Fallout of Pyroclastic Debris from Submarine Volcanic Eruptions

KATHARINE V. CASHMAN* AND RICHARD S. FISKE

Volcanic fallout deposits on land, being widespread and accessible for study, have received much attention and have revealed a great deal about subaerial eruption mechanisms. In contrast, virtually nothing is known about equivalent deposits produced by submarine volcanoes, despite the probable abundance of such material in today's oceans and in accreted volcanic arc terrains. Many submarine deposits may form by the fallout of debris to the sea floor downcurrent from the umbrella region of submarine eruption columns. Experiments on water-saturated pumice and pieces of rock (lithics) show that particles settling to the sea floor at terminal velocities of 10 to 50 centimeters per second will display conspicuous bimodality of particle diameters: pieces of pumice may be five to ten times as large as codeposited lithic fragments. Similar material, erupted into the air and deposited on land, displays less well-developed bimodality; pumice diameters are generally two to three times as large as associated lithics. Submarine fallout deposits are therefore distinctive and may be used to indicate a subaqueous origin for some of the great thicknesses of nonfossiliferous volcanic debris contained in ancient volcanic terrains worldwide whose environment of deposition has been uncertain.

A RECENT COMPILATION OF GLOBAL VOLCANIC ACTIVITY shows that only 13% of the 158 volcanoes reported to have erupted from 1975 to 1985 are located in the oceans of the world (*1*), despite the fact that the oceans cover 71% of Earth's surface. Does this mean that active volcanoes are for some reason underrepresented in today's oceans? Certainly not. Mid-ocean ridges produce an estimated 75% of the annual magmatic output (*2*), and studies have shown that recently active volcanoes dot the sea floor in many other areas, such as along and behind the Izu-Ogasawara arc, south of Japan (*3*). It is clear that the observational record of modern global volcanism is skewed toward eruptions that take place on land or in shallow water, largely because such events attract attention, are relatively easy to observe, and produce deposits accessible to study. In contrast, many, and probably most, submarine eruptions go unnoticed.

K. V. Cashman is in the Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ 08544 and R. S. Fiske is in the National Museum of Natural History, Smithsonian Institution, NHB-119, Washington, DC 20560.

*Present address: Department of Geological Sciences, University of Oregon, Eugene, OR 97403–1272.

Little is known about the nature of submarine pyroclastic eruptions (*4*) or the deposits they produce, even though many such rocks of arc affiliation now exposed in mobile belts on land were deposited in the submarine environment (*5*). Moreover, the relative low density of silicic rocks formed along volcanic arcs and in associated back-arc basins suggests that they are more easily accreted than normal oceanic crust and may therefore be overrepresented in continental crust of all ages. In addition, these mobile belts are the host to more than 1000 massive sulfide deposits worldwide that are major sources of Cu, Pb, Zn, Ag, and Au (*6*); many of these deposits are thought to be genetically related to submarine silicic volcanism. Thus, better understanding of submarine pyroclastic volcanism is of widespread importance, from paleotectonic reconstructions of crustal growth to estimates of the timing and location of volcanism throughout Earth history.

Many submarine pyroclastic rocks preserved in ancient mobile belts have been subjected to varying degrees of alteration, deformation, and metamorphism, although original textures and structures may be preserved in considerable detail (*7*). In many cases marine fossils are absent, and the designation of a subaqueous origin rests only on the often equivocal interpretation of associated lithologies and sedimentary structures. These uncertainties have prompted some geologists to argue that the large volumes of pyroclastic material contained in some ancient marine sequences were actually erupted from volcanoes located on nearby land or in shallow water instead of from volcanoes several hundred meters deep. Some workers have suggested that silicic magmas can only vesiculate significantly, and thus erupt explosively, at water depths of tens of meters or less (*8*), because of the higher confining pressures at greater water depths.

Discoveries in the past few years, however, provide strong evidence that pumice-forming eruptions can take place at much greater depths. Outcrops of deep-sea pumice have been found at depths of greater than 1500 m in the Lau Basin near Tonga (*9*); similar observations were made from research submersibles in the Okinawa Trough south of Japan (*10*); and in 1987 a thermally active, pumice-bearing depression of volcanic origin, the Izena Cauldron, was discovered at a water depth of 1400 m in the Okinawa Trough (*11*). In deep-sea drilling at ocean depths of 2250 and 1113 m in the Sumizu Basin, just west of the Izu-Ogasawara arc, four massive deposits of rhyolitic pumice 8 to 40 m thick were encountered that were deposited 131,000 to 1,000 years ago; this pumice is interpreted to have been derived from nearby volcanoes (*12*). Underlying these deposits is a 135-m-thick accumulation of highly vesicular basalt scoria attributed to an explosive eruption at a water depth of greater than 1800 m (*13*). Collectively, these studies suggest that widely distributed pyroclastic material, much of it highly pumiceous, has recently been erupted from submarine volcanoes located along submerged arcs and in associated back-arc basins.

Despite the apparent abundance of submarine pyroclastic materials, little systematic research has been carried out on the eruption processes involved. As a first step, we focus on the category of submarine pyroclastic eruptions whose eruption columns reach sea level but do not break through into the air (Fig. 1). We restrict our attention to magmatic eruptions that produce pumice, crystals, and ash of andesite to rhyolite composition, along with denser lithic fragments accidentally torn from the volcanic conduit, and we are particularly concerned with the fallout of this debris once it reaches and spreads out beneath the ocean surface. After comparing subaerial and submarine eruption columns, we present the results of theoretical considerations, experiments, and fieldwork that highlight some intrinsic differences in the fallout from submarine and subaerial eruptions.

