[AMERICAN JOURNAL OF SCIENCE, VOL. 274, JUNE, 1974, P. 648-661]

ON VOLCANIC ASH FORMATION

F. D. BENNETT

Department of Mechanics and Materials Science,
The Johns Hopkins University, Baltimore, Maryland 21218

ABSTRACT. The vesiculation and vaporization wave theories of volcanic ash production are examined critically from the point of view of fluid dynamic requirements. In particular, the implications of large and variable viscosity are shown effectively to rule out coalescence of bubbles as an important feature of vesiculation. The necessity of pressure gradients as effective agents of magma disintegration is illustrated in describing several types of expansion process by which volcanic ash can form.

INTRODUCTION

Present ideas of volcanic ash formation were first formalized by Verhoogen (1951), later refined by McBirney (1963) and McBirney and Murase (1970). Briefly, this theory asserts that sudden pressure release over a molten, gas-rich magma causes rapid formation, growth, and coalescence of bubbles in the general process called "vesiculation". The magma expands into a froth which cools and fragments as it issues from the volcanic vent. If residual pressure is high when the fluid loses its coherence, the eruption is explosive; if not, milder effusions ensue. Vesiculation is believed to be the fundamental process that transforms the continuous magmatic liquid to a dispersion of pumice and fine ash. The current account by Meyer (1972) shows how the vesiculation theory is used to explain explosive volcanism of acid magmas. He attempts to connect the released thermal energy of the eruption with the degree of abrasion received by vesiculated, silicic ash fragments owing to their mutual collisions. Verhoogen (1951) points out that instances of explosive ash formation in basaltic magmas are not rare; so the process must be considered general, irrespective of magma type.

Recently, I outlined an alternate approach based on the unsteady expansion of a uniform, high temperature fluid that partially vaporizes (Bennett, 1971). The volatile-rich magma is assumed to follow an equation of state similar to the van der Waals equation. The presence of small percentages of water and other volatile constituents is assumed to have the effect of steeply lowering the two-phase critical temperature from that of the dry parent magma to within a factor of two of typical magma temperatures. During the expansion the magmatic fluid partially vaporizes, the vapor undergoes heterogeneous condensation to fine ash, and the dispersed liquid fraction continues to exsolve gases as it cools and solidifies. Because of its mode of formation, the ash is quite uniformly distributed throughout the erupting expanded fluid.

These two descriptions are partial in that important flow regimes are either ignored or only crudely described and conflicting in the sense that where they overlap they represent very different fluid dynamic situations. Vesiculation theory ignores the early stages of bubble formation and commences with a quasi-steady bubble growth together with a creeping, viscous flow in which near balance is maintained between pressure gradients and viscous forces, so that no major fluid accelerations occur until after coalescence occurs and the magma disintegrates. On the other hand vaporization theory presumes large pressure gradients from the outset, is both dynamic and unsteady, and closely resembles the well known, one-dimensional, shock tube flow. Details of the process of vaporization that separates vapor from liquid in a more or less homogeneous way are undescribed and remain indistinct, although appeal is made to the physically observed process of striation seen in the expansion of superheated metals. Viscosity plays no role except implicitly in the establishment of boundary layers and mixing regions. These are taken to occupy only small regions of the flow field and are neglected in first approximation.

Neither theory is much developed mathematically nor has either received much confrontation with experimental data from real explosive volcanism partly because of the lack of mathematical development and partly because of the comparative rarity and inaccessibility of explosive volcanisms. A further obstacle is the fact that equipment for photographic observation, field measurements, or laboratory simulation has not been attended to.

Vesiculation theory offers a quasi-static explanation of the explosive phase of volcanism and magma disintegration. It obtains qualitative confirmation from studies of weak volcanisms, bubble-filled cooling lavas, and from bedded pyroclasts dating from earlier times. Vaporization wave theory gives the first dynamical explanation of fine ash production in a framework which accounts for the unsteady expansion phase of explosive volcanism. In another context it accounts for the wave speeds inferred from experiments on impulsively evaporated pure metals. In spite of these modest successes neither theory is free of difficulties, and because neither has survived detailed comparison with real explosive volcanism each must be considered problematic at present.

