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Physics of Phreatomagmatism

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Part 2: Eruption Physics (Ken Wohletz)

Since early witnesses of phreatomagmatism at Taal, Surtsey, and Capelinhos in the 1960's, volcanologists have carried an ever-growing awareness of the prevalence of phreatomagmatic eruption into the new millennium. First struck by the similarities of eruption phenomena to high-explosive cratering and surface nuclear tests, these volcanologists have tangled with the term *base surge* and its interpretations, they have been perplexed by the paradox of why all water/magma interactions are not explosive, and they are beginning to appreciate the complexity of such apparently simple physics.

The subject of this presentation deals with the eruptive phenomena and products of phreatomagmatism and how eruption physics can be approached by field and laboratory research. Explosive phreatomagmatism transforms some of magma's internal (heat) energy into mechanical energy that is partitioned into several dominant modes, including fragmentation (surface free energy and electric), seismic, acoustic, and kinetic (crater excavation and fragment acceleration). The proportion of heat converted into mechanical energy appears to be governed largely by the environment of interaction; that is the availability of water, the composition and state of the magma, the ambient pressure (lithostatic or hydrostatic), and the confining strength of earth materials. Fragmentation can be viewed as a starting point for the eruption process, and it is discussed in some detail in Part One of this presentation.

During fragmentation seismic energy is radiated from the interaction zone, and its low-frequency nature is a key to the eruptive and pre-eruptive environment. In order for eruptions to actually start spewing products into the atmosphere, a vent must be formed, and this subject has a close similarity to the broad topic of cratering. With crater formation dispersal of ejecta continues, an it can be simply described by well-known ballistic analysis, but in reality involves modification by aerodynamic drag and turbulence, which result in formation of ground-hugging density currents. The factors of environment, crater formation processes, and tephra dispersal determine the type of vent structure that eventually forms and the characteristics of the ejecta. It is by studying the post-emplacement character of the ejecta that allows reconstruction of the complex chain of events comprising the eruption physics. Despite the complexity of eruption physics and how it manifests itself, phreatomagmatic eruption apparently follows a cyclic pattern of waxing and waning energy release, a pattern that can be characterized and linked to the dominant controls of any given eruption, whether it be the water availability, the magma mass flux or composition, or geological structure. All these above considerations will be covered briefly below. More details on physics are described by Wohletz (1998), while background on the experimental basis mentioned below can be found in Part One of this as well as Zimanowski (1998).

1. Interaction Environments

Because water and water-bearing minerals are so prevalent in the earth's crust, it is a rare circumstance that an erupting magma has not interacted to some degree with water. In fact on a global scale, volcanic eruption is a key geo-mechanism for crustal degasing (Wohletz, 1993). Certainly one may argue between what is *magmatic* water at what is *external* water, and studies of stable isotopes are often cited in justification. For example, water-saturated rocks stoped into a magma chamber may be partially dissolved and, over periods of hundreds or thousands of years, lead to a volatile-overpressured eruption. Careful isotopic studies for this example may in fact document vestiges of a meteoric water signature. Does this case fall into the realm of phreatomagmatism? Without debating this issue further, suffice it to say that phreatomagmatism is most widely recognized where magma interacts with external sources of surface and near-surface water during an a period of eruption. Such areas (or environments) commonly recognized are marine, lacustrine, fluvial, and aquifers (including rocks in the zone of hydrologic saturation). In addition the character of the magma that interacts with water also plays a role that has been less studied in the field but has received experimental consideration (Zimanowski et al., 1986).

