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MODELS OF VOLCANIC ERUPTION HAZARDS

Kenneth H. Wohletz

Earth and Environmental Science Division
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

Volcanic eruptions pose an ever present but poorly constrained hazard to life and property for geothermal installations in volcanic areas. Because eruptions occur sporadically and may limit field access, quantitative and systematic field studies of eruptions are difficult to complete. Circumventing this difficulty, laboratory models and numerical simulations are pivotal in building our understanding of eruptions. For example, the results of fuel-coolant interaction experiments show that magma-water interaction controls many eruption styles. Applying these results, increasing numbers of field studies now document and interpret the role of external water in eruptions. Similarly, numerical simulations solve the fundamental physics of high-speed fluid flow and give quantitative predictions that elucidate the complexities of pyroclastic flows and surges. A primary goal of these models is to guide geologists in searching for critical field relationships and making their interpretations. Coupled with field work, modeling is beginning to allow more quantitative and predictive volcanic hazard assessments.

INTRODUCTION

Prediction of a volcanic eruption requires information on the periodicity and precursor activity for any given volcano that poses a potential hazard to a geothermal installation. Generally, this information is not available for most active and dormant volcanoes. In addition to knowledge of when an eruption will occur, the characteristic hazardous phenomena that accompanies the eruption must be evaluated in order to establish the severity of the hazard and zones of relative safety around the volcano.

Several statistical approaches have been developed for predicting the periodicity of an eruption. These methods primarily include, for example, techniques that evaluate the volume of previous eruption products, their absolute ages, and some statistical analysis (Decker, 1986; Wickman, 1976; Mann, 1988; Carta and others, 1981; Crowe and others, 1982).

The character of potential eruptions is determined by study of stratigraphy in which individual dated eruptive units are interpreted as to their explosive or effusive nature and the areal extent of their dispersal from the volcano. On the basis of this analysis, hazard zonation maps are created which designate areas around the volcano that would likely be affected by each of the recognized eruptive types (for example, Miller and others, 1982). Precursor activity is paramount in establishing short-term forecasts of eruptions and such activity is based on geophysical evidence and changes in hydrothermal manifestations and vent behavior (for example, Dzurisin and others, 1983; Newhall, 1984; Swanson and others, 1983).

All of the preceding techniques require prompt access to the volcano in question and considerable field study to establish baseline behavior. Modeling techniques compliment these approaches by allowing considerable assessment of risk to be accomplished rapidly and also provide prediction of hazard severity and character where field data are incomplete. In this paper, I discuss models based on laboratory experiments of magma/water interaction and numerical simulations in order to illustrate their capabilities in predicting styles of eruption and quantifying their effects.

HYDROVOLCANISM MODELS

Over the last decade, volcanologists have been increasingly documenting the important role of external water in volcanic eruptions. Sheridan and Wohletz (1983) reviewed water/magma interaction (hydrovolcanism) theory. This theory is based on laboratory models in which a magma simulant was introduced to water and the resulting vapor explosion documented. The major finding of these experimental models (Wohletz and McQueen, 1984) was that the explosivity and nature of melt fragmentation and dispersal were strongly controlled by the mass ratio of water to melt (Fig. 1). Later, Wohletz

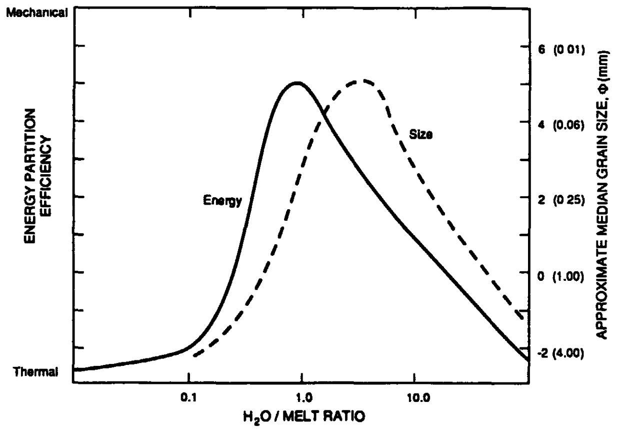

Figure 1. Results of water/magma interaction experiments are plotted showing the effect of water:melt mass ratio on explosive energy and fragment size (adapted from Frazzetta et al., 1983).

