Discrimination of grain-size subpopulations in pyroclastic deposits

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ABSTRACT

A cubic spline curve fit to histograms of grain-size data from pyroclastic deposits affords a rapid means to distinguish subpopulations in complex size distributions. Using interactive microcomputer graphics, the operator can isolate and quantitatively characterize subpopulations by a method of successive Gaussian subtractions. Percentile measures of the entire size range are not needed, and segments of the whole size distribution can be analyzed independently. Recurrent subpopulations with similar means and standard deviations are consistent among the more than 140 samples of pyroclastic-surge deposits from Sugarloaf in Arizona and Vulcano in Italy. The entire data set can be replicated by synthetic curves consisting of various proportions of five identified Gaussian components, each of which we attribute to a specific mechanism of transport and deposition.

INTRODUCTION

A common method currently used to characterize grain-size distributions of clastic materials is based upon the assumption that following a transformation to the log of the base 2 (Wentworth, 1922) the entire sample has an approximately Gaussian distribution (Krumbein, 1938; Inman, 1952). Percentile measures based on the entire population are commonly used to calculate parameters for mean, standard deviation, skewness, and kurtosis (Folk and Ward, 1957).

Researchers in volcanology generally use the graphical mean and standard deviation of the entire size distribution to represent the sample. A common technique is to plot the median size as a function of the standard deviation on a scatter diagram to determine clustering of samples and possible genesis. Plinian-fall and pyroclastic-flow samples may be distinguished by this technique by using the boundaries determined by Walker (1971).

Sheridan (1971) pointed out that the assumption of a single Gaussian distribution does not adequately describe most samples of pyroclastic materials. Some samples may be polymodal due to the overlap of complex processes that selectively remove or concentrate specific size fractions during eruption and transport. Other samples may inadequately represent the deposit from which they were taken due to problems of sampling or methods of analysis. This inadequacy is especially true for coarse deposits that contain a large fraction greater than 16 mm, as well as for fine deposits that contain a large fraction smaller than 62 μm.

Representation of samples by a single Gaussian distribution is wrong where they are polymodal (see Folk, 1966). Quantitative information on the mean, standard deviation, and abundance of the subpopulations is critical in the interpretation of the origin of many deposits. Tennant and White (1959) introduced a graphical method to identify subpopulations in chemical data by using log probability paper. This method has proved to be effective for grain-size analysis of sediments (Visher, 1969) as well as for interpretation of geochemical data (Sinclair, 1974).

Several authors have recently used subpopulations of size-frequency data of tephra identified in histograms as a significant part of their main argument (Carey and Sigurdsson, 1982; Rose et al., 1983; Cornell et al., 1983). Others have treated the problem of non-Gaussian size distributions by devising a few arbitrary divisions useful for their analysis. For example, Sheridan and Updike (1975) made divisions at 2 mm and 62 μm to distinguish bed types in surge deposits. Walker et al. (1980) divided the total distribution at 1 mm and 62 μm to characterize the depletion of the fine tail from pyroclastic flow deposits. Rowley et al. (1985) used 4 mm and 250 μm to construct triangular plots for differentiating pyroclastic flow from pyroclastic surge deposits. Although such arbitrary divisions have proved to be useful in specific cases, they are not based on the actual size distributions of specific samples. Indeed, the dividing points used by the above authors may actually fall at the maxima or shoulder of sample modes rather than at the dividing points between subpopulations.

We have developed a new technique for analysis of multiple subpopulations in grain-size data that is quick and quantitative. This method consists of three programs that utilize operator-interactive analysis of the data sets using microcomputer graphics. Techniques incorporated in these programs allow the quantitative determination of location, shape, and relative abundances of several subpopulations within a complex sample. Analysis of a sample that consists of a single Gaussian population is possible, but the method is best suited for deconvolution of polymodal samples.

