RESEARCH METHODS VOLCANICA

Magma in the microwave

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ABSTRACT

Classroom demonstrations of volcanic processes are typically performed with low-temperature materials designed to exhibit behaviors conceptually analogous to magma. However, there are advantages to finding methods by which *real* magma can be created and used with audiences and students. Here, we describe a method by which magma can be made at home or in a classroom using a standard household microwave. We have tested a particular demonstration of how volatiles such as H_2O exsolve from natural obsidian to form pumice and ash, a direct replica of the volcanic phenomenon that drives eruptions on Earth and other planets. To demonstrate this, we used three obsidian samples—from Mono Craters (U.S.A.), Arteni (Armenia), and Hrafntinnuhryggur (Iceland)—within an off-the-shelf ceramics 'microwave kiln' in both a 700 and 1000 W microwave. We found that millimetric obsidian chips will vesiculate to form pumice-like textures at low microwave power or low initial H_2O content and will fragment safely within the kiln at high microwave power or high initial H_2O content. This can be used to supplement existing well-known demonstrations using low-temperature analogs for magma. The demonstration results in real 'products' that can be examined just as a geologist would examine natural specimens.

KEYWORDS: Outreach; Educational development; Bubbles in magma; Magma dynamics; Experimental science.

1 INTRODUCTION

Classroom demonstrations to simulate volcanic processes are often limited to the use of room-temperature materials that are analogous to magma in terms of their properties or the phenomena they exhibit when used in an experiment. Examples include the use of oils, waxes, syrups, glass beads, and fudge to simulate variably crystallizing flowing lava [Rust et al. 2008; Jones and Ehlers 2021; Poppe et al. 2022], ping-pong balls (or other projectiles) to replicate ejecta during explosive eruptions [Harpp et al. 2005; Wadsworth et al. 2018b], and room-temperature liquids with bubbles to simulate bubbly magma [Smithka et al. 2014], among other applications. Perhaps because of cost, time constraints, safety concerns, and requirement for specialized facilities, it is much less common for demonstrations or classroom activities to involve high-temperature materials such as molten glass or lava/magma itself [Gates 2017; Wadsworth et al. 2022b]. While room-temperature demonstrations are extremely valuable, they involve a level of abstraction for audiences or classrooms to associate them with real magma/lava or natural processes. By contrast, the use of actually molten rocks may provide more immediate pathway to both engagement with, and understanding of, magmatic materials and processes.

Beyond classroom demonstrations, room temperature magma-analog materials are used extensively in laboratories to underpin research-level investigations into magmatic processes [Llewellin et al. 2002; Rust and Manga 2002; James et al. 2006; Namiki and Manga 2008; Kavanagh et al. 2018; Jones et al. 2020; Poppe et al. 2022]. The controllable and chemically stable nature of these oils, waxes, glass beads, and syrups—analog substances—makes them amenable to experimentation at a range of scales and they can be readily combined with solid particles or aerated with bubbles to form almost the full range of magma types and textures, from semi-solid crystalline magmas through to magmatic foams and pumice-like textures. Additionally, the rich body of work detailing the behaviour of suspensions and granular media facilitate theoretical treatment of these analog materials [Carman 1937; Stickel and Powell 2005; Jop et al. 2006; Mader et al. 2013], where the same theory may not yet be available for more complex high-temperature magmas. In turn, this versatility allows dimensional analysis and scaling approaches to be deployed. Such analysis allows natural processes operating over length scales from meters up to tens of meters (e.g. the rise of a Taylor bubble, or 'slug', through a magma-filled conduit [Del Bello et al. 2015]) through to kilometers (e.g. the runout of pyroclastic flows [Lube et al. 2015]) to be scaled down rigorously so that they can be replicated in a laboratory—or a classroom—while still being in the same dynamic physical regime [Kavanagh et al. 2018; Poppe et al. 2022]. However, there are material limits to the efficacy of these scaling approaches, particularly when a specific behaviour or regime cannot be replicated by the chosen material. In volcanology, such scaling challenges typically revolve around thermodynamically mediated micro-processes (such as bubble or crystal growth) and thermal processes (such as cooling or latent heats [cf. Blake and Fink 2000]), which bring with them additional challenges when using the typical recipe book of analog materials.

