Meter-Scale Experiments on Magma-Water Interaction

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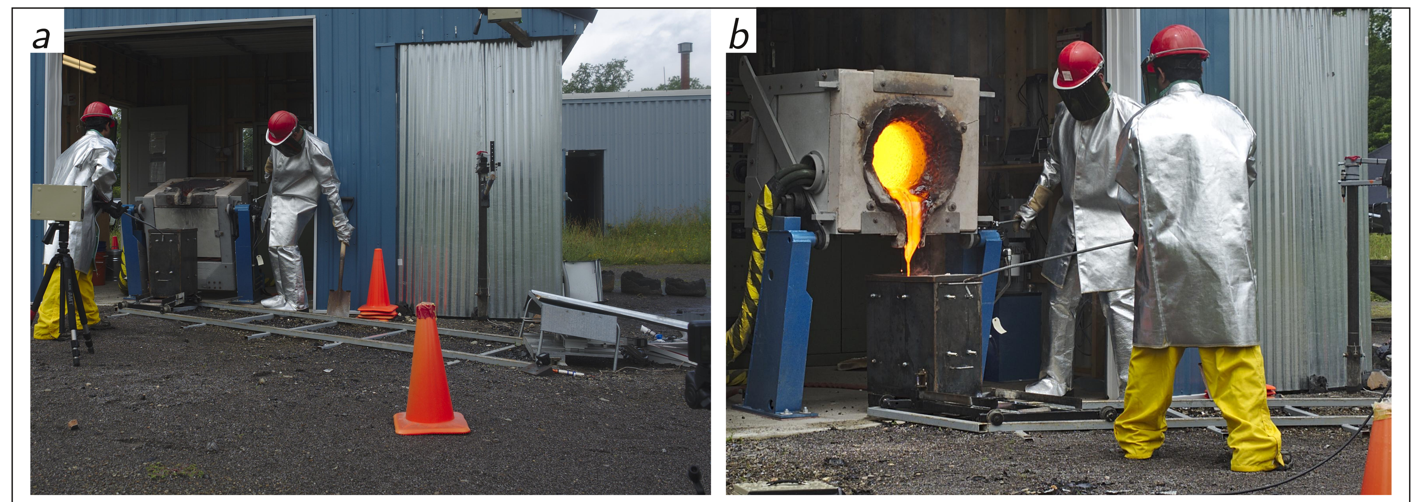

Figure 1: Melt preparation for the experiment. Re-melted volcanic rock is poured from the tilting furnace into an insulated melt container which is mounted on a hand operated "cart on rails" system. (*a*) Furnace (left), cart on tracks (center), injection and trigger system (right). (*b*) A typical pouring process lasts between 10 s and 20 s.

First results of explosive magma-water interaction experiments are presented, that involve a magma-water premix on decimeter scale.

INTRODUCTION

The explosive interaction of magma and external water drives volcanic eruptions in a variety of settings such as maar-diatreme volcanoes (Valentine & White, 2013), eruptions comparable in size to the 2010 Eyjafjallajökull eruption, or possibly large scale phreatoplinian systems. Explosive magma-water interaction is driven by rapid heat transfer ($\sim 10^6\,\mathrm{K s^{-1}}$) which causes brittle failure of magma close to the magma-water interface. The magma's brittle failure is a central component of this violent heat transfer mechanism, since it acts at high speeds as massive feedback loop by exponentially increasing the magma-water interfacial area. Previous experiments revealed those fundamental steps in this process, which is termed "Molten Fuel Coolant Interaction" (e.g. Wohletz, 1986; Büttner & Zimanowski, 1998). They also reveal the great difficulties for the analysis in the context of real world volcanic settings: Water needs to be pre-mixed with the magma body as a liquid prior to the explosion start; timing was shown to play a major role. The length scale of brittle reaction for each water domain is not well understood. The size limitations of closed room laboratory experiments impose a maximum experiment size of about 15 cm for the magma, and several cm for the mixed-in liquid water. Such limitations make it hard to derive robust scale independent quantities such as the often discussed magma to water mass ratio (Wohletz, 2002), an explosion efficiency (Valentine et al., 2014).