METHOD

The method used in this study consists of (1) fitting a spline curve to grain-size frequency data, (2) determining approximate mean, standard deviation, and fraction for synthetic Gaussians to characterize each subpopulation, and (3) visually refining the Gaussians to create a synthetic composite curve for a best fit to the original size spline curve. This spline curve is a continuous line that passes through all the data points. Interpreted values are calculated by a cubic equation that connects all segments into a smooth curve.

The routine consists of three computer programs. The first program (SIZDAT) creates size-data files for full-phi or half-phi data in the range of

−5 to 10 phi. Size-data files can be read from a disk, corrected, stored, or printed.

The second program (SIZAN) is for the analysis of data stored on disk as size-data files or size-spline files. It performs the following tasks: (1) reads size-data files, (2) displays or prints histograms of size data, (3) makes spline interpolations of the size data, (4) saves or reads spline-data sets, (5) displays or prints graphs of spline-size vs. phi-size data, (6) divides spline curves into subpopulations, and (7) determines the phi values of maxima and minima on the spline curves. This program is useful for determining approximate values for the mean, standard deviation, and fraction of the various subpopulations.

The third program (GAUSS) determines more precise values for the subpopulations by using successive Gaussian subtractions. It performs the following functions: (1) reads size-spline files, (2) creates synthetic Gaussian curves to approximate subpopulations, (3) forms composite curves by the addition of individual Gaussians, (4) subtracts individual or composite Gaussian curves from the original size spline curve, (5) saves subtraction (residua) or addition (composite) curves to disk, (6) displays or prints various combinations of synthetic curves and/or the original size spline curve, (7) obtains a goodness of fit or the synthetic curve to the size data, and (8) displays or prints the statistics for the various synthetic Gaussian curves.

A typical graphical analysis is illustrated in Figure 1. The sample data are from large longitudinal dunes of a May 18, 1980, proximal bedded deposit of Mount St. Helens (Rowley et al., 1985). Three modes are easily identified and quantitatively characterized by Gaussians G1, G3, and G4. A fourth mode (G2) is hidden in the saddle between two peaks and would be missed by simple inspection. The area under the residual resulting from subtraction of the synthetic composite curve from the sample spline equals 6% of the area under the sample spline in this example.

The application of a cubic spline curve to interpolate size-frequency data is mathematically sound (Burger, 1976). Use of raw frequency data has an advantage over cumulative size data in that the sample tails, which are commonly ill defined, can be omitted from the analysis. Gaussian component analysis (Kaper et al., 1966; Bevington, 1969; Clark, 1981) is a successful technique in spectral analysis where quantitative determinations of peak location and size are required from complex data sets with many overlapping peaks.

Subtraction of successive Gaussians from a spline curve fit to histogram data, such as a typical grain-size analysis, is a powerful analytical tool. Removal of three or four refined Gaussians is sufficient to reduce the unexplained residua for size data of most tephra samples to 5% to 10% of the area under the original curve. Use of approximate Gaussians from the SIZAN program typically yields a residual of 10% to 20%, whereas use of a single sample Gaussian results in a residual of 20% to 30%. The method of successive Gaussian subtractions could be easily applied to many other types of data sets where Gaussian subpopulations are expected.

EXAMPLES

Published data from two diverse pyroclastic-surge deposits illustrate the potential for interpretation of deconvoluted grain-size data. One set of samples is from Vulcano (Frazzetta et al., 1983), a composite rhyolite tuff cone in Italy, and the other is from the Sugarloaf tephra (Sheridan and Updike, 1975), a rhyolitic tuff ring in Arizona. All samples were collected from single beds or within bed sets of similar sized material to limit the inclusion of extraneous size populations. The analyses from Vulcano were made at half-phi screen intervals, which allowed a more nearly precise definition of the spline curve. Those from Sugarloaf were made at full-phi screen intervals. After the Gaussians for all the subpopulations were determined and plotted, the samples were arranged in order of coarsest at the top to finest at the base to illustrate the gradual change between samples.

