1. Introduction

Explosive volcanic eruption mechanisms are difficult to address experimentally, since many of them involve processes that are important at scales of several meters to hundreds of meters. One such case is phreatomagmatic eruptions where magma and water interact rapidly, resulting in large-scale explosions (White & Valentine, 2016). In nature, one cause for change in the eruption style of a volcanic system from mildly effusive to highly explosive is the availability of groundwater or surface water in the vicinity of magma (Dellino et al., 2012; Gudmundsson et al., 2012; Lorenz, 1987). Explosive interaction occurs at various depths. Diatreme dimensions suggest that subsurface explosions occur at depths of ≥1 km (Delpit et al., 2014; Valentine et al., 2014). Shallow explosions result in ash-rich eruption columns and tephra jets (Houghton et al., 2015). At greater depths, explosions may be partially or fully contained by the host material (Graettinger et al., 2014; Sonder et al., 2015), fracturing and mixing magma and brecciated host rock (Graettinger et al., 2016; Sweeney & Valentine, 2015).

A physical process that is associated with these large-scale phenomena is the violent interaction of liquid water (coolant) with a liquid heat source (fuel). The fuel’s temperature has to significantly exceed the homogeneous nucleation temperature of water. This process, referred to as Molten Fuel Coolant Interaction (MFCI), has been studied experimentally in the context of larger-scale industrial process safety in order to understand accident scenarios in nuclear power plants and metal production sites (e.g., Eckhoff, 2016; Lipsett, 1966; Yuen & Theofanous, 1999). In the context of explosive volcanic eruptions, the process has also been studied in different experimental setups. In one setup, dynamically melted thermite (reacted 2Fe + Al2O3), used as fuel analog to magma, was dropped into water in confined and unconfined containment (Wohletz & McQueen, 1984; Wohletz et al., 1995). In a second setup, water is injected into molten volcanic rock (entrapment configuration) which initially rests in an open crucible, and is brought to explosion by an appropriately timed trigger event (Büttner et al., 2002; Büttner & Zimanowski, 1998).
Throughout the different fields of application, there is rough agreement about several stages through which an explosive process will pass: (1) A premix phase in which liquid water mixes with the molten fuel in several separated volumes of arbitrary shape, referred to as domains. A thin vapor film, caused by the high melt-water temperature difference, separates them from the melt and limits heat transfer (Leidenfrost phenomenon; Leidenfrost, 1756). (2) A propagation phase that directly follows a trigger event in which the melt is hydrodynamically or brittlely fragmented and which is sometimes further subdivided into a trigger phase and a propagation phase. (3) A phase of rapid expansion of the postfragmentation particle-vapor mixture. In natural scenarios, this sequence applies locally, on scales that could be verified experimentally. On larger scales, other complications of mixing dynamics and heterogeneities may become important. The trigger event starting phase (2) establishes direct melt to liquid water contact by rapid elimination of film boiling conditions at the interface, which in turn drastically increases the melt to water heat flux (Henry & Fauske, 1979; Nelson et al., 1999; Zimanowski et al., 1995). Under direct contact between liquid fuel and liquid coolant, the process is governed by the thermo-mechanical properties such as density, compressibility, and critical stresses of the liquid phases of involved materials. This causes high intensity stress release and shortens the interaction time scale, and therefore, the process is also referred to as thermohydraulic explosion (Büttner & Zimanowski, 1998).

For the purpose of modeling the process numerically, it is often assumed that the melt is fragmented hydrodynamically in the propagation phase (Meignen, Picchi, et al., 2014; Theofanous et al., 1999). However, experimental results from silicate and carbonate melts as well as field evidence showed that strongest explosive interaction with those melts is caused by brittle fragmentation of the melt that is close to the water interface, where temperature gradients and stresses are the highest; at larger distances, the same event causes hydrodynamic deformation and fragmentation of the host magma (Büttner et al., 1999; Zimanowski, Büttner, & Nestler, 1997). The reason for different fragmentation mechanisms in these considerations may be related to the different applied melt-water interaction scenarios: The main application scenario for reactor safety considers a melt jet falling into and interacting with a relatively large pool of water (Dinh et al., 1999; Manickam et al., 2016), which is different from the entrapment of water domains by a melt. In the case of silicate melts, however, the jet-falling configuration only rarely leads to explosive interaction, but to lower energy thermal granulation and the production of glassy rinds (Mastin, 2007; Schmid et al., 2010; Sonder et al., 2011). An example of a rare explosive event when melt enters a large water body is the widely reported small-scale explosive incident at the ocean entry of Kilauea’s recent lava flow (fissure #8) activity, where a tourist boat was hit by an ejected lava bomb.

The trigger event that initiates phase (2) establishes direct melt to liquid water contact by rapid elimination of film boiling conditions at the interface, which in turn drastically increases the melt to water heat flux (Henry & Fauske, 1979; Nelson et al., 1999; Zimanowski et al., 1995). Under direct contact between liquid fuel and liquid coolant, the process is governed by the thermo-mechanical properties such as density, compressibility, and critical stresses of the liquid phases of involved materials. This causes high intensity stress release and shortens the interaction time scale, and therefore, the process is also referred to as thermohydraulic explosion (Büttner & Zimanowski, 1998). Experimental and numerical investigations show that melt fragmentation is caused by rapid pressure buildup in the liquid water phase as the vapor film collapses, which applies stress to the adjacent melt on a time scale too short for a viscous response (Büttner et al., 1999; Yuen & Theofanous, 1995).

There is an overall agreement that system size and geometry play an important role in all of the three phases of interaction, and the lack of variety in experimental scales and configurations to date has been a major complication applying experimental results to both industrial and volcanic hazards assessment (Berthoud, 2000; Meignen, Raverdy, et al., 2014). A critical parameter arising from analysis in magma-water interaction settings is the local mass ratio of water and melt that are directly involved in the highly explosive phase (Wohletz et al., 1995). This ratio is defined locally at the length scale of a water domain, not of the entire melt-water premix (White & Valentine, 2016), and therefore changes with premix geometry and timing.

