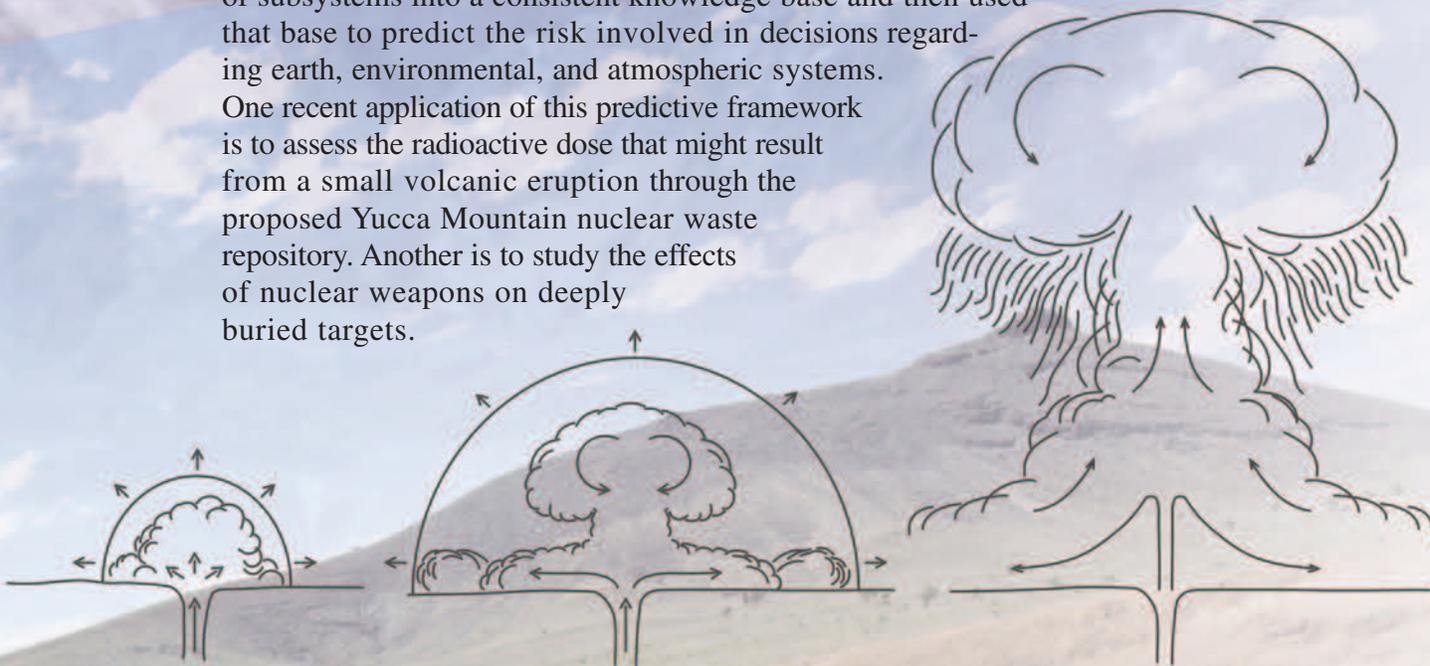


# Predicting Risks in the Earth Sciences

## *Volcanological Examples*

*Greg Valentine*

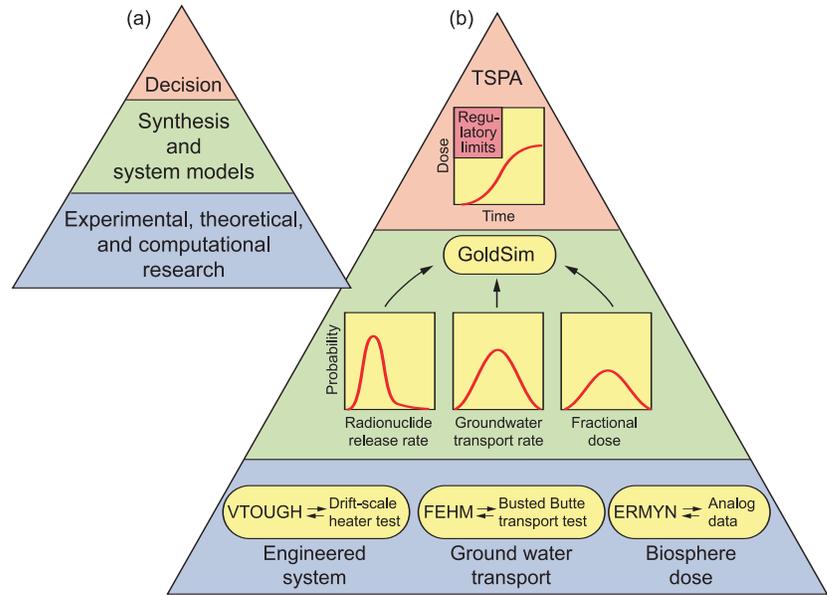
Where can nuclear waste be safely placed? How can humans better manage natural resources? How can humans prevent manmade disasters and prepare for natural ones? Sound decisions require knowledge of the subsystems in each problem and a reliable decision-making framework. Over the last several decades, earth scientists at Los Alamos have integrated experiment, observation, and modeling of subsystems into a consistent knowledge base and then used that base to predict the risk involved in decisions regarding earth, environmental, and atmospheric systems. One recent application of this predictive framework is to assess the radioactive dose that might result from a small volcanic eruption through the proposed Yucca Mountain nuclear waste repository. Another is to study the effects of nuclear weapons on deeply buried targets.



(Left to right) First three photos are courtesy of J. Hughes, J. Franklin, and R. McGimsey, respectively. The last photo is courtesy of the U.S. Geological Survey.



**P**rediction is at the heart of applying earth science to issues of importance to society. A common application of predictive earth sciences is weather forecasting, which is particularly important to mitigating the consequences of severe weather. Other applications include global climate change, availability and quantities of natural resources, natural disaster planning and mitigation, performance of geologic repositories, and nuclear weapon effects. Each of these applications involves systems that are composed of many subsystems; for example, global climate change depends on cloud physics, mass and energy transport between the biosphere and atmosphere, ocean dynamics, and anthropogenic processes, to name only a few. These subsystems may be coupled to each other through nonlinear processes and across a wide range of time and space scales. Data on the subsystems are collected at varying resolutions, and none of the subsystems is fully characterized; in addition, many of the predictions we are interested in often involve extreme rather than normal conditions for the systems or subsystems. All these aspects contribute to an inherent uncertainty in predictions. Finally, the only information we have on the behavior of fully coupled systems, such as climate, is historical; we cannot do controlled experiments on the full systems. Significantly, all the features mentioned above, namely, nonlinearly coupled subsystems, multiple scales, uncertainty, extreme conditions, and an inability to experiment on full systems (except for analyzing



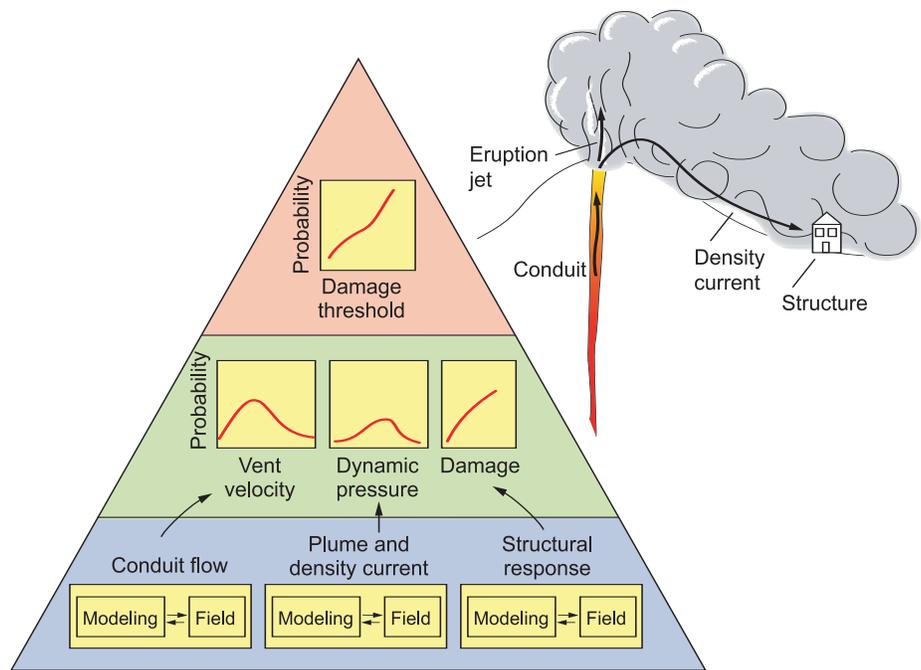
**Figure 1. Framework for Predictive Earth Sciences**