(1986) theoretically supported this result by thermodynamic calculations, and applications of the theory allow geologists to predict eruptive characteristics based upon the hydrologic environment of a volcano (Fig. 2).

Where volcanic edifices are highly saturated with ground or surface water, there is a strong likelihood of Vulcanian or Surtseyan eruption (blasts) that have a high destructive potential even characterized by the production of pyroclastic surges for small volume eruptions of volatile-poor magma. Another hazard common to Vulcanian eruption is production of lahars from condensation of the abundant moisture emplaced with volcanic products. If magmas of a volcano are typically volatile-rich, water interaction can result in very powerful phreatoplinian eruption that produces both extensive ash fallout and pyroclastic flow deposits.

NUMERICAL SIMULATIONS

Numerical simulations of volcanic eruptions have been developed at Los Alamos National Laboratory over the last decade utilizing the Cray computers and adaptations of codes developed and tested for calculating weapons effects (Wohletz and Valentine, 1989). Where knowledge of eruptive type (such as that described by hydrovolcanism models), vent diameter, and magma volume can be prescribed, results of numerical

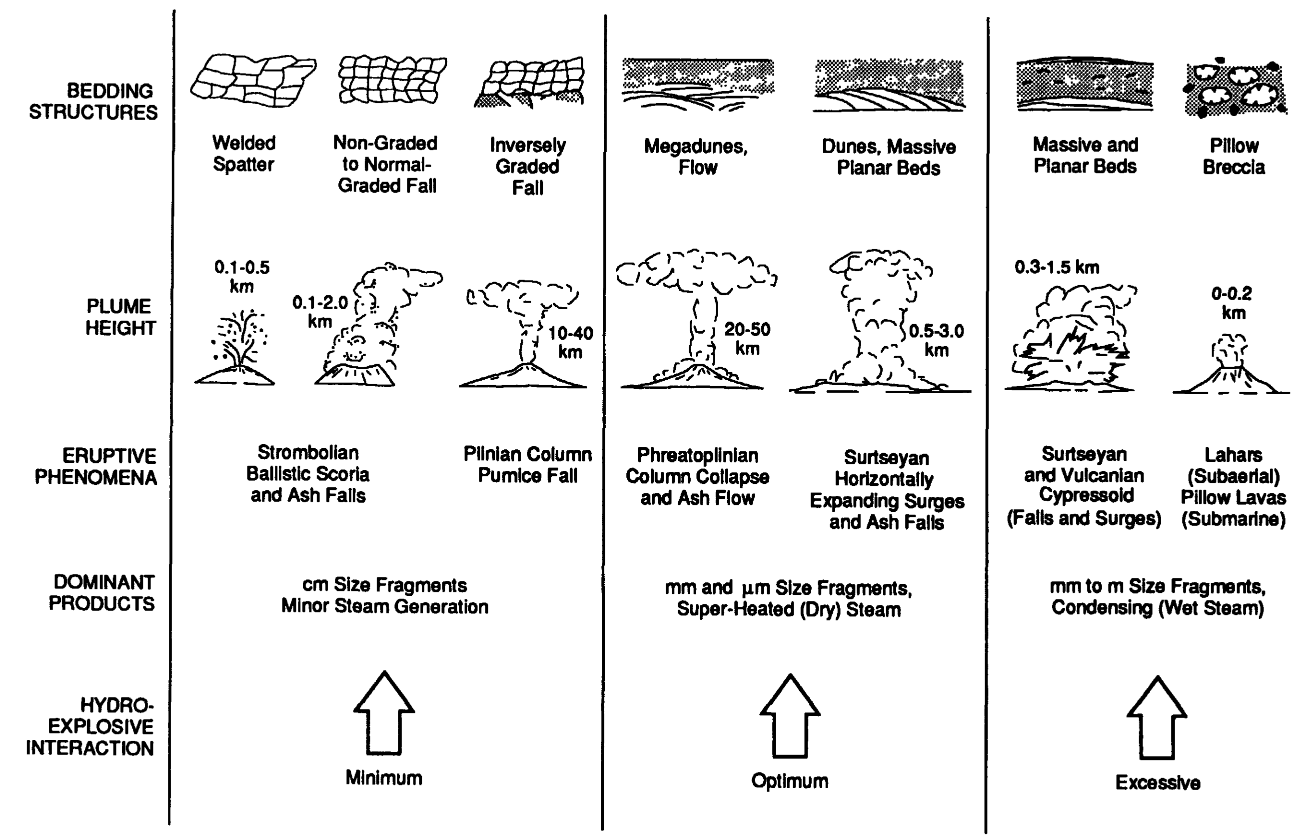

Figure 2. The relationships of volcanic activity are schematically related to the abundance of ground water in and around the volcano (adapted from Sheridan and Wohletz, 1983).

calculations show with high precision the spatial and temporal variation of important physical parameters during an eruption. For any location, one can model the amount of fallout from Plinian style eruptions and the velocities, dynamic pressures, and temperatures of pyroclastic flows and surges moving downslope from a volcano.

