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Physics of Phreatomagmatism

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Part 1: Explosion Physics (Bernd Zimanowski)

Maar volcanoes are the “classical” product of phreatomagmatic explosions. Phreatomagmatic volcanism generally results from interaction between magma and water, i.e. surface and/or groundwater (e.g. Colgate and Sigurgeirson 1973, Lorenz 1987, Sheridan and Wohletz 1983). The style of phreatomagmatic eruptions ranges from relatively mild interactions (during e.g. the inflow of low viscosity lava into a lake or the ocean) to extremely high energy explosions, that produce pyroclastic deposits consisting of more than 90 % fragmented country rock. This most effective and thus most hazardous volcanic mechanism of conversion of thermal into kinetic energy is by phreatomagmatic explosion (Lorenz et al. 1994, Wohletz 1986, Wohletz and Sheridan 1983, Wohletz and Brown 1995, Zimanowski et al. 1997a). The principal physical mechanism of magma/water interaction that produces expansion work, and thus can lead to an explosion, is the large difference in the volumetric thermal expansion between these liquids: cooling of the hot melt creates much less space than needed for an isobaric expansion of heated water. Therefore explosive processes can always occur if magma meets water, even at very high abmient pressures. Phreatomagmatic explosions in sensu strictu (Zimanowski 1998), however, result from short-term near surface magma/water interactions, when rising magma encounters ground or surface water at hydrostatic pressures below the critical pressure for water, i.e. the pressure which limits the phase transition water/steam (~22MPa). Only at distinctly lower hydrostatic pressures the heat transfer through the magma/water interface is limited effectively by the formation of insulating vapor films, the so-called "Leidenfrost phenomenon". Under these conditions explosive premixes of water in magmatic melt can form, if sufficient "mixing energy" is provided by flow processes, i.e. by the hydrodynamic energy of magma and/or water (Wohletz and McQueen 1984, Zimanowski et al. 1991). Once they exist, such explosive premixes can be triggered by seismic shocks or by local spontaneous vapor film collapse, resulting in a complete and very rapid breakdown of all vapor films of this premix. This leads to a strong thermal and mechanical coupling, i.e. the heat-flux from the magma to the water as well as the speed of sound in the premix increase nearly instantly by 1 to 2 magnitudes (Büttner and Zimanowski 1998). The consequence is the transfer of a substantial part of the thermal energy of the involved magma to the involved water in a very short time period (few milliseconds or less). This sudden "overload" of the water/ magma system causes a violent explosion, the phreatomagmatic explosion. In industrial plants (e.g. steel production, power plants, high temperature waste combustion, ore processing) water cooling of high temperature sections is withspread. Thus, structural failure of water tubes or similar events frequently caused severe accidents by explosive water/melt interaction. Analogue phenomena were observed when liquid natural gas and water (in this case the hot liquid) interacted. These so-called "steam explosions" or "Fuel-Coolant-Interactions" have been intensively studied in the course of severe accident research by engineering scientists and physicists (Board and Hall 1975, Corradini 1981, Henry and Fauske 1981, Theofanous 1995). In the case of hot melts interacting with water the more descriptive term Molten Fuel Coolant Interactions (MFCI) is used. Phreatomagmatic explosion may also be referred to as volcanic MFCI.

