I. Characteristics
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GLOSSARY

phreatomagmatism Volcanic activity resulting from the interaction between magma/lava and groundwater or surface water including seawater, meteoric water, hydrothermal water, or lake water.

FCI An abbreviation for fuel-coolant interaction, referring to an industrial analog to phreatomagmatic explosion involving a fuel such as molten iron and a coolant such as water. The interaction of the fuel and coolant has resulted in vapor explosions in industrial environments and are a potential hazard associated with nuclear core meltdown.

superheated liquid A metastable thermodynamic state of a liquid resulting from rapid heating to a temperature well above the boiling point.

Kelvin–Helmholtz and Rayleigh–Taylor instabilities Interfacial fluid instabilities caused by relative motion of two immiscible fluids. Kelvin–Helmholtz instabilities are induced by shear stresses along the interface, whereas Rayleigh–Taylor instabilities develop during acceleration of a denser fluid by a less dense fluid. In both cases fragmentation occurs when surface tension forces are exceeded.

vapor film A layer of vapor formed at the interface of water and a hot liquid or solid body (temperature ≈ boiling point).

wet/dry eruptions At standard conditions (25°C and 0.1 MPa), water is a two-phase (liquid and vapor) fluid. Depending on the quantity of available heat energy, when water comes into contact with magma it may become a liquid-rich fluid or a vapor-rich fluid, resulting in a dry eruption or a wet eruption, respectively.

IT WAS FASCINATING to watch the lava crater and glowing rivers and rivulets flowing down the slopes of the lava dome. Still more exciting, however, was the relentless struggle between the advancing lava and the sea. From the very beginning of the lava eruption it was noteworthy how much of the lava became fragmented when it came into contact with the sea.

—S. Thorarinsson, 1966
The above quote was made by Thorarinsson as he observed the eruption of Surtur volcano and the formation of a new island (Surtsey) off the south central coast of Iceland in 1964. His observations of this eruption led to a new classification of volcanism known as phreatomagmatism and the awareness of fragmentation processes associated with the interaction between magma and nonmagma water.

1. Characteristics

A. Global Occurrence

Phreatomagmatic activity involves the physical interaction of magma or lava with an external source of water either within the Earth or on its surface. A spectrum of activity results when magma contacts water as illustrated by the following examples. (1) Since 1990, lava has been pouring into the sea along the shores near Kalapana, Hawaii, producing a range of activity from the explosive ejection of fragmented lava to a continuous emission of steam and passive quenching of lava (Fig. 1a). (2) The subglacial eruption at Grímsvötn volcano (Iceland) in 1996 caused extensive flooding in south central Iceland and produced explosive jets of ash (Fig. 1b). (3) At Mount Ruapehu (New Zealand) in 1995, a vigorous uprush of water, vapor, and scoria bombs was observed through the crater lake, producing cock's tail explosive jets of ash. (4) In 1977, the two Ukinrek Maars (Alaska) formed by several hundred periodic blasts which were accompanied by a pervasive production of steam when rising magma surfaced into a shallow lake.

The array of eruption styles associated with phreatomagmatic activity reflects the many environments in which magma or lava may encounter water. Specific environments include deep or shallow submarine, littoral, lacustrine, phreatic, and subglacial. Phreatomagmatism is not restricted to magma type or vent type (monogenetic or poly genetic) and reflects the pervasive occurrence of water in the crust. Volcanoes that build up from repeated eruptions (polygenetic) such as stratovolcanoes and shield volcanoes, often have a phreatomagmatic phase or phases (i.e., vulcanian, phreatoplini an, or surtseyan) during an eruption period. The distinguishing features of a phreatomagmatic eruption phase are that plumes tend to be more steam or water rich and the grain size of the eruptive products tend to be finer than those from the associated magmatic eruptive phases. Explosive phreatomagmatic activity is also characterized by intensive fragmentation and ejection of the wall rocks in the vicinity of the explosion site, which results in the formation of large craters. Volcanoes that build up from a single phreatomagmatic eruption (monogenetic) form either a tuff ring, tuff cone, or a maar volcano when rising magma contacts water. The deposits of such volcanoes may consist of some 10 to more than 1000 single layers and result dominantly from

![Figure 1](image-url)
B. Eruption Styles

A phreatomagmatic eruption is driven primarily by the volumetric expansion of external water after it has been rapidly heated by contact with magma. Exsolving magmatic volatiles may also contribute to expansion and fragmentation during a phreatomagmatic event. When water comes into contact with magma, it will either transform to steam (vapor) or a two-phase (liquid and vapor) fluid depending on the relative masses of water and magma interacting. It may also become superheated to a metastable liquid state which will flash to steam when acted on by an external force. In general, the more water available during the interaction, the wetter (liquid-rich fluid) the eruption will be. There is a wide variety of eruption styles that results from magma/water interaction. The style of activity ranges from passive quenching and granulation of magma or lava to large scale thennohydraulic explosions, representing the most energetic result of magma/water interaction.