From the standpoint of physics, it is the abundance of water (with respect to erupting magma) and how fast the two can be supplied to the vent/conduit system that determine the course of phreatomagmatism. This control was first recognized by Heiken (1971). In continental regions where water is available in subsurface aquifers, inspection of lithic fragments excavated by explosive interactions commonly shows eruption progression to greater depths with time, indicating a hydrologic *cone of depression* in the water table. Such environments suggest that the magma supply rate is generally greater than that of water, and eruptions may end in non-explosive intrusion magma in the conduit region or extrusion of lava (*dry* eruptions). On the other hand, phreatomagmatic eruptions can culminate in ejection of very wet surges and even laharic flows, ending with fumarolic activity (*wet* eruptions). This latter behavior is especially common for oceanic environments and those where near-surface water is practically unlimited. These trends in water availability during the course of eruptions or over the life of a volcano give rise to the commonly observed cyclic character of phreatomagmatic eruptions, discussed below.

While the volume of erupted magma can be reliably estimated for any given eruption, it is much more difficult to estimate the volume of water available and actually interacted during and eruption. While hydrological studies may provide measures of rock saturation, permeability, and conductivity, these measures may prove unsatisfactory in explaining observed phreatomagmatism. Such is the case where initial interaction drives hydrofractures that open up an aquifer to produce much more water than say those measured from a water well. Experiments, described in Part One of this presentation, provide a means for inferring interaction ratios from ejecta characteristics (*e.g.*, the degree of fine-ash production). Textural studies of ejecta, combined with theoretical consideration of the thermodynamic state of erupted steam and water, can provide rough estimates of interaction ratio (*e.g.*, ejecta wetness and alteration as a measure of how much saturated steam was erupted). Other approaches (see for example, the discussion of Ukinrek volcano by Ort et al., this volume) can also give bounds on this subject of environment. Still another example of environmental evaluation involved the maar eruptions that produced Kilbourne Hole in New Mexico. The eruptions involved a fully saturated, loose-sand aquifer. By measuring the ratio of sand lithic fragments to basaltic fragments in the ejecta on a bed-by-bed basis and then multiplying that ratio by volume fraction of water in the sandy aquifer, Bahar (1991) found interaction ratios that closely matched those that could be deduced by the degree of fragmentation and deposit sedimentary textures.

2. Seismic and Acoustic Events

Perhaps the first physical phenomena produced by phreatomagmatism are seismic events caused by perturbations in the flow of magma in a conduit before and during an eruption. Long period seismic waves associated with volcanism (LP or tremor) are best explained by pressure pulsations produced by exchange of magmatic heat with water in saturated rocks surrounding a conduit (Morrissey, 1997). Measurement of such pulsations by seismic stations is complicated by the dispersion and attenuation properties of the rocks between the conduit and seismometer. On the other hand, shorter period seismic events (often termed volcano-tectonic or VT earthquakes) produced by phreatomagmatic explosions may show a range of broad-band behavior from discrete high frequency shocks to longer period waves. These behaviors can be related to the nature of interaction, whether there is efficient explosive interaction (as described in Part One of this presentation) or interaction events cause large-scale steam release but never sustain a shock wave.

Seismicity also plays an important role as a trigger for phreatomagmatism. Because water can be heated to a metastable state of superheat, it might exist in this state for prolonged periods of time before explosive expansion. While stable vapor films developed at the interface between magma can serve as insulators, allowing superheat metastability to exist, such films may spontaneously destabilize, or even more likely, may be destabilized by an external trigger such as a propagating seismic disturbance, which leads to a phreatomagmatic explosion. Such a disturbance may be caused by a sector collapse or a volcano seismic event produced by deep seated magma movement and crustal response to it. In certain cases, a small seismic wave generated by a limited water/magma fragmentation event in one part of the conduit may be the trigger for catastrophic water/magma mixing and fragmentation in the rest of the vent system.