GENERAL THEORY

A full treatment of magma eruption from the standpoint of solid and fluid mechanics is presently out of reach, although significant beginnings have been made. Weertman (1971) develops a mathematical model of magma transport based on propagation of vertical cracks in the overlying crust, each crack considered to be an array of infinitesimal edge dislocations. The rise of magma in swarms of intrusive sheets along stress surfaces in a horizontal semi-infinite plate under tension is developed, on more conventional lines of engineering solid mechanics, by Piper and Gibson (1972), while Lang (1972) considers the thermodynamics, hydrodynamics, and pressure history of ascending magmas coming from greater depths. Along the same line McGetchin and Ullrich (1973) describe the ascent of volatile-rich magma from deep reservoirs in terms of steady, turbulent, one-dimensional flow in a rough pipe, of a magmatic liquid always in pressure equilibrium with gravitational forces.

The regime discussed here is that of magma framentation and ash formation after a rising magma column has broken through the Earth's crust and is expanding freely into the atmosphere. This means, among other things, neglect of the possibility that appreciable cavitation and density changes may occur during rapid injection of a magma into a suddenly extended crack. In such an event we assume that recompression and assimilation of expansion products will occur so that the relative homogeneity of the magma is restored. Should the extending crack intercept the surface and open into the lower pressure of the ambient atmosphere, then the expansion we envisage may occur.

Once expansion begins, unless equilibrium is quickly restored, fluid motions must predominate after the lapse of a characteristic time equal to crack diameter divided by speed of sound in the magma. From the point of view of continuum fluid mechanics one would like to specify the fluids, their boundary conditions, and the equations of motion and list the average fluid properties and equations of state. Presumably the problem then becomes that of solving the system of equations to obtain a description of the process through which the incompressible magma is transformed to combined ash and gaseous constituents. Transition between branches of the equation of state may require consideration of kinetic processes by which vapor bubbles form, or vapor pockets produce striations, or other outcomes occur. Unfortunately such a complex problem has not yet been solved even for a single component fluid such as a pure metal. In the case of explosive volcanism there are difficulties in positively identifying the magmatic fluids and their volatile constituents; there are problems in specifying the initial conditions, the fluid properties such as specific heats, viscosity, thermal conductivity; and the relevant equations of state. In spite of these uncertainties some general remarks may be useful in providing orientation.

If the equations governing conservation of mass, momentum, and energy for a viscous, heat-conducting, compressible fluid are made dimensionless by scaling transformations on the dependent and independent variables, then a set of partial differential equations emerges which is not only free of dimensions but also contains dimensionless functional coefficients (groups of parameters) which appear in the denominators of the various terms. Among these are the ratio of specific heats, the Mach number, Froude number, Reynolds number, and Prandtl number. The solutions desired will be functions of the dimensionless variables and these dimensionless groups only. When boundaries are considered or when the flow contains two or more phases, for example, gas bubbles, droplets, or solid particles, the situation is more complicated. Further dimensionless parameters may have to be specified relating to fluxes at the boundaries and to relaxation times describing the lag between particle motions and the ambient fluid flow. Relative motions between particles and fluids are accompanied by boundary layers, flow separations, and wakes, all of which are complex dissipative processes which for the most part defy detailed analysis except in special cases.

Since no developed theories of magma vesiculation or magma vaporization yet exist, legitimately we can only make inferences from the descriptions already given as to what fluid dynamic regimes must obtain. Results gained this way may help to clarify existing problems and set out more precisely what remains to be done.

The focus of vesiculation theory, as presently stated, is on bubble growth and bubble motion up to the point of coalescence. Prior to the appearance of bubbles the fluid is clearly considered incompressible; that ratio of specific heats of the fluid is one ($\gamma = 1$). The problem of bubble nucleation presents such great difficulties that it is bypassed. Bubbles exist, grow, and rise, and problems of metastable states and delay of nucleation are conveniently ignored. The ensuing fluid motions are so slow that the ratio of flow speed to sound speed, namely, the Mach number, is nearly zero ($M < < 1$). This implies that the kinetic energy of a fluid particle is small compared to its thermal energy. Not only is the exterior flow slow and fully viscous, but also the internal flow of vapor into a bubble must be slow; a quasi-static, near equilibrium state prevails. Otherwise we should have to consider the possibility that exsolution or vaporization of gases from the bubble walls might, under some conditions, constitute a compressible radial flow perhaps containing internal, spherical shock waves.