To address such limitations a facility was built that provides general and robust experimentation capabilities based on ~ 65 kg ($25-30$ L) remelted natural volcanic rock material.

EXPERIMENTAL SETUP

The experiments rely on an induction furnace that is placed outside, housed into a lightweight "shack" for weather and melt splash protection. Experiments are conduced in free air.

Magmatic melt is produced by re-melting a natural basaltic deposit that is quarried in Texas. The base material is heated in an induction furnace which is mounted on a hydraulically operated tilting stand. Starting at ambient temperatures melting one crucible filling takes about four hours. Target temperatures can be adjusted between 1200 °C and 1400 °C. When molten, the melt is poured into an insulated container. There it stays ready to experiment, i.e. liquid enough, for about 10 minutes. To protect the furnace from the expected rapid system response, the container is mounted on a hand operated rail & cart system, and pulled into final, locked position, where it is ready for water contact.

When in locked position, 6 mm diameter steel tubes are pushed into the melt through portals in the containers side wall (Figure 3). As soon as the tubes reach final position, water is pumped into the melt at a controlled pressure. To trigger an explosive response, a 4.63 kg (10 lbs) hammer falls on a baffle plate which has direct melt contact. The baffle is made of steel and which insures a good seismic coupling to the melt. Water is injected for a duration between 2 s and 10 s. When the water flow is stopped, the injection tubes are pulled backwards out of the container. Water flow control and all mechanical parts are electronically controlled. The injection tubes are connected to solenoid valves, and mounted on a platform. The platform can be moved forwards and backwards accurately with a linear stepper drive.