MFCI commonly is described in four phases: (1) a **hydrodynamic mixing phase**, (2) a **trigger phase**, (3) a **fine fragmentation phase**, and (4) a **vaporization and expansion phase**.
By sufficient flow energy a premix of water in magma (cm to dm range) forms under stable film boiling conditions.
If low-energy shock waves (<10 J) pass through such a magma-water premix, the vapor films can collapse quasi-coherently (i.e., the induction of vapor film collapse in the premix takes place in a few nanoseconds, and the following reactions have a duration of several hundred microseconds), and the so called "direct contact" between both liquids of the premix occurs (Fröhlich 1991, Zimanowski et al. 1995a).
Direct contact describes the complete hydraulic coupling of both liquids: no vapor phase is separating the liquids and the interface has been transformed from a liquid-gas-liquid (two-phase) state to a liquid-liquid (single phase) state. Consequently, the transfer of heat from magma to water increases by 1-2 orders of magnitude (Fiedler et al. 1980). Simultaneously, an intense thermal fragmentation process is initiated (MFCI fine fragmentation process), resulting in a rapid increase in the area of the direct contact interface. Both processes are coupled in a positive feedback mechanism (Fröhlich et al. 1992, 1993, Zimanowski et al. 1995a). Thus the heat flux from the magma to the water is strongly increased, and the water becomes superheated.
Finally, the superheated water vaporizes. The expanding steam may now drive a volcanic (phreatomagmatic) eruption and further fragmentation processes by disrupting parts of the system that have not been involved in the process yet (Wohletz et al. 1989, Lorenz et al. 1994).
Direct observation of volcanic MFCI is not possible, and therefore experimental studies have to be designed and carried out, with the use of previous research of safety engineers and physicists and with interdisciplinary cooperation. The pioneer of experimental investigation of volcanic MFCI was Ken Wohletz, who (with his co-workers) carried out experiments using metal melt resulting from termite reaction, in some cases mixed with quartz-sand to approximate silicate melt (e.g. Wohletz 1983, 1986, Wohletz et al. 1995). These experiments yielded important first insights into the process concerning water/melt ratios, thermal to kinetic energy conversion ratios and the resulting pyroclast formation. A German group formed in the early 80's, consisting of volcanologists, physicists and engineers, who chose remelted volcanic rocks (ultrabasic to andesitic composition) for experimental studies on explosive MFCI (e.g. Zimanowski et al. 1986, 1991, 1995a). Following the considerations given above, both working groups used entrapment configurations for their experiments, i.e. water was entrapped by a melt volume (Fig. 1).

Fig. 1: Entrapment configurations: A Wohletz et al., B Zimanowski et al. 1 = melt, 2 = water, 3 = diaphragm, 4 = water injection tube (Zimanowski 1998).

The experimental studies on phreatomagmatic explosion called TEE (Thermal Explosion Experiment) were first conducted at the University of Stuttgart and since 1994 at the Physikalisch Vulkanologisches Labor, University of Würzburg (TEE II) by an interdisciplinary group of researchers that include volcanologists, physicists and engineers. The TEE experiments were designed to evaluate:

1) the effect of the mode of contact of water and melt on the explosivity of the interaction
2) the mixing conditions prior to explosion onset (i.e. premixing)
3) the effect of various trigger signals
4) the fragmentation processes in respect to their products
5) identification of explosive MFCI by direct physical measurements

The geometrical scaling of the experiment, i.e. the size and shape of the experimental configuration depends on the scale of the physical process to be investigated. If this real scale exceeds any experimentally achievable sizes, more or less complex scaling operations will be necessary. The optimal balance of experimental scales is the so called **meso scale**, i.e. large enough to represent the real scenario, but as small as possible to minimize the experimental effort. The meso scale for our experimental studies on volcanic MFCI was determined by numerous preliminary tests and then was used as standard configuration in the Thermal Explosion Experiment II (Zimanowski et al. 1997a). Proper scaling can be checked by comparing the experimentally produced pyroclasts with those from natural deposits of phreatomagmatic volcanic eruptions. “Artificial ash” could be generated using the TEE II experiment that was morphologically and chemically indistinguishable from the natural analogue (Büttner et al. 1999).

1 Contact modes and experimental configurations

The design of the TEE experiment allows two geometrical configurations: water entrapment achieved by injection of a water volume into a melt volume and melt entrapment achieved by stratification of a water volume onto a melt volume. The stratification experiments were found to produce only very weak MFCI with low reproducibility and thus to be not useful for the systematic evaluation of volcanic MFCI on a laboratory scale. The entrapment configuration by water injection into a hot melt was found to be useful for the reproducible generation of MFCI with georelevant melts and water on experimental scales from the cm to the dm range (Fig. 1 B).