In contrast, the vaporization wave hypothesis considers the magmatic fluid to remain incompressible only until expansion occurs. Until that point, the flow may be viscous and slow though other alternatives are possible. Vaporization commences at the free boundary between magma and ambient atmosphere where there is no hindrance to expansion. The structure-insensitive nucleation problem of the fluid interior does not arise, and time delays in the start of vaporization need not be expected. The compressible, damp vapor may quickly reach flow speeds comparable with thermal in passing through the expansion wave ($\gamma > 1$), a shock wave may appear ahead of the contact surface between vapor and atmosphere, depending on the initial overpressure. The flow may become supersonic ($M > 1$). The focus here is on the fluid dynamics of the expansion, whereas, in retrospect, it appears that vesiculation applies to developments before expansion. The two theories are to some extent disjoint and propose very different explanations for the process of ash formation.

Froude number, Fr, is a dimensionless group of parameters that measures the ratio of fluid particle kinetic energy to its change of gravitational energy in rising through a characteristic distance. As long as vesiculation theory is concentrated on motions of small bubbles over spans of a few diameters, and vaporization theory is restricted to the immediate neighborhood of the interface, then $Fr > > 1$, and gravitational effects can be neglected. Under these conditions something can be learned about magma disintegration and immediate ash formation, but vertical transport of magma or ash cannot be treated. Gravitational pressure differences are important in the vertical transport of magma and in the convection of ash in the volcanic jet and "pino" cloud. In general, for both theories Fr $\approx$ 1, and the same is true for McGetchin and Ullrich's (1973) pipe flow calculation.

Reynolds number, Re, expresses the ratio of inertial to viscous forces in a flow. If it is larger than 10^3 the flow tends to have turbulent regions; if smaller, the flow tends to be laminar, although for intermediate laminar values (Re $\sim$ 10-100) a variety of wakes and eddy patterns can exist (Van Dyke, 1964). Re can be written as the quotient of a typical length, say bubble diameter, to a "viscous" length ν/U where ν is kinematic viscosity, and U is a typical flow speed. For ν large or flow speed sufficiently low, the viscous length is much larger than the physical length scale, and the flow is laminar and dominated by viscous forces.

Vesiculation theory employs the Stokes flow solution for a sphere at low Reynolds number (Re $\rightarrow$ 0) and neglects non-steady terms and nonlinear inertial terms in the equations of motion. Vesiculation and frothing of the magma must then be thought of as slow and laminar. Typical speeds are never high enough so that compressibility effects can become apparent. Even if the vesiculation expansion ratio is large, the flow must be slow. All violent, turbulent motions are relegated to the period after the magma disintegrates. It is as if the time for vesiculation proper could approach infinity, and on the geologic time scale, this may be a good approximation for the differentiation of an emplaced magma.

Vaporization wave theory is, on the other hand, one of high Reynolds number (Re > 1000) in which inertial forces dominate throughout most of the flow field and for all times save for the initial starting transients. Turbulent regions are considered confined to narrow boundary layers and neglected in first approximation. The expansion is visualized as similar to an unsteady simple wave (Courant and Friedrichs, 1948) and may often relieve a reservoir pressure high enough so that a shock wave quickly appears ahead of the contact surface. The ensuing flow may become supersonic and in two or three dimensional geometries may contain internal shock waves. Magma vaporization (fragmentation) takes place during the first passage of the expansion wave in an interval determined by a characteristic distance and the speed of sound in the vaporizing magma. The process of vaporization takes essentially zero time compared to the rest of the flow, in complete contrast to vesiculation which does the opposite.

Prandtl number is a dimensionless group that can be represented as the ratio of two characteristic diffusion times; $Pr = \tau_h/\tau_v$ where $\tau_v = l^2/\nu$, $\tau_h = l^2/\kappa$, l is a characteristic length, κ is the thermal diffusivity of the fluid. When Pr is near unity, as it is for gases, the decay times for pulses of vorticity or thermal energy are about the same. Prandtl number for a permanent gas decreases slightly with temperature, T, while viscosity increases about like $T^{1/2}$. For a magmatic liquid, Prandtl number is large because viscosity is extremely large and τ_v correspondingly low. Viscosity decreases rapidly with temperature and with volatile content;

therefore, unless there is a corresponding decrease in thermal diffusivity one would expect a decrease in Pr. If this should occur, a distinction based on Prandtl number might be made between a vesiculating liquid and a similar liquid undergoing a damp vaporization. In the first case Pr would be considerably larger than unity and rapidly decrease in the latter case. If reliable values of kinematic viscosity and thermal diffusivity become available for magmatic fluids and their damp vapors, this speculation can be put on a firmer basis. Granitic magmas are known to have large Prandtl number (Shaw, 1965); we infer smaller values for the damp vapor with some confidence; however no direct measurements exist for volcanic smokes or vapors, but see McClaine and others (1968).