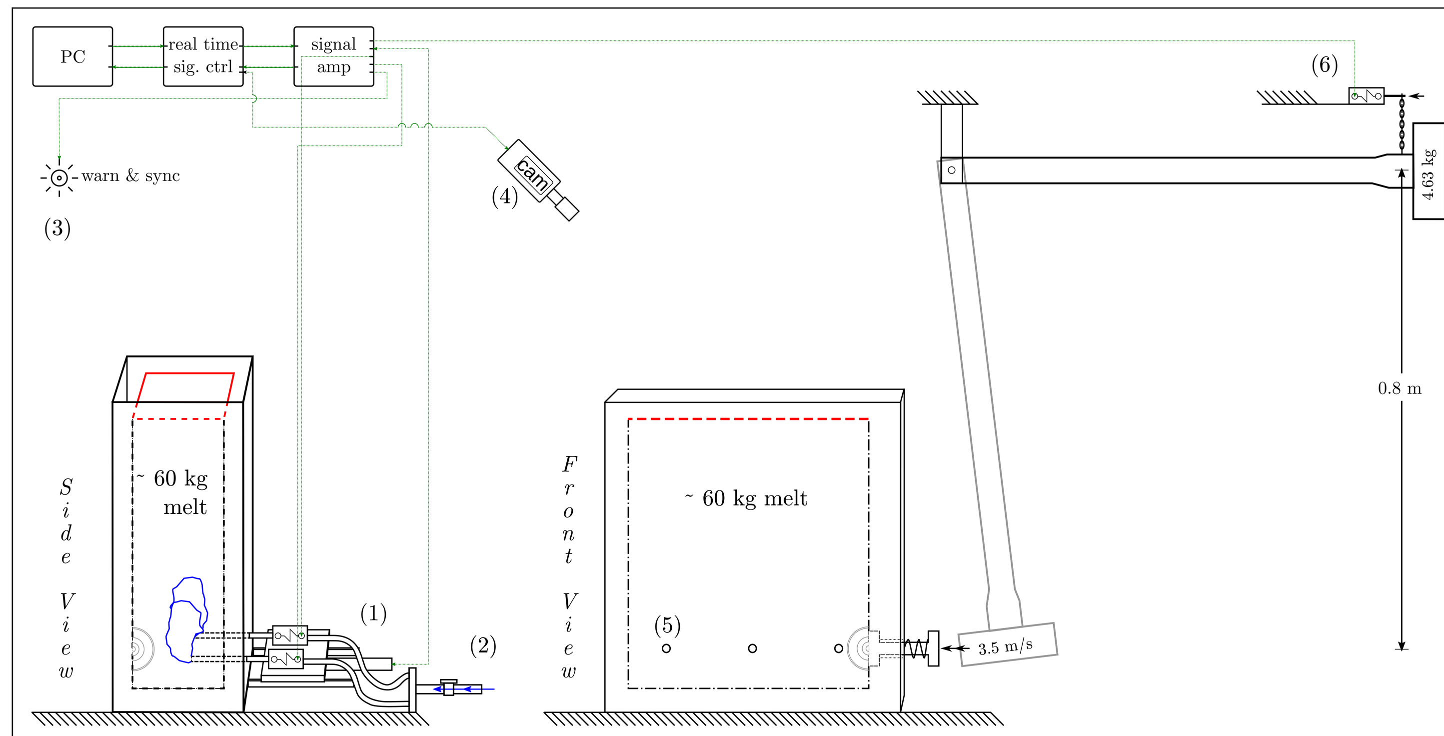

Figure 3: Schematic sketch of the experimental setup. *Left:* Container side view with water injection platform (1) Motorized injection platform consiting of injection tubes, solenoid valves, and linear stepper drive. (2) Supply of pressurized water and transient flow measurement. (3) Synchronizer light source. *Right:* Container front view with hammer based trigger setup. (4) Camera and control electronics. (5) Injection portals in container side wall. (6) Electric hammer release.

CONTROLS & MEASUREMENTS

The parts are remotely controlled and managed by integrated electronics, and a PC. Once the melt is poured, and the container is pulled into locked experiment position, a master timer is started on the controller PC, and the system acts autonomously. The systems latency between a start/stop command and actual action is < 5 ms for the actuated platform and sync light, < 10 ms for the hammer release and target hit, and ~ 100 ms for the solenoid valves. Since the latency is relatively reproducible the oveall timing can be adjusted to better accuracy than the valve latency suggests. Figure 4 shows a typical record of control commands.

Melt temperature is not controlled directly, but measured while in the furnace, and the furnace power can be adjusted. This gives an accuracy of ± 15 K for the initial melt temperature. Pressure of the water supply is controlled by a water pressure tank, that supports operating pressures up to 4 bar. Flow rate is determined from a calibrated dynamic pressure offset measurement.