(a) The framework for predictive earth sciences illustrates the foundation in fundamental experimental, observational, and theoretical and/or computational research on the basis of which decisions are made. (b) Illustrated at right is a specific example for predicting dose from potentially contaminated ground water at Yucca Mountain, showing some components of the multiple-barrier repository system that have been studied in detail by combined experimental and theoretical approaches. For example, the engineered part of the system includes, among other things, the walls of tunnels (or drifts) in the mountain that will experience heating (due to the radioactive decay of the waste) and resulting mass transfer processes. These have been studied with the VTOUGH code coupled with observations from a full-scale test (drift-scale heater test), whereby mock waste packages were emplaced in a tunnel and heated, while the temperature and mass transport were monitored in the tunnel walls. The next barriers that leaking radionuclides would encounter is the thick zone of unsaturated (pore spaces are not completely filled with water) rocks above the water table and then by the saturated zone below the water table, which provides a pathway to a hypothetical future population some 18 km away. Tests such as the Busted Butte transport test, in which surrogates for radionuclides were injected into unsaturated rocks and their migration was monitored, are coupled with codes (for example, the Los Alamos FEHM code) that simulate the detailed physics of flow and transport through rocks. Finally, studies have been conducted to determine the potential radioactive dose a human might receive from any radionuclides that might have migrated sufficiently far. Those studies combined the dose code ERMYN with analog information (for example, studies of dose from atmospheric nuclear testing fallout). The results and uncertainties of these subsystem studies and detailed predictions are then abstracted and integrated with a simulation package (Goldsim) produced by the GoldSim Technology Group, LLC, to produce a prediction of dose as a function of time.

historical data) are similar to the core features that make predicting the reliability of our nuclear weapons stockpile a challenging process (Valentine 2003).

Predictive earth sciences involve the integration of experiment, observation, and modeling to form the basis for decisions involving earth, environmental, and atmospheric systems. Figure 1(a) illustrates the main elements of predictive earth sciences in the form of a pyramid. The foundation for predictions is built upon fundamental experimental (including observations), theoretical, and computational research into the behavior of individual subsystems and, as appropriate, the coupling between them. For some subsystems, the necessary information can be obtained from experimental data, but most of the complex subsystems that we work with involve an iterative approach among experiment, observation, theory, and computation. Once we have an adequate understanding of the important subsystems, we synthesize and simplify that information, accounting for uncertainties, and build it into a system model. The system model accounts for all the couplings between subsystems and their uncertainties, and produces a probabilistic prediction of system behavior that can be used for decision-making.

Figure 1(b) illustrates this framework with a specific example from predicting the performance of a high-level radioactive waste repository at Yucca Mountain, Nevada. Nuclear Regulatory Commission regulations define repository performance in terms of radiation dose to a human population at a location 18 kilometers south of the repository over a period of 10,000 years. In the absence of an unusual, disruptive event, a dose can be received only if radionuclides escape through a series of engineered and natural barriers. Among the engineered barriers are glass or ceramic



**Figure 2. Predicting Volcanic Risk to Buildings**

The predictive earth-science framework shows some of the important components used for predicting risk to buildings from explosive volcanic eruptions. Among these components are the dynamics of flow up the volcanic conduit (red), which determines the initial and boundary conditions for an eruption, the rise and collapse of an eruption jet or volcanic plume and the resulting pyroclastic density current (gray), and the response of building structures to the conditions produced by the currents. Predictions of these individual components, combined with the probability of a volcanic event and with other components that are not discussed here, must ultimately be integrated to produce a probabilistic prediction of damage thresholds that might be exceeded in developed areas around a volcano.

pellets embedded with radioactive spent fuel, cladding that covers the waste, and storage canisters containing spent fuel rods laden with highly radioactive fission products. Water may eventually seep through the repository, corrode the canisters or cladding, dissolve the radionuclides, and carry them into the surrounding rocks. At that point, Mother Nature will have to help contain the waste. Three key natural features make Yucca Mountain desirable as a burial site for nuclear waste: its dry climate, deep water table, and thick water-unsaturated rocks above the water table. The first minimizes water that could seep through the repository and eventually corrode the waste canisters. The second enables building a repository that is deep underground

(300 meters) yet still well above the water table, which is another 240 to 300 meters lower. The third natural feature is a thick zone (several hundred meters thick) of water-unsaturated rocks containing clays, zeolites, and other minerals that adsorb numerous radionuclides and thus effectively slow down leakage of radionuclides into the water table.

If, in spite of these features, radionuclides were to be transported by ground water to the control population, the contaminated water might then be pumped and used for drinking or irrigation of crops, which are pathways for human dose. Within the predictive-earth-sciences framework, each of these barriers or steps in the movement of radionuclides is a subsystem, some of which are shown in Figure 1.

Each of these subsystems has been studied through a closely integrated series of experiments and/or analog observations and through numerical modeling. For example, processes associated with coupled heat (from radioactive decay), which occur in the engineered part of the system fluid flow, in porous and fractured rocks, and in reactive chemical transport within those fluids, have been approached with an experimental program known as the Drift-Scale Heater Test and with the computer code VTOUGH. The test is a full-scale mockup of a heated waste package placed in a tunnel, where instruments measure mass and energy fluxes in the surrounding rocks; the computer code was written at Lawrence Berkeley National Laboratory and was modified by researchers at Lawrence Livermore National Laboratory to simulate the engineered barrier system.

Ground-water flow and radionuclide transport within the unsaturated zone beneath the repository have been studied from results of field-scale experiments such as the Busted Butte transport test and with the finite element heat and mass (FEHM) transport code (Eckhardt et al. 2000). The latter has also been used to study the saturated zone. Actual conversion of the transported radionuclides into human dose has been constrained with analog data and the ERMYN code (BSC 2004). In the simplest sense, the predictions of each of these subsystems are cast into probability distributions of the parameters of interest—for example, the rate of radionuclides released from the engineered system, the rate of radionuclide transport by ground water to the human population, and the fraction of radionuclides from that ground water that is taken in by humans as dose. The probabilistic approach allows us to incorporate the uncertainties inherent in each subsystem. These distributions are then sampled with a Monte Carlo software

engine (for example, GoldSim, which was developed by the GoldSim Technology Group) to produce a simple plot of dose to humans as a function of time, as shown at the top of the diagram. If the predicted dose (which might be the mean value of a large number of realizations, representing uncertainties) crosses over the regulatory limit (represented by the yellow box), the repository is not feasible. Thus, a large amount of complex science on the behavior of numerous subsystems is boiled down into a simple answer, which is directly used by decision makers. The framework shown in Figure 1 is iterative between the apex and the base—in other words, the framework can be reversed to decide which subsystems produce the greatest sensitivity in the final result and therefore might need further research to reduce uncertainties.

The predictive-earth-sciences framework is also being applied to assessing risk from explosive volcanic eruptions. The main body of this article will cover a few of the important components of the volcanic risk problem (see Figure 2). Ultimately, risk is determined by the probability of an event occurring, combined with the probability of damaging effects on humans, buildings, or other infrastructure (Perry et al. 2000; Valentine 1998 and 2003). A chain of events, or subsystems, determines the damaging effects, such as flow of magma up a conduit in the earth's crust, eruption into the air as a jet of gas and particles or clots of magma, and subsequent flow of that mixture across the landscape as a density current. The next few sections will describe models of the three subsystems. Although they are work in progress, our models demonstrate the synergy that must exist among theory, experiment, observation, and computation when predicting complex systems. The last section will also show results of an

integrated volcanic-risk assessment that follows the predictive-earth-science framework but with simpler subsystem models than the ones referred to above. This assessment combines both probability of occurrence and the consequences of a potential volcanic event at the proposed Yucca Mountain, Nevada, high-level radioactive waste repository. Finally, the article will discuss how the predictive-earth-science framework can be applied to other problems of importance for both military application of nuclear weapons and energy security.

### Conduit Flow Models and Quantification through Field Studies

Eruption processes are determined by the velocity, pressure, temperature, and gas content of material exiting a volcanic vent; these, in turn, are determined by processes in the subsurface. At some depth beneath a volcano (typically between 5 and 30 kilometers), magma accumulates in what is typically referred to as a magma chamber. The magma, which is a mixture primarily of silicate melt, crystals, and bubbles, will contain several dissolved gases, or volatiles, of which water (H<sub>2</sub>O) is the most abundant in most cases. As magma rises through a conduit toward the earth's surface, it experiences successively lower pressures with decreasing rock overburden. Because the solubility of volatiles in the magma decreases with decreasing pressure, volatiles that were dissolved at magma chamber depth will come out of solution to form bubbles of gas. As the magma continues to rise and decompress, it releases more volatiles into bubbles, and the bubbles expand. In order to conserve mass, the expanding mixture must accelerate. This acceleration is also determined by the conduit dimensions. The expansion of the magma

mixture and the conduit dimensions are ultimately coupled because the walls of the conduit might be eroded by the magma as it accelerates.