In nature inflow of magma or lava into a water body was directly observed from the beach, by scuba divers, and by submersibles. The fact that these observers have survived can be regarded as an indirect proof, that under these contact conditions explosions are rare and, if they occur, are relatively weak. In the case of large scale geometries, i.e. large melt volumes in excess of many m^3 that are pushed into a larger water body in a short time span, however, locally restricted explosive premixes may occur when water is enclosed by or forced into the melt. In such a case MFCI may play an important role in the dynamics of the eruptive processes, but only a very minor part of the melt will be directly involved and only few pyroclasts will be produced as “direct witnesses” of volcanic MFCI in such “extremely wet” conditions. MFCI by producing strong shock waves that are able to trigger nucleation of juvenile volatiles may be an important mechanism to explain the drastic change from lava sheet and pillow formation to the production of highly fragmented hyaloclastic deposits. Most of the pyroclasts that are generated in such events, however, should be derived from fragmentation of magma by thermal granulation, thus reflecting the high cooling rates ($>10^3$ K/s).

2 Mixing conditions prior to explosion onset

The formation of an explosive configuration between water and a hot melt commonly is described as premixing phase of MFCI. During this phase the start conditions of the short time event “thermohydraulic explosion” (Büttner & Zimanowski 1998) are established. In experimental investigations it was found that not only the probability of an explosion is determined during this phase, but also to a large extend the intensity of the following explosive processes. The effectivity of hydrodynamic mixing processes under confined geometry, i.e. the effectivity of the formation of interfacial area between two liquids is governed by a) the differential flow speed (hydrodynamic energy) of the system and b) by the material properties of the liquids to be mixed. Good mixing (i.e. the generation of a large interfacial area in a short time) is achieved when the flow speed is high, the densities and viscosities of the liquids are similar and low, and the liquid-liquid boundary tension is zero. In volcanism the hot melt is magma, that is in most cases a silicate melt with a density between 2.5 and 3 g/cm^3 and a viscosity ranging from few Pa s to 10^6 Pa s or even more. In contrast water has a density close to 1 g/cm^3 and a viscosity of 10^{-3} Pa s. The boundary tension between water and magma is unknown, however, it can be assumed that at stable film boiling conditions the boundary tension is approximately the arithmetic sum of the surface tension of magma against an ideal gas and the surface tension of water against an ideal gas, and thus is in the range of 200 to 400 mN/m (which is pretty high). Intensive fragmentation or even flooding of water in melt or vice versa therefore can not be expected under differential flow speeds in a georelevant range (i.e. mm/h to some m/s).

In the TEE experiments optimum water/melt volume ratios of 1:10 and optimum differential flow speeds of 5 m/s during the premixing in entrapment configuration were determined (Zimanowski et al. 1997b). These values should more or less be valid for all basic magmas for the case of water intruding into magma. Although the maxima are well defined, explosions occurred in a wide hydrodynamic mixing range. Water/melt volume ratios and differential flow speeds that were needed to produce explosions in the experiments are both in a range that may occur in natural volcanic environments.

3 Trigger signals

Similar to chemical detonations, MFCI needs an initial trigger that “synchronizes” the breakdown of the insulating vapor films and thus establishes mechanical and thermal coupling of the two-liquid-system. The trigger signal needed is very weak in contrast to the energy of the thus “ignited” thermohydraulic explosion. In TEE experiments using 140 cm^3 of melt and 10 cm^3 of water a total kinetic energy release exceeding 10 kJ was determined. The trigger energy needed was found to be less than 10 J.

In TEE experiments pressure waves and shock waves were produced by the impact interaction of a projectile of <10 J kinetic energy with the melt surface. By variation of the projectile geometry diverse pressure wave forms were generated and by variation of the projectile speed the intensity of the pressure signal was varied. In experiments using larger melt crucibles (up to 5 dm^3) multiple explosions were observed, indicating that one explosive interaction had triggered another: even the reduced geometrical scale of the experiments allows the evolution of a propagation mechanism. Consequently it can be assumed, that explosive mixtures on a large scale can be initiated by a trigger of the strength found at the experiments. The quality of the triggering pressure waves of the observed energy can easily be produced by thermal fracturing in any environment with high temperature contrasts, e.g. during contact of a magmatic melt and cold wall rock. Furthermore in volcanic environments, due to volcano-seismic activity, seismic waves exceeding by far the respective energy are abundant. Hence if explosive premixes occur in any volcanic scenario, they will most probably be triggered.