Serial plots of samples showing the individual Gaussians are useful for tracing the changes in the positions and proportions of the subpopulations throughout an entire deposit. Certain Gaussians with consistent mean and standard deviation values occur repeatedly within samples from a single deposit as well as in samples from different deposits. The five most common Gaussians have been labeled A through E in Figure 2.

In the Vulcano samples (Fig. 2, left column) the coarsest (A) and

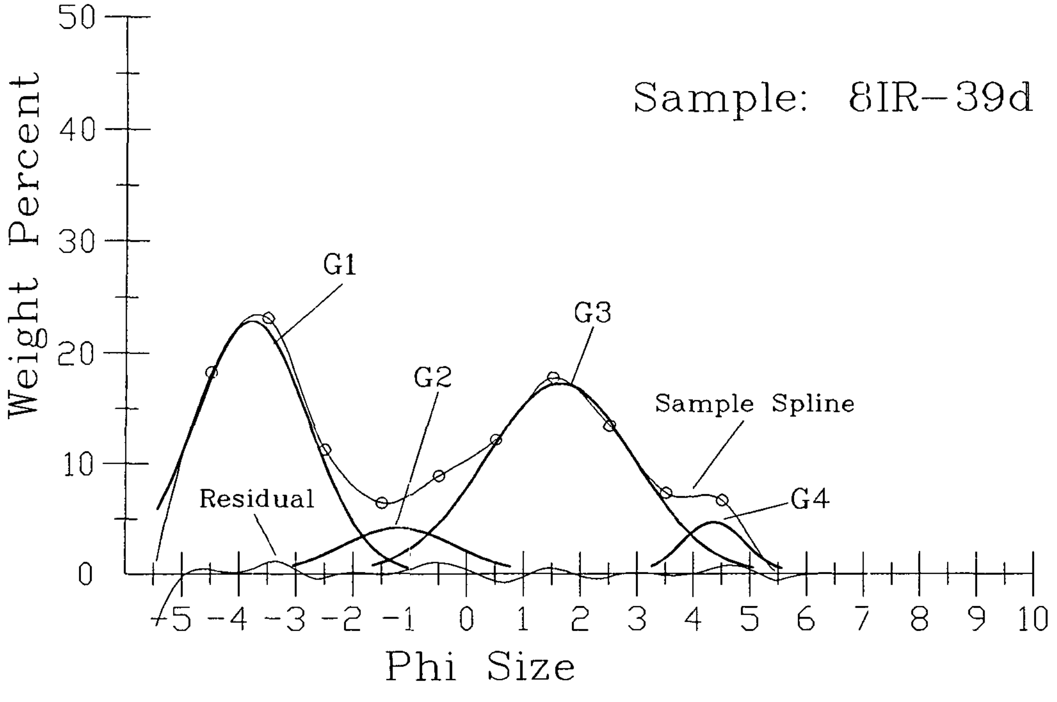

Figure 1. Graphical output from GAUSS program. Circles on sample spline curve are original data points. Four Gaussians (G1, G2, G3, and G4) represent main subpopulations. Residual curve along base of graph is difference between sample spline and synthetic summation of Gaussians. Figured sample (81R-39d) is from large longitudinal dune from May 18, 1980, proximal bedded deposits of Mount St. Helens (Rowley et al., 1985).

finest (E) subpopulations are relatively minor (less than 10% of the total) and are present in only a few of the samples. As the total sample size becomes finer, there is an increase in the fraction of population C (mean about 1 phi) that corresponds to the decrease and disappearance of population B (mean about −1 phi). For finer grained samples, population C decreases as the proportion of population D (mean about 3 phi) grows.

The Sugarloaf samples (Fig. 2, right column) contain the same five subpopulations (designated A through E) as those from Vulcano. Here also populations A and E are of minor importance, and they are present in only a few samples. Starting with the coarse-grained sample at the top of the right column in Figure 2, population B (mean about −1.5 phi) shows a continuous decrease in abundance as population C increases.