Although the MFCI mechanism provides the necessary power density to drive phreatomagmatic eruptions, unsolved questions remain about the relationship of explosivity to system size, geometric constraints, and timing, which complicate the application of experimental research to geologic scales. MFCI is very sensitive to the preexplosive melt-water mixing conditions. Experiments showed that conditions maximizing explosivity are dependent on the mixing speed of water relative to the melt, on water domain size, and on trigger timing (Büttner & Zimanowski, 1998; Wohletz, 2002). These conditions affect the water to melt mass ratio.
$R_m$, which is used as one of the necessary quantities for scaling. $R_m$ is defined as the ratio of water mass to melt mass which are directly involved in the highly explosive phase. Previous experimental considerations suggest that, depending on the experimental implementation, explosive interaction occurs for $R_m$ ranges of 0.03–0.16 (Zimanowski et al., 1991; Zimanowski, Büttner, & Lorenz, 1997) or 0.1–1 (Wohletz, 1983; Wohletz et al., 1995). At too low values, the heat sink is too small to support high heat transfer rates through large enough interfaces: the rapid heat transfer phase ends before the pressure buildup is large enough to cause brittle fragmentation of the melt that would enable rapid thermal feedback. For large $R_m$ values, there will be melt brittle fragmentation, but in this case the water body is large enough to buffer local evaporation.

Similar considerations can be done for the water mixing speed. At very low speeds, significant amounts of water will evaporate before $R_m$ is large enough to be critical. At very high values, film boiling at the interface is not stable due to interfacial stresses, and this also keeps $R_m$ below the critical range. $R_m$ and mixing speed are not independent: A high mixing speed causes inertial forces that act against the interfacial tension and friction to become larger and unstable which causes the water to break up into smaller domains (inertial fragmentation of the water domain; e.g., Landau & Lifschitz, 1991), effectively increasing the interfacial area and this way the amount of water available to explosive interaction. Another factor is the timing and energy of the trigger event that causes coherent vapor film collapse and starts the explosive phase. For metallic melts, there is experimental evidence that a trigger event is not a strictly necessary condition for explosive interaction; explosive interaction can start spontaneously (Spitznagel et al., 2013). For silicate melts, spontaneous explosions have not yet been realized in reproducible experiments. Trigger events in previous experiments created a sharp, not necessarily intense, pressure peak that destabilizes the interfacial vapor film. It is not clear if and how the required trigger energy and timing depend on the size of a melt-water system under consideration. These questions have direct implications for the explosive process on volcanic scale. The time to create a critical premix increases with growing total premix size, but the maximum lifetime of quasi-stable film boiling conditions is limited. It is therefore unlikely, for example, that a relatively pure magma-water contact can evolve over days to an explosive premix that would stretch over a significant volume of a volcanic conduit. Geometric and temporal constraints need to be investigated that put realistic limits to mixing velocities.

As a next step to address those issues, we developed an experimental facility that enables experimentation on a meter scale using remelted volcanic material. It aims to address questions specific to volcanic settings that concern geometries of premix and melt, as well as timing and trigger behavior. One advantage of experiments on the meter scale is that they enable investigation of premix conditions that lead to critical or explosive behavior. Even though critical conditions such as mixing speeds, trigger timing, and mass ratios were determined on decimeter scale in the laboratory, not all of these are easy to scale to larger scenarios. For example, the duration of film boiling can be estimated to be on the order of seconds for a simplified scenario, in which melt is not able to deform, and therefore cannot convect heat (e.g., Dhir, 1993; Schipper et al., 2013). A more realistic scenario in which the water convects and deforms the melt by rising through buoyancy is much more complicated to address, since the film boiling conditions cause reduced friction at the interface and the interfacial tension. Parts of our experimental design build upon the laboratory scale entrapment configuration MFCI experimental setup (e.g., Büttner & Zimanowski, 1998) which provides good control of the premix dynamics. Here entrapment of liquid water is realized by injecting it into the melt. The method allows the control of the water injection speed and overall premix timing (Zimanowski, Büttner, & Lorenz, 1997).

We compare experiments that were conducted in both the laboratory and the large-scale experimental setups. The larger experimental setup was tuned based upon previous small-scale results, but the water to magma mass ratio was kept relatively low for safety reasons. This article explains the general experimental layout and procedure and presents first results related to geometric dependencies, trigger timing, and spontaneous explosive response. We will pragmatically refer to the lab-scale experiments as decimeter-scale experiments, and the larger setup will be called meter-scale experiments. The text will also refer to the following terms that briefly we define here

- **water or melt domain**: We define a water or melt domain as a continuous volume of water or melt, respectively, which may have arbitrary shape.
- **intense interaction**: A qualitative difference of interaction behavior was observed when significant amounts of melt were ejected. This happened in experiments with maximum luminance values $L_{\text{max}} > 0.2 \text{ m}^2$. 


Table 1

Oxides of Major Elements in the Source Rock, Measured in Volatile-Free Basis

| Oxides:   | SiO₂ | TiO₂ | Al₂O₃ | FeO | MnO | MgO | CaO | Na₂O | K₂O | P₂O₅ |
|-----------|------|------|-------|-----|-----|-----|-----|------|-----|------|
| wt.%:     | 38.03| 3.79 | 9.81  | 12.20| 0.20| 15.22| 12.61| 3.05 | 1.19| 0.83 |

- **dynamic pressure offset**: The dynamic pressure offset is the difference between the (slowly changing) driving pressure that is used to push the water through the supply system and injection tube and the pressure measured while the water is being injected.

- **mixing speed**: We refer to the melt-water mixing speed as the relative speed between water and magma. This is different from a possibly more generic mixing speed definition that could be derived from time-dependent ratios of interfacial area and domain volumes.

## 2. Experiments

Although the focus of this work is on the meter-scale experimental setup and preliminary results, a brief description of decimeter-scale experiments is also provided. The latter follow a well-established procedure which is the product of many experiments on MFCI with silicate and metal melts. Decimeter-scale experiments were conducted using the same olivine melilitite base material as the larger experiments, to find critical conditions (e.g., melt temperature ranges and mixing speeds) in which explosive conditions for this particular base material are met and to test data collection methods at the meter scale.

### 2.1. Decimeter-Scale Experiments

Decimeter-scale thermohydraulic explosions were realized in the lab with 0.2 kg of the base material at melt temperatures between 1,200°C and 1,350°C. This experimental setup has been used before with other melts, including, but not limited to, remelted volcanic rocks (Büttner et al., 2002; Spitznagle et al., 2013; Zimanowski et al., 1991), and was used here to determine temperature ranges and specific water speed settings that provide optimal conditions for an explosive response, for application in the meter-scale experiments. Base material was melted in a cylindrical crucible of 5-cm diameter and 8-cm height. Water was injected through a 4 mm-diameter steel tube at controlled speed. A timed pellet (∼5 to 10 J kinetic energy), shot from a setup roughly resembling a low energy air gun, hits the melt-water premix and triggered the explosive interaction. Resulting explosions showed that our base material behaves similar to other basaltic melts that have been extensively tested previously (e.g., Fröhlich et al., 1993; Zimanowski et al., 1995). Strong explosions with > 0.5 kN peak repulsion force, corresponding to a kinetic energy release on the order of 10⁴ J (Büttner & Zimanowski, 1998), were realized at melt temperatures above 1,250°C. Optimal injection speeds are within the known interval of 3 to 5 m/s. The explosive process was recorded on video at 5,000 Hz. The transient repulsion force signals was recorded at 100 kHz. Force and video material were analyzed as described in section 2.3 below and compared to video material of the meter-scale experiments.