The most commonly recognized phreatomagmatic eruption style is that characterized by cypressoidal (cock's tail) explosive jets of ash accompanied by billowing clouds of steam. This style of activity was well described during the emergence of Surtsey volcano off the coast of Iceland in 1964 and appropriately named surtseyan. Ejecta are directed vertically and laterally with the laterally directed ejecta producing a base surge. Similar activity has been observed at Capelinhos (Azores), Taal (Philippines), St. Augustine (Alaska), Ruapehu (New Zealand), and Vulcano (Italy) where magma has come into contact with either seawater or lake water filling a crater. Deposits related to this style of activity have been described as wet deposits, indicating that not all of the water was converted to steam during eruption and deposition.

Other phreatomagmatic eruption styles include vulcanian and phreatoplinian. Vulcanian eruptions are discrete, explosive events that last seconds to minutes. These eruptions are thought to be caused by highly pressurized gases derived from the magma or from a phreatomagmatic interaction. Phreatoplinian eruptions are similar in style to plinian eruptions except that deposits are finer-grained. Deposits related to these two styles of activity are dry relative to surtseyan deposits in that most of the water was converted to steam during eruption and deposition.

C. Tephra Characteristics

The products from a phreatomagmatic eruption are predominantly a mixture of glass, crystals, and foreign or wall rock lithics (fragmented material from the conduit and vent). In many cases, the lithic fragments represent by far the dominant part of the ejecta with grains ranging in size from fine ash to blocks. Their shapes may indicate fragmentation by fracturing (i.e., angular edges) and not by abrasion (i.e., rounded edges). In terms of grain size, phreatomagmatic tephra generally are finer grained than magmatic tephra (Fig. 2a), particularly for high water/magma ratios.

Under optical and electron microscopes, the juvenile (glass) component of phreatomagmatic tephra contains distinct grain shapes. These shapes include blocky, fusiform, mosslike, platey, and spherical or droplike as shown in Fig. 2b. Other distinguishing textural features are particles adhering to glass surfaces, grooves or scratches, chipped edges, and rounded edges. Also, the glass constituents may be more hydrothermally altered than magmatic tephras of equivalent age, especially in samples from wet tephra deposits in which hot water was captured. Basaltic glasses alter to palagonite, whereas rhyolitic glasses alter to a fine-grained mosaic of quartz, potassium feldspar, and clays.

D. Phenomenology

The physical dynamics of phreatomagmatic fragmentation parallel a well-studied process called fuel-coolant interaction (FCI). FCI refers to a heat transfer process which can occur in any environment, converting thermal energy into kinetic energy on a short time scale (<1 ms) during the interaction of a cold volatile fluid (coolant) and a hot fluid (fuel) with a solidus temperature well above the homogeneous nucleation temperature of the coolant. In volcanological terms, the fuel is the magma and the coolant is water. Water at atmospheric conditions has a homogeneous nucleation temperature exceeding 300°C. Magmas have temperatures well above this temperature, therefore, in principle, phreatomagmatic explosive eruptions can occur in any volcanic environment.
FCI may be explosive or nonexplosive depending on the rate of heat transfer between the fuel and coolant and the subsequent pressurization rate of the coolant. The rate of heat transfer is a function of the surface area of the fuel which, in an explosive FCI, increases by a cascading fragmentation process. The fragmentation process is enhanced by thermal expansion of the coolant that creates new contact surfaces.

The physical dynamics of an explosive FCI are represented by the following stages:

1. Initial contact and coarse mixing of fuel and coolant under stable vapor film boiling conditions (Leidenfrost phenomenon).
2. Complete vapor film collapse caused either by the passage of a pressure pulse which may be of external origin (e.g., seismicity) or by a local implosion (i.e., water hammer) due to rapid condensation of coolant vapor. Once the coolant vapor is completely condensed, the fuel and coolant are thermally and mechanically coupled.
3. Episodic increase of heat transfer from fuel to coolant and fine fragmentation leading to superheated and pressurized water. As the coolant is heated, it expands at a rate of <1 ms, leading to rapid increase in load stress on the melt. Relaxation of load stress in the brittle mode (elastic rebound) causes the explosive release of seismic energy. Up to 90% of the total kinetic explosion energy is released in this phase.
4. Volumetric expansion of the fuel–coolant mixture from the transformation of the superheated water to superheated steam. At this stage, the fuel and coolant are thermally and mechanically decoupled.

All FCIs, explosive or nonexplosive, are initiated by Stage 1. A nonexplosive FCI terminates at Stage 1 or Stage 2. The wetness of an explosive FCI reflects the degree of fragmentation and the rate of heat transfer (or the efficiency of the feedback mechanism) during Stages 2 and 3.