The simulations are based upon solution of the full set of Navier-Stokes equations for the separated flow of compressible gas and particle mixtures. For example, the conservation equations for the gas phase are written:

$$\frac{\partial\left(\theta_g\rho_g\right)}{\partial t}+\nabla\cdot\left(\theta_g\rho_g\mathbf{u}_g\right)=J \quad , \tag{1}$$

$$\begin{aligned}\frac{\partial\left(\theta_g\rho_g\mathbf{u}_g\right)}{\partial t}+\nabla\cdot\left(\theta_g\rho_g\mathbf{u}_g\mathbf{u}_g\right)&=-\theta_g\nabla p\\&+K_g\left|\Delta\mathbf{u}\right|+J\mathbf{u}_g+\theta_g\rho_g g-\nabla\cdot\tau_g \quad ,\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial\left(\theta_g\rho_g I_g\right)}{\partial t}+\nabla\cdot\left(\theta_g\rho_g\mathbf{u}_g\mathbf{u}_g\right)&=\\-p\nabla\cdot\left[\theta_g\mathbf{u}_g+\theta_s\mathbf{u}_s\right]+R_g+\left|K_g\right|\left(\Delta\mathbf{u}_g\right)^2&\\+J_e-\tau_g:\nabla\mathbf{u}_g \quad ,&\end{aligned} \tag{3}$$

where the subscripts g and s denote parameters for the gas and solid phases respectively, θ = the phase volume fraction, ρ = density, $\mathbf{u}$ = velocity vector ($\Delta\mathbf{u}$ = the difference between the velocities of the two phases), J = the mass exchange rate between phases (subscript e denotes the energy of phase change), p = pressure, τ = Reynolds stress tensor, I = specific internal energy, R = heat exchange between phases, and K = momentum exchange between phases. When written for both phases and using appropriate closure equations, the solution involves 16 equations with nonlinear term included and 16 unknowns cast into finite difference form and solved for 2-D cylindrical or Cartesian coordinate systems. A typical calculation requires several hours of Cray X-MP time and produces over 20,000 pages of tabulated data that can be then converted to graphical display or video animations.

In cases where eruptions are initially overpressured in the vent, numerical simulations predict a blast-type eruption that sends a shock wave out of the vent followed by ground surges of ash (Fig. 3).

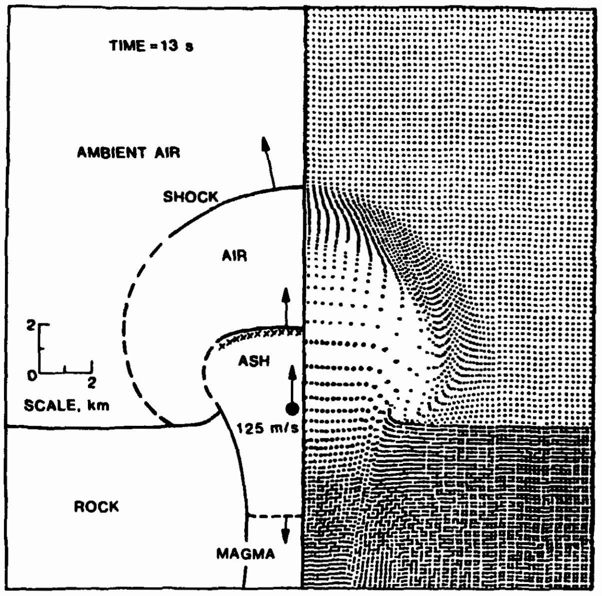

Figure 3. Representation of a volcanic blast eruption predicted by numerical simulation of an overpressured eruption. The right-hand side of the plot shows calculated ash and atmospheric marker particles (Wohletz and others, 1984).