VESICULATION

Ash formation by means of vesiculation occurs, according to Verhoogen (1951), as an outcome of competition between bubble growth by expansion and bubble rising because of buoyancy. If bubbles touch and break before they escape at the surface, the magma is said to have lost coherence. Experiments reported by McBirney and Murase (1970) show that for most magmas rise of bubbles owing to buoyancy is slow, usually much slower than the rise of the magma in the volcanic pipe, and coalescence of bubbles is likewise slow even though bubble walls appear to be close together. In view of these facts, these authors suggest as an alternative criterion that fragmentation may not occur until gas and liquid volumes become equal.

Vesiculation in its own right is a complicated process with many as yet unanalyzed stages. To get some idea of what remains to be done consider an unsteady process of bubble formation and expansion.

Bubble nucleation is still too formidable a kinetic process to allow a detailed analysis. If it occurs by heterogeneous nucleation around ions, impurities, solid particles with gas inclusions, phenocrysts, et cetera, these would have to be specified and the method of gas accretion described; a prospect that suggests case by case study of each magma. If homogeneous nucleation occurs in a uniform magma, the kinetics of the fluctuation process leading to bubble formation must be given. While this can be done for ethanol droplets forming in a gas flow (Wegener, Clumpner, and Wu, 1972), the inverse problem of volatiles collecting into bubbles in a dense inert liquid has not yet been attempted.

During the initial stages of spherical bubble growth, several inertial and pressure forces can be distinguished, namely p_v, p_h, and p_o, surface tension induced pressure $2\ \sigma/a$, kinetic pressure $\rho\ u^2/2$, and viscous normal stress $2\mu\ (\partial u_r/\partial r)_{r\,=\,a}$; where p_v, p_h, p_o are local vapor, hydrostatic and ambient pressure, σ is surface tension, a is bubble radius ρ, μ are magma density and viscosity, and u is local fluid velocity. Ratios of these forces define dimensionless groups of parameters, similar to Reynolds number, whose numerical magnitudes define important flow regimes; for example, one may expect that excess of vapor pressure over hydrostatic must considerably exceed pressure due to surface tension in order for rapid bubble growth to occur, that is $(p_v - p_h)/(2\sigma/a) >> 1$. Under such circumstances neglect of certain terms in the equation of motion may be possible. Fifteen dimensionless groups, not all equally important, can be formed from these quantities. The one just given is the inverse Weber number.

In Verhoogen's treatment of vesiculation, rate of rise is calculated from Stokes' law for a buoyant sphere, and rate of growth from a radial irrotational source flow. Energy is conserved by equating work done by the expanding perfect gas to kinetic energy of liquid, a requirement equivalent in this special case to satisfying the equation of motion for an inviscid fluid (Batchelor, 1967). The resulting inequality between rate of expansion and rate of rise is trivially satisfied for all reasonable values of parameters. The probable reason for failure to obtain useful limits by this procedure is the incompatability of the two flow regimes compared by the inequality. Each represents severe but totally different approximations to the real flow.

Stokes flow is a steady, creeping, viscous motion for which inertial forces are completely negligible, $Re \rightarrow 0$. Bubble sizes as inferred from cold lava samples, for example Green and Short (1971), are small. For the short run, gravitational effect, departures from sphericity and bubble-wake entrainment are neglected. The result underestimates the rate of rise.

On the other hand, the radial expansion represents the limit of an inviscid incompressible flow for which inertial forces are much larger than viscous, $Re \rightarrow \infty$. At hydrostatic pressures of 0.1 kb or higher, the perfect gas assumption will fail. With high variable viscosities neglect of viscous effects, for example shear stresses and viscous normal stresses, is not permissible. But perhaps most important, departures from radial flow and mutual interference of bubbles are not negligible as the bubble walls approach. The radial flow approximation clearly overestimates the rate of expansion, probably by many orders of magnitude. The radial expansion can only be approximately true when bubbles are small enough not to interact. Verhoogen's considerations of oversaturation and surface tension show that while bubbles are likely to be small, their volume ratios will not increase by more than a factor of 10^3. By symmetry each bubble is from the outset immersed in the radial flow of a myriad of others. The resulting induced flows tend to cancel out completely and will continue to do so until bubble walls approach within a few diameters. Beyond this point bubble interaction must be of decisive importance. Since Verhoogen's estimates of bubble growth span only a factor of ten in radius, the rate of growth estimate can apply only through the first one or two doublings of diameter, even if viscous effects can be ignored. The Verhoogen inequality compares two flows at opposite extremes of Reynolds number and can only be true sufficiently near time $t = 0$; so close, in fact, that it yields essentially no information worth using at later times.