### 2.2. Meter-Scale Experiments

The meter-scale experiments are conducted out of doors and are based on material from a natural volcanic deposit that was selected due to its rheological behavior and ready availability in large volumes with little compositional variation. The rock originates from the Balcones Igneous Province in Texas (Griffin et al., 2010) and is a low silica, olivine melilitite (Table 1). For each experiment between 55 and 60 kg were heated to temperatures between 1,280°C and 1,350°C. In this temperature range the material is completely molten and has viscosities on the order of 10 Pa s. In that state it is possible to move the melt quickly from the furnace into the unheated melt container in which experiments are performed and keep enough overheat to compensate for the experiment preparation time span.

The furnace consists of a ≃0.4 m-diameter crucible that is placed at the center of an induction coil and is heated by a controlled, oscillating magnetic field generated by the latter. Crucible and coil are mounted on a hydraulically operated tilt stand that has a pivoting axis about 1 m above ground and allows controlled removal of melt from the furnace (Figure 1a). Melt temperatures are measured in the furnace, prior to the experiment, and were between 1,300°C and 1,350°C for all experiments presented here. Except from the uppermost melt layer which forms a skin during the measurement when the furnace lid is partially removed, temperatures differ by ±15 K around the average value.
1. **Melt handling.** Melt is poured from the furnace into an insulated melt container that is made of a thin, high-temperature resistant steel shell, surrounded by an insulation liner, which is again wrapped by a robust outer steel container. The pouring process typically lasts less than 30 s. The melt container stands on a hand-operated cart on rails and, after pouring, is moved about 5 m away from the furnace into a locked position at the end of the rail line (Figure 1). Container transport, locking, and alignment combined last 30 s. Separate cooling tests were performed, where melt was at rest in the container, without any addition of water, and temperature was measured at several locations. They showed that, except from insignificant portions, melt in the container stays liquid, at temperatures above 1,200°C, for longer than 10 min. Temperatures somewhat decrease near container walls and are approximately constant along the container’s center line within a 3–4 min time window after the melt is poured (Figure 2). After the melt is poured, a thin crust starts growing at the free surface. Depending on the violence of the melt’s response to water injection, this crust is typically smashed by the upward expanding system (supporting information Video S1).

2. **Sensors and Control.** The melt-water premix is created by injecting water into the melt through portals in the container’s side wall. The 6.9 mm inner diameter high temperature steel tubes are used to guide the water into the melt. Water flow is controlled by solenoid valves and a pressurized water reservoir. The valves are mounted on a sliding platform that is driven by a linear stepper drive which moves the tubes within 1 s into the center of the container. A sensor records the time-dependent pressure in the supply tube. The difference between the static, driving pressure and the measured pressure while the water moves through
Figure 2. Raw data of cooling experiments of melt in insulated melt container without injected water. Time-dependent temperatures were measured in the container geometry with the highest surface area to melt volume ratio. Graphs (a and b) show the container outline and temperature probe positions from the side and from the top, respectively. Probes were positioned along the containers center line (black points in a and b and black lines in c) and at 1.25 cm distance from the walls. Initial temperatures differ because the displayed data were acquired in two tests, since it was not feasible to mount all thermocouples at once.

the supply tubes allows determination of the water mass flow rate within an uncertainty of 3% (Supporting Information S1). To trigger interaction, a 4.54 kg sledge hammer falls from 80-cm height and hits a steel plunger that has direct melt contact. This causes a relatively sharp pressure pulse in the melt (Figure 1). At point of impact, the hammer head has a speed of $\approx 3.5 \text{ m/s}$ which corresponds to a kinetic energy of $\approx 28 \text{ J}$. This trigger condition was kept the same for all experiments, except one ("ir13"), when the hammer did not release due to a technical issue. The system’s response is recorded by a set of cameras at different view angles and recording speeds, and the resulting videos were analyzed. A part of the ejected material was collected, and samples were compared to the explosion products of the decimeter-scale experiments.

3. General course of one experiment. After the melt container is locked and aligned in experiment position, control is given to a personal computer which is hooked to real-time hardware that provides the signal input/output system. The signals control position and timing of the water injection platform, solenoid valves, hammer release, and synchronization light. The controller program starts a 45 s countdown during which all personnel leave the location to watch the experiment from safe distance. At 44 s, the injection platform starts moving the tubes into the melt. Then the valves open, and water hits the melt at 45 s driven by the preadjusted reservoir pressure. Meanwhile, the trigger (hammer) is released, timed to hit the plunger at a previously scheduled delay after water injection. After injection duration, the valves close, and the platform pulls the tubes out of the melt. After activity within the system subsides and it is safe to approach the site, the setup is inspected, and ejected melt fragments are collected.

Several parameter sets were tested for each of which one experiment was necessary (Table 2). Experiments presented here cover trigger delays between 0.47 and 1.89 s, water injection speeds between 1.78 and 9.29 m/s, and water injection durations between 1 and 8 s. The experiments were performed in containers with three major geometric configurations, all with a rectangular footprint. Flat, intermediate, and a tall configurations are summarized in Figure 3.

2.3. Analysis

Previous MFCI works used experiment-specific sets of measured observables that enable quantitative comparison between different experimental settings and the derivation of scalable quantities, such as the mixing speed or $R_m$, which can be interpreted in applied volcanic or industrial scenarios. Examples of such specific observables are the transient repulsion force of the crucible in which a thermohydraulic explosion occurred (Fröhlich et al., 1993; Zimanowski et al., 1991), the vertical lift height of an explosive vessel (Wohletz & McQueen, 1984), the height of the ejected particle jet (Wohletz et al., 1995), or the transient electric field generated by melt brittle fragmentation (Büttner et al., 1997). The meter-scale experimental setup has the disadvantage that there is no mechanically stiff enough connection from the melt to the outer side of the container where temperatures would be reasonably low to install a force sensor. The porous insulation liner prevents measurement of high frequency signals, such as the transient repulsion force, similar to the decimeter-scale setup. Instead, to quantify the meter-scale system’s response to the establishment of melt-water premix, videos from several cameras were analyzed. A good way to compare experiments turned
Summary of Experimental Settings and System Behavior

