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CHARACTERISTICS OF DUNE-BEDDED PYROCLASTIC SURGE BEDSETS

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ABSTRACT

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The grainsize characteristics of dune-bedded pyroclastic surge bedsets are surveyed. The variance between coarsest and finest beds ranges from 1 to 6 phi in different surge bedsets, and it increases as the grainsize of the coarsest bed increases, reflecting an increasing velocity of emplacement. Deposits of wet surges, identified as those which contain accretionary and ash-coated lapilli, tend to be finer and show less variance, this partly because wet ash is cohesive, but mainly because wet surges tend to be weaker. Dry surge bedsets are strongly fines-depleted, wet ones less so. The lack of erosion of underlying ash layers shows that the environment is a strongly depositional one. Individual bedsets are demarcated by thin intervening fine ash-fall layers, which are the complementary ash-cloud deposits settled or flushed out after the passage and decay of each turbulent surge. Surge deposits are generally less coarse than the coarsest associated airfall deposits, which shows that they are formed by generally weaker events.

This study helps interpret the dune-bedded parts of the landscape-mantling May 18th 1980 "blast" deposit of Mount St. Helens. The blast was a very violent event, but the variance and the grainsize of the coarsest bed are those of a relatively weak surge. This suggests that the dune-bedding was produced by a weak effect, such as minor turbulence in a thin pyroclastic flow coming to rest in a mountainous terrain roughened by tree stumps and fallen logs.

INTRODUCTION

Base surges produce ring dunes, and deposits that are well stratified and commonly show wavy or dune-type bedding (Fisher and Waters, 1970; Waters and Fishers, 1971; Crowe and Fishers, 1973). Prior to 1965, dune-bedding in pyroclastic deposits was assumed to indicate reworking by running water or wind; the tendency since then has been to regard it as a primary volcanic structure diagnostic of a pyroclastic surge origin.

Recent studies have indicated that not all such primary dune-like bedforms are generated by the pyroclastic surge mechanism. Thus, coarse pumice lenses found among some pyroclastic flow deposits are thought to have formed where the fast-moving flow leaped over the ground on

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the lee-side of topographic elevations, or in standing waves where an exceptionally fast-moving flow travelled over flat ground (Walker et al., 1980 a,b; 1981; Fisher et al., 1980).

The present study characterises dune-bedded surge deposits to provide a basis to distinguish them from primary dune-like deposits having other origins. It surveys the grainsize distributions found in individual beds, and establishes the variance between different beds co-existing in the same bedset. By bedset is meant the assemblage of beds, and the dune structure to which they belong, which can be interpreted to be the product of a single surge.

Close examination of surge deposits reveals the common presence of beds of very fine airfall ash, typically a few centimetres thick and rich in accretionary lapilli, each one characteristically having a nearly uniform thickness when traced laterally. These ash-fall beds are interpreted to represent fine ash left suspended in the air after the passage and decay of the turbulent surge, and they provide a means of demarcating pyroclastic surge bedsets (Fig. 1). It is not unusual to find five or more bedsets in a dune-bedded surge accumulation, and they are normally interbedded with coarse airfall deposits as well as with the fine ash-fall layers referred to. Each surge bedset commonly fluctuates in thickness by a factor or two over a wavelength in the range 3 to 20 m.

Suites of 2 to 15 samples were collected from each of 52 bedsets from surge deposits of 15 volcanoes listed in Table I, each sample being from a single more or less homogeneous bed and each suite including if possible both the coarsest and finest beds or laminae present; laminae as thin as 5 mm were sampled, but in a few cases the finest proved to be too thin to collect. Only dune-bedded surge deposits were sampled, as it is often difficult to distinguish plane-bedded surge from fall and flow deposits.

About one quarter of the pyroclastic surge bedsets sampled contain accretionary or ash-coated lapilli, and these lapilli are regarded as indicating that the surge in question was sufficiently damp or wet to make the fine ash cohesive. Such surges are here termed "wet" surges, as opposed to the more normal "dry" surges which lack such lapilli. "Wet" and "dry" are not defined in any quantitative way, and the grainsize characteristics suggest that the amount of water varied continuously from the most wet to the most dry examples. The accretionary lapilli were undoubtedly size-sorted in some of the surges; it is not certain how they were generated in the surge.