Here we focus in on the small-scale ways in which bubbles form, grow, and interact in magmatic liquids—silicate melts—which are challenging to replicate without using the real thing. It is common for volcanologists to say that bub-

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bles drive volcanic eruptions [Sparks 1978]—a concept that can be challenging for students first encountering the fact that magma contains dissolved volatiles such as H_2O, CO_2, and minor other species, and that these volatiles will exsolve and form bubbles as magmas decompress during ascent in the crust. Simple analogies are often introduced first, such as the everyday experience of opening a bottle of carbonated soda, beer, or sparkling wine, and observing decompression-driven bubble nucleation and growth [Zhang and Xu 2008]. This is sometimes augmented by the introduction of additional fizzing agents, such as salt or Mentos™ to demonstrate the vigor with which fizzing can occur [Goded Merino et al. 2023], making it somewhat reminiscent of volcanic eruptions. However, these demonstrations only build intuition some of the way to understanding bubble formation in magma. The timescales, rates, viscosities, and texture of bubble phenomena in magma are missed, as is any sense of the effect of temperature on the process [Newcomb 2009]. Further, the products of such 'eruptions' do not solidify, so no 'volcanic rocks' are formed to be handled and studied by the students. This eliminates the link between process and product, which is an important theme for students across all areas of geoscience. For this reason, we present a method by which magma itself can be used, experimented upon, and handled safely, without the need for high-cost specialized equipment. The methods we explore here demonstrate directly the dramatic ways in which the physical properties of magma change in response to dynamic environmental conditions. Our principal aim is to bring real magma to the classroom, with the hope that the awe evoked, and the science communicated, will foster better understanding of magma physics, and volcanic hazards.

2 MAGMA DEGASSING

In order to erupt at the surface, magmas migrate up through the crust, decompressing as they go [Gonnermann and Manga 2013]. The reduction in pressure leads to a drop in volatile stability in the magma [Newman and Lowenstern 2002] so that bubbles form and grow [Gardner et al. 2023]. The formation and growth of bubbles confers buoyancy, feeding back into the magma's rate of ascent [Gonnermann and Manga 2007]. When the rate of ascent and associated bubble growth rates are sufficiently high, the magma can fragment, ripping apart to form pyroclasts [Sparks 1978; Gonnermann 2015; Scheu and Dingwell 2022]. Therefore, even this simple picture of magma ascent shows that it is the formation and growth of bubbles that are central to eruption dynamics.

Magma degassing is the process by which H_2O, CO_2, and other volatiles dissolved in a silicate melt come out of solution. This requires that the melt becomes supersaturated with respect to its dissolved volatile load—i.e. that its dissolved volatile concentration exceeds the saturation value for the current conditions of pressure and temperature—following which bubbles can nucleate and grow [Zhang et al. 2007; Wallace et al. 2015; Sullivan et al. 2026]. In magmatic and volcanic systems, supersaturation may be caused by several processes: decompression [Barclay et al. 1995; Mangan and Sisson 2000], heating [Lavallée et al. 2015; Edmonds et al. 2022], increased volatile concentration induced by crystal growth [Sisson and Bacon 1999; Parmigiani et al. 2014], or shear [Roche et al. 2025]. Conversely, if pressure increases, or temperature drops—all igneous rocks are magmas that cooled eventually—then the reverse process occurs: solubility increases and bubbles shrink as volatiles resorb into the magma, perhaps even resulting in their complete removal [Sparks et al. 1999; McIntosh et al. 2014]. Therefore, the pathway through temperature and pressure space is key to understanding magma degassing.

Demonstrating the control of pressure on saturation and bubble formation in magma is not easily accomplished in the classroom. Working at elevated pressure typically requires specialized equipment and restrictive risk controls. However, the same physical principle can be demonstrated by heating a glassy sample that is supersaturated at atmospheric pressure—a characteristic of almost all natural obsidian. Working at elevated temperature is much easier, and the risks are much more easily controlled. Once a sample is heated above its glass transition temperature and returned to a molten state, the supersaturation triggers nucleation and bubble growth, illustrating the same fundamental processes that occur when melt is taken to supersaturation by any change in its physical or chemical state.

3 MATERIALS

The key to developing a method to produce and use real magma in a classroom setting is to be able to reach magmatic temperatures quickly and safely without the use of specialized, expensive, or complex laboratory equipment. Consequently, we advocate for the use of a so-called 'microwave kiln'.

3.1 Kitchen microwaves and the microwave kiln

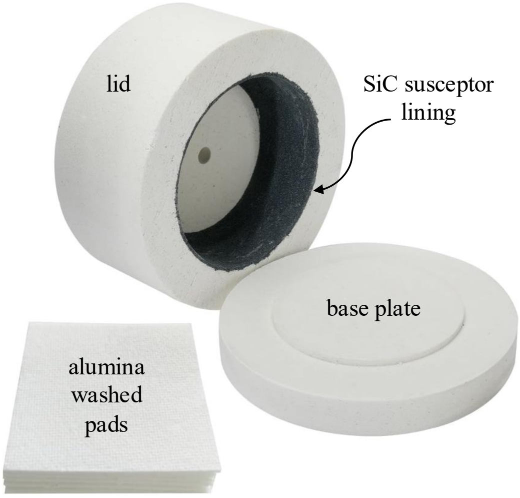

Figure 1: A photograph of the ceramic kiln consisting of a lid with a SiC susceptor lining and a base plate on which the sample sits. We recommend using the alumina-washed pads that often come with the purchase of the kiln to protect the base plate from samples sticking. The hole in the centre of the lid roof is to allow air flow in and out of the kiln.