Table 2

| Water and trigger | Melt geometry | Response |
|-------------------|---------------|-----------|
| Exp. | $\Delta t_{trig}$ | $m_w$ | $m_{w, trig}$ | $v_w$ | $n_{trig}$ | $x_m$ | $y_m$ | $h_m$ | $L_{max}$ | $F_{max}$ | $d_{L, max}$ |
| $\Delta t_{ej}$ | m | ms | cm | cm | cm | $10^{-2} m^2$ | $10^{-2} m^2$ | m/s |
| pr06 | 6.00 ± 0.02 | 4167 ± 77 | 694 ± 13 | 9.29 ± 0.24 | 2 | 0.47 ± 0.02 | 21.0 ± 0.5 | 27.0 ± 0.5 | 45 ± 5 | 79.0 ± 6.7 | 16.5 ± 1.4 | 5 ± 2 |
| pr05 | 6.00 ± 0.02 | 1100 ± 100 | 183 ± 17 | 2.45 ± 0.23 | 2 | 0.98 ± 0.02 | 21.0 ± 0.5 | 27.0 ± 0.5 | 45 ± 5 | 33.7 ± 1.5 | 19.3 ± 0.9 | 2.6 ± 0.6 |
| ir16 | 8.00 ± 0.02 | 1605 ± 5 | 201 ± 1 | 2.68 ± 0.08 | 2 | 0.90 ± 0.02 | 21.0 ± 0.5 | 27.0 ± 0.5 | 45 ± 5 | 40.6 ± 3.3 | 11.7 ± 1.0 | 3.2 ± 0.3 |
| ir15 | 8.00 ± 0.02 | 2715 ± 5 | 339 ± 1 | 4.54 ± 0.13 | 2 | 0.89 ± 0.02 | 21.0 ± 0.5 | 27.0 ± 0.5 | 45 ± 5 | 60.4 ± 2.6 | 1.0 ± 0.1 | 2.6 ± 0.1 |
| ir14 | 8.00 ± 0.02 | 1380 ± 5 | 172 ± 1 | 2.31 ± 0.07 | 2 | 1.89 ± 0.02 | 21.0 ± 0.5 | 27.0 ± 0.5 | 45 ± 5 | 33.9 ± 2.1 | 26.5 ± 1.7 | 1.4 ± 0.1 |
| ir13 | 8.00 ± 0.02 | 1540 ± 5 | 192 ± 1 | 2.57 ± 0.08 | 2 | — | 21.0 ± 0.5 | 27.0 ± 0.5 | 45 ± 5 | 20.2 ± 1.0 | 0.4 ± 0.1 | 1.7 ± 0.1 |
| ir12 | 4.00 ± 0.02 | 985 ± 5 | 246 ± 1 | 2.20 ± 0.06 | 3 | 1.88 ± 0.02 | 17.9 ± 1.0 | 63.5 ± 1.0 | 22 ± 5 | 11.3 ± 0.5 | 0.9 ± 0.1 | 0.76 ± 0.05 |
| ir07 | 2.00 ± 0.02 | 400 ± 5 | 200 ± 2 | 1.78 ± 0.06 | 3 | 1.41 ± 0.02 | 14.6 ± 1.0 | 74.3 ± 1.0 | 23 ± 5 | 13.5 ± 0.5 | 0.0 ± 0.1 | 0.85 ± 0.05 |
| ir06 | 2.00 ± 0.02 | 570 ± 5 | 285 ± 2 | 2.54 ± 0.08 | 3 | 1.89 ± 0.02 | 18.0 ± 1.0 | 41.0 ± 1.0 | 34 ± 5 | 20.3 ± 3.7 | 0.1 ± 0.1 | 2.8 ± 0.9 |
| ir05 | 3.00 ± 0.02 | 920 ± 5 | 307 ± 2 | 2.73 ± 0.08 | 3 | 0.51 ± 0.02 | 14.4 ± 1.0 | 86.1 ± 1.0 | 21 ± 5 | 7.5 ± 0.6 | 0.2 ± 0.2 | 1.6 ± 0.2 |
| ir04 | 3.00 ± 0.02 | 920 ± 5 | 307 ± 2 | 2.73 ± 0.08 | 3 | 0.89 ± 0.02 | 18.0 ± 1.0 | 41.0 ± 1.0 | 34 ± 5 | 33.1 ± 1.4 | 0.8 ± 0.1 | 0.77 ± 0.06 |
| ir03 | 1.00 ± 0.02 | 210 ± 5 | 210 ± 5 | 1.87 ± 0.07 | 3 | 0.88 ± 0.02 | 18.0 ± 1.0 | 41.0 ± 1.0 | 34 ± 5 | 6.0 ± 0.2 | 0.0 ± 0.1 | 1.09 ± 0.04 |

Note: $\Delta t_{trig}$ duration of water flow; $h_m$, melt column height; $m_w$, mass of injected water; $L_{max}$, maximum luminance; $m_{w, trig}$, mass flux of water; $F_{trig}$, luminance at trigger time; $v_w$, injection speed; $m_{w, trig}$, water mass at trigger time; $n_{trig}$, # of injection tubes; $F_{max}$, peak repulsion force; $x_m$, container length; $\Delta t_{trig}$, trig. delay after water; $y_m$, container width.

out to be the calculation of a normalized, cumulative luminance, $L$, computed from each video frame. This method works also as a tool to compare the decimeter- and meter-scale experiments. Roughly speaking, $L$ measures the number of square meters of melt surface area that are present in a camera’s field of view. A high energy process can be expected to eject more melt at higher speeds and finer fragments with more surface area than a low energy process. By comparing absolute values of $L$ and its time derivative, it is possible to quantify how intense a process is. The analyzed videos were recorded at frame rates between 60 Hz and 5 kHz, and the cumulative, time-dependent surface evolution could be measured at these sampling rates. An overview of cameras and their resolutions and frame rates is given in Supporting Information S1.