Continuous emission of ash and gas from the vent produces a Plinian eruption column that disperses fallout ash over a relatively wide sector (Fig. 4). As the pressure at the vent decreases to atmospheric levels and the vent widens, the Plinian column will collapse and produce pyroclastic flows in a fountain-like structure (Fig. 5). In cases where magma silica and volatile contents are low,

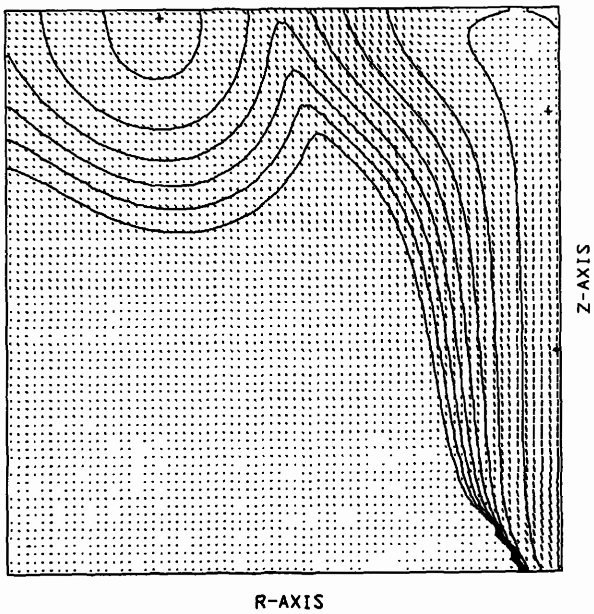

Figure 4. Simulated Plinian eruption column portrayed as contours of volume fraction of volcanic ash. Dots and lines are nodal dust velocity vectors. Note axisymmetry around the vent (lower right) and the 7X7 km calculational regime.

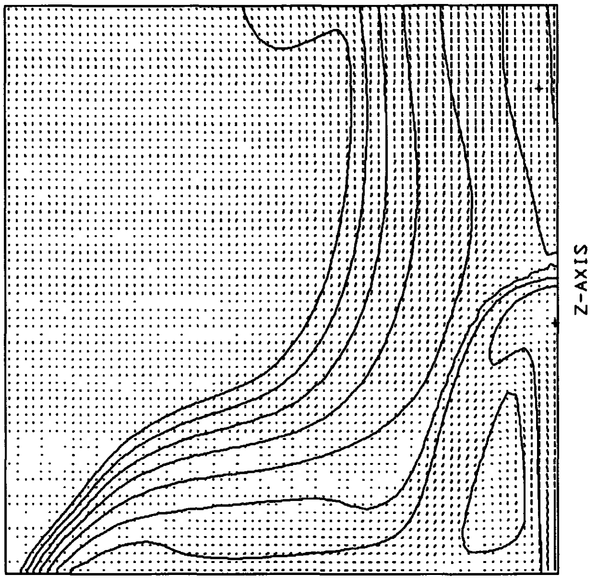

Figure 5. A simulated pyroclastic flow is shown as in Figure 4 with contours of ash concentration. For each point in the grid, various flow parameters may be obtained for hazard assessment.

Strombolian scoria eruptions are simulated. By taking into consideration general knowledge of a volcanoes magmacomposition, typical eruptive volumes, and vent size, these simulations predict the magnitude and area of hazardous effects to be expected. For example, the distance from a volcano where the dynamic pressure of pyroclastic surges or flows is above that required to damage buildings can be determined.

DISCUSSION

Models of volcanic eruption hazards are becoming more sophisticated and should be considered as an important part of hazard evaluation at geothermal installations near volcanoes. Their application compliments more traditional approaches by providing more quantitative measures of hazard. Where extensive field studies are lacking or difficult to obtain, models provide at least some information that can be used to construct hazard zonation maps.

A needed improvement to the numerical simulations described is the ability to incorporate accurate representations of a volcano's topography, since variations in slope greatly affect the runnout of pyroclastic flows and surges (Sheridan, 1979). At present, only simplified topographic simulations are achieved by the methods described above, but the capability to do fully 3-D models can be developed. In the mean time, an analytical approach to modeling topographic effects by using the energy-line method (Malin and Sheridan, 1982) has already been widely tested and can be suitably applied to results of the numerical simulations (for example, Wadge and Isaacs, 1988).

With the rapidly growing capabilities of personal computer systems, the potential of transporting numerical codes from supercomputers is very real and may be only a year or two away.

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