Using a multifield approach for modeling the upward flow of magma, whereby gas and melt are treated as overlapping continua that are coupled by mass, momentum, and energy exchange, Macedonio et al. (1994) developed a system of governing equations to describe conduit flow, the first component for predicting volcanic risk illustrated in Figure 2. The equations (see box at right) include several simplifying assumptions: one-dimensional, steady flow; constant conduit geometry (which assumes that wall-rock materials introduced into the flow are not in sufficient quantities to change the shape of the conduit appreciably); and isothermal flow (thus the lack of an energy conservation equation). However, the equations do account for the rise of separate gas and droplet/particle (incompressible) phases, frictional coupling between those phases, and the introduction of wall-rock debris into the mass and momentum balances. The term  $C_w$ , the mass erosion rate of wall rock per meter into the flow, accounts for the interaction between the flow and the conduit walls. Because the flow is considered to be one-dimensional, steady, and in a constant-geometry conduit, it is implied that the mass erosion rate is small. In reality, there might be more erosion that sufficiently changes the conduit shape to negate the simplifying assumptions in these equations. The current treatment should be regarded only as a first step toward addressing the difficult problem of fully coupled flow and solid walls.

Given the wide range of conditions within volcanic conduits and the even wider range of potential wall-rock properties,  $C_w$  is difficult to constrain theoretically. For that reason, we designed a series of field studies to

**Conduit Flow Model**

Equations of Macedonio et al. (1994)

Mass	{	$G_G = \rho_G \alpha u_G$	Mass flow gas per unit area
		$\frac{dG_L}{dz} = C_w$	Change in particle mass flux/area due to wall-rock erosion ( $C_w$ = mass erosion rate)
Momentum	{	Gas $\rho_G u_G \alpha \frac{du_G}{dz} = -\alpha \frac{dP}{dz} - F_{LG} - F_{WG} - \rho_G g \alpha$	Pressure gradient Friction with particles Friction with walls Gravity
		Particles $\rho_L u_L (1 - \alpha) \frac{du_L}{dz} = -(1 - \alpha) \frac{dP}{dz} + F_{LG} + F_{WL}$	Pressure gradient Friction with particles Friction with walls
		$- \rho_L g (1 - \alpha) + C_w (u_w - u_L)$	Gravity

Assumptions: Steady state, 1-D, isothermal

provide quantitative values for  $C_w$  at extinct volcanoes in the southwestern United States. Field sites were selected according to criteria that allow quantification of the amount of wall-rock debris as a function of depth below the volcanoes: (1) The volcanoes must be old enough that many of their deposits are exposed by erosion, or the deposits might be exposed by quarry operations; (2) the sequence of rocks below the volcanoes must be well constrained in terms of the thickness of individual layers; (3) fragments of those layers should be easily identifiable in the volcanic deposits recording the eruptions; and (4) the different styles of eruption processes must be easily interpreted from the volcanic deposits. At sites that meet these criteria, it is then possible to measure the volume fraction of fragments from each layer of wall rock within volcanic deposits; dividing that value

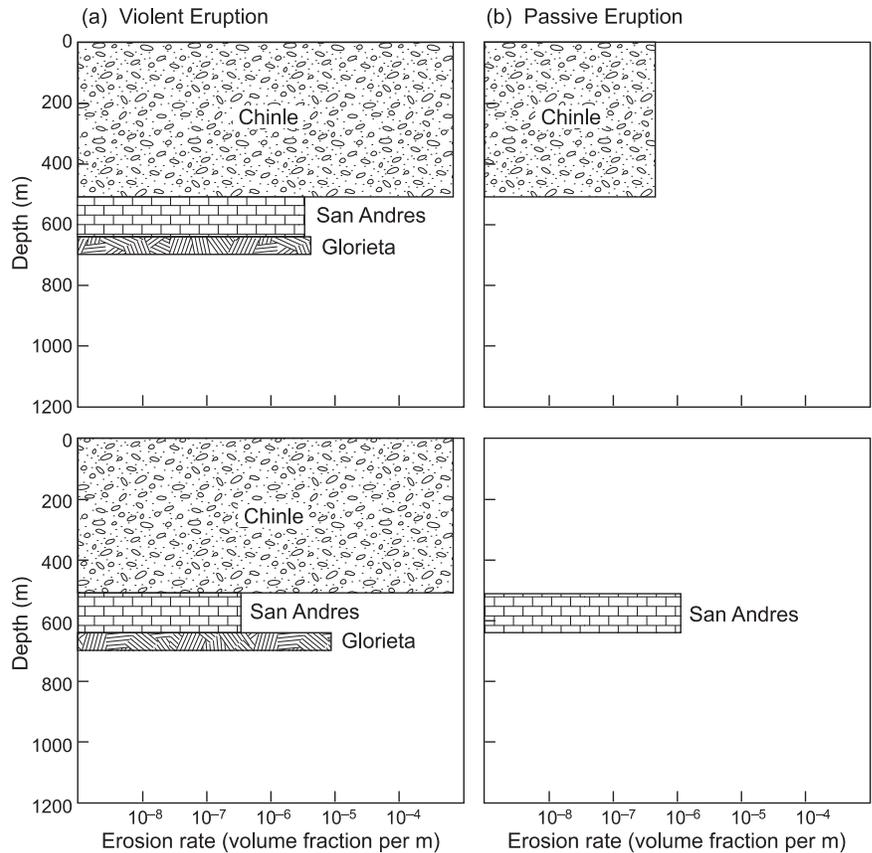
by the thickness of the layer results in an average volume fraction per meter.

Several volcanoes in two regions, the Lucero Volcanic Field of west-central New Mexico and the San Francisco Volcanic Field of northern Arizona, meet these criteria. Wall-rock erosion data from the Lucero Volcanic Field, in particular, illustrate the variations in wall-rock erosion for eruption mechanisms that range from relatively passive eruption of lava to Hawaiian-style lava fountains and from those to very violent eruptions involving explosive interaction of magma (at about 1100°C) with ground water. Figure 3 shows the volume fraction per meter (erosion rate) for the latter type of eruption (left side) and for more passive types (right side), corresponding to the layers of wall rocks beneath the volcanoes. Erosion rates vary over factors of 1000 to 10,000, depending upon the

eruption mechanism and the types of wall rock. These rates can be used to constrain  $C_w$  for the conduit fluid model equations. For more details on these field studies, refer to Valentine and Groves (1996). The main point here is to show that combining theoretical and/or computational modeling with field studies will yield quantitative estimates for volcanic conduit flow, one component of volcanic risk prediction. More data are being collected and implementation of the field-derived  $C_w$  values into the numerical solution of the conduit fluid model is a future goal.

### Plume and Density Current Models

The next process illustrated in Figure 2 is the prediction of volcanic plumes and pyroclastic density currents (PDCs) (the word “pyroclastic,” from the Greek roots for fire and broken, refers to the fragments of quenched magma, such as pumice and smaller fragments misleadingly called ash, as well as fragments of wall rocks that are ejected during explosive eruptions). The volcanic plumes of interest consist of gas (mainly steam that has exsolved from the melt during conduit ascent) mixed with particles or clots of magma. The temperatures of these plumes when they exit the volcano are typically about 1000°C, but the plumes are denser than the atmosphere because particles are present. Flow speeds at the vent are a few hundred meters per second, and the flows are highly turbulent. Despite being denser than the surrounding air, the plume will rise because of its initial momentum. As it rises, it will decelerate and simultaneously mix with and heat ambient air such that the overall mixture density decreases. Sustained volcanic plumes exhibit two end members of behavior that depend upon the flow conditions



**Figure 3. Data on Wall Rock Erosion from Violent and Passive Eruptions** These data on wall rock erosion are from field measurements and are expressed in terms of volume fraction per meter down the conduit for different wall-rock formations (Chinle, San Andres, and Glorieta formations) beneath volcanoes in the Lucero Volcanic Field. (The plots are adapted from Valentine and Groves 1996. Entrainment of Country Rock During Basaltic Eruptions of the Lucero Volcanic Field, New Mexico. *J. Geol.* 104 (1): 71, published by the University of Chicago.)

as the flow exits the conduit (these conditions are calculated with a model such as the one discussed in the preceding section). In one end member, the plume is able to mix with sufficient air that, by the time it reaches the height at which its initial momentum has been lost, the plume is less dense than the surrounding atmosphere and continues to rise until it reaches a neutral buoyancy level (which might range from several kilometers to as much as 50 kilometers above the vent, depending on the eruption energy and on atmospheric conditions). The second end member occurs when the plume is still denser than the atmosphere at the time that it reaches the height determined by its

initial momentum. The plume then collapses and forms a fountain of hot gas and particles, which in turn feeds density currents that flow out across the countryside. The conditions within these PDCs can be extremely damaging, particularly in heavily urbanized regions.