The volcanoes sampled span a wide range of magmatic compositions from tholeiitic basalt (Kilauea), high-alumina basalt (Taal, Anak Krakatau, Tarawera), alkali basalt (Latera, Oahu), and trachyte/phonolite (Sacrafano, Procida, Vesuvius), to rhyolite (La Primavera, Haroharo). The volcanic eruptions spanned a wide range of styles, from phreatic (Tarawera) to pumice-generating magmatic (Haroharo, Procida), with a juvenile magmatic component varying from near 0% to near 100%, and the deposits include

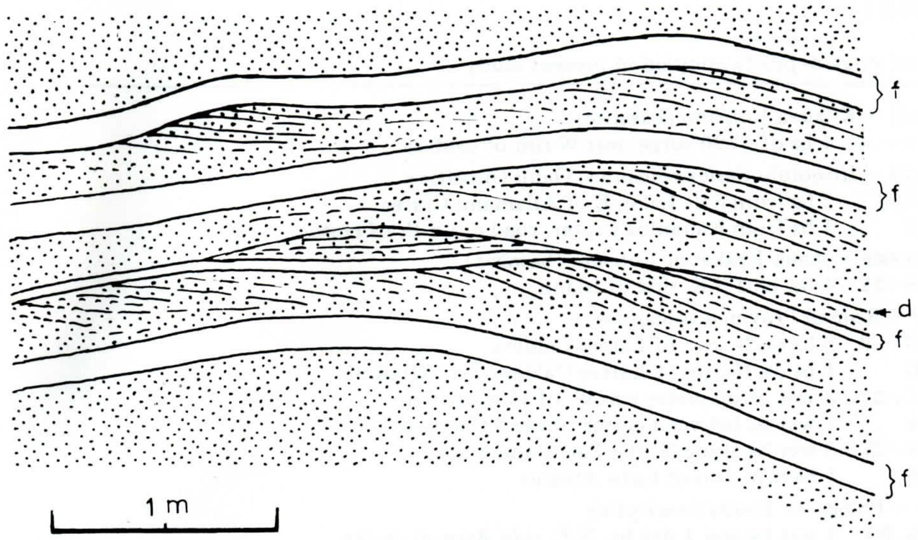

Fig. 1.a. Drawings of base surge bedsets (stippled) separated by fine ash-fall (*f*) layers containing accretionary lapilli, north rim of Latera Caldera, Vulsini volcano, Italy. The discordance (*d*) may also separate surge bedsets. Flow direction left to right.
b. Photograph of base surge bedsets separated by fine ash-fall layers (*f*) which have been chalked to make them visible, Salt Lake crater, Oahu. Scale given by 15 cm rule. Several planes of discordance (*d*) occur without ash-fall layers and probably also separate surge bedsets. Flow direction left to right.

TABLE I

List of surge deposits sampled in present study

Hawaii — Kilauea Volcano (basaltic)	
1— 4	4 bs of 1790 surge near W rim of caldera
Hawaii — Honolulu Series volcanics, Oahu (basaltic)	
5, 6	2 bs from Salt Lake, E of Aliamanu Crater
7	1 bs from Kahauloa Crater, road cut S.E. of crater
Indonesia — Anak Krakatau Volcano (basaltic)	
8—12	4 bs, cliff S.E. side of island
Italy — Roman Province volcanoes	
13—19	8 bs on N. rim of Latera Caldera
20	1 bs on N. rim of Latera Caldera S. of Gradoli
21—23	3 wet bs on crater rim W. of Campagnano
24	1 wet bs between crater rim and Campagnano
25—27	3 wet bs along N. rim Sacrafano crater
28	1 bs S.W. rim of Lake Albano
Italy — Phlegrean Fields (trachytic)	
29, 30	1 wet bs and 1 dry bs, N.E. side Astroni crater
31, 32	2 wet bs Monte di Procida
Italy — Vesuvius Volcano (phonolitic)	
33	1 bs intraplinian in Avellino pumice, Pollena
34, 35	2 bs of A.D.79, Pollena
36, 37	2 bs intraplinian in A.D. 79 pumice, Oplontis Villa
38	1 wet bs above A.D.79 pumice, Pompei
Mexico — La Primavera Volcano (rhyolitic)	
39—43	4 bs S. side of updomed caldera
44	1 bs intraplinian in pumice E, E. side caldera
45	1 bs at base of plinian pumice E, E. side caldera
New Zealand — Okataina Volcanic Centre	
46	1 bs rhyolitic pumice, W. side Haroharo
47	1 bs in Rotomahana mud (phreatic), 1886 Tarawera eruption
Philippines — Taal Volcano (basaltic)	
48—51	4 wet bs of 1965 eruption, W. side of crater
Victoria (Australia) — Purrumbete Volcano (basaltic)	
52	1 bs from climbing dune surge deposit.

bs = bedset.

small and probably originally hot intraplinian surges (La Primavera, Vesuvius).