Most of the ejected material in the presented experiments is melt and is much brighter compared to its background. Similar to the measurement of thermal infrared radiation, the molten rock can be seen and measured at wavelengths visible to the human eye and video cameras. It is difficult to determine the melt temperature from the brightness of such a video recording; but that is not necessary for the purpose of quantifying an intense process which rapidly deforms and accelerates the melt material. Instead, since this is a relatively fast process, the melt is assumed to cool slowly compared to its ejection velocity, and at a given instance in time (i.e., video frame), the visible amount of melt above the container is determined. Ignoring the background signal, the cumulative brightness $B$, computed as the sum over all brightness values at pixel positions $i, j$, is proportional to the total radiative power of the light portion that “hits” the camera sensor during exposure

$$B = \sum_{i=0}^{N_x} \sum_{j=0}^{N_y} b_{ij}.$$ (1)

Here the $b_{ij}$ are the camera-specific gray level brightness values measured at pixel positions $(i, j)$, and $N_x$ and $N_y$ are the number of pixels of the sensor in the horizontal and vertical directions, respectively. The following will assume that each pixel of the camera sensor corresponds to the same cross-sectional area in the observed plane parallel to the sensor where the experiment takes place. This approximation is valid for camera lenses with larger focal length (“tele lenses”). For smaller focal lengths, this is not strictly valid, but the computation
can be corrected to account for these effects. The radiative power across one sensor pixel at sensor position $i, j$ is proportional to $b_{ij}$. Because the main focus is the measurement of the melt surface area, detailed analysis such as the light's wave lengths or a video's color channels is not of much use here. Instead, each video frame is converted to gray-scale according to the ITU BT.709 recommendation (International Communication Union, 2015). For a $D_65$ white point, the gray level brightness is determined from the red, green, and blue channels by $b_{ij} = 0.2125 \, [\text{red}]_i j + 0.7154 \, [\text{green}]_i j + 0.0721 \, [\text{blue}]_i j$. This type of conversion is implemented in a wide range of standard software.

The measured brightness $B$ has to be corrected by the background noise level $B_0$. The latter therefore must be determined from a suitable time period directly before the start of melt ejection separately for each video. Then it is a reasonable assumption that $B_0$ is constant over time. A parcel of melt visible in a frame completely “covers” the background across the cross-sectional area parallel to the camera sensor. The measured brightness value is therefore independent of the background’s brightness at that location, and the brightness correction then is only the difference of measured brightness and background noise, without further location specification. The difference of brightness to background noise $B - B_0$ is then used to quantify the amount of melt visible within a recorded video file. In order to make an index that can be created from different cameras, this difference is normalized to the noise corrected melt brightness

$$l = \frac{B - B_0}{B_{\text{melt}} - B_0}, \quad B_{\text{melt}} = N_x N_y b_{\text{melt}}. \quad (2)$$

Here $B_{\text{melt}}$ is the cumulative brightness that would be measured by a camera if a whole frame was “covered” by melt. $b_{\text{melt}}$ is a typical (averaged) melt brightness reading of one camera pixel. $l$ should have values between 0 and 1. For values larger than 1, while technically possible, the initial assumption, and therefore its meaning, that the ejected melt visible to the camera is much brighter than the average background is not valid. Two different cameras watching the same event, which have the same spatial resolution (i.e., each pixel on the camera sensor corresponds to the same cross-sectional area of the observed object), will measure the same value of $l$. Multiplication of $l$ with the camera’s field of view $S_c$ removes that requirement:

$$L = S_c \, l = a^2 N_x N_y \frac{B - B_0}{B_{\text{melt}} - B_0}. \quad (3)$$

$S_c$ is the real world visible cross-sectional area (e.g., width in meters × height in meters), and $a$ is the spatial resolution (e.g., measured in meters per pixel). These values need to be determined by comparison to an object of known size. $L$ is a quantity that enables the comparison of visible amounts of melt at a given time.
Figure 4. Comparison of transient force (F) and luminance (L) signals of the tx08 decimeter-scale experiment. (a) Transient force record. (b) Signals of time integral of force (system momentum) $P_z = \int F dt$, and time derivative of luminance, normalized to their respective maximum values $L$. (c) Transient luminance record. Peak luminance occurs about 80 ms after peak force. Rising times suggest a close correlation of $\dot{L}$ and $P_z$. The rapid decay of $\dot{L}$ after the maximum is caused by melt material leaving the camera’s field of view. Images on the right are still frames of the high-speed camera recording that produced the $L$ curve at characteristic times: (i) time of peak force, (ii) time of maximum growth rate $\dot{L}_{\text{max}}$, and (iii) time of peak luminance.

from different camera recordings, or even different events. The results shown in Figures 4 and 5 show the practical applicability. The relatively simple definition of L fails if significant amounts of background are light reflecting or if the background noise $B_0$ is time dependent within the recording period. For the experiments presented here, the background noise was constant except from two cases, in which it was possible to correct the measurement manually assuming a linear background drift.

In the decimeter-scale experiments, measurement of the repulsion force was possible and was used to compare the force and luminance signals. The sudden start of explosive interaction accelerates the magma-water premix from rest predominantly upward out of the crucible. The acceleration is recorded as transient force signal $F(t)$ (Figure 4a), which shows a sharp peak at the instant of maximum total system acceleration. The luminance's time dependency has a single maximum, delayed by about 80 ms from the peak force, which is significantly wider (Figure 4c). Strongest correlation between the two signals is the luminance's time derivative $\dot{L} = dL/dt$ and the force's time integral $P_z(t) = \int F(t) dt$ (Figure 4b). The latter may be roughly interpreted as the system momentum in vertical direction. Previous work used the peak force $F_{\text{max}}$ to measure the explosive system response (Fröhlich et al., 1993; Zimanowski et al., 1991). Even though $L$ is not directly proportional to $F$, the maximum values $L_{\text{max}}$ show the same trend (Table 2b) as $F$. 
Figure 5. Luminance-time curves recorded by three different cameras from three different observation angles and distances, illustrating the application of the luminance method to the meter-scale experiments. Gray areas around the curves show the respective measurements uncertainties. Graph (b) shows a closeup of graph (a) in the time interval 0–1 s. Cameras were located at angles of 0° (cam1), 45° (hsc1), and 90° (cam4) relative to the containers long side. In the case of the cam1 and hsc1 cameras, measurable mounts of melt leave the camera’s field of view which results in lower values of $L$ compared to the cam4 camera which caught all of the melt ($t \geq 0.5$ s cam1 and $t \geq 0.75$ s cam4). The smaller differences in the rising curves before that are caused by the different viewing angles of the cameras (b). Images at the right are video frames of the cam4, and the hsc1 curve at times when $L$ reaches maximum $L_{\text{max}}$ or at maximum slope $\dot{L}_{\text{max}}$. (b) Despite different view angles the luminance values are in good agreement. The major differences of the curves can be attributed to the observation directions since the video materials show that the observed process is not entirely rotationally symmetric (iv). The plateau of the hsc1 camera is caused by the limited field of view. Significant melt amounts leave the field of view before the system reaches maximum $\dot{L}_{\text{max}}$ (ii). The maximum growth rate as “seen” by the hsc1 is a local maximum and is in agreement with the other cameras (iii).