II. THEORETICAL AND EXPERIMENTAL RESULTS

A. History

Theoretical and experimental studies at Sandia National Laboratory (New Mexico) in the 1970s and 1980s provided a strong basis for understanding FCIs and a framework for the study of phreatomagmatic activity. These
experiments were designed to investigate the occurrence of steam explosions during core meltdown at nuclear reactors and other industrial environments such as metal smelters. The primary goal of the experiments was to constrain models for the conditions for a steam explosion when a coolant comes into contact with a fuel. Fuel (melt) used in the experiments ranged from molten salts to thermite-generated melts. Results from these studies include the four steps describing the physical dynamics of a FCI.

Phreatomagmatic explosions are complex interactions of four phases which are often internally heterogeneous (magma, magmatic volatiles, external water, and wall rock). Experimental studies of simple systems offer powerful tools for understanding the eruption dynamics.

B. Thermite: Water Experiments

Experiments conducted at Los Alamos National Laboratory were designed to simulate phreatomagmatic activity using an Fe–Al thermite melt and water. The objectives were to monitor dynamic events and to determine what controls the rapid conversion of the melt’s thermal energy into mechanical energy when it interacts with water. The melt, simulating basaltic magma, resulted from an exothermic reaction of fine-grained aluminum (~24 wt%) with magnetite (~76 wt%). In general, this thermite composition yields about 1130 kJ excess heat per mole of iron oxide at 1800 K. The physical and thermal properties of Fe–Al thermite melt are compared with those of a typical tholeiitic basaltic melt in Table I.

Four designs, shown and described in Figs. 3a–3d, were employed to evaluate the effects of contact geometry, the mass ratio of water to melt, and the confining strength (or pressure) on the explosivity of the experimental phreatomagmatic eruption. High speed cameras were used in all experiments and samples of ejected thermite were collected from some of the experiments.

More than one style of melt ejection, each resembling a type of natural volcanic activity, resulted from these experiments:

1. Continuous fountaining of centimeter-sized liquid fragments of thermite melt, which resembled a Hawaiian eruption
2. Pulsating ballistic ejections of partially quenched and vesicular (scoriaceous) fragments, which resembled astrombolian eruption
3. Dry vapor-rich explosions ejecting micrometer-sized fragments in expanding jets of superheated steam, which resembled a surtseyan eruption
4. Wet vapor explosions ejecting millimeter-sized fragments in ballistic plumes of condensing steam
5. Passive chilling of the thermite melt into centimeter-sized fragments with quenched surfaces, which was analogous to the formation of pillow lavas or peperites

A fifth experiment was designed to resemble a propulsion rocket (Fig. 3e) in order to quantify the water-to-melt mass ratio and confining pressure controls on the mechanical energy of an interaction. In this design, ejection of high pressure steam and fragmented thermite passing through the vent caused the vessel to lift off the ground. Measurements of the internal pressure history and ejecta characteristics were recorded, as was the maximum height reached by the vessel. Three confining pressures were used, 6.8, 16.3, and 35.7 MPa; the last exceeds the critical pressure of water (22.0 MPa). The water-to-melt mass ratio investigated ranged from 0.38 (1.82 kg of water and 4.73 kg of melt) to 2.00 (4.00 kg of water and 2.00 kg of melt).

The results from these experiments include three distinct pressurization histories or groups which were found to correspond to three specific ranges of lift-off heights (LOH) and produced clasts with distinct morphologies. The three pressurization histories are characterized by (1) exponential pressure–time curves; (2) an initial linear pressure rise and after approximately 0.3 to 0.8 s, a parabolic pressure increase to a value near the confining pressure; and (3) an initial linear pressure increase followed by an event that pressurized the chamber to a maximum value within 5 to 20 s.

Although the number of experimental samples is limited, an interesting correlation was observed between the six distinct grain shapes (Fig. 4a) identified in recovered samples and the three pressure groups: Group 1 experiments produced predominantly mosslike grains; Group 2 produced mainly spherical or droplike and aggregate

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grains; Group 3 experiments produced mainly blocky and irregularly shaped grains. Platelike grains were found in the fine-grain fraction of most samples. The correlation between grain shapes and the three pressure groups suggests that the grains are a consequence of the dynamic behavior of water as it is being heated by the melt during preburst interaction. Although sampling did not adequately represent the fraction of the sample finer than 62 μm (4 φ), the distributions shown in Fig. 4b are very similar to some phreatomagmatic tephra size distributions (Fig. 2a).

In order to facilitate the use of these experiments as analogs of hydrovolcanic eruptions of much larger scale, the explosive energy is expressed as the ratio of the measured and calculated mechanical energy to the initial internal (thermal) energy of the melt. This ratio is called the conversion ratio (MCR) and was calculated from the conservation of momentum.