DISCUSSION

The consistent locations and standard deviations of the five subpopulations in these two deposits suggest a physical significance for their origin. There are several possible causes for the existence of the designated subpopulations. These include (1) size populations inherited from the initial fragmentation of the magma and country rock; (2) size populations related to clast type and density (e.g., crystals, lithics, pumice, and glass); and (3) size populations related to transport and deposition processes.

All of the above factors contribute to the observed variations in grain-size distributions of these deposits, but their relative importance is highly variable. The sizes inherited from the initial fragmentation during eruption are not known and are very difficult to evaluate. At any rate, this factor does not appear to contribute to the great difference in proportion of modes between samples because there is not a systematic change in size with stratigraphic position. Lithic and crystal abundances in the two example suites are low and do not show a strong systematic variation among samples. Thus, the effect of fragment type on the frequency of a single subpopulation is minor. All of the samples were collected within 1500 m of the vent; therefore, normal sorting by air fall seems to be unimportant. Because of the correlation of grain-size modes to the various bed forms (coarse-and-fine, sand wave, massive, and planar), we consider transport and depositional processes to be responsible for the origin of these modes.

Although we do not know the actual conditions of transport and deposition of the tephra, consideration of field evidence, experimental studies (Bagnold, 1941; Iversen and White, 1982), and theoretical work (Sagan and Bagnold, 1975; White et al., 1976) permits us to tentatively assign certain Gaussians to specific transport modes. Similar reasoning was used by Visher (1969) and Eschner and Kircher (1984) to attribute subpopulations of subaqueous sediments to the transport and depositional processes associated with traction, saltation, suspension, or intermittent conditions between the end members.

With these considerations, we have made the following preliminary interpretations of subpopulations. Gaussians A and E are relatively minor and therefore are not attributable to the principal mechanisms of transport in the basal region of the surge. The coarsest population (A) consists of particles that have probably followed a single ballistic trajectory from the vent; only minor additional movement has occurred along the ground surface. This population is similar to that of single layers of certain fall origin in these deposits. Population E consists of very fine particles that could remain suspended in the surge cloud even at very low transport velocities. This Gaussian has the mean and standard deviation characteristic of known ash-cloud deposits at Mount St. Helens (see Kuntz et al., 1981) and is attributed to particles transported by suspension.

The remaining three Gaussians constitute the major part of the samples from both deposits. Because these deposits are of surge origin, these modes must be related to transport along the ground or near the ground (Wohletz and Sheridan, 1979). Population B represents particles that are too large (2 to 4 mm) to travel by saltation but probably moved by rolling