Based on field evidence (characteristics of deposits left behind), we can make several inferences about PDCs. (1) These mixtures of hot gas and particles can flow at a range of speeds from a few meters per second (m/s) to more than 300 m/s. This means that the flows cover a wide range of incompressible to compressible regimes in terms of the Mach number (note that the sound speed of typical



**Figure 4. The Destructive Power of Pyroclastic Density Currents (PDCs)**  
 This picture is of the landscape north of Mt. St. Helens after the devastating blast on May 18, 1980. The kinetic energy released during that volcanic event was equivalent to 7 Mt, and the thermal energy was equivalent to 24 Mt of explosive TNT equivalent. The field of view extends more than 10 km into the distance, over terrain with relief of hundreds of meters. Before the blast, the landscape was covered by a dense forest of large conifers. Their notable absence after the eruption attests to the destructive power of PDCs. The volcano in the background is Mt. Rainier.

(Photo is courtesy of J. Franklin, Mount St. Helens National Volcanic Monument photo library.)

gas-particle mixtures in PDCs can be significantly lower than in the surrounding atmosphere). (2) PDCs range in particle concentration from very dilute, essentially like sand storms (volume fractions less than  $10^{-3}$ ), to dense granular dispersions with particle volume fractions as high as approximately 0.5. At low particle concentrations, the particle and momentum transport mechanisms might be dominated by turbulence although mixture density gradients and basal traction zones can complicate the transport mechanisms. At high particle concentrations, the basal portions of the flows might have particle and momentum transport dominated by particle-particle collisions. The range of particle sizes (micrometers to meters) and densities—from about 500 to 3000 kilograms per cubic meter ( $\text{kg}/\text{m}^3$ )—combined with the depth scales of the flows, places the mixtures in a region that is some-

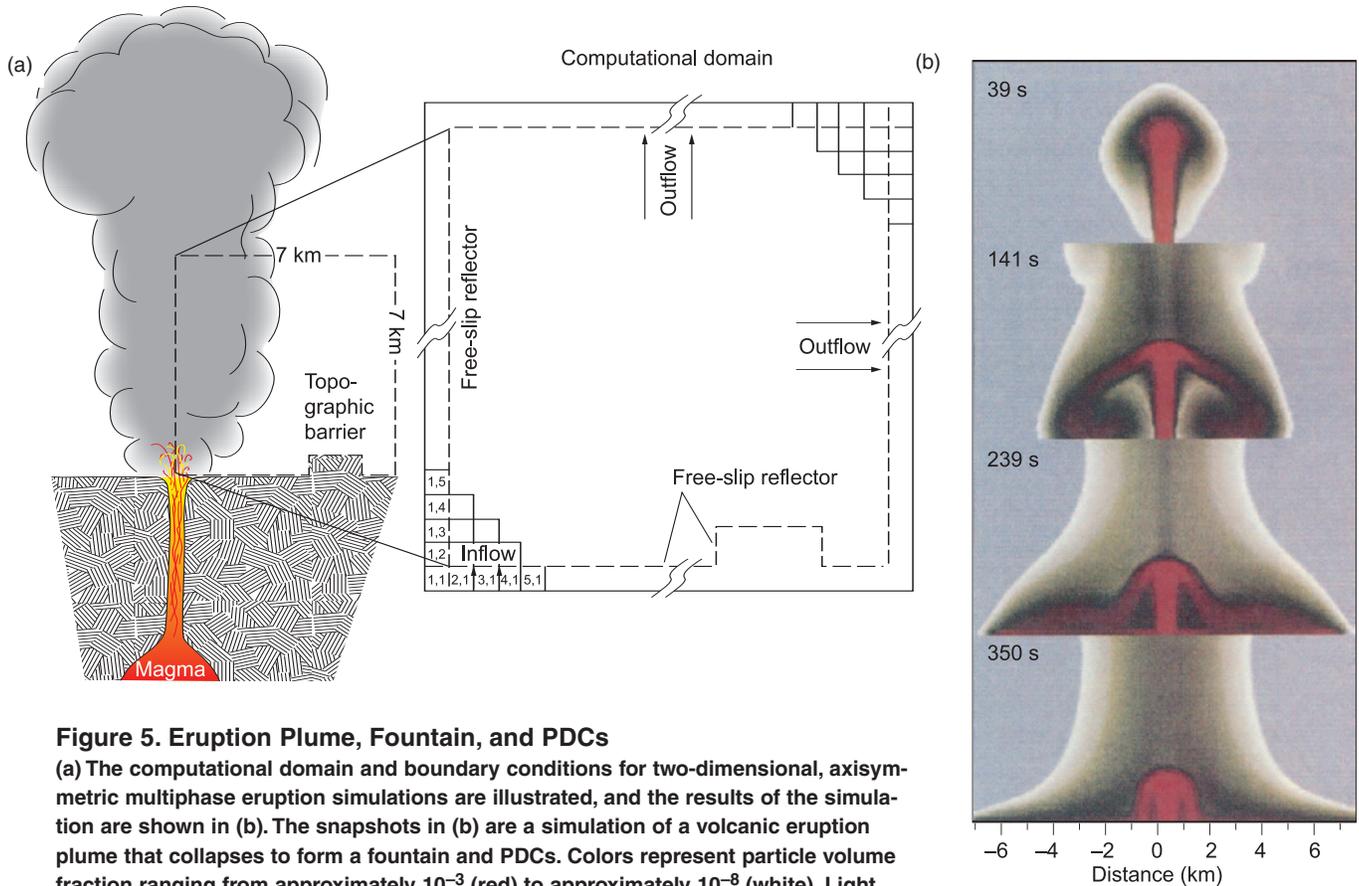
where between the applicability of simple, effective continuum approaches and discrete particle approaches. (3) PDCs can be variably affected by the topography over which they flow, sometimes channeling strongly into topographic lows and sometimes seeming to blanket highs and lows nearly equally. (4) Temperatures of PDCs can range up to approximately  $1000^\circ\text{C}$ . (5) The flows can be quite destructive (see Figure 4) and can travel more than 100 kilometers from their source volcanoes in some instances. All these factors make the prediction of PDCs very difficult and, potentially, extremely intensive computationally, depending upon the theoretical approach one takes.

**Connecting PDCs to Nuclear Weapon Phenomenology.** As a side note, there is a strong connection between our understanding of PDCs and nuclear weapons phenomenology.

One of the founders of modern volcanology, the late Richard V. Fisher of the University of California at Santa Barbara, was assigned to Los Alamos just after World War II as a young member of the military. Later he was present at Bikini Atoll and witnessed the shallow-submarine Baker test. As the explosion column from Baker rose out of the water, a collar of water droplets mixed with steam and air collapsed back to the surface and moved outwards across the sea in a phenomenon that came to be known as the base surge. Twenty years later, Fisher, by then a professor and well-known interpreter of volcanic deposits, realized that some pyroclastic deposits around explosive volcanoes are produced by a base surge-like process as he had seen at Bikini. This connection revolutionized our understanding of volcanic processes and hazards in the 1960s. Indeed, for many years, the volcanic process was referred to as base surge or pyroclastic surge, following the nuclear weapons terminology. Recognition of a range of complications in the volcanic processes has eventually led us to the term pyroclastic density current. An interesting description of the evolution of these concepts and the nuclear weapons connection can be found in Fisher's autobiography (Fisher 1999).