A speed quantity can be derived from a transient luminance signal for parts of the recorded time interval. The time derivative $\dot{L}$ (the dot stands for $d/dt$) of the luminance describes the rate of change of an area, but not of a length. Since the observed melt domain geometries do not follow any foreseeable pattern that can be described by an obvious geometry parameter which would allow an exact conversion from this area to a length, a pragmatic way to derive a length from $L$ is to compute its square root. A speed is then obtained from that square root’s time derivative

$$\dot{d}_l = \frac{d}{dt} \sqrt{L} = \frac{\dot{L}}{2\sqrt{L}}.$$  \hspace{1cm} (4)

As above, the dot on top of a symbol stands for the time derivative $d/dt$. Interpretation of $\dot{d}_l$ depends on the geometry of the observed (luminating) surface shape. If the observed object is a sphere that grows only radially at rate $r$, then $\dot{d}_l$ is proportional to that rate: $d_l = r \sqrt{\pi}$. If the observed object is a cylinder that only changes in length at speed $l$, then $\dot{d}_l = \alpha l$, where $\alpha$ is the cylinder’s (time dependent) aspect ratio. The time evolution of the observed melt domains may be approximated by several simplified geometries, such as a (partial) growing sphere or as elongating cylinders. As this happens at different velocities in the same image, there is no direct possibility to separate the domains from each other and determine such a geometry factor. In a strict sense, $\dot{d}_l$ therefore only relates to a speed in a meaningful way if only one melt domain is observed. Such a condition may be achieved manually by selection of a suitable subset in a certain time interval of a
Figure 6. Measured maximum luminance values. Circle sizes are plotted proportional to initial melt height $h_m$ (height of melt column above water portals). Gray ellipses and black lines are standard deviations of the respective measurement uncertainties. In the “ir13” experiment (diamond marker), the hammer did not release. (a) Luminance correlates very roughly with initial melt height $h_m$. (b) Correlation with injection speed $v_w$ is stronger. There is a strong increase between 2 and 3 m/s. Below 1.78 m/s, experiments did not respond with enough ejected material to be shown on this graph. (c) Correlation with total water mass flux $\dot{m}_w$ is weak. (d) Melt height is a crucial factor that enables close coupling of water and melt. Since $L_{\text{max}}$ rises with increasing $h_m$, $v_w$, their product provides the best dependency for the luminance $L_{\text{max}}$.

A moment when this condition is met in all decimeter-scale and meter-scale experiments is the first appearance of melt above the container/crucible. This moment is also often a moment of particularly high ejection speed, especially in the case of the decimeter-scale setup. Analysis showed that typical maximum ejection speeds at explosion beginning produce motion blur in all camera recordings which used minimum shutter times of $5 \times 10^{-5}$ s. For example, manual tracking of melt motion gives maximum speeds of 210 m/s for the tx58 decimeter-scale experiment. Maximum value for $\dot{d}_L$ of that experiment is 55 m/s. Both speeds were measured from the same source frames.

3. Results at the Meter Scale

The system response to water injection varied from mild, evaporation-dominated processes, in which only a little melt was ejected from the container alongside some steam, to stronger reactions with visible steam jets, and with melt domains ejected to several meters height (maximum 4–5 m). In experiments with low energy response, the main melt body domed upward, and most of the water escaped as steam. On the camera recordings, this is virtually indistinguishable from fluctuations in air density caused by the heat of the melt before water injection. In those experiments, the crust that formed on top of the melt during melt transport was not broken but “tilted” to one side. More intense responses typically started with a large initial growth rate, ejecting a significant amount (i.e., several kilograms) of melt, which result in an initial “pulse” before settling to a slowly declining lower value of activity, which consists of smaller ejected melt domains and recurring overpressured steam jets (e.g., Figure 5 and Video S2). These experiments with high intensity response had...
Figure 7. Typical patterns of ejected melt material. Particles show fluidal shapes and brittle fragmentation features (marked by red arrows in e and g). (a–g) Ejected products of meter-scale experiment. Larger particle shapes are dominated by elongated hydrodynamic features of micrometer to centimeter thickness. Hydrodynamic features are abundant in fractions finer than 0.25 mm (ϕ > 2), except of Pele’s hair. (h–k) Ejected products of decimeter-scale experiment. Hydrodynamic features are present in all particle fractions.

maximum luminance values of $L_{\text{max}} \geq 0.25$ m$^2$. The current data set does not allow to tie the recurrence frequency to either the melt column height or the water injection velocity. In all experiments, only a part of the injected water was converted to steam. Significant amounts of liquid water droplets were ejected together with the melt at similar speeds (Video S3). A determination of how much of the water was evaporated is currently not possible. Injecting water at speeds less than 1.7 m/s produced no measurable response ($L \approx 0$). In the 2 to 3 m/s range of injection speed, the response changes rapidly (Figure 6). Within that interval, the melt height plays an important role. A change of melt height $h_m$ from 33 to 45 cm changes $L_{\text{max}}$ by a factor
Figure 8. Effect of the trigger event on the system response. Luminance curves of the four experiments ir13, ir14, ir15, and pr06 are shown. Zero second on the time axis refers to the start of water flow. Red vertical lines mark the time of hammer impact on the plunger. Green vertical lines mark a local maximum following trigger impact, which is interpreted as response to the trigger event, except for experiment ir13, where the trigger failed to release. Photos at the right are frame grabs of the respective video recordings at the red marked trigger time and at the green marked time of system response to the trigger. Response in the ir13 experiment is overall lower compared to the other cases and starts more gradually. The 1.8 s frame shown illustrates the slow start of this experiment and has no relation to the trigger event. The ir14 curve shows a significant response before trigger hit and a minor increase of L after the hit. ir15 shows a clear response to the trigger event. For experiment pr06, it is unclear if the hammer is effective or not. Activity for ir14 starts at t ≃ 0.8 s, for ir15 at t ≃ 1 s, eventhough amount of water mixed with the melt at 0.8 s was larger for ir15 (m_{w,trig} = 0.27 kg) compared to ir14 (m_{w,trig} = 0.14 kg).

1.5 to 2 at same v_w (Figures 6a and 6b). A clean dependency of L on the mass flow rate of water entering the melt cannot be established clearly with the current data set. At v_w > 3 m/s, maximum response in luminance increased at a less steep trend than in the 2- to 3-m/s interval.

After cooling, almost all ejected materials were dark and glassy. The majority of the ejected melt mass is deformed hydrodynamically. Coarse particle fractions (ϕ < 0) are dominated by fluidal shapes. For finer fractions, angular shapes become more common and are dominant for ϕ > 2. For the fine fractions, the only hydrodynamic shapes are Pele’s hair-like, long, thin cylinders. Particles of angular shape include thin shards (rinds) with smooth surface (Figures 7d and 7f), medium “thick” plated material with more irregular (stepped) surface structure (Figures 7d and 7g), and thicker (nontransparent) particles (other photos shown in Figure 7).
Figure 9. Comparison of two experiments; one is a decimeter-scale (tx08, orange curve), the other a meter-scale experiment (pr06, blue curve). Gray-shaded areas around the curves are the measurement uncertainties (standard deviations). Graphs (a) and (b) show luminance values \( L \); graphs (c) and (d) show its time derivative \( \dot{L} \). (a) and (c) show unscaled values; (b) and (d) show values scaled by water/melt mass ratio \( R_m \), evaluated at trigger time. (a and b) Scaled and unscaled luminance values of the decimeter-scale experiments are always smaller, compared to the meter scale. (c and d) For the time derivative, the situation is different. The decimeter-scale experiment’s unscaled values are about a factor 4 higher compared to the meter-scale run. When scaling \( \dot{L} \) with \( R_m \), the maxima of the two curves are comparable.