Inferred Behavior of Submarine Eruption Columns

Subaerial pyroclastic eruptions give rise to eruption columns that are a dispersion of gas and solid particles. Such columns have been subdivided into three regimes of physical behavior (*14*): (i) a basal gas-thrust region occupying only a small part of the total column height, (ii) a buoyancy-dominated convective region, whose top is defined by the level at which the bulk density of the column equals that of the surrounding air, and (iii) an umbrella region, where continued column rise is due to excess momentum and where the column starts to spread laterally. Models relating variations in eruption mechanisms and column behavior to resulting pyroclastic deposits illustrate the importance of understanding eruption processes in order to interpret eruptive products.

While virtually nothing is known about submarine eruption columns, we present an heuristic model based on expected similarities and differences relative to the model of subaerial eruption columns presented above. The submarine column might contain: (i) A basal gas-thrust region, similar to its subaerial counterpart, where momentum generated from the physical conditions of the eruption play a dominant role. Whereas subaerial gas-thrust regions are characterized by rapid deceleration and a decrease in bulk density, submarine gas-thrust regions will not only experience more drastic deceleration because of the density of the overlying water column but will also cool rapidly as seawater is entrained into the rising column and converted, through an endothermic process, to steam. (ii) A turbulent three-phase region in which the eruption column is converted from a two-phase mixture of gas and entrained solids to a two-phase mixture of water and entrained solids. (iii) A buoyancy-driven convection column where upward motion is driven chiefly by thermally induced density contrasts between the column and surrounding cold seawater. We believe that there are important differences between submarine and subaerial eruption columns in this region. Sparks (*14*) stated that a smooth transition from gas thrust to convective behavior (without column collapse) requires that the bulk column density be less than the surrounding medium; this condition may be more easily achieved in water than in air because of the relatively high density of seawater. The small density difference between seawater and pyroclasts also implies that much slower upward velocities are necessary to entrain particles; thus, upward particle transport can occur in much less energetic eruption columns than in air. Finally, steam-inflated pumice fragments would themselves be buoyant and could provide additional lift to the rising column. (iv) An umbrella, or cap region at the sea surface. In contrast to subaerial eruptions we expect that this region would be thin, with abrupt lateral transport away from the column because continued upward motion is prevented by the extreme density contrast at the interface between seawater and air. Transport of material through the sea surface into the air is possible only during shallow eruptions, where the column has sufficient momentum [such as at Myojin-sho, Japan (*15*), and Surtsey, Iceland (*16*)].

Lateral transport of pyroclasts in subaerial eruption columns is strongly controlled by column behavior and interaction with winds in the umbrella region (*17*); similarly, lateral transport of pyroclasts in submarine eruptions will be dominated by current transport of the umbrella region near the sea surface. Fallout from this region is a primary process leading to deposition of pyroclastic material away from the vent; an understanding of the fallout process is critical to recognition of such deposits and to their sedimentological and volcanological interpretation (such as provenance, eruption parameters, current direction, and water depth); much as fallout from subaerial eruptions has been used to constrain eruption dynamics, column height, and paleo-wind direction (and velocity).

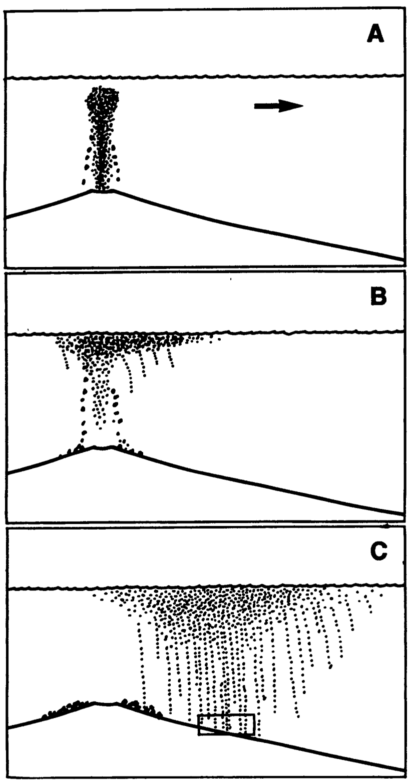

Fig. 1. Schematic representations of fallout from a short-lived submarine eruption; arrow shows current direction. (**A**) Particles with the highest V_T's fall from margin of rising eruption column and are deposited close to the vent area. (**B**) Particles with lower V_T's begin to fall from base of expanding umbrella region. (**C**) Extensive fallout occurs from vestiges of laterally drifting umbrella region; rectangle shows hypothetical area of interest in this study.

What Is the Density of Silicic Pumice?

Many submarine pyroclastic deposits contain both pumice and lithic particles (7), yet much silicic pumice has a bulk density of less than 1 g/cm^3 and will therefore float in water, sometimes for long periods of time (*1, 18*). How then can submarine pyroclastic deposits contain codeposited pumice and lithic fragments? A partial answer to this question was provided by Whitham and Sparks (*19*), who found that pumice, when heated to >700°C and plunged into water, rapidly became saturated and sank. The air that initially filled the vesicles was apparently displaced by steam, which condensed on cooling to form a partial vacuum and to draw in some of the surrounding water. As a by-product, these workers also discovered that the vesicles in pumice are generally interconnected, greatly enhancing water saturation. Implicit in these findings is that the bulk density of heated pumice is increased when its vesicles are suddenly filled with water, causing it to sink. In contrast, when similar pumice at temperatures less than 100°C is exposed to water, steam does not form and the pumice floats.