GRAINSIZE CHARACTERISTICS OF INDIVIDUAL BEDS

Samples were sieved using a set of sieves having a one-phi spacing. Typical cumulative curves are shown in Fig. 2. For some samples, the cumulative curve is very nearly a straight line on a logarithmic probability plot, indicating that the grainsize distribution is nearly lognormal. For many

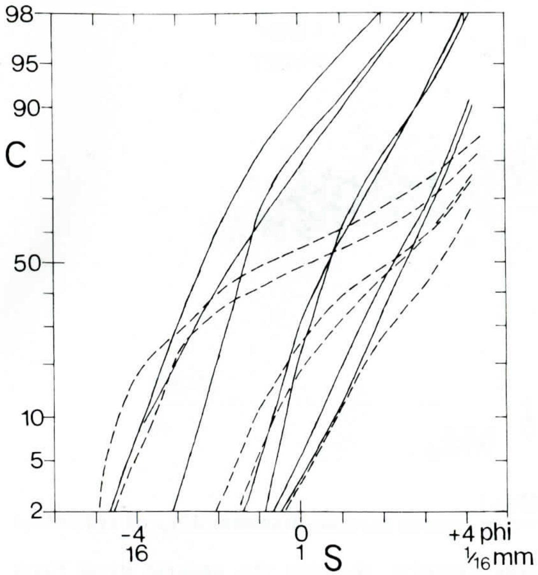

Fig. 2. Cumulative curves of co-existing beds from a typical dry pyroclastic surge bedset (no. 2, Table I) showing cumulative weight % (C) coarser than sieve aperture size (S). The curves are positively skewed or closely approximating lognormal distributions. Dashed lines = co-existing beds from a wet surge bedset (no. 31, Table I), showing strong positive skewness.

samples the plot is positively skewed (Fig. 3). In some this may be attributed to the cohesive nature of damp ash which added a "tail" of fairly fine material. The strong positive skewness of the coarser samples changes to a zero or small negative skewness of the finer samples (Fig. 3). The negative skewness could be due to a depletion in the finest ash fractions. A few of the wet surge samples have a weakly bimodal grainsize distribution, with a lesser mode of finer ash which is thought to have accreted because of its cohesion.

Plots of σ_ϕ against Md_ϕ (Fig. 4), and of the weight percentage finer than $\frac{1}{16}$ mm against that finer than 1 mm (Fig. 5) have been contoured following Walker (1971). Individual beds vary in Md_ϕ from -3 to +4 phi, a range of 7 phi (Fig. 4). The sorting, σ_ϕ varies from 1 to 3.5 and tends to be highest for beds in wet surge deposits; the explanation seems to be that fine material, because of its cohesion when damp, accumulated together with the coarser to extend the range of grainsizes present.

Figure 5 shows that the content of fine ash and dust (material finer than $\frac{1}{16}$ mm) varies from less than 1 to 48 wt.%, tending to be highest in the wet surge deposits, but in most samples it is low and the median value is about 8%. Compared with pyroclastic flow deposits, practically all samples are significantly or strongly fines-depleted.

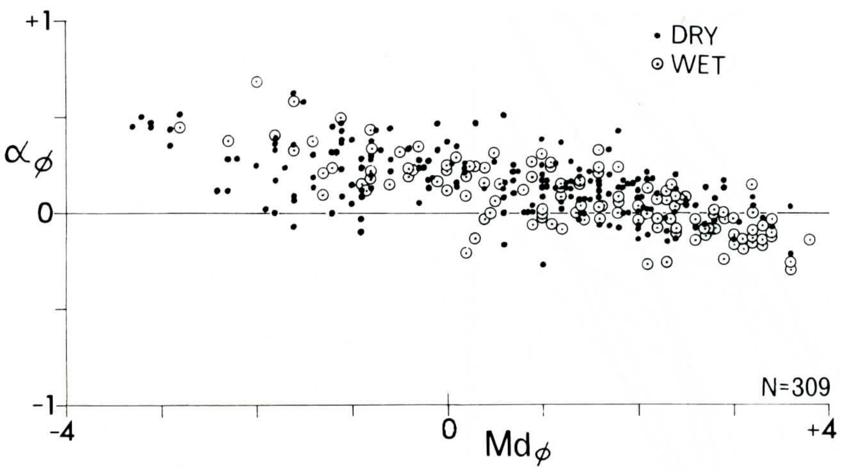

Fig. 3. Skewness $\alpha_\phi = \frac{[\frac{1}{2}(\phi_{84} + \phi_{16}) - Md_\phi]}{\sigma_\phi}$ versus median diameter Md_ϕ of individual beds from the studied dune-bedded surge deposits, showing the general trend from positive skewness in coarser samples to zero or a weak negative skewness in the finer samples.