#### **Multiphase Eruption Modeling.**

In recent years, an important thrust in the volcanological community has been the application of multiphase flow theory to predict the behavior of eruption plumes and PDCs. This approach originated at Los Alamos in the 1970s (Sandford et al. 1975) and was further developed at the Laboratory during the 1980s (Wohletz et al. 1984; Horn 1989) and 1990s, as summarized by Valentine (1998). Ongoing development by Italian volcanologists (Neri et al. 2003; Todesco et al 2002; Ongaro et al. 2002) and others applies multiphase theory to



**Figure 5. Eruption Plume, Fountain, and PDCs**

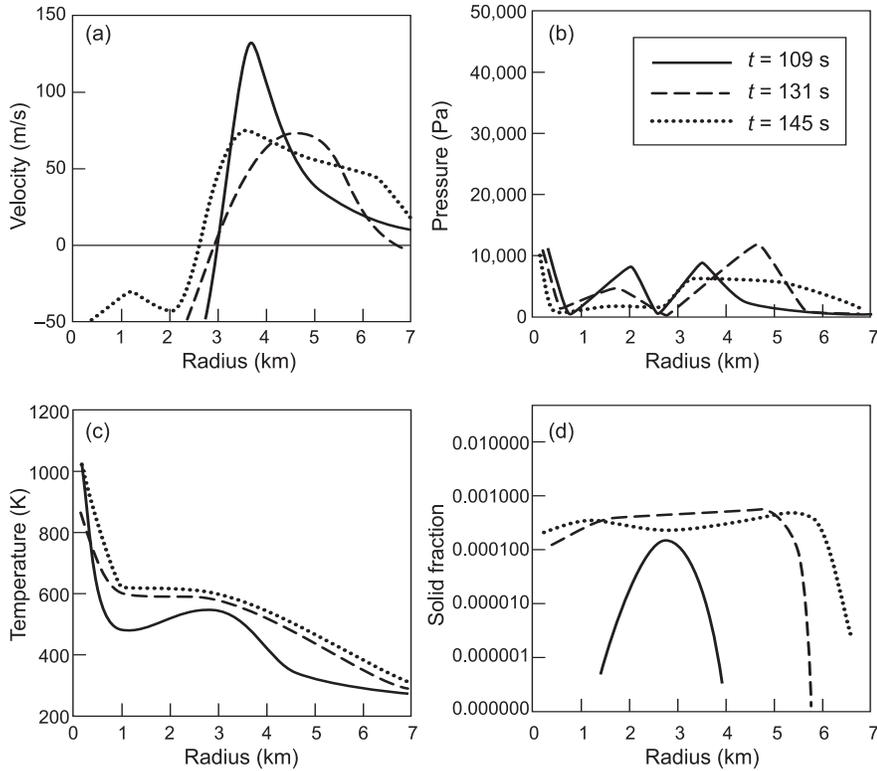
(a) The computational domain and boundary conditions for two-dimensional, axisymmetric multiphase eruption simulations are illustrated, and the results of the simulation are shown in (b). The snapshots in (b) are a simulation of a volcanic eruption plume that collapses to form a fountain and PDCs. Colors represent particle volume fraction ranging from approximately  $10^{-3}$  (red) to approximately  $10^{-8}$  (white). Light blue represents “clean” ambient atmosphere. Vertical and horizontal scales are each 7 km. (Figure is adapted from Valentine et al. 1992 courtesy of the Geological Society of America.)

predict hazards to urban areas such as Naples, Italy, and to better understand the transport and deposition processes of PDCs. As in the conduit fluid model, the multiphase modeling of eruption plumes and PDCs computes the motion of a continuous, compressible gas phase (a mixture of erupted volatiles and entrained air) and one or more particle fields, as if they are interpenetrating fluids. In other words, the gas and particles are each treated as a fluid field, occupying the same volume according to their individual volume fractions (which must sum to unity). Each of these fields has an accompanying set of mass, momentum, and energy conservation equations. The fields can be coupled together by mass exchange, drag (momentum exchange), and heat exchange along with heat generated by

valid only for problems in which the control volume (or representative elementary volume) is sufficiently large for particle behavior to be described as a field, rather than by each particle’s dynamics. Valentine (1994) presented a multifield framework for a wide range of volcanic processes, including plumes and PDCs.

Figure 5 illustrates the results of a two-dimensional, time-dependent multiphase calculation (Valentine et al. 1992). This calculation, which would now be considered a first-generation multiphase volcano calculation, was axisymmetric (the symmetry axis is in the center of the snapshots—in reality, only a half-space calculation was done, and the results were “reflected” for the purposes of illustration). It accounts for one particle size and one gas species, and it has a regular, uniform grid ( $100 \times 100$

meters). A mixture of hot (1200 kelvins) gas and particles with an initial velocity of 290 m/s and gas pressure of 0.1 megapascal (equal to ambient) is injected into the atmosphere. The mass fraction of gas (water vapor) at the “vent” is 1.7%. Colors in the figure indicate particle volume fraction ranging from a high of about  $10^{-3}$  (red) through black and white to a low of  $10^{-9}$  (blue—relatively “clean” ambient atmosphere). The jet rises to an initial height of approximately 4 kilometers, at which point its initial momentum or kinetic energy is spent. Because the mixture is denser than the surrounding air at that point, the bulk of the material collapses to form a fountain while a dilute plume continues to rise above the eruption. At the spot where the collapsing mixture impacts the ground, it flows both outward and



**Figure 6. Damage-Causing Parameters Resulting from PDCs**  
 Plots of radial (a) velocity, (b) dynamic pressure, (c) particle temperature, and (d) particle volume fraction are “measured” along the ground in a two-phase eruption simulation. These parameters are important for predicting hazards (for example, to buildings or people) in the area affected by PDCs. (Figure is adapted from Valentine and Wohletz 1989.)

ventward as a PDC. The ventward-flowing material is recycled into the eruptive jet, reducing the jet’s vertical momentum and causing the fountain to decrease in altitude. The outward flowing material moves at velocities of several tens of meters per second, in a manner that varies with time as the overall dynamics evolve.

While the general fluid dynamics of these eruptions are of interest from a research perspective, in this section, we focus on parameters that relate to potential damage to structures on the ground. These parameters are flow temperature, velocity, and particle concentration. Flow velocity and particle concentration (through its effect on flow density) determine the

dynamic pressure,  $P_{\text{dyn}}$  ( $P_{\text{dyn}} = 1/2\rho u^2$ , where  $\rho$  is the density of the mixture and  $u$  is the horizontal component of velocity), experienced by any object in the flow path. As an example, Figure 6 shows these parameters along the ground for three different times in a calculation similar to that discussed above. Figure 6(a) indicates that, as the PDC flows away from the point where the fountain impacts the ground (near the point where flow speeds cross from negative, or ventward-flowing, velocities to positive, or outward-flowing, velocities), it initially attains peak values approaching 150 m/s. As the flow field evolves, the peak PDC velocities decrease to about 70 m/s, and the radial distribution of velocity changes.

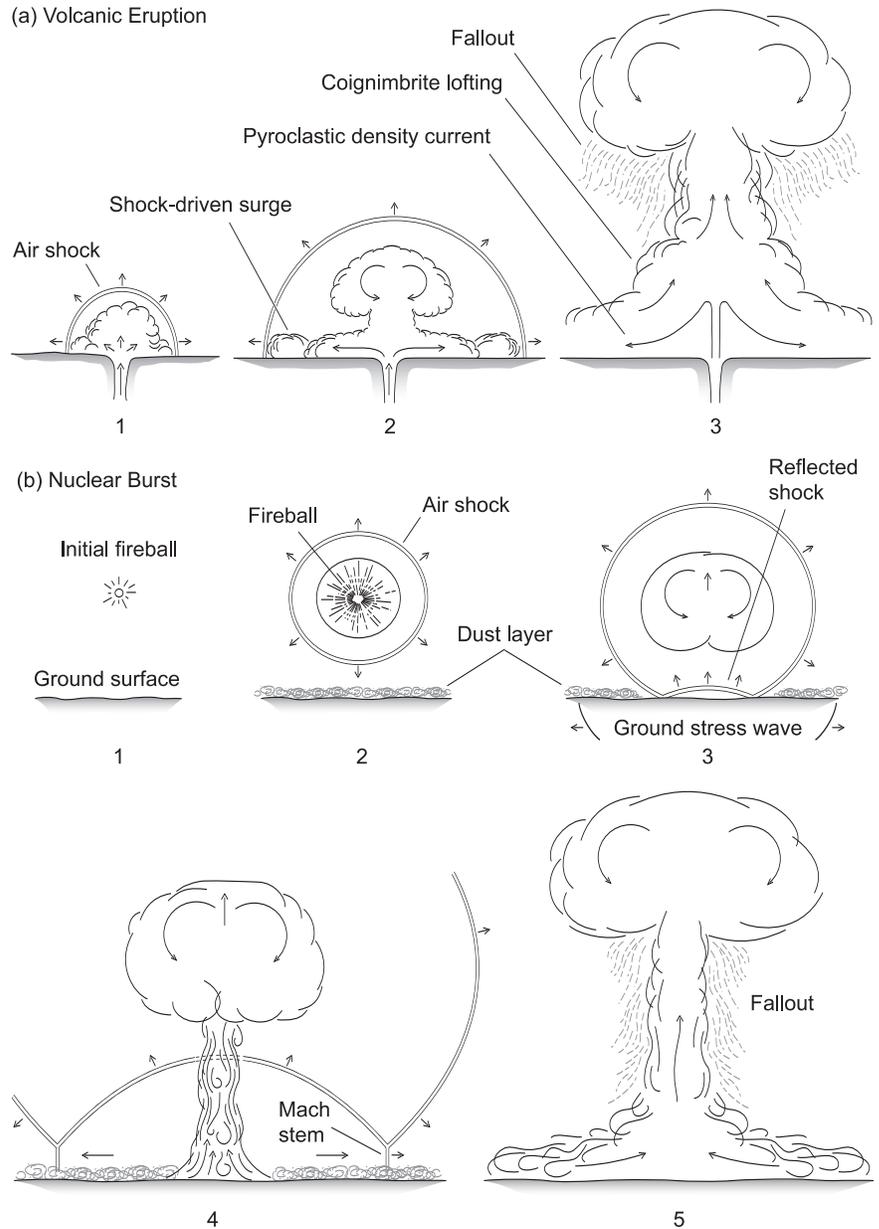
Dynamic pressure—refer to Figure 6(b)—evolves through time as well, with values ranging from 5 to 10 kilopascals, spreading outward radially as the flow evolves. Temperatures on the ground—see Figure 6(c)—evolve toward a radially decreasing pattern, reflecting progressive heat transfer from particles and mixing with cooler atmosphere. The volume fraction of particles along the ground—shown in Figure 6(d)—stabilizes at about  $1 - 2 \times 10^{-4}$  during this simulation. Results such as those illustrated in Figure 6 can be combined with information on the response of buildings to elevated temperature and dynamic pressure, for example, to predict damage from an eruption.