As shown in Fig. 5, a positive correlation was found between MCR and the water-to-melt mass ratio (Rw) within the three pressure groups. This plot shows that the observed pressurization mode is strongly linked to the resulting conversion ratio for each experiment. The pressure–time histories associated with each pressure group reflects the degree to which the water–thermite melt interaction approached thermal equilibrium. Thus,

FIGURE 3 Schematic drawings of the five thermite–water interaction experiments conducted at Los Alamos National Laboratory. (a) Emplacement of 10 kg of thermite in an iron pipe above a second pipe filled with water; (b) immersion of a Plexiglas tube in a large Plexiglas box filled with >1 cubic meter of water; (c) emplacement of 90 kg of thermite held above water by an aluminum disk in a sealed steel cylinder with a vent at the top that burst open when the internal pressure exceeded 7 MPa; and (d) same as design (c) except the vent pipe extended down through the thermite into the water compartment. (e) The lift-off experiment designed similarly to (d) except the burst valve is located at the base of the vessel.
water–melt interactions involved with Group 1 experiments were the most efficient and explosive, and came closest to thermal equilibrium. These equate to “dry” phreatomagmatic events. Water–melt interactions involved with Group 3 experiments were the least efficient and explosive and did not approach thermal equilibrium. These experiments were considered analogs to submarine phreatomagmatic events. Group 2 experiments fell between Groups 1 and 3 and were considered analogs to “wet” phreatomagmatic events.

C. Experiments Utilizing Rock Samples

A series of thermal explosion experiments (TEE) at University of Wuerzburg were designed to study phreatomagmatic fragmentation using remelted volcanic rock samples with compositions ranging from ultrabasic to andesitic. The experiments evaluated the effect of the mode of contact between water and melt, the mixing conditions, the fragmentation processes during an explosive FCI which is also termed a thermohydraulic explosion, and the expansion phase of an explosive FCI. All experiments involved high resolution measurements of physical processes and properties associated with an explosive FCI and the evaluation of fragmented melt.

These experiments included two configurations: (1) water entrapment achieved by injection of a water volume into a melt volume and (2) melt entrapment achieved by the stratification of water and melt on an experimental scale of 5–20 cm (Fig. 6). The latter produced only very weak FCI with low reproducibility and thus were not useful analogs to phreatomagmatic explosions. The former were useful as these produced energetic explosions very effectively. For timing purposes, an explosion in each experiment was initiated by a projectile
that was fired at the melt surfaces to breakdown insulating vapor films.

A third experiment was designed to identify and quantify fragment populations generated by processes associated with the expansion of superheated steam (Stage 4 of a FCI). These experiments involved a sudden release of a compressed inert gas (argon) in the melt filled crucible (Fig. 6).

![Figure 6](image_url)

**FIGURE 6** Entrapment of water in melt. Schematic cross sections of crucible used in the experiments: (A) A thin walled steel tube is inserted into the melt to the desired depth. (B) Water is injected into the melt; thus a local water/melt premix is produced. (C) After triggering, the escalating process of thermohydraulic explosion takes place in this premixed zone, during which water is superheated. Once the superheat reaches a critical value the phase transition to superheated steam is enforced, resulting in very rapid volume expansion. (D) The superheated steam finally expands to ambient pressure in an adiabatic way, thus accelerating the overlying melt strata out of the crucible.

Results from the first two experimental designs suggested that heat loss from the melt during the initial contact and premixing phase is critical for the generation of an explosion. Two contact modes were investigated, hot melt surrounded by excess water or water surrounded by excess melt. When the melt was dispersed in excess water, the heat transfer, even under stable vapor film boiling conditions, was very effective such that melt particles with diameters <1 cm completely solidified or a thick crust formed around larger melt particles within <1 s. In this case explosive FCI did not occur. In the case of water entrapment by excess melt, an explosive FCI was found to be highly probable. Here, the intensity of a resulting thermohydraulic explosion is proportional to the initial contact areas.

The mixing phase was found to be the primary control on the intensity of an explosive FCI. The available interfacial area between the two liquids is governed by (a) the differential flow speed (hydrodynamic energy) between the two fluids and (b) by the material properties of the fluids. Efficient mixing (i.e., creation of a large interfacial area in a short time), was achieved when the flow speed is high, and the densities and viscosities of the liquids are similar and low. Silicate magmas have densities between 2500 and 3000 kg m⁻³ and viscosities ranging from few Pa s to >10⁶ Pa s. In contrast, water has a density near 1000 kg m⁻³ and a viscosity of 10⁻³ Pa s. In Figs. 7 and 8, the optimum mixing conditions for low viscosity, ultrabasic melts are the maximum values for the water-to-melt volume ratios and the differential flow speeds which correspond to 11 vol% water and

![Figure 7](image_url)

**FIGURE 7** Water/melt volume ratios of mixing in entrapment configuration. The melt used in this experiments was a remelted olivine-mellitite at 1350°C and a viscosity of about 1 Pa s.
Three fragmentation regimes were distinguished:

1. Fragmentation of the melt inside the crucible without measurable expansion of the mixture during fine-fragmentation and heat transfer (Stage 3 of a FCI).
2. Fragmentation of melt strata during acceleration of the melt by expansion of superheated steam inside the crucible.
3. Fragmentation of the melt during high speed ballistic trajectory outside the crucible.