We propose the use of a microwave and a microwave kiln to run classroom demonstrations at magmatic temperatures (Figure 1). A microwave susceptor kiln [Bhattacharya and Basak 2016; Akinwekomi et al. 2020; Cheng et al. 2024], otherwise known as a hobbyist's microwave kiln, is a product commonly used by amateur arts-and-crafts enthusiasts for glass art, glass fusion, or ceramics projects. A kiln can be purchased from a major online vendor for approximately £25–40 (GBP) in the U.K. in 2018–2025 or for $30–40 (USD) in 2025. It consists of a low-density ceramic 'fibre' lidded chamber lined with a 'susceptor' coating of silicon carbide, typically adhered to the inside of the lid of the chamber, which absorbs radiation in the microwave wavelengths and emits in the infrared, thus heating the sample within [Bhattacharya and Basak 2016]. A single-use alumina-washed pad is placed at the base of the kiln to prevent microwaved magma from fusing to the base of the kiln (a pack of several-hundred alumina-washed pads were included with the purchase of our kilns; they can be purchased separately for approximately £10 (GBP) or $15 (USD) per 100 sheets from a major online vendor). The kiln and sample are loaded into the microwave in the usual way. In Figure 1 we show a commercial photograph of one of these susceptor-based microwave kilns.

In our development of the method, we tested 700 W and 1000 W household (kitchen) microwaves. We used a Galanz Retro Countertop Microwave Oven (700 W) and a Toshiba EM131A5C-BC Countertop Microwave Oven (1000 W). Note that the 700 W model used here was several years old and acquired for free following a kitchen renovation; any microwave should do the trick. After a few minutes of heating, an incandescent red glow is visible through the vent hole at the top of the kiln. The susceptor lining makes it possible to achieve internal temperatures in the kiln >900 °C. This temperature is an estimate based on the vesiculation of obsidian in our tests (introduced later), which generally requires temperatures at least that high [Coumans et al. 2020]. Following a 14-minute run in a 1000 W microwave, we inserted a k-type thermocouple through the vent hole and measured a temperature of 850 °C. This measurement was made a few seconds after the microwave stopped running and so is not the peak temperature.

Heat-resistant gloves and a heat-resistant surface will be necessary for safely handling the microwave susceptor kiln in a time-efficient manner at the conclusion of the demonstration. Specifically, gloves should be selected that are rated to temperatures in excess of 1000 °C: these are available from many laboratory suppliers. The laboratory surface needed does not need to be resistant to those same temperatures since the base of the kiln (though not the top or interior) is typically cool after removal from the microwave oven, but surfaces such as stone countertops are ideal. We recommend the use of eye protection in the unlikely event that a vesiculated sample undergoes explosive fragmentation after the kiln lid is removed (a protective screen to shield the audience may also be prudent). Metal tweezers or forceps are useful for transferring samples off the hot kiln base. Removal of the kiln and sample should only be done by the instructor or other responsible person in the classroom. When opening the kiln, extreme care should be used, and appropriate safety screens to protect the audience/students may be needed (note that hot rocks can explode unpredictably). We encourage any user of this technique to undertake a risk assessment that is consistent with their institution's policies on health, safety, and best practice in laboratories and teaching environments.

3.2 Starting material for making magma: obsidian

Any natural obsidian should be appropriate for use in the 'magma in the microwave' demonstration. If natural obsidian cannot be obtained from field localities directly (subject to sampling regulations and/or permission from landowners) then obsidian specimens specifically for scientific purposes can be obtained inexpensively from laboratory suppliers (e.g. 'Wards Science Essentials Obsidian'*).

The processes replicated here involve degassing of dissolved H_2O from the obsidian glass into nucleated bubbles. The rate of that process, and therefore the timescales involved, depend to some extent on the initial H_2O concentration in the obsidian. We note that obsidian in nature has a range of dissolved H_2O concentrations; in Figure 2 we demonstrate this via a compilation of published data ($n = 161$) from published sources [Taylor et al. 1983; Newman et al. 1988; Tuffen et al. 2008; Tuffen and Castro 2009; Castro et al. 2012; Owen et al. 2012; Barnes et al. 2014; Castro et al. 2014; Wadsworth et al. 2022a]. The arithmetic mean of this compilation is 0.34 ± 0.02 wt.% (Figure 2). The low-end of dissolved H_2O concentrations match published bubble formation-and-growth experiments [Coumans et al. 2020], and we can be