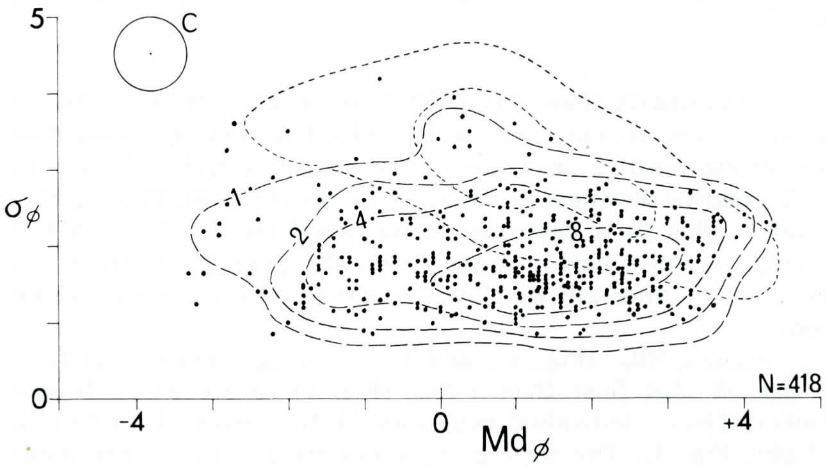

Fig. 4. σ_ϕ/Md_ϕ of individual beds from studied dune-bedded surge deposits, including data from Bond and Sparks (1976), Crowe and Fisher (1973), Fisher and Waters (1970), Sheridan (1971), Sheridan and Updike (1975), Sparks et al, (1981), Waters and Fisher (1971) and Yokoyama and Tokunaga (1978). N = number of analyses. The field is contoured (dashed lines); contours give the percentage of N lying within a circle of size C centred at any point. All but 3% of the samples lie within the 1% contour. 2% and 8% contours for the pyroclastic flow field (dotted lines) are included for comparison; these contours are based on 932 samples and are an update from Walker (1971).

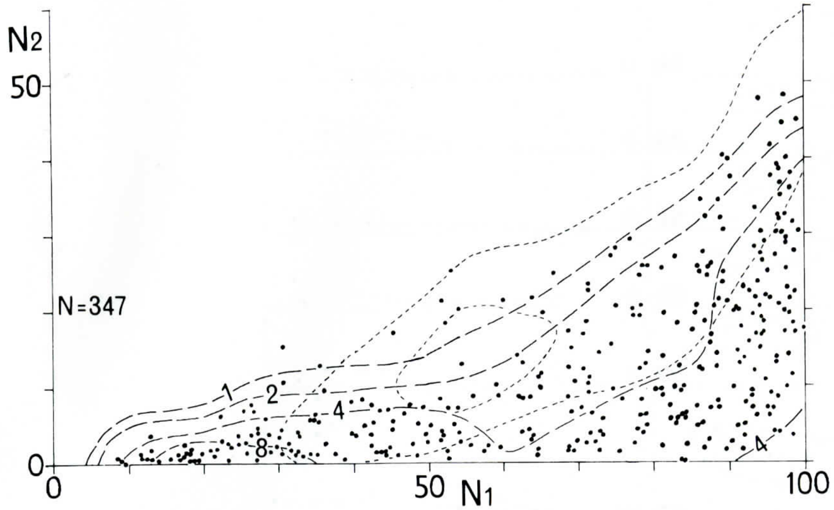

Fig. 5. Fines-depletion plot of individual beds from studied dune-bedded deposits together with data from the literature (caption to Fig. 4), showing N_2 (wt.% finer than 1/16 mm) against N_1 (wt.% finer than 1 mm). The field is contoured (dashed lines) as Fig. 4. 2% and 8% contours for the pyroclastic flow field (dotted lines) are included for comparison.