Particles produced by the fine-fragmentation, regime 1, resembled the ash-sized particles generated by the LANL experiments. The fine-fragmentation phase was found to be the crucial phase for an explosive FCI, during which the maximum kinetic energy (explosion energy) is released. This phase produced angular shaped particles with diameters between 30 and 130 μm. Fragmentation during melt acceleration in a confined geometry produced spherical fragments with diameters between 90 and 180 μm. Fragmentation during decelerated movement of melt on ballistic trajectories in free air produced elongated shapes to hairlike shapes similar to Pele’s hair, depending on the ejection velocity.

An experimental explosive FCI is a highly energetic, short-time process occurring on a timescale of <1 ms. Within this time frame, new surfaces were created by a brittle type of fine fragmentation. The particles exclusively produced during this event were identified and quantified. The total of new surface area was found to correlate linearly with the respective explosion intensity.

### III. Fragmentation Mechanisms

#### A. Types of Fragmentation

A fragmentation mechanism associated with each phreatomagmatic grain type (i.e., blocky, fusiform, moss-like, platey, and spherical or drop-like) can be inferred from results of the phreatomagmatic analog experiments and FCI theory. The blocky grains found in tephra deposits and produced in lab experiments resemble shattered glass or glass that has been partially twisted and deformed while still plastic. These fragments form when stress waves propagate through a melt and produce deformation rates that exceed its bulk modulus (Fig. 9). Also it is envisioned that the local temperature of the melt is near solidus and brittle fractures develop in response to thermal contraction or tensile stress waves produced by vapor film collapse. Because stress waves typically propagate faster than thermal waves, it is likely that thermal contraction affects only melt surfaces while...
the bulk of the melt is rapidly subjected to mechanical stresses.

In quenched portions of the melt, fractures tend to propagate at angles less than 45° to the melt surface, forming block-shaped clasts with planar to curvilinear surfaces. Vapor film oscillation may produce turbulence that tends to spall quenched melt fragments from the surface of the molten body and expose unquenched surfaces (Fig. 9). For portions of the melt that fragment prior to quenching, vapor turbulence can cause deformation of unquenched shards with melt surface tension promoting formation of fluidal surface textures.

Moss-like grains develop by viscous deformation under tensile stress conditions created during rapid vapor formation. These conditions are predicted by the development of Rayleigh–Taylor and Kelvin–Helmholtz instabilities. These instabilities are caused by the relative motion of the vapor along the melt surface (Fig. 10). They perturb the melt surface and introduce additional morphological characteristics. Tiny plumes of melt rise from the surface when surface tension forces are exceeded by Rayleigh–Taylor instabilities (Fig. 11). Kelvin–Helmholtz instabilities are induced by shear stresses that further stretch and disperse the melt surface. Because these instabilities form with a range of wavelengths and orientations, melt surfaces can become very convoluted, resulting in tortuous, high surface area fragments.

Spherical or droplike grains develop from the effect of surface tension when magma is still hot enough to behave like a fluid. As with moss-shaped grains, melt surface instabilities both grow and detach to form spherical or elongated ribbon-like structures in response to the force of locally collapsing vapor films (Fig. 12). The most rapid mechanism contributing to production of these grains occurs when compression waves associated with vapor film collapse become large enough to shatter the surface undulations produced by instabilities; this results in the production of a multitude of fine-grained fragments. When axisymmetric collapse of vapor films produces accelerations sufficient to overcome surface tension forces of fluid melt, water jets can penetrate into the melt and become partially or completely entrapped beneath the surface. The trapped water becomes superheated and expands, thus causing additional fragmentation of melt.

Platey grains have been interpreted as pieces of quenched crust stripped off the surface of the magma (Fig. 9b). The stripping process can be attributed to the turbulence of vapor film oscillation, vaporization wave
propagation, or Kelvin–Helmholtz instability. High velocity ejection of liquid melt leads to the formation of rock wool.