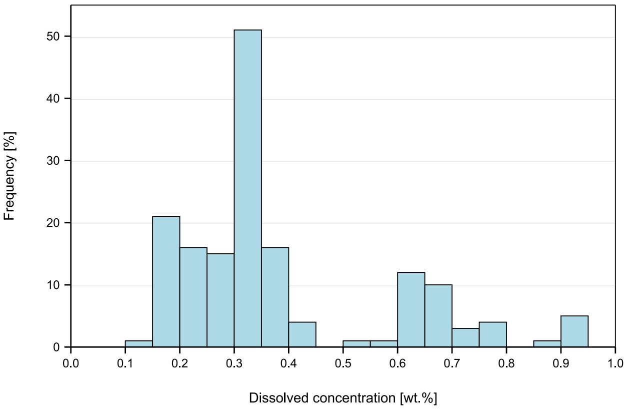

Figure 2: The distribution of the dissolved concentration of total H_2O (in wt.%) in effusively erupted obsidian (i.e. not including pyroclastic obsidian) ($n = 161$), compiled from published sources [Taylor et al. 1983; Newman et al. 1988; Tuffen et al. 2008; Tuffen and Castro 2009; Castro et al. 2012; Owen et al. 2012; Barnes et al. 2014; Castro et al. 2014; Wadsworth et al. 2022a]. The arithmetic mean is 0.34 ± 0.02 wt.%, and the histogram bin size is 0.05 wt.%. We note that the highest H_2O tested here is approximately 0.5 wt.% (see text), and, as such, we cannot attest to the behaviour during heating of obsidian with higher H_2O concentrations up to 0.9–1.0 wt.% that are represented in this figure. For this reason, we urge caution and pre-testing of any obsidian with unknown H_2O concentrations.

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*Available from `https://dabos.com/`.

Table 1: A matrix of experimental tests performed using the microwave kiln.

	Obsidian source		
	Mono Craters, U.S.A. [Gardner et al. 2017]	Arteni, Armenia [Aghamalyan et al. 2019]	Hrafntinnuhryggur, Iceland [Tuffen and Castro 2009; Foster et al. 2024]
H_2O content (wt %, approximate)	0.5	0.2	0.1
	Experimental times in minutes		
Time to vesiculation (700 W)	8.5	25	n/a
Time to vesiculation (1000 W)	5.5	15	20
Time to fragmentation (700 W)	9	n/a	n/a
Time to fragmentation (1000 W)	6	n/a	n/a

relatively sure that the bubble formation and growth in the microwave kiln will be slow and gentle. By contrast, rapidly heating H_2O-rich obsidian (0.8–1.0 wt.% H_2O; the high-end in Figure 2) can result in such vigorous bubble growth that fragmentation—explosive destruction of the sample—occurs [Forte and Castro 2019; Browning et al. 2020], so this should be considered when selecting an obsidian to use. For the purposes of the demonstrations explored herein, we choose obsidian from three locations: (1) from Hrafntinnuhryggur, Krafla, Iceland, with ~ 0.11–0.14 wt.% H_2O [Tuffen and Castro 2009; Wadsworth et al. 2019; Coumans et al. 2020; Seropian et al. 2022; Weaver et al. 2022], (2) from the 1325–1350$_{\text{CE}}$ North Mono explosive eruption of Mono Craters, U.S.A., with ~0.49 wt.% H_2O [Gardner et al. 2017], and (3) from Arteni, Armenia, with 0.22 wt.% H_2O concentration [Chataigner and Gratuze 2013; Aghamalyan et al. 2019].

4 TURNING OBSIDIAN INTO PUMICE

The exercise proposed here is one in which obsidian pieces can be turned into a vesicular ('bubbly') material that resembles pumice. In order to achieve this, a piece of obsidian (sub-centimetric chips work well) should be placed on the base plate of the microwave kiln, ideally sitting on top of an alumina-washed pad. Reasonable caution should be exercized if producing obsidian pieces for this experiment using a rock hammer or similar. The lid of the microwave kiln is placed on top of the base on which the obsidian is sitting and the whole lid-plus-base assembly is then loaded into a microwave (the kilns are designed to fit into a standard kitchen microwave). In Figure 3 we show the recommended workflow. Then, depending on the power of the microwave and the type of obsidian, the instructor would pick a power (e.g. full power) and a cooking duration. In our testing, we used the 700 W microwave at full power for 8–8.5 minutes for relatively high-H_2O Mono Craters obsidian chips, which was sufficient to produce the pumice-like texture; 25 minutes in the 700 W microwave was required to vesiculate the lower-H_2O Arteni obsidian. The Hrafntinnuhryggur obsidian chip did not produce vesicles in that time (Figure 4) in the 700 W microwave; we were successful after 20 minutes at full power in a 1000 W microwave (Figure 4). For this reason, we highly recommend that instructors perform tests ahead of deploying this with audiences and we provide Table 1 as a guide matrix designed to act as a starting point (but not as a substitute for instructor testing). Once cooked, the kiln should be left to cool for several minutes, ideally with the microwave door open, before the instructor carefully extracts the kiln, removes the lid, and reveals the result (Figure 3).