As with seismic wave propagation, atmospheric media greatly disperse and attenuate acoustic waves driven by high speed ejecta movement. Pressure waves that move faster than the sound speed of the media through which they travel are shock waves, and in atmospheric cases produce the common signature heard as a sonic booms and/or seen as *flashing arcs* or condensation fronts. Whether or not such acoustic waves are heard is determined by the vent geometry and character of the eruption plume. While development of a conical vent crater generally focuses acoustic energy along the axis of the cone, substantially minimizing radiation along the ground surface surrounding the vent, gas-particle interactions in the erupted plume greatly influence the thermodynamic behavior of the media through which the waves travel, thus causing variable amounts of dispersion (frequency change) and attenuation (amplitude change). For these reasons when phreatomagmatic eruptions open a new vent, large reports can be monitored, but as the eruption progresses, these sounds become muffled and in some cases inaudible.

3. Crater Formation

For analogies of volcanic to man-made explosions, phreatomagmatic eruptions provide the closest match in that they can best approximate a point source. Unlike magmatic eruptions that result from rapid, linear accelerations along the course of a conduit, phreatomagmatic eruptions initially produce ground accelerations in all directions, and only with repeated bursts and formation of a vent structure do they become more directed. For that reason the craters formed by phreatomagmatic eruption tend to be more bowl-shaped like those of buried HE. It is only with repeated eruptions and vent collapse events that steep-side craters (maars) or conical craters form. It is this point-source character that allows crater formation to be evaluated from the standpoint of classical cratering mechanics, where rock movement and acceleration is initially driven by energy scaling and later, during the ejecta phase, by gravitational scaling. By utilizing energy scaling, crater dimensions are proportional to the cube-root of explosive yield with proportionality dependent upon depth of burst and host-rock strength. HE cratering experiments provide abundant and detailed literature about such scaling, and it is often appropriate to apply such insight (Gaffney et al., 1987; Wohletz and Heiken, 1992).

By analogy to HE and impact craters, one may theorize that during the process of crater formation, country rock accelerations are initially radially directed away from the explosive center, following a spherically diverging shock wave. With momentum exchange to the stationary rock, the downward and outward pointing velocity vectors of rock movement begin to curve upward such that the ground surface above the explosion lifts as a bulge. When the shock wave reaches the surface, it reflects back downward as a rarefaction wave that initiates fragmentation of the country rock in its wake. The accelerated rock mass then begins to move upward as a fragmented mass, each fragment traveling in a more or less ballistic trajectory . In this fashion, strata nearest the surface produce the first ejecta, followed by ejecta from increasingly deeper levels, the result being deposition of inverse stratigraphy in ejecta layers surrounding the crater during initial these initial moments of crater formation. Because excavation energy and hence fragment velocities decrease with the cube-root of distance from the explosive center, fragments from rock around the periphery of the developing crater follow the shortest ballistic paths while those from near the center of the crater follow the longest paths. This distribution of ejecta velocities can produce what is known as an overturned flap, a phenomena in which crater formation seemingly causes an orderly overturn of surface strata as it is removed and folded outward. Subsequent volcanic activity generally obscures evidence of this phenomena, but it does contribute to an inverse stratigraphy in early ejecta deposits that are often interpreted as a deepening of the explosive center with time.

Once the crater is fully open, crater formation continues by repeated collapses of crater wall materials down into the vent where some of the material is re-entrained into the eruptive plumes. From an initial bowl-shaped crater, collapse may either cause steep vertical crater walls to form, common to many maar craters, or produce sloping walls of a inverse cone, typical of evolved vents formed by prolonged eruptions.