B. Growth and Evolution of Fragmentation Events

Phreatomagmatic fragmentation evolves in a number of different manners depending upon the primary controlling parameters of viscosity, temperature, confining pressure, and water/magma contact mode (i.e., mixing conditions and mass ratio). These parameters are largely determined by the environmental setting of the volcano and its magma characteristics, discussed below, and they determine the rate of heat transfer from the melt to water. Fragmentation events follow a complex growth history that includes premixing, pressure growth, triggering, failure, and ejection. These stages are similar to those associated with an FCI.

Premixing is an increased intermingling of water with the melt, which leads to a large increase in surface area, and hence in heat transfer. The intermingling is driven by diffusional and kinetic mechanisms, including hydraulic fracturing, stress corrosion, capillarity, vapor–film collapse and water jetting, molecular diffusion, and Taylor and Helmholtz instability. It is important to note that this intermingling occurs over a wide range of scales from submicrometers to meters, and that it occurs without significant heat transfer to the water, because of vapor–film insulation.

After premixing, thermal energy is transferred to the water over a large effective surface area, and with this transfer, pressure builds, in many cases making the water a supercritical fluid or a metastable superheated fluid. From experiments this phase of pressure growth may show several different temporal patterns, including exponential, parabolic, and cyclic growth with time. For exponential growth pressure increases with surface area during premixing, which requires that premixing produces melt fragments that decrease in size linearly with time. This produces an exponential rise in surface area, hence in heat transfer with time, and an accompanying exponential rise in water pressure. On the other hand, a parabolic pressure rise probably reflects simple thermal diffusion in which heat transfer is initially rapid and slows with time as diffusional distances increase. Cyclic pressure increases best reflect cyclic growth and collapse of vapor films as premixing progresses. Rapid heat transfer at a water–melt interface causes a vapor film to pressurize and rapidly expand past its stable size, leading to overcooling of the film and its immediate condensation and collapse, which may produce water jets that

FIGURE 11 Fluid instabilities can form at the contact of water with melt. These instabilities are of a Rayleigh–Taylor or Kelvin–Helmholtz type, both of which may cause axisymmetric film collapse that causes water jets to penetrate the melt. The result is high surface-area fragmentation, rapid heat exchange, followed by vapor explosion. The explosion then generates new contact areas and/or a shock wave that fragments more melt and acts as a detonation wave. This process requires abundant water to be present. [Reprinted with permission from Wohletz, 1983.]

FLUID INSTABILITY FRAGMENTATION

1. H2O Superheated Vapor Film
   Melt

2. Film Collapse Fluid Instability - Water Jet Mixing
   High Surface Area Particles

3. Vaporization Wave Mossy Grains
   Vapor Explosion Co-penetration of Melt and Water

FIGURE 12 Fluid instabilities will form spherical or drop-like shapes of melt if viscosity is low and surface tension effects are strong. [Reprinted with permission from Wohletz, 1983.]
impinge the surface of the melt. The initial film pressure then becomes the force exerted on the melt surface by the film's collapse, which leads to the eventual breakup of the melt into smaller particles and an increase in heat transfer surface area. As the surface area grows, the pressure of each cycle of film growth also increases.

Premixing and pressure growth may continue or may decline with time, the latter case resulting in a highly metastable situation that can exist only in high confining pressures (>16 MPa). However, for the former case, water will gradually increase in temperature until it spontaneously vaporizes in whole or part. If a small portion of the water reaches this point first, its vaporization produces a pressure pulse that triggers the vaporization of the rest of the water and may cause an explosion.

An explosive vapor expansion drives a shock wave by which the melt is rapidly accelerated. This acceleration produces stresses that can exceed the bulk modulus of the melt, leading to its whole-scale failure and production of fragments; fragments formed during premixing are further comminuted and intact melt is torn apart. The mode of failure is largely determined by the properties of the melt, and it ranges from brittle to ductile in behavior.

The final stage of fragmentation is the ejection phase where fragments are moving at high speeds. If the explosion originates away from a free surface, then as the shock wave emerges through the free surface it will create a rarefaction wave that propagates in the opposite direction. This rarefaction wave allows immediate vapor expansion as it propagates into the conduit. It is at this stage when the wall rock (nonjuvenile lithics) becomes fragmented and incorporated into the erupting mass. With vapor expansion, fragments are accelerated and ejected out of the system. During this ejection, the speed of the fragment is proportional to its size because of inertial effects, such that fragments will move at different speeds and collide with one another, leading to further fragmentation.