While useful in considering how volcanoes on land can contribute material to the marine environment, the above study relates to geologically hybrid situations where pyroclastic material is initially erupted into air and then enters the sea while it is still hot. Far more general, and less well understood, is the situation where pumice is erupted directly into seawater from a submarine volcano. The vesicles in pumice are formed by the exsolution of gases from the erupting magma; the most abundant gas in H_2O, followed by other species such as CO_2, H_2S, CO, and H_2 (*20*). The vesicles in pumice erupted below sea level, and remaining below sea level, will contain no air and will be inflated only with these hot magmatic gases. As the surrounding seawater quenches this pumice, its contained gases are rapidly cooled, and, more importantly, condensation of the magmatic steam allows the pumice to become saturated with seawater. If the pumice cools fast enough, it will become saturated before reaching the ocean surface (*21*). Thus, the bulk density of pumice depends not only on the intrinsic properties of the pumice itself, such as the density of its constituent volcanic glass, the number and kind of phenocrysts that it might contain, and its vesicularity, but also on the environment in which it cools.

Theory of Particle Fallout

A particle will fall from a submarine eruption column when its settling velocity exceeds the upward lift of the column. In this study, we focus attention on the material having settling velocities less than that of the rising column; this material begins its fall back to the sea floor from the thin umbrella region that spreads laterally just below sea level (Fig. 1). The fallout of volcanic particles may be approximated by considering the fallout of rigid spheres of differing densities (*22*). For a solid spherical particle falling freely in an infinite medium (that is, no interaction with adjacent particles), the terminal velocity (V_T) is the velocity at which the force of gravity is exactly balanced by the drag force exerted on the particle. The drag

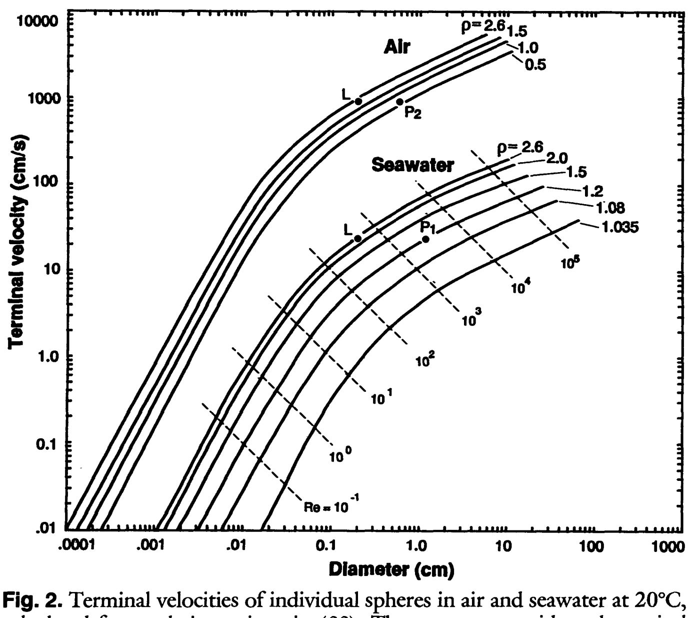

Fig. 2. Terminal velocities of individual spheres in air and seawater at 20°C, calculated from relations given in (*22*). These curves provide a theoretical basis for discriminating submarine fallout deposits from subaerial counterparts. For example, in seawater, sphere L ($\rho = 2.4$ g/cm^3), has the same V_T as sphere P_1 ($\rho = 1.2$ g/cm^3); in air, sphere L has the same V_T as sphere P_2 ($\rho = 0.6$ g/cm^3). The diameter ratio of P_1 to L is 6:1; and P_2 to L is 3:1.

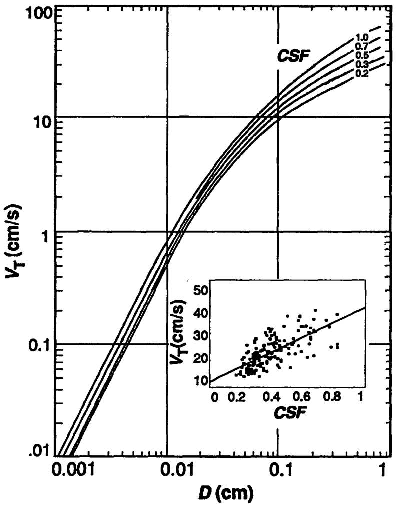

Fig. 3. Terminal velocities of quartz grains ($\rho = 2.65$ g/cm^3) in water as a function of nominal diameter and Cory shape factor (*CSF*), after Komar and Reimers (*24*). The splaying apart of the curves shows the increasing effect of grain shape on V_T at higher *Re* flow. The inset shows the relation of *CSF* to measured V_T's of individual grains of crushed marble in the size range 4 to 8 mm. Variations in grain shape and diameter in this size range result in a spread in V_T's of more than a factor of 2.

coefficient (C_d) is a function of the Reynolds number ($Re = \rho_f V_T D/\mu_f$; ρ_f is the fluid density, μ_f is the fluid viscosity, and D is the particle diameter); when *Re* is small (<0.5), $C_d = 24/Re$ and the terminal velocity is that of Stokes' flow

$$V_T = gD^2\Delta\rho/18\mu \quad (1)$$

When $0.5 < Re < 750$ it is most convenient to express the empirical relations between *Re*, C_d, and V_T as dimensionless forms of size (N_D) and velocity (N_V) (*22*):

$$N_D = 4\rho\Delta\rho g D^3/3\mu^2 \quad (2)$$

$$N_V = Re/C_d = 3\rho^2 V_T^3/4\Delta\rho g\mu \quad (3)$$

For large *Re* ($750 < Re < 3.5 \times 10^5$), C_d is approximately constant at a value of 0.445, and by substitution into Eq. 3, V_T is proportional to $D^{0.5}$, in contrast to the D^2 proportionality of Stokes' flow. At higher *Re* ($<3.5 \times 10^5$), C_d falls abruptly to lower values and can be multivalued for a single *Re*. For this reason, the behavior of particles at these higher *Re* will be neglected in our model although we recognize that high *Re* regimes are geologically important and deserve future consideration.