4.1 Use as a general demonstration

It is not possible to directly observe the cooking of the obsidian (the kiln is opaque and sealed inside the microwave while cooking), so we recommend that the instructor uses the cooking time to discuss with the audience the processes that are occurring during the cooking process. Typically, incandescence is seen after around 10 minutes (using the 1000 W microwave) through the air escape hole at the top of the kiln, which persists during cooling. Here we do not specify what those topics might include or how an instructor might run the demonstration session in detail, except to point out that any links between H_2O dissolved within magmas and the bubbles that drive eruptions [Verhoogen 1951; Sparks 1978; Gardner et al. 2023] could be good conceptual links to make before revealing the direct evidence for H_2O exsolution and bubble growth that will be preserved in the pumice-like material that is produced by the microwave technique. Using a document camera or video projector can be an excellent way to demonstrate the before-and-after details of the materials produced, which is especially useful when dealing with very large audiences. In our experience the vesiculated 'pumice' produced floats in water—dropping a piece of the starting obsidian and a piece of the (cooled) pumice into a glass of water therefore provides a direct and easily understood demonstration of the transformation that has occurred.

4.2 Blowtorches and laboratory furnaces

Another way to produce vesicles in obsidian is to heat a chip with a blow torch. Standard butane torches can achieve the effect (Figure 5), but a Methylacetylene-Propadiene Propane (MAPP) gas torch is more effective, if available. The edges of obsidian chips can froth up by exposing them to the flame of one of these torch types (compare Figure 5B with Figure 5C). This can be a useful secondary demonstration, which we have used while the main obsidian chip is 'cooking' in the

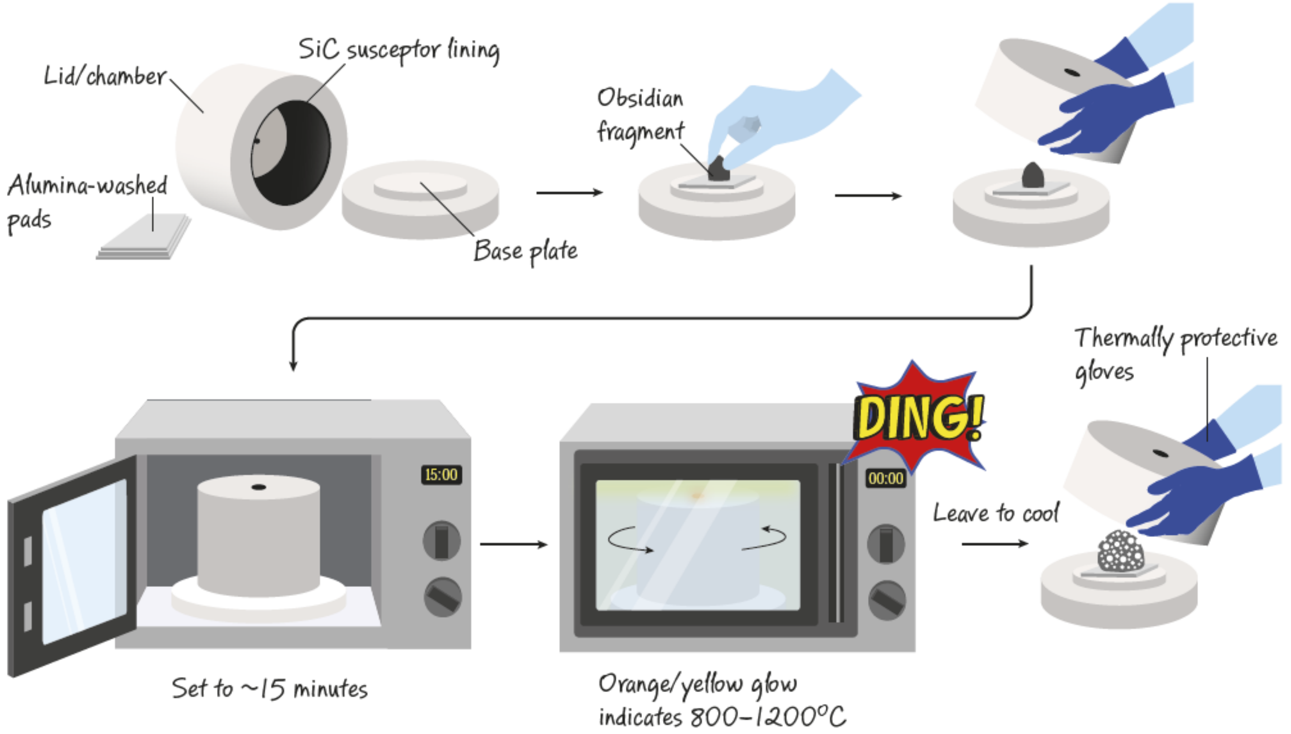

Figure 3: A schematic workflow of the use of the microwave kiln to turn obsidian into pumice by (1) heating the sample via microwave absorption and infrared emission from the SiC susceptor lining, (2) the temperature-induced reduction in H_2O solubility in the obsidian, and (3) degassing of obsidian forming bubbles, preserved as vesicles in the final material.

microwave kiln. The use of two contrasting methods can facilitate lively discussion. The use of a torch can also be more 'live' in nature because the process can be captured with a projection camera, allowing the audience to see the vesiculation directly. Care must be taken because some chips of obsidian can crack or explode when exposed to torch flames—the use of safety goggles and/or a screen to protect an audience is recommended.