Melt fragment shapes and size distributions are controlled by the types of premixing, triggering, failure modes, and ejection. Although growth and evolution cannot be directly observed, the overall pattern of phreatomagmatic fragmentation is portrayed by eruption phenomena. In this light, fragmentation evolution can be classified as: (1) escalating, (2) declining, (3) cyclic, or (4) delayed. Escalating fragmentation during eruption results in larger and larger volumes of tephra produced in each successive burst. Such behavior requires the mass of magma fragmented to increase by an increase in the water flux and/or magma flux. As discussed above, the water/melt mass ratio ($R_w$) determines in part the energy of fragmentation with higher fragmentation energy leading to more magma fragmentation. Conversely, decreasing fluxes or a change in $R_w$, away from high energy fragmentation leads to a declining fragmentation evolution. Cyclic evolutions are common where fragmentation repeatedly grows and then declines. This situation is most common where water supply is depleted after large fragmentation events, resulting in less energetic ones until the water supply is reestablished. Delayed fragmentation refers to a situation where a fragmentation event occurs after a prolonged period after premixing. Prior to fragmentation, the system is metastable, requiring a trigger. This type of fragmentation, although well-observed in experiments, is difficult to sustain in volcanic situations. Such situations might include a upper-crust magma chamber that interacts with water saturated rocks for a long time prior to eruption.

C. Fragmentation Controls

Through the experiments and theory described above and observations at numerous volcanoes around the world, it has become clear that phreatomagmatic fragmentation is largely controlled by three key parameters: magma viscosity, temperature/pressure, and water/magma contact mode. The third is a function of the supply rate of magma and external water which is determined by the hydrology of and around the vent and conduit.

During phreatomagmatic fragmentation part of the thermal energy of the magma is converted to mechanical energy, including seismic and acoustic energy, fragmentation energy, and kinetic energy of fragment motion. With an increasing efficiency or conversion ratio, more mechanical energy is released and fragmentation increases. In field observations at volcanoes, the relative efficiency of phreatomagmatic fragmentation is reflected by fragment size distribution and mode of fragment dispersal.

In general, (1) higher temperature melts have greater thermal energy available for conversion to mechanical energy, (2) viscosity retards the mixing of magma and water in a manner that generally predicts that fragmentation will be greater in lower viscosity magmas, and (3) the amount of water relative to that of magma involved in fragmentation determines the intermediate and final thermodynamic states of water for phreatomagmatic eruptions. Magma and water temperatures prior to interaction influence the heat transfer rates and equilibrium temperature approached during mixing. In a simple way, the higher the equilibrium temperature,
the more energy is available for mechanical work, but the rate of heat transfer is complexly linked to water temperature, rising rapidly with temperature until the onset of vapor-film boiling. Thermal equilibrium is probably never reached during fragmentation because instability and vapor expansion occurs before this point is reached. For the instantaneous heating case, the temperature of the interface, \( T_i \), is theoretically constrained by

\[
T_i = \frac{T_m(\alpha_m/\sqrt{\kappa_m}) + T_w(\alpha_w/\sqrt{\kappa_w})}{(\alpha_m/\sqrt{\kappa_m}) + (\alpha_w/\sqrt{\kappa_w})},
\]

where \( \alpha \) and \( \kappa \) are thermal conductivity and diffusivity, respectively, of the respective phases water, \( w \), and melt, \( m \). If \( T_i \) is greater than the spontaneous nucleation temperature of water, then a spontaneous superheat vaporization would occur.

The effect of ambient (or confining) pressure is less understood. Pressure is thermodynamically linked to temperature, and, as such, the pressure-volume work of a fragmentation should increase with pressure, but there are some experimental indications that pressure also acts to subdue interaction because it limits vapor-film growth and the amount of premixing. However, the most violent experimental fragmentations have occurred where confining pressure is in excess of the critical pressure of water.

The viscosity of magmas ranges from few Pa·s in the case of basaltic composition to millions of Pa·s in the case of silicic magmas. Viscosity is additionally coupled to temperature in magmas (higher temperature magmas have generally lower viscosities). While temperature may vary several hundreds of degrees, viscosity varies over many orders of magnitude. Viscosity (and surface tension) is an important parameter for growth and propagation of fluid instabilities at the interface between magma and water. Such instabilities have been cited as likely mechanisms.

The combined effect of viscosity and temperature on the efficiency of fragmentation is markedly less than that of water/magma ratio, which varies over two orders of magnitude. This observation reflects the major control of water expansion during fragmentation, a control determined by intermediate and final thermodynamic states of water. If very little water is available, it can be heated to high temperatures and pressures, but fragments only a relatively small volume of magma. At the other extreme, abundant water may never get enough thermal energy for fragmentation. At intermediate mass ratios, there is enough thermal energy to take all the water to high states of internal energy, thus resulting in rather complete magma fragmentation.

Water involved in the interaction may not always be a pure liquid, it may contain particles (sediment or tephra) or other impurities such as dissolved compounds (seawater or hydrothermal fluids). The effects of these impurities on the fragmentation process are related to the changes in the physical properties of the impure water. Depending on the concentration of impurities in the water, its viscosity may increase up to an order of magnitude, the density may double and the heat capacity may decrease by one-fourth.