GRAINSIZE CHARACTERISTICS OF BEDSETS

The individual beds of each bedset typically plot in a narrow band on a σ_ϕ/Md_ϕ diagram, Fig. 6 and 7b, and vary little in σ_ϕ but show a considerable range of Md_ϕ values. The range of Md_ϕ values is here termed the "variance", and ranges in different bedsets from 1 to 6 phi. A direct relationship exists between the variance and the grainsize of the coarsest bed, Fig. 7a. The interpretation is that an increasing variance and an increasing coarsest grainsize are correlated with an increasing velocity of emplacement. This is consistent with the finding by Yokoyama and Tokunaga (1978) that increasing grainsize is correlated with increasing wavelength of the ring dunes, and by Moore (1967) at Taal that the wavelength increased towards the vent as the surge velocity increased.

Deposits of wet base surges tend to plot near the "weak" end of the band on Fig. 7; this is partly because the retention of fine material by its coherence reduces Md of the coarsest beds and hence also reduces the variance, but it cannot be fully accounted for by this effect and must be partly due to a general tendency for wet surges to be weaker than dry surges.

Channel samples were collected from some bedsets, and samples from others were averaged, Fig. 8 to estimate the overall grainsize composition of bedsets (but it is emphasised that the grainsize population of an entire surge deposit has never rigorously been determined, nor has any estimate

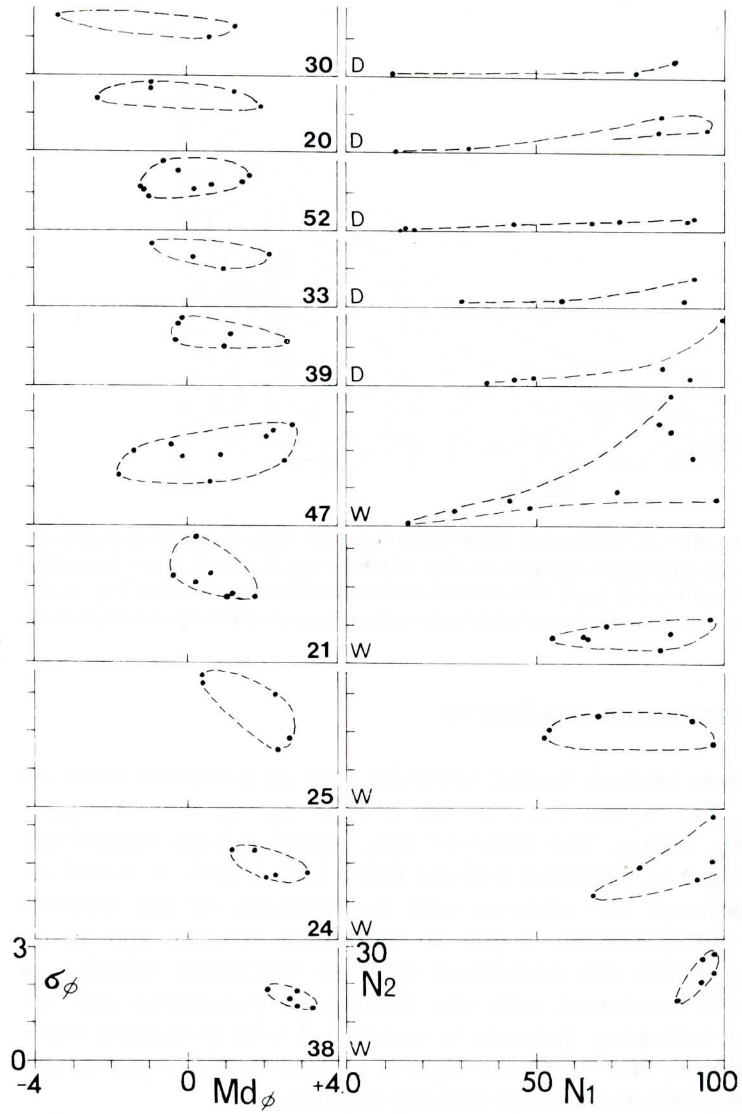

Fig. 6. Plots of representative surge bedsets to illustrate the variance between co-existing beds, left, on a σ_ϕ/Md_ϕ plot and, right, on a fines depletion plot (N_1 = wt.% finer than 1 mm; N_2 = wt.% finer than 1/16 mm). Numbers identify the bedsets as listed on Table I. D = dry, W = wet, as defined in the text.

yet been made of the whole assemblage of particles, including lost dust, participating in one pyroclastic surge).