4 Fragmentation processes in respect to their products

The TEE experiments feature complete recovery of the particles (“artificial pyroclasts”) that are produced in each individual run. The crucial phase of MFCI during which the heat energy transfer from melt to water takes place is the fine-fragmentation phase. In combination with the angular shape characteristics of the particles which are produced during this phase (i.e. interactive particles), a brittle process can be inferred as the major mechanism of MFCI fine-fragmentation.

Two effective mechanisms for the physical description are reasonable:

Thermal granulation caused by stress induced by extremely high cooling rates. For MFCI experiments conducted using metal melts, cooling rates for the fine fragments with diameters d ($100< d <200$) µm were determined to have exceeded 10^7 K/s. Because thermal conductivities of silicate melts are significantly lower than those of metal melts, the cooling rates for interactive particles with typically ($32 < d <130$) µm are expected to have experienced cooling rates in excess of 10^6 K/s. If a subliquidus silicate system is exposed to such extreme cooling rates, it is conceivable that an intense brittle reaction (thermal granulation) is induced.

Brittle reaction of the melt caused by excess fluid pressure. During the escalative heat transfer from the melt to the water, the water becomes superheated in an extremely short period of time. For thermodynamic reasons this quasi-isochoric process will result in a rapid pressurization of the water in the liquid state. Under direct contact conditions the water-melt system is hydraulically coupled, and thus very high stress rates will act on the melt. If these stress rates by far exceed the respective temperature dependent critical stress value, an intense brittle reaction is induced and the melt behaves as a solid material on this time-stress scale.

In the course of MFCI fine-fragmentation, extremely high cooling rates occur in combination with very high stress rates caused by the pressurized water. Therefore both physical mechanisms play a role. The brittle type fragmentation was experimentally proved by direct optical observation using a transparent magma simulant (carbonate melt at 900 °C) and ultra high-speed cinematography (Zimanowski et al. 1995b, 1997c).

Size and shape properties of the particles that were determined to be produced exclusively by MFCI fine-fragmentation are in good agreement to the descriptions of ash sized particles generated by phreatomagmatic fragmentation as deduced from field observations and the Los Alamos experiments (e.g. Heiken and Wohletz 1985).

In nearly all cases, volcanologists are restricted to deductive analysis, based on the characteristics of the pyroclast deposits. In scaled laboratory experiments carried out in the Physikalisch Vulkanologisches Labor, the major fragmentation processes (aerodynamic, hydrodynamic, and brittle) were studied with the use of remelted volcanic rocks. The results should also be valid for natural systems. During real volcanic events, however, further processes may influence the shapes and distribution patterns of pyroclasts: degassing of magma and variations in vesiculation, crystallization and chemical variations in the erupted magma reservoir, coalescence of particles and formation of aggregates, transport and depositional processes, syn-eruptive and/or posteruptive chemical alteration.

Nevertheless, the occurrence of specific particle families allow the identification or even the reconstruction of eruption mechanisms. Further experimental work with various melt compositions in various states of vesiculation will enhance the application to natural systems.

5 Identification of explosive MFCI by direct physical measurements

Experimental explosive MFCI (thermohydraulic explosion) is a highly energetic short time process taking place in a "time window" of less than one millisecond. In this timespan new surface is created by a brittle type fine-fragmentation process. The particles exclusively produced during this event could be identified and quantified. With the use of nitrogen sorption technique (BET) the total surface of all particles produced by each TEE run was measured and the proportion created during explosive MFCI (i.e. "interactive surface area") was calculated (Zimanowski et al. 1997a). It was found, that this interactive surface area correlates in a linear way with the respective explosion intensity (Fig. 2).