4. Ejecta Dispersal

The topic of phreatomagmatic eruptions is perhaps best known because of the attention focused on the phenomena of pyroclastic surge. The fast moving, ground-hugging, density currents of ash and steam were early recognized for their destructive capability, characteristic deposits, and similarities to the base surge of underground HE and nuclear explosions. Recalling the physics of crater formation and noting that initial ejecta acceleration is ballistic in nature, determined by energy scaling, following trajectories determined by gravity scaling, a first-order analysis of ejecta dispersal involves ejecta deposit thickness variation with distance in order to estimate total ejecta energy. Because the dominant volume of ejecta consists of particles less than a centimeter in diameter for typical phreatomagmatic eruptions, the ballistic analysis is imprecise and neglects the turbulence dissipation caused by aerodynamic drag. Proportional to particle size, this drag initially causes small particles to decelerate more rapidly than larger ones, leading to particle collisions and development of the fluctuating particle velocity vectors of turbulence. Recognition of this phenomena prompted early workers to concentrate ballistic analysis only on large blocks and bombs (Lorenz, 1970; Self et al., 1980). Muzzle velocities calculated from their ballistic range then could be used as a measure of the kinetic energy for all ejecta (Steinberg, 1977). A question regarding muzzle velocity for phreatomagmatic bursts then gets back to how momentum is imparted to the ejecta. Do all ejecta particles have the same initial muzzle velocity or does this initial velocity depend upon particle size? If ejecta are accelerated by Bernoulli flow in a stream of escaping steam in the vent, then larger particles would travel more slowly than smaller ones (Fudali and Melson, 1972). On the other hand if acceleration occurs by impulse then large blocks and bombs might be expected to travel at higher initial speeds than ash.

Recognizing that turbulence greatly affects ejecta ballistics is important but not sufficient to understand the formation of the base surge. As Young (1965) first concluded from his analysis of Test Baker and other workers from observations of numerous buried explosions, surge formation is initially caused by the rapid overturn of surface strata during crater excavation and later by bulk subsidence of ejecta reaching the apex of their ballistic trajectories directly above the crater. This second stage is known as stem fallback or column collapse, where large-scale convective rise above the inertial rise zone is limited because of the quenched nature of the ejecta. A third factor in surge formation, described by Wohletz (1998), involves the propagation of shock waves within the ejecta cloud, which cause the ejecta to pile up into waves that surge outward.

One cannot overlook the importance of water/steam in ejecta dispersal, because it is the dominant medium in which ejecta travel. Depending upon the eruption environment, the ratio of water to magma interacting, phreatomagmatic eruptions may produce steam in superheated or supercritical vapor states to condensing steam, consisting of liquid water droplets and vapor, to liquid water. Eruptions with low water/magma ratios have been termed *dry* because after explosive expansion to atmospheric pressure, water is superheated vapor (dry steam), while those eruptions with moderate ratios can form after expansion partially saturated steam (wet steam), hence the term *wet* eruption. For very high water/magma ratios all steam might condense during expansion to form slurries of liquid water and ejecta. The thermodynamic state of water in the ejecta cloud is an important control on ejecta trajectories. Dry steam is optically transparent and behaves pretty much as an ideal gas. Once it condenses, it has a small optical depth (essentially opaque) and becomes a two-phase media that displays rather variable sound speed depending upon its liquid fraction. Besides drastically altering acoustic propagation, condensing steam tends to nucleate on ejecta particles forming a liquid film that can carry an electric charge and make particles sticky, leading to lightning discharge and formation of accretionary lapilli. Cohesivity of phreatomagmatic ejecta is a distinguishing characteristic that brings about some remarkable flow perturbations, leading to rapid decay of flow speeds. Another important consideration is the volume fraction of steam in a base surge. Deposition of the ejecta is influence by the inter-particle spacing. With an increasing volume fraction of steam in a surge cloud, particles are more separated from one another, their turbulent motions can better develop, and they interact with the substrate more freely. However, if the steam volume fraction is low, either by originating from a steam-poor eruption or by flow segregation of steam from the ejecta, particles cannot move freely and frequently collide with one another, damping turbulence, and dissipating kinetic energy through inelastic effects.

5. Vent Morphology

Depending upon the environment of phreatomagmatism, typical vent morphologies develop as a function of crater excavation and ejecta dispersal. Since Heiken's (1971) work, a wide range of vent morphologies have been recognized. Overall, one may classify a vent structure by the ratio of its characteristic ejecta diameter over ejecta thickness. Low-profiled vents, such as maars or tuff rings, have much higher ratios than do tuff cones, and these in general indicate higher characteristic eruptive energies.