McBirney and Murase (1970) taking note of earlier observations seem to visualize a nearly static vesiculation process in which rise of bubbles plays little part because it is so slow. Bubble expansion is supposed to continue up to a volume ratio of gas to liquid of approximately one, $v_g/v_l = 1.08$, a condition reached, if spheres centered on cubic lattice points expand until they become tangent. The liquid could lose continuity at this expansion ratio, although these authors point out that other conditions may have to be satisfied. If one attempts to fill in smaller tangent spheres at the cube corners and at the edge centers, the expansion ratio increases only to about 3.16. Therefore, if sphere sizes cluster closely about those inscribed in adjacent cubes, large expansion ratios are not likely ever to occur. When we consider the effects of viscosity later, it will be apparent that the fluid can be effectively trapped in complex channels bounded by the distorted spherical caps of adjacent bubble surfaces. Thus geometry and viscosity place an effective limit on expansion ratio.

In addition to the surface tension stress on bubbles, McBirney and Murase suggest that the liquid tensile strength for short-term stresses must be an important factor. This can be true under two conditions: either the vesiculated magma is cool and nearly rigid, or the stress of pressure release is very large, that is, the magma fragments during the passage of the first expansion wave. The first alternative is a nearly static situation where bubble growth can occur. The second is similar but on a much shorter time scale; fragmentation occurs in an interval comparable with $2a/c_l$ where a is bubble radius, and c_l is speed of sound in the liquid. Intermediate cases, which presumably constitute the great majority of flows, will allow vesiculation, as it is ordinarily understood, to occur by bubble growth and exsolution of volatiles. Here the fluid dynamic effects of viscosity must play the principal role, a fact that no author emphasizes sufficiently until now. We develop this idea more fully.

Viscosity of magmas is known to depend strongly on silica content, temperature, and dissolved volatiles such as water (McBirney and Murase, 1970; Bottinga and Weill, 1972; Shaw, 1972). Of great importance for vesiculation theory is the noticeable trend that as a magma cools and exsolves steam its viscosity increases very rapidly. The effect is much larger for rhyolites than for basalts; for the former it may change by a factor of 10^9, for the latter by no more than 10^3. The variations in water content for this range of values can be as large as 10 percent; whereas for actual magmas, total water content and variation can be much smaller. The effects of other volatiles such as CO_2 on viscosity are not well known but may be important (Tazieff, 1970) and for the present will be assumed to be similar to those of water.

The effects of viscosity in a flow are felt in two major ways, namely, by dissipation associated with dilation and by frictional effects in shear flow.

When a bubble filled liquid undergoes a uniform dilatation it exihibits an effective expansion viscosity κ which may be much larger than the shear viscosity μ (Batchelor, 1967, p. 154, 253, 479). At the bubble surface there is a normal shear stress, $\sigma_{rr} = -2\mu\ (\partial u_r/\partial r)_{r=a}$, which opposes the expansion just as do the hydrostatic and surface tension pressure. The cumulative effect of the normal shear stresses gives rise to a non-equilibrium pressure in the liquid, $p - p_e = K\Delta$; where $\Delta = \nabla \cdot u$ is the dilatation. While the radial expansion about a bubble is irrotational and free of shearing friction as Verhoogen points out, normal stresses are still present and give rise to non-equilibrium effects of dilation. For spherical bubbles and uniform dilatation, $p - p_e = 4\mathring{a}/a$; $\mathring{a} = da/dt$. The same result is obtained from a calculation of the shear stress except for sign. If, following Verhoogen, we take typical bubble size to be $a = 10^{-4}$ cm and assume growth to that size in 10^{-3} sec, then $\mathring{a}/a = 10^3\ \text{sec}^{-1}$. With an intermediate $\mu = 10^5$ poise (dyne sec/cm^2) we obtain a normal stress, or dilatational pressure increment, of 0.4 kb, a value that suggests that viscous forces may significantly impede rapid bubble expansion. In their discussion of various pressure terms operative during bubble expansion, McBirney and Murase (1970) introduce the viscous normal stress as given above but without explanation and in an obscure way. In estimating its size they evidently consider much slower rates of bubble growth and smaller viscosity values than those used here.