Terminal velocity curves for individual spheres falling in seawater ($\rho_f = 1.027$ g/cm^3) and air ($\rho_f = 1.205 \times 10^{-3}$ g/cm^3) are shown in Fig. 2. From these curves, we can see that spheres of similar diameter but different bulk densities fall through either seawater or air with different terminal velocities. Conversely, and more important for our discussion here, spheres of different bulk densities falling at the same V_T through either of these two fluids will vary in diameter. The density difference between dry pumice ($\rho = 0.6$ g/cm^3) and lithic particles ($\rho = 2.4$ g/cm^3) will result in diameter ratios of 2:1 to 3:1 for fallout in air. Although the density difference between water-saturated pumice ($\rho \approx 1.1$ to 1.3 g/cm^3) (*23*) and the same lithics is less than in air, the small density contrast ($\Delta\rho$) between water-saturated pumice and the surrounding water will result in significantly lower V_T's, and hydraulically equivalent assemblages of pumice and lithics will have diameter ratios of 5:1 to 10:1 (Fig. 2).

Experiments

The V_T curves shown in Fig. 2 were derived under the oversimplifying assumptions that the particles are spherical and that they fall alone, without interference from nearby particles. Obviously neither of these assumptions is valid for fallout of material from the umbrella region of a submarine eruption column, where large numbers of particles, most having highly irregular shapes, fall through the water column at the same time. We have performed a series of experiments to determine (i) how variations in particle shape affect V_T's, (ii) whether a population of particles falling through seawater will attenuate as predicted because of V_T differences, and (iii) whether particle-to-particle interactions influence fallout patterns.

Corrections for particle shape (nonsphericity) are empirical and are based on computing different shape parameters (*22*). Many shape parameters have been suggested, but most are both difficult to measure accurately and are calibrated only for low *Re* flow. Because we are concerned with particles >1 mm in diameter ($Re > 10^2$), we have followed Komar and Reimers (*24*) in their use of the Corey Shape Factor (*CSF*)

$$CSF \equiv c/(ab)^{1/2} \tag{4}$$

where a, b, and c are the three principal axes, and $a > b > c$. Variations in *CSF* are progressively more important in the region where *Re* is greater than 10^2, as shown in Fig. 3. To investigate the effect of *CSF* on fall velocities, we measured the V_T's of individual fragments of crystalline marble (ρ = 2.8 g/cm^3) in the 4- to 8-mm size class. The measured V_T generally decreased as a function of *CSF* (inset, Fig. 3); the scatter evident in the data is due both to surface roughness, which the *CSF* does not take into account, and to the particle size variations within the 4- to 8-mm size class. Particle shape, however, is clearly an important influence on particle terminal velocity.

Earlier experimental and theoretical work by Greenspan and Ungarish (*25*) has shown that an originally homogeneous mixture of particles composed of a number of discrete sizes (or densities) will attenuate while falling through water to form a layered sediment, and the number of layers equals the number of discrete sizes present. In a study of the sedimentation of a homogeneous mixture of four discrete particle sizes (mode fraction of solids N_{TOT} = 0.2), they found that (i) layers ordered by hydraulic equivalence, (ii) sorting increased upward in the sequence (that is, with increasing sedimentation time resulting from the different relative velocities of the boundaries between size classes), and (iii) the overall settling time was longer than it would be for any individual particle, because of return flow caused by the high fraction of solids.

In order to study the attenuation of a group of particles of differing diameter and densities falling through seawater, as would result from a submarine pyroclastic eruption, we used a large separation tube (35 cm in diameter and 3.4 m high) to carry out a series of simple experiments. The tube was submerged vertically in seawater and 500-cm^3 batches consisting of equal volumes of four to five size classes of particulate polyester resin (ρ = 1.25 g/cm^3) and crushed marble (ρ = 2.8 g/cm^3) were released at its top. These materials were chosen to model the contrasting densities of a mixture of lithic and pumice fragments while avoiding the variations in particle bulk density inherent in natural pyroclastic assemblages. Scuba divers collected assemblages of particles having prescribed V_T ranges from a drawer at the bottom of the tube.

Frequency distributions of the various size classes collected in each of four V_T ranges (Fig. 4, A to D) is strongly bimodal, with a six- to eightfold difference in average particle diameters of polyester resin and marble. It is clear that V_T differences produced a distinct separation of particles in the 3.4 m of vertical fall through seawater; this relation suggests that broad segregation of faster from slower particles is not hindered at the low volume of solids (<1%) used in our experiments.