Vent morphology generally remains fairly simple for monogenetic volcanoes but for polygenetic constructs can be quite complex. Because wet eruptions emplace very cohesive ejecta, large angles of repose >25º can result producing a steep sided cone. In contrast dry eruptions emplace ejecta that on a flat substrate produce very gentle slopes of 10º or less. But on polygenetic volcanoes where lava flows and domes exist these simple relationships are not apparent. Although not well documented, polygenetic volcanoes having numerous wet eruptions tend to have broader summit craters than do those having dryer eruptions. The reason for this apparent correlation is that wet eruptions have the capacity to excavate larger amounts of lithic material within and below the vent resulting in a broader crater, while drier ones are often associated with Strombolian bursts where crater development is a function surface ejection dynamics and not deep-seated explosions.

6. Fragment Character

Phreatomagmatism results in a wide range of volcanic fragments from ultra-fine ash particles to centimeter-sized hyaloclastite shards. When sampled from a deposit, representing a single eruption or interaction event, phreatomagmatic fragments show a distribution in size, shape, and chemical affinities that are a product of the environment, type of water/magma interaction, and subsequent secondary processes. Also, deposit bedforms of these phreatomagmatic fragments have a macroscopic character displayed as variations in sorting, grading, and bed shape.

As discussed in Part One of this presentation it is the fine volcanic ash the characterizes the truly explosive interaction of water and magma, showing that shock dynamics have developed and interacted with the melt at a size-range characterized sub-microsecond brittle failure. Larger particle fragmentation is the result of less energetic hydrodynamics caused by fluid instability and rapid heat exchange. These experimental and theoretical relationships suggest that particle size distributions are a distinguishing feature of phreatomagmatism, and indeed they are from a traditional empirical standpoint. With development of sequential fragmentation/transport theory there is now at least a mathematical basis for relating particle size distributions with interaction physics. The theory recognizes that the characteristically polymodal, nearly log-normal/Weibull distributions are predictable by solution of the integrative processes intrinsic to the incremental breakdown of magma into tephra. Preliminary work has shown the potential of the theory to distinguish particles from explosive interactions, including those from brittle events and those from hydrodynamic processes, such as Taylor instability. Realizing that size distributions are also a product of transport sorting processes, application of this theoretical analysis can further distinguish fragment subpopulations as a function of their dominant transport mode, whether it is ballistic, tractive, saltation, or turbulent suspension.

Along with a wide range of fragment sizes are a range of observed fragment shapes that experiments and theory have also predicted. Depending on the melt rheology and the strain rates produced by interaction and subsequent ejection, fragments range from a characteristic blocky shape of brittle failure of glassy solids to fluidal forms to complex, high-surface area particles and particle aggregates. Scanning electron microscopy coupled with digital image processing allows rapid and reproducible fragment sample characterization that then is amenable to theoretical analysis in determining the fragmentation history of phreatomagmatic samples. High resolution images of phreatomagmatic tephra show an increase in the abundance of spherical particles with decreasing particle size. Originally interpreted as a product of hydrodynamic instability fragmentation, new experimental evidence (Zimanowski, 1998) suggests that these spheres are the product of surface tension relaxation after brittle fragmentation.

Not only are these physical features important in fragment character, but chemical changes are also produced by phreatomagmatism. It is important to appreciate that water heated to supercritical states takes on a completely different chemical activity than has been studied at lower temperatures and pressures. Supercritical water most readily dissolves covalent-bonded materials (including hydrocarbons), almost an exact opposite of its behavior at room conditions. This well documented behavior suggests that glassy fragments might be rapidly attacked by water during the explosive phase, and especially were they are very small with an extremely high surface area to mass ratio, the results of rapid dissolution and redeposition can effectively change the bulk composition of erupted fragments. Texturally this phenomena is revealed by hydration rinds on glass fragments, but on micrometer-sized fragments, the whole particle may be chemically altered. Along with this rapid chemical process, is that of post-emplacement alteration, commonly displayed as palagonitization in basaltic ejecta, which happens at much lower temperature over the period of years. Wohletz (1987) showed bulk chemical analyses of glassy phreatomagmatic tephra that shows a strong relationship to sample grain size and depositional bedform.