There have been a number of important advances in multifield modeling approaches for explosive eruptions over the past decade, most of which are described in Neri et al. (2003), Darteville (2004) and Darteville et al. (2004). Among them are the following: variable meshes that provide much better resolution for dynamics adjacent to boundaries such as the ground surface, where particle settling can produce steep gradients in flow properties and terrain can be represented; large-eddy simulation turbulence model; constitutive models that account for momentum transfer by particle collision whenever solid volume fraction is sufficiently high; capability for  $n$  particle classes (determined, for example, by size and/or material density), each represented by a set of mass, momentum, and energy field equations; and multiple gas species (for example, steam, air, or carbon dioxide). Using these new capabilities, Todesco et al. (2002) and Ongaro et al. (2002) are predicting values of damage-producing parameters for potential eruptions of the Vesuvius volcano in Italy that could endanger the heavily urbanized surroundings.

## Structural Damage

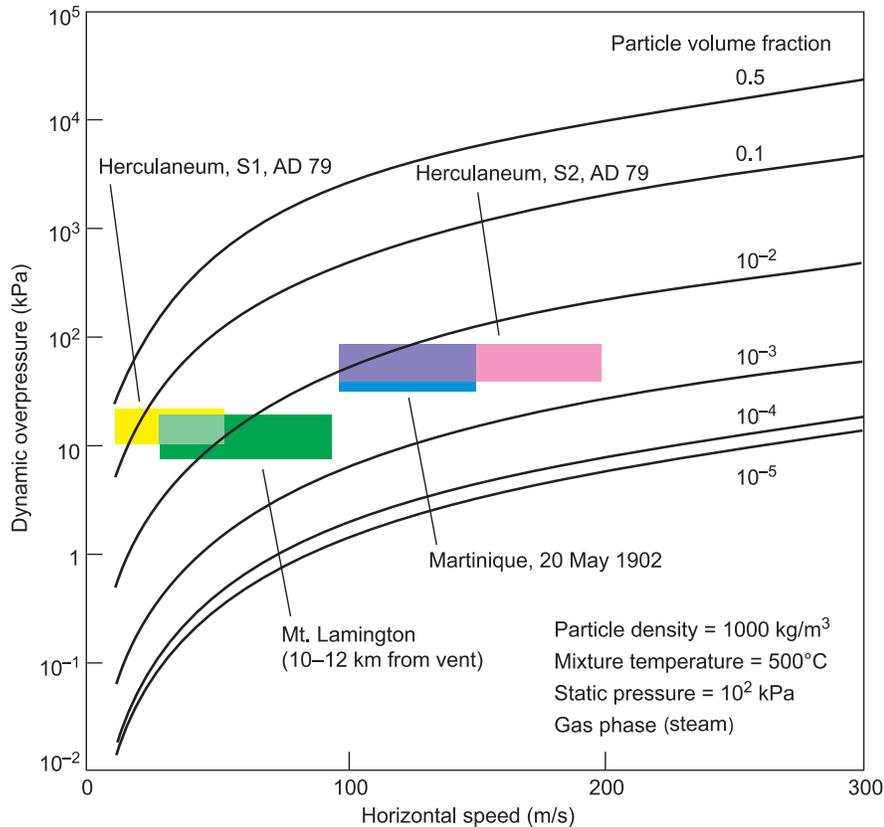
The next step in predicting risk from explosive eruptions is to quantify the effects on people, buildings, and other infrastructure; here, we will focus on buildings. When exposed to a PDC, buildings can be damaged by thermal effects, high static pressures, dynamic pressure, projectiles (for example, large rocks or debris from upstream buildings), and potential burial by depositing particles. Thermal effects depend on the temperature conditions within the PDC, ignition conditions, and availability of oxygen for combustion. Data on the effects of projectiles on buildings are being compiled. Sources used are observations from recent eruptions as well as damage caused by debris from tornadoes and hurricanes.

Dynamic pressure from a passing PDC produces a lateral load on a building. Simple estimates of dynamic pressures produced by PDCs indicate that  $P_{\text{dyn}}$  could range from as high as approximately 10 megapascals (for a PDC with velocity of 300 m/s and particle volume concentration of 0.5) to approximately 1 kilopascal for a dilute, relatively slow current (velocities of a few tens of meters per second, particle volume concentrations of about  $10^{-4}$ ). Most buildings will experience severe damage with lateral loads of about 8 to 40 kilopascals—1 to 5 pounds per square inch—depending upon the type of construction (see, for example, Glasstone and Dolan 1977). Clearly, based on the reasonable range of  $P_{\text{dyn}}$  given above, many PDCs will totally destroy any buildings in their paths, and there is no point in understanding the details of structural response in regimes above approximately 100 kilopascals, except for extremely strong monumental buildings. Nevertheless, many PDCs may result in lateral loads that would be expected to produce partial damage; however, even for the most



**Figure 7. Comparing Volcanic Eruptions and Low-Altitude Nuclear Explosions**

(a) An explosive volcanic eruption may generate an air shock because of the decompression of volcanic gases and the impulse of material flowing into the atmosphere. As the explosion grows, shock waves may drive a surge of particle-laden gas along the ground. Finally, as the eruption continues, the particle gas mixture may behave like a fountain, with PDCs flowing along the ground and a buoyant plume rising above the vent from which particles deposit by fallout. (b) A low-altitude nuclear explosion generates an air shock from the rapidly expanding fireball. An outward-moving Mach stem shock forms at the intersection of the incident and reflected air shock. As the fireball continues to expand, it also begins to rise; entrainment of ground debris into the rising fireball produces the characteristic fireball. Blast damage on the ground is caused by the Mach stem shock, which produces short-lived lateral forces on any structure in its path. (Adapted from *Journal of Volcanology and Geothermal Research*, 87, G. A. Valentine 1998, pp. 117–140 with permission from Elsevier.)



**Figure 8. Dynamic Pressure as a Function of Velocity for Different Particle Volume Fractions**

This plot shows dynamic pressure from PDCs as a function of velocity for different particle volume fractions. The colored boxes represent regimes for four historical eruptions. A combination of data was used, including structural damage and damage criteria from nuclear tests, as a proxy for PDC-induced damage. Although the quality of information on damage produced by historical eruptions is imprecise, the range of PDC speeds and particle concentrations that can be estimated from the damage includes consistent values that are suggested by, for example, evidence from sediment transport theory. (Adapted from *Journal of Volcanology and Geothermal Research*, 87, G. A. Valentine 1998, pp. 117–140, with permission from Elsevier.)

damaging PDCs, there will be zones around their margins, where conditions are not so severe. Understanding these factors is important for emergency mitigation and response planning in regions that are vulnerable to PDCs.