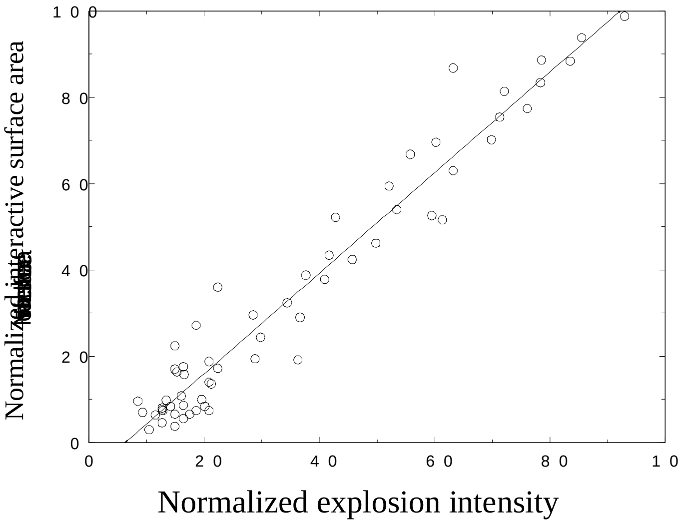

Fig. 2: Explosion intensity versus interactive surface area of experimental MFCI

If a material is fragmented on a short time scale and new surface is produced, the electrostatic balance of this material gets disturbed. This non equilibrium state causes a time dependent disturbance of the electrostatic field in the vicinity of the process, once the fragmented system starts to expand. High resolution measurements of the electrostatic field were performed during TEE runs and strong electrical signals were (Büttner et al., 1997). This electrical signal was found to show a linear proportionality to the explosion intensity and therefore also to the surface area created during explosive MFCI (Fig. 3). Thus, in laboratory experiments it is possible to measure the fragmentation directly by detecting the electrostatic field and the explosion energy can directly be calculated with high precision.

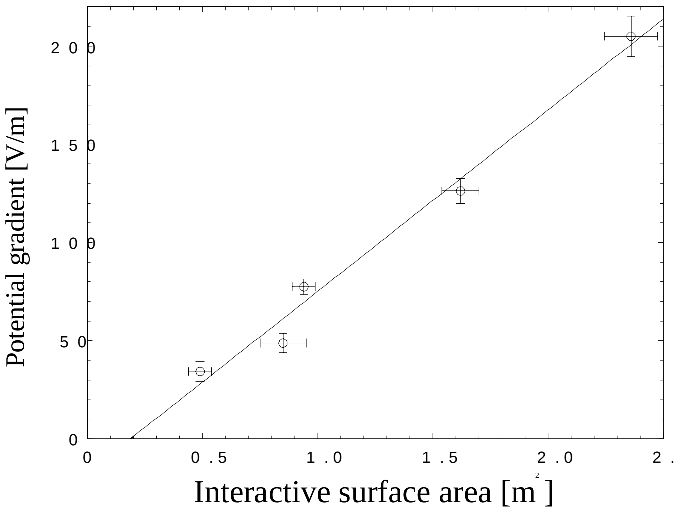

Fig. 3: Interactive surface area generated during brittle type fine-fragmentation of experimental MFCI with remelted basic volcanic rock plotted versus the experimentally measured potential gradient.

In the time span (< 1 ms) of the fine-fragmentation and thermal energy transfer more than 80% of the totally released kinetic energy is emitted as seismic energy (shock waves) during experimental MFCI. The quality of this signal can also be used for identification of explosive MFCI under laboratory conditions, where the elastic properties of the media between source and detector are known.

The experimental results, as well as many observations of the few directly visible scenarios of interaction between water and magma (Hawaii, La Reunion, Surtsey) show, that volcanic MFCI rarely occurs when magma enters a water body. In this case the probability of water to get entrapped into magma is low, because in such a case the extremely different material properties hinder hydrodynamic mixing processes. Once both liquids meet under confined conditions, e.g. in a feeder dyke, a sill, or a conduit (vent or lava tube), water cannot escape easily and mixing can be achieved under realistic differential flow speeds. In such a scenario triggering will also be very probable, as during dyke propagation into country rock seismicity will be high and thermal cracking of wall rock will frequently occur. Thus, phreatomagmatic explosions often occur during initial emplacement of magma, at the end of quiet periods between magma pulses, when the magma production rate jumps from low to high rates and when tectonic events occur (land slides, crater collapses, lava bench collapses, faulting in general) due to "structural failure" of the volcano itself or of the wall rock. One major hazard of such explosions is the opening of large vents, the resulting decompression of magma reservoirs and thus the triggering of large scale eruptions.

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