Viewed as a package, size, shape, and chemical alteration characteristics in the field combine to form distinct bedform character. From the well sorted, generally non-graded beds of ballistic fallout lapilli through planar, inversely graded beds of coarse ash to beds of medium-ash dunes and fine-ash massive beds, the amount of visible alteration also varies as does the abundance of lithic fragments. On this macroscopic scale, deposit textures indicate that as phreatomagmatic eruptions conditions of water/magma ratio, explosivity, and environment change through the course of an eruption, so does the character of fragmental deposits. For example, phases of the eruption that caused the greatest amount of vent widening might produce ejecta abundant in lithic fragments and coarse, fresh lapilli emplaced in poorly bedded deposits, followed by massive beds of altered fine ash. Such a sequence might indicate a very explosive interaction that first fractured a lot of vent rocks that were ejected prior to the finely fragmented magma. Such cycles within single eruptions are a common signature of phreatomagmatism, but cycles also develop over a longer period of time during the evolution of polymodal volcanoes, as discussed below.

7. Eruption Cycles

From the first microseconds of a water/magma interaction event, the physical phenomena of phreatomagmatism may stretch over decades, centuries, or millennia. Because phreatomagmatism most likely occurs in regions where the presence of water exists for long periods of time, if magma rises in a volcano vent repeatedly over centuries, then phreatomagmatism will likely reoccur. For such polygenetic volcanoes a cyclicity can develop, and two basic cycles are well documented: a *dry cycle* in which the water supply is gradually diminished with successive eruptions perhaps over a period of years or more so that wet eruptions give way to dry eruptions, ending in nonexplosive lava explosion; and a *wet cycle* for which initial lava eruptions are later followed by Strombolian eruptions (driven by deep interaction with small amounts of external water), then Vulcanian activity, ending in fumarolic activity. Individual volcanoes tend to display one type of cycle repeated several times over years or centuries. In a way these cycles mimic the progress of individual eruptions that might show a less pronounced increase/decrease in water interaction. From studies of numerous volcanoes Wohletz and Heiken (1992) show that volcanoes consisting mainly of dry magmatic products display wet cycles (*e.g.*, Vesuvius, Mayon) and those being built mostly from phreatomagmatic tephra follow dry cycles (*e.g.*, Vulcano).

The cyclicity of small volume volcanoes can easily be related to environment, such as situation within a standing body of water (*e.g.*, Taal), but larger volcanoes develop a more complex relationship with their environment. In such cases the rise of magma within the plumbing system places a deviatoric stress on the regional stress field and fractures are reopened and created, opening flow paths for groundwater to enter the conduit region. While the dry cycle followed by a volcano such as Taal can be related to the gradual sealing-off of water access by congealing lava in conduit/vent margins, the wet cycle followed by calderas in the Latium volcanic province of Italy is related to the gradual opening of fractures within the subvolcanic aquifer rocks such that more and more water is able to flow into the conduit as the eruption progresses. This kind of wet trend is well documented by studies of the abundance and type of lithic fragments erupted (Funiciello et al., 1976).

Recognizing the cyclicity of phreatomagmatism, one may predict phreatomagmatic activity by foreknowledge of hydrologic environment or, conversely, predict the nature of an unknown hydrologic environment by detailed study of volcanic products. Because mineral and geothermal resources are so closely tied to hydrothermal processes, both of these predictive tools are of great utility in energy and minerals exploration.

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