We additionally compared these methods with the result when a piece of obsidian is touched to a plate that was pre-heated to 1200 °C (Figure 5D). We note that this method does require some specialized equipment to pre-heat the plate (a laboratory furnace), but we find it informative to compare with the other non-specialized methodologies for producing bubbles in obsidian described here. We also note that the example in Figure 5D utilizes a synthetically hydrated obsidian, a process that also requires specialized laboratory equipment [Gardner and Ketcham 2011]. The same result could be obtained using natural obsidian.

4.3 Developing teaching exercises around this demonstration

If this microwave technique is deployed for teaching purposes, an instructor might remind an audience that the amount of dissolved H_2O in obsidian (Figure 2) is generally much lower than the amount dissolved in magmas that are stored at several kilometers depth in the Earth's crust, which can exceed 4 wt.% [Humphreys et al. 2008; Popa et al. 2021]. Therefore, it might be considered surprising that relatively small amounts of remnant H_2O left over in obsidian are sufficient to produce such vesiculation as observed with the microwave. A simple calculation that can be deployed alongside the demonstration is a computation of the vesicularity ϕ expected from exsolving a certain amount of H_2O. This calculation is [Wadsworth et al. 2020]:

$$\phi = \frac{\rho \Delta C}{100\rho_g + \rho \Delta C}, \tag{1}$$

where ΔC is the change in H_2O concentration from an initial value to the final value (in wt.%), ρ is the obsidian melt density, and ρ_g is the gas density. The value 100 is involved in the conversion from wt.% to a weight fraction of H_2O. Using this equation and assuming $\rho = 2300$ kg m^{-1} and $\rho_g = 1$ kg m^{-1}, we can see that a decrease of just $\Delta C = 0.1$ wt.% can result in $\phi = 0.7$ or 70 % vesicularity. Put another way, this calculation confirms that even a tiny release of dissolved water from the molten sample can causes extreme vesiculation, if sufficient time is available for the bubbles to nucleate and grow to equilibrium at a pressure of one atmosphere (see Figure 2 for a range of possible ΔC values found in nature that could be used in this calculation).

The calculation in Equation 1 leads naturally to discussions around what causes the change in H_2O concentration ΔC, the answer to which demands discussion of solubility of H_2O in silicate melts [Newman and Lowenstern 2002; Liu et al. 2005]. Similarly, the realization that large ΔC values would predict $\phi = 0.98$ or 98 % vesicularity (e.g. if you take $\Delta C = 4$ wt.%)

Figure 4: Photographs of obsidian chips before and after heating in the microwave kiln. Before heating, we used obsidian chips from [A] Mono Craters (U.S.A.), [B] Arteni (Armenia), and [C] Hrafntinnuhryggur (Iceland). Examples of these chips after heating appear in panels [D], [E], and [F]; note that the Hrafntinnuhryggur obsidian in [F] did not foam up because at 700 W for 15 minutes, the temperature and time were insufficient to promote bubble growth for the low H_2O concentration in this obsidian. In [G] and [H] we show an example of the Hrafntinnuhryggur obsidian that was held for longer (20 minutes) before and after, where [H] is the same pumice product as in [G] but seen from a different angle. The scale bar in [C] applies to [A] and [B].

leads to a discussion as to why natural pumice does not in fact always have those very high values [Klug and Cashman 1996; Mueller et al. 2005], which can very quickly get to the heart of modern ideas of volcanic processes in conduits, including the roles played by permeable outgassing during degassing [Eichelberger et al. 1986; Jaupart and Allègre 1991], disequilibrium degassing [Mangan and Sisson 2000; Iacono Marziano et al. 2007; Watkins et al. 2017; Coumans et al. 2020], and fragmentation and re-sintering [Rust et al. 2004; Wadsworth et al. 2020; Ellis et al. 2023; Weaver et al. 2023]. Therefore, we propose that the microwave kiln demonstration could be used in conjunction with simple calculations to engage students at a range of levels with one of the grand challenges of modern volcanology—understanding degassing, outgassing, and explosivity of magmas. Importantly, we propose that by using real obsidian, instead of low-temperature analogs for magma, learners can more easily access and appreciate these topics in the classroom.