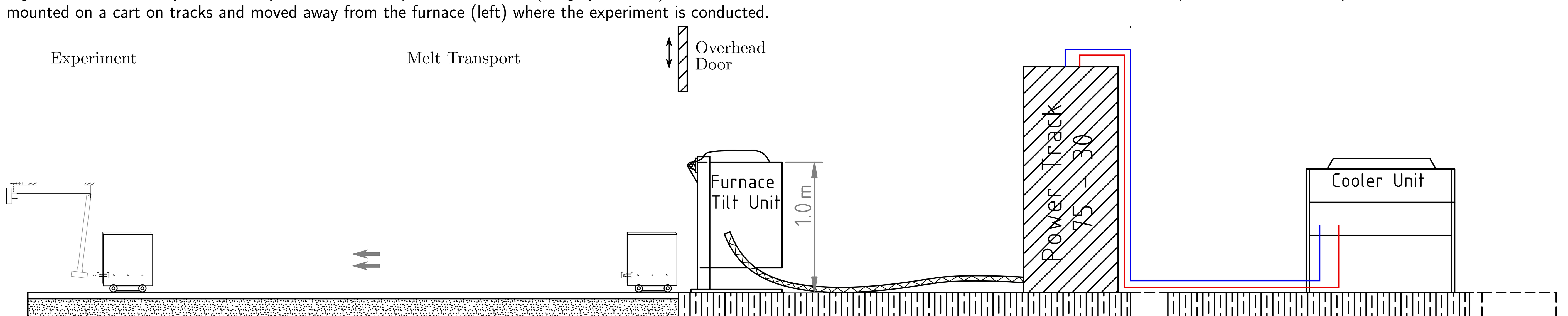

Figure 2: Schematic layout of melt production and experiment location (roughly to scale). Raw material is heated in the induction furnace until molten. For experimentation melt is poured into a container that is mounted on a cart on tracks and moved away from the furnace (left) where the experiment is conducted.