The second major effect of viscosity is friction produced in regions of shear flow. As bubbles grow the flow between them departs from radial symmetry and must ultimately become like shear flow through a network of tortuous cusped channels. For steady flow in a circular pipe of a fluid with constant viscosity and under constant pressure gradient (Poiseuille flow), the speed varies like $1/\mu$. If one can accept that the transverse viscous flow between approaching bubble boundaries is similar to Poiseuille flow, at least in its dependence on μ, then clearly as the bubbles grow their rates of rise and of expansion must be enormously affected by changes in shear viscosity. There are two ways in which they may occur.

If the expansion is adiabatic and furthermore performs work in lifting the vesiculating mass, the temperature must fall, and viscosity will increase. As pressure drops or bubble size increases, volatiles will exsolve from the magma through the walls. Adjacent regions of liquid are depleted in volatiles *via* diffusion. A nonlinear gradient of volatile content and of viscosity coefficient will result. Both normal stresses and shear flow stresses will be linearly increased by the corresponding increases in viscosity coefficient. The resulting concentration gradient between bubble surfaces will be accompanied by viscosity gradients perhaps as high as 5 to 8 orders of magnitude in rhyolite melts and 2 orders in basalts. Since bubbles may not grow unless the fluid between is pressed out, and since the speed of the channel flow goes as $1/\mu$, vesiculation times will likely increase by similar orders of magnitude thereby becoming inaccessible to observation. We seem to have in the combined effects of variable viscosity and variable volatile content an efficient, and sufficient, mechanism for prevention of rapid bubble growth. Unless gradients remain high, vesiculation can proceed only up to the point where all remaining incompressible fluid is effectively frozen by viscous resistance into the network of interconnecting channels.

If pressure gradients remain high at this stage and a free surface exists, a new mode of disintegration can occur. At the free surface thin bubble walls will burst outward toward the much lower ambient pressure. Pressure relief in the outermost bubbles will subject these immediately underneath to an expansion wave, and these will burst outward also. The expansion propagates inward, bursting wall segments as it goes until the viscous channel flow through the interconnected burst bubbles sustains a pressure drop equal to the gradient. Specimens of Hawaiian basalt show burst bubble walls into the interior as just described. I have seen a specimen of more silicic vesiculated lava that when oriented by hand shows that all the surface bubbles had burst in a particular direction. If the vesiculated magma is still molten when the pressure drop occurs, the fluid will disintegrate into ropy, stringy filaments, possibly forming Pele's hair, by entrainment in the gas flow as bubble walls burst. Thus a type of expansion wave is not only possible but also may be necessary for rapid disintegration of a vesiculating magma. Coalescence does not seem to be a factor of importance.

McBirney and Murase do not remark on the enormous changes in flow speeds implied by the viscosity curves. Instead, they propose that vesiculation is hindered by surface tension changes caused by variable contamination of bubble surfaces by impurity molecules similar to those that produce detergent frothing. They apply the classical explanation of detergent effects to account for the reluctance of magma bubbles to coalesce. Content of volatiles does not seem to have a strong effect on magma surface tension. The effect may be noticeable, but surface tensions are typically only a few hundred dyne/cm. Order of magnitude variations such as occur in viscosity coefficient cannot occur except toward zero. Such changes might conduce to ease of frothing but not toward coalescence. The answer seems to lie elsewhere.

With large pressure release on a nearly incompressible liquid, only very small expansions are necessary to compensate. If the liquid contains a small percentage of volatiles which exsolves into bubbles, the volume change will be larger but only enough to accommodate expansion of the gas to the new lower pressure. Since bubble volumes grow with radius cubed, a ratio of about 10 is sufficient to reduce kilobar initial pressures to ambient atmospheric values. The interstitial fluid need expand very little. Thus, bubbles may grow and take on eccentric shapes as equilibrium is approached. Unless both a free surface and sizeable pressure gradients exist no disruption of the magmas is to be expected. Without a free surface, existing pressure gradients will merely cause transient expansion waves, cavitation, and recompression of the fluid. With a free surface but mild pressure gradients, an effusing, vesiculating magma can occur with comparatively little disruption and ash formation.

The evidence appears to be weak that bubble coalescence is a necessary condition for magma disintegration. The experiments of McBirney and Murase (1970) may even be taken as evidence that coalescence does not occur. If this interpretation is allowed, coalescence may be discounted as a process in magma fragmentation. From the argument just given, three necessary conditions for explosive magma fragmentation must be (1) volatile content sufficient to produce a high internal vapor pressure at the magma temperature, (2) a free surface at low pressure, and (3) pressure gradients arising fom expansion waves. Actually, item (3) follows from the fluid dynamic implications of (1) and (2) but may need explicit statement to focus attention on the necessity of large gradients to produce violent motions. Previous vesiculation theory has hinted at these conditions on pressure but not developed the ideas far enough to show that coalescence may play no role in fragmentation.