Four out of six experiments that were conducted in the “tall” melt geometry showed significant response before the hammer hit its target (Table 2). For melt columns smaller 30 cm, this spontaneous response behavior was not observed. Further refined dependency tests, for example, on injection speed or amount of water in the system, gave no clear answers to date. In one case (ir13), the hammer did not release, and the overall response was significantly lower compared to similar injection speeds and melt heights where the trigger release had functioned. In experiment ir15, there was very little activity observable before hammer hit, the hammer effect is clearly visible. In experiment ir14, activity started significantly before the hammer hit, and there is only a relatively small effect of the hit observable (Figure 8 and Videos S4 and S5). Except from the melt height threshold, no clear dependency of spontaneous start on injection speed or trigger timing was observed.

4. Discussion

When the water enters the melt body, the relative speed between the two liquids has a strong influence on shape and temporal evolution of the interface. At low mixing speeds, the interfacial tension can act effectively against buoyancy and the water’s momentum (inertia), creating a single, relatively compact domain with a small surface area. Smaller domains will have shapes closer to spherical, while larger domains will be deformed by buoyancy, since the total upward force is proportional to its volume, that is, \( \sim r^3 \), if \( r \) is the sphere’s radius, while the total surface reducing force goes with \( \sim r \). At higher speeds, Kelvin-Helmholtz instabilities will form, which can cause the hydrodynamic breakup of a single domain into several. The quantification of this behavior is difficult, since the conditions at the interface change from approximately full slip under film boiling conditions to no slip under direct contact. The change from film boiling to direct contact depends not only on the temperature difference at the interface but also on hydrodynamic states, such as the velocity...
difference between the two fluids (e.g., Dhir, 1993). Büttner and Zimanowski (1998) showed experimentally that the combined thermo-hydrodynamic process, when triggered appropriately within a certain time interval, creates most explosive conditions for mixing speeds around 4 m/s. The buoyant rise of water domains is not an effect that the lab-scale setup was designed to observe, but the meter-scale setup is able to capture.

The significant rise of the system response amplitude \( I_{\text{max}} \geq 0.2 \, \text{m}^2 \), at water injection speeds between 2 and 3 m/s, is in agreement with the decimeter-scale experiments, which show the same behavior (Zimanowski, Büttner, & Lorenz, 1997). In contrast to the decimeter scale, the meter-scale experiments did not find a maximum response at 4 m/s. Reasons likely are the relatively small total amount of water used in the meter-scale experiments or the effect of less geometric and size restrictions for the premix evolution. Buoyant rise of the liquid water appears to happen on a similar time scale as the vapor film collapse, on the order of 1 s. The inertial breakup of a water domain into several smaller ones could happen faster than 1 s, but if buoyancy contributes to the speed, the 1 s time scale is likely to play a role. More experiments with larger water amounts are necessary to clarify that. On the meter scale, maximum values of luminance’s time derivative \( L \) are lower by a factor 4 compared to the lab-scale counterpart. Maximum values of ejection velocity and \( \Delta \) are a factor 10 smaller compared to the smaller scale. This is not surprising, since the maximum amount of water relative to melt was intentionally kept lower for these first experiments, in order to not end up with broken equipment. For example, the mass ratio of water to melt at time of trigger, \( R_{m} \), of the experiments shown in Figure 9 is \( 5.5 \times 10^{-3} \) for the meter-scale pr06 experiment and \( 23 \times 10^{-3} \) for the decimeter-scale tx08 run. Scaling the system response by that mass ratio yields maximum values \( R_{m} \cdot L_{\text{max}} \) of \( 4.3 \times 10^{-3} \, \text{m}^2 \) for pr06 and \( 1.0 \times 10^{-3} \, \text{m}^2 \) for tx08 (Figure 9b). The time derivative shows a different behavior. Here the decimeter scale is a factor 4 larger than the meter scale (Figure 9c). Maximum values of the scaled curves \( R_{m} \cdot L_{\text{max}} \) end up at the same scale (Figure 9d).

A definition problem for \( R_{m} \) arises that highlights different approaches of the previous experiments. The thermite-based confined vessel approach (e.g., Wohletz et al., 1995) defines \( R_{m} \), per explosion, not tied to a specific moment during the process, while the decimeter-scale setup uses the mass of water in the system at trigger time to derive \( R_{m} \). For a system that consists of several bursts and is active over a certain period, both definitions are problematic. For example, in the case of the ir15 experiment, the maximum response occurs about 6.4 s after the trigger (7 s after start of water injection). That luminance maximum is probably caused by more water than was present at trigger time, even though the trigger clearly starts the response (Figure 8b). It is difficult to estimate the water mass, since at time of \( I_{\text{max}} \), an unknown amount already left the container. The maximum \( R_{m} \) value that can be calculated for the two examples as the ratio of all injected water over the whole injection period is low, \( 7.5 \times 10^{-3} \) (pr06) and \( 6.1 \times 10^{-3} \) (ir15), for the time-independent method.

The ejected interaction products show that part of the melt experienced brittle fragmentation. In the given setup with a 10 Pa s viscosity melt, the only known mechanism that can achieve brittle fragmentation is MFCI. Another source of the brittle particles that cannot be ruled out completely could be the partially fractured skin on top of the melt column. The amount of cleanly collected melt particles is however not large enough to determine if and to which extent the meter-scale experiments produce more or less brittle products compared to fluidal shapes than the decimeter-scale experiments. Particle shapes are in agreement with field samples related to explosive magma-water interaction (e.g., Dellino et al., 2012) and products of previously conducted MFCI experiments (Büttner et al., 1999; Zimanowski, 1998). The significant pretrigger activity, especially with a significant vertical melt column, shows that at a total premix size of several decimeters, spontaneous explosive activity becomes increasingly likely.