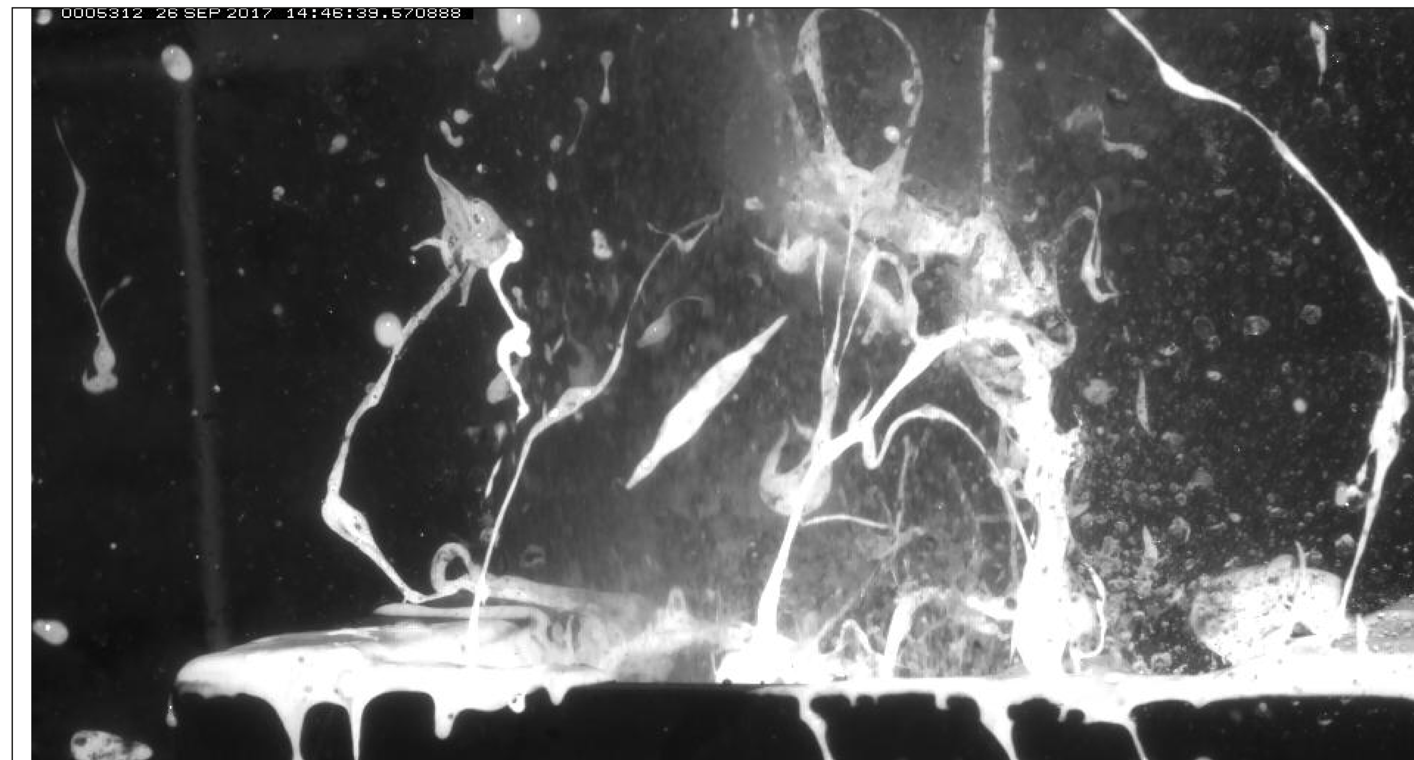

Figure 4: Detailed view of the melt ejection process at the container exit. The melt is partially broken into particles. Other parts are deformed hydrodynamically, and form fluidal shapes, such as Pele's hair. Water leaves the container as a mix of steam jets and liquid water droplets. Some water droplets come (again) in contact with melt. The contact can last several seconds, since film boiling reduces the heat tranfer rate.

FIRST RESULTS

Response Intensity Main focus areas in these initial experiments were the water injection speed, and the relative timing between injection start, and trigger time, as well as particle ejection speeds. For comparison purposes, laboratory scale MFCI experiments were performed at the Würzburg/Germany based Physical Volcanology lab. These experiments reliably produce explosive magma-water interaction using a ~ 10 cm diameter crucible. There the measured repulsion force is used to quantify the processes intensity (explosivity). This is difficult in this larger case setup. This method is very difficult to realize on the meter scale.

Therefore we developed an automated method that determines the *melt surface area* from video material for each recorded frame. This method works, if the observed melt surface is significantly brighter compared to the background brightness. Then the sum over all brightness values in a video frame, the cumulative brightness

$$B = \sum_{i,k=0}^{N_x,N_y} b_{i,k}$$

will increase with an increase of visible melt surface (i,k are the indexes in horizontal and vertical direction, and N_x, N_y are the corresponding total numbers of pixels). Together with the spatial resolution a, cumulative melt brightness B_{melt} (B for a video frame that is completely "covered" with melt), and cumulative background brightness B_0, a projected melt surface area, called 'luminance' L can be derived as (Sonder et al., 2018)

$$L = a^2 N_x N_y \frac{B - B_0}{B_{\mathrm{melt}} - B_0}\quad.$$

L can be used to compare the response of the system to injection of water at various speeds, and trigger (hammer) delays (Figure 5). The measurement is independent of the camera that was used to record it. This way it is possible to compare decimeter- and meter-scale experiments. The time derivative $\dot{L} = dL/dt$ scales with water to magma mass ratio R_m (Figure 6).

Trigger Timing/Spontaneous Response In two experiments significant activity could be observed before the trigger hit the baffle (Figure 5). This may be seen as a hint that at natural scale a magma-water premix could start explosive activity without significant external trigger event. On laboratory scale silicate melt based MFCI experiments have to be triggered with a low energy (~ 5 J) air gun pellet. Similar experiments with metal melts showed spontaneous response (Spitznagel et al., 2013).