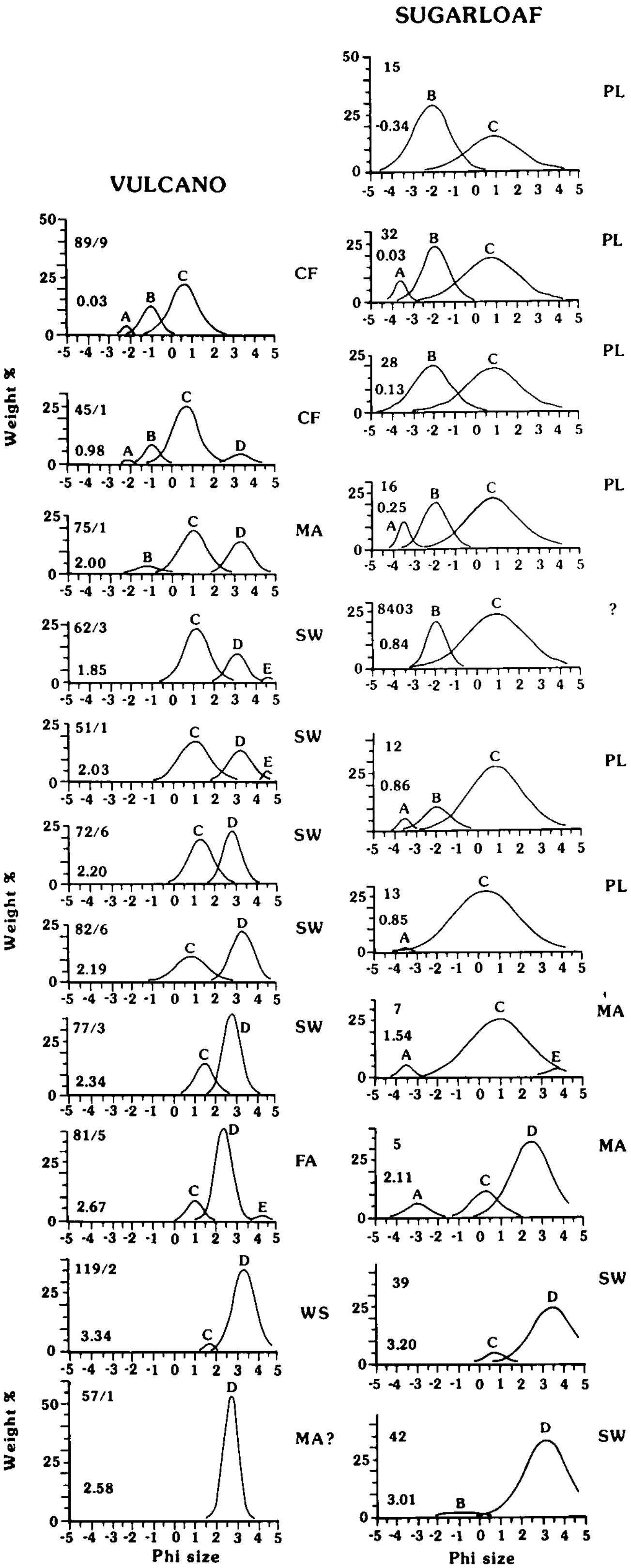

Figure 2. Representative Gaussian curves for subpopulations. Upper number on left of each analysis is sample number; lower number is median grain size in phi units. CF = coarse-and-fine beds, PL = planar beds, MA = massive beds, SW = sand-wave beds, WS = wet-surge beds, and FA = fall beds. Letters A through E indicate specific recurrent subpopulations. Descriptions of samples and unit stratigraphy of Sugarloaf can be found in Sheridan and Updike (1975); those of Vulcano are in Frazzetta et al. (1983).

in a traction carpet. Their presence in inversely graded planar beds, presumably deposited from the traction carpet of surges (Sheridan and Updike, 1975; Wohletz and Sheridan, 1979), supports this interpretation. The mean size of population D (0.12 mm) corresponds to the diameter most easily transported by saltation, and we attribute that mechanism to the transport of these particles. We consider the grains in population C, which have a mean grain size between those of Gaussians B and D (0.5 mm), to have moved by intermittent rolling and saltation. The high frequency of this subpopulation in nearly all the samples is due to the pulsating nature of the surge cloud and the numerous instabilities in the boundary layer that cause an alternation in transport and deposition modes for grains of this size.

CONCLUSIONS

We have devised a new, rapid method to deconvolute complex grain-size distributions into their constituent subpopulations by using Gaussian component analysis. A spline curve is created for the weight percent data, approximate parameters are determined for the various subpopulations, and quantitative values are calculated by Gaussian subtraction from the sample spline curve. The mean, standard deviation, and fraction of the subpopulations are calculated and recorded. The Gaussian components can be plotted as individuals, or they can be combined for a visual comparison with the original spline curve. The sum of the Gaussian curves also can be tested quantitatively for goodness of fit to the original data by various tests.

For the Sugarloaf and Vulcano tephra the mean and standard deviation parameters of the various subpopulations remain fairly consistent, both among surge samples from a single deposit and among samples from different deposits. The ratios of various subpopulations show a consistent change from the coarsest to the finest samples of a single deposit. Samples collected from similar bed-form types have similar ratios of subpopulations. The five recurrent subpopulations have a physical significance that may be attributed to their mechanism of transport and deposition by fall, rolling, intermittent rolling and saltating, saltation, and suspension.

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