Natural phreatomagmatic systems are exemplified by maar-diатreme volcanoes, small, usually monogenetic volcanoes whose formation is dominated by subsurface explosive magma-water interaction. Exposed diатremes, which extend hundreds of meters to >1 km into the subsurface, preserve magmatic intrusive bodies that might be analogous to batches of magma that, under the right conditions, explode. Intrusion forms in diатremes typically fall into three categories — dikes, sills, and irregularly shaped intrusions (see, e.g., Valentine & van Wyk de Vries, 2014). Valentine et al. (2014) compiled data from the literature indicating that intrusion volumes can range from as small as \( 10^2 \) to \( 10^4 \, \text{m}^3 \), sometimes exceeding \( 10^5 \, \text{m}^3 \). The experimentally found dependency of interaction intensity, as quantified by luminance \( L \) and change of luminance \( L \), on the buoyant rise of water through the melt, may provide an additional factor for the mixing of magma and water, besides the possible overpressure of the external water source.
Figure 10. Schematic drawing of three possible but idealized magma-water interaction scenarios that depend on the location (depth) of explosive interaction. Comparison starts from a magma-water premix under film boiling conditions. Vertical gray lines mark the host-magma border. (a) Film boiling breaks down slowly/incoherently, the water domain continuously transitions into steam while moving vertically through the melt, by that increasing volume. (b) Water domain rises under film boiling conditions, direct contact occurs at shallow depth, and explosive interaction eventually start close to surface and results in ejection of tephra jets event. (c) Explosive interaction occurs at large depth, fragmenting melt and turning the water to steam, which then rises and erupts as gas burst, creating predominantly inertial fragmentation patterns. MFCI = Molten Fuel Coolant Interaction.
In a scenario with a high melt column above the mixing location and a small magma to water mass ratio, so that the water would not significantly reduce the magma’s overall heat content, the following picture is likely. The dependency on the melt height indicates that when water mixes on larger scale with magma, mixing, that is, the differential speed between water and magma, may increase with the distance vertically traveled by the water domain in the melt due to buoyancy. Though not strictly accurate, a formula for the terminal velocity $v_t$ of a buoyant spherically shaped fluid domain rising in another fluid is (e.g., Batchelor, 1990):

$$v_t = \frac{g r^2 \Delta \rho}{3 \eta}.$$  \hspace{1cm} (5)

For a melt to water density difference $\Delta \rho = 1.5 \times 10^3$ kg/m$^3$, a viscosity $\eta = 10$ Pa s, $g = 9.81$ m/s$^2$, and a water domain radius $r = 0.1$ m, $v_t = 4.9$ m/s. At such a speed, the water domain may break up into several smaller domains due to the involved body forces and may so increase the interfacial area under film boiling conditions prior to brittle fragmentation. Our experiments show that relative melt to water velocities of $\approx 5$ m/s are in a range which can affect the overall system behavior. Under film boiling conditions, buoyancy could cause large enough mixing speeds for water to make a magma-water premix critical. Given that such effects can be measured in a system of “only” 45-cm maximum melt column, premixes at volcanic scale may need a very small initial speed to become critical.

At longer mixing times, if no explosion occurred, some of the liquid water will be hot enough to evaporate. Decreasing density in such a melt-water-steam mix would cause stronger buoyancy effects due to the steam’s reduced density and would cause faster upward acceleration. Given that such effects can be measured in a system of only 45 cm maximum melt column, premixes at volcanic scale may need a very small initial speed to become critical. For high magma columns, the temperature of rising steam will increase on the way upward until it reaches “ambient” magmatic conditions. If at that point steam has not left the magma body buoyant rise will continue less accelerated, caused by the density difference and the roughly constant magma-column pressure gradient, similar to the rise of volcanic gases. The end member of this picture would be the rise of a water/steam system through a magma column caused by buoyancy that may cause conditions such as mixing speeds $> 3$ m/s at the water’s entry point that are optimal to start the thermohydraulic explosion engine without significant external start event.

Different scenarios can result from this picture (Figure 10). (a) If water mixes with melt and the water domain(s) moves upward and heat transfer occurs in a way so that the liquid to steam phase transition is somewhat continuous, the water would eventually rise to the surface as vapor bubble(s) or slug and may burst causing the ejection of mostly inertially fragmented magma domains. (b) If water mixes with melt, potentially at low initial velocities, the domain can rise in the magma column under film boiling conditions, rising speed may cross $\approx 3$ m/s, and spontaneous explosive interaction would become possible higher in the magma column (relative to the initial mixing location). A local MFCI-style explosion may then occur at significant vertical distance from its starting point. If the explosion occurs close to the surface, this would result in ejection of fine ash and steam and some inertially fragmented melt domains. (c) If initial mixing occurs at large enough speed and explosive interaction occurs without significant vertical displacement and at depths large enough to contain the blast, the postexplosion steam domain created by the interaction would rise in the magma column after the explosion and erupt with, qualitatively, similar surface dynamics as case (a). The two latter scenarios (Figures 10b and 10c) could cause local brecciation of wall rock, fragments of which could be incorporated into the melt column around the explosion site. If in case (c), the lithic-enriched magma is drawn upward by vapor domain rise, it might eject fluidal bombs that contain lithic debris from the explosion site. Such composite clasts (Lorenz et al., 2002; White & Houghton, 2006) might be simple cored bombs or breccia bombs (also called loaded bombs; e.g., Doubik & Hill, 1999; Lefebvre et al., 2013; Rosseel et al., 2006). Such processes could also result in peperite-bearing bombs, providing an alternative to the magma-wet sediment mixing mechanism of Valentine and van Wyk de Vries (2014).

5. Conclusions and Outlook

The main motivation for developing the experimental approach described here is to move toward experimental scales that can incorporate a certain amount of previously ignored complexities, such as geometrical configurations that are closer to geological situations, given uncertainties in the role of scale, geometry, and timing that were described in section 1. The presented experimental setup produces intense magma-water interaction as intended on meter scale. The first experiments mark the overall lower end of water content in
the premix and are therefore low in energy relative to the amount of melt involved. More experiments that realize a higher water content are necessary and will be the next step. This can be achieved by increasing the number of injection points, which will also allow to study effects of local water (domain) concentration and lifetime. The luminance scale allows to quantitatively compare explosive and nonexplosive system response between different experiments and different experimental setups. It is also compatible with the magma-water mass ratio for the comparison of the decimeter and the meter-scale experiments. Due to their size, the interaction is less singular compared to the decimeter scale setup. Whether the weaker cyclic behavior of the later phase activity is caused by the system geometry or by melt-water mixing dynamics may provide insight into the dynamics of real-scale process, but more experiments are necessary to provide such insight. These first results already show that with a melt column as low as 0.35 m above the magma-water premix, intense interaction can start spontaneously without an external trigger event. This value suggests that magma-water premixes in almost any relevant geologic setting can start explosive interaction spontaneously.

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