The maxima of the observed distribution of particles in the experiments (Fig. 4, A to D) agree well with the calculated curves (Fig. 2) for slower settling spheres and polyester resin but progressively diverge at faster settling assemblages. This relation is the result of the offsetting effects of particle nonsphericity and particle interaction. As discussed above, nonspherical particles settle more slowly than spheres of equivalent diameter, and this process affects all particles used in our experiments (which range from angular to subangular in shape). Partly offsetting this is a speeding up of slower particles due to particle interaction when all particles are released together at the top of the separation tube. We have observed that a dense slug forms as the particles are released and that this slug travels faster than the V_T of the slower particles. In less than a second, however, the slug begins to attenuate as particles with faster V_T's pull away, and the slower particles assume their lower V_T's. As greater attenuation is achieved [resulting in a modal fraction of solids (N_{TOT}) of less than 0.01], all particles settle independently through the tube, apparently little affected by differing V_T's of their neighbors.

In our experiments, particle assemblages arriving at the bottom of the separation tube have progressively lower V_T's, reflecting the

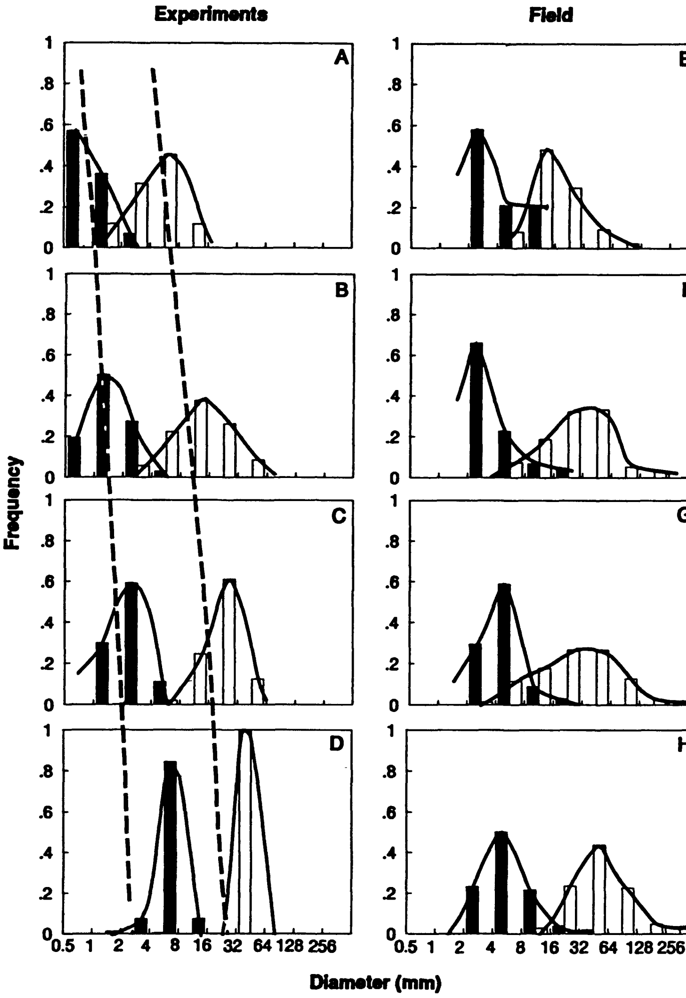

Fig. 4. Plots of frequency versus particle diameter for experimental and field results. (**A** to **D**) Experimental results. Histograms of mixtures of crushed marble (black) and polyester resin (non-patterned) for the following V_T intervals; (A) 19 to 14 cm/s, (B) 25 to 20 cm/s, (C) 32 to 27 cm/s, and (D) 38 to 32 cm/s. The sloping dashed lines are reference segments of the calculated V_T curves from Fig. 2 for sphere densities of 2.8 g/cm^3 (marble) and 1.25 g/cm^3 (polyester resin). Each histogram is the average of three individual experiments. (**E** to **H**) Field results from the Shirahama Group, Japan. Histograms of lithics (black) and pumice (non-patterned) measured on the outcrop at the following stratigraphic levels above the base of the fallout zone: (E) 3.8 m, (F) 3.2 m, (G) 2.0 m, and (H) 1.2 m.

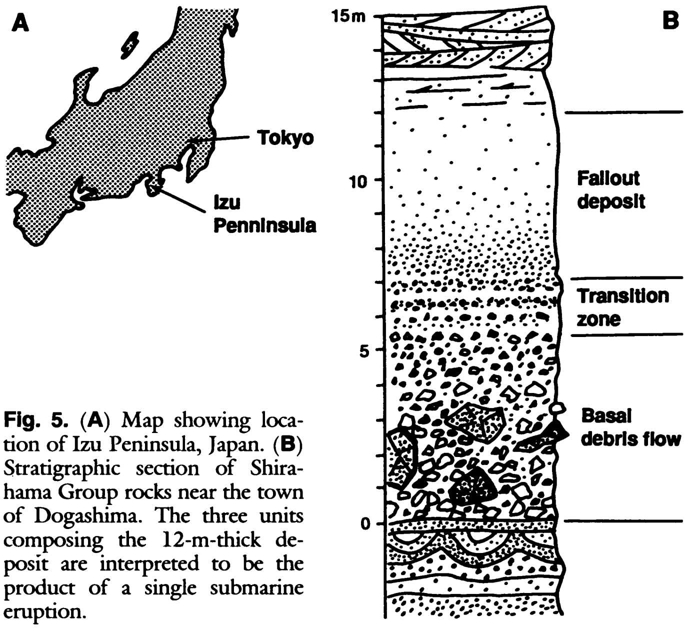

Fig. 5. (**A**) Map showing location of Izu Peninsula, Japan. (**B**) Stratigraphic section of Shirahama Group rocks near the town of Dogashima. The three units composing the 12-m-thick deposit are interpreted to be the product of a single submarine eruption.

gradual clearing of the water in the tube during a single fallout cycle. In nature, similar patterns should be expected from fallout from the umbrella region of submarine eruption columns produced by individual, short-lived pyroclastic eruptions.