IV. Field Observations

Hydrologic settings for phreatomagmatic fragmentation vary from deep ocean (marine) to near shore (littoral) to lake (lacustrine) to surface drainages (fluvial) and groundwater (phreatic) settings. The hydrological settings affect the abundance and supply rate of water and the ambient pressure at which interaction occurs. Accordingly, the character of phreatomagmatic fragmentation varies in a systematic manner with setting.

For marine settings, deep water explosive fragmentations are not generally observable. In fact, many researchers propose that for depths where hydrostatic pressure is greater than the critical pressure of water, explosive fragmentation does not occur. These researchers explain deep ocean hydroclasts to have resulted from simple quench fragmentation of extruded lava, because most hydroclasts are blocky shaped and coarse to medium in size. On the other hand, experimental and theoretical evidence shows that the critical pressure of water is not the maximum pressure at which explosive fragmentation may occur. In fact, for most substances that undergo such rapid vaporization (leading to explosive expansion), the phase change may occur well above the critical pressure. Future research involving actual observation of deep water eruption or documentation of explosive effects in deep water tephra deposits may resolve this debate.

Littoral fragmentations have been well documented in Hawaii where lava flows enter the sea. A large variation in fragmentation dynamics is observed from passive steam and quench-fragmentation to violent bursts that form high-speed sprays of fine-grained hydroclasts. One control is thought to be whether or not lava contacts water within the confined space of a lava tube or not. The fragmentation starting in a lava tube is observed to be very violent, suggesting that such confinement allowed buildup of high pressure during the event. Con-
Phreatomagmatic fragmentation in fluvial or phreatic hydrogeological environments is governed by a limited supply of water. Such fragmentation, though, can be the most violent because water/magma ratios are in the range of optimal interaction and the contact modes under confined conditions (i.e., in hydraulically active fault systems) are optimal for the generation of thermohydraulic explosion. Tuff rings (e.g., Crater Elegante, Mexico; Panum crater, United States) in these settings show wide-area, high energy dispersal with superheated vapor that does not produce such wet deposits; hence palagonitization is limited. Such fragmentation is called dry and in many places occurs with scoria deposits that result from little or no water interaction. Typically the fragments are fine-grained ash, showing a range of shapes from blocky to mossy aggregates to micrometer-sized spheres. Tuff cones (e.g., Cerro Colorado, Mexico; Koko crater, United States) show low energy dispersal with saturated steam that produce palagonitized deposits. Such fragmentation is called wet and in many places produce basal surge deposits that result from a progressively water-rich interaction. Typically the fragments are fine- to medium-grained ash, showing a range of shapes from blocky and platey with dust-sized fragments adhering to surfaces, forming accretionary type grains.

The depth of fragmentation is likely determined by the depth of the aquifer. During eruption, an aquifer may be drawn down such that fragmentation level gets deeper while the hydrostatic pressure on the system is more or less constant. Explosions propagating downward will fragment and erupt wall rock at deeper and deeper levels, thus enlarging the conduit (e.g., a diatreme) to the depth of the aquifer. The amount of lithic ejecta also reflects the stability of the walls. Very little fragmented wall rock is erupted when the walls are stable and the eruption is fairly continuous and weak. If the walls are unstable, then the walls may be eroded during a weak eruption, thus producing a significant amount of fragmented wall rock. The collapse of eroded wall rock can trigger a strong, discrete explosive phreatomagmatic eruption that erupts mostly lithic material.

V. SUMMARY AND
FUTURE RESEARCH

1. Phreatomagmatic fragmentation is quite distinct from magmatic fragmentation in both the eruptive phenomena and the driving mechanisms as well as in the types of fragments produced. Phreatomagmatism produces unique juvenile grain populations that reflect the relative amount of water and magma involved in the interaction. The quantity of nonjuvenile (fragmented wall rock) material found in deposits reflect the stability of the conduit walls and the explosivity of the eruption.

2. Phreatomagmatic fragmentation results in a spectrum of eruptive activity ranging from passive quenching of magma/lava to explosive ejections of ash. The style of eruption primarily reflects the hydrologic environment in which magma/lava come into contact with water.

3. Much of our understanding of phreatomagmatic fragmentation stems from laboratory experiments related to fuel–coolant interactions (FCIs) as well as field observations and laboratory analysis of the fragments. It is future experimental studies that may best improve our current knowledge of the controls of phreatomagmatism. For example, experiments have thus far only covered a rather narrow range of melt compositions, including thermitic melts and some remelted volcanic rocks. Detailed experiments may reveal how fragmentation is affected by compositions ranging from mafic to silicic and with different proportions of dissolved volatiles. Similarly, experimental coolants have been pure or nearly pure water, so very little is known about how impurities in the coolant effect the fragmentation process. These areas for future research are just a few that could further the relevance of experimental analogs to phreatomagmatic volcanism.

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