Interestingly, similar issues faced civil defense planners in the early years of the Cold War, but they were related to damage caused by nuclear weapons (eventually, with the adoption of the strategy of mutually assured destruction and large-yield fusion weapons, the details of damage

to cities for civil protection became more or less moot). During those years, full-scale tests were conducted, whereby real buildings were exposed to nuclear blast loading; it is possible to use the structural response information from those tests as rough analogs for conditions in PDCs. Figure 7 illustrates the phenomena associated with an explosive eruption and a low-altitude nuclear burst. In a volcanic eruption, initial decompression of the erupting gas-particle mixture into the atmosphere can drive a shock wave that expands outward into the air. This

might be followed by a blast-driven surge and, eventually, by full-scale PDCs that are of interest here. In a low-altitude nuclear burst, the expanding fireball pushes a strong air shock that expands spherically until it intersects the ground. The shock is then reflected upward from the ground, and a vertically oriented “Mach stem” shock forms at the intersection between the reflected and the incident shocks as the Mach stem continues to move outward. As it passes over a structure, the Mach stem creates a lateral load by two processes: (1) “diffraction” loading, which occurs as the shock is passing over the structure and the upstream side of the structure experiences a high pressure while the downstream side is still at ambient pressure; and (2) dynamic pressure loading, after the shock has passed and the building is subjected to a strong outward wind. All of this takes place in a very short time (seconds) in a nuclear case. In the volcanic case of PDCs, lateral loading is almost entirely due to dynamic pressure from the particle-laden flow, and that might be sustained for much longer times than in the nuclear case. In the absence of detailed data on damage from PDCs, however, it is reasonable to use nuclear effects data as a starting point.

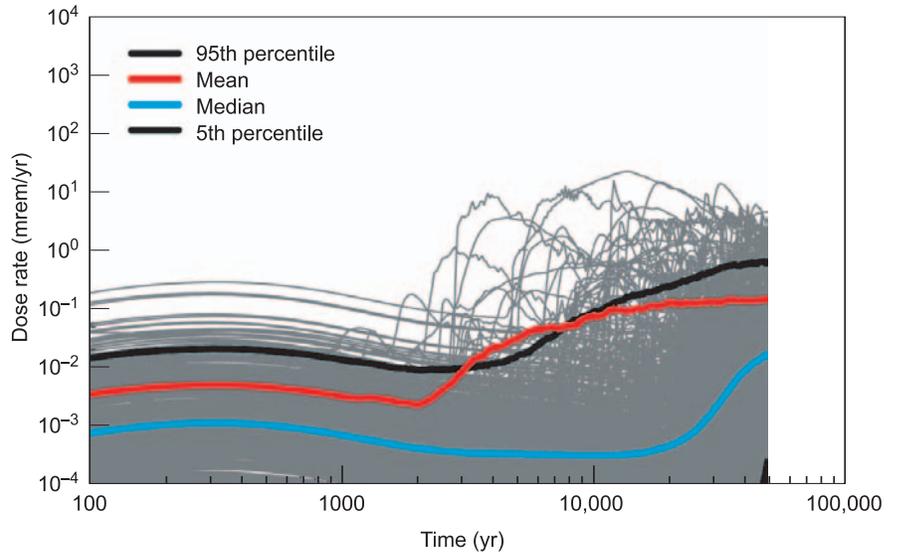
Figure 8 shows the range of dynamic pressure as a function of PDC speed for several values of particle loading (volume fractions ranging from  $10^{-5}$  to 0.5). Superimposed on these curves are boxes that represent the range of possible conditions as inferred from comparisons of nuclear effects data with observations of damage from four historical PDCs: the 1951 eruption of Mt. Lamington in Papua, New Guinea (Taylor 1958); the 1902 eruption of Mt. Pelee in Martinique (Lacroix 1904); and two PDCs that damaged the town of Herculaneum during the 79 AD eruption of Mt. Vesuvius. The height of each box represents our best estimate

of the possible range of dynamic pressures that could account for observed damage. The length of each box represents the range of PDC velocities as constrained by observations (or, in the case of Herculaneum, inferred from the characteristics of the deposits). Indirect information on the possible range of particle concentrations in these PDCs is consistent with the conditions indicated by the boxes.

The work described above served as a useful starting point for determining how structures respond to PDCs. In the past few years, there have been important new advances in observational data (mainly from the island of Montserrat, where PDCs that flowed out over residential areas were observed and the resulting damage was carefully documented—Baxter et al. (in press) and theoretical studies (Nunziante 2003). As a result, our understanding of PDC-induced damage is growing rapidly. This recent work indicates that the nuclear effects data, as applied by Valentine (1998), underestimates the damage caused by real PDCs for a given dynamic pressure. This greater damage results from several factors, such as shadowing or channeling effects by nearby structures, PDCs lasting longer than nuclear blasts, projectiles in the flows (particularly those derived from buildings just upstream), and heat. It is interesting to note that these results might, in turn, be used in studies of nuclear effects because there is now a great deal of interest in effects of low-yield devices in densely developed urban areas (for example, a terrorist device in a major city).

### Examples of Applications

The predictive-earth-sciences framework plays an important role in addressing many problems of national importance: repository science neces-



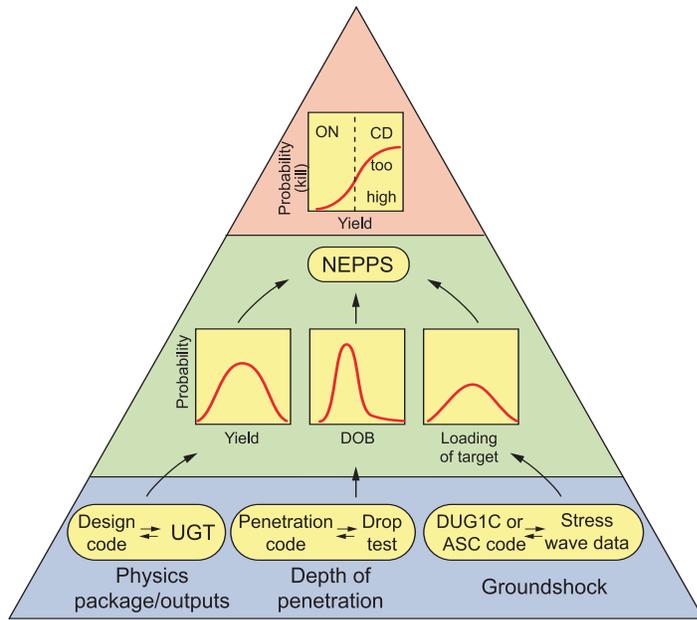
**Figure 9. Predictions of Radiation Dose for Yucca Mountain**

Predictions of radiation dose from a volcanic eruption are for a population located 18 km south of the proposed Yucca Mountain, Nevada, radioactive waste repository. The predictions are weighted by the probability of such an eruption, and they include processes such as waste entrainment into eruptive conduits, dispersion into the atmosphere and subsequent fallout, and contamination of ground water by damaged waste packages that remain in the underground environment. Gray curves indicate individual realizations of the integrated models. These predictions were for the Site Recommendation in 2001 (U.S. Department of Energy 2001) and are being updated for the December 2004 license application.

sary for closing the loop on current and future nuclear-fuel cycles; water resources research aimed at predicting the impacts of climate change and water usage on resource availability; sequestration of excess CO<sub>2</sub> into underground reservoirs to counter global warming due to use of fossil fuels; homeland security issues that involve interaction between terrorist events, the environment, humans, and infrastructure; and nuclear weapons effects from targeting, military vulnerability, and homeland vulnerability perspectives.

**Predicting Volcanic Risk at Yucca Mountain.** The research discussed above is guided by and fit together through the ultimate need to produce integrated predictions of the risk to humans who live around explosive volcanoes. One application

of volcanology, in which the predictive-earth-sciences framework has played an especially strong role, is predicting the radioactive dose that might result if a small volcano were to erupt through the proposed Yucca Mountain repository. Figure 9 (U.S. Department of Energy 2001) shows the rolled-up results of those models that account for a probability distribution for occurrence of a volcanic event, subsurface interaction between rising magma and the repository, and subsequent eruption of nuclear waste onto the surface. The results of these simple models were cast in terms of probability distributions and then sampled by a Monte Carlo approach to produce a large number of runs, sampling all the modeled processes, and represented by the gray curves in Figure 9. This figure shows the predicted dose as a function of time into



**Figure 10. Predicting the Defeat of Deeply Buried Targets**

This example of the predictive-earth-sciences framework is used for predicting the defeat of deeply buried targets by nuclear earth-penetrator weapons. Some of the components of the overall predictive system that need to be understood are the following: (1) the weapon outputs (neutrons, gamma rays, and x rays), which are predicted by a design code in conjunction with test data (either from historical underground nuclear tests or from other tests); (2) the depth of warhead penetration into the ground, which determines the amount of energy transmitted into the ground and is generally predicted on the basis of solid mechanics codes coupled with drop test and other data; and (3) propagation of that energy as a shock through heterogeneous rock types to produce shock loading at the underground facility. Predictions of ground shock propagation integrate continuum mechanics codes from a package such as an ASC code package with data from underground explosives tests. Other components that are not illustrated include the accuracy of the weapon regarding the intended detonation point, the response of the underground target itself to shock loading, and potential collateral effects such as air blast and fallout. All these can be integrated, accounting for uncertainty in each component, through a simulation tool such as NEPPS (developed in the Systems Engineering and Integration Group at Los Alamos), to produce, for example, a prediction of the probability of rendering the target ineffective as a function of weapon yield.

the future, the primary criterion for determining whether the repository will perform as specified by regulations. At early times (the first 1000 years), the mean value is dominated by dose produced by eruption of waste and direct fallout onto a hypothetical population. At later times, the mean value is dominated by contamination of ground water because of magma-induced damage to waste packages. The predictions represented by Figure 9 are being superseded by

new calculations that incorporate more detailed models of magma–repository interactions that will form part of the basis for a license application in December 2004.