5 DISCUSSION AND CONCLUSIONS

Magma is a multiphase fluid in which bubbles and crystals grow dynamically. Without specialized equipment, this dynamism is not easy to convey to an audience or in a teaching laboratory setting. The result is that students of the geosciences do not always get a visceral or experiential exposure to the timescales and materiality of magmatic processes; in-

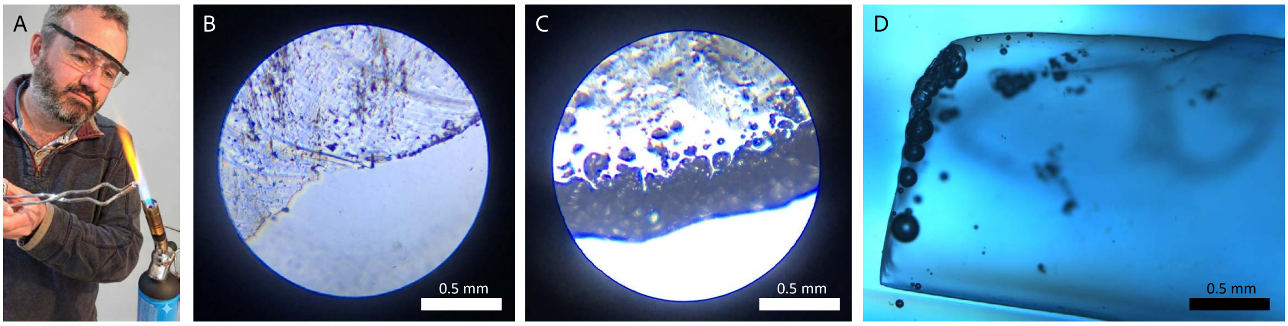

Figure 5: An additional exercise to go along with the microwave kiln experiments proposed here is to use a blow torch to heat obsidian chips—technique shown in [A]. [B] A photomicrograph of the edge of the obsidian chip before heating (top left of the image is obsidian glass). [C] The same obsidian edge after heating with the blow torch, showing bubbles which appear as dark/black outlines overlapping up to the edge of the glass. [D] A few spherical bubbles at the edge of a rectangular piece of hydrated obsidian (synthetically produced in a laboratory) after being placed in contact with a hot metal plate heated to 1200 °C. The contact time was 20 seconds. Photographed in [A] is E. Llewellin performing material tests with F. Wadsworth in 2019; an A.I. tool was used to remove the background of this image.

stead they are asked to take abstract imaginative steps in connecting observed petrographic textures in rocks with a complex sequence of physical processes that occur in nature. The ability to make magma and pyroclastic materials in a standard household microwave creates an engaging, exciting, thought-provoking opportunity to introduce non-specialists to volcanoes, volcanic products, volcanic hazards, and experimental volcanology. We are providing a method by which students can see and experience the changes in magmas in near real-time, cementing the more conceptual learning that is the mainstay of petrology and volcanology classes. The scalability of this activity—from a quick show-and-tell demonstration, to the seeds of a hypothesis-driven class project—is rich with potential.

5.1 Deployment of the microwave demonstration in real demonstrations

As part of preparing this article, we deployed the microwave kiln techniques described in several teaching settings. First, we used the demonstration in the context of a public lecture (delivered by E. Llewellin at Durham University in 2018) with a focus on the phenomenology of bubble formation in magmas at high temperatures. Second, we used the demonstration in the context of a research-level workshop (delivered by T. Carley and D. Sahagian jointly at Lafayette College and Lehigh University in 2025) with a focus on the demonstration that even obsidian with low dissolved H_2O concentrations can produce prodigious bubble nucleation and growth. Finally, we used the demonstration during an end-of-term science open house (delivered by T. Carley in 2025) where the focus was the striking change in color, density, and texture in these volcanic materials for an unsuspecting audience of undergraduate students and faculty from a diversity of academic backgrounds. In all cases, the audience feedback was positive, with excited discussions about how the kiln could be used differently or how hypotheses could be tested with the kiln process. As this demonstration is used more in the future, rigorous metrics could be applied to quantitatively test the impact on student learning.

Our experiences with using the microwave kiln to produce bubbly magma—synthetic pumice—from obsidian have been effective for general and specialist audiences. However, to elevate the demonstration to a classroom and to embed it with learning outcomes is a different matter. For those purposes, it would be particularly effective to combine these demonstrations with worked examples of mathematical models that recreate the same process quantitatively. An example might be to use downloadable and open-source codes for vesiculation processes in magmas [Coumans et al. 2020; Sullivan et al. 2026] or analytical models that do not require code to run [Barclay et al. 1995; Browning et al. 2020]. In turn, this provides opportunities for classroom explorations of scaling and discussions of uncertainties when experiments are compared with predictions. Because each use case will be different, we leave the details of how the demonstration is deployed in classrooms to instructor professionals. At its core, this proposed teaching package is about bringing the dynamic and experiential to petrological and volcanological classrooms at minimal added cost to course directors.