Eruptions in which surges develop are characterised by a high degree of fragmentation of the ejecta. Figure 8 plots whole-deposit grainsize populations (A,B) for two strongly fragmented phreatomagmatic ash deposits

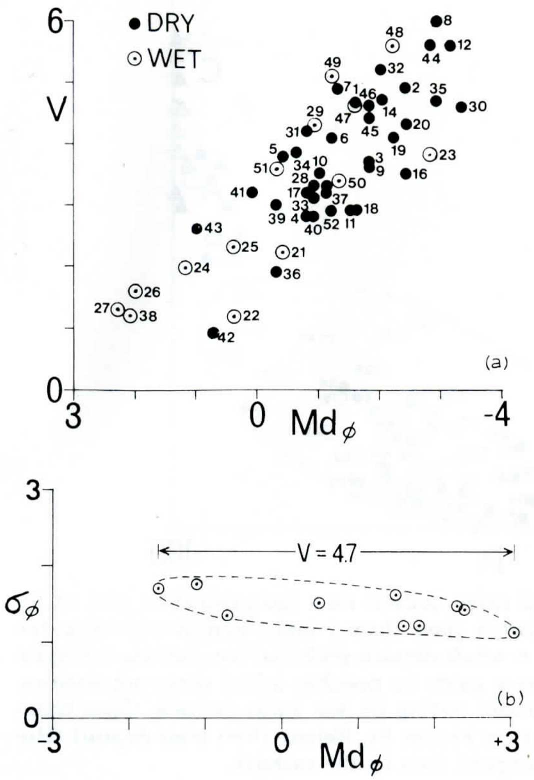

Fig. 7.a. The 52 studied surge bedsets showing relationship between *V*, the variance, and Md_ϕ of the coarsest bed. The trend towards the top right corner is interpreted to mark increasing velocity of emplacement. Numbers identify the bedsets as listed on Table I.
b. A σ_ϕ/Md_ϕ plot of the ten analysed samples from bedset no. 1 (Table I) showing the variance *V*.

(Walker, 1981a), and (C) the May 18th 1980 airfall ash of Mount St. Helens (Carey and Sigurdsson, 1982). Also plotted is the average grainsize (D) of two typical ignimbrites (from Rabaul, Walker, 1981b), and an estimated initial grainsize population (E) of the erupted mix from which the Taupo ignimbrite formed (Walker and Wilson, 1982).

These various ash-fall and ignimbrite grainsize populations are assumed to be typical of the kinds of populations that participate in pyroclastic surges. Comparison of these with the average surge deposit bedsets, in which 1 to 44 wt.% are finer than $\frac{1}{16}$ mm (the median values are 6.5% for dry and 19% for wet surges), suggests that the surge deposits have suffered strong fines depletion. The amount of depletion is less for the wet surge deposits but is appreciable even for them.

The fine ash-fall deposit immediately overlying each surge bedset is considered to contain some at least of this fine material. Analyses have

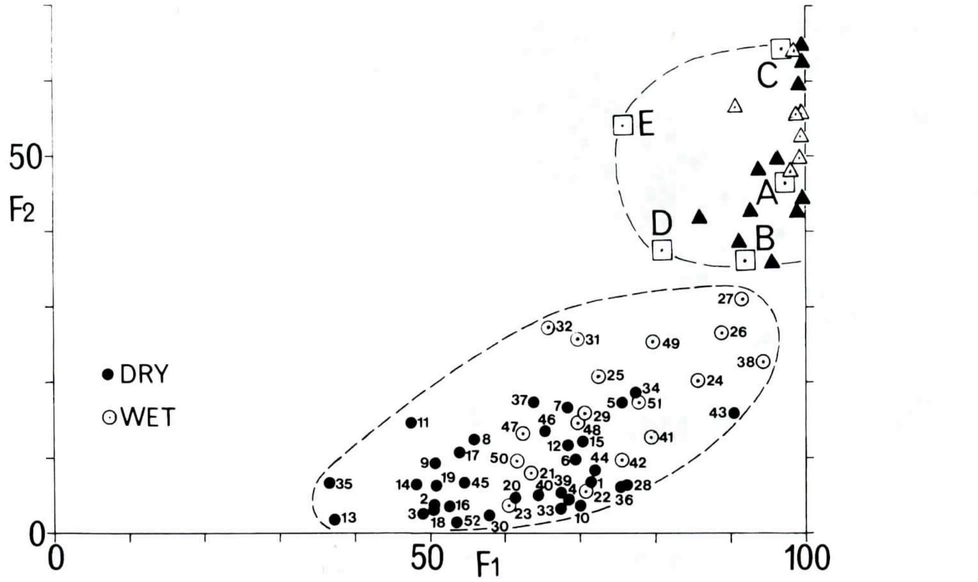

Fig. 8. Average grainsize of dune-bedded surge bedsets on a fines depletion plot of F_2 (wt.% finer than 1/16 mm) against F_1 (wt.% finer than 1 mm); numbers identify the bedsets listed in Table I. Open squares = whole-deposit grainsize populations for pyroclastic deposits (identified in the text) as a guide to possible initial surge populations. Filled triangles = fine ash-cloud fall deposits resting on the surge bedsets. Open triangles = fine ash-cloud fall deposits resting on Mount St. Helens 1980 blast deposit (Hoblitt et al., 1981; Kuntz et al., 1981; and unpubl. data by the author).