EXPANSION AND VAPORIZATION

When a vesiculated magma disintegrates explosively or a condensed magma dynamically vaporizes an expansion must take place. The central assumption of vaporization wave theory is that a high temperature, condensed fluid suddenly released will undergo an unsteady, simple-wave expansion of the type already known in conventional shock-tube flow (Courant and Friedrichs, 1948). In the shock tube the one-dimensional expansion of the compressed driver gas creates and drives a shock wave ahead of the contact surface between driver and ambient gas. The driver gas expands through an unsteady simple wave from the high reservoir pressure to that of the flow behind the shock, in the process both accelerating and decreasing in density.

The same general type of expansion must occur in explosive volcanism except that the fluid expands into a half space, that is, spherical geometry rather than one-dimensional flow in a tube, and the initial condition of the driver fluid is presently obscure. We can discern at least three possibilities. A plenum of permanent gases or high temperature volatiles compressed above a rising column of magma expands after bursting through the surface, in which case the flow resembles that of gases in a spherical sector shock tube. The case of a solid or molten, vesiculated magma at high pressure is somewhat similar, although the expanding flow quickly becomes that of a dusty, particle laden gas. Noticeable relaxation effects will occur in the driver fluid behind the contact surface, as particles are accelerated to flow speed by drag forces (Rudinger and Chang, 1964; Rudinger, 1973). In the third case the driver fluid is initially a molten, condensed magma at high pressure owing to the presence of volatiles. When sudden pressure release occurs, the fluid may expand along adiabats into the two-phase field of its state equation, partially vaporizing in the process. During the unsteady flow, the partially vaporized magmatic fluid cools and expands to the point that its volatile components successively condense into liquid or solid particles which are then accelerated and carried in the flow of the remaining permanent gases.

One fundamental feature of the unsteady expansion common to all the alternatives is the shock wave driven ahead of the contact surface. Now shock waves are observed during explosive volcanisms (see pl. 9-B of Green and Short, 1971) according to Perret, but they have not been studied in any great detail and implicitly are believed to be rare or of no great importance. On the contrary, a shock wave must appear ultimately ahead of every unsteady expansion through a finite pressure difference providing the reservoir is large enough. Shock waves are *prima facie* evidence of underlying simple wave expansions. Any very loud volcanic explosion may be presumed to comprise both shock and expansion waves.

While vesiculation theory attempts to avoid problems of nucleation by presupposing small bubbles already exist, the problem at first glance does not appear to arise in vaporization wave theory because expansion begins at the surface of contact between two fluids, magma and gas, of greatly different densities. The surface ideally may be considered free, and evaporation of molecules from it unhindered by problems of nucleation and cavity formation which dominate events interior to the fluid. Experience with impulsively vaporized pure metals in experiments with exploding wires shows that density is not uniform behind the contact surface during the process of expansion and shock formation, but the fluid takes the form of striations which appear like ragged, narrow cavities forming initially at the contact surface and propagating inward (Thomer, 1953; Müller, 1957; Fansler and Shear, 1968). The fluid dynamic and molecular kinetic aspects of striation formation are not well understood. One is tempted to say that the nucleation problem has been exchanged for the striation problem.

While vaporization waves can be related convincingly to high-temperature, free expansion of pure metals, and there are general arguments supporting the view that all high temperature, condensible fluids should show vaporization wave phenomena, other examples in ordinary laboratory experience are not easy to find. The two-phase shock tube using water or other condensible fluids such as the freons has not been very much developed. The only experiments with the steam shock tube are at such low temperatures that the vaporization wave speed is small and the expansion process is obscured by competing phenomena involving slug flows, cavity formation, and gross liquid motions. The possible applications to problems of volcanism and geyser activity may provide impetus for further development of these laboratory tools.

SUMMARY

Present views of volcanic ash formation are based on two major alternative types of fluid motions. These are represented by ideas related

to vesiculation and vaporization. In terms of continuum fluid mechanics, vesiculation appears to be mainly a small Reynolds number theory while vaporization wave theory is not. Upon closer examination it appears that vesiculation compares a slow viscous Stokes flow with an inviscid source flow in which inertial terms dominate, a contradictory procedure. Critical examination of the vesiculation process shows that the effects of variable viscosity owing to cooling and loss of volatiles are likely to place stringent limits on bubble growth and coalescence, practically eliminating the latter as a factor of any importance.