A Submarine Fallout Deposit from the Shirahama Group

The rocks of the Mio-Pliocene Shirahama Group, Izu Peninsula, Japan, (Fig. 5A) contain a superb record of submarine pyroclastic volcanism. These rocks, now exposed at the extreme northern tip of the Philippine Sea plate, were formed by eruptions 3 to 6 million years ago from submarine volcanoes located several hundred kilometers to the southeast (*26*). Northwestward motion of the Philippine Sea plate carried the Shirahama rocks to their present location; gentle arching of this plate, just before subduction beneath the Eurasian plate, has lifted the Shirahama rocks above sea level, where they are accessible for detailed study.

The rocks of the Shirahama Group are remarkably fresh and little deformed; volcanic glass is preserved in most deposits, and the degree of lithification is so slight that many deposits can be disaggregated into their constituent pyroclastic particles. At least six eruptive centers have been identified and are surrounded by aprons of primary and reworked pyroclastic debris ranging in composition from basalt to dacite (*27*). Numerous marine fossils in the Shirahama Group indicate that these eruptive centers were located in a shallow marine environment (*28*).

A 12-m-thick deposit consisting of a basal pyroclastic debris flow, an intermediate transition zone, and what we interpret to be an overlying fallout deposit is well exposed in the Shirahama Group on the west coast of the Izu Peninsula (Fig. 5B). Chilled margins and constant high-temperature (250° to 450°C) thermoremanent magnetism of andesitic blocks in the basal pyroclastic debris flow indicates that the individual clasts were hot (about 450°C) when deposited (*29*); these relations provide strong evidence that the debris flow in which they are contained was the direct product of a volcanic eruption. All three units making up the deposit are characterized by extreme depletion of particles <1 mm in diameter. In addition, average grain size decreases systematically upward from the basal debris flow, through the transition zone, and to the top of the fallout deposit. We interpret these relations to indicate that all three units were the product of the same submarine eruption (*30*).

More than 95% of the fallout deposit is composed of lithic fragments, pieces of pumice, and broken crystals. Casual inspection of the outcrop reveals that most pumice fragments are conspicuously larger than associated lithics. In an effort to quantify this relation, we measured pumice, lithic, and crystal sizes and abundances at ~0.5-m intervals through the deposit using a portable grid (90 cm by 40 cm) to point count the deposit directly on the outcrop. At every location, the particle at each of the 171 grid intersections was identified, measured, and counted.

The results indicate that there is a strong 5:1 to 8:1 bimodality of pumice to lithic diameters throughout the deposit (Fig. 4, E to H). The similarity of these histograms to those obtained experimentally (Fig. 4, A to D) is striking and provides a physical basis, independent of associated sedimentary structures or fossils, for concluding that the deposit formed as a result of fallout through water.

Implications of Submarine Fallout

Theoretical, experimental, and field measurements show that a family of curves relating terminal velocity and diameter of individual spheres (Fig. 2) can reveal fundamental differences between submarine and subaerial fallout deposits. Because the bulk density of saturated pumice is only slightly greater than seawater, submarine fallout deposits contain pumice fragments five to ten times as large as codeposited lithics (Fig. 6). This bimodality tends to be preserved because of the relative uniformity of fallout distance from the thin umbrella regions capping submarine eruption columns. In contrast, the curves in Fig. 2 indicate that subaerial fallouts will tend to form deposits containing pumices only two to three times as large as associated lithics. Moreover, this material has a more variable fallout distance from the more diffuse umbrella regions at the top of subaerial columns, and much of it, especially pumice, has high V_T's in air and tends to break on impact (*31*). Both of these effects blur aerodynamically produced particle size bimodality that might ideally be preserved in subaerial fallout deposits.

The bimodality of pumice and lithic particles in submarine fallout deposits, including those of the Shirahama Group, must result ultimately from the bimodal density distribution of the pyroclastic debris that is erupted. A fallout deposit, either submarine or

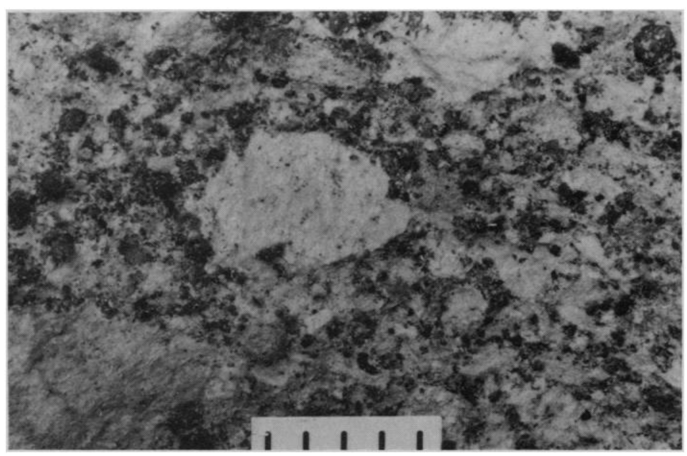

Fig. 6. Submarine fallout deposit in the Shirahama Group, 500 m west of Senjojiki near the southern end of the Izu Peninsula. Bimodal texture defined by pieces of pumice (light-colored) whose average diameters are six to seven times as large as codeposited lithics (dark-colored). Ash matrix (<2 mm) forms less than 5% of the rock. Scale units in centimeters.