been made of the ash-cloud deposits from the 1790 eruption of Kilauea, the 1965 eruption of Taal, Salt Lake and Kahauloa on Oahu, and one of the La Primavera occurrences, and reveal that they are extremely fine grained, 35 to 65 wt.% being finer than $\frac{1}{16}$ mm. This gives general support to the complementary nature of their origin. The ash-fall is invariably thinner than the associated surge deposit, but it may be much more widely dispersed and hence does not necessarily contain a lesser volume of material; the extent of fines depletion indicated by Fig. 8 implies that it must in fact contain a substantial proportion of the total volume.

CONTINUITY OF ASH-CLOUD BEDS, AND EROSION BY SURGES

One unexpected observation is the continuity of the fine ash-fall layers between surge bedsets, even where the ash bed is only 1 cm thick. In places where there are short interruptions in continuity there is generally no evidence for any significant removal of material from below the ash-fall layer. Also, although cross-bedding does locally occur within the dunes, there is a general scarcity of abrupt bed truncations over the dune crests, and on close examination continuity of attenuated beds is generally seen.

These observations indicate that the environment in which dune-bedded surge deposits form is a strongly depositional one: the surges were heavily laden, and as they slowed down they rapidly shed their load. In all examples observed the dunes are of the prograded type. Excessive deposition without erosion has resulted in the formation of climbing dunes in some examples (Fig. 9).

Fig. 9. Climbing dune base surge deposits in Purrumbete ash-ring, Victoria, Australia; the climbing dunes are interpreted to have formed in an environment that was dominated by the deposition of material. Photograph reversed to give a flow direction left to right. White bar is 1 m long.

In some places it is possible to relate this depositional environment to the local topography. Thus the western side of Koko Head cone on Oahu (Hawaii) stands at the angle of repose of loose pyroclasts, and the deposits there are plane-bedded and lack dune structures. At the foot of the cone, however, where the slope decreases rapidly from 30° to about 10°, spectacular dune-bedded deposits having a regular wavelength of about 6 m are developed. The interpretation is that pyroclastic surges travelled at a high velocity down the steep cone slope, and deceleration accompanied by rapid deposition of the heavy load of pyroclastic material resulted as soon as gentler slopes were reached.

Intraformational erosion gullies are commonly developed among pyroclastic deposits of the types which include pyroclastic surge bedforms.

Such erosional features as gullies and chute-and-pool structures have been interpreted to have been eroded by base surges (Richards, 1959; Schmincke et al., 1973), or alternatively to be water-cut gullies modified in form by base surges (Fisher, 1977). Intraformational channels of similar form are, however, common also in phreatomagmatic ash deposits which lack base surge structures, and these must have been cut by water. Water-cut channels in ashes may result from high-intensity rain-showers; alternatively they may be eroded by water erupted from the volcano, as is deduced to have happened at Taupo (Walker, 1981a) and is known to have happened at Rabaul in 1937 (Stehn and Woolnough, 1937).

The coarsest airfall beds are often appreciably coarser than the coarsest associated surge bed at the same distance from the vent. Thus the 1790 base surges exposed near the western rim of Kilauea caldera contain few clasts exceeding 5 cm in size, yet 50 cm lithic blocks are common in an associated fall deposit dating from the same eruption.

Coarse airfall ejecta are dispersed over a distance determined by their initial velocity and ejection angle from the vent, and smaller non-ballistic ones by the column height and wind velocity. The more violent or powerful a volcanic eruption and the stronger the wind, the farther away from vent that pyroclasts of any given size and density travel. Ejecta in surges are subjected to similar dispersal mechanisms; although they do not enter the convective plume and hence are not carried so high or exposed for so long to dispersal by wind, they are carried laterally supported by turbulence in a density flow. Despite the advantage of this additional transport mechanism, ejecta of a given size in surge deposits extend less far than in the airfall deposit, and this suggests that the base surges resulted from explosions that were generally weaker than those which generated the coarsest airfall beds.