The methods proposed here by which a magma fragments or recondenses into particles of various sizes, including fine ash, all depend on the presence of pressure gradients. When these are caused by pressure release at a free surface, the various forms a magma or its vapors may initially take will all be more or less rapidly reduced to ash. These forms include gases and saturated magma vapor trapped over a rising column, vesiculated magma in solid or molten state with included bubbles at high pressure, and wet magma containing volatiles at high vapor pressure.

References

Batchelor, G. K., 1967, An Introduction to Fluid Dynamics: New York and London, Cambridge Univ. Press, 615 p.

Bennett, F. D., 1971, Vaporization waves in explosive volcanism: Nature, v. 234, p. 538-539.

Bottinga, Yan, and Weill, D. F., 1972, The viscosity of magmatic silicate liquids: a model for calculation: Am. Jour. Sci., v. 272, p. 438-475.

Courant, Richard, and Friedrichs, K. O., 1948, Supersonic Flow and Shock Waves: New York, Interscience Publishers, Inc., 464 p.

Green, Jack, and Short, N. M., eds., 1971, Volcanic Land Forms and Surface Features, a Photographic Atlas and Glossary: Berlin, Springer-Verlag (no page numbers).

Fansler, K. S., and Shear, D. D., 1968, Correlated X-ray and optical streak photography of exploding wires, *in* Chace, W. G. and Moore, H. K., eds., Exploding Wires, v. 4: New York, Plenum Press, 348 p.

Lang, A. R., 1972, Gradient of pressure and temperature in ascending magmas: Nature Phys. Sci., v. 238, p. 98-100.

Meyer, J. D., 1972, Glass crust on intratelluric phenocrysts in volcanic ash as a measure of eruptive violence: Bull. volcanol., v. 35, p. 358-368.

McBirney, A. R., 1963, Factors governing the nature of submarine volcanism: Bull. volcanol., v. 26, p. 455-469.

McBirney, A. R., and Murase, T., 1970, Factors governing the formation of pyroclastic rocks: Bull. volcanol., v. 34, p. 372-384.

McClaine, L. A., Allen, R. V., McConnell, Jr., R. K., and Suprenant, N. F., 1968, Volcanic smoke clouds: Jour. Geophys. Research, v. 73, p. 5235-5246.

McGetchin, T. R., and Ullrich, G. W., 1973, Xenoliths in maars and diatremes with inferences for Moon, Mars and Venus: Jour. Geophys. Research, v. 78, p. 1832-1853.

Müller, Werner, 1957, Der ablauf einer electrischen drahtexplosion, mit hilfe der Kerrzellen-kamera untersucht: Zeitschr. Physik, v. 149, p. 397-411.

Piper, J. D. A., and Gibson, J. L., 1972, Stress control of processes at extensional plate margins: Nature Phys. Sci., v. 238, p. 83-87.

Rudinger, George, 1973, Wave propagation in suspensions of solid particles in gas flow: Appl. Mech. Revs., v. 26, p. 273-279.

Rudinger, George, and Chang, Angela, 1964, Analysis of nonsteady two-phase flow: Physics Fluids, v. 7, p. 1747-1754.

Shaw, H. R., 1965, Comments on viscosity, crystal settling and convection in granitic magmas: Am. Jour. Sci., v. 263, p. 120-152.

——— 1972, Viscosities of magmatic silicate liquids, empirical method: Am. Jour Sci., v. 272, p. 870-893.

Tazieff, Haroun, 1970, New investigations on eruptive gases: Bull. volcan., v. 34, p. 421-439.

Thomer, G., 1953, Wirkungsweise und anwendung eines doppel-Röntgen-blitze-rohres., Zeitschr. angew. Phys., v. 5, p. 217-221.

Verhoogen, John, 1951, Mechanics of ash formation: Am. Jour. Sci., v. 249, p. 729-739.

Van Dyke, Milton, 1964, Perturbation Methods in Fluid Mechanics: New York, Academic Press, 229 p.

Weertman, Johannes, 1971, Theory of water filled crevasses in glaciers applied to vertical magma transport beneath oceanic ridges: Jour. Geophys. Research, v. 76, p. 1171-1183.

Wegener, P. P., Clumpner, J. A., and Wu, B. J. C., 1972, Homogeneous nucleation and growth of ethanol drops in supersonic flow: Physics Fluids, v. 15, p. 1869-1876.