subaerial, consisting of particles having the same density, or particles whose bulk densities span a wide range of values, would not display grain-size bimodality. Inspection of Fig. 2 shows that the difference between pumice and lithic diameters in submarine fallout deposits is maximized in relatively coarse-grained deposits, or, more correctly, in deposits composed of particles having relatively high V_T's; the difference in particle size for constant pumice and lithic densities decreases as the slope of the V_T curves in Fig. 2 increases. The implications of this observation are twofold: (i) conspicuous particle bimodality will be limited to relatively coarse-grained fallout deposits formed at specific distances from the volcanic vent that depend on current velocity, water depth, and specific pumice and lithic densities, and (ii) pumice per se has a minimum size limit below which it is reduced to glass shards and crystal fragments. Thus, particles <0.1 mm in diameter will no longer display a clear bimodal density distribution.

It is fortuitous that the 5:1 to 10:1 ratios of pumice and lithics are best developed in coarse-grained submarine fallout deposits, making this diagnostic texture megascopic and easy to recognize in outcrops, hand specimens, and drill cores, provided that postdepositional alteration and deformation have not destroyed original textures. As noted earlier, these deposits, on casual inspection, might be described as poorly sorted (by grain size); such a description conveys the erroneous impression that the particles were chaotically mixed together. It is clear, however, that these deposits are extremely "well sorted" when considering the hydraulic equivalence of their constituent particles.

In conclusion, much of Earth's history has involved volcanic eruptions that took place in ancient seas, and the products of this volcanism form important parts of mobile belts of all geologic ages. The generation of pumice in water depths of greater than a few tens of meters is not only a plausible interpretation of recent submarine observations but is also consistent with recent estimates of volatile contents of rhyolitic melts (*32*). We have demonstrated that high (>20 m/s) eruption-column velocities are not required for substantial vertical particle transport as in subaerial eruptions; thus, many of the processes in submarine eruptions may be quite different from their subaerial counterparts. Future modeling of submarine eruption columns could provide the framework for analysis of interaction between physical parameters affecting both the eruption and mode of deposition (such as volatile content, exit velocity, column height, water depth, and current velocity) similar to recent models for subaerial eruptions (*17*). Characterization of a three-dimensional distribution of submarine pyroclastic material (in contrast to the two-dimensional exposures we studied in Japan) would allow estimates of water depth as a function of current velocity (*33*), and may potentially supply important constraints on the early development and emergence of volcanic arcs.

