secondary pyroclastic flows; Hoblitt et al. envisaged the material to have traveled out from the vent and crossed ridges in the form of an expanded pyroclastic surge, and then to have deflated. A similar interpretation was given by Fisher et al. (1980) for layer 1 at Mount Pelée.

Sparks et al. (1978) have summarized quantitative data showing how rapidly clasts drop out from an expanded mix.

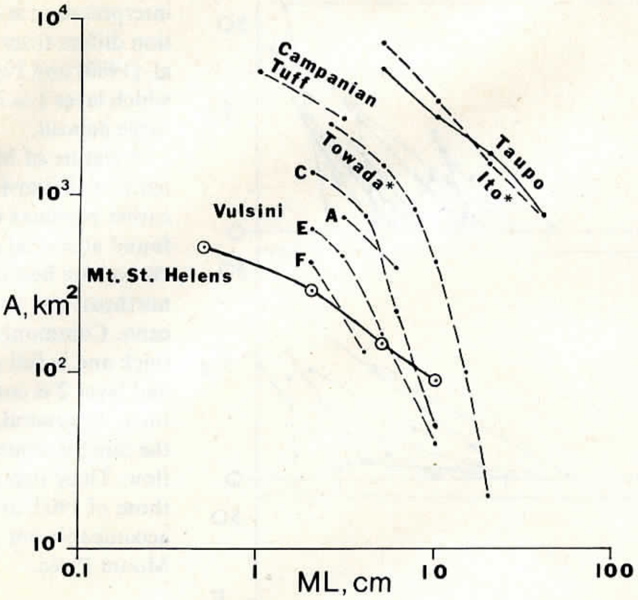


Figure 4. Plot of areas enclosed by isopleths of maximum lithic size for Mount St. Helens "blast" deposit (after Moore and Sisson, 1981) compared with various ignimbrites (Ito—Yokoyama, 1974; Taupo—Walker et al., 1981a; Towada—Kuno et al., 1964; Campanian Tuff—Barberi et al., 1978; Vulsini A, C, E, and F—Sparks, 1975). Asterisk indicates data related to ground layer or other lithic concentration parts rather than main body of ignimbrite. Note similarity in slope between Mount St. Helens, Taupo, and Ito, suggestive of similar causative mechanism.

Heavy clasts settle out much more slowly from a concentrated pyroclastic flow. Figure 4 shows the area enclosed by isopleths of maximum lithic size in layer 1 of the Mount St. Helens deposit and in several ignimbrites. Comparable data are not yet available for unequivocal surge deposits, but the similarity of the Mount St. Helens plot with known pyroclastic-flow deposits suggests that the Mount St. Helens deposit has a pyroclastic-flow origin.

Characteristics of the deposits of the May 18, 1980, blast and the May 8 and 20, 1902, nuées ardentes are consistent with the interpretation that they are flow deposits of low-aspect-ratio type deposited from fast-moving pyroclastic flows. Reasons for arriving at this interpretation include the close similarity of the deposits to other described examples of the type, the presence locally of unequivocal pyroclastic flow deposits, and the fact that the dune-bedded deposits have features indicative of a weak pyroclastic surge. Additionally, it seems to us unlikely that a highly expanded pyroclastic-surge cloud could travel as far as 30 km outward from Mount St. Helens against air resistance (no example of unequivocal pyroclastic surge is known to have traveled much farther than about 5 km). A pyroclastic flow, with its much lower profile, will be affected much less by air resistance. Moreover, the coarsest clasts in the deposits seem too big to have been transported to where they are now in an expanded system.

Eyewitness reports of the initial phases of the eruption at Mount St. Helens indicate that the "blast" material traveled as a ground-hugging flow that disappeared from view as it plunged into valleys, and then reappeared as it crossed ridges (Rosenbaum and Waitt, 1981).

Around their periphery the pyroclastic flows, greatly reduced in thickness due to continuous deposition on the journey out from the vent, may have become pyroclastic surges; it is speculated that part or all of the seared zone, which varies from 0.5 to 5 km wide around the margin of the Mount St. Helens devastated area, is indeed the area embraced by this pyroclastic surge.

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