APPLICATION TO MOUNT ST. HELENS

The dune-bedded parts of the landscape-mantling May 18th 1980, "directed blast" deposit of Mount St. Helens are now considered. Most of the deposit is divisible into three layers: a basal gravelly or sandy layer (Layer A1, of Waitt, 1981), a generally finer and thicker layer (Layer A2 of Waitt) in the middle, and a fine capping ash-cloud deposit (Layer A3 of Waitt). The "blast" has been interpreted as a pyroclastic surge (Moore and Sisson, 1981; Hoblitt et al., 1981), partly because of the occurrence of dune-bedding in parts of layer 2. (Note that unequivocal base surge deposits occur around certain phreatomagmatic rootless explosion craters, but are very local in distribution and are not considered here).

Sample suites were collected from four dune-bedded bedsets, Fig. 10a, and were processed in the same way as the normal pyroclastic surge bedsets described in this paper. These bedsets have the variance and maximum grainsize of a relatively weak surge, yet the May 18th 1980 blast was manifestly a very violent event. This suggests that the dune-bedding was generated by a weak secondary effect such as minor turbulence induced in a thin pyroclastic flow that was coming to rest in a mountainous terrain roughened by tree stumps and fallen logs.

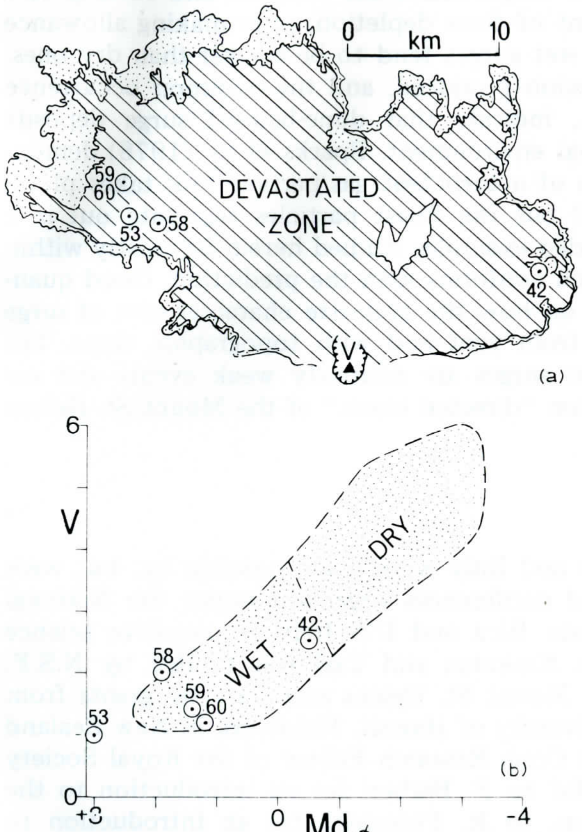

Fig. 10. Plot of Mount St. Helens dune-bedded layer 2 bedsets. a. Map showing location of studied bedsets. b. Variance *V* versus *Md* of coarsest bed on the dune-bedded surge field of Fig. 7. V = vent.

CONCLUSIONS

The basic unit in a dune-bedded pyroclastic surge accumulation is the bedset, interpreted to be deposited from a single surge event. The internal stratification is laterally discontinuous, and is marked by significant variations in grainsize but generally only small variations in sorting. Deposition was from a highly turbulent gas/particle system, and the grainsize variance between associated beds is best attributed to rapid time fluctuations in velocity.

When comparing bedsets, the variance between co-existing beds and the extent of fines depletion as well as the grainsize and dune wavelength all increase with increasing surge velocity. These relationships provide a qualitative means of assessing the violence. A complicating factor is that the cohesion of damp ash in wet surges alters the variance and sorting, and significantly reduces the extent of fines depletion; after making allowance for this effect, it seems that wet surges tend to be weaker than dry ones.

The limited amount of erosion produced, and the common occurrence of climbing dune structures, indicate that dune-bedded surge deposits form in a strongly depositional environment. Sparks et al. (1978) demonstrated how rapidly deflation of a turbulent gas/particle mix takes place, and predicted that almost all but the finest particles segregate out in a few kilometres. The dune-bedded examples studied herein lie mostly within 3 km of the vent centre, which conforms with the prediction. Good quantitative data are now needed on how the grainsize characteristics of surge deposits vary with distance from vent and with topographic slope, but the overall impression is that surges are relatively weak events and are on a totally different scale from "directed blasts" of the Mount St. Helens type.

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