REFERENCES AND NOTES

1. Smithsonian Institution/SEAN, *Global Volcanism 1975–1985* (Prentice-Hall, Englewood Cliffs, NJ, and American Geophysical Union, Washington, DC, 1989).
2. J. A. Crisp, *J. Volcanol. Geotherm. Res.* **20**, 177 (1984).
3. S. H. Bloomer, R. J. Stern, N. C. Smoot, *Bull. Volcanol.* **51**, 210 (1989); Y. Ikeda and M. Yuasa, *Contrib. Mineral. Petrol.* **101**, 377 (1989); M. Yuasa, in *Formation of Active Ocean Margins,* N. Nasu *et al.*, Eds. (Terra, Tokyo, 1985), p. 483; M. Yuasa, in preparation.
4. We use the term "pyroclastic" for fragmental material produced and deposited as the direct result of contemporaneous volcanic activity, as defined by R. V. Fisher and H.-U. Schmincke, *Pyroclastic Rocks* (Springer-Verlag, Berlin, 1984).
5. W. B. Hamilton, *Geol. Soc. Am. Bull.* **100**, 1503 (1988).
6. H. Ohmoto and B. J. Skinner, in *The Kuroko and Related Volcanogenic Massive Sulfide Deposits,* H. Ohmoto and B. J. Skinner, Eds. (*Econ. Geol. Mono. 5*, Economic Geology, El Paso, TX, 1983) p. 1.
7. C. J. Busby-Spera, *J. Geophys. Res.* **89**, 8417 (1984); S. N. Carey and H. Sigurdsson, *J. Volcanol. Geotherm. Res.* **7**, 67 (1980); R. A. F. Cas, *Geol. Mag.* **120**, 471 (1983); E. Dimroth and H. Yamagishi, *Rep. Geol. Surv. Hokkaido* **58**, 55 (1987); R. M. Easton, *Ont. Geol. Surv. Misc. Pap.* **132**, 141 (1986); R. S. Fiske and T. Matsuda, *Am. J. Sci.* **262**, 76 (1964); B. F. Houghton and C. A. Landis, *Bull. Volcanol.* **51**, 433 (1989); E. H. Francis and M. F. Howells, *J. Geol. Soc. London* **129**, 621 (1973); M. F. Howells, A. J. Reedman, S. D. G. Campbell, *ibid.* **143**, 411 (1986); B. P. Kokelaar, R. E. Bevins, R. A. Roach, *ibid.* **142**, 591 (1985); B. P. Kokelaar, M. F. Howells, R. E. Bevins, R. A. Roach, P. N. Dunkley, *Geol. Soc. Lond. Spec. Publ.* **16**, 245 (1984); R. V. Fisher, *ibid.*, p. 5.
8. R. A. F. Cas and J. V. Wright, *Volcanic Successions* (Allen and Unwin, Boston, 1987).
9. Y. Fouquet *et al.*, *Geology* **19**, 303 (1991).
10. Y. Kato, *J. Geol. Surv. Jpn.* **93**, 11 (1987); K.-I. Nakamura, personal communication.
11. P. Halbach *et al.*, *Nature* **338**, 496 (1989).
12. A. Nishimura *et al.*, in *Sedimentation in Volcanic Settings*, R. V. Fisher and G. A. Smith, Eds. (*Spec. Publ. 45*, Society of Economic Paleontologists and Mineralogists, Los Angeles, in press).
13. J. Gill *et al.*, *Science* **248**, 1214 (1990).
14. R. S. J. Sparks, *Bull. Volcanol.* **48**, 3 (1986).
15. R. Morimoto and J. Ossaka, *Bull. Earthquake Res. Inst.* **33**, 221 (1953).
16. S. Thorarinsson, *Surtsey* (Viking, New York, 1967).
17. S. Carey and R. S. J. Sparks, *Bull. Volcanol.* **48**, 109 (1986).
18. T. Simkin and R. S. Fiske, *Krakatau 1883* (Smithsonian Institution, Washington, DC, 1983).
19. A. G. Whitham and R. S. J. Sparks, *Bull. Volcanol.* **48**, 209 (1986).
20. W. F. Giggenbach, *ibid.* **39**, 132 (1976).
21. The rapid absorption of seawater by hot submarine pumice was independently recognized by Y. Kato [*J. Geol. Soc. Jpn.* **93**, 11 (1987)] and R. S. Fiske and K. V. Cashman [*Geol. Soc. Am. Abstr. Progr.* **19**, 664 (1987)].
22. R. Clift, J. R. Grace, M. E. Weber, *Bubbles, Drops, and Particles* (Academic Press, New York, 1978); S. A. Morsi and A. J. Alexander, *J. Fluid Mech.* **55**, 193 (1972).
23. The bulk density of water-saturated pumice may be stated as $\rho_{bulk} = \rho_{solids}(1 - \nu) + \rho_{fluid}(\nu)$, where ν is vesicularity. In this relation, it is assumed that the vesicles are completely interconnected; the presence of isolated vesicles will lower ρ_{bulk}. For ν of 0.90 to 0.75, ρ_{solids} of 2.4 g/cm^3, and 1 to 5% of the vesicles not saturated at the time of fallout, ρ_{bulk} of dacite pumice will range from 1.11 to 1.36 g/cm^3.
24. P. D. Komar and C. E. Reimers, *J. Geol.* **86**, 193 (1978); W. E. Dietrich, *Water Resourc. Res.* **18**, 1615 (1982).
25. H. P. Greenspan and M. Ungarish, *Int. J. Multiphase Flow* **8**, 587 (1982).
26. T. Matsuda, *J. Phys. Earth* **26**, 409 (1978); K. Nakamura, K. Shimazaki, N. Yonekura, *Bull. Geol. Soc. France* **2**, 224 (1984); Y. Tamura, thesis, University of Tokyo (1988).
27. K. Kano, *J. Volcanol. Geotherm. Res.* **37**, 59 (1989); R. Matsumoto, T. Katayama, A. Iijima, *J. Geol. Soc. Jpn.* **91**, 43 (1985); Y. Tamura, thesis, University of Tokyo (1990).
28. M. Ibaraki, *Rep. Fac. Sci. Shizuoka Univ.* **2**, 1 (1976); *J. Geol. Soc. Jpn.* **87**, 417 (1981); ______ and R. Tsuchi, *Rep. Fac. Sci. Shizuoka Univ.* **12**, 115 (1978); R. Tsuchi, *ibid.* **1**, 47 (1965).
29. Y. Tamura, M. Koyama, R. S. Fiske, Paper presented at IAVCEI General Assembly, Sante Fe, NM, June 1989, *Bull. NM Bureau Mines Mineral Resourc.* **131**, 265 (1989).
30. R. S. Fiske and K. V. Cashman, *ibid.*, p. 92.
31. A smooth, spherical piece of dry pumice, 3 cm in diameter and with a ρ of 0.5 g/cm^3, falling through air, strikes the ground at a V_T of about 20 m/s (Fig. 2); the same piece of pumice, water saturated (ρ = 1.32 g/cm^3), strikes the sea floor at a V_T of only 0.5 m/sec, 1/40th as fast.
32. L. A. Silver and E. Stolper, *J. Geol.* **93**, 161, 1985; L. A. Silver, P. D. Ihinger, E. Stolper, *Contrib. Mineral. Petrol.* **104**, 142, 1990.
33. For example, if the lateral current velocity is 0.5 m/s and if a conspicuously bimodal fallout facies consisting of particles with a V_T of 0.30 m/s is found 1 km downcurrent from a known source vent, a water depth at the site of deposition of about 600 m is indicated.

34. Supported by NSF grants EAR8804857 and EAR9017364 (to K.V.C.) and the Smithsonian Marine Station at Link Port, FL (SMSLP), and Scholarly Studies Fund of the Smithsonian Institution (to R.S.F.). For support in Japan, we thank C. Aomori, T. Ito, K. Kano, C. Klug, M. Koyama, I. Kushiro, K.-I. Nakamura, S. Oshima, K. Seki, W. Soh, and Y. Tamura. For work in the laboratory and at SMSLP, we thank W. Lee, E. O'Leary, J. Piraino, S. Reed, H. Reichardt, M. Rice, and T. Rose. For help with equipment fabrication, we thank H. Campbell, J. Collins, J. Reuter, T. Rose, and W. Sorrell. We appreciate careful reviews by two anonymous reviewers. SMSLP contribution 271.