5.2 Potential use of the microwave kiln as a laboratory tool

Here we have focussed on the use of the microwave kiln as a teaching or demonstration tool only. The off-the-shelf versions of microwave kilns do not have an immediately obvious way to ascertain the temperature within the kiln atmosphere during an experiment. Any use of in-run thermocouples would present difficulties during active operation of most microwave mechanisms [Wang et al. 2012]. However, the temperature in these kilns reaches a steady state if the microwave is run for sufficient time [Bhattacharya and Basak 2016], and heat loss is slow in the insulated environment after the kiln is removed from the microwave if the lid remains in place, so there is the possibility of calibrating that isothermal temperature for a given microwave setting, power, and kiln size/construction. With that in mind, we can conceive of use cases of the microwave kiln in research laboratory settings. For example, for synthesis of magmatically relevant glasses [Jochum et al. 2000] for a low-cost method of exploring experimental volcanology and petrology [Dingwell 2024].

5.3 Extensions of the microwave kiln to produce magmatic fragmentation

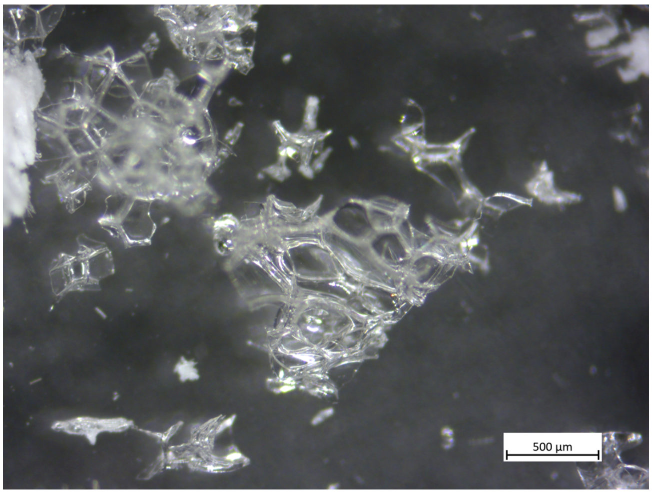

Figure 6: An example of explosive fragmentation that occurred using the Mono Craters (U.S.A.) obsidian. This is deemed safe because it occurs within the confines of the closed microwave kiln. Note the bubbly nature of the fragments produced.

When water-rich obsidian is used in the microwave kiln, it can actively fragment. In Figure 6 we show an example of this found when experimenting with the Mono Craters (U.S.A.) obsidian, which has an especially high initial H_2O concentration [Gardner et al. 2017] and fragmented after 9 minutes in a 700 W microwave and 5-6 minutes in a 1000 W microwave. If carefully deployed with safety in mind, this could be a very exciting demonstration of yet another process that is central to volcanology and our understanding of volcanic eruptions: magma fragmentation during explosive, ash-producing eruptions [Gonnermann 2015]. The fact that the remnant fragments from a fragmentation experiment in the microwave kiln are themselves vesicular (Figure 6), points to the process that operates in natural magma fragmentation—namely viscoelastic failure of bubble walls to produce ash and other pyroclasts [Verhoogen 1951; Gonnermann 2015]. In fact, in the test we performed that resulted in fragmentation, the shards left behind look very similar to many volcanic ash fragments [Heiken 1972]. This could be another extension to the exercises available using a microwave kiln with audiences and classrooms.

6 OUTLOOK

The use of room-temperature analogs for magmas is essential and has and will continue to yield important insights into magmatic processes. However, the use of high temperature materials, including creating magma itself in front of audiences, can have a profound effect in terms of imparting a visceral and direct understanding of the timescales and forces involved in magmatic processes. We propose that the microwave kiln could have a role in volcanology education and outreach alongside the classic classroom demonstrations of volcanic eruptions and that this demonstration lends itself easily and naturally to quantitative discussions/lessons/exercises. By observing the formation of magma and the processes of magma vesiculation that drives volcanic eruptions, students can step into 'Vulcan's forge' [Wadsworth et al. 2018a] and safely experience the excitement of volcanoes in action! Crucially, by making magma in the microwave, students can connect a conceptual process to a real end-result sample that they can then inspect and analyse, which is a core skill in geoscience.

AUTHOR CONTRIBUTIONS

The study was conceived by F. Wadsworth and E. Llewellin. T. Carley further developed the methodology and performed the test experiments that appear here. A. Foster assisted with presentation. P. Sullivan provided insights into bubble dynamics in magma. J. Gardner and D. Sahagian provided some of the obsidian used herein. All authors wrote and contributed to the manuscript.

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DATA AVAILABILITY

All data are provided in the manuscript.

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