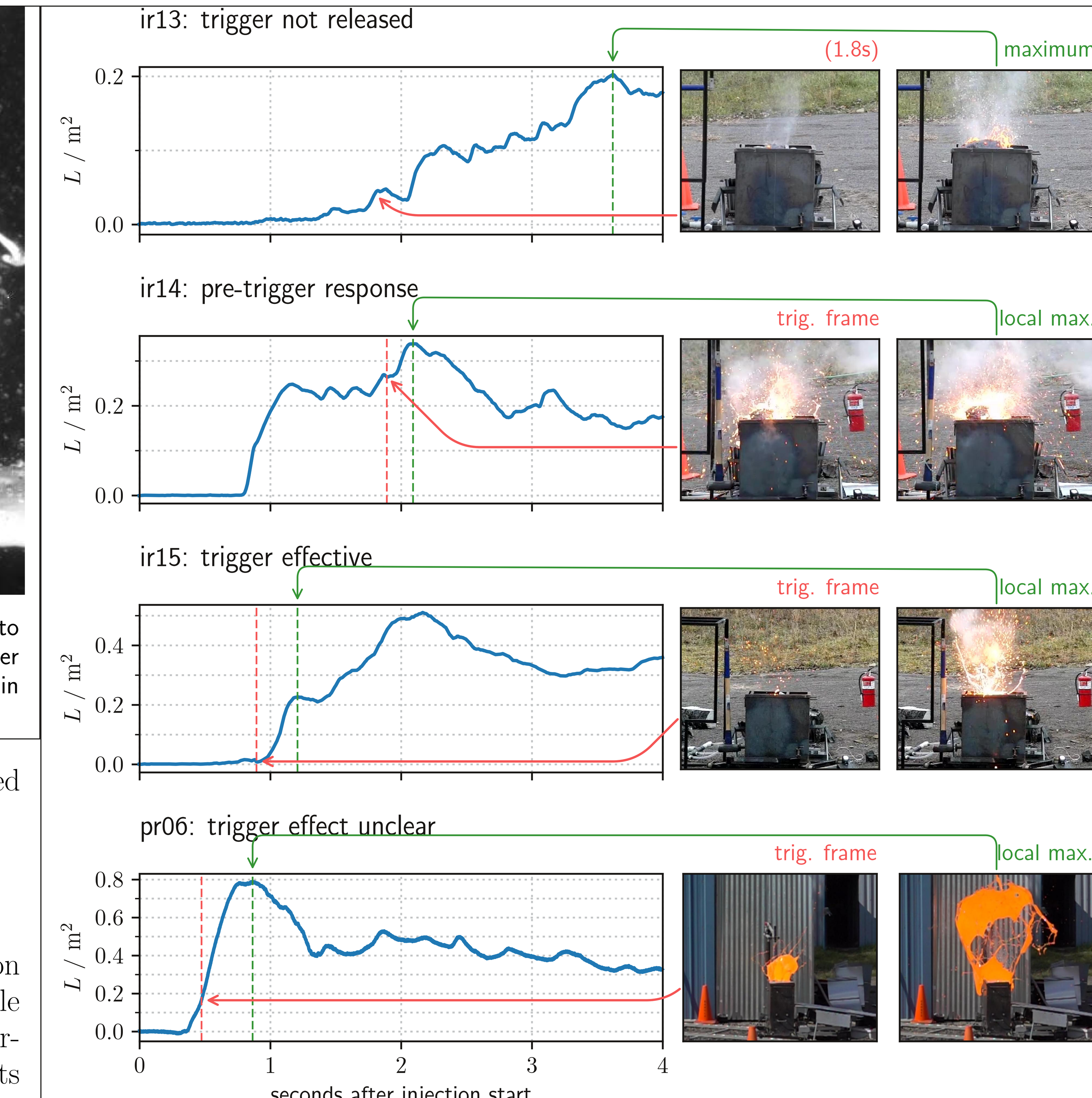

Figure 5: Hammer (trigger) effect on the interaction intensity. At 0 s water started to flow. Red lines mark hammer impact. Green lines mark a local maximum following trigger impact. Response for ir13 is lower compared to the other cases, and starts gradually. The ir14 curve shows a significant response before trigger hit, and a minor increase of L after the hit. ir15 shows a clear response to the trigger event. For pr06 it is unclear if the trigger is effective or not.

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→ This research is supported by the National Science Foundation (project #EAR-1347992), and by the University at Buffalo Research Foundation.

→ The Rock Melting Facility is part of the Geohazards Field Station at University at Buffalo, and is open to external researchers to conduct their own experiments.