**Defeating Underground Targets.**

The predictive-earth-science framework can also be used to study the effects of nuclear weapons as applied to defeating underground targets (see Figure 10). Several processes are involved in defeating a deeply buried

target with a nuclear weapon: delivery of the weapon to the target, penetration into the ground if it is an earth penetrator, performance of the nuclear physics package, coupling and propagation of energy as groundshock to the underground target, and response of the target itself. Each of these processes requires a physics-based understanding in order to capture the inherent uncertainties. Probability distributions of each process are then rolled up in a Monte Carlo approach such as NEPPS (for Nuclear Earth Penetrator Planning System, developed in the Systems Engineering and Integration Group at Los Alamos), to produce a high-level prediction that might take the form of a probability of target defeat (or some other combination of parameters).

**Concluding Remarks**

Finally, a focus on predictive earth sciences provides a driver for several classes of underpinning basic research. These include upscaling, coupling across chemical and physical regimes (for example, coupling global climate predictions to regional scales for water resources studies), stochastic processes, extreme events (such as weapon effects or natural disasters), and the effects of having humans in the loop in environmental processes. In general, as with the Stockpile Stewardship Program, predictive earth sciences involve predicting the performance of coupled, nonlinear, multi-scale processes that involve materials whose properties are heterogeneous and imperfectly characterized, where much of the data on the full-system performance are historical. ■

## Further Reading

- Baxter, P. J., R. Boyle, P. Cole, A. Neri, R. Spence, and G. Zuccaro. The Impacts of Pyroclastic Surges on Buildings at the Eruption of the Soufriere Hills Volcano, Montserrat. (Submitted to *J. Volcanol. Geotherm. Res.*)
- BSC (Bechtel SAIC Company). 2004. Biosphere model report. MDL-MGR-MD-000001, Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company.
- Dartevelle, S. 2004. Numerical Modeling of Geophysical Granular Flows: 1. A Comprehensive Approach to Granular Rheologies and Geophysical Multiphase Flows. *Geochem. Geophys. Geosyst.* **5** (8).
- Dartevelle, S., W. I. Rose, J. Stix, K. Kelfoun, and J. W. Vallance. 2004. Numerical Modeling of Geophysical Granular Flows: 2. Computer Simulations of Plinian Clouds and Pyroclastic Flows and Surges. *Geochem. Geophys. Geosyst.* **5** (8).
- Eckhardt, R., D. L. Bish, G. Y. Bussod, J. T. Fabryka-Martin, S. S. Levy, P. W. Reimus et al. 2000. Yucca Mountain—Looking Ten Thousand Years into the Future. *Los Alamos Science* **26**: 464
- Fisher, R. V. 1999. *Out of the Crater: Chronicles of a Volcanologist*. Princeton, New Jersey: Princeton University Press.
- Gable, C. W. 2000. Mesh Generation for Yucca Mountain. In *Los Alamos Science* Number 26, Vol. 2, p. 472.
- Glasstone, S., and P. J. Dolan. 1977. *The Effects of Nuclear Weapons*. US Department of Defense and the Energy Research and Development Administration.
- Horn, M. 1989. "DANIEL: A Computer Code for High-Speed Dusty Gas Flows with Multiple Particle Sizes." Los Alamos National Laboratory report LA-11445-MS.
- Lacroix, A., 1904. *La Montagne Pelée et ses Éruptions*. Paris, France: Masson et Cie.
- Macedonio, G., F. Dobran, and A. Neri. 1994. Erosion Processes in Volcanic Conduits and Application to the AD 79 Eruption of Vesuvius. *Earth Planet. Sci. Lett.* **121**: 137.
- Neri, A., T. E. Ongaro, G. Macedonio, and D. Gidaspow. 2003. Multiparticle Simulation of Collapsing Volcanic Columns and Pyroclastic Flow. *J. Geophys. Res.* **108** (B4): 2202. Nunziante, L., M. Fraldi, L. Lirer, P. Petrosino, S. Scotellaro, and C. Ciciirelli. 2003. Risk Assessment of the Impact of Pyroclastic Currents on the Towns Located Around Vesuvio: A Non-Linear Structural Inverse Analysis. *Bull. Volcanol.* **65** (8): 547.
- Ongaro, T. E., A. Neri, M. Todesco, and G. Macedonio. 2002. Pyroclastic Flow Hazard Assessment at Vesuvius (Italy) by Using Numerical Modeling. II. Analysis of Flow Variables. *Bull. Volcanol.* **64** (3–4): 178.
- Perry, F. V., B. M. Crowe, and G. A. Valentine. 2000. Analyzing Volcanic Hazards at Yucca Mountain. *Los Alamos Science* **26**: 492.
- Sandford II, M. T., E. M. Jones, and T. R. McGetchin. 1975. Hydrodynamics of Caldera-Forming Eruptions. *Geol. Soc. Am. Abstr. Programs* **7** (7): 1257.
- Sigurdsson, H., S. Carey, W. Cornell, and T. Pescatore. 1985. The Eruption of Vesuvius in AD 79. *Natl. Geogr. Res.* **1** (3): 332.
- Taylor, G. A. M. 1958. "The 1951 Eruption of Mount Lamington, Papua." In *Aust. Bur. Miner. Resour. Geol. Geophys. Bull.*, Vol. 38. Australian Geological Survey Organization: Canberra, Australia.
- Todesco, M., A. Neri, T. E. Ongaro, P. Papale, G. Macedonio, R. Santacroce, and A. Longo. 2002. Pyroclastic Flow Hazard Assessment at Vesuvius (Italy) by Using Numerical Modeling. I. Large-Scale Dynamics. *Bull. Volcanol.* **64** (3–4): 155.
- US Department of Energy. 2001. "Yucca Mountain Science and Engineering Report—Technical Information Supporting Site Recommendation Consideration." US Department of Energy, Office of Civilian Radioactive Waste Management report DOE/RW-0539.
- Valentine, G. A. 2003. Towards Integrated Natural Hazard Reduction in Urban Areas. In *Earth Science in the City: A Reader*. Edited by G. Heiken, R. Fakundiny, and J. F. Sutter. Washington, DC: American Geophysical Union.
- . 1998a. Damage to Structures by Pyroclastic Flows and Surges, Inferred from Nuclear Weapons Effects. *J. Volcanol. Geotherm. Res.* **87** (1–4): 117.
- . 1998b. Eruption Column Physics. In *From Magma to Tephra: Modelling Physical Processes of Explosive Volcanic Eruptions*. Edited by A. Freundt, and M. Rosi. Amsterdam: Elsevier.
- . 1994. Multifield Governing Equations for Magma Dynamics. *Geophys. Astrophys. Fluid Dyn.* **78**: 193.
- Valentine, G. A., and K. R. Groves. 1996. Entrainment of Country Rock During Basaltic Eruptions of the Lucero Volcanic Field, New Mexico. *J. Geol.* **104** (1): 71.
- Valentine, G. A., and K. H. Wohletz. 1989a. Environmental Hazards of Pyroclastic Flows Determined by Numerical Models. *Geology* **17** (7): 641.
- . 1989b. Numerical Models of Plinian Eruption Columns and Pyroclastic Flows. *J. Geophys. Res.* **94** (B2): 1867.
- Valentine, G. A., K. H. Wohletz, and S. W. Kieffer. 1992. Effects of Topography on Facies and Compositional Zonation in Caldera-Related Ignimbrites. *Geol. Soc. Am. Bull.* **104** (2): 154.
- Wohletz, K. H., T. R. McGetchin, M. T. Sandford II, and E. M. Jones. 1984. Hydrodynamic Aspects of Caldera-Forming Eruptions: Numerical Models. *J. Geophys. Res.* **89** (B10): 8269.

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