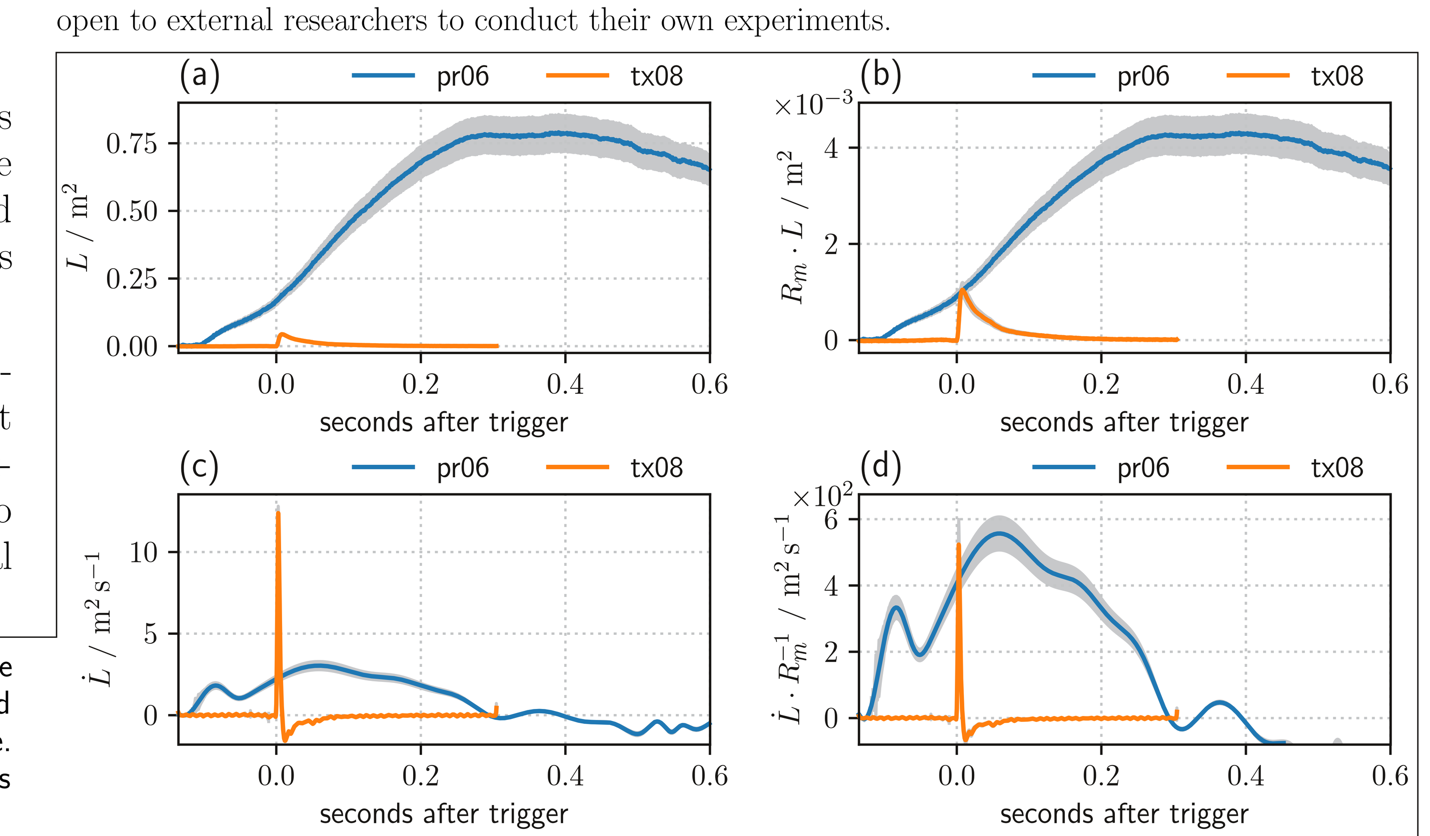

Figure 6: Scaling behavior of melt-water interaction. Lumincance L and it's time derivative $\dot{L} = dL/dt$ are shown for decimeter-scale (orange, tx08) and meter-scale experiments (blue, pr06), as well as versions scaled by the water to melt mass ratio R_m. (a) Absolute values for L indicate the different melt amounts un use. (b) At the current stage the decimeter-scale experiments are more impulsive. While the scaled luminances show differences (b), the scaled time derivatives have similar maximum values (d).